Investigation of the Performance of the New Orleans Flood Protection Systems in Hurricane Katrina on August 29, 2005

Volume I: Main Text and Executive Summary

by

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Report No. UCB/CCRM – 06/01
May 22, 2006

DRAFT FINAL REPORT

This project was supported, in part, by the National Science Foundation
under Grants No. CMS-0413327 and CMS-0611632.
Any opinions, findings, and conclusions
or recommendations expressed in this report are those of the author(s)
and do not necessarily reflect the views of the Foundation.

This report contains the observations and findings of an investigation by an independent team of professional engineers and researchers with a wide array of expertise. The materials contained herein are the observations and professional opinions of these individuals, and do not necessarily reflect the opinions or endorsement of any other group or agency.

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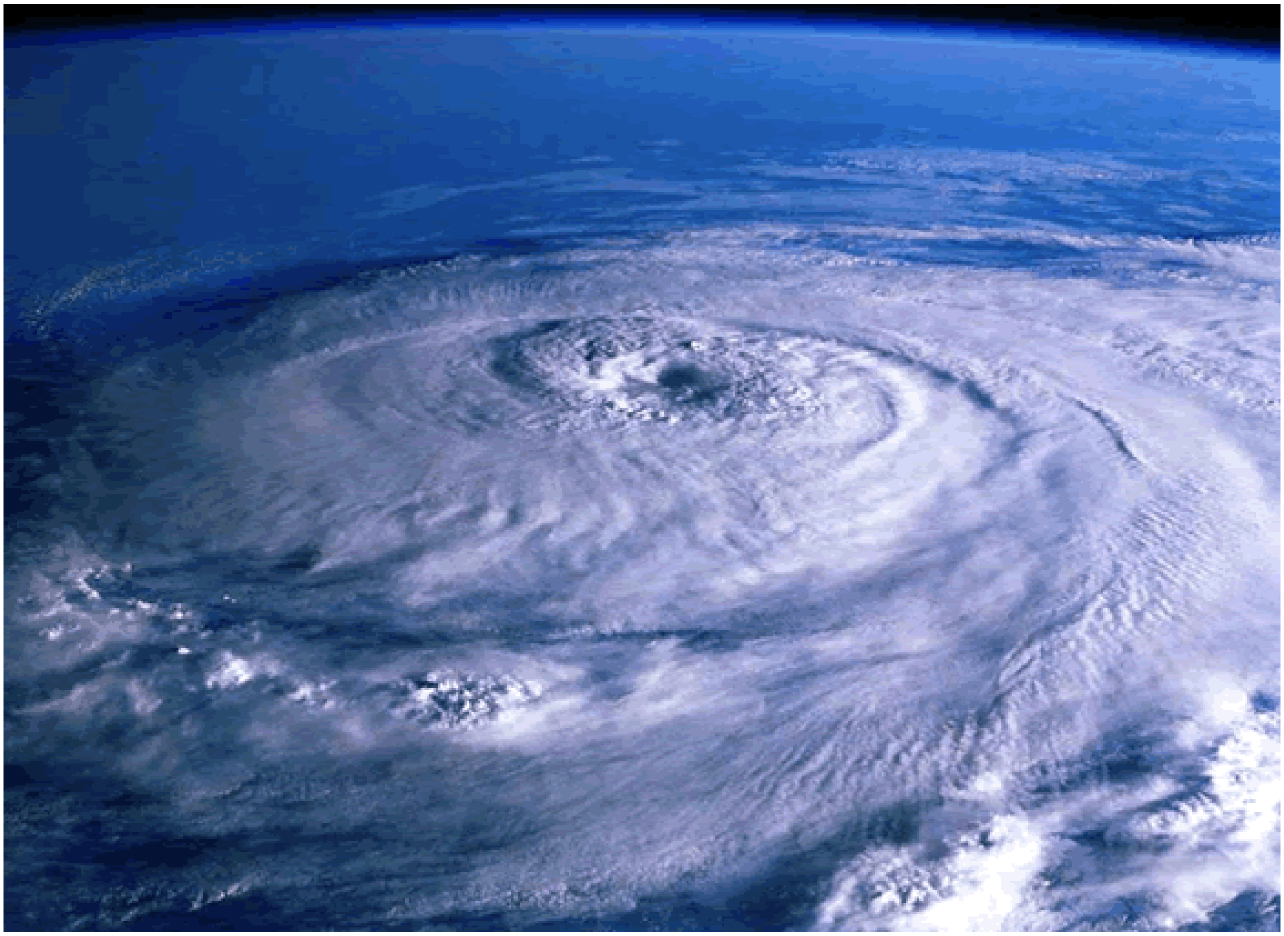

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This report is dedicated to the people of the greater New Orleans region;
to those that perished, to those that lost friends and loved ones,
and to those that lost their homes, their businesses, their place of work,
and their community.

New Orleans has now been flooded by hurricanes six times
over the past century; in 1915, 1940, 1947, 1965, 1969 and 2005.

It must be our goal that it not be allowed to happen again.

DRAFT FINAL REPORT

This report is a Draft Final Report. The original intent had been to issue the Final Report before the end of May; a timing designed to make the data, studies and findings available in a timely manner for the many governmental bodies, agencies, groups and even individuals in need of the insights provided.

As these studies have proceeded, it became increasingly clear just how large and complex this catastrophic event was, and how many details played pivotal roles in the events as they unfolded. Our investigation team has not yet managed to complete our internal review process to our full satisfaction, and this Draft Final Report is an interim product likely to change a bit as it moves towards finalization. The Final Report is now targeted for the end of June, 2006.

The USACE's IPET investigation are similarly working to get the full measure of this event and its ramifications, and they are now planning to issue a Draft Final Report on June 1, 2006, and to finalize their review processes and issue a Final Report in September of 2006. The third principal investigation team, Team Louisiana, had initially targeted a nominal May 1 report date, and are also working to get their report issued as soon as possible.

It is important to make every effort to get the details right.

It is also important to get the gist of the results and findings to date into the hands of the USACE, the IPET investigation team, Federal government bodies in Washington, and State and local government bodies and agencies in Louisiana and New Orleans, as these all wrestle with the ongoing emergency and interim repair and reconstruction, with understanding of what happened and what must now be done, and with the beginnings of development of longer term plans for continuing to move forward. The people of the devastated region also have an urgent need to know and understand what happened as they now face important personal decisions regarding whether or not to return to New Orleans to reinvest and rebuild their lives.

The results and findings of our study are now more than 95% complete. Minor revisions can be expected as we continue to review and sift through details, and a few additional sections not yet ready for dissemination will be added to produce the Final Report by the end of June. Major revisions of the principal findings contained herein are not expected, and it is judged that the information, data and findings of this current Draft Final Report are of sufficient accuracy, and sufficient urgency and value to ongoing decisions and efforts, that it would be a disservice to withhold these for an additional month while the remaining sections are completed.

Sections still to come will include comments and observations regarding the interim repair and reconstruction efforts, and a number of more technical nuances that will complete the treatment of some of the studies and analyses to our team's full technical and professional satisfaction. Some additional data has been delayed and is continuing to arrive, and we have not yet been able to access two important sites to obtain samples of the reconstruction works as these works are still urgently in progress in preparation for the June 1 start of the next hurricane season as we do not want to impede those important efforts.

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EXECUTIVE SUMMARY

This report presents the results of an investigation of the performance of the New Orleans regional flood protection system during and after Hurricane Katrina, which struck the New Orleans region on August 29, 2005. This event resulted in the single most costly catastrophic failure of an engineered system in history. Current damage estimates at the time of this writing are on the order of $100 to $150 billion in the greater New Orleans area, and the official death count in New Orleans and southern Louisiana at the time of this writing stands at 1,293, with an additional 306 deaths in nearby southern Mississippi. An additional approximately 400 people are currently still listed as "missing"; it is expected that some of these missing were temporarily lost in the shuffle of the regional evacuation, but some of these are expected to have been carried out into the swamps and the Gulf of Mexico by the storm's floodwaters, and some are expected to be recovered in the ongoing sifting through the debris of wrecked homes and businesses, so the current overall regional death count of 1,599 is expected to continue to rise a bit further. More than 450,000 people were initially displaced by this catastrophe, and at the time of this writing more than 200,000 residents of the greater New Orleans metropolitan area continue to be displaced from their homes by the floodwater damages from this storm event.

This investigation has targeted three main questions as follow: (1) What happened?, (2) Why?, and (3) What types of changes are necessary to prevent recurrence of a disaster of this scale again in the future?

To address these questions, this investigation has involved: (1) an initial field reconnaissance, forensic study and data gathering effort performed quickly after the arrival of Hurricanes Katrina (August 29, 2005) and Rita (September 24, 2005), (2) a review of the history of the regional flood protection system and its development, (3) a review of the challenging regional geology, (4) detailed studies of the events during Hurricanes Katrina and Rita, as well as the causes and mechanisms of the principal failures, (4) studies of the organizational and institutional issues affecting the performance of the flood protection system, (5) observations regarding the emergency repair and ongoing interim levee reconstruction efforts, and (6) development of findings and preliminary recommendations regarding changes that appear warranted in order to prevent recurrence of this type of catastrophe in the future.

In the end, it is concluded that many things went wrong with the New Orleans flood protection system during Hurricane Katrina, and that the resulting catastrophe had it roots in three main causes: (1) a major natural disaster (the Hurricane itself), (2) the poor performance of the flood protection system, due to localized engineering failures, questionable judgements, errors, etc. involved in the detailed design, construction, operation and maintenance of the system, and (3) more global "organizational" and institutional problems associated with the governmental and local organizations responsible for the design, construction, operation, maintenance and funding of the overall flood protection system.

After eight months of detailed study, a much clearer picture has now emerged regarding the causes and mechanisms of this catastrophe. Many of the findings of this study represent a different view of key elements of this event than has been publicly presented to date.

Hurricane Katrina was a large hurricane, and its arrival at New Orleans represented the root cause of a natural disaster. This disaster grew to a full blown catastrophe, however, principally due to the massive and repeated failure of the regional flood protection system and the consequent flooding of approximately 85% of the greater metropolitan area of New Orleans.

As Hurricane Katrina initially approached the coast, the resulting storm surge and waves rose over the levees protecting much of a narrow strip of land on both sides of the lower Mississippi River extending from the southern edge of New Orleans to the Gulf of Mexico. Most of this narrow protected zone, Plaquemines Parish, was massively inundated by the waters of the Gulf.

The eye of the storm next proceeded to the north, on a path that would take it just slightly to the east of New Orleans.

Hurricane Katrina has been widely reported to have overwhelmed the eastern side of the New Orleans flood protection system with storm surge and wave loading that exceeded the levels used for design of the system in that area. That is a true statement, but it is also an incomplete view. The storm surge and wave loading at the eastern flank of the New Orleans flood protection system was not vastly greater than design levels, and the carnage that resulted owed much to the inadequacies of the system as it existed at the time of Katrina's arrival. Some overtopping of levees along the eastern flank of the system (along the northeastern frontage of the St. Bernard and Ninth Ward protected basin, and at the southeast corner of the New Orleans East protected basin), and also in central areas (along the GIWW channel and the IHNC channel) was inevitable given the design levels authorized by Congress and the surge levels produced in these areas by the actual storm. It does not follow, however, that this overtopping had to result in catastrophic failures and breaching of major portions of the levees protecting these areas, nor the ensuing catastrophic flooding of these populous areas.

The northeast flank of the St. Bernard/Ninth Ward basin's protecting "ring" of levees and floodwalls was incomplete at the time of Katrina's arrival. The critical 11 mile long levee section fronting "Lake" Borgne (which is actually a Bay, connected directly to the Gulf of Mexico) was being constructed in stages, and funding appropriation for the final stage had long been requested by the U.S. Army Corps of Engineers (USACE), but this did not arrive before Katrina struck; as a result large portions of this critical levee frontage were several feet below final design grade. In addition, an unfortunate decision had been made to use local dredge spoils from the excavation of the adjacent MRGO channel for construction of major portions of the levees along this frontage. The result was that major portions of these levees were comprised of highly erodible sand and lightweight shell sand fill.

When the storm surge arrived, massive portions of these levees eroded catastrophically and the storm surge passed through this frontage while still on the rise, crossed an open swamp area that should have safely absorbed most of the overtopping flow from the outer levees (if they had not catastrophically eroded), and it then crossed easily over a secondary levee of lesser height that had not been intended to face a storm surge largely undiminished by the minimal interference of the too rapidly eroded outer levees fronting Lake Borgne. The resulting carnage in St. Bernard Parish was devastating, as the storm surge rapidly filled the protected basin to an elevation of approximately +12 feet above sea level; deeply inundating even neighborhoods with ground elevations well above sea level in this area.

The storm surge swelled waters of Lake Borgne also passed over and then through a length of levees at the southeast corner of the New Orleans East protected basin. Here too, the levees fronting Lake Borgne had been constructed primarily using materials dredged from the excavation of an adjacent channel (the GIWW channel), and these levees also contained major volumes of highly erodible sands and lightweight shell sands. These levees also massively eroded, and produced the principal source of flooding that eventually inundated the New Orleans East protected area. Here again there was an area of undeveloped swampland behind the outer levees that might have absorbed the brunt of any overtopping flow, and a secondary levee of lesser height was in place behind this swampland that might then have prevented catastrophic flooding of the populous areas of New Orleans East. This secondary levee was not able to resist the massive flows resulting from the catastrophic erosion of the highly erodible section of the Lake Borgne frontage levee, however, and the floodwaters passed over the secondary levee and began the filling of the New Orleans East protected basin.

The catastrophic erosion of these two critical levee frontages need not have occurred. These frontages could instead have been constructed using well compacted clay fill with good resistance to erosion, and they could have been further armored in anticipation of the storm surge and wave loading from Lake Borgne. The levee at the northeast edge of St. Bernard Parish could have been completed in a more timely manner. The result would have been some overtopping, but not catastrophic erosion and uncontrolled breaching of these critical frontages. Some flooding and damage would have been expected, but it need not have been catastrophic.

The storm surge swollen waters of Lake Borgne next passed laterally along the east-west trending GIWW/MRGO channel to its intersection at a "T" with the north-south oriented IHNC channel, overtopping levees along both banks to a limited degree. This produced an additional breach of a composite earthen levee and concrete floodwall section along the southern edge of New Orleans East, adding additional uncontrolled inflow to this protected basin. This failure could have been prevented at little incremental cost if erosion protection (e.g. a concrete splash pad, or similar) had been emplaced along the back side of the concrete floodwall at the levee crest, but the USACE felt that this was precluded by Federal rules and regulations regarding authorized levels of protection.

The surge next raised the water levels within the IHNC channel, and produced a number of failures on both the east and west banks. Two major failures occurred on the east side of the IHNC, at the west edge of the Ninth Ward. Overtopping occurred at both of these locations, but this was not the principal cause of either of these failures. Both failures were principally due to underseepage flows that passed beneath the sheetpile curtains supporting the concrete floodwalls at the crests of the levees. Like many sections of the flood protection system, these sheetpiles were too shallow to adequately cut off, and thus reduce, these underseepage flows. The result was two massive breaches that devastated the adjacent Ninth Ward neighborhood, and then pushed east to meet with the floodwaters already rapidly approaching from the east from St. Bernard Parish as a result of the earlier catastrophic erosion of the Lake Borgne frontage levees.

Several additional breaches also occurred farther north on the east side of the IHNC fronting the west side of New Orleans East, but these were relatively small features and they just added further to the uncontrolled flows that were now progressively filling this protected basin. These breaches occurred mainly at junctures between adjoining, dissimilar levee and floodwall sections, and represented good examples of widespread failure to adequately engineer these "transitions" between sections of the regional flood protection system.

Several breaches occurred on the west side of the IHNC, and these represented the first failures to admit uncontrolled floodwaters into the main metropolitan (downtown) protected area of New Orleans. These features did not scour and erode a path below sea level, however, so they admitted floodwaters for a number of hours and then these inflows ceased as the storm surge in the IHNC eventually subsided. Only 10% to 20% of the floodwaters that eventually inundated a majority of the main (downtown) New Orleans protected basin entered through these features.

These failures and breaches on the west side of the IHNC all appear to have been preventable. One failure was the result of overtopping of an I-wall, with the overtopping flow then eroding a trench in the earthen levee crest at the inboard side of the floodwall. This removal of lateral support unbraced the floodwall, and it was pushed over laterally by the water pressures from the storm surge on the outboard side. Here again the installation of erosional protection (e.g. concrete splash pads or similar) might have prevented the failure.

The other failures in this area occurred at "transitions" between disparate levee and floodwall sections, and/or at sections where unsuitable and highly erodible lightweight shell sand fills had been used to construct levee embankments. Here, again, these failures were as much the result of design choices and/or engineering and oversight issues as the storm surge itself.

As the eye of the hurricane next passed to the northeast of New Orleans, the counterclockwise swirl of the storm winds produced a storm surge against the southern edge of Lake Pontchartrain. This produced additional temporary overtopping of a long section of levee and floodwall at the west end of the lakefront levees of New Orleans east, behind the old airport, adding further to the flows that were progressively filling this protected basin.

The surge against the southern edge of Lake Pontchartrain also elevated the water levels within three drainage canals at the northern edge of the main metropolitan (downtown) New Orleans protected basin, and this would produce the final, and most damaging, failures and flooding of the overall event.

The three drainage canals should not have been accessible to the storm surge. The USACE had tried for many years to obtain authorization to install floodgates at the north ends of the three drainage canals that could be closed to prevent storm surges from raising the water levels within the canals. That would have been the superior technical solution. Dysfunctional interaction between the local Levee Board (who were responsible for levees and floodwalls, etc.) and the local Water and Sewerage Board (who were responsible for pumping water from the city via the drainage canals) prevented the installation of these gates, however, and as a result many miles of the sides of these three canals had instead to be lined with levees and floodwalls.

The lining of these canals with levees topped with concrete floodwalls was rendered very challenging due to (a) the difficult local geology of the foundation soils, and (b) the narrow right of way (or available "footprint") for these levees. As a result of the decision not to install the floodgates, the three canals represented potentially vulnerable "daggers" pointed at the heart of the main metropolitan New Orleans protected basin. Three major breaches would occur on these canals; two on the London Avenue Canal and one on the 17th Street Canal. All three of these breaches eroded and scoured rapidly to well below sea level, and these three major breaches were the source of approximately 80% of the floodwaters that then flowed into the main (downtown) protected basin over the next three days, finally equilibrating with the still slightly elevated waters of Lake Pontchartrain on Thursday, September 1.

The central canal of the three, the Orleans Canal, did not suffer breaching, but a section of floodwall topping the earthen levee approximately 200 feet in length near the south end of the canal had been left incomplete, again as a result of dysfunctional interaction between the local levee board and the water and sewerage board. This effectively reduced the level of protection for this canal from about +12 to +13 feet above sea level (the height of the tops of the floodwalls lining the many miles of the canal) to an elevation of about +6 to +7 feet above sea level (the height of the earthen levee crest along the 200 foot length where the floodwall that should have topped this levee was omitted). As a result of the missing floodwall section, flow passed through this "hole" and began filling the heart of the main New Orleans protected basin. This flow eventually ceased as the storm surge subsided, and so was locally damaging but not catastrophic.

The three breaches on the 17th Street and London Avenue canals were catastrophic. None of these failures were the result of overtopping; surge levels in all three drainage canals were well below the design levels, and well below the tops of the floodwalls. Two of these breaches were the result of stability failures of the foundation soils underlying the earthen levees and their floodwalls, and the third was the result of underseepage passing beneath the sheetpile curtain and resultant catastrophic erosion near the inboard toe of the levee that eventually undermined the levee and floodwall.

A large number of engineering errors and poor judgements contributed to these three catastrophic design failures, as detailed in Chapter 8. In addition, a number of these same problems appear to be somewhat pervasive, and call into question the integrity and reliability of other sections of the flood protection system that did not fail during this event. Indeed, additional levee and floodwall sections appear to have been potentially heading towards failure when they were "saved" by the occurrence of the three large breaches (which rapidly drew down the canal water levels and thus reduced the loading on nearby levee and floodwall sections.)

The New Orleans regional flood protection system failed at many locations during Hurricane Katrina, and by many different modes and mechanisms. This unacceptable performance was to a large degree the result of more global underlying "organizational" and institutional problems associated with the governmental and local organizations jointly responsible for the design, construction, operation, and maintenance of the flood protection system, including provision of timely funding and other critical resources.

Our findings to date indicate that no one group or organization had a monopoly on responsibility for the catastrophic failure of this regional flood protection system. Many groups, organizations and even individuals had a hand in the numerous failures and shortcomings that proved so catastrophic on August 29th. It is a complex situation, without simple answers.

It is not without answers and potential solutions, however, just not simple ones. There is a need to change the process by which these types of large and critical protective systems are created and maintained. It will not be feasible to provide an assured level of protection for this large metropolitan region without first making significant changes in the organizational structure and interactions of the national and more local governmental bodies and agencies jointly responsible for this effort. Significant changes are also needed in the engineering approaches and procedures used for many aspects of this work, and there is a need for interactive and independent expert technical oversight and review as well. In numerous cases, it appears that such review would have likely caught and challenged errors and poor judgements (both in engineering, and in policy and funding) that led to failures during Hurricane Katrina.

Simply updating engineering procedures and design manuals will not provide the needed level of assurance of safety of the population and properties of this major metropolitan region. Design procedures and standards employed for many elements of the flood protection system can be traced back to initial development and use for design and construction of levees intended for protection of largely unpopulated agrarian land, not a major urban region. Design levels of safety and reliability were nowhere near those generally used for major dams; largely because dams are considered to pose a potential risk to large populations. There are few U.S. dams that pose risk to populations as large as the greater New Orleans region, however, and it is one of the recommendations of this study that standards and policies much like those used for "dams" should be adopted for levee systems protecting such regions.

Simply addressing engineering design standards and procedures is unlikely to be sufficient to provide a suitably reliable level of protection. There is also a need to resolve dysfunctional relationships between federal and more local government and the federal and local agencies responsible for the actual design, construction and maintenance of such flood protection systems. Some of these groups need to enhance their technical capabilities; a long-term expense that would clearly represent a prudent investment at both the national and local level, given the stakes as demonstrated by the losses in this recent event. Steady commitment and reliable funding, shorter design and construction timeframes, clear lines of authority and responsibility, and improved overall coordination of disparate system elements and functions are all needed as well.

And there is some urgency to all of this. The greater New Orleans regional flood protection system was significantly upgraded in response to flooding produced by Hurricane Betsy in 1965. The improved flood protection system was intended to be completed in 2017, fully 52 years after Betsy's calamitous passage. The system was incomplete when Katrina arrived. As a nation, we must manage to dedicate the resources necessary to complete projects with such clear and obvious ramifications for public safety in a more timely manner.

New Orleans has now been flooded by hurricanes six times over the past century; in 1915, 1940, 1947, 1965, 1969 and 2005. It should not be allowed to happen again.

THE INVESTIGATION TEAM

The University of California at Berkeley led Independent Levee Investigation Team (ILIT) grew through the course of this investigation, and eventually numbered 36 very dedicated and accomplished individuals.

The team included a large number of leading experts across a diverse range of fields. Team members came from six states, and they came from universities, private engineering firms, and state and federal agencies.

As a group, the investigation team had very impressive prior experience with forensic studies of major disasters and catastrophes. For example, the team members had previously investigated 12 major earthquakes and 8 major hurricanes (both domestic and foreign), 14 dam failures, more than a dozen levee failures, numerous landslides, one tsunami, the pivotal Kettleman Hills waste landfill failure, the Challenger and Columbia space shuttle disasters, the Exxon Valdez tanker disaster, and a number of major offshore pipeline and oil platform failures. They are well experienced with the carnage and disarray of disasters, and with the unforgettable smell of death. They are also well experienced at the delicate and deliberate art and science of piecing their way through the devastation, carefully and professionally, and figuring out what had happened, and why; the art and science of engineering forensics.

The calibre of these assembled experts is such that we could never possibly have afforded to hire them. Instead, excepting a handful of graduate research students who worked for very low wages, these world class experts all volunteered, and they worked pro bono (for free.) They did this for the intellectual challenge, for the camaraderie of a very special group of accomplished colleagues, for the chance to make a positive difference, because it was important, and most importantly because it was the right and necessary thing to do.

The pages that follow list the names and affiliations of the members of the Independent Investigation Team. I have had the opportunity to work on a number of investigations of major catastrophes and disasters, but I have never worked with a finer group. They are all heroes in my book.

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ACKNOWLEDGEMENTS

This report would not have been possible without the generous help of many individuals and organizations.

This project was supported, in part, by the National Science Foundation (NSF) under Grants No. CMS-0413327 and CMS-0611632, and additional support was provided by the Center for Information Technology Research in the service of Society (CITRIS) at the University of California at Berkeley. This support is gratefully acknowledged.

The authors also wish to express their gratitude to the U.S. Army Corps of Engineers (USACE) for their considerable assistance with numerous elements of this work. Their field investigation team from the Engineer Research Development Center (ERDC) in Vicksburg hosted and assisted our own field investigation team in the critical early days of late September and early October. The USACE has also posted massive amounts of background documents on their website, and this has been an invaluable resource. The USCAE, and the Interagency Performance Evaluation Team (IPET) have graciously shared much of their field and laboratory data, and we have done the same. This positive sharing and collaboration helps everyone by providing the best possible basis for study and analysis of this event.

We are also deeply grateful to the honorable men and women of the USACE who have taken extra measures to help to provide additional documents, data and insight. Many of these prefer not to be named, but their dedication to service of the greater public good in this difficult situation has been admirable.

We are deeply grateful to the members of the State of Louisiana's independent investigation team, Team Louisiana, for their tremendous efforts and dogged persistence under very difficult circumstances, and for their generous mutual sharing of data and insights throughout this investigation. This team consists of Dr. Ivor Van Heerden, Dr. Paul Kemp and Dr. Hassan Mashriqui (all from the Louisiana State University Hurricane Research Center), Billy Prochaska and Dr. Lou Cappozzoli (both local geotechnical consultants), and Art Theis (retired head of the Louisiana Department of Public Works.) The people of Louisiana, and the nation, owe these gentlemen a great debt as their persistent efforts have, time and again, produced critical data and insights that would not otherwise have been available.

We are also grateful to the members of the field investigation team of the American Society of Civil Engineers, who jointly formed a combined team with ours in the urgent initial post-event field studies when it was of vital importance to gather all possible data and observations while (fully necessary) emergency repair operations were already damaging and burying critical evidence. This was a very strong field forensics team, and their collaboration both in the field and in the subsequent preparation of an initial Preliminary Report which was issued in early November of 2005, was of great value.

Finally we are deeply grateful to the many others who will remain anonymous, but who have assisted by providing information, data, background history and other information that might otherwise not have been available.

A great many people gave generously of themselves, their time, and their expertise to assist these studies. It was important, and we are profoundly grateful.

CHAPTER ONE: INTRODUCTION AND OVERVIEW

1.1 Introduction

This report presents the results of an investigation of the performance of the New Orleans regional flood protection system during and after Hurricane Katrina, which struck the New Orleans region on August 29, 2005. This event resulted in the single most costly catastrophic failure of an engineered system in history. Current damage estimates at the time of this writing are on the order of $100 to $150 billion in the greater New Orleans area, and the official death count in New Orleans and southern Louisiana at the time of this writing stands at 1,293 with an additional 306 deaths in nearby southern Mississippi. An additional approximately 400 people are currently still listed as "missing"; it is expected that some of these missing were temporarily lost in the shuffle of the regional evacuation, but some of these are expected to have been carried out into the swamps and the Gulf of Mexico by the storm's floodwaters, and some are expected to be recovered in the still ongoing sifting through the debris of wrecked homes and businesses, so the current overall regional death count of 1,599 is expected to continue to rise a bit further. More than 450,000 people were initially displaced by this catastrophe, and at the time of this writing, more than 250,000 residents of the greater New Orleans metropolitan area continue to be displaced from their homes by the floodwater damages from this storm event.

This investigation targets three main questions as follow: (1) What happened? (2) Why? and (3) What types of changes are necessary to prevent recurrence of a disaster of this scale again in the future?

To address these questions, this investigation has involved: (1) an initial field reconnaissance, forensic study and data gathering effort performed quickly after the arrival of Hurricanes Katrina (August 29, 2005) and Rita (September 24, 2005), (2) a review of the history of the regional flood protection system and its development, (3) a review of the challenging regional geology, (4) detailed studies of the events during Hurricanes Katrina and Rita, as well as the causes and mechanisms of the principal failures, and studies of sections that performed successfully as well, (5) studies of the organizational and institutional issues affecting the performance of the flood protection system, (6) observations regarding the emergency repair and ongoing interim levee reconstruction efforts, and (7) development of findings and preliminary recommendations regarding changes that appear warranted in order to prevent recurrence of this type of catastrophe in the future.

1.2 Initial Post-Event Field Investigations

A critical early stage of this investigation was the initial field investigations performed by collaborating teams of engineers and scientists in the wake of the passage of Hurricane Katrina, to study performance of the regional flood protection system and the resulting flooding that occurred in the New Orleans area. The principal focus of these efforts was to capture perishable data and observations related to the performance of flood protection system before they were lost to ongoing emergency response and repair operations.

Several independent investigation teams jointly pooled their efforts in order to capture as much data as possible in the precious timeframe available. The two principal participating teams were from the University of California at Berkeley (UC Berkeley), and a team from the American Society of Civil Engineers (ASCE) organized by its Geo-Institute and by its Coasts, Oceans, Ports, and Rivers Institute. A team from Louisiana State University's Hurricane Research Center (LSU/HRC) also accompanied the field investigation teams during their first week of investigations. These teams were accompanied and assisted in the field by members of the U.S. Army Corps of Engineers (USACE) levee investigation team from the Engineer Research and Development Center (ERDC). All of these investigative teams shared data and findings freely and openly, and the mutual pooling of talents and expertise greatly benefited all as it enabled the field teams to gather more data in the critical days available.

These initial field investigations occurred over a span of approximately three weeks, from September 26 through October 15, 2005, and the preliminary observations and findings were presented in a report jointly authored by the UC Berkeley-led field investigation team and the ASCE field investigation team (Seed, et al.; November 15, 2005.)

1.3 Current Studies and Investigations

Subsequent to these initial field investigations, three main investigations have been carried forward. The largest of these is the U.S. Army Corps of Engineers' own internal investigation, the Interagency Performance Evaluation Team (IPET) study. The IPET study is by far the largest of the three investigations, and has a budget of approximately $20 million. The American Society of Civil Engineers (ASCE) has been hired, for an additional $2 million, to form a review panel (called the External Review Panel, E.R.P.) to review the results of the IPET studies. This ASCE review panel works and consults closely with the IPET studies and is focused specifically on reviewing the IPET investigation efforts, data and findings. The National Research Council (NRC) has also been hired, by the Department of Defense, to provide an additional review of the IPET studies after the ASCE's E.R.P. completes its task. This NRC review panel has announced its intention of reviewing input from all investigation teams and efforts as part of this task.

The IPET study is narrowly focused and constrained in its first year to consideration and study of only "what happened" in a strictly physical sense; it is specifically not to address underlying faults or to assign "responsibility" in its initial studies (Final Draft Report due to the ASCE review panel on May 15, 2006, and Final Report due on June 1, 2006), but rather to wait and study "organizational issues", "human factors", etc. during the following year.

The second investigation team moving forward is Team Louisiana, representing the interests of the State of Louisiana in performing an investigation independent of the USACE. Team Louisiana is led by Dr. Ivor Van Heerden, and its core is formed by a number of his colleagues from the Louisiana State University (LSU) Hurricane Research Center (LSU/HRC), with additional members from a number of local engineering consulting firms and state organizations. Team Louisiana does not have the massive funding or manpower of the IPET team, but they are strongly motivated and have worked very hard and well given their logistical limitations and the difficult situation of the region (which has directly affected some of the team's members, as well as many of their friends and colleagues.)

The third investigation team moving forward is our own UC Berkeley-led Independent Levee Investigation Team (ILIT). Our budget is also not as large as that of the IPET study, and currently stands at approximately $350,000. We have, however, managed to assemble a team of 36 outstanding engineers and researchers. Pages "ix" through "x" describe the team. As a group, the conjugate forensic experience in prior investigations of numerous major engineering and natural disasters is very impressive. This is an amazingly strong team, and we could never possibly have afforded to hire them within our small budget. These leading experts have, instead, volunteered to work for free (pro bono), and our budget is thus devoted instead towards covering travel expenses, field borings and sampling, and laboratory testing, etc. We have elected to decline proffered offers of additional funding as it appears important that our investigation team maintain its demonstrable independence and neutrality in these studies.

1.4 Organization of this Report

This report presents the results of studies directed towards answering three main sets of questions as follow:

1. **What happened?** What events transpired during Hurricane Katrina and during its aftermath? How did the regional flood protection system perform? What were the successes, and what were the shortcomings and failures? What mechanisms and forces, etc., led to these performances?

2. **Why did this happen?** What were the underlying issues that led to the observed performance of the system elements? What were the influences of regional and local geology? How did the history of the evolution of the flood protection system contribute to its performance? What were the design assumptions, engineering studies and analyses, etc., and what effect did these have on the performance of the system elements? What over-arching organizational, institutional, political and funding issues may have played a role?

3. **What can be done to ensure that a similar catastrophe does not recur in the future?** This report presents preliminary findings and recommendations regarding changes in organization of the overall governmental/institutional "system" responsible for the conception, design, construction, operation and maintenance of the complex regional flood defense system, as well as the making of political decisions regarding levels of protection to be provided, and the provision of funding to support the creation and operation/maintenance of such a system. This report also presents preliminary findings and recommendations regarding a number of focused areas for improvement of the conceptual design, analysis and engineering design, and construction and maintenance of such a system.

In the end, it is concluded that many things went wrong with the New Orleans flood protection system during Hurricane Katrina, and that the resulting catastrophe had it roots in three main causes: (1) a major natural disaster (the Hurricane itself), (2) the poor performance of the flood protection system, due to localized engineering failures, questionable judgements, errors, etc. involved in the detailed design, construction, operation and maintenance of the system, and (3) more global "organizational" and institutional problems associated with the governmental and local organizations responsible for the design, construction, operation, maintenance and funding of the overall flood protection system.

Chapter 2 presents an overview of the principal events that occurred during and after the arrival of Hurricane Katrina in the New Orleans area, with emphasis on the storm surge and wave loadings, and the resulting performance of the regional flood protection system.

Chapter 3 presents a review of the history of the development of the New Orleans regional flood protection system. It is a truism of levees and flood protection that the fabric and history of a given region is usually closely interwoven within the fabric of the levees and flood protection systems that are created in that region.

Chapter 4 presents a summary overview of the challenging regional and local geology that so strongly affects the difficulties associated with the creation of regional flood protection systems, and their performance as well.

Chapters 5 through 8 present the results of studies and analyses of the performance of the four main levee-protected areas principally affected by Hurricane Katrina. These chapters present overviews of the performance of the flood protection system in each of the four areas, of the flooding that occurred within each of these areas, and detailed analyses of the performance of critical sub-elements of the system within each area. These analyses include an investigation of the causes of critical failures, and the apparent reasons for these including both engineering/construction types of issues as well as organizational/institutional issues. These chapters also present observations, recommendations and findings related to some of the emergency post-hurricane repair and reconstruction efforts.

Chapters 9 and 10 present the results of studies of issues associated with erosion and scour; a key phenomenon involved in both the successful and unsuccessful performances of numerous critical levee and floodwall sections throughout the region.

Chapter 11 briefly addresses a series of "other issues", including observations regarding apparent damage and distress at locations away from the four main New Orleans flood-protected areas that are the principal focus of these studies, and a brief overview of the performance of the pumping systems that "unwater" the protected areas of these studies, and observations and comments regarding the initial emergency levee and floodwall breach repair efforts, and the ongoing interim repair and reconstruction efforts, at a number of locations.

Chapters 12 through 14 examine a number of organizational and institutional issues that affected the performance of the regional flood protection systems during Hurricane Katrina. They also address recommendations for moving forward; recommendations for a number of changes to ensure that we never again have to study a catastrophe of this type and scale in southern Louisiana.

Chapter 12 begins with a review of background and history pertaining to these types of issues. Chapter 13 then presents a review and examination of critical organizational, institutional, political and funding issues that directly affected the performance of the New Orleans regional flood protection system, and also some of the post-hurricane repair and reconstruction efforts. These organizational/institutional issues had a dominant impact on the overall performance of the regional flood protection systems, and many of the problems that led to the catastrophic flooding of much of the greater New Orleans region can be traced directly (at least in large part) to these types of underlying issues.

Chapter 14 presents preliminary recommendations for changes that can and should be made in moving forward, in order to ensure that a catastrophe of this scale is never repeated in the future. The New Orleans regional flood protection system did not perform well in Hurricane Katrina. We can do better. This chapter presents recommendations for changes in specific engineering analysis and design procedures, conceptual design features and approaches, specific system elements, etc. This chapter also presents recommendations regarding changes in the overall system of governmental bodies, governmental agencies, outsourced (private sector) engineering and construction, local oversight agencies, and the regulations and procedures involved in the overall conception, design, construction, operation and maintenance of complex and regionally massive systems protecting vital public safety for populous regions such as this.

Finally, Chapter 15 presents a summary overview of these studies, and of the principal findings and recommendations.

1.5 Elevation Datum

There are a number of datums that have been and continue to be used for elevation references throughout the New Orleans Region. A good discussion of these is presented in the IPET Interim Report No. 2 (IPET; April 1, 2006). The situation is further confused as some regional benchmarks which were considered stable have recently been found to have instead subsided, so that elevations based on these require correction. In this present report, all elevations are stated in terms of local Mean Sea Level (MSL), which corresponds approximately to the NAVD88 (2004.65) datum. [This NAVD88 (2004.65) datum is currently thought to be within approximately 3-inches of Mean Sea Level in the New Orleans area.] All elevations in this report have been resolved, as best we were able with the information available, to this MSL (or approximately NAVD88; 2004.65) datum.

1.6 References

Seed, Raymond B., et al., "Preliminary Report on the Performance of the New Orleans Levee Systems in Hurricane Katrina on August 29, 2005," Report No. UCB/CITRIS - 05/01, November 17, 2005.

CHAPTER TWO: OVERVIEW OF HURRICANE KATRINA AND ITS AFTERMATH

2.1 Hurricane Katrina

The path of Hurricane Katrina's eye is shown in Figures 2.1 and 2.2. Hurricane Katrina crossed the Florida peninsula on August 25, 2005 as a Category 1 hurricane. It then entered the Gulf of Mexico, where it gathered energy from the warm Gulf waters, producing a hurricane that eventually reached Category 5 status on Sunday, August 28, shortly before making its second mainland landfall just to the east of New Orleans early on Monday, August 29, as shown in Figures 2.1 and 2.2. The Hurricane had weakened to a Category 4 level prior to landfall on the morning of August 29, and it weakened further as it come ashore.

Because the eye of this hurricane passed just slightly to the east of New Orleans, the hurricane imposed unusually severe wind loads and storm surges (and waves) on the New Orleans region and its flood protection systems.

2.2 Overview of the New Orleans Flood Protection Systems

Figure 2.3 shows the main study region. The City of New Orleans is largely situated between the Mississippi River, which passes along the southern edge of the main portion of the city, and Lake Pontchartrain, which fronts the city to the north. Lake Borgne lies to the east, separated from developed areas by open swampland. "Lake" Borgne is not really a lake at all; instead it is a bay as it is directly connected to the waters of the Gulf of Mexico. To the southeast of the city, the Mississippi River bends to the south and flows out through its delta into the Gulf of Mexico.

The flood protection system that protects the New Orleans region is organized as a series of protected basins or "protected areas", each protected by its own perimeter levee system, and these are "unwatered" by pumps.

As shown in Figures 2.4 and 2.5, there are four main protected areas that comprise the New Orleans flood protection system of interest. A number of additional levee-protected units also exist in this area, but the focus of these current studies is the four main protected areas shown in Figures 2.4 and 2.5. These were largely constructed under the supervision of the U.S. Army Corps of Engineers, to provide improved flood protection in the wake of the devastating flooding caused by Hurricane Betsy in 1965.

Figures 2.4 and 2.5 show the locations of most of the levee breaches and severely distressed (but non-breached, or only partially breached) levee sections covered by these studies. Levee breaches are shown with solid blue stars, and distressed sections as well as minor or partial breaches are indicated by red stars. The original base maps, and many of the stars, were graciously provided by the USACE (2005), and a number of additional blue and red stars have been added to the map in Figure 2.4 as a result of the studies reported herein. The yellow stars shown in these figures correspond to deliberate breaches made after Hurricane Katrina, to facilitate draining the flooded areas after the storm.

The pink shading in Figures 2.4 and 2.5 shows developed areas that were flooded, and the areas shaded with blue cross-hatching indicate undeveloped swamp land that was flooded. The deeper blue shading (near the east end of New Orleans East) denotes areas that still remained to be unwatered as late as September 28, 2005. As shown in these figures, approximately 85% of the metropolitan area of New Orleans was flooded during this event.

As shown in Figure 2.4, the Orleans East Bank (Metro Orleans) section is one contiguously protected section. This protected unit contains the downtown district, the French Quarter, the Garden District, and the "Canal" District. The northern edge of this protected area is fronted by Lake Pontchartrain on the north, and the Mississippi River passes along its southern edge. The Inner Harbor Navigation Canal (also locally known as "the Industrial Canal") passes along the east flank of this protected section, separating the Orleans East Bank protected section from New Orleans East (to the northeast) and from the Lower Ninth Ward and St. Bernard Parish (directly to the east.) Three large drainage canals extend into the Orleans East Bank protected section from Lake Pontchartrain to the north, for the purpose of conveying water pumped north into the lake by large pump stations within the city. These canals, from west to east, are the 17th Street Canal, the Orleans Canal, and the London Avenue Canal.

A second protected section surrounds and protects New Orleans East, as shown in Figure 2.4. This protected section fronts Lake Pontchartrain along its north edge, and the Inner Harbor Navigation Canal (IHNC) along its west flank. The southern edge is fronted by the Mississippi River Gulf Outlet channel (MRGO) which co-exists with the Gulf Intracoastal Waterway (GIWW) along this stretch. The eastern portion of this protected section is currently largely undeveloped swampland, contained within the protective levee ring. The east flank of this protected section is fronted by additional swampland, and Lake Borgne is located slightly to the southeast.

The third main protected section contains both the Lower Ninth Ward and St. Bernard Parish, as shown in Figure 2.4. This protected section is also fronted by the Inner Harbor Navigation Canal on its west flank, and has the MRGO/GIWW channel along its northern edge. At the northeastern corner, the MRGO bends to the south (away from the GIWW channel) and fronts the boundary of this protected area along the northeastern edge. Open swampland occurs to the south and southeast. Lake Borgne occurs to the east, separated from this protected section by the MRGO channel and by a narrow strip of undeveloped marshland. The main urban areas occur within the southern and western portions of this protected area. The fairly densely populated Lower Ninth Ward is located at the west end, and St. Bernard Parish along approximately the southern half of the rest of this protected area. The northeastern portion of this protected section is undeveloped marshy wetland, as indicated in Figure 2.4. A secondary levee, operated and maintained by local levee boards, separates the undeveloped marshlands of the northeastern portions of this protected area from the Ninth Ward and St. Bernard Parish urban areas.

The fourth main protected area is a narrow, protected strip along the lower reaches of the Mississippi River heading south from St. Bernard Parish to the mouth of the river at the Gulf of Mexico, as shown in Figure 2.5. This protected strip, with "river" levees fronting the Mississippi River and a second, parallel set of "storm" levees facing away from the river forming a protected corridor less than a mile wide, serves to protect a number of small communities as well as utilities and pipelines. This protected corridor also provides protected access for workers, supplies and gas and oil pipelines servicing the large offshore oil fields out in the Gulf of Mexico. This will be referred to in this report as "the Plaquemines Parish" levee protected zone.

The current perimeter levee and floodwall defense systems for these four protected areas were largely designed and constructed under the supervision of the U.S. Army Corps of Engineers in the wake of the catastrophic flooding caused by Hurricane Betsy of 1965. These flood protection improvements typically involved either new levee construction, or raising existing levee defenses and/or adding new floodwalls, to provide storm flood protection for higher elevations of storm surge waters at locations throughout the region.

2.3 Overview of Flood Protection System Performance During Hurricane Katrina

2.3.1 Storm Surge During Hurricane Katrina

The regional flood protection system had been designed to safely withstand the storm surges and waves associated with the Standard Project Hurricane, which was intended to represent a scenario roughly "typical" of a rapidly moving Category 3 hurricane passing close to the New Orleans metropolitan region. Chapter 12 (Section 12.5.1) presents a more detailed discussion of the "Standard Project Hurricane", and the criteria for which the regional flood protection system was designed. In simple terms, the system was intended to have been designed to safely withstand storm surge levels (plus waves) to specified elevations at various locations, as shown in Figures 2.6 and 2.7.

In general, the "Standard Project Hurricane" provided for design to safely withstand storm surge rises (plus waves) to prescribed elevations at various locations throughout the system. The levels selected correspond generally to the storm surge level (mean peak storm surge water elevation, without waves) associated with the "Standard Project Hurricane" conditions plus an additional allowance for most (but not all) of expected additional wave run-up.

As shown in Figures 2.6 and 2.7, this resulted in a targeted protection level of about elevation +17 feet to +19 feet (MSL), or 17 to 19 feet above Mean Sea Level, at the eastern flank of the system, and + 13.5 feet to +18 feet (MSL) along much of the southern edge of Lake Pontchartrain. The storm surge levels within the various drainage canals and navigational channels varied, and the storm surge levels for design were typically on the order of Elev. + 14 feet to + 16 feet (MSL) along the GIWW and IHNC channels, and Elev. + 12.5 feet to + 14.5 feet (MSL) along the 17th Street, Orleans, and London Avenue Canals in the "Canal District". There is some minor confusion as to the most recent "Standard Project Hurricane", and the most recent storm surge design levels at some locations; the values indicated in Figure 2.6 are an interpretation by the Government Accountability Office (GAO, 2006) based in part on initial research by the staff of the New Orleans Times Picayune, and the values shown in Figure 2.7 have been added to this figure by our team, and are our own current best interpretation.

The situation is further clouded a bit, as the actual targeted levee and floodwall heights along a given section also varied slightly as a function of waterside topography, obstacles and vegetation, levee geometry, orientation and potential wind fetch (distance of potential wind travel across the top of open water), etc. as these would affect the potential run-up heights of storm waves. Variations for these types of issues were typically minor, on the order of two feet or less.

There is, however, no "typical" hurricane, nor associated storm surge, and the actual wind, wave and storm surge loadings imposed at any location within the overall flood protection system during an actual hurricane are a function of location relative to the storm, wind speed and direction, orientation of levees, local bodies of water, channel configurations, offshore contours, vegetative cover, etc. These loadings vary over time, as the storm moves progressively through the region.

Figures 2.8 and 2.9 show plots of storm surge levels resulting from numerical modeling simulations performed by the LSU Hurricane Research Center, for two different points in time during Hurricane Katrina, based on analyses of the storm track, wind speeds, regional topography and local conditions (marsh growth, soil stiffness, offshore contours, etc.) (Louisiana State University Hurricane Center, 2005.) The water levels shown in Figures 2.8 and 2.9 were predicted using a regionally calibrated numerical model, and the results shown in Figure 2.8 represent a point in time when the eye of the hurricane was first approaching the coast from the Gulf of Mexico, and those shown in Figure 2.9 correspond to a time when the eye of the storm was passing slightly to the east of New Orleans. These calculations are part of an overall single analysis of storm surge levels throughout the region, and throughout the continuous period of time as the storm approached and then passed through the region. Based on actual field observations and measurements of maximum storm surge levels at more than 100 locations throughout the region, this global analysis of storm surge levels is expected to be accurate (relative to surge levels that actually occurred) within approximately ± 15% at all locations of interest for these current studies (IPET, 2006.)

Predicted and actual storm surge heights varied over time, at different locations, and the water levels shown in Figures 2.8 and 2.9 do not represent predictions of the peak storm surges noted at all locations. Instead, these images shows calculated conditions at two interesting points in time when: (a) [Fig. 2.8] the initial large surge was being driven up against the coast of the Gulf of Mexico in the New Orleans region by the approaching storm, and (b) [Fig. 2.9] at a particularly critical moment when a large storm surge had first "inflated" (raised the level of) Lake Borgne, then the locally prevailing westward swirl of the counterclockwise hurricane winds threw the risen waters of Lake Borgne westward over the adjacent levees protecting eastern flanks of the New Orleans East and St. Bernard/Lower Ninth Ward protected areas, as shown schematically in Figure 2.11.

These types of storm surge modeling calculations are being performed by a number of research and investigation teams, and are constantly being calibrated and updated based on actual field measurements of high water marks, etc. The USACE's IPET investigation team are devoting significant effort to these types of hydrodynamic analytical "hind-casts", and the IPET back analyses provided to date to our UC Berkeley-led ILIT study team are in good agreement with the storm surge predictions shown in Figures 2.8 and 2.9 at most locations of interest for these studies (IPET, 2006).

Figure 2.10 shows an aggregate summary of the calculated peak storm surges, at any point in time during Hurricane Katrina, based on similar calculations performed by the IPET study (IPET, 2006). These calculations are very similar to those developed by the Louisiana investigation team, and both the IPET and Team Louisiana analyses will be used as a partial basis for estimation of storm surge levels and wave conditions in these current studies. The maximum flood stages calculated (predicted) by the two sets of analyses are generally in good agreement at most points of interest. Agreement regarding storm waves is also generally good, but the differences between the two sets of predicted storm waves are a bit more significant at a few locations of interest. Discussions of the IPET and Team Louisiana hydrodynamic storm surge and storm wave calculations will be presented, in more detail, at locations of interest in the chapters that follow.

It should be noted that a number of different datums have been used as elevation references throughout the historic development of the New Orleans regional levee systems, and this situation is further complicated by ongoing subsidence in the region. This investigation has elected to resolve these differences between different datums, and to refer to all elevations in this report (as consistently as possible) in terms of elevation with respect to the NAVD88 (2004.65) datum; approximately "mean sea level" in the region. This particular version of the NAVD88 datum is currently thought to be within about 3-inches of Mean Sea Level (MSL) in the New Orleans region. For a more in-depth discussion of differences between the various datums used in the greater New Orleans region, please see IPET Interim Report No. 2 (IPET, 2006).

2.3.2 Overview of the Performance of the Regional Flood Protection System

Hurricane Katrina, as expected, produced a large onshore storm surge from the Gulf of Mexico. As shown in Figures 2.8 through 2.10 this produced significant overtopping of storm levees along the lower Mississippi River reaches in the Plaquemines Parish area, and numerous levee breaches occurred in this area, as shown previously in Figure 2.5. In simple terms, the "storm" levees of Plaquemines Parish were largely overwhelmed by the large storm surge; they were overtopped by the storm surge and by the large storm waves that accompanied the average rise (storm surge) in water levels. Fortunately, the Plaquemines Parish protected corridor is only sparsely populated, and the local inhabitants were acutely aware of the risk that they faced so that evacuation in advance of the storm was unusually complete.

Plaquemines Parish was largely inundated by the massive storm surge and the numerous resulting levee breaches. Most breaches appear to have been primarily the result of overtopping and erosion, and it is interesting to note that these breaches occurred mainly in the "storm" levees, while the "river" levees often better withstood the storm surge (and waves) without catastrophic erosion. The devastation within Plaquemines parish produced by this flooding was very severe, as described in Chapter 5. By approximately 7:00 a.m. on the morning of Monday, September 29, most of Plaquemines Parish was under water.

A more detailed discussion of the performance of the flood protection systems in the Plaquemines Parish area is presented in Chapter 5.

As the storm surge began to raise the water levels throughout the New Orleans region, it began to raise the water levels within the GIWW, MRGO and IHNC channels. As the water level within the IHNC began to rise, the first "breach" within the metropolitan New Orleans Region (north of Plaquemines Parish) occurred at about 5:00 a.m. somewhere along the IHNC. This was evidenced by a pronounced, and short-lived, decrease in the rate of water level rise at two gage stations along the IHNC at this point in time. There are several breaches along this section of the IHNC that might have accounted for this observed water level gage behavior, and this is discussed in Chapter 8. This was a "non-catastrophic" failure; although the breach eroded and became enlarged by the flow, the "lip" of the breach remained above sea level. As a result, although water flowed for a while into the protected area, this flow later stopped as the storm surge subsequently subsided. Simple calculations, based on flood stages and breach sequences and dimensions, suggest that less than 5% of the water that eventually flowed into the main Orleans East Bank (downtown) protected zone entered through this breach.

The large onshore storm surge also raised water levels within Lake Borgne (which is directly connected to the Gulf.) Lake Borgne rose up, and outgrew its normal banks. As the storm then passed to the east of New Orleans, the prevailing counterclockwise swirl of the storm winds drove the waters of Lake Borgne as a large storm surge to the west, against the eastern flank of the regional flood protection systems as shown schematically in Figure 2.11. This produced a storm surge estimated at approximately +16 to +18 feet (MSL), as shown in Figures 2.9 and 2.10.

This storm surge level exceeded the crest heights of the levees along a nearly 11-mile long stretch of the northeastern edge of the St. Bernard/Lower Ninth Ward protected area. The levees along this frontage were intended to be built to provide protection to a level of approximately +17.5 feet (MSL), but at the time of Hurricane Katrina many of the levees along this frontage had crest elevations approximately 2 to 4 feet lower than that. This was because the levees along this frontage had not yet been completed. These were "virgin" levees, being constructed on swampy foundation soils that had not previously had significant levees before. Accordingly, the swampy shallow foundation soils were both weak and compressible, and the levees were being constructed in stages to allow time for consolidation and settlement of the foundations soils. This process also allowed time for the drying of the very wet locally excavated soils used for some portions of the levee embankment fills, and also for increases in strength of the underlying foundation soils as they compressed under the weights of the growing levees.

Construction of the first phase of the levees along this frontage began in the late 1960's. The last major work in this area prior to Katrina had been the construction of the third phase, in 1994-95. Since that time, the USACE had been waiting for Congressional appropriation of the funds necessary to construct the final stage (to the full design height, with allowance for anticipated future settlements.) Now it is too late.

In addition to the levees along this frontage being well below design grade, the manner of construction and the materials used were non-typical of most other USACE levees in the region. Ordinarily, the USACE requires the use of "cohesive" (clayey) soils to create an embankment fill that is both strong and relatively resistant to erosion. The levees along the "MRGO" frontage at the northeast edge of the St. Bernard Parish/Ninth Ward protected area were instead "sand core" levees (USACE, 1966). These levees were constructed using locally available soils, including dredge spoils from the excavation of the adjacent MRGO channel.

This is a region with predominantly marshy deposits, consisting largely of organic soils and soft paludal swamp clays with very high water contents. Beneath these generally poor surficial soils, the most common materials occurring at shallow, relatively accessible depths tend to be predominantly sandy soils that are highly erodeable and generally unsuitable for levee embankment fill. A decision was made, however, to attempt to use the locally available soils rather than importing higher quality soil fill materials. The USACE Design Memorandum describing this design refers to these as "sand core" levees (USACE, 1966).

The levees along this MRGO frontage section (along the northeastern edge of the St. Bernard protected area) were, in the end, constructed using large volumes of the spoil material excavated during the dredging of the adjacent MRGO shipping channel, and they contained unusually large quantities of highly erodeable sandy soils. In addition, some of the more cohesive (clayey) soils were too wet to be compacted effectively, and some sections of the embankments remained wet and soft for many years after construction. Chapter 6 presents a more detailed discussion of the erodeability of the levee embankments along the MRGO frontage. In simple terms, these levees were unusually massively erodeable, and this (combined with their lack of crest height) caused them to be unusually rapidly eroded as the storm surge from Lake Borgne approached and passed over, and through, these levees.

Based on analytical storm surge analyses and analytical "hindcasts" performed by various investigation teams, as well as eyewitness reports and timings of flooding and damages in St. Bernard Parish and the Ninth Ward, it is estimated that the storm surge passed over and through the MRGO levee frontage between approximately 6:00 to 7:00 a.m. The storm surge along the northeastern frontage of the St. Bernard Parish protected area peaked at approximately 7:30 to 8:00 a.m. (see Figure 2.9.) By the time the storm surge peaked along this important frontage, however, the unfinished "sand core" levees fronting Lake Borgne had been massively eroded and the brunt of the storm surge passed over and through the levees and raced across the undeveloped swamplands shown in Figure 2.11 towards the developed areas of St. Bernard Parish.

This is illustrated schematically in Figure 2.11. The levees along this frontage were so badly eroded, and so rapidly, that they did little to impede the passage of the storm surge which then crossed the roughly 7 to 10 miles of open swamp and reached the secondary levee that separates the northern (undeveloped) swampy section of this protected area from the populated southern section.

The secondary levee had not been intended to face the full fury of a storm surge of this magnitude; it had been assumed that the MRGO frontage levees would absorb much of the energy and provide more resistance. Accordingly, the storm surge passed over the secondary levee (which had lesser typical crest heights of only + 7.5 feet to + 10 feet, MSL) and washed into the populated regions of St. Bernard Parish. A number of minor breaches were produced by the overtopping (and erosion) of this secondary levee, but it is interesting to note that although this secondary levee must have been massively overtopped along much of its length, relatively little erosion damage resulted. The secondary levee was properly constructed, using compacted clayey soils, and the resulting levee embankment generally performed well with regard to resisting erosion. It was not, however, tall enough to restrain the massive overtopping from the storm surge which had passed so easily through the MRGO frontage levees.

The resulting carnage in St. Bernard Parish was devastating. A wall of water raced over the secondary levee; pushing homes laterally (Figure 2.16), flipping cars like toys and leaving them leaning against buildings, and driving large shrimp boats deep into the heart of residential neighborhoods (see Chapter 6.) The flooding of St. Bernard Parish was unexpectedly rapid. The peak depth of flooding in St. Bernard Parish was also unexpectedly deep because the floodwaters were pushed by the still rising storm surge (rather than having to flow more slowly, over time, through more finite breaches as the storm surge subsided, as occurred in most other parts of the greater New Orleans area) so that the top of the floodwaters at their peak within the developed areas were at an elevation well above mean sea level (approximately Elev. +12 feet, MSL.) Indeed, after the storm surge subsided, "notches" were excavated through a number of local levees to let floodwaters drain under gravity loading from the significantly "plus mean sea level" flooding entrapped in some areas.

Figure 2.12 shows a plot of the locations where dead bodies were retrieved after the disaster from December 2005. This map shows locations only for some of the approximately 1,296 official deaths (to date) in the greater New Orleans area, but this map serves well to show the general distribution of deaths attributed to the flooding produced by this event. As shown in Figure 2.12, approximately 30% of these deaths occurred in St. Bernard Parish. In addition to those who perished, considerable damage was done to many thousands of homes and businesses in this area (see Chapter 6.)

The same storm surge from Lake Borgne that topped and eroded the levees along the "MRGO" frontage also pushed westward over the southeastern corner of the New Orleans East protected section, as shown in Figures 2.9 through 2.11, and this produced overtopping and a number of breaches, as shown previously in Figure 2.4. This was a principal source of the catastrophic flooding that subsequently made its way across the local undeveloped swamplands and into the populated areas of New Orleans East.

This storm surge from Lake Borgne also passed westward into a V-shaped "funnel" as it entered the shared GIWW/MRGO channel that separates the St. Bernard and New Orleans East protected areas, and this in turn resulted in an elevated surge of water that passed westward along the waterway to its juncture (at a "T") with the IHNC channel, overtopping a number of levees and floodwalls on both the north and south sides of this east-west trending channel and producing levee distress and several breaches (as shown in Figures 2.4 and 2.11.) After reaching the "T" intersection with the IHNC channel, the surge then passed to the north and south (from the "T") along the IHNC channel, periodically overtopping many (but not all) of the sections of levees and floodwalls lining the east and west sides of the IHNC, and causing a number breaches as shown in Figures 2.4 and 2.11. By about 6:45 to 7:00 a.m. overtopping (by up to as much as 1 to 2 feet at it s peak at most locations) was occurring along a number of levee and floodwall sections lining the IHNC channel. This overtopping did not occur at all locations, and was only of limited duration (typically several hours or less) where it did occur.

A pair of major breaches occurred at the west end of the Lower Ninth Ward as this overtopping occurred along the IHNC, and the larger of these two breaches is shown (roughly seven weeks later, after construction of an interim repair embankment just outside the breach) in Figure 2.13. A large barge passed in through this breach, and can be seen in the rear of the photo. It is worth noting the tremendous scour-induced damage to the homes immediately inboard of this massive breach; most of the homes in Figure 2.13 were washed off of their foundations and transported laterally (often in pieces) by the inrushing floodwaters. A more detailed examination of the two large breaches at the west end of the Ninth Ward is presented in Chapter 6; Sections 6.4 and 6.5. The large breaches at the west end of the Lower Ninth Ward appear to have occurred at approximately 7:45 a.m. (Louisiana State University Hurricane Center, 2006; IPET, 2006).

Like St. Bernard Parish, the breaches at the west end of the Lower Ninth Ward occurred before the storm surge peaked (at about 8:30 a.m. in the IHNC channel), so the Lower Ninth Ward was flooded to a level well above mean sea level before the storm surge subsequently subsided. This neighborhood, which had ground surface elevations of generally between about -3 to -6 feet (MSL) was flooded to elevations of up to as much as 10 to 12 feet above sea level. The resulting carnage, in terms of both loss of life (as shown in Figure 2.12) and destruction of homes and businesses was considerable, as the flooding rose above the tops of many of the one-story homes in this densely packed neighborhood.

The protected area of New Orleans East, directly to the north of the St. Bernard Parish/Ninth Ward protected area, had been breached at its southeastern corner by the initial storm surge and lateral rush from Lake Borgne (as shown schematically in Figure 2.11) by about 7:00 a.m., though the resulting breaches were confined to several locations so that the inflowing waters began to make their way across the undeveloped swamplands of the eastern portion of this protected area and timing is thus difficult to pin down with exactitude. The storm surge then passed laterally along the GIWW/MRGO east-west channel and produced another finite breach on the north side of this channel and several additional distressed sections. This breach added to the sources of water beginning to flow into this protected area.

The surge that passed west along the GIWW/MRGO east-west channel then pushed north along the IHNC, and produced several additional breaches and distressed sections, of varying severity, along the IHNC frontage as shown in Figure 2.4. These, too, added to the flow into the protected area of New Orleans East.

The lateral storm surge that passed westward along the east-west trending GIWW/MRGO channel between New Orleans East and St. Bernard Parish also attacked the west side of the IHNC channel, at the eastern edge of the main Orleans East Bank (downtown New Orleans) protected area. This produced three additional breaches along this frontage, as shown in Figures 2.4 and 2.11. Floodwaters began to flow into the main New Orleans metropolitan (downtown) protected area through these breaches between approximately 7:00 to 8:30 a.m. Although two of these breaches were relatively long, all three breaches along this frontage failed to scour to significant depths. As a result, all three either had “lips” with lowest elevations above mean sea level, or there were points along the path from the IHNC to the breach that were above mean sea level. Accordingly, although all three breaches allowed some flow of water into the main Orleans East Bank (downtown) protected area, they allowed only limited flow and this flow stopped as the storm surge subsequently subsided. It would be the subsequent breaches in the drainage canals, to the northwest (along the edge of Lake Pontchartrain) that would prove to be devastating for this main (downtown) protected area.

As the hurricane then passed northwards to the east of New Orleans, the counterclockwise direction of the storm winds also produced a well-predicted storm surge southwards towards the south shore of Lake Pontchartrain. The lake level rose, but mainly stayed below the crests of most of the lakefront levees. The lake rose approximately to the tops of the lakefront levees at a number of locations, especially along the shoreline of New Orleans East, and there was moderate overtopping (or at least storm wave splash-over) and some resulting erosion on the crests and inboard faces of some lakefront levee sections along the Lake frontage. Significant overtopping occurred over a long section of floodwall near the west end of the New Orleans East protected area lakefront (behind the Old Lakefront Airport), where the floodwall appears to have been inexplicably lower than the adjacent earthen levee sections. This, too, added to the flow into the New Orleans East protected area, which was now beginning to fill with water even as the original storm surges subsided.

Farther to the west, the storm surge along the Pontchartrain lakefront (which peaked at about 9:00 to 9:30 a.m. at an elevation of about +10 feet, MSL) did not produce water levels sufficiently high as to overtop the crests of the concrete floodwalls atop the earthen levees lining the three drainage canals that extend from just north of downtown to Lake Pontchartrain; the 17th Street Canal, the Orleans Canal, and the London Avenue Canal. Three major breaches occurred along these canals, however, and these produced significant flooding of large areas within the Orleans East Bank protected area (as shown in Figure 2.4.) Figure 2.13 shows military helicopters lowering oversized bags of gravel into the levee breach on the east side of the 17th Street Canal, near the north end of the canal. Note that the flood waters have equilibrated, and that there is no net flow through the breach at the time of this photo.

The first breach along the drainage canals occurred near the south end of the London Avenue canal, between about 7:00 to 8:00 a.m. The second breach occurred near the north end of the London Avenue canal, and the best current estimates of the timing of this breach are between about 7:30 to 8:30 a.m. The third major breach occurred near the north end of the 17th Street canal. The main breach here occurred between about 9:00 to 9:15 a.m., but this may have been preceded by earlier visually observable distress at this same location. All three of these breaches rapidly scoured to depths well below mean sea level, so they continued to transmit water into the main Orleans East Bank (downtown) protected area after the storm surges subsided. A more detailed discussion and analyses of these catastrophic drainage canal breaches are presented in Chapter 8.

The resulting flooding of the main Orleans East Bank (Downtown) protected area was catastrophic, and resulted in at least 588 of the approximately 1,204 deaths attributed (to date) to the flooding of New Orleans by this event. Contributions to this flooding came from the overtopping and breaches along the IHNC channel at the east side of this protected area, but the majority of the flooding came from the three catastrophic failures along the drainage canals at the northern portion of this protected area.

In addition, one of the drainage canals (the Orleans Canal) had not yet been fully "sealed" at its southern end, so that floodwaters flowed freely into New Orleans during the storm surge through this unfinished drainage canal. A section of levee and floodwall approximately 200 feet in length had been omitted at the southern end of this drainage canal, so that despite the expense of constructing nearly 5 miles of levees and floodwalls lining the rest of this canal, as the floodwaters rose along the southern edge of lake Pontchartrain, the floodwaters did not rise fully within the Orleans canal; instead they simply flowed freely into downtown New Orleans.

Chapters 4 through 8 present a more detailed discussion of the performance of the flood protection systems nominally intended to protect the main Orleans East Bank area, and studies of the major failures and near failures within this critical area.

By approximately 9:30 a.m. the principal levee failures had occurred, and most of New Orleans was rapidly flooding.

2.3.3 Brief Comments on the Consequences of the Flooding of New Orleans

The consequences of the flooding of major portions of all four levee-protected areas of New Orleans were catastrophic. Approximately 85% of the metropolitan area of greater New Orleans was flooded, as shown in Figures 2.4 and 2.5. In Figure 2.4, the flooded areas are shown in pink, and those that remained still to be "unwatered" as late as September 28th are shown in darker blue. The blue cross-hatched areas were open, undeveloped swamplands, and these were also flooded but were not counted in determining the 85% flooding figure.

Large developed areas within all of the four main "protected areas" were flooded, and most remained inundated for two to three weeks before levee breaches could be repaired and the waters fully pumped out.

Figure 2.15 shows the approximate depth of flooding that remained on September 2nd, four days after Hurricane Katrina, in the St. Bernard Parish and Lower Ninth Ward protected area, based on an estimated surface water elevation of approximately +5 ft. (MSL) at that time. This is a significantly lower flood level than the estimated peak flooding to an elevation of up to +10 to 12 feet above mean sea level during the actual hurricane. The undeveloped swampland to the north of the populated areas can be seen in this Figure to also still be flooded on September 2nd, but the flood depths are not indicated.

Figure 2.16 shows the approximate depth of flooding that remained on September 2nd, again four days after the hurricane, in the New Orleans East protected area. As this protected area filled slowly during and after the hurricane, and as it was "unwatered" relatively slowly over the days and weeks that followed, this represents nearly the full depth of flooding in this area.

Figure 2.17 shows the approximate depth of flooding of the main Orleans East Bank (downtown) protected area on September 2nd. Like the New Orleans East protected area, this large protected "basin" filled relatively slowly over time. By September 2nd, the breaches has not yet all been closed by emergency repairs, so the depths of flooding in Figure 2.17 represent the nearly the full depth of flooding at its worst in this area.

Neighborhoods that were inundated exhibit stark evidence of this catastrophic flooding. Water marks, resembling oversized bathtub rings, line the sides of buildings and cars in these stricken neighborhoods, as shown in Figure 2.18. Household and commercial chemicals and solvents, as well as gasoline, mixed with the salty floodwaters in many neighborhoods, and at the time of this investigation's first field visits shortly after the event the paint on cars below the watermarks on adjacent buildings had been severely damaged, and bushes and shrubs were browned below the watermarks, but often starkly green above. Driving through neighborhoods that had been flooded, there was often the impression that one was viewing a television screen where the color of the picture was somehow distorted or altered below a horizontal line; the level at which the floodwaters had been ponded. The devastation in these neighborhoods, and its lateral extent across many miles of developed neighborhoods, was stunning even to the many experienced members of our forensic teams that had seen numerous devastating earthquakes, tidal waves, and other major disasters.

Close to major breaches, the hydraulic forces of the inflowing floodwaters often had devastating effect on the communities. Figure 2.13 shows the devastation immediately inboard from the large breach at the west end of the Ninth Ward site after the area had been unwatered. Note the numerous empty slabs where homes had been stripped away and scattered, mostly in pieces, across a large area.

Figure 2.19 shows another aspect of the flooding. This photograph shows a region within St. Bernard Parish in which some of the homes were transported from their original locations by the floodwaters, and then deposited in new locations. Figure 2.20 shows a number of homes in the Plaquemines Parish polder that were carried across the narrow polder (from left to right in this photograph) as the west side (left side of photo) "hurricane levee" or back levee was breached, and were then deposited on the crest of the Mississippi River levee. The water side slope face of the Mississippi River levee is clearly shown in this photograph, as evinced by the concrete slope face protection on the outboard side of the riverfront levee in the right foreground of the figure.

Figures 2.18 through 2.25 show examples of the devastation that occurred within the stricken flooded areas. The spray painted markings on the sides of the buildings in these areas are left by search and rescue teams, and they denote a number of important findings within each dwelling, including toxic contamination, etc. The most important numbers are those centered at the base of the large "X", as these denote the number of dead bodies found within the building. In most cases this number was "0", as for example in Figures 2.18 and 2.22. But this was not always the case. Figure 2.24 shows the outside of a dwelling in the Ninth Ward with a "3" beneath the X, indicating three deaths within. This was a housing unit, and the wheelchair ramp from the front door is askew at the bottom of the photograph. Figure 2.25 shows the muddy devastation, and a wheelchair, within this flooded structure.

Figure 2.26 gives another sense of perspective regarding the terrible and pervasive devastation wreaked by the flooding of large urbanized areas. This photo shows the flooding of an area of New Orleans East, but it could just as well be any of a number of large areas of New Orleans. Figure 2.27 gives a similar sense of perspective. In this photo, the flooded Lower Ninth Ward is in the foreground, and virtually every neighborhood shown (including those in the far background behind the tall downtown buildings) is flooded, excepting only the small area occupied by the tall buildings of the downtown area.

At the time of the writing of this report, the death toll from the flooding of New Orleans has risen to a bit more than 1,200. It is expected to continue to climb a bit higher as some of those currently listed as "missing" will likely have been drawn out into the swamps and the Gulf by the floodwaters. Loss projections continue to evolve, but estimates of overall losses have now climbed to the $100 to $ 200 billion range for the metropolitan New Orleans region.

The members of this investigation team extend their hearts and their deepest condolences to those who were devastated by Hurricane Katrina, and by the flooding of most of New Orleans. The suffering and losses of those most intimately involved are almost beyond comprehension. It must be the goal and objective of all of us that a catastrophe of this sort never be allowed to happen again.

2.4 References

Interagency Performance Evaluation Task Force, (2006), "Performance Evaluation, Status and Interim Results, Report 2 of a Series, Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System," March 10, 2006.

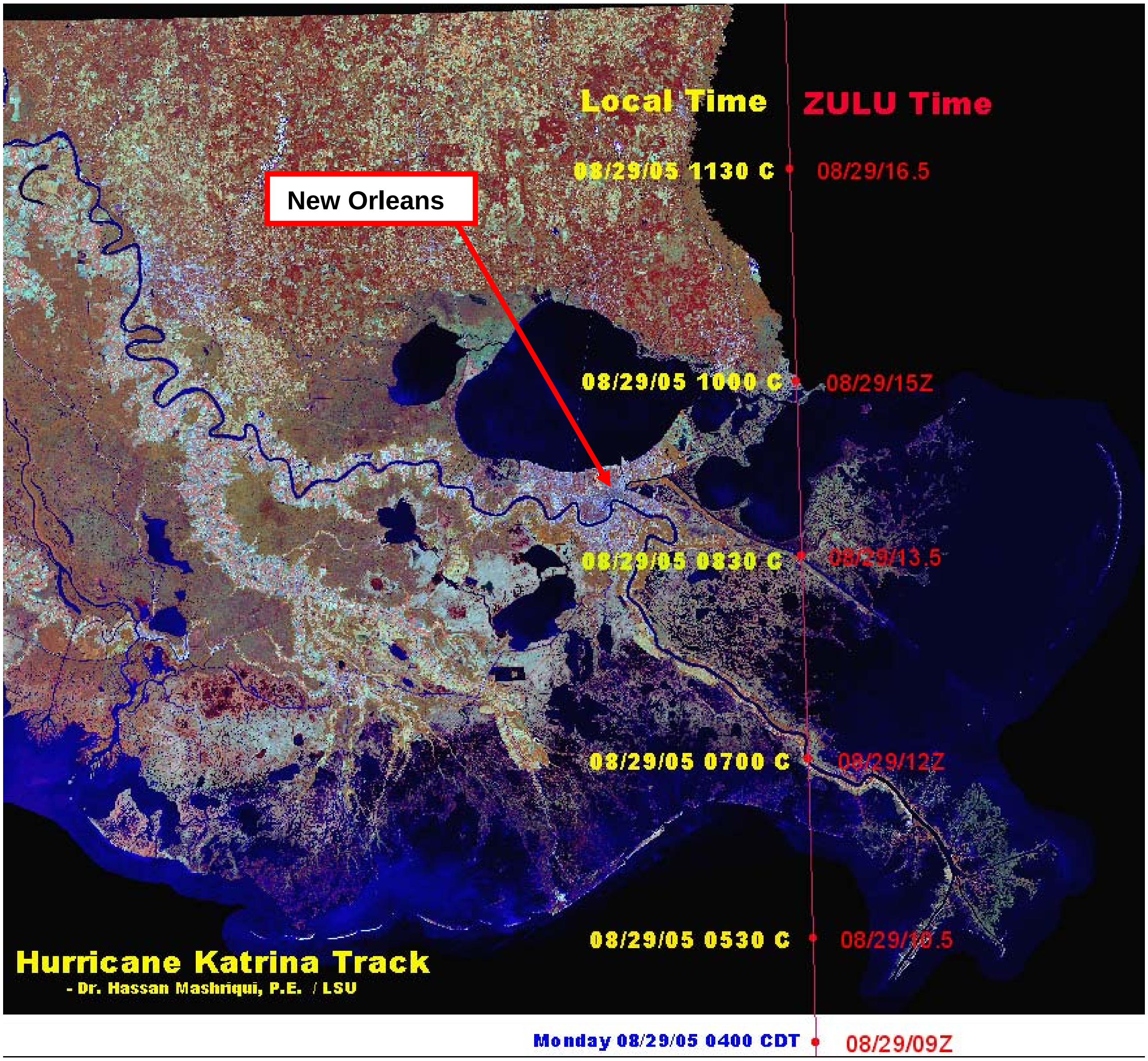
Louisiana State University Hurricane Center, (2005), "Hurricane Katrina Advisory #22," available from: http://hurricane.lsu.edu/floodprediction/katrina22/, date accessed: November 10, 2005.

United States Army Corps of Engineers, (1967), "Lake Pontchartrain, LA, and Vicinity, Chalmette Area Plan, Hurricane Protection Levee First Lift, Sta. 594+00 – Sta. 770+00 (Not Continuous)," File No. H-8-24100, May 11, 1967.

_______, (1966), "Lake Pontchartrain, LA. and Vicinity, Chalmette Area Plan, Design Memorandum No. 3, General Design," November, 1966.

Source: http://flhurricane.com/googlemap

Figure 2.1: Location of New Orleans, and map of the path of the eye of Hurricane Katrina.



Source: Mashriqui, 2006

Figure 2.2: Traced path of the eye of Hurricane Katrina at landfall in the New Orleans area.

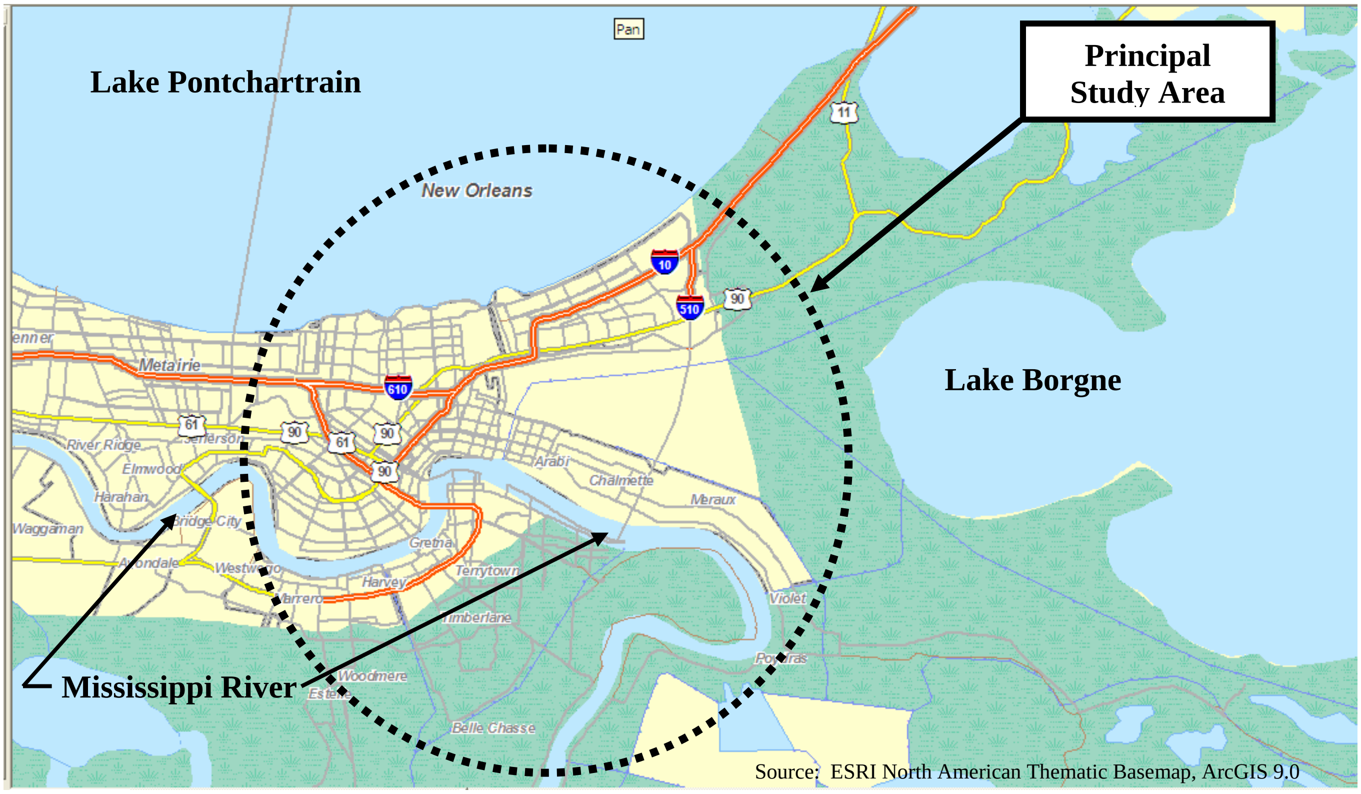
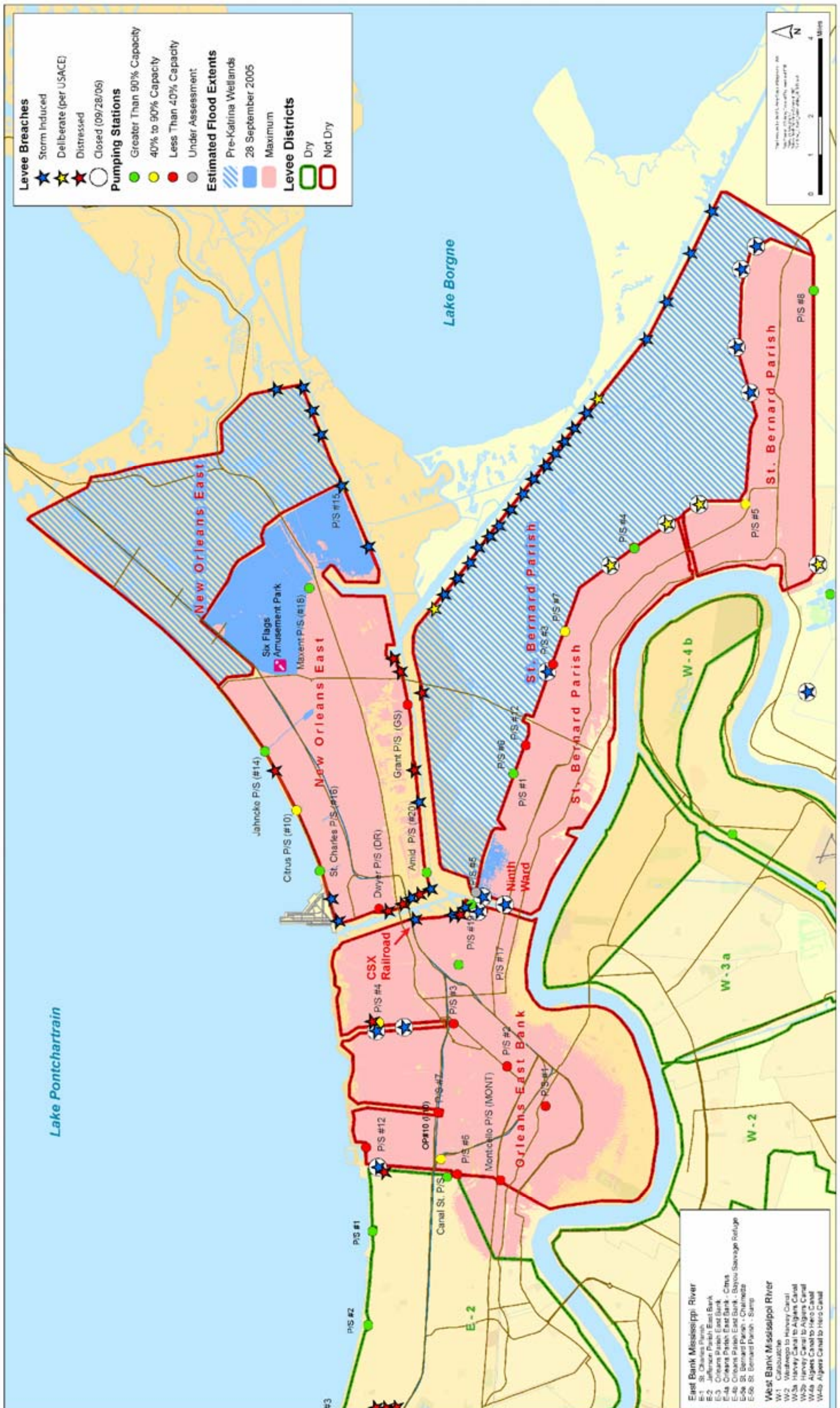
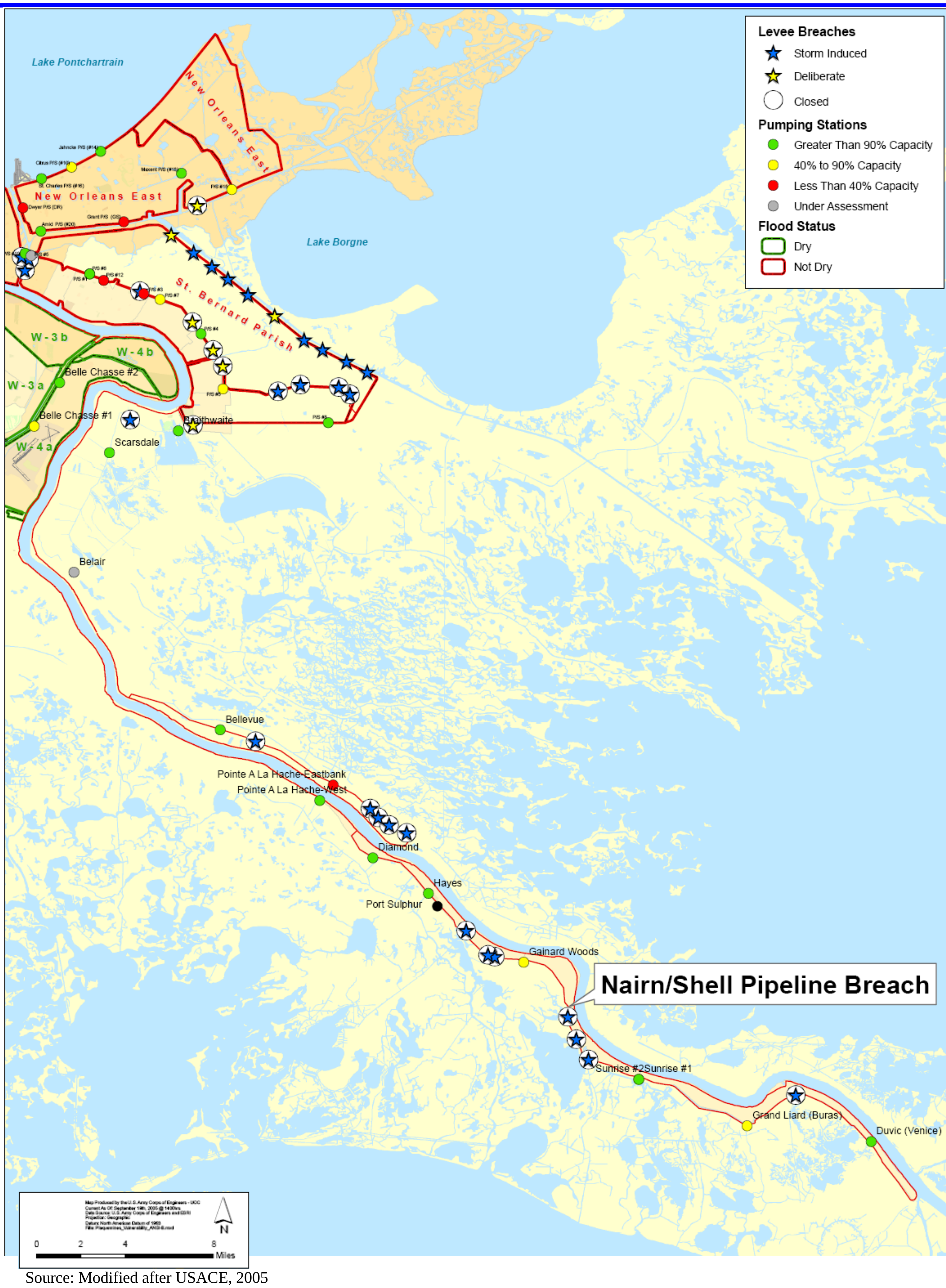


Figure 2.3: The greater New Orleans region levee and flood protection system Study Area.



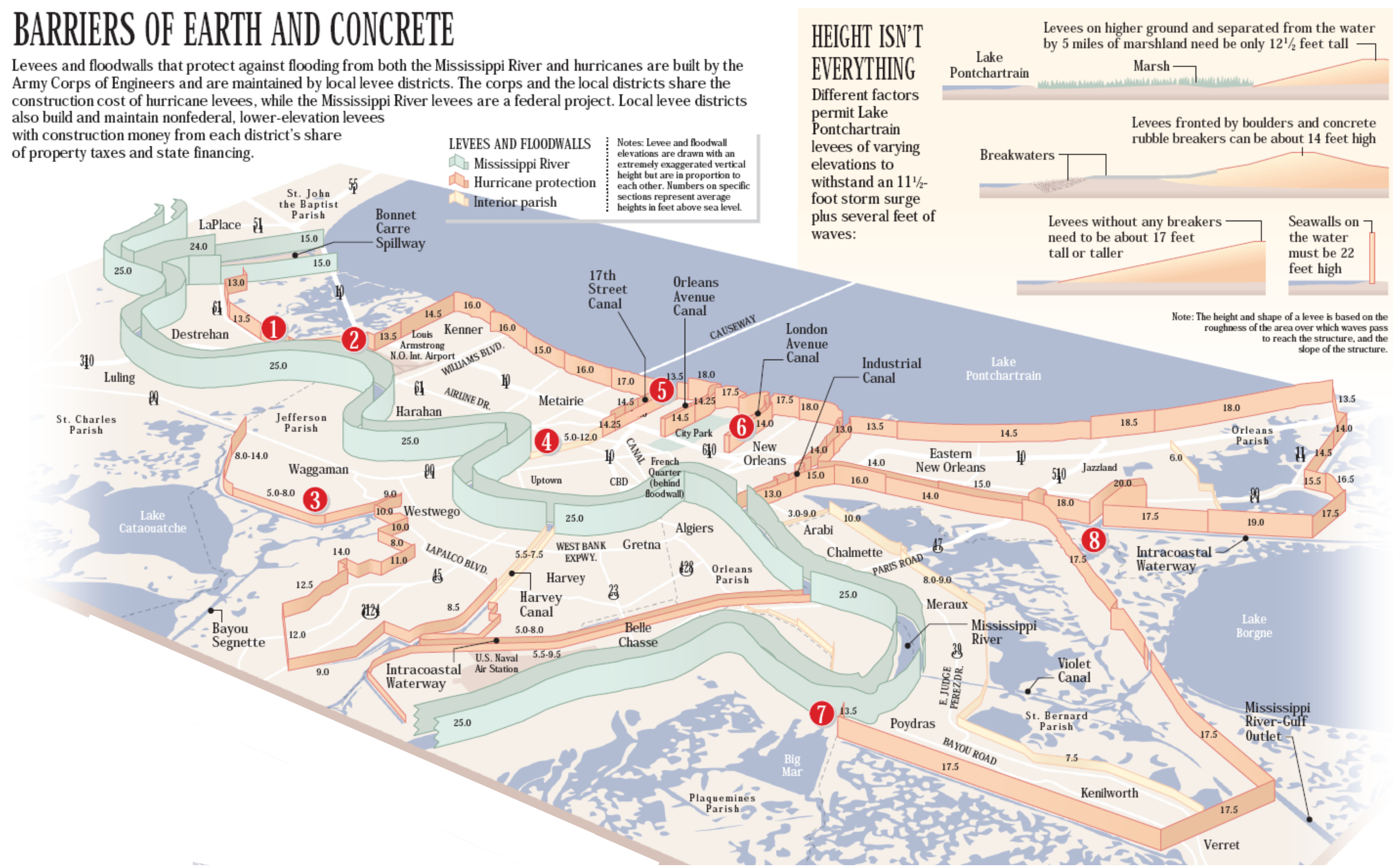
Source: Modified after USACE, 2005

Figure 2.4: Map showing principal features of the main flood protection rings or "protected areas" in the New Orleans area.



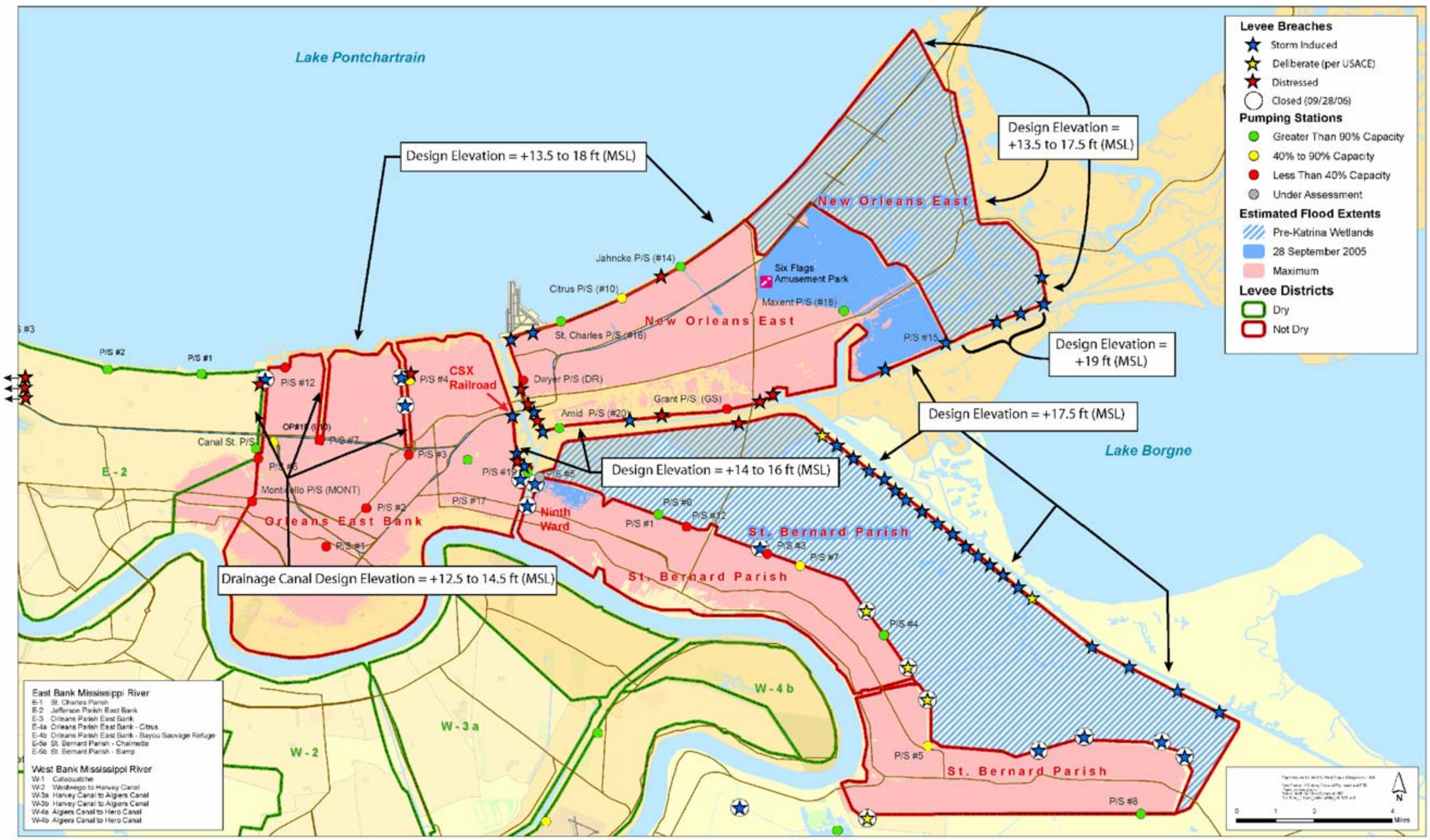
Source: Modified after USACE, 2005

Figure 2.5: Map showing the levee protected areas along the lower reaches of the Mississippi River (in the Plaquemines Parish Area.)



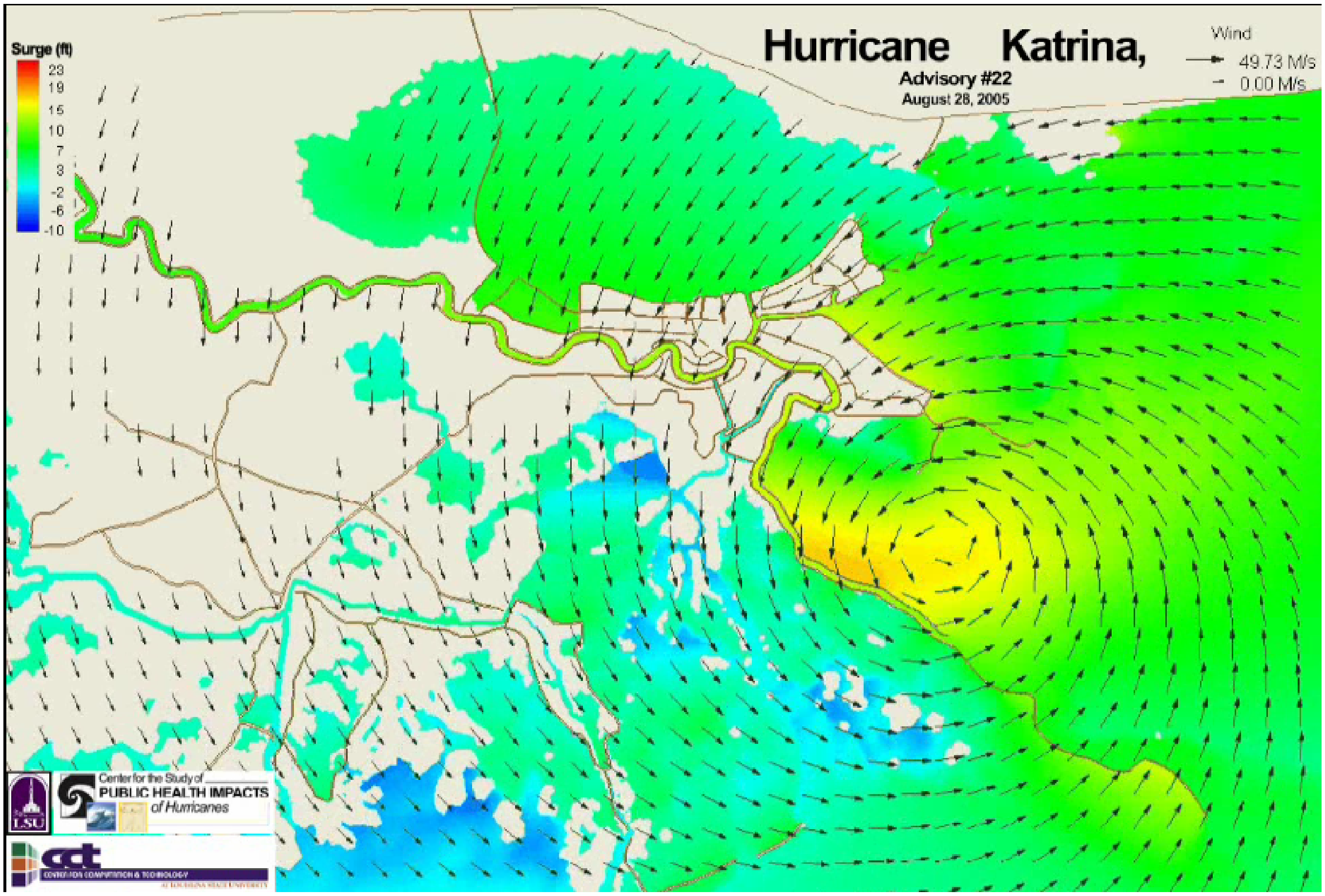
Source: Graphic by Emmet Mayer III/emayer@timespicayune.com (2005)

Figure 2.6: Map showing design flood stage elevations throughout the New Orleans region.



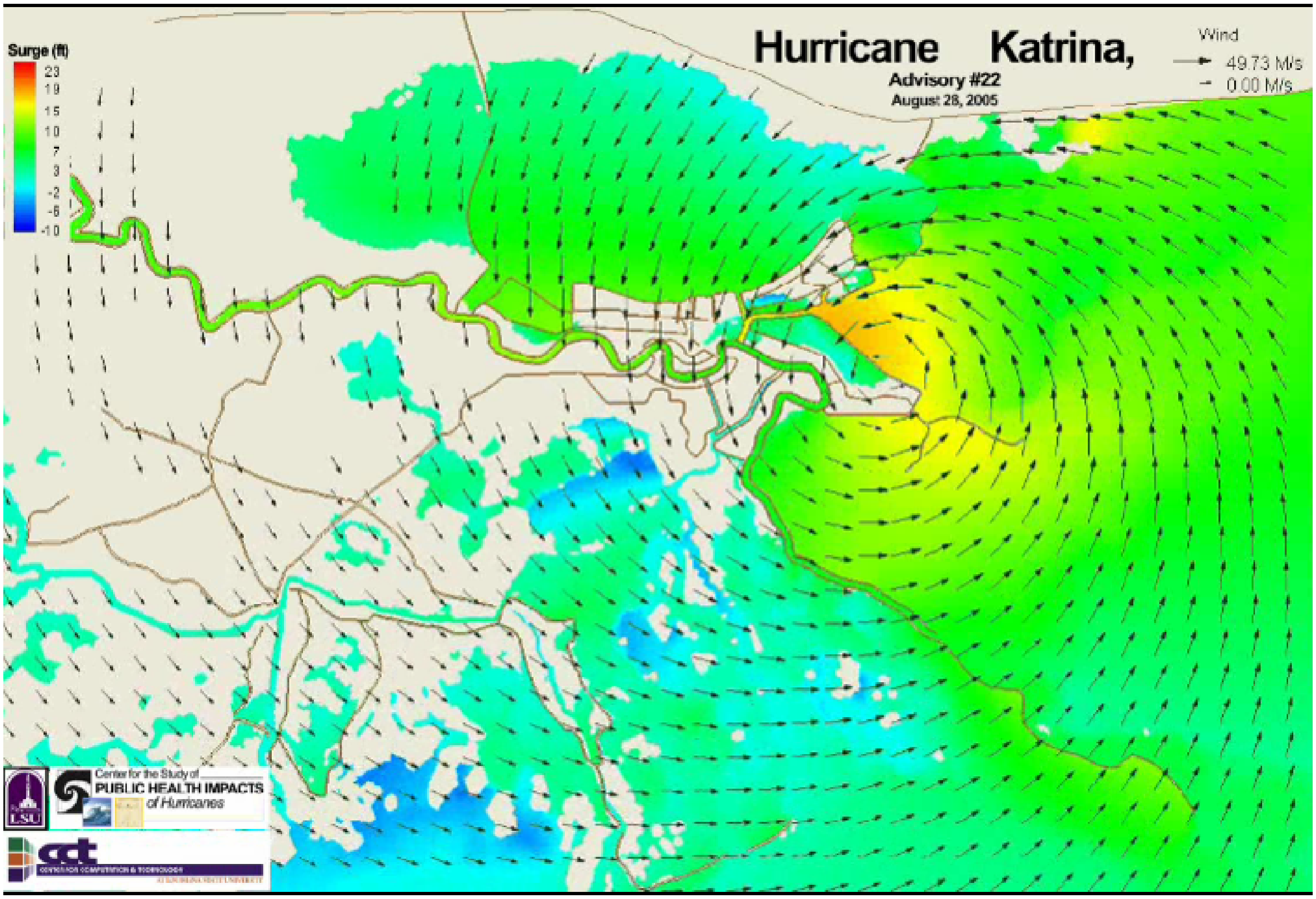
Source: Modified after USACE, 2005

Figure 2.7: Map showing the design flood stage levels for selected locations in the New Orleans Area.



Source: http://hurricane.lsu.edu/floodprediction/

Figure 2.8: Calculated storm surge against the coast at about 7:30 am (CDT), August 29, 2006.



Source: http://hurricane.lsu.edu/floodprediction/

Figure 2.9: Map of calculated storm surge levels, at time when the eye of the storm passed close to the east of New Orleans at about 8:30 am (CDT).

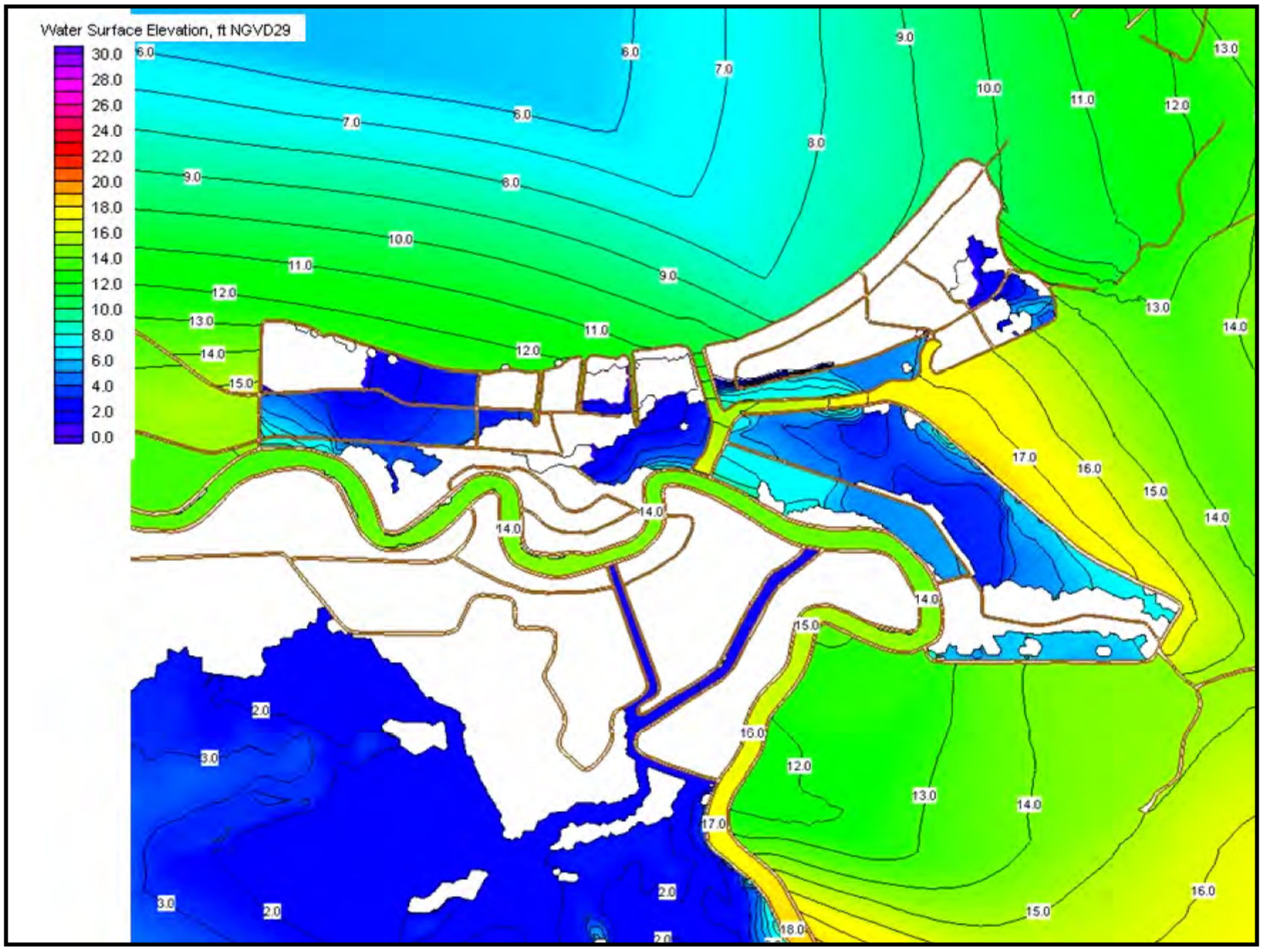
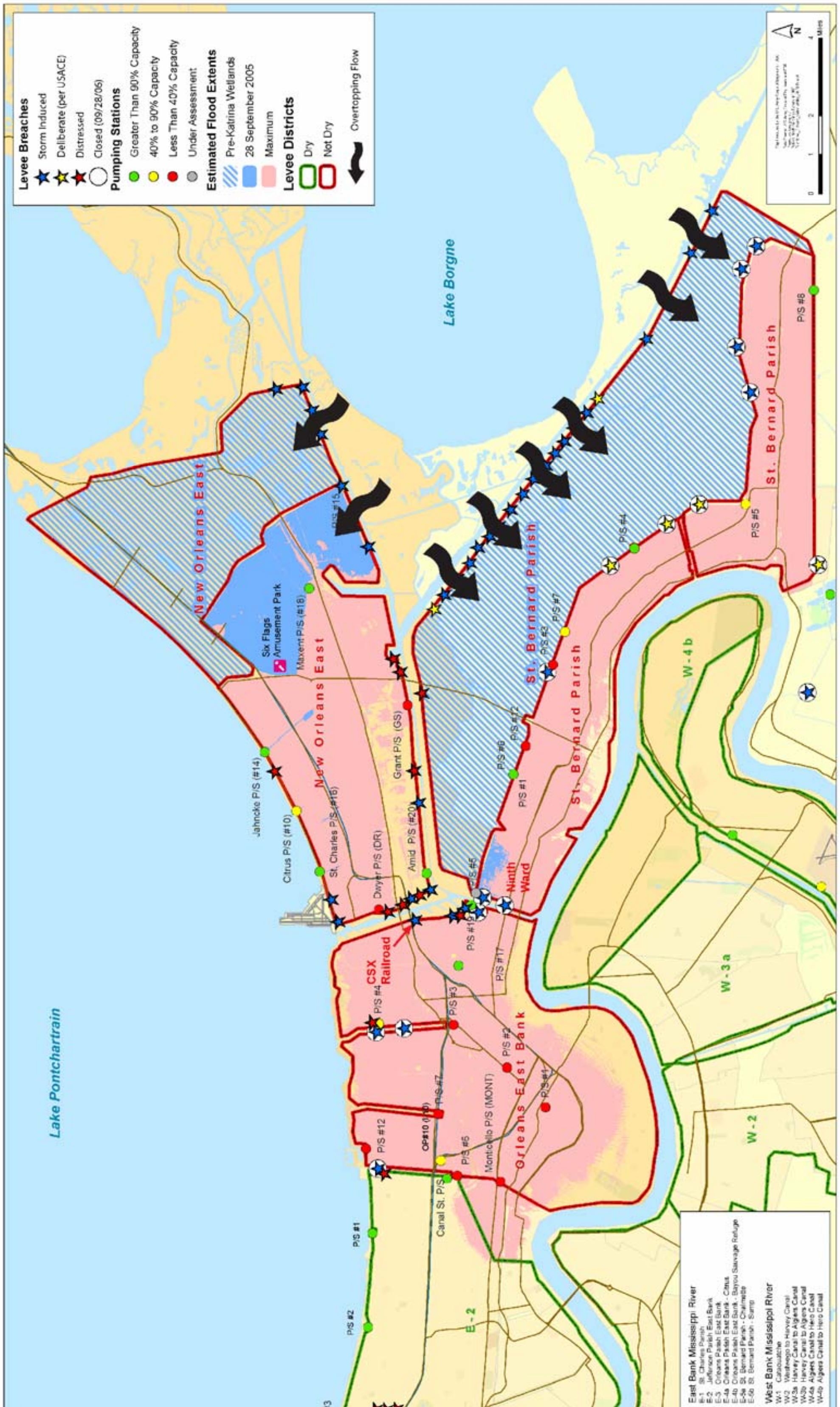


Figure V-37. Maximum computed storm surge using the ADCIRC model, metropolitan New Orleans vicinity (water levels in feet, NGVD 29)

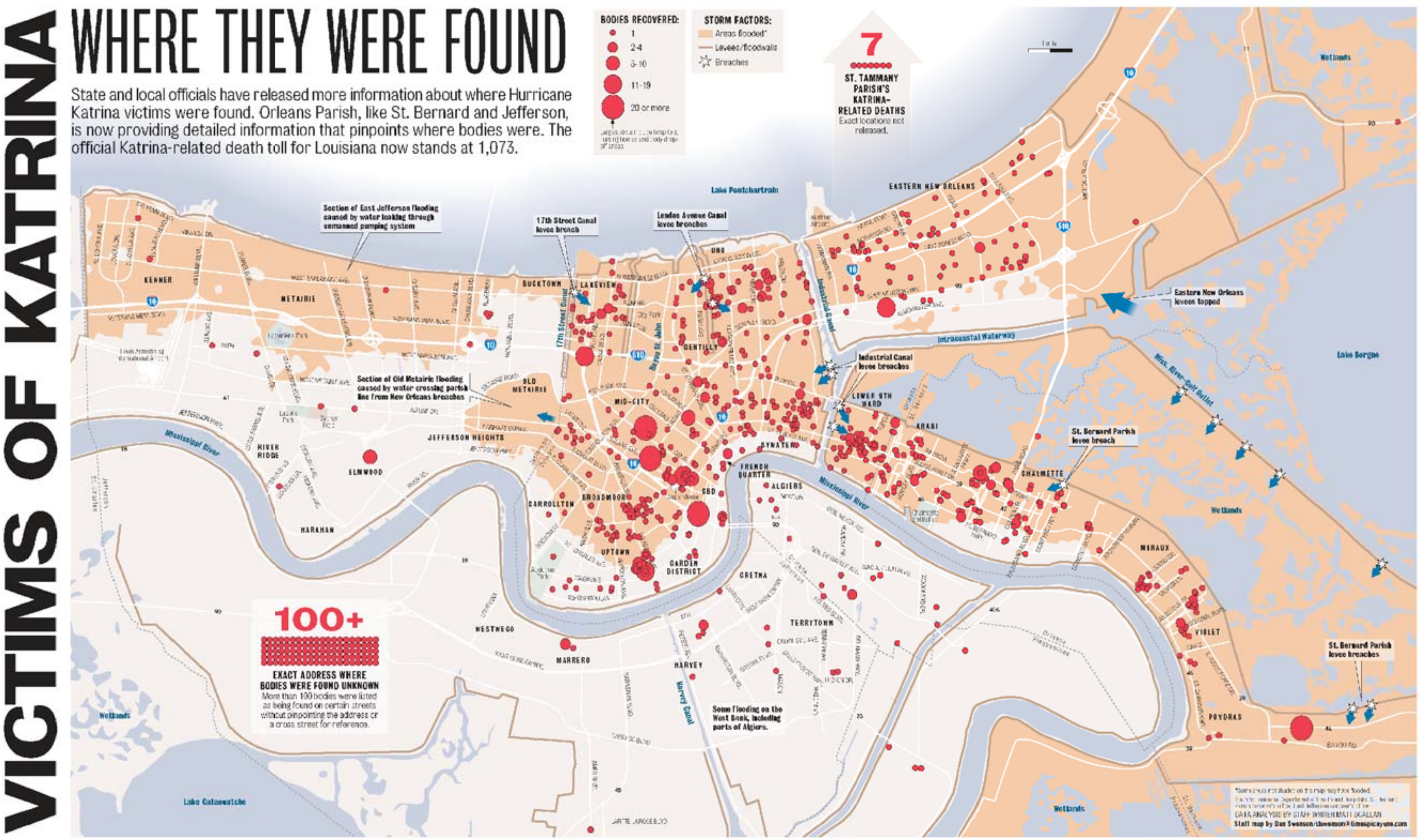
Source: IPET Interim Report No. 2; April, 2006

Figure 2.10: Map showing calculated aggregate maximum storm surge levels (maximum values at any point in time).



Source: Modified after USACE, 2005

Figure 2.11: Storm surge overtopping the eastern flank of the regional flood protection system at the northeast edge of the St. Bernard Parish and Ninth Ward protected areas.



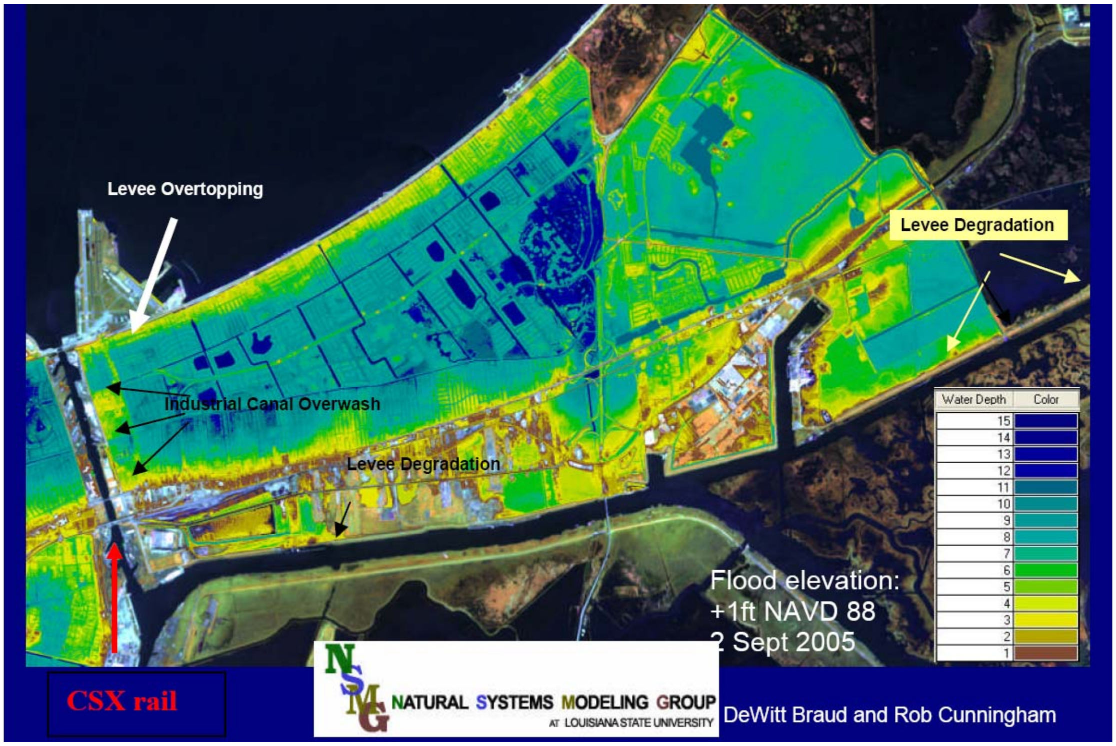
Source: Times Picayune (2005)

Figure 2.12: Map showing locations of confirmed deaths (as of December 2005) as a result of Hurricane Katrina.

Photograph by Les Harder

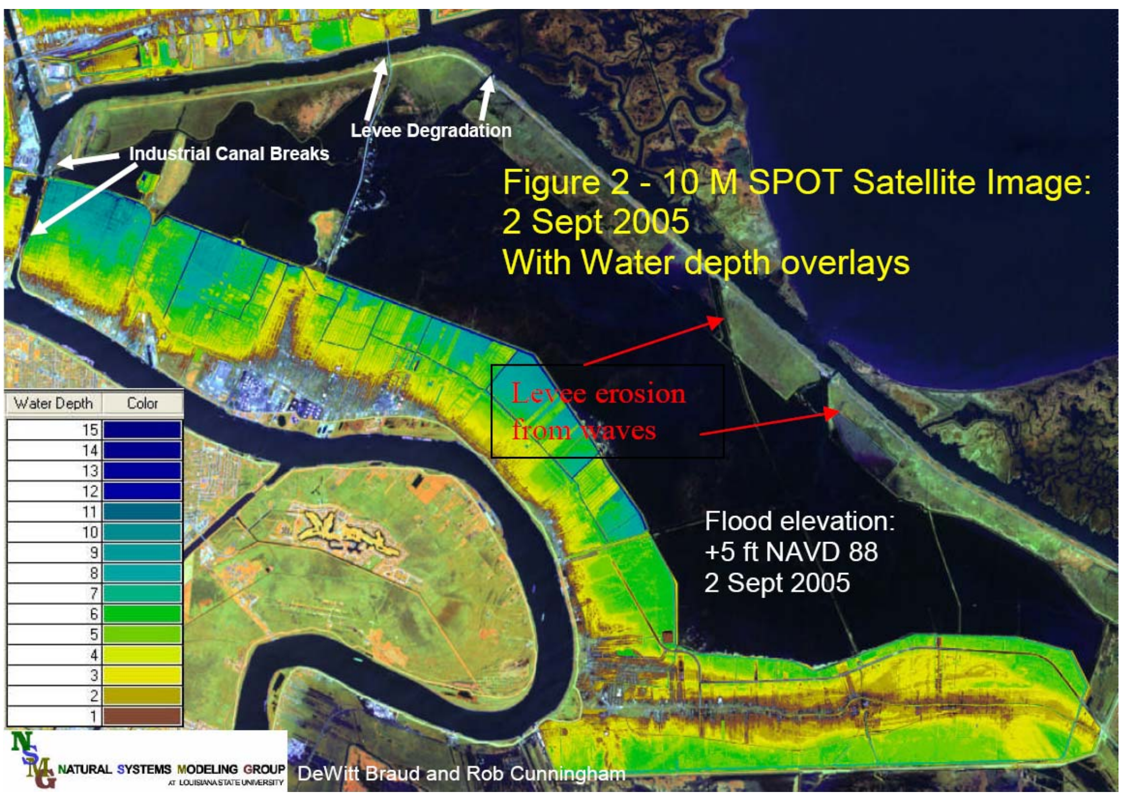
Figure 2.13: Oblique view of the (south) levee break at the Inner Harbor Navigation Canal into the lower Ninth Ward.

Figure 2.14: Initial closure of the large breach at the north end of the 17th Street Canal.



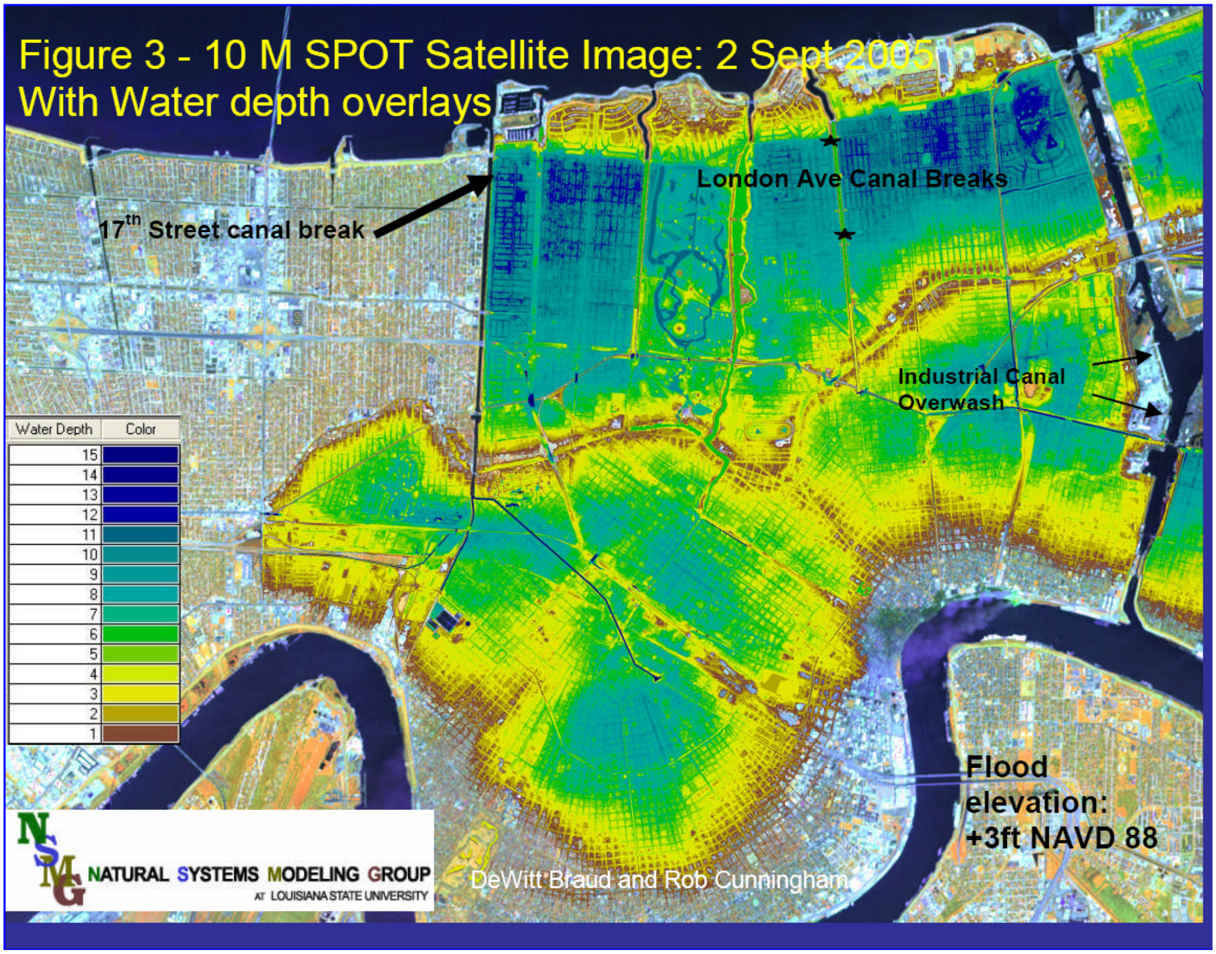
Source: LSU Hurricane Center, 2006

Figure 2.15: Depth of flooding of New Orleans East on September 2nd (4 days after Hurricane Katrina)



Source: LSU Hurricane Center, 2006

Figure 2.16: Depth of flooding of St. Bernard Parish and the Lower Ninth Ward on Sept. 2nd (4 days after Hurricane Katrina).



Source: LSU Hurricane Center, 2006

Figure 2.17: Depth of flooding of the Orleans East Bank (Downtown) protected area on September 2nd (4 days after Hurricane Katrina).

Photograph by Rune Storesund

Figure 2.18: High water marks remain on structures after temporary levee repairs have been completed and flood waters have been pumped out.

Photograph by Les Harder

Figure 2.19: Flooded neighborhood in St. Bernard Parish, showing homes floated off their foundations and transported by floodwaters.

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Photograph by Les Harder

Figure 2.20: Homes in Plaquemines Parish carried from left to right in photo and strewn across the crown of the Mississippi Riverfront levee.

Photograph by Rune Storesund

Figure 2.21: Damage to a residential neighborhood in the 17th Street Canal area due to flooding.

Photograph by Rune Storesund

Figure 2.22: Search and rescue markings on a residence in the Canal District.

Photograph by Rune Storesund

Figure 2.23: Another view of flooding damage in the Canal District.

Photograph by Les Harder

Figure 2.24: Search and rescue team markings on a building in the lower Ninth Ward where three inhabitants died.

Photograph by Les Harder

Figure 2.25: View inside structure shown previously in Figure 2.21.

Photo Courtesy of http://www.wwltv.com/sharedcontent/breakingnews/slideshow/083005_dmnkatrina/7.html

Figure 2.26: Neighborhood in New Orleans East fully flooded.

Photo courtesy of http://www.wwltv.com/sharedcontent/breakingnews/slideshow/083005_dmnkatrina/7.html

Figure 2.27: View of the City of New Orleans at the peak of the flooding.

CHAPTER THREE: GEOLOGY OF THE NEW ORLEANS REGION

3.1 General Overview of the Geology of New Orleans

3.1.1 Introduction

Hurricane Katrina brought devastation to New Orleans and the surrounding Gulf Coast Region during late August 2005. Although there was wind damage in New Orleans, most of the devastation was caused by flooding after the levee system adjacent to Lake Pontchartrain, Lake Borgne and Inner Harbor areas of the city systematically failed. The storm surge fed by winds from Hurricane Katrina moved into Lake Pontchartrain from the Gulf of Mexico through Lake Borgne, backing up water into the drainage and navigation canals serving New Orleans. The storm surge overwhelmed levees surrounding these engineered works, flooding approximately 80% of New Orleans.

Although some levees/levee walls were overtopped by the storm surge, the London Avenue and 17th Street drainage canal walls were not overtopped. They appear to have suffered foundation failures when water rose no higher than about 4 to 5 feet below the crest of the flood walls. This occurrence has led investigators to carefully investigate and characterize the foundation conditions beneath the levees that failed. A partnership between the U.S. Geological Survey's Mid-Continent Geologic Science Center and the University of Missouri – Rolla, both located in Rolla, MO, was established in the days immediately after the disaster to make a field reconnaissance to record perishable data. This engineering geology team was subsequently absorbed into the forensic investigation team led by the University of California, Berkeley.

The team has taken multiple trips to the devastated areas. During these trips team members collected physical data on the levee failures, much of which was subsequently destroyed or covered by emergency repair operations on the levees. Our team also logged a series of subsurface exploratory borings to characterize the geological conditions present in and around the levee failure sites.

3.1.2 Evolution of the Mississippi Delta beneath New Orleans

The Mississippi River drains approximately 41% of the Continental United States, a land area of 1.2 million mi^2 (3.2 million km^2). The great majority of its bed load is deposited as subaerial sediment on a well developed flood plain upstream of Baton Rouge, as opposed to subaqueous deposits in the Gulf of Mexico. The Mississippi Delta has been lain down by an intricate system of distributary channels; that periodically overflow into shallow swamps and marshes lying between the channels (Figure 3.1, upper). The modern delta extends more or less from the present-day position of Baton Rouge (on the Mississippi River) and Krotz Springs (on the Atchafalaya River). The major depositional lobes are shown in Figure 3.1 (lower).

Between 12,000 and 6,000 years ago sea level rose dramatically as the climate changed and became warmer, entering the present interglacial period, which geologists term the Holocene Epoch (last 11,000 years). During this interim sea level rose approximately 350 feet, causing the Gulf of Mexico to retreat into southeastern Louisiana inundating vast tracts of coastline. By 7,000 years ago sea level had risen to within about 30 feet of its present level. By 6,000 years ago the Gulf had risen to within 10 to 15 feet of its present level.

The modern Mississippi Delta is a system of distributary channels that have deposited large quantities of sediment over the past 6,000 to 7,000 years (Figure 1 –upper). Six major depositional lobes, or coalescing zones of deposition, have been identified, as presented in Figure 3.1 (lower). In southeastern Louisiana deltaic sedimentation did not begin until just the last 5,000 years (Saucier, 1994). Four of these emanate from the modern Mississippi River and two from the Atchafalaya River, where the sediments reach their greatest thickness. The St. Bernard Delta extending beneath Lake Borgne, Chandeleur and Breton Sounds to the Chandeleur and Breton Shoals was likely deposited between 600 and 4,700 years ago. The 50+ miles of the modern Plaquemines-Balize Delta downstream of New Orleans has all been deposited in just the last 800 to 1,000 years (Darut et al. (2005)).

During this same period (last 7,000 years) the Mississippi River has advanced its mouth approximately 200 river miles into the Gulf of Mexico. The emplacement of jetties at the river's mouth in the late 1870's served to accelerate the seaward extension of the main distributary passes (utilized as shipping channels) to an average advance of about 70 meters per year, or about six times the historic rate (Coleman, 1988; Gould, 1970). The combination of channel extension and sea level rise has served to flatten the grade of the river and its adjoining flood plains, diminishing the mean grain size of the river's bed load, causing it to deposit increasing fine grained sediments. Channel sands are laterally restricted to the main stem channel of the Mississippi River, or major distributary channels, or "passes", like the Metairie-Gentilly Ridge. The vast majority of the coastal lowland is infilled with silt, clay, peat, and organic matter.

Geologic sections through the Mississippi Embayment show that an enormous thickness of sediment has been deposited in southern Louisiana (Figure 3.2). During the Quaternary Period, or Ice Ages, (11,000 to 1.6 million years ago) the proto Mississippi River conveyed a significantly greater volume of water on a much steeper hydraulic grade. This allowed large quantities of graveliferous deposits beneath what is now New Orleans, reaching thicknesses of up to 3600 feet (Figures 3.2 and 3.3). These stiff undifferentiated Pleistocene sands and gravels generally lie between 40 and 150 feet beneath New Orleans, and much shallower beneath Lake Pontchartrain and Lake Borgne (as one approaches the Pleistocene outcrop along the North Shore of Lake Pontchartrain).

Just south of the Louisiana coast, the Mississippi River sediments reach thicknesses of 30,000 feet or more. The enormous weight of this sediment mass has caused the earth's crust to sag in this area, resulting in a structure known as the Gulf Geosyncline (Figure 3.2). Flow of mantle material from below the Gulf Geosyncline is causing an uplift along about the latitude of Wiggins, MS. This is one cause of subsidence in South Louisiana (discussed in Section 3.7.2).

Figure 3.4 presents a generalized geologic map of the New Orleans area, highlighting the salient depositional features. Depth contours on the upper Pleistocene age (late Wisconsin glacial stage) horizons are shown in red. Sea level was about 100 feet lower than present about 9000 years ago, so the -100 ft contour represents the approximate shoreline of the Gulf at that time, just south of the current Mississippi River channel. Figure 3.5 presents a more detailed view of the dissected late Wisconsin stage erosional surface beneath New Orleans. This system emanates from the Lake Pontchartrain depression and reaches depths of 150 feet below sea level where it is truncated by the modern channel of the Mississippi River, which is not as deeply incised. A veneer of interdistributary deltaic deposits covers this older surface and is widely recognized for having spawned differential settlement of the cover materials where variations in thickness are severe, such as the Garden District.

3.1.3 Pine Island Beach Trend

Relict beach deposits emanating from the Pearl River are shown in stippled yellow on Figure 3.4. Saucier (1963) named these relict beaches the Pine Island and Miltons Island beach trends. These sands emanate from the Pearl River between Louisiana and Mississippi, to the northeast. The Miltons Island Beach Trend lies beneath the north shore of Lake Pontchartrain, while the Pine Island Beach Trend runs northeasterly, beneath the Lakeview and Gentilly neighborhoods of New Orleans up to the Rogolets. The Pine Island Beach Trend is believed to have been deposited when sea level had almost risen to its present level, about 4500 years ago. At that juncture, the rate of sea level rise began to slow and there was an unusually large amount of sand being deposited near the ancient shoreline by the Pearl River, which was spread westerly by longshore drift, in a long linear sand shoal, which soon emerged into a beach ridge along a northeast-southwest trend (Saucier, 1963). The subsequent development of accretion ridges indicate that shoreline retreat halted and the beach prograded southwestward, into what is now the Gentilly and Lakeview areas. By about 5,000 years ago, the beach has risen sufficiently to form a true barrier spit anchored to the mainland near the present Rigolets, with a large lagoon forming on its northern side (what is now Lake Pontchartrain, which occupies an area of 635 mi^2).

Sometime after this spit formed, distributaries of the Mississippi River (shown as yellow bands on Figure 3.4) began depositing deltaic sediments seaward of the beach trend, isolating it from the Gulf of Mexico. The Pine Island Beach Trend was subsequently surrounded and buried by sediment and the Pine Island sands have subsided 25 to 45 feet over the past 5,000 years (assuming it once stood 5 to 10 feet above sea level). The distribution of the Pine Island Beach Trend across lower New Orleans is shown in Figure 3.6. The Pine Island sands reach thicknesses of more than 40 feet in the Gentilly area, but diminish towards the Lakeview area, pinching out near the New Orleans/Jefferson Parish boundary (close to the 17th Street Canal breach). The Pine Island beach sands created a natural border that helped form the southern shoreline of Lake Pontchartrain, along with deposition by the Mississippi River near its present course. Lake Pontchartrain was not sealed off entirely until about 3,000 years ago, by deposition in the St. Bernard's Deltaic lobe (Kolb, Smith, and Silva, 1975). The Pine Island Beach Trend peters out beneath Jefferson Parish, as shown in Figures 3.6 and 3.13.

3.1.4 Interdistributary Zones

Most of New Orleans' residential areas lie within what is called an interdistributary zone, underlain by lacustrine, swamp, and marsh deposits, shown schematically in Figure 3.7. This low lying area rests on a relatively thin deltaic plain, filled with marsh, swamp, and lacustrine sediments. The drainage canals were originally constructed between 1833-78 on interdistributary embayments, which are underlain by fat clays deposited in a quiet water, or paludal, environment (Kolb and Van Lopik, 1958).

Interdistributary sediments are deposited in low lying areas between modern distributory channels and old deltas of the Mississippi River, shown schematically in Figure 3.8. The low angle bifurcation of distributary streams promotes trough-like deposits that widen towards the gulfward. Sediment charged water spilling over natural channel levees tends to drop its coarse sediment closest to the channel (e.g. Metairie and Gentilly Ridges) while the finest sediment settles out in shallow basins between the distrubutaries. Fine-grained sediment can also be carried into the interdistributary basins through crevasse-splays well upstream, which find their way into low lying areas downstream. Storms can blow sediment-laden waters back upstream into basins, while hurricanes can dump sediment-laden waters onshore, though these may be deposited in a temporarily brackish environment.

Considerable thickness of interdistributary clays can be deposited as the delta builds seaward. Kolb and Van Lopik (1958) noted that interdistributary clays often grade downward into prodelta clays and upward into richly organic clays of swamp or marsh deposits. The demarcation between clays deposited in these respective environments is often indistinct. True swamp or marsh deposits only initiate when the water depth shallows sufficiently to support vegetation (e.g. cypress swamp or grassy marsh). The interdistributary zone is typified by organic clays, with about 60% by volume being inorganic fat clays, and 10% or less being silt (usually in thin, hardly discernable stringers). Kolb and Van Lopik (1958) reported cohesive strengths of interdistributary clays as ordinarily being something between 100 and 400 psf. These strengths, of course, depend also on the past effective overburden pressure.

Careful logging is required to identify the depositional boundary between interdistributary (marsh and swamp) and prodelta clays (Figure 3.9). The silt and fine sand fractions in interdistributary materials are usually paper-thin partings. Prodelta clays are typified by a massive, homogeneous appearance with no visible planes or partings. Geologically recent interdistributary clays, like those in lower New Orleans, also tend to exhibit underconsolidation, because they were deposited so recently. Interdistributary clays in vicinity of South Pass (45 miles downstream of New Orleans) exhibit little increase in strengths to depths of as much as 375 ft. This is because these materials were deposited rapidly, during the past 600 to 1,000 years, and insufficient time has passed to allow for normal consolidation, given the low drainage characteristics of the units. This phenomenon was noted and analyzed for offshore clays by Terzaghi (1956). The older prodelta clays underlying recent interdistributary clays tend to exhibit almost linear increase of density and strength with depth, because these materials were deposited very slowly. So, the environment of deposition greatly impacts soil strength.

3.1.5 Paludal Environments

Paludal environments on the Mississippi River deltaic plain are characterized by organic to highly organic sediments deposited in swamps and marshes. Paludal environments are typified half-land and half-water, with water depths seldom exceeding two feet above mean gulf level. 90% of New Orleans is covered by swamp or marsh deposits (excluding filled areas). Lacustrine (lake) and tidal channel deposits can be complexly intermingled with swamp and marsh deposits.

3.1.5.1 Marshes

More than half of the New Orleans area was one covered by marshes, essentially flat areas where the only vegetation is grasses and sedges. Tufts of marsh grass often grow with mud or open water between them. When these expanses are dry, locals often refer to them as "prairies." As the marshes subside, grasses become increasingly sensitive to increasing salinity. As grasses requiring fresh water die out, these zones transition into a myriad of small lakes, eventually becoming connected to an intricate network of intertidal channels that rise and fall with diurnal tides. These are often noted on older maps as "brackish" or "sea marshes" to discern them from adjoining fresh water swamps and marshes (Figure 3.9).

<u>Marsh deposits</u> in New Orleans are typically comprised of organic materials in varying degrees of decomposition. These include peats, organic oozes, and humus formed as marsh plants die and are covered by water. Because the land is sinking, subaerial oxidation is limited, decay being largely fomented by anerobic bacteria. In stagnant water thick deposits consisting almost entirely of organic debris are commonplace. The low relative density of these materials and flooded nature provides insufficient effective stress to cause consolidation. As a consequence, the coastal marsh surface tends to "build down," as new vegetation springs up each year at a near-constant elevation, while the land continues to subside. In areas bereft of inorganic sediment, thick sequences of organic peat will accumulate, with low relative density. If the vegetation cannot keep pace with subsidence, marine waters will inundate the coastal marsh zone, as noted in the 1849 map in Figure 3.10.

<u>Peats</u> are the most common variety of marsh deposits in New Orleans. They usually consist of brown to black fibrous or felty masses of partially decomposed vegetative matter. Materials noted on many of the older boring logs as "muck" or "swamp muck" are usually detrital organic particles transported by marsh drainage or decomposed vegetative matter. These mucks are watery oozes that exhibit very low shear strength and cannot support any appreciable weight.

<u>Inorganic sediments</u> may also accumulate in marshes, depending on the nearness of a sediment source(s). Common examples are sediment-laden marine waters and muddy fluvatile waters. Brackish marsh deposits interfinger with fresh water deposits along the southern shore of Lake Pontchartrain, but dominate the shoreline around Lake Borgne. Floating marsh materials underlie much of the zone along old watercourses, like Bayou St. John and Bayou des Chapitoulas. Kolb and Van Lopik (1958) delineated four principal types of marsh deposits in New Orleans:

1. Fresh water marsh consists of a vegetative mat underlain by clays and organic clays. Fresh water marshes generally form as a band along the landward border of established marshes and in those areas repeatedly subjected to fresh water inundation. In most instances an upper mat of roots and plant parts at least 12 inches thick overlies fairly soft organic clays, which become firmer and less organic with depth. Peat layers are often discontinuous and their organic content is usually between 20 and 50%.

2. Floating marsh or flotant is a vegetative mat underlain by organic ooze. This is sometimes referred to as a "floating fresh marsh" or "floating three-cornered grass marsh." The vegetative mat is typically between 4 and 14 inches thick, floating on 3 to 15 ft of finely divided muck or organic ooze, grading into clay with depth. The ooze often consolidates with depth and grades into a black organic clay or peat layer.

3. Brackish-fresh water marsh sequence consists of a vegetative mat underlain by peat. The upper mat of roots and recent marsh vegetation is typically 4 to 8 inches thick and underlain by 1 to 10 ft of coarse to medium textured fibrous peat. This layer is often underlain by a fairly firm, blue-grey clay and silty clay with thick lenses of dark grey clays and silty clays with high organic contents. The great majority of marsh deposits in New Orleans are of this type, with a very high peat and humus content, easily revealed by gravimetric water content and/or dry bulk density values.

4. Saline-brackish water marsh is identified by a vegetative mat underlain by clays. These are sometimes termed "drained salt marshes" on older maps. The typical sequence consists of a mat of roots, stems, and leaves from 2 to 8 inches thick, underlain by a fairly firm blue-grey clay containing roots and plant parts. Tiny organic flakes and particles are disseminated through the clay horizon. The clays tend to become less organic and firmer with depth. The saline to brackish water marsh occupies a belt ½ to 8 miles wide flanking the present day shoreline, along the coast.

The strengths of marsh deposits are generally quite low, depending on their water content. Embankments have been placed on vegetative mats underlain by ooze, supporting as much as 2 or 3 psi of loading, provided it is uniformly applied over reasonable distances, carefully (Kolb and Van Lopik, 1958). Field observations of sloped levees founded on such materials indicate failure at heights of around 6 feet, which exert pressures close to those cited above.

3.1.5.2 Swamps

Before development, swamps in the New Orleans were easily distinguishable from marshes because of the dense growth of cypress trees. All of the pre-1900 maps make reference to extensive cypress marshes in lower New Orleans, between the French Quarter and Lake Pontchartrain (Figure 3.11). Encountering cypress wood in boreholes or excavations is generally indicative of a swamp environment. These cypress swamps thrived in 2 to 6 feet of water, but cannot regenerate unless new influx of sediment is deposited in the swamp, reducing the water depth. Brackish water intrusion can also cause flocculation of clay and premature die out of the Cypress trees.

Two layers of cypress swamp deposits are recognized to extend over large tracts of New Orleans (WPA-LA, 1937). The upper layer is the historic swamp occupying the original ground surface where infilling has occurred since the founding of the city in 1718; and the second; is a pervasive layer of cypress tree stumps that lies 20 to 30 feet below the ground surface, around -25 ft MSL. This older cypress forest was undoubtedly killed off and buried in a significant pre-historic flood event, fomented by considerable deposition of inorganic sediment. This sudden influx of sediment may have come from a crevasse-splay along the Mississippi River upstream of New Orleans, as in most of the damaging floods that befell the city prior to 1849.

There are two principal types of swamps in the New Orleans area, inland swamps and mangrove swamps. Inland swamps typically occupy poorly drained areas enclosed by higher ground; either natural levee ridges (like Metairie Ridge) or, much older (Pleistocene age) Prairie Terraces. These basins receive fresh water from overflow of adjacent channels during late spring and early summer runoff. The trees growing in inland swamps are very sensitive to increases in salinity, even for short-lived periods. Continued subsidence allows eventual encroachment of saline water, gradually transforming the swamp to a grassy marsh. The relative age of the tree die-off is readily seen in the form of countless dead tree trunks, followed by stumps, which become buried in the marsh that supersedes the swamp. As a consequence, a thin veneer of marsh deposits often overlies extensive sequences of woody swamp deposits. The converse is true in areas experiencing high levels of sedimentation, such as those along the historic Mississippi and Atachafalaya River channels, where old brackish water marshes are buried by more recent fresh water swamp deposits. Swamp deposits typically contain logs, stumps, and aboreal root systems, which are highly permeable and conductive to seepage.

Mangrove swamps are the variety that thrives in salt water, with the two principal varieties being black and honey mangrove. Mangrove swamps are found along the distal islands of the Mississippi Delta, such as Timbalier, Freemason North, and the Chandeleur Islands, well offshore. Mangrove swamps also fringe the St. Bernard Marsh, Breton and Chandeleur Sounds, often rooting themselves on submerged natural levees. Mangrove swamps can reach heights of 20 to 25 feet in Plaquemines Parish. A typical soil column in a mangrove swamp consists of a thin layer of soft black organic silty clay with interlocking root zone that averages 5 to 12 inches thick. Tube-like roots usually extend a few inches above the ground surface. Thicknesses of five feet or more are common. Where they grow on sandy barrier beaches, the mangrove swamps thrive on the leeward side, where silts and clays intermingle with wash-over sands off the windward side, usually mixed with shells.

Surficial swamp deposits provide the least favorable foundations for structures and man-made improvements, like streets and buried utilities. Kolb and Saucier (1982) noted that the amount of structural damage in New Orleans was almost directly proportional to the thickness of surficial organic deposits (swamps and marshes). This peaty surface layer reaches thicknesses of up to 16 ft, as shown in Figure 3.12. Most of this foundation distress is attributable to differential settlement engendered by recent de-watering (discussed in Section 3.7.4).

3.1.5.3 Lacustrine Deposits

Lacustrine deposits are also deposited in a paludal environment of deltaic plains. This sequence most often occurs as marshes deteriorate (from lack of sediment) or subside (or both). These lakes vary in size, from a few feet in diameter to the largest, Lake Salvador (a few miles southwest of New Orleans), which measures 6 by 13 miles. Lake Pontchartrain (25 x 40 miles) is much larger, but is not a true marshland lake. The depths of these lakes varies from as little as 1.5 feet to about 8 feet (Lake Pontchartrain and Lake Borgne average 15 and 10 feet deep, respectively).

Small inland lakes within the marsh environment usually evolve from subsidence and erosion from wind shear and hurricane tides. Waves set up a winnowing action which concentrates the coarser material into the deepest portion of the lake. These lakes are generally quite shallow, often only a foot or two deep, even though up to a mile long. They are simply water-filled depressions on the underlying marsh, often identified in sampling by fine grained oozes overlying peats and organic clays of the marsh that preceded the transition to lake. The ooze become increasingly cohesive with age and depth, but is generally restricted to only 1 to 3 feet in thickness in small inland lakes.

Transitional lakes are those that become larger and more numerous closer to the actively retreating shoreline of the delta. These lake waters are free to move with the tides and currents affecting the open water of adjacent bays and sounds. Fines are often winnowed from the beds of these lakes and moved seaward, leaving behind silts and fine sands. Sediments in these lakes are transitional between inland lakes and the largely inorganic silty and sandy materials flooring bays and sounds.

Large inland lakes are the only lacustrine bodies where significant volumes of sediment are deposited. Principal examples would be the western side of Lake Borgne, Lake Pontchartrain, and Lake Maurepas, among others. Lacustrine clays form a significant portion of the upper 20 to 30 feet of the deltaic plain surrounding New Orleans. Lake Pontchartrain appears to have been a marine water body prior to the deposition of the Metairie Ridge distributary channel, which formed its southern shoreline, sealing it off from the Gulf. The central and western floor of Lake Pontchartrain is covered by clays, but the northern, eastern and southern shores are covered by silts and sands, likely due to the choppy wave-agitated floor of the shallow lake. Deeper in the sediment sequence oyster shells are encountered, testifying that saline conditions once existed when the lake was open to the ocean. The dominant type of mollusk within Lake Pontchartrain today is the clam Rangia cuneata, which favors brackish water. Dredging for shells was common in Lake Pontchartrain until the late 1970's.

During Hurricanes Katrina and Rita in 2005, wind shear removed extensive tracts of marsh cover, creating 118 square miles of new water surface in the delta. Forty-one square miles of shear-expanded pools were added to the Breton Sound Basin within Plaquemines

Parish. This was more erosion and land loss than had occurred during the previous 50 years combined (Map USGS-NWRC 2006-11-0049).

3.1.6 Recognition Keys for Depositional Environments

Marsh deposits are typified by fibrous peats; from three principal environments: Fresh water marshes; 2) floating marsh – roots and grass sitting on an ooze of fresh water; and 3) saltwater marshes along the coast. The New Orleans marsh tends to be grassy marsh on a flat area that is "building down," underlain by soft organic clays. Low strength smectite clays tend to flocculate during brackish water intrusions, most commonly triggered by hurricanes making landfall in the proximate area.

Typical recognition keys for depositional environments have been summarized as follows.

- Cypress wood = fresh water swamp
- Fibrous peaty materials = marshes
- Fat Clays with organics; usually lacustrine. A pure fat clay has high water content (w/c) and consistency of peanut butter
- Interdistributary clays; paludual environments; lakes - Silt lenses when water is shallow and influenced by wind swept waves
- Lean clays CL Liquid Limit (LL) <50, silty and w/c <60%
- Fat clays CH Liquid Limit (LL) >50 no silt and w/c >70%

Abandoned meanders result in complex mixtures of channel sands, fat clay, lean clay, fibrous peat, and cypress swamp materials, which can be nearly impossible to correlate linearly between boreholes. The New Orleans District of the Corps of Engineers has historically employed 3-inch diameter Steel Shelby tubes and 5-inch diameter piston sampler, referring to samples recovered from the 5-inch sampler as their "undisturbed samples." These are useful for characterizing the depositional environment of the soils. The larger diameter "undisturbed" samples are usually identified on boring logs and cross sections in the New Orleans District Design Memoranda by the modifier "U" for "undisturbed" samples (e.g. Boring prefixes X-U, UMP-X, MUE-X, MUG-X, and MUW-X).

3.1.7 Holocene Geology of New Orleans

The surficial geology of the New Orleans area is shown in Figure 3.13. The Mississippi River levees form the high ground, underlain by sands (shown as bright yellow in Figure 3.13). The old cypress swamps (shown in green) and grassy marshlands (shown in brown) occupied the low lying areas. The Mid-town area between the Mississippi and Metairie Ridge was an enclosed depression (shown in green) known as a "levee flank depression" (Russell, 1967). The much older Pleistocene age Prairie formation (shown in ochre) lies north of Lake Pontchartrain. This unit dips down beneath the city and is generally encountered at depths greater than 40 feet between the city (described previously).

The levee backslope and former swamplands north of Metairie Ridge are underlain by four principal stratigraphic units, shown in Figure 3.14. The surface is covered by a thin veneer of recent fill, generally a few inches to several few feet thick, depending on location. This is underlain by peaty swamp and marsh deposits, which are highly organic and susceptible to consolidation. Entire cypress trunks are commonly encountered in exploratory borings, as shown in Figure 3.15. This unit contains two levels of old cypress swamps, discussed previously, and varies between 10 and 40 feet thick, depending on location. The clayey material beneath this is comprised of interdistributary materials deposited in a paludal (quiet water) environment, dominated by clay, but with frequent clay stringers. This unit pinches out in vicinity of the London Avenue Canal and increases in thickness to about 15 feet beneath the 17th Street Canal, three miles west. Occasional discontinuous lenses of pure clay are often encountered which formed through flocculation of the clay platelets when the swamp was inundated by salt water during severe hurricanes.

The area east of the Inner Harbor Navigation Canal (IHNC) is quite different (Figure 3.14), in that these deposits are dominated fine-grained lacustrine deposits deposited in proto Lake Pontchartrain, and the Pine Island Sands are missing. These lacustrine materials extend eastward and are characterized by clays and silty clays with intermittent silt lenses and organics.

The lacustrine facies is underlain by the distinctive Pine Island Beach Sand, described previously. These relict beach sands thicken towards the east, closer to its depositional source. They reach a maximum thickness of about 30 ft. It thins westward towards Jefferson Parish, where it is only about 10 feet thick beneath the 17th Street Canal, as shown in Figure 3.14. The Pine Island sands are easily identified by the presence of mica in the quartz sand, and were likely transported from the mouth of the Pearl River by longshore drift (Saucier, 1963). Broken shells are common throughout the entire layer.

A bay sound deposit consisting of fine lacustrine clays begins just east of the Inner Harbor Navigation Canal; it begins near the 40 foot depth, has about a 10 foot thickness and continues to the west across the city, thickening along the way (Figure 3.14). It reaches its greatest thickness of about 35 feet just east of the 17th Street Canal. It is interesting to note that this area has experienced the greatest recorded settlement in the city, which may be attributable to dewatering of the units above this compressible lacustrine clay, increasing the effective stress acting on these materials (areas to the east are underlain by much more sand, which is less compressible).

The Holocene age deposits reach their greatest thickness just east of the 17th Street Drainage Canal where they are 80 feet thick (Figure 3.5). Undifferentiated Pleistocene deposits lie below these younger deposits.

For the most part, this area sits below sea level with the exception of the areas along old channels and natural levees. The Metairie-Gentilly Ridge lies above the adjacent portions of the city because it was an old distributary channel of the Mississippi River (Figure 1-upper). The same is true for the French Quarter and Downtown New Orleans which are built on the natural sand levee of the Mississippi River.

Geology from the Inner Harbor Navigation Canal to the east becomes exceedingly complex. Although the surficial 10 feet consist of materials from an old cypress swamp, this is an area dominated by the Mississippi River and its distributaries, especially the old St. Bernard delta (See Figure 3.1-lower). Distributaries are common throughout the area and consist of sandy channels flanked by natural levees. 10-15 feet of interdistributary materials, mainly fine organic materials, are present between distributaries. Relic beaches varying in thickness from 10 to 15 feet are present below the interdistributary deposits. These beaches rest atop a 5-10 foot thick layer of nearshore deposits which are then followed by a thick sequence of prodelta clays leading out into the Gulf of Mexico.

3.1.8 Faulting and Seismic Conditions

Subsidence of the Gulf Geosyncline has led to numerous "growth" faults in South Louisiana. One group, the Baton Rouge Fault Zone (shown in Figure 3.7), is currently active and passes in an east-west direction along the north shore of Lake Pontchartrain. Localized faulting is also common near salt domes. There has been no known faulting in the New Orleans area which has been active in Holocene times. The area is seismically quiescent. The earthquake acceleration with a 10% chance of being exceeded once in 250 years is about 0.04g.

3.2 Geologic Conditions at 17th Street Canal Breach

3.2.1 Introduction

The 17th St. Canal levee (floodwall) breach is one of New Orleans' more interesting levee failures. It is one of several levees that did not experience overtopping. Instead, it translated laterally approximately 50 feet atop weak foundation materials consisting of organic-rich marsh and swamp deposits. Trees, fences, and other features on or near the levee moved horizontally but experienced very little rotation, indicating the failure was almost purely translational in nature.

3.2.2 Interpretation of Geology from Auger Borings

A series of continuously sampled borings was conducted and logged using 3-inch Shelby tubes in the vicinity of the 17th St. Outlet Canal levee failure on 2-1-2006 (east side) and 2-7-2006 (west side) to characterize the geology of the materials serving as a foundation for the levee embankments and floodwalls. Drilling on the east bank took place just behind (east) of an intact portion of the levee embankment that had translated nearly 50 feet while drilling on the west side took place directly across the canal from the middle of the eastern breach. This drilling uncovered a wide range of materials below the embankments and provided insights into the failure.

Drilling on the east side of the levee was started at approximately 2-3 feet above sea level. A thin layer of crushed rock fill placed by contractors working for the U.S. Army Corps of Engineers to provide a working surface at the break site was augered through before reaching the native materials. Upon drilling at the east side of the levee, organic matter was encountered almost immediately and a fetid swamp gas odor was noted. This organic matter consisted of low-density peat, humus, and wood fragments intermixed with fine sand, silt, and clay, possibly due to wind shear and wave action from prehistoric hurricanes. This area appears to have been near the distal margins of a historic slough, as shown in Figure 3.16. At 4-6 feet, highly permeable marsh deposits were encountered and drilling fluid began flowing from a CPT hole several feet away, indicative of almost instantaneous conductivity at this depth. The CPT was sealed with bentonite before proceeding to prevent further fluid loss. The bottom of this sample was recovered as a solid 3-inch core of orange-red cypress wood indicating that this boring had passed through a trunk of stump of a former, but geologically young, tree.

A suspected slide plane was discovered at a depth between 8.3 and 11 feet below the ground surface depending on the location of the borings, indicative of an undulating slip surface. Gray plastic clays appeared to have been mixed with dark organics by shearing and this zone was extremely mushy and almost soupy in texture. The water content was very high, possibly both due to dilation during shear and low density of the under-consolidated materials.

Organic rich deposits continue to a depth of about 20 feet below the surface while showing an increasing clay and silt content. Most clays are highly plastic with a high water content although there are lenses of lower plasticity clay, silt, and some sand. The variability of grain sizes and other materials is likely due to materials churned up by prehistoric storms. The clays are usually gray in color but vary and are olive, brown, dark gray, and black depending on the type and amount of organic content. Some organic matter towards the base of this deposit was likely roots that grew down through the pre-existing clays and silts or tree debris and that were mixed by prior hurricanes. Some woody debris came up relatively free of clays and closely resembled cypress mulch sold commercially for landscaping purposes. Full recoveries of material in this zone were rarely achieved in this organic rich zone. It appears that the low-density nature (less than water) of these soils caused them to compress due to sampling disturbances.

Most material below 21 feet was gray plastic clay varying from soft to firm and nearly pure lacustrine in origin. This clay included many silt lenses which tended to be stiffer and had some organics at 26 feet. It is likely that the silt and organics were washed into an otherwise quiet prehistoric Lake Pontchartrain by storms.

Sand and broken shells showed up at 30 feet in depth and continued to increase in quantity and size until 35.5 feet when the material became dirty sand with very little cohesion. This hole was terminated at 36 feet. These sands appears to be the Pine Island Beach Trend deposits, described in Section 3.1.3.

The geologic conditions beneath the 17 Street Canal breach are shown in Figures 3.17 thru 3.20. Figure 3.17 shows the relative positions of the cross sections presented in Figures 3.18 and 3.19. Figure 3.18 is a geologic section through the 17th Street Canal breach, extending into the canal. It was constructed using Brunton Compass and tape techniques commonly employed in engineering geology (Compton, 1962). In this section the landside of the eastern levee embankment translated laterally about 48 feet. The levee had two identifiable fill horizons, separated by a thin layer of shells, likely used to pave the old levee crest or the road next to the levee prior to 1915 (similar to the conditions depicted in Figure 4.18). A distinctive basal rupture surface was encountered in al the exploratory borings, as depicted in Figures 3.18 and 3.19. This rupture surface was characterized by the abrupt truncation of organic materials, including cypress branches up to two inches in diameter (shown in the inset of Figure 3.18). The rupture surface was between ¾ and 1 inch thick, and generally exhibited a very high water content (measured as 279% in samples recovered and tested). This material had a liquid consistency with zero appreciable shear strength. It could only be sampled within more competent materials in the Shelby Tubes. A brecciated zone three to four inches thick was observed in samples immediately above the rupture surface. This contained chunks of clay with contrasting color to the matrix materials, and up to several inches across, along with severed organic materials.

The geologic cross section portrayed in Figure 3.19 was taken on the north side of the same lot, using the same Brinton Compass and tape technique. It was located between 80 and 100 feet north of the previous section described above, as shown in Figure 3.17. In this location the landside of the levee embankment translated about 52 feet laterally, to the east. These offsets were based on tape measurement made from the chain link right-of-way fences along the levee crest. No less than four distinct thrust planes were identified in the field, suggesting a planar, translational failure mode, as sketched in the cross section. As with the previous section, the old swamp deposits are noticeably compressed beneath the levee embankment, likely due to fill surcharge and the fact that the drainage canals have never been drained over their lifetime (in this case, since 1858 or thereabouts, described in Section 4.6). This local differential settlement causes the contact between the swamp deposits and the underlying lacustrine clays to dip northerly, towards the sheetpile tips supporting the concrete I-walls constructed in 1993-94. There was ample physical evidence that extremely high pre pressures likely developed during failure and translation of the levee block, in the form of extruded bivalve shells littering the ground surface at the second toe thrust, as shown in Figure 3.20 and indicated on the cross section (Figure 3.19).

Planar translational failures are typical of situations where shear translation occurs along discrete and semi-continuous low strength horizons (Cruden and Varnes, 1996). Additional evidence of translation is the relatively intact and un-dilated nature of the landside of the failed levee embankment, upon which the old chain link right-of-fence was preserved, as well as a substantial portion of the access road which ran along the levee crest, next to the concrete I-wall. Wherever we observed the displaced concrete I-wall in this area it was solidly attached to the Hoesch 12 steel sheetpiles, each segment of which was about 23 inches wide (as measured along the wall alignment) and 11 inches deep, with an open Z-pattern. The thickness of the sheets were about 7/16ths of an inch. The observed sheetpiles interlocks were all attached to one another. The entire wall system was quite stiff and fell backward (towards the canal) *after* translating approximately the same distance as the landslide of the levee embankment. The sheetpiles and attached I-walls formed a stiff rigid element. The sheetpiles were 23 ft-6 inches long and were embedded approximately 2 to 3 feet into the footings of concrete I-walls.

The geology of the opposite (west) bank was relatively similar except that the organics persist in large quantities, to a depth of 36 feet. The marsh deposits appeared deeper here and root tracks filled with soft secondary interstitial clay persisted to a depth of 39 feet. Sand and shells were first encountered at 40 feet and cohesionless send was found at 41 feet. This hole was terminated at 42 feet.

3.2.3 Interpretation of data from CPT Soundings

Six distinctive geologic formations are identified studying the Cone Penetrometer Test (CPT) soundings which were done in the vicinity of 17th Street Canal: Fill, swamp/marsh deposits, Intermixing deposits, lacustrine deposits, Pine Island beach sand deposits and Bay Sound deposits. The description and coverage of these geologic formations from CPT soundings are explained in the following paragraphs. These unit assignments are shown graphically in Figure 3.20.

FILL: Fill is not present in all CPT soundings. It is characterized *by stiff silty clay to sandy clay and sandy silt with some silt lenses.* It is differentiated from the swamp deposits by having little or no organic matter in its content. Along the breached area, the fill appears to be missing in the CPT soundings. Fill thickness is around 10 ft (down to -8 ft below sea level) on the west bank of the 17th street Canal. Just north of the breached area (east bank), the thickness of the fill ranges from 14 ft to 16 ft (down to -10 ft). Fill materials for the drainage canals appear to have been placed in three sequences: 1) during the original excavation of the various canals, between 1833-1878; 2) after the 1915 Grand Isle Hurricane; and 3) after the October 1947 hurricane (the history of the drainage canals is described in Chapter 4, Section 4.6).

SWAMP/MARSH DEPOSITS: Marsh deposits consists of *soft clays, organic clays usually associated with organic material (wood and roots)*. The organic materials are readily identifiable by observing the big jumps in the friction ratios of the CPT's. The thickness of swamp/marsh deposits is around 9.5 ft on the west bank of the canal and 4 to 6 ft on the east bank of the canal. The depth at which swamp/marsh deposits encountered on banks ranges from approximately -8.5' (on the west side) to -10' (on the east side), using the NAVDD882004.65 datum.

INTERMIXING ZONE: This zone consists of mixture of *soft clays, silt lenses with little or no organic material*. The thickness of intermixing zone ranges from 3 ft to 8.5 ft on the east bank of the canal. No intermixing zone is interpreted on the west bank of the canal. However the contact between marsh and intermixing zone is highly irregular and should be correlated with borehole data.

LACUSTRINE DEPOSITS: Lacustrine deposits consist of *clays to organic clays with thin silt and fine sand lenses*. *No organic matter* is found in these deposits. The thickness of lacustrine deposits is around 17-19 ft on the west bank of the canal and 15-22 ft on the east bank of the canal. The depth at which lacustrine deposits encountered ranges from -17 (on the west side) to 14-23 (on the east side).

PINE ISLAND BEACH TREND SANDS: Beach sand is identified by its *sand and silty sand* content. It is easily recognized in the CPTs by a large jump in the tip resistance and a drop in the pore pressure. The depth at which beach sand encountered ranges from -37 (on the west side) to -36 ft (on the east side) and it has fairly uniform 6 ft of thickness.

BAY SOUND: This deposit contains *stiff organic clays and stiff clays*. It is easily recognized in the CPTs by a large drop in the tip resistance and an increase in the pore pressure. Bay sound deposits are only encountered on the east side of the canal and only top of bay sound deposits encountered in this area –not bottom. The depth at which these deposits encountered is around -42 ft (which appears to be uniform in this area).

3.3 Geologic Conditions at London Avenue Canal (North) Breach

3.3.1 Introduction

The London Ave. Outlet Canal Levee system catastrophically failed on its western bank just south of Robert E. Lee Blvd. during Hurricane Katrina between 9 and 10 AM on August 29, 2005. The hurricane induced a storm surge from the Gulf of Mexico that moved into Lake Pontchartrain and subsequently backed up into the canal. The levee failed in two locations by translating laterally atop poor foundation materials, not by overtopping. One break formed on the west bank levee just south of Robert E. Lee Blvd. The toe of this break appears to have thrust over the surrounding landscape 6-8 feet in places.

The east bank levee directly opposite this break translated by about two feet, but did not breach catastrophically. An imminent failure was likely but hydrostatic pressure was relieved by the break opposite this bank and a break on the east bank further south near Mirabeau Ave. Floodwall panels here have been displaced, tilted, and distressed

Cohesionless beach sands from the micaceous Pine Island beach strand comprise the majority of the deposits beneath the London Ave. Canal Levee. These sands were quickly eroded and deposited in great quantities in the neighborhoods surrounding the breaks. Much of the sand was also likely in the bottom of the canal prior to the breaks.

3.3.2 Geology Beneath the Levees

A series of continuously sampled borings was conducted and logged using 3-inch Shelby tubes where cohesive soil was present. Cohesionless sands were sampled using the material recovered during the Standard Penetration Tests (SPT). CPTs were conducted alongside many of the other borings.

The first two feet of material appeared to be topsoil heavily influenced by modern vegetative growth. The material was a dark brown silty clay with many roots and organics and a relatively low water content.

The next 0.65 feet contained highly plastic and water-rich organic clay and contained what appeared to be the slide plane at 2.65 feet in depth. Although the slip surface was likely deeper under the levee, it was thrusting to the surface at this point. There was a return to the dark brown organic silty clay at this point, which continued to 3.1 feet where there was a strong contact. A gray clayey sand remained in the last 0.5 feet of the tube.

From 4-6 feet appeared to be a deposit of shallow marsh materials transitioning to beach sands from Lake Pontchartrain. The first part of the tube contained gray organic rich clays and silts with a fetid odor and transitioned to a relatively clay gray sand. Cohesion dropped beyond 6 feet in depth and sampling was no longer possible using a Shelby tube.

Sampling continued using an SPT split spoon sampler down to 44 feet where clays were again encountered. The entire layer of sand appeared to be beach sand. Shells were included throughout the layer and most sand was mica rich, likely brought in by long shore drift from the Pearl River. Shells were included throughout the layer and most sand was mica rich, likely transported by longshore drift from the Pearl River. This is the "relic beach" of the Pine Island Beach Trend described in Section 3.1.3.

The clay recovered from 44-46 feet was, silty, blue-gray in color, and very plastic. Sand and shell fragments were mixed in with this clay, possibly due to wave action and mixing due to storms. Additional boring logs show a lacustrine bay sound material at this depth. No sampling was conducted by our team below this depth. All recovered sediment was Holocene in age.

Boring logs from Design Manual 19A (U.S. Army Corps of Engineers, 1984) show similar results. In addition, the transitional layer of clayey sand is shown beneath the breach but not below adjacent unfailed sections of the levee. The marsh deposits and transitional zone extend up to 10 feet deeper beneath the breached levee (west) and distressed levee (east) than below the unbroken portions of the levee. Marsh deposits begin near the surface and transition to sand at around 10-15 feet in depth. The sand continues to around 45 feet where lacustrine bay sound material is found. This continues down to Pleistocene materials at 65-75 feet.

3.4 Geologic Conditions at London Avenue (South) Canal Breach

3.4.1 Introduction

The London Ave. Outlet Canal levee system catastrophically failed on its eastern bank just north of Mirabeau Ave. during Hurricane Katrina between 7 and 8 AM on August 29, 2005. This failure appears to have been induced by concentrated zone of underseepage, because the failure was relatively deep, and did not extend over a long zone of the canal. Nor was there any physical evidence of overtopping. The seepage appears to have been driven by high water level in the canal, caused by the storm surge coming up the canal from its mouth along Lake Pontchartrain.

Post failure reconnaissance revealed that micaceous sands from the Pine Island Beach Strand were eroded from this breach and, possibly, from within the canal where they were deposited throughout the surrounding neighborhood.

3.4.2 Geology Beneath the Levees

The section of levee incorporated in the London South breach is founded upon geology similar to the northern London Ave. Canal failure. The levee was constructed upon approximately ten feet of organic-rich cypress swamp deposits. Borings by the Corps of Engineers indicate that the swamp deposits extended three to five feet deeper below the failure area than the areas immediately adjacent to the breach (north or south of it). Unlike the London Avenue northern breach, where there is a transition of clayey sand between the marsh deposits and the underlying Pine Island Trend sands, there is a more definite transition at this location. These differences in foundation conditions are indicated on the boring logs within Design Manual 19A (U.S. Army Corps of Engineers, 1984).

3.5 Geologic Conditions along the Inner Harbor Navigation Canal

3.5.1 Introduction

Levees surrounding the Inner Harbor Navigation Canal (IHNC) were overtopped and breached catastrophically during Hurricane Katrina. Some of New Orleans' worst devastation occurred at two large breaches on the east side of the IHNC in the Lower Ninth Ward. These breaches washed houses from their foundations, leaving many blocks of the neighborhood as little more than piles of used lumber, destroyed automobiles, and other debris. Although the primary mode of failure at this site was land-side scour caused by overtopping, some translation of the embankments atop their foundations appears to have occurred.

3.5.2 Geology

The geology beneath the IHNC levees is far more complex and variable than that of the foundation materials at the London Ave. and 17th St. Canals. The foundation materials here tend to be fluvially dominated by past distributaries of the Mississippi River with the exception of the area near Lake Pontchartrain. Conditions near the lake more resemble those under the London Ave. Canal but with a slightly thicker marsh deposit. The buried beach deposit is present below the marsh and eventually transitions into prodelta clays.

As with most modern fluvial systems, the geology of this Holocene deposit is complex and varies widely in both vertical and horizontal extent. The area was once covered by the marshes and swamps once common to the area. Organic fat clays are dominant and contain peat and other organic materials. Some wood is present but not in the quantities found at the 17th St. Canal site, indicating that marshes were more pronounced at this location. These deposits vary in thickness between 10-20 feet, depending on the location.

Interdistributary materials consisting largely of fat clays dominate much of the IHNC geology below the marsh deposits. This layer, which also contains zones/lenses of lean clays and silt, is approximately 30-35 feet thick.

A complex estuarine deposit exists below the interdistributary layer and is comprised of a complex mix of clays, silts, sands, and broken shell material. This deposit is about 30 feet thick and is underlain by Pleistocene deposits (undifferentiated, but commonly a stiff clay). Cross sections from The New Orleans District's Design Manual 02 Supplement 8 (U.S. Army Corps of Engineers, 1968, 1969, 1971) do not always do a good job of differentiating this material, but much of the material appears to be sand mixed with clays and silts. These deposits lie at sufficient depth as to preclude their having any significant impact on levee stability.

Abandoned distributaries cut across the IHNC in some locations. Materials in the old channels are highly variable. Although basal units usually consist of sands, upper units are heterogeneous layers of silts, clays, sandy silts, and silty sands. Natural levee deposits are commonly found around these old channels.

3.6 Paleontology and Age Dating

3.6.1 Introduction

Micropaleontology was used in conjunction with carbon 14 dating to determine both the age and depositional environment of the sediments below levee failure sites in New Orleans, LA. Foraminifera, single-celled protists that secrete a mineralized test or shell, were identified as these organisms grow in brackish or marine settings but not freshwater. Their presence in sediments indicate that they were deposited in-situ or were transported from brackish Lake Pontchartrain or marine environments by Hurricanes. Palynology, the identification and study of organic-walled microfossils, commonly pollens and spores, was conducted to aid in the re-creation of paleoenvironments beneath the levees. Macrofossils of the phylum *Mollusca*, including classes *Gastropoda* and *Bivalvia* are common in sands of the Pine Island Trend (Rowett, 1958). Most recovered samples contained heavily damaged shells or fragments.

3.6.2 Palynology

Although varying sediment types including clays, peats, and sands were studied, similar palynomorphs were found throughout the samples. These samples came from different depths and locations throughout New Orleans. The commonalities between the sediments may be due to transportation of the palynomorphs by wind and water or the mixing of materials by hurricanes. Pollens of the family *Taxodiaceae*, genus *Cupressacites* (cypress) are common. Species of cypress are common in perennially wet areas such as swamps. Cypress is common throughout the swamps of the Gulf Coast Region. Cypress wood, including trunks, roots, and stumps, was unearthed by scour during the levee failures and subsequent construction to temporarily patch the levees. Samples recovered in 3” Shelby tubes commonly included cypress fragments resembling commercially available landscaping mulch and cores of intact wood. Cypress trees are freshwater and die if exposed to salt water for a prolonged amount of time.

Dinocysts/Dinoflagellates were also discovered among the samples taken for palynology. Dinoflagellates are single-celled algae belonging to the Kingdom Protista. They live almost exclusively in marine and brackish water environments, with very few freshwater species. The discovery of these organisms was not surprising, given the close proximity to brackish Lake Pontchartrain (essentially a bay). On the other hand, several exclusively marine species that live in the open ocean were recovered. These species were transported a far distance inland, indicating transport by a catastrophic event, possibly a hurricane storm surge or tsunami.

3.6.3 Foraminifera

Foraminifera were identified in the Pine Island Trend, a micaceous quartz beach sand that was deposited in the Holocene Gulf of Mexico by the Pearl River of Mississippi. This sand was subsequently formed into a large sand spit by long shore drift, separating Lake Pontchartrain from the rest of the Gulf of Mexico (Saucier, 1994). Lake Pontchartrain is a brackish body of water with only a small connection to the Gulf. Agglutinated, planispiral, and uniserial foraminifera were discovered where the sand grades into the silts and clays deposited in the low energy environments of Lake Pontchartrain. Although foraminifera are abundant at these locations, their diversity is low. This is indicative a stressed environment and is not surprising, given the brackish nature of Lake Pontchartrain.

3.6.4 Carbon 14 Dating

We are awaiting the results of six C14 age dating by the age dating laboratory at the University of New Mexico in Albuquerque, NM. These are samples of the cypress wood and fibrous peats recovered at the 17th Street Canal failure area.

3.7 Mechanisms of Ground Settlement and Land Loss in Greater New Orleans

3.7.1 Settlement Measurements

URS Consultants (2006) in Baton Rouge recently completed a study for FEMA of the relative ground settlement in New Orleans since 1895, using the Brown (1895) map, which has 1 foot contours ands extended north to the Lake Pontchartrain shoreline. This comparison was made by creating Digital Elevation Models (DEMs) of the 1895 map (Figure 3.22) relative to Mean Gulf Level against the 1999/2002 DEM extracted from LiDAR data and New Orleans network of benchmarks. The resulting product was a map noting relative settlement between 1895 and 1999 (in feet), shown in Figure 3.23. This study suggests that the entire city has settled between 2 and 10 feet. During this same interim, sea level has risen approximately 12 inches. The area with the greatest settlement (> 8 feet) were north of I-610 in the Lakeview area and north of Mirabeau Ave. in the Gentilly area, exclusive of the 1931 fill along Lake Pontchartrain (which extends a half mile into the Lake).

3.7.2 Tectonic Subsidence

Tectonic subsidence is caused by sediment compaction at great depths (Figure 3.24). Salt and muds flow towards the continental shelf. Pressure ridges and fold belts develop; which are akin to sitting on a peanut butter and jelly sandwich and watching material ooze out and shift. The Continental Slope and Shelf is blanketed by large subaqueous landslides.

3.7.3 Lystric Growth Faults

As compacting materials move seaward, the ground surface drops. If sediment is not added at the ground surface, the seaward side of these features gradually subsides below sea level. The delta’s lystric growth faults have been grouped into bands thought to be more or less related to one another. The relatively recent emergence of the Baton Rouge Fault Zone along the northern shore of Lake Pontchartrain, thence towards Baton Rouge, is the most striking example, and one of the furthest inland (Figures 3.25 and 3.26).

3.7.4 Compaction of Surficial Organic Swamp and Marsh Deposits

The interdistributary sediment package covering the old back swamps around New Orleans are highly compressible and the neighborhoods built on these materials exhibit obvious signs of differential settlement. This is particularly true of the West End, Lakeview, City Park, Fillmore, St. Anthony, Dillard, Milneburg, Pontchartrain Park, Desire, and Gentilly neighborhoods flanking Lake Pontchartrain. Most of this settlement is ascribable to oxidation-induced settlement of underlying peaty soils, caused by local drawdown of the ground water table, as sketched in Figure 3.27. The amount of post-development settlement is more-or-les proportional to the thickness of the peaty surface layer, shown in Figure 3.12. It varies in thickness from a few feet to as much as 20 feet, depending on location (WPA-LA, 1937; Kolb and Saucier, 1982).

The mechanisms promoting surficial settlement in lower New Orleans are thought to be: 1) drainage of the near surface soils, through simple near-surface dewatering and the storm water collection system; and 2) biochemical oxidation of organic materials above the [lowered] water table. Simple drainage of the surficial peaty soils can induced consolidation of up to 75% of their original thickness (Kolb and Saucier, 1982), which in of itself, could account for up to 12 ft of settlement, if the local water table was lowered >15 feet. But, biochemical oxidation continues afterwards, with greater severity during extended periods of drought, as occurred in the late 1990s-early 2000s around New Orleans. Oxidation continues until only the mineral constituents of the soil are left remaining.

Dense urban development also leads to increased subsidence because the absorptive capacity of the peaty soils is decreased by the mass implementation of impervious surfaces, such as streets, parking lots, sidewalks, roofs, driveways, etc. Increasing the area of impervious surfaces decreases overall seasonal infiltration and increases the peak runoff through hardened impervious surfaces. As a consequence, the Sewerage & Water Board of New Orleans had to continually increase the capacity of their drainage collection, conveyance and discharge system during the post-1945 period. These examples are from the Lakeview area adjacent to the 17th St. Canal failure, where the ground appears to have settled 10 to 16 inches since 1956.

The Lakeview and Gentilly neighborhoods were intensely developed in the post World War II era, mostly between 1946-70 (although infilling of newer structures continued up through 2005, as older structures were torn down). Most residential structures built in lower New Orleans after the mid-1950s are concrete slabs founded on wood pilings 6 to 8 inches in diameter, driven about 30 feet deep (Waters, 1984). From inspection, it appears that the ground beneath the foundations has settled 10 to 40 inches over the past 50 +/- years since these homes were constructed. This development was accompanied by a lowering of the ground water table to accommodate normal living conditions and combat mildew and mold in the crawl spaces beneath the homes (Figure 3.28 - upper). Since the historic groundwater table was at or within a few inches of the ground surface in this area, the lowering of the water table by 2 to 10 feet in this area hastened near-surface settlement through oxidation of the organic rich peat soils underlying the area.

As the peats oxidized, the ground settles, creating a depressed area beneath pile supported homes (Figure 3.28-upper). Groundwater pumping, drainage, and structural and earthen surcharges all contribute to the observed settlement. Historic measurements of ground settlement in the Kenner area of Jefferson Parish are shown in Figure 3.29.

During this 130 to 170 years since the drainage canals were constructed upon what became the Lakeview and Gentilly areas, these channels have never been drained for any significant period of time, because they were open to Lake Pontchartrain. As a consequence, the peaty soils immediately beneath these canals (17th Street, Orleans, and London Avenue) and Bayou St. John have not experienced significant near-surface settlements like those fomented by oxidation of peaty soils in the adjoining neighborhoods, although they have experienced gross ground settlement due to the other causes described in Section 3.7.

This history of near-continual ground settlement necessitated raising of the old drainage canal embankments on three occasions in the 20th Century, following hurricane-induced flooding from storm surges off Lake Pontchartrain, in: 1915, 1947, and 1965. Earth fill was placed upon the levee embankments in 1915 and 1947. After flooding associated with Hurricane Betsy in 1965 steel sheetpiles were used in selective zones to increase the freeboard for Category 3 storm surge (a figure that shifts each decade, as new information and models are developed). In the 1990s sheetpile–supported concrete I-walls wee constructed along the crests of the drainage canals and on either side of the IHNC.

3.7.5 Structural Surcharging

An interesting aspect of the recent URS (2006) study for FEMA is the marked increase in settlement noted in the Central Business District, where tall structures are founded on deep piles. This area settled 5 inches in 100 years, but much less further away from the city’s tallest and heaviest structures. The sandy natural levees along the Mississippi River even settled 2 inches; likely due to surcharging by the Corps’ Mississippi River & Tributaries Project (MR&T) sequences of levee enlargements, between1928-60.

3.7.6 Extraction of Oil, Gas, and Water

Since the 1960s groundwater withdrawal has been recognized as contributing to subsidence of the Gulf Coast area, especially adjacent to deep withdrawal points for industrial consumption (Kazmann and Heath, 1968). More recently, R.A. Morton of the USGS has blamed oil and gas extraction for the subsidence of the Mississippi Delta. Morton has constructed convincing correlations between petroleum withdrawal and settlement rates on the southern fringes of the delta, near the mouth of the Mississippi River (Morton, Buster, and Krohn, 2002). But, other factors are likely involved as well, as petroleum withdrawal alone cannot account for marked settlement well inland of Lake Pontchartrain, where little withdrawal has occurred. Figure 3.30 presents Saucier’s (1994) map of the Mississippi Delta, which summarizes the structural geologic framework of the area. This shows salt basins, salt domes, and active growth faults that pervade the delta region. Solutioning of salt diapirs and seaward migration of low density contrast materials likely exacerbate settlement, but more slowly that fluid/gas withdrawal.

3.7.7 Coastal Land Loss

The U.S. Geological Survey's National Wetlands Research Center (USGS-NWRC) has about 100 years of land loss information. Since 1973, satellites have allowed monitoring of sediment expulsion from the delta and the nefarious shoreline, which is continuously sinking. The USGS-NWRC has been monitoring coastal land loss over the past 50 years using 1956 and 1978 imagery published by Cahoon and Groat (1990) and LANDSAT Thematic Mapper satellite imagery from 1993 and 2000 (Barras et al., 2003).

Coastal lands loss is a high visibility problem along the Gulf Coast, especially in the Mississippi Delta.

- USGS and NGS state that the approximate rate of subsidence is between 1/3" to ½" per year; or about 4.2 ft/100 yrs
- Sea level rise is running about 1 ft/100 yrs (Burkett, Zilkowsi, and Hart, 2003)
- 15% of New Orleans is already more than -10 ft below sea level (URS, 2006)
- The average current rate of coastal land loss is between 25 and 118 square miles per year (the record of 118 mi^2 being a result of Hurricanes Katrina and Rita in 2005)
- The 2050 Reclamation Plan would restore 25 to 30 mi^2 over the next 40 to 50 yrs at a cost of $14 billion

The USGS National Wetlands Research Center has determined that Hurricane Katrina created as much new standing water area in the Mississippi Delta (below sea level) as occurred naturally over the previous 50 years! This was due to increased traction shear, which tore out large tracts of peat bogs, to depths of several feet (USGS-NWRC, 2006).

3.7.8 Negative Impact of Ground Settlement on Storm Surge

As large tracts of land along coastal Louisiana sink below sea level, less protection is afforded inland areas from the destructive impacts of storm surges caused by hurricanes. The absolute level of storm surges on the Louisiana Coast is also likely exacerbated by the loss of coastal vegetation, such as cypress swamps, which mollify wave energy through mechanical obstruction and tortuous flow path (increased boundary shear) as high water sweeps onto the land. The diminution of storm surge height would depend on the speed and duration of the storm as it makes landfall, and the density and height of the cypress swamps and the vegetation they support.

Many figures have been cited in the non-technical literature in regards to this "protective impact;" the most common being that every 4-1/2 miles of mature cypress swamp absorbs one foot of storm surge coming from the Gulf (Hallowell, 2005). Although the concept of storm surge mollification through turbulent boundary shear at the ground surface is conceptually possible, we were unable to find any measurements that quantified this effect through credible scientific study of historic storm events (NRC, 2006).

3.7.9 Conclusions about Ground Settlement

Multiple physical factors have combined to cause marked historic settlement of the New Orleans area. These include:

1) The average silt load of the Mississippi River (550 million tons [mt] per year prior to 1950; now 220 mt/yr) causes continuous crustal loading of the Mississippi River Delta, causing isostasy-driven settlement, which has been recognized since 1937 (Meade and Parker, 1985; Russell, 1940, 1967).
2) Tectonic compaction caused by sediment compaction at great depths, with associated pressure ridges and fold belts.
3) Subsidence along the seaward side of lystric growth faults perturbing the Mississippi Delta.
4) Drainage of near-surface soils causing an increase in effective stress and resulting primary consolidation
5) Oxidation of near-surface peaty soils due to lowering of the groundwater table in developed areas, or drainage of historic marshes and swamp lands. This component is often exacerbated by New Orleans residents who routinely fill in portions of their yards adjacent to protruding foundations (Figure 3.28), driveways and sidewalks, creating additional loads on the compressible materials lying beneath them.
6) Consolidation of soft compressible soils (with high water contents), due to surcharging by earth filling and other man-made improvements.
7) Structural surcharging. Settlements measured in vicinity of downtown high rise structures suggests that a portion of the observed settlement may also emanate from deeper horizons, caused by loads transferred to those horizons along friction piles and caissons for heavy structures.
8) Fluid extraction of oil, gas, and water from the subsurface. Extraction of fluids and natural gas is a pressure depletion that increases effective stresses acting on underlying sediments, hastening consolidation.
9) Solutioning of salt diapirs (salt domes) and seaward migration of low density contrast materials (salt and mud), as well as large subaqueous slope movements on the continental slope and shelf. When large volumes of material move laterally, adjoining areas drop to compensate for the volumetric strain.

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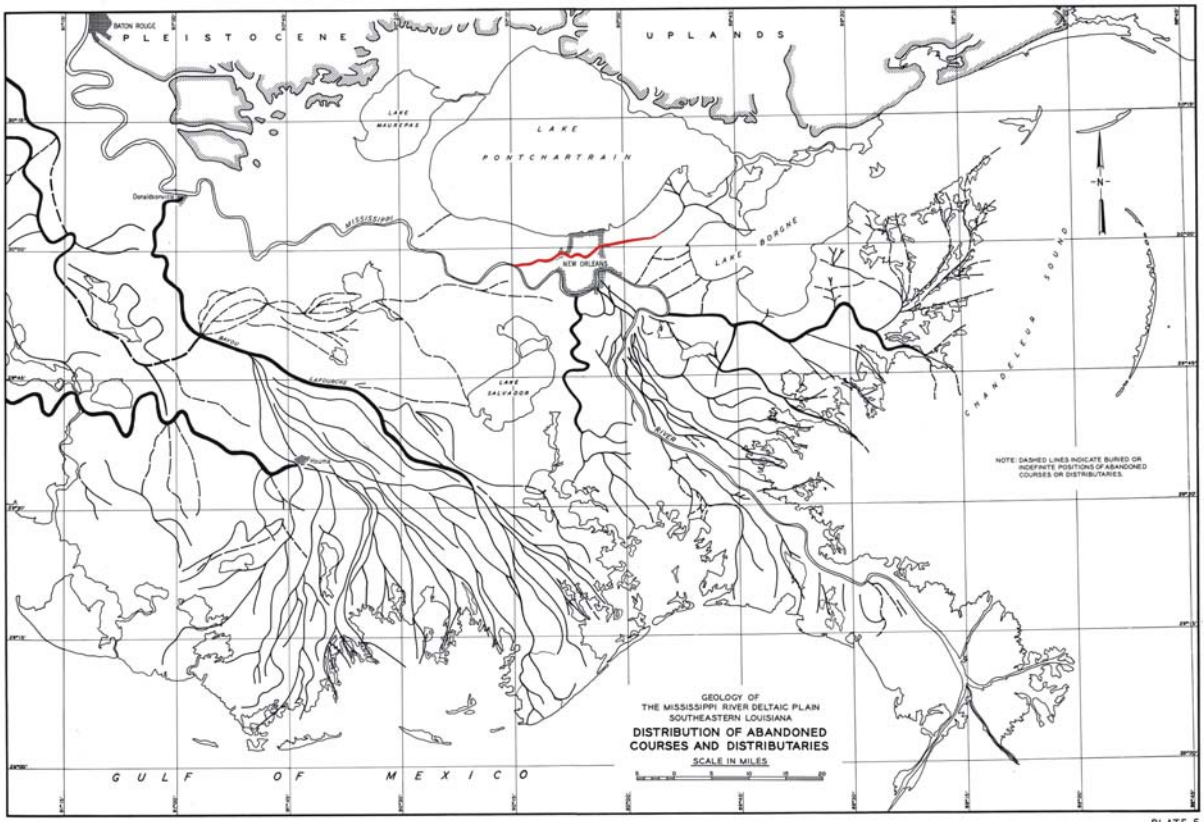
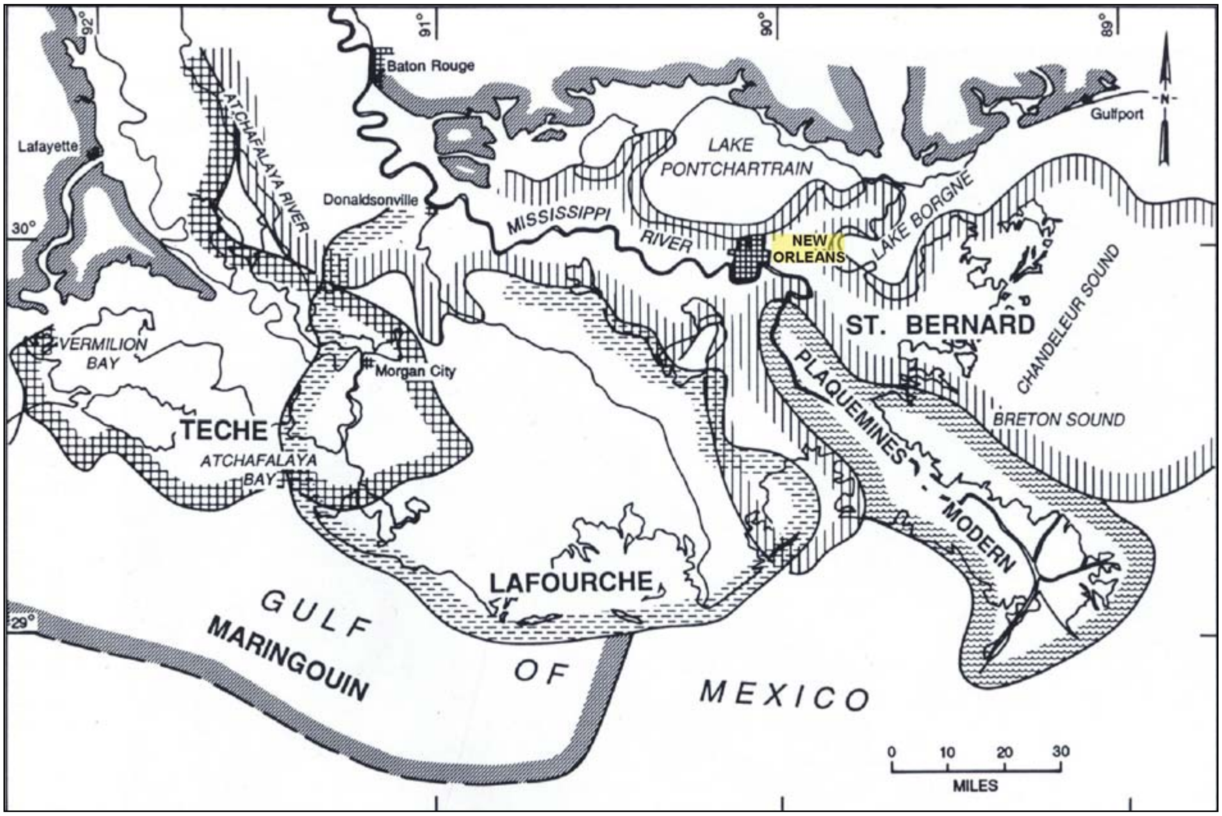


PLATE 5

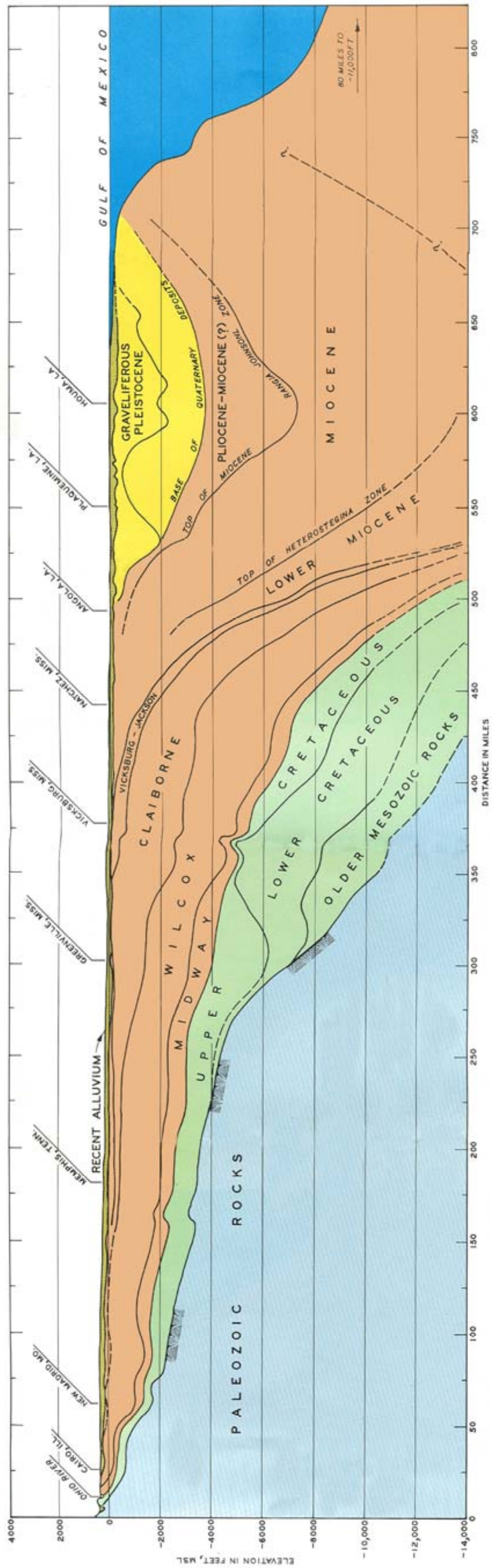
Source: Kolb (1958)

Figure 3.1 (upper): Areal distribution of abandoned channels and distributaries of the Mississippi River. The Metairie Ridge distributary channel (highlighted in red) lies between two different depositional provinces in the center of New Orleans (shown in Figure 3.6).



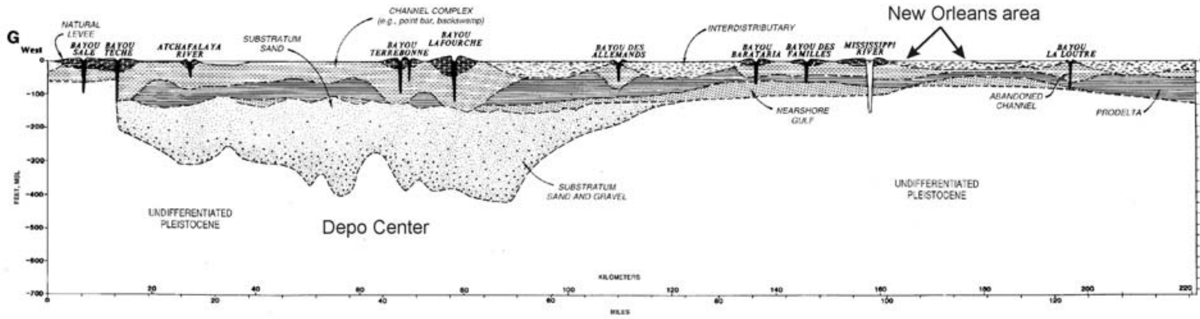
Source: Saucier (1994)

Figure 3.1 (lower): Major depositional lobes identified in lower Mississippi Delta around New Orleans.



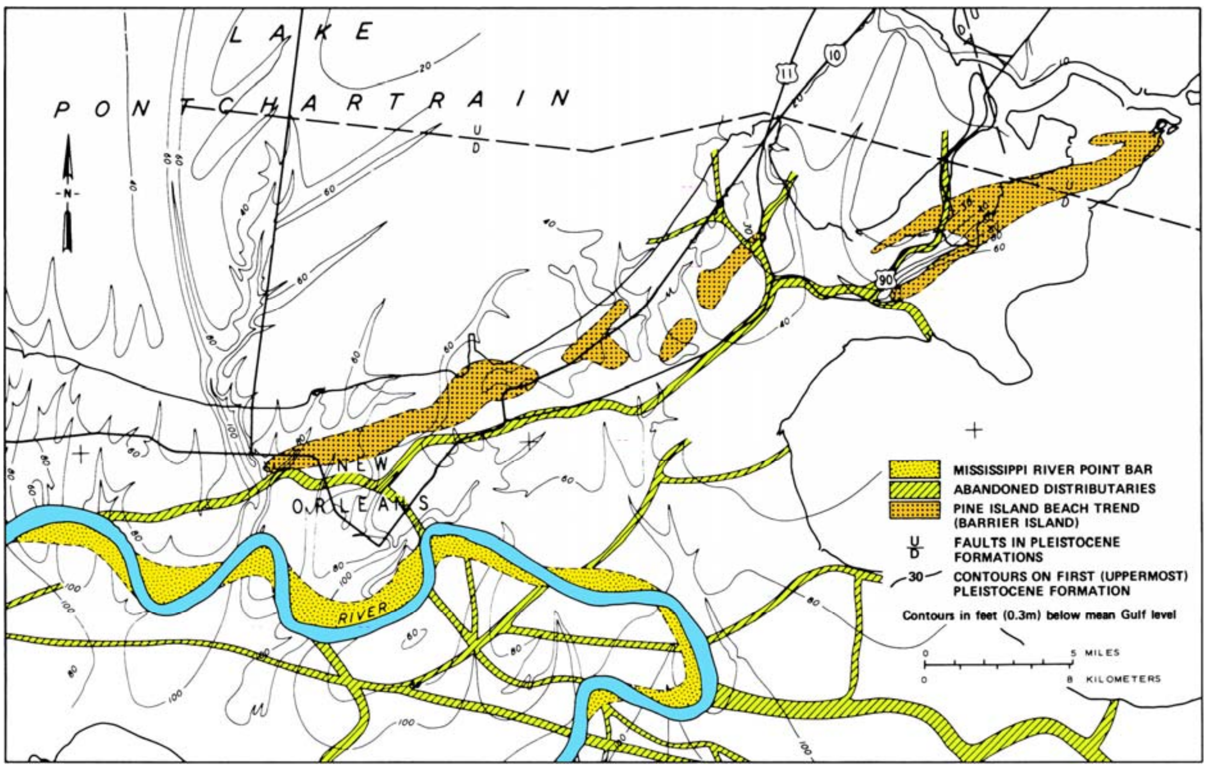
Source: Moore (1972)

Figure 3.2: North-south geologic cross section through the central Gulf of Mexico Coastal Plain, along the Mississippi River Embayment. Note the axis of the Gulf Coast Geosyncline beneath Houma, LA, southwest of New Orleans. In this area the Quaternary age deposits reach a thickness of 3600 ft.



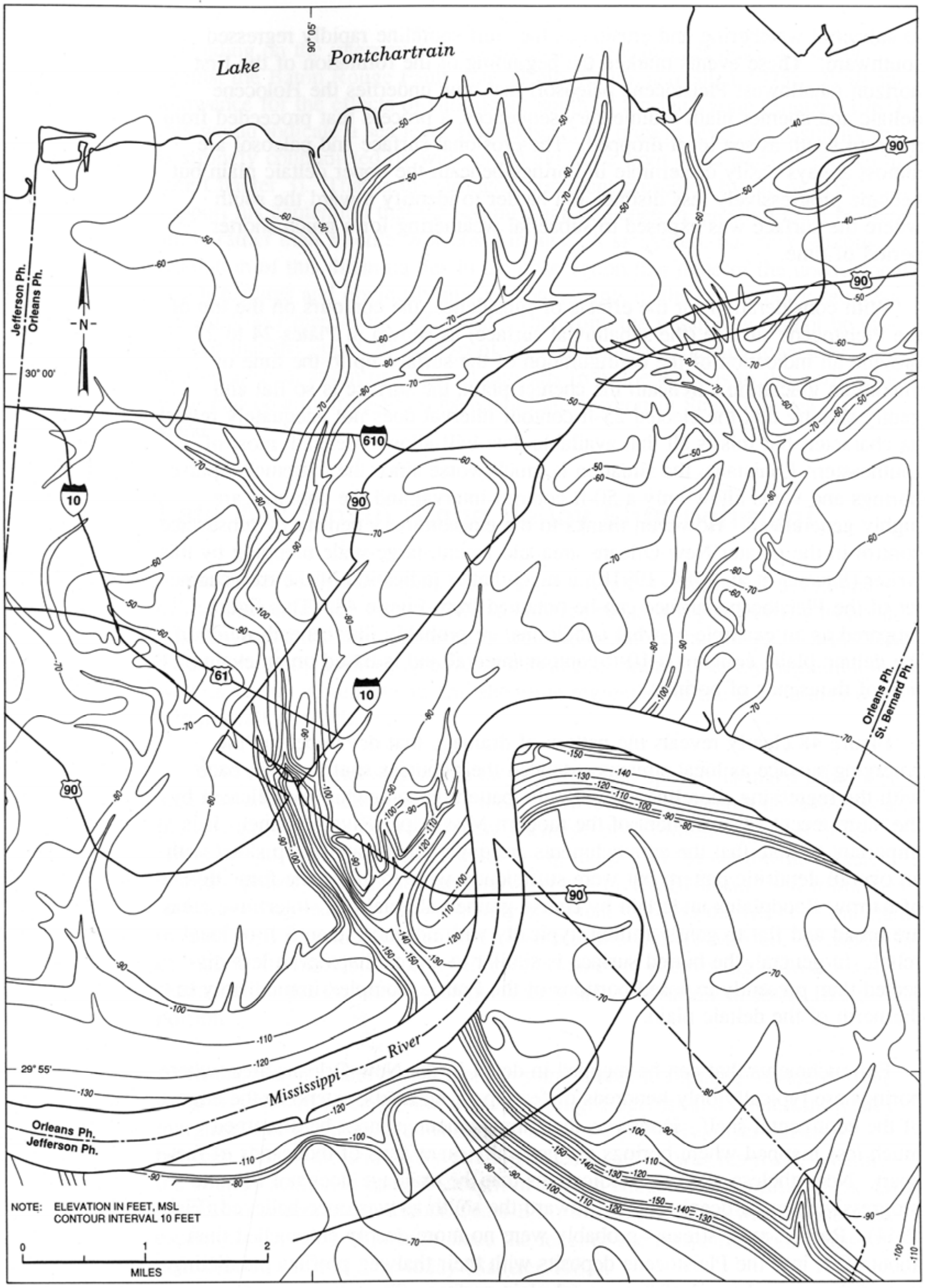
Source: Modified from Saucier (1994)

Figure 3.3: Transverse cross section in a west to east line, across the Mississippi River Delta a few miles south of New Orleans, cutting across the southern shore of Lake Borgne. New Orleans is located on a relatively thin deltaic plain towards the eastern side of the delta's depositional center, which underlies the Atchafalaya Basin, west of New Orleans.



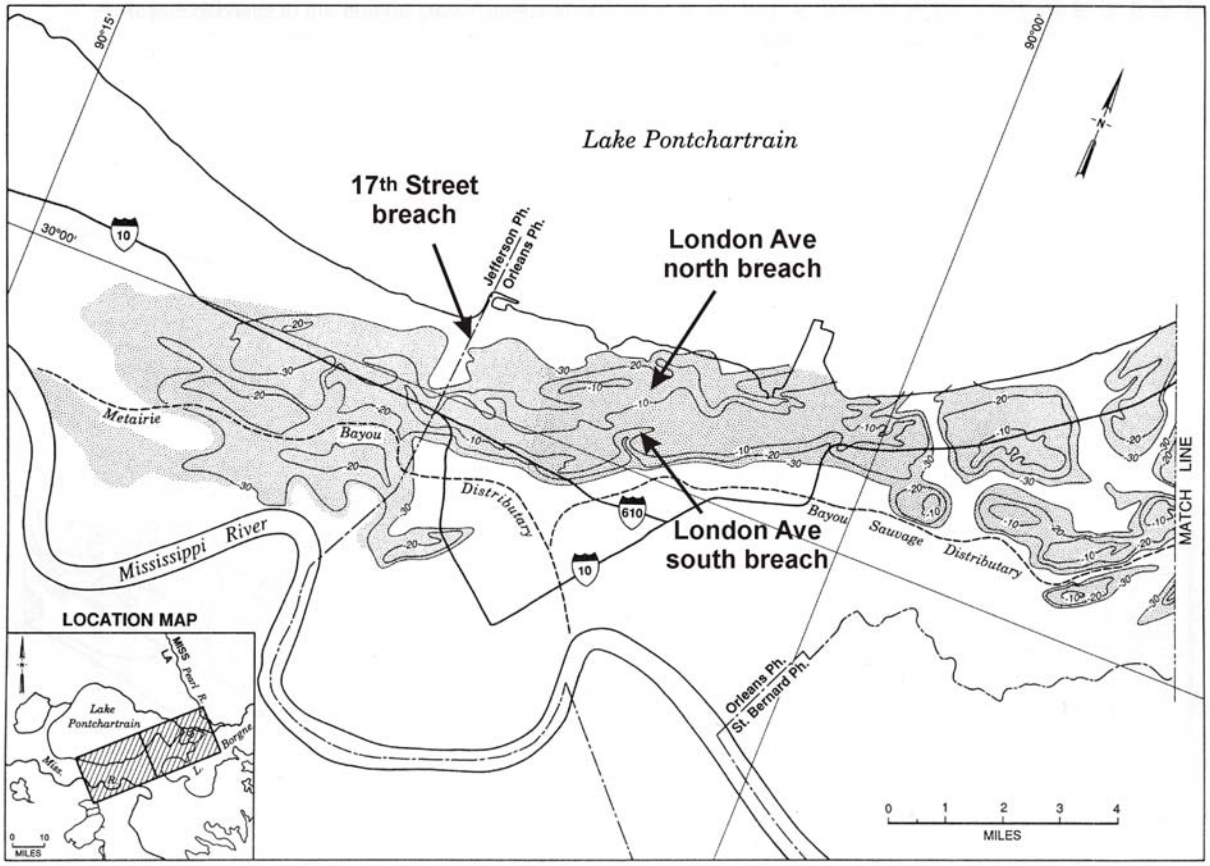
Source: Kolb and Saucier (1982)

Figure 3.4: Pleistocene geologic map of the New Orleans area. The yellow stippled bands are the principal distributory channels of the lower Mississippi during the late Pleistocene, while the present channel is shown in light blue. The Pine Island Beach Trend is shown in the ochre dotted pattern. Depth contours on the upper Pleistocene age horizons are also shown.



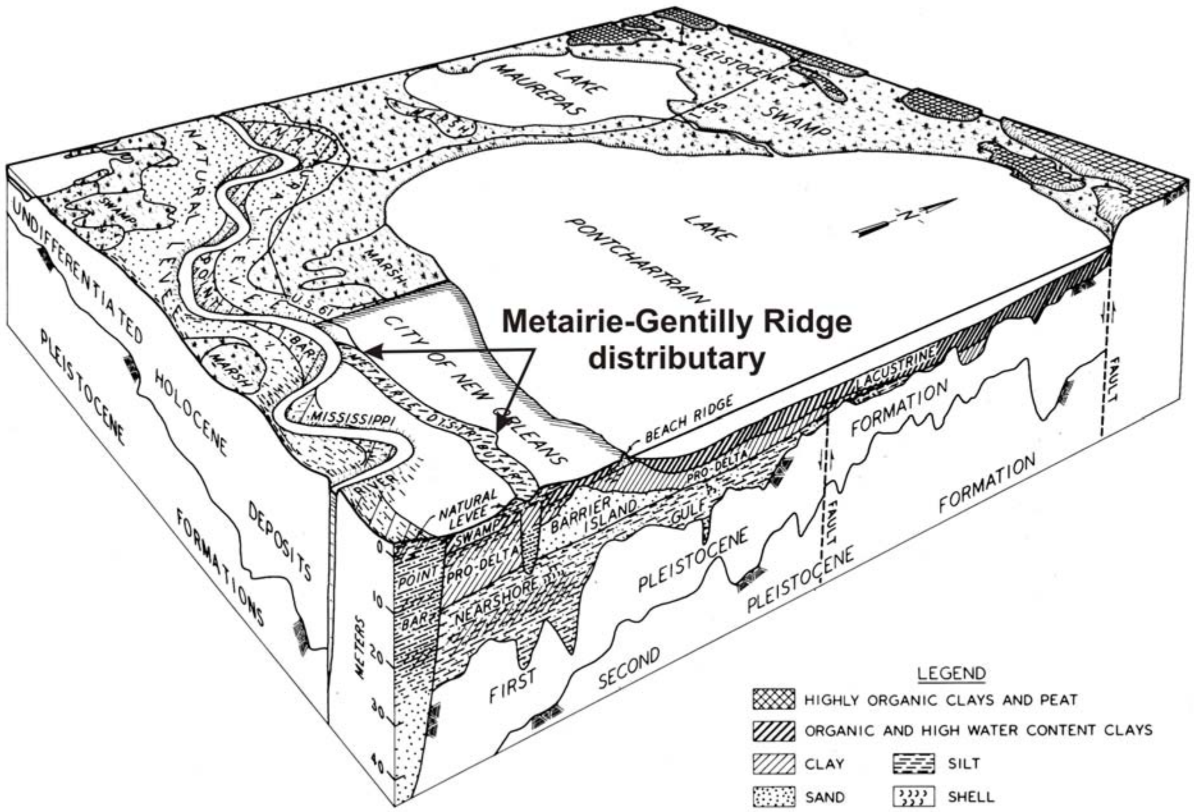
Source: Saucier (1994)

Figure 3.5: Contours of the entrenched surface of the Wisconsin glacial age deposits underlying New Orleans. Note the well developed channel leading southward, towards what used to be the oceanic shoreline. This channel reaches a maximum depth of 150 feet below sea level.



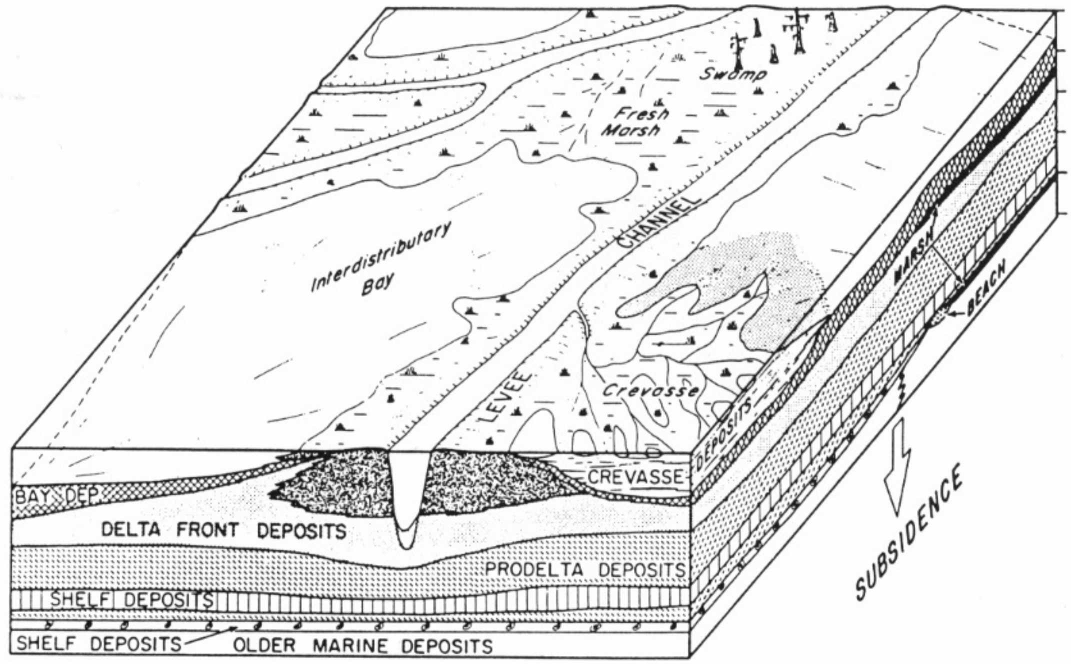
Source: Modified from Saucier (1994)

Figure 3.6: Areal distribution and depth to top of formation isopleths for the Pine Island Beach Trend beneath lower New Orleans.



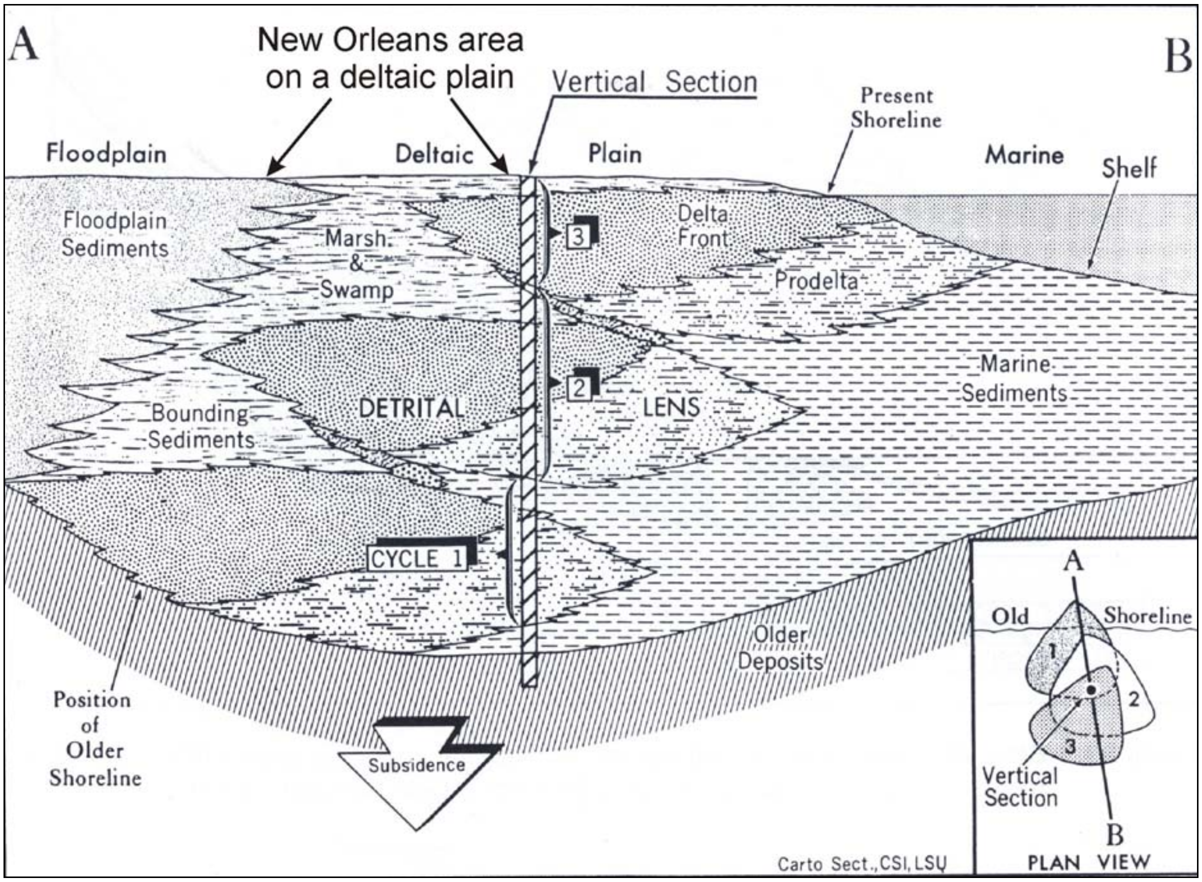
Source: Modified from Kolb and Saucier (1982)

Figure 3.7: Block diagram of the geology underlying New Orleans. The principal feature dividing New Orleans is the Metairie distributary channel, shown here, which extends to a depth of 50 feet below MSL and separates geologic regimes on either side. Note the underlying faults, especially that bounding the northern shore of Lake Pontchartrain.



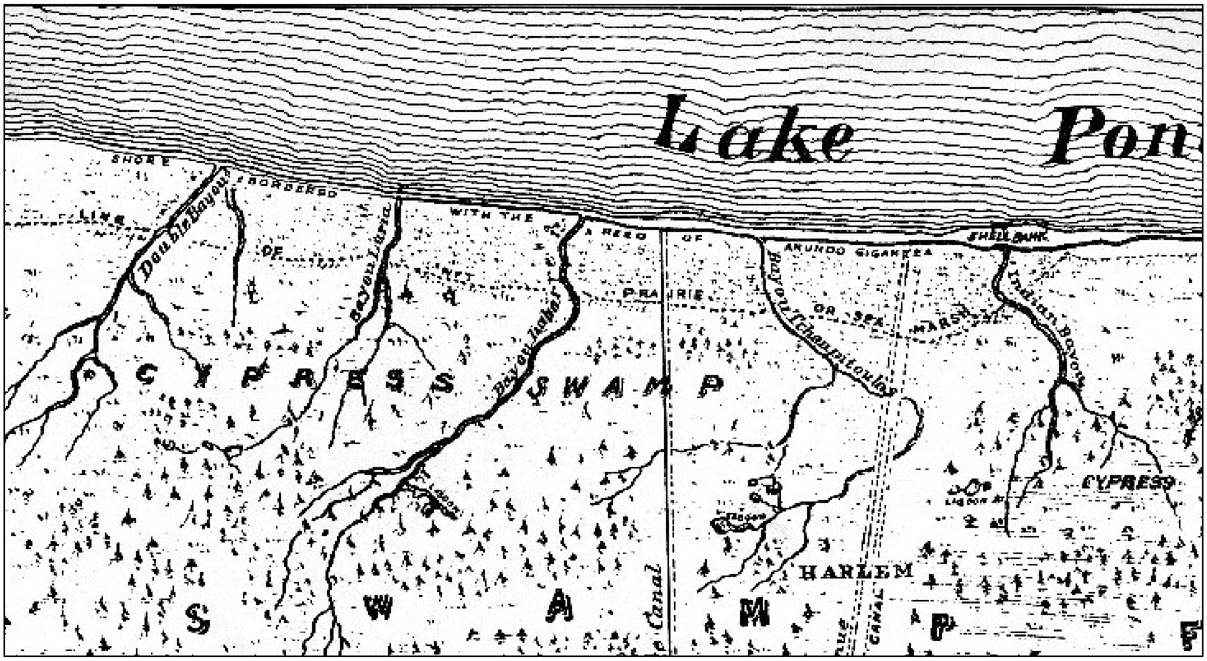
Source: Coleman and Roberts (1991)

Figure 3.8: Block diagram illustrating relationships between subaerial and subaqueous deltaic environments in relation to a single distributary lobe. The Lakeview and Gentilly neighborhoods of New Orleans are underlain by interdistributary sediments, overlain by peaty soils lain down by fresh marshes and cypress swamps.



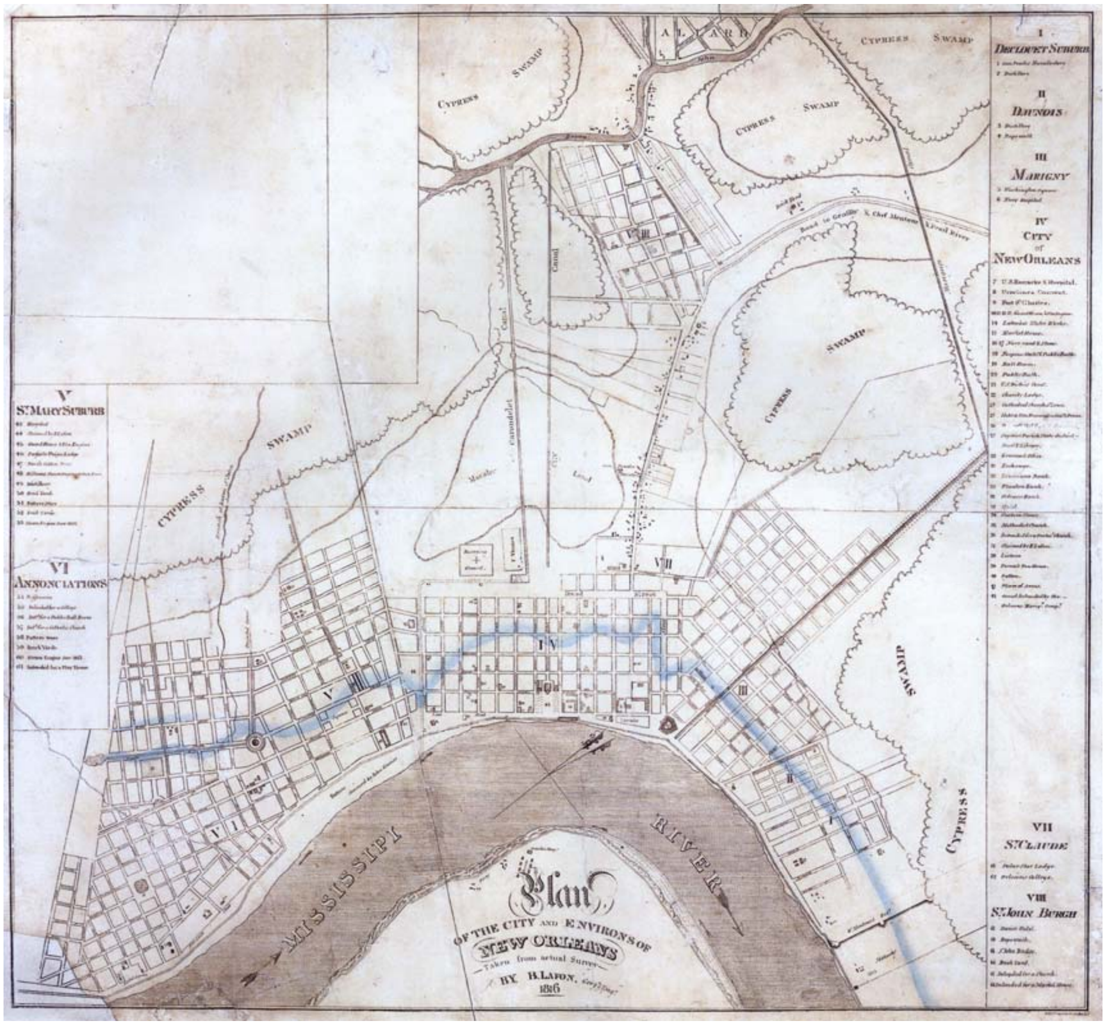
Source: Modified from Coleman and Gagliano (1964)

Figure 3.9: Sedimentary sequence caused by overlapping cycles of deltaic deposition, along a trend normal to that portrayed in the previous figure. As long as the distributary channel receives sediment the river mouth progrades seaward. Lower New Orleans lies on a deltaic plain with marsh and swamp deposits underlying the Lakeview and Gentilly neighborhoods and delta front deposits closer to Metairie-Gentilly Ridge, the nearest distributary channel.



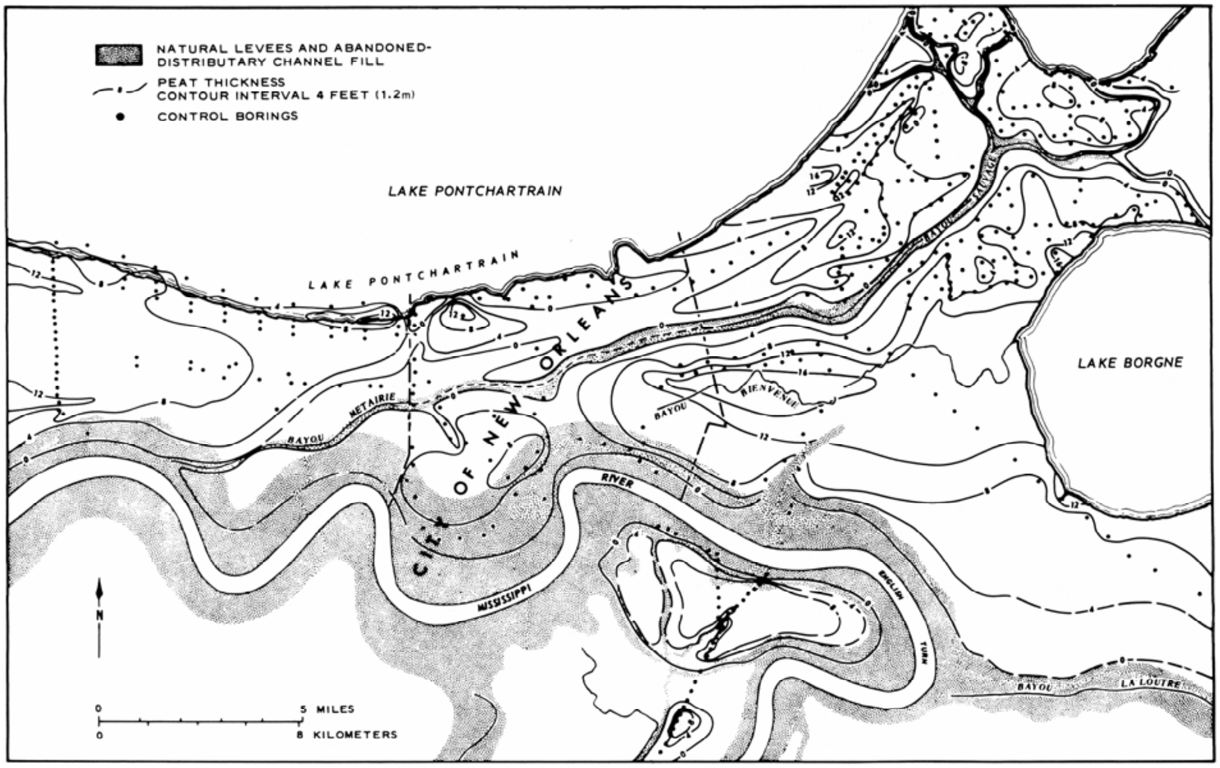
Source: WPA-LA (1937)

Figure 3.10: Portion of the 1849 flood map showing the mapped demarcation between brackish and fresh water marshes along Lake Pontchartrain. This delineation is shown on many of the historic maps, dating back to 1749.



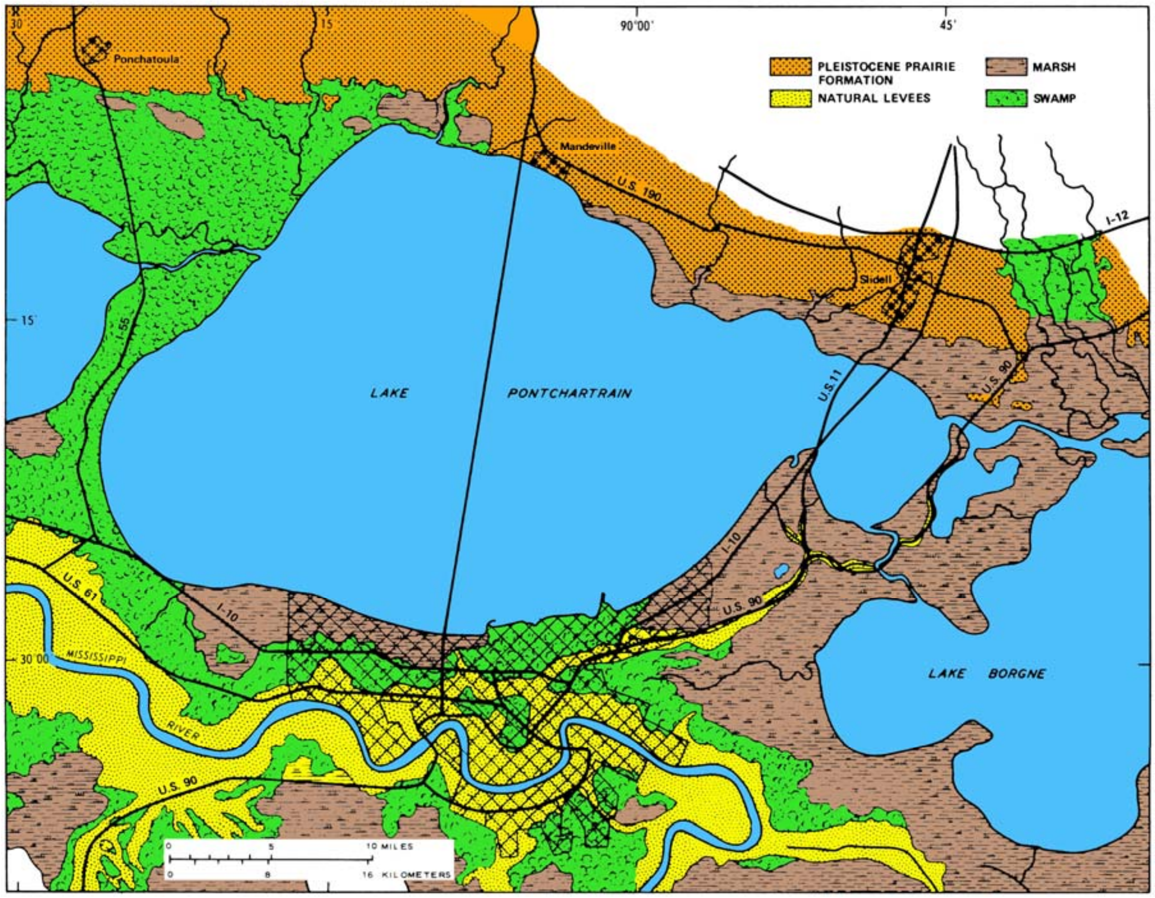
Source: Historic New Orleans Collection

Figure 3.11: 1816 flood map of New Orleans showing areal distribution of cypress swamps north of the old French Quarter. These extended most of the distance to the Lake Pontchartrain shore.



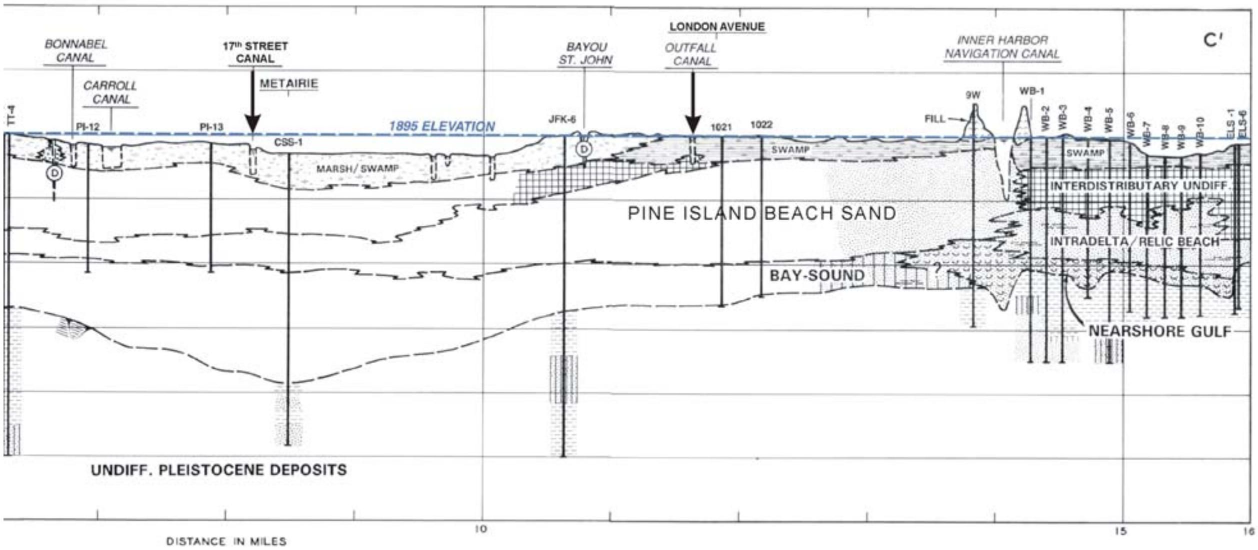
Source: Kolb & Saucier (1982) and Gould & Morgan (1962)

Figure 3.12: Distribution and apparent thickness of surficial peat deposits in vicinity of New Orleans.



Source: Modified from Kolb and Saucier (1982)

Figure 3.13: Geologic map of the greater New Orleans area. The sandy materials shown in yellow are natural levees, green areas denote old cypress swamps and brown areas are historic marshlands. The stippled zone indicates the urbanized portions of New Orleans.

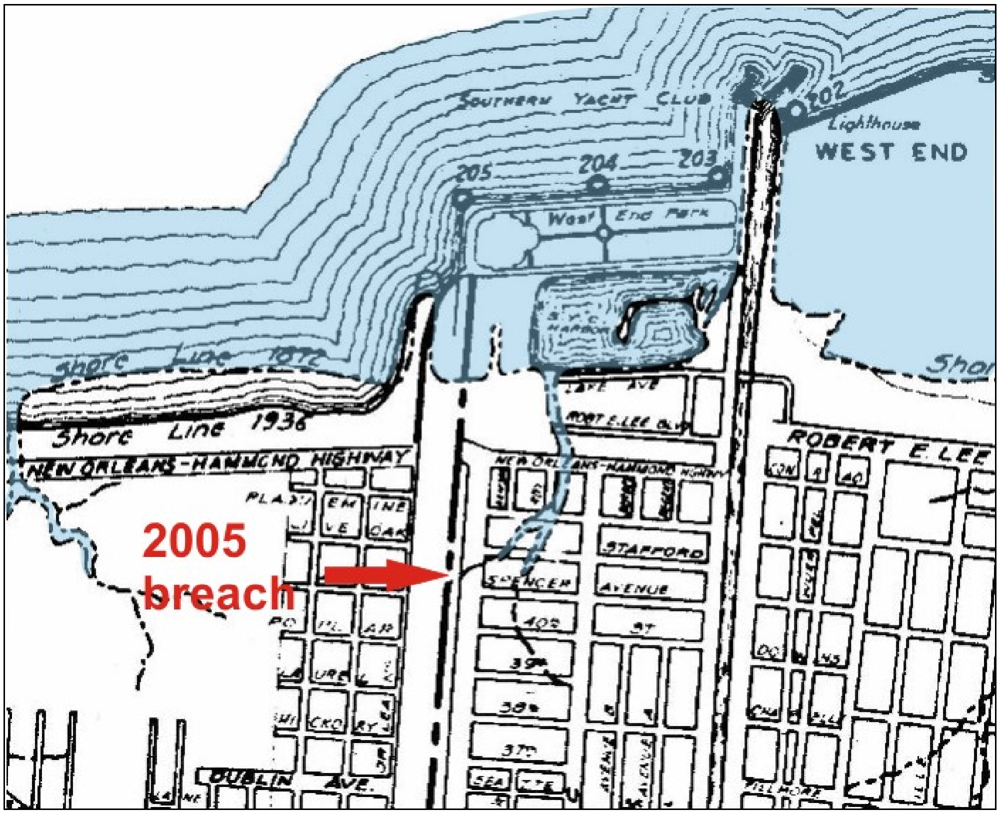


Source: May et al. (1984)

Figure 3.14: Geologic east-west cross section along south shore of Lake Pontchartrain in the Lakeside, Gentilly, and Ninth Ward neighborhoods, where the 17th Street, London Avenue, and IHNC levees failed during Hurricane Katrina on Aug 29, 2005. Notice the apparent settlement that has occurred since the city survey of 1895 (blue line), and the correlation between settlement and non-beach sediment thickness.

Photograph by C.M. Watkins

Figure 3.15: Wood and other organic debris was commonly sampled in exploratory borings carried out after Hurricane Katrina throughout the city. This core contains wood from the old cypress marsh that was recovered near the 17th Street (Metairie Relief) Canal breach. Organic materials are decaying throughout the city wherever the water table has been lowered, causing the land surface to subside.



Source: WPA-LA (1937)

Figure 3.16: Overlay of 1872 map by Valery Sulakowski on the WPA-LA (1937) map, showing the 1872 shoreline and sloughs (in blue) along Lake Pontchartrain. Although subdivided, only a limited number of structures had been built in this area prior to 1946. The position of the 2005 breach along the east side of the 17th Street Canal is indicated by the red arrow.

Figure 3.17: Aerial photo of the 17th Street Canal breach site before the failure of August 29, 2005. The red lines indicate the positions of the geologic sections presented in Figures 3.17 (south cross section) and 3.18 (north cross section).

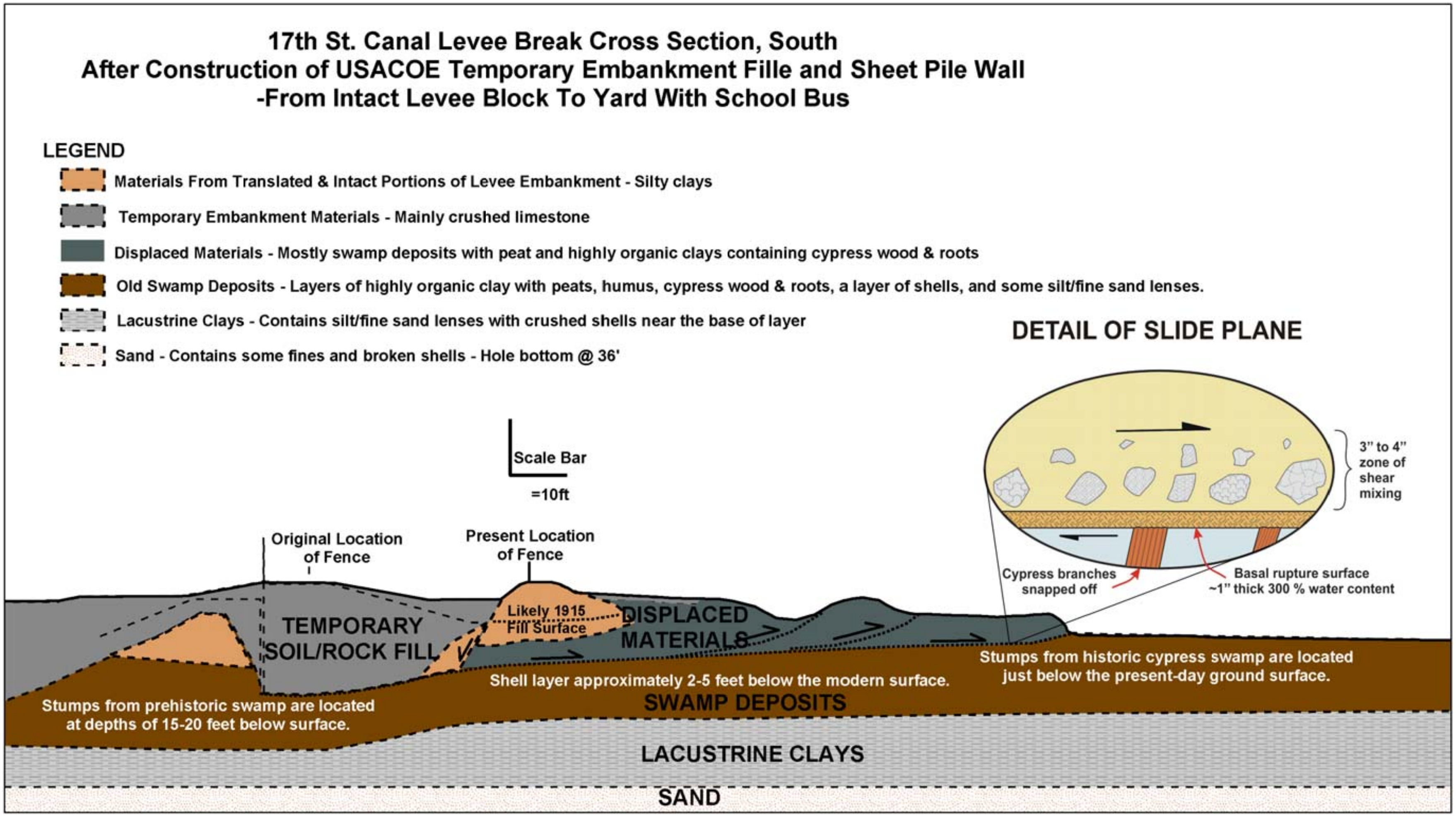


Figure 3.18: West-to-east geologic cross section through the 17th Street Canal failure approximately 60 feet north of the northern curb of Spencer Avenue, close to the yellow school bus. A detailed sketch of the basal rupture surface is sketched above right. The slip surface was about one inch thick with an extremely high moisture content (watery ooze). A zone of brecciation 3 to 4 inches thick was above this. Numerous pieces of cypress wood, up to 2 inches diameter, were sheared off along the basal rupture surface.

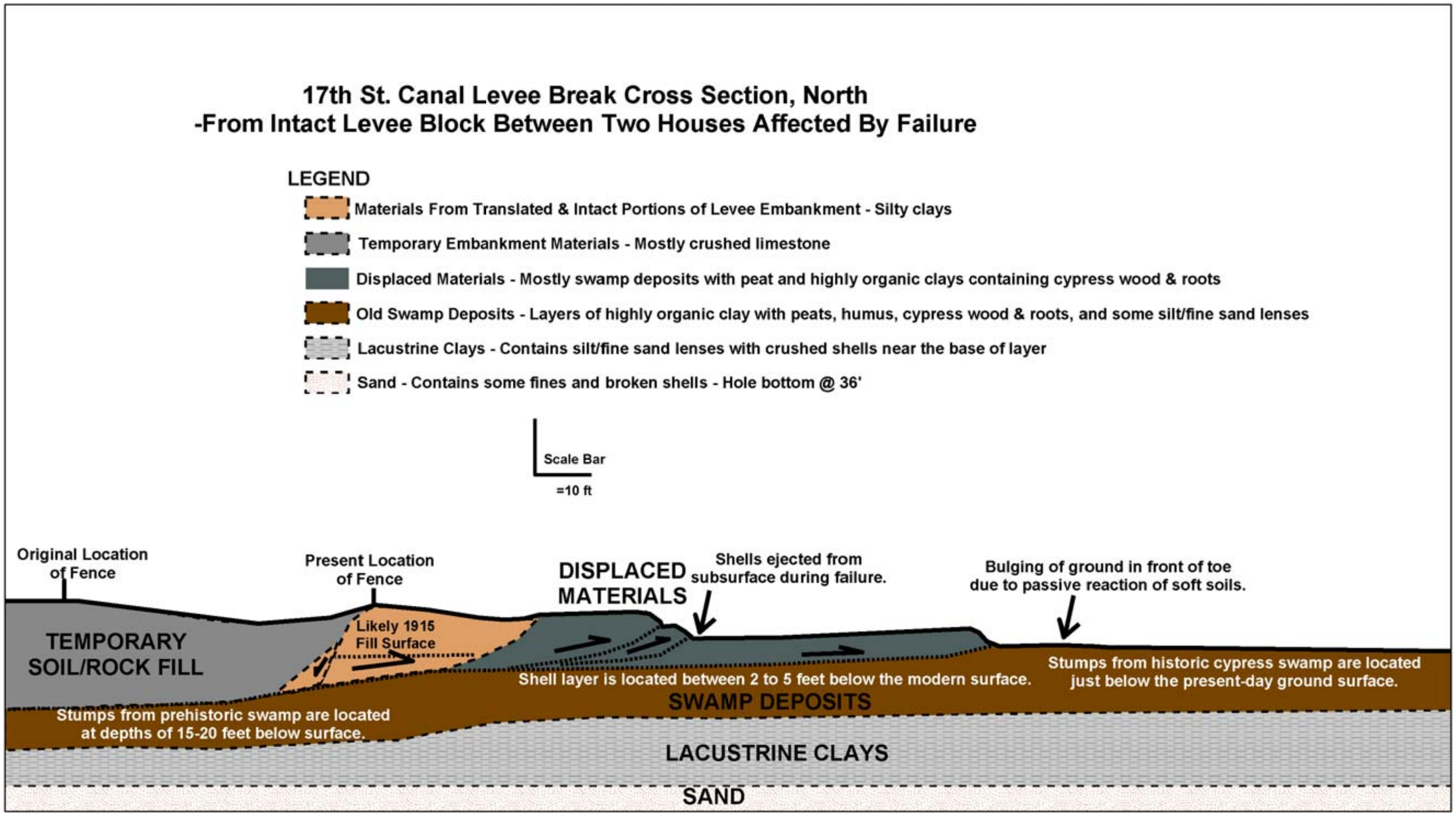
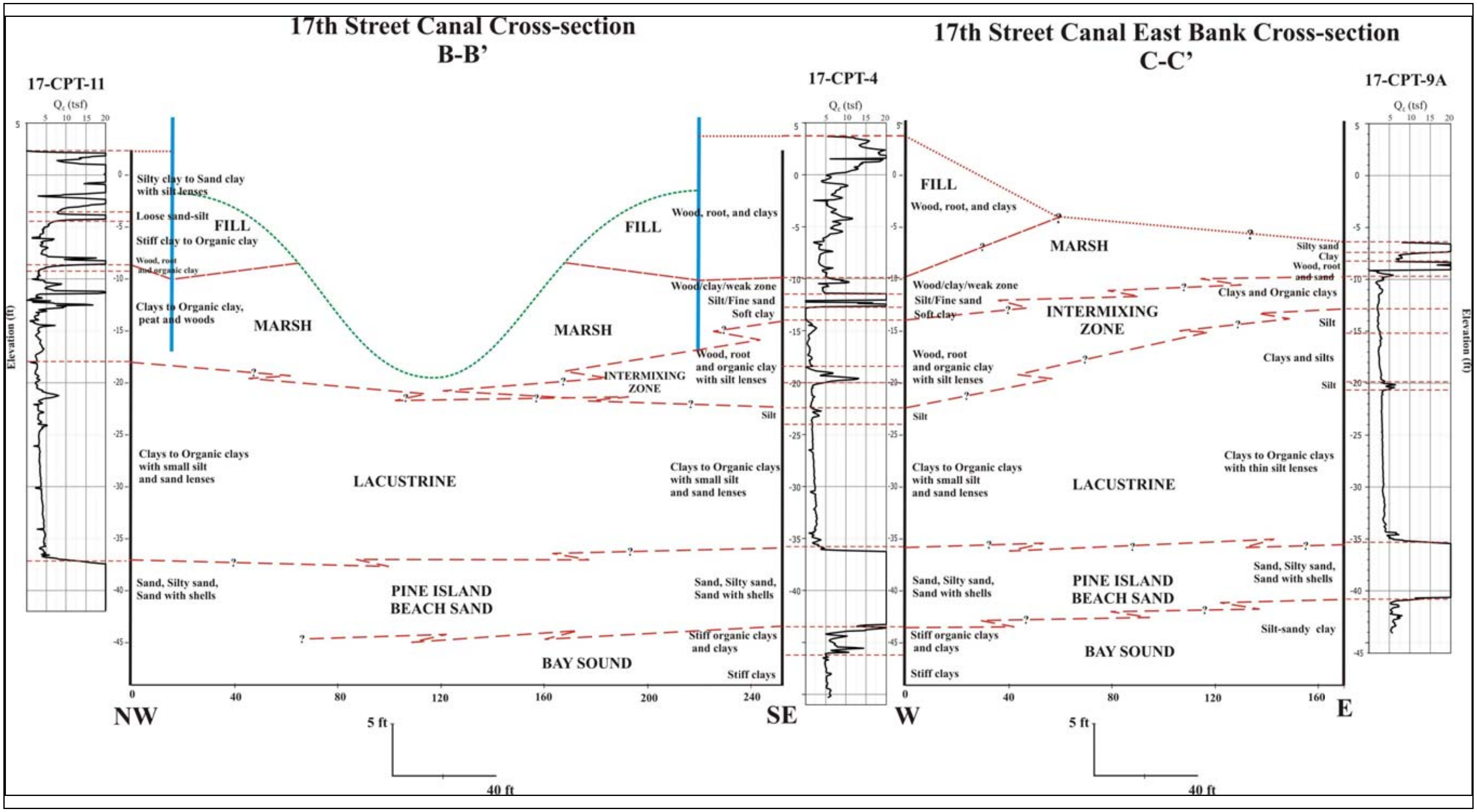


Figure 3.19: West-to-east geologic cross section through the 17th Street Canal failure approximately 140 feet north of the northern curb of Spencer Avenue, just north of the first surviving home next to the canal. Large quantities of bivalve shells were extruded by high water pressure along the regressing toe thrusts (shown in Figure 3.20). Note the slight back rotation of the distal thrust block.

Photograph by C.M. Watkins

Figure 3.20: Bivalve shells ejected by high pore pressures emanating from toe thrusts on landside of failed levee at the 17 Street Canal (detail view at upper left). These came from a distinctive horizon at a depth of 2 to 5 feet below the pre-failure grade.



Source: IPET (2006)

Figure 3.21: Stratigraphic interpretations and cross-canal correlations in vicinity of the 17th Street Canal breach on August 29, 2005. The swamp much appeared to be thinning northerly, as does the underlying Pine Island Beach Trend. The lacustrine clays appear to thicken northward, as shown. The approximate positions of the flood walls (light blue) and canal bottom (dashed green) are indicated, based on information provided by the Corps of Engineers.

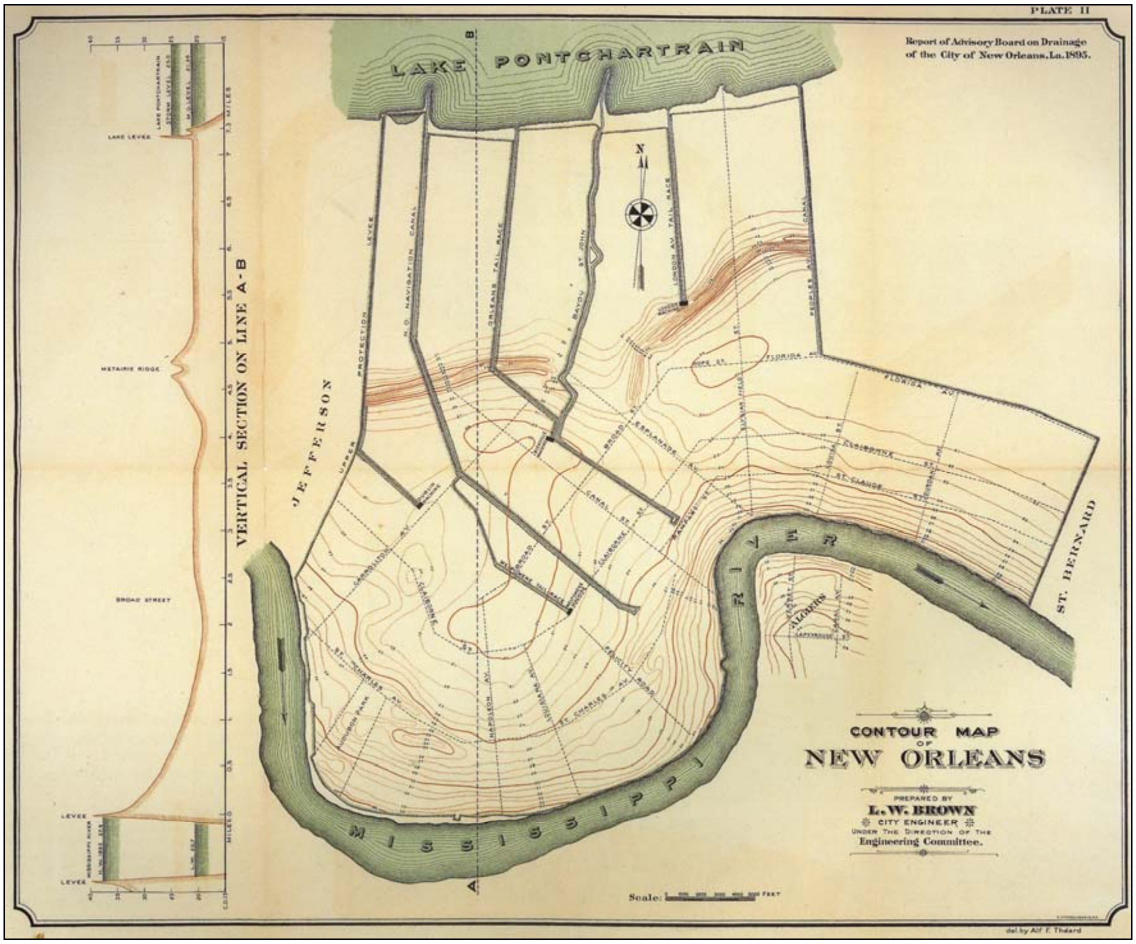
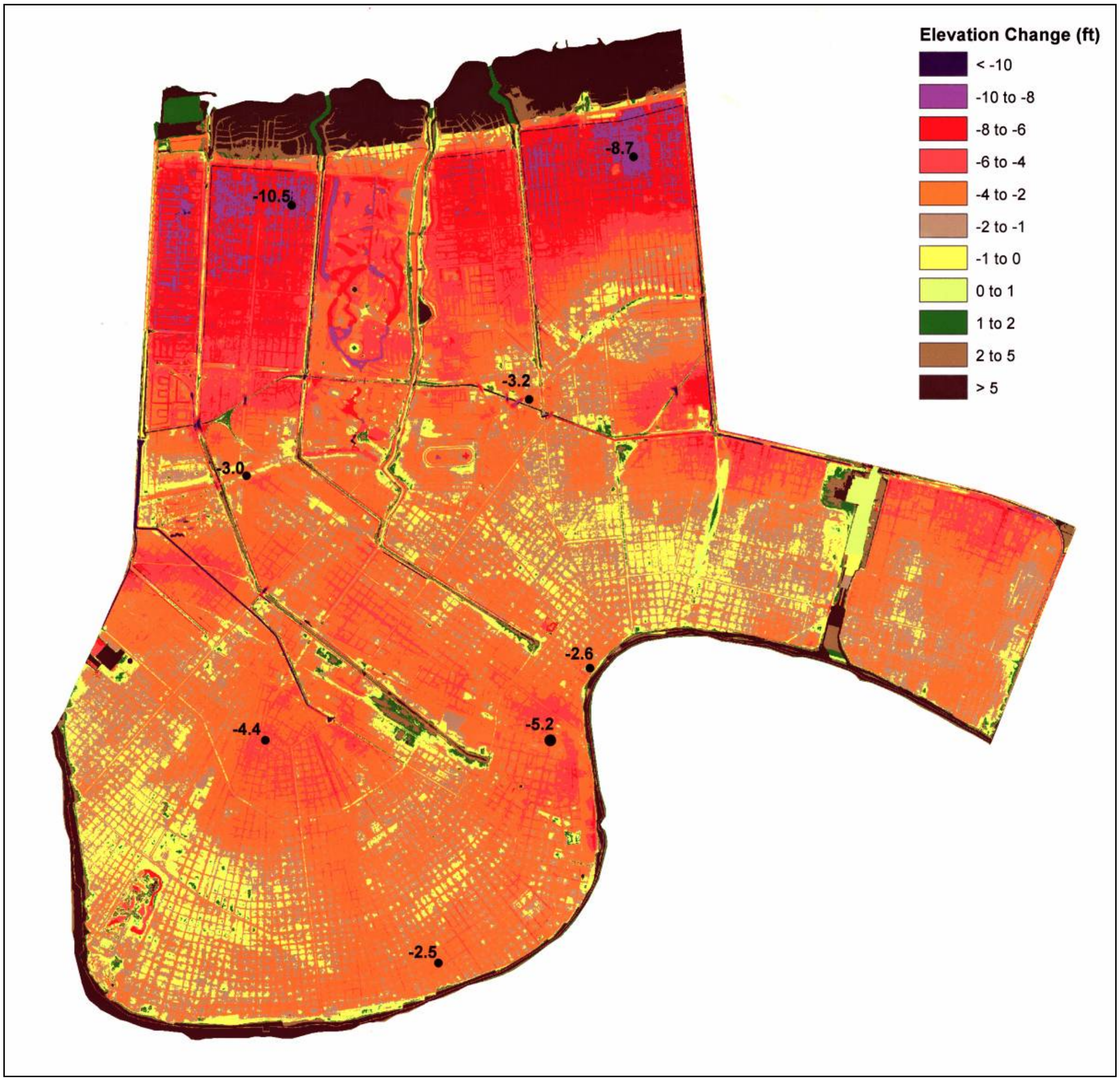
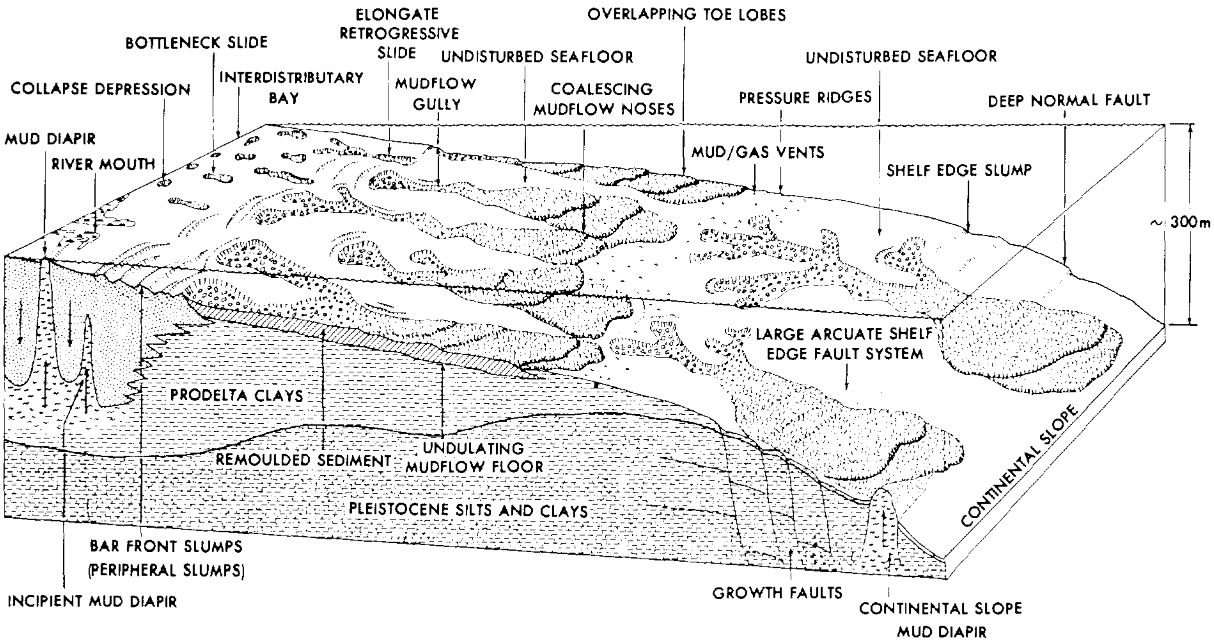


Figure 3.22: Topographic map with one foot contours prepared under the direction of New Orleans City Engineer L.W. Brown in 1895. This map was prepared using the Cairo Datum, which is 21.26 feet above Mean Sea Level.



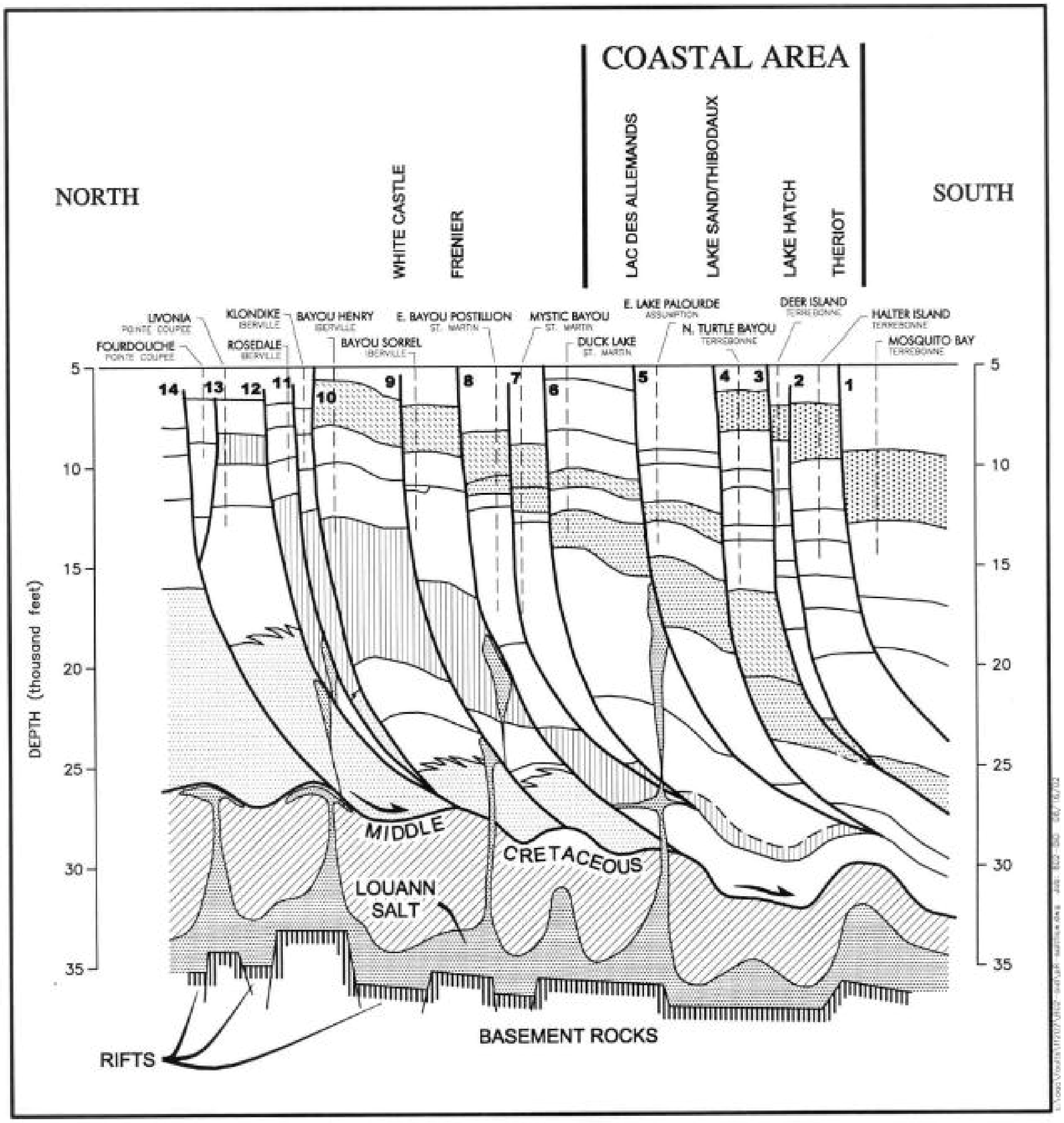
Source: URS (2006)

Figure 3.23: Map showing relative elevation change between 1895 and 1999/2002. The approximate net subsidence was between 2 and 10+ feet, depending on location. The brown colored zones along Lake Pontchartrain and the Mississippi River are areas where substantive fill was placed during the same interim.



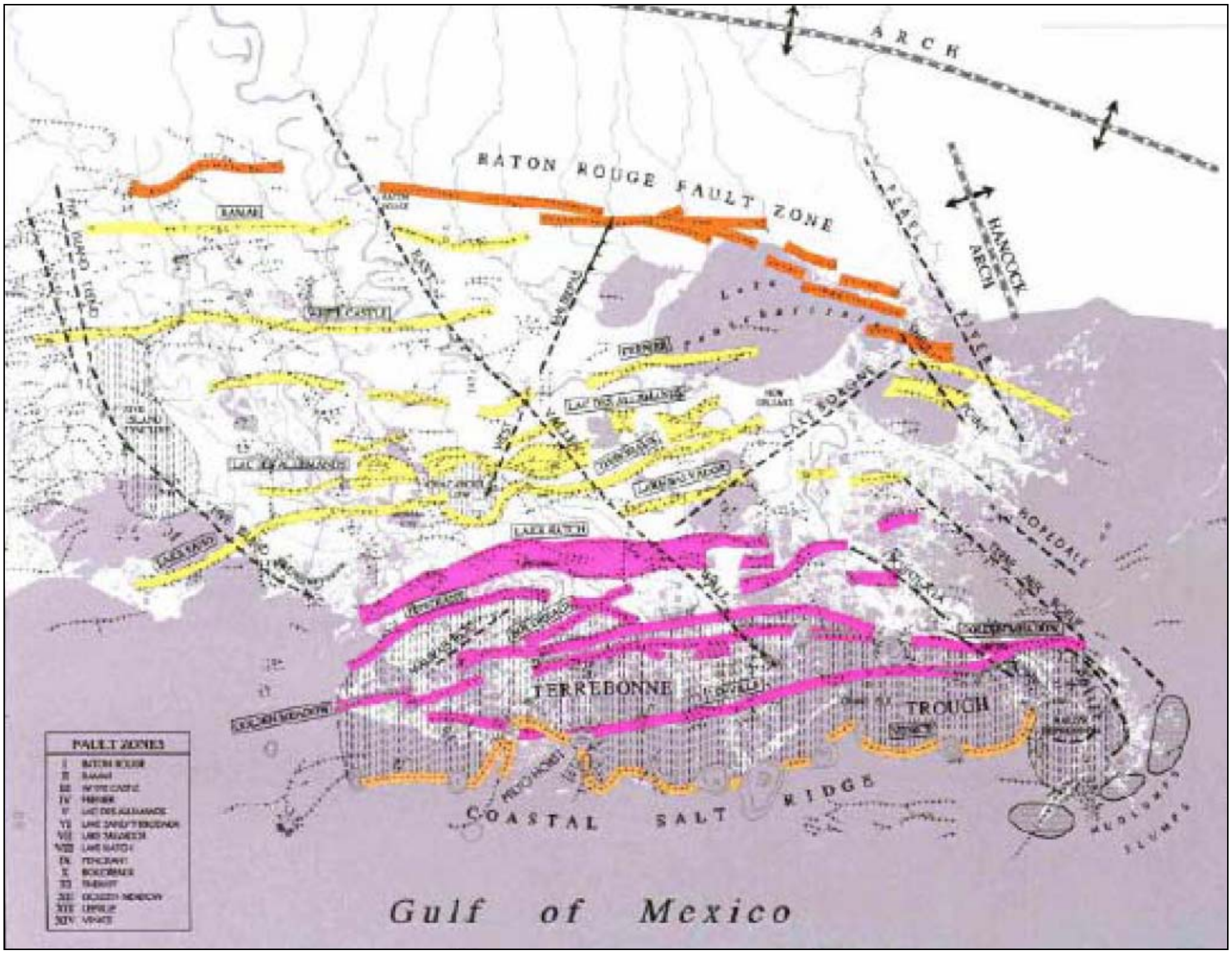
Source: Coleman (1988)

Figure 3.24: Block diagram illustrating various types of subaqueous sediment instabilities in the Mississippi River Delta.



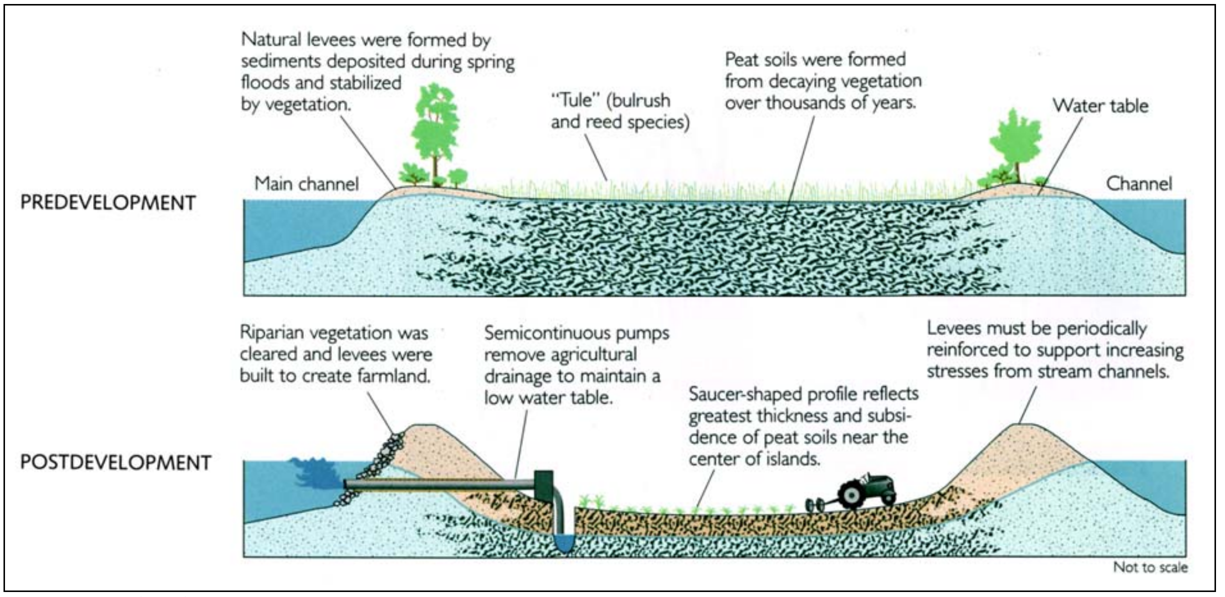
Source: Adams (1997)

Figure 3.25: Geologic cross section through the Gulf Coast Salt Dome Basin. This shows the retrogressive character of young lystric normal faults cutting coastal Louisiana, from north to south. The faults foot in a basement-salt-decollement surface of middle Cretaceous age (> 100 Ma).



Source: Coastal Environments (2001)

Figure 3.26: Structural geologic framework of southeastern Louisiana. This plot illustrates the en-echelon belts of growth faults forming more or less parallel to the depressed coastline. The Baton Rouge Fault Zone (shown in orange) is graphic fault scarp feature that has emerged over the past 50 years, north and west of Lake Pontchartrain.

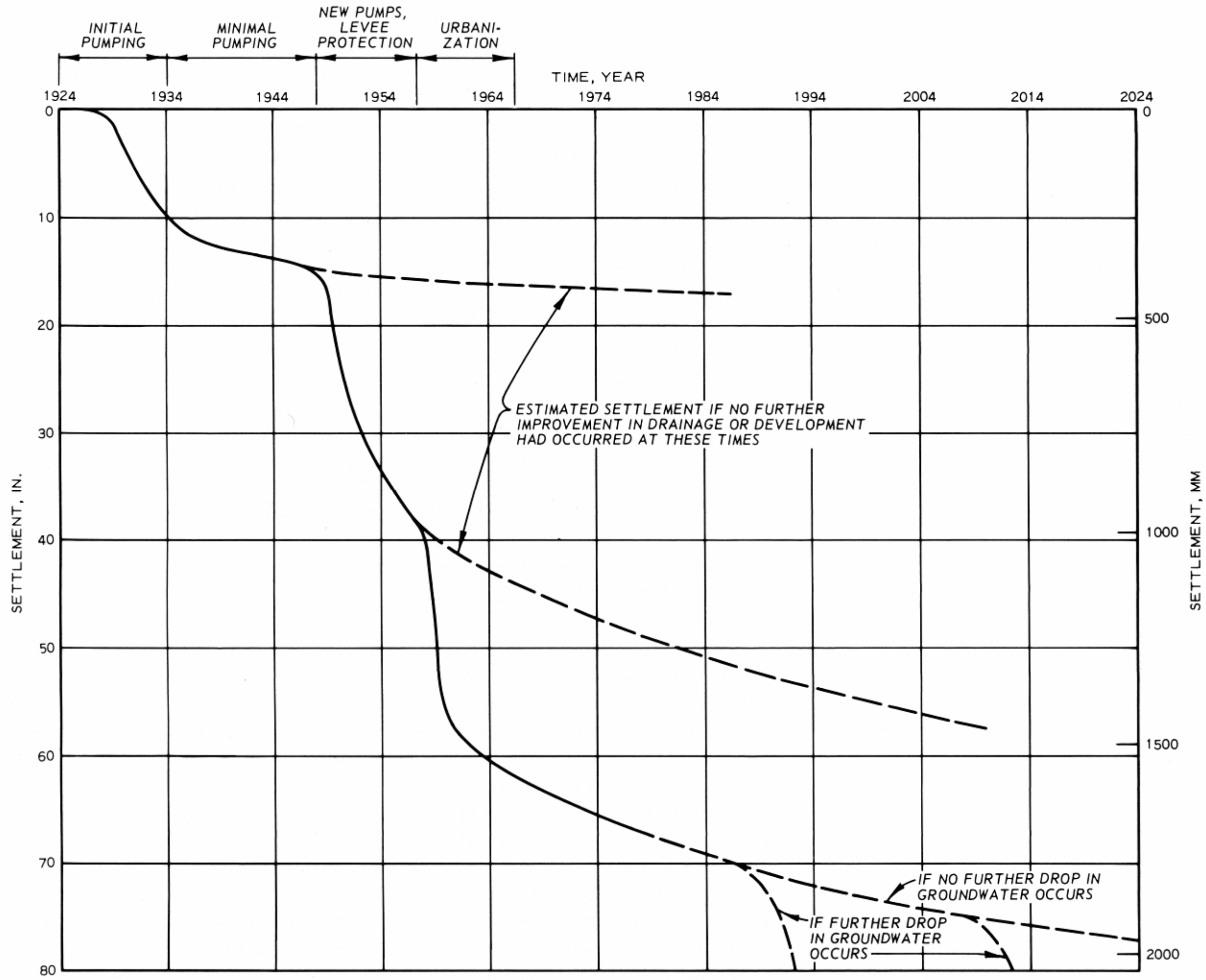


Source: AIPG (1993)

Figure 3.27: Settlement of surficial peaty soils is usually triggered by lowering of the local groundwater table, either for agriculture or urban development. Lowering the water table increases the effective stress on underlying sediments and hastens rapid oxidation of organic materials, causing settlement of these surficial soils.

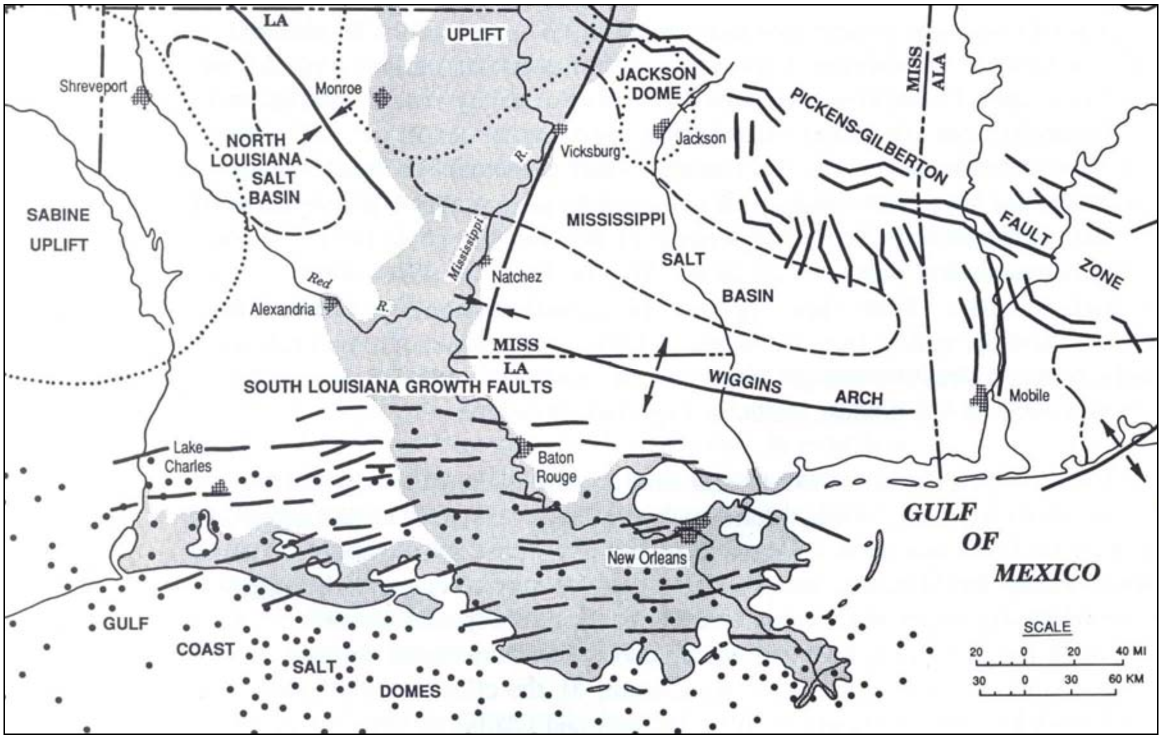
Photographs by J.D. Rogers

Figure 3.28: Upper photo shows gross near-surface settlement of homes in the Lakeview neighborhood, close to the 17th Street Canal breach. Most of the homes were constructed from 1956-75 and are founded on wood piles about 30 feet deep. The lower photo shows protrusion of a brick-lined manhole on Spencer Avenue, suggestive of at least 12 inches of near surface settlement during the same interim.



Source: Kolb and Saucier (1982)

Figure 3.29: Record of historic settlement in the town of Kenner, which is characterized by 6.5 to 8 feet of surficial peaty soils (taken from Kolb and Saucier, 1982). The earlier episodes of settlement were triggered by groundwater withdrawal (for industrial and municipal usage), while the later episode was caused by drainage associated with urban development. This area was covered by dense cypress swamps prior to development.



Source: Saucier (1994)

Figure 3.30: Structural geologic framework of the lower Mississippi River Delta. Growth faults (solid black lines) perturb the coastal deltaic plain, as do salt domes (shown as dots). The nearest salt domes to New Orleans are 9 to 15 miles southwest of New Orleans. This study did not uncover evidence of growth faults materially affecting any of the levee failures from Hurricane Katrina, although such possibility exists.

CHAPTER FOUR: HISTORY OF THE NEW ORLEANS FLOOD PROTECTION SYSTEM

4.1 Origins of Lower New Orleans

New Orleans is a deep water port established in 1718 about 50 miles up the main stem of the Mississippi River, on the eastern flank of the Mississippi River Delta. New Orleans was established by the French in 1717-18 to guard the natural portage between the Mississippi River and Bayou St. John, leading to Lake Pontchartrain. The 1749 map of New Orleans by Francois Saucier noted the existence fresh water versus brackish water swamps along the southern shore of Lake Pontchartrain.

The original settlement was laid out as 14 city blocks by 1721-23, with drainage ditches around each block. The original town was surrounded by a defensive bastion in the classic French style. The first levee along the left bank of the Mississippi River was allegedly erected in 1718, but this has never been confirmed (it is not indicated on the 1723 map reproduced in Lemmon, Magill and Wiese, 2003). New Orleans early history was typified by natural catastrophes. More than 100,000 residents succumbed to yellow fever between 1718 and 1878. Most of the city burned to the ground in 1788, and again, in 1794, within sight of the largest river in North America. The settlement was also prone to periodic flooding by the Mississippi River (between April and August), and flooding and wind damage from hurricanes between June and October. Added to this was abysmally poor drainage, created by unfavorable topography, lying just a few feet above sea level on the deltaic plain of the Mississippi River, which is settling at a rate of between 2 and 10 feet (ft) per century.

The tendency to flooding during late spring and summer runoff came to characterize the settlement. The natural swamps north of the original city were referred to as “back swamps” in the oldest maps, and “cypress swamps” on maps made after 1816. During the steamboat era (post 1810), New Orleans emerged as the major trans-shipment center for river-borne to sea-born commerce, vice-versa, and as a major port of immigration. By 1875 it was the 9th largest American port, shipping 7,000 tons annually. In 1880, after completion of the Mississippi River jetties (in 1879), New Orleans experienced a 65-fold increase in seaborne commerce, shipping 450,000 tons, jumping it to the second largest port in America (New York then being the largest). New Orleans would retain its #2 position until well after the Second World War, when Los Angeles-Long Beach emerged as the largest port, largely on the strength of its container traffic from the Far East. New Orleans remains the nation’s busiest port for bulk goods, such as wheat, rice, corn, soy, and cement.

New Orleans has always been a high maintenance city for drainage. The city’s residential district did not stray much beyond the old Mississippi River levee mound until after 1895, when serious attempts to bolster the Lake Pontchartrain “back levee” and establish a meaningful system of drainage were undertaken by the city. Most of the lowland cypress swampland between Mid-Town and Lake Pontchartrain was subdivided between 1900-1914, after the City established and funded a Drainage Advisory Board to prepare ambitious plans for keeping New Orleans dry all the way to Lake Pontchartrain’s shoreline. This real estate bonanza increased the City’s urban acreage by 700% and their assessed property values by

80% during the same interim (Campanella, 2002). Most of these lots were developed after the First World War (1917-18). Another 1,800 acres was reclaimed from the south shore of Lake Pontchartrain in 1928-31, between the mouth of the 17th Street Canal on the west and the Inner Harbor Navigation Canal (IHNC) on the east. The entire area was subsequently built-out following the Second World War, between 1945-70.

4.2 Mississippi River Floods

The Mississippi River drains 41% of the continental United States, with a watershed area of between 1,245,000 square miles (mi^2), according to the U.S. Army Corps of Engineers. This makes it the third largest watershed of any river in the world. Although its official length is 2,552 miles (if measured from Itasca State Park in Minnesota), when combined with the Missouri River (2,540 miles long), it is the longest river in North America, with a combined length of 3,895 miles. Prior to 1950, the sediment load (suspended and dissolved) transported by the Mississippi River averaged between 550 and 750 million tons per annum (Meade and Parker, 1985). Since 1950, the average annual suspended discharge of the river has decreased to 220 million tons/yr (Meade and Parker, 1985), because of the construction of dams and maintenance of the navigation channel (which includes dredging). The Mississippi River now ranks as the 6th largest silt load in the world.

The Mississippi's flood plain upstream of Baton Rouge is an alluvial valley that, prior to 1928, was periodically subject to inundation by flooding. Vast tracts of the flood plain were periodically inundated. 26,000 square miles of land (mi^2) was inundated during the 1927 flood; 20,312 mi^2 in the 1973 flood, and 15,600 mi^2 in the 1993 flood (which focused on the lower Missouri watershed). 75% of the sediment deposited on the North American continent is overbank flood plain silt, which spills onto the flood plain when floods spill over natural or man-made levees. At its widest point in the Yazoo Basin, the Mississippi flood plain is more than 80 miles wide.

4.2.1 Mississippi River is the High Ground

The river is the high ground in the Mississippi Embayment (Figure 4.1). A vexing problem with a high silt load river is that it tends to build up its own bed, which prevents drainage of the adjoining flood plains. Sediment is deposited on the adjoining lowlands when the river spills up out of its channel during flood stage. Sediments are hydraulically sorted during this process, becoming increasingly fine-grained and soft with increasing distance from the river channel, as sketched in Figure 4.2. Millions of acres of flood plain swamps and marshlands in the Mississippi Embayment downstream of Gape Girardeau, MO were reclaimed by mechanically excavated drainage ditches, beginning around 1910, when large rail-mounted dragline excavators became available. This machinery was also employed for levee construction on the MR&T Project (after 1928) as well as drainage work for agricultural reclamation.

4.2.2 Flooding from the Mississippi River

A great number of floods have occurred in the lower Mississippi Valley during historic time, including: 1718, 1735, 1770, 1782, 1785, 1971, 1796, 1799, 1809, 1811, 1813, 1815, 1816, 1823, 1824, 1828, 1844, 1849, 1850, 1851, 1858, 1859, 1882, 1892, 1893, 1903, 1907, 1908, 1912, 1913, 1916, 1920, 1922, 1923, 1927, 1929, 1932, 1936, 1937, 1945, 1950, 1957, 1958, 1973, 1974, 1975, 1979, 1983, 1984, 1993, and 1997.

The most damaging to New Orleans were those in: 1816, 1826?, 1833?, 1849, 1857?, 1867, 1871, 1874, 1882, 1884, 1890, 1892, 1893, 1897, 1903, 1912, 1913, 1922, 1927, 1937, 1947, 1965, 1973, 1979, 1993, and 2005. But, the last flood of any consequence to affect the City of New Orleans emanating from the Mississippi River was in 1859!

New Orleans was founded in 1718. In April 1719 the town's founder Jean Baptiste le Moyne, Sieur de Bienville, reported that water from the Mississippi River was regularly inundating the new settlement with half a foot of water. He suggested constructing levees and drainage canals, and soon required such drainage work of all the landowners. In 1734-35 the Mississippi River remained high from December to June, breaking levees and inundating the settlement.

Flood protection from the Mississippi River was originally afforded by heightening of the river's natural bank overflow levees (Hewson, 1870), like those shown in Figure 4.3. Crevasses, or crevasse-splays, (Figure 3.8) are radiating tensile cracks that form in the bank of a river, natural levee, man-made levee, or drainage canal. Crevasse-splays are often triggered by underseepage along preferential flow conduits, such as old sand-filled channels or the radiating distributaries of previous channel breaks. For these reasons, crevasse-splays often occur at the same locations repeatedly.

On May 5, 1816 the Mississippi levee protecting New Orleans gave way at the McCarty Plantation, in present-day Carrollton, and within a few day water filled the back portion of the city, extending from St. Charles Avenue to Canal and Decatur Streets, flooding the French Quarter. The water was only drained after a new drainage trench was excavated through Metairie Ridge and channels connecting to Bayou St. John.

On May 4, 1849 the Mississippi River broke the levee at the Suavé Plantation at River Ridge, 15 miles upstream of New Orleans. Within four days this water reached the New Basin Canal, and within 17 days was flooding the French Quarter in New Orleans proper, flooding the area downslope (north of) of Bienville and Dauphine Streets. The 1849 flood waters rose at an average rate of one foot every 36 hours, which allowed residents ample time to evacuate. Uptown residents thought about severing the levee along the New Basin Canal to prevent water levels building up on their side, but those living on the opposite side of the canal threatened to prevent such measures using armed force. Shortly thereafter the New Basin upper levee collapsed, diverting flood waters to Bayou St. John and thence, into Lake Pontchartrain. A nine foot deep lake developed in what is now the City's Broadmoor area, flooding 220 city blocks and necessitating the evacuation of 12,000 residents.

The 1849 crevasse at Suavé Plantation was eventually plugged by driving a line of timber piles and piling up thousands of sand bags against these on the land-side of the pile wall. This work was of unprecedented proportions until that time and took six weeks to complete before the river's waters were once again confined to their natural channel. Drainage trenches were then excavated through Metairie [distributary] Ridge to channel ponded water out to Lake Pontchartrain. By mid-June 1849 the water was finally receding and residents began re-entering their flooded homes, spreading lime to combat mold, mildew, and impurities.

Between 1849 and 1882, four major crevasse-splays occurred at Bonnet Carré, on the eastern bank of the Mississippi River, about 33 river miles upstream of New Orleans. The Bonnet Carré crevasses left a large fan-shaped imprint on the landscape. In fact, during the flood of 1849, a 7,000-foot-wide crevasse developed at Bonnet Carré which diverted flow from the Mississippi into Lake Pontchartrain for more than six months. This breach had to be filled so sufficient discharge could flow down the main channel to allow ocean going vessels to reach New Orleans.

The 1849 floods were the last time that the eastern bank of the Mississippi River was breached affecting New Orleans proper. In 1858 high water lapped over the east bank levee, but this was followed a few days later by a break on the west bank of the river (at Bell Plantation), which drew down the high water threatening New Orleans. The Bell Plantation crevasse remained open for six months. In 1859 the rear portion of New Orleans again flooded, between Carrollton and Esplanade Avenues, flooding one-third of the City between January and March.

The City of New Orleans and the Mississippi River became important battlegrounds during the American Civil War between 1861-65. Early in the conflict a principal goal of the Union forces west of the Appalachian Mountains was to sever the Confederacy along the Mississippi River. Union forces had a distinct advantage insofar as they retained most of their naval power, allowing them to blockade Confederate ports. General Ulysses Grant achieved considerable notoriety for his early campaigns up the Cumberland and Tennessee Rivers, and later, in the successful siege of Vicksburg, which gave northern forces control of the Mississippi, isolating 40,000 Confederate troops west of the river, where they played no further significant role in the conflict. Grant recognized the pivotal military role of the great river, because it was his Army's vital supply line. Grant turned to his engineers on numerous occasions and ordered the construction of cutoffs (Figure 4.4), some of which were successful, while others, such as that a short distance downstream of Vicksburg, were not.

The success or failure of the man-made cutoffs depended on a number of factors, such as time of year, severity of the spring flood, and ability to meter flows into the cutoffs trying to control the erosion caused by dropping the water over oversteepened gradients. These experiences were drawn upon soon after the war (Hewson, 1870) to create an inland empire through drainage of low lying swamps and construction of thousands of miles of privately constructed levees to keep the river from flooding reclaimed tracts.

During the post Civil War boom that witnessed significant reclamation of flood-prone tracts in the Mississippi flood plain, a pattern of protection emerged as the established cities like New Orleans battled the Mississippi: that being of adjacent breaks, upstream at Bonnet Carré and downstream, in Plaquemines Parish, often providing "safety valves" that reduced high water in the river along the New Orleans waterfront. The western bank would breach again in 1893, at the Ames Plantation in Marrero. Breaks in adjoining areas gradually give rise to rumors about levees being purposefully undermined to save the more valuable property within the city, which reached epic proportions during the record flood of 1927, when the levees adjoining Plaquemines Parish were dynamited no less than seven times, by City officials worried that their own protective works would crumble and give ay (Barry, 1997).

Army Engineer A.A. Humphreys and civilian engineer Charles Ellet were funded by Congress in separate contracts to make a scientific examination of the Mississippi River in 1850. Ellet completed his work in 1851, but Humphries did not completing his report until 1861, after suffering a nervous breakdown (Barry, 1997). Humphreys controlled the Mississippi River as Chief of the Corps of Engineers between 1866-1879. He was the father of the Corps' flawed "levees only policy" of flood control, which remained in effect till the wake of the 1927 flood ushered in the adoption of the Jadwin Plan, embodied in the Federal Flood Control Act of 1928 (Morgan, 1971; Shallat, 1994). The "levees only policy" maintained that the Mississippi River could be constrained within its natural low flow channel by extending its natural levees upward, assuming the channel would downcut its bed vertically during high flows, thus remaining in an artificially confined channel. This logic was hopelessly flawed in that it ignored the river's serpentine curvature, which causes it to loop on itself in an endless seemingly series of "meander belts" across the floodplain. Because of this curvature, the channel is seldom symmetrical (like Figure 4.2), but generally exhibits marked asymmetry, like that shown in Figure 4.5.

In 1871 the Mississippi River once again spilled its eastern bank at Bonnet Carré, 33 miles upstream of New Orleans. The massive break diverted much of the river's flow into Lake Pontchartrain, raising its level. A strong north wind pushed lake water up into the Metairie and Gentilly ridges, filling the then-existing system of drainage canals. A levee on the Hagan Avenue (now the Jefferson Davis Parkway) drainage canal gave way, flooding the back side of New Orleans, including the Charity Hospital, a town landmark.

The 1927 flood was the largest ever recorded on the lower Mississippi Valley (Figure 4.6). The deluge was preceded by a record 18 inches of rain falling on New Orleans in a 48 hour period in late March 1927, which was followed by six months of flooding. The levees that were supposed to protect the valley broke in 246 places, inundating 27,000 square miles of bottom land; displacing 700,000 people, killing 1,000 more (246 in the New Orleans area), and damaging or destroying 137,000 structures.

There was an enormous public outcry for the government to do something more substantive about flood control. Fearing the worst, the political leadership of New Orleans sought relief by dynamiting the Mississippi levee in Plaquemines Parish, downstream of New Orleans. By the time promises were made regarding damage compensation and the necessary permission was granted, the flood had crested and begun to subside. No less than seven sequences of dynamiting ensued, all promoted by fear. The initial dynamiting of the Caernarvon levee below New Orleans with 30 tons of dynamite devastated much of St, Bernard and Plaquemines Parishes, and their residents were never remunerated in any meaningful way for their damages. The saddest aspect of the dynamiting was that it was unnecessary, as several levees gave way upstream of New Orleans, one the very afternoon of the dynamiting and the river level at New Orleans never regained its maximum crest the remainder of that record year (Barry, 1997).

4.3 The Mississippi River and Tributaries Project 1931-1972

The Corps of Engineers Mississippi River & Tributaries (MR&T) Project was authorized by Congress in the Flood Control Act of 1928, which emanated from the Great Flood of 1927 on the lower Mississippi River. At the time of its introduction it was referred to as The "Jadwin Plan," because Major General Edgar Jadwin was the Army's Chief of Engineers at the time it was issued, on December 1, 1927 (Jadwin, 1928). It was incorporated into the Federal Flood Control Act of May 15, 1928, which authorized $325 million to the Mississippi River Commission (created in 1879) controlled by the Corps of Engineers to provide for flood protection along the Mississippi River between Cape Girardeau, MO and Head-of-Passes, LA. In essence the Mississippi River Commission adopted the Mississippi River & Tributaries Project, and the commission's responsibilities, annual budget, expenditures and importance increased by an order of magnitude, where it remains more-or-less today. Actual construction did not begin until 1931, when the authorized funds were finally appropriated by Congress.

The original flood control plan selected a project flood of 2,360,000 cubic feet per second (cfs) at the mouth of the Arkansas River and 3,030,000 cfs at the mouth of the Red River. These figures were about 11% greater than the record 1927 flood at the junction of the Mississippi and Arkansas Rivers and 29% greater than 1927 flood at the junction of the Mississippi and Red Rivers, 60 miles downstream of Natchez, MS.

The Jadwin Plan proposed four major elements to control the flow of the Mississippi River. These were: 1) levees to contain flood flows wherever practicable, or necessary to avoid razing large sections of existing cities and transportation infrastructure; 2) bypass floodways to accept excess flows of the river, passing these into relatively undeveloped agricultural basins or lakes; 3) channel improvements intended to stabilize river banks, to enhance slope stability and commercial navigation; and 4) improvements to tributary basins, wherever possible. This category included dams for flood storage reservoirs, pumping plants, and auxiliary channels.

The main stem levees (Figure 4.7) were intended to protect the Mississippi alluvial valley against flooding by confining the river to its low flow channel. The main stem, or so-called "federal levees," extend 1,607 miles along the Mississippi River, with another 600 miles along the banks of the lower Arkansas, Red, and Atchafalaya Rivers.

A vexing problem with maintaining 1,552 miles of flood control levees in the lower Mississippi Valley has been the complex and ever-changing foundations upon which they are founded (Figure 4.7). In addition, channel curvature promotes undercutting the outboard banks of bends, often depositing these materials in semi-linear stretches of channel a short distance downstream, because of lower gradients. This sediment reduces freeboard and raises flow levels, often beyond design assumptions. Crevasses are often sand-filled distributary channels that form preferred seepage paths beneath the flood plain during high flow. These high permeability corridors lie beneath earthen levees like ticking time bombs, waiting to explode (areas indicated by red arrows on Figure 4.8).

The 1928 Jadwin Plan also sought to emplace storage facilities wherever practicable in the four principal watersheds bordering the lower Mississippi Valley: the St. Francis Basin in southeastern Missouri and northeastern Arkansas; the Yazoo Basin in northwestern Mississippi; the Tensas Basin in northeastern Louisiana; and the Atchafalaya Basin in southern Louisiana. Five flood control reservoirs were constructed in these basins as part of the MR&T Project: Wappapello Dam and Reservoir in the St. Francis Basin; and four dams in the Yazoo Basin: Arkabutla, Sardis, Enid, and Grenada.

Bypass floodways were constructed by the Corps of Engineers. These included: 1) the Birds Point-New Madrid Floodway between Cairo, IL and New Madrid, MO (which depends on a fuse plug levee in lieu of a spillway; only used once, in 1937); 2) The Old River or Red River Landing Diversion structure, intended to divert half the project flood (1,500,000 cfs) from the main channel into the Atchafalaya River through the Morganza and West Atchafalaya floodways; 3) The Bonnet Carré bypass and floodway, a concrete spillway capable of diverting 250,000 cfs into Lake Pontchartrain during periods of high flow, about 30 miles upstream of New Orleans. The locations of MR&T structures in proximity of New Orleans are shown on Figure 4.9.

This was followed numerous Channel improvement and stabilization measures have been implemented as needed along the entire course of the navigable river channel, to enhance river bank stability and commercial navigation. The Corps typically employs channel cutoffs to shorten the river channel and increase hydraulic grades, which reduces flood heights. They employ armored revetments to retard channel migration and meandering. Countless dikes have been employed to direct the river's flow, beneath the channel surface. Annual dredging is required to maintain navigable channels, as sediment is deposited by seasonal high flows. These activities have combined to reduce the annual sediment yield of the river by 60% (Kesel, 2003).

The Bonnet Carré bypass and Old River Control Structure (into the Atchafalaya Basin) are major elements of the MR&T Project that protect New Orleans from a Mississippi River flood by reducing the volume of flow that passes the city. The Bonnet Carré spillway was the first structural element of the MR&T Project to be constructed, in 1931, and initially used during the 1937 flood. It is opened up whenever the river level exceeds 19.0 to 19.6 ft in New Orleans and can draft off 25,000 cfs into Lake Pontchartrain.

The Old River Control Structure was not authorized by Congress until 1954. It was intended to draft off 600,000 cfs of the Mississippi's flow during an extreme flood event and prevent capture of the Mississippi River by the Atchafalaya River, which would have occurred naturally by 1975 (because the flow distance of the Atchafalaya to the Gulf of Mexico is only one-third the distance taken by the present channel of the Mississippi; see Fisk, 1952 and McPhee, 1989). The Corps constructed the Old River Control Structure and lock from 1961-63. The project was intended to divert 30% of the Mississippi River Project Flood into the Atchafalaya Basin. The Old River Control Structure has only been used once, during the Flood of 1973, when it nearly failed catastrophically (MRC, 1975; Noble, 1976). In the wake of this failure, the capacity was doubled with construction of an auxiliary structure, completed by the Corps of Engineers in 1986, doubling the bypass capacity at Old River into the Atchafalaya-Morganza Basin to 1,220,000 cfs.

The average height of the MR&T levees above the natural levees in the Gulf Region is about 16 ft (Kolb and Saucier, 1982). The crest of the flood protection levee along the eastern bank of the Mississippi River is 24.5 feet MGL at Carrolton in New Orleans, as shown in Figure 4.10. The Lake Pontchartrain protection levee is 13.5 feet MSL, as shown in Figure 4.10. All of the neighborhoods north of Metairie Ridge lie below sea level. The worst flooding scenario for New Orleans would be a breach of the Mississippi River levee because of its elevated position, which would engender rapid erosion and high spill velocities, which could overwhelm the City's lowest neighborhoods before residents could affect an escape.

From its inception the 1928 Flood Control Act has been modified every few years by additional authorizations from Congress, usually based on modifications requested by the Corps of Engineers. These included expenditures for establishment of an emergency fund for maintenance and rescue work (1930) and acquisition of lands for floodways, etc. These early changes resulted in the Flood Control (Overton Act) Act of 1936, which established a national flood control policy to be administered by the Corps of Engineers, beyond the lower Mississippi Valley. Even with these sweeping changes, more acts followed in quick succession throughout the late 1930s and 1940s (for instance, a 1937 act authorized $52 million for strengthening of levees following the disastrous 1937 flood in the Ohio and Mississippi Valleys). This pattern of amended flood control acts and authorized expenditures continued throughout the 1940s, 50s, 60s, and 70s, usually following flood years.

Today, 3,714 miles of flood control levees have been authorized for construction under the Mississippi River & Tributaries Project. 3,410 miles of levees have been completed and 2,786 miles are in place to grade and section. On the main stem of the Mississippi River, 1,602 miles of levees have been completed. Work on the main stem levees of the Mississippi River is approximately 89 percent complete wand work on tributary levees is approximately 75 percent complete.

The breaches of August 29, 2005 during Hurricane Katrina occurred near the lowest possible elevations of the city, which retarded peak inflows to very low values, allowing residents to literally walk out of the neighborhoods, had they chosen to do so (most had already evacuated the city).

4.3.1 Dimensions of Navigation Channels Maintained by the Corps of Engineers on the Lower Mississippi River

Over the next 60 years Congress added new river borne transport projects, extending up the Mississippi drainage, and elsewhere, creating an intricate system of barge commerce that demands constant maintenance, clearing, patching, and dredging. In addition to insuring flood protection, the Corps of Engineers was also charged with maintaining year-round navigation for the Port of New Orleans, which was the nation's second largest port facility when MR&T project work commenced in 1931.

After the mouths of the Mississippi River had been opened and maintained in a navigable state (the first jetty was completed in 1879), navigation interests lobbied Congress to establish and maintain "feeder" channels to the Mississippi River and deepen the main stem channel to accommodate more modern vessels, with deeper draft. In 1945 Congress authorized the development of a navigation channel for oceangoing traffic in the lower reaches of the Mississippi River. Over the past 60 years this system has been expanded greatly through a series of Congressional acts, until today it consists of 12,350 miles of navigable inland waterways. The depths and widths of the Mississippi River channel between Baton Rouge and the Gulf of Mexico have been established as:

- Baton Rouge to New Orleans - 40 by 500 feet
- Port of New Orleans - 35 by 1,500 feet, with portion 40 by 500 feet
- New Orleans to Head of Passes - 40 by 1,000 feet
- In Southwest Pass - 40 by 800 feet
- In Southwest Pass Bar Channel - 40 by 600 feet
- In South Pass - 30 by 450 feet
- In South Pass Bar Channel - 30 by 600 feet
- Mississippi River-Gulf Outlet - 36 by 500 feet
- Mississippi River-Gulf Outlet Bar Channel - 38 by 600 feet

4.4 Flooding of the New Orleans Area by Hurricanes

Hurricanes strike the Louisiana Coast with a mean frequency of two every three years (Kolb and Saucier, 1982). Since 1559, 172 hurricanes have struck southern Louisiana (Shallat, 2000). Of these, 38 have caused flooding in New Orleans, usually via Lake Pontchartrain. Some of the more notable events have included: 1812, 1831, 1860, 1893, 1915, 1940, 1947, 1965, 1969, and 2005.

In 1722 a hurricane destroyed most of embryonic New Orleans and raised the river by 8 feet. Had the river not been running low prior to the storm, the river might have overtopped its banks by as much as 15 feet. In 1778, 1779, 1780 and 1794 hurricanes struck the New Orleans area destroying many buildings and sinking ships. The worst storm of the early year was "The Great Louisiana Hurricane" of August 9, 1812. It rolled over the barrier islands and drowned Plaquemines and St. Bernard Parishes and the area around Barataria Bay under 15 feet of water. The parade ground at Fort St. Phillip was inundated by 8 feet of water and the shoreline along Lake Pontchartrain was similarly inundated, though this was far enough below the French Quarter to spare any flooding of the City.

The back side of New Orleans was afforded some natural protection by the Metairie, Gentilly, and Esplanade Ridges, which are recent distributary channels of the Mississippi River. These "ridges" were originally about 4 feet higher than the surrounding marshland, but much of the former cypress swamps and marshes (comprised of compressible peaty soils) have settled as much as 10 feet over the past 110 years , while the ridges, being underlain by sand, have only settled 1 to 2 feet. The ridges performed as quasi flood protection levees from storm surges emanating from Lake Pontchartrain during hurricanes. But, the ridge also prevented drainage from moving between the old French Quarter and Lake Pontchartrain. The Carondelet, or Old Basin, canal was excavated between Basin Street and Bayou St. John, which formed the one low point between the elevated Metairie and Gentilly Ridge channels. The Old Basin Canal drained the French Quarter and allowed smaller craft to transit through the ridge to Lake Pontchartrain.

In June 1821 easterly winds surged off Lake Pontchartrain and pushed up Bayou St. John, flooding fishing villages and spilling into North Rampart Street until the winds abated and allowed the water to drain back into the lake. It was an ominous portent of things to come.

On August 16, 1831 "The Great Barbados Hurricane" careened across the Caribbean, striking the Louisiana coast west of New Orleans. The area south of town was again inundated by storm surge, while a three foot surge entered the city from Lake Pontchartrain. The Mississippi levee at St. Louis Street gave way, flooding the French Quarter. Heavy rains accompanying this storm added to the flooding and boats were the only means of moving about for several days.

Southeastern Louisiana suffered through three hurricanes during the summer and fall of 1860. On August 8th a fast moving hurricane swept 20 feet of water into Plaquemines Parish. The third hurricane struck on October 2nd making landfall west of New Orleans. It inundated Plaquemines, St. Bernard, and Barataria, causing a significant storm surge in Lake Pontchartrain which destroyed 20 lakeside settlements, washing out a portion of the New Orleans and Jackson Great Northern Railroad. Surge from this storm overtopped the banks of the along the Old and New Basin drainage canals and a levee along Bayou St. John gave way, allowing the onrushing water to flood a broad area extending across the back side of New Orleans.

Between 1860 and 1871 the city avoided serious flooding problems caused by hurricanes. In 1871 three hurricanes caused localized flooding, which proved difficult to drain. Flooding emanating from storm surges on Lake Pontchartrain during these storms overtopped the Hagen Avenue drainage canal between Bayou St. John and New [Basin] Canal, spilling flood waters into the Mid-City area. City Engineer W. H. Bell warned the city officials about the potential dangers posed by the drainage canals leading to Lake Pontchartrain, because the Mid-City area lay slightly below sea level (as seen on the 1895 Brown map in Figure 3.17).

The record hurricane of October 2, 1893 passed south of New Orleans generated winds of 100 mph and a storm surge of 13 feet, which drowned more than 2,000 people in Jefferson Parish, completely destroying the settlements on the barrier island of Cheniere Caminada. This represented the greatest loss of life ascribable to any natural disaster in the United States up until that time. Seven years later, in August 1900, a hurricane passed directly over Galveston, TX, demolishing that city and killing between 6,000 and 8,000 people, which remains the deadliest natural disaster in American history. Prior to impacting Galveston, that hurricane tracked westerly parallel to the Gulf Coast about 150 miles south of New Orleans. Its flood surges were noted along the Gulf Coast, including Lake Pontchartrain's south shore (Cline, 1926).

Prior to Katrina's landfall in 2005, the most damaging hurricane to impact New Orleans was the Grand Isle Hurricane of September 29, 1915, a Category 4 event which produced winds as great as 140 miles per hour (mph) at Grand Isle. It slowed as it made landfall and eventually passed over Audubon Park, seriously damaging structures across New

Orleans. Electrical power was knocked out, preventing the City's new pumps from functioning. The storm surge on Lake Pontchartrain rose to 13 ft, easily overtopping 6-foot high shoreline levee and destroyed the lakefront villages of Bucktown (at end of 17^{th} Street Canal), West End, Spanish Fort, and Lakeview (these lakeside settlements were swallowed up by the infilling of the Lake Ponchartain shoreline in 1928-31). The drainage canals were also overtopped, flooding the city behind Claiborne, leaving Mid-City and Canal Street under several feet of water. This storm overwhelmed the City's defenses so quickly that 275 people were killed, mostly in the Lake Pontchartrain shoreline zone.

On September 19, 1947 an unnamed hurricane made landfall near the Chandeleur Islands, producing wind gusts between 90 and 125 mph, with 1 minute maximum of 110 mph. A storm surge of 9.8 ft reached Shell Beach on Lake Borgne. The runways at Moisant Airport were covered by 2 ft of water while Jefferson Parish was flooded to depths of 3+ ft. Sewage from an overwhelmed City treatment plant stagnated in some of the drainage canals, producing sulfuric acid fumes that nearby homes in the Lakeview area painted with lead-based paint turned black. 51 people drowned and New Orleans suffered $100 million in damages. City officials were unable to clear floodwaters through the drainage canals in the Lakeview, Gentilly, and Metairie neighborhoods for nearly two weeks. This was the first significant hurricane to strike New Orleans which generated a large body of reliable storm surge data, which was subsequently used in design of flood protection works by the Corps of Engineers (Figure 4.11). The New Orleans Times-Picyaune prepared a map that showed reported depths and locations of flooding in the 1947 hurricane.

After the 1947 storm, hurricane protection levees were heightened along the south shore of Lake Pontchartrain and extended westward, across Jefferson Parish (constructed in 1949). In addition, the embankments along the old drainage canals were raised by earthfill to protect the Orleans and Jefferson Parishes from future storm surges off Lake Pontchartrain. The precise height of these additions depended on position and historic settlement up till that time. The entire Lakeview area north of what is now Interstate 610 (excluding the area filled by the Lakefront Improvement Project) was already <-2 ft below sea level by the late 1930s (WPA-LA, 1937).

Hurricane Betsy was a fast moving storm that made landfall at Grand Isle, LA on September 9-10, 1965. Wind meters at Grand Isle recorded gust of up to 160 mph and a 15.7 ft storm surge that overwhelmed the entire island. Winds gusts up to 125 mph were recorded in New Orleans along with a storm surge of 9.8 ft, which overwhelmed both sides of the Inner Harbor Navigation Canal (IHNC), flooding the Ninth Ward, Gentilly, Lake Forest, and St. Bernard Parish areas (Figure 4.12), as well as all of Plaquemines Parish, causing the worst flooding since 1947, and revealing inadequacies in the levee protection system surrounding the city. 81 people were killed by the storm (58 in Louisiana), which was the first natural catastrophe in America to exceed $1 billion in damages (USACE, 1965). Damage in southeast Louisiana totaled $1.4 billion, with $90 million of that being to New Orleans.

In October 1965 Congress approved a $2.2 billion public works bill that included $250 million for Louisiana projects and $85 million down payment for a system of levees and barriers around New Orleans (Figure 4.13). This work included raising the Lake Pontchartrain levee to a height of 12 ft above Mean Gulf Level (MGL) in response to the flooding caused by Betsy. The Orleans Levee Board also let contracts to pound steel sheetpile walls along the crests of their drainage canal levees to increase their effective height, so storm surges on Lake Pontchartrain would not overtop the drainage canals (which had occurred in 1915, 1947, and 1965, but without catastrophic loss of the canal levees). The uncased sheetpiles were intended to be a temporary measure, awaiting a permanent solution that envisioned placement of concrete flood walls using the sheetpiles as their foundations, funded by the Federal government. These short-term improvements spared the city from similar flooding in 1969 when Hurricane Camille struck the area.

Prior to Katrina, the only other Category 5 hurricane to make landfall on the United States was Hurricane Camille in August 1969 (the atmospheric pressure on landfall was second only to the Labor Day Hurricane of 1935). Camille made landfall on August 17th, its eye crossing the Mississippi Coast at Pass Christian, about 52 miles east northeast of New Orleans. Wind velocities in the eye of the storm reached 190 mph, while gusts on land exceeded 200 mph, casing most wind meters to fail (the highest recorded gust was 175 mph). Camille annihilated the coastal communities between Henderson Point and Biloxi, and caused extensive flooding 3,900 mi^2 of coastal lowland between lower Plaquemines Parish and Perdido Pass, AL. The peak storm surge measured 25 feet above MSL near Pass Christian, MS (a record), 15 ft in Boothville, LA, 9 ft in The Rigolets, and 6 ft in Mandeville, LA. The death toll form Camille was 258 people, with 135 of these being from the Mississippi coast (9 were killed in Louisiana). 73,000 families either lost homes or experienced severe damage and the official damage toll was $1.4 billion, with damages in Louisiana totaling $350 million. A particularly vexing aspect of Camille was that it occurred just four years after Hurricane Betsy, which had been touted as something between a 1-in-200 to 1-in-300 year recurrence frequency event (USACE, 1965).

On September 28, 1998 Hurricane Georges wrecked havoc across the Caribbean, pummeling Haiti, the Dominican Republic, Puerto Rico and other islands. Georges appeared to be headed straight for New Orleans, but suddenly turned east, making landfall near Biloxi, MS on September 28th (about 68 miles east northeast of New Orleans). Georges produced sustained winds of over 100 mph at landfall, generating a storm surge of 8.9 ft at Point à la Hache, LA. Maximum storm surge along the Gulf Coast was 11 ft, in Pascagoula, MS. Hurricane Georges severely eroded the Chandeleur Islands in outer St. Bernards Parish. Despite forewarnings and evacuation orders 460 people were killed, all outside of Louisiana. Dozens of camps not protected by levees were destroyed along the south shore of Lake Pontchartrain. Hurricane Georges provided the last pre-Katrina test of the vulnerability of New Orleans levee protection system to hurricanes, and efforts resumed to improve the levee system along the canals that connect the city with Lake Pontchartrain.

4.5 Flooding of New Orleans Caused by Intense Rain Storms

As mentioned previously, the New Orleans area receives an average of about 52 cumulative inches each year. In the winter of 1881 severe rainstorms caused flooding of the downtown area, up to 3 feet deep. Rain storms of severe intensity also caused significant flooding of New Orleans in 1927, 1978 and 1995.

The 1927 storm dumped 14 inches on Good Friday, overwhelming Sewerage & water Board's vaunted system of Wood pumps, at least temporarily. Uptown streets were flooded, with the Broadmoor and Mid-City areas inundated by 6 feet of water and 2 feet in the old French Quarter. This storm occurred simultaneously with the onset of the record high flows along the lower Mississippi River, which lasted almost six months.

On May 3, 1978 a line of rain squalls approaching New Orleans from the west became stalled over the city when it intersected a stationary front sitting over Lake Pontchartrain. The resulting storm dropped 10 inches of rain during the morning, with a peak sustained intensity of two inches per hour rain. The runoff exceeded the aggregate capacity of the city's pumps operated by the S&WB, causing extensive flooding of low lying areas that lasted about 24 hours.

A series of intense rain storms struck Louisiana, Mississippi, and Alabama in two consecutive sequences in March and April of 1980. The first storm occurred from March 26 to April 2nd, striking southeastern Louisiana and portions of Mississippi. The second storm sequence rolled through the same area from April 11 to April 13, affecting much of Mississippi, but especially intense in the area bounded by Baton Rouge and New Orleans to Mobile, Alabama. The 2-hour rainfall in Mobile on April 13 had a recurrence interval of 100 years. As a result of this rainfall, Mobile experienced the worst flash floods in the city's history. In New Orleans flood waters being pumped into the London Avenue Canal overtopped the eastern side of the Canal just south of Robert E. Lee Boulevard, where steel sheetpiles providing additional flood freeboard had recently been removed. This was the same portion of the northern London Avenue Canal which subsequently experienced incipient failure during Hurricane Katrina in 2005, moved two feet laterally (the area shown in Figure 4.20 - upper).

On the evening of May 8-9, 1995 a cold front approaching New Orleans from the west staled after moving east of Baton Rouge. A nearly continuous chain of thunder storms befell the New Orleans area, dropping 4 to 12 inches of rain across New Orleans. The storm's intensity overwhelmed the S&WB's pump capacity (47,000 cfs) and almost the entire city experienced severe flooding, including the Interstate highways. More severe storms struck the coast the following evening, but was not as severe over New Orleans proper, though the two day totals reached a record 24.5 inches in Abita Springs, LA. The 1995 storm sequence had a duration of 40 hours and damaged 44,500 homes and businesses, causing $3.1 billion in damages. This was the costliest single non-tropical weather related event to ever affect the United States.

4.6 New Orleans Drainage Canals

The drainage canals of New Orleans are a unique feature of the bowl-shaped city that are much older than most people realize. The city's first drainage canal was the Old Carondelet Canal originally excavated in 1794, by order of Spanish Governor Baron de Carondelet. It was dug by convicts and slaves and it was later enlarged to accommodate shallow draft navigation (row boats and keel boats) between the City and Lake Pontchartrain. Its name was later changed to the Basin Canal because it terminated at Basin Street, in the French Quarter. Its name was later changed to the Old Basin Canal. It was infilled in the

1920s, when it became Lafitte Avenue and railroad tracks were placed down the street's centerline. Figure 4.14 shows the systems of drainage ditches and canals established by 1829, leading to Bayou St. John.

The New Basin Canal was excavated by Irish immigrants in the early 1830s in the American Sector, but an outbreak of yellow fever killed 10,000 workers. The New Orleans City Railroad paralleled this canal in post Civil War era. The New Basin Canal was the first to cut through Metairie Ridge. The severing of Metairie Ridge was a double edged sword, as flood waters came up the Old Basin Canal and inundated the downtown area in 1871. The portion south of Metairie Ridge was filled in the 1930s; and the remainder in the 1950s, with the Pontchartrain Expressway replacing the old canal.

The six piece Topographic Map of New Orleans and Vicinity prepared by Charles F. Zimpel in 1833-34 suggest that portions of the Orleans Canal had been excavated and were proposed to be extended by that date to convey water from Bayou Metairie to Lake Pontchartrain (Lemmon, Magill, and Wiese, 2003). The Turnpike Road ran along the west side of this canal. In 1835 the New Orleans Drainage Company was given a 20-year charter by the city to drain the cypress swamps between the riverbank and Lake Pontchartrain. The company consulted State Engineer George T. Dunbar and evolved a scheme to drain the area using underground canals beneath prominent uptown streets which would collect water and convey it down the natural slope to the Clairborne Canal and then to the newly completed Orleans Canal (then called the Girod Canal) into Lake Pontchartrain. This ambitious scheme was derailed by the financial panic of 1837, though a system of ditches were completed which conveyed runoff from the French Quarter to the upper Orleans Canal, from which it had to be transferred to Bayou St. John using steam-powered pumps.

A review of historic maps (Figures 4.15 thru 4.17) suggests that the Upper Line Protection Levee or 17th St. Canal along the Orleans-Jefferson Parish boundary was excavated between 1854 and 1858 (shown as completed). The 17th Street Canal is not indicated on the 1853 Pontchartrain Harbor and Breakwater Map, although the Jefferson and Lake Pontchartrain Railroad is shown along the Orleans-Jefferson Parish boundary. The 1858 map shows 17th Street canal just east of the railroad tracks and the new village of Bucktown, along the shore of Lake Pontchartrain adjacent to the mouth of the 17th St. Canal. The 1878 Hardee map (Figure 4.17) calls the 17th St. Canal the "Upper Line Protection Levee and Canal." 17th Street was renamed Palmetto Avenue in 1894. The early rail lines serving the docks on Lake Pontchartrain remained in operation for many years after the Civil War (Figure 4.16).

Disastrous outbreaks of yellow fever in the 1850s spurned new ideas to drain the cypress swamps. Between 1857-59 City Surveyor Louis H. Pilié developed a drainage plan using open drainage canals with four steam-powered paddle wheel stations to lift collected runoff into brick-lined channels throughout lower New Orleans, which was poorly drained because the Metairie-Gentilly Ridge presented a natural barrier between the downtown slope and Lake Pontchartrain (Figure 4.18). In 1858 the Louisiana Legislature divided the city into four "draining districts," providing a commission for each district and a method of assessment for the operation and maintenance of drainage facilities. These names of these were the New Orleans First and Second, Jefferson City, and Lafayette Draining Districts (Beauregard, 1859). In 1859 the legislature mandated issuance of 30-year bonds totaling $350,000 for each of the four districts. This allowed a program of local taxation to fund the pumps and maintain the four lift stations were called "draining machines."

These steam-powered pumping machines were located at: the Dublin machine at the head of the New Canal (old 17th St.) at Dublin and 14th Streets; the Melpomene machine at the head of the Old Melpomene Canal (at Melpomene and Claiborne); the Bienville machine at the head of Bayou St. John (at Hagan and Bienville); and the London machine (just north of Gentilly and London Avenues). These facilities became a city trademark for many years thereafter. Shortly before the outbreak of the American Civil War in 1861, the legislature passed another bill that allowed any of the draining districts to make special assessments to make necessary repairs, based on the recommendations of their respective boards.

Figure 4.16 is a portion of the Map of New Orleans area completed under direction of Brigadier General Nathaniel P. Banks of the Union Army in February 1863, during the American Civil War. This map shows the position of the Jefferson and Lake Pontchartrain Railroad along the 17th St. Canal alignment, but not the canal itself. It also shows the New Basin Canal (a short distance east), the upper Orleans Canal, feeder canals emptying into Bayou St. John, and the Pontchartrain Railroad (near today's IHNC), which operated between 1831-1932, its northern terminus being named Port Pontchartrain.

The upper end of the London Avenue Canal appears to have been constructed in the 1860s, north of Bayou Gentilly. One of the afore-mentioned steam-powered draining machines was located near the intersection of London and Pleasure Street, which lifted water from the upper London Canal into the cypress swamp near what is now Dillard University, north of Gentilly Ridge. Based on a comparison of the 1873 Valery Sulakowski map and the 1878 Thomas Hardee maps, the lower London Avenue Canal appears to have been extended out to Lake Pontchartrain sometime between 1873-78.

In 1878 City Engineer and Surveyor Thomas S. Hardee compiled the most accurate map of the City to that date, after a yellow fever epidemic that year which killed 4% of New Orleans' population (which brought to City's accumulated death toll to Yellow Fever in excess of 100,000 people). The map sought to delineate improvements for the city's drainage system to enhance sanitation. It would take another two decades before a substantive drainage plan eventually evolved.

New Orleans drainage dilemma can be appreciated from a review of the earliest cross section drawn through the city, reproduced in Figure 4.19. The Mississippi River's natural levees form the highest ground in New Orleans. The natural levee slopes northerly towards Lake Pontchartrain. This slope is interrupted by the Metairie-Gentilly Ridge, a geologically-recent distributary channel, lying between 3 and 6 feet above the adjacent swamp land.

The protection levee along Lake Pontchartrain (Figure 4.19) was erected after the 1893 hurricane, which generated a storm surge of up to 13 feet (described in Section 4.4). This protective structure was known as the "shoreline levee" and was 6 feet above the normal surface of Lake Pontchartrain. The creation of this structure was a double-edges sword: it served to keep rising water from Lake Pontchartrain out of the city, but also prevented gravity drainage from the city into the Lake, except through drainage canals, into which runoff must be pumped to gain sufficient elevation to flow by gravity into the Lake. Discharge could not be conveyed to Lake Pontchartrain during hurricane-induced storm surges. The gravity of this problem was not fully appreciated until the 1915 Grand Isle Hurricane.

4.7 City Adopts Aggressive Drainage System

The failure of the Hagan Avenue Canal levee in 1871 signaled the beginning of a political crisis, hastened by hurricane-induced surges on Lake Pontchartrain. The City sought to consider a better solution than it had heretofore employed in providing for reliable drainage to Lake Pontchartrain, and vice versa. New Orleans City Surveyor W.H. Bell warned of the potential dangers posed by the big outfall drainage canals. He told city officials to place pumping stations on the lakeshore, otherwise "*heavy storms would result in water backup within the canals, culminating in overflow into the city*."

A new attempt to construct an integrated drainage system was undertaken by the Mississippi and Mexican Gulf Ship Canal Company, which excavated many miles of canals in New Orleans between 1871-78, before going out of business. By 1878 the City assumed responsibility for maintenance of a 36-mile long system of drainage canals feeding into Lake Pontchartrain. The city's old network of steam-powered paddle-wheel lift stations could only handle 1.5 inches of rainfall in 24 hours, which represented slightly more than a nominal 1-year recurrence frequency storm. This meant that the city began suffering flooding problems with increasing frequency because of insufficient runoff collection, conveyance, and pumping/discharge capacity.

The drainage problem was greatly exacerbated by a growing sewage treatment crisis. The City's population grew from about 8,000 in 1800 to nearly 300,000 residents by 1900. The need for space enticed development into the low lying cypress swamps, which were being reclaimed by construction of shallow drainage ditches feeding into the newly completed system of drainage canals. In the 1880s houses began to appear on the old marsh and swamp areas below Broad Street. No one regulated the inflow to the drainage canals and the abject lack of a modern sewerage collection, conveyance, treatment, and outfall system. Residents on the high ground near the Mississippi River could install pipes that conveyed their effluent to the Mississippi River, but this was not a practical option for people living below Broad Street, which lay below the river level.

The drainage crisis grew throughout the 1880s. In 1890 the Orleans Levee Board offered $2500 for the best drainage plan for the troubled city, but no suitable plans were submitted because of the paucity of reliable topographic data. In the wake of this disappointing result, newspaper editorials and civic leaders recognized the city could not continue growing without a substantive effort to handle drainage and sewage. After several more unsuccessful attempts to encourage someone credible to come forward with a plan, in February 1893 the City Council created a Drainage Advisory Board (DAB) and provided $700,000 to gather the necessary topographic and hydrologic data, study the situation, and make recommendations on how the problems might be solved. The DAB sought to gather together the City's best and brightest engineers from public, private, and academic ranks.

Chief among this work was the preparation of an accurate topographic map of the city, prepared under the direction of City Engineer L. W. Brown (shown in Figure 3.22).

The first DAB's findings were presented to the city in January 1895 (Advisory Board, 1895; Kelman, 1998). The Drainage Board recommended that the city create a modern system of drainage collection, conveyance, and discharge, which included street gutters, drop inlets, buried storm drains beneath city streets, with gravity flow to the principal drainage canals leading to Lake Pontchartrain. At that juncture, the conveyance problems became unprecedented, insofar that the city would need to install a series of pump stations to convey collected runoff into Lakes Borgne and Pontchartrain. The projected cost of such a system would be enormous.

The following year (1896) the Louisiana legislature authorized the creation of the Drainage Commission of New Orleans, which began preparing a comprehensive drainage plan for the city, and, how to fund such work. In 1897 the Drainage Commission began issuing contracts for new pumping stations, an electric power generations station, and the construction of additional feeder canals into the existing network of drainage canals.

In June 1899 voters passed a municipal bond referendum in a special election, which allowed a property tax of two mils per dollar to fund municipal waterworks, sewerage and drainage. With this revenue mechanism in place, the Sewerage & Water Board (S&WB) of New Orleans was shortly thereafter established (in 1899) by the State Legislature to furnish, construct, operate, and maintain a water treatment and distribution system and sanitary sewerage system. In 1900 the Drainage Commission began re-aligning and shifting the existing system of drainage canals, filling in a number of the cross-cutting canals and feeder canals which contained much stagnant water, which was encouraging the proliferation of mosquitoes and summertime yellow fever epidemics. In 1903 the S&WB was merged with the Drainage Commission to consolidate operations under one agency for more efficient operations. The drainage infrastructure at this time is shown in Figure 4.20.

The combined organization retained the name Sewerage & Water Board, which it retains today. S&WB then set about the Herculean tasks at hand, which more or less continued at a feverish pace until the early 1930s, when the economic downturn caused by the Great Depression curtailed revenue. By 1905 the S&WB had completed 40 miles of drainage canals (in addition to the 36 they inherited), constructed six new electrically powered pumping stations and had a pumping capacity of 5,000 cfs, which represented about 44% of the original plan. At this time the S&WB provided drainage for 34.4 mi^2 of city area, all on the eastern side of the Mississippi River.

As the S&WB tackled the tough drainage problems plaguing lower New Orleans, rapid development of these low lying areas ensued, with the real estate values increasing dramatically, with many of the city's residents engaged in speculation, purchasing lots and then selling them as prices inflated. Because of this, many of the lots in lower New Orleans were developed in different eras instead of all at once, leading to the heterogeneity of architectural styles and ages that have made New Orleans neighborhoods famous. An unforeseen downside of the rapid pace of development was the increase in runoff which accompanied the emplacement of impervious surfaces, such as streets, roofs, sidewalks, and the like, which increased drainage problems, necessitating enlargement of pump capacity each decade.

By 1910 the S&WB system was rapidly being overwhelmed and something needed to be done to increase capacity. A. Baldwin Wood was a young Sewer & Water Board mechanical engineer who joined the Sewer & Water Board as assistant manager of drainage upon his graduation from Tulane University in 1899. Wood was a retiring and shy personality who took on the various challenges facing the S&WB with unparalleled enthusiasm and imagination. Within a few years (at age 27 in 1906) Wood filed his first patent, for a 6-ft diameter centrifugal water pump that was the largest of its kind in the world. After this he invented an ingenious flap-gate that prevented backflow when the pumps were not in use.

In 1913 Wood made his greatest contribution to New Orleans continued growth when he introduced his novel design for the low-lift "Wood Screw Drainage Pump," an enormous 12-foot diameter screw pump that employed an enormous impellor powered by a 25 cycle per second (or Hertz, abbreviated as Hz) Alternating Current (AC) electrical motor. The motive power was highly efficient, using 20 feet diameter Allis Chalmers dynamos that spin up to 87 rpm. The low-lift screw pumps employ a siphon action to maximize hydraulic efficiency. This was followed in 1915 by Wood's patented Trash Pump, capable of pumping record volumes of water as well as flotsam and trash without risk of shutting down the pumps (Junger, 1992). This latter feature was of particular value in maintaining pumping during storm events, which brought large volumes of organic debris into the drainage canals. In 1915 the City let a $159,000 contract for thirteen patented Wood screw pumps, installing 11 of them in three pump stations by the end of the year, when the Grand Isle Hurricane struck the city, causing widespread flooding of the old back swamps, which already lay at sea level. By that time (1915) there were 70 miles of drainage canals in place.

By 1926 the New Orleans S&WB was serving an area of 47 mi^2 with a 560 mile long network of drainage canals and storm drains with a total pumping capacity of 13,000 cfs. This impressive infrastructure had been constructed over a period of 47 years at a cost of $27.5 million (1879-1926). Up to this time (1926) most of the S&WB's revenue had been generated by the special two-mill tax on all property and half of the surplus from the 1% debt tax. As the city grew and the S&WB's jurisdictional area increased to other areas adjacent to the city, the tax structure saw a number of amendments. Today the S&WB is funded by a number of sources, including three, six, and nine-mil property taxes.

The integrated drainage network allowed the water table of the old cypress swamps to be dropped so that subterranean cellars and burials became possible, and deaths from malaria and typhoid dropped 10-fold between 1899-1925. The City's last bout with summertime yellow fever was in 1905 (Campanella, 2002). During this same interim (195-26), the port authority saw enormous growth with the development of a massive Army Supply Depot along the riverfront during the First World War (1917-18) and the long-anticipated completion of the Inner Harbor Navigation Canal (IHNC) between the river and Lake Pontchartrain in mid-1923.

In the mid-1920s Wood increased the capacity of his patented screw pump to 14 feet diameter, using the same powerful siphon action to lift water. This increased the capacity of each pump unit by almost 40%. His improved capacity screw pumps were eventually marketed across the world; in China, Egypt, India, and Holland. Wood retired from the S&WB in 1945 and died in May 1956.

4.7.1 Pre-Katrina Conditions and Maintenance by the S&WB

Today the S&WB is responsible for draining 95.3 mi^2 of New Orleans and neighboring Jefferson Parish, which receive an average annual rainfall of 52 inches per year. The general layout of the drainage system is presented in Figure 4.22. The pre-Katrina system was intended to handle an average annual discharge of 12.9 billion cubic feet of water that had to be collected and pumped into Lake Pontchartrain, Lake Borgne, and the Mississippi River. The City's 22 main pump stations and 10 underpass pump stations still use about 50 of A.B. Wood's old pumps, and their system can lift an aggregate total of 47,000 cfs of water under peak operating conditions (the State Department of Transportation maintains the pumps for the General DeGaulle underpass at the Mississippi River Bridge ramps and on the East Bank at the Pontchartrain Expressway at the Southern Railway tracks and Metairie Cemeteries). A typical pump station (Pump Station No. 6) can lift 9,600 cfs using its old Wood pumps. New Orleans also employs vertical pumps with impellors to lift water from subterranean (below street) storm drains to the drainage canals, which outfall in Lake Pontchartrain. The S&WB maintains 90 miles of covered drainage canals, 82 miles of open channel canals, and several thousand of miles of storm sewer lines feeding into their system.

The S&WB maintains that their agency installed two sets of piezometers along the canal in the early 1980s, but that these revealed little correlation between transient flow levels in the canals and the adjacent piezometers. They took this result to mean that the canal floored in materials of relatively low permeability. In 1988 the S&WB received a permit from the Corps of Engineers to deepen and widen the 17th Street Canal, based on the "positive" indicators garnered from the piezometers that had been installed a few years previous. The Corps warned that dredging might weaken the stability of the canal, but a system of monitoring pore water (groundwater) pressures adjacent to the canal was not undertaken and the canal was substantially enlarged using a track-mounted excavator.

Although the S&WB system is highly efficient from an energy expenditure perspective, the 25 Hz AC electrical power requires the board to produce its own electricity, in lieu of purchasing 60 Hz AC off the national electrical power grid. As a consequence, approximately 60% of the S&WB's electrical power has to be generated locally, at their own 20 MW generator stations (Snow, 1992). Unfortunately, all of these generating stations are located below mean sea level and subject to shut-down by flooding.

4.7.2 Damage to S&WB facilities and capabilities caused by Hurricanes Katrina and Rita

During Hurricane Katrina the following pump stations were incapacitated and closed due to flooding: Pump Station #1 (2501 S. Broad Street), #3 (2252 N. Broad St.), #4 (5700 Warrington Dr.), #6 (345 Orpheum), #7 (5741 Orleans Ave.), #10 (9600 Haynes Blvd.), #14

(12200 Haynes Blvd.), #15 (Intercoastal Waterway), #16 (7200 Wales St.), and #19 (4500 Florida Ave.). These pump stations were gradually brought back online and were all at least partially operational within six months. 100% pumping capacity had not been restored to the S&WB system by the time of this writing (May 1, 2006). Drainage for Jefferson Parish, west of the city, remained online in wake of Hurricanes Katrina and Rita. This failure of the S&WB drainage system was without historic precedent, and pointed to fundamental flaws in the drainage system, with respect to operational redundancy.

During Hurricanes Katrina and Rita the Eastbank Sewer Treatment Plant was also closed (and has not reopened as of May 1, 2006). City residents were immediately advised to boil water before using by the city's Department of Health and Hospitals immediately following flooding of the city. This restriction was lifted for the neighborhoods west of the IHNC on October 6, 1005 and for the New Orleans East, Southshore and Ventian Isles areas on December 8, 2005. Water quality had not been restored to The Lower Ninth Ward in Zip Code 70117 by the time of this writing (May 1, 2006).

4.7.2 Reclamation of the Mid-City Lowlands (early 1900s)

The Mid-City area occupies a natural basin that formed between the levees of the Mississippi River and Metairie Ridge. The City's original network of pie-shaped property boundaries and streets converged on this area from their points of origin perpendicular to the broad crescent-shaped bend of the Mississippi River upstream of the French Quarter, from which the city derives its motto "the Crescent City." The area was a close depression (Figure 4.18), which had to fill up with water to drain into Bayou St. John, thence three miles into Lake Pontchartrain. A series of feeder canals were excavated to convey drainage into Bayou St. John and the New Basin Canal after the Civil War. But, stagnant water occupied these feeder ditches, promoting the existence of mosquitoes and yellow fever outbreaks, which were recognized to favor poorly drained areas decades before the scientific connection between the two was established (beginning around 1905). In the early 1900s it was decided to begin filling the lowest areas of the Mid-City area to provide better drainage and accommodate growth into this area, which had been subject to frequent flooding. Sand from Metairie Ridge and from dredging of nearby canals was used to provide the fill material and the feeder canals in this area were filled in and replaced with buried storm drain pipes beneath the streets (discussed in Section 4.7).

4.7.3 1915 Flood triggers heightening of drainage canal levees

On September 29, 1915 The Grand Isle Hurricane lifted the water level in Lake Pontchartrain to 13 feet above mean gulf level. The Lake Pontchartrain shoreline levee and many of the drainage canals were overtopped and much of the lower city flooded, killing 275 people. The City's new pump system was overwhelmed when the power generating stations for the new Wood screw pumps were flooded. After the 1915 flood, Sewerage and Water Board General Superintendent George Earl ordered the levees along the drainage canals to be raised approximately three feet, while the Pontchartrain shoreline levee was also raised. It is not known if this work was carried out by the S&WB or the Orleans Levee District.

4.7.4 The Lakefront Improvement Project (1926-34)

The southern shore of Lake Pontchartrain supported a number of small commercial wharves and fishing camps during the late 19th Century, including Milneburg, Spanish Fort, and West End. Shanties and structures along the shore were founded on wood pilings. The old Lake Pontchartrain shoreline levee had been constructed along the south shore to protect New Orleans from flood surges off the lake around 1893. This levee was overtopped by the storm surge on Lake Pontchartrain during the Grand Isle Hurricane in 1915 (described in Section 4.4). This levee was difficult to maintain because the shoreline was actively receding southward, towards New Orleans (Figure 3.16). In 1921 the Orleans Levee Board were granted increased powers by the state legislature to reinforce the Pontchartrain shoreline. In 1924 the board's chief engineer, Colonel Marcel Garsaud, embarked on developing an ambitious plan to construct a permanent seawall along Pontchartrain's south shore and reclaim several square miles of land by filling the gap between the new seawall and the eroding shoreline.

In 1926 the levee board began construction of a temporary wooden bulkhead wall constructed one-half mile north of the existing shoreline, within Lake Pontchartrain. This temporary structure extended two feet above mean sea level (MSL). The nearshore area between this bulkhead wall was initially backfilled to an elevation of +2 feet above MSL, creating 1,800 acres of "made ground." The fill material was sand taken from the floor of Lake Pontchartrain, placed using hydraulic dredges. The wooden bulkhead was then raised another two feet and hydraulic fill placed behind it to a level of +4 ft. This process was repeated yet again, creating a fill platform 4 to 6 feet above MSL and up to 10 ft higher than the old cypress swamps that subsequently became the Lakeview and Gentilly neighborhoods (even higher than the Metairie-Gentilly Ridge). The reclamation plan envisioned the construction of a permanent stepped concrete seawall along the new shoreline, replacing the wooden bulkhead wall and construction of this permanent barrier began in 1930.

To offset the hefty price tag of $27 million for this work, the levee board secured special legislation (in 1928) creating the Lakefront Improvement Project, which allowed them sweeping powers to reclaim land along the Pontchartrain shoreline. In 1931-32 another sizable fill was placed along Lake Pontchartrain behind another concrete seawall to create an additional 300-acre fill for a municipal airport. This was christened Shusan (now Lakefront) Airport, which has a 6,900 ft runway, used as a flight training facility during World War II.

When the lakefront improvement project was completed in 1934, a public debate erupted as to how best utilize the reclaimed land. A battle soon developed between private development, public access to the shoreline, and those forces promoting its adoption as open space parkland. A compromise plan was eventually adopted which allowed public access for recreation along with residential and public facility development (University of New Orleans). The new acreage was sold to developers to help the levee board pay off the construction bonds, and the Lakeshore, Lake Vista, Lake Terrace, and Lake Oaks neighborhoods were developed between 1939-1960.

After the Second World War the Lakeview, City Park, Fillmore, Gentilly, and Pontchartrain Park areas behind the lakefront emerged as desirable bedroom communities with yacht harbors, parks, and pleasant summer breezes. This area experienced unprecedented growth, between 1945-75, adding about 100,000 residents to the City.

4.7.5 Second Generation of Heightening Drainage Canal Levee Embankments (1947)

The hurricane of September 1947 caused storm surges of up to 10 ft above MSL along the shores of Lakes Borgne and 5.5 ft along the south shore of Lake Pontchartrain which overwhelmed levees in the Inner Harbor Navigation Canal (IHNC) and the old drainage canals, within a mile of their respective mouths. After several of these drainage canal levees were overtopped in 1947, the state's congressional delegation asked the federal government to assist in protecting the city (culminating in the Lake Pontchartrain and Vicinity Hurricane Protection Plan passed by Congress in 1955). The Orleans Levee Board spent $800,000 to raise its levees, including both sides of their drainage canals (with the exception of 17th Street, the west side of which is owned by the Jefferson Levee Board). Sheet piles were also reportedly used in by the port authority in the inner harbor area. We have not been able to determine how much additional freeboard was added by filling and/or sheet pile extensions in 1947-48.

4.7.6 Federal Involvement with the City Drainage Canals (1955 – present)

Federal involvement in the city's drainage canals began in 1955 with approval of the Lake Pontchartrain and Vicinity Hurricane Protection Project by Congress. The Corps studied the problems posed by the drainage canals, which had settled as much as 10 feet since their initial construction in the mid-19th Century. This settlement had necessitated two generations of heightening following hurricane-induced overtopping in 1915 and 1947. Each of these upgrades likely added something close to three additional feet of embankment height to keep water trained within the drainage canals and provide sufficient freeboard to prevent storm surges emanating from Lake Pontchartrain from overtopping the canal levees. The maximum design capacity of the three principal drainage canals (17th Street, Orleans, and London Avenue) was about 10,000 cfs, but this figure was being reduced by settlement and sedimentation problems.

The Corps had several non-federal partners in the venture: the Orleans and Jefferson Parish Levee Boards, and the Sewerage & Water Board of New Orleans. The levee districts maintained the canals and the S&WB maintained the pump stations and controlled the discharge in the drainage canals. If the S&WB pumped at maximum capacity, the increased flow could accelerate erosion of the unlined canals, which floor in extremely soft soils. If they didn't pump much water, then the canals could fill up with sediment, and thereby experience diminished carrying capacity. By the time the Corps got involved, a dense network of single family residences abutted the drainage canals along their entire courses (the canals are 2-1/2 to 3-1/2 miles long). The encroachment of these homes adjacent to the canal embankments circumvented any possibility of using conventional methods to heighten the levees, which is usually accomplished by adding compacted earth on the land-side of the levees (Figure 4.23, which would require the condemnation and removal of hundreds of residences, which would be costly and time-consuming (not to mention unprecedented).

In 1960 the Corps of Engineers New Orleans District office issued its initial report detailing their plan for remedying the ongoing problems with the slowly sinking drainage canals. The Corps plan opted to solve the drainage canal freeboard problem by installing tidal gates and pumps at the drainage canal outfalls along Lake Pontchartrain. This obviated the need for condemning all the homes built along the canal levees. The Corps soon found itself embroiled in a clash of cultures and goals with the levee districts, the S&WB, and the local citizenry, who flatly opposed the Corps' proposal. The S&WB and local residents feared that the tidal gates would malfunction, inhibiting outflow of pumped storm water, which would, in turn, allegedly, cause flooding.

The following year (1961) the Corps of Engineers unveiled a more grandiose plan to provide hurricane flood protection for New Orleans by constructing large flow barriers at the passes (The Rigolets) leading into Lake Pontchartrain, to prevent storm surges from reaching the lake. This scheme was expensive, and never garnered sufficient political support to gain appropriations (it was also proposed in the era before environmental assessments were required).

The issue of how to address improvement of the drainage canals dragged on for another 17 years. Between 1960-77 what few lots remained in lower New Orleans were rapidly built out by the end of the decade, and most of the post-1970 development in New Orleans focused on the areas east of the IHNC, in Jefferson Parish (west of New Orleans), and across the Mississippi River (Algiers, etc). In 1977 the U.S. Circuit Court of Appeals ruled against the Corps of Engineers plans for tidal gates at the mouths of the drainage canals because the Corps failed to examine the impacts of alternative schemes. From this juncture, the Corps focus shifted to heightening the drainage canal levees using concrete walls (Figure 4.24-lower), which was what the opposing groups desired. These walls were to be designed to withstand a Category 3 storm surge with 12 ft tides and 130 mph winds.

Construction began in 1993, but the wrong benchmark datums were selected for the contract drawings, so some of these walls were constructed almost two feet lower than assumed (IPET, 2006). Although the concrete flood walls were completed by 1999, concrete skirt walls on many of the bridges crossing the drainage canals had not been completed when Hurricane Katrina struck on August 29, 2005. So, the drainage canal system was not "tight," but it was generally believed that it could survive a Category 3 storm surge by surviving 6 to 8 hours of overtopping. The design storm surge values used by the Corps of Engineers are reproduced in Figure 4.25.

Flow records for the drainage canals in New Orleans indicate that between 1932-2005, a flow stage of +4 ft MSL was exceeded on at least 29 occasions; +5 feet was exceeded 13 times (including during Hurricanes Betsy in 1965 and Camille in 1969; +6 ft was exceeded only three times (including during Hurricanes Juan in 1985 and Isadore in 2002); and exceeded +7 feet for the first and only time on August 29, 2005 during Hurricane Katrina.

4.7.7 Hurricane Katrina strikes New Orleans – August 2005

A complex network of levees protected the City of New Orleans from flooding (Figure 4.26). New flood walls were constructed in the 1990s on the crowns of drainage canals and the Inner Harbor Navigation Canal to accommodate functionality during high storm surges. The walls in the lower Lakeview and Gentilly Districts topped out at +14 ft above MSL. Figure 4.28 shows deflection of the western 17th Street Canal flood wall, opposite the August 29, 2005 break of the eastern wall, near the Hammond Highway Bridge.

This system of flood walls quickly failed on the morning of August 29, 2005, when water levels rose above 7 feet MSL, higher than ever previously recorded in the drainage canals since 1932 (cited in previous section). Prior to Hurricane Katrina, the drainage canals feeding into Lake Pontchartrain never exceeded a flow height of between 6 and 7 feet above MSL. Many of the recording tidal gages failed during Hurricane Katrina. The incomplete record of the gage located closest to the 17th Street Canal failure is reproduced in Figure 4.27. This record shows several interesting trends. The first is the increase in diurnal high tide level each day after August 22nd. The second is a dramatic departure from the normal tidal cycle beginning the day before Hurricane Katrina made landfall, around 5 PM on August 28th. The third interesting aspect is the sharp increase in surge level on the morning of August 29th, which is much steeper than the assumed design storm surge for Lake Pontchartrain shown on the lowest curve in Figure 4.25.

4.8 Commercial Navigation Corridors

4.8.1 Inner Harbor Navigation Canal/Industrial Canal

Ever since the founding of the city by the French in 1718, the concept of a navigation channel between the Mississippi River and Lake Pontchartrain had been proposed, which would allow intercoastal commerce to connect with river and seaborne commerce traveling up and down the Mississippi River. The Port Authority of New Orleans was established in 1896 as an agency of the State of Louisiana. The port engineers recognized that the problem with establishing a water borne link was the fluctuating flow of the river, which raised and lowered 20 feet, depending on flood stage. The river was also 10 to 26 feet higher than normal level of Lake Pontchartrain, so some impressive locks would be needed to control the flow between the river and the lake.

The idea never progressed too far until construction of the Panama Canal between 1906-14, which heralded advances in excavation and grading technology that allowed widespread programs of public works, drainage, and flood control in succeeding half century. In July 1914 New Orleans received authorization from the state legislature to locate and construct a deep water canal between the Mississippi River and Lake Pontchartrain, which was supposed to boost the capacity of the port by as much as 100%. The expansion of ship building facilities triggered by the First World War and construction of the Army's enormous supply depot along the river front hastened action. While the war was still raging, a committee was formed early in 1918 to examine the feasibility of a connecting canal, using the most modern technology. Their initial report was released in May 1918 and it surprised everyone by envisioning a much larger project than most supposed, with the creation of ship building facilities within a protected, fixed-level harbor, increasing the available wharf space by almost 60%. The canal would be 5.3 miles long and up to 1,600 ft wide, located just downstream of the Army's new riverfront Supply Center (about 2 miles downriver and parallel to Elysian Fields Avenue).

The Port Authority's Dock Board retained the services of the George W. Goethals Company as consulting engineers, borrowing upon General Goethals renown as chief engineer of the Panama Canal project a few years earlier. The local firm of J. F. Coleman Engineering Co. performed most of the actual detailed design work, as well as assisting the Port Authority in construction management. Construction commenced on June 6, 1918. The superior elevation of the Mississippi River dictated that excavation would necessarily proceed from the lake side towards the river, which the massive locks, the project's kingpin structure, would be placed at the river end of the canal.

Excavation work initiated with the construction of parallel dikes on either side of the proposed canal, from which hydraulic fill could be loosed through sluice pipes. Hydraulic excavation was used wherever possible to excavate the channel, when the materials were easily loosed (e.g low cohesion materials, such as gravel, sand, organic ooze and swamp muck). When more resistant clay was encountered large front tower cableway dragline excavators or conventional dragline excavators (Figure 4.29) were employed to scoop out the clay and drag it up onto the dikes, which were gradually built um to become permanent protective levees. The draglines employed 3.5 cubic yard buckets and could handle about 150 cubic yards per hour. From the onset, contractors battled problems with slope stability, as the soft oozy soils constantly slid back into the excavation (Campanella, 2002). Buried cypress stumps slowed progress by jamming suction dredges and stalling dragline buckets.

During construction the Port Authority decided to increase the size of the channel to a minimum depth of 30 feet at low water, with a minimum bottom width of 150 feet and a minimum channel width of 300 feet, roughly double the original design. Abreast of the new wharves the bottom width was increased to 300 feet, with a minimum canal width of 500 feet near piers and slips, and 600 feet adjacent to quays (Dabney, 1921). The canal excavation was completed in just 15 months, in September 1919. Everyone's attention then turned to the lock structure, located 2,000 ft from the Mississippi River, at the south end of the canal. The normal flow level of the river was 10 ft above that of Lake Pontchartrain, so cofferdams had to be constructed on either end of the locks to allow safe access and dewatering of the exposed foundations. The lock is 640 ft long and 74 ft wide. The footing excavations were 50 feet deep, where timber piles were pounded into the underlying sands. The lock structure was finally completed on January 29, 1923, and dedication ceremonies for the entire Inner Harbor Navigation Canal (IHNC) were convened on May 5th, 1923. The residents of New Orleans often refer to the IHNC as the "Industrial Canal."

Almost immediately upon completion, the Port Authority set about developing piers, docks, and quays to increase cargo handling. Their first large structure was the Galvez Street Wharf, which was 250 ft wide and 2,400 ft long, costing $1.8 million (1923 dollars), completed in 1924. It was constructed of reinforced concrete and fitted with tracks for a local Beltline railroad. The Port Authority also made available adjacent lands for use by industries, but it took many years until the envisioned development occurred. The IHNC benefited from the completion of the Intracoatsal Waterway in the mid 1930s, as a cargo handing and provisioning stop. This was an unforeseen benefit, serving smaller vessels, which provided an economical means of transport prior to the establishment of the Interstate Highway network in the 1960s.

The massive Florida Avenue Wharf was added during World War II while the Gentilly Road section of the canal witnessed the sprawling expansion of shipbuilding facilities operated by Andrew Jackson Higgins, who pioneered the development of wooden PT boats and landing craft crucial to the war effort. Much of the area flanking the west side of the IHNC was built out during World War II (Figure 4.30). The eastern side was developed much later, after the Korean War (1950-53) and completion of the MRGO channel in 1964 (Figure 4.29). The immense France Road and Jordan Road Container Terminals (Berths 5 and 6) near the head of the MRGO channel were completed in the 1980s and 90s. The narrow width of the 1923 lock (74 feet) has restricted the passage of commerce, in particular, river barges, which often wait up to 36 hours to pass through.

4.8.2 Flooding problems around the IHNC

During the 1947 hurricane (Figure 4.11) a back protection levee adjacent to the IHNC was overtopped at Tennessee Street, spilling 10 feet of water into the East Side of New Orleans. Fortunately, the levee did not collapse, the area was undeveloped, and the flooding was quickly cleaned up. There was also quite a bit of flooding in the Metairie and Jefferson Parish areas, also attributable to temporary overtopping. There was a flood inundation map published in the *New Orleans Times-Picayune.*

Both sides of the IHNC experienced breaks and overtopping during Hurricane Betsy in September 1965. 6,560 homes and 40 businesses were flooded in water up to 7 ft deep on the west side of the IHNC. The east side of the IHNC also failed, flooding the west end of St. Bernard's Parish. A map of the flood inundation of New Orleans caused by Hurricane Betsy in September 1965 is shown in Figure 4.12. The Corps' report on Hurricane Betsy (USACE, 1965) states that both internal levee failures and overtopping occurred along the Inner Harbor Navigation Canal, on both the west and east sides. No details about the mechanisms of failure were described, however.

The IHNC was heightened using steel sheetpiles and concrete I-walls in the 1980s and 90s. On August 29, 2005 during Hurricane Katrina both sides of the IHNC were overtopped by the storm surge converging on the IHNC from Lakes Borgne and Pontchartrain. Sustained overtopping flow undermined the landside toe of the I-walls, in places gouging down as much as 5+ feet below the crest of the earthen levee. In addition, there was ample physical evidence of underseepage at both the eastern IHNC breaches, in the form of linear sand boils. These sheetpile-supported I-walls appear to have failed after about 3 to 4.5 hours of overtopping (between 4:30 and 9 AM on 8-29-05), allowing a large volume of water to sweep into the Lower Ninth Ward of New Orleans and the Chalmette area of St. Bernard Parish, to depths of up to 9 feet (Figure 4.31).

4.8.3 Intracoastal Waterway

The Intracoastal Waterway (ICW) was originally conceived in 1808, but not authorized by Congress until 1919. The ICW was excavated by dredge in the late 1930s to a channel size measuring 9 ft deep by 100 feet wide, and completed between New Orleans and Corpus Christi, Texas by mid-1942. This was enlarged to 12 feet deep by 125 ft wide channel and officially completed in June 1949. The ICW forms a protected shipping lane between Port Isabel, Texas (the Mexican border) and Apalachee Bay, Florida. The first 15% of the Mississippi River-Gulf Outlet Channel follows the ICW, which then diverges northeastward, about five miles east of the Inner Harbor. The ICW then runs east, towards The Rigolets and on into the State of Mississippi.

4.8.4 Mississippi River Gulf Outlet

When the IHNC was completed in 1923 the Port Authority announced that it intended to lobby the federal government to construct a Mississippi River Gulf Outlet (MRGO) channel connecting to the IHNC, to increase shipping capacity (Dabney, 1921). The idea didn't surface appreciably until 1943, during the Second World War, when thousands of amphibious assault craft and shallow draft vessels were being fabricated along the nation's inland waterways. The Corps of Engineers felt that a tidewater canal serving New Orleans and the nation's interior waterways would be able to compete with the Panama Canal for east-west shipping, crucial to the war effort (most industrial goods were manufactured in the eastern United States, which was being shipped to the Pacific via the Panama Canal). Competing priorities placed the project in limbo until the late 1940s, when it was resurrected. In the early 1950s the project was repeatedly voted down in Congress, because of competition with the St. Lawrence Seaway project between Canada and the U.S (approved in 1954).

After passage of the competing seaway, the Mississippi River Gulf Outlet (MRGO) project was authorized by Congress in March 1956. Kolb and Van Lopik (1958) of the Corps of Engineers prepared a geology report on the MRGO alignment in 1957-58. This study showed that the upper 2 to 5 feet was fibrous peat, although highly organic marsh deposits extend to depths of between 5 and 16 feet. These highly compressible materials are underlain by interdistributary and intratidal complex silts and clays over much of the proposed alignment (Figure 4.32). They graded these materials as soft marsh (500 to 900% water content), firm marsh (100 to 500% water content), and swamp substrate (highly organic peat with 600 to 800% water content). They noted that the soft marsh and swamp substrate materials would be unable to provide competent foundations for the protective levees bordering the channel, and these same materials would be unsuitable for use in such embankments.

During the first phase of dredging in 1958-59, 20 million cubic yards (mcy) of material was excavated between the IHNC and Paris Road (now I-510), essentially widening the ICW. In 1959-60 contractors excavated a "pilot channel" between the ICW and Breton Sound, excavating and placing 27 mcy of material. In the third and fourth phases completed between 1960-65, 225 mcy were excavated between Paris Road and Breton Sound. Dredge spoils were placed in a strip of land 4000 ft wide corridor paralleling the southwest side of the MRGO channel in St. Bernard Parish. The dredge soils from the initial excavations (1958-59) were placed on the land which now underlies the Jourdan Road Container Terminal, near the intersection of the MRGO and IHNC.

The MRGO channel was excavated as 500-feet minimum width channel with a minimum (low tide) depth of 36 feet (excavated to -38 feet; accepted at -36 ft). The route of the MRGO channel crosses 45 miles of delta marshland in Orleans and St. Bernard Parishes, with another 30 miles of open (dredged) channel across Breton Sound. This offshore section is slightly larger. Its 75 mile path is 37 miles shorter than that of the deep water navigation channel connecting New Orleans to the Gulf of Mexico via Southwest Pass. The project was finalized in 1968.

The flanking levees have experienced significant settlement since the project's completion, due to consolidation of prodelta clays underlying the flanking levee embankments, as well as plastic sagging due to low strength and creep properties of underlying organic material. The amount of settlement varies between 1.5 and 8 feet, depending on location. Many estimates have been offered regarding the tectonic rate of subsidence of the Mississippi Delta; from 0.4 ft/century (Saucier, 1963) to as much as 1.3 ft/century (Watson, 1982). The Corps of Engineers authorized two sequences of levee heightening, in

Since its completion, the seaway has eroded to a width of 2000 ft in places (Coastal Environments, 1984), due in large part to ship wakes in the relatively confined channel. In addition, siltation necessitates ongoing dredging, which cost the Corps of Engineers about $16 million per year. Salt water intrusion along the channel has impacted adjacent marshes, although significant quantities of salt water have not been conveyed inland during hurricanes, because the channel's width is relatively insignificant when compared to adjoining bodies of water, such as Breton Sound and Lake Borgne.

During Hurricane Katrina the MRGO channel was overtopped by the near-record storm surge that came from the east off of Lake Borgne, probably between 6 and 7 AM (CDT) on August 29th (because the flood waters reached Paris Road in Chalmette between 8 and 8:30 AM [CDT]). The overtopping caused by the severe storm surge quickly eroded the MRGO levees in those reaches where the levees were comprised of materials with little of no cohesion and high organic content. In long stretches the entire levee was washed away down to its original marsh foundations without a trace (Figure 4.33).

4.9 Influence of Elevation Datums on New Orleans Flood Protection System

4.9.1 Introduction

Persistent subsidence of the Gulf Coast/Mississippi River Delta region has led to a complex relationship between the various geodetic datums used during historic surveys of the area. The underconsolidated and organic rich sediments of the Mississippi Delta are continually subsiding due to their compressible nature, the biochemical oxidation of the entrained organics, and all the other factors described in Section 3.7. Tectonic activity along active normal faults is also contributing to subsidence of nearly the entire Gulf Coast region. Rates of subsidence are highly variable throughout the region, resulting in a complex relationship between different geodetic datums at benchmarks in the New Orleans area. Subsidence combined with a slow rise in sea level (about 1 ft per century) has caused much of the Gulf Coast Region surrounding New Orleans to drop ten or more feet relative to sea level in historic times, both of which have made the city more vulnerable to tropical storms.

It is important to accurately determine elevations in relation to sea-level in order to design and construct flood protection systems in areas vulnerable to tropical storms. Unfortunately outdated terrestrial datums were referenced when constructing many of the floodwalls protecting New Orleans. Variations of the NGVD29 datum were used, which is based on terrestrial reference points, not sea level. The use of the outdated datums also neglected subsidence and sea level rise, resulting in a lesser protection height than intended in the floodwall designs. The subsidence of the region has made the correlation of datums a complex task. No single conversion factor may be used when converting between two datums.

4.9.2 17th Street Outfall Canal

Between 1952 and 2005, there has been a 2.345 foot decrease in the elevation of the benchmark ALCO at the mouth of the 17th St. Outfall Canal due to subsidence and adjustment of datums. In 1952, the benchmark elevation was 8.235 feet while it had decreased to 5.89 feet by 2005 (post Katrina) according to the NGVD29 (1952) and LMSL (1983-1992) datums, respectively.

When the concrete I-walls were placed atop the 17th St. Outfall Canal Levees during the 1990's, their tops were to extend to an elevation of 14.0 feet according to the NGVD datum. Contract reports do not specify which NGVD epoch was to be used in design and construction. It is possible that NGVD29 (09 Apr 1965) was used. In addition, NGVD is a terrestrial datum and is not directly referenced to sea level as is LMSL. The top of the 17th Street Outfall Canal Floodwall is presently between 1.3 and 1.9 below the design level of 14.0 feet according to LMSL (1983-1992). This is likely due to the use of an outdated datum (1.6 feet of difference) and settlement of the levee embankments and floodwalls (0.3 feet).

4.9.3 London Avenue Outfall Canal

The floodwalls bordering the London Avenue Outfall Canal were also designed and built during the 1990's. According to contract documents, the NGVD29 (09 Apr 1965) datum was used. The use of an outdated, terrestrial datum in conjunction with settlement has resulted in the floodwall heights being 1.6-1.8 feet below their intended heights of 14.4 feet (LMSL (1983-1992)).

4.9.4 Orleans Outfall Canal

The NGVD29 (01 Sep 1982) datum was referenced during the design and construction of the Orleans Outfall Canal floodwalls in the 1990's. Presently, the floodwalls surrounding this canal are up to 0.8 feet lower than called for than the 14.0-14.9 foot elevation called for in the designs (according to LMSL (1983-1992)).

4.9.5 Inner Harbor Navigation Canal – East Levee

Floodwalls were placed atop the Inner Harbor Navigation Canal's East Levee in 1970. The walls were to extend to 15.0 feet (MSL) according to the 1969 contract documents. MSL was tied to an earlier terrestrial datum and the exact correlation to modern adjustments has yet to be determined. Floodwalls presently reach heights between 12.3 and 13.2 feet according to the LMSL (1983-2001) datum. Overtopping did contribute to the three breaches that formed in this levee during Katrina.

4.9.6 Inability to Apply Universal Corrections for Elevation Datums

Although subsidence has played a role in the differences between designed and actual floodwall heights, most of the variance appears to have been caused by datum abnormalities. It is standard engineering practice to use an NGVD datum to determine sea level. The use of NGVD is not cause for concern in portions of the country away from coastlines but becomes troublesome in areas at or just above sea level.

Due to the highly variable rates of subsidence throughout the region, a common conversion factor cannot be used to adjust between datums, even over a short distance. The complex relationships between the various geodetic datums in the New Orleans Region are not discussed in great detail in this report. A more thorough discussion of this subject is presented in Chapter III of IPET's (2006) second report.

4.10 Names of New Orleans Neighborhoods

Figure 4.35 presents the official neighborhood names recognized by the City of New Orleans. Local residents also use local ward and district numbers, and parish names to describe an area. A common example would be the Lakeview and Gentilly areas, which are used in a general sense to describe the former Cypress swamplands that now are among the City's lowest lying areas. The "Lakeview district" more or less encompasses Lakewood West End, Lakewood, Lakeview, Navarre, and City Park neighborhoods. The "Gentilly district" more or less includes the Fillmore, St. Anthony, Dillard, Milneburg, Gentilly Terrace, Pontchartrain Park and Gentilly Woods neighborhoods.

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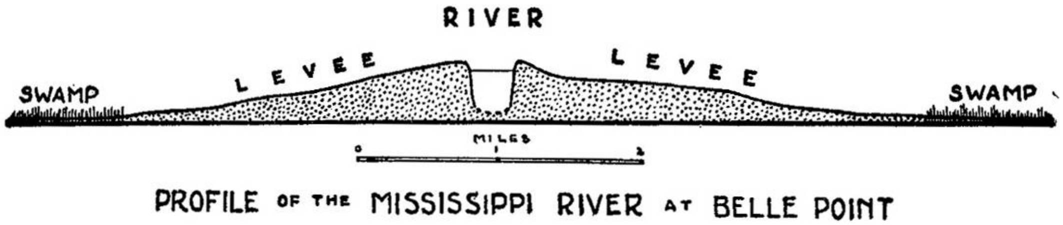


Source: Williams (1928)

Figure 4.1: Typical cross section through the sandy bank levees of the Mississippi River, illustrating how the river's main channel lies above the surrounding flood plain, which were poorly drained swamp lands prior to reclamation in the post Civil War era.

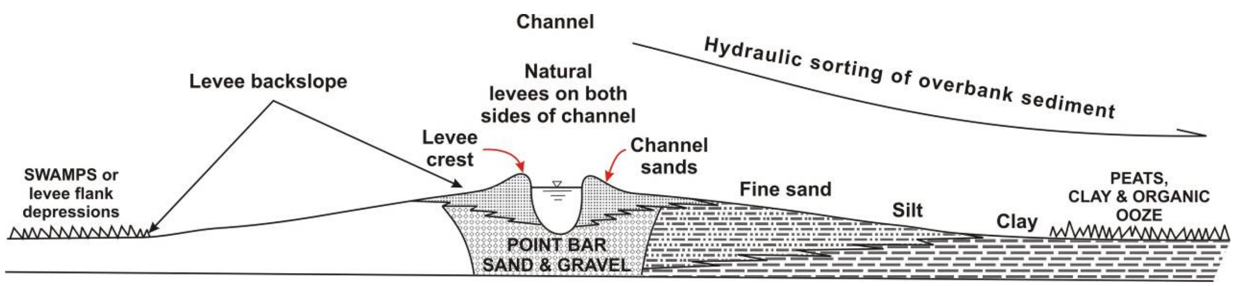
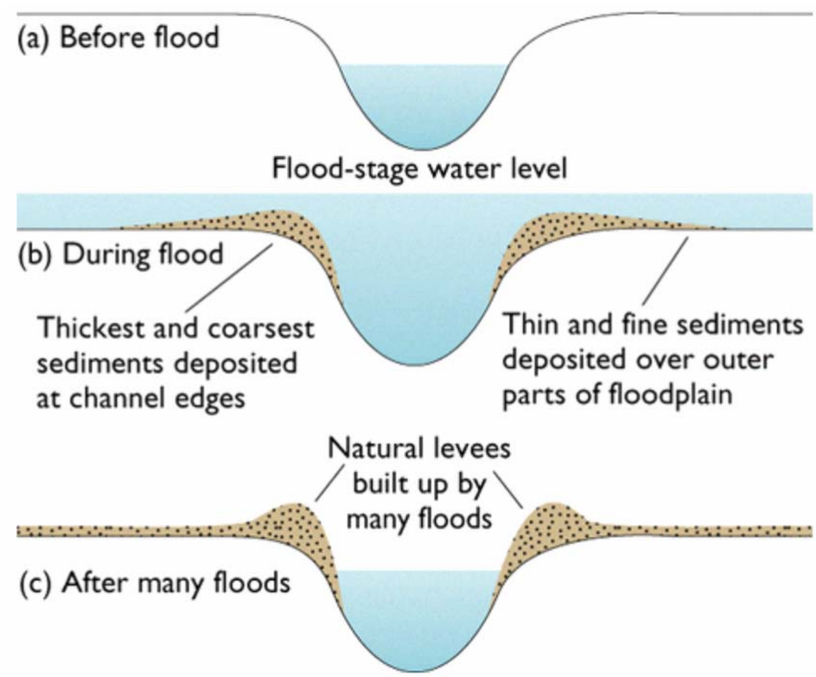
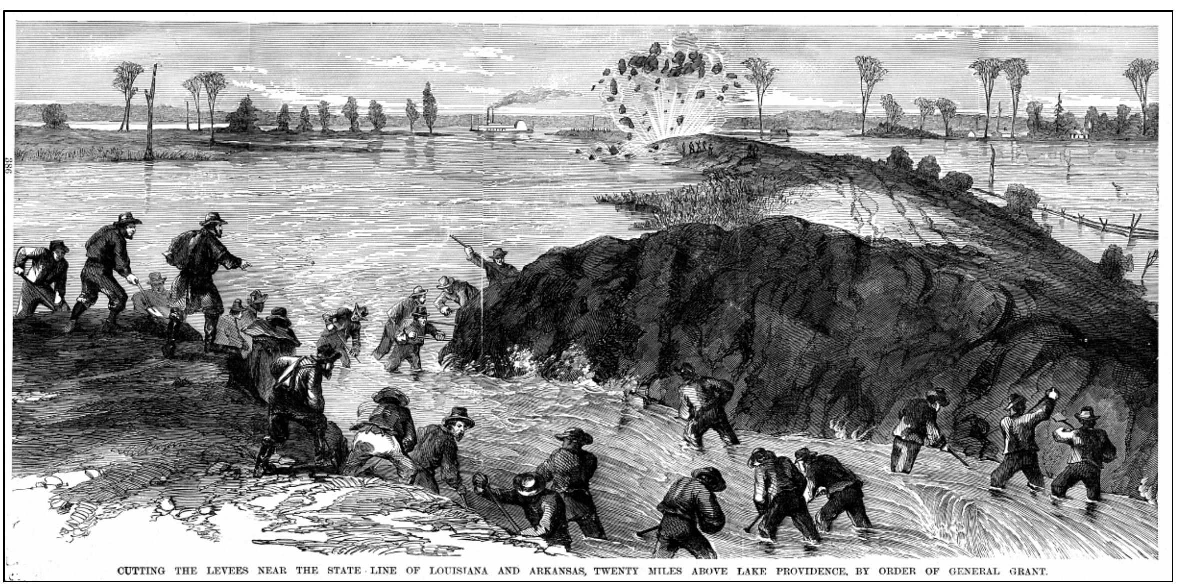


Figure 4.2: Same typical cross section, showing the hydraulic sorting of sediments moving away from the Mississippi River channel. The levee backslope zone lies between the elevated levees and the poorly drained swamps. In New Orleans, the Carrollton, Uptown, French Quarter, and Central Business Districts are situated on the natural levee and its backslope, while the Mid-City area was built on a levee flank depression between the Mississippi and Metairie levees. The Lakeview, Gentilly, and Ninth Ward areas occupy the old cypress swamps.



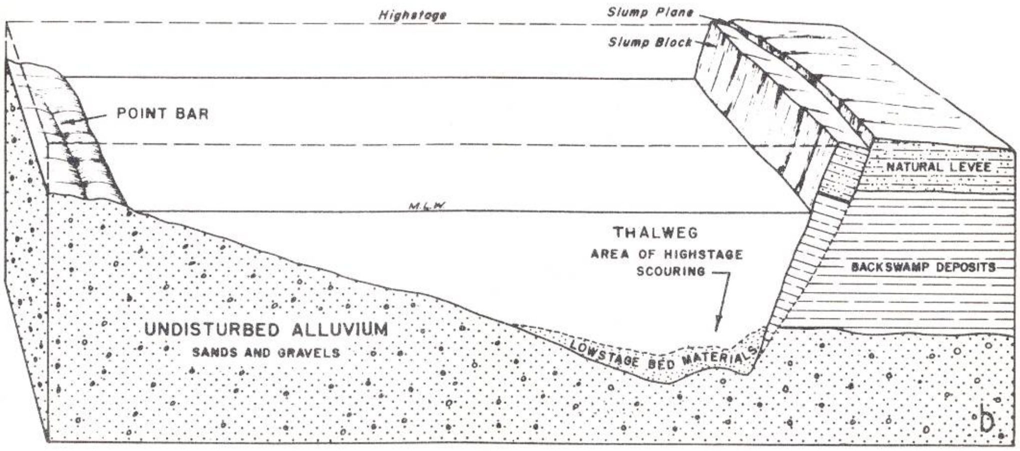
Source: Press and Siever (1997)

Figure 4.3: Natural levees exist along most perennial channels subject to periodic overbank flooding emanating from a prominent low flow channel, as sketched above. Man-made levees originated by piling up additional earthen fill on top of these natural levees.



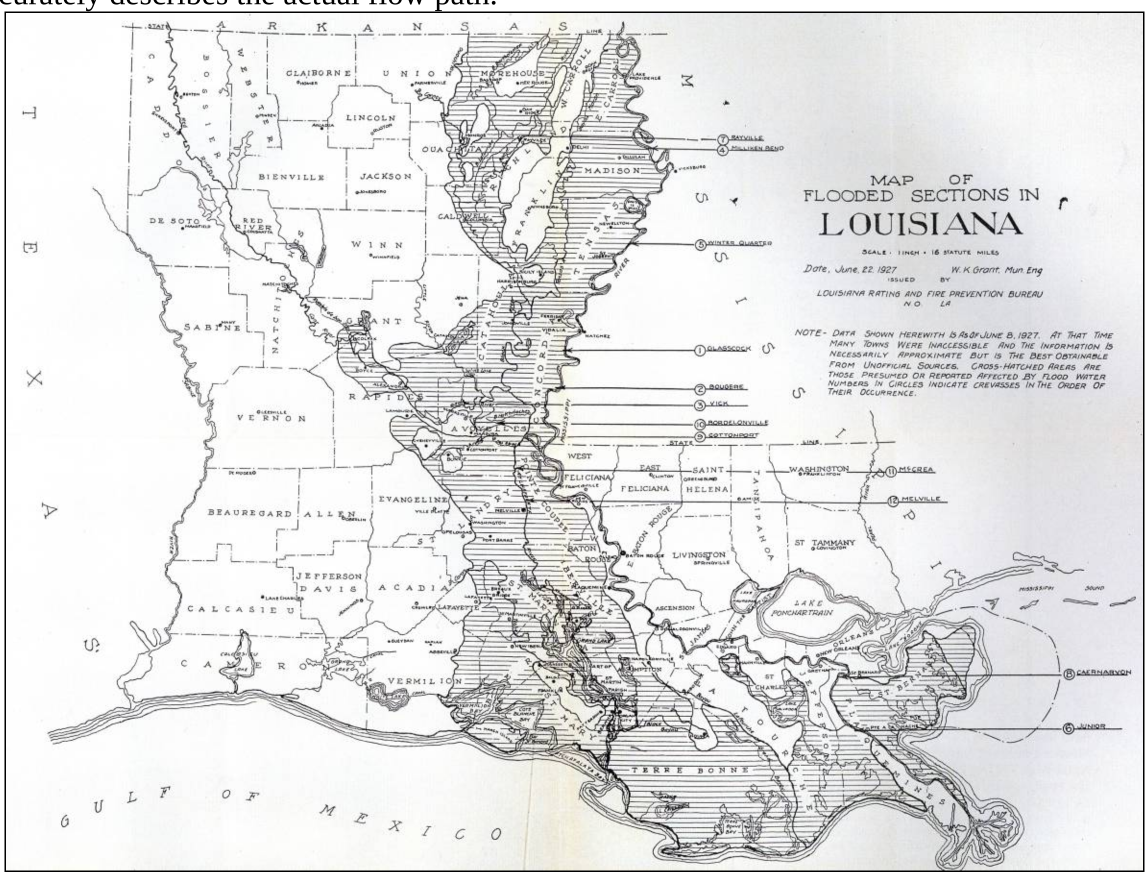
Source: Moat and Leslie (1896)

Figure 4.4: Union forces under General Grant cutting the levee near the state line of Louisiana and Arkansas, 20 miles above Lake Providence. In describing this activity, Moat and Leslie (1896) noted: *"The soil is very tough, and will not wash away. The levees consequently have to be blown up with gunpowder. The soil is then loosened with spades."* Levees constructed of cohesive clay were found to be the most resilient, but those constructed of other materials, such as overbank silt, peat, or organic ooze were easily eroded.



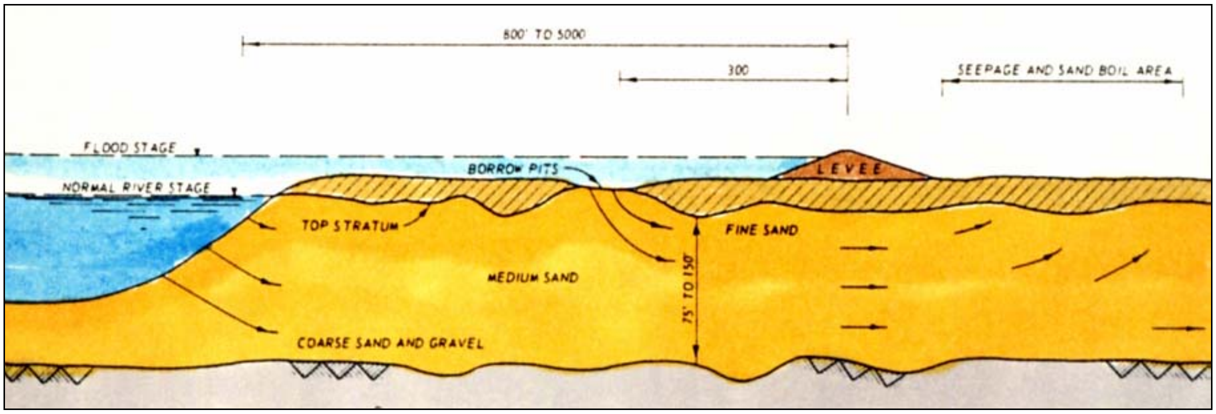
Source: Fisk (1952)

Figure 4.5: Asymmetric channel cross section typical of the Mississippi River, showing slumping of the oversteepened banks on the outside of its turns and the relative position of the river's thalweg, the line connecting the lowest points along the bed of the river. River mileage is measured along the thalweg, not along the river centerline, because this line more accurately describes the actual flow path.



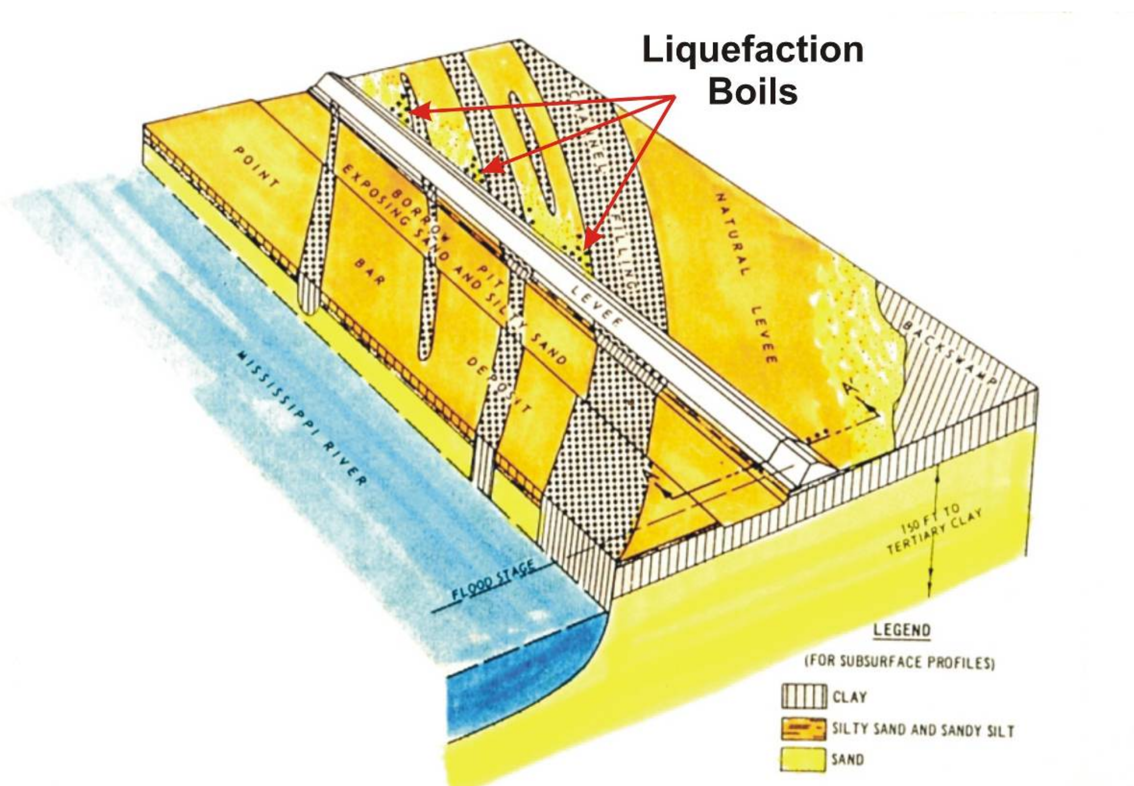
Source: Barry (1997)

Figure 4.6: Map showing the lands inundated in Louisiana during the height of the great Mississippi River Flood of 1927 (from the Historic New Orleans Collection). Concerns over long term safety from flooding caused many businesses and financial institutions to depart New Orleans to seemingly safer havens, such as Houston, TX.



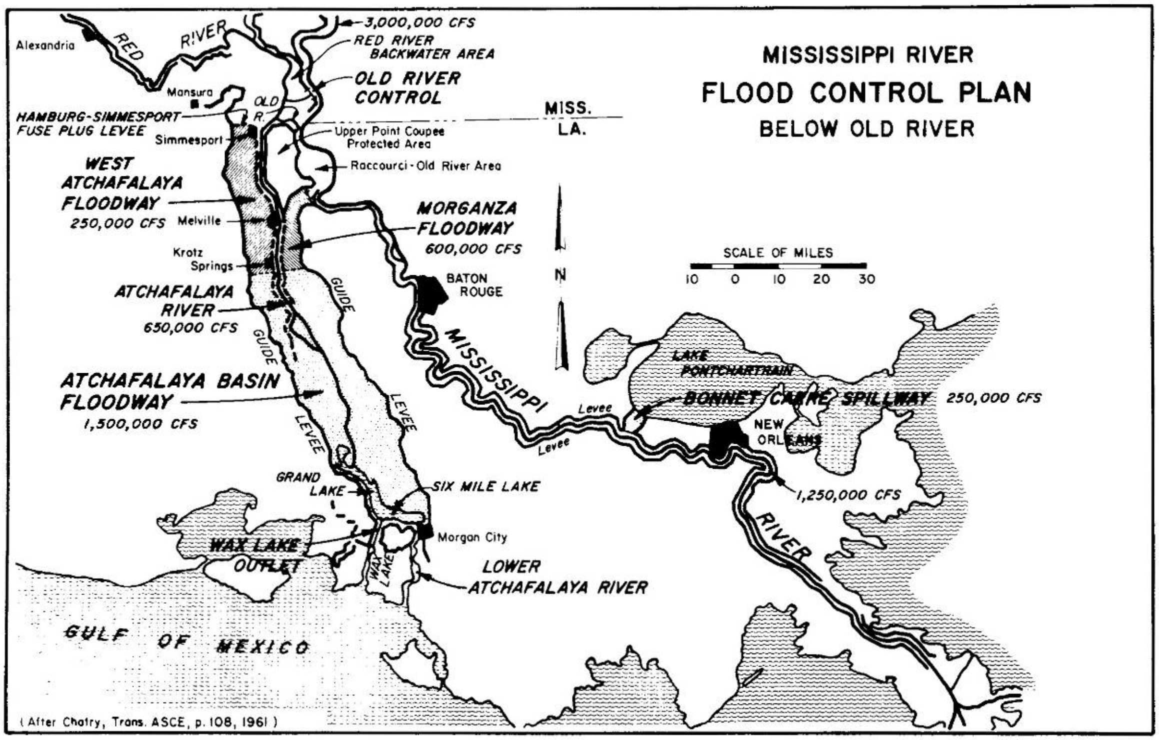
Source: Mansur and Kaufman (1956)

Figure 4.7: Cross section through a typical Corps of Engineers levee in an alluvial valley. Analyses of levee stability depend in large measure on various assumptions made about seepage conditions beneath and adjacent to such structures. For instance, the coarse sand and gravel shown here may be 1000x more permeable than the overlying medium sand.



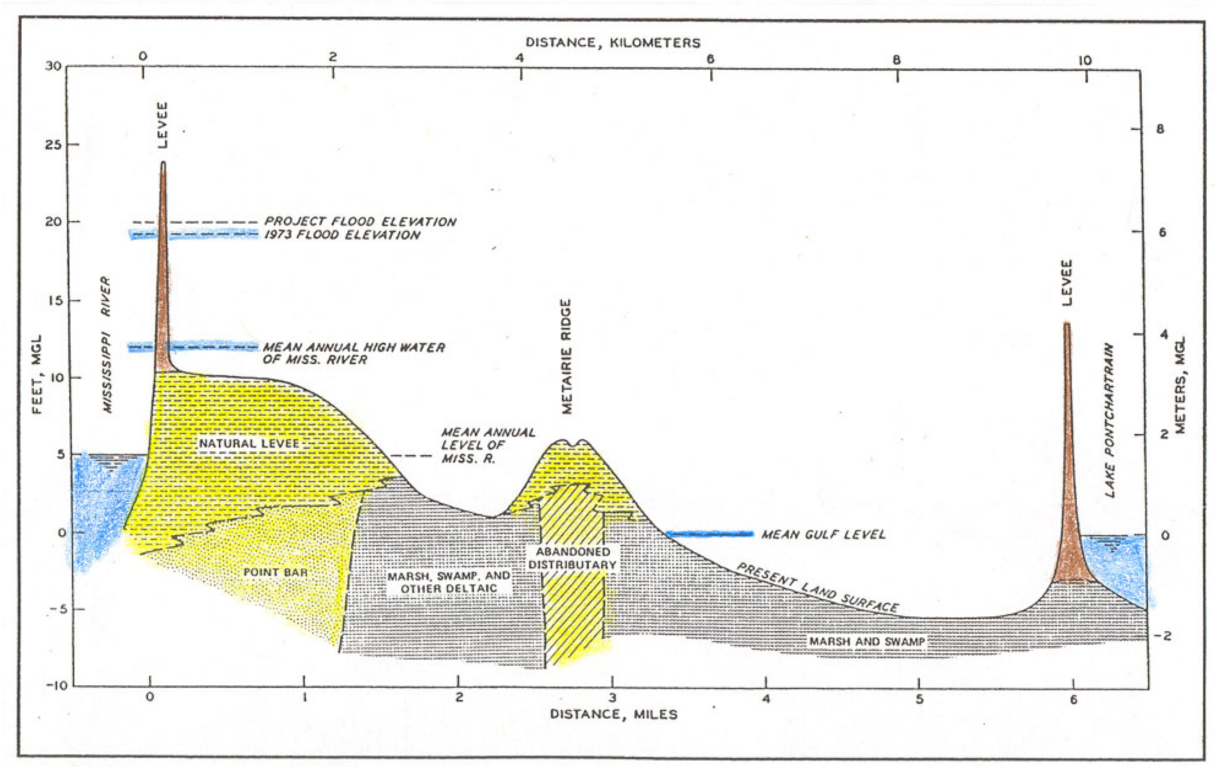
Source: Kolb (1976)

Figure 4.8: A major problem with man-made levees constructed during the MR&T Project is that they are necessarily constructed upon highly heterogeneous foundations, as portrayed here. The sharp contrast between highly organic channel fills (stippled zones) and natural levee sands and gravelly point bars promotes dangerous concentrations of seepage and differential settlement.



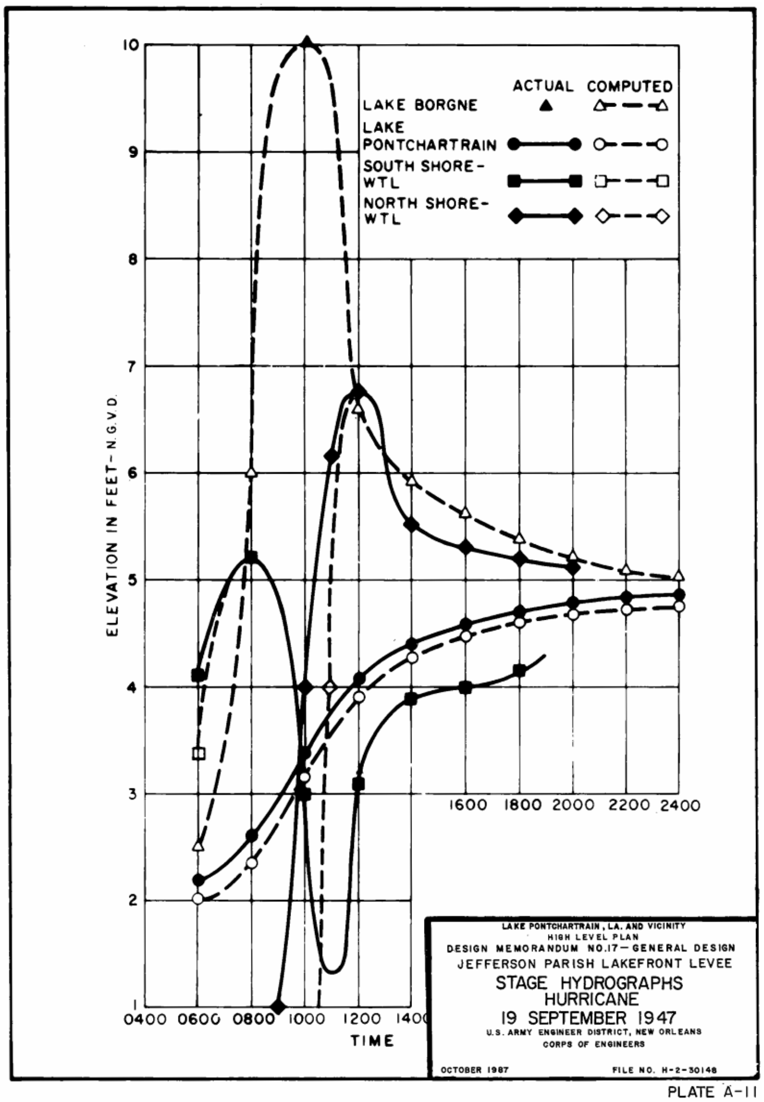
Source: Chatry (1961)

Figure 4.9: Map showing principal elements of the Mississippi River & Tributaries Project flood control for the lower Mississippi River Delta region. Note the much shorter flow channel to the Gulf of Mexico along the Atchafalaya River as opposed to the Mississippi River. The Mississippi River would have switched to this channel by 1975 if the Old River Control Structure had not been constructed in 1961-63.



Source: Kolb and Saucier (1982)

Figure 4.10: This cross section illustrates how much of New Orleans lies below mean gulf level, requiring every drop of rain water to be pumped out. The height of the Mississippi River levee is 24.5 ft while the Lake Pontchartrain levee crests at 13.5 ft.



Source: USACE (1987)

Figure 4.11: Stage hydrographs on Lakes Borgne and Pontchartrain from the September 1947 hurricane. The 10 foot surge on Lake Borgne was the highest recorded value up to that time, though short-lived. A 13 foot surge was reported along Lake Pontchartrain during the 1915 Grand Isle Hurricane, but this was before storm surge recorders were emplaced along the shorelines.

Source: USACE (1965)

Figure 4.12: Portion of the flood inundation map from Hurricane Betsy in 1965, showing the areas on either side of the Inner Harbor Navigation Channel which were affected by overtopping, from storm surges on Lakes Borgne and Pontchartrain.

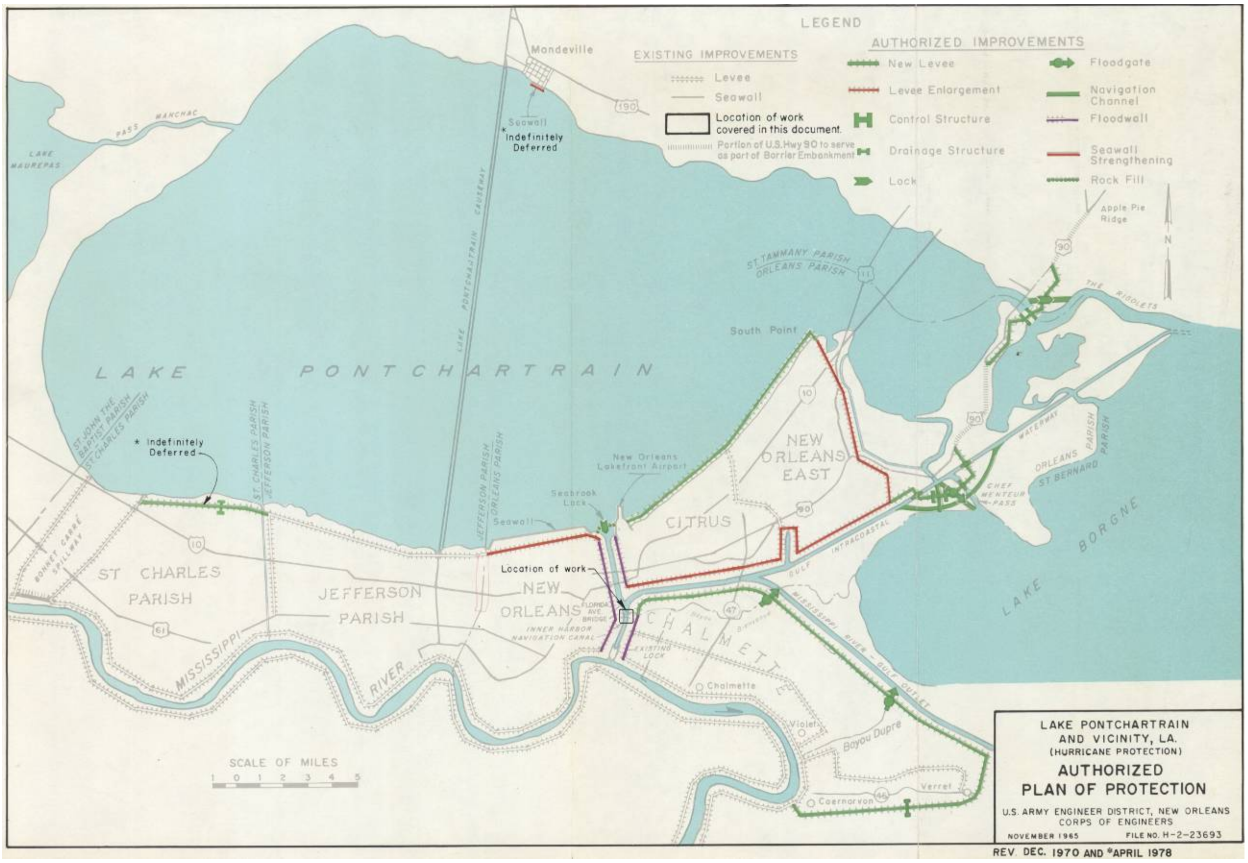
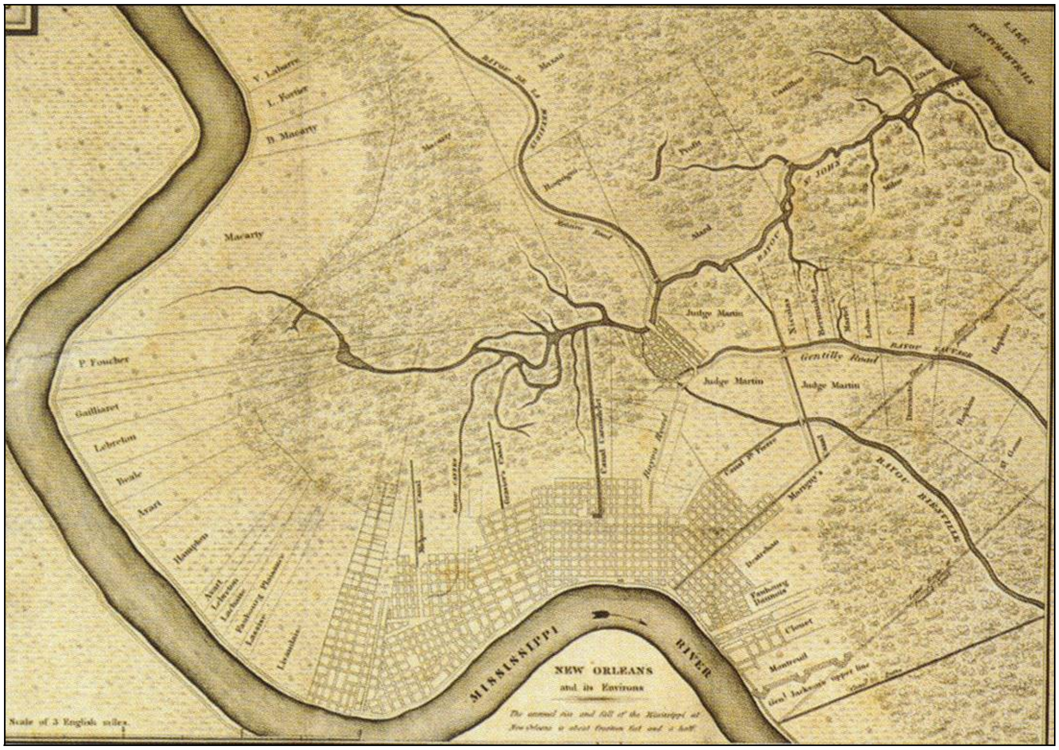
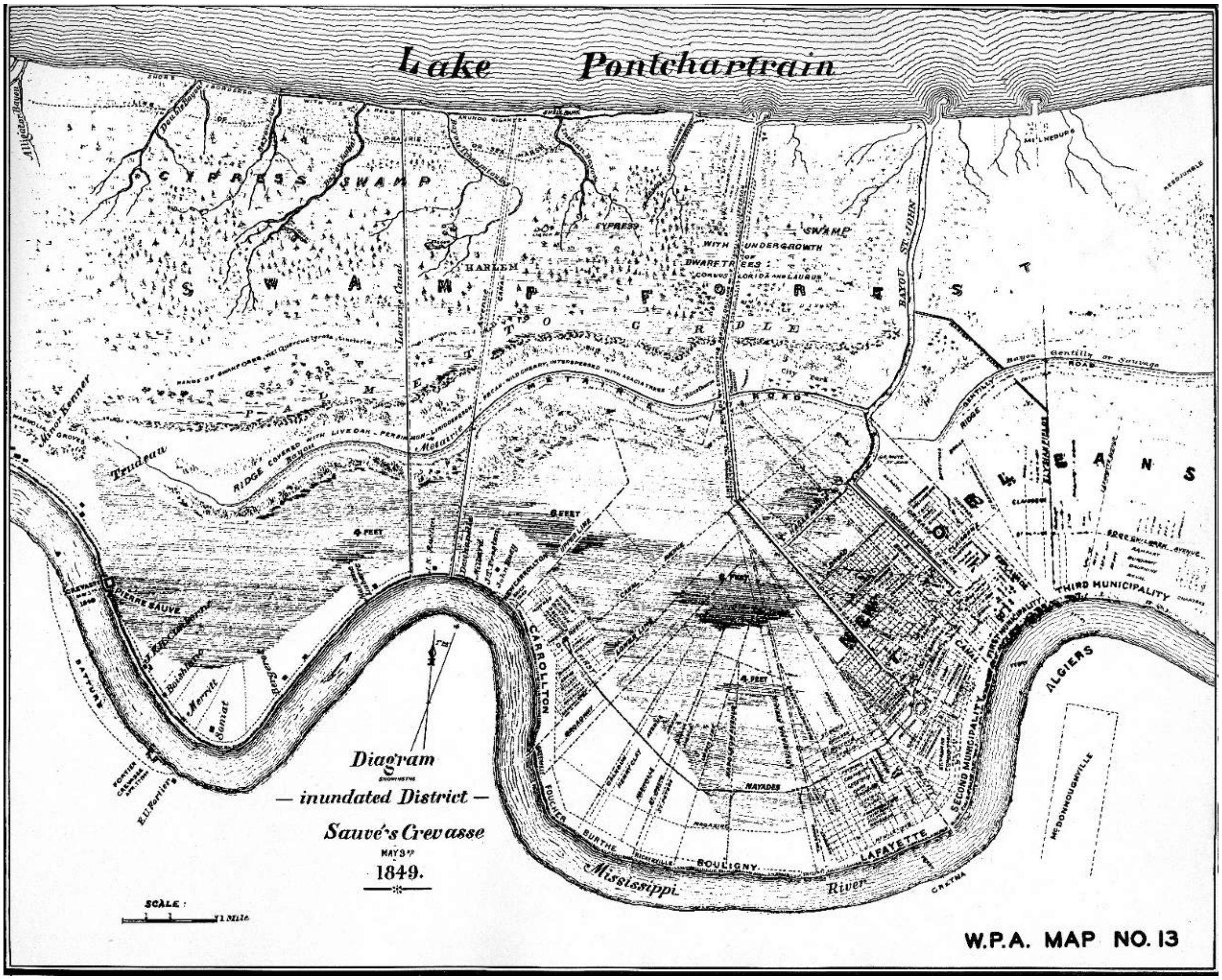


Figure 4.13: South Lake Pontchartrain flood protection measures authorized by Congress in the wake of Hurricane Betsy in 1965. These included heightening of the protective levees along the IHNC and the Lake Pontchartrain shoreline to the Orleans-Jefferson Parish boundary, and around Chalmette in St. Bernard's Parish. This system was subsequently enlarged to include the Pontchartrain levee all the way to the Bonne Carré Spillway and along the principal drainage canals in New Orleans and Jefferson Parishes.



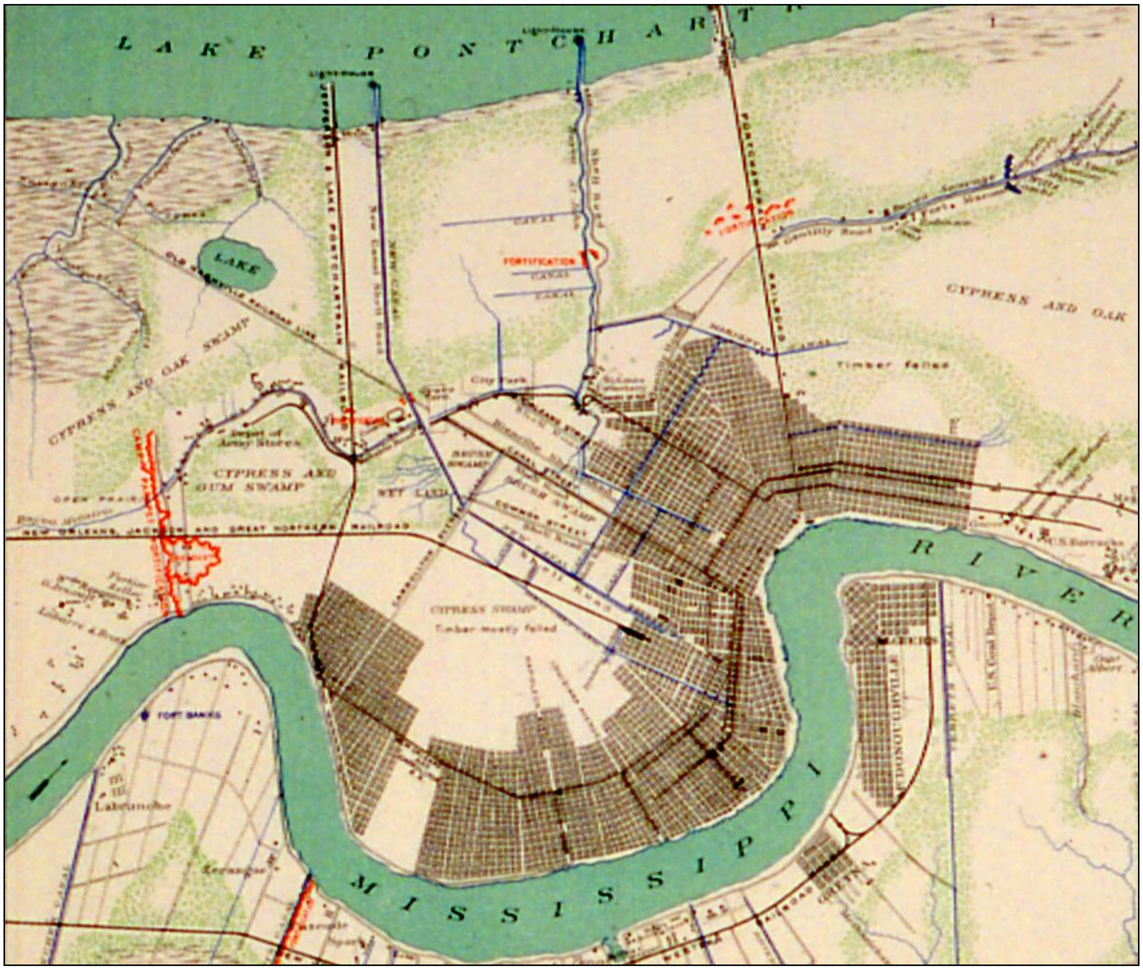
Source: Historic New Orleans Collection

Figure 4.14: Plan of the City of New Orleans prepared by Francis Ogden in 1829. Note the linear drainage canals feeding into Bayou St. John, thence into Lake Pontchartrain.



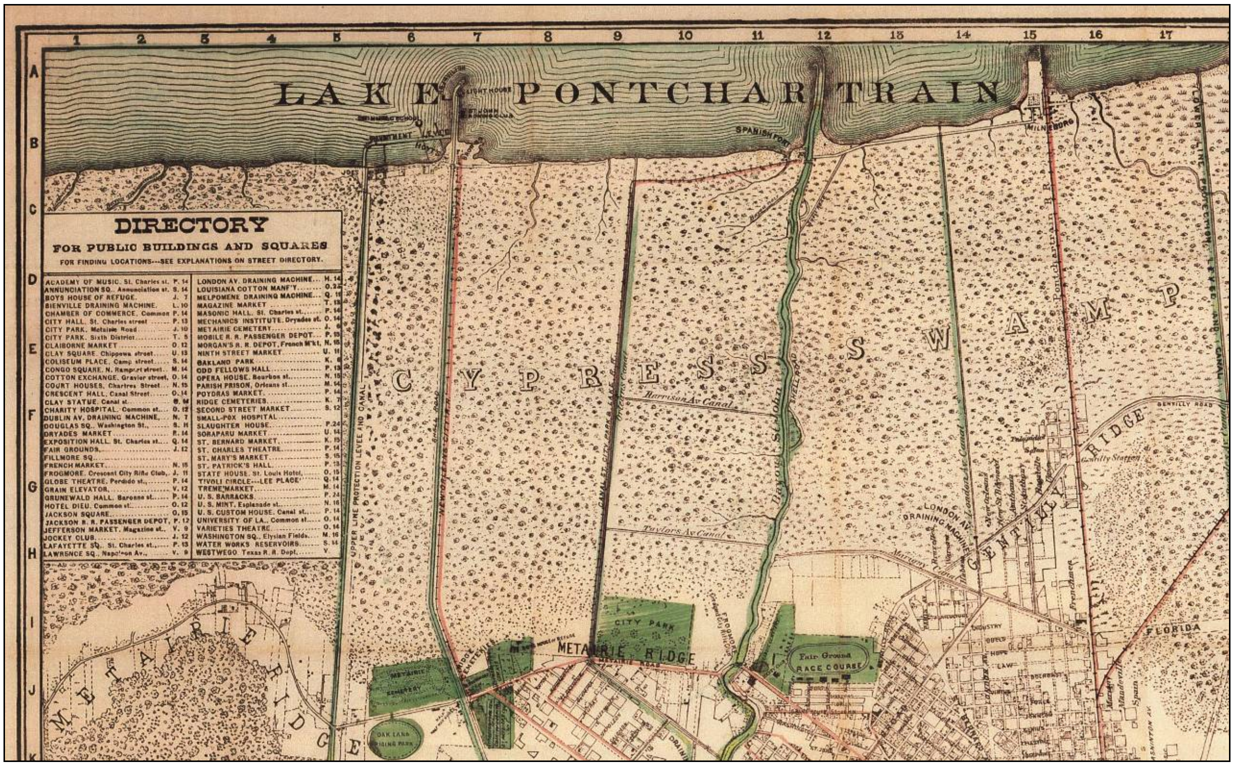
Source: WPA (1937)

Figure 4.15: Map of Sauvés Crevasse and the portions of New Orleans inundated by the flooding of 1849, the last significant flood to affect the city emanating from the Mississippi River. This 1849 map shows the extensive cypress swamps lying between the uptown and French Quarter areas and Lake Pontchartrain. The Carondelet and New Orleans Canals are clearly shown, but curiously omits the New Basin Canal (built in the 1830s). The map clearly shows the projected path of the 17th Street Canal between Orleans and Jefferson Parishes, suggesting it was being proposed (it appears to have been completed in 1857-58). The Labarre Canal in Jefferson Parish (near today's Bonnabel Canal) was likely never built.



Source: Historic New Orleans Collection

Figure 4.16: By 1863 there were a series of east-west feeder canals serving Bayou St. John from the west side and a series of north northeasterly trending drainage canals in St. Bernard Parish.

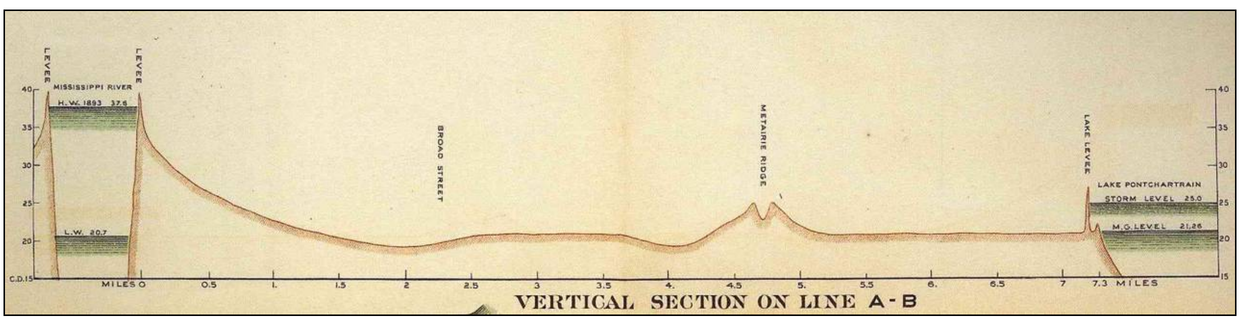


Source: Historic New Orleans Collection

Figure 4.17: All 36 miles of drainage canals in the Lakeview and Gentilly areas are shown in this portion the 1878 Hardee Map. The canals are, from left: 17th Street, New Basin (infilled), Orleans, Bayou St. John, and London Avenue, and the Lower Line Protection Levee.

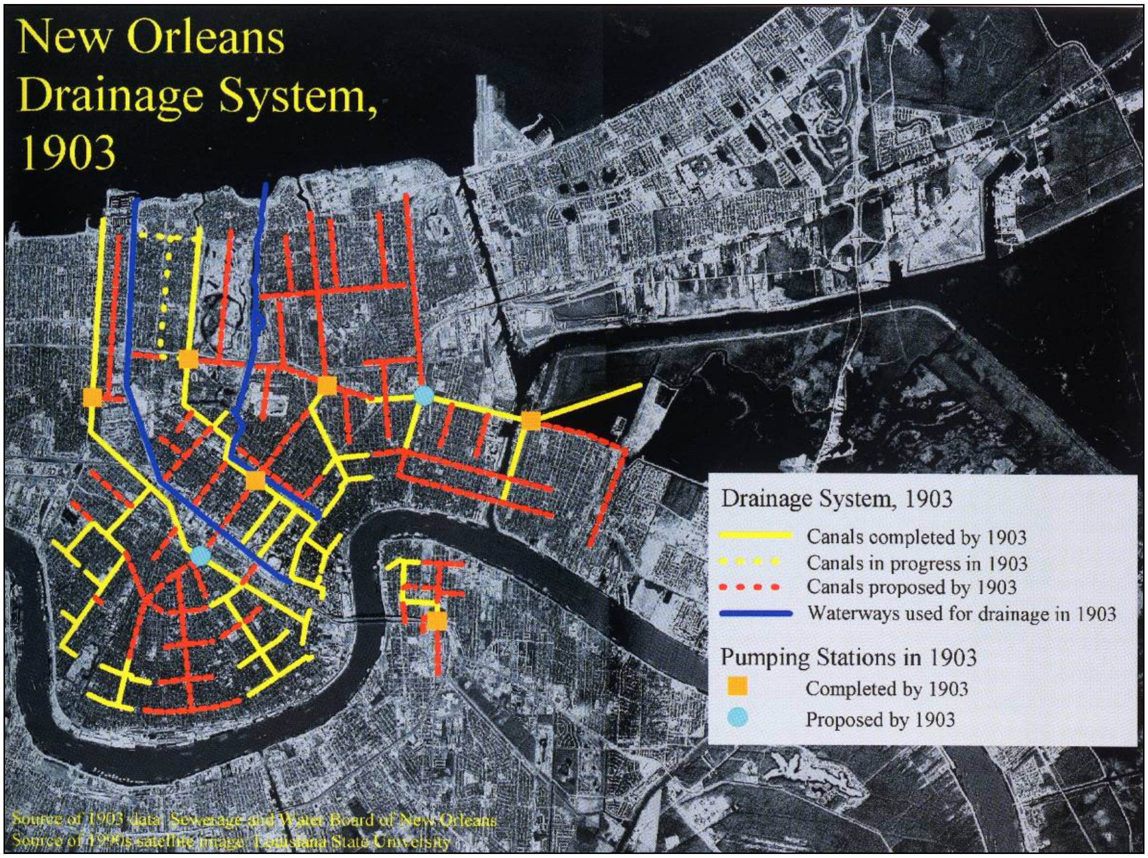
Source: University of New Orleans Special Collections, New Orleans Views

Figure 4.18: Photo taken in 1890 looking north along the "shell road" than ran along the west side of the New Basin Canal, seen at extreme right. Note the modest height of the original embankment, no more than 5 feet above the adjacent cypress swamp at left. The original embankments were heightened after hurricane-induced overtopping in 1915 and 1947.



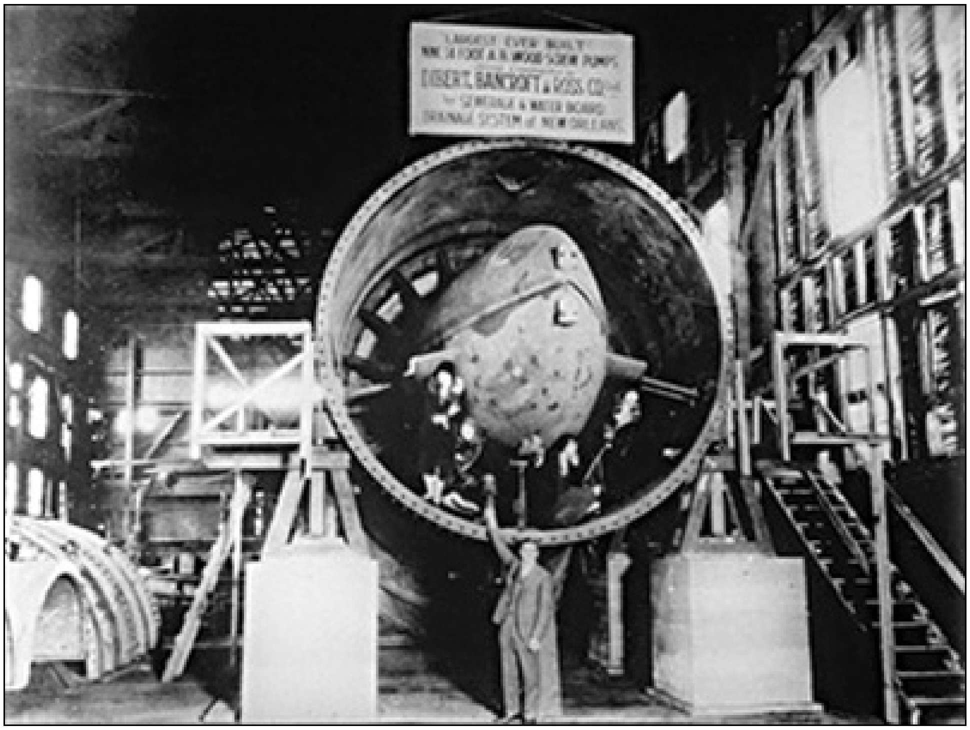
Source: Historic New Orleans Collection

Figure 4.19: Cross section through New Orleans prepared by City Engineer L. W. Brown in 1895. This shows the elevated position of the Mississippi River and the Metairie-Gentilly Ridge distributary channel, which lies 3 to 6 feet above the surrounding area. The green lines denote high and low levels in the river and Lake Pontchartrain. Elevations are in the old Cairo Datum (21.26 ft above MSL).



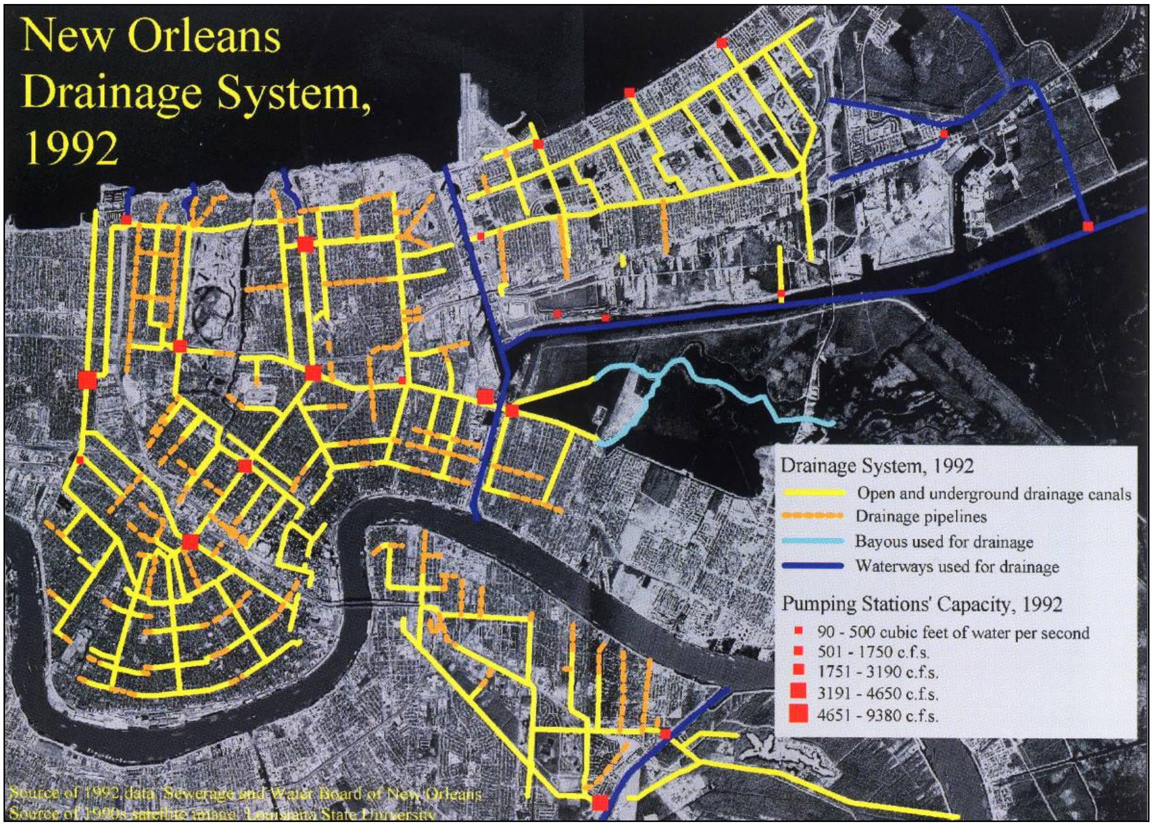
Source: Campanella (2002)

Figure 4.20: Principal elements of drainage system infrastructure as it existed in 1903. The 17th Street and London Avenue Canals had already been in operation for several decades.



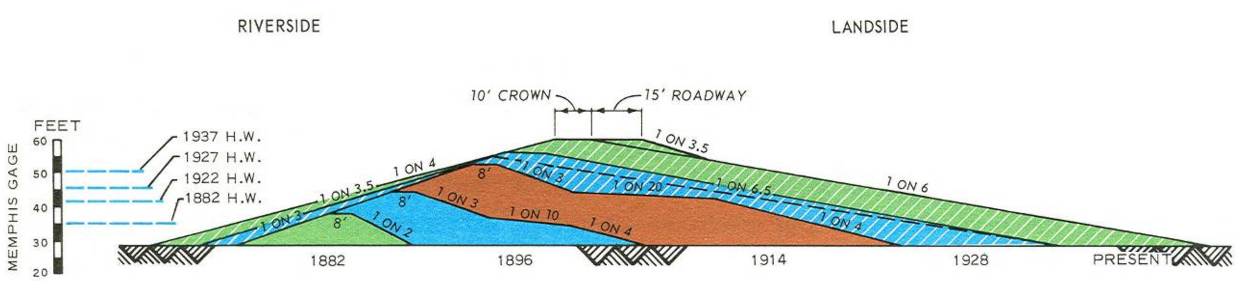
Source: Sewerage & Water Board of New Orleans

Figure 4.21: S&WB engineer A. Baldwin Wood standing next to one of his 14-foot diameter screw pumps in 1929 with several of the board's secretaries sitting inside the housing for scale.



Source: Campanella (2002)

Figure 4.22: Principal elements of the pre-Katrina drainage system infrastructure as it existed in 1992. The aggregate pump capacity could have cleared the city of flood waters in less than three days if the levees had simply been overtopped without failing.



Source: Moore (1972)

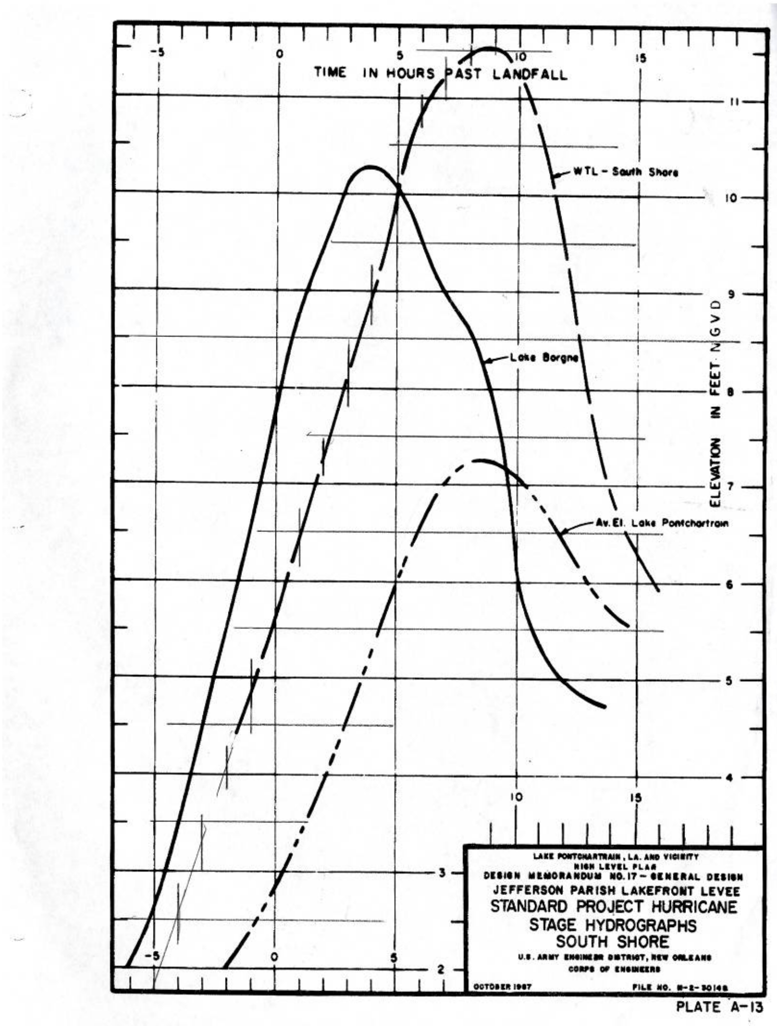
Figure 4.23: Evolution of the Corps of Engineers' standard levee section, 1882 to 1972. Earth embankments levees are generally heightened sequentially by compacting additional soil on the land side of the embankments (each sequence of heightening shown as different colors). Levees adjacent to drainage canals or perennial channels are not raised on the river side of the embankment because excess moisture would prevent meaningful compaction of the fill. Existing homes abutted the landslide of the drainage canal levees in New Orleans by the time the Corps of Engineers began analyzing them in the 1960s.

Photograph by C.M. Watkins

Figure 4.24 (upper): View looking up the east side of the London Avenue Canal near Robert E. Le Boulevard crossing showing the encroachment of homes against the slope of the levee. This situation was common across New Orleans.

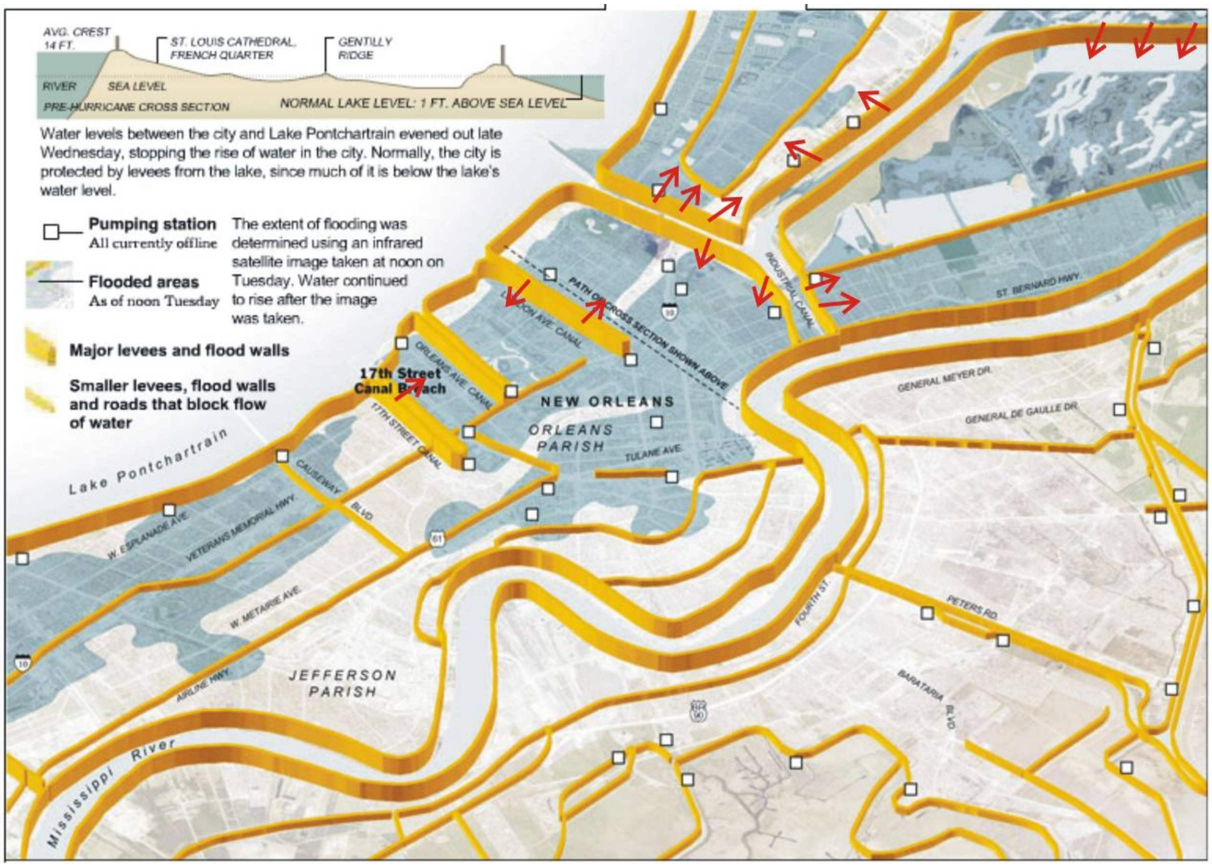
Photograph by J.D. Rogers

Figure 4.24 (lower): Concrete flood wall along the west side of the 17^{th} Street Canal in Jefferson Parish, where a street runs along the toe of the embankment. This scene is typical of the concrete I-walls constructed on steel sheetpiles driven into the crest of the drainage canal embankments in New Orleans in the 1990s to provide additional flood freeboard from hurricane-induced storm surges.



Source: USACE (1987)

Figure 4.25: Assumed Category 3 storm surge curves for the Gulf of Mexico shoreline, Lake Borgne, and Lake Pontchartrain used by the Army Corps of Engineers for planning and design purposes prior to Hurricane Katrina in 2005. Note the short duration of extreme surges, about 12 hours duration above 5 ft MSL for Lake Pontchartrain.



Source: New York Times

Figure 4.26: Schematic layout of levees and flood walls protecting the New Orleans area at the time Hurricane Katrina struck on August 29, 2005. Red arrows denote locations of levee failures.

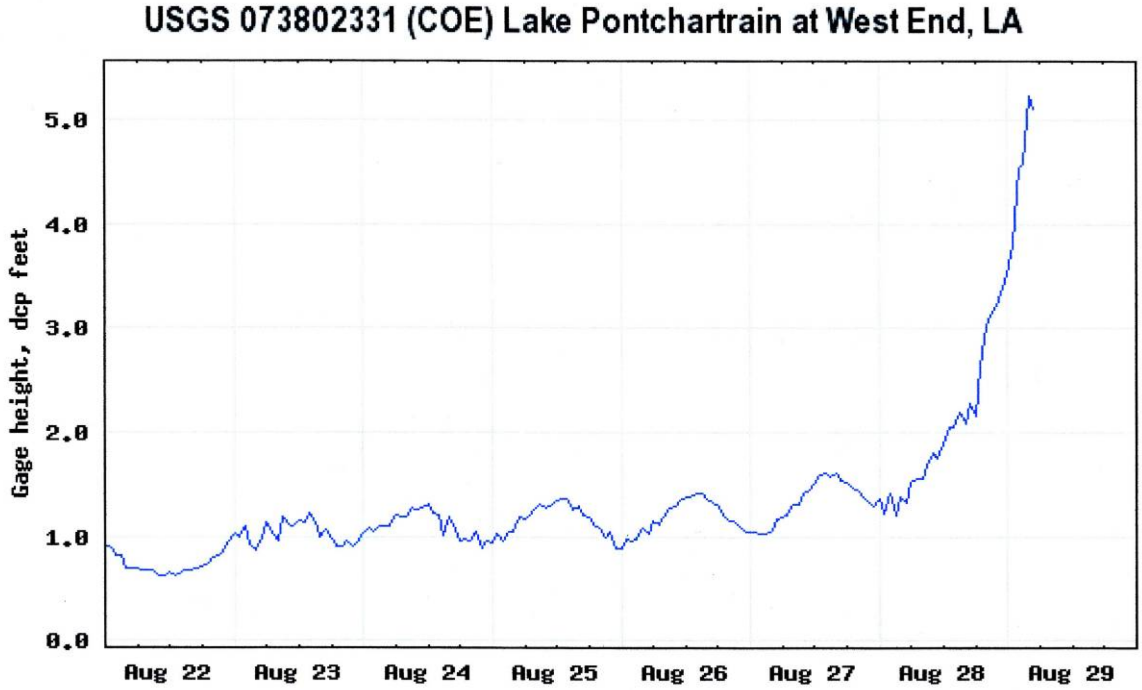
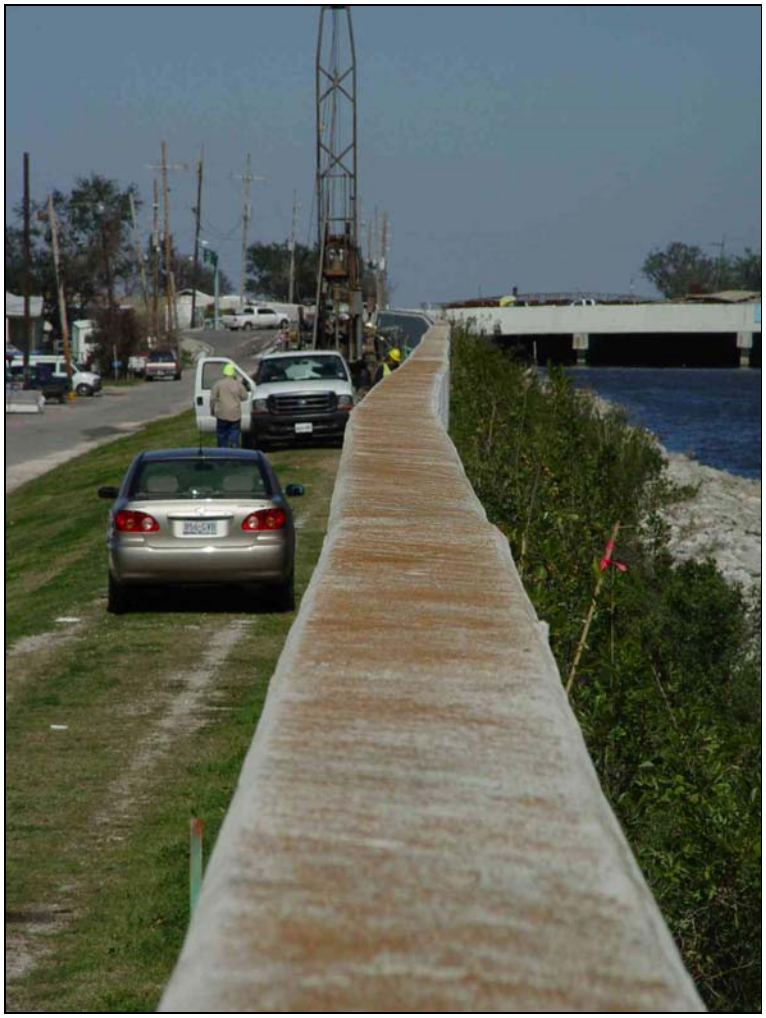


Figure 4.27: Incomplete record of the Lake Pontchartrain tidal stage gage at West End, near the mouth of the 17th Street Canal during the early stages of Hurricane Katrina (from U.S. Geological Survey). This record shows several steps in the storm surge, known as "ramping," beginning on August 28th, with the sharpest increase on the morning of August 29th, when the hurricane made landfall. The gage failed when the lake level reached 5.3 ft, before the peak surge was recorded.



Photograph by J.D. Rogers

Figure 4.28: Localized deflection of the west flood wall on the Jefferson Parish side of the 17th Street Drainage Canal (looking north), opposite the breach that occurred on the eastern side on August 29, 2005. The gap formed at the construction joint was wider at the base than the crest, suggesting deep-seated strain beneath the embankment.

Source: Elliot (1932)

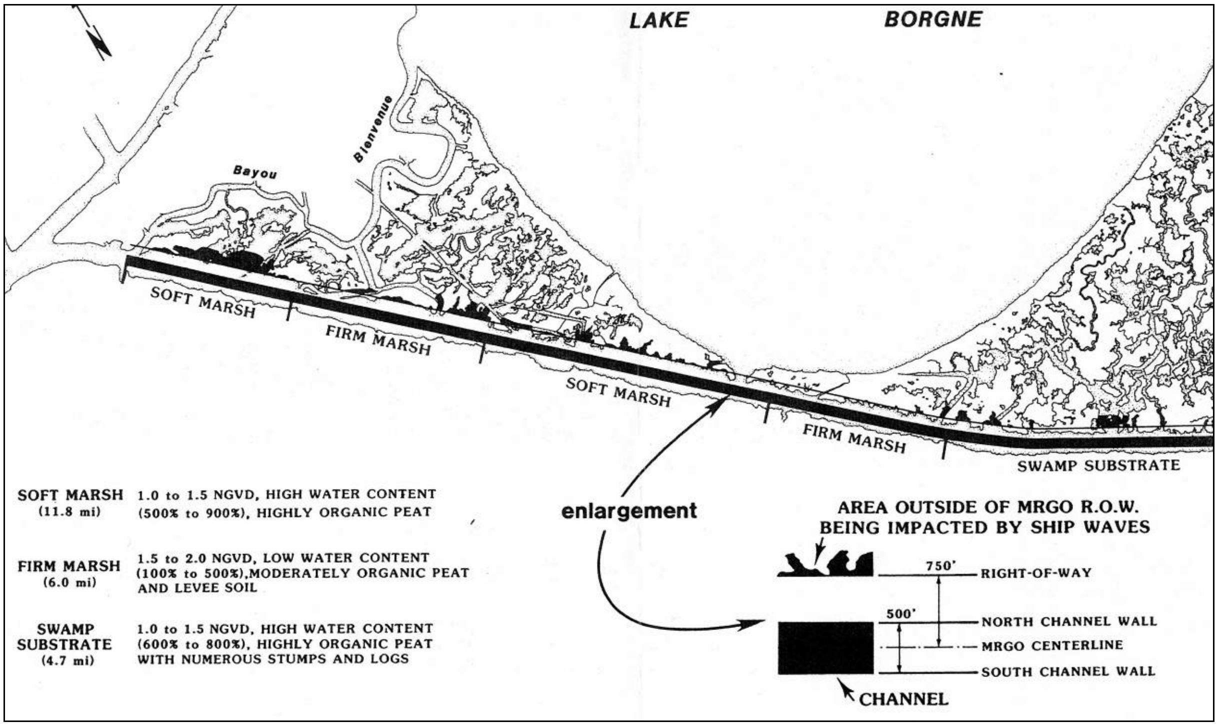
Figure 4.29: Mobile dragline constructing the Morrison-Picayuneville Levee about 25 miles south of New Orleans in June 1931. Tower draglines could excavate materials up to a quarter mile away, dragging it back up onto the new levee.

Source: U.S. Army Cops of Engineers

Figure 4.30: Aerial oblique view of the Inner Harbor Navigation Canal between 1960-64, after the entry to the Mississippi River-Gulf Outlet Channel had been enlarged (upper right), connecting to the inner harbor area.

Photograph by U.S. Army Corps of Engineers

Figure 4.31: Seepage crevasse splay exposed on the water side of the east levee of the IHNC breach after Hurricanes Katrina and Rita. This same section of the IHNC levee failed in 1965 during Hurricane Betsy. Levees tend to fail during sustained high flow events because of underseepage problems, toe scour, and overtopping. Note the anomalous seepage in lower foreground, which suggests much higher permeability in this particular portion of the dike, close to the south end of the failed section.



Source: Coastal Environments, Inc. (1984)

Figure 4.32: Portion of a map of the upper MRGO channel adjacent to Lake Borgne from the report by Coastal Environments, Inc. (1984). This shows the major soil subdivisions they identified: soft marsh, firm marsh, and swamp substrate. Much of this material was unsuitable for using in the adjoining levee embankments.

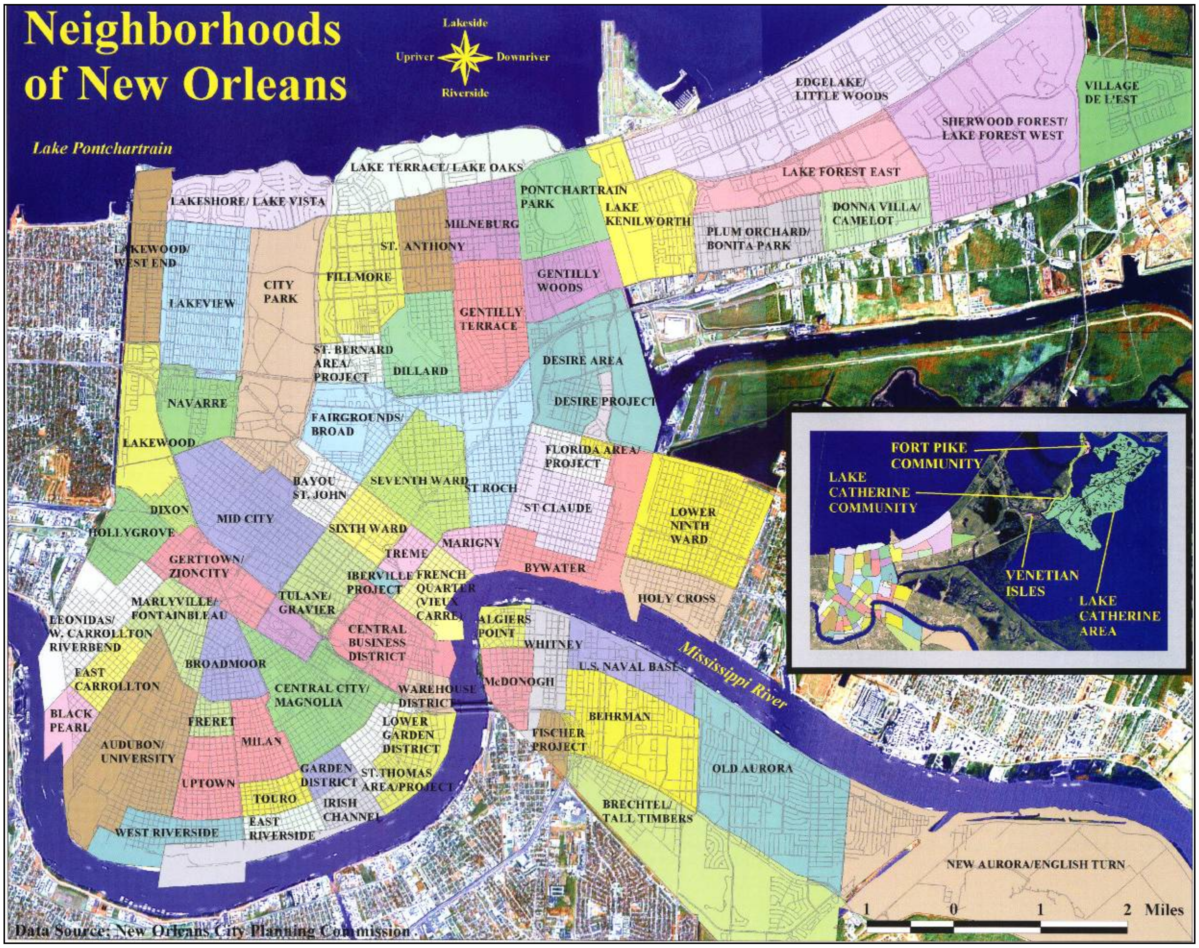
Photograph by L.F. Harder

Figure 4.33: Area where the southwest bank of the MRGO channel levee within two miles southeast of Bayou Dupree was completely swept away by overtopping from Lake Borgne.

Datum	Conversion to Mean Sea Level 1929
Ellet Datum of 1850	unknown
Delta Survey Datum of 1858	0.86
Old Memphis Datum of 1858	-8.13
Old Cairo Datum of 1871	-21.26
New Memphis Datum of 1880	-6.63
Mean Gulf Level Datum (preliminary) 1882	0.318
Mean Gulf Level Datum of 1899	0
New Cairo Datum of 1910	-20.434
Mean Low Gulf Level Datum of 1911	-0.78

Source: Denny (2002)

Figure 4.34: Table relating correction factors used when comparing various historic datums in the New Orleans area. Blanket corrections can no longer be made to adjust elevations to NAVD88-2004.65, which is the most oft cited datum currently used in New Orleans. The reason for these disparities is the gross differential settlement between reference benchmarks, which can be significant (order of magnitude difference).



Source: Campanella (2002)

Figure 4.35: Official neighborhood names recognized by the City of New Orleans. The Ninth Ward used to extend across the IHNC, but that portion east of the IHNC has been re-named the "Lower Ninth Ward."

CHAPTER FIVE: THE LOWER MISSISSIPPI REGION AND PLAQUEMINES PARISH

5.1 Overview

Plaquemines Parish is the area where the last portion of the Mississippi River flows out into the Gulf of Mexico (see Figures 2.6 and 5.1). Extending southeast from New Orleans, Plaquemines Parish straddles both sides of the lower reaches of the Mississippi River for about 70 miles out to the river's mouth in the Gulf. This protected strip, with "river" levees fronting the Mississippi River and a second, parallel set of "storm" levees facing away from the river forming a protected corridor less than a mile wide, serves to protect a number of small communities as well as utilities and pipelines. This protected corridor also provides protected access for workers and supplies servicing the large offshore oil fields out in the Gulf of Mexico.

It is an area that is sparsely populated, with a population of only about 27,000 people in the entire parish just prior to Hurricane Katrina's arrival (see Plaquemines Parish Government Website: http://www.plaqueminesparish.com). Most of these people live in small, unincorporated towns and villages along the river. Not only are these communities subject to potential flooding from the Mississippi River, but they are also vulnerable to flooding from hurricane surges because the parish extends so far out into the Gulf from the mainland.

For flood protection from the Mississippi River, large federal project levees were constructed along both sides of the river with design crest elevations of approximately +25 feet (MSL). For many of the communities lying closely alongside the Mississippi River levees, "hurricane" or back levees were also constructed behind them to protect them from hurricane surges coming from the Gulf. These hurricane levees were constructed with lesser crest heights than the river levees, and typically had crest heights on the order of +17 to +18 feet (MSL). Thus, many of the homes in these areas are sandwiched between two sets of levees: one along the river and the other behind the towns.

The Independent Levee Investigation Team was not able to devote significant time to detailed investigations and analyses of the numerous individual levee failures that occurred along this protected corridor. Accordingly, this chapter will present only a brief overview of the performance of the flood defenses in this parish during Hurricanes Katrina and Rita.

As described previously in Chapter 2, Plaquemines Parish was the first developed area to be severely affected by the large onshore storm surge as Hurricane Katrina approached the southern coast in the early morning of August 29, 2005.

Hurricane Katrina devastated many of the Plaquemines Parish communities. Hurricane Katrina was reported to have induced storm surges on the order of up to 20 feet in this region, as shown in Figure 5.2. In addition, large storm waves atop this surge rose to greater heights. This storm surge, and the waves that accompanied it, overtopped and damaged many portions of the "storm" levees. Both the United States Army Corps of

Engineers (see Figures 2.6 and 5.1) and the Plaquemines Parish Government website report numerous breaches of the storm levees and widespread deep flooding and destruction.

Figures 5.3 through 5.12 show examples of the types of damage and flooding that resulted from the overtopping and breaching of the protective hurricane levees.

Figure 5.3 shows an aerial view of the inundation of the hamlet of Myrtle Grove, on the west side of the Mississippi River, as it appeared on September 25, 2005, one day after the second Hurricane (Rita) again inundated this section.

Figure 5.4 shows an aerial photograph of a levee breach of the hurricane (back) levee on the western side of the Mississippi River near the community of Sunrise. The breach occurred at a "transition" between an earthen levee section with a sheetpile-supported concrete I-wall, and a plain structural floodwall section. Failures at transitions between different adjoining sections were relatively common throughout the affected area during Hurricane Katrina.

Figure 5.5 shows an aerial photograph of a breach of the hurricane (back) levee at another "transition" near the Hayes Pump Station. This time the failure occurred at a sheetpile transition between an earthen embankment and a structural floodwall section, and sheetpile to earthen embankment connection appears to have been the weak link.

Figure 5.6 shows a pair of large shrimp boats on Highway 23, near the foot of the Empire High Rise Bridge. As illustrated by this photo, overtopping was quite severe, and large objects were floated up onto, and sometimes over, the levees.

5.2 Point a la Hache

Point a la Hache is the parish seat for Plaquemines Parish and is located along the east side of the Mississippi River. Storm surges from the east largely overwhelmed the back levee, breached it in several places, and inflicted deep flooding and widespread destruction in this town. Figure 5.7 presents an aerial photograph of one such breach taken on September 25, 2005 (from Plaquemines Parish Government Website). Shown in this photograph is a temporary road constructed across the interim breach repair to facilitate access and repairs.

Figure 5.8 shows this same levee breach a few weeks later during the installation of a sheetpile cutoff that was undoubtedly intended to be part of an interim, and perhaps permanent repair. The team members viewing the installation believed that the sheetpile wall was a good concept to affect a positive cutoff of seepage through the deeply scoured breach and loose debris. However, during the installation, team members noted that the contractor was having difficulty advancing the southern portion of the sheetpiles very far into the ground using the equipment in use at the time of the team's visit. It is hoped that the pilings ended up being driven to their needed depths.

Residences in Pointe a la Hache were commonly inundated to depths of 12 to 18 feet (see Figure 5.9). Inundation flooding was so great that water flowed across the community from the east towards the Mississippi River, and even overtopped the Mississippi River levee (at least with significant wave splashover) by several feet. Based on debris found on tractor equipment left on the levee crown along the Mississippi River, overflows or splashover of up to 4 feet were estimated. For most of the areas visited by our team, relatively little significant damage was observed on the Mississippi River levees, possibly because the river sides of the levees viewed by the team were paved with concrete slope protection (see previous Figure 2.17). Damage to the "storm" levees was significant at many locations, however,

Like many New Orleans residences, the small wooden homes in Pointe a la Hache were commonly founded on cinderblock piers. As a result of the deep flooding and the flow towards the Mississippi River, homes in Pointe a la Hache were commonly picked up and floated away from their foundations. Many ended up being deposited on or across the Mississippi River Levee as a result of storm surges flowing from the overtopped "storm" levees towards the "river" levees alongside the Mississippi River (see Figures 5.10 through 5.12).

5.3 Erosion Studies

Although overtopping caused numerous breaches in the "storm" levees facing away from the Mississippi River, less erosion was observed along most of the Federal "river" levees. This may have been due in part to the fact that the river-side levee embankments slope faces were paved with concrete slope face protection (as shown previously in Figure 2.17, which clearly shows this river-side slope face protection.) It may also have been due in part to the fact that the backsides of these river levees, which had no formal slope face protection, were at least partially protected from the full energy of the storm surge and the wind driven waves by the obstacles presented by the "hurricane" levees, and by other obstructions including buildings and trees, etc.

Nonetheless, it is a noteworthy performance on the part of these levee embankments, and it merits further study. It is hoped that with further testing trends will emerge showing that soil type and character, as well as placement and compaction conditions, can be used as a relatively reliable basis for prediction of the level of vulnerability of levee embankment soils to erosion and scour. Issues associated with erosion are discussed in more detail in Chapter 9.

5.4 Summary

Plaquemines Parish is the most obviously exposed populated and flood protected area in the region. It juts out into the Gulf of Mexico much like a boxer's chin, almost daring a knockout blow.

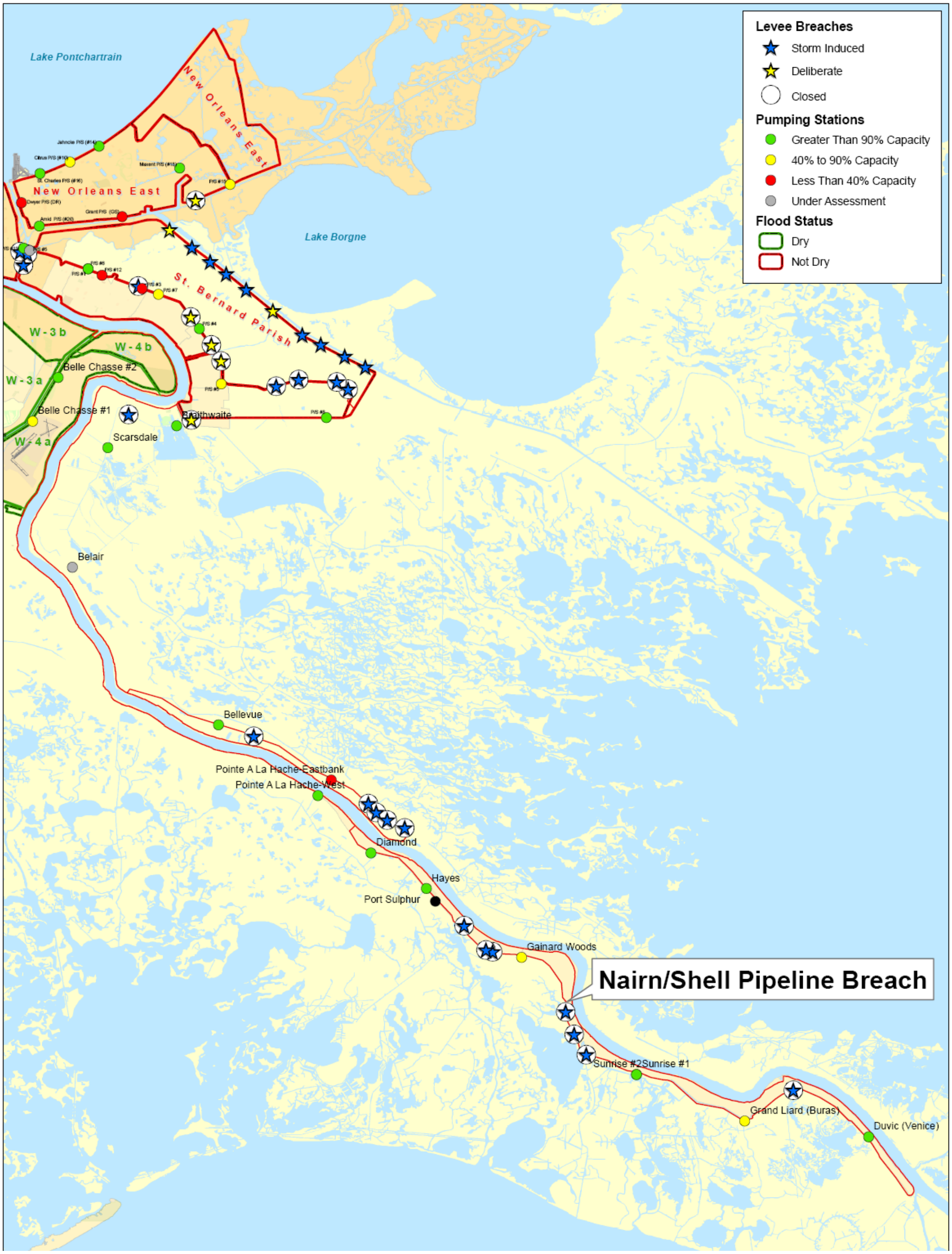
Because Plaquemines Parish is so obviously exposed, the evacuation of the Parish was unusually comprehensive prior to Katrina's arrival. That was a good thing, as most of the lower reaches of the Parish were catastrophically flooded. Massive damage was done to homes and businesses in the many small and generally unincorporated townships, and there was at least one major rupture in an oil transmission line. The best information available to this investigation team at this time is that approximately 60 lives were lost in Plaquemines Parish during hurricane Katrina.

The merits of expending Federal dollars to attempt to defend the full Parish, or even large portions of it, in the face of ongoing regional subsidence, sea level rise, and increasing projected hurricane intensity due to rising Gulf water temperatures, warrant further study. Recent requests for up to $3 billion in Federal funds to repair and upgrade the levees for a narrow strip of land into which less than 15,000 to 20,000 people are currently expected to return would represent an expenditure of approximately $150,000 to $200,000 per capita. In the mean time, large amounts of Federal funds are currently being expended to repair the damaged levees in this Parish.

5.5 References

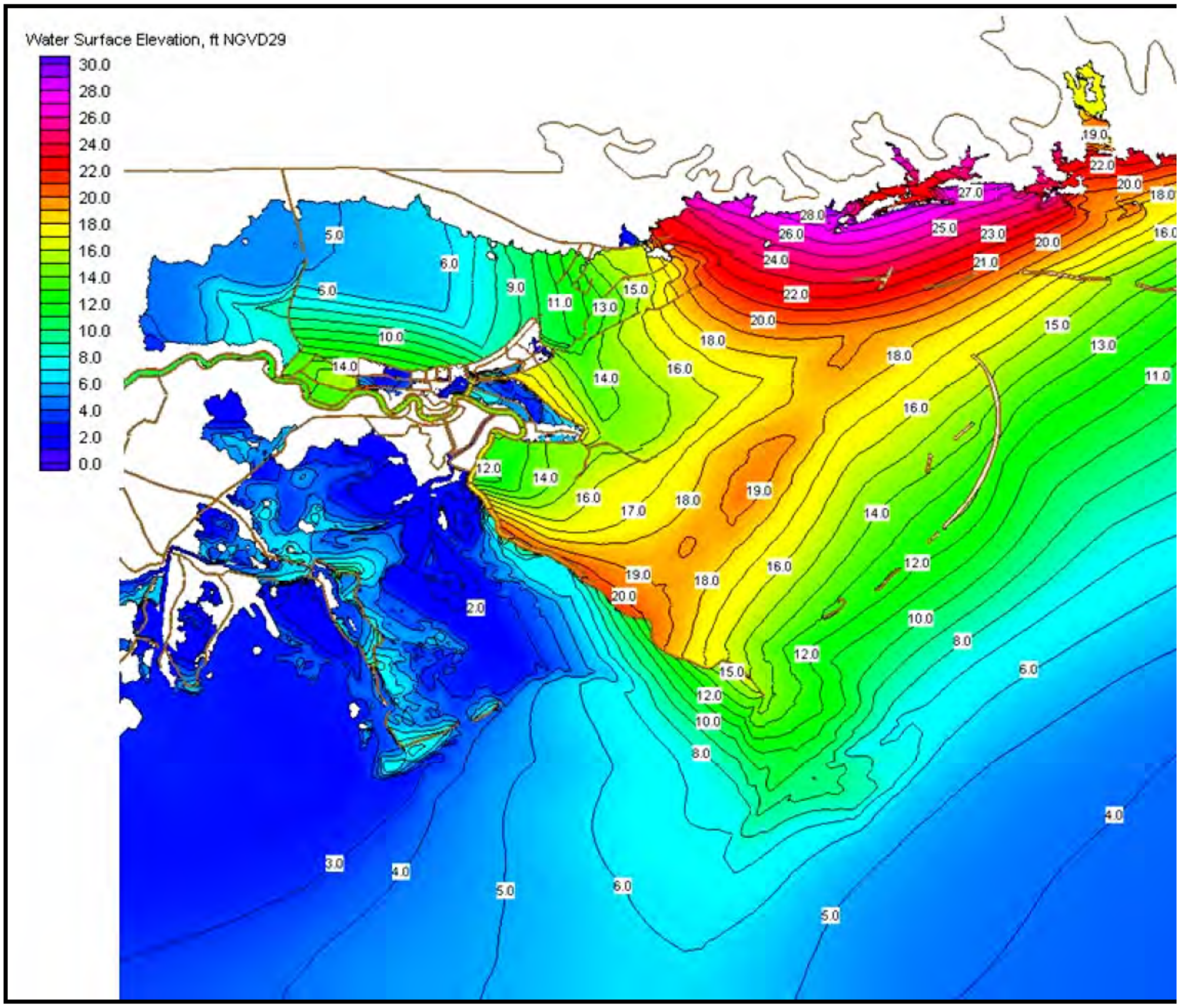
Interagency Performance Evaluation Task Force, (2006), "Performance Evaluation, Status and Interim Results, Report 2 of a Series, Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System," March 10, 2006.

Plaquemines Parish Website, (2006), http://www.plaqueminesparish.com



Source: Modified after USACE

Figure 5.1: Map showing the levee protected areas along the lower reaches of the Mississippi River (in the Plaquemines Parish Area).



Source: IPET (2006)

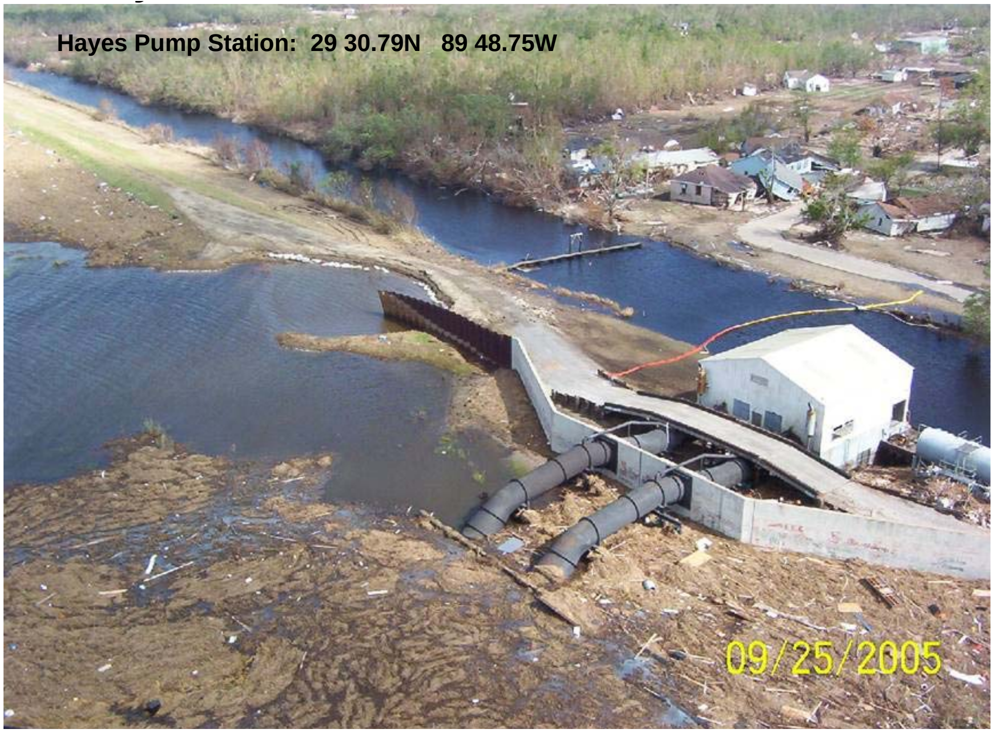
Figure 5.2: Aggregated maximum storm surge elevations (maximum among all times).

Source: http://www.plaqueminesparish.com/

Figure 5.3: Aerial photograph of inundated portion of Myrtle Grove along western side of the Mississippi River. [September 25, 2005]

Source: http://www.plaqueminesparish.com/

Figure 5.4: Aerial photograph of levee breach of storm (back) levee along western side of the Mississippi River near the community of Sunrise. [September 25, 2005]



Source: http://www.plaqueminesparish.com/

Figure 5.5: Aerial photograph of levee breach of storm (back) levee at levee-to-wall transition near Hayes Pump Station. [September 25, 2005]

Source: http://www.plaqueminesparish.com/

Figure 5.6: Aerial view of two large shrimp boats deposited on Highway 23 at the foot of the Empire High Rise Bridge.

Source: http://www.plaqueminesparish.com/

Figure 5.7: Aerial photograph of levee breach of storm (back) levee East of Pointe a la Hache. [September 25, 2005]

Photograph by Les Harder

Figure 5.8: Photograph of Sheetpile Cutoff Being Placed into Levee Breach of Storm (Back) Levee East of Pointe a la Hache. [October 12, 2005]

Photograph by Les Harder

Figure 5.9: Photograph of flood elevation on trees landward of hurricane levee East of Pointe a la Hache – illustrating that flood waters remained to large depths for extended periods. [October 12, 2005]

Photograph by Les Harder

Figure 5.10: Photograph of Pointe a la Hache home deposited on Mississippi River levee crown after storm surges overtopped the storm levee from the East (left) towards the River – which is to the right in this photograph.

Photograph by Les Harder

Figure 5.11: Photograph of Pointe a la Hache homes deposited on Mississippi River Levee after storm surges overtopped the levee from the East (left) towards the River (right). [October 12, 2005]

Photograph by Les Harder

Figure 5.12: Photograph of Pointe a la Hache home site where a wood home was floated off of its cinderblock piers. [October 12, 2005]

CHAPTER SEVEN: THE NEW ORLEANS EAST PROTECTED AREA

7.1 Introduction

The New Orleans East (NEO) protected area includes some of the lowest ground in the metropolitan region. Therefore, it is not surprising that damage to the surrounding levee system caused significant flooding in this protected area. The NEO protected area had a pre-Katrina population of approximately 96,000 people residing in over 30,000 households. Most of these residences were located in the western portion of the polder between Lake Pontchartrain and Chef Menteur Highway. The residential neighborhoods are suburban in character, with many of the homes dating to the 1960s and 1970s. Ironically, a number of these homes were built in response to the devastation inflicted by Hurricane Betsy in 1965, which left much of New Orleans East submerged by floodwater. The NEO protected area also includes an industrial corridor located adjacent to the Gulf Intracoastal Waterway (GIWW). The eastern limits of the NEO protected area is largely comprised of wetlands that border Lake Pontchartrain/Lake Borgne water systems.

The NOE protected area extends over approximately 70 square miles and is bounded by Lake Pontchartrain to the north and east, the GIWW to the south, and the Inner Harbor Navigation Channel (IHNC) to the west. Elevations typically range from approximately 10 feet to -5 feet (MSL), with the higher elevation reaches located south of Chef Menteur Highway. Figure 7.1 shows the primary levee system surrounding the protected area. This protection system, which includes earthen levees, I-wall, T-wall, and sheet pile sections, was designed by the USACE as part of the Lake Pontchartrain and Vicinity Hurricane Protection Project. The NEO protected area also includes a secondary or "local" levee that separates the developed portions of the region from the wetlands to the east (Figure 7.1). The primary purpose of the secondary levee is interior drainage control rather then hurricane protection and as such, its performance was not evaluated as part of this study.

7.2 New Orleans East Hurricane Protection System

The New Orleans East hurricane protection system is shown in Figure 7.1. The figure is an as-built overview map used by the USACE New Orleans District for design and planning and includes the elevations of the levee system throughout the NEO protected area. The map divides the levee system into individual segments, or "reaches," which are defined by physical characteristics, elevation, and/or potential consequences. For consistency, the names assigned to the individual reaches by the USACE will be used in this chapter. The New Orleans East Lakefront reach is approximately 12.5 miles in length and largely consists of an earthen levee having 3 to 4 horizontal: 1 vertical side slopes. To the east is the New Orleans East Levee, an approximately 8.5 mile long earthen segment having a similar cross section. The southern boundary of the protected area is fronted by the New Orleans Back Levee (to the east) and the adjacent Citrus Back Levee (to the west). These reaches, which together measure approximately 18 miles in length, are largely comprised of earthen levee sections interspersed with shorter concrete floodwalls and/or sheet pile wall segments. The IHNC East Levee is an approximately 3-mile reach primarily comprised of floodwall. As its name implies, the portion of the levee system separates the polder from water in the adjacent

IHNC. Continuing clockwise to are the New Orleans Lakefront and Citrus Lakefront Levees. These reaches include both earthen and floodwall sections.

7.3 Performance of the New Orleans East Hurricane Protection System in Hurricane Katrina

7.3.1 Overview

Figure 7.2 shows the location of damage to the levee system surrounding the NOE protected area. The most significant damage to the system occurred to East Back Levee that fronts the GIWW. Here the storm surge completely destroyed large expanses of earthen levee in the southeastern corner of the NEO protected area. Additionally, many smaller but nevertheless significant breaches also occurred along other portions of these reaches. Damage (mostly in the form of scour) also occurred along the IHNC East Levee and portion of the New Orleans Lakefront Levee located near the Lakefront Airport. Other portions of the levee system fronting Lake Pontchartrain, such as the New Orleans Lakefront, Citrus Lakefront, and New Orleans East Lakefront Levees, generally performed well in the hurricane, as did most of the New Orleans East Levee located to the east.

7.3.2 Chronology of Events in the New Orleans East Protected Area

It is believed that water first entered the NOE protected area in the 5:00 AM hour on August 29 after a large section of earthen levee in the southeastern corner of the polder eroded and ultimately, breached, as a result of wave action and possible seepage associated with the rising storm surge from Lake Borgne. The levee system at this location was so severely damaged that it ultimately did little, if anything, to impede the storm surge that later peaked at this location. Water entering the NEO protected area through this breach then crossed the adjacent wetlands before being channeled, initially, by the Bayou Sauvage ridge (high ground underlying Highway 90) to the west. Video footage recorded at the Entergy Power Utility Plant near the Michoud Canal show this inflowing water at 6:15 AM. Storm surge simulations by the IPET team (IPET Report 2, March 10, 2006) indicate relatively low water levels in the adjacent GIWW at the 6:00 AM hour, thus suggesting that the water first arriving at the Entergy plant did not result from simple overtopping of the bordering levee system.

It is thought that the storm surge then passed westward along the GIWW channel and produced levee damage and several smaller breaches on the north side of the channel. These breaches added to the water already flowing into the area along the major breach in the southeast corner. The surge then continued westward reaching the GIWW's “T” intersection with the IHNC channel. The surge passed to the north (and south) along the IHNC, and damaged several sections along the IHNC frontage.

As the hurricane then passed northward to the east of New Orleans, the counterclockwise direction of the storm winds also produced a storm surge southward towards the shore of Lake Pontchartrain. The lake level rose, but largely stayed below the crests of most of the lakefront levees. The lake rose approximately to the tops of the lakefront levees at a number of locations, especially along the shoreline of New Orleans East, and there was modest overtopping (storm surge wave splash-over) and some resulting erosion on the crests and inboard faces of some lakefront levee sections along the Lake frontage. However, there were no breaches in this area. Overtopping occurred over a section of floodwall near the west end of the New Orleans East protected area lakefront, where the floodwall was lower than the adjacent earthen levee sections. This, too, added to the flow into the New Orleans East protected area, which was now beginning to fill with water even as the original storm surges subsided. As shown in Figure 7.3, water depths ultimately approached 10 feet in area. Sadly, some of the deepest waters were found in the NOE protected area's residential neighborhoods.

7.3.3 Damage to Levee System Frontages

The following sections summarize damage to the individual frontages of the levee system (Figures 7.1 and 7.2). For consistency, locations are referred to using the designations assigned by the USACE Task Force Guardian levee system rebuilding team.

7.3.3.1 GIWW Frontage (Citrus Back and New Orleans East Back Levees)

<u>Southeast Corner and Vicinity:</u> As noted earlier, the most severe damage to the NOE Levee System occurred along an approximately 5300 foot long section of the New Orleans East Back levee, which is situated in the southeast corner of the protected area (Figure 7.2). The protection system at this location consists of earthen levee sloped at 4 horizontal: 1 vertical with a 10-foot wide crown. This damage to this segment of the levee system was similar to that which occurred along the Mississippi River Gulf Outlet (MRGO) levees in St. Barnard Parish: entire sections were completely eroded leaving virtually no trace of the original earthen levee (Figure 7.4). As with the severely damaged MRGO levees (see Chapter 6), it is believed that the breaching occurred as a result of erosion of the flood-side face due to wave action on the rising waters of Lake Borgne. This erosion occurred prior to the peak of the storm surge. It is possible that seepage forces, also resulting from the rising waters, further destabilized the levees. The detrimental effects of these seepage forces would have been most pronounced on the back or protected side of the levees. These two mechanisms, working alone or in combination, ultimately destroyed the earthen levees before the storm surge peaked, and therefore, it is not likely that the protection system was overtopped at this location.

Damage to the levee system also occurred further west between the southeast corner and the Michoud Canal. Several sheet pile levee sections located near Pump Station 15 deflected and tilted inward (i.e., toward the protected side, see Figure 7.5), as the result of erosion at the base of the wall. Sheet piling was used at these locations to transition between conventional concrete floodwall and earthen levee sections. The tops of the damage sheet pile walls had pre-Katrina elevations that were less then the immediately adjacent wall sections, and hence scour at these locations was worsened by preferential overtopping during the peak of the storm surge. Further to the west near the Air Products Corporation site a similar sheet pile transition section overturned and collapsed in response to scour and the associated loss of passive resistance on the protected side (Figure 7.6). Once again, the top of the damaged section was at a lower elevation then adjacent levee segments resulting in highly concentrated overflow at this location.

Michoud Levee System: The Michoud area levee systems site extends along the GIWW from Michoud Slip to Michoud Canal. The site is located below and immediately west of the Interstate 510/Highway 47 bridge near the Entergy New Orleans Corporation's power utility plant. Scour was noted at the base of the floodwalls surrounding both Michoud Slip and Michoud Canal; however, breaching did not occur at this location and overall system performance was good (Figure. 7.7). In addition to the video of early morning flooding here highlighted earlier, mounted security cameras later captured dramatic images of levee overtopping during the peak of the storm surge.

Citrus Back Levee Floodwall: This site is located in the industrial corridor south of Chef Menteur Highway along the GIWW. Because its protection system consists of a relatively short floodwall segment situated between longer stretches of earthen levee, the site provides a unique opportunity to compare the performance of different types of levees subjected to identical storm surge loadings. The levee system at the site principally consists of an approximately 3000 foot long I-wall with a short (~ 80 feet) T-wall and 50 foot gate section. The adjacent earthen levee sections are sloped at 4 horizontal: 1 vertical and include a 10 foot wide crown. The I-wall tilted and deflected significantly in response to the rising storm surge, but did not fully collapse. Deflection ranged over the 3000-foot length of the floodwall section from severe (i.e., almost completely tilted over, Figure 7.8a) to moderate (i.e., lateral movement of several feet, with limited tilting, Figure 7.8b). Deflections were generally greater near the eastern and middle segments of the floodwall. Scour trenches developed along the length of the floodwall on the protected side. In many instances, these trenches were located several feet from the base of the wall and had widths of 7 feet or more. A massive scour hole was found behind to the most tilted segment of the I-wall system. Localized scour was also noted at the western edge of the I-wall where it connects to the earthen levee.

As noted above, the floodwall protection system included two isolated segments T-wall segments, both of which performed well (i.e., little if any permanent deflection) despite the scour that occurred along their base. The earthen levee sections east and west of the floodwalls also performed well (i.e., no breaching or significant distress), though at some sections, particularly to the east of the floodwalls, small, isolated scour holes developed along the slopes of the protected side (Figure 7.9). The soil exposed in these scours indicated the levee was comprised of largely cohesive materials.

The damage patterns at the site suggest that the I-walls initially deflected and tilted inward in response to water pressure from the rising storm surge. This deflection may have been exacerbated by a gap at the front (flood side) base of the wall, which would have further increased hydrostatic forces on the wall. In fact, such a gap was clearly observed on the flood side of the wall shortly after the Hurricane (Figure 7.8b). The tilting of the wall effectively reduced its top elevation, which is likely to have initiated (or attracted additional) overtopping at this location. The soil along much of the base of the wall (Figure 7.8a) was not eroded, suggesting that the wall tilted prior to overtopping.

Topographic maps of the area show a localized low area close to the large scour hole. This low area may have attracted runoff from the overtopping, causing localized erosion that ultimately developed into the large scour hole. This may have, in turn, further exacerbated tilting of the floodwall due to loss of passive soil resistance. It is worth noting that damage to the levee system at this location was almost entirely limited to the relatively short floodwall segment. The adjacent earthen levee segments performed well despite having been subjected to an identical storm surge loading.

7.3.3.2 IHNC Frontage (IHNC East Levee)

The levee system located along the IHNC is primary comprised of conventional floodwall sections interspersed with a number of gate and transitions structures. Overtopping occurred along almost all of this levee system; nevertheless, overall performance was good along the section and no large, catastrophic breaches developed in direct response to the storm surge. As with other overtopped floodwall sections throughout the protected area, scour occurred at the base of the walls nearly along their entire length (Figure 7.10). As shown in Figure 7.11, damage tended to be most severe at gate structures and transition sections because of concentrated flow. At one location along the levee system a gate was inoperable owing to structural damage that occurred prior to Hurricane Katrina. This allowed largely unimpeded flow into the protected area as the storm surge passed through the IHNC.

7.3.3.3 Lake Pontchartrain (New Orleans Lakefront, Citrus Lakefront and New Orleans East Lakefront Levees) and East Side Frontages (New Orleans East Levee)

The lakefront levee system includes both earthen and floodwall sections, which with one exception, performed well. Scour, possibly resulting from wave overtopping, occurred at the base of the floodwall located near the Lakefront Airport (Figure 7.12). Despite this, overall performance was generally good and no breaches developed in this immediate area. However, as shown in Figure 7.13, significant scour and erosion occurred along a nearby segment, ultimately resulting in a breach at this location. The breach was located in a section having a maximum elevation that was below that of the adjacent levee segments. Moreover, the damaged location served as the transition between a floodwall section and an adjoining, and more erodible, earthen segment. The combination of these factors was ultimately responsible for the breach at this location.

Only modest damage, primarily in the form of scour, occurred along the remainder of the Lake Pontchartrain frontage. The levee system along this reach was comprised of both floodwall and conventional earthen sections. Storm surge simulations indicate that the lake levels were close to but not greater then the top of the levees, and therefore the scour most likely resulting from wave splash over rather then overtopping.

Similar performance was also noted along the eastern levee frontage, which is buffered from the nearby lake systems by a large stretch of wetlands to the east. The only notable damage that occurred in this area was scour in a floodwall-earthen levee transition section that was part of a railroad gate structure.

7.4 Summary of Findings for New Orleans East Protected Area

The key findings of this chapter may be summarized as follows:

- The catastrophic breaching of the New Orleans East Bask Levee System in the southeast corner of the polder was responsible for much of the flooding of the NEO protected area. While there is limited data as to the exact time that the breach developed, the available evidence strongly suggests this occurred prior to the peak of the storm surge. This implies that the levee at this location failed not in response to simple overtopping, but rather as a result of wave action and, possibly, seepage, related to the rising water levels in the GIWW.

- With the notable exception of the levee system in the southeast corner, the conventional earthen levees that protect most of the NEO area performed quite well. This is despite, in some cases, that significant overtopping that occurred during the peak of the storm surge.

- The performance of floodwalls was uneven. In some cases these systems performed well even when overtopped (e.g. along the IHNC). In other situations (e.g. collapsed Citrus Back Levee Floodwall) the performance was unsatisfactory.

- Levee transition sections and gate structures were problematic, often because of the differences in elevation between adjacent sections, which resulted in concentrated or preferential overtopping. In many instances, damage also occurred at these locations because of the contrast in erosion resistance between adjoining sections (e.g. flood wall-earthen levee transitions).

7.5 References

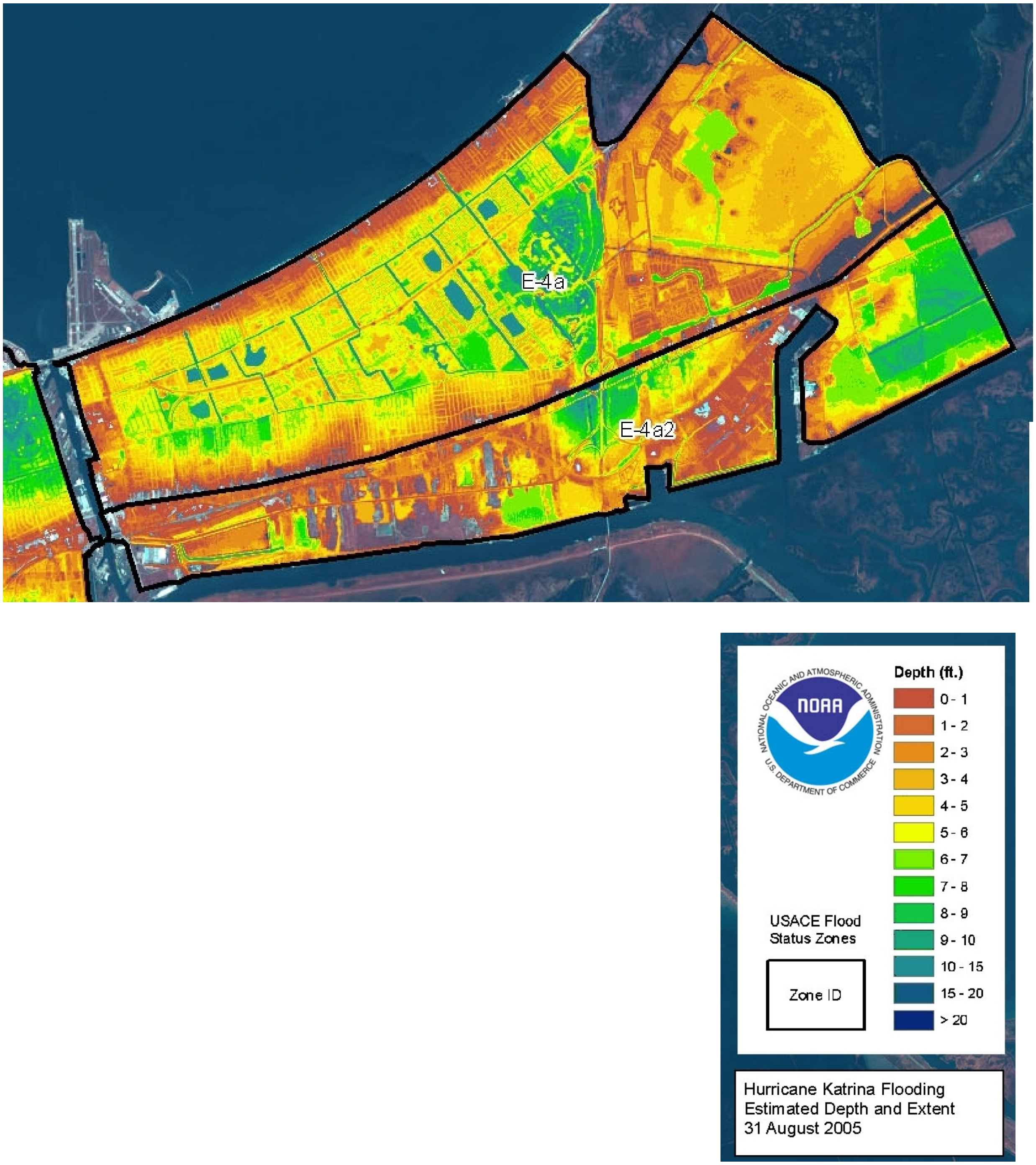
Interagency Performance Evaluation Task Force, (2006), "Performance Evaluation, Status and Interim Results, Report 2 of a Series, Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System," March 10, 2006.

Source: IPET (2006)

Figure 7.1: Map of NOE levee system.

Source: IPET (2006)

Figure 7.2: Damage locations in the NOE protected area (base map from USACE, color indicates severity of damage, with red being the worst).



Source: NOAA

Figure 7.3: Depth of flooding in NOE protected area on August 31, 2005.

Source: USACE

Figure 7.4: The most severe damage to the NOE Levee System occurred along this section of the New Orleans East Back levee, which is situated in the southeast corner of the protected area.

Photographs by J. Wartman

Figure 7.5: Deflected and tilted sheet pile sections near Pump Station 15.

Source: USACE

Figure 7.6: Overturned sheet pile transition section near the Air Products Corporation site.

Photographs by J. Wartman

Figure 7.7: Scour at the base of floodwalls near the Michoud Canal

Photographs by J. Wartman

Figure 7.8: Deflection of the Citrus Back Levee Floodwall ranged from severe (upper image) to moderate (lower image). Note the mound of soil at the base of the wall in the upper photograph, and the gap in the front of the all in the lower image.

Photographs by J. Wartman

Figure 7.9: Isolated scour holes developed along the Citrus Back Levee.

Photograph by J. Wartman

Figure 7.10: Minor scour along the base of the IHNC floodwall. Note the boat pushed against the flood side of the wall.

Photography by J. Wartman

Figure 7.11: Erosion of ballast at a railroad gate structure along the IHNC.

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Photograph by J. Wartman

Figure 7.12: Scour near the base of a floodwall near the Lakefront Airport.

Photograph by J. Wartman

Figure 7.13: Localized erosion and scour at the transition between a floodwall and earthen levee section. The vehicle in the photograph was parked at the top of the levee in the hope of avoiding high water damage.

CHAPTER EIGHT: THE ORLEANS EAST BANK (DOWNTOWN) AND CANAL DISTRICT PROTECTED AREA

8.1 Overview

The most populous of the four major protected areas that suffered significant flooding during Hurricane Katrina was the Orleans East Bank (downtown) protected area. As shown in Figures 2.4, 8.1 and 8.2, the Orleans East Bank (downtown) section is one contiguously protected section. This protected unit contains the downtown district, the French Quarter, the Garden District, and the "Canal" District. The northern edge of this protected area is fronted by Lake Pontchartrain on the north, and the Mississippi River passes along its southern edge. The Inner Harbor Navigation Canal (also locally known as "the Industrial Canal") passes along the east flank of this protected section, separating the Orleans East Bank protected section from New Orleans East (to the northeast) and from the Lower Ninth Ward and St. Bernard Parish (directly to the east.) Three large drainage canals extend into the Orleans East Bank protected section from Lake Pontchartrain to the north, for the purpose of conveying water pumped north into the lake by large pump stations within the city. These canals, from west to east, are the 17th Street Canal, the Orleans Canal, and the London Avenue Canal.

Figure 8.2 shows how this single, contiguously protected unit can be sub-divided into several localized sub-basins separated by a series of ridges, levees and canals. The base map of Figure 8.2 is the flooding map of Figure 2.17 (repeated here) which shows the flooding on September 2, four days after the passage of Katrina. The elevation of the top of the floodwaters in this figure is Elev. + 3 feet (NAVD 88). This is approximately the peak flooding, and the depths of flooding shown at this point in time serve well to illustrate how the overall protected zone can be approximately subdivided into four separate zones based on topography and basins.

The original city of New Orleans had been founded on the high ground adjacent to the Mississippi River (along the southern edge of this protected area.) The river "climbs" within its own channel, periodically depositing overbank sediment deposits which form "natural levees" to constrain its path, until it rises above the surrounding countryside. Then, periodically, the river breaks through its own "natural levees" and takes a new path to the Gulf. The riverbank deposits thus represent the highest ground locally, and it was here that the city began.

As shown in Figure 8.2, this high ground adjacent to the river now comprises much of the expensive Garden District, and much of downtown New Orleans and the historic French Quarter as well. Due to their elevation (typically Elev. +2 feet above Mean Sea Level and higher) these areas remained largely unflooded. Most of the remainder of this large and densely populated protected zone lies at lower elevations, however, and most of the rest was flooded.

As also shown in Figure 8.2, a ridge of high ground known as Metairie Ridge separates the low-lying northern (Canal District) portion of this protected area from the southern half. Metairie Ridge is the result of a previous river "stand", and resulting river deposits. The Metairie Ridge did not quite successfully separate the northern and southern halves of this protected section during Katrina; flow passed over the ridge at a number of locations carrying floodwaters from the catastrophic northern drainage canal breaches into much of the rest of the protected area to the south. This flow over (across) the Metairie Ridge was noted by eyewitnesses (Van Heerden, 2006), and is also confirmed by calculations of flows through the various breaches.

As described previously in Chapter 2, the initial breaches in this protected area occurred along the eastern flank (on the west bank of the IHNC). Several breaches occurred along this frontage. These breaches allowed significant amounts of water to flow into the adjacent neighborhoods, but these breaches were non-catastrophic; these breaches did not scour to a depth below mean sea level, so that as the storm surge subsequently subsided the flow inwards through these breaches was eventually halted as the IHNC water levels fell below the (mean sea level plus) "lips" of these breaches. Our current estimates, based on simplistic calculations of flow and surge heights vs. time, suggest that approximately 10% to 20% of the eventual flow into the overall Orleans East Bank (Downtown) protected area came through these breaches. Similar calculations, in a bit more detail, by Team Louisiana suggest that approximately 12 to 15% of the overall floodwaters eventually filling the Orleans East Bank protected area came through the breaches on this east bank of the IHNC (Mashriqui, 2006.)

The majority of the flow into the Orleans East Bank came through the three subsequent, catastrophic breaches in the drainage canals at the northern edge of the Orleans East Bank protected area. As shown in Figures 8.1 and 8.2, one catastrophic breach occurred on the 17th Street drainage canal and two catastrophic breaches occurred on the London Avenue drainage canal. These all eroded (scoured) to depths well below mean sea level, and they continued to admit flow into the city from Lake Pontchartrain well after the initial storm surge had subsided. The drainage canal between these two (the Orleans Canal) did not suffer any breaches, but the southern end of this canal was unfinished and a "gap" in the floodwall at the southern end of this canal allowed water to flow freely into New Orleans for a number of hours during the peak of the storm surge.

It was, however, mainly the flow through the three catastrophic breaches in the 17th Street and London Avenue drainage canals that accounted for approximately 85% of the flooding that slowly filled this Orleans East Bank protected area during and after the storm. Flow from the canals overfilled the northern basin and eventually also flowed over the Metairie Ridge and into the other zones shown as flooded in Figures 8.1 and 8.2. This flooding continued to progress after the initial storm surge had subsided, and flooding in the southern portions of this protected zone continued to worsen overnight and into the two days that followed, finally equilibrating with the slightly inflated water levels in Lake Pontchartrain on Thursday (September 1.)

As discussed in Chapter 2, this flooding had catastrophic consequences, accounting for approximately half of the total loss of life in this event, and a similar share of the economic damages as well. The performance of the flood protection system in this Orleans East Bank (downtown) basin is thus of great importance, and was studied in some detail by this investigation.

8.2 Performance of the Flood Protection System Along the West Bank of the Inner Harbor Navigation Channel (IHNC)

8.2.1 An Early Breach at About 4:45 a.m.

As described previously in Chapter 2, the first levee breach and failure in the metropolitan New Orleans area appears to have occurred along one of the banks of the IHNC.

Figure 8.3 shows water elevations at three gage stations as well as at a manual water elevation station in the IHNC as the hurricane storm surge initially began to raise the water levels throughout the IHNC region on the morning of August 29th. As the storm began to approach the coast, water levels within the IHNC began to rise. By about 4:30 a.m. the water level within the IHNC had risen to approximately +9 to +9.5 feet (MSL). Then, at approximately 4:45 a.m., two of the gauges near the Highway I-10 bridge registered a sudden change in the otherwise relatively constant rate of rise in water levels. The U.S. Geological Survey (USGS) gage at this location shows a precipitous drop in water levels at approximately 4:45 a.m. The Orleans Levee District gage is “sampled” less frequently, and also shows a reduction in rate of local water level rise between about 4:45 and about 5:00 a.m.

These gage readings appear to indicate that a levee breach occurred at about 4:45 a.m. near the I-10 Bridge across the IHNC channel, resulting in a local and temporary drawdown of the otherwise rising water levels in the IHNC.

A number of levee breaches occurred during Hurricane Katrina along the north-south channel of the IHNC, so there is no shortage of candidate sites for this breach.

Many of the partial breaches and distressed levee sections of New Orleans East fronting the IHNC (on the east bank of the IHNC) were relatively minor features, with minor flow potential, and could not have accounted for the significant changes observed in the gage readings shown in Figure 8.3. In addition, a number of these features showed evidence of erosion and scour specifically due to overtopping, indicating that significantly greater water elevations than +9 feet (MSL) eventually occurred at their locations.

Similarly, the timing(s) of the occurrences of the two large breaches on the east side of the IHNC at the edge of the Ninth Ward are well-established by eye witnesses as well as by “stopped clock” data, and these two major breaches appear to have occurred considerably later at about 7:45 a.m.

A significant breach occurred on the west side, behind the main Port of New Orleans, due to overtopping and erosion of soil support for an I-wall. The elevation of the I-wall, and the observed overtopping erosion, indicate that this failure occurred later in the morning as well when the storm surge had risen high enough to pass water over this floodwall.

That leaves only three candidate breach sites that might have caused the drop in water level rise shown at about 5:00 a.m. in Figure 8.3.

One of these is the breach on the east side of the IHNC at the CSX railroad crossing and roadway crossing over the levee, as described in Chapter 7.

A second candidate site is the pair of breaches that occurred closely adjacent to each other at the south end of the main Port of New Orleans, as described in Section 8.2.3. These were large breaches, and might well have had sufficient flow as to account for the drop in water level rise shown in Figure 8.3. In addition, these sections were constructed of highly erodeable lightweight shell-sand fill, and might well have eroded early due to through-passage of seepage flows through the “earthen” levee embankment as the storm surge rose (but prior to full overtopping of the levee embankment at this location.) This is discussed a bit further in Section 8.2.3.

A third candidate breach site is the west bank of the IHNC at the CSX railroad crossing, as described in Section 8.2.2. At this location, a steel “storm gate” on rollers had been damaged by a train accident several months prior to Hurricane Katrina, and was away for repair. In lieu of this missing gate, a sandbag levee crest section had been constructed in the opening left by the missing floodgate. The sandbags washed out at some point during Katrina, and this may have been the early breach reflected by the gage readings shown in Figure 8.3. At this same site, flow along the juncture between the railroad embankment and the adjacent embankment fill supporting an asphalt paved roadway passing over the earthen Federal levee resulted in erosion and scour that produced a second breach feature at essentially this same site, as is also described in Section 8.2.2.

In the end, based on the information currently available to this investigation team, any of these three candidate breach sites might have been responsible for the for the observed gage level drops shown in Figure 8.3.

8.2.2 The CSX Railroad Breach

As shown in Figure 8.2, the CSX railroad crosses the IHNC channel immediately to the south of the I-10 Highway bridge. On both the east and west banks of the IHNC, the railroad passes through the levee system by means of a gate through a structural concrete floodwall. Steel gates are used to close these openings during storms.

Figure 8.4 shows the concrete structural floodwall on the west side of the IHNC, at the east edge of the Orleans East Bank (Downtown) protected area. Note that there is no steel gate shown in this photograph. The steel gate at this location had been damaged by a train accident several months prior to Katrina’s arrival, and it was away for repair at the time of the hurricane.

In lieu of this missing steel gate, a temporary sandbag “levee” was erected across the opening. At some point during the storm this sandbag “levee” section either was pushed over by the rising storm surge or was overtopped and washed away.

In addition, erosion occurred at the juncture between the railroad embankment fill and the fill supporting an adjacent roadway passing over the earthen federal levee at this location, as shown in Figure 8.5. This roadway passed over the levee crest to provide access to port facilities on the outboard (water) side of the Federal levee system. This is shown in Figure 8.5, which is a view from the inboard side of this breach showing the erosion of the roadway fill. The elevated I-10 highway bridge is at the left of this photo, and the CSX railroad is just to the left (north) of the roadway. The roadway fill at this location was comprised largely of highly erodeable lightweight “shell sand” fill; a material not suitable for levee fill (especially without sheetpile cutoff or similar features to prevent erosion.) The flow appears to have passed initially through the pervious gravel ballast supporting the train rails (which is the “low point” at this complicated location), and then undermined the less competent fill beneath the roadway. The resulting flow through the eroded breach then passed to the inboard (protected) side and made its way into the adjacent neighborhood.

The erosion and scour at this conjoined pair of breach locations did not erode the base (lips) of these breach features to a level below mean sea level. Accordingly, although flow passed through this pair of features for a number of hours, the flow eventually ceased as the storm surge (water level rise in the IHNC) eventually subsided.

The failure at this site is an excellent example of a failure produced by multiple adjoining jurisdictions, and a lack of overall coordination of the various system elements constructed and operated by each. The Federal levee system was “penetrated” here by both the railway and the Port roadway, and the interactions of the pervious railway ballast and the highly erodeable roadway fill combined to fail the overall flood protection system at this location. Lack of coordination, and lack of authoritative oversight, of these disparate organizations and their disparate system components was a critical problem here.

8.2.3 Breaches and Distressed Sections at the Port of New Orleans

Three breaches occurred to the south of the CSX railroad breach on the west side of the IHNC at the main Port of New Orleans. Several additional levee and floodwall sections were “distressed” or damaged, but did not fully breach along this same section. These breach and distress sites along this reach are indicated as the suite of “Industrial Canal Overwash Sites” in Figure 8.2.

As the storm surge raised the water levels in Lake Borgne, and then pushed the elevated waters (and flow) westward through the “funnel” at the east end of the east/west trending GIWW/MRGO channel between new Orleans East and St. Bernard Parish, large flows and a major rise in water elevations pushed westward along the GIWW/MRGO channel to this channel’s “T” intersection with the IHNC channel, and raised the water levels within the IHNC channel.

This resulted in rising waters rushing directly at the west bank of the IHNC, coupled with overall raising of the water levels throughout the IHNC region, and this produced distress, and several breaches, on the west side of the IHNC in the general vicinity of the main Port of New Orleans. The sub-sections that follow will describe each of these in turn.

8.2.3.1 Breach at Rail Yard Behind the Port of New Orleans

The northern-most of these features was a breach in a combined earthen levee and concrete I-wall section, as shown in Figures 8.6 and 8.7. This breach occurred behind the main Port of New Orleans, just to the south of the juncture between the east-west trending GIWW/MRGO channel and the IHNC, so the water pressures and overtopping from the lateral flow from the east-west trending GIWW/MRGO channel were particularly severe at this location.

At the time of our field team's arrival in September, this site was already under repair. The field team arrived at this site on the morning of September 30, 2005, and at that time the trench that had been scoured behind the wall on the north end of the breach had been "filled" with clayey backfill and additional backfill had been placed behind the wall to form an additional buttressing berm, as shown in Figure 8.6. A temporary access road through the breach had also been placed, as is also shown in this photo.

Figure 8.7 shows conditions on the south side of this breach, at the same point in time on September 30. The interim repair efforts had not yet reached the south side of the breach, and the mechanisms that contributed to this failure were still clearly evident here. As shown in Figure 8.7, significant overtopping had passed over the concrete I-wall and then cascaded down the backside, resulting in erosion of a "trench" at the base of the backside of the I-wall.

The initial height of the compacted embankment fill on the backside of the I-wall prior this erosion can be clearly seen in Figure 8.7 by the dark soil markings on the I-wall at the left of the photograph. The depth of this erosion (scour) from the elevation of the top of the pre-event I-wall/soil crest contact to the base of the eroded trench was 4.5 feet at the location of the photographer taking the photo of Figure 8.7, and it deepened progressively towards the actual breach location approximately 25 feet to the North. Just before reaching the actual displaced I-wall section shown in Figure 8.7 this depth of erosion was approximately 5.5 feet, so that the depth of erosion at the location of the actual I-wall failure was likely on the order of 5.5 to 6.5 feet.

The depth of the sheetpiles was unusually shallow at this location, as shown in Figure 8.8. The I-wall "stick-up" had not been large at this location, and it was not felt that very long sheetpiles were needed to support this I-wall by means of cantilever action given its relatively short unsupported length (stick-up). There was no sign of lateral embankment movement at this site, and the sheetpiles and I-wall showed no signs of flexure on their vertical axis (along their length from top to bottom.) The I-wall failed by "toppling" laterally to the inboard (protected) side in a "rigid, post-hole" toppling mode as it became progressively unbraced by the erosion of the supporting soil at the inboard toe and thus became unable to support the water pressures on the outboard (canal) side due to the storm surge and hydrodynamic forces.

As shown in the cross-section of Figure 8.8, the sheetpiles at this section were only 14 feet in length, and were tipped at a base elevation of approximately -6 feet (MSL). As the overtopping cascaded over the top of the concrete I-wall, the resulting trench eroded to a depth of approximately 6 feet below the original wall/soil crest contact, and the critical section achieved approximately the geometry shown in Figure 8.8. Soil properties are not well established at this location, as site specific investigation was not possible within the budget and time constraints of this independent investigation. Accordingly, soil stratigraphy and soil properties used in our analyses are inferred from the original design data available from the USACE.

Based on the field observation that no embankment foundation failure or embankment displacement had occurred, the most significant properties for analysis of this section were the sheetpile sections (which were PZ-22) and the properties of the engineered embankment fill (which was a moderately compacted silty clay of medium plasticity.) Shear strength of the embankment fill was modified to determine the strength (and stiffness) at which the observed failure would be expected to occur, and it was found that the I-wall section would be marginally unstable with a fill strength of approximately 500 to 1000 lb/ft^2. This appeared to be well-representative of the strength of the observed fill, and the failure mode (shown in Figure 8.9) matched well with the field observations. Figure 8.9 shows the results of Finite Element Analyses (FEA) performed using the program PLAXIS; in this case for embankment shear strength of approximately 800 lb/ft^2, and with a trench to a depth of 6 feet behind the floodwall. This Figure shows calculated displacements, and the rigid toppling mode of wall failure can be clearly seen.

It appears that this failure could have been prevented, simply and at little incremental cost, by installation of concrete "splash pads" or other erosion protection at the base of the inboard side of the I-wall to prevent the observed erosion. Similarly, this failure would have been prevented if the floodwall had been a "T-wall" section, as illustrated in Figure 8.10(b), rather than the less expensive "I-wall" section, as illustrated in Figure 8.10(a). The I-wall sections are supported laterally only by the cantilever action of their supporting sheetpile walls. T-walls, on the other hand, have lateral concrete stems at their bases and these are supported both laterally and rotationally by battered piles (providing a much higher level of rotational resistance.)

Instead a significant breach occurred, and floodwaters passed through the adjacent railroad yard and into the adjacent neighborhoods for a number of hours. This breach was located well inboard from the actual edge of the IHNC channel, however, and the breach did not erode its front lip to a depth below mean sea level, so this flow eventually ceased as the storm surge subsequently subsided.

8.2.3.2 Erosional Distress at Floodgate Structure Behind the Port of New Orleans

Just a few hundred yards to the south of the breach described in the previous section, significant erosional distress occurred at a concrete I-wall and floodgate structure behind the Port of New Orleans. As shown in Figure 8.11, this concrete wall and steel gate structure provided access from the rail yard (on the protected side) to Port facilities (on the water side) which can be closed off by means of a rolling steel floodgate.

Significant erosional distress occurred at each end of this floodgate structure as it "transitioned" to join the earthen levee and floodwall at each end. An example, at the north end of this structure, is shown in Figure 8.12. In this figure, the canal is on the left and the "protected" side is on the right. The trench-like feature at the outboard side toe of the floodwall is the "gap" left when the wall displaced to the right as overtopping eroded a trench on the right side of this wall, unbracing the very short sheetpiles and wall. New fill has been placed on the right side (as an interim repair), so this erosion is no longer visible. The concrete wall of the gate structure has not displaced, as it is supported on a T-wall basis, and the rotational stiffness of the battered piles has been sufficient to prevent wall rotation.

The erosion at the juncture between the concrete gate structure and the adjacent concrete I-wall was locally exacerbated by the disparity in top elevations between these two walls; which acted to locally concentrate the overtopping flow. Erosional distress of this sort, at the "transitions" between differing elements of the flood protection system, was a recurring theme in Hurricane Katrina.

8.2.3.3 Two Adjacent Erosional Embankment Breaches at the North End of the Port of New Orleans

Additional erosional "distress" and two large erosional breaches occurred slightly farther to the south, at the southern end of the main Port of New Orleans.

Figures 8.13 and 8.14 show two views of a large breach through an earthen levee at the contact ("transition") between the levee and a concrete floodwall section. As shown in Figure 8.14, the embankment fill material is lightweight shell-sand, a material known to be unusually highly erodeable. This type of shell-sand material performed notably poorly at a number of locations during Hurricane Katrina, and is a material not suitable for construction of critical levees protecting large populations. At this location, no provisions (e.g. a sheetpile cut-off, etc.) had been made to prevent catastrophic erosion of this shell-sand fill due to either overtopping or through-erosion (erosion due to through-flow prior to full overtopping.) In the absence of an eyewitness, it was not possible to discern from evidence at this site whether the embankment was actually overtopped, or whether flow through this highly erodeable fill caused progressive erosional failure prior to full overtopping.

Figure 8.15 shows a second large erosional breach, less than 50 yards from the breach shown in Figures 8.13 and 8.14. This embankment section was also comprised largely of highly erodeable shell-sand fill. A large scour hole can be seen to the right, immediately inboard of this large breach. The massive flows have rippled the asphalt tarmac, and detritus from the shell sand fill is scattered over a large area.

Although these two adjacent erosional breaches were both of good size, both were located some distance inboard from the IHNC, and neither eroded a pathway all the way back to the IHNC that was continuously below sea level. As a result, although both breaches admitted significant volumes of water into the adjacent neighborhoods, flows through these two breaches eventually ceased as the storm surge subsequently subsided.

8.2.4 Summary and Findings

The breaches along the west bank of the IHNC were each "non catastrophic" as none of them eroded or scoured to such depth that their lip dropped below mean sea level. Accordingly, although they admitted significant volumes of floodwaters into the greater

Orleans East Bank (downtown) protected area, these flows eventually ceased as the storm surge subsided. Together, these features appear to have contributed approximately 10% to 20% of the overall volume of floodwaters that eventually flowed into the Orleans East Bank (downtown) protected area.

Although they were each “non-catastrophic”, these features each had the potential to cause significant localized flooding and damage. They were also each the result of engineering lapses and/or lapses in oversight during design and construction, and none of the failures in this area should have been allowed to occur at the storm surge and wind/wave loadings produced at these locations by Hurricane Katrina.

The removal of the steel floodgate at the CSX Railroad crossing, and the inadequate sandbagging of the resulting “gap” in the overall regional flood protection system should not have been permitted. The steel gate should have been immediately replaced with a suitable and serviceable temporary replacement until the original gate could be repaired and returned. In view of the events during Katrina, it is difficult to justify the decision to remove the gate and thus maintain the “operability” of the railroad line when it placed the “operability” of the flood protection system, and the safety of the community, at risk.

Similarly, the confluence of the CSX railroad embankment and the adjacent roadway both passing over/through the Federal levee system immediately to the south of the I-10 bridge represents one of many “transitions” between disparate flood protection system elements that performed poorly as an apparent result of lack of appropriate oversight and/or poor design with regard to how abutting elements of the system joined at their edges. In addition, highly erodeable shell sand fill was used at this roadway location without suitable cut-off by means of sheetpiles, etc., representing a hazardous condition that should have been caught and remedied prior to Katrina’s arrival.

The erosional “distress” that occurred at the junctures of structural I-wall sections and the structural T-wall gate structure at the rail yard behind the Port of New Orleans represent additional examples of inadequate attention to details at “transitions” between adjacent sections of differing type and geometry.

The two large erosional breaches at the south end of the Port of New Orleans were clearly the result of use of inappropriate fill materials (highly erodeable lightweight shell-sand fill) in earthen embankment sections with no suitable provisions to reduce the obvious risk of catastrophic erosion and breaching. This, too, should have been spotted and remedied prior to Katrina’s arrival. It is not clear whether these two breach sections were overtopped by the rising storm surge, or whether the embankment sections eroded as a result of “through flow” prior to full overtopping as the waters rose within the IHNC.

Finally, the I-wall section breach behind the Port of New Orleans was the result of overtopping and subsequent erosion at the base of the inboard toe of the concrete I-wall. This failure could have been prevented, at relatively little incremental cost, by installation of concrete splash pads or other erosion protection at the inboard toe of this floodwall.

8.3 The Canal District Failures

8.3.1 Introduction

As the eye of the hurricane began to pass to the northeast of New Orleans, the counterclockwise swirl of the storm winds caused a surge in water levels along the southern end of Lake Pontchartrain. The storm surge along the Pontchartrain lakefront (which peaked at about 9:00 to 9:30 a.m. at an elevation of about +10 feet, MSL) did not produce water levels sufficiently high as to overtop the crests of the concrete floodwalls atop the earthen levees lining the three drainage canals that extend from just north of downtown to Lake Pontchartrain; the 17th Street Canal, the Orleans Canal, and the London Avenue Canal. Three major breaches occurred along these canals, however, and these produced catastrophic flooding of large areas within the Orleans East Bank protected area (as shown in Figure 8.2.)

The first major breach along the drainage canals occurred near the south end of the London Avenue canal, between about 7:00 to 8:00 a.m. The second breach occurred near the north end of the London Avenue canal, and the best current estimates of the timing of this breach are between about 7:30 to 8:30 a.m. The third major breach occurred near the north end of the 17th Street canal. The main breach here occurred between about 9:00 to 9:15 a.m., but this may have been preceded by earlier visually observable distress at this same location. All three of these breaches rapidly scoured to depths well below mean sea level, so they continued to transmit water into the main Orleans East Bank (downtown) protected area for three days after the initial peak storm surge subsided. More detailed discussions and analyses of these catastrophic drainage canal breaches are presented in the sections that follow.

The resulting flooding of the main Orleans East Bank (Downtown) protected area was catastrophic, and resulted in approximately half of the 1,293 deaths attributed (to date) to the flooding of New Orleans by this event. Contributions to this flooding came from the overtopping and breaches along the IHNC channel at the east side of this protected area, as described previously in Section 8.2, but the majority of the flooding (approximately 80% to 90% of it) came from the three catastrophic failures along the drainage canals at the northern portion of this protected area.

In addition, one of the drainage canals (the Orleans Canal) had not yet been fully "sealed" at its southern end, so that floodwaters flowed freely into New Orleans during the storm surge through this unfinished drainage canal. A section of levee and floodwall approximately 200 feet in length had been omitted at the southern end of this drainage canal, so that despite the expense of constructing nearly 5 miles of levees and floodwalls lining the rest of this canal, as the floodwaters rose along the southern edge of lake Pontchartrain, the floodwaters did not rise fully within the Orleans canal; instead they simply flowed freely into downtown New Orleans.

By about 9:30 a.m. all of the levee failures had occurred, and the main Orleans East Bank (downtown) protected area was slowly filling with water. As the northern end filled from the three catastrophic breaches along the drainage canals, water eventually began to pass over low spots in the Metairie Ridge and flowed into the southern zones within this protected area as well.

The sections that follow present more detailed examinations of the performance of the flood protection system in the "Canal District".

8.3.2 The Lining of the Drainage Canals

There were a number of lapses, errors and poor decisions that led to the catastrophic breaches along the drainage canals and thus the flooding of the main section of metropolitan New Orleans. Several of these began right at the start, in the aftermath of Hurricane Betsy and the flooding caused in New Orleans by that event.

The decision was made, in the wake of Hurricane Betsy, to raise the level of flood protection throughout the region. The three drainage canals (the 17th Street, Orleans and London Avenue canals) were problematic in this regard, however, due to limited right-of-way adjacent to the existing embankments lining these canals.

As described in Chapter 3, the USACE argued that the low-rise levees lining the canals were not adequately stable as to sustain a significant raising, and that the preferred solution would be to place storm gates at the north ends of the three canals which could be closed in the event of a Hurricane to prevent storm surge rise within the canals.

This proposal was bitterly contested by the local Water and Sewerage Board, who were concerned that the gates would be under the control of the local Levee Board, and that they might therefore be impeded in their efforts to operate the massive pumps to "unwater" the city from heavy rainfall (which is a source of frequent, minor flooding problems.)

The USACE was, in the end, not allowed to install the floodgates, which would have been the technically superior solution, largely as a result of the internecine distrust between the local Levee Board and the local Water and Sewerage Board. In response, the USACE attempted to "exempt" the three canals from the otherwise contiguous levee system around the main metropolitan Orleans East Bank (downtown) protected area.

As discussed in Chapter 3, lobbying by State and local interests next resulted in a Senate rider (inserted clause) on a bill that un-exempted the three canals and specifically required the USACE to raise the level of flood protection along these three canals. This was the first of a number of causative errors that would prove catastrophic here. The canals would remain open to hurricane-induced storm surges at the south end of Lake Pontchartrain; essentially "allowing the enemy (storm surges) right into the backyard" of metropolitan New Orleans.

A second problem now arose. The existing levees were low, and they were relatively narrow as well. Homes had been constructed throughout the area, and the private property at the inboard (protected side) toes of these existing levees left inadequate space for construction of wider levees. Accordingly, a decision was made to raise the level of flood protection by adding reinforced concrete floodwalls to the crests of the existing earthen embankments.

This, in effect, represented a decision to work within the narrow space available rather than purchasing additional property to allow construction of wider, and more stable, levee sections. That was a second issue that contributed significantly to the catastrophic failures that occurred along the drainage canals.

It also resulted in difficulties with regard to both maintenance and inspection, as private homes at the toes of the levees often had property lines interfering with inspection of conditions at the inboard (protected side) toes. In some locations, private property (mainly people's back yards) extended up the inboard slope faces of the levee embankments, and trees grown on these faces and at the inboard toes of the levees represented an obvious hazard both with regard to seepage erosion and also with regard to the possibility that trees would blow over (in water softened ground) during hurricanes, leaving large voids (the sizes of their root balls) at a very dangerous location (right at the inboard toes of the levees) at a time when storm surges in the canals were simultaneously rendering seepage erosion, and inboard slope stability, very tenuous. During Hurricane Katrina a number of large trees did indeed topple, leaving dangerous voids at the toes and on the inboard slope faces of the levees along these canals.

In addition, along some sections private homeowners excavated and constructed in-ground swimming pools in close proximity to the inboard toes of these levees, effectively partially undermining them and rendering them less stable. This, too, should have been prevented.

The abutting private properties also led to inspection difficulties, as inspection of conditions immediately inboard of the levee toes is of great importance and private property rights largely prevented inspectors from walking these critical areas. Reports of seepage and wetness at some locations were made to the local Water and Sewerage Board (who were responsible for "unwatering", and were thus the group to whom such reports were made), but this investigation team has not been able to determine whether these were then passed along to the local Levee Board or to the USACE, to whom they might have represented unanticipated seepage problems warranting further investigation. Certainly the USACE has stated that they were unaware of such reports.

Lack of appropriate control of conditions at the inboard levees toes, and lack of suitable access for inspection and maintenance at the inboard toes, represented additional inadvisable sources of increased hazard.

8.3.3 The E-99 Sheetpile Wall Test Section:

In order to effect the raising of the flood protection levels within the narrow right-of-way available, the decision was made to erect concrete floodwalls at the crests of the existing earthen levee embankments. To facilitate the analysis and design of these challenging sections (on narrowly confined rights-of-way, and on very difficult foundation soil conditions) the New Orleans District of the USACE made an admirable decision to construct a test section and perform a full-scale test of this type of design.

Very similar (difficult, swampy, riverine delta) soil conditions exist nearby in the Atchafalaya river basin (approximately 80 miles to the west), and a site in this area was selected. A sheetpile "I-wall" and contiguous sheetpile curtain, was constructed on the inboard side stability berm of a federal levee in the Atchafalaya basin in a configuration that was very similar to the eventual installation of similar sheetpile-supported floodwalls at the crests of the low-rise levees along the drainage canals in New Orleans (Foott and Ladd, 1977). The swampy foundations soils at this test site were remarkably similar to those at the north end of the 17th Street canal in New Orleans. A sheetpile cofferdam was constructed adjacent to the full-scale test section, and was filled with water to load the test section's I-wall and its supporting sheetpile curtain.

Two important lessons were learned from this test, and from subsequent analyses (Jackson, 1988; Foott and Ladd, 1977; Oner, Dawkins and Mosher, 1997; Oner, Dawkins, Mosher and Hallal, 1997). One was that a gap opened between the sheetpile curtain and the outboard side earthen embankment, and then water penetrated into this gap. This effectively cut the supporting embankment in half, and the water pressures applied against the lower sheetpile sections helped to push the inboard half of the embankment, as well as the I-wall and its supporting sheetpile curtain, towards the inboard (protected) side. This was a failure mechanism that had not traditionally been considered in the local design of floodwall systems in the New Orleans District. The other lesson was the shape of the failure surface, which was more curved than the deeply plunging three-wedge "planar" failure surfaces considered in the "method of planes" used for analysis of these types of sections in the New Orleans District of the USACE.

Unfortunately, despite publication of these important findings in both internal USACE reports as well as in electronic professional journals (e.g.: Oner, Dawkins and Mosher, 1997; Oner, Dawkins, Mosher and Hallal, 1997), and despite the fact that these studies had been undertaken to facilitate the design of the challenging floodwalls along the drainage canals and the IHNC, neither of these lessons were then incorporated in the subsequent design of the floodwalls along the 17th Street, Orleans and London Avenue drainage canals, nor along the IHNC.

8.3.4 Field Tests for Assessment of Underseepage Risk at the Canals

The USACE also commissioned a pair of local permeability tests at two sections along the drainage canals to assess the rate at which changes in water levels within the canals were transmitted through the soils beneath the embankments. The intent here was to assess whether or not it would be necessary to drive the sheetpile curtains deep enough to "cut off" such underseepage flows for the transient loading conditions represented by a storm surge that would raise and then lower the canal water levels within a matter of hours.

The two sections selected were instrumented with piezometers at a series of stations orthogonal to the canals so that the water levels (phreatic surface) could be observed. The canal sections were then excavated to increase the cross-section available for pumping flows. It was assumed that this excavation and deepening would remove the sediment that "sealed" the canals, and would result in an increase in the observed phreatic surface. If little rapid rise was observed, then that would indicate that the increased hydraulic pressures of a transient storm surge would not propagate rapidly under the levees.

There were two critical flaws to this reasoning. One was the assumption that two such tests could suitably characterize the highly variable soil conditions along many miles of the three drainage canals (and also the IHNC). The other was that this testing program failed to note the alternate possibility that the canals were not well "sealed" at all; in which case simply excavating the canals to greater depth would result in no net change in the observed phreatic surface in the piezometers installed inboard at the test sections (the canal water levels would be unchanged by the excavation of the canal bases, and if "steady state" seepage conditions were already established based on full connectivity between the canals and the inboard toe areas then no net change in phreatic surfaces would be observed.)

When the canals were excavated, no significant change in inboard water levels was noted, and it was concluded that underseepage would not pose a significant risk for a short-lived (transient) storm surge. That would be a very serious error, and would result in sheetpiles throughout the system (the three drainage canals and the IHNC as well) routinely being far too short to adequately cut off underseepage. Several major failures along the drainage canals and the IHNC would result from underseepage during Hurricane Katrina, and the short sheetpiles continue to pose a risk to the remaining sections today.

8.3.5 Water Levels Within the Canals During Hurricane Katrina

Figure 8.16 shows the calculated peak storm surge heights along the southern shore of Lake Pontchartrain based on the most recently available IPET analyses (IPET Report No. 2: April, 2006). These are in close agreement with similar analyses by Team Louisiana along the canal frontage (Kemp and Mashriqui, 2006). As shown in this figure, the storm surge was estimated to be a bit higher at the west end of the "Canal District" than at the east. The water elevations shown in Figure 8.16 are based on the NGVD 29 datum, and must be reduced by about 1 foot to be compatible with the approximate local Mean Sea Level datum used in this report. With this adjustment, the projected peak water levels at the northern ends of the drainage canals are on the order of +10 to +11 feet (MSL) based on these hydrodynamic analyses.

Figure 8.17 shown locations at which relatively reliable high water marks near the mouth of the 17th Street Canal [IPET Report No. 2, 2006]. These high water locations were selected so as to be affected as little as possible by wave action, so that the water levels recorded would be the mean surge height (without wave action.) Based on these data, the IPET study concluded that the maximum storm surge rise at the mouth of the 17th Street Canal was on the order of +11 feet (NAVD 88;2004.66 datum, which is approximately MSL).

Figure 8.18 shows a hydrograph of estimated water elevations vs. time within the 17th Street Canal, based on the hydrodynamic calculations performed by IPET and on observations of water levels at nearby sites [IPET Report No. 2; April, 2006]. This hydrograph peaks at an assumed height of approximately +11 feet, and it peaks fairly sharply between about 9:00 to 10:00 a.m.

Based on the watermark data, our own field observations, and observations and data provided by Team Louisiana (Kemp, Mashriqui and Van Heerden, 2006), our team feel that these are realistic estimates of the surge heights near the mouths of the three key drainage canals (the 17th Street, Orleans, and London Avenue canals), but that they likely slightly overestimate the water levels. Our team has assumed a peak surge height of approximately +10 to +10.5 feet (MSL) at the mouth of the 17th Street Canal, and slightly lesser heights of on the order of +9.5 to +10 feet (MSL) at the mouths of the Orleans and London Avenue canals.

Accordingly, the hydrograph of Figure 8.17, but with a slight reduction of peak surge height (to approximately +10 to +10.5 feet, MSL in the 17th Street Canal, and +9.5 to +10 feet, MSL in the Orleans and London Avenue Canals) will be used for these current studies.

8.3.6 The Orleans Canal

As described previously in Chapter 3, the U.S. Army Corps of Engineers had lobbied and fought for many years to install floodgates to close off the three drainage canals (the 17th Street, Orleans, and London Avenue canals) during hurricanes so that storm surges would not push their way up into these canals. That would have been a superior technical solution, but it was not allowed as there was internecine fighting between the local Levee Board (who are in charge of "protection"; including levees, walls and floodgates) and the local Water and Sewerage Board (who are in charge of "unwatering" by means of pumping for both rainfall and other flooding.) The Water and Sewerage Board were concerned that the floodgates would not be under their control, and so their ability to pump out rainwater from rainstorms (also a cause of flooding in New Orleans) might be obstructed.

As a result of the two disparate local Boards being unable to resolve their differences in the interest of the greater Public good (and safety), the sides of all three drainage canals were instead lined with floodwalls topping the earthen levees along both sides. This, in effect, opened many additional miles of narrow levees and floodwalls atop difficult (and often marshy) foundation soil conditions to storm surges; greatly increasing vulnerability by "allowing the enemy right into the backyard" of this protected area.

An extreme example of the dangers resulting from the poor interaction between the local Water and Sewerage Board and the local Levee Board occurred at the south end of the Orleans Canal.

At the south end of this canal, the main pumping plant crosses the end of the canal as a "T". Levees and floodwalls provide storm surge protection to an elevation of approximately +13 feet (MSL) along essentially the full length of both sides of the canal, except at the southern end.

The pumping plant is a brick masonry building that was constructed in 1903, and it houses several of the large capacity Woods pumps of that same era. When the water level within the canal rises three to four feet above normal, the operators report that water seeps through the wall of the building that fronts the canal. It is clear that raising the water level significantly higher against the brick face of this old structure would induce water pressures that would collapse this wall.

The obvious solution would have been either (1) for the Levee Board to construct a floodwall across the south end of the canal, joining to the levees and floodwalls lining the east and west banks of the canal, to seal the end of the canal and simultaneously protect the ancient structure, or (2) for the Water and Sewerage Board to construct a stronger wall, to achieve the same two purposes.

Neither happened.

The Levee Board did not construct the wall to protect the property of the Water and Sewerage Board (and the safety of the Public by closing the base of the canal), and the Water and Sewerage Board did not assist the Levee Board by closing off the end of the canal (and protecting their own building at the same time.) Instead, an opening of approximately 200 feet in length was left "open" on the east side at the south end of the otherwise continuous levee and floodwall system lining the rest of this canal. A concrete "spillway" section occupies this gap, to prevent erosion from further exacerbating the flows emanating from this hole in an otherwise continuous flood protection system.

Figure 8.19 is a view of the south end of the Orleans canal, showing the brick masonry pumping house, the levees and floodwalls on both sides of the canal, and the "gap" at the south end of the east bank (on the left side of this photo.) Figure 8.20 shows this "gap" from the outboard side, with elevations of key features indicated. Figure 8.21 shows an oblique view from rotation of three-dimensional LIDAR survey measurements (see Appendix A) of this same section. All dimensions, and elevations, are captured by this LIDAR dataset to an accuracy of approximately ±0.1 feet (or less). The "spillway" section across the open gap has a crest elevation of approximately + 6.8 feet (MSL), with a marginally lower "low spot" slightly to the north of the concrete "spillway" section at Elev. + 6.5 feet (MSL). The "gap" thus represents a long opening in the otherwise contiguous levees and floodwalls along many miles of both sides of this canal, and with a top elevation of approximately 6 feet below the top of the adjacent floodwalls topping the levees (permitting overflow at approximately Elev. + 6.5 to + 6.8 feet, MSL.)

As a result, while the storm surge along the southern shore of Lake Pontchartrain was raising the water levels within the full lengths of the adjacent 17th Street and London Avenue drainage canals, the rising storm surge (after reaching an elevation of approximately + 6.8 feet, MSL) simply caused floodwaters to flow freely into the heart of New Orleans through this "gap" in the flood protection system.

The opening left at the south end of the Orleans canal resulted in lower water levels toward the south of the canal, but did little to alleviate the storm surge rise at the north end. The lack of failures along the north end of the canal must therefore have been the result of more favorable embankment and floodwall geometries and/or foundation soil properties than occurred along failed sections of the nearby London Avenue and 17th Street drainage canals.

On both sides of this canal there was considerably more right of way available, and the earthen levee embankments along the Orleans canal are considerably wider than those along the 17th Street or London Avenue canals. Figure 8.22 shows a view of these levee and floodwall sections along the east side of the Orleans canal. The embankment widths shown in this photo are in strong contrast to the narrower embankments (and crowding from adjacent homes and yards) along the London Avenue and 17th Street canals, as shown in Figures 8.109 and 8.30.

An additional factor working in favor of the stability of the Orleans Canal levees and floodwalls was the fact that the relationship between effective soil overburden stress and resulting soil shear strength in the soft clayey and organic marsh soils near the north end of the Orleans Canal embankments and floodwalls had been better treated during initial analysis and design than it was for 17th Street Canal embankments and floodwalls for similar soils.

8.3.7 The 17th Street Canal

8.3.7.1 The Breach on the East Bank

(a) Introduction

One of the most catastrophic failures during Hurricane Katrina was a breach near the north end of the 17th Street Canal, on the east side, just to the south of the Hammond Highway bridge. The location of this breach is shown in Figures 8.1 and 8.2.

Figure 8.24 (which is a repeat of Figure 2.14) shows the use of military helicopters to place oversized bags of gravel into this breach. This photo shows a number of important features at this breach site. In this photo, it can be clearly seen that the inboard side of the levee embankment (on the "protected" side of the floodwall) has translated laterally to the east (to the right in this photo, which is taken looking north.) The translated embankment section is relatively intact along the northern two-thirds of this breach, and appears to have swung much like a door about the northern end. Severe scour and damage to structures on the inboard ("protected") side at the south end of this feature support this mode; the major rush of inflow was concentrated near the southern end of this breach.

A number of borings and Cone Penetration Test (CPT) probes were performed at this site by the IPET investigation, by Team Louisiana, and by the ILIT investigation team. In addition, several borings had been performed earlier, as part of the initial design studies for the raising of the floodwalls at this location. Figure 8.25 is an approximate plan view of this site, showing the locations of these borings and CPT. This plan view also shows the locations of a number of important features that help to shed light on the causes and mechanism of this failure.

Figure 8.26 shows two views of a cross-section through the heart of this breach along Section A-A′ from Figure 8.25. Figure 8.26(a) shows this cross-section before the failure, and Figure 8.26(b) shows this same section after the failure. Nearby cultural features (including buildings, fences, and floodwall sections) as well as boring logs and CPT probes are projected to this cross section for graphical clarity.

As shown in Figures 8.25 and 8.26, the intact levee segment near the center of the breach moved laterally approximately 49 feet. To the inboard side ("protected" side) of the displaced levee embankment sections, three sets of exiting toe overthrust features were mapped, as also shown in these figures.

As shown in Figure 8.26(b), the breach was the result of a translational failure of the inboard section of the embankment, pushed laterally by the pressures exerted by the storm surge on the outboard face of the floodwall and sheetpile curtain. Figure 8.27 illustrates the sequence of movements associated with this failure, again for the cross-section through Section A- A′. As discussed in the text sections that follow, the rising waters in the canal pushed laterally against the floodwall and eventually opened a gap between the floodwall and the outboard section of the levee embankment, as illustrated in Figure 8.27(b). Water then entered this gap, and increased the lateral push against the sheetpile curtain and floodwall. A shear failure then occurred in the foundation soils beneath the embankment, and the embankment section along with the sheetpile curtain/floodwall slid inboard, pushed by the storm surge as illustrated in Figures 8.27(c) and (d).

Figure 8.28 is an oblique aerial view of this breach section, showing tops of the I-wall sections that "pushed" the inboard section of the earthen embankment (driven by water pressures on their outboard sides), and then toppled backwards towards the canal as the translating levee embankment section finally came to rest and as water pressures equilibrated when the neighborhood filled with water and the storm surge eventually subsided. It also shows two sections of floodwall at the northern end of the failure (the near end in this photo) toppled forward (toward the "protected" side) by the inrushing floodwaters at the north end of this breach.

Figure 8.29 shows the tops of the I-wall sections at the very southern end of the breach, which were also left "toppled forward" (towards the inboard, or "protected" side) by the inrushing floodwaters passing through the breach opening.

Figure 8.30 shows a collapsed metal shed, with a corrugated roof, that was pushed against the side of the home at 6914 Belaire Drive by "plowing" at the toe of the laterally translating earthen embankment section, as is also shown in Figures 8.26 and 8.27.

Figure 8.31 shows a foundation slab at the toe of the failed section, immediately to the south of the home at 6914 Belaire Drive. The final exiting toe thrust feature rises just at the near end of this slab, which was partially laterally displaced despite being supported by piles, as shown previously in Figures 8.26 and 8.27. Scour caused by the floodwaters also left an erosional depression beneath and behind this slab, resulting in the "pond" shown in the background of Figure 8.31. Also clearly visible in this photo are blocks of peat that were scoured from the foundation strata by the inrushing floodwaters.

Figure 8.32 shows a piece of one of the exiting toe thrusts (Toe Thrust #1, from Figure 8.27) at a location between the slab of Figure 8.31 and the home and collapsed shed of Figure 8.30.

The general failure mode involved water pushing on the canal side of the floodwall, resulting in the opening of a gap between the sheetpile curtain/floodwall and the outboard side of the earthen embankment. Water then flowed into this gap, and the resulting water pressures pushed the inboard half of the earthen embankment (and the sheetpile curtain/floodwall) sideways. This "cutting the embankment in half, opening a gap, filling it with water, and then pushing the inboard half of the embankment (along with the sheetpile curtain/floodwall)" mode of failure had not been considered or analyzed during the original design of the floodwalls along the drainage canals. It was, however, not an unexpected mode of failure as it had been clearly evinced in the E-99 full-scale test section experiment near Atchafalaya in 1978 (as described previously in Section 8.3.3.

In the second IPET interim report (IPET; April 1,2006) this mode was selected as the likely mode of failure based on stability analyses and centrifuge model testing performed as part of the IPET studies. Our own investigation team had favored this failure mode from the time of the initial post-event field observations in September and October of 2005. It was apparent that this mode had been in operation at this site based on the field observations made at that time. In addition, the same mode had also been in operation, and was "frozen" in place as a partially developed or incipient failure, on the east bank near the north end of the London Avenue drainage canal (see Section 8.3.8), and the field evidence also clearly indicated that this same "half embankment with a water-filled crack pushing laterally" had been the mode of failure at the large breach on the west bank near the north end of the London Avenue Canal (see Section 8.3.8). Also, we had read the E-99 full-scale test section reports, and were aware of the likelihood of this mechanism.

The deeper question is: What was the underlying mechanism that produced the observed failure in the foundation soils beneath the embankment?

Here the findings of our investigation differ significantly from those of the second IPET interim report. The IPET report's finding was that the failure was the result of a largely rotational failure, shearing mainly through the soft gray clays occurring beneath the organic, marshy layers that support the base of the embankment. Our own studies found that there were two mechanisms that were each capable of producing the failure and breach, and that the margins of safety associated with each of these did not differ by large amounts. The actual failure that occurred followed the weakest and least stable of these two mechanisms, and was a largely translational failure along a relative thin but laterally continuous stratum of weak and highly sensitive clay embedded within the "marsh" layer shown in the cross-sections of Figures 8.27(a) and (b).

An examination of the various soil units, the various potential failure modes, and analyses and explanation of the findings as to the nature of the actual failure mechanism, follow.

(b) Geotechnical Analyses of the Failure

As shown previously in Figures 4.16 and 4.17, the north end of the 17th Street Canal is situated atop largely paludal marsh clays and organic marsh deposits, in an area long riven with erosional drainage features associated with the Lake Pontchartrain basin.

Figures 8.33(a) and (b) present two additional cross-sections showing conditions prior to the failure along Sections B-B and C-C in Figure 8.25. As shown, the foundation soil conditions differed somewhat, but were largely similar along the width of the breach (failure) section.

As shown in Figures 8.26, 8.27 and 8.33, the levee embankment was comprised of two distinct soil fill zones. The upper embankment was a moderately compacted imported brown clay fill, placed in the early 1970's. This fill had raised the pre-existing levee, which was comprised largely of locally available gray clay fill from the local swamp deposits. Placement of the original layer of gray clay fill dated back to the previous century, and these earlier "historic" fills had consisted of simply piling up locally available gray paludal marsh clays without compaction.

These two embankment fill zones were underlain by a layer of "marsh" deposits. This was actually a relatively complex and layered zone, consisting of strata of peaty organics interbedded with soft, sensitive organic clayey silts and plastic clays with very high water contents, and of varying organic and fibrous organic contents. Cypress tree root systems were common in this mixed "marsh" layer, apparently representing two distinct "stands" or levels of cypress marsh as shown in Figure 8.27, and these root systems often interfered with drilling and sampling.

The "marsh" layer was underlain by a transitional layer of progressively less organic soils, with fewer fibrous and peaty inclusions and an increasing fraction of soft, plastic gray clays. Beneath this transitional "intermixing" zone, the foundation consisted of soft, weak gray paludal marsh clays (CH) of high natural water content (natural water contents of $w_o \approx$ 87 to 94 %.) These marsh clays were both weak and "sensitive". Sensitivities (the ratio of peak undrained shear strength vs. residual undrained shear strength) were typically on the order of 2 to 5.

These soft gray clays were underlain by fine sands. These sands are adequately strong and competent relative to the softer (and weaker) overlying soil units that they were not involved in the failure. Similarly, although these sands were relatively pervious, this was not a significant issue at this site as they occurred at sufficient depth that they were effectively "capped" by the relatively thick low permeability layer of soft gray clays.

The plan view of Figure 8.25 shows the locations of borings and CPT probes performed for the original design studies, as part of the IPET investigation, and as part of our own studies. The pre-design and IPET borings generally used 5-inch diameter thin-walled fixed-piston samplers to obtain samples. Most shear strength data reported from both efforts that are currently available to our investigation team are the result of unconsolidated-undrained triaxial tests (UUTX) performed on these samples, although some samples were tested in unconfined compression (q_{unc}). A limited number of in-situ vane shear test results (VST) were also reported for some sites.

Our own field investigations involved primarily the use of 3-inch diameter thin-walled, fixed-piston Shelby tube samples, and laboratory UUTX tests were performed on many of these samples. The Shelby tubes were "modified" prior to use to eliminate the "roll-in" that produces overcutting and then allows lateral expansion of the sample during sample entry into the tubes. It has been shown (e.g. Lunne and Lacasse, 1994) that the use of this type of constant tube diameter, sharp-edged, thin-walled fixed piston sampling with good technique can greatly reduce the disturbance otherwise associated with sampling of the soft, clayey soils of principal concern at this site.

Some of the borings were sampled continuously and the samples were extruded onsite to examine the stratigraphy and geology in detail. Some of the borings were not sampled at all; instead in-situ vane shear tests were performed at selected depths within these boreholes. Some of the samples were retrieved and brought to the laboratory for testing. Finally, some of the samples were subjected to rather unusual laboratory vane shear testing, and this will be discussed in detail a bit later in this section.

The boring logs for all borings performed as part of these current studies are presented in Appendix B. Laboratory test data, including laboratory vane shear strength test data, are presented in Appendix D. In-situ vane shear strength test data for tests performed within the borings is summarized on the boring logs in Appendix B.

In addition to the borings, in-situ and laboratory vane shear and laboratory testing, both the IPET investigation and our own team performed a number of piezocone Cone Penetration Test (CPTU) probes. Logs of the CPTU probes performed as part of our studies are presented in Appendix C.

Figure 8.34 shows a summary of the shear strength test data currently available for the embankment fill at and near the 17th Street drainage canal breach site. Shear strength of the embankment fill is not of significant direct importance for the conventional overall stability analyses that will follow, as the embankment fill "went for the ride" and was carried along on shear surfaces that sheared through lower, weaker foundation soil units. The strength data from Figure 8.34 was of some importance, however, in selection of properties to model the nonlinear stiffness of these embankment soils in finite element modeling of this levee and floodwall section. The heavy line shown in Figure 8.34 is the shear strength modeled through the embankment fill along the embankment centerline (directly beneath the levee crest) in these studies. The strength lines representing CPT data in Figure 8.34 are based on interpretation of the CPT data using a cone tip factor of $N_k = 12$ in the upper, brown clay fill and $N_k = 12$ in the lower, gray clay fill.

Figure 8.35 shows a summary of available CPTU data beneath the central portion of the levee embankment, for "Marsh", "Intermixing Zone" and "Gray Clay" strata shown in the cross-sections of Figures 8.27 and 8.33. Figure 8.36 shows a similar summary of CPTU data, but this time for locations outboard of the toe of the levee embankment. As expected, shear strengths are notably lower here, due to lesser effective vertical stresses resulting from lesser overburden loads.

As shown in Figures 8.35 through 8.38, there are distinct differences between the "gray clay" strata and the "marsh" strata, and these will therefore be treated separately.

Beginning with the deeper unit, the gray clays, it must be observed that our interpretation differs somewhat from that presented in the second IPET interim report. The IPET report assumed that these clays were normally consolidated as they had been protected from dessication by the overlying swamp deposits. Our interpretation differs, as we found three separate "stands" in the evolution of this layer of soft gray clays and the overlying marsh deposits, with three corollary dessication-induced overconsolidation profiles associated with these.

The shear strength data based on UUTX tests from the initial design studies, as well as the IPET studies, showed considerable scatter and this was considered likely to reflect the issues associated with sampling disturbance for these soft, sensitive soils. The CPTU data from both the IPET and our own (ILIT) studies, on the other hand, appeared far more consistent within this stratum (as shown in Figures 8.35 and 8.36.) Figure 8.37 shows a typical plot of the pore pressure parameter B_q from a CPTU performed through the crest of the levee ($B_q = \Delta u/(q_t - \sigma_{vo})$), highlighting the value of B_q where the clay appears to be normally consolidated. Figure 8.37 then shows these values of transposed onto the relationships of Lunne et al. (1985) and Karlsrud et al. (1996) to determine appropriate values of the cone tip factor N_{kt} for conversion of CPT tip resistance to undrained shear strength. As shown in this Figure, the value determined for this stratum was approximately $N_{kt} = 12$.

Figure 8.39 then shows the values of $[Su/P]_{OC}/[Su/P]_{NC}$ vs. OCR determined for minerologically similar Mississippi clays of similar depositional history in Atchafalaya as determined by Foott & Ladd (1977). The SHANSEP exponent for these similar clays was found to be $\lambda = 0.75$, a relatively normal value for clays of this plasticity and character.

Using a value of $N_{kt} = 12$, and $\lambda = 0.75$, the CPTU data within the soft gray clay foundation stratum was then processed to develop plots of Su/P vs. depth, and OCR vs. depth, for CPT beneath the full height of the levee (Figure 8.40) and inboard of the levee toe where effective overburden stresses were significantly lower (Figure 8.41).

As shown in Figures 8.40 and 8.41, the results show a pleasingly consistent pattern. The clay inboard of the levee toe clearly evinces three "stands" of the marsh development, with three OCR profiles associated with surficial dessication. The clays beneath the levee embankment loads show just the residual tips of these same three OCR "crusts", as the clays have been further loaded by the placement of the overlying embankment fill and so are more nearly normally consolidated over most of the stratum. Near the base of this stratum, the clays inboard of the levee toe show a minor degree of overconsolidation associated with secondary compression (as verified by subsequent consolidation analyses using the program PLAXIS which successfully modeled the evolution of this site and accurately reproduced this basal OCR profile).

In establishing the plots shown in Figures 8.40 and 8.41, the value of $(S_u/\sigma_v')_{NC} = 0.31$ was found to best fit the data. This is a fairly normal value for clays of this plasticity, and it was exactly the same value found by Foott & Ladd (1977) for the minerologically similar clays at Atchafalaya.

The green lines in Figure 8.42 shows the resulting profiles of S_u vs depth within the soft gray clay foundation stratum (a) beneath the crest of the levee, and (b) inboard of the levee toe, based on $S_u/P = 0.31$ and $\lambda = 0.75$. Also plotted on this figure are the CPTU tip resistance data converted to Su based on $N_{kt} = 12$, and the results of UUTX tests on "undisturbed" ILIT samples, lab vane tests (LVT) on ILIT samples and in situ field vane shear strength tests (FVT). The overall "fit" to all the data is generally very good.

Figure 8.43 then repeats Figure 8.42, but adds the rest of the available IPET and pre-Katrina strength data (including UUTX, FVST and CPT data.) For the "toe" region some adjustment of this data is necessary in viewing this figure, as some of the IPET data is located such that some portion of the embankment overburden stresses slightly increase the shear strengths for some of the "toe" data; as a result these data tend to drift to the right a bit (including the CPT), especially at depth. Overall, these additional also well support the relationships developed.

Figure 8.44 then shows the selected value of $(S_u/P)_{NC} = 0.31$ for UUTX, field vane and lab vane tests plotted vs. data for other clays (Ladd, 2003). It also shows the value of $(S_u/P)_{NC}$ for direct simple shear (DSS) tests on the minerologically similar Atchafalaya clays by Foott and Ladd (1973). Both sets of data fit well with the overall background relationship implied for other clays. This suggests that an appropriate scaling factor for the S_u values for conversion from "triaxial" conditions to the DSS stress path conditions that will better represent the stability and deformation analyses for this embankment and floodwall system is approximately 0.80 to 0.84, as shown in Figure 8.45. A value of $S_{u,dss} = 0.82 \times S_{u,tx}$ was used for this soft gray clay in these studies.

Figure 8.46 shows similar treatment of the derivation of the CPT cone factor N_{kt} based on B_q, this time for the "marsh" deposits overlying the soft gray foundation clays. Based on a B_q value of $B_q = 0.25$ to 0.40, a value of $N_{kt} = 16$ was determined and used to process the CPT data for this unit.

A second approach was used to also develop profiles of S_u/P vs depth and OCR vs. depth for these marsh deposits, as shown in Figure 8.47. The relationship of Mayne and Mitchell (1978) was used, in conjunction with the available UUTX, LVST and FVST data to iteratively develop relationships for Su/p vs. depth and OCR vs. depth, as a function of Plasticity Index (PI, %) over the range PI ≈ 55% to 140%, which encompasses the range observed in this complex soil unit. The resulting relationships confirm the classic dessicated OCR crust profile shown previously in Figure 8.41 for this "marsh" deposit.

Figure 8.48 then shows the resulting interpretation, based on all available data, of strength vs. depth within this complex marsh unit for conditions (a) beneath the overburden of the central embankment, and (b) inboard of the toe of the levee. The green lines in this figure represent the final interpreted soil shear strength profiles at these two indicative locations.

The red zone near the center of the "marsh" deposits shown in Figure 8.48 is a thin layer of soft, highly sensitive organic silty clay that varies slightly in depth across the profile (and so is thinner than it appears in this figure.) This was the material in which the main lateral translational shear failure occurred at this site.

Figure 8.50 shows a sample of this thin layer at one of three boreholes within the slide region (near to the large, relatively intact displaced levee block) that captured a sheared sample of this layer. The material is completely remolded and sheared to a fully residual condition with negligible remaining strength, and uni-directional extension and tearing of organic fibers across the sheared zone clearly indicate the shear failure within this sample.

This layer is typically only one to several inches in thickness, but was found to be laterally continuous across essentially the full site (as well as at the distressed section on the opposite, west side of the canal.) It is exceedingly difficult to spot, and to sample, because it is closely overlain (and even partially mixed with) a layer of leaves and twigs and bark that is typically also one to several inches in thickness, as illustrated on the auger stem in Figure 8.49. The very dark, shiny material also coating the auger stem in this photo is the sensitive organic silty clay and indicates that we have just drilled through the layer in question (and so now have to move our hole laterally a few feet and re-drill to attempt to sample it.)

This layer of sensitive organic silty clay is the result of a previous major storm that churned up organics and sediments, mixed them with the locally prevalent clays, and also greatly (temporarily) increased the salinity of the water so that the ensuing deposit is unusually heavily flocculated. The result is a material of low strength and extremely high sensitivity (sensitivities of between about 10 and 20+.)

The same storm was accompanied by winds that knocked down leaves and twigs and bark (and other organic detritus), accounting for the closely overlying layer of organic impediments that "mask" this thin layer.

Figure 8.51 shows a plan view of the site, highlighting with red the 10 locations at which this layer was positively identified. It was not always possible to positively identify this thin layer in CPT, as the strength of this layer is not much less than that of the closely overlying and underlying soils; it is the combination of low strength and high sensitivity that made this thin layer so dangerous. "Thin layer" effects also made spotting this layer in CPT (based on tip resistance) difficult. The best initial "marker" or signature of the presence of this layer was found to be a positive spike in friction ratio; as the sleeve continued to drag through the overlying and underlying deposits but the tip resistance dipped a bit.

Also, we were not able to conclusively spot this thin layer in the borings of Figure 8.51 that were not performed by our own team.

Figure 8.52 shows a photo of an "undisturbed" sample of this sensitive organic silty clay. The local clays have a gray, peanut butter-like appearance and consistency. They are not highly shiny, but rather semi-glossy, and their stiffness and texture are not unlike peanut butter. The sensitive organic clay, on the other hand, is dark and has a very shiny and translucent appearance; much like "jelly", as shown in Figure 8.52. In Figure 8.52, hints of the organic detritus that closely overlies and masks access to this thin layer can also be seen.

Two approaches were taken to attempt to characterize the strength (and stress-deformation) behavior of this material. At any location, the precise depth of this layer was first determined by drilling to encounter it. One approach was then to move the drill rig laterally several feet and to re-drill to within one foot of this layer. A 3-foot long Shelby tube, 3-inches in diameter (and modified to eliminate the turn-in that produces overcutting at the mouth) was then used, with a fixed piston system, to drive the tube approximately two feet past the target layer so that more competent underlying soils would "plug" the bottom of the tube and permit careful withdrawal of a sample. Otherwise, the samples remoulded upon attempted withdrawal and slopped out of the base of the tube making sample recovery nearly impossible.

The samples thus obtained were then taken to the lab at U.C. Berkeley, where they were subjected to an unusual process, as illustrated in Figure 8.53. The tubes were cut off in 2-inch increments, and a small spoon was used to carefully dig ahead into the remaining tube. When the tell-tale organic detritus was encountered digging stopped and the organic material was hand-plucked form the tube to daylight the underlying sensitive layer. A lab vane shear test was then performed.

The second method used to evaluate the strength of this material also began by pre-locating the precise depth of this layer, usually by sacrificial "oversampling" it (to plug the base of the tube (to foment retrieval) and then extruding the sample to determine the precise location of the layer. A second, adjacent hole was then carefully hand augered, and an in situ vane shear test was performed using a shallow-bladed vane. Insertion disturbance, and obstruction by unremoved organic detritus (mixed in the top of the layer) sometimes defeated this effort, making multiple attempts necessary. Unacceptable insertion disturbance was apparent when the characteristically brittle peak to residual transition was absent and the material exhibited only residual strength.

Figure 8.54 shows typical stress-displacement plots for tests on the thin layer of highly sensitive organic silty clay, and on the local deposits of sensitive gray clay. As shown in Figure 8.54(b), which shows normalized behavior in the form of shear strength divided by maximum shear strength on the vertical axis, the sensitive organic clay was more highly brittle, failed at lower displacement, and exhibited even more pronounced sensitivity and rapid post-peak strength degredation. It was the combination of low strength, and this very brittle sensitivity, that caused this material to "capture" the failure surface at this site.

Finite element analyses were performed for this levee and floodwall section using the program PLAXIS. Figure 8.55 shows the principal parameters and the mesh used for these analyses. The gray foundation clays (CH) and the "marsh layer" were modeled using the "soft soil" effective stress model within PLAXIS, and the soil parameters used were fitted to the values of S_u/p vs. OCR as described previously to match the evaluated strengths of these units and their distribution.

It was necessary to establish the stress state at the end of incremental construction and consolidation of the embankment and foundation. Initial overconsolidation profiles due to dessication and secondary compression were input, and embankment construction was modeled in two stages (the "historic" fill, and the more recent engineered top fill), and both the OCR vs. depth and the settlement pattern (the bowl shaped pattern at the base of the oldest fill) were well matched to the observed field conditions. Figure 8.56 shows the settlements calculated at the end of initial construction and consolidation.

The front lip of the embankment was then "excavated" and the floodwall installed (as with the actual field case), and displacements were re-zeroed to prepare for the remaining analyses to follow.

Water levels within the canal were incrementally raised, and within a range of stiffnesses considered reasonable it was found that initiation of "gapping" between the outboard toe of the floodwall and the outboard embankment section typically initiated at a surge elevation of between about 7.5 to 8 feet, as illustrated in Figure 8.57. This Figure shows normalized shear strain contours, with the red color indicating shear strains equal to or greater than the shear strain to "peak" shear strength (and thus localized failure.) As shown in this figure, with a water elevation of +8 feet (MSL) gapping has opened partially down the front face of the sheetpile curtain, and the thin, sensitive organic silty clay layer has already sheared to failure along a short segment inboard of the crest of the levee.

If one looks very carefully at Figure 8.57, a second "lighter" area can be seen beneath this shear zone, representing the beginning of shear deformations along a more "rotational" shear surface passing through the deeper soft gray foundation clays (CH). A dashed line has been added to indicate this surface. This deeper, and more rotational failure surface has a calculated factor of Safety only slightly higher than that calculated for the upper sensitive organic silty clay layer, and this deeper surface represents the mechanism favored by the IPET studies reported to date.

As the analysis calculated tensile effective stresses between the front of the sheetpiles and the soil, the mesh was revised to model the development of a "gap" between these, and the intrusion of water into the gap as well. Once this "gapping" began, it then developed rapidly. Figure 8.58 shows the situation with an additional foot of storm surge rise to Elev. + 9 feet (MSL) based on our best estimate of the soil parameters. As shown in this figure, the gap has now extended nearly to the base of the sheetpiles. Further extension of the gap is temporarily held up by the malleability of the marsh soils, but further gapping does not provide significant additional lateral water pressures against the front of the sheetpile curtain because the lateral permeability of the "marsh" deposits is relatively high. At this stage, the shear failure along the thin layer of sensitive organic silty clay is well developed, and embankment movements are now signficant. This figure also shows quite clearly the deeper, more rotational failure surface that represents the second least stable mechanism at this site.

Figure 8.59 shows calculated displacements for a surge height of 8.5 feet, with displacements exaggerated times two for clarity. Initially, the floodwall tilts slightly forward as it compresses the soils a bit. As sliding then develops, the floodwall base begins to move along with the displacing embankment and the whole moving mass (inboard embankment section, floodwall and sheetpile curtain) displace laterally together, as shown previously in Figure 8.___.

Figure 8.60 shows the Factors of Safety calculated (by c-Ø) reduction using PLAXIS for a variety of water levels in the canal. Three cases are presented: (1) failure dominated by the thin layer of sensitive organic silty clay, but without gapping between the sheetpile curtain and the outboard side soils, (2) a more rotational failure through the deeper soft gray foundation clays, again without gapping, and (3) failure dominated largely by the upper sensitive organic silty clay layer, but this time with a water-filled gap on the outboard side of the sheetpile curtain.

As shown in this figure, the Factors of Safety for the upper lateral shear failure, and the deeper more rotational failure, are not very different. The heavy red line shows the best-estimated path to failure at this site. Based on these analyses, it appears that gapping would have developed at a surge height of between about 7.5 to 9 feet (MSL), and the intrusion of water into this gap would have increased the lateral forces and rapidly driven the section to instability.

Figure 8.62 shows the cross-section and principal soil properties used to perform more classical limit equilibrium analyses (using Spencer's Method, cross-checked against Morgenstern's and Janbu's Methods) using the program SLOPE/W.

Figure 8.63 shows the most critical failure mode for the "no gapping" case with a surge height to Elevation + 6 feet (MSL). The PLAXIS analyses had shown very little likelihood of gapping at this water elevation, and this probably represents the best estimate of Factor of safety for this surge height. As shown, the calculated Factor of Safety is FS = 1.51 for this case, and as shown in Table 8.1, the associated probability of failure for this surge height is approximately $P_f = 0.05$. These calculated low probabilities of gapping and of failure are reassuring, as the water in the canal had previously reached an elevation of approximately + 6.5 feet (MSL), and no gapping or failure had occurred.

Figures 8.64 and 8.65 show the most critical failure surfaces for a surge to Elev. + 9.5 feet (MSL) for (a) a shallow translational failure dominated by sensitive organic silty clay layer, and (b) a deeper, more rotational failure through the soft gray foundation clays. In both analyses, a water-filled gap was modeled at the outboard side of the sheetpile curtain. This water elevation is approximately the maximum elevation achieved (maximum surge at this location is estimated by our team to be approximately Elev. + 9.5 to + 10 feet, MSL). The calculated Factors of safety are again similar for both modes, and the shallow lateral translation along the sensitive organic silty clay again provides the lower Factor of Safety.

Figure 8.66 shows calculated Factors of Safety for various water elevations (Spencer's Method) for the four cases of principal interest: (a, b) lateral translation along the sensitive organic silty clay layer, with and without a water-filled gap, and (c, d) deeper and more rotational failure, again with and without a water-filled gap. The solid red line again shows the best-estimated path to failure at this site, this time based on the suite of limit equilibrium analyses.

Table 8.1 presents a tabular summary of the estimated probabilities of failure for these conditions. The coefficient of variability in soil shear strengths was taken as 25% to 30% in analyses of the four individual failure modes. The probability of cracking is a judgmental estimate based on the preceding finite element analyses (and supported in part by the observed field behavior). It should be noted that the stiffnesses used in the PLAXIS analyses to estimate inception of cracking are a bit time dependent, so that a slower rising and falling storm surge would be a bit more deleterious here. The conjugate probability of failure at each surge height is then calculated based on the probabilities of failure (and non-failure) for each of the four individual modes analyzed, and the estimated probabilities of gap development at each water elevation.

As shown in Table 8.1, the probability of failure was found to be very low for surge heights of less than about Elev. + 7 feet (MSL), and they rise rather quickly as the surge elevation passes above about +8.5 feet (MSL). Failure at the estimated actual maximum surge elevation of approximately + 9.5 to + 10 feet (MSL) is calculated to have had a likelihood of approximately $Pf \approx 0.8$ to 0.95. Failure at the intended "design" surge height of Elev. + 12.5 feet (MSL) was essentially certain.

Finally, Figure 8.67 shows a comparison between the observed failure mode and the rotational mode determined by IPET in their second interim report (IPET, April, 2006). The rotational IPET failure is superimposed, as carefully as possible, onto our own team's more detailed cross-section. The two modes are not dissimilar, and both lead to low factors of Safety. More detailed examination of the IPET mode, however, shows it to be problematic with regard to agreement with key field evidence. The rotational IPET mode would have left the chain link at the edge of the crest road (on the displaced intact levee block) rotated backwards, but as shown clearly in Figure 8.26 this crest fence was essentially perfectly vertical at the end of the displacements. Also, the IPET rotational mode would have significantly back-rotated the floodwall; but the floodwall traveled the full lateral distance in contact with the displacing levee embankment section, and then toppled backwards as the water pressures began to equilibrate (as illustrated in the top of Figure 8.67, and in Figure 8.28. The IPET mode also fails to explain the large lateral extent of the mapped toe exit features, as shown in the Figure at the top of Figure 8.67.

Overall, it can be concluded that there are two potentially critical failure modes at this site, but that the lateral translational failure along the sensitive organic silty clay layer within the "marsh" deposits was the weaker of the two, and that this was the mode of failure at this site.

(c) Initial Section Design Studies

The obvious next question to address is then how the original design studies failed to note this. The answer is a bit complex as a number of poor judgements and errors contributed to the mis-perception of the "design" section as being adequately stable (and reliable.) The following are significant errors and poor judgements during initial design that contributed to this failure:

1. Figure 8.68 shows the longitudinal cross section along the segment of the east bank of the 17th Street Canal as developed for the original design studies. An early error in the design process was the use of borings that were too widely spaced to attempt to characterize challenging and complex foundation geology. The savings achieved by not performing more borings now appear miniscule relative to the cost of the catastrophe that has ensued.

2. The longitudinal section of Figure 8.68 was prepared by the USACE, and was based on a number of assumptions; including the assumption the "marsh" deposits were typically flat-bottomed. The history of previous drainage channel erosion across this area would lead to the expectation of likely non-level transitions even for swamp bottoms, and Figure 8.69 shows our own team's re-interpretation of the original (sparse) longitudinal data to develop an alternative longitudinal subsurface soil profile. This difference in interpretation might be considered the second problem at this site during original design.

3. The USACE then passed the design on to outsourced engineers, who developed the strength data and interpretations for analysis of stability of the intended levee and floodwall section. A major problem occurred here, as data from far to large a lateral distance was eventually transposed to the design analysis cross-section. In the vicinity of the actual failure, there are only 5 sample locations shown within the "marsh deposits" in the 4 borings shown intersecting this unit.

4. Two of the sample locations shown within the "marsh" deposit of Figure 8.69 were non-recovered samples, and at approximately the same depth in adjacent borings. <u>This is the location of the sensitive organic silty clay layer that actually caused this failure and breach.</u> Failure to note the importance of the non-recovery of testable samples, and in two adjacent widely spaced borings at essentially the same elevation, should have represented a red flag and an effort should have been made to further investigate this location.

5. Figure 8.70 shows the calculations for critical section nearest to the actual breach and failure. The limit equilibrium method used for these was the "Method of Planes", a three-wedge analysis with conservative side force assumptions. This method continues to be preferred by the New Orleans District of the USACE, but it is now a relatively archaic anachronism given the availability of more accurate methods and the availability of the simple computer programs necessary to run these. The method itself provides a slightly conservative answer so long as the most critical failure surface can be closely represented by the steeply plunging wedges at the front and back, and the horizontal surface in between. In the original design analyses, layers were assumed to be laterally horizontal, so this analysis was a good fit for the cross-sections analyzed. Unfortunately, the actual stratigraphy was not horizontally layered (see for example <u>any</u> of the cross-sections analyzed in these current studies), so this method was poorly suited to the finding of the failure mechanism that was actually most critical.

6. And the assumption of laterally horizontal layering was itself a major problem too. It was born of necessity, as no borings had been performed off the embankment alignment to permit development of full cross-sections. Again, the minimal savings on exploration and testing costs here pale relative to the costs of the catastrophe that ensued. Stratigraphy is a vitally important issue, especially given the low strengths of many of the foundation soils. Looking at the cross-sections at the 17th Street canal breach site as analyzed in this current study, for example, one

will note a subtle "bowl shaped" settlement pattern at the base of the embankment fill, and a corresponding bowl shape to the critical sensitive organic silty clay layer just beneath it. Without this "bowl shape", the original embankment would have been unstable during initial construction; it would have slid sideways on the sensitive layer if that layer had been horizontal. Instead the layer dipped in the center, so that the evolving embankment would have had to slide up a small slope (up a hill) to fail during construction. Minor changes in stratigraphy details can have a major impact on overall stability on these soft, weak soils. Use of "assumed" horizontal layers therefore missed a vitally important element of the problem.

7. Figure 8.71 shows the now well-circulated summary of strength data for stability analyses at this section. The data are based on UU triaxial tests and on vane shear tests. Scatter in the data is considerable, and is likely due in large part to sampling disturbance issues for these sensitive soils. Most samples were obtained from borings through the crests of the levees (the most accessible location) and so represent strength information for locations under full embankment overburden stresses. Shear strengths of soils are very strongly a function of effective overburden stress, so these samples would consistently underestimate the strengths under the levee toes, and in the "free field" out beyond the levee toes. This fundamental principle of soil mechanics was ignored, and the result was a massive increase in the unconservative error in the overall stability analyses. The green lines on Figure 8.71 represent our own team's assessment of the strength vs. depth at two locations (a) beneath the crest of the levee, and (b) inboard of the levee toe from these current studies. The contrast is very significant.

8. Figure 8.72 repeats Figure 8.71, but with our own strength interpretations omitted. The solid lines in this figure show the strength interpretation used in the actual design analyses. This line represents an unconservative assessment of the data points presented, in both sides of the figure, even without allowance for the additional effects of overburden stress reduction away from the levee centerline. This interpretation is especially unconservative at elevations of between + 10 feet to – 10 feet (Cairo datum), which corresponds approximately to Elev. -10 feet to -30 feet (MSL), and this is the region in which strengths are important in the "Method of Planes" analysis performed for this location in the original design studies. As shown in Figure 8.70, the resulting calculated Factor of Safety was found to be FS = 1.30….., barely enough to satisfy the design criteria which required a FS of at least 1.3 for the case of "transient" storm surge loading.

9. And the use of a design Factor of Safety of only 1.3 was also a major problem. As discussed in detail in Chapters 11 and 12, this was far too low a value for a system protecting a large urban population. This value has a history of development that is traced in Chapter 11 back to use for design of levees protecting agricultural lands in the first half of the last century, and failure to update this in the face of both time and level of potential consequences associated with flood protection of a major urban area was a major mistake that left little room for the other errors and poor judgements cited above.

8.3.7.2 Distressed Section on the West Bank

There is a "distressed" levee and floodwall section on the west bank of the 17th Street Canal, across from the large breach discussed above. This "distress" was visually minor, but this section was studied both as a check of the ramifications of "minor" visually observable distress, and also because it provided an opportunity to see if the same analysis methods that correctly predicted the failure on the east bank could also accurately predict the observed performance of a second section that it was hoped would be somewhat similar.

Figure 8.73 shows measurement of observed lateral wall offset at the point of maximum offset. Wall tilt is less than 0.75 inches, and the maximum lateral offset is approximately 3.5 inches.

As shown previously in Figure 8.25, only a few borings and CPT were performed at this distressed section on the west bank of the canal, so data is sparse. Figure 8.75 presents the interpreted cross-section used for analysis at this site. The same basic sequence of strata observed on the east bank are again present, but the details of the stratigraphy differ a bit.

Passing quickly through intermediate details (as were presented in detail in Section 8.3.6), the same procedures were used to process and interpret the limited available data, and this was supplemented by the knowledge gained from across the canal. Figures 8.76 and 8.77 show an example determination of the value of N_{kt} = 12 for the soft gray foundation clay (CH), and this matches with this same deposit on the east bank. Using the same methods, and the same SHANSEP exponent λ = 0.75, Figure 8.78 shows the iterative processing of the CPTU data to develop profiles of S_u/p vs depth, and OCR vs depth for this clay unit. These too match well with the east bank deposit data.

Figure 8.79 then presents our SHANSEP-based profiles of strength vs. depth (a) beneath the crest, and (b) at the toe, along with the available strength and CPT data. The fit with the available data is excellent.

Figure 8.80 shows the use of the correlation proposed by Mayne and Mitchell to develop profiles of Su/P vs depth and OCR vs. depth within the "marsh" deposits overlying the soft gray clays. This matches well with the CPTU-based interpreted OCR profile within this stratum, and with the data from the east bank as well.

Figure 8.81 presents the resulting overall profiles of strength vs. depth within the marsh deposits (a) beneath the crest, and (b) at the toe, along with all available data (including CPT tip resistances interpreted using N_{kt} = 16. The thin layer of sensitive organic silty clay was encountered in one boring, again at the approximate mid-point in the "marsh deposits, and again closely overlain by leaves and twigs. Strengths for this thin layer were based on Su/P values from the east bank deposit. This thin layer was not critical at this west bank site, as the sheetpiles penetrated well below this sensitive layer and so forced a deeper, more rotational failure through the soft gray clays to be the most critical mode.

Figures 8.82 and 8.83 show the most critical failure surfaces (without gapping) for a storm surge level of + 9 feet (MSL) for failure (a) to the top of the soft gray clay, and (b) within the lower marsh deposits. These both give low Factors of Safety, but the failure through the lower marsh strata is the more critical case.

Figures 8.84 and 8.85 show these same two potential failure modes, again for a storm surge elevation of + 9 feet (MSL), but this time with an assumed water-filled gap at the outboard face of the sheetpile curtain. Once again the lower marsh units present the more critical mechanism.

Figure 8.86 shows calculated Factors of Safety vs. canal water elevation for the failure through the lower marsh stratum, both with and without gapping. The heavy red line in this figure shows the best estimate of the likely critical failure path, based on these limit equilibrium analyses. It is judged that gapping is most likely to be initiated at surge elevations of approximately + 10 to +11 feet (MSL) as the Factor of Safety (without gapping) drops below about 1.25 to 1.35. Gapping was relatively unlikely during Katrina (max surge level ~ +10 feet, MSL), and indeed no gap could be seen.

Based on these analyses, Table 8.2 presents estimated probabilities of failure vs. canal water elevation. The probability of failure at the actual peak Katrina water elevation of approximately + 10 feet (MSL) was low, but it was not negligible. Moreover, it would have decreased rapidly with even minor additional increase in canal water level. The probability of failure becomes very high at the "design" water level of + 12 feet (MSL).

It should be noted that the marsh soils have likely been sheared (and thus softened) a bit, and that the overall strength of this section was therefore likely slightly degraded by the loading it received during Katrina. Accordingly, it may not perform quite as well in subsequent loading in the future.

This levee and floodwall section protects the large population of the still undamaged Jefferson Parish. If the canal floodgate currently being installed, and future control of pumping, cannot guarantee that canal water levels will never exceed about Elev. + 5 to 6 feet (MSL), then this section should be remediated.

8.3.8 The Breach Near the South End of the London Avenue Canal

A major breach occurred on the east bank, near the south end of the London Avenue Canal, as shown in Figures 8.1 and 8.2. Figure 8.87 shows an oblique aerial view of this breach under repair. The breach was approximately 80 feet in length, and it scoured to significant depth. Sands from the inrushing floodwaters blanketed the neighborhood inboard of the breach to considerable depth over a surprisingly wide area, as shown for example in Figure 8.88.

Figures 8.88 and 8.89 show the floodwall sections at the south and north ends of the breach, respectively. In these photos it can be seen that these wall sections have not displaced (translated) laterally towards the inboard ("protected") side; instead they have simply "dropped" into the hole eroded by the scour of the breach flow.

Clearance for the footprint of the levee and floodwall was very limited, and the neighboring homes and their back yards encroached closely on the levee. Levee maintenance was very poor along this section, and numerous large trees had been allowed to grow along the inboard toe. Many of these were actually rooted part way up the inboard slope face of the levee embankment itself. These trees at the inboard toe represented an unacceptable risk as they can be blown over by storm winds, creating sudden voids that represent favorable paths for concentration of seepage flows and erosion in the critical toe area. Also, when they die the rotting root system can leave voids the can pose a significant hazard with regard to seepage and erosion in the critical inboard toe area.

Several large trees did topple at this site during Katrina, but in the absence of eyewitnesses it is not possible to be certain if they toppled before the breach, or as a result of erosion and scour after the breach opened. Figure 8.92 shows toppled trees at this site. Two large trees from the levee toe area within the breach footprint toppled during this event.

This breach was much shorter in length than the large breaches at the 17th Street Canal, the north end of the London Avenue Canal, and the southern breach on the IHNC at the west side of the Ninth Ward (each of which were hundreds of feet in length.) Instead, like the northern breach at the IHNC at the west end of the Ninth Ward, this was a narrow and deep breach; suggesting that underseepage rather than foundation instability may have been the key issue here.

As discussed previously in Chapter 4, the geology of the London Avenue canal differs significantly from that of the north end of the 17th Street Canal. The buried sand "ridge" runs laterally across the canal region, as shown in figures in Chapter 4, and relatively thick sand strata occur at shallow depths in the London Avenue Canal (and the south Orleans Canal) region. On the south side of this buried sand ridge, the sands tend to be dense as a result of wave action and energy from the Gulf side. On the lee side (the north side), the sands, especially at shallow depth, were protected and tend to be looser.

Figure 8.93 shows the locations of borings and CPT probes performed by the ILIT investigation at this site. Figure 8.94 shows a cross-section through the breach, based on our own (ILIT) data as well as IPET data and data available prior to Katrina. The embankment has a modern (engineered fill) crown consisting of lightly compacted clay and silty clay, underlain by older fill of more variable composition. The embankment section rests atop variable "marsh' deposits consisting primarily of variably interbedded clays and organics. This "marsh" stratum is relatively thin, with a thickness of only 3 to 4 feet at the inboard toe, and it is underlain by about 2 to 3 feet of soft gray clay (CH).

This thin surficial marsh and clay "crust" is underlain by deep deposits of medium dense and then dense sands. In addition to the sheetpile curtain supporting the current concrete floodwall, there is an older sheetpile curtain on the outboard side that used to support a previous small floodwall at this location.

Strengths of the marsh deposits and the thin layer of underlying clay were determined based on the available data, and the resulting strength characterizations are summarized in the table within Figure 8.95, along with the estimated friction angles for the underlying sand units. Stability analyses showed high factors of safety with regard to "landslide type instability failure", even for steady state seepage conditions at the maximum storm surge height of approximately Elev. + 9 feet (MSL). Figure 8.104 shows the most critical potential slide surface for these worst case steady state seepage conditions. It was concluded that this breach was unlikely to have resulted from conventional foundation stability failure.

Numerous analyses of seepage were performed, varying the horizontal and vertical permeabilities of the various soil units and strata (in both the horizontal and vertical directions) over ranges considered reasonable for these soils. For all reasonable ranges of conditions, it was found the soils in the inboard toe area were vulnerable to erosion and potential piping at storm surge levels of less than Elev. + 9 feet (MSL).

An example is shown in Figure 8.96, which shows the flownet and flow velocity vectors for a surge to Elev. + 9 feet (MSL). Figure 8.97 is a closeup from this figure showing conditions in the vicinity of the levee and floodwall. The sheetpiles are nowhere near deep enough to be effective in reducing massive underseepage flows through the pervious sands, and exit gradients near the inboard toe are unsafe with regard to erosion and the initiation of potential piping.

Figure 8.98 shows pore pressure contours from this same flow analysis. Hydraulic uplift forces at and just inboard of the toe exceed the weight of soil overburden, suggesting the possibility that hydraulic uplift ruptured the less pervious thin clay and marsh crust causing a "blowout" failure in this toe area.

Figure 8.99 shows hydraulic gradients for this same flow analysis. The exit gradients at the inboard toe are on the order of $i_o \approx 0.5$, representing a factor of safety with respect to erosion of approximately

$$FS = \gamma_b / (i_o \bullet \gamma_w)$$

where γ_b is the buoyant unit weight of soil, γ_w is the unit weight of water, and i_o is the exit gradient. For the lightweight marsh soils, with light buoyant unit weights, the calculated factor of safety is on the order of $FS \approx 0.8$ to 1.05 for the conditions shown in Figure 8.99. Any "bunching" or localized constriction of the flownet near the exiting face would further exacerbate the tendency to initiate erosion and the beginning of piping. Given the high variability of the thin surficial marsh deposits that "cap" this site, erosion and piping are highly under these conditions.

Figures 8.99 through 8.103 illustrate how such erosion can rapidly escalate as the flownet converges on even a slight void (Figure 8.100) to rapidly increase the localized exit gradient and accelerate the erosion process. This is actually a three-dimensional process, so the rate of acceleration of this erosion and "piping" process is actually more severe than can be properly illustrated in the two-dimensional figures.

Figure 8.105 is a schematic illustration of this process. As the flownet increasing converges, and erosion continues to accelerate, the erosion literally tries to "tunnel" back under the levee embankment. This produces slumping and periodic collapses into the opening void, but these was out quickly and the process continues to accelerate until the crest is finally breached, at which point the inrushing flows rapidly further scour the breach.

An additional possibility is that this type of erosion process may have been exacerbated by the toppling of a tree near the levee toe, as illustrated schematically in Figure 8.106. Flow towards the toe (and the trees rootball zone) weakens the ground and thus weakens the tree's resistance to pullout failure under storm wind loading. Many trees toppled in this manner during the hurricane. If the tree near the toe topples, it created a large void toward which the exiting flownet would rapidly converge, initiating or greatly accelerating the type of erosion and piping process described above.

Figure 8.107 shows another view of this breach section, this time from the waterside and in late September of 2005. In this photo it can be clearly seen the breach is a very narrow feature, deeper at the north end (to the left in this view). On the inboard side our field team felt that the evidence suggested that the breach initiated either as a seepage erosion "blowout" or similar near the north end of the feature. There was a large tree that was uprooted at that location, but it could not be determined whether the tree fell before or after (as a result of) this failure and breach.

In the end, this breach scoured to significant depth and was then rapidly buried by the emergency embankment repair section, so there is no conclusive evidence left with which to determine which of the above described possible mechanisms (in detail) caused the actual failure. It is apparent, however, that this failure was the result of underseepage and erosion of some form. The lack of sufficient sheetpile depth as to adequately reduce underseepage flows and toe exit gradients was an engineering lapse, and so was allowing the rampant growth of large trees in the inboard toe area.

8.3.9 The Breach and Distressed Sections Near the North End of the London Avenue Canal

An additional major breach occurred on the west bank near the north end of the London Avenue Canal, as shown in Figures 8.1 and 8.2. This too was a catastrophic breach as it rapidly scoured below mean sea level and so was one of the three large drainage canal breaches that continued to push water into downtown New Orleans for three days after Hurricane Katrina's passage.

Figure 8.108 shows an aerial view of the breach on the west bank. There was also a "distressed" section on the opposite side (on the east bank) that represents an incipient failure in progress; this failure was arrested in a partially developed state by the failure of the west bank section (which drew down the water level and thus saved the east bank.)

Figure 8.109 shows a view looking south along the canal, with the emergency repair embankment section on the west bank on the right, and the incipient failure section on the left side. If one looks closely, the floodwall on the left (east) side can be seen to be leaning away from the canal in this photo.

This was one of the most challenging sites for our investigation. Foundation soil conditions, and embankment and floodwall geometries, were similar on both sides of the canal. One side failed catastrophically, and the other appears to have begun to fail but to have been saved by the failure on the opposite bank. It was a challenge to develop a model that would predict the failure of the west bank before the east bank failure was able to fully develop. There are also a variety of data and evidence suggestive of a number of potential failure and distress modes evident at both sites (both sides of the canal), and sorting through these posed a significant challenge as well.

Figure 8.110 shows a view of the main breach on the west bank, taken from the south end of the breach on the outboard (water) side. In this photo it can be clearly seen that the toe section of the earthen embankment is still in place, and that the floodwall/sheetpile curtain and the inboard side of the earthen levee have been separated from it and pushed to the inboard side.

Figure 8.112 shows a view of the inboard toe of the displaced embankment section, taken on the outboard (water) side. As shown in this photo, the concrete floodwall leaned away from the canal, and a gap with a maximum width of 2.5 feet (and a common width of 1.5 to 6 feet) opened between the outboard side of the earthen levee embankment and the concrete floodwall (and its supporting sheetpile curtain.)

Figure 8.113 shows the other side of this same floodwall section. As shown in this photo, the displaced floodwall leaned to the inboard with a readily discernable tilt of up to 8º. The next photo, Figure 8.114, shows conditions along the inboard base of the floodwall (at the feet of the photographer who took the photo of Figure 8.113.) A series of apparent "sinkholes" occurred along the inboard side contact between the concrete floodwall and the crest of the earthen levee at this location.

Figure 8.115 shows conditions at the inboard toe immediately below the sinkholes of Figure 8.114. A prominent sand boil feature, with sandy ejecta, occurred at this location. Less apparent, but important, was the hummocky wrinkling of the nearly level ground inboard of the toe of the levee, and the slight overthrust feature adjacent to the sand boil. This overthrust feature was apparently missed by many field investigators, but our team noted it and went back and excavated it during our subsequent filed boring, sampling and CPT program and found that it was indeed the toe thrust of the beginning of a translational instability event.

Figure 8.116(a) shows a cross-section through the west side breach prior to Katrina, and Figure 8.116(b) shows this same section after the failure. The failure on the west side was a translational failure of the embankment, sliding along the interface between the foundation sands and the overlying less pervious layer of silty clay (CL/ML).

Figure 8.117(a) shows a cross-section through the east side "distressed" section prior to Katrina, and Figure 8.117(b) shows this same section after the hurricane. The displacement and tilting of the floodwall was the result of the initiation of slippage, once again at the interface between the foundation sands and the overlying less pervious layer of silty clay. Unlike the west bank, this slippage progressed only enough to produce displacements of approximately 1.5 to 2.5 feet, whereupon these movements were arrested as the failure and breaching on the opposite bank rapidly drew down the canal water level and reduced the lateral push against the sheetpile curtain and floodwall.

Figure 8,118 shows a plan view of both sides of the canal, indicating the locations of the borings and CPT performed as part of this investigation.

Figure 8.119 shows the longitudinal subsurface soil profile developed along this section of levee on the west bank during the original design studies, and Figure 8.120 shows the re-interpretation of this section by this study team based on the original boring data. Figures 8.121 and 8.122 show the same pairing of profiles for the east bank side.

Processing of the available geotechnical data was performed using essentially the same methods and procedures as were described in detail in the preceeding sections, and much of the detail will be omitted here in the interest of brevity.

Figures 8.123 and 8.124 show the best estimated profiles of strength vs. depth and Su/P vs depth on the west bank (breach) side for profiles (a) beneath the full levee embankment overburden, and (b) inboard of the levee toe.

Figure 8.125 shows estimated friction angles across the transition from the base of the silty clay stratum (CL/ML) into the underlying clayey sands and sands. Friction angles were estimated from the CPT data using two correlations, and they were also estimated based on the SPT data available from the borings. Also shown are the results of two direct shear tests performed on "undisturbed" samples as part of these studies.

Figure 8.107(a) shows an "undisturbed: sample from the transition across the silty caly into the underlying sands. As shown in this figure, this transition was semi-gradational rather than abrupt. The base of the silty clay layer is underlain by fine clayey sands wth variable fines content. Near the contact the fines content is high enough that the clayey fines dominate the shear strength behavior. The fines content rapidly decreases over the next 6 inches or so, and eventually the fines content of the remainder of the layer remains relatively stable at between 5% to 10%. The green line in this figure represents our best estimate of the approximate operative effective friction angle through this zone.

It was not possible to discern with certainty the elevation to which pore pressures arising from underseepage passing beneath the sheetpile curtain through the more open, pervious sands at depth due to the transient rising storm surge. Accordingly, various combinations of partial pore pressure development may be postulated at different elevations across this transition, and these may be paired with various effective friction angles to evaluate the shear strength within this narrow, and critical zone.

Several combnations were postulated and analyzed in these studies. Higher (more completely penetrating) pore pressures approaching steady state flow are clearly appropriate at the base of this transition zone, and these would be paired with friction angles on the order of Ǿ ≈ 30 to 32º. A few inches higher in the transition zone the effective friction angle would be somewhat lower, but this would be offset by reduced penetration of pore pressures, resulting in largely similar estimates of resultant frictional shear strength. In the end, an effective friction angle of 31º was selected, and this was coupled with assumed rapid development of steady state pore pressures as the storm surge rose.

Figures 8.126 through 8.129 show the same sequence of figures, this time for conditions on the east bank (distressed) side of the canal. Once again the transition between the silty clay and the underlying clayey sand is the critical region. As with the west bank, an effective friction angle of 31º was selected for analysis, and this was coupled with assumed rapid development of full steady state underseepage as the storm surge rose within the canal.

Figure 8.129 shows the analysis cross-section and principal soil properties modeled for analysis of the west bank breach site. Analyses were performed using both finite element analysis methods (again using the program PLAXIS) and limit equilibrium methods (Spencer's Method).

Figure 8.130 shows normalized shear strain contours for the west bank (breach) section at a storm surge level of Elev. +9 feet (MSL). Gapping initiated at the outboard side of the floodwall and its supporting sheetpile curtain initiated in this analysis at a surge elevation of between +7 to +8 feet (MSL), and was fully developed by a surge elevation of + 9 feet, as shown in this figure.

Figure 8.130 shows normalized shear strain contours for the east bank (distressed) section, this time for a surge to elevation +10 feet (MSL). This the upper bound estimate of the surge elevations achieved during Katrina. Gapping developed in this east bank section at a surge elevation of between +7 to +8 feet, and was fully developed by a surge elevation of +9 feet (MSL).

These conditions produce a predicted failure of the west (breach) side at a surge elevation of +9.5 feet in these PLAXIS analyses, and the east side displaces a bit (with associated lateral displacement and tipping of the floodwall) but remains barely stable to a surge elevation of +10 feet (MSL).

Figures 8.132 and 8.133 show a simultaneous analysis of both sides of the canal, and the predicted conditions for a storm surge to elevation +9 feet (MSL). Figure 8.132 shows normalized shear strain contours, and Figure 8.133 shows the associated predicted deformations and displacements. The west side has failed catastrophically, and the east side section is "distressed" (with lateral displacements of approximately 2 to 3 feet and some tilting of the floodwall. This closely matches the field observations.

Figure 8.134 shows the associated PLAXIS-based prediction of the critical path to failure for each side of the canal. Once gapping occurs, the extra "push" of the water in the gap is sufficient to destabilize the west bank at a surge height of approximately +9 to +9.5 feet (MSL), but the east bank section remains barely stable until a surge height of +10 feet (the upper bound of the estimated surge height that actually occurred).

Figures 8.135 through 8.157 repeat these same analyses, this time using classic seepage analyses to predict pore pressures and gradients resulting from the underseepage flows as the storm surge rises, and limit equilibrium analyses (Spencer's Method) coupled with these predicted pore pressure and gradient conditions to evaluate overall stability for both sides of the embankment. Once again, rapid development of essentially full steady state underseepage was assumed, and an effective friction angle of 31º was modeled at the interface between the silty clay and the underlying clayey sand.

Figures 8.140 and 8.144 show the most critical failure surfaces on the west bank (breach) side for a surge elevation of +9 feet (MSL), with and without gapping respectively. Figures 8.151 and 8.155 show the same two cases for the east bank (distressed) side, again for a surge height of +9 feet (MSL).

Figure 8.157 summarizes the results of these limit equilibrium analyses for both sides of the canal, and the heavy red lines show the estimated most critical paths to failure. Once again the west bank side fails at a surge height of slightly less than +9 feet, but the east bank (distressed) side remains barely stable at this surge elevation. The blue horizontal dashed line in this figure represents our investigation team's best estimated surge elevation in the canal at the time of the breach and failure of the west bank section.

These analyses show that the observed behaviors were not the result of underseepage and resultant piping erosion. The behaviors on both sides of the canal were, instead, the result of lateral transitional instability (and incipient instability), with the critical potential failure mode on both banks being lateral translational sliding on the interface between the silty clay and the underlying clayey sands.

This exactly fits with the observed field data. The "sinkholes at the crest of the embankment on the east side were the result of tilting of the slightly displaced floodwall, and the resulting opening of a gap between the floodwall and the embankment into which embankment soils could fall. This correlates with the observation the "sinkhole features" were all narrow, and were all parallel and adjacent to the floodwall (see Figures 8114 and 8.117.)

8.3.10 Summary and Findings

A large number of critical errors and poor judgements jointly contributed to the catastrophic failures that occurred along the drainage canals. There were conceptual errors in the layout and fundamental design of the levees and floodwalls, there were policy and funding issues that greatly reduced the level of safety of the overall system, and there were engineering errors in the analysis and design of individual sections.

No one organization, agency or group of individuals had a monopoly on their contribution to this disaster. Federal government (including the Congress), the Corps of Engineers, local government and local oversight agencies (including the local Levee Board and the local Water and Sewerage Board), and outsourced engineering firms all contributed.

The resulting system failed catastrophically, and at multiple locations. And it failed at significantly less than the intended level of (storm surge) loading. Moreover, it is clear that additional sections were saved from failure only by the catastrophic failure of nearby breaches, which drew down the water levels and so reduced the loading on additional potentially unstable levee and floodwall sections.

The results of these failures were catastrophic. The vast majority (approximately 80%) of the eventual flood flows into the main Orleans East Bank (downtown) protected area came through the breaches in the drainage canals. These flows overfilled the sub-basin north of the Metairie Ridge, and then crossed this ridge and flowed into the southern areas as well where they greatly exacerbated flooding that had already occurred as a result of overtopping and failures of levees and floodwalls along the west side of the IHNC. In the absence of the drainage canal failures there would still have been localized flooding and damage near the IHNC, but this would have been minor relative to the eventual damages that resulted when the canal breaches filled a majority of the overall basin.

The localized flooding near the IHNC would have posed relatively little threat of loss of life, and the damages would have been limited and the floodwaters could have been pumped out in a matter of days. Instead, roughly half of the 1,293 fatalities (to date) attributed to flooding of the New Orleans region occurred in the Orleans East Bank (downtown) protected basin, and a roughly similar fraction of the devastating regional economic damages as well.

The following is a listing of critical errors and poor judgements and decisions that contributed significantly to the poor performance of the drainage canal levees and floodwalls during Hurricane Katrina:

1. The decision not to install floodgates at the north ends of the three drainage canals to prevent uncontrolled water level rise due to storm surge within the canals was largely the result of poor interaction between the local Levee Board and the local Water and Sewerage Board, and their inability to resolve their differences in the interests of the greater Public good (and safety). As a result, the canals remained open to storm surges; essentially inviting the enemy (storm surge) into a poorly protected section of the interior of the protected ring around metropolitan New Orleans.

2. The decision not to purchase additional land (right of way) to permit widening of the levees required that the system be extended vertically without allowing provision of additional levee width and mass with which to resist the increased floodwater forces associated with the increased height. Short-term savings here resulted in tens of billions of dollars in losses.

3. Similarly, the failure to garner access and control of property at the inboard (protected side) toe of the levees prevented full and proper inspection of this critical area. It also led to unacceptable risk associated with growth of trees on the inboard side levee slopes and toes, and the literal undermining of levee toes by excavation of in-ground swimming pools in this critical inboard toe area.

4. The designers failed to take advantage of critical lessons from an expensive and well-directed research program that involved construction of a full-scale model levee and floodwall on nearly identical foundation soils in nearby Atchafalya. This model was

loaded to failure, and the failure mode observed involved opening of a gap on the outboard side of the floodwall, water entering into the gap, and subsequent pressures on the floodwall and sheetpiles pushing the inboard side section of the earthen embankment sideways (the "cut the cake in half and slide it" failure mode). This failure mode was neglected in the subsequent design of the levees and floodwalls lining the canals, and at least two of the catastrophic failures (breaches), and two additional "incipient" failures were the result of this failure mechanism.

5. The designers also failed to take account of the influence of stress history and effective overburden stresses on the strengths of the foundation soils beneath many of the embankments. This played a critical role in the catastrophic failure of near the north end of the 17th Street canal.

6. Optimistic assumptions, and misinterpretation of two field tests, led to the assumption that system permeability was low enough that underseepage would not be a critical issue during "transient" (short-term) rises in canal water levels during hurricane induced storm surges. This was a critical error, and it resulted in inadequate sheetpile lengths throughout the drainage canals, and along the IHNC. These sheetpile curtains routinely extend to insufficient depths as to adequately "cut off" underseepage flows, and the resulting underseepage flows were principal contributors to the catastrophic failures observed at both major breach sections on the London Avenue canal. These inadequate cut-offs continue to be a potentially critical issue at other sections that did not (yet) breach during hurricane Katrina, and they appear to have been a principal factor in the two massive breaches on the east bank of the IHNC (at the edge of the Ninth Ward; see Chapter 6) as well.

7. Insufficient site investigation was performed for the design of these critical systems protecting a major metropolitan population. Given the difficult and complex foundation soil conditions, additional borings and testing would have represented a very modest incremental expenditure, and would have greatly improved the information available as a basis for analysis and design of these important sections.

8. Errors and poor judgements were made in engineering analysis and design of these sections. Soil properties were extrapolated laterally over inappropriately large distances, and without adjustment for the resulting uncertainties. Archaic analysis techniques were employed, and project-specific research (a full scale test embankment and floodwall near Atchafalya) was ignored, resulting in failure to analyze the failure mode ("cut the cake in half and slide it") that proved critical for at least two of the catastrophic drainage canal breaches, and likely also for the two massive breaches at the east side of the IHNC (adjacent to the Ninth Ward.) This mode was also evident at an additional "incipient" failure section on the London Avenue canal that was saved from failure, by the failure of the even weaker section on the opposite shoreline (which immediately drew down the local water levels.) The stability of the entire canal system should be considered potentially suspect until it can be properly re-evaluated with regard to this potentially critical mechanism.

9. Design review was inadequate. Errors and questionable judgements that would have been expected to be caught and challenged by a properly convened external review panel went unchallenged. On one occasion when reviewers from another USACE District did catch and challenge such issues, they were rebuffed by the local District Chief who declared those issues to be a matter of "judgement".

10. The Factor of Safety (FS) used for design of these vital levees and floodwalls was set at only FS = 1.3 for the case of "transient" storm surge loading. As discussed in detail in Section 8.3.7.1 this is inappropriately low for systems critical for the safety of large populations, and for the difficult and challenging foundation soils conditions of the region. This issue is discussed in significantly more detail in Chapter 11 and 12.

11. Congressional funding (appropriations) were problematic. Funding was irregular and somewhat unpredictable, representing a difficult basis for design and construction of a system intended to be contiguous (seamless) and to protect a large metropolitan population. Strategic decisions, and conceptual design, were often driven by a need for frugality. In addition, when appropriations did arrive, some elements of the system had to be further streamlined for economy. The relatively minor savings achieved now pale in comparison to the many tens of billions of dollars in losses that ensued.

12. Pace of funding was also problematic. At the time of Katrina's arrival, the flood protection system in the canal district was still incomplete…. fully 51 years after the flooding from Hurricane Betsy that inspired the inception of construction of the improved flood protection system. Three of the bridges across the drainage canals still had not yet had their side walls raised, so three "holes" remained in an otherwise contiguous system. These "holes" at the bridges were not critical during Hurricane Katrina only because: (a) the storm surge was less than the full design load case, and (b) catastrophic nearby breaches (failures) occurred. (An additional "hole" in the system, at the south end of the Orleans Canal, was yet another result of dysfunctional interactions between the local levee board and the local water and sewerage board, as discussed previously in item #1 above.)

Many of the issues above, from conceptual design issues through engineering analysis details and even selection of appropriate Factors of Safety would have been expected to be challenged by a properly convened independent review panel. Unfortunately, in the current system with myriad local interests and no strong local entity able to convene appropriate levels of unbiased expert review capability, this critical element was absent during the design and construction of these important flood protection system elements.

In addition, there was a lack of centralized authority, and of clear areas of responsibility. Involvement of a significant "local" institutional presence of significant stature and resources was lacking. The local levee board lacked the resources and funding to mount serious review of the Federal plans and designs, and the mandate to challenge problems that should have been apparent at early stages.

In the end, the performance of the flood protection system along the three drainage canals was unacceptable, and resulted in catastrophic loss of life and property throughout a major metropolitan region.

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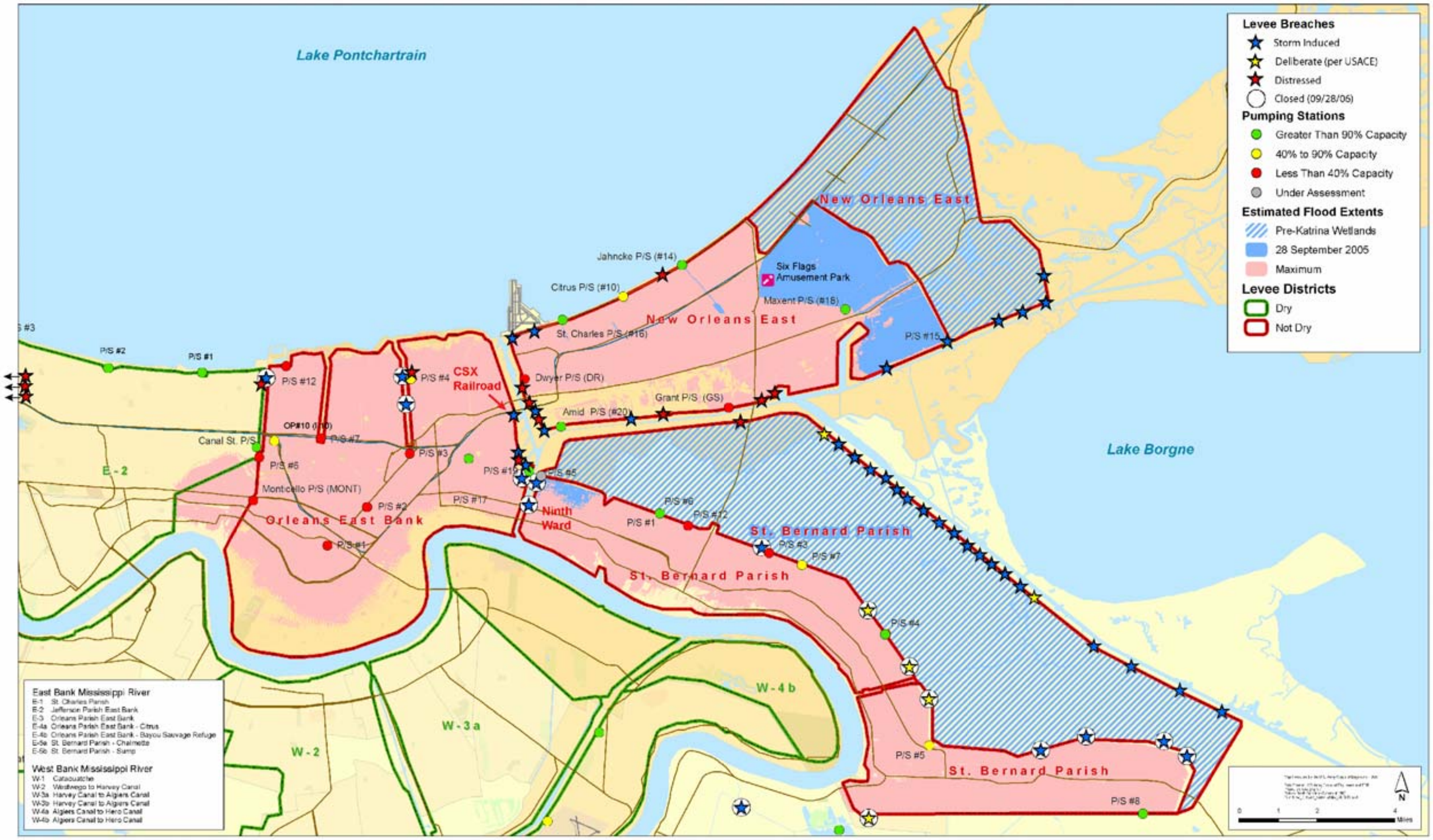


Figure 8.1: Map showing principal features of the main flood protection rings or "protected areas" in the New Orleans area. [Modified after USACE, 2005]

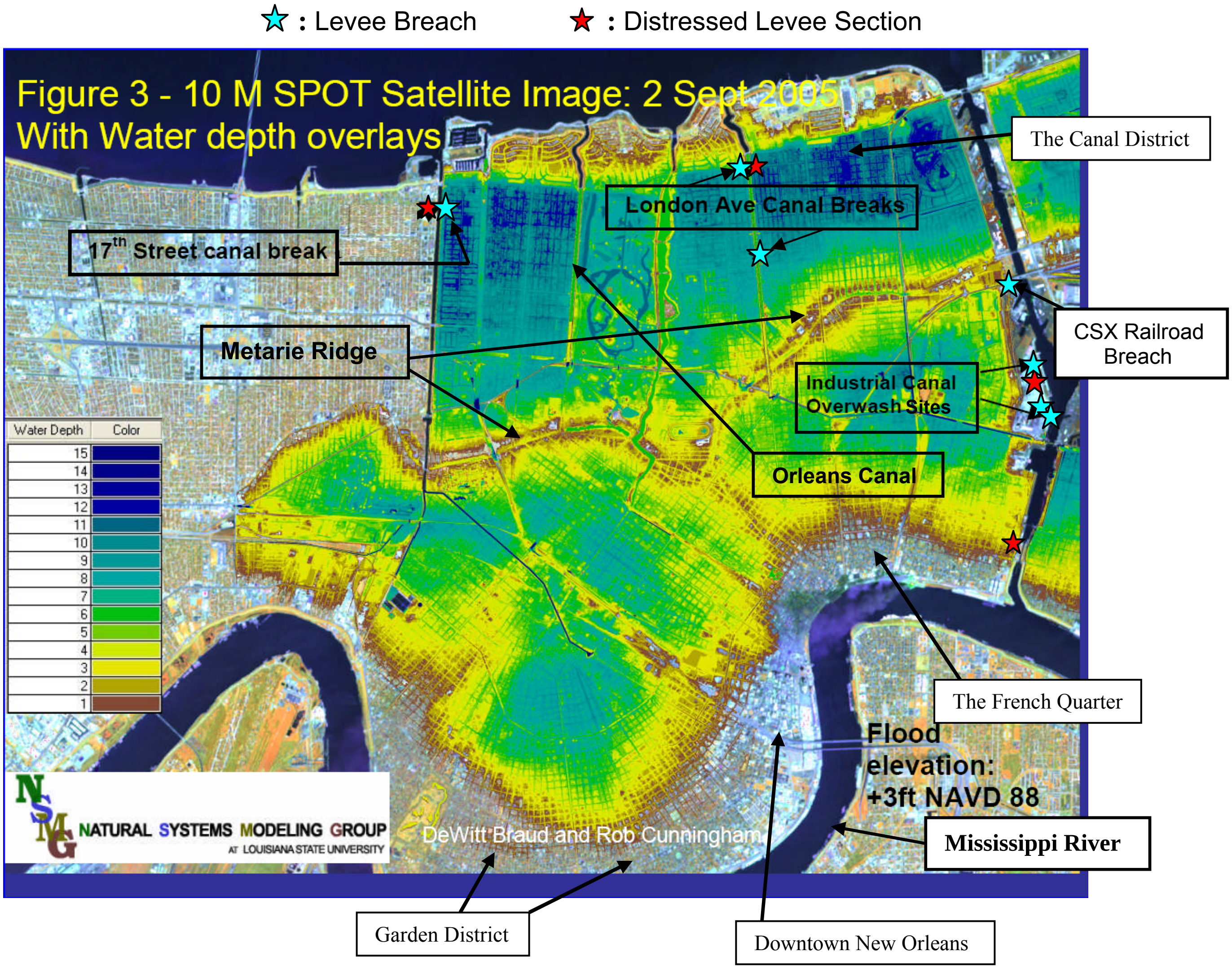
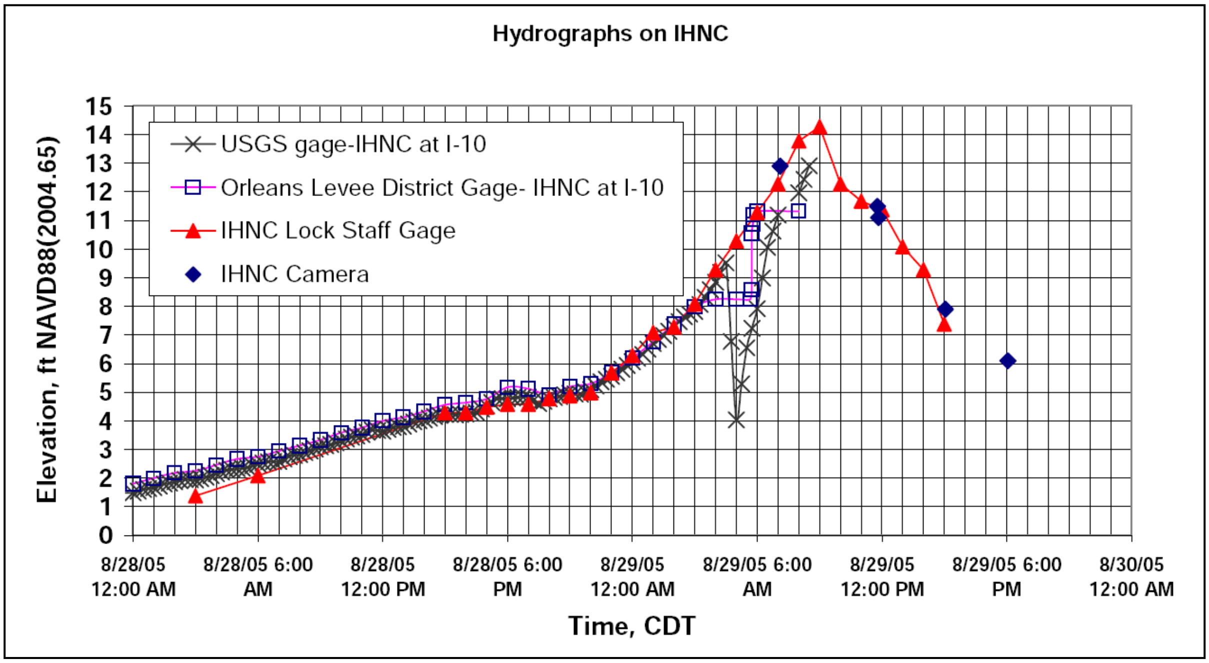


Figure 8.2: Plan View of the Orleans East Bank (Metro) protected area showing approximate depth of flooding on September 2, 2005.

[Modified after Mashriqui, 2006]



Source: IPET Interim Report No. 2; April, 2006

Figure 8.3: Hydrographs showing measured (and photographed) water levels at gage stations along the Inner Harbor Navigation Channel (IHNC).

Photograph by Rune Storesund

Figure 8.4: Concrete storm gate at the west bank of the CSX Railroad crossing of the IHNC, after Hurricane Katrina, showing the steel floodgate missing.

Photograph by Rune Storesund

Figure 8.5: View from the inboard side of the CSX Railroad breach site from Figure 8.4 showing scour of the roadway fill adjacent to the railway embankment fill.

Photograph by Rune Storesund

Figure 8.6: The I-wall section breach behind the Port of New Orleans, showing floodwall failure.

Photograph by Rune Storesund

Figure 8.7: Second view of the I-wall failure at the Port of New Orleans showing the trench scoured by overtopping flows.

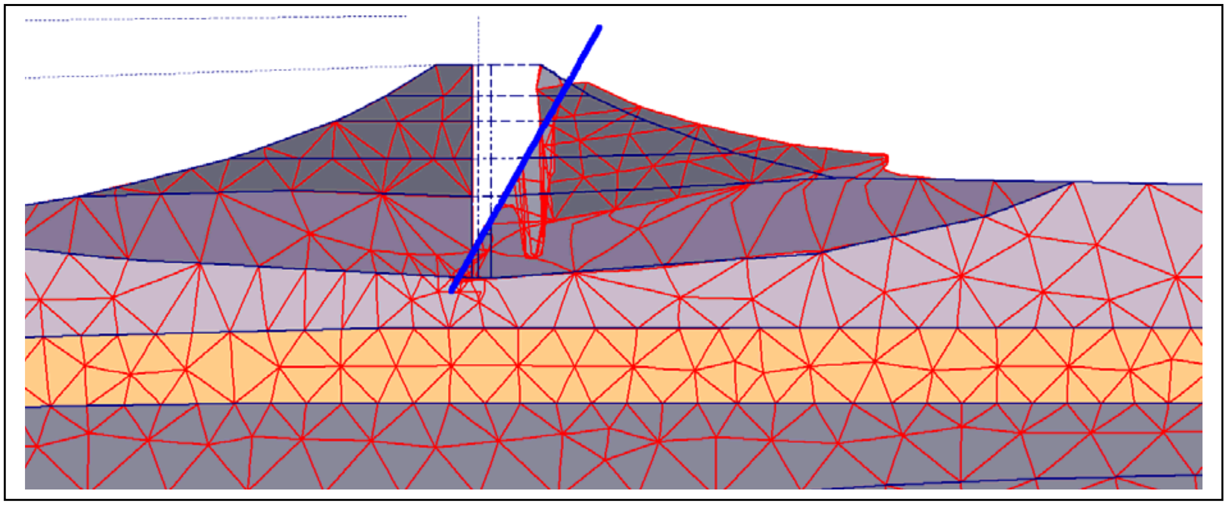


Figure 8.8: Deformed mesh of I-wall failure at the IHNC behind the Port of New Orleans.

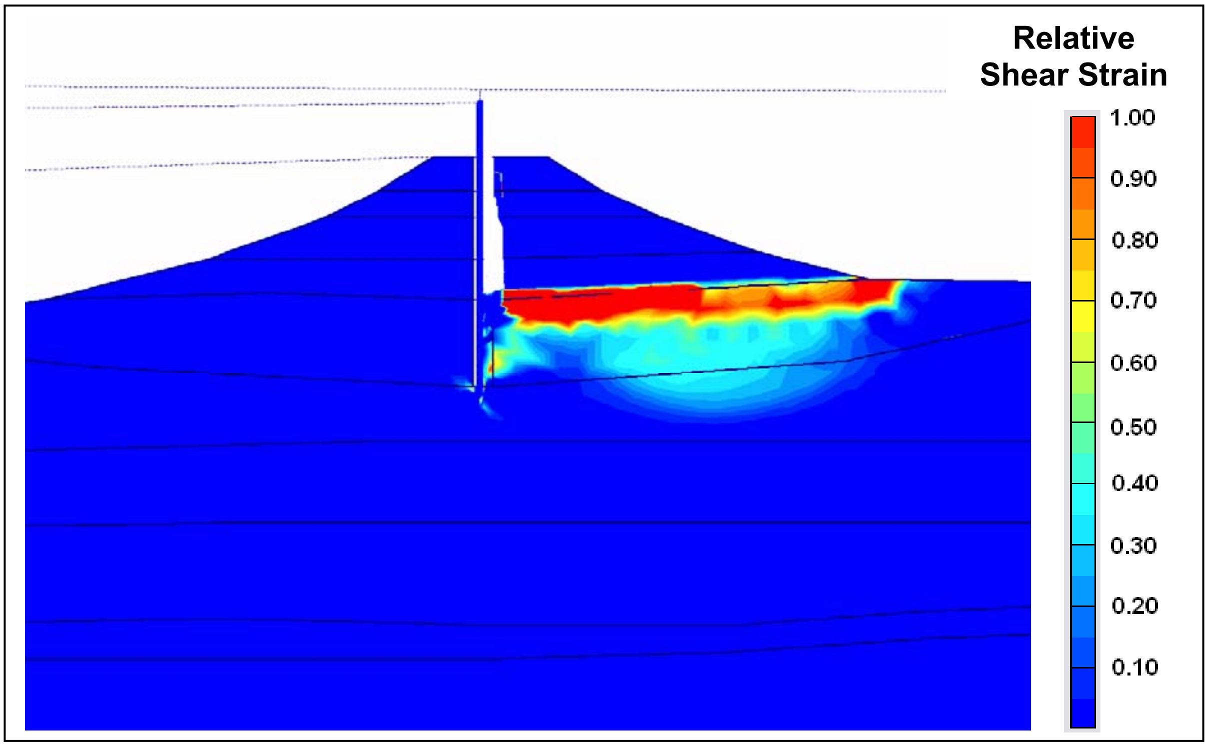
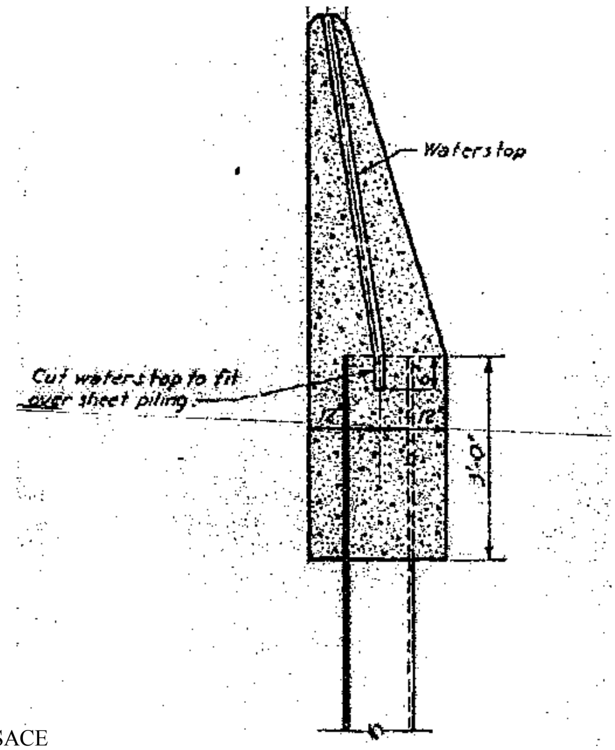
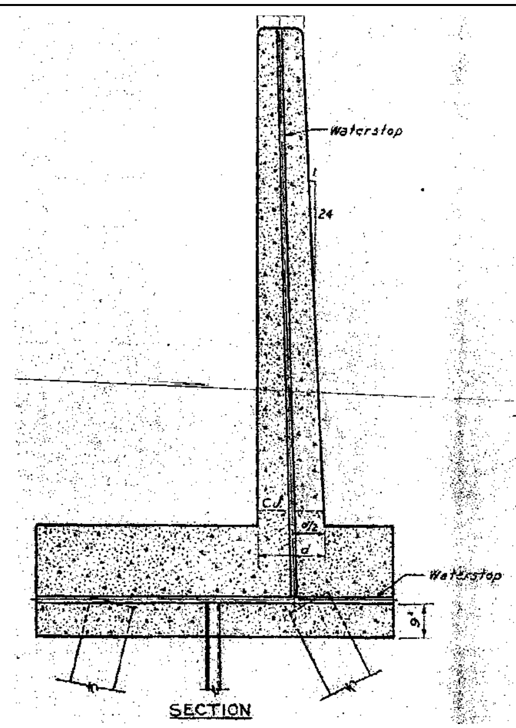


Figure 8.9: Finite element analysis of I-wall failure at the IHNC behind the Port of New Orleans, showing shear strain contours at point of wall failure.



Source: USACE

Figure 8.10(a): Typical reinforced concrete I-wall atop a sheetpile curtain.



Source: USACE

Figure 8.10(b): Typical reinforced concrete T-wall atop a sheetpile curtain.

Photograph by Rune Storesund

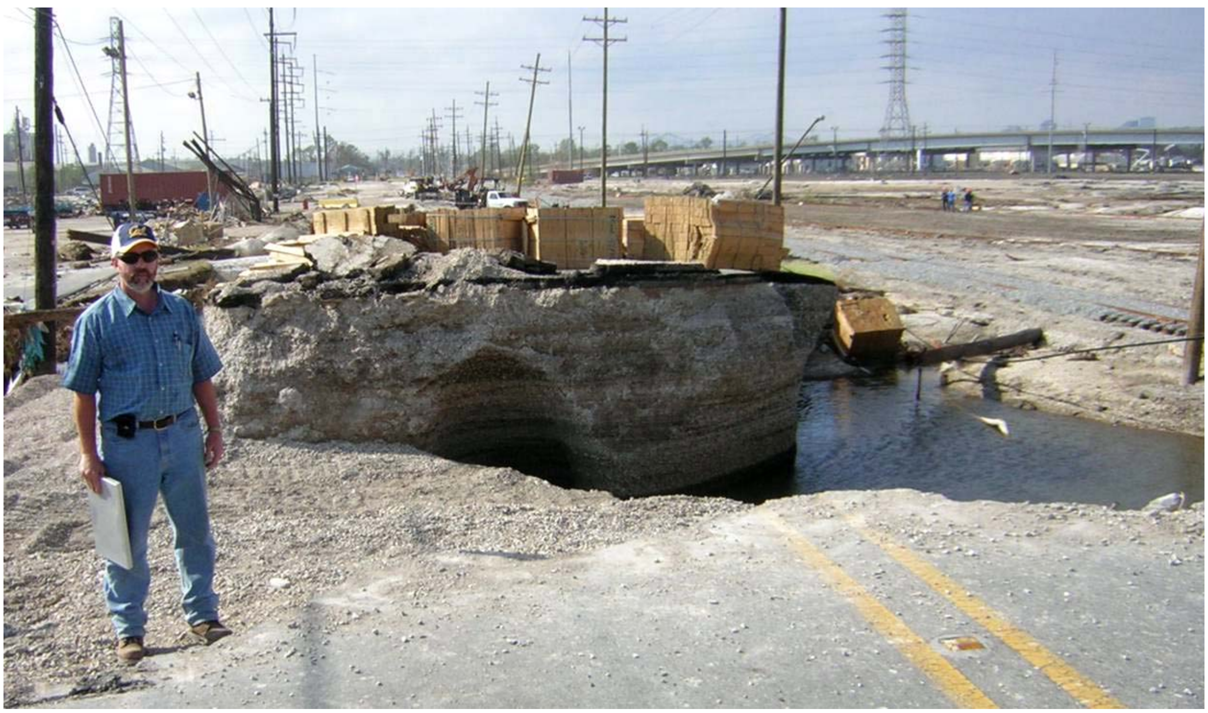
Figure 8.11: Concrete floodwall and steel floodgate structure at railroad yard behind the Port of New Orleans.

Photograph by Rune Storesund

Figure 8.12: Erosion, gapping and offset of adjacent wall sections at the east end "transition" of the concrete floodwall and gate structure from Figure 8.11.

Photograph by Rune Storesund

Figure 8.13: Erosional breach behind the southern end of the Port of New Orleans at contact between embankment section and structural concrete monolith.

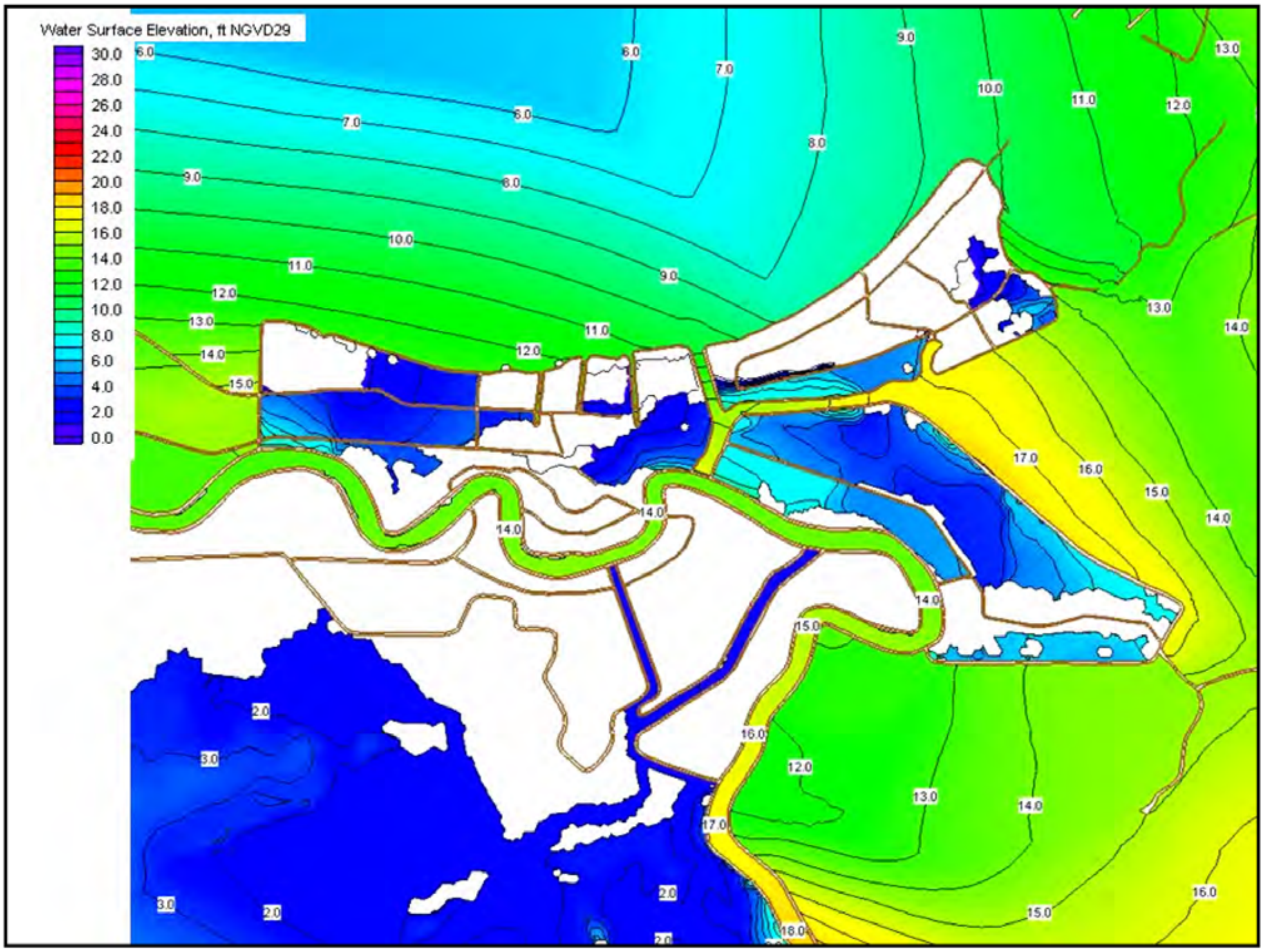


Photograph by Rune Storesund

Figure 8.14: Close-up view of the highly erodeable shell sand fill at the breach shown above in Figure 8.12.

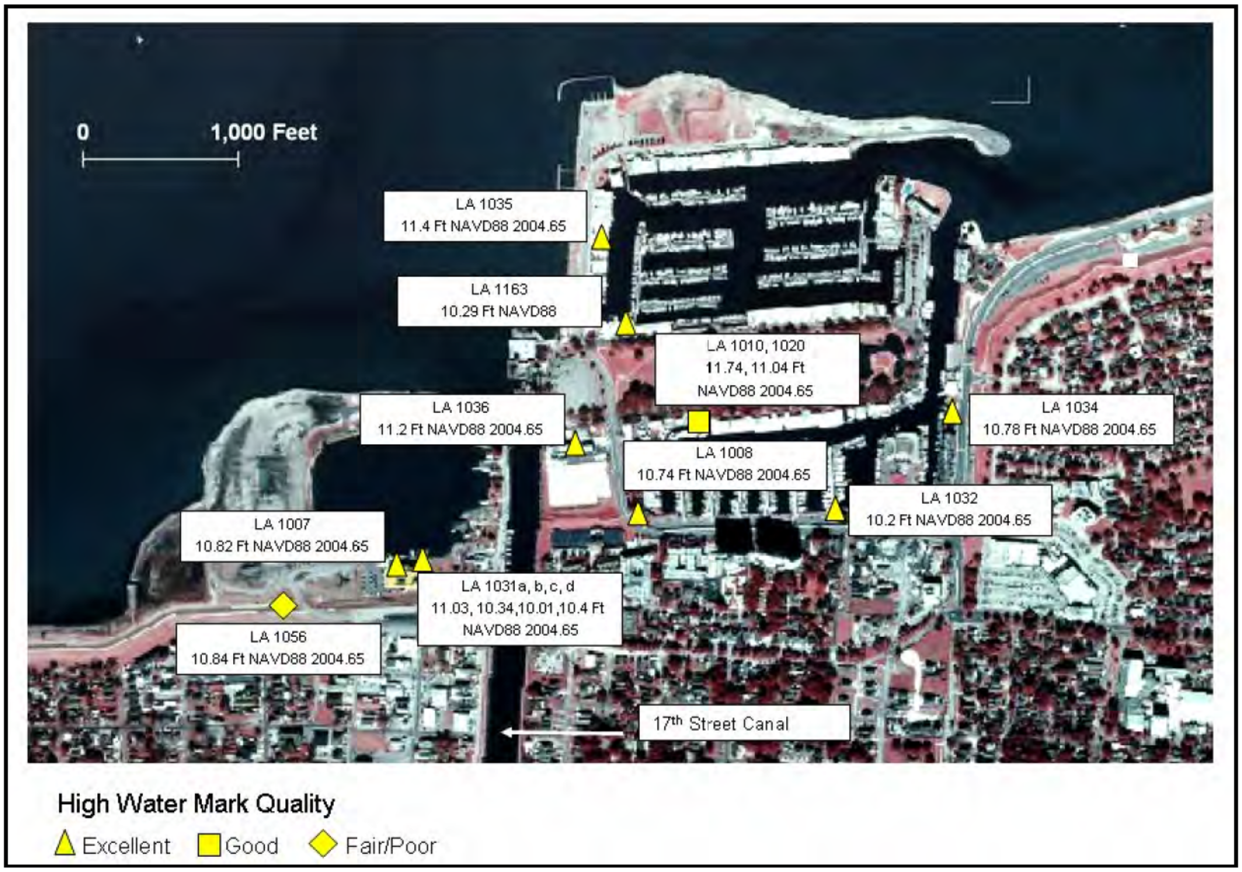
Photograph by Rune Storesund

Figure 8.15: View of second large erosional breach behind the southern end of the Port of New Orleans.



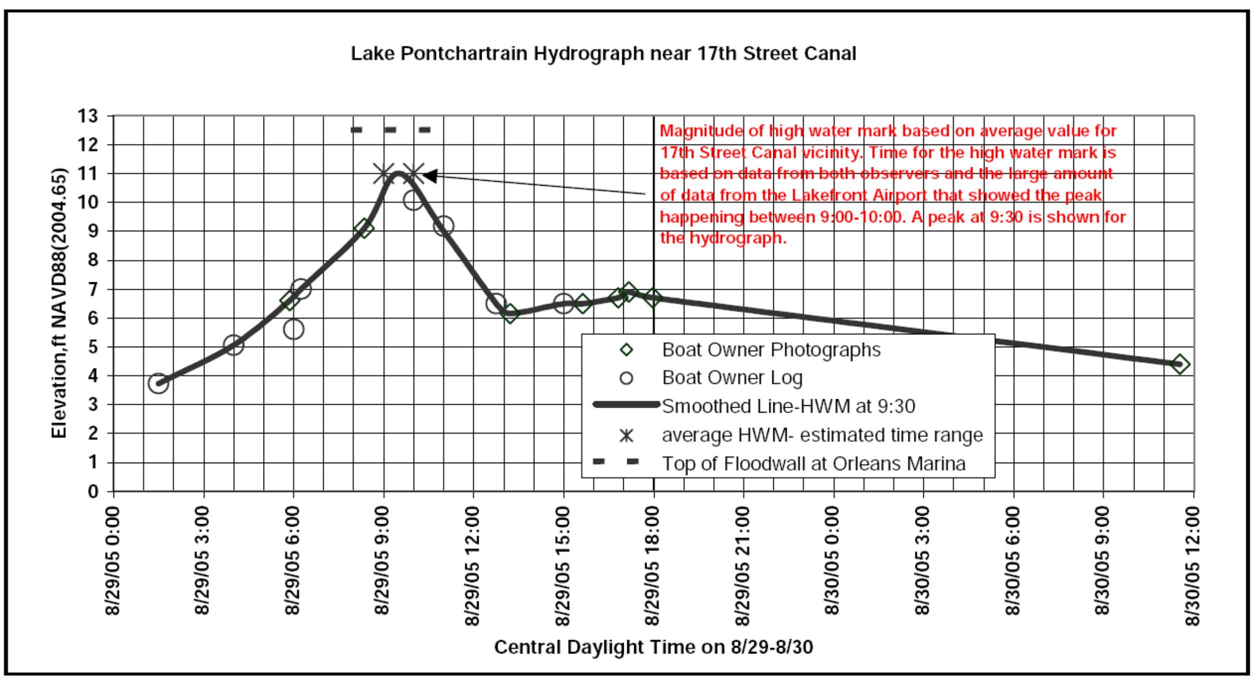
Source: IPET Report No. 2, April, 2006

Figure 8.16: Approximate contours of maximum storm surge heights along the southern end of Lake Pontchartrain. [Note: Elevations in Feet, NGVD29]



Source: IPET Report No. 2; April, 2006

Figure 8.17: High water marks near the mouth of the 17th Street Canal.



Source: IPET Report No. 2, April, 2006

Figure 8.18: Hydrograph proposed by IPET for the 17th Street drainage canal.

Photograph by Rune Storesund

Figure 8.19: View of the pump house, levees and floodwalls, and the "gap" at the south end of the Orleans canal.

Photograph by Rune Storesund

Figure 8.20: Side view of the "gap" at the south end of the Orleans canal.

Figure 8.21: Oblique view of LIDAR survey of the southern end of the Orleans Canal, showing the “gap” on the east side where the levee and floodwall that should have sealed the end are omitted, and a “spillway” replaces them.

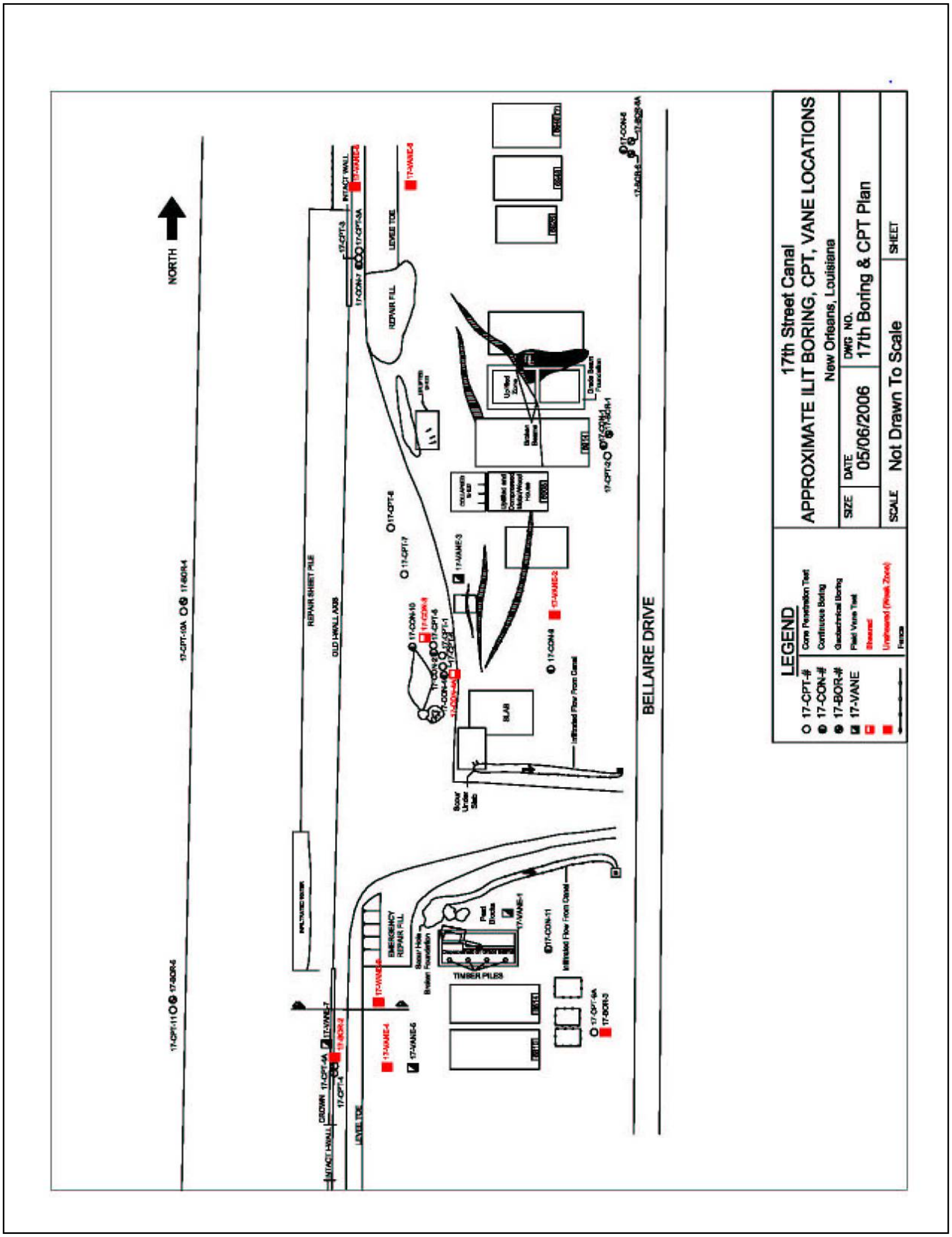
Photograph by Rune Storesund

Figure 8.22: View of the earthen levee embankments and floodwalls along the east side of the Orleans Canal (view looking to the North.)

Photograph by Rune Storesund

Figure 8.23: View of the earthen levee embankments and floodwalls along the west side of the Orleans Canal (view looking to the North.)

Figure 8.24: Oblique aerial view of the breach at the 17th Street Canal.


NORTH
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17th Street Canal
APPROXIMATE ILIT BORING, CPT, VANE LOCATIONS
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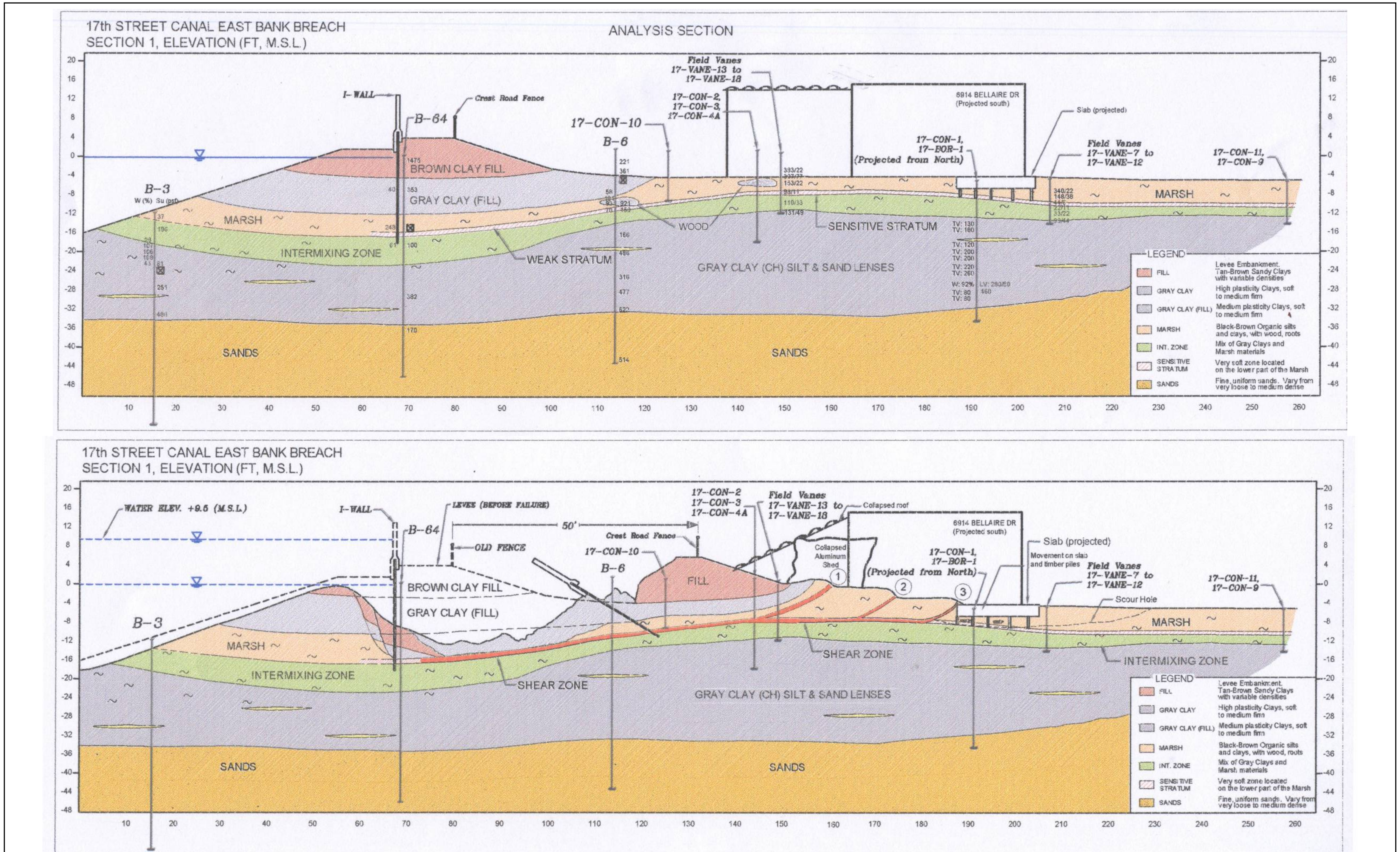


Figure 8.26: Cross-section through the 17[th] Street Canal breach showing conditions (a) before the hurricane, and (b) after the breach and failure.

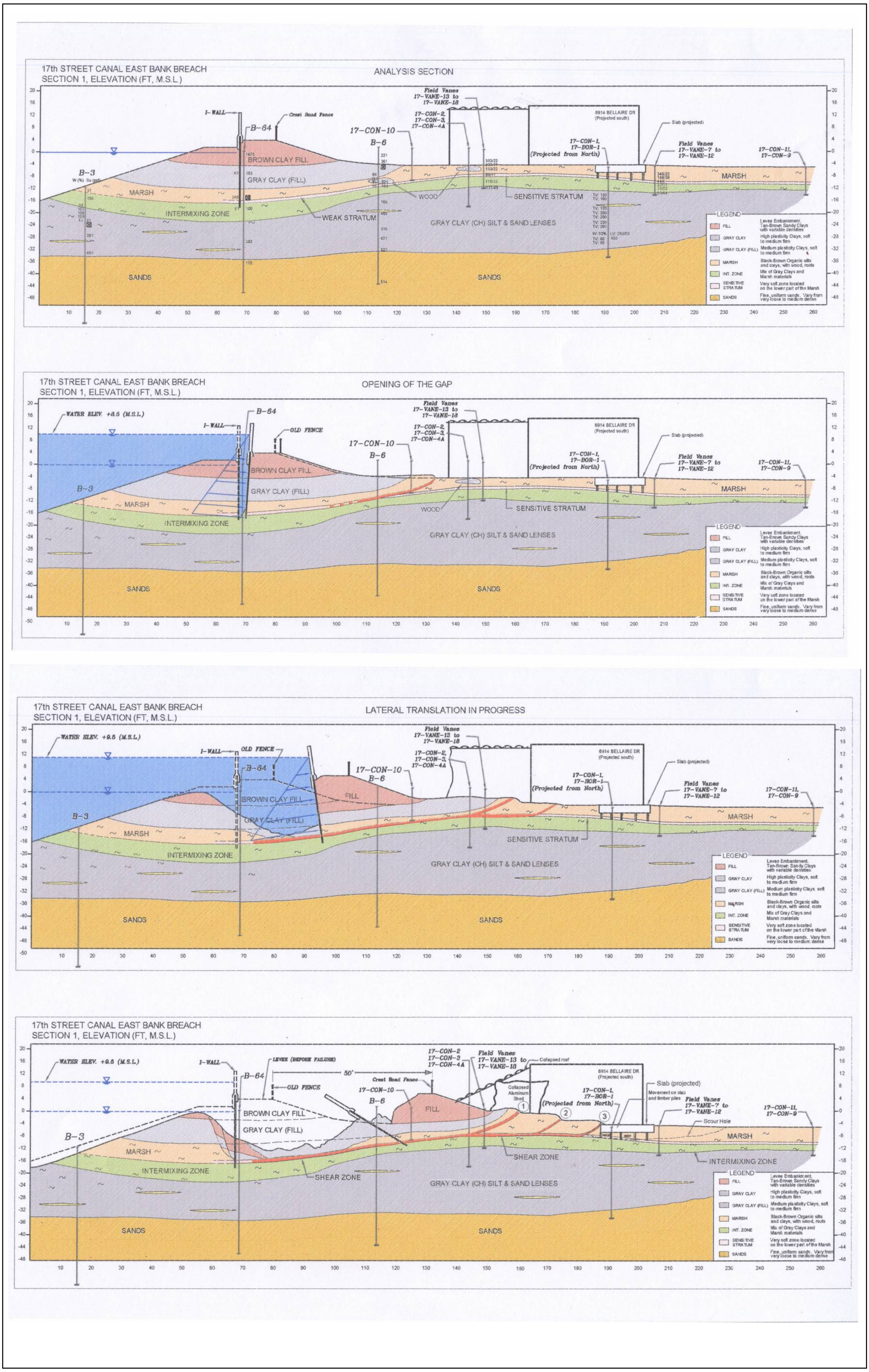


Figure 8.27: Cross-sections through the 17th Street Canal breach showing conditions as: (a) pre-storm surge, (b) a gap opens between the outboard side of the earthen embankment and the sheetpile curtain (and I-wall), (c) the elevated water levels increase within this gap pushing the I-wall and the inboard side of the embankment laterally away from the canal, and (d) final configuration at the end of displacement after I-wall topples backwards towards the canal.

Figure 8.28: View of the 17th Street Canal breach site showing the tops of the I-wall sections that "pushed" (and followed) the displaced levee embankment section, and then toppled backwards towards the canal.

Figure 8.29: View of the 17th Street canal breach site showing the I-wall sections at the south end of the breach toppled forward (to the inboard side) by the inrushing flood-waters. Note the severe scour inboard of the failure at this location.

Figure 8.30: Side view of the collapsed shed pushed into the house at 6914 Belaire Drive as illustrated in the cross-section of Figure 8.27.

Photograph by Joseph Wartman

Figure 8.31: View of the foundation slab shown in the cross-section from Figure 8.27.

Figure 8.32: View of the exit of the upper failure surface (shear surface No.1 from Figure 8.27) at the inboard toe of the failure.
[IPET Interim Report No. 2, April 1, 2006]

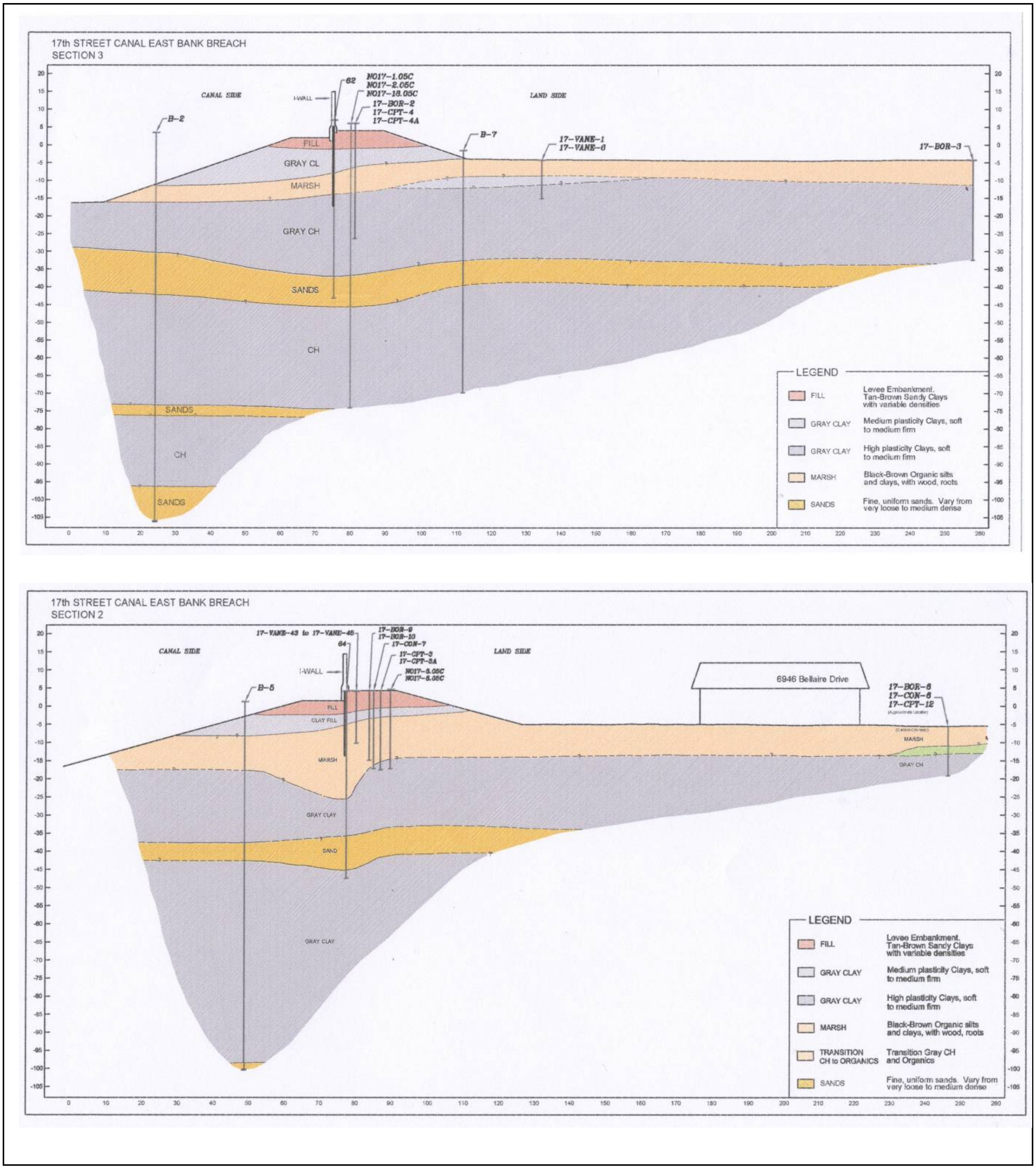


Figure 8.33: Two additional cross-sections through the breach section on the east bank of the 17th Street canal showing: (a) Cross-Section B-B′ and (b) Cross-Section C-C′.

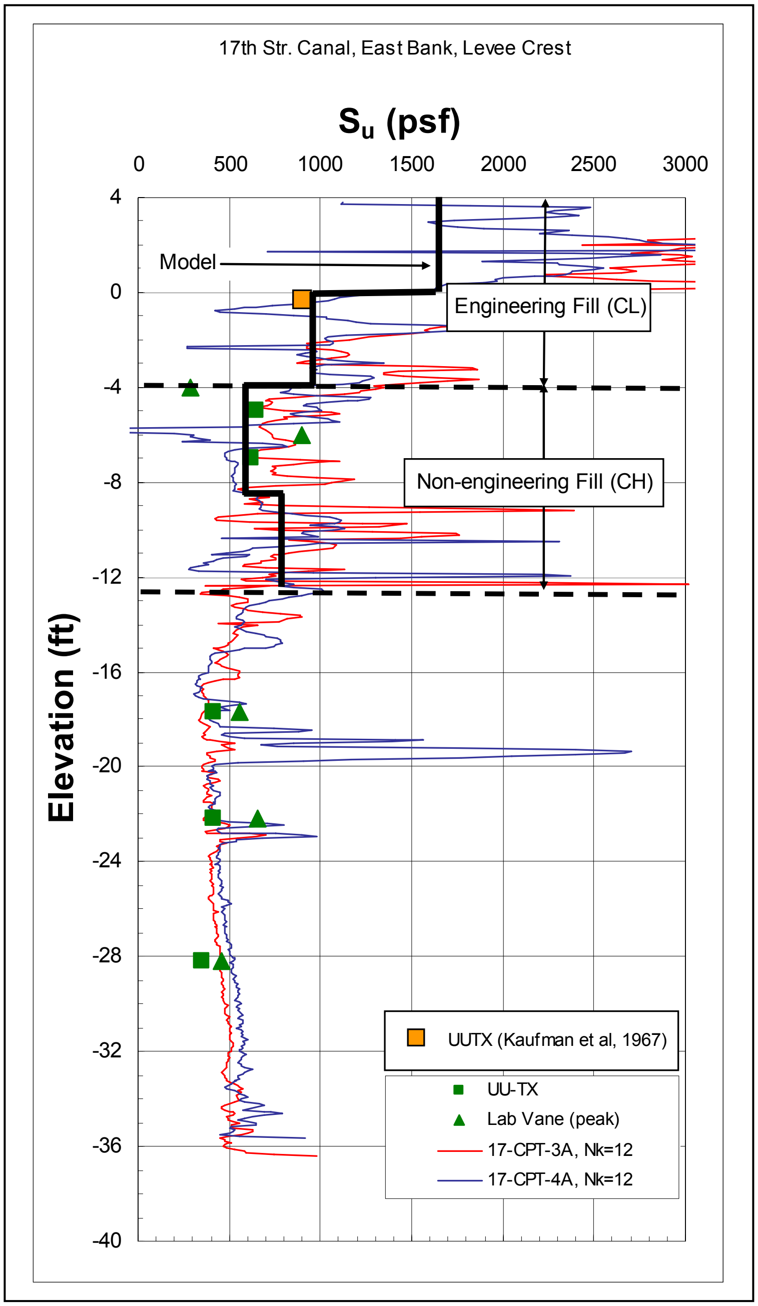


Figure 8.34: Summary of shear strength data within the 17th Street drainage canal levee embankment fill at and near the east bank breach section.

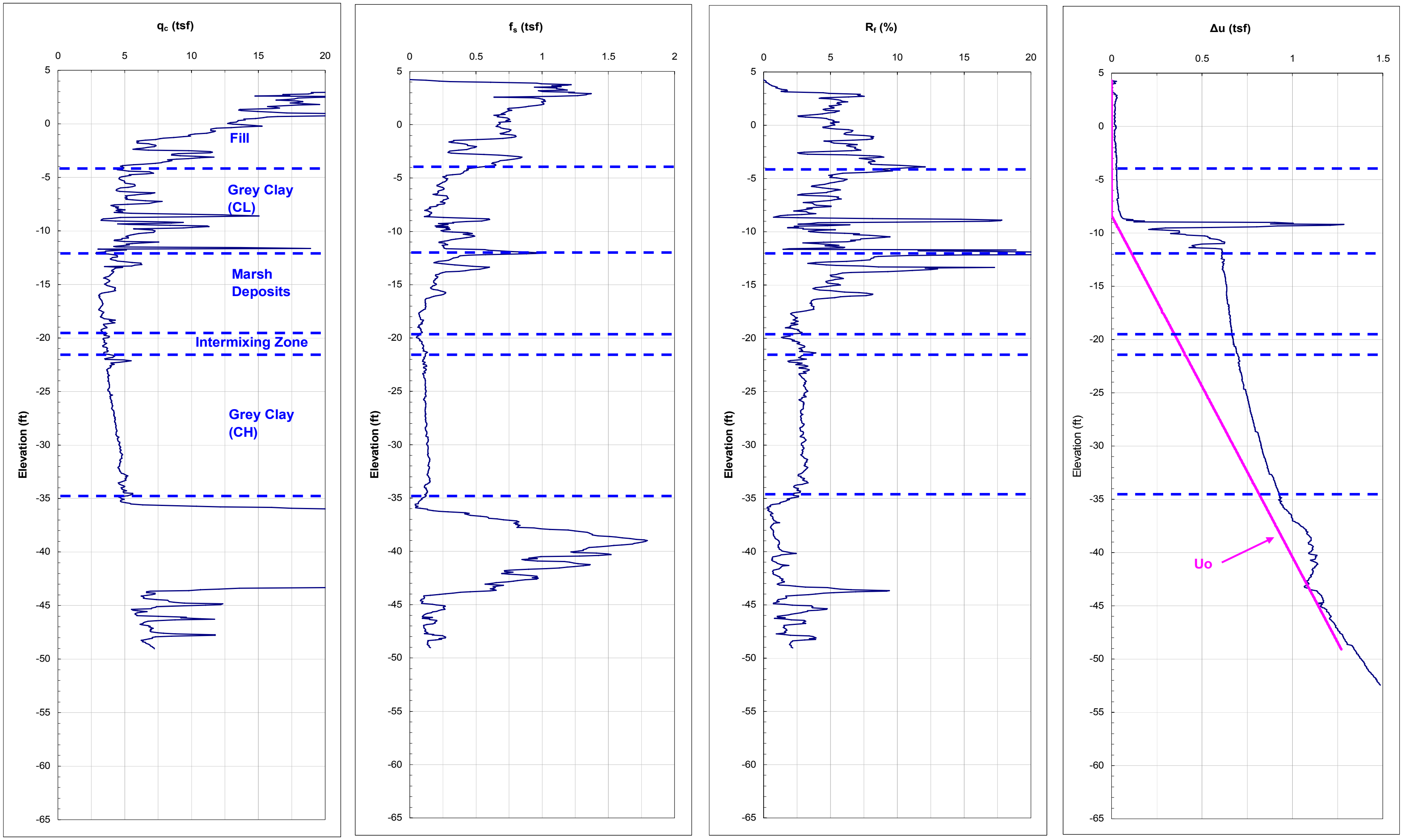


Figure 8.35: Summary of CPT test data for locations beneath the levee embankment at and near the 17th Street canal breach section.

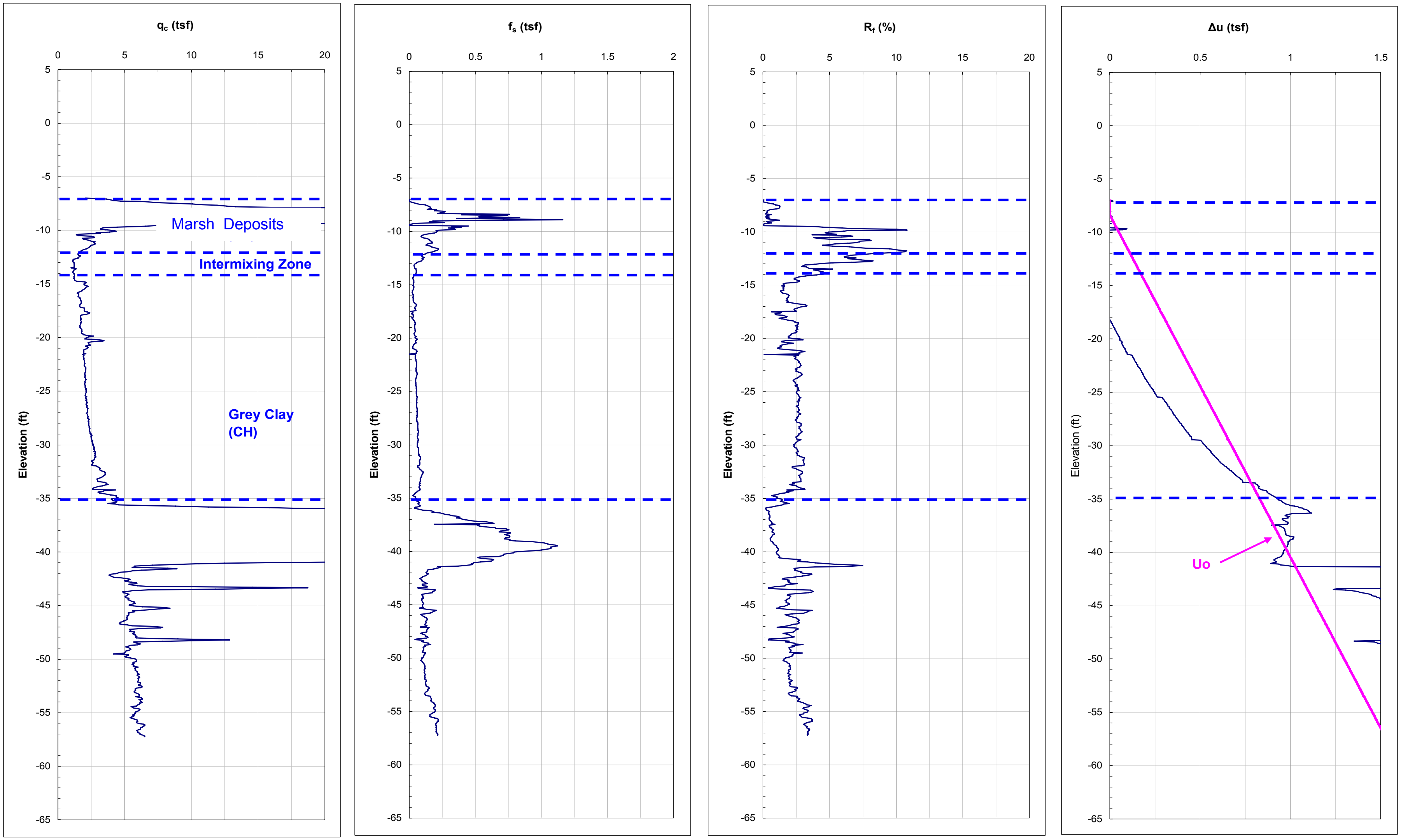


Figure 8.36: Summary of CPT test data for locations inboard of the toe of the levee embankment at and near the 17th Street Canal breach section.

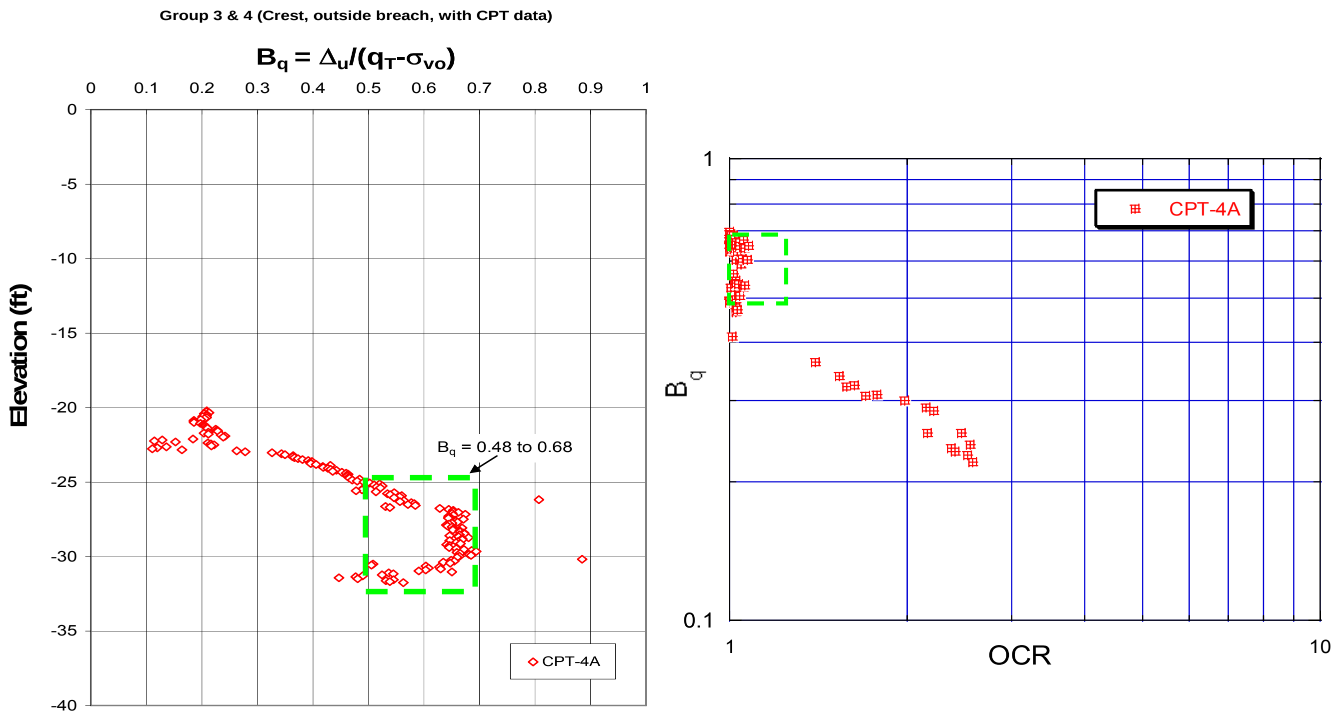


Figure 8.37: Pore Pressure parameter B_q vs. OCR and vs. depth within the soft gray clay (CH) foundation layer under full embankment overburden load.

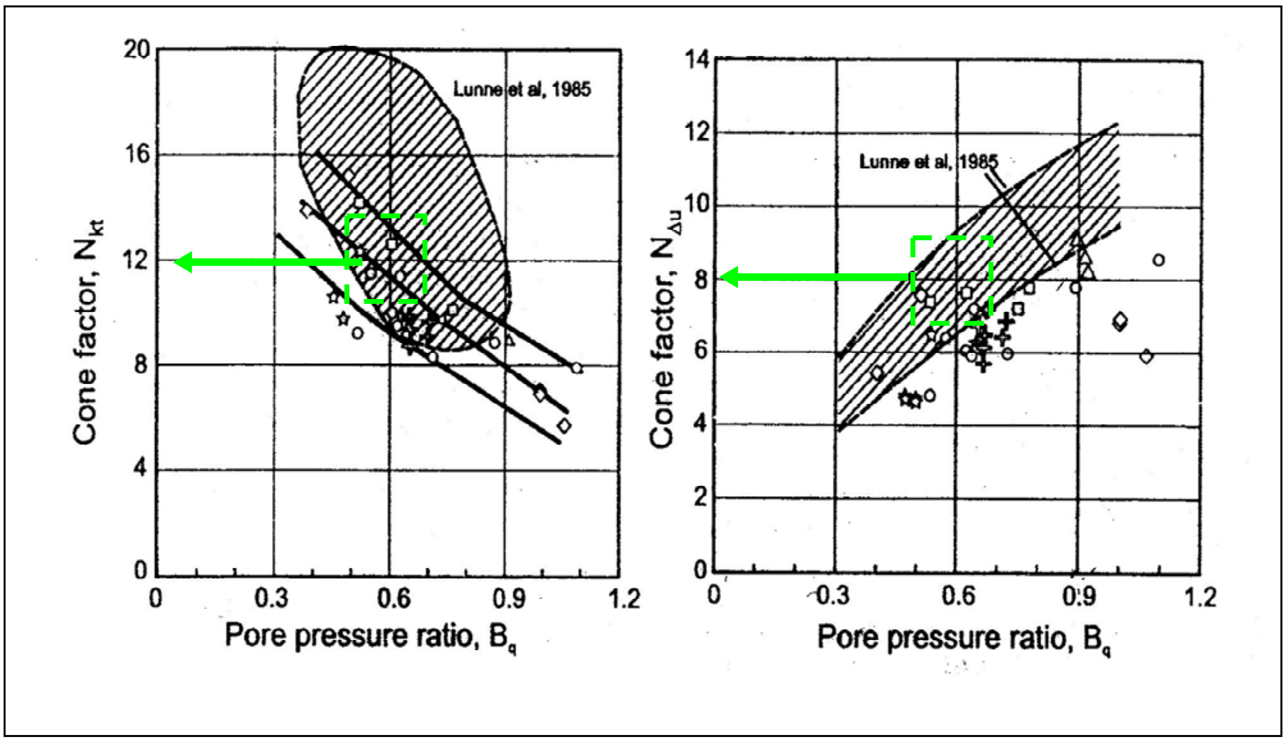


Figure 8.38: CPT cone factor N_{kt} based on B_q (after Lunne et al., 1985 and Karlsrud et al., 1996) for the soft gray clay (CH) under full embankment overburden load.

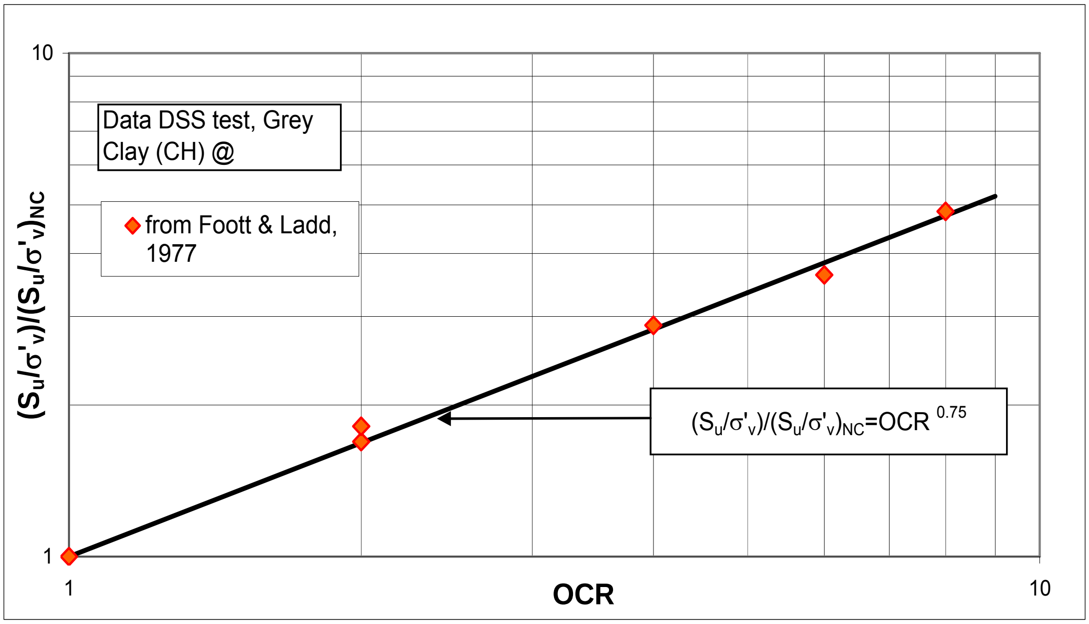


Figure 8.39: Relationship between S_u/P vs. OCR for mineralogically similar gray marsh clays (CH) at Atchafalia.

[Foott & Ladd, 1977]

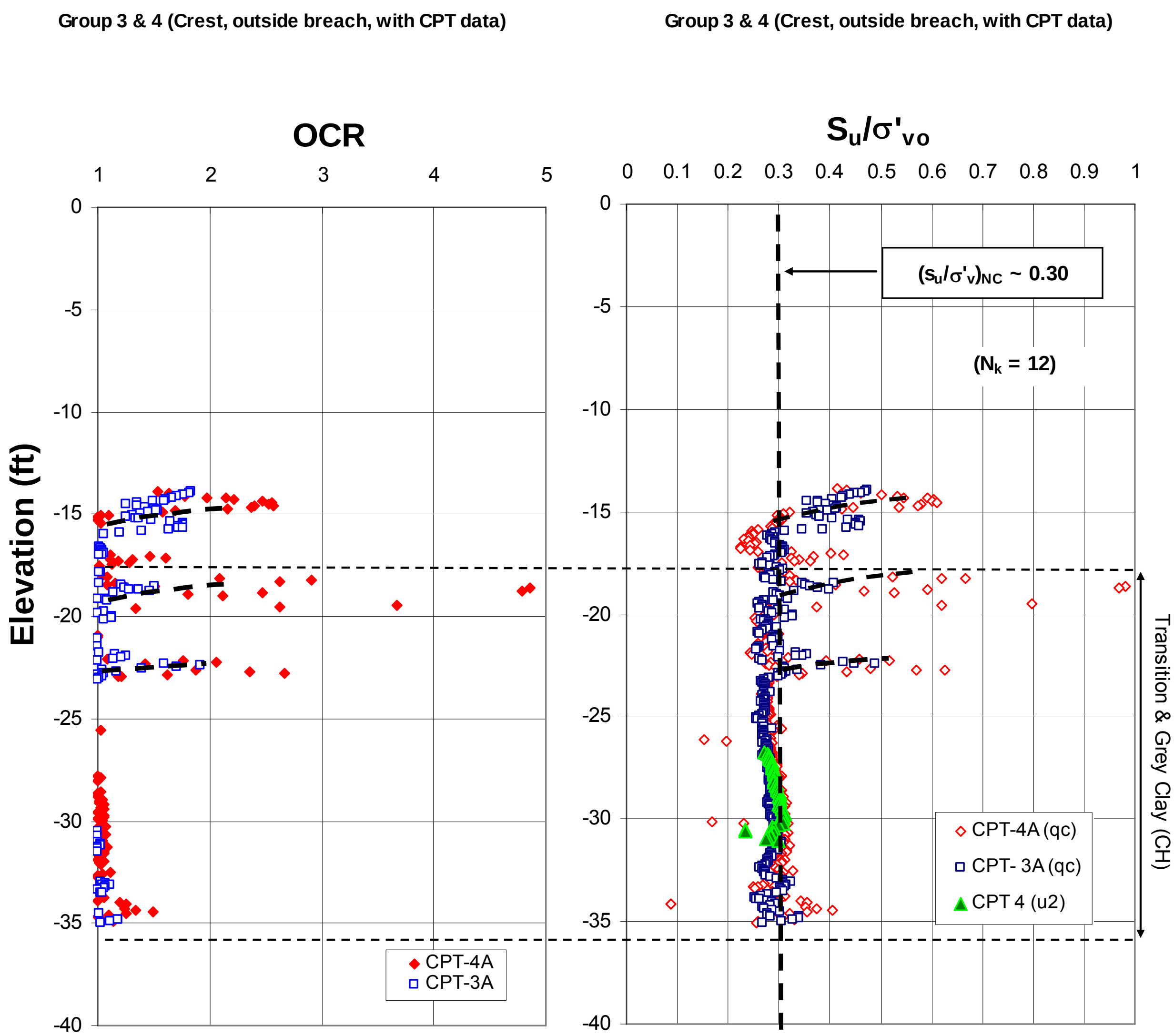


Figure 8.40: Plots of (a) OCR vs. Depth and (b) S_u vs. Depth for the soft gray marsh clay (CH) beneath the full embankment overburden pressure.

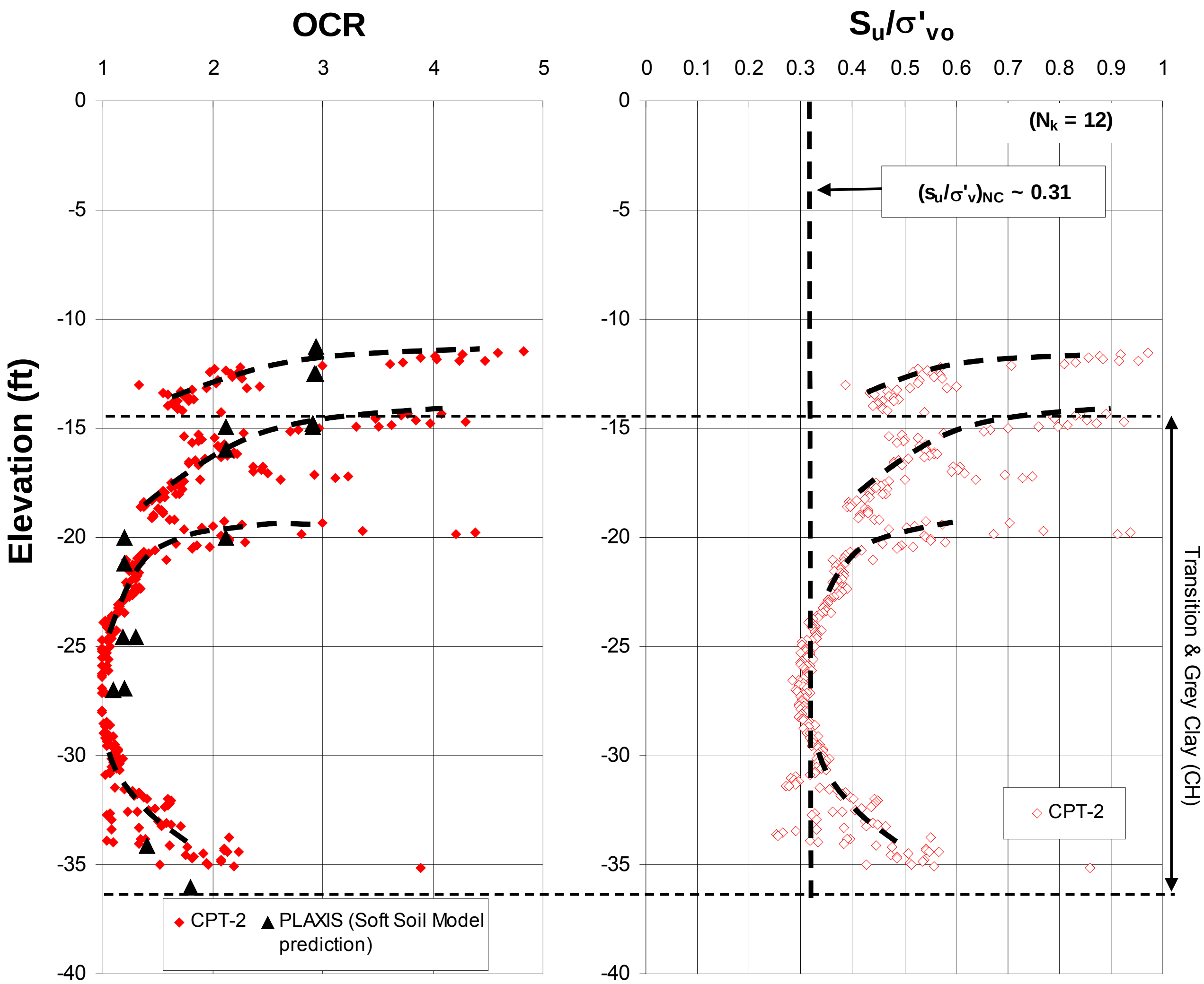


Figure 8.41: Plots of (a) OCR vs. Depth and (b) S_u vs. Depth for the soft gray marsh clay (CH) at the inboard toe and further to the landside (not under levee embankment overburden pressure) – 17th Street Canal breach site.

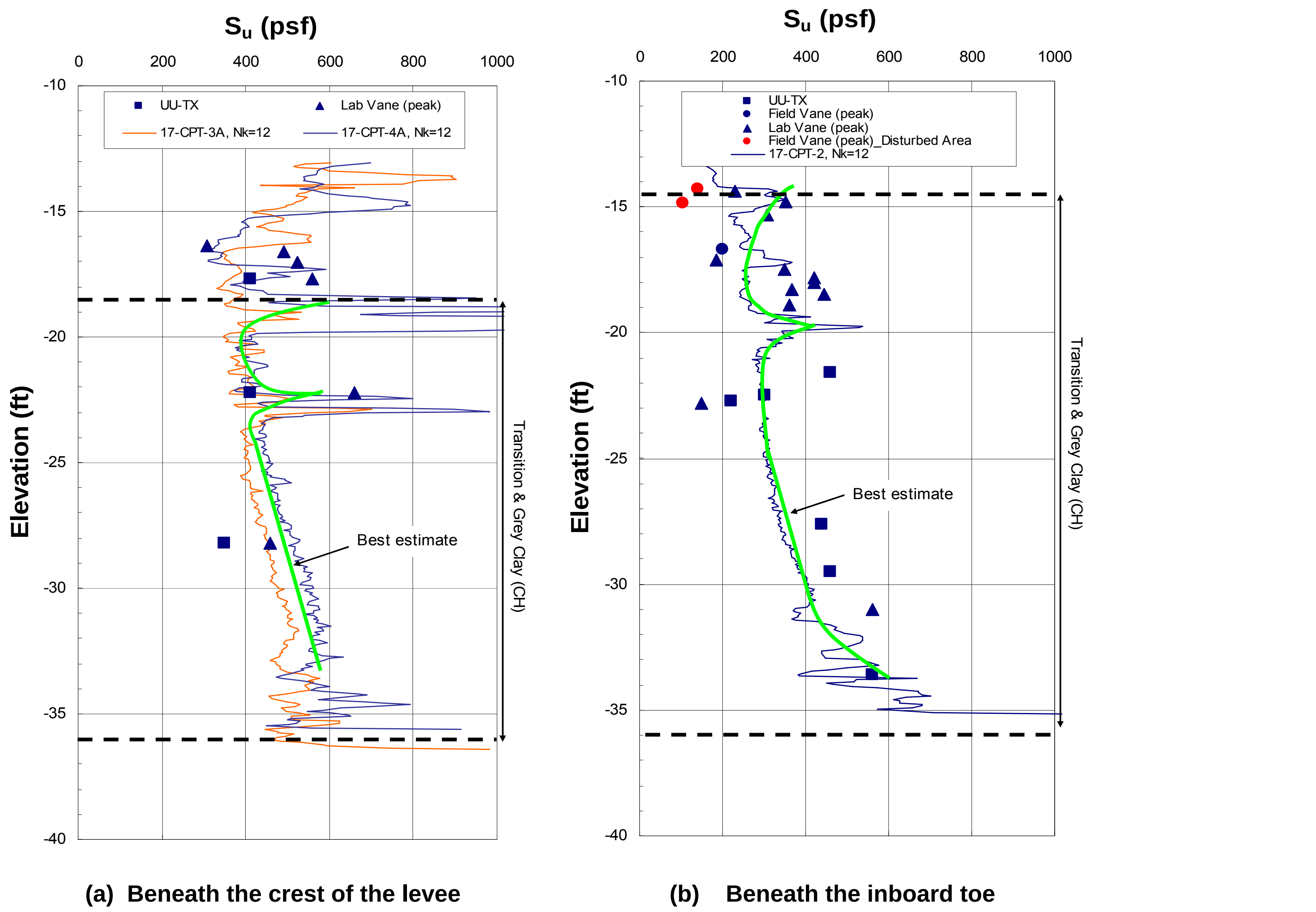
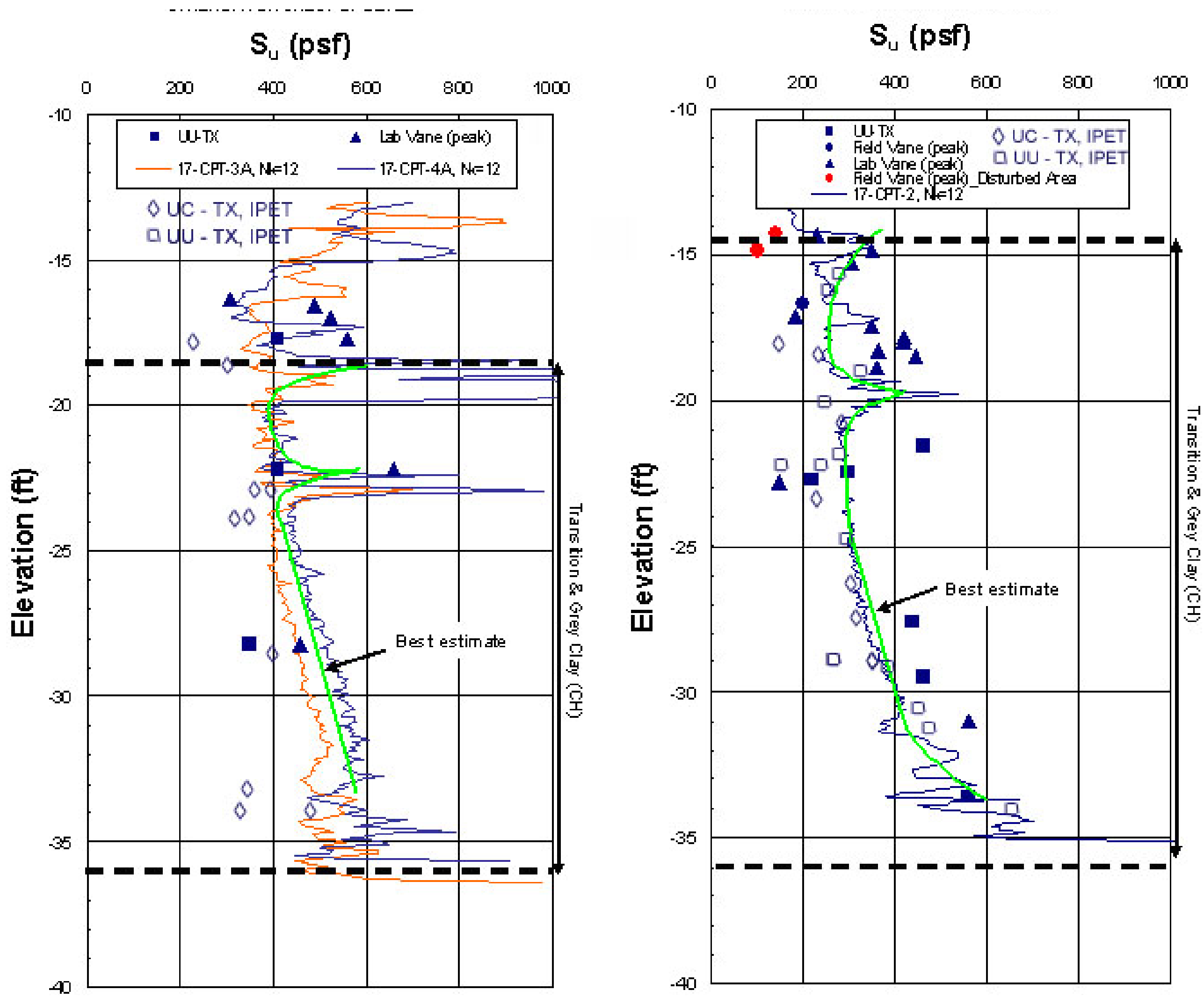


Figure 8.42: Profiles of shear strength vs. depth within the soft gray foundation clay at the 17th Street Canal breach site (a) beneath the crest of the levee, and (b) inboard of the toe of the levee.



a) beneath the crest

b) at or near inboard toe of levee

Figure 8.43: Profiles of shear strength vs. depth within the soft gray foundation clay at the 17th Street Canal breach site (a) beneath the crest of the levee, and (b) at and near the inboard toe of the levee, including the ILIT, IPET and pre-Katrina data.

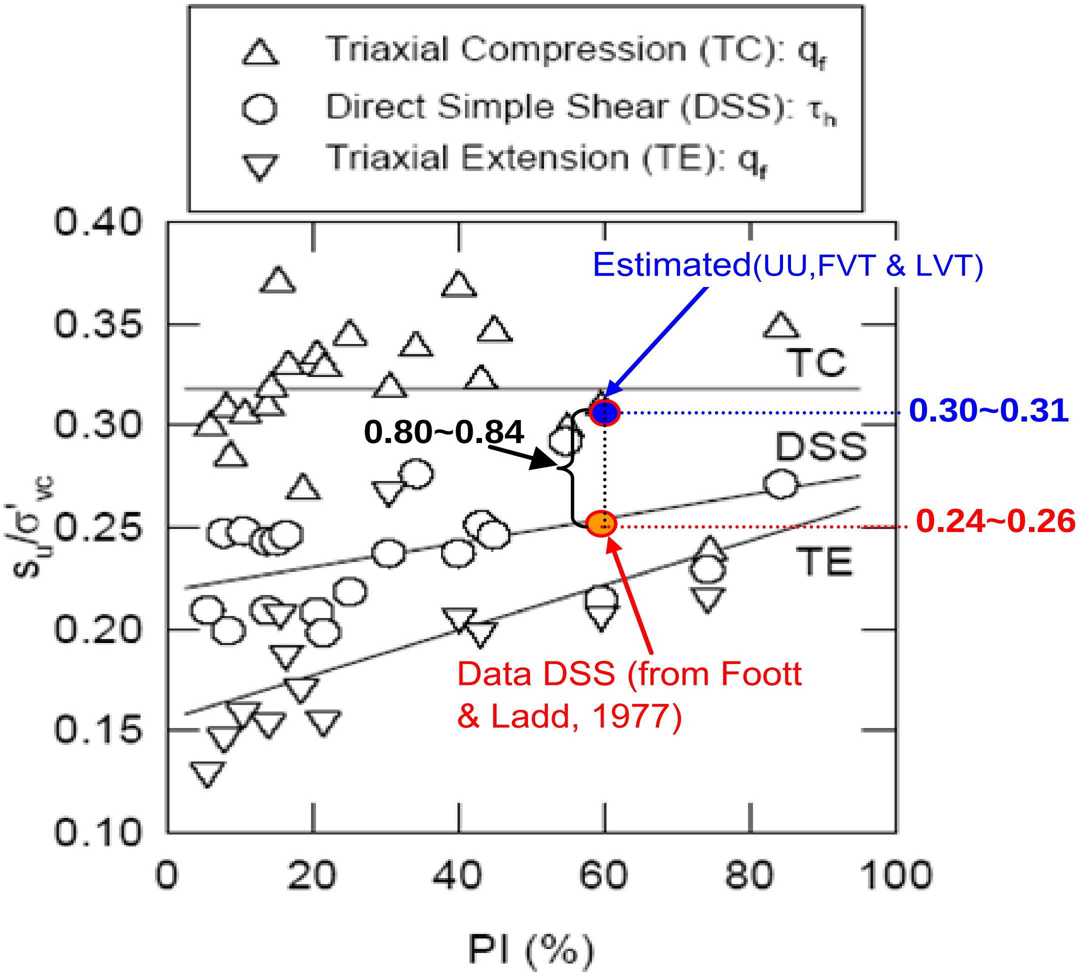


Figure 8.44: Undrained shear strength for UU-triaxial loading vs. undrained shear strength for DSS loading. [Base figure from Ladd, 2003]

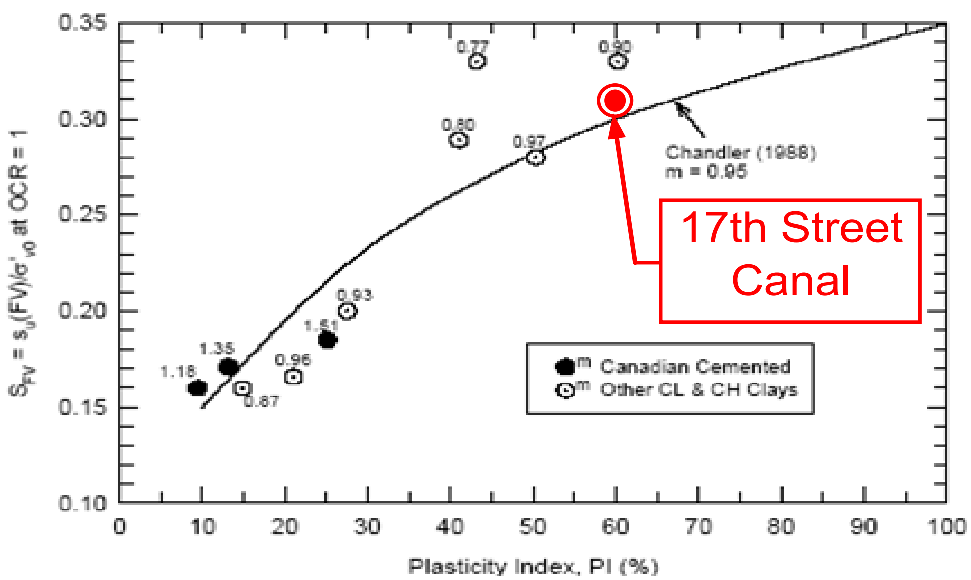


Figure 8.45: Su/P for in situ field vane testing vs. Plasticity Index (PI) for normally consolidated clays (OCR = 1). [Base Figure from Ladd, 2003]

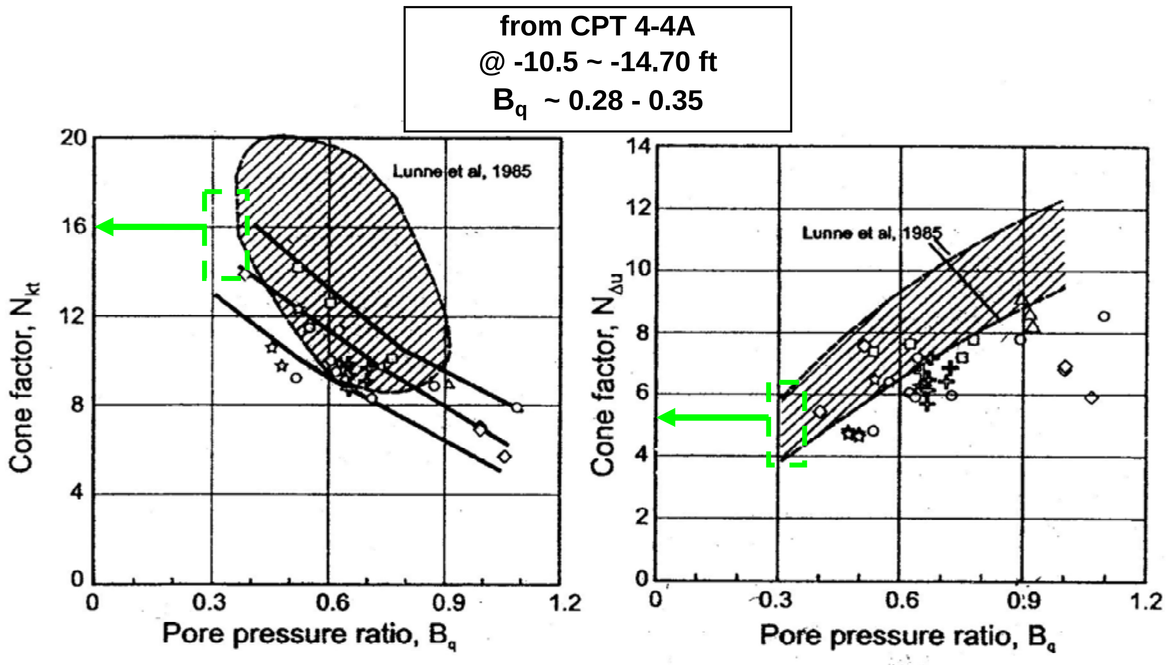
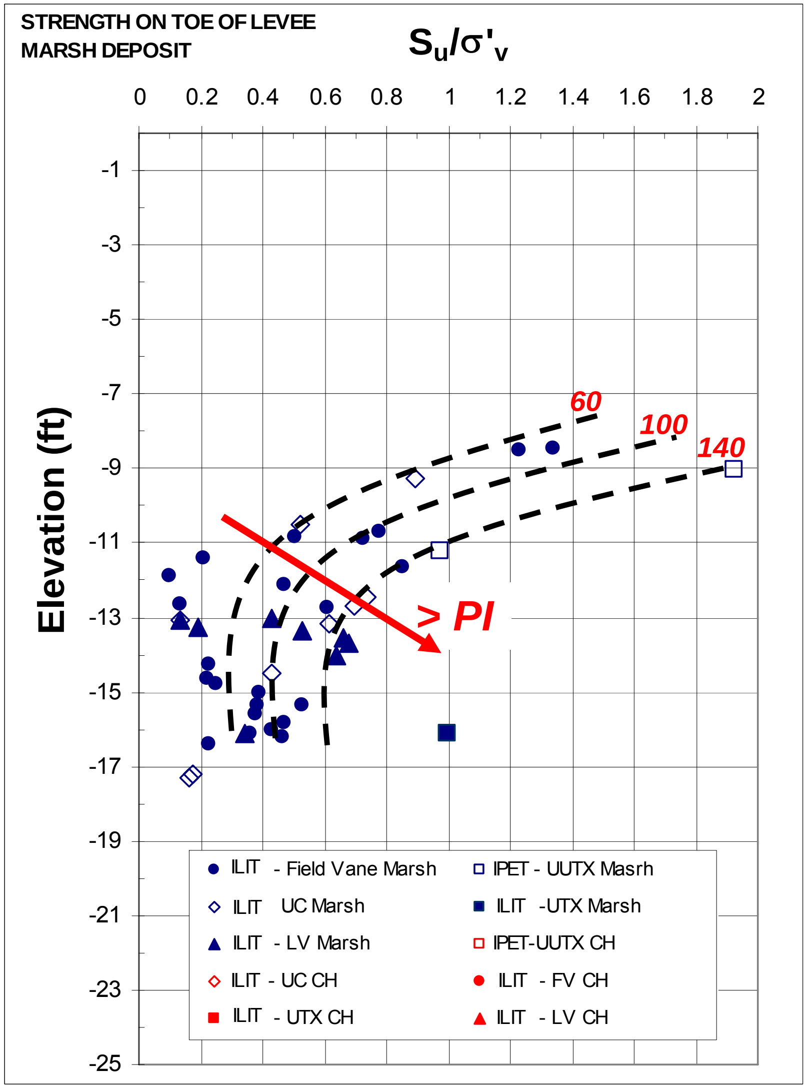


Figure 8.46: CPT cone factor N_{kt} based on B_q (after Lunne et al., 1985 and Karlsrud et al., 1996) for the marsh deposits under full embankment overburden load; 17th Street Canal breach site.



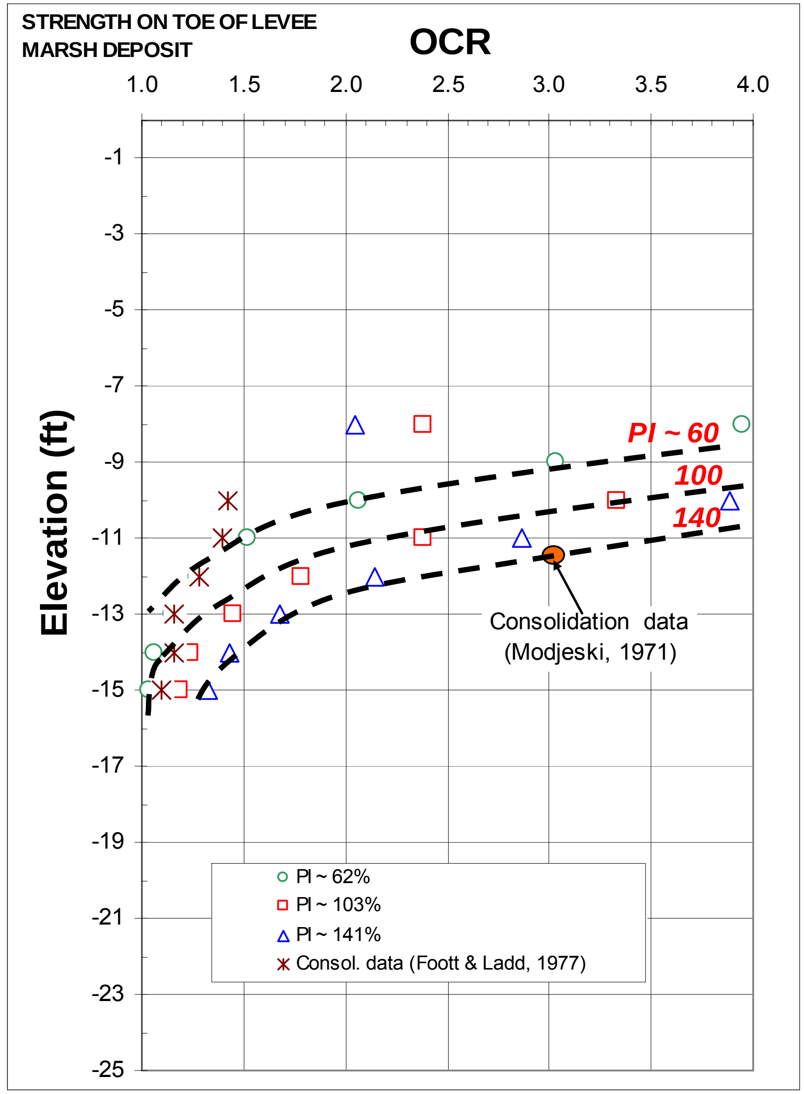
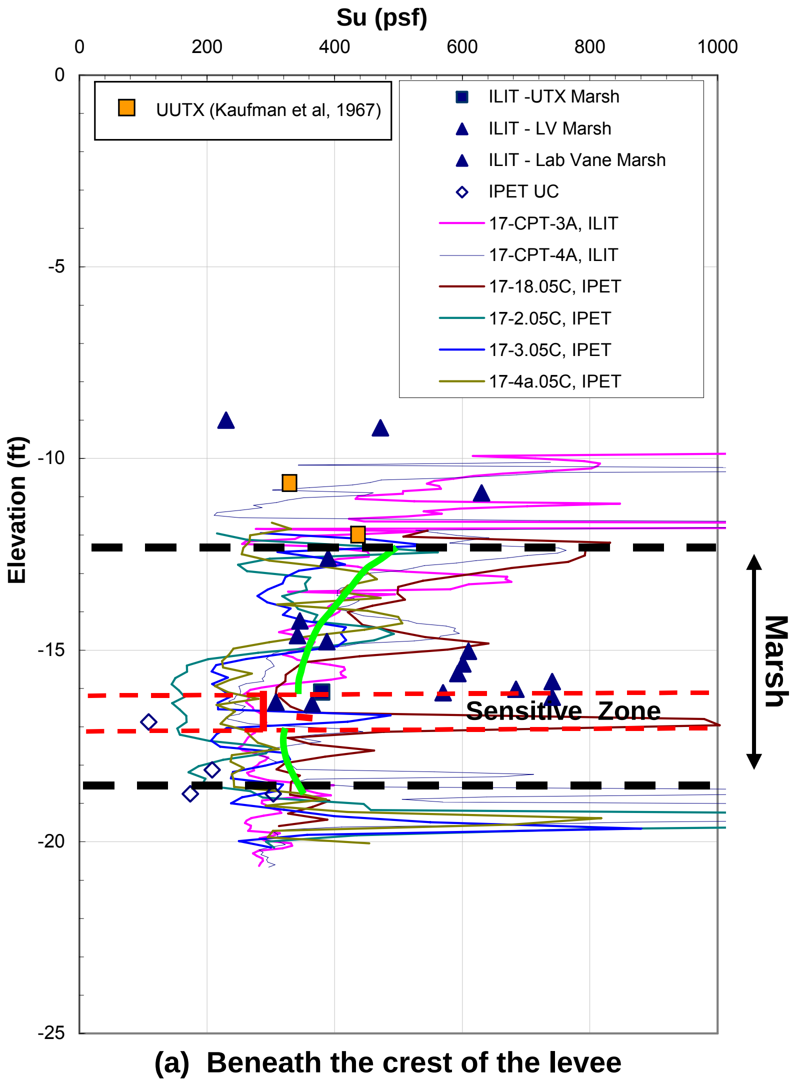


Figure 8.47: Undrained shear strength vs. depth, and OCR vs. depth, within the marsh deposits beneath the inboard toe based on Mayne and Mitchell (1988) – 17th Street Canal breach site.



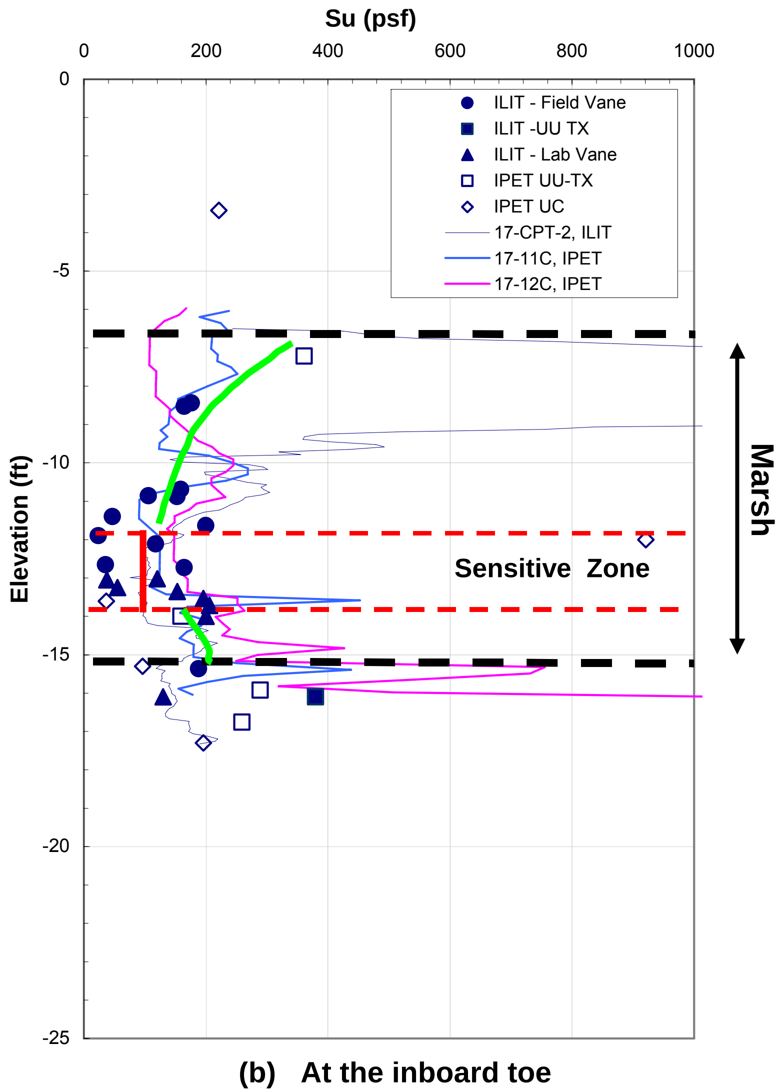


Figure 8.48: Shear strength vs. depth within the marsh deposits at the 17th Street Canal breach site (a) beneath the crest of the levee, and (b) at the inboard toe.

Figure 8.49: Shiny dark brown to black sensitive organic clay on auger stem and (inset) closeup view of leaves and twigs; 17th Street Canal breach site.

Figure 8.50: Shear zone within disturbed area, middle of 17th Street Canal breach, adjacent to displaced block at Elev. -9 feet (MSL).

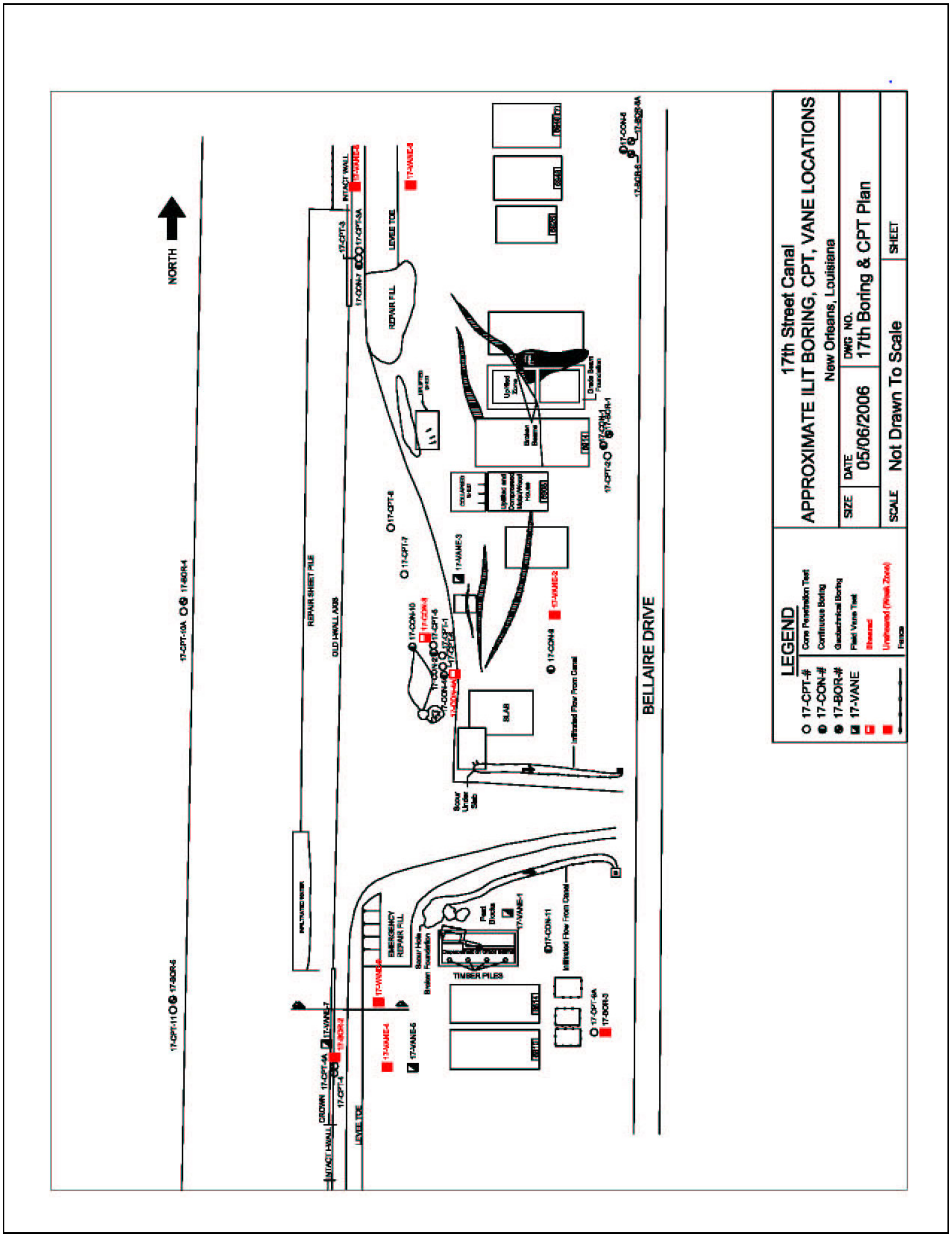


Figure 8.51: Plan view of the 17th Street Canal breach site showing locations at which the shear zone and/or the "sensitive layer" within the marsh deposits was positively identified, sampled, or tested.

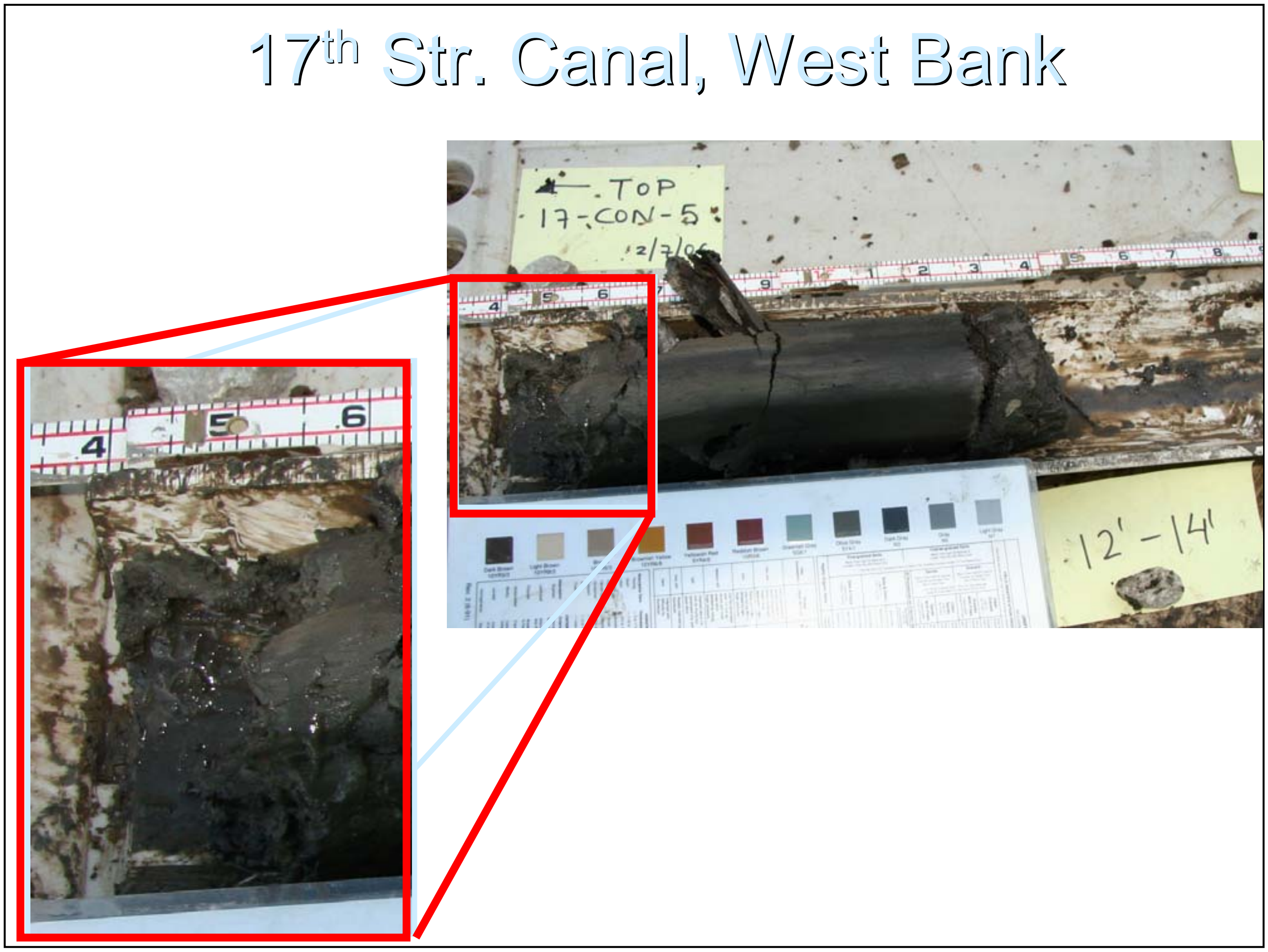


Figure 8.52: Photo of an "undisturbed" sample of the sensitive organic silty clay.

Figure 8.53: Laboratory vane shear testing of the thin layer of sensitive organic silty clay.

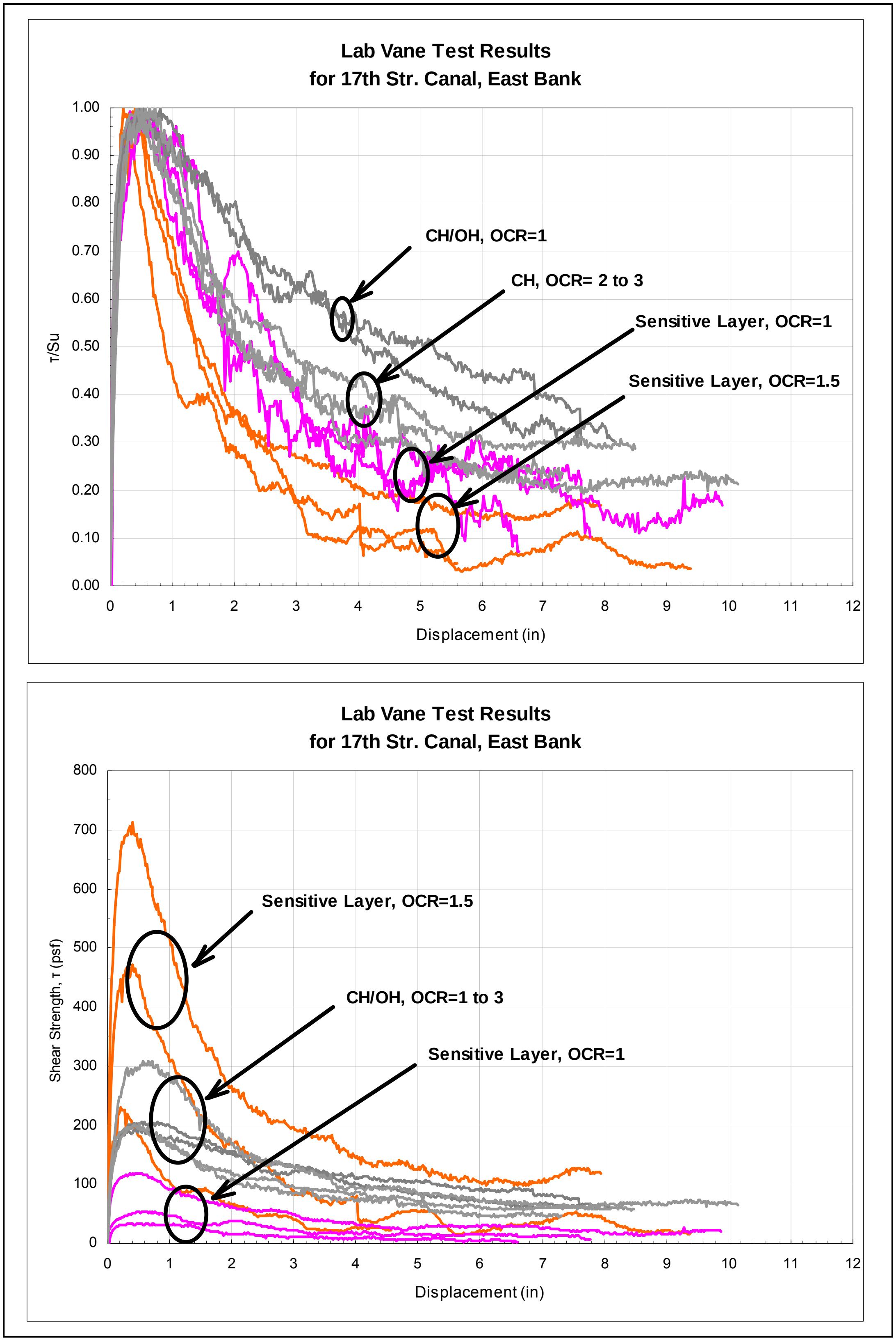


Figure 8.54: Stress-displacement behavior for soft gray clay (CH and CH/OH) and "sensitive" layer of organic clay within marsh deposit.

Geotechnical parameters for the Finite Element Analysis Model

ID	Soil Model	Name	Type	g_unsat [lb/ft^3]	g_sat [lb/ft^3]	k_x [ft/day]	k_y [ft/day]	nu [-]	E_ref [lb/ft^2]	c_ref [lb/ft^2]	phi [°]
CF	Mohr Coulomb	ML-silt (Compacted Fill)	Undrained	105	115	0.0028	0.00028	0.35	234000	900	0.001
Upper CH		CH-Upper Fat Clay	Undrained	90	95	0.00028	0.000028	0.35	180000	600	0.001
SC		SC (Sand)	Drained	110	110	0.28	0.28	0.30	1000000	0.01	38

ID	Soil Model	Name	Type	g_unsat [lb/ft^3]	g_sat [lb/ft^3]	k_x [ft/day]	k_y [ft/day]	lambda* [-]	kappa* [-]	n_ur [-]	K0nc [-]	M [-]	c_ref [lb/ft^2]	phi @ pref [°]	OCR
M2	Soft Soil	Marsh 2	Undrained	80	80	28.3	2.8	0.21	0.033	0.15	0.60	1.90	0	36	2.25
M1		Marsh 1	Undrained	80	80	28.3	2.8	0.21	0.033	0.15	0.60	1.90	0	36	1.1
IZ		Intermixing zone	Undrained	85	85	28.32	2.8	0.10	0.02	0.15	0.61	1.27	0	23	3
CH1		Grey Clay	Undrained	90	95	0.00028	0.000028	0.17	0.03	0.15	0.63	1.24	0	22	2.2
CH2-a		Grey Clay	Undrained	90	95	0.00028	0.000028	0.17	0.03	0.15	0.63	1.24	0	22	1.25
CH2-b		Grey Clay	Undrained	90	95	0.00028	0.000028	0.17	0.03	0.15	0.63	1.24	0	22	1.5

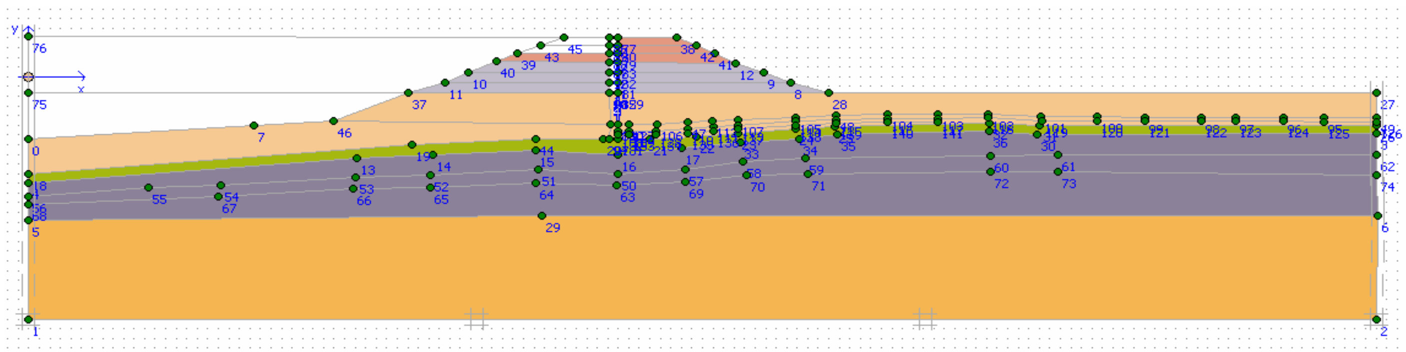


Figure 8.55: Parameters (and model) used in PLAXIS model for the 17th Street Canal breach site.

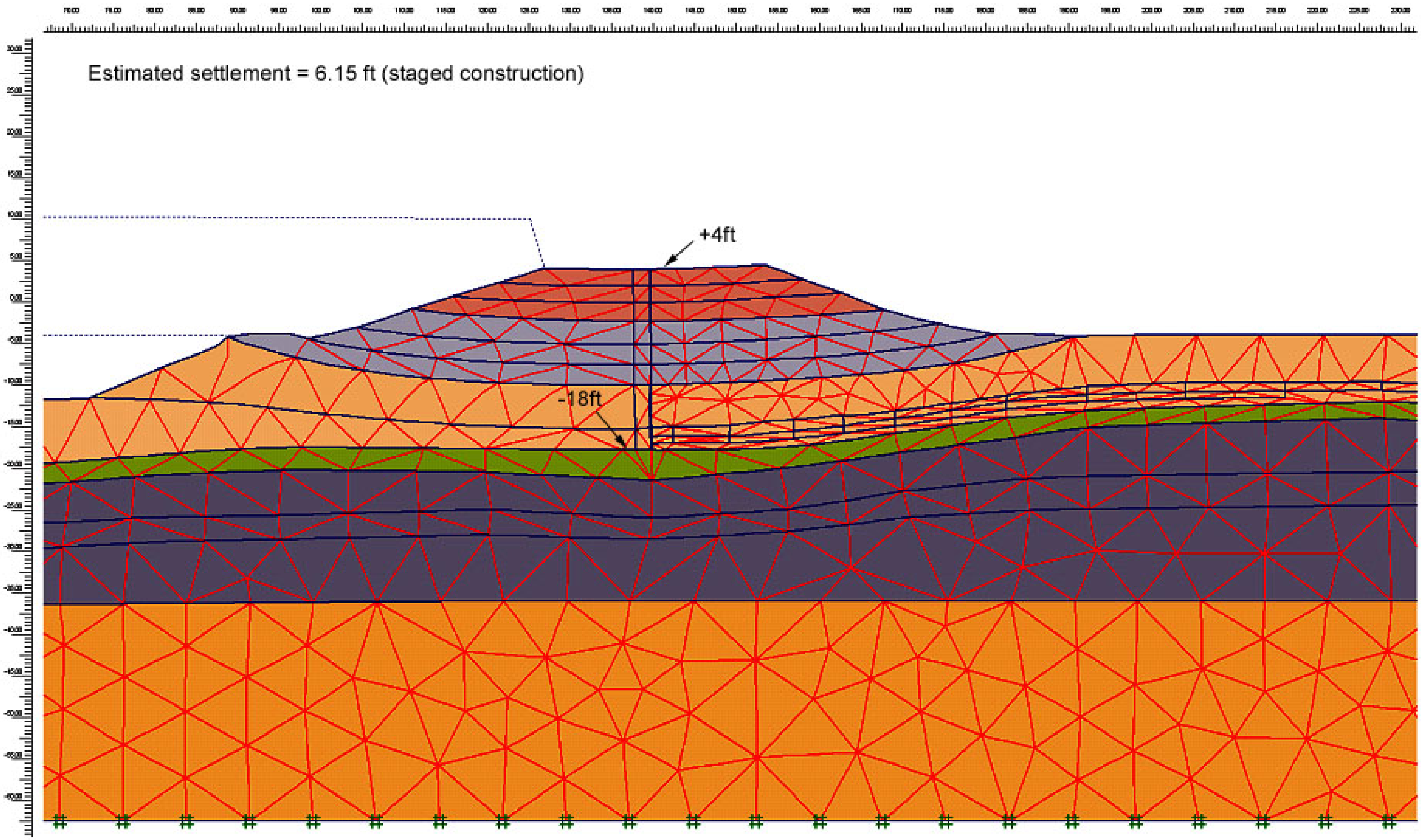


Figure 8.56: Deformed mesh at the end of initial construction of embankment and consolidation; 17th Street Canal breach section.

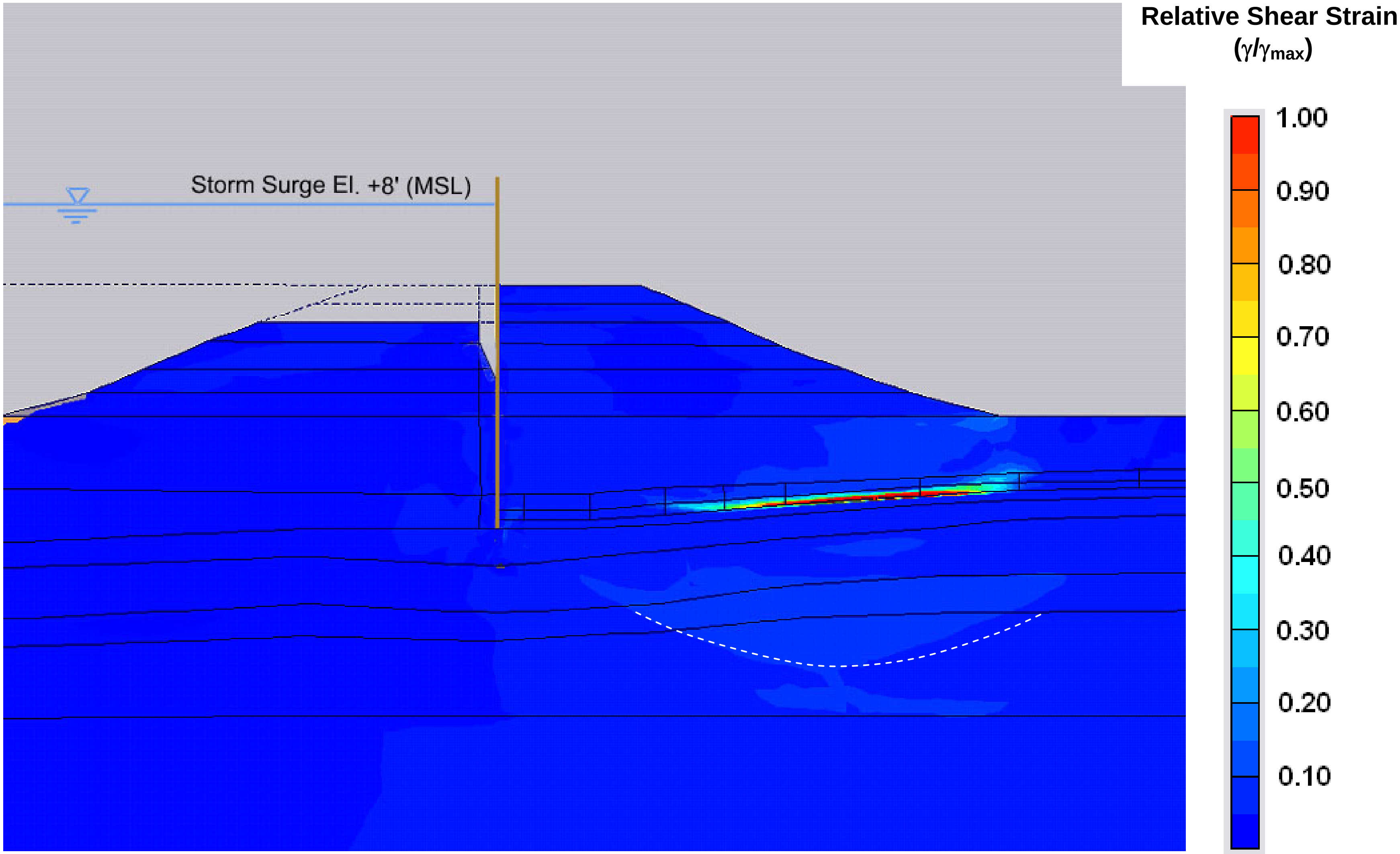


Figure 8.57: Normalized shear strain contours (shear strain divided by strain to failure) for a storm surge at Elev. + 8 feet (MSL) At the 17th Street Canal breach site; initiation of gapping at outboard toe of floodwall.

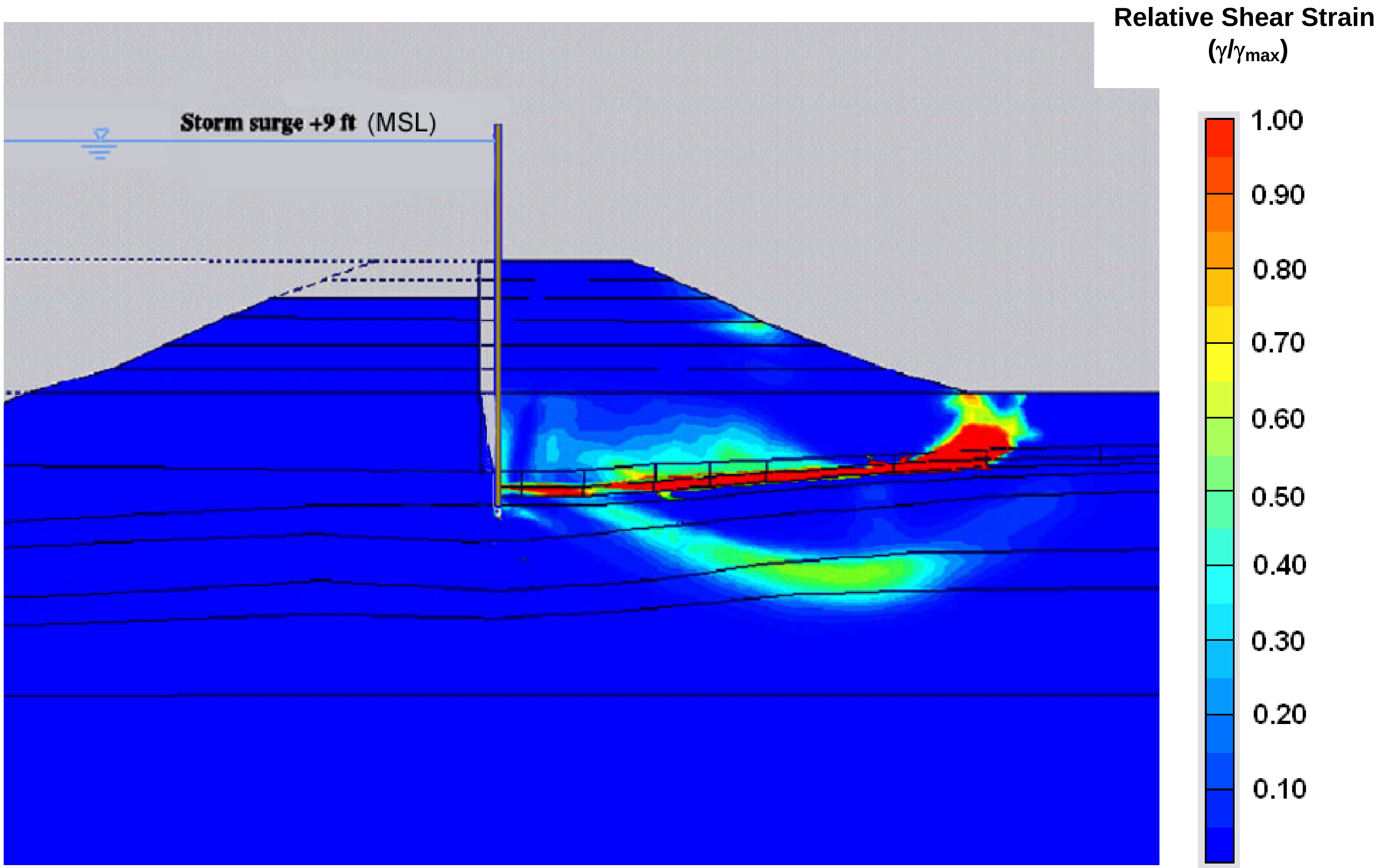


Figure 8.58: Normalized shear strain contours (shear strain divided by strain to failure) for a storm surge at Elev. + 8 feet (MSL) at the 17th Street Canal breach site; gapping at outboard toe of floodwall is now developed to full depth.

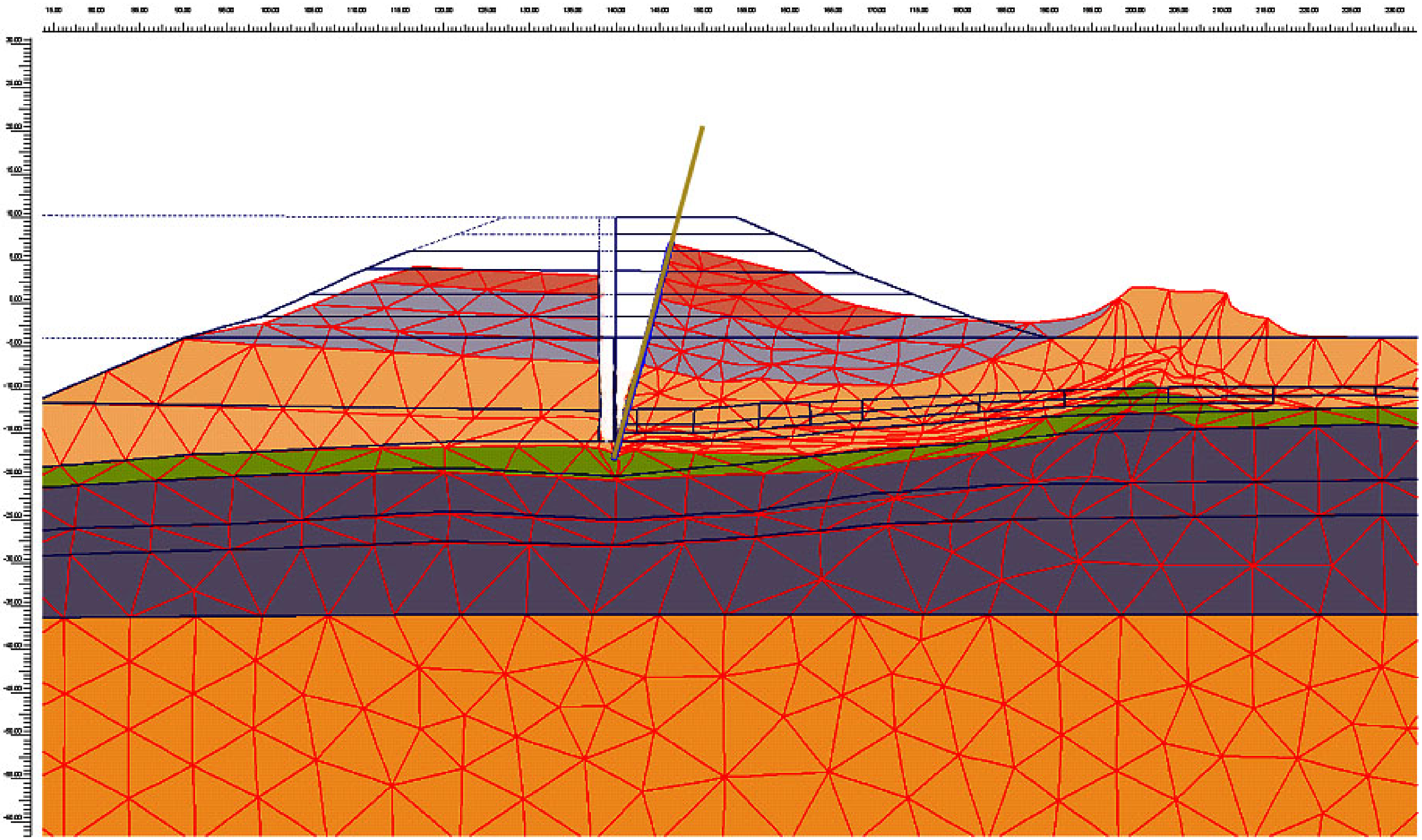


Figure 8.59: Displaced mesh for storm surge height at Elev. + 8.5 feet (MSL) at the 17th Street Canal breach site; displacements are increased by a factor of 3 in this figure.

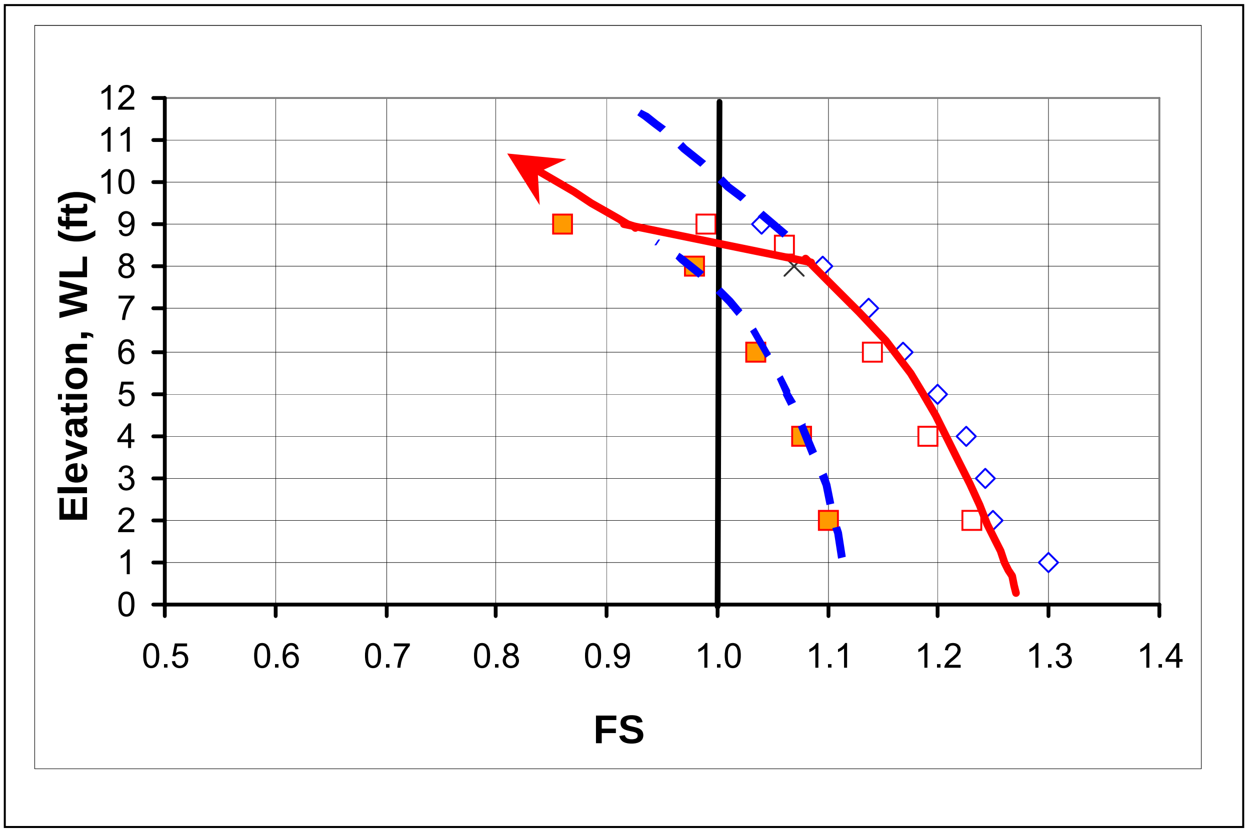


Figure 8.60: Calculated Factors of Safety for three modes based on PLAXIS analyses of the 17th Street Canal breach section for various canal water elevations; showing the best-estimated path to failure.

ID	Soil Model	Type	γ [lb/ft^3]	c [lb/ft^2]	phi [°]	Su/p'
Upper fill	Mohr-Coulomb	Undrained	110	800	0	
Lower fill	Mohr-Coulomb	Undrained	85	550	0	
Marsh, beneath crest	Mohr-Coulomb	Undrained	80	375	0	
Marsh, free field	Mohr-Coulomb	Undrained	80	200	0	
Sensitive layer, beneath crest	Mohr-Coulomb	Undrained	80	240	0	
Sensitive layer, beneath toe	Mohr-Coulomb	Undrained	80	180	0	
Sensitive layer, free field	Mohr-Coulomb	Undrained	80	70	0	
Overconsolidated Grey CH	Mohr-Coulomb	Undrained	90	400	0	
Normally consolidated Grey CH	SHANSEP	Undrained	90			0.26
Sand	Mohr-Coulomb	Drained	110	0	33	

Geotechnical Parameters for the Limit Equilibrium Analyses for 17th Street Canal levee, East Bank.

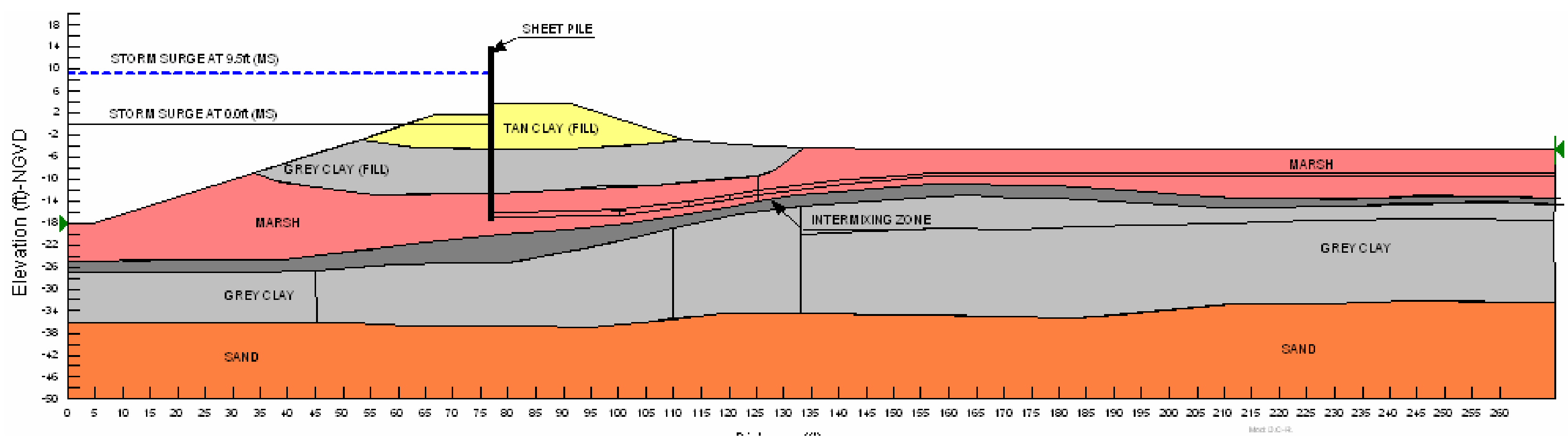


Figure 8.61: Cross-section and parameters used for conventional stability analyses of the breach section on the east side of the 17th Street Canal.

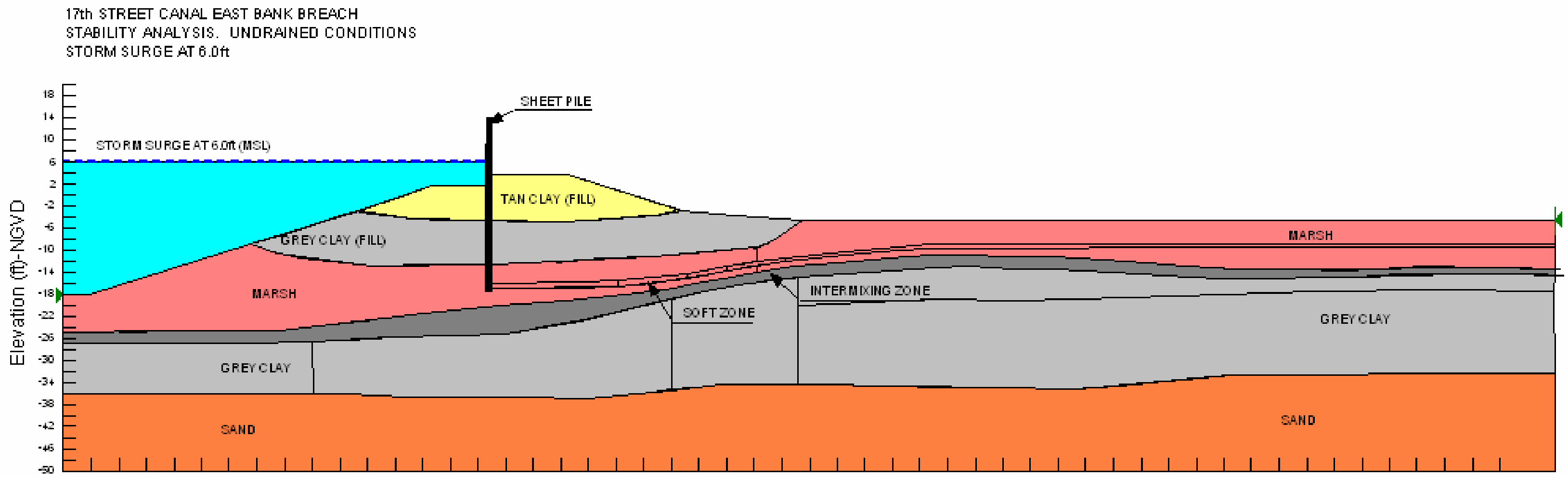


Figure 8.62: Cross-section at 17th Street Canal breach site for static slope stability analyses.

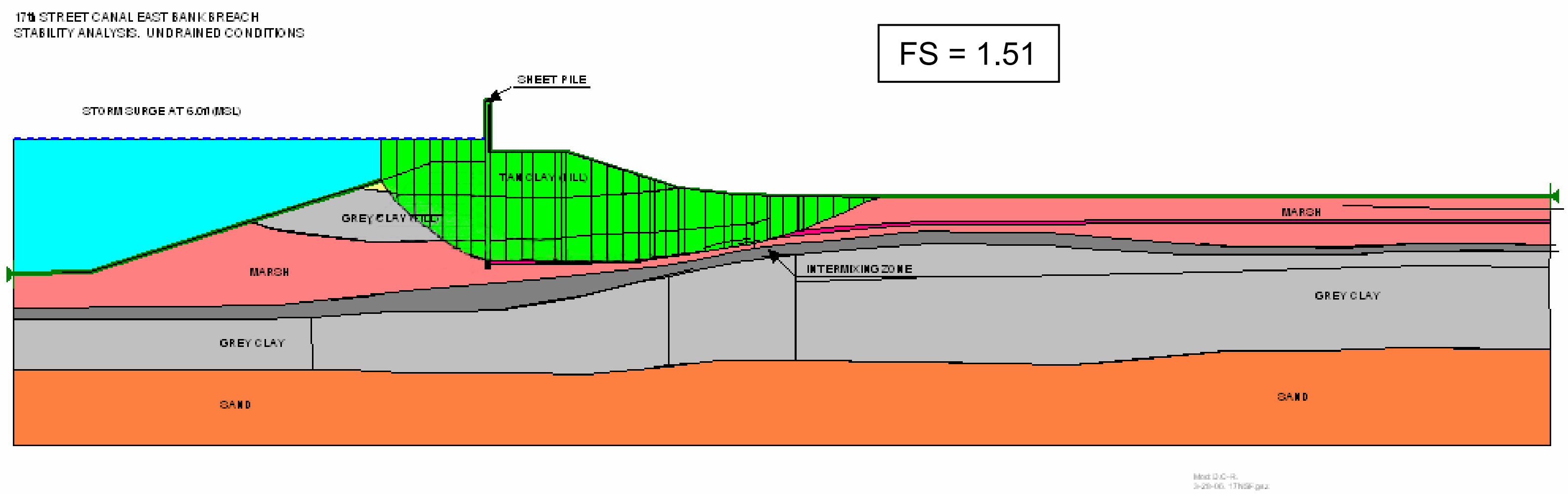


Figure 8.63: Stability analysis (worst case) for storm surge to Elev. + 6 feet (MSL) at the 17th Street Canal breach section.

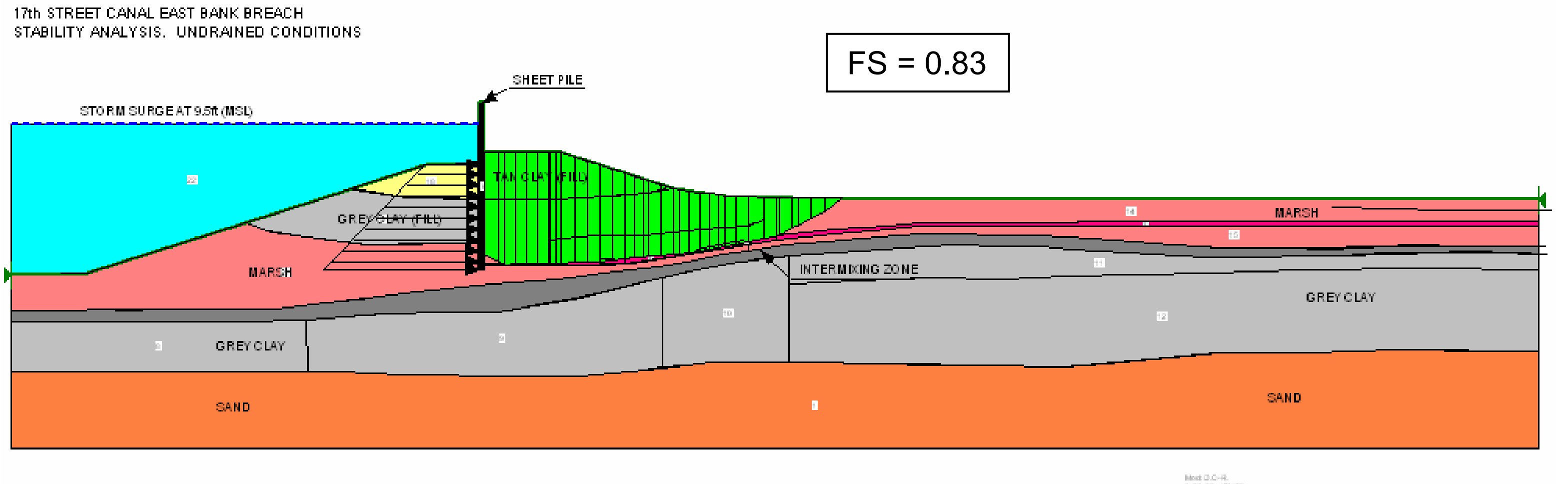


Figure 8.64: Stability analysis for actual observed failure mechanism at the 17th Street Canal breach section, with storm surge at Elev. + 9.5 feet (MSL) and with fully developed crack at the outboard side of the sheetpile/floodwall.

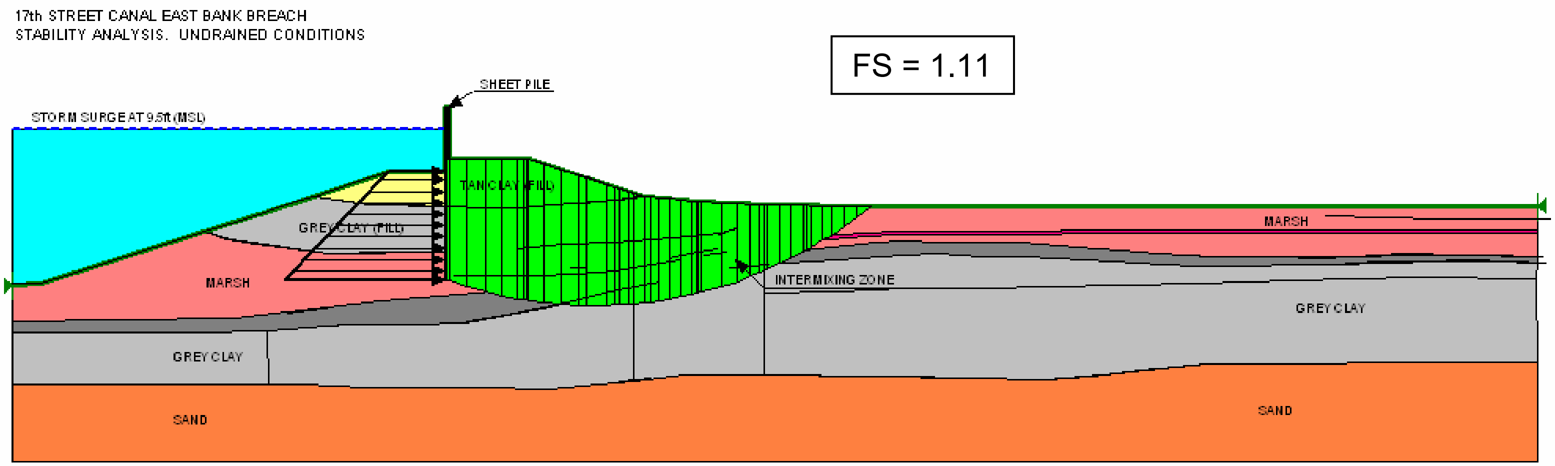


Figure 8.65: Stability analysis for shear failure through the deeper soft gray clays (CH) at the 17th Street Canal breach section, with storm surge at Elev. + 9.5 feet (MSL) and with fully developed crack at the outboard side of the sheetpile/floodwall.

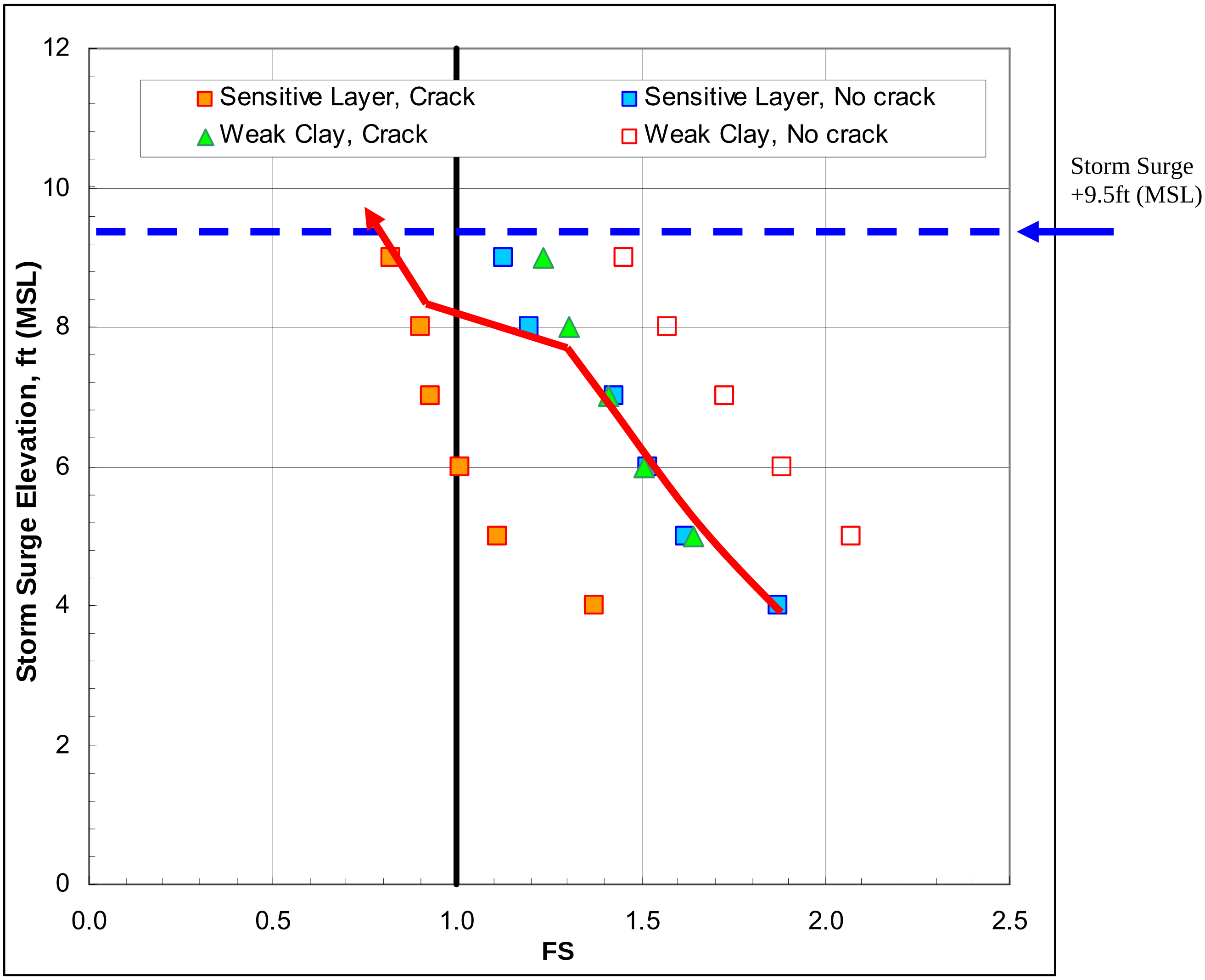


Figure 8.66: Factor of safety for four modes of failure at the 17th Street Canal breach site as a function of canal water elevation based on static slope stability analyses: again showing the best-estimated path to failure.

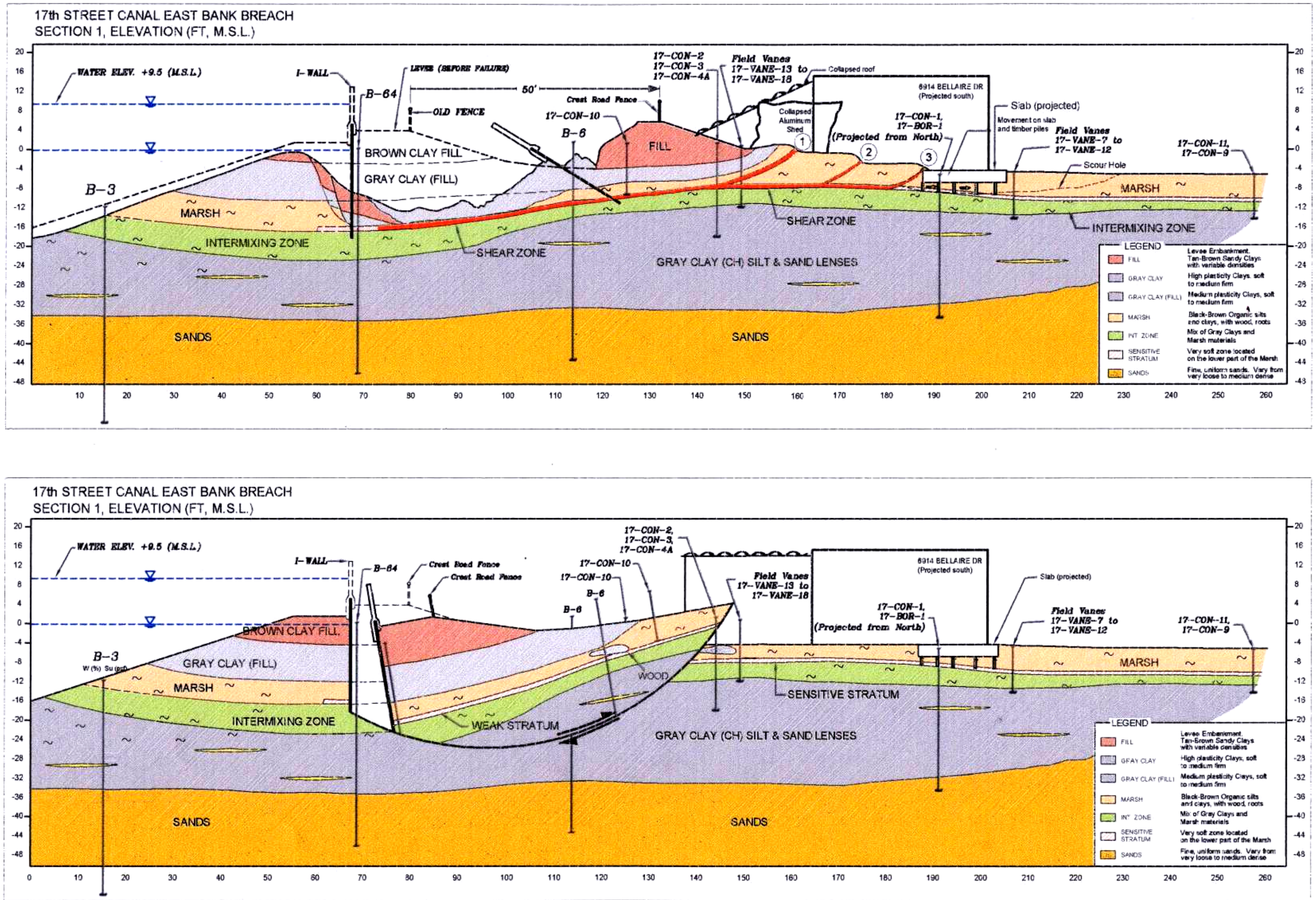


Figure 8.67: Comparison between deep rotational failure through the soft gray clay (CH) and translational failure along the sensitive clay layer within the marsh deposits as actually observed.

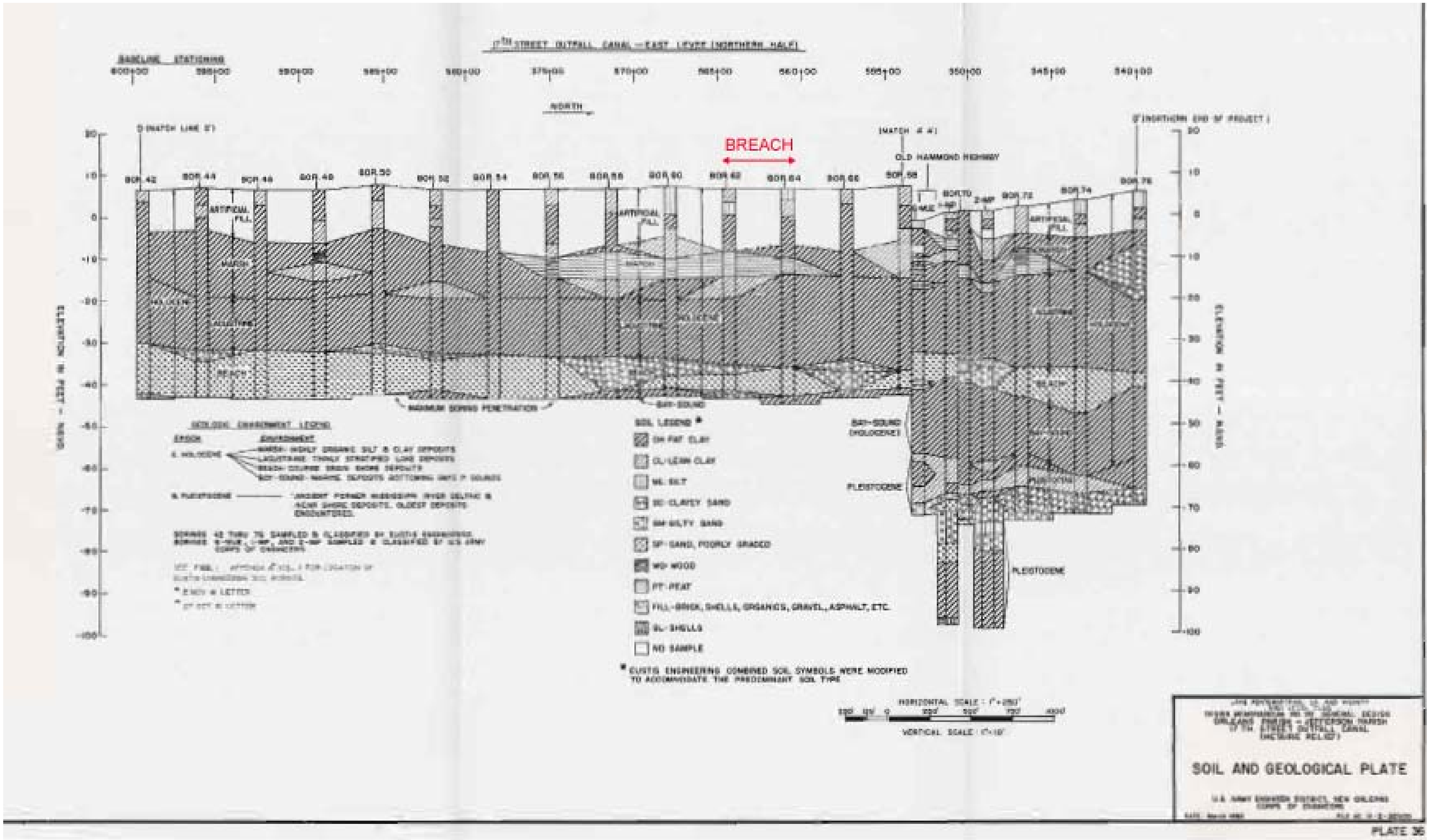


Figure 8.68: Initial longitudinal subsurface profile used for initial design at the 17th Street Canal breach site.
[USACE, DM-20, Vol. 1, 1990]

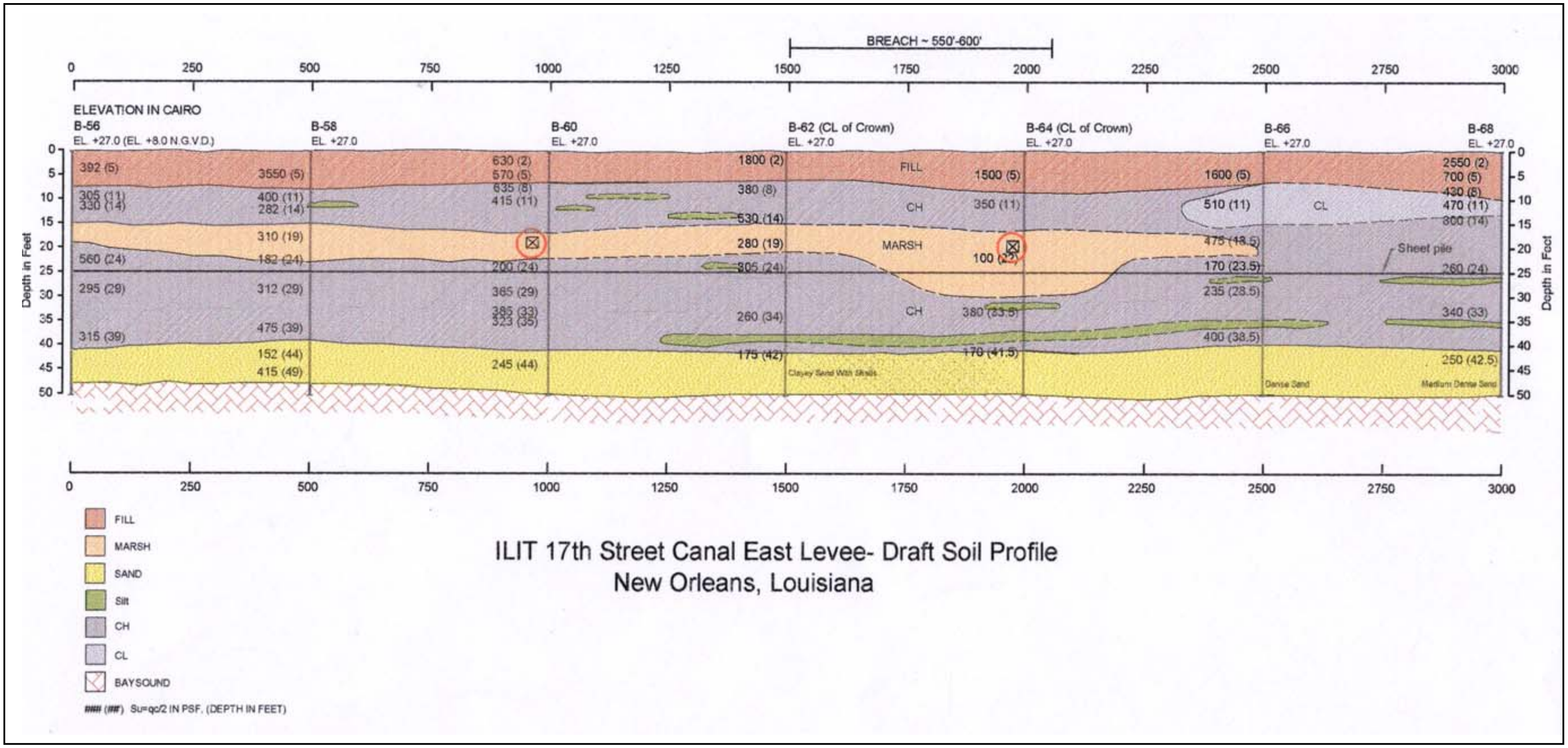


Figure 8.69: Re-interpreted longitudinal subsurface soil profile, showing location of breach section on the east side of the 17th Street Canal, and with non-tested samples highlighted.

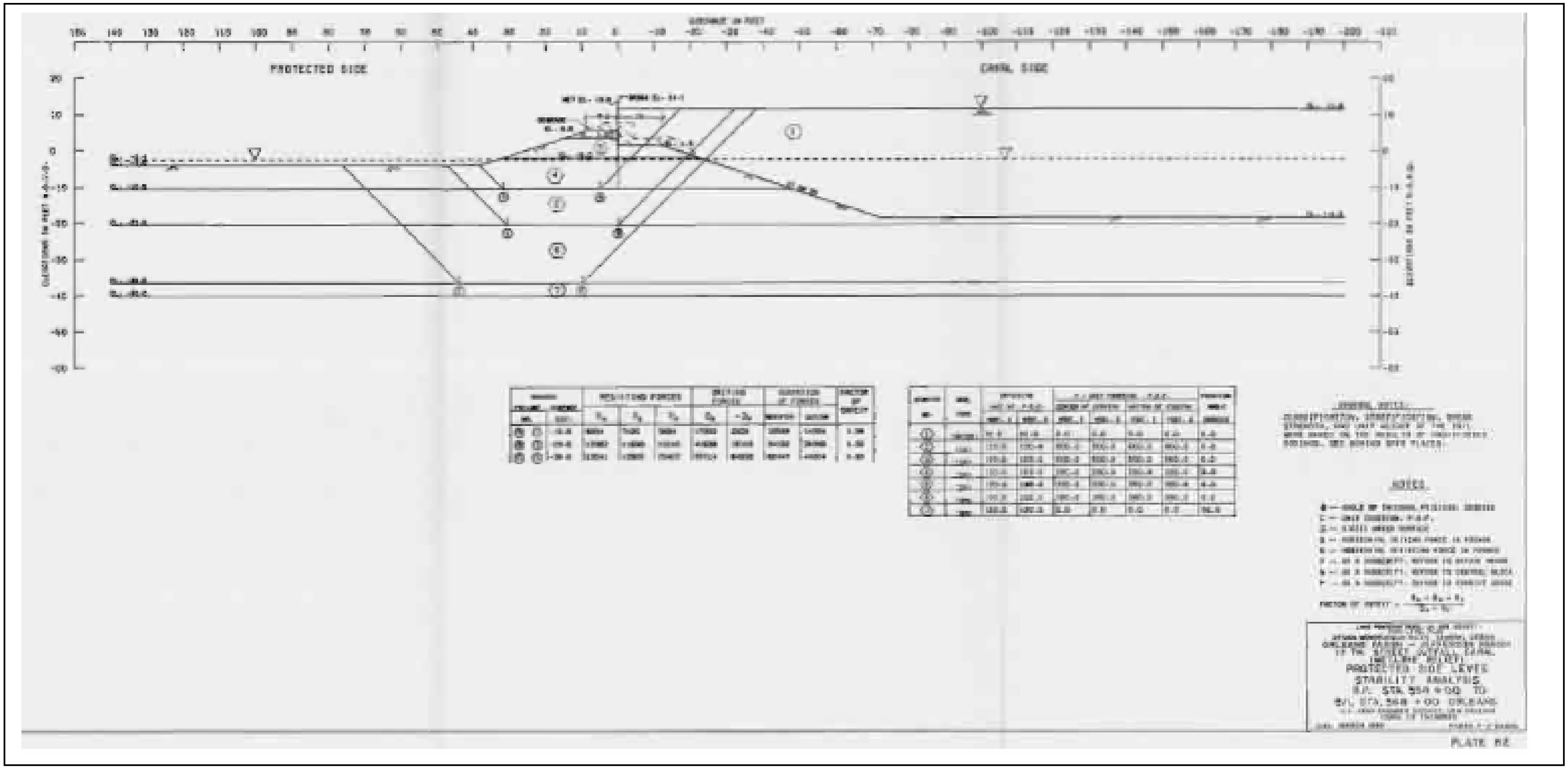


Figure 8.70: Use of the "Method of Planes" in original design stability analysis calculations; 17th Street Canal.
[USACE, DM-20, Vol.1, 1990]

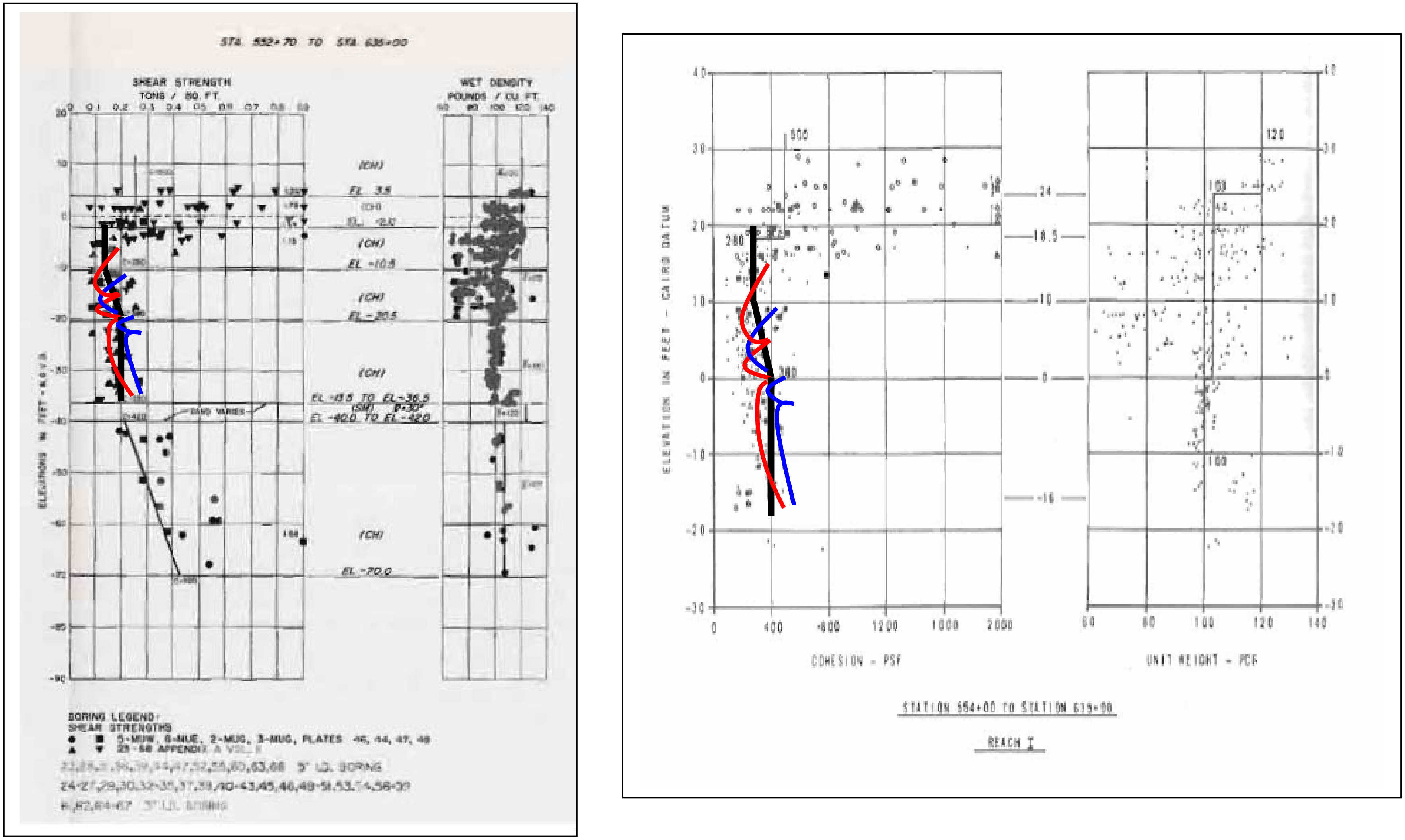
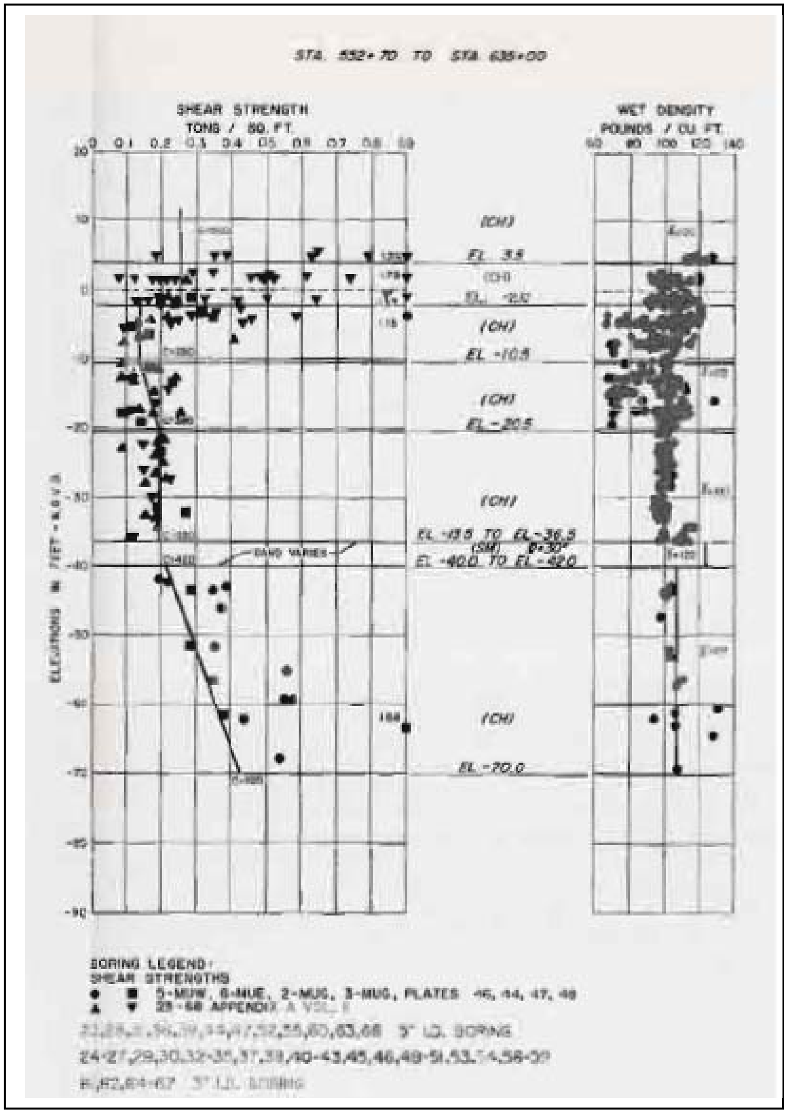


Figure 8.71: Profile of shear strength vs. depth used in original stability analyses for design at the 17th Street Canal breach site, and this investigation team's best estimated profiles of undrained shear strength vs. elevation (a) beneath the centerline of the levee embankment [blue line], and (b) inboard of the toe of the embankment [red line].

[USACE, DM-20, Vol.1 & 2, 1990]



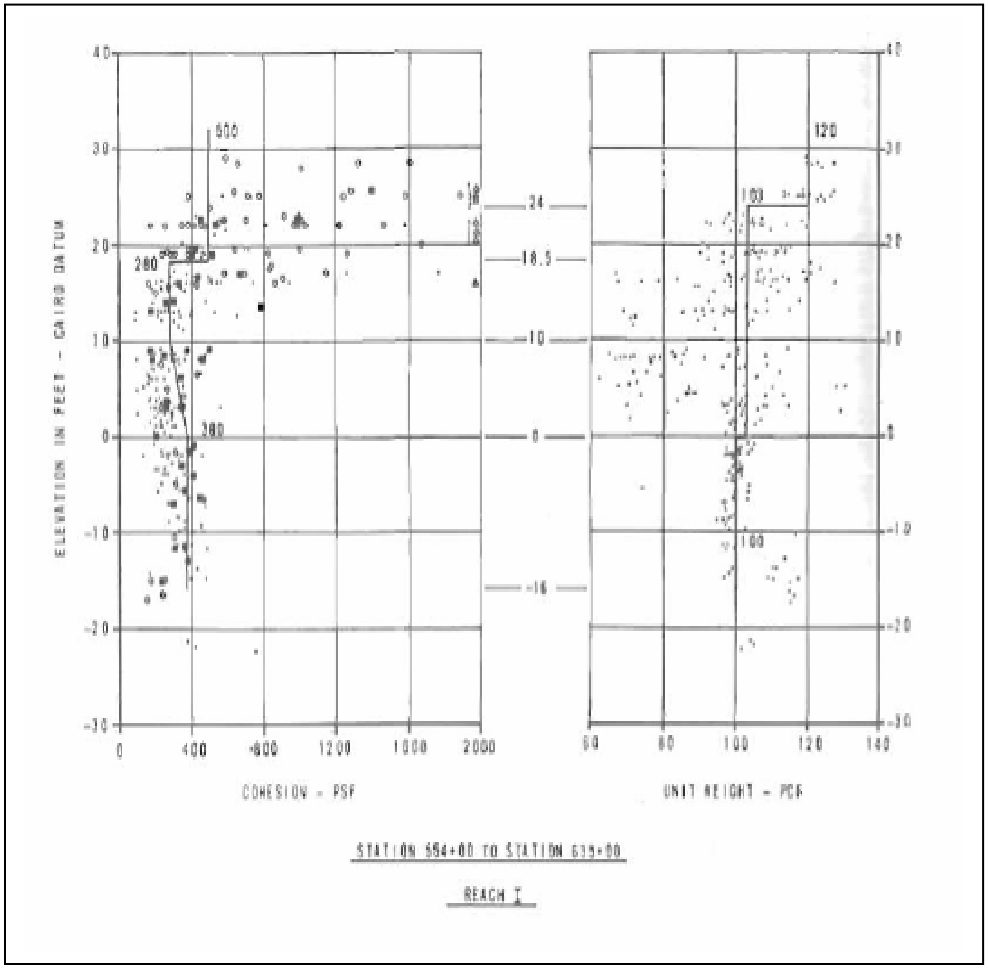


Figure 8.72: Profile of shear strength vs. depth used in original stability analyses for design at the 17th Street Canal breach site. [USACE, DM-20, Vol.1 & 2, 1990]

Figure 8.73: View of floodwall displacement on the west bank of the 17th Street Canal.

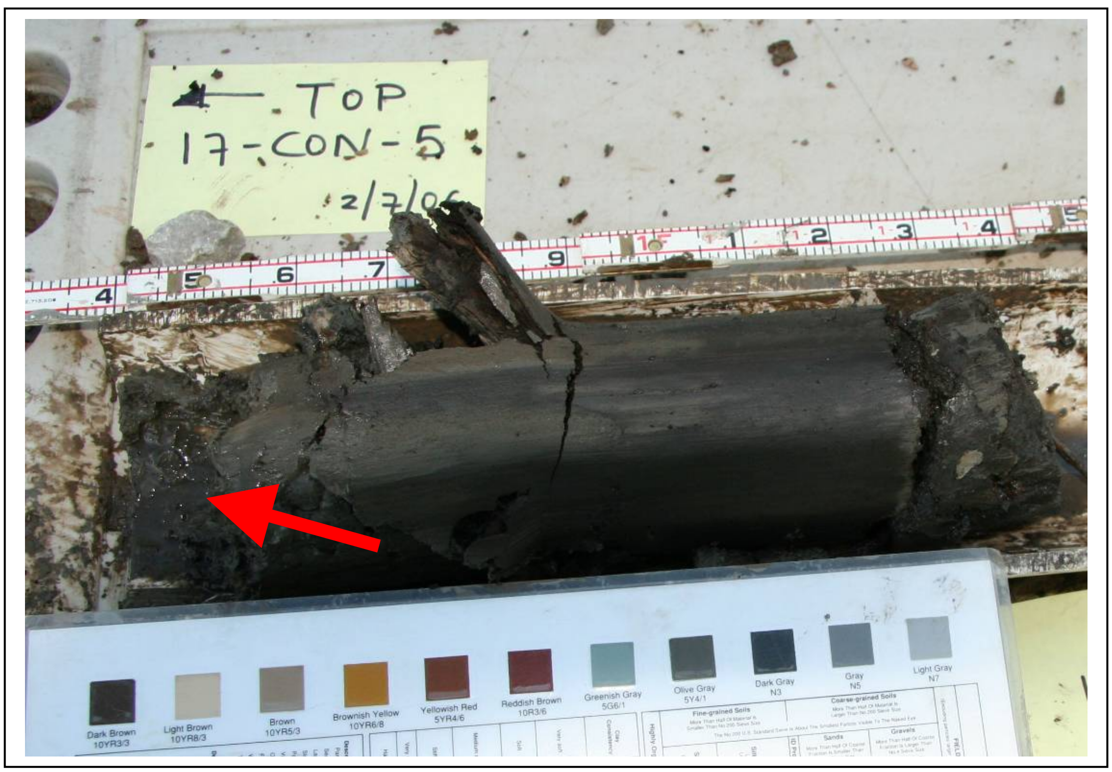


Figure 8.74: View of sample of "sensitive" clay layer within the marsh soils at the west side of the 17th Street Canal.

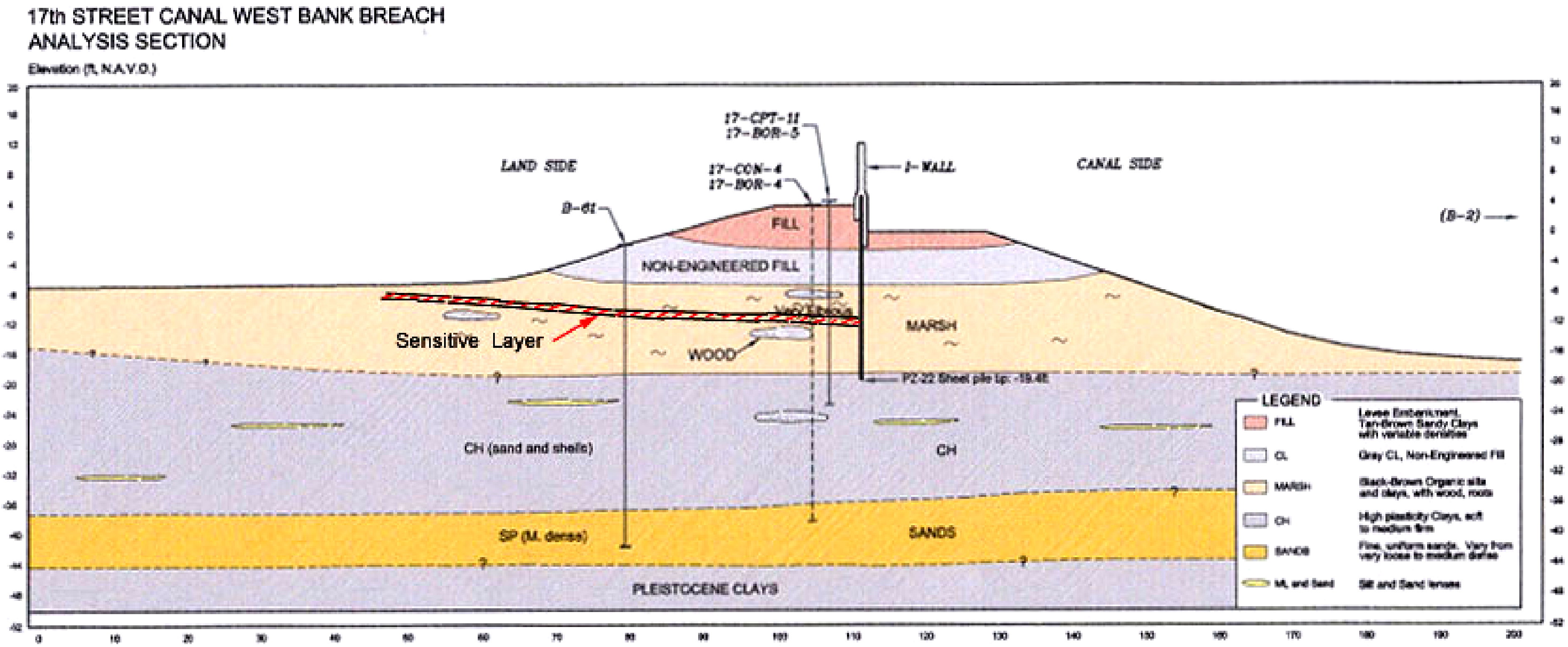


Figure 8.75: Analysis cross-section for the site on the west bank of the 17th Street Canal.

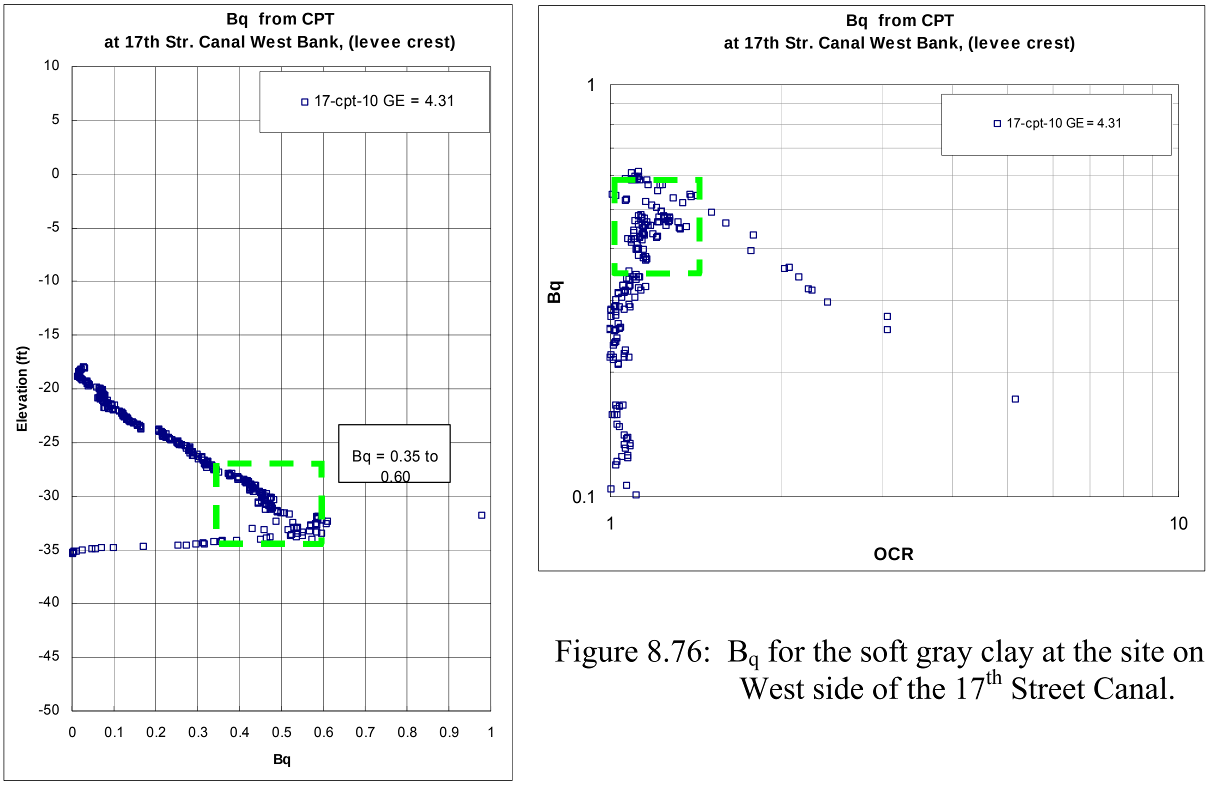


Figure 8.76: B_q for the soft gray clay at the site on the West side of the 17[th] Street Canal.

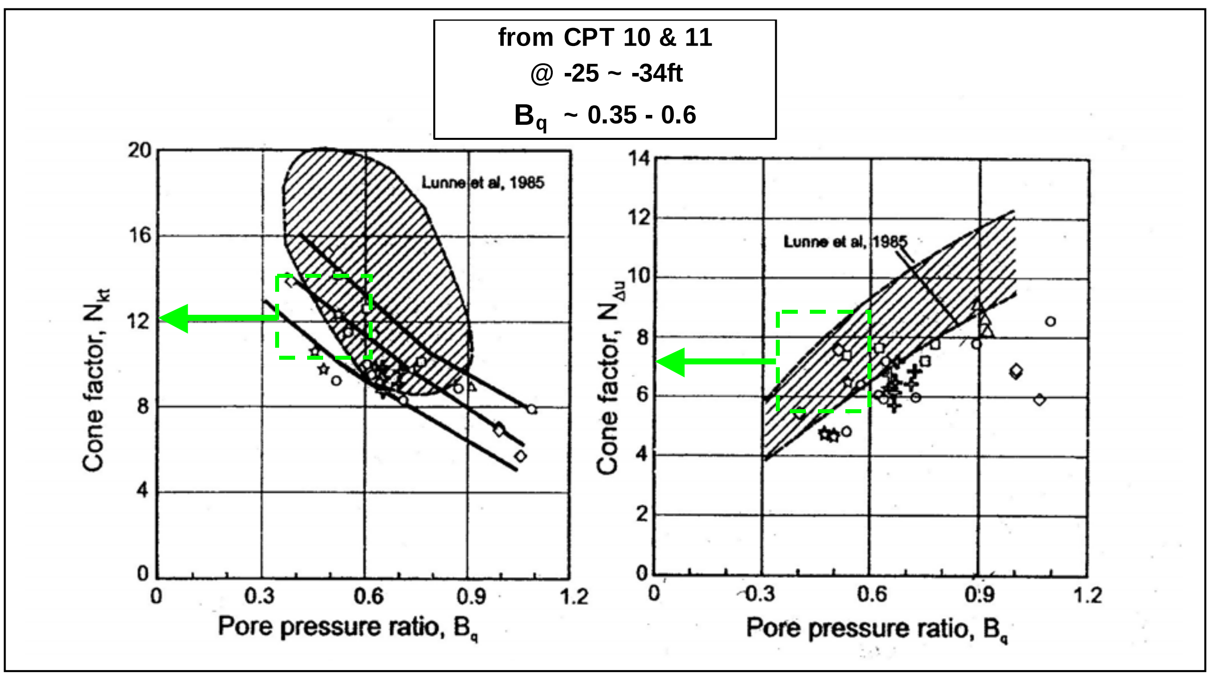


Figure 8.77: N_{kt} and $N_{\Delta u}$ for the soft gray clay at the site on the west side of the 17[th] Street Canal based on CPTU.

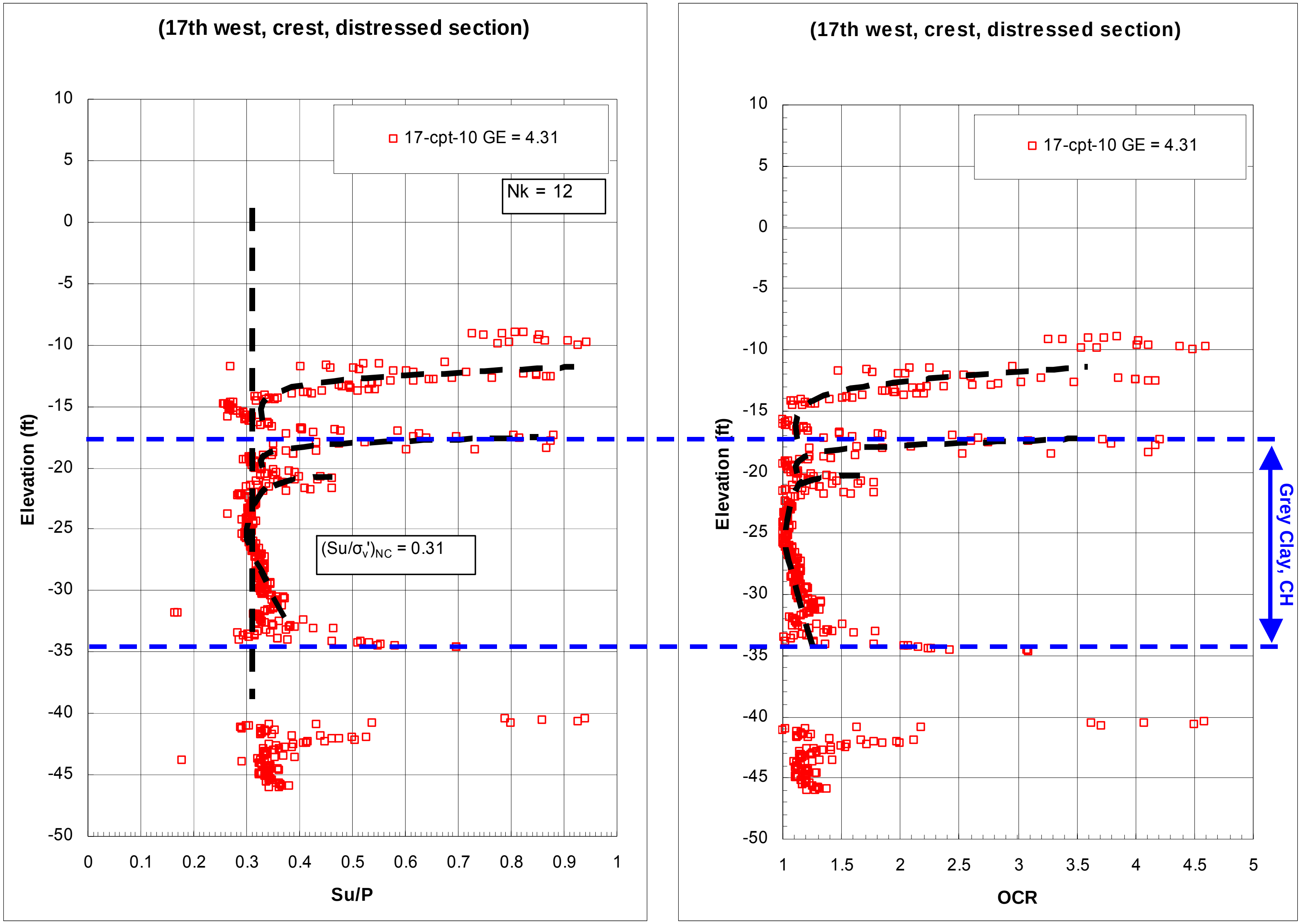
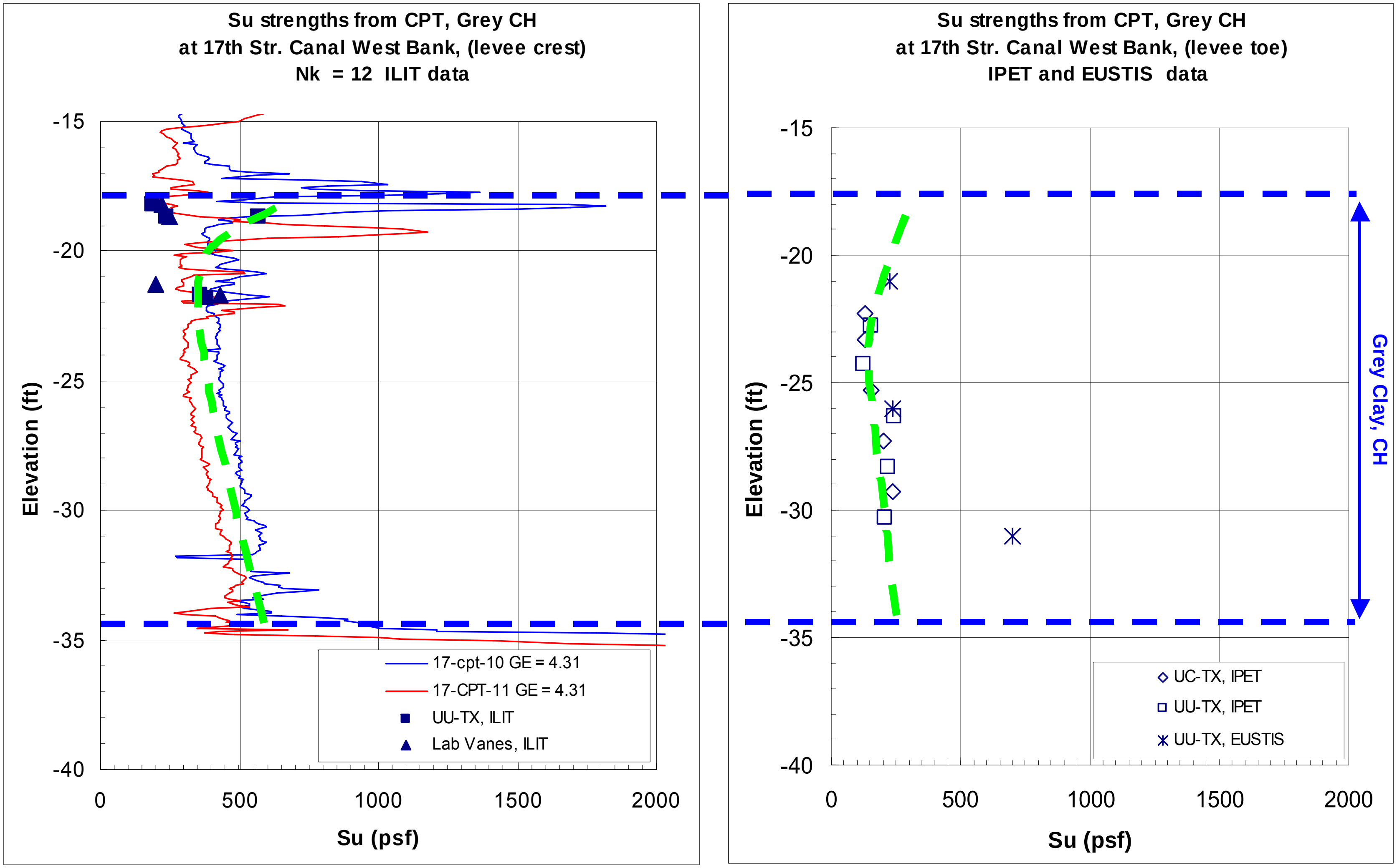
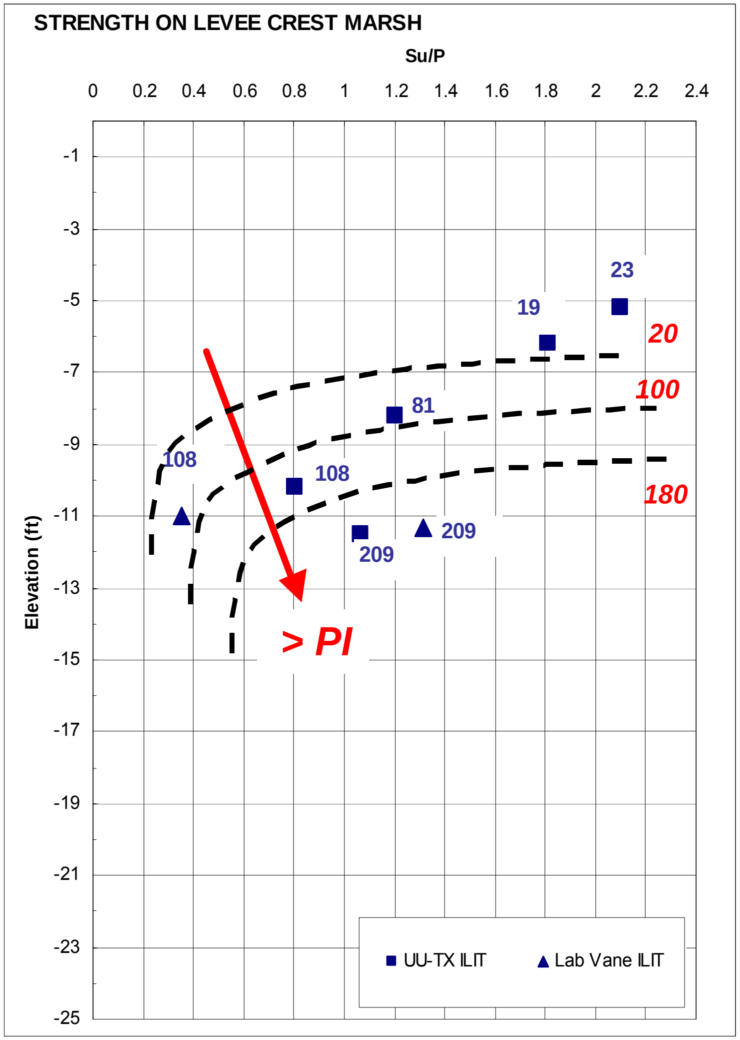


Figure 8.78: Su/P vs. depth and OCR vs. depth for soft gray clay (CH) beneath the crest of the embankment for the site on the west side of the 17th Street Canal.



(a) Beneath the levee crest **(b) Beneath the inboard of the levee toe**

Figure 8.79: Shear strength vs. depth for the site on the west side of the 17th Street Canal (a) beneath the crest of the levee, and (b) beneath the inboard side toe of the levee embankment.



Ref: Mayne, P.W and Mitchell, J.K (1988)

	$S_u/\sigma'v$			OCR= α_{VST} ($S_u/\sigma'v$)		
	PI (%)			$\alpha_{VST} = 22\ PI^{-0.48}$		
elev (ft)	20	100	180	5.2	2.4	1.8
-5	2.4			12.5		
-6	2.2			11.5		
-7	1.2			6.3		
-8	0.6	2.2		3.1	5.3	
-9	0.34	0.9	3	1.8	2.2	5.5
-10	0.27	0.6	1.4	1.4	1.4	2.5
-11	0.22	0.4	0.8	1.1	1.0	1.5
-12	0.2	0.4	0.6	1.0	1.0	1.1
-13	0.2	0.4	0.55	1.0	1.0	1.0
-14	0.2	0.4	0.55	1.0	1.0	1.0

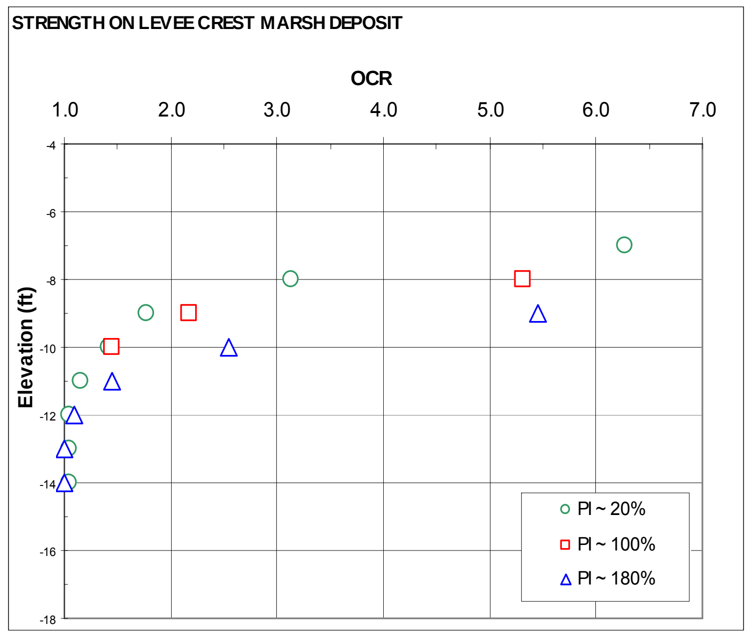


Figure 8.80: Su/P and OCR estimation from PI and vane shear tests for the marsh deposits at the site on the west side of the 17th Street Canal.

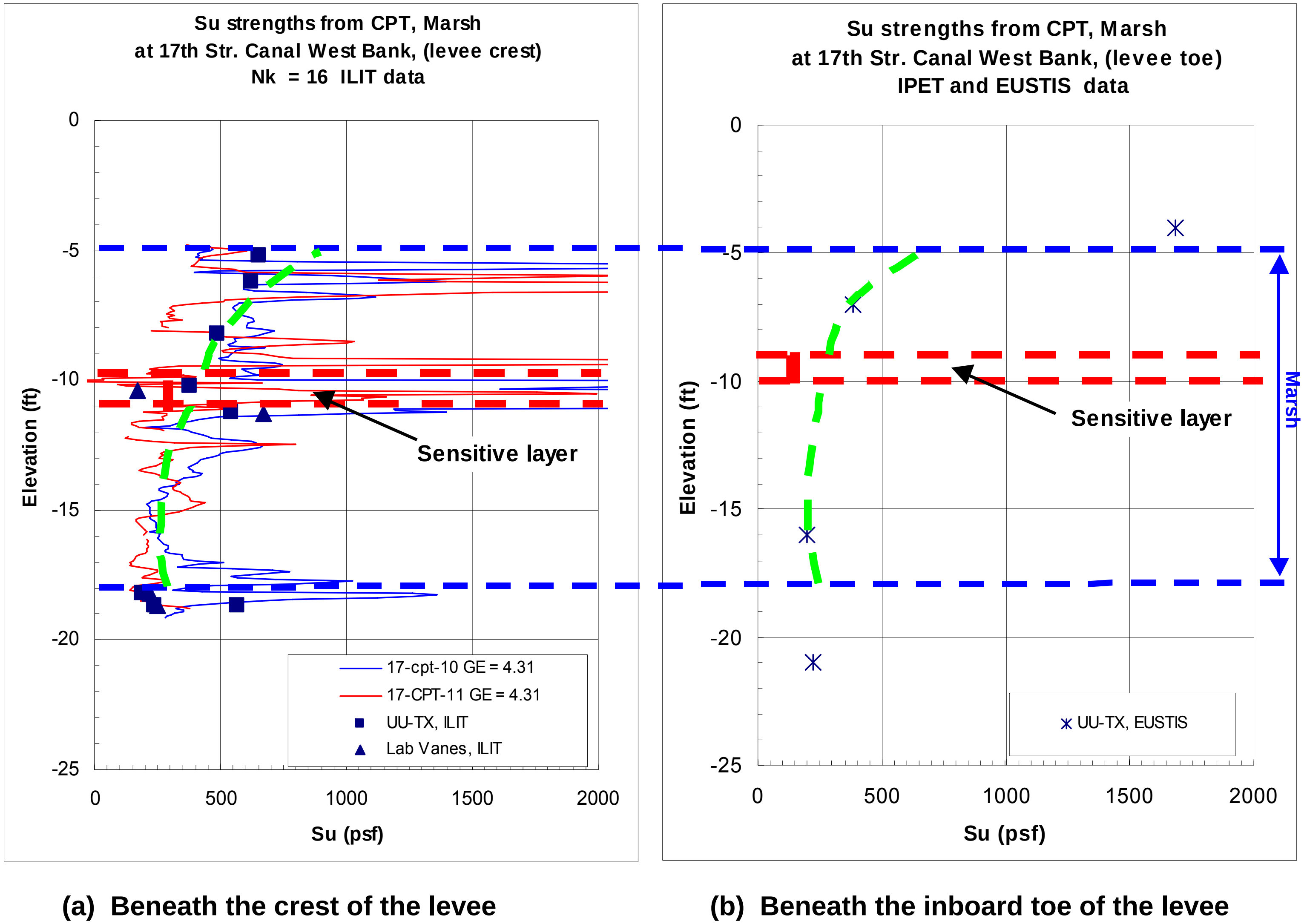


Figure 8.81: Shear strength vs. depth within the marsh deposits at the site on the west side of the 17th Street Canal (a) beneath the crest of the levee, and (b) beneath the inboard toe of the embankment.

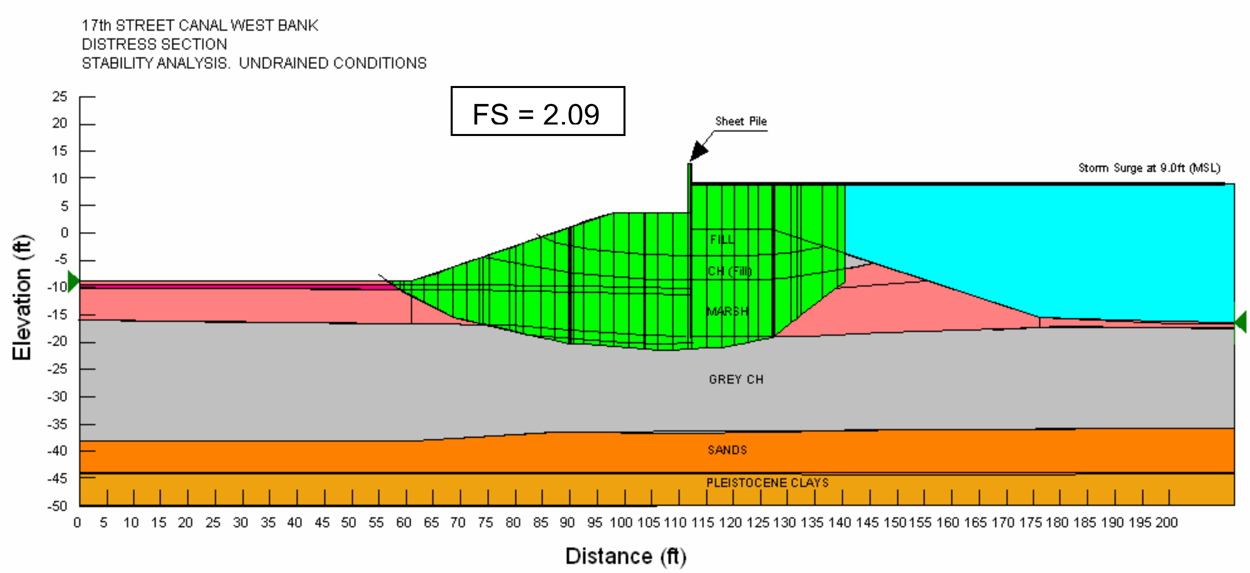


Figure 8.82: Stability analysis of the west side of the 17th Street Canal with water at Elev. + 9 feet (MSL) for case of rotational failure through the soft gray clay (CH) with no gap developed.

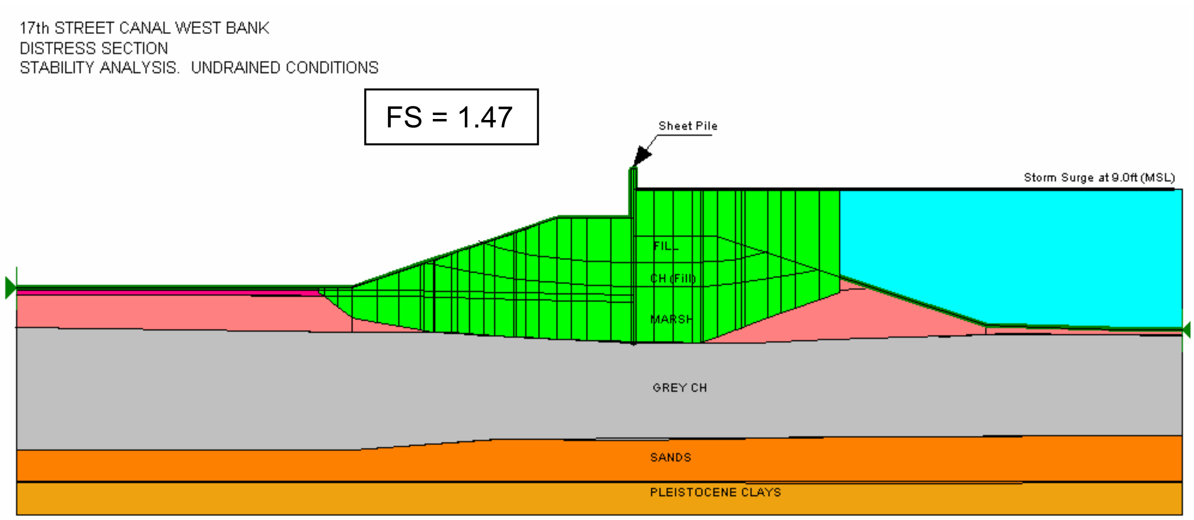


Figure 8.83: Stability analysis of the west side of the 17th Street Canal with water at Elev. + 9 feet (MSL) for case of failure through the base of the “marsh”layer (with no gap developed).

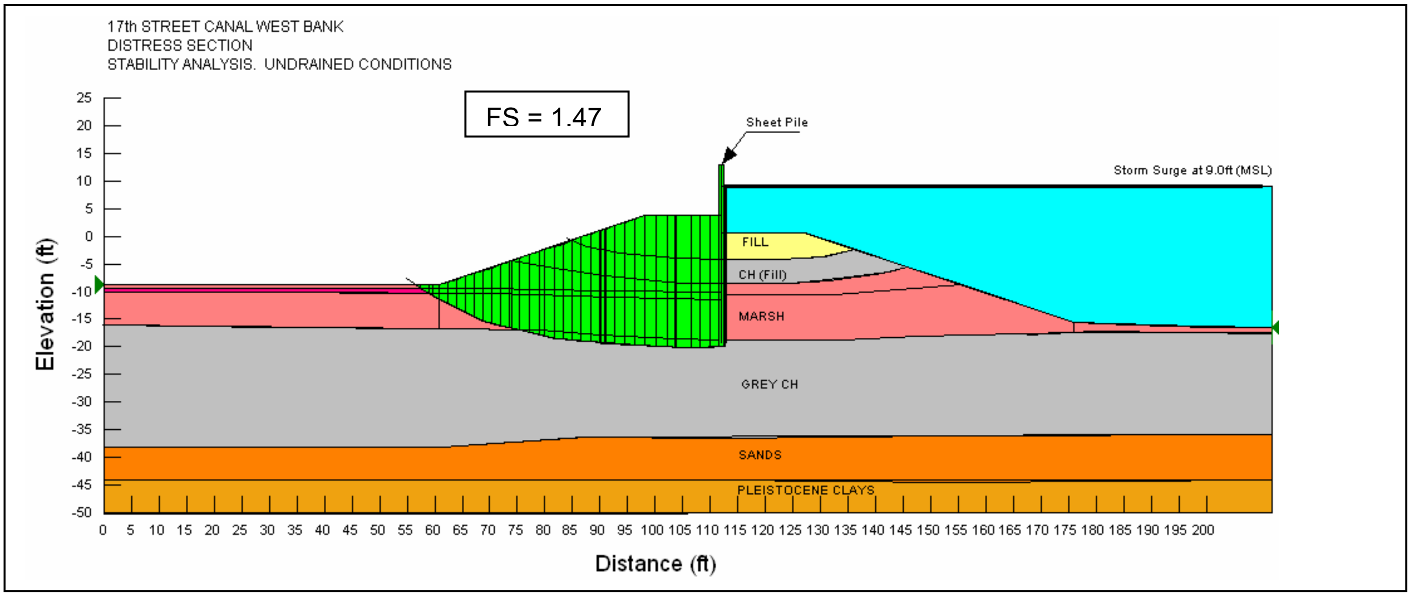


Figure 8.84: Stability analysis of the west side of the 17th Street Canal with water at Elev. + 9 feet (MSL) for case of rotational failure through the soft gray clay (CH) (with water-filled gap).

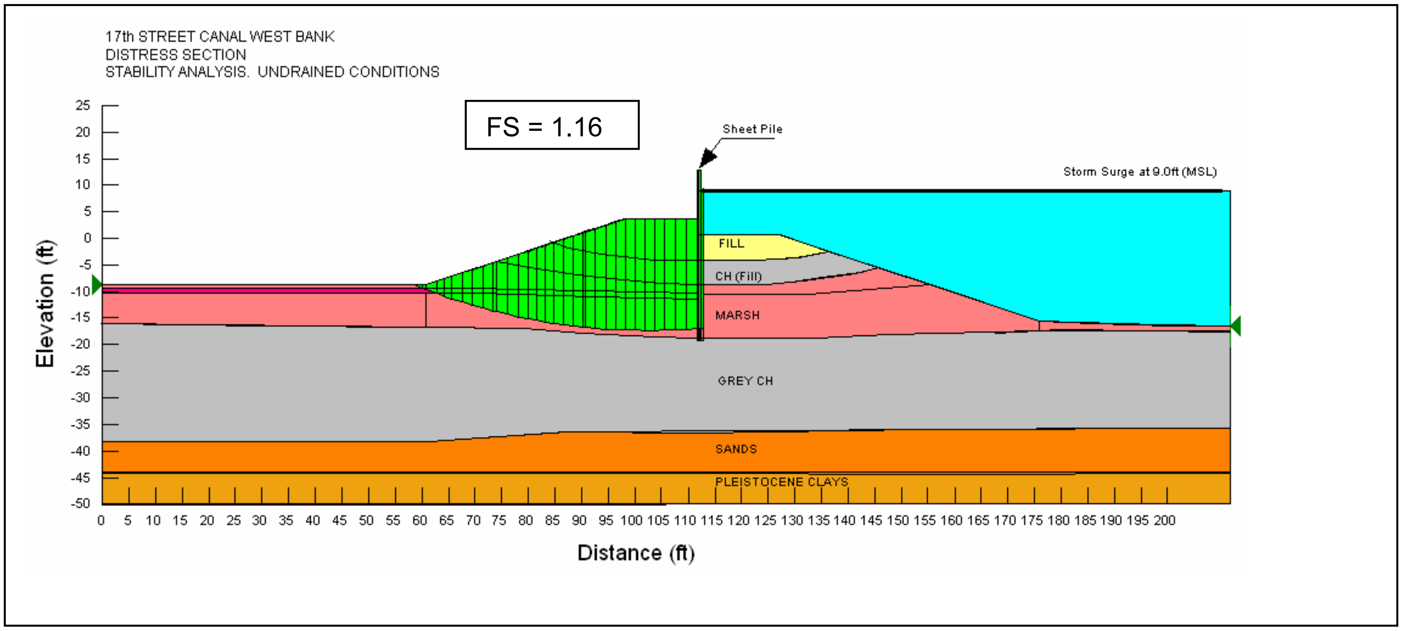


Figure 8.85: Stability analysis of the west side of the 17th Street Canal with water at Elev. + 9 feet (MSL) for case of failure along through the base of the "marsh" layer (with water-filled gap).

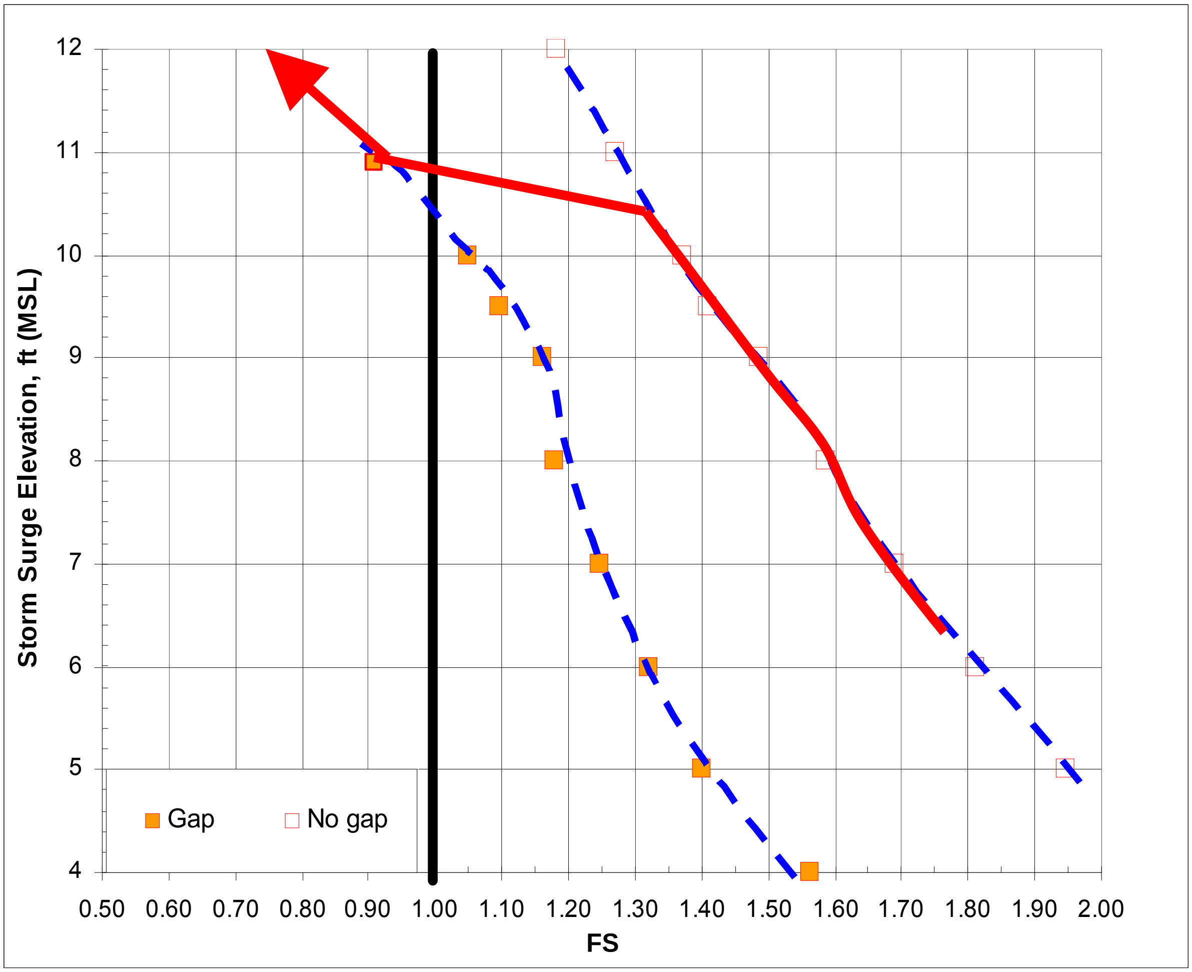


Figure 8.86: Factor of safety vs. water level on the west bank of the 17th Street Canal.

Figure 8.87: View of failure and breach on the east bank near the south end of the London Avenue Canal.

Figure 8.88: View of sands piled in neighborhood inboard of the south London Avenue Canal breach.

Figures 8.89 and 8.90: Views of floodwall panels "dropping" into the eroded void at the north and south ends of the south London Avenue canal breach.

Figure 8.91: View of trees at the inboard levee toe immediately to the north of the end of the south breach in the London Avenue Canal.

Figure 8.92: View of toppled trees at the London Avenue Canal south breach site.

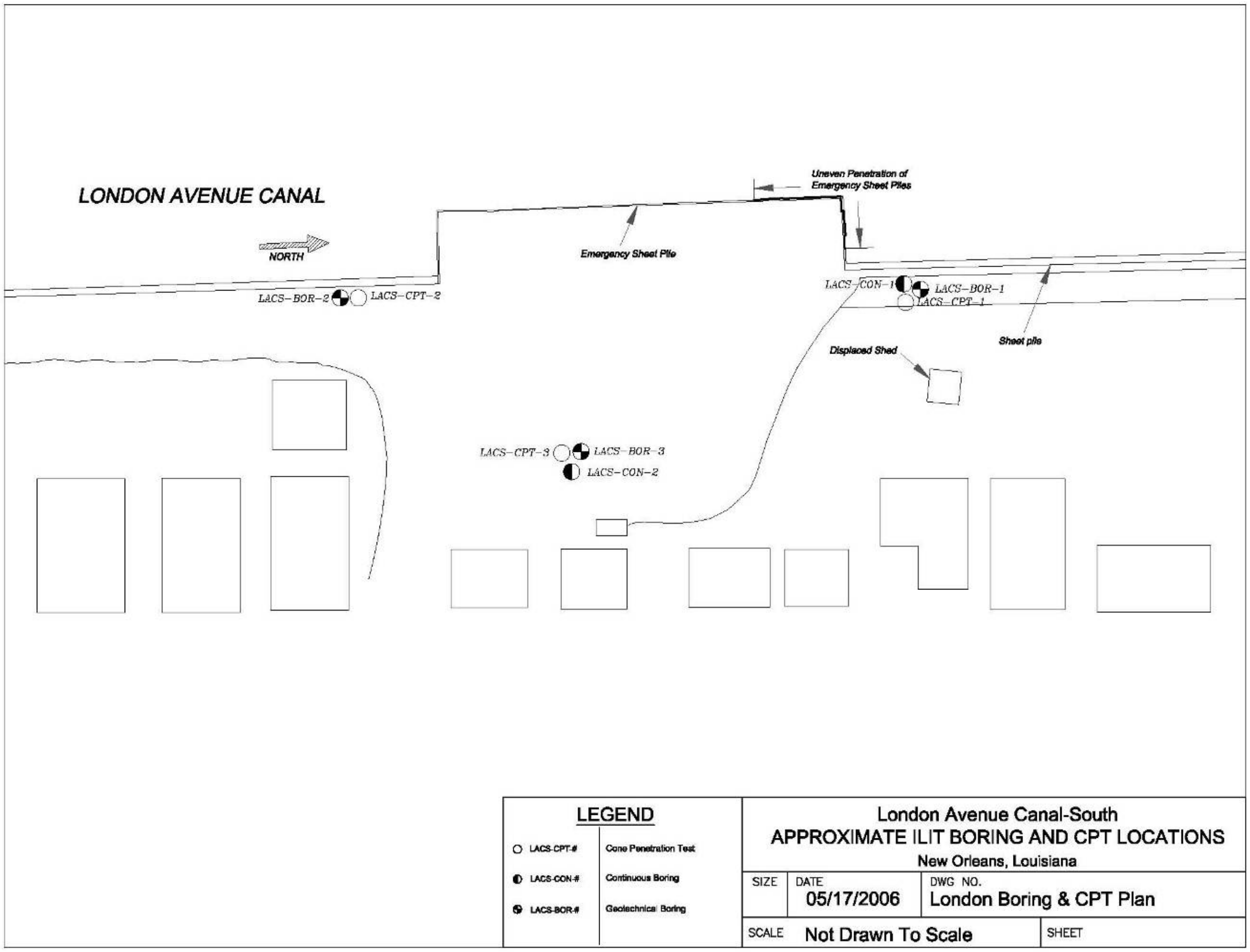


Figure 8.93: Plan view of the London Avenue Canal (South) breach site.

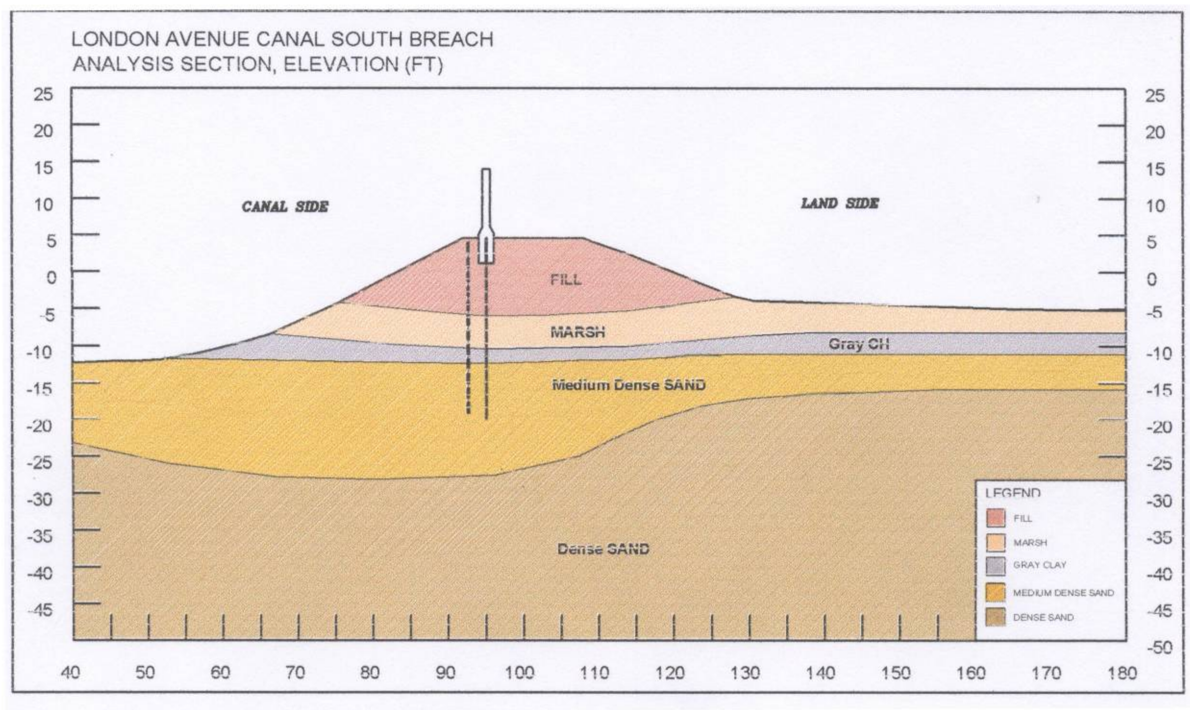
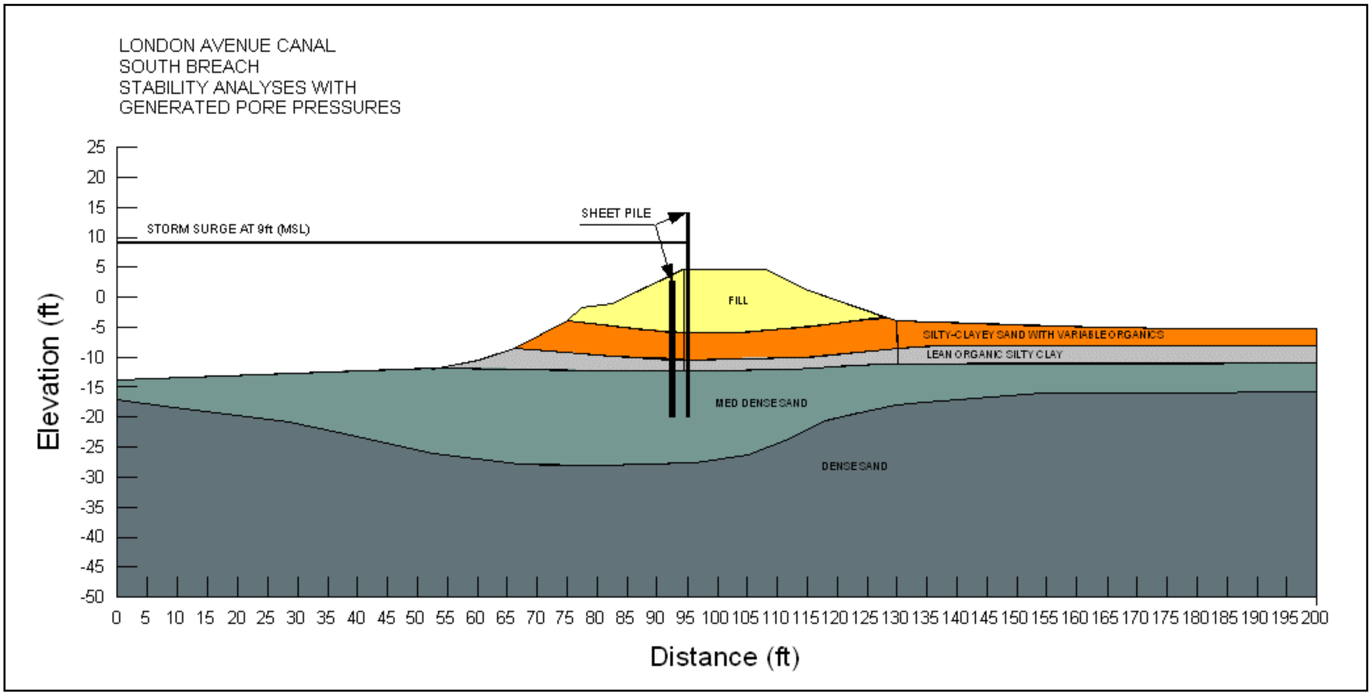


Figure 8.94: Cross-section through the breach near the south end of the London Avenue Canal.



ID	Soil Model	Type	□ [lb/ft^3]	c [lb/ft^2]	phi [°]	k [ft/hr]
Upper fill	Mohr-Coulomb	Undrained	100	800	0	1.20E-03
SM/SC w/organics, crest	Mohr-Coulomb	Undrained	90	250	0	0.011
SM/SC w/organics, free field	Mohr-Coulomb	Undrained	90	200	0	0.011
Lean organic silty clay, crest	Mohr-Coulomb	Undrained	100	500	0	3.60E-03
Lean organic silty clay, free field	Mohr-Coulomb	Undrained	100	300	0	3.60E-03
Medium Dense Sand	Mohr-Coulomb	Drained	100	0	33	1.100
Dense Sand	Mohr-Coulomb	Drained	110	0	35	0.600

Figure 8.95: Geotechnical cross-section for analysis of the London Avenue south breach.

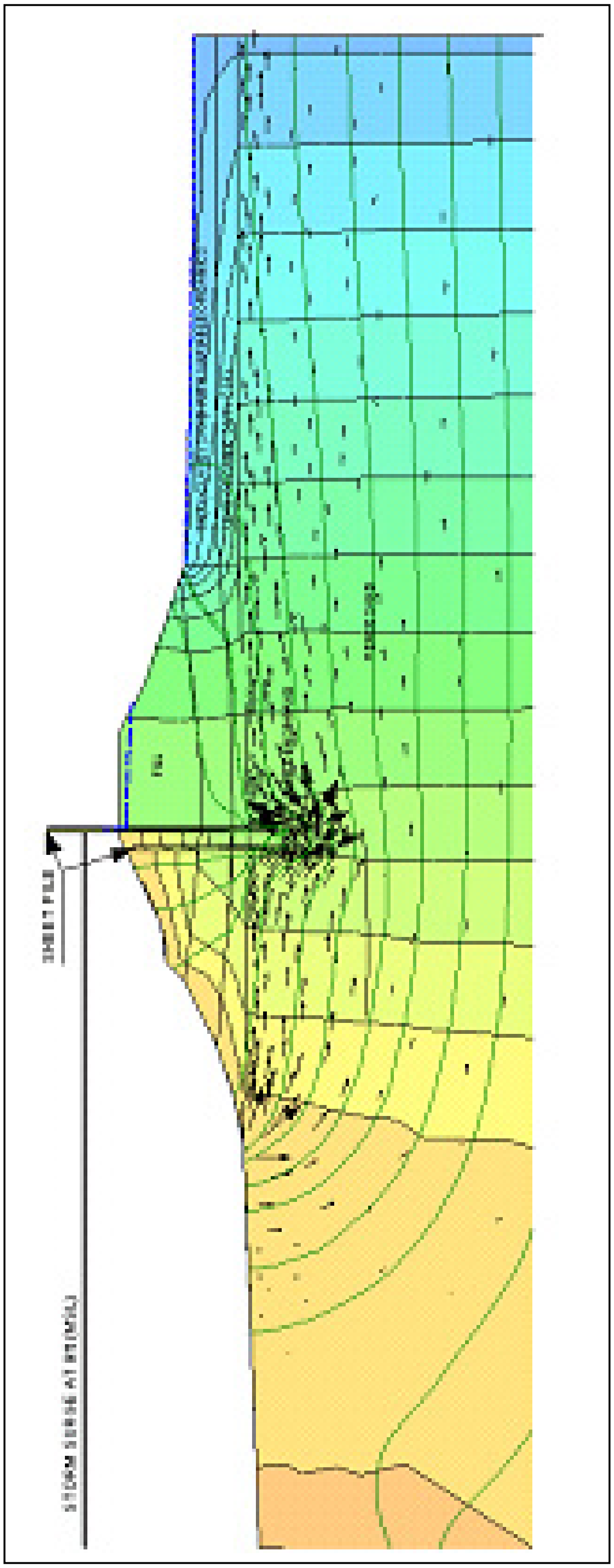


Figure 8.96: Flow vectors and head contours for seepage analysis of the south London Avenue Canal breach for a surge at Elev. + 9 feet (MSL).

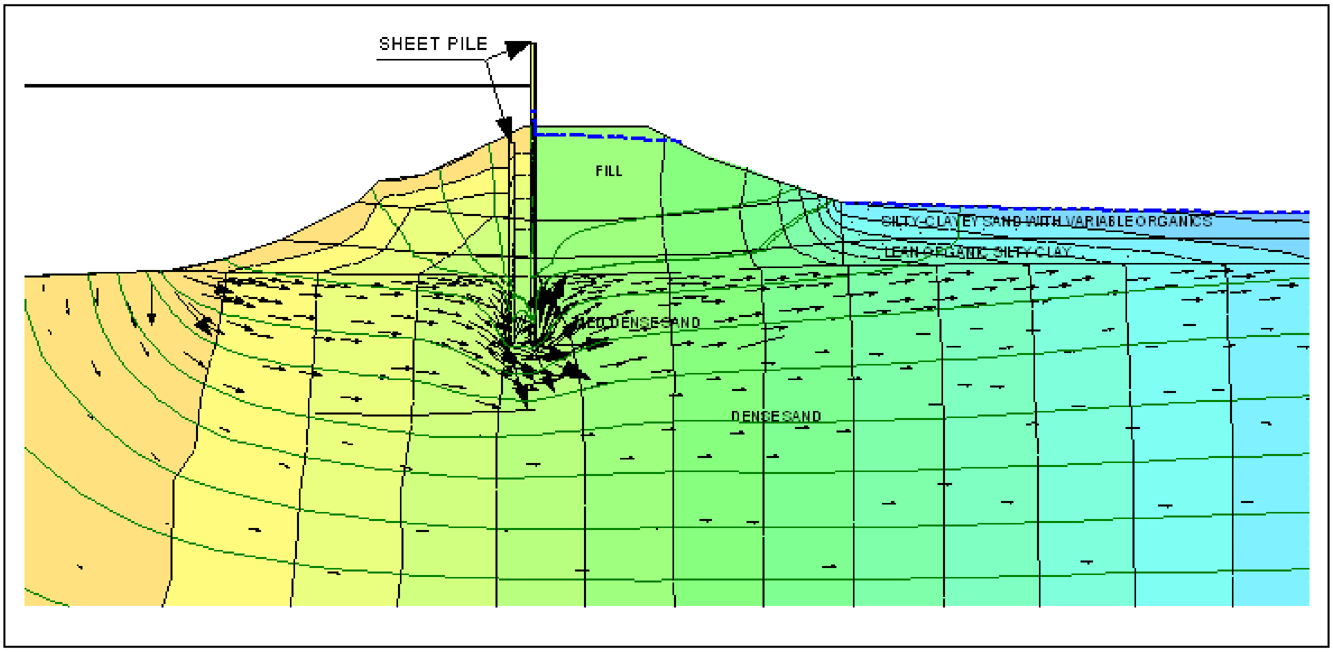


Figure 8.97: Closeup of flownet for StormS urge at + 9ft (MSL) in the London Avenue Canal south breach. (Equipotential contours at intervals of one foot of head)

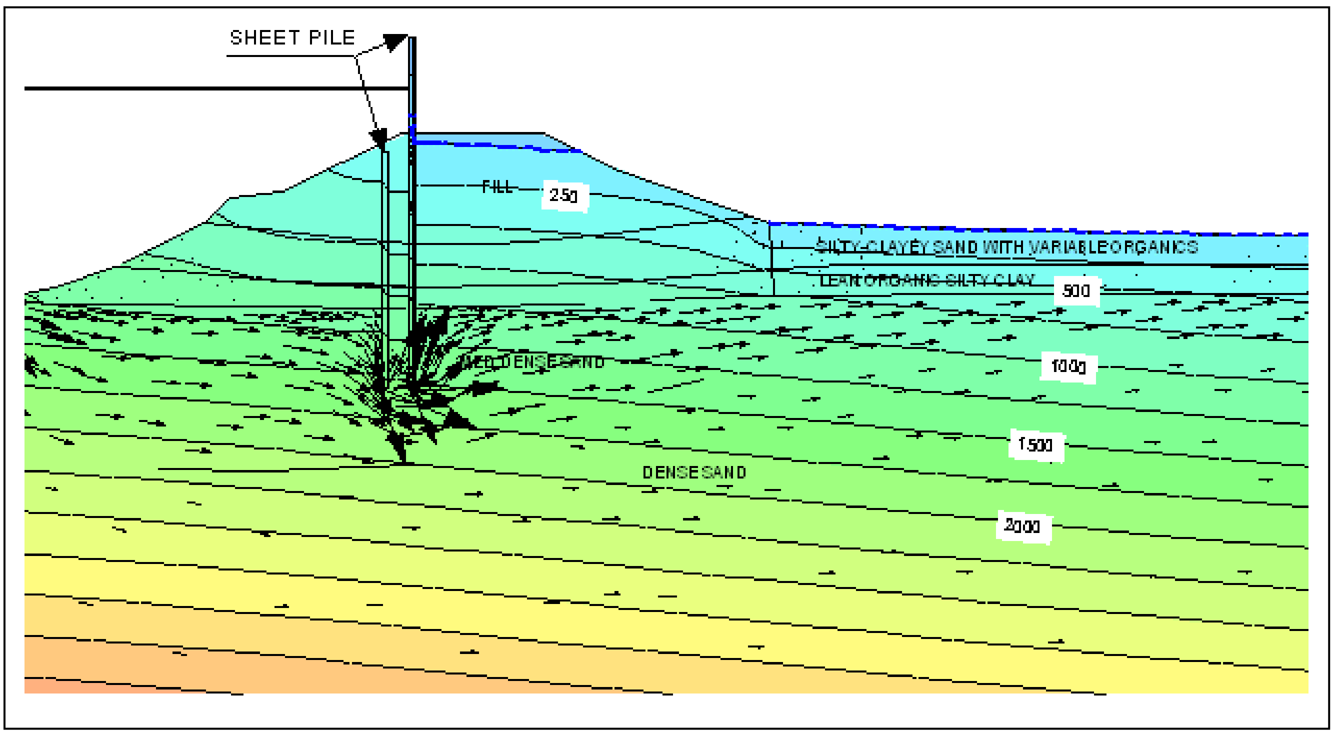


Figure 8.98: Pressure contours for Storm Surge at 9ft (MSL) in the London Avenue Canal South breach. (Pressure contours every 250 lb/ft^2)

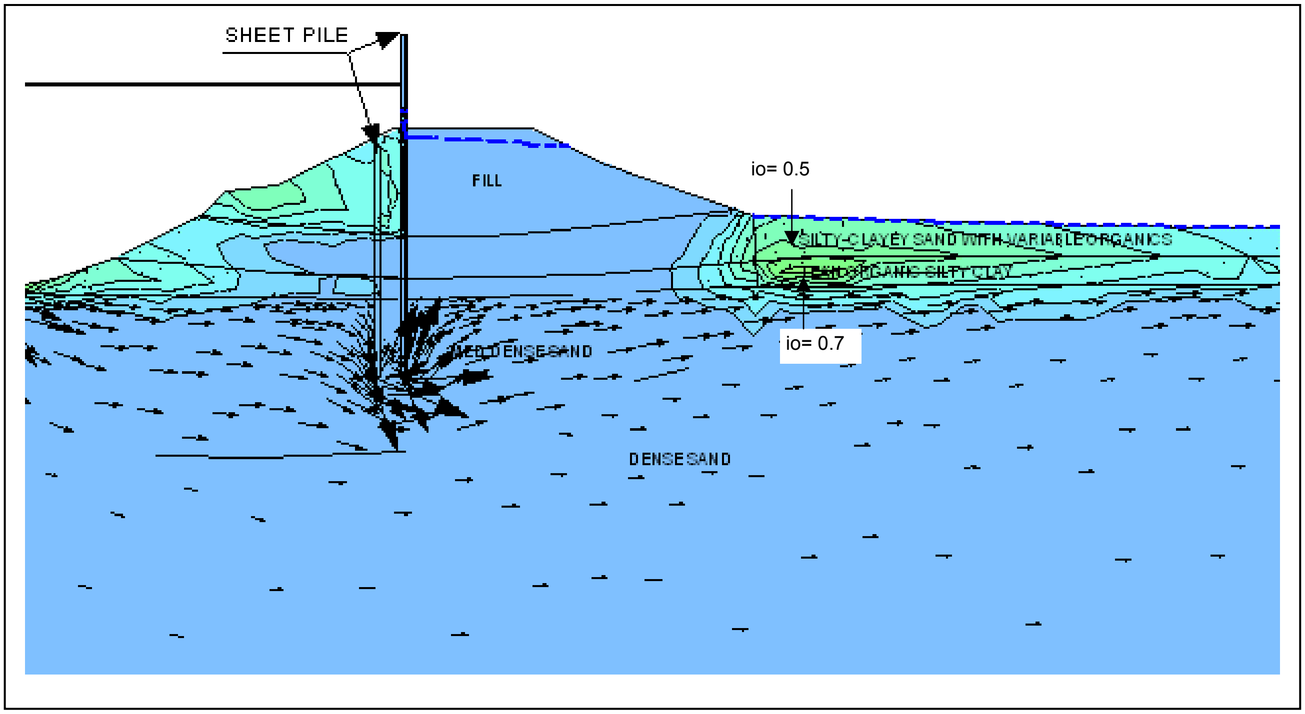


Figure 8.99: Hydraulic gradients for Storm Surge at +9ft (MSL) in the London Avenue Canal South breach. (Maximum toe exit gradient i_o= 0.7)

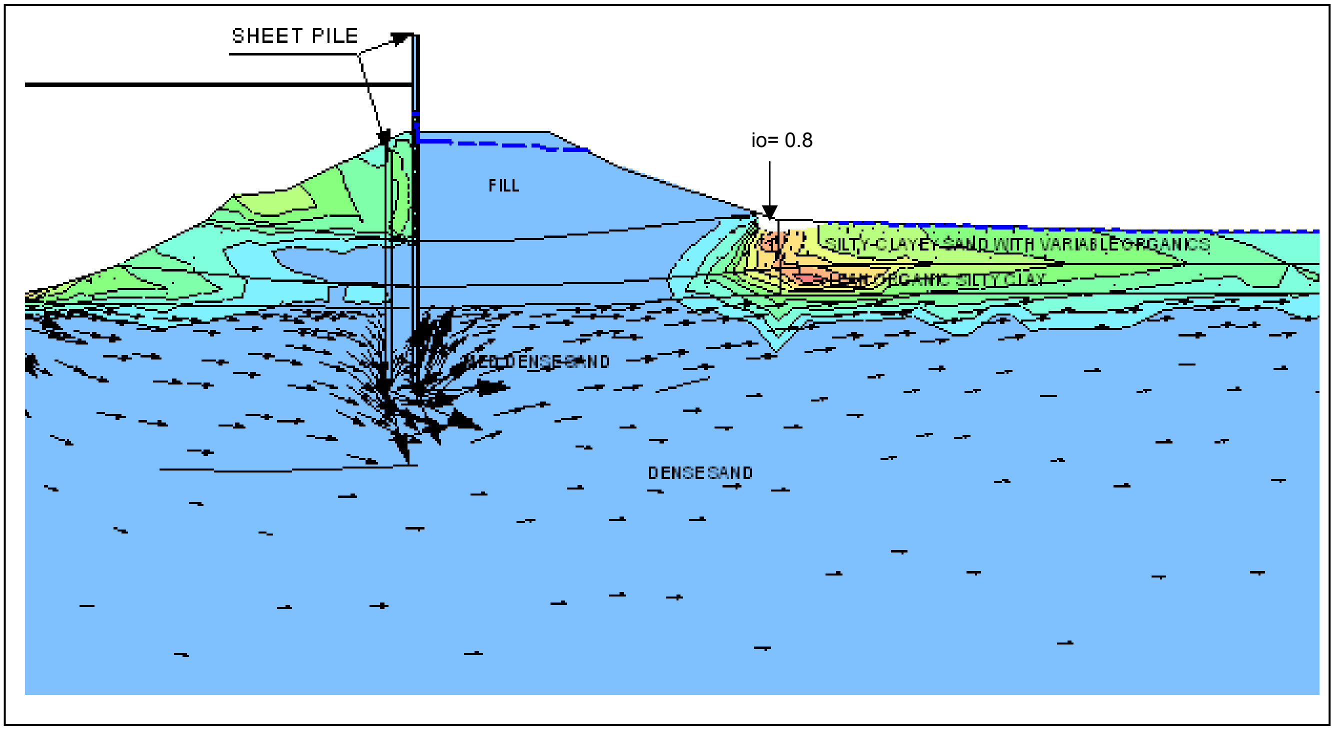


Figure 8.100: Hydraulic gradients for Storm Surge at +9ft (MSL) in the London Avenue Canal South breach: initiation of erosion at levee toe. (Maximum gradient i_o= 0.8)

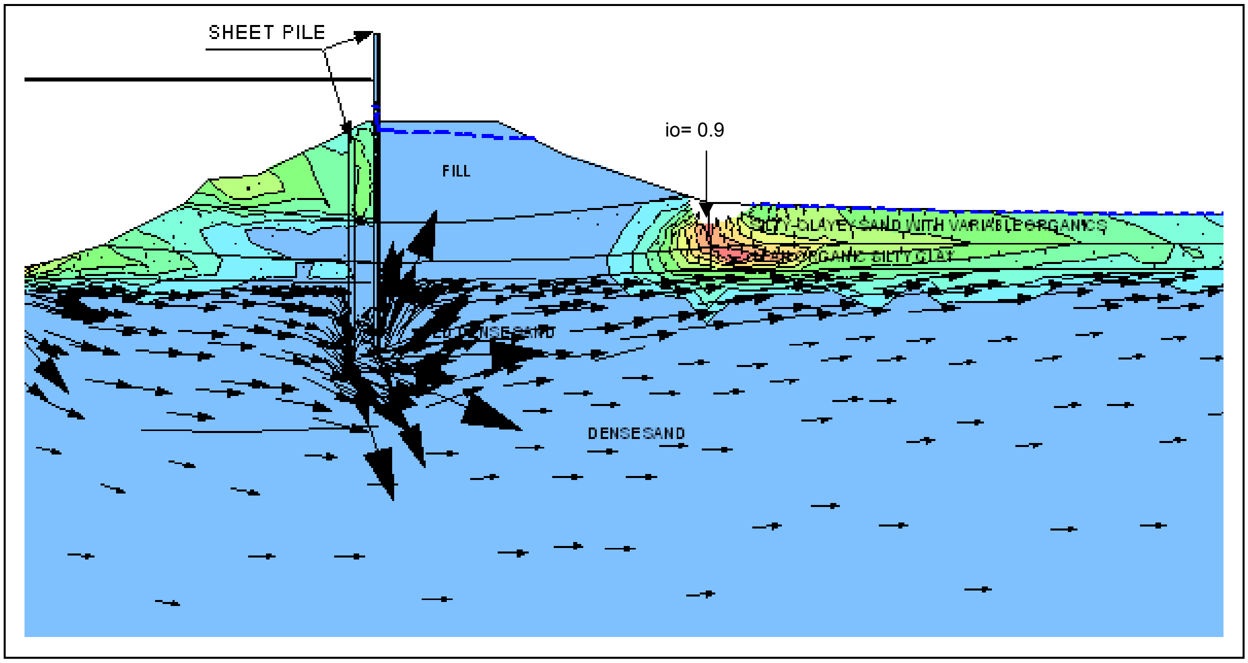


Figure 8.101: Hydraulic gradients for Storm Surge at +9ft (MSL) in the London Avenue Canal South breach; development of erosion at levee toe. (Maximum gradient i_o= 0.9).

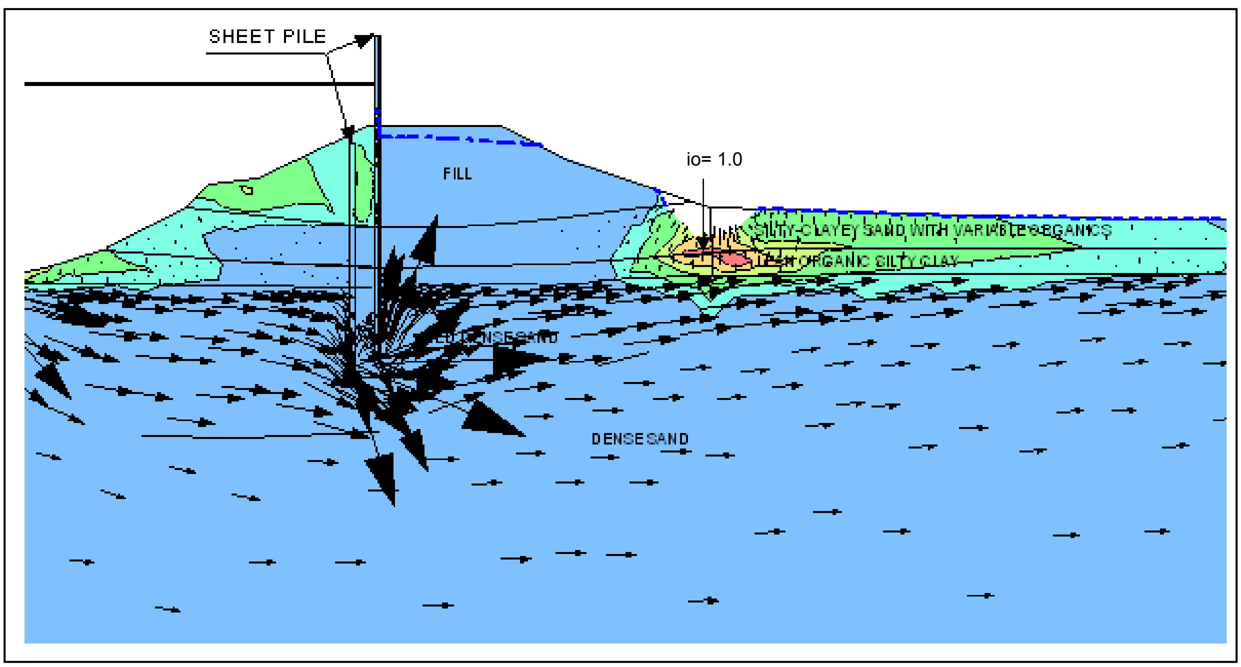


Figure 8.102: Hydraulic gradients for Storm Surge at +9ft (MSL) in the London Avenue Canal South breach; development of erosion at levee toe. (Maximum gradient i_o = 1.0.)

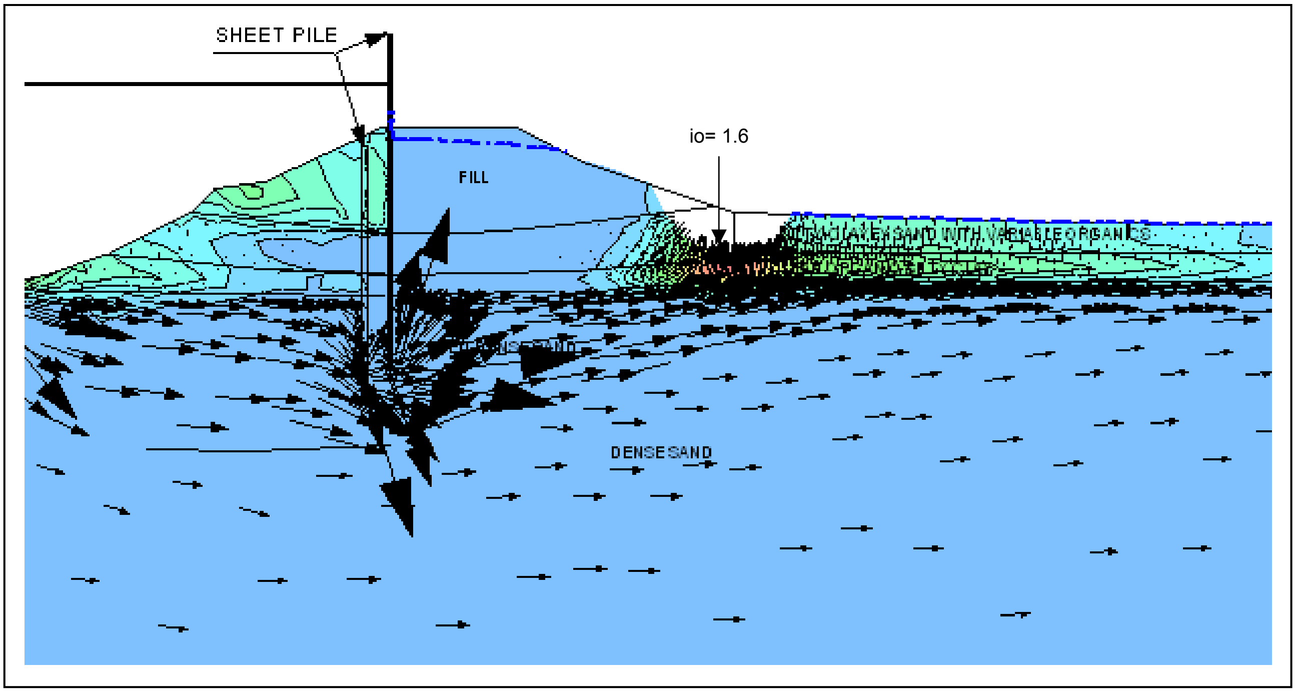


Figure 8.103: Hydraulic gradients for Storm Surge at +9ft (MSL) in the London Avenue Canal South breach; development of erosion at levee toe. (Maximum gradient i_o= 1.6.)

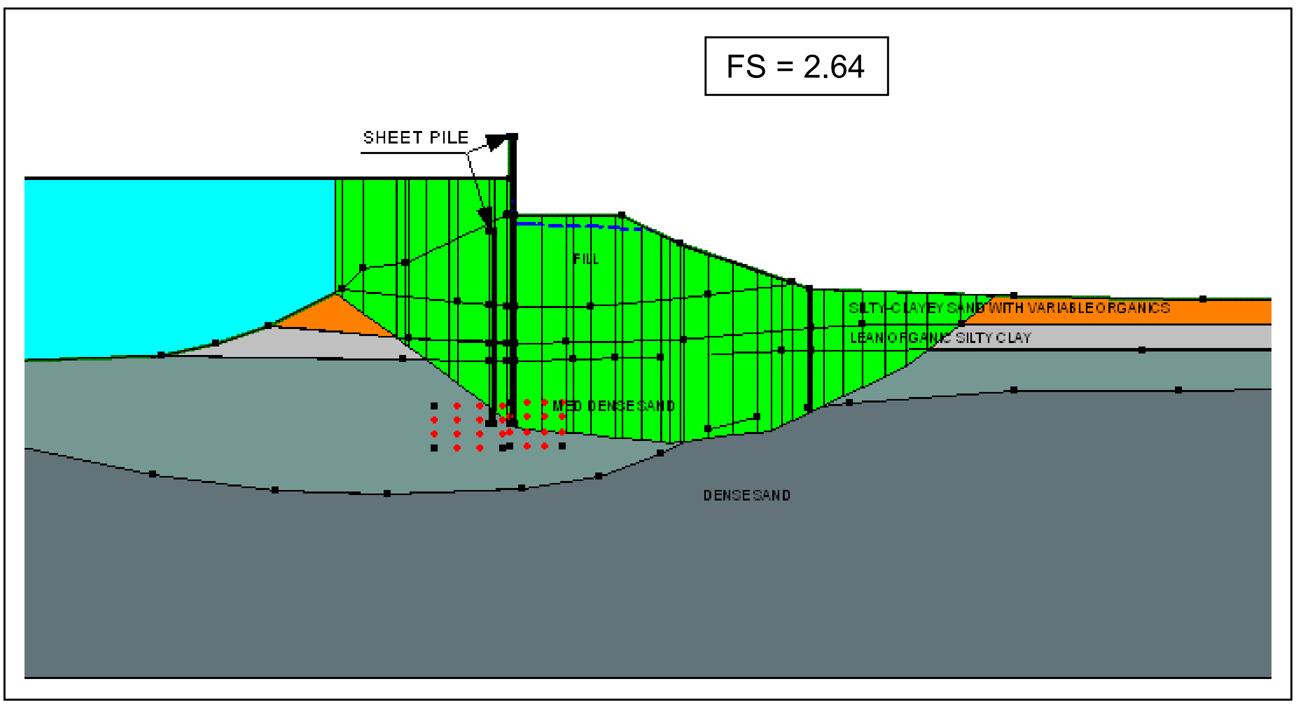


Figure 8.104: Stability analysis for the South London Avenue canal breach section for storm surge at Elev. + 9 feet (MSL) and steady state seepage.

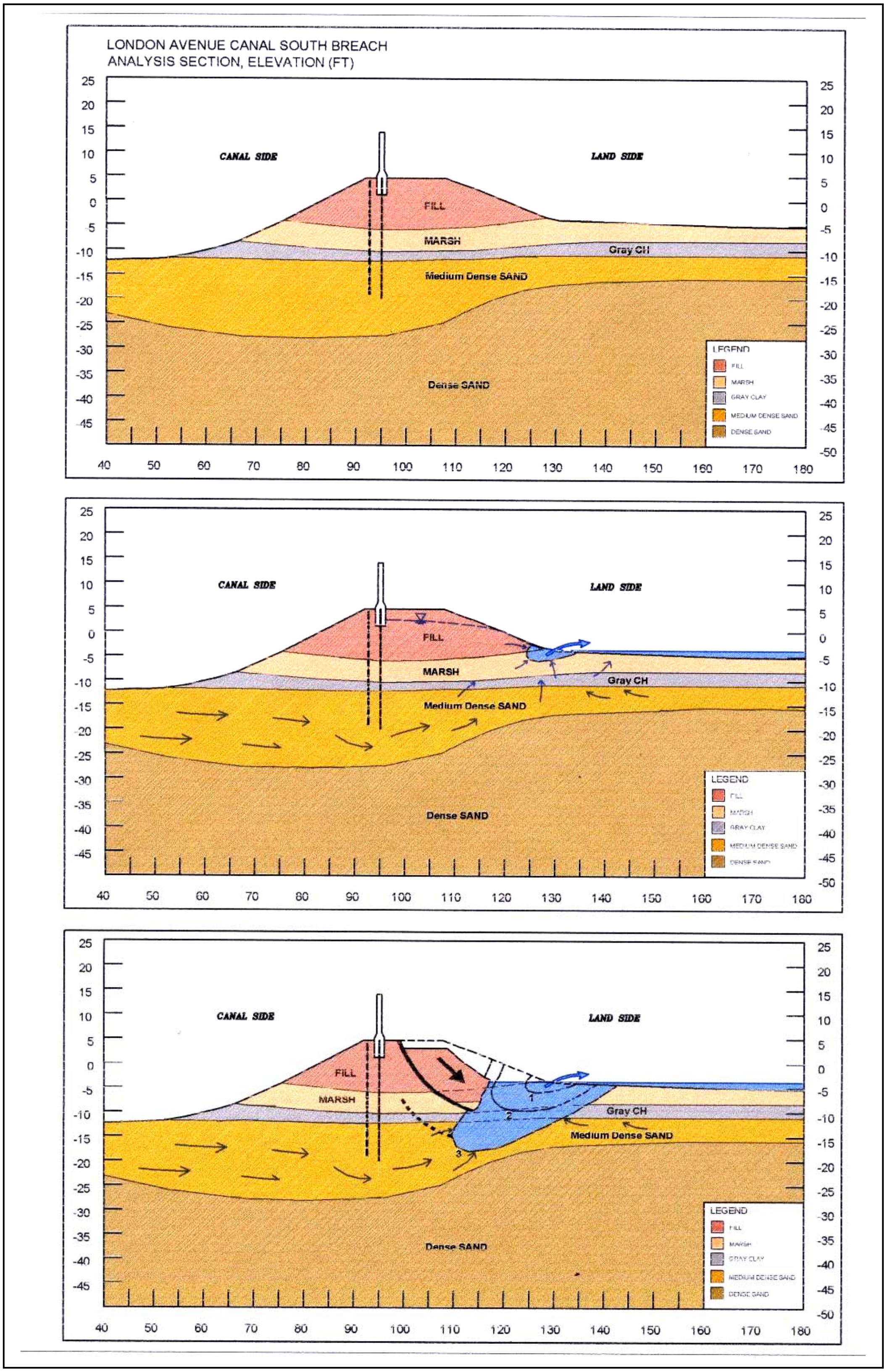


Figure 8.105: Schematic illustration of progressive erosion development at inboard toe.

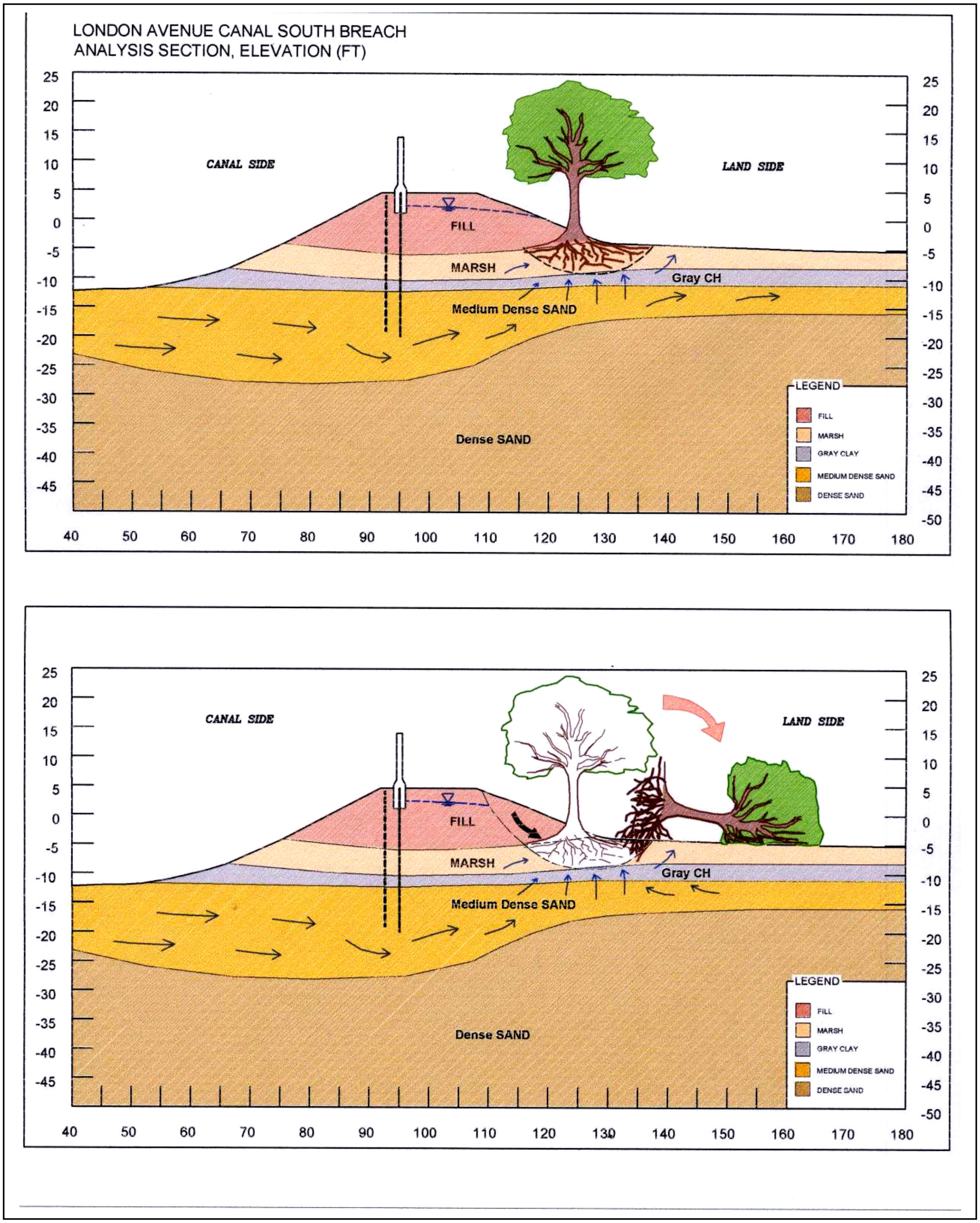


Figure 8.106: Schematic illustration of toppling of tree at inboard toe of levee.

Figure 8.107: View of the breach near the south end of the London Avenue Canal from the canal side in late September of 2005.

Figure 8.107(a): Sample across transition zone at London Avenue Canal, South Breach Section

Figure 8.108: Overhead view of the breach section on the west bank near the north end of the London Avenue Canal.

Figure 8.109: Oblique aerial view of the breached section on the west bank of the London Avenue Canal (North) and the “distressed” section on the east bank (on the left in this photo, which is taken looking to the south.)

Figure 8.110: View of the west bank breach near the north end of the London Avenue Canal from the south end showing the outboard side embankment section still in place.

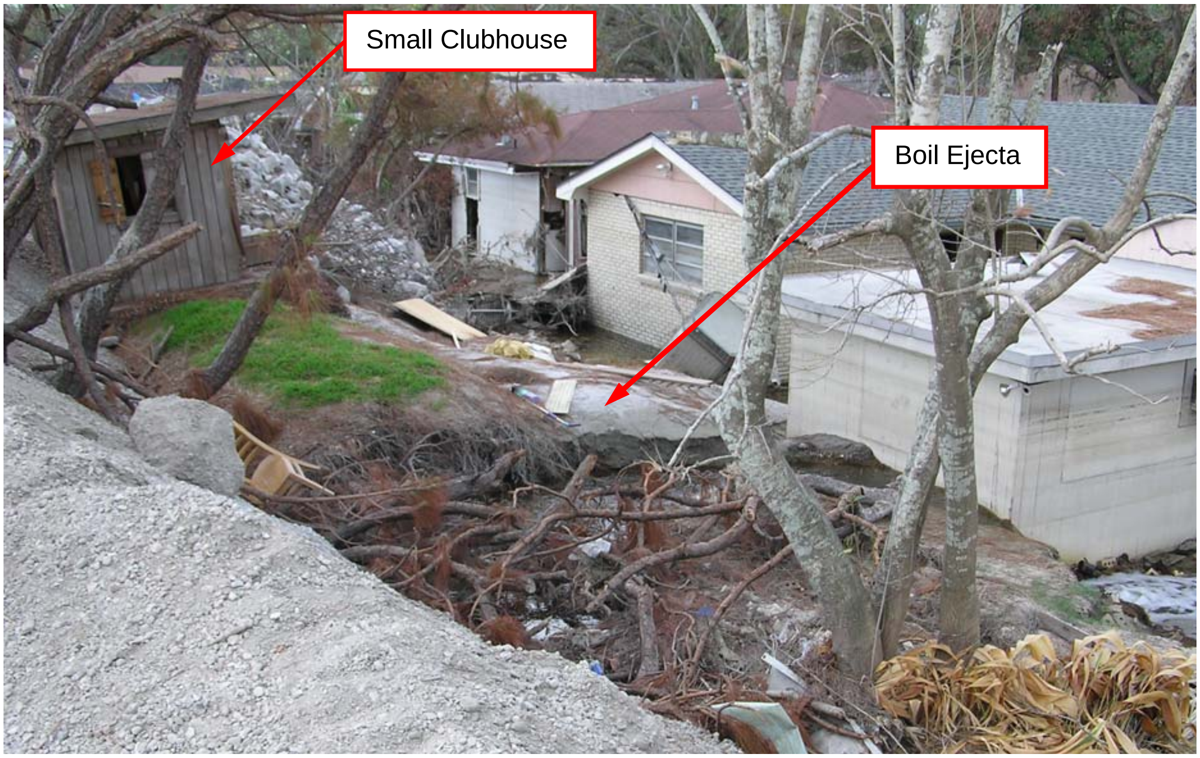
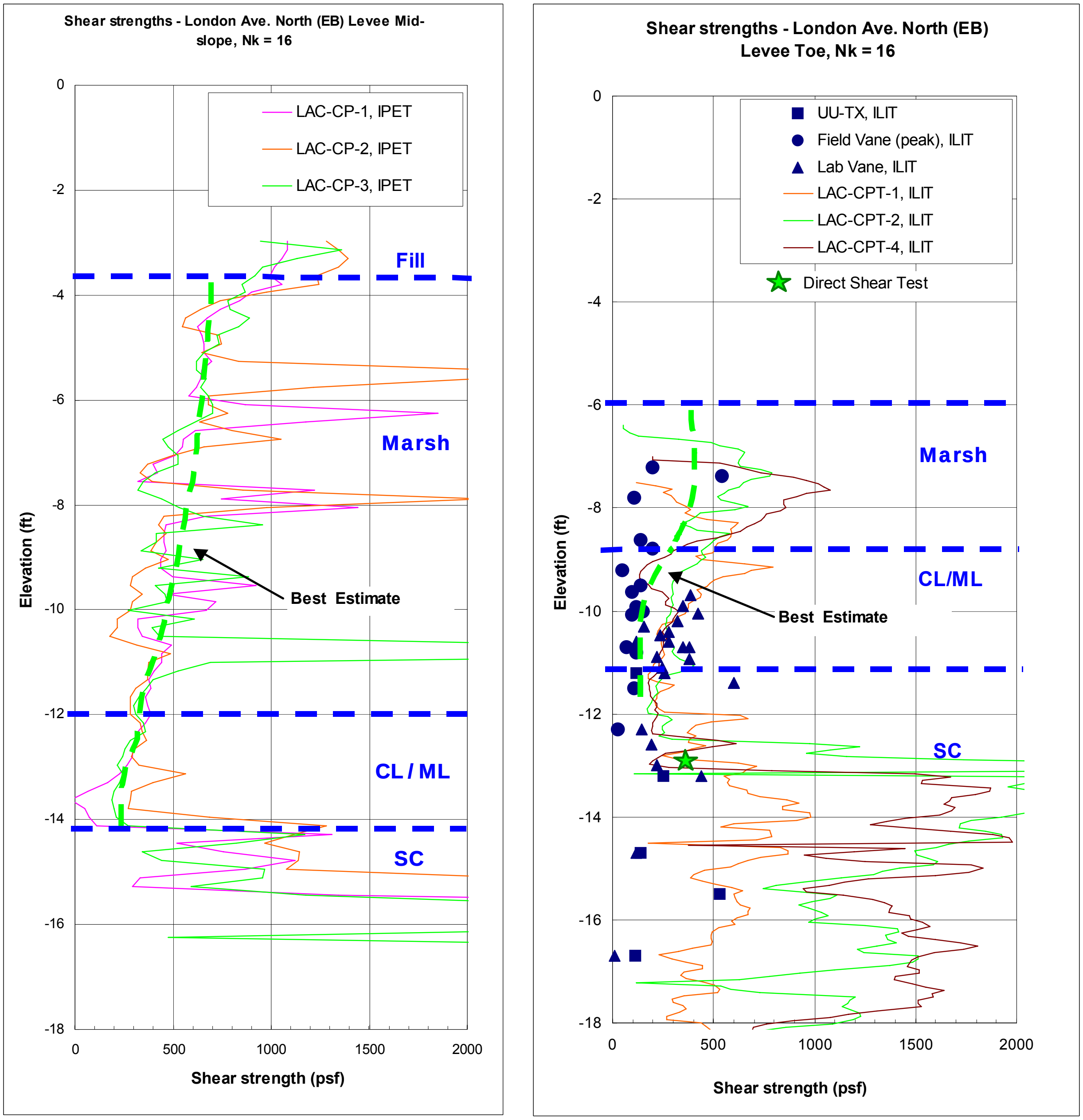
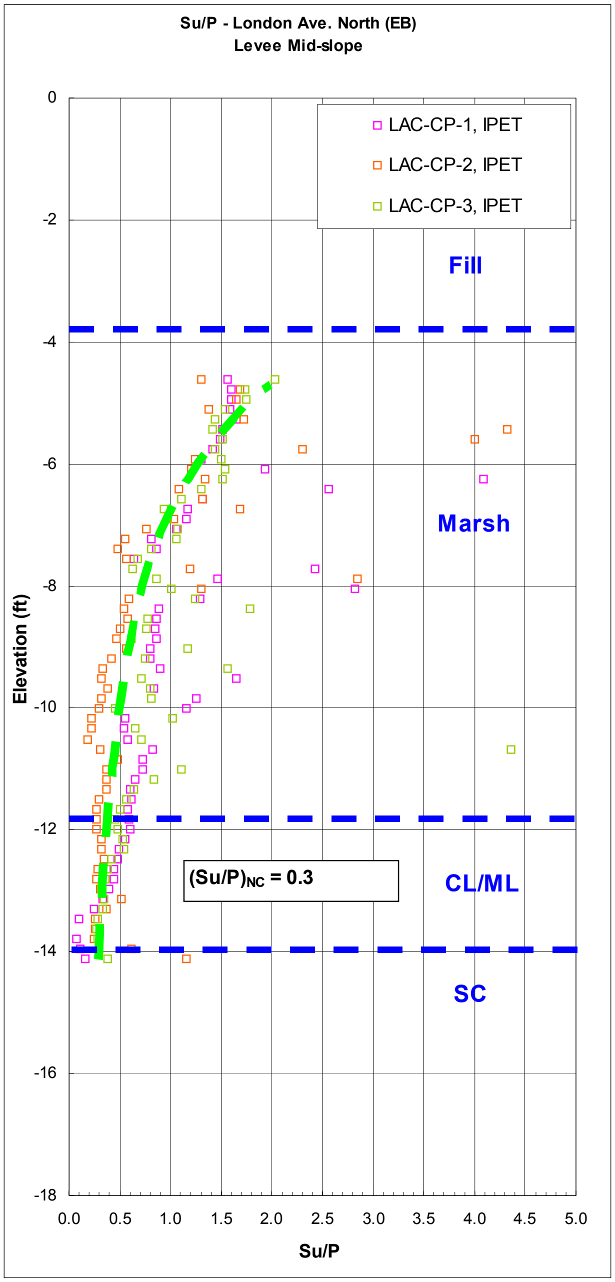


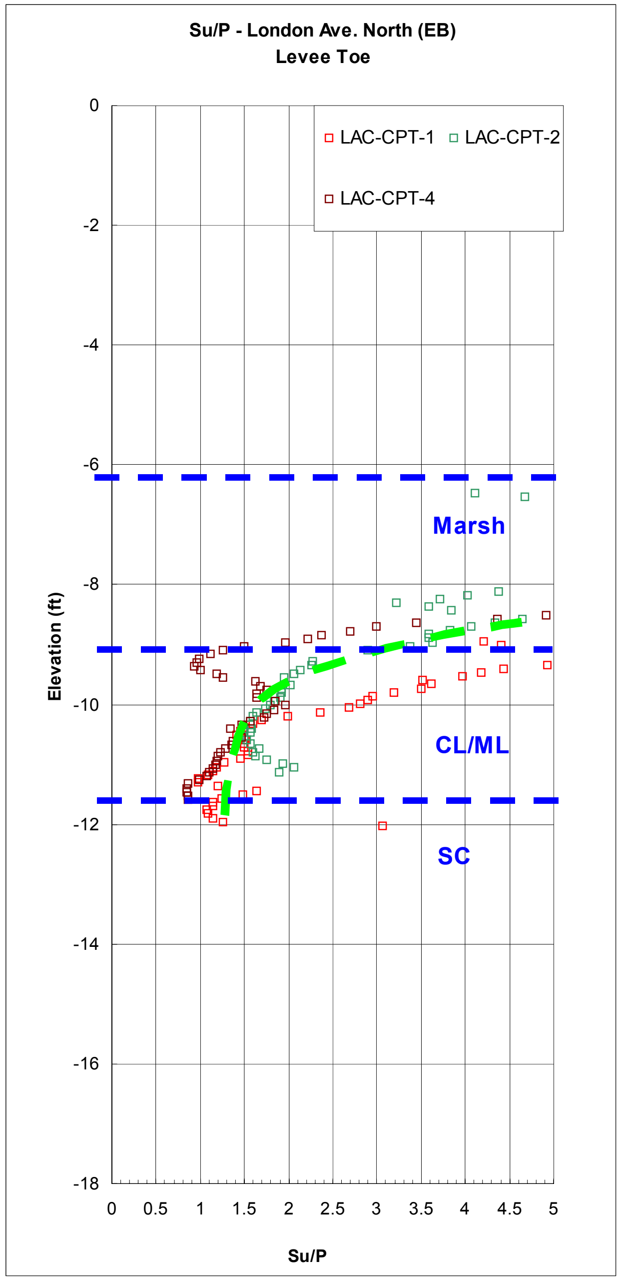
Figure 8.111: View of the inboard of the displaced embankment on the west side of the London Avenue canal showing heaving at the toe (and beneath the small wooden clubhouse), and the boil ejecta in front of the heave feature.



a) beneath crest of levee **b) at or near toe of levee**

Figure 8.126: Best-estimate for shear strength (Su) from CPT-data for London Avenue Canal distressed section (east bank) a) beneath the crest of the levee and b) at or near the toe of the levee.





a) beneath crest of levee **b) at or near toe of levee**

Figure 8.127: Best-estimate for Su/P from CPT-data for London Avenue Canal distressed section (east bank) a) beneath the crest of the levee and b) at or near the toe of the levee

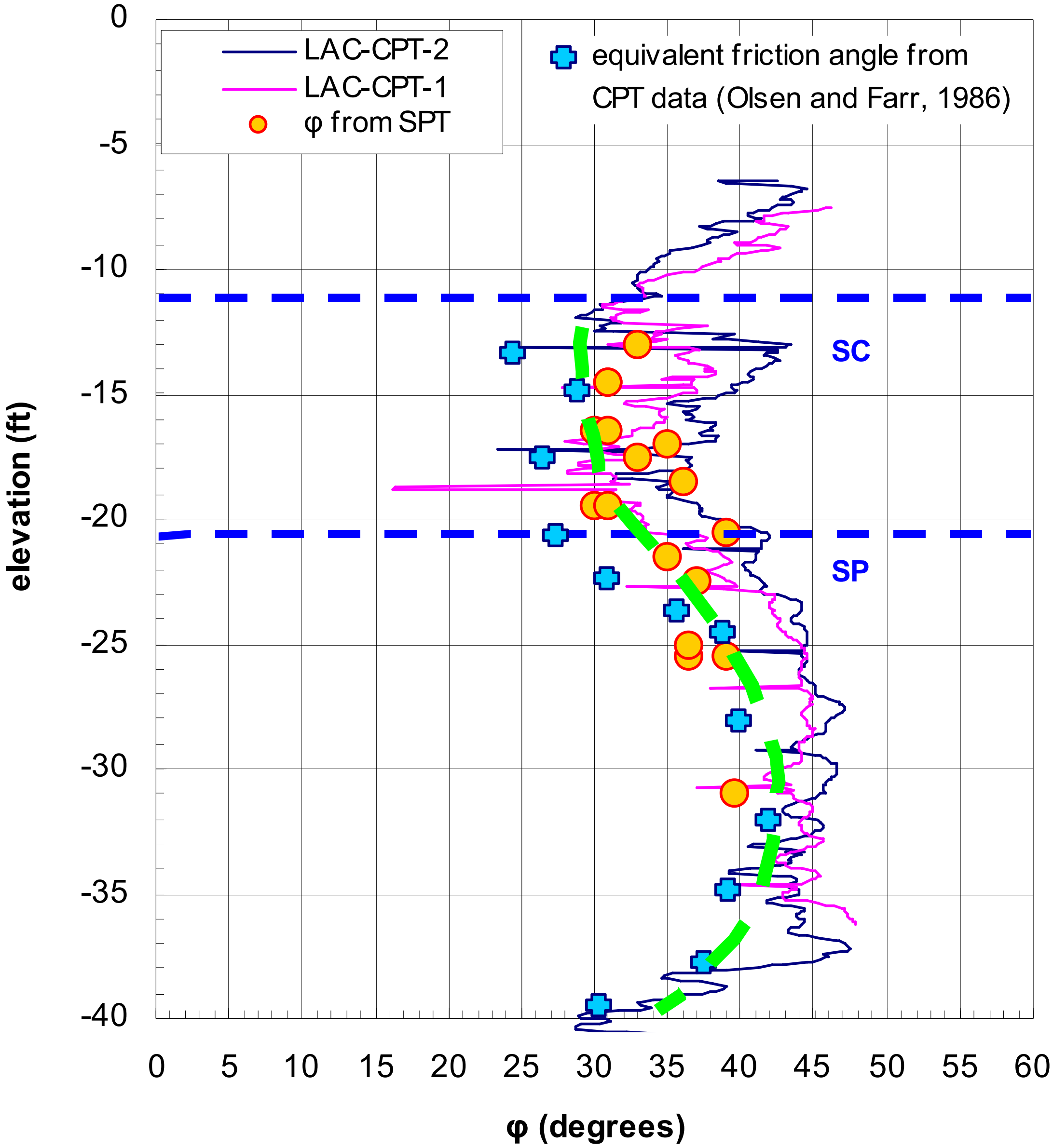


Figure 8.128: Estimation of friction angle for cohesionless materials for London Avenue Canal distressed section (east bank).

*Continuous lines are from Robertson and Campanella (1983)
** φ from SPT is based on Prof. Seed's table

London Avenue Canal, North, East Bank

Geotechnical parameters for the Finite Element Analysis Model

ID	Soil Model	Description	Type	γ_{unsat} [lb/ft³]	γ_{sat} [lb/ft³]	k_x [ft/day]	k_y [ft/day]	nu [-]	E_{ref} [lb/ft²]	c_{ref} [lb/ft²]	φ [°]
fill	Mohr Coulomb	(Non-engineered Fill / Fill)	Undrained	70	90	2.80E-03	2.80E-04	0.35	1.00E+06	800	0.001
marsh		marsh	Undrained	50	80	28.3	2.83	0.35	2.80E+05	550	0.001
CL/ML		silty low-PI clay (traces organic)	Undrained	70	90	2.80E-03	2.80E-04	0.35	9.00E+05	250	0.001
SC/SM		clayey, silty sand	Drained	90	100	2.33	1.15	0.3	5.00E+05	0.001	30
SP_1		loose sand	Drained	90	100	2.33	2.33	0.25	9.00E+05	0.001	33
SP_2		medium dense sand	Drained	100	110	2.33	2.33	0.25	1.00E+06	0.001	36
SP_3		dense sand	Drained	110	115	2.33	2.33	0.25	1.50E+06	0.001	40
CH		grey clay (Bay Sound)	Undrained	95	105	2.80E-03	2.80E-04	0.35	1.00E+06	600	0.001

London Avenue Canal, North, West Bank

Geotechnical parameters for the Finite Element Analysis Model

ID	Soil Model	Description	Type	γ_{unsat} [lb/ft³]	γ_{sat} [lb/ft³]	k_x [ft/day]	k_y [ft/day]	nu [-]	E_{ref} [lb/ft²]	c_{ref} [lb/ft²]	φ [°]
fill	Mohr Coulomb	(Non-engineered Fill / Fill)	Undrained	70	90	2.80E-03	2.80E-04	0.35	1.00E+06	800	0.001
marsh		marsh	Undrained	50	80	28.3	2.83	0.35	2.80E+05	450	0.001
CL/ML		silty low-PI clay (traces organic)	Undrained	70	90	2.80E-03	2.80E-04	0.35	9.00E+05	300	0.001
SC/SM		clayey, silty sand	Drained	90	100	2.33	1.15	0.3	5.00E+05	0.001	29
SP_1		loose sand	Drained	90	100	2.33	2.33	0.25	9.00E+05	0.001	33
SP_2		medium dense sand	Drained	100	110	2.33	2.33	0.25	1.00E+06	0.001	36
SP_3		dense sand	Drained	110	115	2.33	2.33	0.25	1.50E+06	0.001	40
CH		grey clay (Bay Sound)	Undrained	95	105	2.80E-03	2.80E-04	0.35	1.00E+06	600	0.001

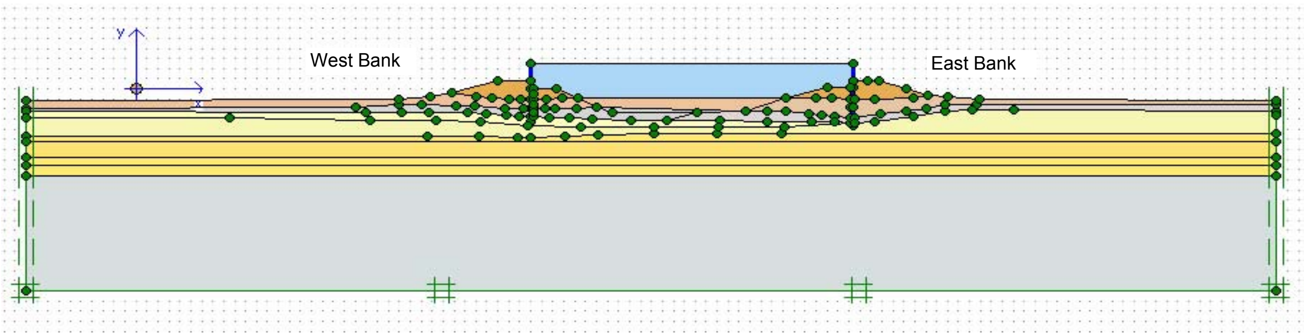


Figure 8.129: Geometry and input parameters for FEM analyses for London Avenue Canal, North (east and west banks)

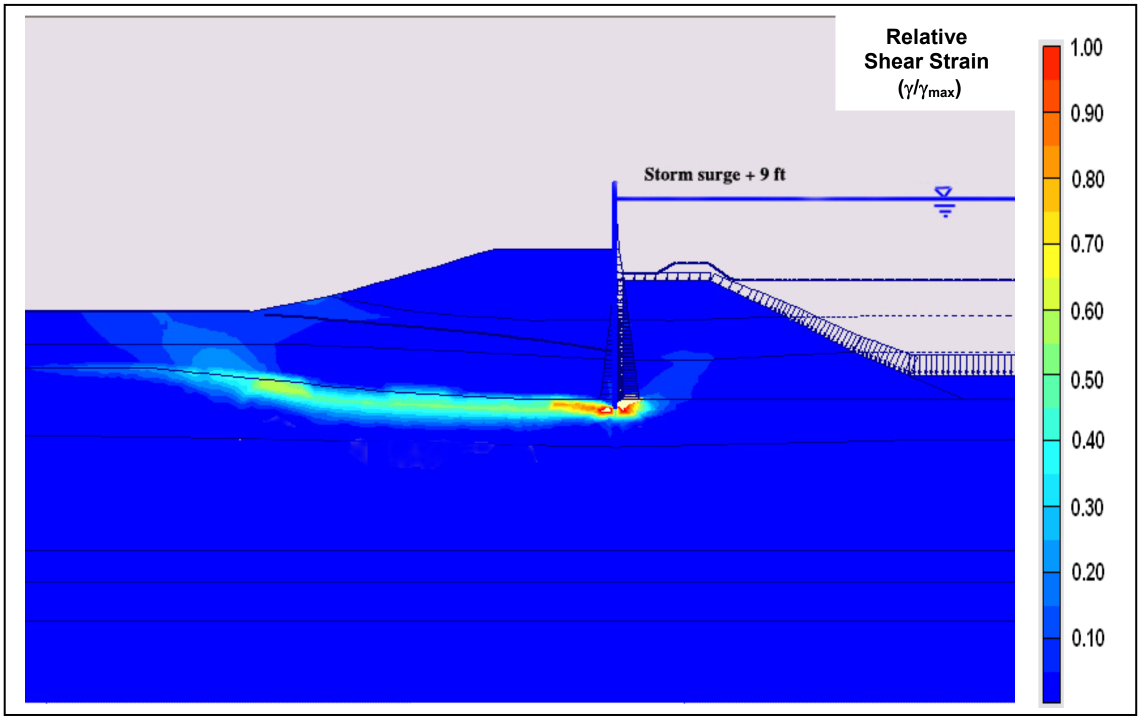


Figure 8.130: Normalized shear strain contours (shear strain divided by strain to failure) for a storm surge at Elev. + 9 feet (MSL) at the London Avenue Canal breach site (west bank); gapping at outboard toe of floodwall is developed to full depth.

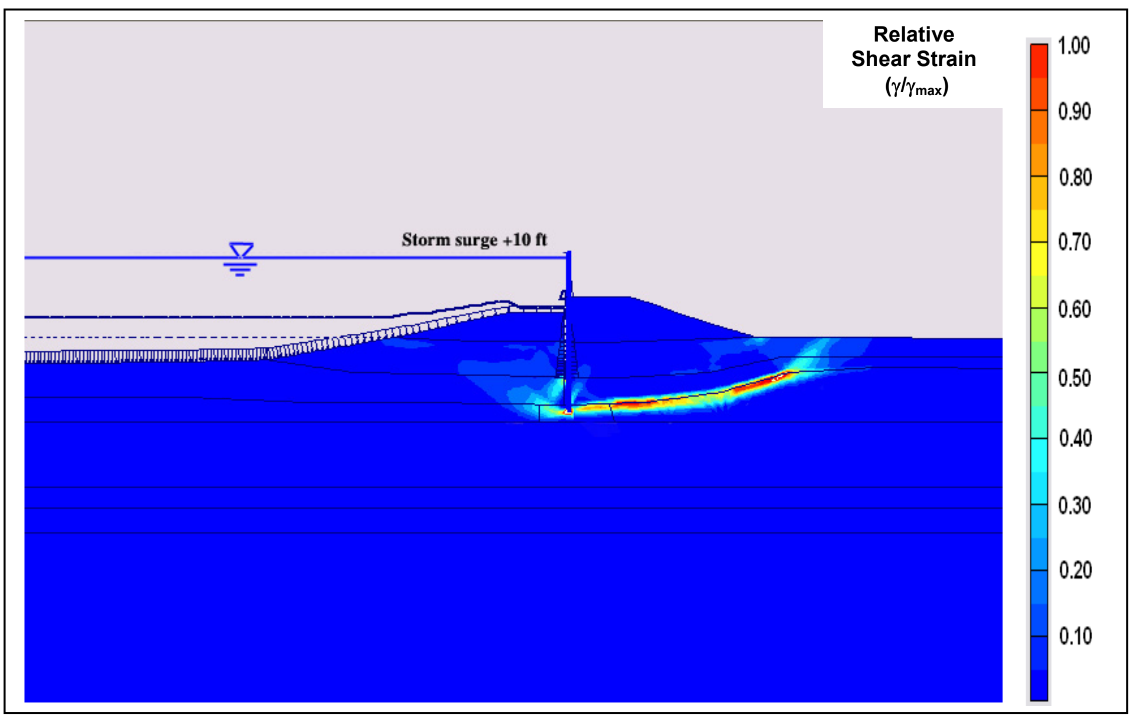


Figure 8.131: Normalized shear strain contours (shear strain divided by strain to failure) for a storm surge at Elev. + 10 feet (MSL) at the London Avenue Canal distressed site (east bank); gapping at outboard toe of floodwall is developed.

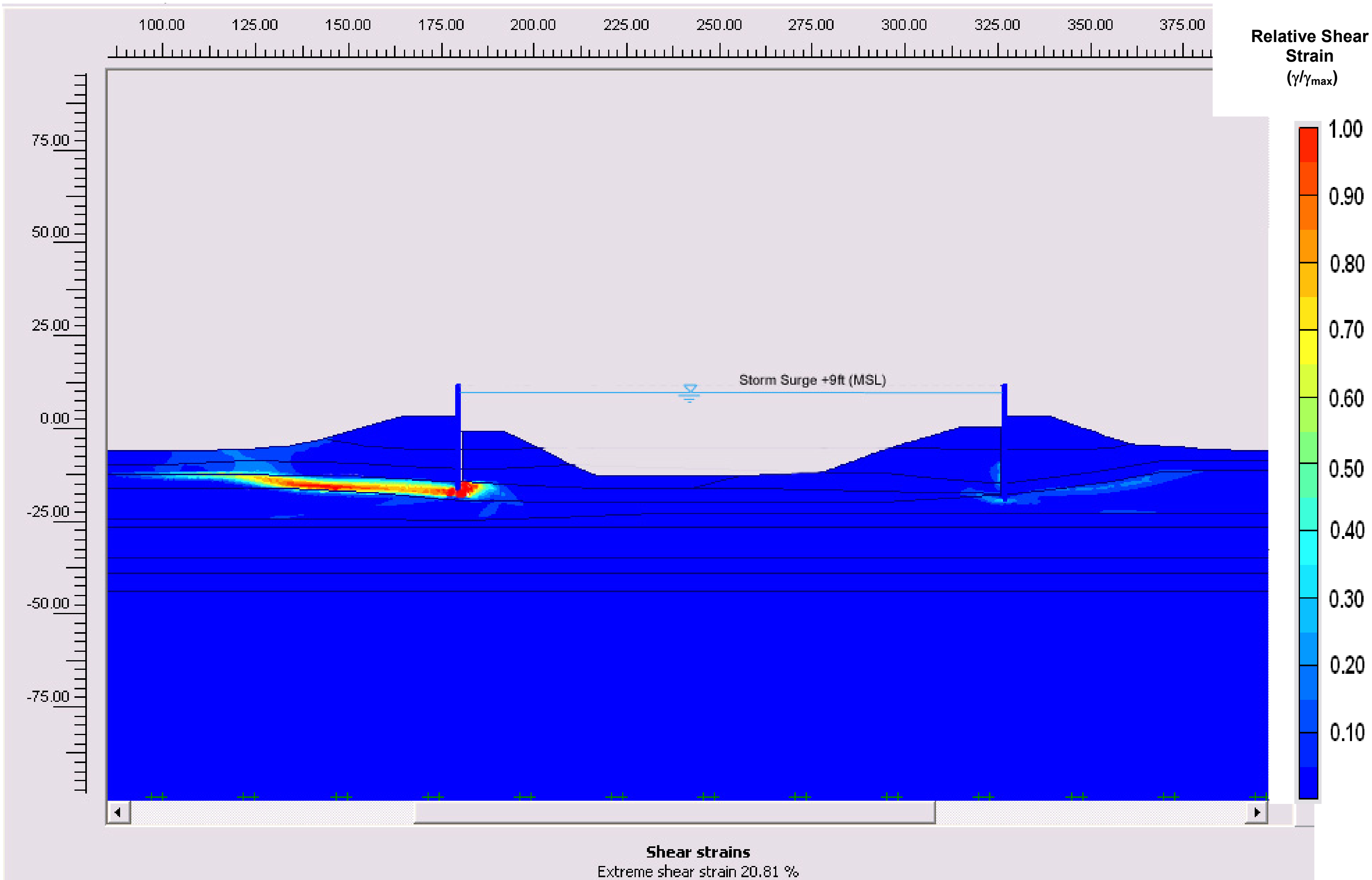


Figure 8.132: Normalized shear strain contours (shear strain divided by strain to failure) for a storm surge at Elev. + 9 feet (MSL) at the London Avenue Canal (east and west banks).

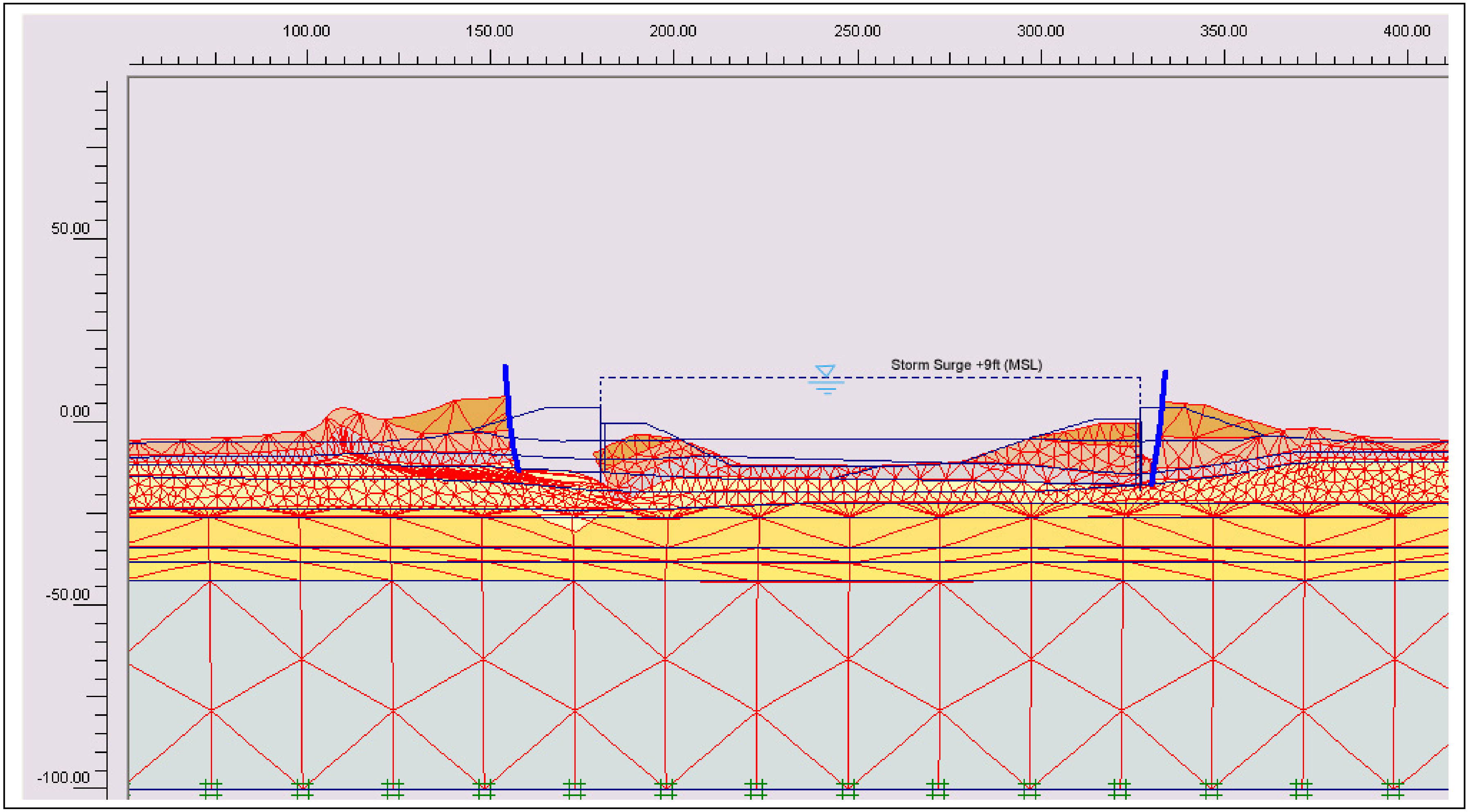


Figure 8.133: Deformed mesh for a storm surge elevation + 9 feet (MSL), London Avenue Canal (east and west banks).

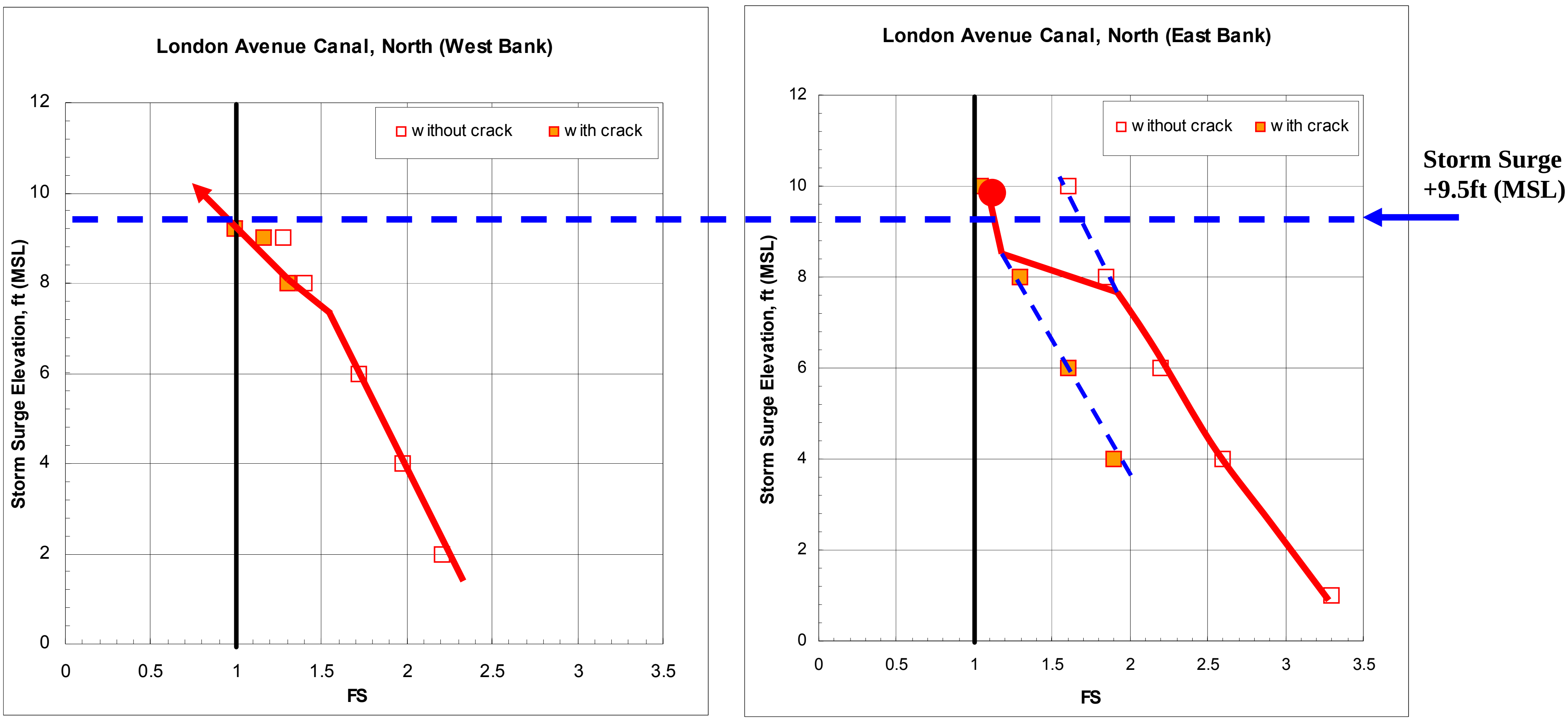


Figure 8.134: Calculated Factors of Safety for two modes based on PLAXIS analyses of the London Avenue Canal breach and distressed section for various canal water elevations; showing the best-estimated path to failure.

ID	Soil Model	Type	γ	c	phi	k
			[lb/ft^3]	[lb/ft^2]	[°]	[ft/hr]
Upper fill	Mohr-Coulomb	Undrained	100	800	0	1.17E-04
Marsh, crest	Mohr-Coulomb	Undrained	80	475	0	1.17
Marsh, free field	Mohr-Coulomb	Undrained	80	200	0	1.17
CL/ML, crest	Mohr-Coulomb	Undrained	85	500	0	2.00E-04
CL/ML, free field	Mohr-Coulomb	Undrained	85	300	0	2.00E-04
SC	Mohr-Coulomb	Drained	100	0	30	0.097
Loose Sand	Mohr-Coulomb	Drained	100	0	33	0.333
Dense Sand	Mohr-Coulomb	Drained	105	0	36	0.09
Stiff Clay	Mohr-Coulomb	Undrained	90	600	0	2.00E-04

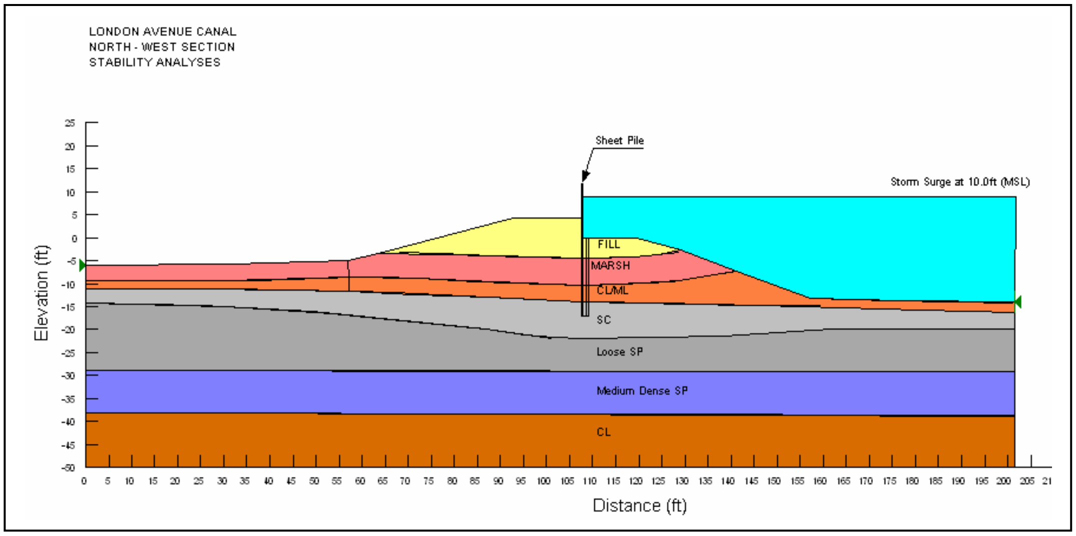


Figure 8.135: Geometry and input parameters for Limit Equilibrium and Steady State seepage Analyses for London Avenue Canal North, West bank.

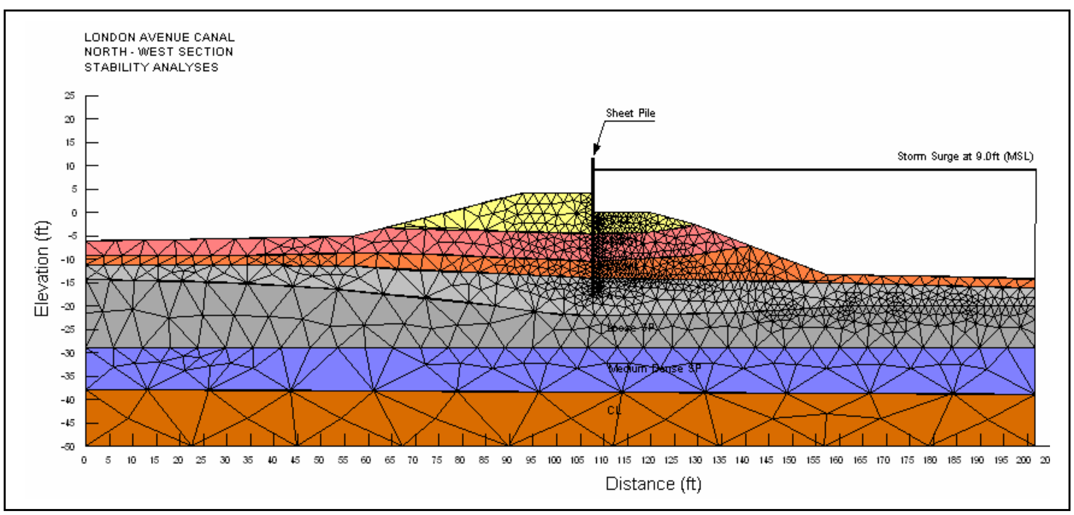


Figure 8.136: Finite Difference mesh for Steady State seepage Analyses for London Avenue Canal North, West bank.

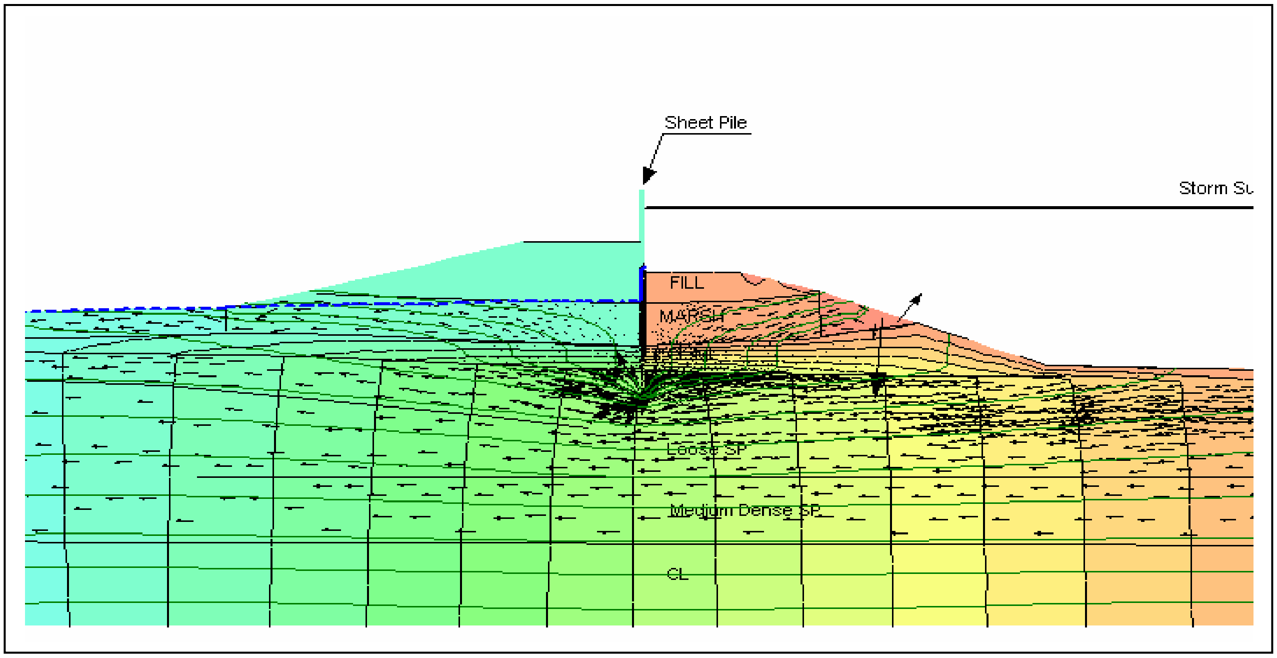


Figure 8.137: Flow net generation without the gapping in the outboard toe of the floodwall, London Avenue Canal North, West bank. Storm surge at 9ft (MSL).

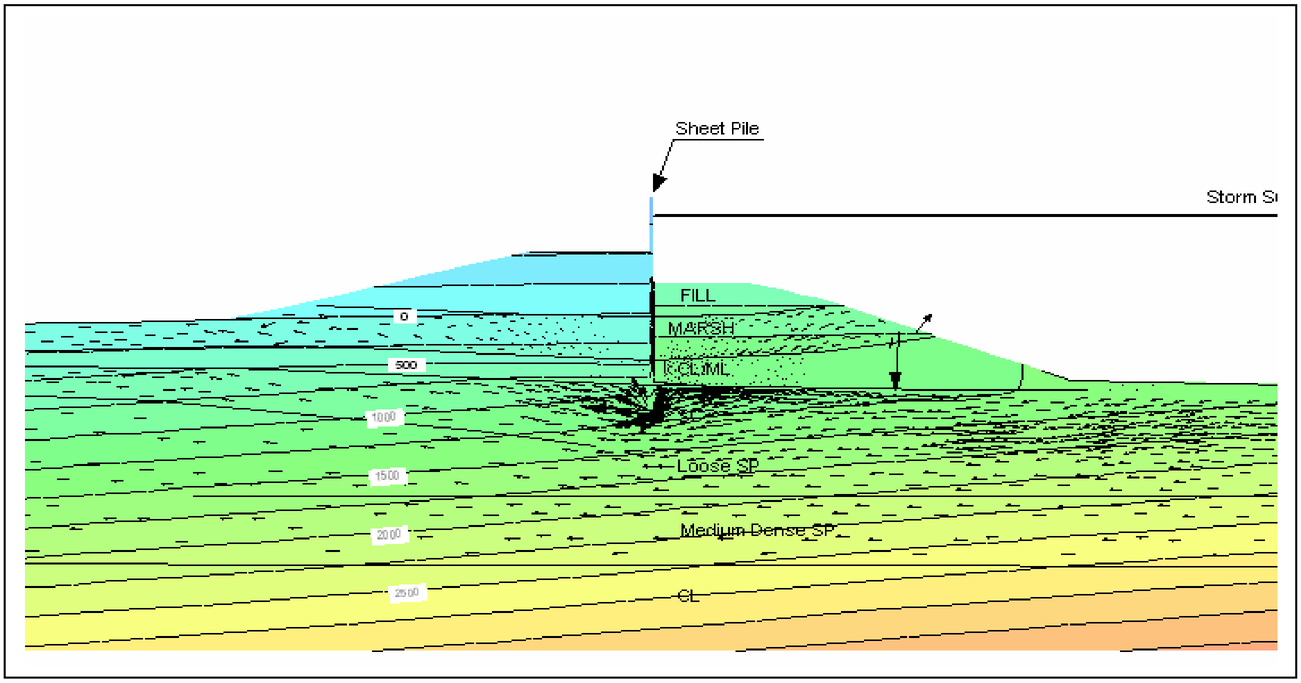


Figure 8.138: Pore water pressure contours without the gapping in the outboard toe of the floodwall, London Avenue Canal North, West bank. Storm surge at 9ft (MSL).

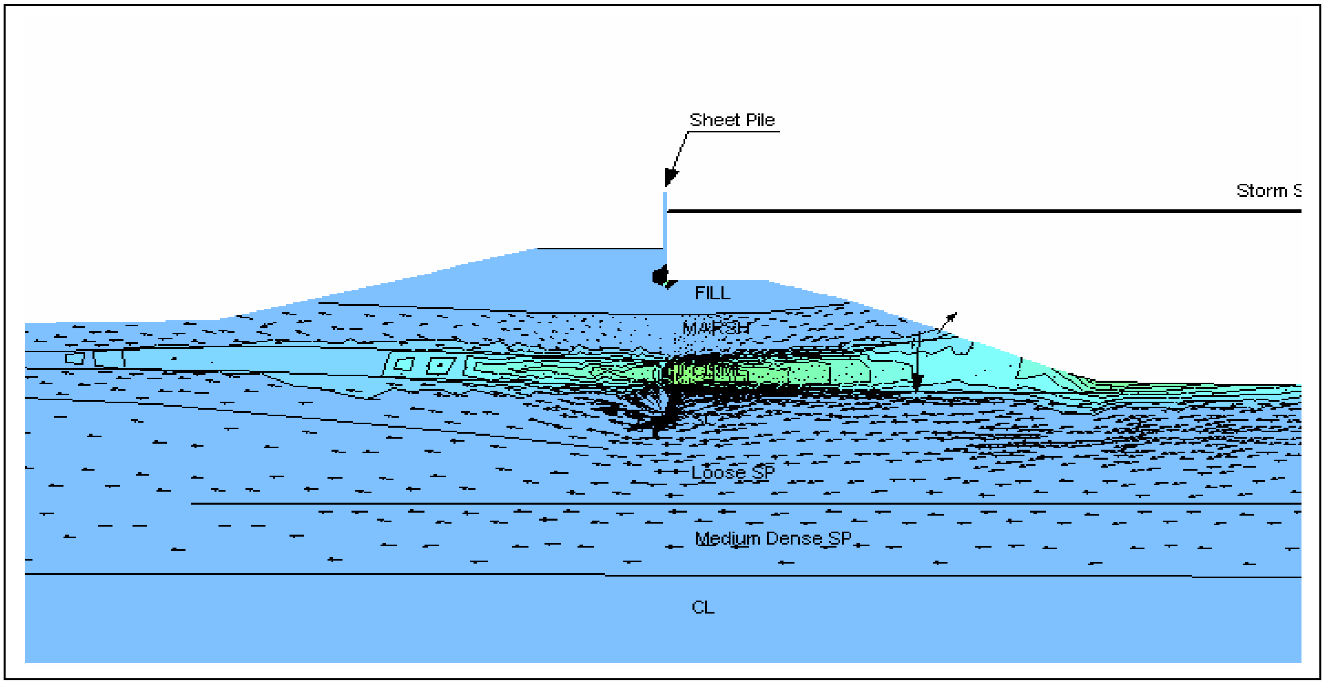


Figure 8.139: Hydraulic gradient contours without the gapping in the outboard toe of the floodwall, London Avenue Canal North, West bank. Storm surge at 9ft (MSL). Exit gradient at the inboard toe is 0.20.

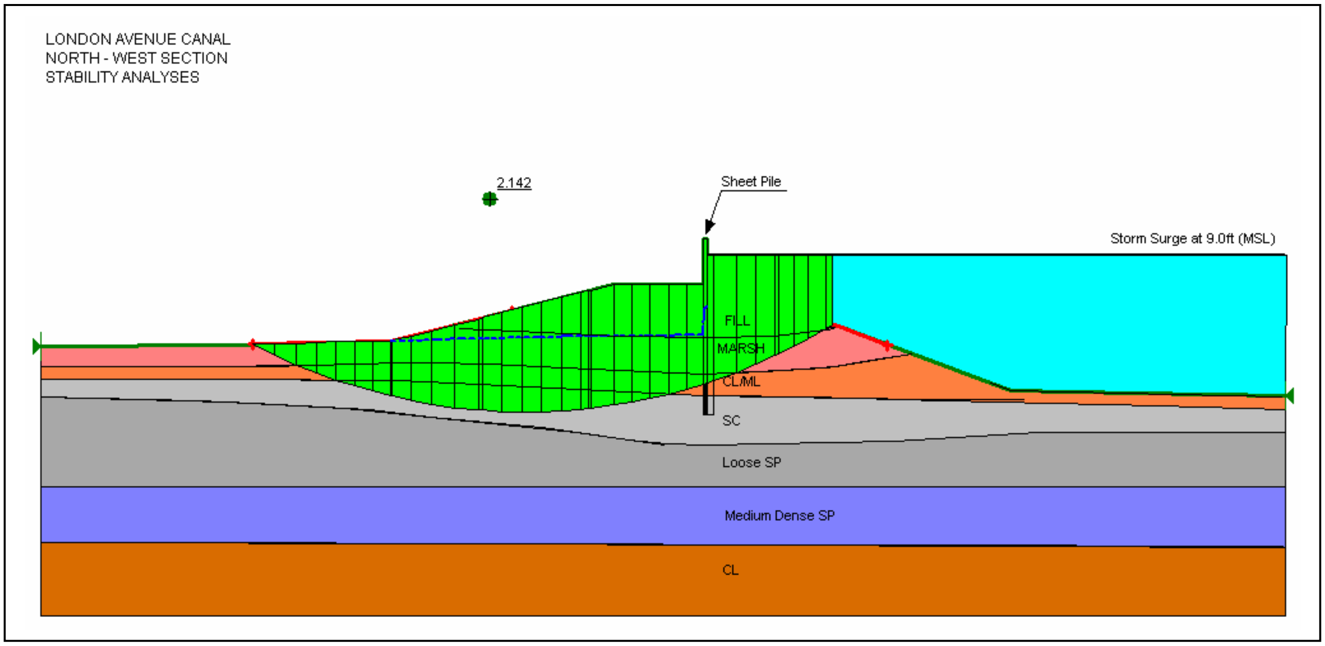


Figure 8.140: Critical failure surface without the gapping in the outboard toe of the floodwall, London Avenue Canal North, West bank. Storm surge at 9ft (MSL).

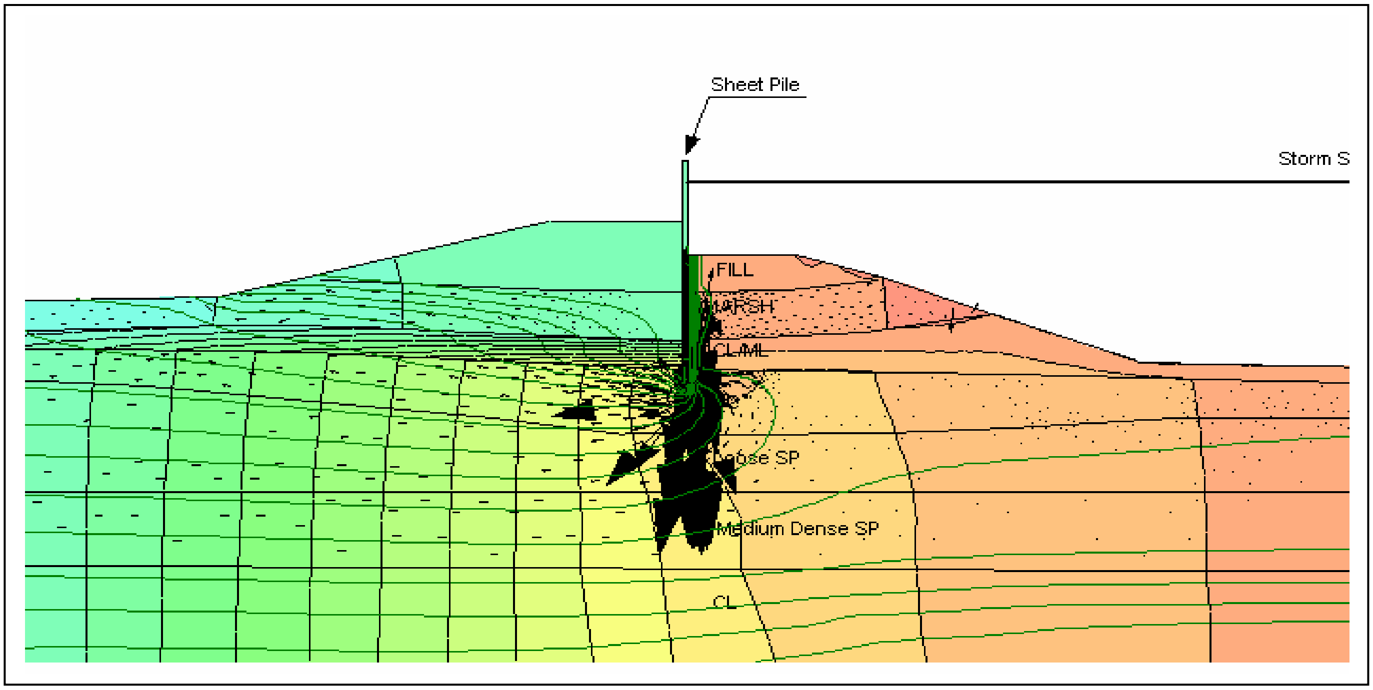


Figure 8.141: Flow net generation with the gapping in the outboard toe of the floodwall, London Avenue Canal North, West bank. Storm surge at 9ft (MSL).

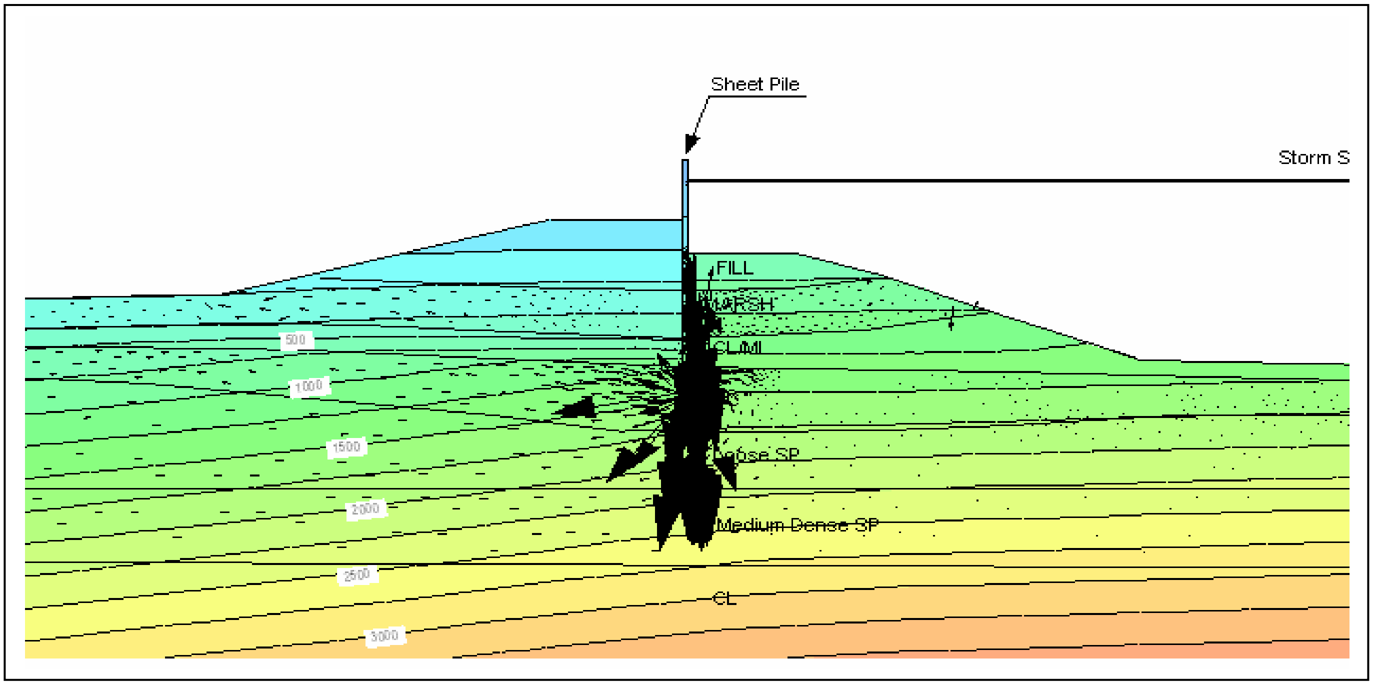


Figure 8.142: Pore water pressure contours with the gapping in the outboard toe of the floodwall, London Avenue Canal North, West bank. Storm surge at 9ft (MSL).

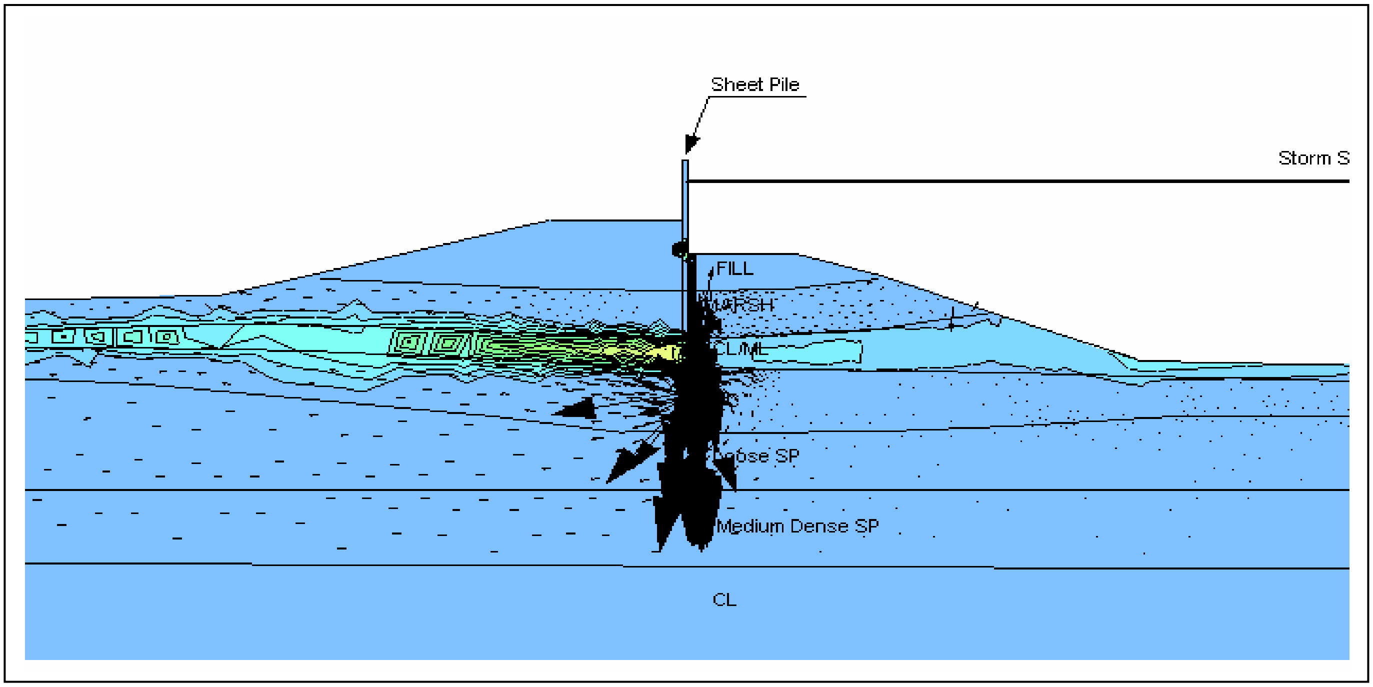


Figure 8.143: Hydraulic gradient contours with the gapping in the outboard toe of the floodwall, London Avenue Canal North, West bank. Storm surge at 9ft (MSL). Exit gradient at the inboard toe is 0.20.

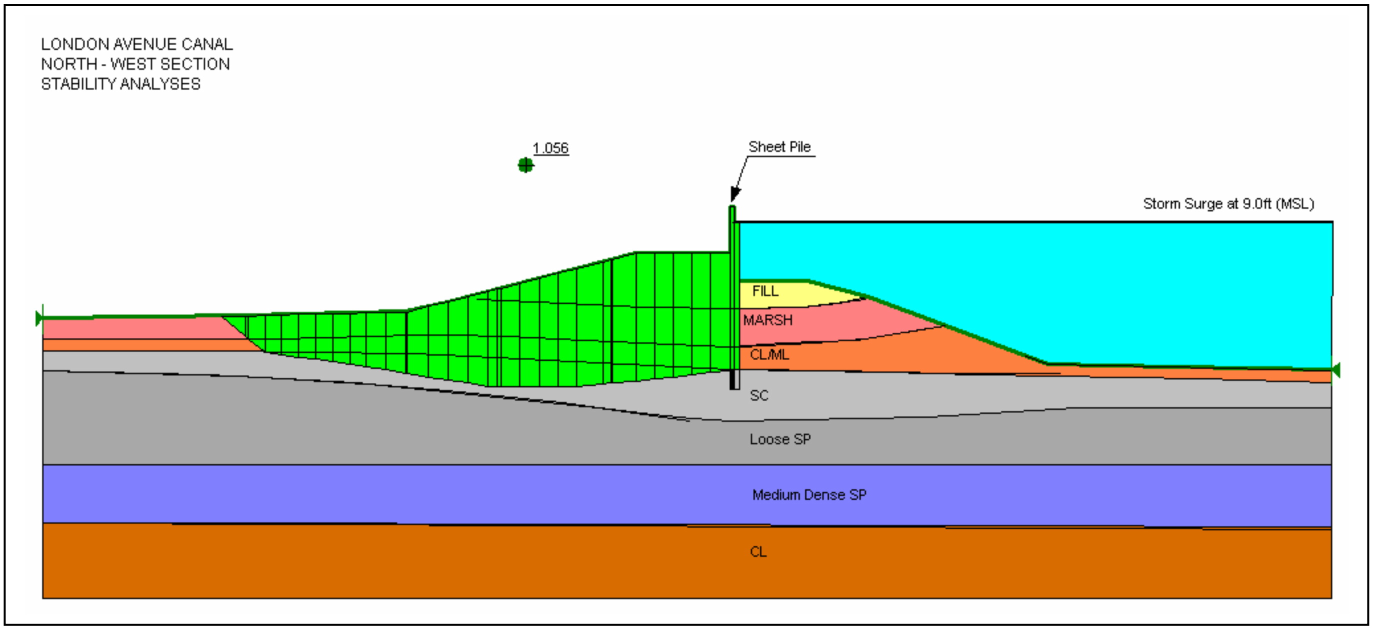


Figure 8.144: Critical failure surface with the gapping in the outboard toe of the floodwall, London Avenue Canal North, West bank. Storm surge at 9ft (MSL).

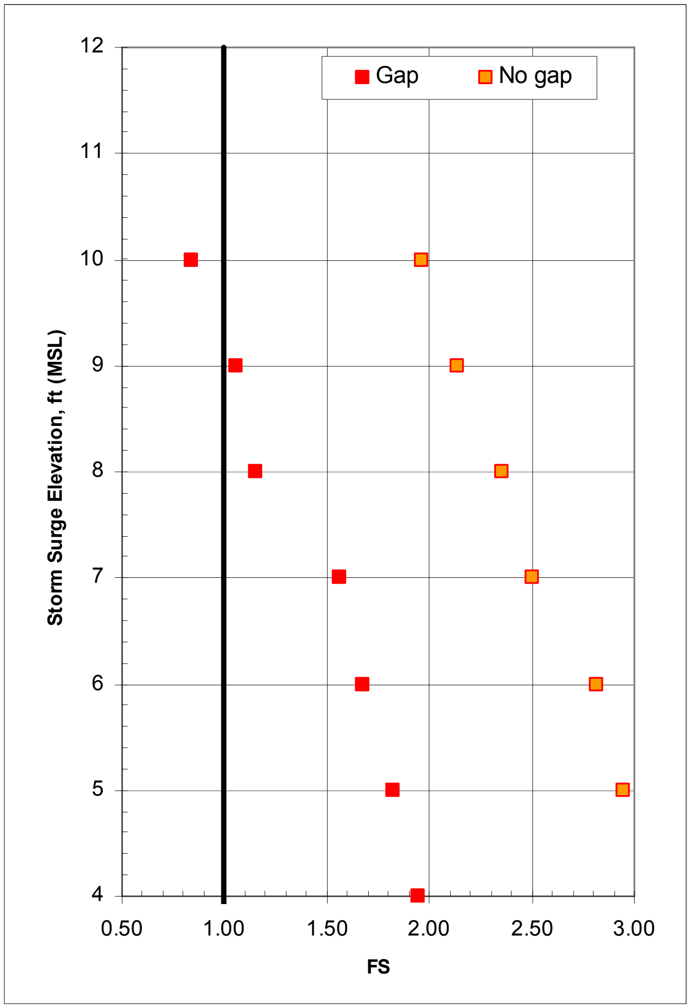


Figure 8.145 : Calculated Factors of Safety for two models based on Limit Equilibrium Analyses of the London Avenue Canal, North West bank.

ID	Soil Model	Type	γ [lb/ft^3]	c [lb/ft^2]	phi [°]	k [ft/hr]
Upper fill	Mohr-Coulomb	Undrained	100	800	0	1.17E-04
Marsh, crest	Mohr-Coulomb	Undrained	80	550	0	1.17
Marsh, free field	Mohr-Coulomb	Undrained	80	300	0	1.17
CL/ML, crest	Mohr-Coulomb	Undrained	85	275	0	2.00E-04
CL/ML, free field	Mohr-Coulomb	Undrained	80	200	0	2.00E-04
SC	Mohr-Coulomb	Drained	100	0	30	0.097
Loose Sand	Mohr-Coulomb	Drained	100	0	33	0.333
Dense Sand	Mohr-Coulomb	Drained	115	0	36	0.09
Stiff Clay	Mohr-Coulomb	Undrained	95	600	0	2.00E-04

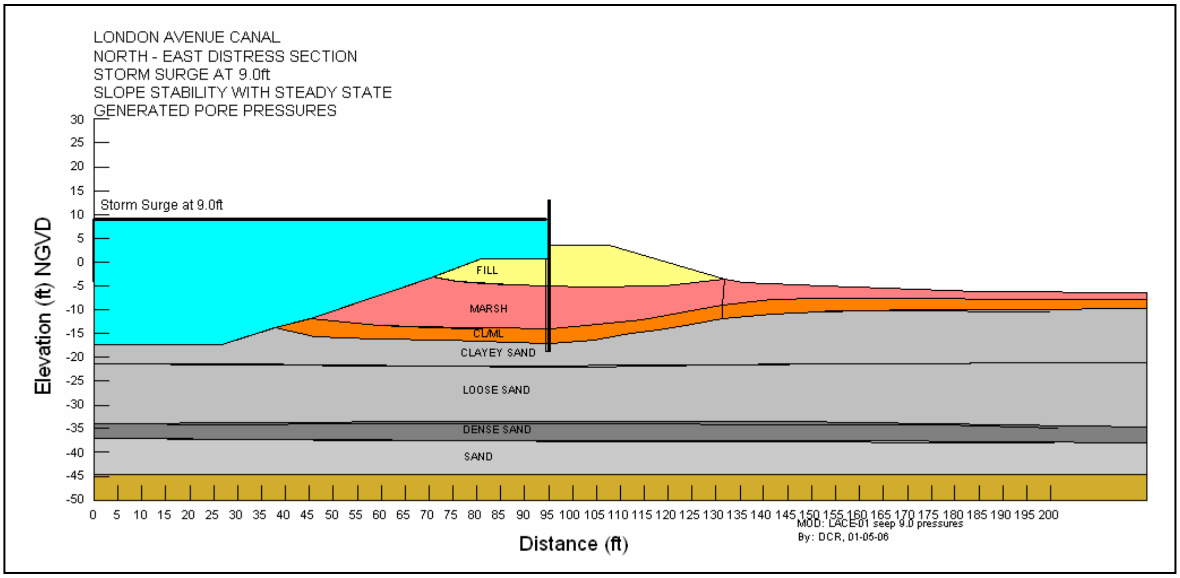


Figure 8.146: Geometry and input parameters for Limit Equilibrium and Steady State seepage Analyses for London Avenue Canal North, East bank.

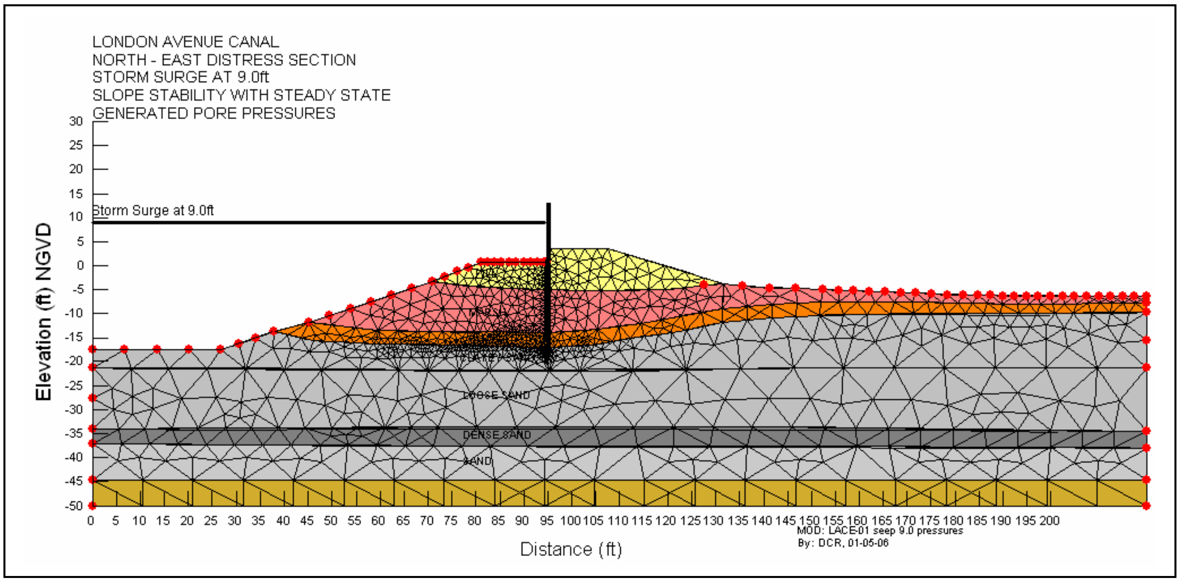


Figure 8.147: Finite Difference mesh for Steady State seepage Analyses for London Avenue Canal North, East bank.

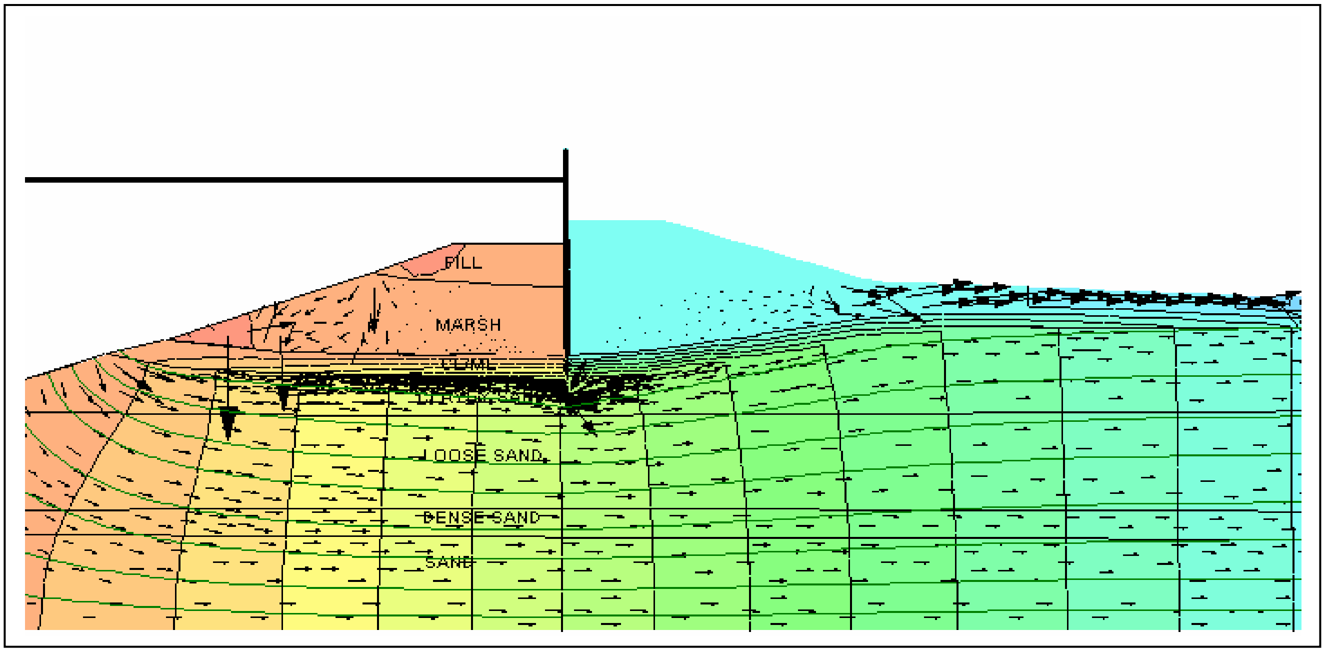


Figure 8.148: Flow net generation without the gapping in the outboard toe of the floodwall, London Avenue Canal North, East bank. Storm surge at 9ft (MSL).

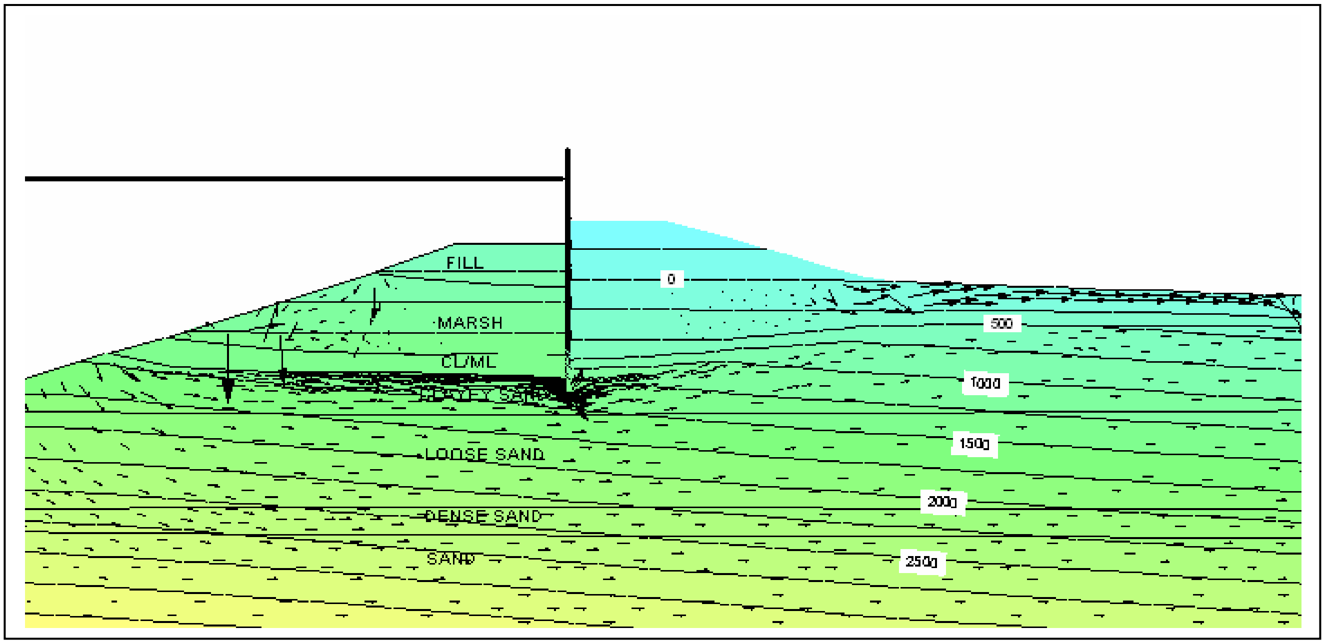


Figure 8.149: Pore water pressure contours without the gapping in the outboard toe of the floodwall, London Avenue Canal North, East bank. Storm surge at 9ft (MSL).

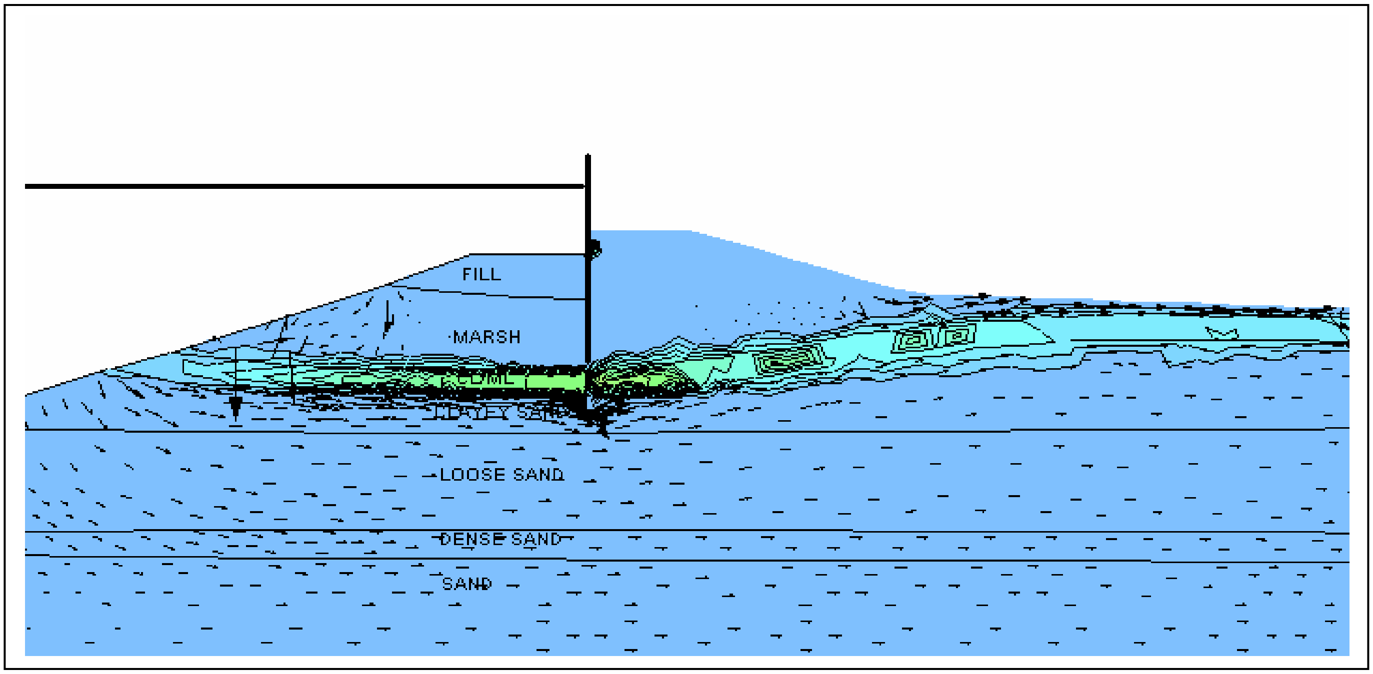


Figure 8.150: Hydraulic gradient contours without the gapping in the outboard toe of the floodwall, London Avenue Canal North, East bank. Storm surge at 9ft (MSL). Exit gradient at the inboard toe is 0.20.

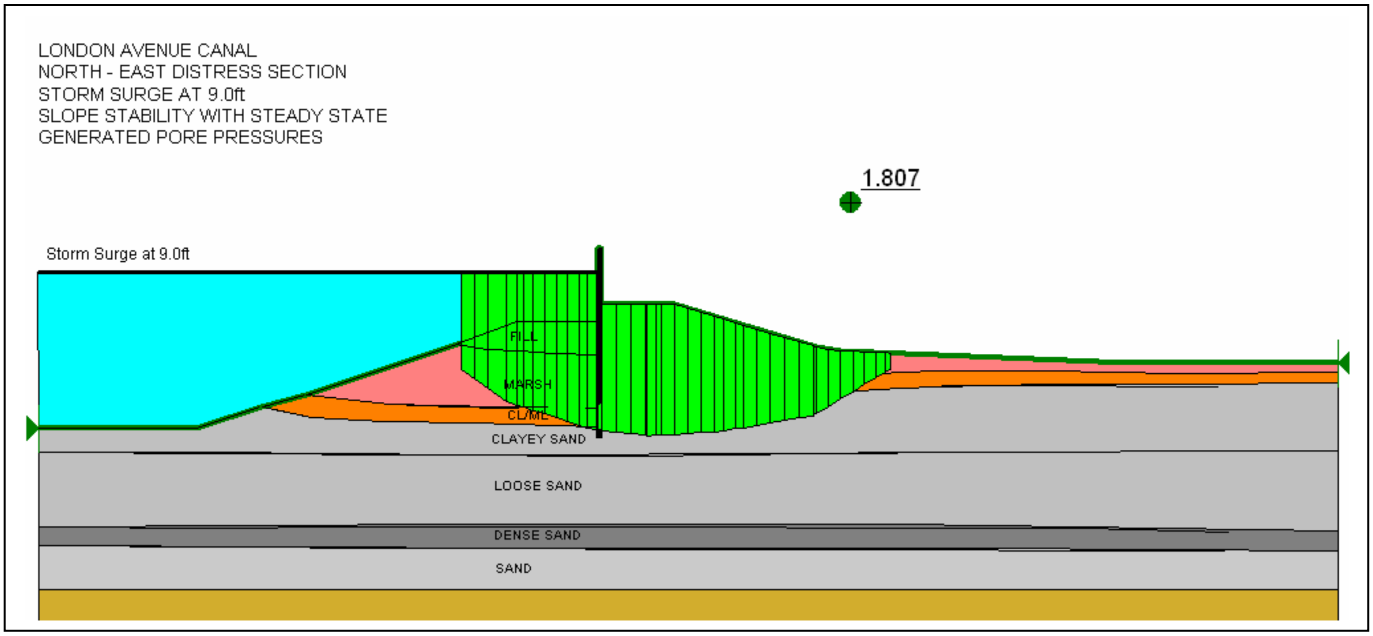


Figure 8.151: Critical failure surface without the gapping in the outboard toe of the floodwall, London Avenue Canal North, East bank. Storm surge at 9ft (MSL).

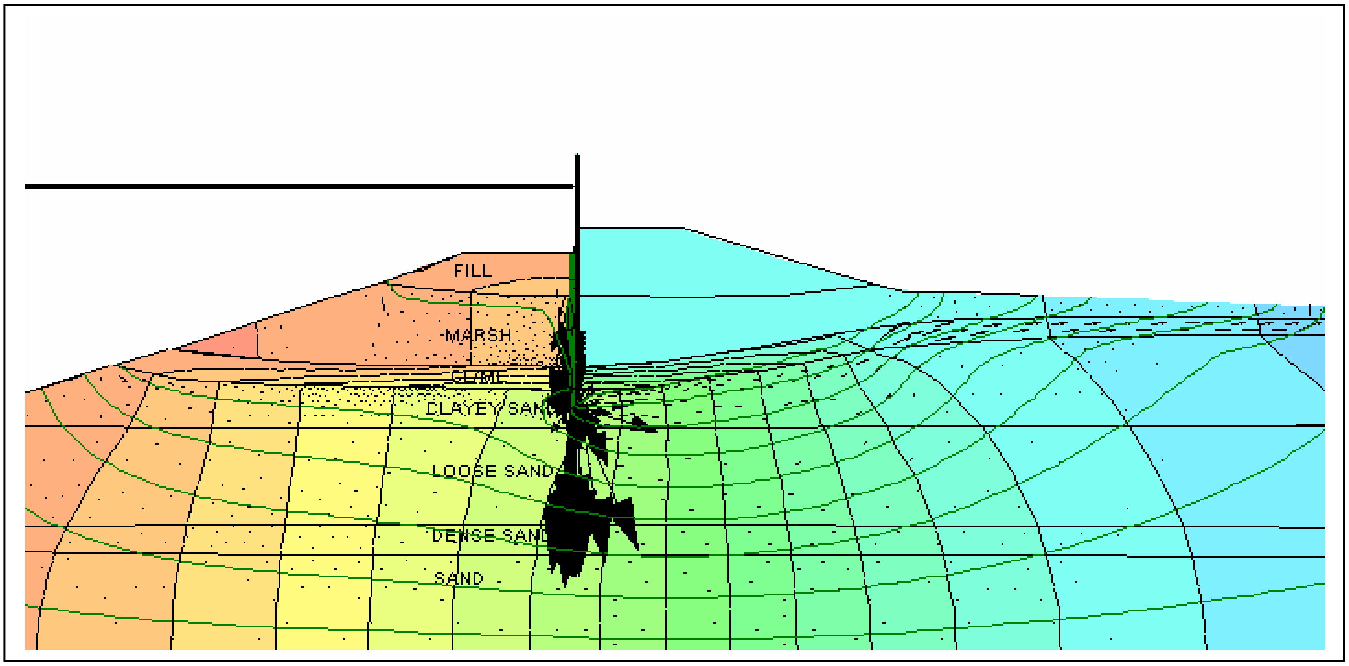


Figure 8.152: Flow net generation with the gapping in the outboard toe of the floodwall, London Avenue Canal North, East bank. Storm surge at 9ft (MSL).

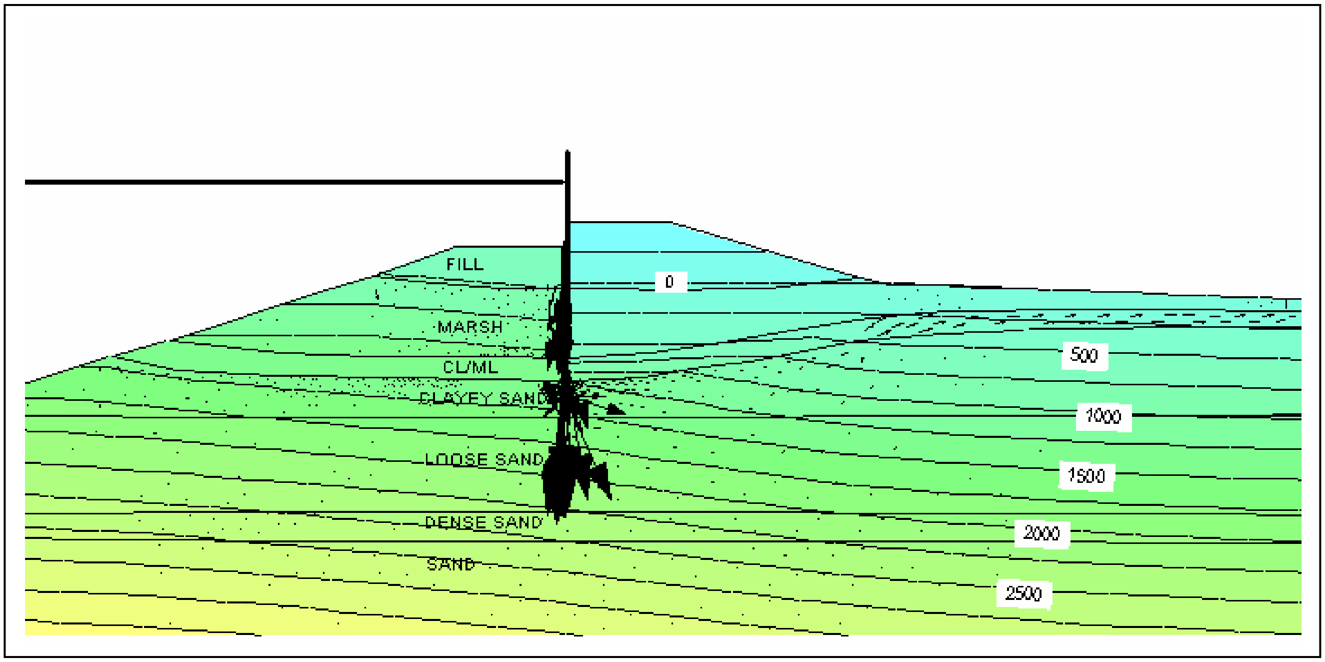


Figure 8.153: Pore water pressure contours with the gapping in the outboard toe of the floodwall, London Avenue Canal North, East bank. Storm surge at 9ft (MSL).

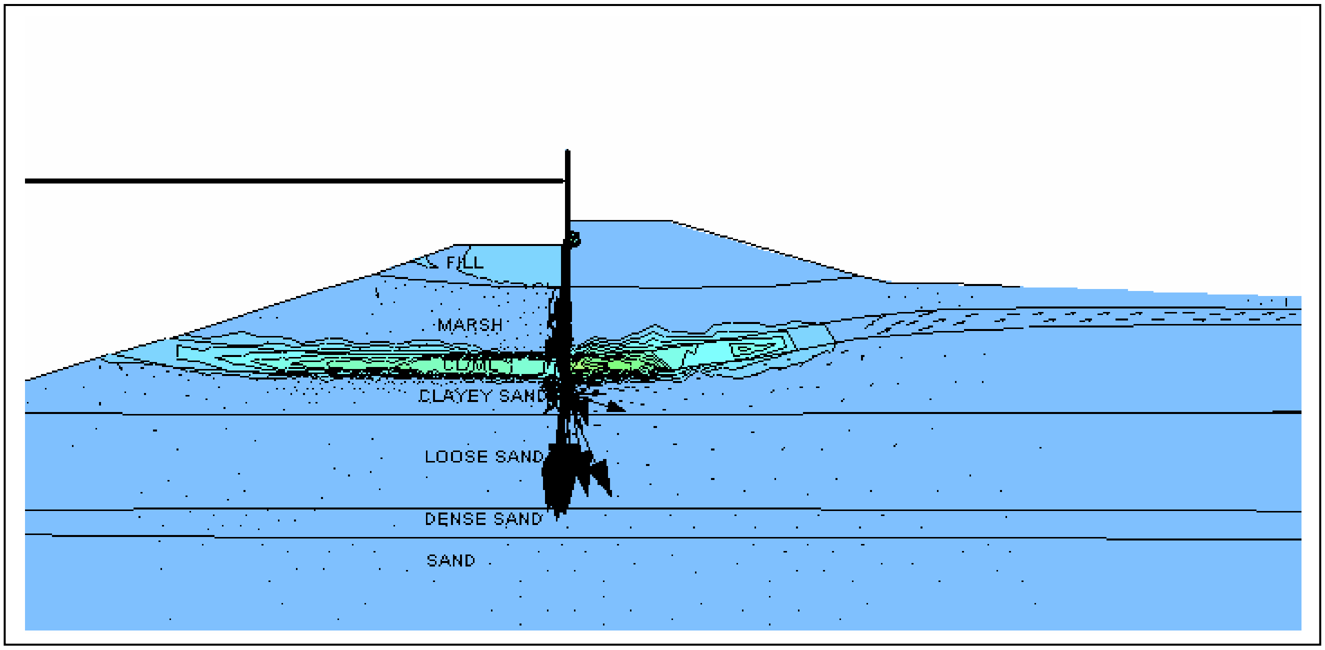


Figure 8.154: Hydraulic gradient contours with the gapping in the outboard toe of the floodwall, London Avenue Canal North, East bank. Storm surge at 9ft (MSL). Exit gradient at the inboard toe is 0.25.

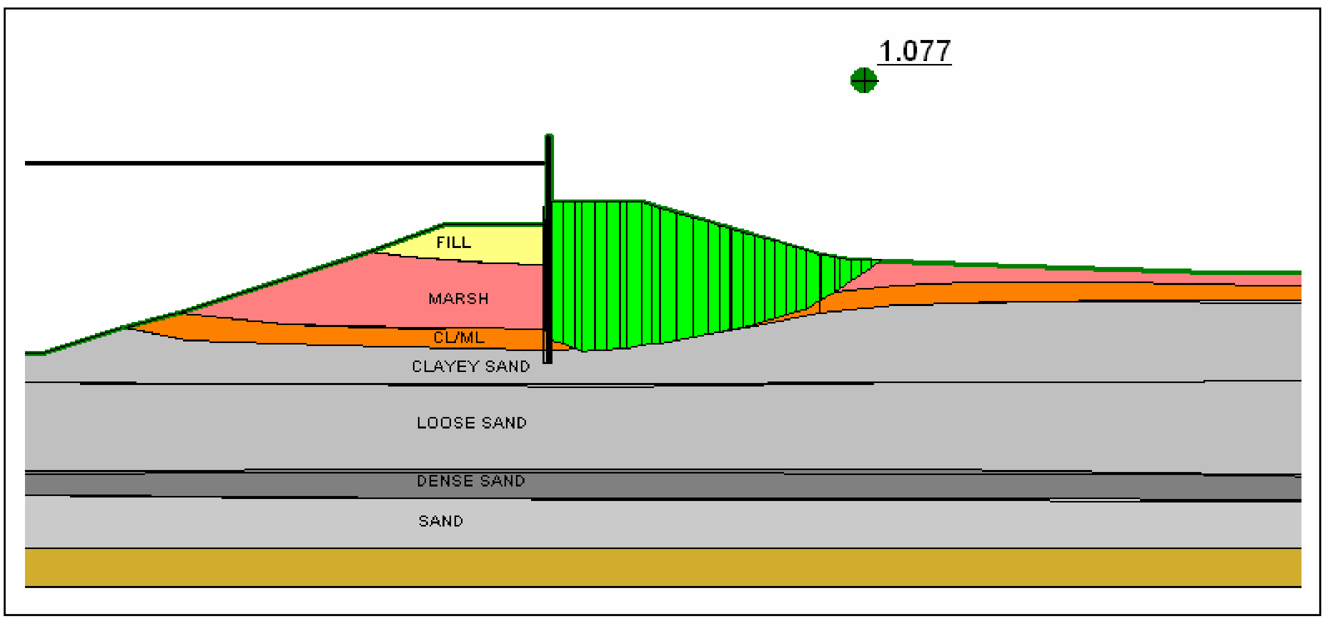


Figure 8.155: Critical failure surface with the gapping in the outboard toe of the floodwall, London Avenue Canal North, East bank. Storm surge at 9ft (MSL).

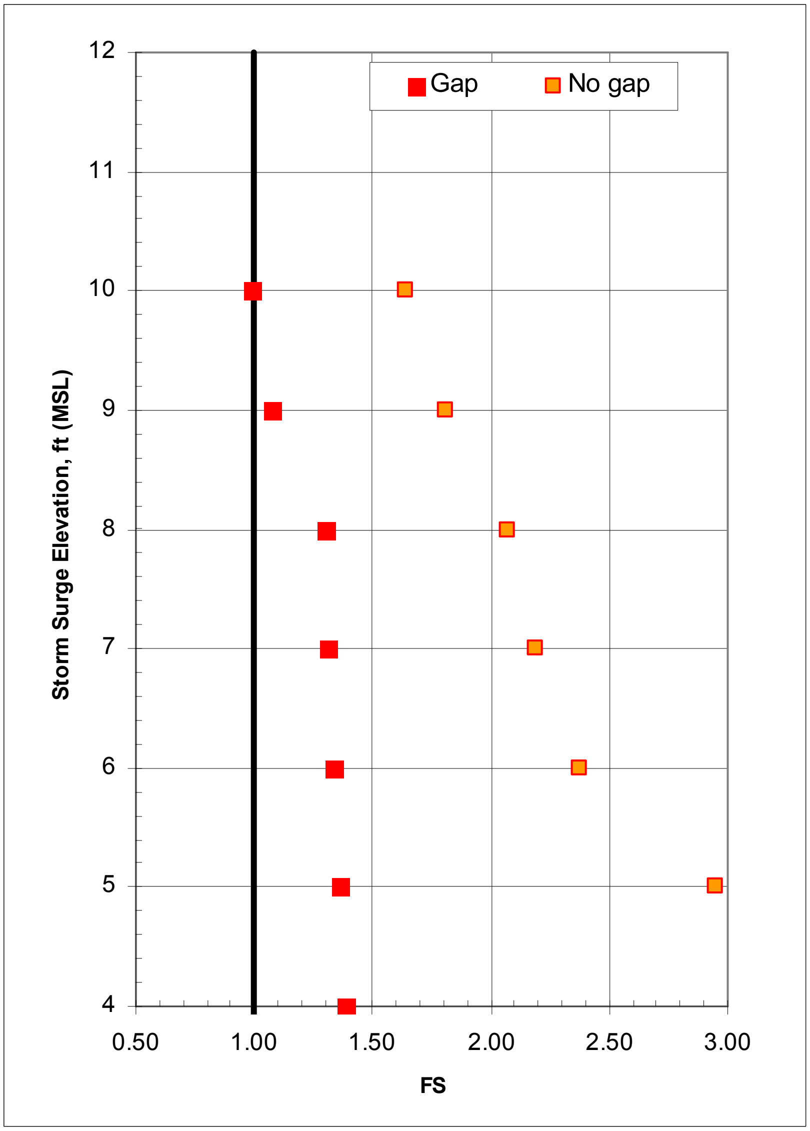


Figure 8.156 : Calculated Factors of Safety for two models based on Limit Equilibrium Analyses of the London Avenue Canal, North East bank..

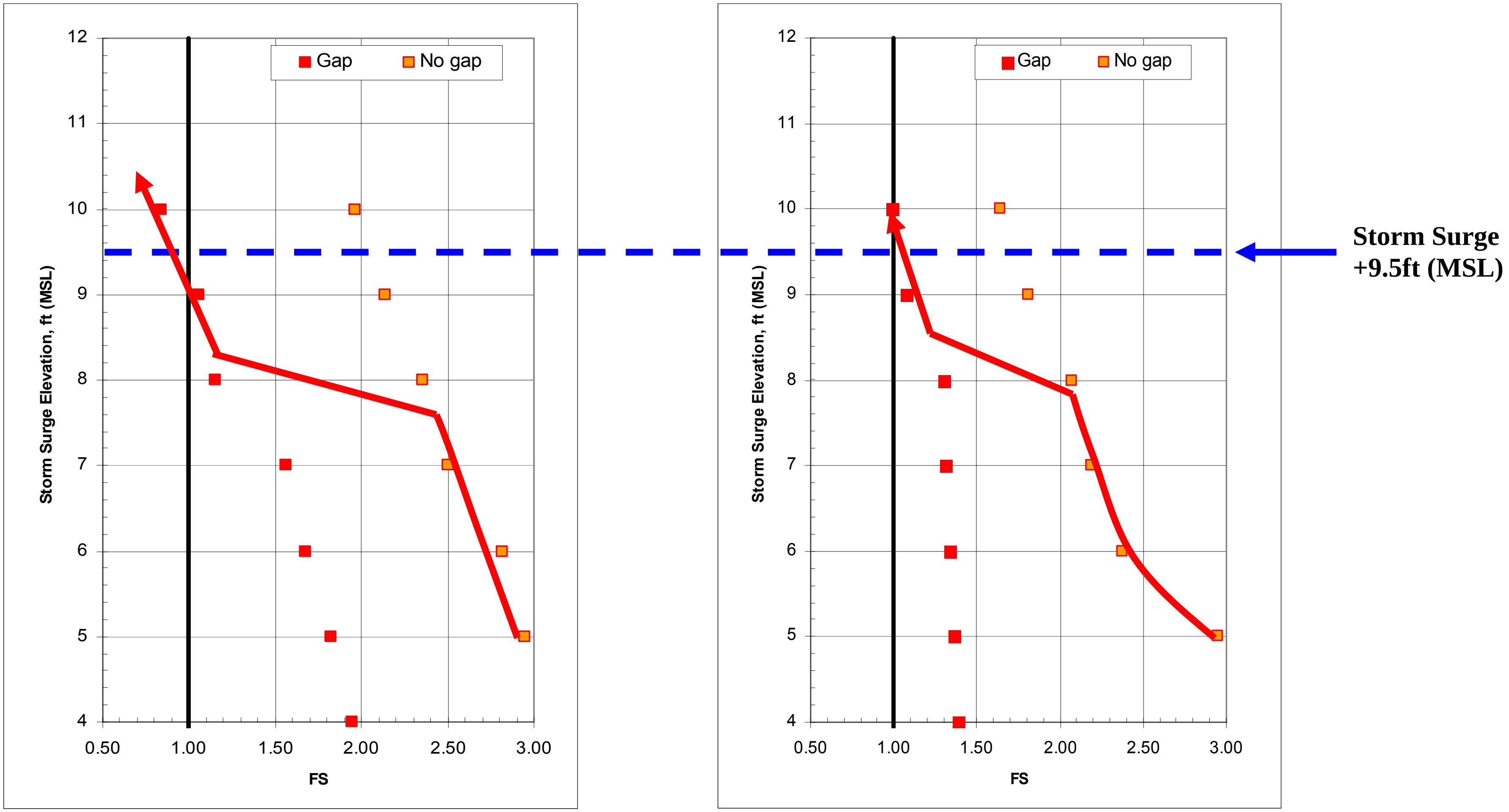


Figure 8.157: Calculated Factors of Safety for two modes based on Limit Equilibrium Analyses of the London Avenue Canal breach and distressed section for various canal water elevations; showing the best-estimated path to failure.

CHAPTER NINE: EROSION TESTS ON NEW ORLEANS LEVEE SAMPLES

9.1 Erodibilty: A Definition

Erodibility is a term often used in scour and erosion studies. Erodibility may be thought of as one number which characterizes the rate at which a soil is eroded by the flowing water. With this concept erosion resistant soils would have a low erodibility index and erosion sensitive soils would have a high erodibility index. This concept is not appropriate; indeed the water velocity can vary drastically from say 0 m/s to 5 m/s or more and therefore the erodibility is a not a single number but a relationship between the velocity applied and the corresponding erosion rate experienced by the soils. While this is an improved definition of erodibility, it still presents some problems because water velocity is a vector quantity which varies everywhere in the flow and is theoretically zero at the soil water interface. It is much preferable to quantify the action of the water on the soil by using the shear stress applied by the water on the soil at the water-soil interface. Erodibility is therefore defined here as the relationship between the erosion rate $\dot{z}$ and the hydraulic shear stress applied τ (Figure 9.1). This relationship is called the erosion function $\dot{z}(\tau)$. The erodibility of a soil or a rock is represented by the erosion function of that soil or rock. This erosion function can be obtained by using a laboratory device called the EFA (Erosion Function Apparatus) and described later.

9.2 Erosion Process

Soils are eroded particle by particle in the case of coarse-grained soils (cohesionless soils). In the case of fine-grained soils (cohesive soils), erosion can take place particle by particle but also block of particles by block of particles. The boundaries of these blocks are formed naturally in the soil matrix by micro-fissures due to various phenomena including compression and extension.

The resistance to erosion is influenced by the weight of the particles for coarse grained soils and by a combination of weight and electromagnetic and electrostatic inter-particle forces for fine grained soils. Observations at the soil water interface on slow motion videotapes indicates that the removal of particle or blocks of particles is by a combination of rolling and plucking action of the water on the soil.

9.3 Velocity vs. Shear Stress

The scour process is highly dependent on the shear stress developed by the flowing water at the soil-water interface. Indeed, at that interface the flow is tangential to the soil surface regardless of the flow condition above it; very little water if any flows perpendicular to the interface. The water velocity in the river is in the range of 0.1 to 3 m/s, whereas the bed shear stress is in the range of 1 to 50 N/m2 (Figure 9.2) and increases with the square of the water velocity. The magnitude of this shear stress is a very small fraction of the undrained shear strength of clays used in foundation engineering (Figure 9.3).

It is amazing to see that such small shear stresses are able to scour rocks to a depth of 1,600 m, as in the case for the Grand Canyon over the last 20 million years at an average scour rate of 9.1x10-6 mm/hr. This leads one to think that even small shear stresses if applied cyclically by the turbulent nature of the flow can overcome, after a sufficient number of cycles, the crystalline bonds in a rock and the electromagnetic bonds in a clay. This also leads one to think that there is no cyclic stress threshold, but that any stress is associated with a number of cycles to failure. (Gravity bonds seem to be an exception to this postulate, because it appears that gravity bonds cannot be weakened by cyclic loading.) This postulate contradicts the critical shear stress concept discussed later.

The profile of the water velocity versus depth in the flow (Figure 9.4) indicates a maximum velocity at the free surface and a zero velocity at the bottom of the flow. This zero velocity boundary is due to the fact that the water does not flow below the flow bottom. While the velocity is zero at the bottom, the shear stress is maximum because the shear stress is proportional to the slope of the velocity profile versus depth. This is explained in Figure 9.4. One can think of the water element in contact with the bottom as a simple shear test on water. Since water is a Newtonian fluid, the shear stress that it develops is proportional to the rate at which it is sheared. This governs the equation in Figure 9.4.

9.4 Erosion Threshold and Erosion Categories

The critical velocity is the velocity at which the soil starts to erode. The critical shear stress is the shear stress at which the soil starts to erode (Figures 9.1 and 9.2). Below these values there is no erosion, above these values the soil erodes at a certain rate. This threshold of erosion is very useful in engineering but it is not obvious that such a clear threshold truly exists physically. Indeed a sample of granite, for example, has a very high critical shear stress. Yet common sense tells us that a pebble made of granite and left under a dripping faucet for 20 million years would develop a hole. In this case, the critical shear as we conceive it would not have been reached yet the rock would have been eroded. The reason for the hole in the pebble may be that there is no such thing as a cyclic threshold for materials and that cyclic stresses even very small can destroy any material bonds; it is only a matter of the number of cycles to break the bond. So one has to accept a practical definition of the critical shear stress. The critical shear stress is defined here as the shear stress corresponding to a rate of erosion of 1 mm/hr in the Erosion Function Apparatus. Values of critical shear stresses are shown in Figure 9.2.

If the critical shear stress is exceeded, it becomes important to know how fast the soil is eroding at a given velocity. The relationship between the erosion rate and the velocity or the interface shear stress is a function. In order to quantify this erosion function using a single number, the following scheme is proposed. It consists in placing the erosion function on the erosion chart of Figure 9.5 and deciding what erodibility category fits best for the soil considered. This approach holds promise to use only one number to characterize a function. Work is ongoing to tie a number of soil types into erodibility categories.

9.5 Erodibility of Coarse-Grained Soils

Clean sands and gravels erode particle by particle. This has been observed on slow motion videotapes. Three mechanisms seem to be possible: sliding, rolling, and plucking.

A simple sliding mechanism (Figure 9.6) consists of assuming that the soil particle is a sphere, that the resultant force exerted by the water on the soil particle is a shear force parallel to the eroding surface, and that neighboring particles do not exert forces on the particle being analyzed because they move at the same rate. Electromagnetic and electrostatic forces between particles are neglected because the analysis is done for a sand or a gravel particle. As the velocity increases, the shear stress τ imposed by the water on the particle becomes large enough to overcome the friction between two particles staked on top of each other, and sliding takes place. The critical shear stress τ_c is the threshold shear stress at which erosion is initiated. Referring to Figure 9.6, horizontal equilibrium leads to (White 1940):

$$\tau_c A_e = W \tan \varphi \tag{1}$$

where A_e = effective friction area of the water on the particle; W = submerged weight of the particle; and φ = friction angle of the interface between two particles. If the particle is considered to be a sphere, (1) can be rewritten as

$$\tau_c\ \alpha\ (\pi D_{50}^2/4) = (\rho_s - \rho_w)\ g\ (\pi D_{50}^3/6) \tan \varphi \tag{2}$$

or

$$\tau_c = 2\ (\rho_s - \rho_w)\ g\ D_{50}\ (\tan \varphi)/3\alpha \tag{3}$$

where α = ratio of the effective friction area over the maximum cross section of the spherical particle; D_{50} = mean diameter representative of the soil particle size distribution; ρ_s and ρ_w = mass density of the particles and of water, respectively; and g = acceleration due to gravity. Eq. (3) shows that the critical shear stress is linearly related to the particle diameter. Briaud et al. (1999b) showed experimentally for a sand and a gravel tested in the EFA that an approximate relationship is:

$$\tau_c\ (\mathrm{N/m^2}) = D_{50}\ (\mathrm{mm}) \tag{4}$$

Using (3) and (4), and assuming reasonable values for ρ_s, ρ_w, g, and φ, leads to a value of α equal to about 6. This value is many times higher than would be expected and shows that the sliding mechanism is not the eroding mechanism, or at least not the only one involved.

A simple rolling mechanism (Figure 9.7) consists of assuming that the soil particle is a sphere, that the resultant force exerted by the water on the soil particle is a shear force parallel to the eroding surface, that neighboring particles do not impede the process, and that rotation takes place around the contact point with the underlying particle. Electromagnetic and electrostatic forces between particles are neglected because the analysis is done for a sand or a gravel particle. At incipient motion and referring to Figure 9.7, moment equilibrium around the contact point O leads (White 1940) to:

$$\tau_c\ A_e\ a = W\ b \tag{5}$$

or

$$\tau_c\ (\alpha\ \pi D_{50}^2/4)\ (D_{50}/2 + D_{50}(\cos\beta)/2) = (\rho_s - \rho_w)\ g\ (\pi D_{50}^3/6)\ (D_{50}(\sin\beta)/2) \tag{6}$$

or

$$\tau_c = 2\ ((\rho_s - \rho_w)\ g\ D_{50} \sin\beta)/(3\alpha\ (1 + \cos\beta)) \tag{7}$$

Eq. (7) confirms that τ_c is linearly proportional to D_{50}. For reasonable values of ρ_s, ρ_w, and g, and for $\alpha = 1$, using (4) and (7) leads to β values equal to about 10–12^0, which is indicative of a loose arrangement; indeed, the sand and the gravel tested to obtain Eq. 4 were placed in a very loose condition in the EFA. Therefore it appears that rolling is more reasonable a mechanism than sliding. Eq. (7) tends to indicate that, while τ_c is linearly proportional to D_{50}, the proportionality factor may depend on the relative density. The dominant value of the angle β can be obtained from a contact angle distribution diagram such as the ones shown in Figure 9.8.

A simple plucking mechanism consists of assuming that the particles are cubes with a side a. The water pressure on top of the cube is u_t and the water pressure at the bottom of the cube is u_b. If it is assumed that all particles are plucked up at the same time, the differential pressure between the top and bottom necessary to initiate plucking of the particle or block of particles is:

$$W = (u_b - u_t)\, a^2 \tag{8}$$

or

$$\rho_s\, g\, a = u_b - u_t \tag{9}$$

The differential pressure u_b-u_t is made up of the hydrostatic differential water pressure $(u_b - u_t)_o$ and the differential water pressure created by the flow Δu

or

$$u_b - u_t = (u_b - u_t)_o + \Delta u \tag{10}$$

For a particle with a = 1 mm, the hydrostatic differential water pressure $(u_b - u_t)_o$ is 10 N/m^2 . This hydrostatic differential water pressure reduces the weight of the particle to its buyant weight. The additional differential water pressure necessary to pluck the particle away Δu is 15 N/m^2. This value of Δu is equivalent to 1.5 mm of water and it is easy to conceive that such a small differential pressure can be developed. It is created dynamically by the water flow including the fluctuations and the turbulence in the water. These pressure fluctuations are very difficult to measure (Einstein and El-Samni, 1949 and Apperley, 1968). These pressure fluctuations can be calculated through advanced numerical simulations.

These simplistic analyses of the sliding, rolling, and plucking mechanisms help to clarify the important factors affecting the incipient motion of coarse grained soils. However, they are not reliable for prediction purposes, and today experiments are favored over theoretical expressions to determine τ_c for example. Shields (1936) ran a series of flume experiments with water flowing over flat beds of sands. He plotted the results of his experiments in a dimensionless form on what is now known as the Shields diagram. This data as well as other data on sand gathered at Texas A&M University are plotted in Figure 9.2 as critical shear stress τ_c versus mean grain size D_{50}. Eq. (4) is shown in Figure 9.2 and seems to fit well for sands. Shields did not perform any experiments on silts and clays. The data developed for silts and clays at Texas A&M University show that Eq.(4) is not applicable to fine grained soils and that D_{50} is not a good predictor of τ_c for those types of soils.

There seems to be consensus in using the shear stress applied by the water to the soil at the soil water interface as the major parameter causing erosion. It is likely that the hydraulic normal stress or pressure created by the water at that interface also contributes to the process.. Nevertheless, the use of the shear stress only has remained common practice and the role of the normal stress that generates bursts of uplift forces during turbulent flow has yet to be included in common approaches to scour.

9.6 Erodibility of Fine-Grained Soils

In the case of silts and clays, other forces come into play besides the weight of the particles; these are the electrostatic and Van der Waals forces. Figure 9.10 and 9.11 show cartoons of the forces and pressures acting on the soil particle in the general case. The water pressure u_w surrounds the particle if the soil is saturated. The contact forces f_{ci} exist at the contact point and have normal as well as shear components. The electrostatic and Van der Walls forces f_{ei} are also shown on the figure. Figure 9.10 refers to the case where the water is not moving. In this case the water pressure is smaller on the top of the particle than on the bottom of the particle but the difference is not significant. This difference is equal to the hydrostatic pressure difference due to the height of the particle and creates the buoyancy of the soil particle. In Figure 9.11, the water is moving and the difference between the top and bottom water pressure has increased. Note that the water pressure u_w and therefore the uplift force on the particle is a function of time t and fluctuates during the flow. The cartoon shows a situation where the water pressure may be such that the particle weight is overcome.

The electrostatic forces are likely to be repulsive because clay particles are negatively charged. Van der Waals forces are relatively weak electromagnetic forces that attract molecules to each other (Mitchell 1993); although electrically neutral, the molecules form dipoles that attract each other like magnets. The Van der Waals forces are the forces that keep H_2O molecules together in water. The magnitude of these Van der Waals forces can be estimated by (after Black et al. 1960):

$$f(\mathrm{N/m^2}) = 10^{-28} / d(\mathrm{m})^4 \quad (11)$$

where d(m) = distance in m between soil particles; and f = attraction force in $\mathrm{N/m^2}$. By multiplying f by the particle surface area, one can obtain the inter-particle force. Table 9.1 shows the value of these forces for a sand and a clay particle.

In both cases the soil particle was assumed to be spherical and the distance between particles was taken equal to the particle diameter. While such an evaluation of the Van der Waals force can only be considered as a crude estimate, the following observations regarding the numbers in Table 9.1 are interesting. First, the ratio between the weight and size of the sand particle and the clay particle are similar to the ratio between the weight and size of a Boeing 747 and a postage stamp; therefore, if the critical shear stress is proportional to the particle weight, the critical shear stress for clays should be practically zero. Second, the ratio between the Van der Waals force and the weight of the sand particle indicates that the Van der Waals force is truly negligible for sands. Third, the same ratio for the clay particle, while 10^{17} times larger than for sand, also indicates that the Van der Waals forces are negligible compared with the weight of the clay particle. This would lead one to think that the critical shear stress, τ_c , is essentially zero for clays. Note that the electrostatic forces have not been calculated here but since they are predominantly repulsive they would decrease, if anything, the attraction due to the Van der Waals forces. Other phenomena give cohesion to clays; they include water meniscus forces, such as those developing when a clay dries, and diagenetic bonds due to aging, such as those developing when a clay turns into rock under pressure over geologic time. Because of the number and complexity of these bonds, it is very difficult to predict τ_c for clays empirically on the basis of a few index properties. Several researchers however have proposed empirical equations for τ_c in clays, such as Dunn (1959) and Lyle and Smerdon (1965).

One problem associated with measuring τ_c is determining the initiation of scour. When the particles are visible to the naked eye, it is simple to detect when the first particle is scoured away. For clays this is not the case, and various investigators define the initiation of scour through different means; these vary from ‘‘when the water becomes muddy’’ to extrapolation of the scour rate versus shear stress curve back to zero scour rate. Table 9.2 shows a variety of measured τ_c values. The lack of precise definition for the initiation of scour may be in part responsible for the wide range of values.

Beyond the critical shear stress, a certain scour rate $\dot{z}$ (mm/hr) is established. This scour rate is rapid in sand, slow in clay, and extremely slow in rock. The example of the Grand Canyon rock cited earlier leads to a value of $\dot{z}$ equal to 9.1 x 10^{-6} mm/ hr, whereas fine sands erode at rates of 10^4 mm/hr as measured in the EFA. Clays scour at intermediate rates with common values in the range of 1 to 1,000 mm/hr. The high scour rate in sand exists because once gravity is overcome, no other force slows the scour process down. The very low scour rate in rock exists probably because it takes a large number of shear-stress cycles imposed by the turbulent nature of the flow to overcome the very strong crystalline bonds binding the rock together. Note that rock scour can also occur at larger rates if the rock is fractured and the water flow provides very high velocities as in the case of the downstream end of high dam spillways. The low scour rate in clays is probably associated with the fact that it takes a large number of shear stress cycles to overcome the electromagnetic bonds created by the Van der Waals forces between clay particles. Even though these bonds are relatively weak, as discussed previously, they are sufficient to slow the scour process significantly. The scour rate $\dot{z}$ versus shear stress τ_c curve (Figure 9.1) is used to quantify the scour rate of a soil as a function of the flow. Several researchers have measured the rate of erosion in cohesive soils; most have proposed a straight line variation (Ariathurai and Arulanandan, 1978), while some have found S shape curves (Christensen, 1965). Some of the rates quoted in the literature are given in Table 9.3.

Some of the factors influencing the erodibility of fine grained soils are listed in Table 9.4. Although there are sometimes conflicting findings, the influence of various factors on cohesive soil erodibility is shown in Table 9.4 when possible.

The critical shear stress of coarse grained soils is tied to the size of the particles and usually ranges from 0.1 N/m^2 to 5 N/m^2. The rate of erosion of coarse grained soils above the critical shear stress increases rapidly and can reach tens of thousands of millimeters per hour. The most erodible soils are fine sands and silts with mean grain sizes in the 0.1 mm range (Figure 9.2). The critical shear stress of fine grained soils is not tied to the particle size but rather to a number of factors as listed in Table 9.4. The critical shear stress of fine grained soils however varies within the same range as coarse grained soils (0.1 N/m^2 to 5 N/m^2) for the most common cases. One major difference between coarse grained and fine grained soils is the rate of erosion beyond the critical shear stress. In fine grained soils (often called cohesive soils), this rate increases slowly and is measured in millimeters per hour. This slow rate makes it advantageous to consider that erosion problems are time dependent and to find ways to accumulate the effect of the complete velocity history rather than to consider a design flood alone.

9.7 Erodibility and Correlation to Soil Properties

There is a critical shear stress τ_c below which no erosion occurs and above which erosion starts. This concept while practically convenient may not be theoretically simple. Indeed, as seen on Figure 9.1, there is no obvious value for the critical shear stress. The critical shear stress is arbitrarily defined as the shear stress which corresponds to an erosion rate of 1 mm/hr. The critical shear stress is associated with the critical velocity v_c. One can also define the initial slope $S_i = (d\dot{z}/d\tau)_i$ at the origin of the erosion function. Both τ_c and S_i

are parameters which help describe the erosion function and therefore the erodibility of a material.

In coarse grained soils (sands and gravels), the critical shear stress has been empirically related to the mean grain size D_{50} (Briaud et al., 2001a).

$$\tau_c\ (N/m^2) = D_{50}\ (mm) \tag{11}$$

For such soils, the erosion rate beyond the critical shear stress is very rapid and one flood is long enough to reach the maximum scour depth. Therefore there is a need to be able to predict the critical shear stress to know if there will be scour or no scour but there is little need to define the erosion function beyond that point because the erosion rate is not sufficiently slow to warrant a time dependent analysis.

In fine grained soils (silts, clays) and rocks, equation 11 is not applicable (Figure 9.2) and the erosion rate is sufficiently slow that a time rate analysis is warranted. Therefore it is necessary to obtain the complete erosion function. An attempt was made to correlate those parameters, τ_c and S_i, to common soil properties in hope that simple equations could be developed for everyday use. The process consisted of measuring the erosion function on one hand and common soil properties on the other (water content, unit weight, plasticity index, percent passing sieve no. 200, undrained shear strength). This lead to a database of 91 EFA tests (Table 9.5) which was used to perform regression analyses and obtain correlation equations (Figure 9.12 to 9.15). All attempts failed to reach a reasonable R^2 value.

The fact that no relationship could be found between the critical shear stress or the initial slope of the erosion function on one hand and common soil properties on the other seems to be at odds with the accepted idea that different cohesive soils erode at different rates. Indeed if different clays erode at different rates then the erosion function and therefore its parameters should be functions of the soils properties. The likely explanation is that there is a relationship between erodibility and soils properties but that this relationship is quite complicated, involves advanced soil properties, and has not been found. Instead, it was found much easier to develop an apparatus which could measure the erosion function on any sample of cohesive soil from a site. This apparatus was called the Erosion Function Apparatus or EFA.

9.8 The EFA: Erosion Function Apparatus

The EFA (Briaud et al. 1999, Briaud et al., 2001a) was conceived by Dr. Briaud in 1991, designed in 1992, and built in 1993 (Figure 9.16). The sample of soil, fine-grained or not, is taken in the field by pushing an ASTM standard Shelby tube with a 76.2 mm outside diameter(ASTMD1587). One end of the Shelby tube full of soil is placed through a circular opening in the bottom of a rectangular cross section pipe. A snug fit and an O-ring establish a leak proof connection. The cross section of the rectangular pipe is 101.6 mm by 50.8 mm. The pipe is 1.22 m long and has a flow straightener at one end. The water is driven through the pipe by a pump. A valve regulates the flow and a flow meter is used to measure the flow rate. The range of mean flow velocities is 0.1 m/s to 6 m/s. The end of the Shelby tube is held flush with the bottom of the rectangular pipe. A piston at the bottom end of the sampling tube pushes the soil until it protrudes 1 mm into the rectangular pipe at the other end. This 1 mm protrusion of soil is eroded by the water flowing over it.

9.8.1 EFA test procedure

The procedure for the EFA test consists of

1. Place the sample in the EFA, fill the pipe with water, and wait one hour.
2. Set the velocity to 0.3 m/s.
3. Push the soil 1 mm into the flow.
4. Record how much time it takes for the 1 mm soil to erode (visual inspection)
5. When the 1 mm of soil is eroded or after 30 minutes of flow whichever comes first, increase the velocity to 0.6 m/s and bring the soil back to a 1 mm protrusion.
6. Repeat step 4.
7. Then repeat steps 5 and 6 for velocities equal to 1.0 m/s, 1.5 m/s, 2 m/s, 3 m/s, 4.5 m/s, and 6 m/s. The choice of velocity can be adjusted as needed.

9.8.2 EFA test data reduction

The test result consists of the erosion rate dz/dt versus shear stress τ curve (Figure 9.1, and 16). For each flow velocity v, the erosion rate dz/dt (mm/hr) is simply obtained by dividing the length of sample eroded by the time required to do so.

$$dz/dt = h/t \qquad (12)$$

Where h is the length of soil sample eroded in a time t. The length h is 1 mm and the time t is the time required for the sample to be eroded flush with the bottom of the pipe (visual inspection through a Plexiglas window). After several attempts at measuring the shear stress τ in the apparatus it was found that the best way to obtain τ was by using the Moody Chart (Moody, 1944) for pipe flows.

$$\tau = f \rho v^2/8 \qquad (13)$$

Where τ is the shear stress on the wall of the pipe, f is the friction factor obtained from Moody Chart (Figure 9.17), ρ is the mass density of water (1000 kg/m3), and v is the mean flow velocity in the pipe. The friction factor f is a function of the pipe Reynolds number Re and the pipe roughness ε/D. The Reynolds number is Re = vD/ν where D is the pipe diameter and ν is the kinematic viscocity of water (10^{-6} m^2/s at 20^0C). Since the pipe in the EFA has a rectangular cross section, D is taken as the hydraulic diameter D = 4A/P (Munson et al., 1990) where A is the cross sectional flow area, P is the wetted perimeter, and the factor 4 is used to ensure that the hydraulic diameter is equal to the diameter for a circular pipe. For a rectangular cross section pipe:

$$D = 2ab/(a + b) \qquad (14)$$

Where a and b are the dimensions of the sides of the rectangle. The relative roughness ε/D is the ratio of the average height of the roughness elements on the pipe surface over the pipe diameter D. The average height of the roughness elements ε is taken equal to $0.5D_{50}$ where D_{50} is the mean grain size for the soil. The factor 0.5 is used because it is assumed that the top half of the particle protrudes into the flow while the bottom half is buried into the soil mass. During the test, it is possible for the soil surface to become rougher than just 0.5 D_{50}; this occurs when the soil erodes block by block rather than particle by particle. In this case the value used for ε is estimated by the operator on the basis of inspection through the test window. Typical EFA test results are shown on Figure 9.1 for sand and then clay.

9.9 Some Existing Knowledge on Levee Erosion

9.9.1 Current Considerations in Design

The US Army Corps of Engineers' design manual (USACE, 2000) outlines the steps followed in the design and construction of levees (Table 9.6). The procedure does not include an evaluation of the erodibility of the soils used for the levees. A more in-depth discussion of design requirements is presented in Chapter 10.

9.9.2 Failure Mechanism

Flowing water exerts a tractive shear stress along the soil-water interface. The erosion process begins when this tractive shear stress exceeds the resistive force of the backslope soil (AlQaser, 1991). Hanson et al. (2003) describe four stages of erosion during the overtopping of cohesive embankments (Figure 9.18):

Stage I: Minor headcut movement up to the downstream embankment crest; surface erosion occurs.

Stage II: Headcut progresses from the downstream embankment crest to the upstream embankment crest.

Stage III: The crest lowers and breach formation begins as the headcut continues to migrate upstream of the embankment crest.

Stage IV: Erosion of the breach opening has progressed to near the base of the upstream toe of the embankment; driven by erosion of the sidewalls and development of an overhang, resulting in episodic mass failures and breach widening (Hunt et al., 2004).

Erosion typically occurs adjacent to some change or interruption in the flow pattern (Ralston, 1987). The turbulence associated with the flow disturbance breaks down the protective boundary laminar flow layer. This leads to the occurrence of full hydraulic stress intensity as well as rapid stress reversals, greatly increasing the erosion rate.

Gradually varied flow also leads to non-uniform erosion along the backslope producing overfalls. The overfall will advance progressively headward as long as the remaining embankment material can support the dam crest and upstream slope (Figure 9.19). The base of the overfall will deepen and widen.

As the eroding vertical overfall face advances headward, the overflow crest elevation will lower, cutting into the adverse grade of the upstream slope. This erosion pattern will continue and progress until the flow pattern changes into a free surface flow (Figure 9.20, AlQaser, Ruff, 1993). Headward advance of the overfalls is due to a combination of the following:

1) Insufficient soil strength to stand vertically due to the height of the face, stress relief cracking, and induced hydrostatic pressure in the cracks
2) Loss of foundation support for the vertical face due to the waterfall plunging effect and its associated lateral and vertical scour. As the vertical overfall gets higher, impact energy of the water fall increases, the rate of erosion increases and the

scour hole becomes larger. The supporting foundation of the overfall face and sidewalls is thus removed.

The erosion pattern of embankments using non-cohesive soil is affected by the existence and location of a cohesive soil zone. For purely non-cohesive embankments, the erosion occurs on a uniform, but gradually flattening gradient. This erosion pattern can be modeled using the theory of tractive stress. The breach development is consistent with the principle of minimum rate of energy dissipation for streams (Coleman et al., 2002). Breaches, like streams, tend to alter their geometry in order to produce a minimum rate of energy dissipation. When the embankment includes a zone of cohesive soil, the overfall development will be retarded. If the zone is symmetrical, erosion will behave similar to that of a cohesive soil embankment. If the zone is an upstream sloping section, the overflow crest will degrade. This is due to undermining of the downstream non-cohesive zone. Portions of the overhanging cohesive zone will subsequently break off as the allowable bending moment is exceeded.

9.9.3 Numerical modeling

Erosion computer models are used to describe and quantify the complexities associated with an embankment breach. OVERFALL, a computer program developed by AlQaser (1991), predicts the heights and numbers of overfalls along the backslope of an overtopped embankment. Key features of breaches can also be reproduced with SIMBA, or SIMplified Breach Analysis (Temple et al., 2005). This model has been verified against embankment breach tests. Presently, SIMBA is only capable of addressing homogeneous embankment conditions. Future work will allow for applications to non-homogeneous field conditions, though.

Breach and discharge characteristics can be modeled and predicted with BREACH (Fread, 1988). BREACH allows for predictions of the size, shape, and time of formation of an earthen dam breach. A breach outflow hydrograph is also provided from the analysis. The extent of the enlargement, the peak outflow, and the time to peak flow are determined by the internal friction angle and the cohesive strength of the embankment soil. The BREACH model was verified by comparing the results of the model and several overtopping failure tests. These tests were conducted in different countries at varying scales with different homogeneous materials and construction practices. A summary of dam break numerical models that can be used for gradual failure is shown in Table 9.7.

9.9.4 Laboratory Tests

Nairn (1986) conducted two-dimensional flume tests to study cohesive shore erosion. Tests were conducted on artificial clay, composed of a bentonite-silt mixture, with and without an overlying veneer of sand. Surprisingly, the flume tests with sand did not lead to failure as the sand acted as an armor over the clay. Tests without sand, however, produced responses close to those observed in the field. Table 9.8 displays the erosion rate results for the flume tests conducted by Nairn. Dodge (1988) also conducted laboratory flume tests to study erosion of a clayey sand (Figure 9.21). The results of the tests were not verified with field observations; they serve to provide a qualitative assessment of erosion.

AlQaser (1991) performed two laboratory tests to study progressive failure of an overtopped embankment (Figure 9.22). Both tests had the same design, but differed in the percent of sand in the soil. The first sample consisted of 80% clay and 20% sand. The other had 50% clay and 50% sand. Results show that the presence of more clay in the soil mixture leads to a greater vertical overfall height. The soil with more sand in the mixture, however, resulted in more horizontal overfall regression. It is concluded, therefore, that the physical and the geometrical properties of the embankment affect the number and heights of the developed overfalls.

9.9.5 Field Tests

Hanson, Cook, and Hahn (2001) describe preliminary evaluation of the headcut migration rates during overtopping and breaching tests on large-scale models. The headcut advance threshold was evaluated based on an energy dissipation term:

$$E = q\gamma_w H \quad (1)$$

Where q = unit discharge, γ_w = unit weight of water, and H = Headcut height. The headcut migration rates for each test section were evaluated and compared to measured soil properties, such as erodibility and soil strength. The results show that as soil strength decreases, the headcut migration rate increases (Figure 9.23).

The breaching of non-cohesive homogeneous embankments under constant-reservoir levels was studied using flume tests (Figure 9.24) by Coleman et al. (2002). This experiment simulated the failure of an embankment restricting a very large upstream reservoir. A small V breach was initiated and grew as erosion took place. A wide range of uniform non-cohesive soils were tested. The quantitative findings of these tests have not been verified by the results from large scale embankments.

It was found from the flume tests conducted by Coleman et al. (2002) that erosion progresses from primarily vertical to lateral in nature. This occurs as the breach channel invert approaches the foundation level. The channel invert slope will flatten as it rotates about a fixed pivot point, X_P, on the embankment (Figure 9.25).

The location of this pivot point is a function of the embankment sediment size. In plan view, the breach channel develops into an hourglass (or Venturi) shape (Figure 9.26). The curvature of the channel increases with time until the embankment foundation impedes the vertical erosion of the breach. This leads to an increase in the rounding of the approach and exit channels.

After the preliminary studies of 2001, Hanson, Cook, et al. (2003) performed a second study of the headcut migration and erosion widening rates during overtopping. They used large-scale models and three soils including two non-plastic (SM) silty sand materials and a (CL) lean clay. The width of the breach during testing was evaluated using photographic measurements of the model embankment (Figure 9.27). Details of the testing indicated that headcut erosion was an important erosion process in the failure of cohesive embankments. It can influence the breach initiation time, breach formation time, breach width, peak discharge, and the overall outflow hydrograph.

The headcut migration rates (Figure 9.28), as well as the erosion widening rates (Figure 9.29), show a direct correlation to the compaction water content. The rate of breach widening was found by taking the linear regression of the breach width measurement from left bank to right bank versus time (Figure 9.30). The observed breach widths during testing were equal to two to five times the dam height. Figure 9.31 indicates that the head cutting rate for stages II and III of the erosion process is larger than the widening rate at the beginning but becomes approximately equal to it towards the end of the breaching process.

9.9.6 Factors Influencing Resistance to Overtopping

For a given soil, Hanson et al. (2003) show that erodibility correlates well with compaction water content, energy, density, and texture. By contrast, Cao et al. (2002) using a large data base found no relationship between common soil properties and the erodibility of cohesive soils. Dodge (1988, Figure 9.32) gave some trends of erodibility for cohesive soils using the plasticity chart. The FHWA (Chen, Cotton, 1988) also presents a plot of permissible shear stresses for cohesive soils based on the plasticity index (Figure 9.33).

Choliaras et al. (2003) concludes that the main measure of erosivity of overland flow is shear stress flow. He states that the increase of erosion rate is linear with shear stress of flow. He adds that for low values of surface shear stress, the erodibility of a soil decreases with increasing soil strength while for high values of surface shear stress, the erodibility of the soil increases with increasing surface strength.

According to Fread (1988), the growth of a breach is dependent on the soil properties of the dam. Unit weight, friction angle, and cohesive strength are shown to influence the size, shape, and time of formation of a breach. The amount of grass cover on the dam is also a factor in breach formation.

The results of the research performed by AlQaser (1991) point to poor compaction as a source of breaching. According to model tests conducted by Dodge (1988), the volume of scour produced during flow can be decreased by increasing the compaction of the soil.

Similarly, for clay soils, an increase in density reduces erodibility (Choliaras et al., 2003). For silty and sandy soils, the density or compaction of the soil does not significantly influence erodibility.

1953 Levee (Dike) failures in Netherlands

The Netherlands is a country of 8.5 Million people and 26% of them live below mean sea level protected by levees (Gerritsen, 2006). The following is a summary of an excellent article by Gerritsen in Geo-Strata (2006) which describes the 1953 disaster and the steps taken since then by the Netherlands. Prior to 1953 the dikes were at a height equal to the maximum recorded water level plus 0.5 m. The height of some of the levees had been increased by constructing concrete walls along the levee crest. During World War II, the levees were used as a defense system and many holes were dug to that effect. After the war, the damage done to the levees was not adequately repaired.

On January 31, 1953, a North Sea storm combined with hide tide and raised the water level to unprecedented height and 150 levee breaches occurred. During that storm, 1836 people died, 100,000 people evacuated, tens of thousands of livestock perished, and 136,500 hectares were inundated. The levee breaches were attributed to sustained wave overtopping. The land side of the levees was typically at a steeper slope (1v to 1.5h or 1v to 2h) than the sea side (1v to 3h or more). The failure process initiated from the land side and progressed backward towards the sea side. One sign of imminent failure was a longitudinal crack forming along the crest of the levee which was quickly filled by the rushing water.

On February 18, 1953, a committee was formed called the Delta Committee with the task of ensuring that such a disaster would not happen again. The committee chose to solve the problem not by increasing the height of the levees but rather by recommending the Delta Plan. This plan consisted of closing the shoreline completely through a series of permanent barriers to be built over a 20 year period. In 1975, due to political pressures from the fishing industry, the barriers were changed from complete damming to moveable storm surge barriers to be closed only in the event where a North Sea storm would coincide with a high tide.

The Netherlands now requires that the flood protection systems satisfy the following

- Be able to resist a storm surge with a probability of occurrence of 1/10,000 for the Province of Holland;
- Be able to resist a storm surge with a probability of occurrence of 1/4000 for less populated coastal areas; and
- Be reviewed and evaluated every 5 years with associated recommendations to be constructed in the following 5 years.

9.9.7 Influence of Grass Cover on Surface Erosion

Grass makes a difference in the resistance to surface erosion (Figure 9.34). The physical vegetative coverage on slopes provides increased resistance through underground soil reinforcement and surface protection (Li and Eddleman, 2002). Root systems aid slope stabilization through soil-root interaction. The mechanics of root-reinforcement are similar to the basic mechanics of engineering reinforced-earth systems (Coppin and Richards, 1990). The vegetation root growth reinforces the upper soil layers increasing the soil shear strength by over 33 % (Bhandari et al., 1998). Many researchers have developed theoretical models of root-reinforced soils, including Gray and Leiser (1982), Greenway (1987), Coppin and Richards (1990), Styczen and Morgan (1995), and Wu (1995). In general, the vegetative methods for surface erosion control include two types: herbaceous and woody. They all have the following four mechanisms in controlling surface erosion (Gray 1974; Greenway, 1987; Coppin and Richards, 1990):

1. Restraint: The root system binds the soil particles. The foliage residues restrain soil particle detachment via shallow, dense root systems, consequently reducing sediment transport.

2. Retardation: The foliage and stems increase the surface roughness and slow surface runoff.
3. Interception: The foliage and plant residues absorb the rainfall energy by intercepting the raindrops to reduce raindrop impacts.
4. Transpiration: Absorption of soil moisture by plants delays the initiation of saturation and increases shear strength by reducing pore-pressures.

The level of vegetation for protecting the soil depends on the combined effects of roots, stems and foliage (Coppin and Richards, 1990). Woody vegetation installed on slopes and streambanks provides resistance to shallow mass-movement by counterbalancing local instabilities. In order to achieve optimum stabilization, vegetation must establish quickly and solidly. For biotechnical stabilization techniques that only use vegetative materials, the stabilization is vulnerable at the early stage but becomes stronger as the vegetation is established (Li and Eddleman, 2002). For techniques that combine plant and inert materials such as dead wood, rocks or geosynthetics, inert materials support major loads at the early stage. As the vegetation matures, root systems will bind soils, inert materials and vegetation altogether on the slope or streambank, and increase the safety factor of structural protection (Biedenharn et al., 1997).

From the engineering perspective, vegetation's use on slopes or streambanks may not be always ideal. Trees planted on certain parts of levees may have roots undermining the levee stability (USACE, 1999). Greenway (1987), and Coppin and Richards (1990) have analyzed vegetation's engineering functions and determined that its effects are both adverse and beneficial, depending on the circumstances. Therefore, selecting appropriate plant type becomes very critical in such conditions. This can be done by testing at large scale facilities such as the one at Texas A&M University which grows grass and tests it on slopes of various geometries.

Johnston (2003) prepared the chart of Figure 9.35 which gives the allowable shear stress at the interface between the soil and the water flowing on a slope. Different covers are represented including bare soil, grass covered, geosynthetic matting, hard armor. The depth D is the depth of water flowing over the slope S. Note that overall the range of slope covered is fairly shallow.

9.10 Soil and Water Samples Used for Erosion Tests

A total of 11 locations were identified for studying the erosion resistance of the levee soils. Emphasis was placed on levees which were very likely overtopped. These locations are labeled S1 through S15 for Site 1 through Site 15 on Figure 9.36. The samples were taken by pushing a Shelby tube when possible or using a shovel to retrieve soil samples into a plastic bag. For example at Site S1, the drilling rig was driven on top of the levee, stopped at the location of Site 1, a first Shelby tube was pushed with the drilling rig from 0 to 2 ft depth and then a second Shelby tube was pushed from 2 to 4 ft depth in the same hole. These two Shelby tubes belonged to boring B1. The drilling rig advanced a few feet and a second location B2 at Site S1 was chosen; then two more Shelby tubes were collected in the same way as for B1. This process at Site S1 generated 4 Shelby tube samples designated

- S1-B1-(0-2ft)

- S1-B1-(2-4ft)
- S1-B2-(0-2ft)
- S1-B2-(2-4ft)

Four such Shelby tubes were collected from sites S1, S2, S3, S7, S8, and S12. In a number of cases, Shelby tube samples could not be obtained because access for the drilling rig was not possible (e.g.: access by light boat for the MRGO levee) or pushing a Shelby tube did not yield any sample (clean sands). In these cases, grab samples were collected by using a shovel and filling a plastic bag. The number of bags collected varied from 1 to 4. Plastic bag samples were collected from sites S4, S5, S6, S11, and S15. The total number of sites sampled for erosion testing was therefore 11. These 11 sites generated a total of 23 samples. One of the samples, S8-B1-(2-4ft), exhibited two distinct layers during the EFA tests and therefore lead to two EFA curves. All in all 24 EFA curves were obtained from these 23 samples: 14 performed on Shelby tube samples and 10 on bag samples. The reconstitution of the bag samples in the EFA is discussed later.

Water salinity has an effect on erosion. The salinity of the water was determined by using the soil samples collected at the sites. Samples S11 and S15 were selected because one was on the Lake Pontchartrain side and the other on the Lake Borgne side. The procedure to obtain theconsisted of:

1. Dry the soil (about 70 g) in an oven for 12 hr
2. Weigh a quantity of soil, e.g. 10 g and place it in a PE bottle
3. Add deionized (DI) water in the ratio of 2 ml water for one sample and 5 ml water for another sample to each gram of soil
4. Soil: DI water = 10 g: 20 ml or 10g: 50 ml
5. Shake the bottle to thoroughly mix the soil and water
6. Allow the soil to settle for 12 hr
7. Use a pH meter (Orion model 420 A) to measure the pH and a calibrated conductivity meter (Corning model 441) to measure the conductivity of the water.
8. Perform a calibration of the conductivity meter by using known concentrations of salt.
9. Use the conductivity to salinity calibration curve to obtain the salinity of the water created in steps 1 to 7.

Then it becomes necessary to correct the salinity of this water because the amount of water added to the soil for the salinity determination test does not correspond to the amount of water available in the soil pores in its natural state (in the levee). This is done by calculating the amount of water available in the pores of the samples in its natural state. This requires the use of the void ratio and the degree of saturation of the samples calculated using simple phase diagram relationships. The results obtained are shown in Table 9.9.

9.11 Erosion Function Apparatus (EFA) Test Results

9.11.1 Sample Preparation

No special sample preparation was necessary for the samples which were in Shelby tubes. The Shelby tube was simply inserted in the hole on the bottom side of the rectangular cross section pipe of the FEA (described previously).

For bag samples obtained by using a shovel to collect the soil, there was a need to reconstruct the sample. These samples were prepared by re-compacting the soil in the Shelby tube (Figure 9.37). The same process as the one used to prepare a sample for a Proctor compaction test was used. Since it was not known what the compaction level was in the field, two extreme levels of compaction energy were used to recompact the samples. The goal was to bracket the erosion response of the intact soil.

For the high compaction effort (100% of Modified Proctor compaction effort), the sample was compacted in an 18-inch long Shelby tube as follows:

1) The total sample height was 6 inches. The sample was compacted in eight layers.
2) To form each layer, the soil was poured into the Shelby tube from a height of 1 inch above the top of the tube.
3) The soil was compacted using a 10 lb hammer (Modified Proctor hammer) with a drop height of 1.5 feet. Each layer was compacted by 8 hammer blows, i.e. 8 blows/layer.
4) This process was repeated until a 6 inch sample was obtained.
5) The corresponding compaction energy was equal to the Standard Modified Proctor Compaction energy.

For the low compaction effort (1.63% of Modified Proctor compaction effort), the sample was compacted in an 18-inch long Shelby tube as follows.

1. The total sample height was 6 inches. The sample was compacted in eight layers.
2. To form each layer, the soil was poured into the Shelby tube from a height of 1 inch above the top of the tube.
3. The soil was compacted using a 10 lb hammer (Modified Proctor hammer) with a drop height of 1 inch. Each layer was compacted by 3 hammer blows, i.e. 3 blows/layer.
4. This process was repeated until a 6 inch sample was obtained.
5. The corresponding compaction energy was 1.63% of the Standard Modified Proctor Compaction energy.

9.11.2 Sample EFA Test Results

The procedure described earlier was strictly followed for the EFA tests. The results were prepared in the form of a word file report and an accompanying excel spread sheet detailing the data reduction and associated calculations. The main result of an EFA test is a couple of plots: one is the plot of the erosion rate versus mean velocity in the EFA pipe, the other is the plot of the erosion rate versus shear stress at the interface between the soil and the water. These two plots are collected in Appendix A for all 24 EFA tests. Figs. 9.38 and 9.39 show two examples of results for a very erodible soil and a very erosion resistant soil.

9.11.3 Summary Erosion Chart

In an effort to give a global rendition of the EFA results, an erosion chart was created. The blank erosion chart has been presented earlier and is reproduced here for convenience (Figure 9.40). This chart allows one to present the erosion curves in a way which categorizes the soils according to one erosion category. Category 1 is very erodible and refers to soils such as clean fine sands. Category 5 is very erosion resistant and refers to soils such as some of the highly compacted and well graded clays.

Figure 9.41 shows the erosion chart populated with the EFA results for all 24 EFA tests. The legend contains the sample/test designation which starts with the site number (Figure 9.36), followed by the boring number, the depth, and letter symbols including SW, TW, LC, HC, and LT. SW stands for Sea Water and means that the water used in the EFA test was salt water at a salinity of approximately 35000 ppm. TW stands for Tap Water and means that the water used in the EFA test was Tap Water at a salinity of approximately 500 ppm. LC stands for Low Compaction, refers to bag samples only, and means that the sample was prepared using 1.6% of Modified Proctor compaction effort. HC stands for High Compaction, refers to bag samples only, and means that the sample was prepared using 100% of Modified Proctor compaction effort. LT stands for Light Tamping and refers to the preparation of some bag samples used in some early tests; it is very similar to the LC preparation.

One of the first observations coming from the summary erosion chart on Figure 9.41 is that the erodibility of the soils obtained from the New Orleans levees varies widely all the way from very high erodibility (Category 1) to very low erodibility (Category 5). This explains in part why some of the overtopped levees failed while other overtopped levees did not. This finding points to the need to evaluate the remaining levees for erodible soils (weak links).

9.11.4 Influence of Compaction on Erodibility

Several of the bag samples were tested at two extreme compaction efforts: 100% Modified Proctor and 1.6% Modified Proctor. Because the low and high compaction samples originated from the same bag of collected soil, it is reasonable to assume that the samples are very similar. The EFA tests results aimed at identifying the influence of the compaction effort are isolated in Figure 9.42. Sample S4 shows a major influence of the compaction effort on the erodibility. Indeed, the low compaction sample is at the border between Category 1 and Category 2 (very high to high erodibility) while the high compaction sample is at the border between Category 4 and Category 5 (very low to low erodibility). However, Samples S15 and S11 do not show much difference between the high compaction and the low compaction.

The index properties of the samples tested are presented in a following section. Sample S4 is a high plasticity silt. It has 90.47 % fines, a plasticity index of 30, and a USCS classification of MH. Sample S11 is a clean uniform sand It has 0.1 % fines, and a USCS classification of SP. Sample S15 is a silty sand. It has 29.89 % fines, and a USCS classification of SM. These three data points tend to indicate that compaction has a more significant influence on erodibility for some soils (higher fine content) than for others (lower fine content).

9.11.5 Influence of water salinity on erodibility

Salinity can have an influence on the erodibility of a soil. Several of the samples were tested by using water at two extreme salt concentrations: 35000 ppm to simulate sea water and 500 ppm to simulate water with a very low salt concentration. Because the samples used to check the influence of the water salinity originated from different Shelby tubes at two different depths (0-2 ft and 2-4 ft), it is possible that the samples may have had different erodibility to start with. This may have clouded the influence of the water salinity.

The EFA tests results for the tests aimed at identifying the influence of the water salinity are isolated in Figure 9.43. Conclusions are difficult to draw because the samples may not be from the same soil. One sample (S8-B1) actually was made of two separate layers which had two different erosion functions and lead to two EFA curves for the same Shelby tube.

Nevertheless, the following observations can be made. Samples S12 show that an increase in water salinity increases the resistance to erosion, samples S2 and S8 show no influence, while samples S1 and S7 show a reverse influence of the water salinity. The index properties of the samples tested are presented in a following section. All samples exhibit a high clay content.

9.12 Index Properties of the Samples Tested in the EFA

A set of index property tests were performed on the samples used in the EFA. Some of the tests were performed by Soil Testing Engineering in Baton Rouge, the remainder of the tests were performed at Texas A&M University. Table 9.10 shows a summary of the results as well as the classifications according the Unified Soil Classification System. As can be seen there are no gravels, and mostly sands, silts, and clays.

9.13 Levee Overtopping and Erosion Failure Guideline Chart

In an effort to correlate the results of the EFA erosion tests with the behavior of the levees during overtopping flow, Figure 9.44 was prepared. It seems reasonably sure that the levees at sites S4, S5, S6, and S15 were overtopped and failed. At the same time it seems reasonably sure that the levees at sites S2, and S3 were overtopped and resisted remarkably well. The dark circles on Figure 9.44 correspond to samples taken from levees that were overtopped and failed by erosion while the open circles correspond to samples taken from levees that were overtopped and held during overtopping.

Figure 9.44 shows a definite correlation between the EFA tests results and the behavior of the levees during overtopping. Figure 9.45 was generated from Figure 9.44 as a levee guideline for erosion resistance during overtopping. It is suggested that such EFA erosion tests should be used in the future to predict levee behavior and ensure erosion resistance to overtopping.

9.14 Redundancy in Levee Systems

Levee systems are long linear systems. For example there are about 350 miles of levees protecting the New Orleans area. If any one part of this long linear system fails, there is no redundancy in place to help people escape. There is a need for such redundancy in the system. Some ideas are presented in Figures 9.46 and 9.47. First of all, it is recommended that houses in flood prone areas be elevated above ground (Figure 9.46). The additional cost of this feature is small in the total price of the house. Typically, the cost of the foundation is about 10% of the cost of a house. If elevating the house above ground increases the foundation cost by 50%, the increase on the cost of the house is only 5%. This seems well worth it. Second, one could conceive building escape structures (Figure 9.47). In tornado areas there are tornado-shelters, similar escape structures could be placed judiciously around a city such as New Orleans. They could be small hills disguised as parks or it might simply be a matter of making some major buildings easy to climb. A more redundant system than the current long linear levee systems is suggested.

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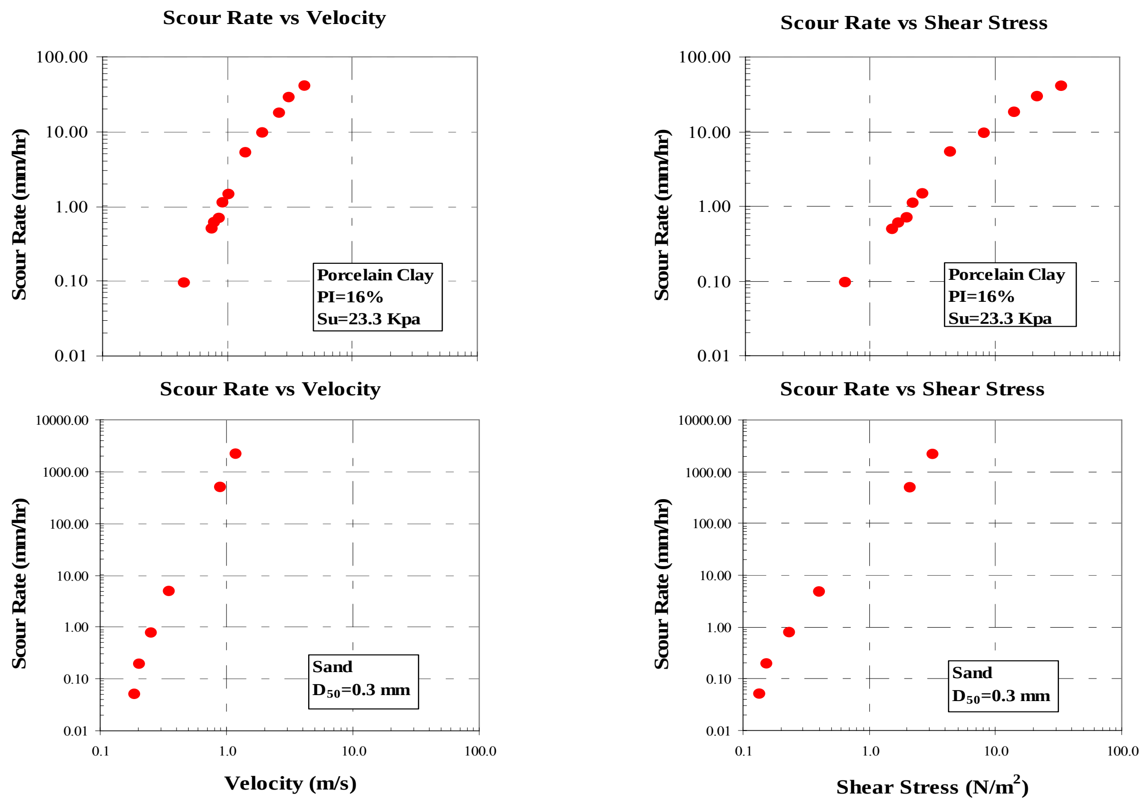


Figure 9.1: Erodibility function for a clay and for a sand.

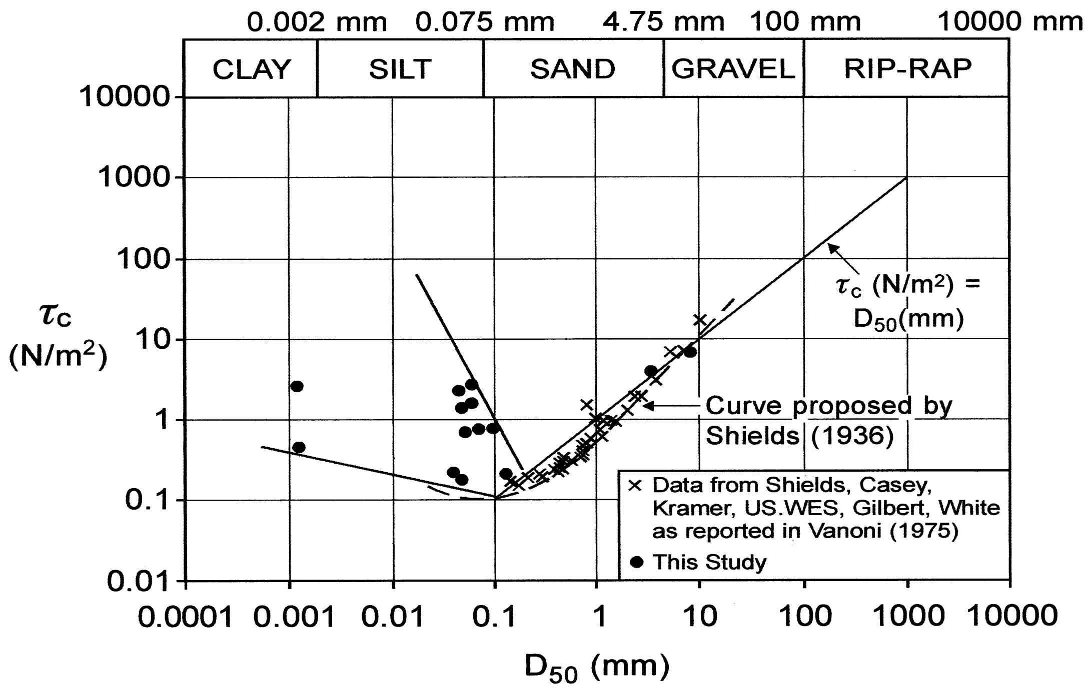


Figure 9.2: Critical shear stress versus mean soil grain size.

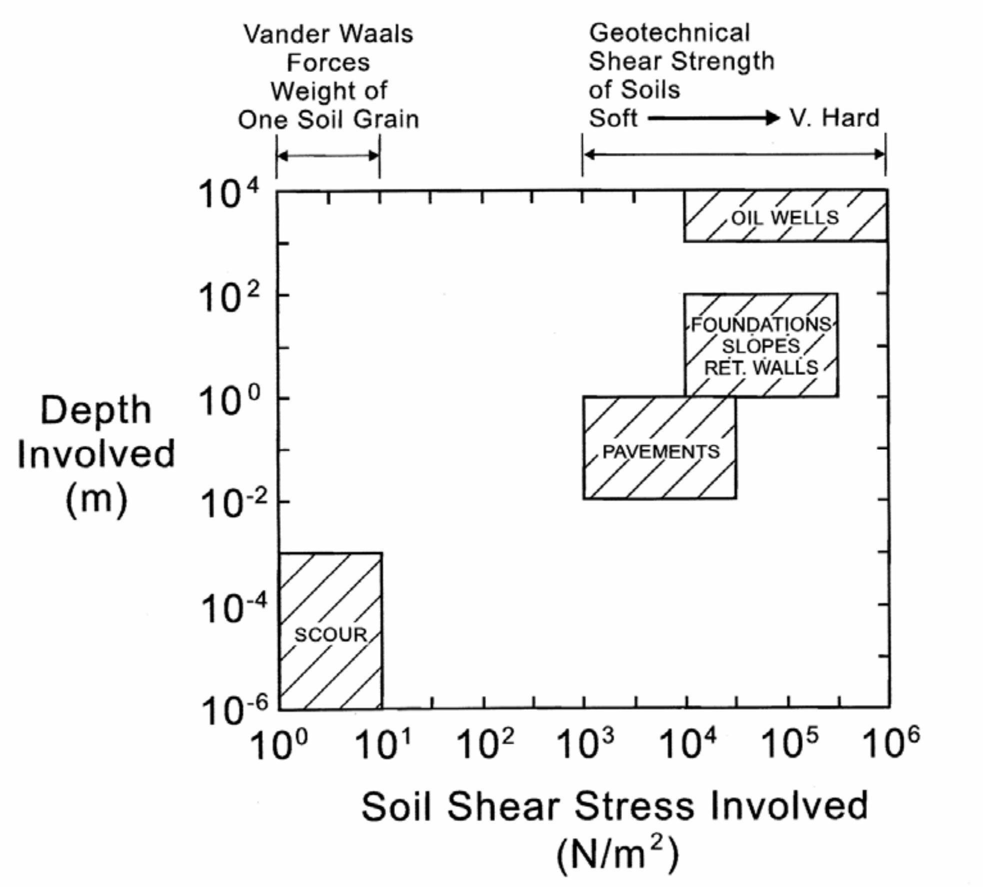


Figure 9.3: Magnitude of shear stresses involved in various fields of engineering.

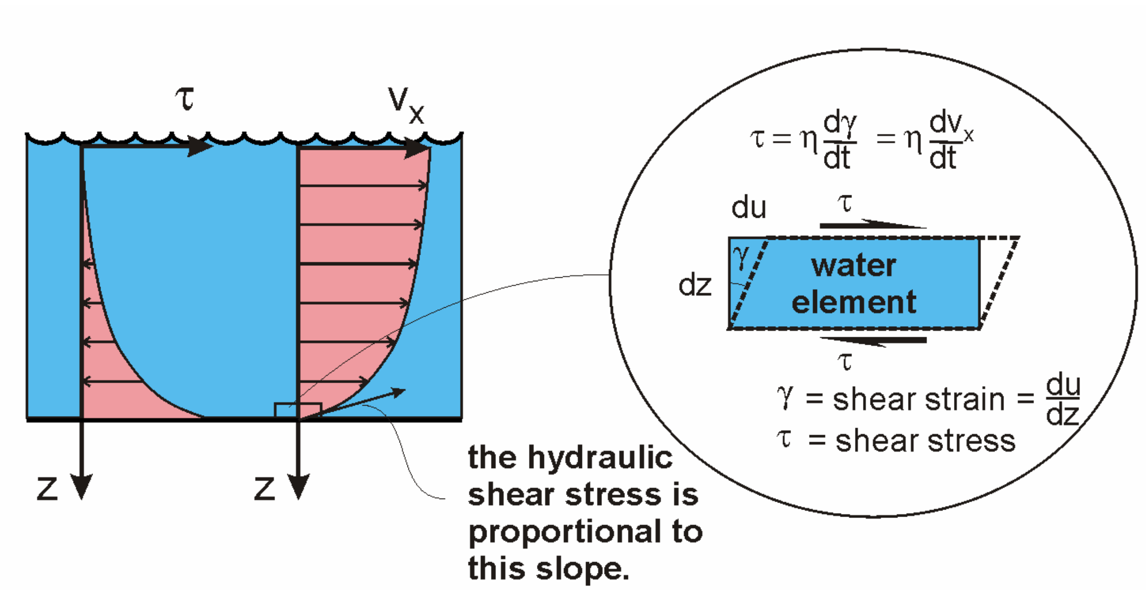


Figure 9.4: Velocity and shear stress within the flow depth.

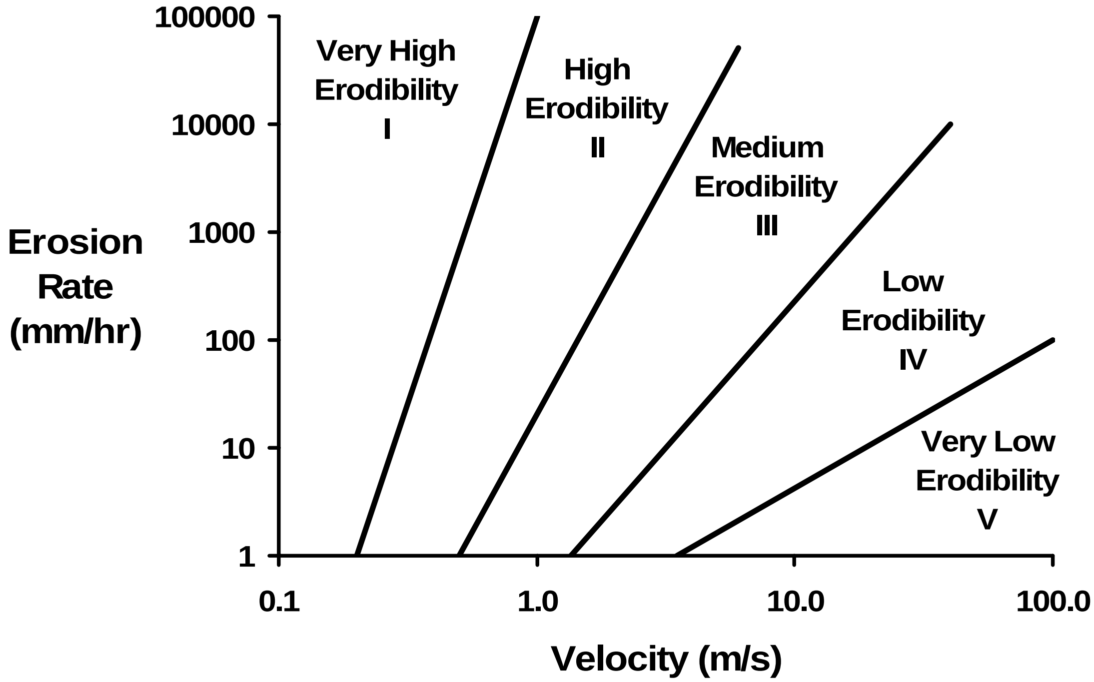


Figure 9.5: Erosion Categories.

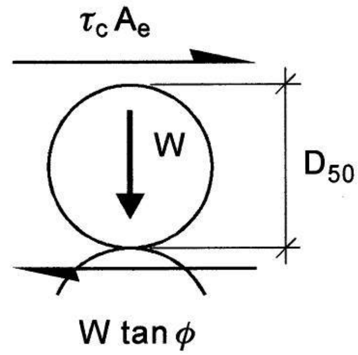


Figure 9.6: Particle diagram for a simple sliding mechanism.

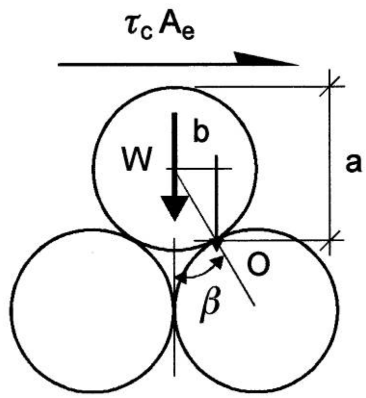


Figure 9.7: Particle diagram for a simple rolling mechanism.

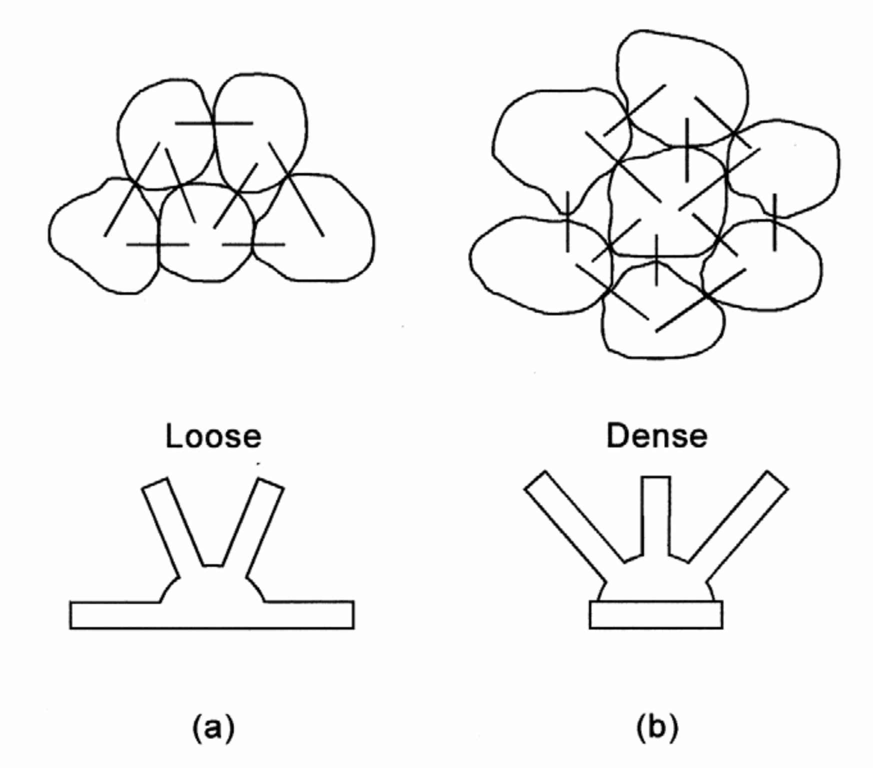


Figure 9.8: Contact angle distributions in coarse grained soils.

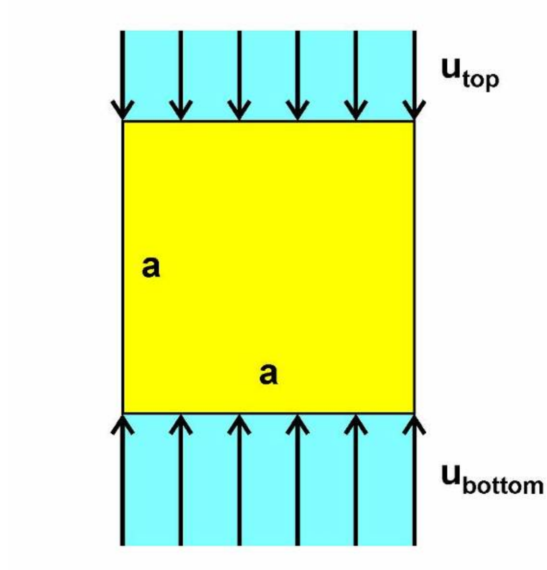


Figure 9.9: Particle diagram for a simple plucking mechanism.

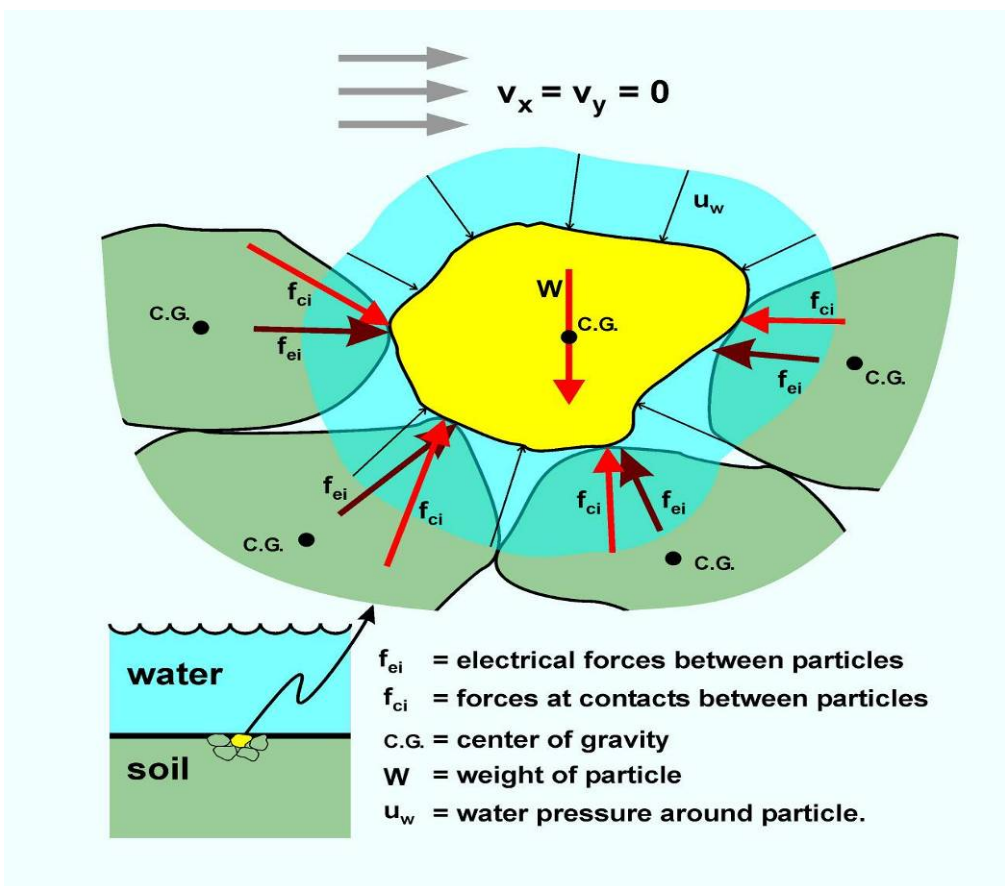


Figure 9.10: Forces and pressure on particle: no flow condition

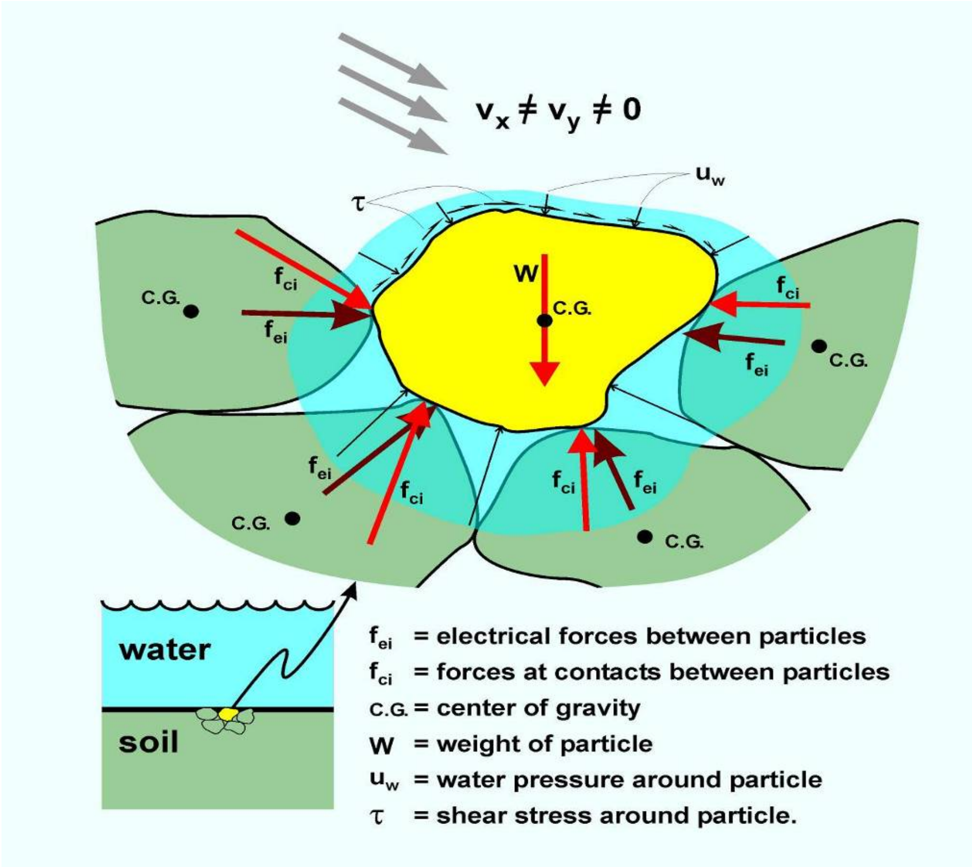


Figure 9.11: Forces and pressure on particle: flow condition.

Table 9.1: Gravity and Van der Waals Forces for Sand and Clay Particle

	Sand particle	Clay particle
Diameter d (m)	2×10^{-3}	1×10^{-6}
Weight W (N)	1.1×10^{-3}	1.36×10^{-13}
Van der Waals attraction F_{VDW} (N)	7.85×10^{-23}	3.14×10^{-16}
F_{VDW}/W	7.1×10^{-20}	2.3×10^{-3}

Table 9.2: Measured Critical Shear Stress in Clays

Authors	Range of τ_c (N/m2)
Dunn (1959)	2–25
Enger et al. (1968)	15–100
Hydrotechnical Construction, Moscow (1936)	1–20
Lyle and Smerdon (1965)	0.35–2.25
Smerdon and Beasley (1959)	0.75–5
Arulanandan et al. (1975)	0.1–4
Arulanandan (1975)	0.2–2.7
Kelly and Gularte (1981)	0.02–0.4

Table 9.3: Measured erosion rates in clay

Authors	Results	Inferred scour rate (mm/hr)*
Richardson, Davis (1995)	Maximum scour depth reached in days	10-100
Arulanandan et al. (1975)	1-4 g/cm^2/min	300-1200
Shaikh et al. (1988)	0.3-0.8 N/m^2/min	9-24
Ariathurai, Arulanandan (1978)	0.005-0.09 g/cm^2/min	1.5-27
Kelly, Gularte (1981)	0.0057-0.01 g/cm^2/s	100-180

* Erosion rate dz/dt = (weight loss rate per unit area dw/a dt)/(unit weight γ)

Table 9.4: Factors influencing the erodibility of fine grained soils

When this parameter increases	Erodibility
Soil water content	
Soil unit weight	decreases
Soil plasticity Index	decreases
Soil undrained shear strength	increases
Soil void ratio	increases
Soil swell	increases
Soil mean grain size	
Soil percent passing sieve #200	decreases
Soil clay minerals	
Soil dispersion ratio	increases
Soil cation exchange capacity	
Soil sodium absorption ratio	increases
Soil pH	
Soil temperature	increases
Water temperature	increases
Water chemical composition	

Table 9.5: Database of EFA tests

Woodrow Wilson Bridge (Washington)	Tests 1 to 12
South Carolina Bridge	Tests 13 to 16
National Geotechnical Experimentation Site (Texas)	Tests 17 to 26
Arizona Bridge (NTSB)	Test 27
Indonesia samples	Tests 28 to 33
Porcelain clay (man-made)	Tests 34 to 72
Bedias Creek Bridge (Texas)	Tests 73 to 77
Sims Bayou (Texas)	Tests 78 to 80
Brazos River Bridge (Texas)	Test 81
Navasota River Bridge (Texas)	Tests 82 and 83
San Marcos River Bridge (Texas)	Tests 84 to 86
San Jacinto River Bridge (Texas)	Tests 87 to 89
Trinity River Bridge (Texas)	Tests 90 and 91

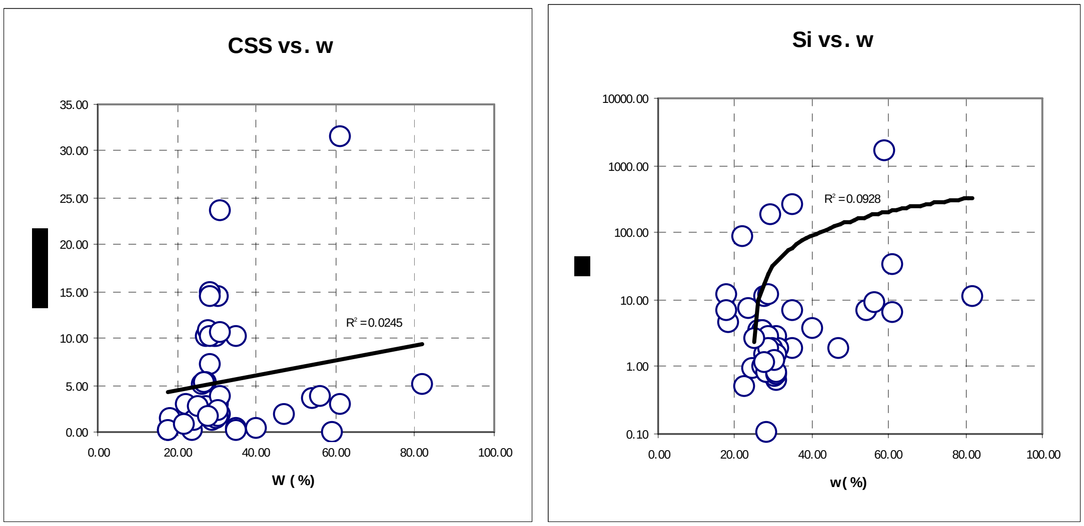


Figure 9.12: Erosion properties as a function of water content.

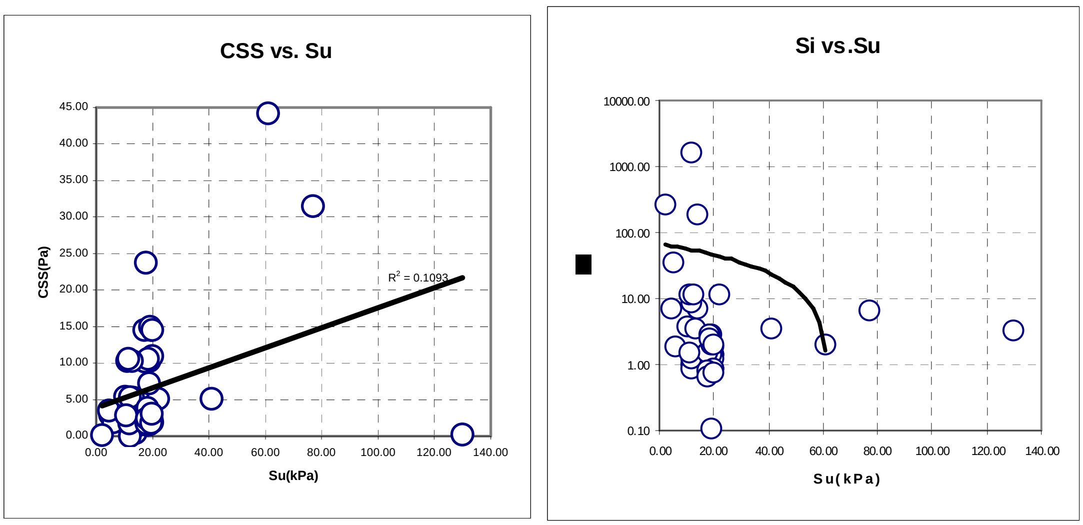


Figure 9.13: Erosion properties as a function of undrained shear strength.

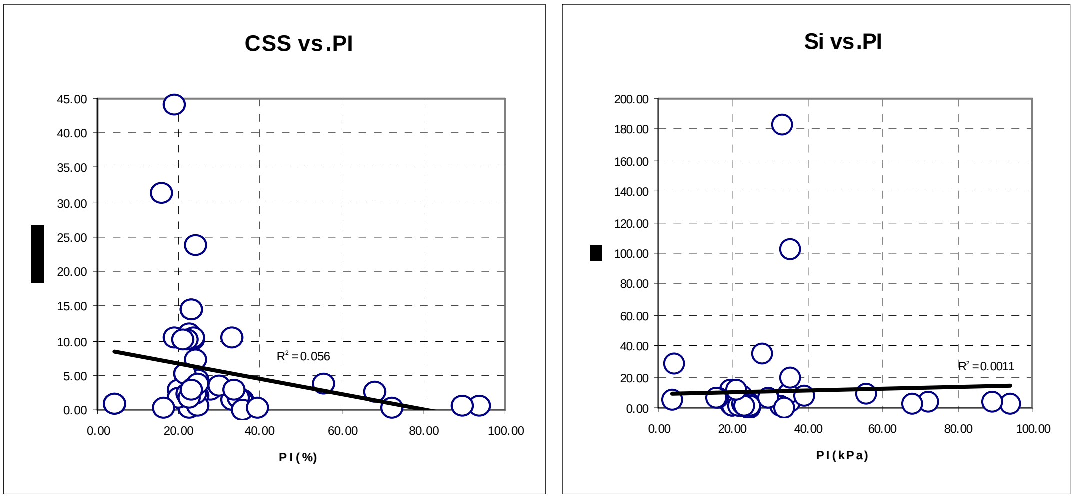


Figure 9.14: Erosion properties as a function of plasticity index.

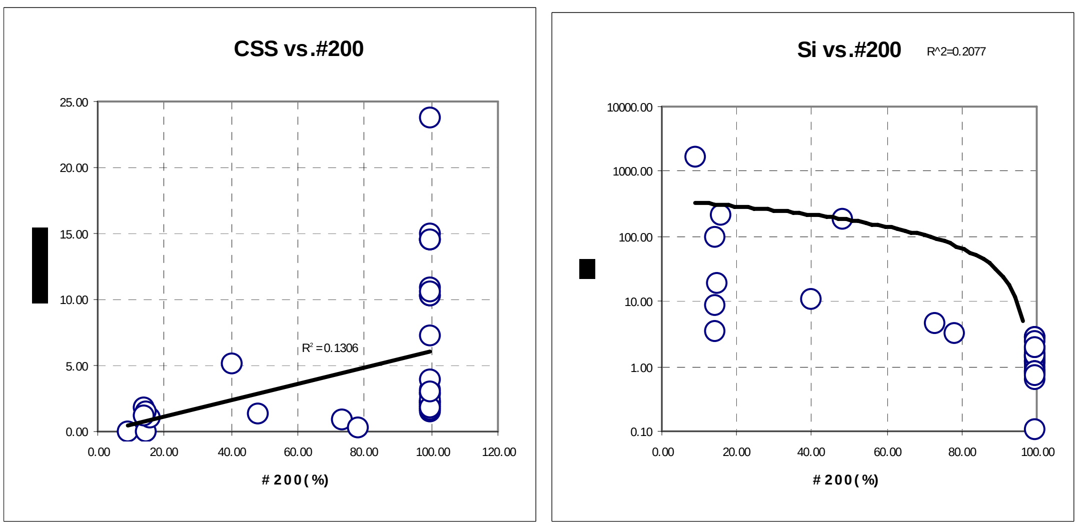
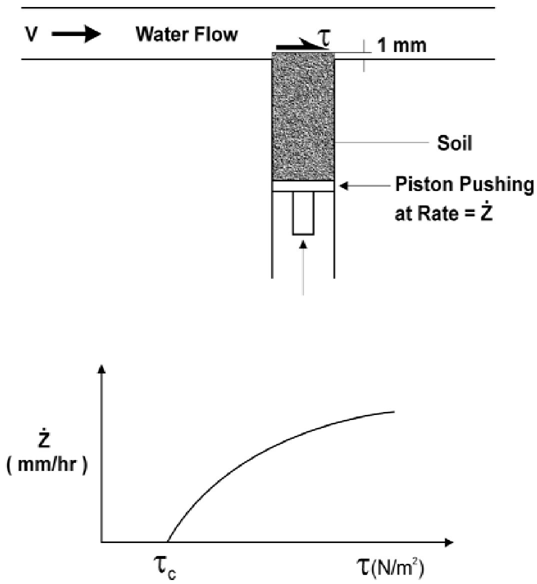
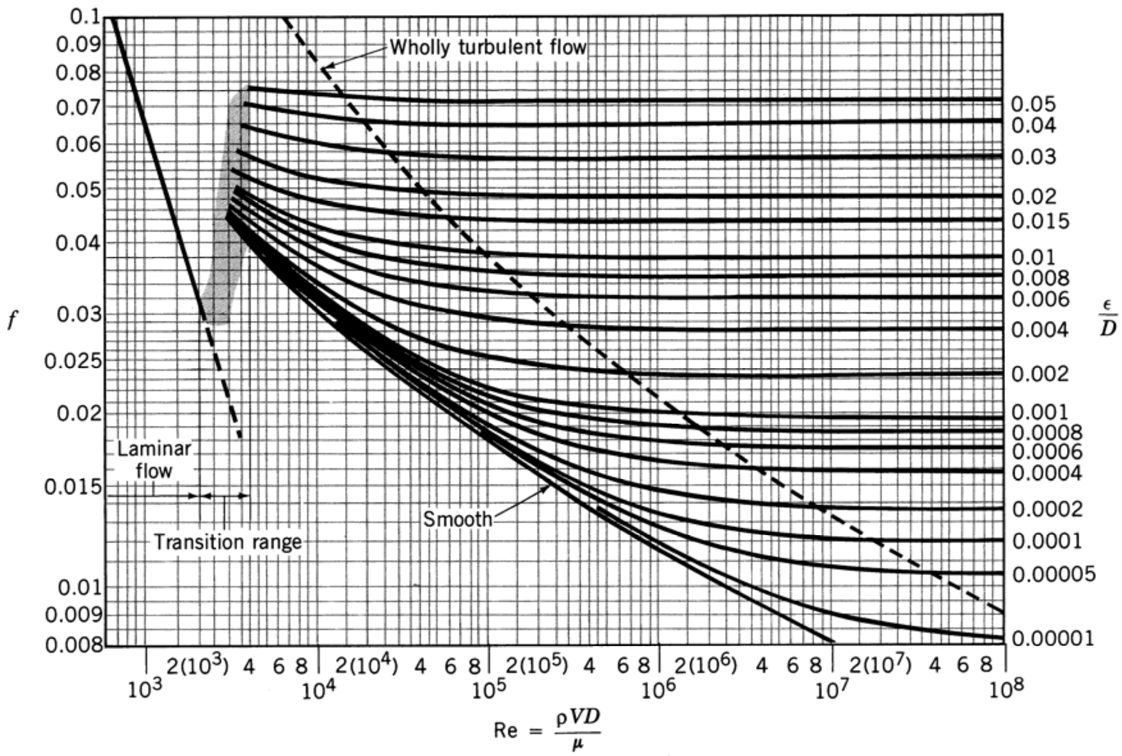


Figure 9.15: Erosion properties as a function of percent passing sieve #200.



Source: Briaud et al (2001)

Figure 9.16: EFA (Erosion Function Apparatus).

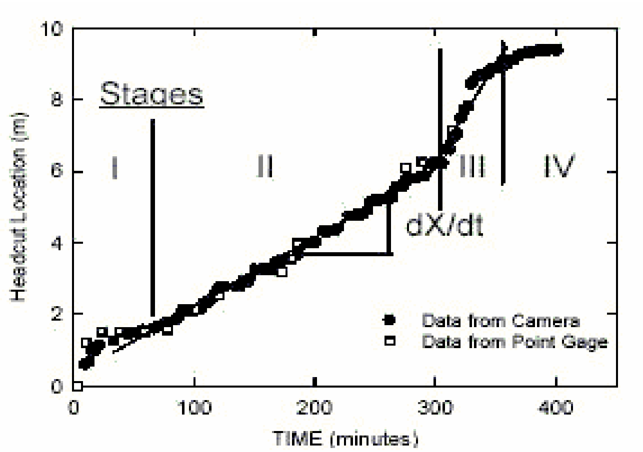


Source: Munson et al (1990)

Figure 9.17: Moody Chart.

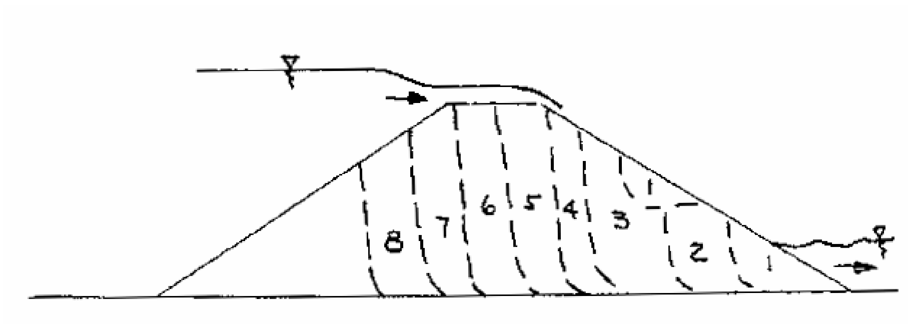
Table 9.6: Procedure for Levee Design and Construction (USACE, 2000)

Major and Minimum Requirements	
Step	**Procedure**
1	Conduct geological study based on a thorough review of available data including analysis of aerial photographs. Initiate preliminary subsurface explorations.
2	Analyze preliminary exploration data and from this analysis establish preliminary soil profiles, borrow locations, and embankment sections.
3	Initiate final exploration to provide: a. Additional information on soil profiles. b. Undisturbed strengths of foundation materials. c. More detailed information on borrow areas and other required excavations.
4	Using the information obtained in Step 3: a. Determine both embankment and foundation soil parameters and refine preliminary sections where needed, noting all possible problem areas. b. Compute rough quantities of suitable material and refine borrow area locations.
5	Divide the entire levee into reaches of similar foundation conditions, embankment height, and fill material and assign a typical trial section to each reach.
6	Analyze each trial section as needed for: a. Underseepage and through seepage. b. Slope stability. c. Settlement. d. Trafficability of the levee surface.
7	Design special treatment to preclude any problems as determined from Step 6. Determine surfacing requirements for the levee based on its expected future use.
8	Based on the results of Step 7, establish final sections for each reach.
9	Compute final quantities needed; determine final borrow area locations.
10	Design embankment slope protection.



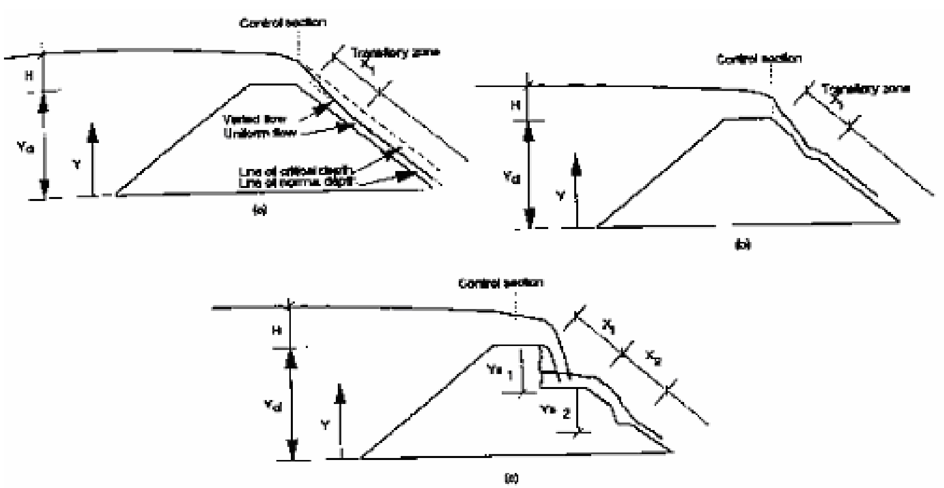
Source: Hanson et al. (2003)

Figure 9.18: Headcut Location as a Function of Time.



Source: Ralston (1987)

Figure 9.19: Stages of Progressive Erosion.



Source: AlQaser, Ruff (1993)

Figure 9.20: Progressive Failure of an Overtopped Embankment.

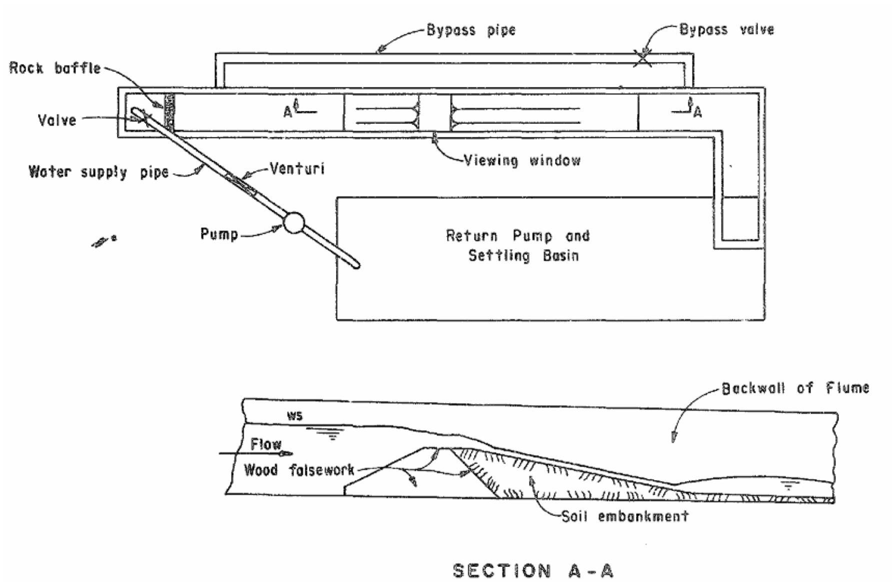
Table 9.7: Summary of Dam Break Computer Models (AlQaser, 1991)

<table>
<tr><th>Model (Yr of Publ)</th><th>Hydrodynamic Approach</th><th>Sediment Transport</th><th>Solution Algorithm</th><th>Breach Morphology</th><th>Characteristic Parameters</th><th>Other Features</th></tr>
<tr><td>Cristofano (1965)</td><td rowspan="3">Broad-crested weir hydraulic relation</td><td>Empirical relation</td><td>Manual-iterative</td><td>Constant width</td><td>Proportionality constant, angle of repose</td><td>No tailwater effects, no sloughing</td></tr>
<tr><td>Harris & Wagner (1967)

BRDAM Brown & Rogers (1977, 1981)</td><td>Schoklitsch bed-load formula</td><td>Numerical</td><td>Parabolic shape</td><td>Grain size, critical discharge value, breach dimensions and slope</td><td>No tailwater effects, no sloughing</td></tr>
<tr><td>DAMBRK – Fread (1977)</td><td>Linear pre-determined rate of erosion</td><td></td><td>Rectangular, triangular, trapezoidal</td><td>Failure duration tim, terminal size and shape of breach</td><td rowspan="3">No sloughing</td></tr>
<tr><td>Lou (1981)</td><td rowspan="2">St. Venant system of equations</td><td>Empirical relation</td><td rowspan="2">Preissmann's 4-point finite difference</td><td rowspan="2">Regime type relation between top width and flow rate</td><td rowspan="2">Coefficients of the regime relation, critical shear stress</td></tr>
<tr><td>Ponce & Tsivoglou (1981)</td><td rowspan="2">Meyer-Peter and Mueller bed-load formula</td></tr>
<tr><td>BREACH – Fread (1984)</td><td rowspan="3">Broad-crested weir hydraulic relation</td><td rowspan="3">Numerical iterative</td><td>Rectangular changing to trapezoidal</td><td>Critical shear stress grain size cohesion friction angle</td><td>Tailwater effects and sloughing are included</td></tr>
<tr><td>BEED – Singh 1989)</td><td>Einstein-Brown bed-load formula</td><td rowspan="2">Rectangular or trapezoidal</td><td>Friction angle, dimensionless shear stress 1/ψ</td><td>Neglects the triggering mechanism of failure, sloughing is incorporated</td></tr>
<tr><td>Froelich (1990)</td><td>linear predetermined rate of erosion</td><td>Dam height above the breach volume of water in the reservoir</td><td>Regression relations to predict breach parameters and time of failure</td></tr>
</table>

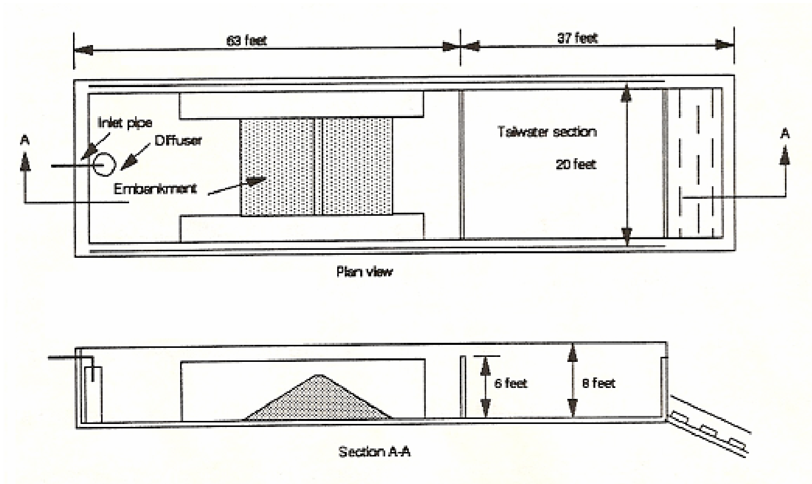
Table 9.8: Results from Flume Tests (Nairn, 1986)

Run	Description	Duration	Erosion Rate (m^3/m hr)
A	no bluff, composite slope, sand veneer	6 hrs.	0.0066
B	bluff, composite slope, toe sub-merged 3 cm, sand veneer	6 hrs.	0.0046
C	bluff, composite slope, toe submerged 5 cm, no sand	6 hrs.	0.0127
F	bluff, constant 1:20 slope, toe at NWL, no veneer	3.5 hrs 6.5 hrs.	0.0109 0.0098
G	bluff, constant 1:20 slope, toe at NWL, sand veneer	1 hr.	negligible, profile armoured with sand



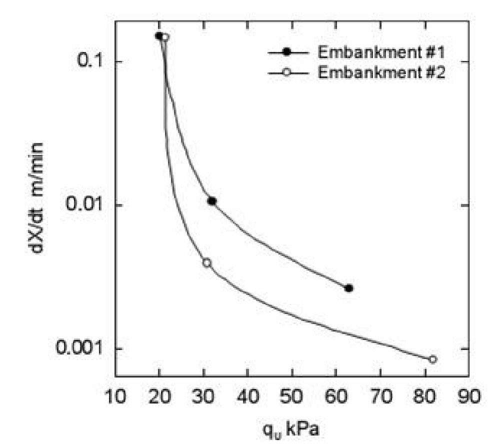
Source: Dodge (1988)

Figure 9.21: Laboratory Test Facility.



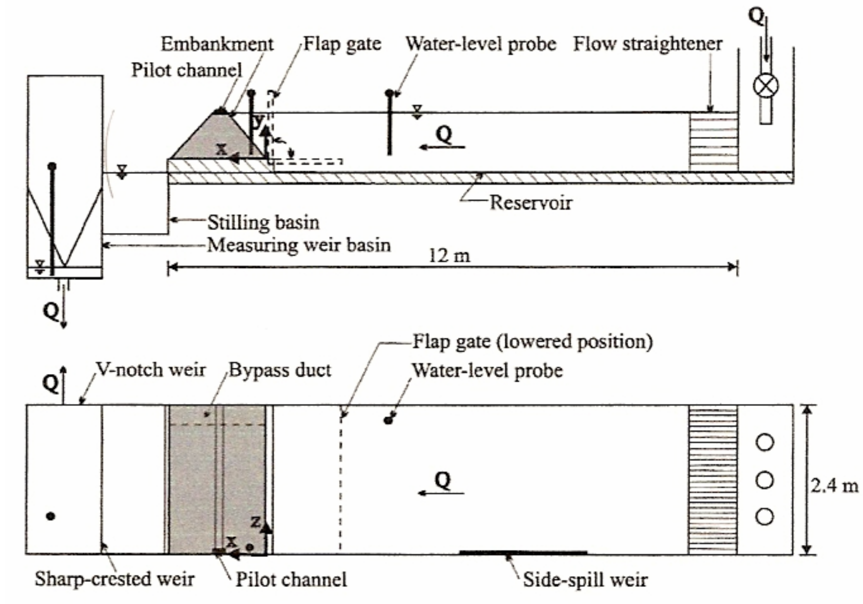
Source: AlQaser (1991)

Figure 9.22: Testing Facility.



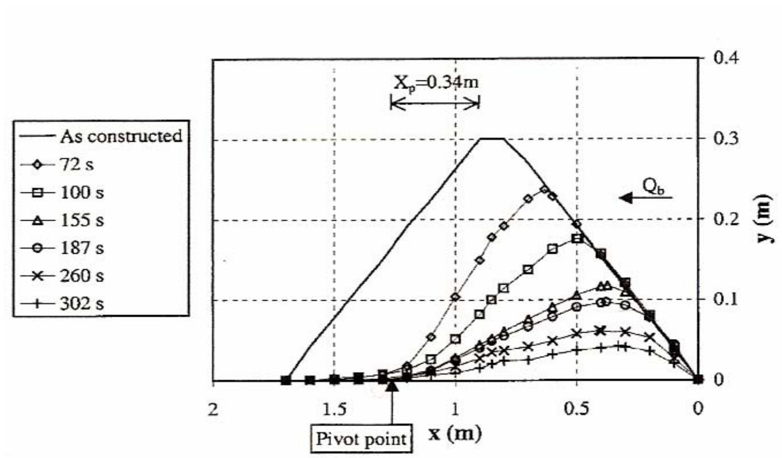
Source: Hanson et al. (2001)

Figure 9.23: Migration Rate vs. Unconfined Compression Tests.



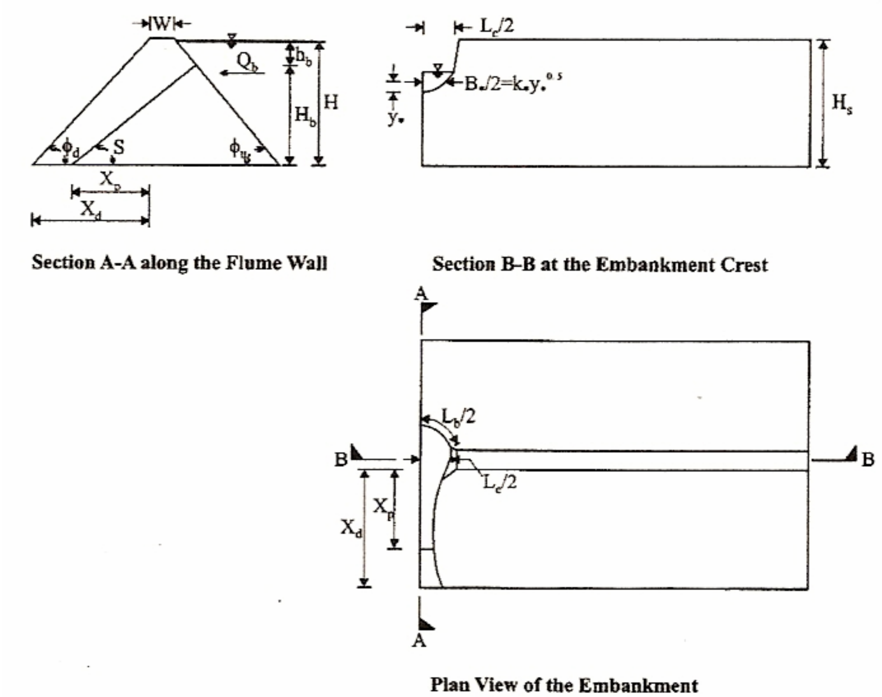
Source: Coleman et al. (2002)

Figure 9.24 : Experimental Setup.



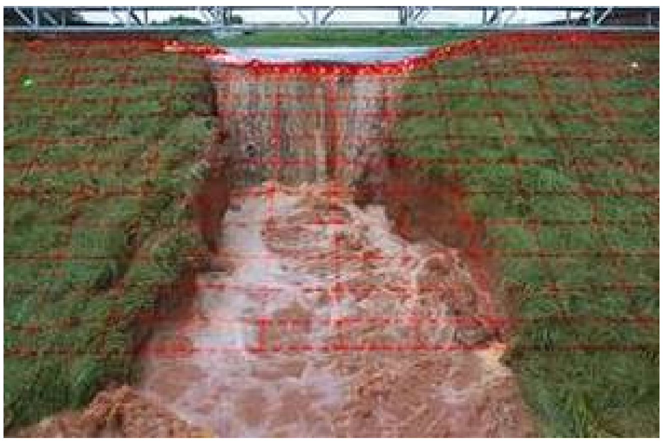
Source: Coleman et al. (2002)

Figure 9.25: Longitudinal Profiles Along Breach Channel Centerline for Medium-Sand Embankment.



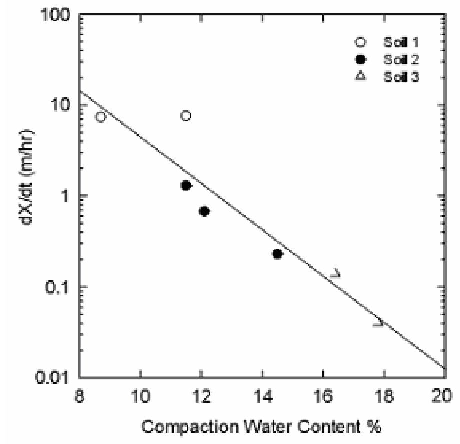
Source: Coleman et al. (2002)

Figure 9.26: Geometry Parameters for Breached Embankment.



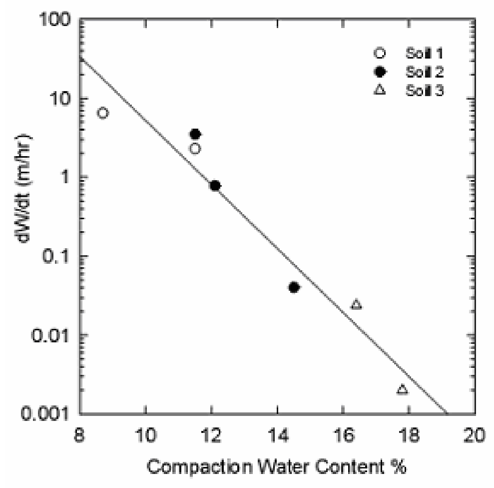
Source: Hanson et al. (2003)

Figure 9.27: Photographic Measurements of Erosion Width.



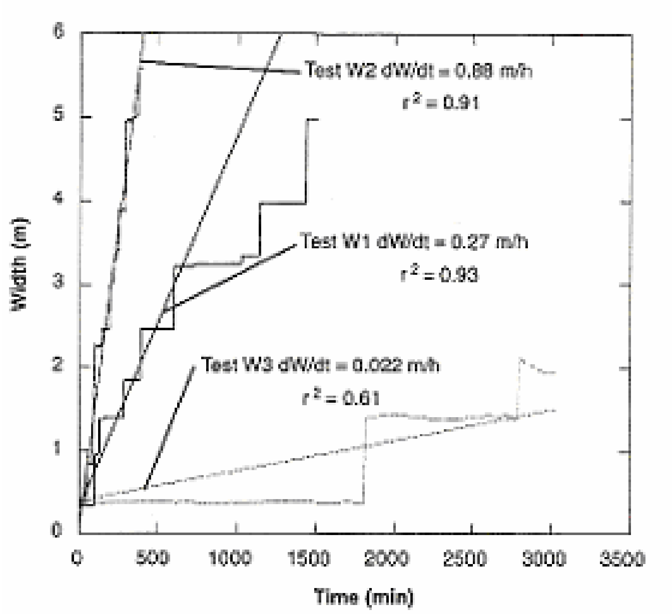
Source: Hanson et al. (2003)

Figure 9.28: Headcut Migration Rate vs. Compaction Water Content.



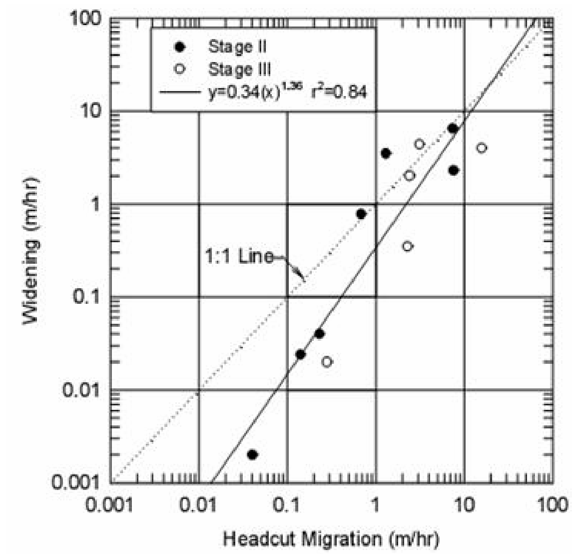
Source: Hanson et al. (2003)

Figure 9.29: Rate of Erosion Widening vs. Compaction Water Content.



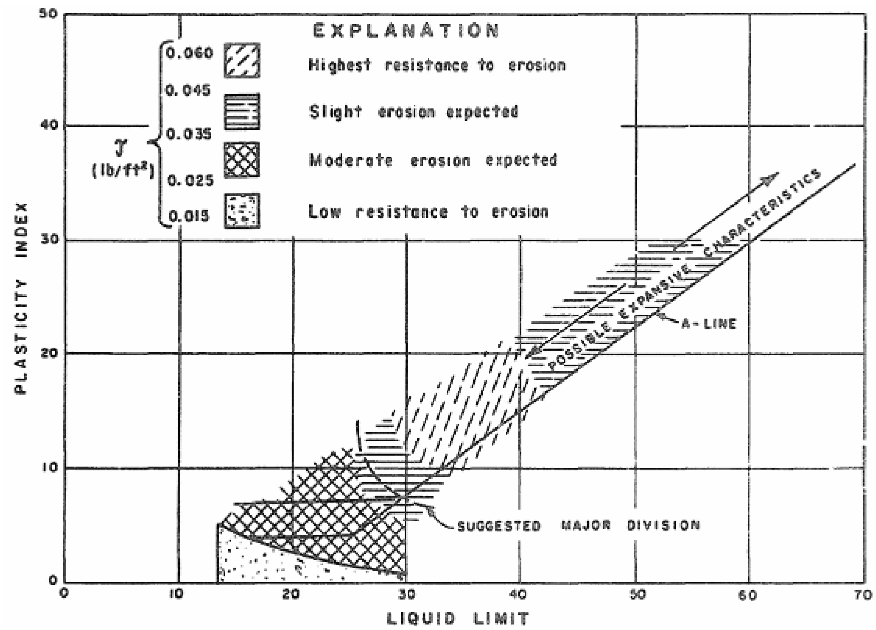
Source: Hunt et al. (2004)

Figure 9.30: Breach Width vs. Time.



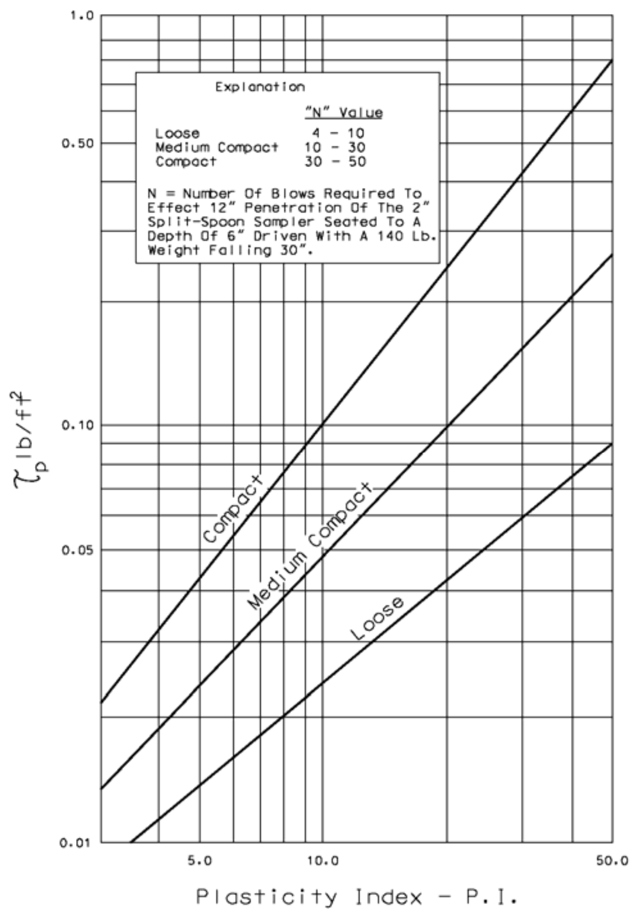
Source: Hanson et al., (2003)

Figure 9.31: Headcut Migration Rate vs. Rate of Widening.



Source: Dodge (1988)

Figure 9.32: Erosion Characteristics with respect to Plasticity.



Source: Chen & Cotton (1998)

Figure 9.33: Permissible Shear Stress for Cohesive Soils.

Figure 9.34: Difference in erosion resistance between grass cover and no grass cover.

RANGES OF SHEAR (pounds per square foot) BY DEPTH AND SLOPE

Note: This is Example A of a chart for a region with 30-40 inches of rainfall a year (good veg.)
Generally "good soil" for vegetation growth. Soil silt, sand, clay mixture.
The user should further refine this Example to a specific area of use.

Note: This assumes a "hydraulically wide" channel with generally straight alignment
shear (psf) = unit wt of water (pcf) * depth (ft) * slope (ft/ft) .
If the channel is "hydraulically narrow" then replace D with R (area / wp)
Shear around bends can be greater than these values depending upon ratio of bend radius to bottom width.
This chart is intended to be used as a quick visual guide and does not take the place of individual site analysis.
The divisions between the different levels are "fuzzy" and should not be taken literally off of this chart.

Legend: Tan = soil can handle under 0.5 psf (depending upon type of soil)
Green = grasses under 3 or 4 psf (depending upon type and condition of vegetation)
Yellow = soft armor, geosynthetic matting, under 6 to 8 psf
Red = hard armor, over 7 to 8 psf

Note: The colored "ranges" change from Example A to B to C

D (ft) \ S (ft/ft)	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009	0.010	0.012	0.014	0.016	0.018	0.020	0.025	0.030	0.035	0.040	0.045	0.050	0.055	0.060
0.1	0.01	0.01	0.02	0.02	0.03	0.04	0.04	0.05	0.06	0.06	0.07	0.09	0.10	0.11	0.12	0.16	0.19	0.22	0.25	0.28	0.31	0.34	0.37
0.3	0.02	0.04	0.06	0.07	0.09	0.11	0.13	0.15	0.17	0.19	0.22	0.26	0.30	0.34	0.37	0.47	0.56	0.66	0.75	0.84	0.94	1.03	1.12
0.5	0.03	0.06	0.09	0.12	0.16	0.19	0.22	0.25	0.28	0.31	0.37	0.44	0.50	0.56	0.62	0.78	0.94	1.09	1.25	1.40	1.56	1.72	1.87
0.7	0.04	0.09	0.13	0.17	0.22	0.26	0.31	0.35	0.39	0.44	0.52	0.61	0.70	0.79	0.87	1.09	1.31	1.53	1.75	1.97	2.18	2.40	2.62
1.0	0.06	0.12	0.19	0.25	0.31	0.37	0.44	0.50	0.56	0.62	0.75	0.87	1.00	1.12	1.25	1.56	1.87	2.18	2.50	2.81	3.12	3.43	3.74
1.2	0.07	0.15	0.22	0.30	0.37	0.45	0.52	0.60	0.67	0.75	0.90	1.05	1.20	1.35	1.50	1.87	2.25	2.62	3.00	3.37	3.74	4.12	4.49
1.4	0.09	0.17	0.26	0.35	0.44	0.52	0.61	0.70	0.79	0.87	1.05	1.22	1.40	1.57	1.75	2.18	2.62	3.06	3.49	3.93	4.37	4.80	5.24
1.6	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	1.20	1.40	1.60	1.80	2.00	2.50	3.00	3.49	3.99	4.49	4.99	5.49	5.99
1.8	0.11	0.22	0.34	0.45	0.56	0.67	0.79	0.90	1.01	1.12	1.35	1.57	1.80	2.02	2.25	2.81	3.37	3.93	4.49	5.05	5.62	6.18	6.74
2.0	0.12	0.25	0.37	0.50	0.62	0.75	0.87	1.00	1.12	1.25	1.50	1.75	2.00	2.25	2.50	3.12	3.74	4.37	4.99	5.62	6.24	6.86	7.49
2.2	0.14	0.27	0.41	0.55	0.69	0.82	0.96	1.10	1.24	1.37	1.65	1.92	2.20	2.47	2.75	3.43	4.12	4.80	5.49	6.18	6.86	7.55	8.24
2.4	0.15	0.30	0.45	0.60	0.75	0.90	1.05	1.20	1.35	1.50	1.80	2.10	2.40	2.70	3.00	3.74	4.49	5.24	5.99	6.74	7.49	8.24	8.99
2.6	0.16	0.32	0.49	0.65	0.81	0.97	1.14	1.30	1.46	1.62	1.95	2.27	2.60	2.92	3.24	4.06	4.87	5.68	6.49	7.30	8.11	8.92	9.73
2.8	0.17	0.35	0.52	0.70	0.87	1.05	1.22	1.40	1.57	1.75	2.10	2.45	2.80	3.14	3.49	4.37	5.24	6.12	6.99	7.86	8.74	9.61	10.48
3.0	0.19	0.37	0.56	0.75	0.94	1.12	1.31	1.50	1.68	1.87	2.25	2.62	3.00	3.37	3.74	4.68	5.62	6.55	7.49	8.42	9.36	10.30	11.23
3.2	0.20	0.40	0.60	0.80	1.00	1.20	1.40	1.60	1.80	2.00	2.40	2.80	3.19	3.59	3.99	4.99	5.99	6.99	7.99	8.99	9.98	10.98	11.98
3.4	0.21	0.42	0.64	0.85	1.06	1.27	1.49	1.70	1.91	2.12	2.55	2.97	3.39	3.82	4.24	5.30	6.36	7.43	8.49	9.55	10.61	11.67	12.73
3.6	0.22	0.45	0.67	0.90	1.12	1.35	1.57	1.80	2.02	2.25	2.70	3.14	3.59	4.04	4.49	5.62	6.74	7.86	8.99	10.11	11.23	12.36	13.48
3.8	0.24	0.47	0.71	0.95	1.19	1.42	1.66	1.90	2.13	2.37	2.85	3.32	3.79	4.27	4.74	5.93	7.11	8.30	9.48	10.67	11.86	13.04	14.23
4.0	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	3.00	3.49	3.99	4.49	4.99	6.24	7.49	8.74	9.98	11.23	12.48	13.73	14.98
4.2	0.26	0.52	0.79	1.05	1.31	1.57	1.83	2.10	2.36	2.62	3.14	3.67	4.19	4.72	5.24	6.55	7.86	9.17	10.48	11.79	13.10	14.41	15.72
4.4	0.27	0.55	0.82	1.10	1.37	1.65	1.92	2.20	2.47	2.75	3.29	3.84	4.39	4.94	5.49	6.86	8.24	9.61	10.98	12.36	13.73	15.10	16.47
4.6	0.29	0.57	0.86	1.15	1.44	1.72	2.01	2.30	2.58	2.87	3.44	4.02	4.59	5.17	5.74	7.18	8.61	10.05	11.48	12.92	14.35	15.79	17.22
4.8	0.30	0.60	0.90	1.20	1.50	1.80	2.10	2.40	2.70	3.00	3.59	4.19	4.79	5.39	5.99	7.49	8.99	10.48	11.98	13.48	14.98	16.47	17.97
5.0	0.31	0.62	0.94	1.25	1.56	1.87	2.18	2.50	2.81	3.12	3.74	4.37	4.99	5.62	6.24	7.80	9.36	10.92	12.48	14.04	15.60	17.16	18.72
5.5	0.34	0.69	1.03	1.37	1.72	2.06	2.40	2.75	3.09	3.43	4.12	4.80	5.49	6.18	6.86	8.58	10.30	12.01	13.73	15.44	17.16	18.88	20.59
6.0	0.37	0.75	1.12	1.50	1.87	2.25	2.62	3.00	3.37	3.74	4.49	5.24	5.99	6.74	7.49	9.36	11.23	13.10	14.98	16.85	18.72	20.59	22.46
6.5	0.41	0.81	1.22	1.62	2.03	2.43	2.84	3.24	3.65	4.06	4.87	5.68	6.49	7.30	8.11	10.14	12.17	14.20	16.22	18.25	20.28	22.31	24.34
7.0	0.44	0.87	1.31	1.75	2.18	2.62	3.06	3.49	3.93	4.37	5.24	6.12	6.99	7.86	8.74	10.92	13.10	15.29	17.47	19.66	21.84	24.02	26.21

shear3.xls Shear A

R Chan Associates - Austin

Source: Johnston (2003)

Figure 9.35: Range of shear stresses allowable on slopes for different covers.

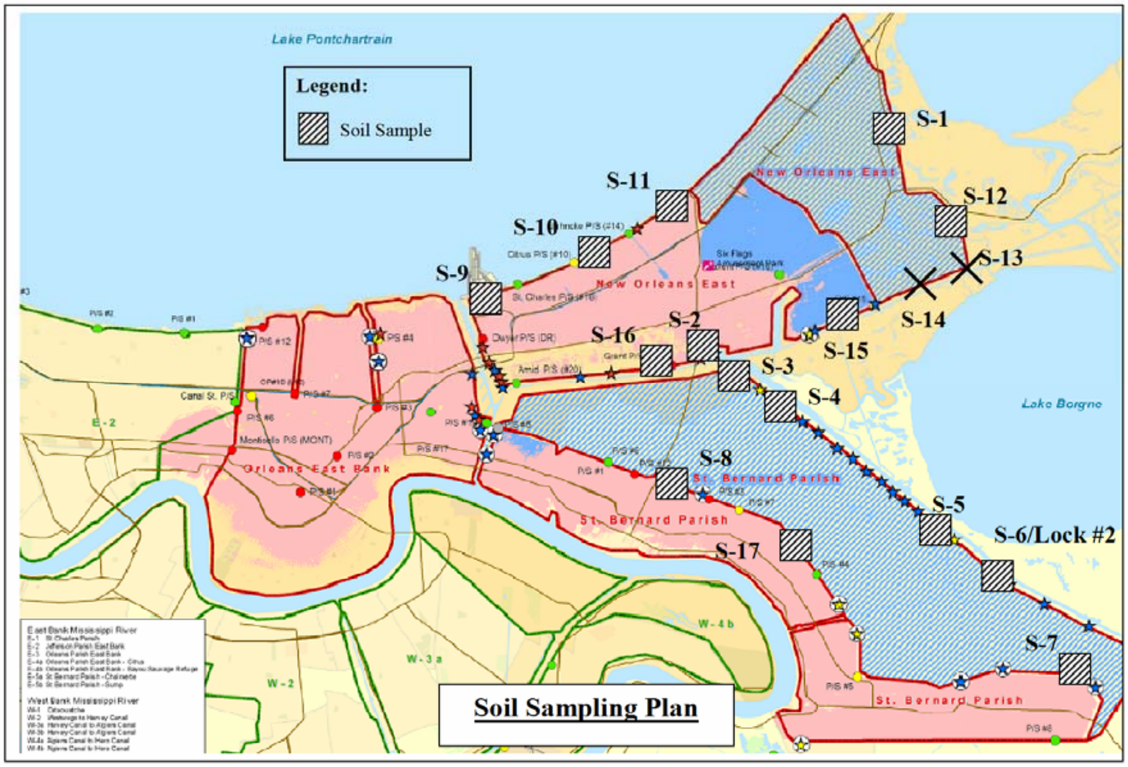


Figure 9.36: Location of samples.

Table 9.9: Salinity and pH of water associated with the samples

	pH	Salinity (ppm)
Sample S11	8.61	3287
Sample S15	8.09	4199
Typical sea water	7.9	30000 to 35000
Typical tap water	7.0	500

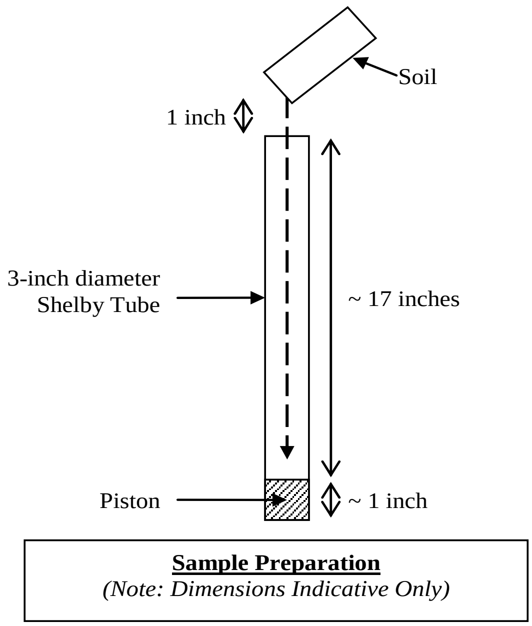
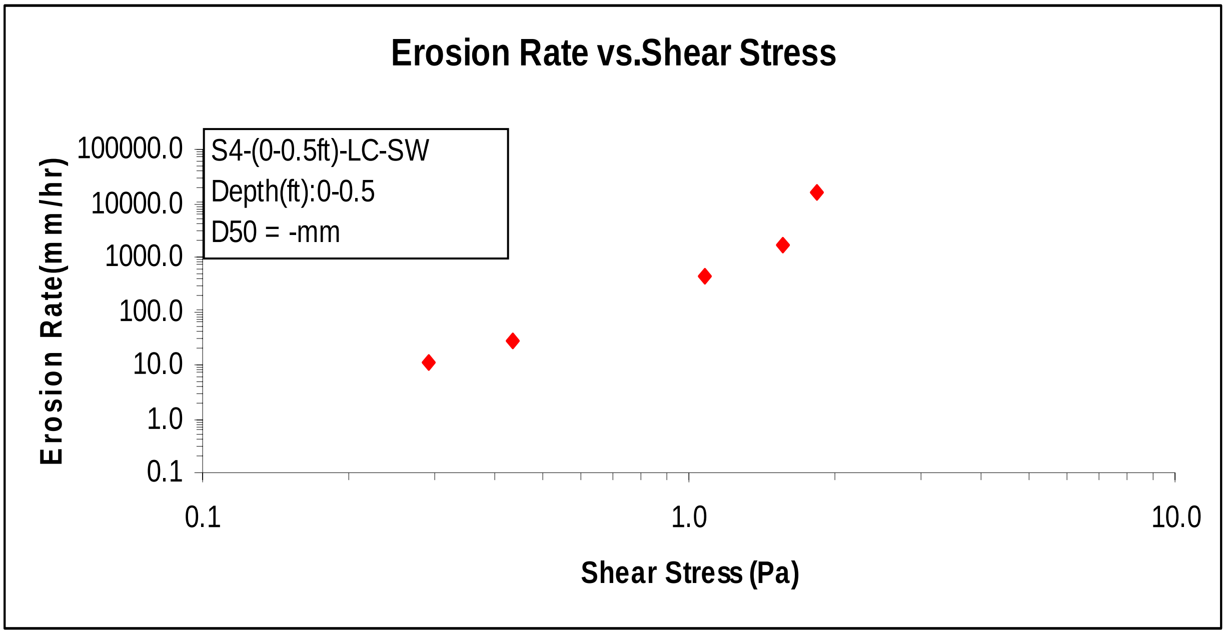


Figure 9.37: Soil preparation by re-compaction for bag samples.

EFA Test Results for Sample No. S4-(0-0.5ft)-LC-SW

Sample Type: Bulk Sample
Water Salinity: 36.1 PPT (Salt Water)
Compaction Effort: Low = 1.6% Modified Proctor Compaction



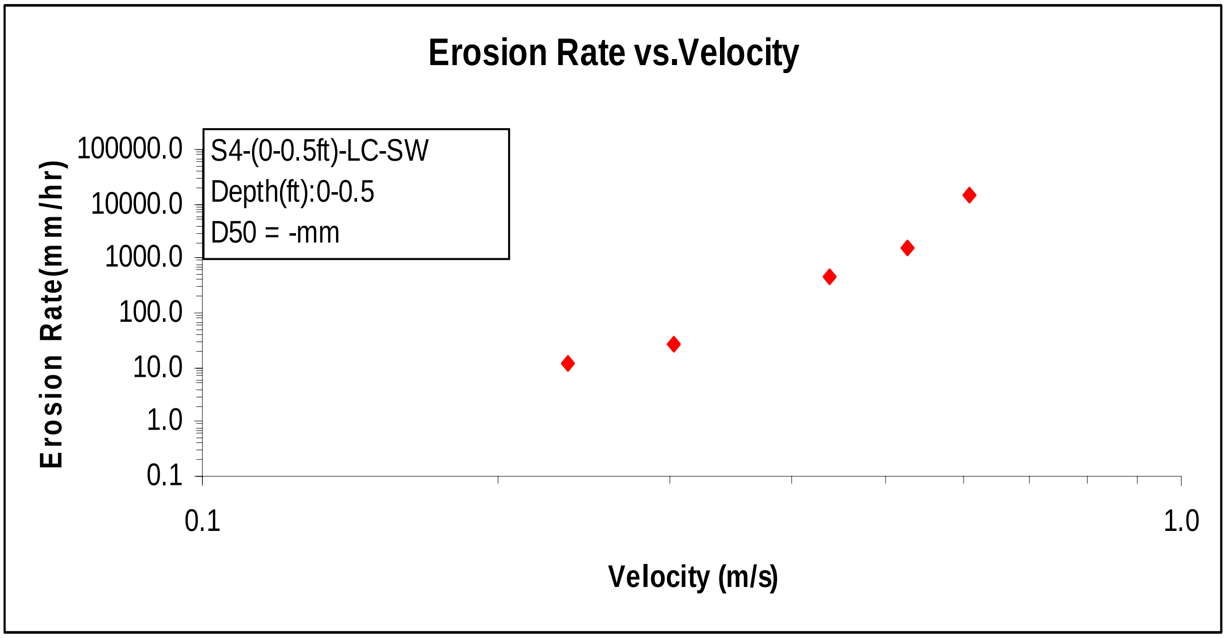
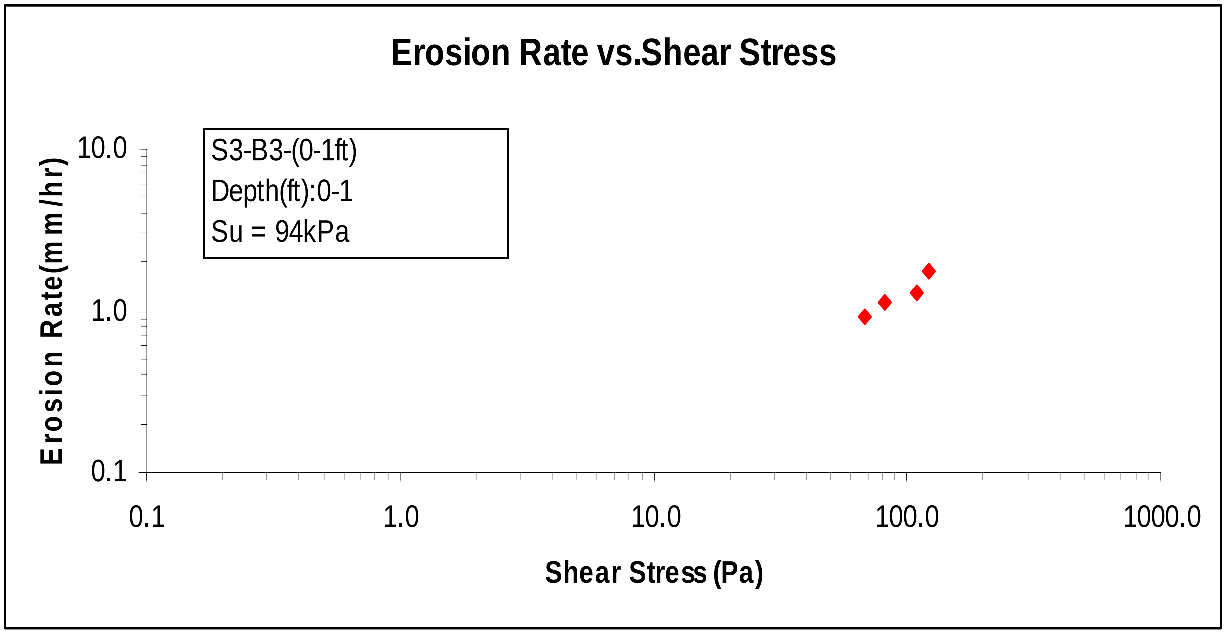


Figure 9.38: EFA test results for sample S4 (0-0.5 ft), low compaction, salt water.

EFA Test Results for Sample No. S3-B3-(0-1ft)-SW

Sample Type: Shelby Tube
Water Salinity: 36.4 PPT (Salt Water)
Compaction Effort: N/A



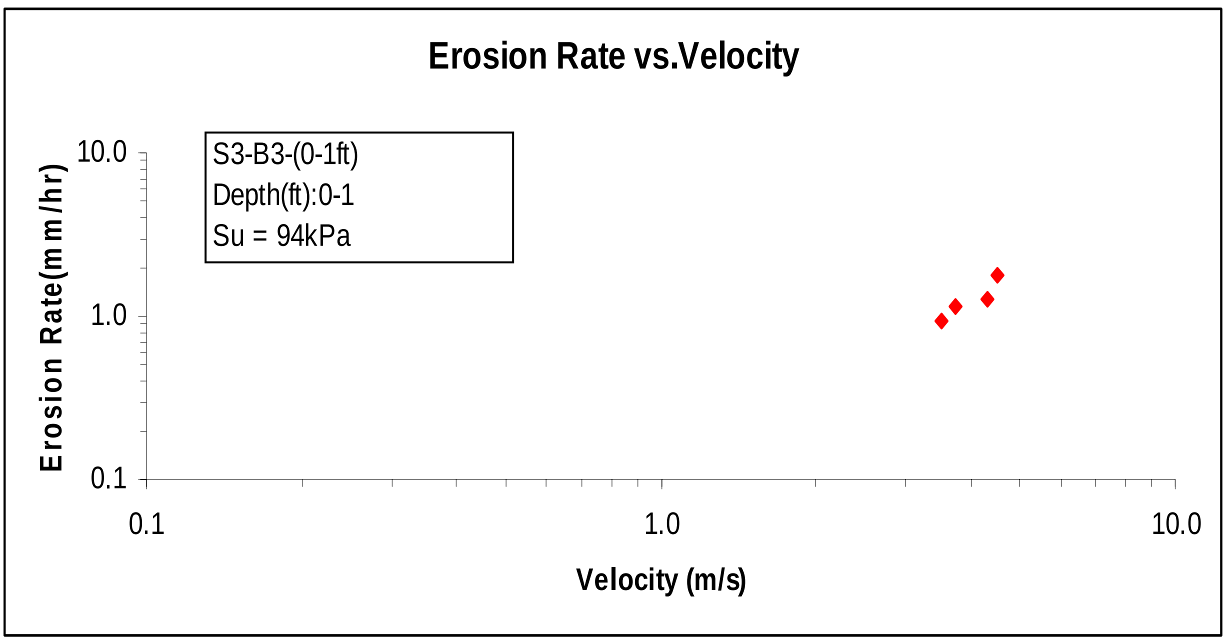


Figure 9.39: EFA test results for sample S3-B3 (0-1 ft), salt water.

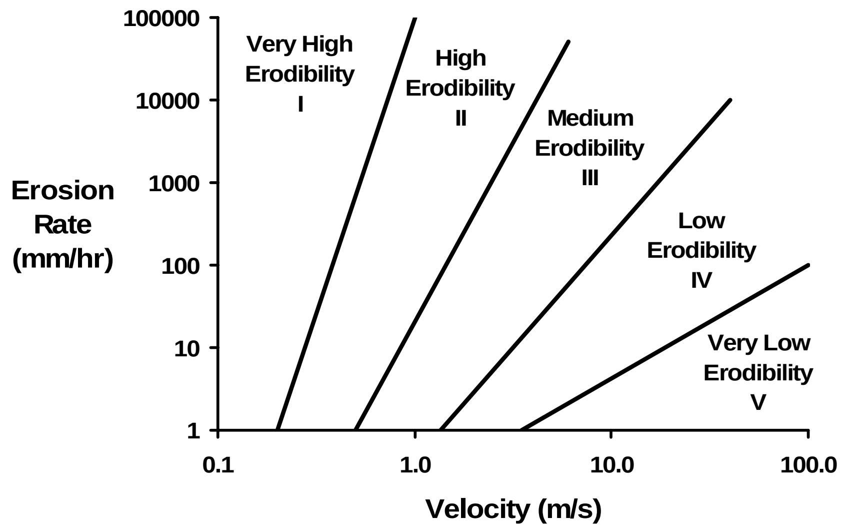


Figure 9.40: Erosion Chart.

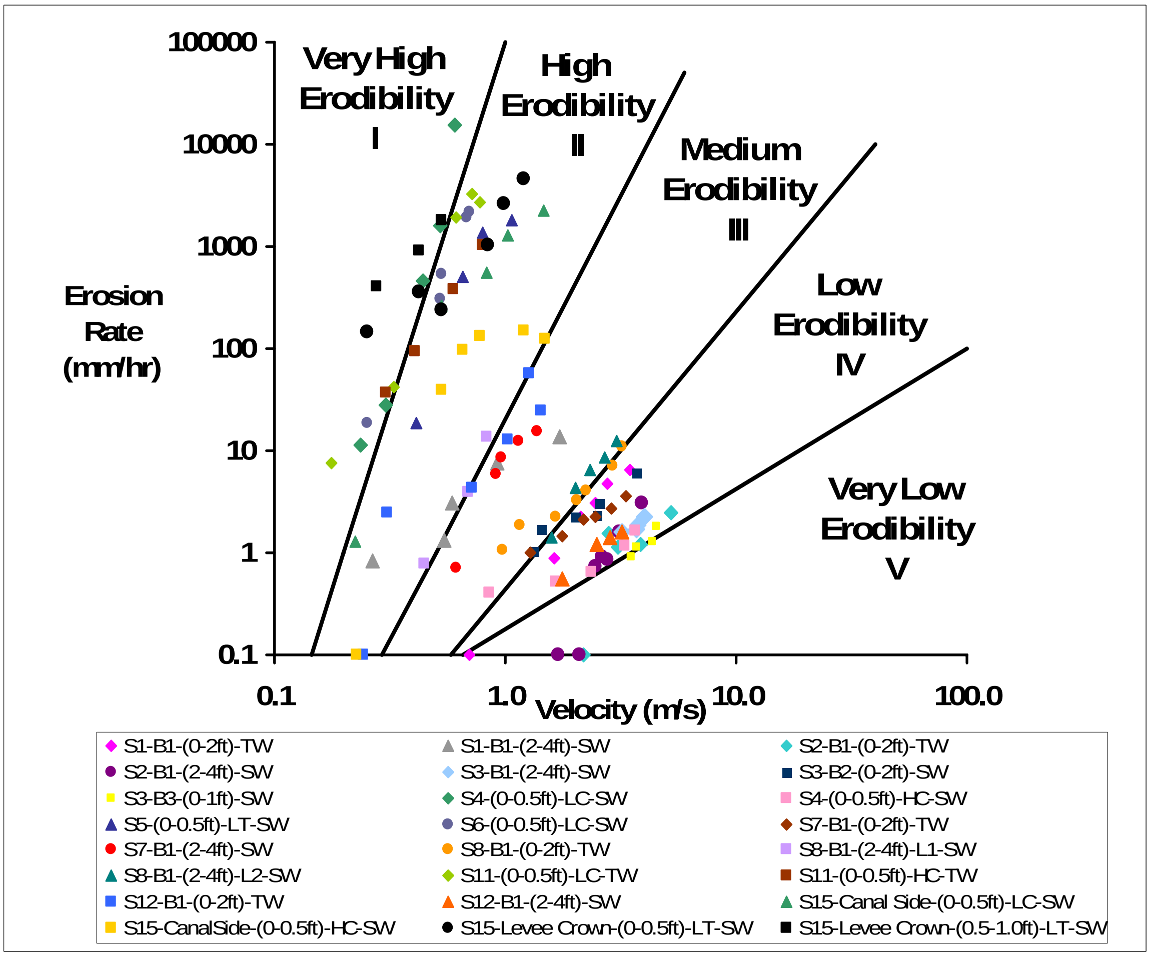


Figure 9.41: EFA test results for 24 levee samples.

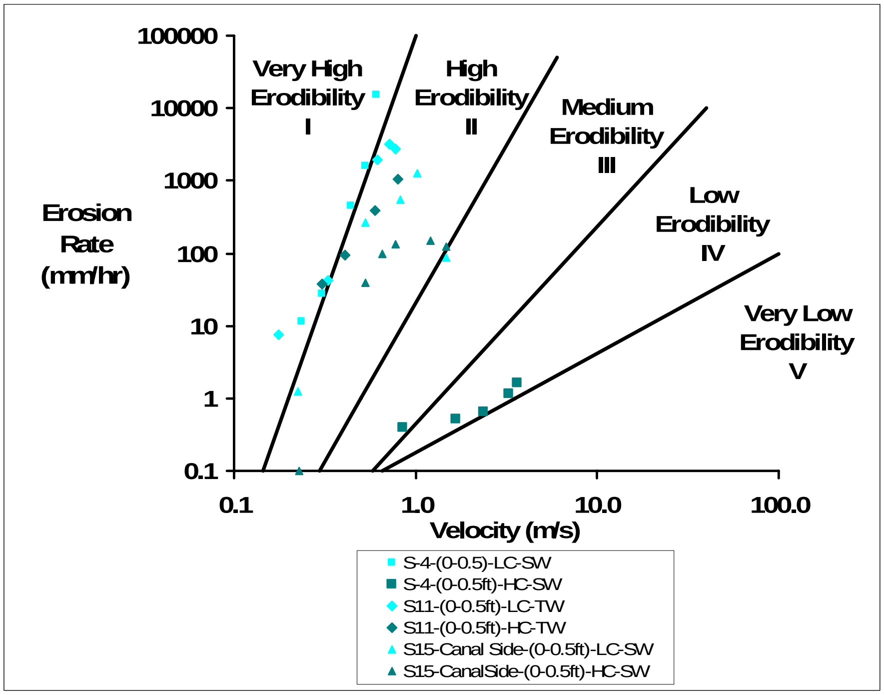


Figure 9.42: Influence of compaction on erodibility

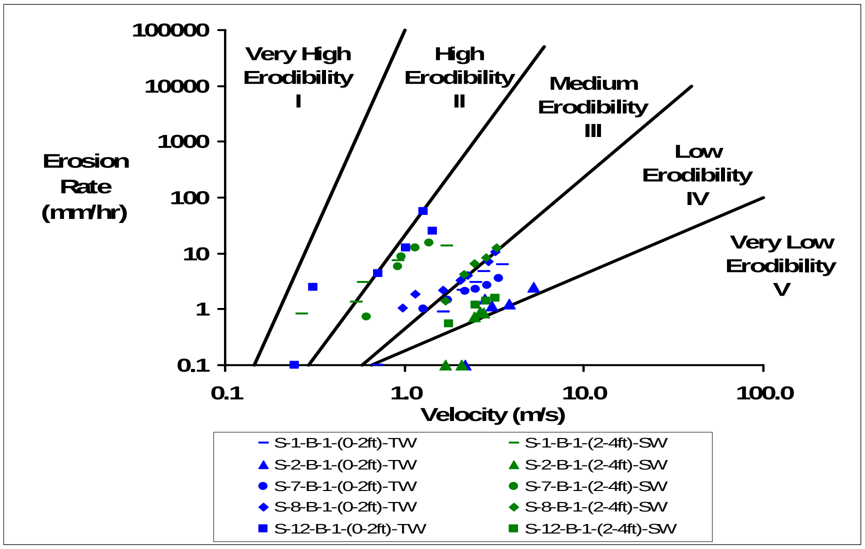


Figure 9.43: Influence of water salinity on erodibility

Table 9.10: Results of the index property tests.

Sample	Soil Description	Classification	γ_t (kN/m3)	γ_{dry} (kN/m3)	w (%)	Tested at Texas A&M University					Tests Performed by STE			
						% fines	LL	PL	PI	Organic Content%	% fines	LL	PL	PI
S1-B1-(0-2ft)-TW	Clay with hard clay grain mixture	CH	20.23	15.37	31.66	-	71	25	46	3.09	89.9	65	22	43
S1-B1-(2-4ft)-SW	Clay with rootlets	CH	19.10	15.69	21.77	-	56	19	37	1.91				
S2-B1-(0-2ft)-TW	Clay with rootlets	CL	19.74	17.00	16.11	-	46	17	29	16.94	67.2	49	17	32
S2-B1-(2-4ft)-SW	Clay	CL	20.26	16.71	21.23	69.1	41	16	25	1.62				
S3-B1-(2-4ft)-SW	Clay	CL-CH	17.60	13.86	27.00	-	48	17	31	2.50	90.3	54	19	35
S3-B2-(0-2ft)-SW	Clay with some sand	CH	20.20	17.26	31.66	-	69	23	46	-				
S3-B3-(0-1ft)-SW	Clay	CL-CH	17.16	13.95	23.00	-	32	12	20	2.60				
S4-(0-0.5ft)-LC-SW	Clat with some sand	CL	13.87	10.42	33.14	90.5	60	30	30	8.16	-	-	-	-
S4-(0-0.5ft)-HC-SW	Clay with some sand		17.69	13.23	33.14									
S5-(0-0.5ft)-LT-SW	Silt-Clay		21.85	18.15	20.40	54.4	-	-	-	0.69	-	-	-	-
S6-(0-0.5ft)-LC-SW	Sand w/Some Clay	SP	13.45	12.79	5.21	8.9	-	-	-	0.71				
S7-B1-(0-2ft)-TW	Clay	CH	17.39	13.73	26.65	-	68	24	44	3.78	90.1	78	32	46
S7-B1-(2-4ft)-SW	Clay with hard clay grain mixture	CH	16.52	13.42	23.04	-	-	-	-	7.14				
S8-B1-(0-2ft)-TW	Clay with 1.5" thick grass on top of sample	CH	17.71	13.38	32.34	-	-	-	-	-	97.3	85	36	49
S8-B1-(2-4ft)-L1-SW	Clay with 2 layers	CH	18.74	14.00	33.87	-	-	-	-	2.28				
S8-B1-(2-4ft)-L2-SW	Clay with 2 layers	CH	18.74	14.00	33.87	-	54	21	33	15.37				
S11-(0-0.5ft)-LC-TW	Sand	SP	12.30	12.23	1.02	0.1	-	-	-	0.32	-	-	-	-
S11-(0-0.5ft)-HC-TW	Sand	SP	13.26	13.12	1.02		-	-	-	0.35				
S12-B1-(0-2ft)-TW	Clay with decomposed wood	CH	14.77	10.19	44.94	-	67	27	40	16.91	92	67	21	46
S12-B1-(2-4ft)-SW	Clay	MH-CH	17.56	12.64	38.94	-	58	32	26	5.28				
S15-CanalSide-(0-0.5ft)-LC-SW	Sand w/Some Clay	SM	13.85	12.21	13.43	29.9	-	-	-	1.28	-	-	-	-
S15-CanalSide-(0-0.5ft)-HC-SW	Sand w/some clay		19.63	17.31	13.43		-	-	-					
S15-LeveeCrown-(0-0.5ft)-LT-SW	Sand w/Some Clay		13.29	11.94	11.29		-	-	-	2.16				
S15-LeveeCrown-(0.5-1ft)-LT-SW	Sand w/Some Clay		13.57	12.46	8.93		-	-	-	1.01				

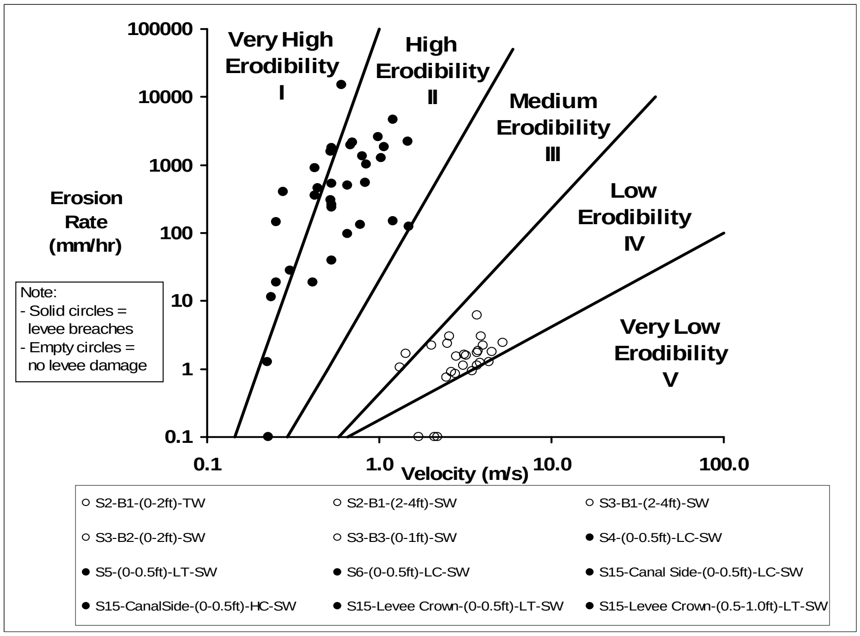


Figure 9.44: EFA test results and overtopping levee failure/no failure chart.

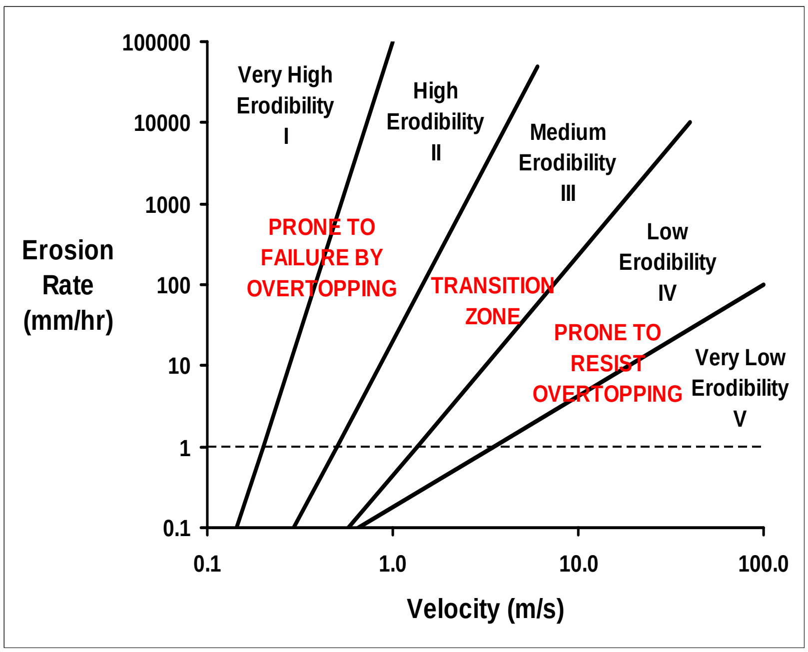


Figure 9.45: Guidelines for levee overtopping.

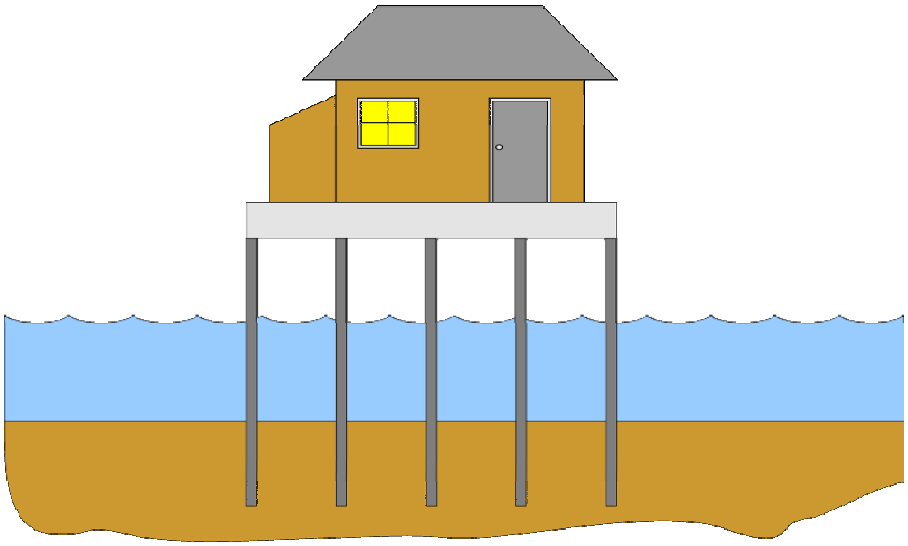


Figure 9.46: Elevated houses as a redundancy.

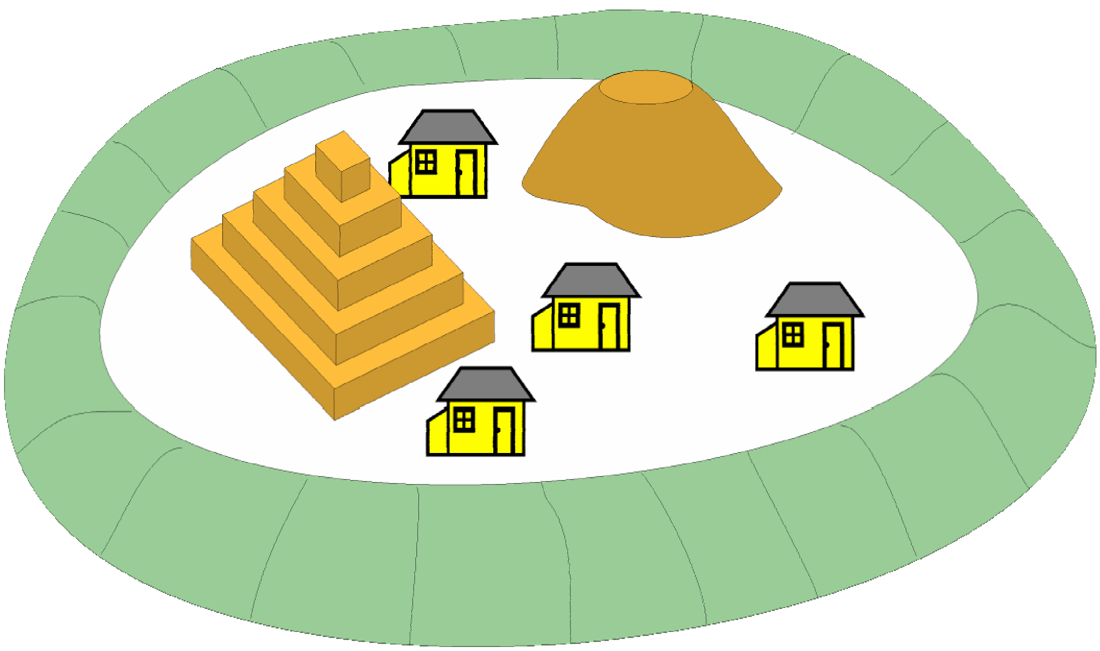


Figure 9.47: Escape structures as a redundancy.

CHAPTER TEN: EVALUATION OF EARTHEN LEVEES

10.1. Overview

The vast majority of flood protection assurance for the greater New Orleans area is strongly dependent upon the presence and ability of earthen levees to separate large water bodies, such as Lake Pontchartrain, Lake Borgne, the Mississippi River, and the Gulf of Mexico from inundating developed land areas and causing flooding of homes and businesses. Earthen levee flood protection systems not having redundancy can be viewed as series systems, where failure at one location, or failure of one component, can result in catastrophic failure of the entire flood protection system and result in tragic loss of life, damage to fundamental infrastructure (basic services such as water, sewage, and electricity), and substantial economic impact to the immediate and surrounding regions. These systems can be in place for a short duration (a few years) or for a very long duration (hundreds of years). In order to ensure the desired level of flood protection system performance, identification and mitigation of “weak links” in the system are crucial maintain long-term system integrity.

Few studies have analyzed actual long-term performance of earthen levees to confirm effective design parameters, assumed loading conditions, and actual performance after major flooding events. Additionally, evaluations of component transitions (i.e. earthen levee to concrete structure transitions), erodibility, overtopping, wave-scour, and effective inspection programs have not been well documented and are critical components to high reliability flood protection systems.

The primary focus of this chapter is on the performance of earthen levees from an erosion standpoint (performance of floodwalls and other physical structures are not included in this chapter). Due to access restrictions, the study area consists primarily of the earthen levees situated within the New Orleans East and St. Bernard Parish protected areas. These were also the regions that were most notably impacted by the storm surge associated with Hurricane Katrina.

The main goals associated with our evaluation of the earthen levees in the New Orelans area are to: (1) provide a summary of “lessons learned” based on the performance of the flood protection system during Hurricane Katrina and Rita, (2) identify “weak link” features not specifically addressed in standard design methods so that appropriate design modifications can be implemented to improve levee performance, (3) establish an index erodibility testing methodology by which to survey and assess existing earthen levees, and (4) validate effective design parameters based on the performance of the earthen levee flood protection system in response to Hurricanes Katrina and Rita.

10.2. Levee Failure Mechanisms

There are numerous failure mechanisms that result in the breaching of earthen levees and the flooding of protected areas. These failure mechanisms can occur as a single mode or several different types of failure modes can act in unison. Levees can fail as a result of damage to the levee itself, or if the foundation on which the levee is constructed fails. An overview of commonly-observed failure mechanisms is presented here:

10.2.1. Structural Causes

This category includes future mechanisms where the dominant parameter is the soil's strength. Such mechanisms include:

Structural Impacts – Structural impacts occur when physical objects collide with the levee. This can occur during storm events when boats or barges become loose from their moorings and are driven into the levee by wind forces, or simply from accidental boats impacts due to operator error.

Tree Damage – Trees that are planted on top of or adjacent to the levee structure can result in significant damage. Trees that are blown over in high wind conditions, not only create a large void that can destabilize the levee, but the root systems associated with the tree can result in preferred piping channels if the roots are pulled out of the levee (such as if a tree is blown over in a strong wind storm). To mitigate possible impacts of tree damage on levees, design and maintenance guidelines generally specify that trees be kept clear of the levee structure.

Slope Failures – If the underlying foundation materials that support the levee are weak, or become destabilized, a slope failure could develop and result in catastrophic failure of the levee. Slope failures can be minor or they can be significant enough to result in the catastrophic failure of the levee system. Engineered levees are required to be designed against slope failures.

Sliding – As water levels rise on the outboard side of the levee, the weight of the water induces a lateral force on the levee that results in a sideways "push." The weight of the levee and the friction between the bottom of the levee and the levee foundation materials must be sufficient enough to resist this lateral push. If there is insufficient resistance to sliding, the levee is pushed in, resulting in catastrophic damage. Engineered levees are required to be designed against sliding failures.

10.2.2. Causes due to Hydraulic Forces

This category includes failure mechanisms when the dominant parameters involve groundwater flow and pressure. Among these are:

Underseepage – As shown in Figure 10.1 (red lines), if the underlying foundation materials that support the levee are highly permeable, water can quickly travel through these porous materials as the water differential between the outboard and inboard sides of the levee increases. This underseepage (which is very similar to internal erosion and piping with the exception that the foundation materials are internally eroded, not the levee materials) can result in the catastrophic failure of the levee in that once the foundation materials have been eroded, the levee (which may be completely undamaged) has no underlying support and falls into the resulting void and essentially washes away. Engineered levees are required to be designed against underseepage failures.

Bottom Heave - This is a variant of underseepage, but involves the hydraulic pressure, rather than internal erosion. A wave of water pressure caused by, say, a storm surge can travel through a permeable zone in a levee's foundation. If the water pressure exceeds the total overburden pressure at, say, the landside toe of the levee, the (clay) overburden can be displaced by heave, leading to complete levee failure.

Internal Erosion and Piping – As shown in Figure 10.1 (blue lines), internal erosion and piping occurs when there is a difference in water elevations (generating a high pressure gradient) between the outboard and inboard sides of the levee. Materials that have high permeabilities (such as sand and gravel) allow for water to rapidly flow from high pressure areas to low pressure areas. As the water flows through the levee, smaller/finer soil particles are "washed" out of the levee resulting in the internal erosion of the levee. Enough internal erosion of the levee can lead to the collapse and subsequent "wash-out" of the levee. For levees constructed of layers with significantly different permeabilities, the layer with the highest permeability becomes the main "conduit" by which the water flows through the levee. This concentrated flow can lead to higher water velocities through the levee and more rapid degradation. The major design standards specifically address internal erosion and piping and levees are required to be engineered against this failure mechanism. Utilization of low permeability materials, such as clay, is the primary mechanism by which this failure mode is mitigated. Other mitigation strategies such as internal drains or filters are also commonly used. Effectively mitigating internal erosion and piping can be hampered by the presence of burrowing animals that carve intricate tunnel networks in the earthen levees. Effective detection and corresponding correction of these animal-induced internal erosion channels is very challenging and many levee failures are a result of this failure mechanism.

Liquefaction – If the levee is founded on relatively loose materials (such as sands). These loose materials tend to be sensitive to vibrations and if they are over-excited (by cyclical perturbations such as earthquakes or heavy wave pounding), they will self-compact themselves and densify. During the self-compaction process, the soils temporarily become "fluidized" as the water between the soil particles rises to the surface, allowing the soil particles to densify. During the "fluidized" state, the foundation for the levee becomes unstabilized and can result in catastrophic failure of the levee foundation. In seismic areas, levees are generally required to be designed against liquefaction failures, but the impact of wave perturbations on loose foundation materials is not well established.

10.2.3. Causes Involving Surface Degradation

These include the various forms of surface erosion which can occur due to surface water flowing over or against the surface of the levee.

Overtopping – As shown in Figure 10.2, overtopping occurs when the water level on the outboard side of the levee exceeds the crest elevation of the levee. The inboard side of the levee acts as a spillway for the overtopping water and damage is inflicted on the levee as a result of water scour. Levees are not generally designed for overtopping and as a result, if overtopping does occur, they are highly susceptible for catastrophic failure unless highly erosion-resistant materials are used to construct the levee.

Overtopping and Jetting – This is more likely to occur on levees with floodwalls. As shown in Figure10.3, jetting occurs when the water level on the outboard side of the levee exceeds the top of wall elevation for structural walls that are founded within the earthen levee. Unlike overtopping of a conventional earthen levee, the floodwall acts as a weir and water impacts the levee in a concentrated stream that is much more energy intensive than conventional overtopping. For typical New Orleans floodwalls, the water impact velocities are on the order of 7 to 8 m/s. Levees are not generally designed for overtopping and jetting and as a result, if overtopping and jetting does occur, a deep scour trench can develop against the land-side face of the floodwall. This reduces the earth pressure supporting the wall, making the wall highly susceptible for catastrophic failure unless "splash-pads" or other energy dissipating devices are installed and highly erosion-resistant materials are used to construct the levee.

Surface Erosion – As shown in Figure 10.4, surface erosion generally occurs on the outboard side of the levee and is the result of water flowing past the levee face. If the imposed shear stress from the water abrading against the soil levee face is high enough, soil scour occurs and the integrity of the overall levee is significantly reduced. Levees that are exposed to chronic water flow, such as river levees, are generally designed and constructed with armoring or erosion prevention devices to minimize scour-induced surface erosion. In general, well-compacted levees constructed of high-plasticity clays are much more resistant to surface erosion than uncompacted silty sands. Surface protection such as rip-rap, concrete pads, soil-cement reinforcement, and select vegetation coverings are typical methods used to protect levee faces from surface erosion.

Wave Impacts – As shown in Figure 10.5, wave impacts can cause significant erosion to levee faces. Wave-induced erosion consists of run-up (sloshing up and down of water as a result of staggered wave arrival) and "mini-jetting" when the crest of the waves breaks on the levee face. Levees that are anticipated to be impacted by waves are generally designed with armoring to prevent damage from wave impacts.

The fore-mentioned failure mechanisms are not intended to be an exhaustive list, but rather to highlight common failure modes of the earthen levees in New Orleans.

10.3. Design Standards

Design standards are not just the primary means by which earthen levees are designed, but they are also the main metric by which proposed levee design and construction projects are critiqued by reviewers. Incomplete, inaccurate, or inappropriate design standards can lead to actual performance which is less than desired. As part of this study, current earthen levee design standards from the United States Army Corps of Engineers and the United States Federal Emergency Management Administration were reviewed. A summary of the design guidelines for the USACE and FEMA are presented in Sections 10.4 and 10.5, respectively.

10.3.1. United States Army Corps of Engineer Design Standards

The primary manual and summary of design standards for earthen levees for the United States Army Corps of Engineers (USACE) is EM 1110-2-1913, "Engineering and Design – Design and Construction of Levees." This design manual covers the topics of: field investigations, laboratory testing, borrow areas, seepage control, slope design and settlement, levee construction, and special considerations (such as pipelines and other utility crossings, access roads and ramps, levee enlargements, junctions with concrete closure structures, and other special features such as landside ditch construction and levee vegetation management.

10.3.1.1. Primary Design Procedure

The design procedure and requirements for levee design are established by EM 1110-2-1913. The outlined design procedure provides guidance from the initial preliminary evaluation through final design. These requirements are summarized in Table 10.1, below.

Table 10.1 Summary of Major and Minimum Levee Design Requirements

Step	Procedure
1	Conduct geologic study based on a thorough review of available data including analysis of aerial photographs. Initiate preliminary subsurface explorations.
2	Analyze preliminary exploration data and from this analysis establish preliminary soil profiles, borrow locations, and embankment sections.
3	Initiate final exploration to provide: a. Additional information on soil profiles b. Undisturbed strengths on foundation materials c. More detailed information on borrow areas and other required excavations
4	Using the information obtained in Step 3: a. Determine both embankment and foundation soil parameters and refine preliminary sections where needed, noting all possible problem areas. b. Compute rough quantities of suitable material and refine borrow area locations.
5	Divide the entire levee into reaches of similar foundation conditions, embankment height, and fill material and assign a typical trial section to each reach.
6	Analyze each trial section as needed for: a. Underseepage and through seepage. b. Slope stability. c. Settlement. d. Trafficability of the levee surface.
7	Design special treatment to preclude any problems as determined from Step 6. Determine surfacing requirements for the levee based on its expected future use.
8	Based on the results of Step 7, establish final sections for each reach.
9	Compute final fill quantities needed; determine final borrow area locations.
10	Design embankment slope protection.

Further engineering analysis guidance for the design of levees is provided in the following manuals:

- Slope Stability Analyses EM 1110-2-1902
- Settlement Analyses EM 1110-2-1904
- Levee/Structure Transitions EM 1110-2-2502

The punch list of design steps identified in Table 10.1 provides an overview of design parameters for levee design. EM 1110-2-1913 prescribes required Factors of Safety for slope stability of newly designed levees, existing levees, and other embankments and dikes. These Factors of Safety vary from 1.0 for short-term loading conditions to 1.4 for long-term (steady state conditions). Specific design criteria are not provided for settlement and erosion-susceptibility.

In addition to these design parameters, material specifications and construction procedures, critical elements in the actual lifetime performance of levees, have also been defined by the USACE. These components are described in more detail in the following sections.

10.3.1.2. Material Selection

Acceptable soils for the construction of levees (borrow materials) are defined by EM 1110-2-1913 as "any soil is suitable for constructing levees, except very wet, fine-grained soils or highly organic soils." Choosing a material type is generally a function of accessibility and proximity to the project area. The design guidelines emphasize that studies should be performed to ascertain the in-situ moisture contents of the borrow materials. It is noted that "the cost of drying borrow material to suitable water contents can be very high, in many cases exceeding the cost of longer haul distances to obtain material that can be placed without drying." Thus, any materials may be used in the construction of levees so long as they are not overly wet fine-grained soils or highly organic soils.

10.3.1.3. Required Levee Soil Compaction

Three types of compacted levees are presented in the EM 1110-2-1913 design criteria. These are compacted, semicompacted, and uncompacted levees. The USACE notes that traditionally, areas of high values and/or high land use, steep-sloped embankments with controlled compaction during construction are utilized in good foundation conditions. Areas of low values, poor foundations, or high rainfall during the construction season generally warrant specification of semicompacted or uncompacted levees.

According to the USACE design guidelines, compacted levees are required to be constructed in areas where strong embankments of low compressibility are needed adjacent to concrete structures or forming parts of highway systems. Compacted levees require specification of borrow material water content range (with respect to standard effort optimum water content), loose lift thickness of 6 to 9 inches, compaction equipment type (sheepsfoot or rubber-tired rollers), number of passes to attain a given percent compaction or standard maximum density, and the minimum required density (relative compaction).

Semicompacted levees are recommended by the USACE to be constructed in areas where there are no space limitations and steep-sloped embankments are not required, onsite foundation conditions are relatively weak and unable to support steep-sloped embankments, underseepage conditions require a wide base, and/or water content of borrow materials or rainfall during construction does not allow for the proper compaction of levee fill material. Semicompacted levee require the specification of lift thickness (approximately 12 inches) and are compacted by the movement of hauling and spreading equipment or sheepsfoot or rubber-tired roller compaction equipment.

The USACE recommends uncompacted levees only to be used for temporary/emergency use. These levees are constructed by fill cast or dumping in place thick layers of borrow materials with little or no spreading or compaction. Hydraulic fill by dredge, often from channel excavations, ~~is~~ a common source for uncompacted levees. Hydraulic fills are known to be highly susceptible to erosion upon overtopping and are not recommended to be used in the normal construction of levees, except in locations where the levees are protecting agricultural areas whose failure would not endanger human life or for zoned embankments that include impervious seepage barriers.

10.3.1.4. Embankment Geometry

Embankment geometry is controlled primarily by material selection and compaction efforts during construction, but the foundation soils may govern. Maximum side slopes for levees are 1V on 2H. These levees are required to be constructed from high-grade borrow materials that are compacted near optimum moisture content and with appropriate compaction equipment. Levees with non-ideal borrow materials, such as sand levees, are required to have much shallower side slopes (on the order of 1V to 5H) to prevent damage from seepage and wave action.

Final top of levee elevations must also account for future settlements, as determined by EM 1110-2-1904. In the past, the USACE specified a certain freeboard distance between the final top of levee elevation and the design storm water level to account for hydraulic, geotechnical, construction, operation, and maintenance uncertainties. The updated design procedures set forth in EM 1110-2-1913 are risk-based, and are assumed to directly account for hydraulic uncertainties and establish a nominal level of protection.

10.3.1.5. Identified Failure Modes

The principal causes of levee failures, as identified by EM 1110-2-1913, consist of the following mechanisms (but see also Section 10.2 of this chapter):

- Overtopping;
- Surface erosion;
- Internal erosion (piping); and
- Slides within the levee embankment or the foundation soils.

Considerable discussion is presented in the design manual to mitigate effects of internal erosion/piping (see EM 1110-2-1913 Chapter 5 – *Seepage Control*). Guidance on overtopping, surface erosion, and slides within the levee embankment or the foundation soils is not well-developed in this design manual. However, guidance is provided for the augmentation of soil-cement protection applied to exposed slopes, susceptible to erosion.

10.3.1.6. Erosion Susceptibility

Although not directly addressed or identified in EM 1110-2-1913, general guidelines for erosion susceptibility of fine-grained cohesive soils are presented in EM 1110-2-1100 [Coastal Engineering Manual Part III], EM 1110-2-1100 [Coastal Engineering Manual Part VI], and

"Channel Rehabilitation: Processes, Design, and Implementation," (1999). These manuals provide insights on erosion and critical values of average overtopping discharges.

For coastal grass covered sea-dikes and protected embankment seawalls, EM 1110-2-1100 indicates that no damage occurs for overtopping discharges less than about 0.15 ft^3/s per foot. Significant damage is expected for overtopping flows greater than 0.35 ft^3/s per foot. The overtopping discharge flows were based on wave runup exceeding the crest of the embankment or floodwall crest and include impact forces associated with the wave action impacting the embankment. These values were based on field studies conducted both in the United States and in the Netherlands. Discharge flow values are not based on sustained overtopping discharge as a result of the mean storm water level rising above the crest of the embankment or floodwall.

Maximum permissible velocities for flow within river and stream channels are summarized in USACE (1999) and are based on field research from 1915 to about 1926. Permissible velocities (for a canal type section with an average depth of 3 feet) are presented in Table 10.2.

Table 10.2 Permissible canal velocities with average flow depth of 3 feet

Material	Clear water, no detrius (ft/s)	Water transporting colloidal silts (ft/s)	Equivalent Shear Stress[1] (lb/ft^2)
Fine sand (noncolloidal)	1.5	2.5	2.4 - 6.3
Sandy loam (noncolloidal)	1.75	2.5	3.1 - 6.3
Silt loam (noncolloidal)	2	3	4.0 - 9.0
Alluvial silt (noncolloidal)	2	3.5	4.0 - 12.3
Ordinary firm loam	2.5	3.5	6.3 - 12.3
Fine gravel	2.5	5	6.3 - 25.0
Stiff clay	3.75	5	14.1 - 25.0
Alluvial silt (colloidal)	3.75	5	14.1 - 25.0
Coarse gravel (noncolloidal)	4	6	16.0 - 36.0
Shales and hardpans	6	6	36.0

[1]Assuming a roughness constant equal to 1 and fluid consisting of seawater.

Equivalent shear stress was calculated using the following equation (Munson et al, 1990):

$$\tau_w = K\rho V^2/2 \qquad \text{Equation 9.1}$$

In this correlation, the shear stress (τ_w) imposed on the surface exposed to the water flow is a function of the surface roughness (K), the density of the fluid (ρ), and the velocity of the fluid (V). Based on this table, permissible water velocities vary between 1.5 ft/s for highly erosion susceptible materials to as much as 6 ft/s for highly erosion resistant materials. Correspondingly, allowable shear stresses vary from a low of 2.4 lb/ft^2 for highly erosion susceptible materials to as much as 36 lb/ft^2 for highly erosion resistant materials. Again, erosion plus jetting can lead to impact velocities 3 to 4 times the maxima above.

10.3.2. United States Federal Emergency Management Agency Design Standards

Design criteria for levee systems required by the United States Federal Emergency Management Agency (FEMA) are presented in the Title 44, Volume 1, Part 65 of the Code of Federal Regulations. These criteria establish the minimum standards to which levees must adhere in order to satisfy the 100-year level (referred to as the base flood) of protection mandated by FEMA. The main design criteria for FEMA approved levees are: freeboard, closures/transitions, embankment protection, embankment and foundation stability, settlement, interior drainage, and other specialty design criteria deemed appropriate by FEMA for unique situations.

10.3.2.1. Freeboard

Levees constructed adjacent to rivers are mandated to have a minimum freeboard of three feet above the water surface level of the base flood. In areas where the levee is constructed adjacent to structures, such as bridges, an additional one foot of freeboard is required extending 100 feet to either side of the structure. Levees constructed on the coast must have a minimum freeboard of one foot above the height of the calculated one percent wave or the maximum wave runup (whichever is greater) associated with the 100 year stillwater surge elevation. This category best fits the New Orleans Hurricane Protection System. Exceptions may be granted, based on site-specific engineering studies, but a freeboard of less than two feet is not deemed acceptable under any circumstance.

10.3.2.2. Closures

Closures refer to openings within the flood protection system. These closures can be for through traffic (such as railroad traffic which is frequently grade controlled and can not easily be diverted over levees), for pipeline crossings, or for maintenance purposes. FEMA requires all closures to be structural parts of the flood protection during operation and be designed in accordance with sound engineering practice.

10.3.2.3. Embankment Protection

Engineering analyses are required to be performed to demonstrate no appreciable erosion of the levee embankment during the base flood due to currents or waves, and that any anticipated erosion may not result in failure of the levee embankment or foundation either directly or indirectly through seepage or subsequent instability. Specific factors to be analyzed to determine the adequacy of embankment protection are: expected flow velocities (especially in constricted areas), expected wind and wave action, ice loading, impact of debris, slope protection techniques, duration of flooding at various stage and velocities, embankment and foundation materials, levee alignment, bends, and transitions, and levee side slopes. The FEMA guidelines do not, however, provide guidance on acceptable performance criteria/standards of the identified embankment protection factors to be evaluated.

10.3.2.4. Embankment and Foundation Stability

Stability analyses for levee embankments are required to be submitted that demonstrate the adequacy of both short-term and long-term slope stability of flood protection levees.

Stability analyses are required to include the expected seepage during the storm loading conditions and demonstrate that seepage into or through the embankment will not result in unacceptable stability performance. FEMA provides for the use of the USACE Case IV (as defined by EM 1110-2-1913, "Design and Construction of Levees") as an additionally acceptable engineering analysis method. The required factors for evaluation include: depth of flooding, duration of flooding, embankment geometry and length of seepage path at critical locations, embankment and foundation materials, embankment compaction, penetrations, other design factors affecting seepage (such as drainage layers), and other design factors affecting embankment and foundation stability (such as interior berms). These requirements do not, however, specify the nature of embankment stability to be evaluated, such as sliding (horizontal displacement) resistance. The FEMA guidelines do not, however, provide guidance on acceptable performance criteria/standards of the identified stability to be evaluated.

10.3.2.5. Settlement

Once levees have been constructed to the specified crest elevation, their ability to provide the desired degree of flood protection against the base flood is generally controlled by settlements of the foundation materials beneath the levee. In order to demonstrate the adequacy of the crest elevation over the intended service life, FEMA requires that engineering analyses be submitted that assess the potential and magnitude of future losses of freeboard as a result of levee settlement and demonstrate that freeboard will be maintained within the minimum freeboard requirements for the duration of the levee service period. Detailed analysis procedures, such as those specified in the USACE EM 1110-2-1904, "Soil Mechanics Design – Settlement Analyses," are expected. The required factors for evaluation include: embankment loads, compressibility of embankment soils, compressibility of foundation soils, age of the levee system, and construction compaction methods. The FEMA guidelines do not provide guidance on acceptable performance criteria/standards of the identified stability factors to be evaluated.

10.3.2.6. Interior Drainage

FEMA requires that the protected side of the flood protection system be capable of draining onsite water. An analysis is required to be submitted that identifies the source(s) of potential flooding, the extent of the flooded area, and, if the average depth of flooding is greater than one-foot, the water-surface elevation(s) of the base flood. The analysis is required to be based on the joint probability of interior and exterior flooding and the capacity of facilities (such as drainage lines and pumps) for draining interior floodwater.

10.3.2.7. Other Design Criteria

In areas where levee systems have relatively high vulnerabilities, or other unique situations, FEMA may require other design criteria and analyses be submitted for review and approval. The rationale for the requirement of additional analyses will be provided by FEMA. The review and subsequent evaluation standard of the analyses for the specified design criteria were to be based on "sound engineering practice."

10.3.2.8. Other FEMA Requirements

In order for the levee flood protection system to be recognized by FEMA as providing protection for the base flood, additional requirements, beyond the established design procedure and criteria, are required to be in place. Maintenance and operation plans are required to be submitted that detail how the flood protection system will be maintained and operated during its service period. In addition, FEMA has certification requirements which require that a registered professional engineer certify the levee design and certified as-built plans of the completed levee be submitted. Federal agencies with responsibility for levee design may also certify that the levee has been adequately designed and constructed to provide the desired degree of protection against the base flood.

10.4. Storm Surge and Wave Action During Hurricane Katrina

During Hurricane Katrina, the earthen levees were subjected to storm surges and wind generated wave action. Accurately determining the magnitude of these forces is reliant on numerical simulations and modeling with calibration from field data such as in-place instrumentation that recorded data during Hurricane Katrina as well as post-hurricane field assessments, such as high-water marks. The most reliable storm surge and wave action information collected and recorded during Hurricane Katrina was captured by instrumentation installed at select locations within the greater New Orleans area. However, the number of instrumentation locations is extremely limited, and as a result, little reliable storm surge and wave action information is available. Many of the instruments were damaged during the storm and only partial records were collected.

Instruments that recorded useful data used to establish storm surge and wave action information were located at the following locations (IPET 2006):

- Lake Pontchartrain near 17th Street Canal (*hydrograph & wave characteristics*)
- Pump station #6 on the 17th Street Canal (*hydrograph*)
- Lake Pontchartrain at the Lakefront Airport (*camera-based hydrograph)*
- Inner Harbor Navigation Channel at I-10 (*hydrograph*)
- Inner Harbor Navigation Channel at the Lock (*hydrograph*)
- Gulf Intracoastal Waterway at I-510 (*hydrograph*)

A detailed review and reconstruction of the storm surge and wave action during Hurricane Katrina based on the data from the installed instruments, measured high water marks and interviews was completed by IPET (2006). The storm surge and wave action information presented by IPET was used in our performance evaluation of the levees. A discussion of the maximum storm surges is presented in the following section along with an overview of our field reconnaissance and levee condition survey and mapping.

10.5. Field Reconnaissance and Levee Condition Mapping

Field reconnaissance was a vital part to assessing and understanding the performance of the earthen levee flood protection systems. Multiple field visits were performed by the team to visually observe and evaluate the performance of the levee systems. The initial levee assessment occurred during the first two weeks of October 2005. The purposes of this visit were to perform a cursory survey of major damage areas, and to note and record time sensitive storm related data (such as high water marks, scour zones, etc.) before full-scale repair operations commenced and destroyed or obscured storm-related levee system performance information. The results of our initial observations are presented in Seed et al., (2005).

Subsequent to the initial field reconnaissance, a series of field survey explorations have occurred to complete the extents of the visual survey and to collect physical samples for testing to ascertain susceptibility to erosion. The earthen levee flood protection components provided a unique learning opportunity in that a majority of the levee systems were overtopped, impacted by moving objects and debris (such as steel barges and fishing boats), and attacked by wind-generated waves. Some sections performed extremely well, while other sections performed poorly. Figure 10.6 shows the extents of the visual reconnaissance (the dashed black line) that was completed as part of our study. Due to access, schedule, and funding limitations, the Independent Levee Investigation Team was not able to complete a full and comprehensive survey of the entire greater New Orleans area. Locations of notable performance have been identified in the numbered boxes on Figure 10.6 and are discussed in further detail below (refer to Figure 2.6 in Chapter 2 for a summary of design elevations for the flood protection system). Please note that these locations are intended only to represent typical findings and are not intended to summarize the complete performance of the overall flood protection system. In addition, the specified design flood protection system component crest elevations may not be the actual crest elevations due to factors such as incomplete staged construction, consolidation, subsidence, etc.

It is important to emphasize that accurately determining elevations in the greater New Orleans area is extremely complicated. Factors that exacerbate the problem include regional subsidence, localized consolidation settlement, and the temporal variation in completion of individual projects. A tremendous effort has been undertaken by the IPET team to "equalize" all the locations that are part of the New Orleans Flood Defense System and merge the component-specific elevations to one common project-specific elevation datum.

Following is a summary and discussion of levee performance at select locations along the perimeter of the New Orleans Flood Defense System.

10.5.1. Location 1 – Lakefront Airport

Location 1 is situated near the intersection of Downman Road and Hayne Boulevard, south of the Lakefront Airport. At this location, an earthen levee connects to a railroad bridge and vehicular underpass and a concrete flood gate structure and the levee is situated parallel to an active railroad line. High water marks, as reported by IPET (2006), at this location reached approximately Elevation +12 feet (MSL). The design elevation of the levee system at this location was Elevation +13.5 feet (NGVD29). Exact datum conversions in this area are not clearly established and are still under review by the IPET team, but the design elevation has been identified as Elevation +11.8 feet (MSL), resulting in a minor degree of overtopping at this location.

Storm-surge induced overtopping traveled through the granular gravel ballast for the railroad line and eroded the railroad line embankment, which served as a transition levee between the concrete floodwall (design Elevation + 13.5 feet MSL = +11.8 feet NAVD 88-2004.65) and the earthen levee (design Elevation +14.5 feet MSL = +12.8 feet NAVD88-2004.65) shown in Figure 10.7. Figure 10.8 shows the location where overtopping occurred resulting in significant scour around the floodwall and Figure 10.9 provides a view across the railroad line where the railroad line embankment was eroded allowing for the terminus of the earthen levee to be scoured. Note that at the time of our visit, the railroad embankment had been repaired by railroad personnel.

Performance factors of the levee system that impacted the performance of the flood protection components included the following: unprotected high-permeability ballast which allowed high water levels to seep through the gravel ballast and erode the supporting embankment, transition details between the flood protection components at Elevation + 13.5 feet MSL (+11.8 feet NAVD 88-2004.65), allowed for low points to be exploited, and the embankment and levee materials were not erosion resistant and resulted in scour as a result of overtopping. Without redesigning this transition area, future performance at this location (under similar or more severe storm surge conditions) is anticipated to be poor and it will likely breach again.

10.5.2. Location 2 – Jahncke Pump Station Outfall

Location 2 is situated near the intersection of Hayne Boulevard and Jahncke Road, near Lake Pontchartrain. At this location a concrete outfall structure protrudes through the flood protection levee. High water marks, as reported by IPET (2006), at this location reached a maximum Elevation of +12 feet (NAVD88-2004.65). The design elevation of the levee system at this location was Elevation +14.5 feet (NGVD29). Exact datum conversions in this area are not clearly established and are still under review by the IPET team, but the design elevation has been identified as Elevation +12.8 feet (NAVD88-2004.65), resulting in a minor degree of overtopping at this location. Our field reconnaissance verified that minor overtopping occurred at this location, as can be seen in Figures 10.10 and 10.11.

Figure 10.10 provides an eastward looking view. Small patches can be seen on the levee crest where minor erosion occurred. Figure 10.11 presents a view of scour-related erosion behind the concrete outfall structure transition.

Performance factors of the levee system that impacted the performance of the flood protection components included the following: placement of rip rap boulders along the Lake Pontchartrain margin which aided in damping wind-waves approaching the levee, presence of the active railroad line which also aided in damping wind-waves, and utilization of moderately erosion-resistant embankment materials. Future performance at this location under similar conditions is anticipated to be adequate, however more severe storm surge conditions will likely result in overtopping-induced erosion, which may cause significant breaching of the levee.

10.5.3. Location 3 – Eastern Perimeter of New Orleans East

Location 3 is situated approximately 0.6 miles east of Highway 11 and approximately 1 mile north of Chef Menteur Highway (Hwy 90). In this vicinity, the flood protection system consists primarily of earthen levees that are protected by both low-lying swamp lands and trees at the flood side and protected side of the levee. High water marks, as determined through numerical modeling by IPET (2006), at this location reached a maximum Elevation of approximately +16 feet (NAVD88-2004.65). The design elevation of the levee system at this location was Elevation +14.5 feet (MSL). Exact datum conversions in this area are not clearly established and are still under review by the IPET team, but the design elevation has been identified as Elevation +12.4 feet (NAVD88-2004.65), resulting in moderate to major overtopping at this location.

Figure 10.12 provides a southward looking view. The overall condition of the levees in this area is excellent and no observable damage or erosion was encountered. An outfall access structure, near Hwy 90, was in the process of being outfitted with a rock-gabion transition zone to minimize scour around the concrete access structure, as seen in Figure 10.13.

Performance factors of the levee system that impacted the performance of the flood protection components included the following: presence of low-lying swamp areas which aided in damping wind-waves approaching the levee, presence trees and shrubs which also aided in damping wind-waves, and utilization of moderately to highly erosion-resistant embankment materials. Future performance at this location under similar or more severe conditions is anticipated to be good. Significant overtopping should be expected for larger storm surge events.

10.5.4. Location 4 – Southeast Corner of New Orleans East

Location 4 is situated at the southeast corner of the New Orleans East polder. In this vicinity, the flood protection system consists primarily of earthen levees adjacent to the ICWW, Lake Borgne. A small stretch of low-lying swamp protects the levees in this area from the ICWW. High water marks, as determined by IPET (2006) using numerical simulations, at this location reached a maximum Elevation of approximately +16 feet (NAVD88-2004.65). The design elevation of the levee system at this location was Elevation +19 feet (MSL). Exact datum conversions in this area are not clearly established and are still under review by the IPET team. Our field reconnaissance indicated that significant breaching occurred at this location, most likely as a result of overtopping or wave-induced surface erosion.

Figure 10.14 shows zones or “slots” of the original levee that was breached and scoured as a result of storm-surge induced erosion during the hurricane. Figure 10.15 shows completed levee rehabilitation work at the southeast corner. At the time of our visit, construction activities had shifted approximately 1 mile west and consisted of belly-dump trucks placing borrow material which was being spread by bulldozers and track-walked. Dump trucks were also directed to travel over the newly placed levee, following the semicompaction technique defined in EM 1110-2-1913.

Performance factors of the levee system that impacted the performance of the flood protection components included the following: lack of slope protection to minimize surface erosion during the storm facilitated scour of the earthen levee and subsequent breaching, location close to the relatively deeper waters of Lake Borgne allowing for relatively larger wind-waves to form and scour the flood side of the levee, location relative to the approach direction of the hurricane resulting in a larger magnitude surge than the Lake Pontrchartrain side of the flood defense system, and utilization of moderately to highly erosive embankment materials. Future performance at this location under similar conditions is anticipated to be adequate to poor. Significant overtopping and erosion should be expected for larger storm surge events.

10.5.5. Location 5 – Entergy Michoud Generating Plant

Location 5 is situated along the ICWW/MRGO intersection and immediately beneath the Hwy 47/Paris Road bridge. In this vicinity, the flood protection system consists primarily of earthen levees. High water marks, as reported by IPET (2006), at this location reached a maximum Elevation of +16.3 feet (NAVD88-2004.65). The design elevation of the levee system at this location was Elevation +15 feet (MSL). Exact datum conversions in this area are not clearly established and are still under review by the IPET team, but the design elevation has been identified as Elevation +13.2 feet (NAVD88-2004.65), resulting in moderate to major overtopping at this location.. Our field reconnaissance verified that moderate overtopping occurred at this location.

Figure 10.16 shows actual overtopping of the levee as captured by a security camera at the Entergy Michoud Generating Plant during Hurricane Katrina. Figure 10.17 presents a post-Hurricane Katrina view of the levee shown in Figure 10.16. Only minor damage occurred on the protected side, with a majority of the damage a result of wave reflection from the adjacent bridge abutment. The overall condition of the levees in this area was good and no major damage or encountered.

Performance factors of the levee system that impacted the performance of the flood protection components included the following: utilization of moderately to highly erosion-resistant embankment materials and the small fetch of the ICWW/MRGO canal at this location which limited the height of the wind-generated waves. Future performance at this location under similar or more severe conditions is anticipated to be good. Significant overtopping should be expected for larger storm surge events.

10.5.6. Location 6 – ICWW/MRGO Southern Levee

Location 6 is situated along the ICWW/MRGO interchange beneath the Hwy 47/Paris Road bridge and immediately south of Location 5. In this vicinity, the flood protection system consists primarily of earthen levees with a concrete floodwall beneath the bridge that connects the eastern and western levee segments. High water marks, as reported by IPET (2006), at this location reached a maximum Elevation of +16.3 feet (NAVD88-2004.65). The design elevation of the levee system at this location was Elevation +14 feet (MSL). Exact datum conversions in this area are not clearly established and are still under review by the IPET team, but the design elevation has been identified as Elevation +13.2 feet (NAVD88-2004.65), resulting in moderate to major overtopping at this location. Our field reconnaissance verified that moderate overtopping occurred at this location.

The overall condition of the levees in this area was good and no major damage was encountered. The concrete floodwall constructed beneath the Hwy 47/Paris Road bridge, due to its top of wall elevation being lower than that of the neighboring earthen levees, acted as a weir during the high water period and “sucked” in nearby steel barges, as shown in Figure 10.18. Despite the collision impact of the barges with the concrete wall, the system performed well. Some scour-related damage was observed at the transition between the concrete flood wall and the earthen levee. Figure 10.19 presents an eastward looking view of the levee, just west of the washed up barges. East of the Hwy 47/Paris Road bridge, Figure 10.20 shows a gas processing barge that collided with the earthen levee. The impact did not result in any significant damage to the levee.

Performance factors of the levee system that impacted the performance of the flood protection components included utilization of moderately to highly erosion-resistant embankment materials; these erosion-resistant materials were also capable of absorbing impact loads from the barges allowing the barges to rest on the levee without breaching it. The small fetch of the ICWW /MRGO canal at this location may also have limited the height of the wind-generated waves, thereby minimizing wave-induced erosion of the levee materials. Future performance at this location under similar or more severe conditions is anticipated to be good. Significant overtopping should be expected for larger storm surge events. Scour-related erosion should be anticipated at the transition between the concrete floodwall and earthen embankment if no protective measures are installed.

10.5.7. Location 7 – Bayou Bienvenue Control Structure

Location 7 is situated along the at the north end of the MRGO. In this vicinity, the flood protection system consists primarily of earthen levees that connect, via a concrete and steel flood access structure to a concrete control structure across Bayou Bienvenue. High water marks, as reported by IPET (2006), at this location reached a maximum Elevation of +18.4 feet (NAVD88-2004.65). The design elevation of the levee system at this location was Elevation +17.5 feet (MSL). Exact datum conversions in this area are not clearly established and are still under review by the IPET team, but the design elevation has been identified as Elevation +13.2 feet (NAVD88-2004.65), resulting in moderate to major overtopping at this location. It is also not known if the levee had reached final design elevation. Our field reconnaissance verified that moderate to major overtopping occurred.

Figure 10.21 shows an aerial photograph of the Bayou Bienvenue control structure. The floodwall to the north of the control structure performed very well, withstanding an impact load from a steel barge which became lodged atop the concrete flood wingwall for the control structure. The southern side of the control structure did not perform well, with significant erosion and scour as a result of the overtopping. The southern side of the control structure was built using excavated spoils from within the MRGO channel that are more erosion-susceptible than the clays on the northern side of the control structure. It is important to note that both sides of this control structure were subjected to similar loading conditions and overtopping occurred on both sides and as a result, this site offers a unique. example of the importance of erosion-resistant soil materials. In addition, the southern portion of the control structure abuts the abandoned Bayou Bienvenue channel, as shown in Figure 10.21. It is not conclusive whether the backfill materials into the abandoned channel impacted the performance of the control structure, but further investigation should be employed to determine the performance factors for this side of the control structure.

Figure 10.22 shows a close up view of the flood control gate structure that acted as a weir as the water overtopped the flood protection system. Significant scour and erosion was observed around the structure. Upon a follow up visit in March of 2006, splashpads had been installed behind the flood gate structure. In addition, the steel barge had been removed from the concrete control structure and a vast sea of rip-rap protection installed around the control structure. Figure 10.23 presents a picture of the installed splash pads and Figure 10.24 presents a view of the control structure with the barge removed and placement of rip-rap. Figure 10.25 presents a schematic of the mapped scour around this concrete structure observed in October of 2005. Around the ends of the concrete wall, about 10 feet of soil have been eroded.

Factors of the levee system that impacted the performance of the flood protection components included the following: utilization of moderately to highly erosion-resistant embankment materials on the northern end of the control structure, utilization of moderately to highly erosion-susceptible embankment materials on the southern end of the control structure, and possible effects of the old Bayou Bienvenue channel abandonment backfill materials on the southern portion of the control structure. Future performance at this location under similar or more severe conditions is anticipated to be good for the northern half of the control structure and poor for the southern half of the control structure. Significant overtopping should be expected for larger storm surge events.

10.5.8. Location 8 – Mississippi River Gulf Outlet

Location 8 is situated along the western edge of the MRGO, south of the Bayou Bienvenue Control structure and north of the Bayou Dupre Control structure. In this vicinity, the flood protection system consists primarily of earthen levees constructed from excavated materials from the MRGO channel. High water marks, as reported by IPET (2006), at this location reached a maximum Elevation of approximately +18 feet (NAVD88-2004.65). The design elevation of the levee system at this location was Elevation +17.5 feet (MSL), however, reports indicated that these levees were not fully completed and had crest elevations that were 3 to 4 feet lower than the specified design elevation. In addition, exact datum conversions in this area are not clearly established and are still under review by the IPET team, but the design water level has been identified as Elevation +12.7 feet (NAVD88-2004.65), however, it is our understanding that these levees were not fully completed and were on the order of 3-4 feet below the target design elevation. During Hurricane Katrina, moderate to major overtopping occurred at this location. Our field reconnaissance verified that moderate to major overtopping occurred.

Figure 10.26 shows a composite United States Geological Survey topographic map of the MRGO area. The identified "spoil area" corresponds to the zone of poor levee performance. Figure 10.27 shows aerial photography taken by NOAA in early September 2005 along the MRGO and shows severe erosion/breaches in the levee and barges that floated over the top of the levee and came to rest inside St. Bernard Parish after water elevations receded. Figure 10.28 shows close up aerial photographs of the severely eroded levees.

A bank erosion study was performed by the USACE (1988) that identified the presence of highly erosion-susceptible soils within the MRGO alignment. Merchant shipping traffic that traversed the MRGO created wake-induced waves and drawdown that were eroding the channel banks, resulting in the widening of the MRGO from an intended 650 feet to an actual average width of 1,500 feet, more than double the design width. Comments submitted from the Lower Mississippi Valley District on the report made the following comment in response to selecting the bank erosion mitigation alternative of decommissioning the MRGO:

> *The alternative to completely close the MRGO waterway should be evaluated….This alternative will control all future channel maintenance problems by controlling bank erosion, preventing the associated biological resource problems, preventing saltwater intrusion, and lessening the recreational losses. In addition to solving the aforementioned problems, it will also reduce the possibility of catastrophic damage to urban areas by a hurricane surge coming up this waterway and also greatly reduce the need to operate (and could possibly eliminate) the control structures at Bayous Dupre and Bienvenue*

Slope protection measures were recommended to aid in stabilizing these highly erosive deposits against wave-induced erosion. At the time of Hurricane Katrina, slope protection measures along the flood side of the MRGO levee were not in place. As identified in the above comments, the Hurricane Katrina storm-surge massively eroded the levees and resulted in catastrophic failure.

Performance factors of the levee system that impacted the performance of the flood protection components included the following: utilization of highly erosive embankment materials, lack of appropriate surface slope protection to minimize erosion of the flood side of the levee during the storm-surge, and as-constructed crest elevations below design elevations allowing for significantly higher water overtopping heights. Future performance, based on prior performance, at this location under similar or more severe conditions is anticipated to be poor unless improved materials and construction methods are used. We were unable to sample this location and test the materials for erodibility, but we did perform a follow up visual reconnaissance in April of 2005. During our reconnaissance, we did not detect the use of unsuitable fills, but we would like to sample and test the soils used to construct the levee in this section of the MRGO.

10.5.9. Location 9 – Bayou Dupre Control Structure

Location 9 is situated approximately 6.5 miles southeast of the Bayou Bienvenue Control structure, on the west side of the MRGO. In this vicinity, the flood protection system consists primarily of earthen levees that connect via a concrete and steel flood access structure to a concrete control structure across Bayou Dupre. High water marks, as reported by IPET (2006), at this location reached a maximum Elevation of +17 to +22 feet (NAVD88-2004.65). The design elevation of the levee system at this location was Elevation +17.5 feet (MSL). Exact datum conversions in this area are not clearly established and are still under review by the IPET team, but the design water elevation has been identified as Elevation +12.7 feet (NAVD88-2004.65), resulting in moderate to major overtopping at this location. Our field reconnaissance verified that moderate to major overtopping occurred.

Figures 10.29 and 10.30 show aerial photographs of the Bayou Dupree control structure. The area to the south of the control structure performed very well, while the northern side of the control structure did not perform well, with significant erosion and scour as a result of the overtopping. The northern portion of the control structure abuts the abandoned Bayou Dupre channel, as shown in Figure 10.31. It is not conclusive whether the backfill materials into the abandoned channel impacted the performance of the control structure, but further investigation should be employed to determine the performance factors for this side of the control structure.

Figures 10.32 and 10.33 show aerial photographs of repair operations underway at Bayou Dupre in January 2006. As can be seen in Figure 10.33, sand borrow material has been imported to be used in the backfilling repair operations in the deep scour pools on the north side of the control structure.

Performance factors of the levee system that impacted the performance of the flood protection components included the following: utilization of highly erosive embankment materials, lack of appropriate surface slope protection to minimize erosion of the flood side of the levee during the storm-surge, as-constructed crest elevations below design elevations allowing for significantly higher water overtopping heights, and possible effects of the old Bayou Dupre channel abandonment backfill materials on the northern portion of the control structure. Future performance, based on prior performance, at this location under similar or more severe conditions is anticipated to be poor unless significant improvements are made in material selection and construction methods. We did not have the opportunity to review the engineering details associated with the repairs conducted on the structure since Hurricane Katrina.

10.5.10. Location 10 – St. Bernard Parish Interior Levee

Location 10 is situated north of the Corinne Canal and approximately ¾ miles east of Hwy 47/Paris Road. In this vicinity, the flood protection system was designed to be a secondary containment system for potential overtopping-related flooding behind the MRGO levees and to act as a barrier against rainwater that is discharged into the swamp area. The flood protection system consists primarily of earthen levees with a design Elevation of +8.0 to 9.0 feet (MSL). The actual elevation of this system during Hurricane Katrina was on the order of 5 to 6 feet (MSL) (note that IPET did not establish NAVD88-2004.65 elevations at this location). High water marks were not reported by IPET at this location. Based on our field reconnaissance, it was apparent that major overtopping occurred at this location.

Figure 10.34 shows an eastward looking view of the earthen levee. Although this levee was significantly overtopped, it did not experience significant damage. Figure 10.35 shows a fishing boat that was washed over the levee shown in Figure 10.34 and came to rest in a residential neighborhood.

Upon a subsequent visit to this location in March of 2006, we observed that the levee had been raised by several feet to a new Elevation of approximately +10 feet (MSL). Figure 10.36 presents the same view as in Figure 10.34, but 5 months later. Based on our observations, it appeared that cohesive soils and semi-compaction construction methods were used.

The performance factor of the levee system that impacted the performance of the flood protection components included the following: utilization of moderately to highly erosion-resistant embankment materials. Future performance at this location under similar or more severe conditions is anticipated to be good, however, significant overtopping should be expected for larger storm surge events where the MRGO levees to breach.

10.5.11. Summary of Observed Performance Factors

Based on observations from our field reconnaissance and review of aerial photographs, it is apparent that the performance and post Hurricane Katrina conditions of the New Orleans Flood Defense earth levee systems varied from good performance in areas with major overtopping to poor performance in areas with minor degrees of overtopping. The majority of levees were overtopped as a result of the large storm surge that rushed onshore. The magnitude of the storm surge and resulting overtopping did not directly relate to the performance of the levees. This observation demonstrates the importance of material erosion resistance. Table 10.3 presents a summary of the 10 locations evaluated as part of this study.

Table 10.3 Performance summary of select levee locations

Location	Design Water Elevation (ft)[1]	Maximum Storm Surge Elevation (ft)[2]	Overtopping	Post Hurricane Levee Condition	Anticipated Future Performance
1 - Lakefront Airport	[13.5] 11.8	12	Minor	Poor	Poor
2 - Jahncke Pump Station Outfall	[14.5] 12.8	12	Minor	Adequate	Adequate to Poor
3 - Eastern Perimeter of New Orleans East	[14.5] 12.4	~18?	Moderate to Major	Good	Good
4 - Southeast Corner of New Orleans East	[19.0] 13.0	~18?	Moderate to Major	Poor	Adequate to Poor
5 - Entergy Michoud Generating Plant	[15.0] 13.2	16	Moderate to Major	Good	Good
6 - IWW/MRGO Southern Levee	[14.0] 13.2	16	Moderate to Major	Good	Good
7 - Bayou Bienvenue Control Structure	[17.5] 13.2	18	Moderate to Major	Good/Poor	Good/Poor
8 - Mississippi River Gulf Outlet	[17.5] 12.7 (~10[3])	17-22	Major	Poor	Poor
9 - Bayou Dupre Control Structure	[17.5] 12.7 (~10[3])	17-22	Major	Poor	Poor
10 - St. Bernard Parish Interior Levee	[8] ~6[4] (~3[3])	Not Established	Major	Good	Good

[1]Elevations converted from NGVD29 elevation (in brackets) to equivalent NAVD88(2004.65) elevation, from IPET (2006)

[2]Based on NAVD88(2004.65) vertical datum. From IPET (2006)

[3]Elevation at the time of Hurricane Katrina was below the design elevation

[4]A conversion between the original design elevation from the NGVD29 to the new NAVD88(2004.65) elevation was not available from IPET

Table 10.4 presents a summary of the types of failure mechanisms of earthen levees that were observed in the greater New Orleans area flood defense system, including the ten locations identified above. In addition, the required design evaluations per the USACE and FEMA guidelines have also been summarized in this table.

Table 10.4 Levee Failure Mechanisms

Failure Mechanism	USACE Guidelines	FEMA Guidelines	Observed in Greater New Orleans Area
Overtopping	Not allowed	Not allowed	Yes
Jetting	Not allowed	Not allowed	Yes
Internal Erosion and Piping	Design criteria provided	Analyses required	Yes
Surface Erosion	Protection required	Protection required	Possibly
Wave Impacts	Protection required	Protection required	Yes
Structural Impacts	Not addressed	Not addressed	Yes
Slope Failures	Design criteria provided	Analyses required	Yes
Sliding	Design criteria provided	Analyses required	Yes
Underseepage	Design criteria provided	Analyses required	Yes
Liquefaction	Not directly addressed	Not directly addressed	Possibly
Bottom Heave	Not directly addressed	Not directly addressed	Yes

Overtopping, jetting, internal erosion and piping, structural impacts, underseepage and heave failure mechanisms were observed in the Orleans, Orleans East, and St. Bernard Parish protected areas. We did not observe any significant levee breaches due to surface erosion-induced failures. Surface erosion failures are common along river levees, where a steady and chronic shear stress is applied to the levee face as the river water flows past it. Surface erosion most likely exacerbated the levee breaches just south of the Bayou Bienvenue and Bayou Dupre control structures. There were multiple locations where trees that were rooted within the levee zone had fallen over and may have contributed to the failure of the levee. There was not strong evidence for this, however. Liquefaction may have been a partial contributor to some of the failures along the MRGO levee system. The force associated with the breaking waves impacting the MRGO levee may have been sufficient enough to induce liquefaction in the relatively weak foundation materials. During our field observations, we did not find strong evidence for this, however.

Some notable attributes were observed to be associated with levees that performed well during the hurricane. These attributes included:

- Utilization of erosion-resistant soils for levee construction;
- Gradual soil/structure transition zones (rock gabions around concrete structures);
- Presence of low-lying swamp and vegetation to dampen wind-waves; and
- Presence of rip-rap protection.

Some notable attributes were observed to be associated with levees that performed poorly during the hurricane. These attributes included:

- Utilization of low erosion-resistant construction material;
- Transitions between different flood protection component types;
- Lack of surface slope protection for erosion-susceptible soil levees; and
- Abandoned channel backfill procedures.

These basic and qualitative observations and evaluations formed the basis by which a more detailed field exploration and laboratory testing program was developed. The intent of the field exploration and laboratory testing program was to ascertain distinguishing engineering characteristics associated with the high-performance levees from the low-performance levees.

10.6. Erosion Evaluation

To date, the field of scour and erosion has not been well characterized and there are very few case studies that relate actual performance to design parameters. Both the USACE and FEMA design guidelines do not specifically provide acceptability criteria for erosion susceptibility due to the lack of comprehensive knowledge in this area. As a result of the NOFDS being "loaded to failure," it has provided an unfortunate opportunity to recognize lessons learned and improve our body of knowledge for the performance of levee flood protection devices.

It is imperative to note the magnitude of devastation caused to the flood protection system as a result of erosion. The levee system along the MRGO, which is the main protection mechanism for the 100,000+ citizens of St. Bernard Parish (and the Lower 9th Ward) against storm surges from the Gulf of Mexico, was catastrophically degraded as a result of erosion during Hurricane Katrina. Figure 10.37 shows a comparison of two LiDAR surveys of the MRGO levee system at the Bayou Bienvenue control structure, near the intersection of the GIWW at the northeast corner of St. Bernard Parish. Effects of subsidence can be clearly seen in the elevation differences on the north side of the control structure and the control structure itself between 2000 and immediately following Hurricane Katrina in 2005. The levee on the north side of the Bayou Bienvenue control structure was largely undamaged. The levee on the south side of the control structure was catastrophically damaged. The magnitude of the erosion has been highlighted and white "splotches" of displaced levee materials can be seen in the aerial photograph.

There are many factors that influence the erosion susceptibility of soils and a more comprehensive discussion is presented in Appendix E. Fundamentally, soil erosion is controlled by the resisting characteristic of the soil (soil type, soil fabric structure, in-situ density, etc.) and eroding forces (the magnitude of the shear stress applied to the soil) from the contacting water surface.

A sampling and laboratory testing program was devised upon completion of our field levee condition survey and mapping in October of 2005, to try to understand and characterize the properties associated with the levees that performed well and the characteristics of the levees that did not perform well during Hurricane Katrina. The intent of this study was to better understand the nature of the levee materials that performed well during the extreme conditions in order to provide recommendations on how to improve the sections of earthen levees that did not perform well.

In-situ samples were collected and from select levee sites during January and February of 2006. The selected sampling sites included levees that performed very well during Hurricane Katrina, levees that performed moderately well, and levees that did not perform satisfactorily. Figures 10.38 and 10.39 identify the locations where samples were collected for laboratory analyses.

Erosion susceptibilities of the soils were characterized using a state of the art erosion index testing method, developed by Dr. Jean-Louis Briaud at Texas A & M University, known as an Erosion Function Apparatus (EFA). This test method required undisturbed samples to be sampled from the field and be carefully transported back to Texas A&M University for analyses.

As described in Chapter 9, the EFA is a test that determines the shear stress and velocity of flowing water required to erode soil from a cylindrical tube that is slowly advanced into a rectangular pipe of flowing water. The more erosion resistant the soil, the faster the water (and the higher the shear stress) is required to flow in the rectangular pipe in order to erode the soil sample. A diagram of the EFA is presented in Figure 10.40. The measured shear stress at the point at which the soil begins to erode is defined as the critical shear stress. Shear stress less than the critical shear stress will not result in erosion, whereas applied shear stresses in excess of the critical shear stress will result in erosion. Determination of the erodibility index is useful in completing analyses for overtopping and surface erosion.

Upon completion of the test, the erodibility index of the soil was defined and the rate of erosion as a function of applied shear stress (or velocity) established. This relationship can then be compared with anticipated shear stresses the soil will experience in the field. If the estimated field shear stresses are less than the shear stress required to erode the soil, no erosion is anticipated to occur. If the field shear stresses exceed the laboratory determined critical shear stress, the erodibility index provides a means by which to estimate the magnitude of the overall erosion.

In addition to the erosion testing, engineering characteristics of the earthen levees were also characterized. These characteristics included the following:

- Gradation, including passing the Number 200 sieve (ASTM D422)
- Hydrometer (ASTM D422)
- Atterberg Limits Determination (ASTM D4318)
- Unconfined Compression (ASTM D2166)
- Dry density and moisture content determination (ASTM D4937/2216)
- Maximum dry density determination (ASTM D1557)

Table 10.5 presents a summary of the locations where samples were collected for analyses.

Table 10.5 Summary of sampling locations for laboratory testing

Site No.	Description	Latitude (°N)	Longitude (°W)	Performance
1	Levee east of Hwy 11 and North of Hwy 90	30.0895	89.8587	Good
2	Entergy Powerplant	30.0065	89.9389	Good
3	MRGO North Control Structure (North)	29.9996	89.9170	Good
4	MRGO Levee (northern section)	Not Established		Poor
5	MRGO Levee (middle section)	Not Established		Poor
6	MRGO Levee (southern section)	Not Established		Poor
7	St. Bernard Parish South	29.8769	89.7818	Good
8	St. Bernard Parish North	29.9558	89.9466	Good
9	Lakefront Airport Transition Levee	30.03344	90.026	Moderate
10	Hayne Blvd	30.05908	89.96697	Good
11	Hayne Blvd and Paris Road (Beach)	30.07577	89.94467	Not Applicable
12	Orleans East Southeast RR Transition	30.06156	89.83352	Poor
13	Orleans East Southeast Corner	30.04481	89.83089	Poor
14	Intracoastal Waterway North (New Levee)	30.03542	89.85399	Unknown
15	Intracoastal Waterway North (Remaining Levee)	30.02707	89.87448	Poor
16	Levee west of Entergy Plant	30.00465	89.95062	Good
17	St. Bernard Parish (Middle)	29.92541	89.8948	Good

Note: Geographical coordinates based on WGS84 datum.

The samples were collected by pushing an approximately 3-inch diameter steel (Shelby) tube into the ground to retrieve soil samples using a geotechnical testing drill rig. Sites 4, 5, and 6 were located along the MRGO section of levee that suffered severe overtopping and erosion. At these sites the levee materials were collected in a soil sample bag and reconstituted back in the laboratory due to the highly disturbed nature of the levee materials. A more detailed discussion of the field sampling program is presented in Appendix E.

The erosion susceptibilities of all the samples collected are presented in Figure 10.41. The test result designations are based on the Site Number, the boring number at the site, the depth interval over which the sample was collected and sample notes. Thus, a sample marked as S1-B1-(0-2ft)-TW indicates that the sample came from Boring 1 at Site No. 1 (Levee east of HWY 11 and North of HWY 90) from a depth of 0 to 2 feet below the crest of the levee.

The results of the EFA test results are presented in Table 10.6. The EFA test results matched very well with the observed performance in the field. Areas where the levee performance was observed to be good generally had low to very low erosion susceptibilities. In areas where the levee performance was poor the materials had a high to very high erosion susceptibility.

Table 10.6 Summary of sampling locations for laboratory testing

Site No.	Description	Performance	EFA Erosion Susceptibility Determination
1	Levee east of Hwy 11 and North of Hwy 90	Good	Low (IV)
2	Entergy Powerplant	Good	Low to Very Low (IV-V)
3	MRGO North Control Structure (North)	Good	Low to Very Low (IV-V)
4	MRGO Levee (northern section)	Poor	High (II)
5	MRGO Levee (middle section)	Poor	High (II)
6	MRGO Levee (southern section)	Poor	High (II)
7	St. Bernard Parish South	Good	Medium (III)
8	St. Bernard Parish North	Good	Medium (III)
9	*Lakefront Airport Transition Levee*	*Moderate*	*Not Tested*
10	*Hayne Blvd*	*Good*	*Not Tested*
11	Hayne Blvd and Paris Road (Beach)	Not Applicable	Not Applicable
12	Orleans East Southeast RR Transition	Poor	High to Medium (II-III)
13	*Orleans East Southeast Corner*	*Poor*	*Not Tested*
14	*Intracoastal Waterway North (New Levee)*	*Unknown*	*Not Tested*
15	Intracoastal Waterway North (Remaining Levee)	Poor	Very High to High (I-II)
16	*Levee west of Entergy Plant*	*Good*	*Not Tested*
17	*St. Bernard Parish (Middle)*	*Good*	*Not Tested*

The effects of material compaction were also evaluated. Previous work has been performed in this area and a design guideline prepared by FHWA (1988). Figure 10.42 shows that for a material of a given plasticity index, the permissible shear stress increases nearly ten-fold when the material is properly compacted.

Figure 10.43 shows the dramatic impact proper compaction has on the erodibility of soils. Materials sampled from the MRGO levee were tested at two compaction levels: low compactive effort and high compaction effort. The corresponding results speak volumes to the importance of compaction in earthen levees. The low-compaction sample was found to be very highly erodible, whereas the high-compaction sample exhibited low erodibility characteristics. High compaction effort is based on 90-95% relative compaction per the Modified Proctor test (ASTM D1557).

Figure 10.44 provides a summary from the pioneering erodibility work performed by Dr. Briaud et.al. at Texas A & M University. Soils that fell within the very high to high erodibility categories are prone to failure by overtopping. Soils that fell within the medium erodibility catergory fell in a transition zone, and soils that fell within the low to very low erodibility categories were shown to be resistant to erosion induced failure as a result of overtopping. These laboratory test results were validated by actual levee performance during Hurricane Katrina.

A more detailed discussion of the erosion testing and a more comprehensive discussion of overtopping was presented in Chapter 9.

10.7. Establishment of Design Criteria and Acceptable Performance

Varying degrees of levee integrity performance are required based on the assets the levees are protecting. Originally, most levees protected agricultural farm lands, where the consequences of levee breaching and subsequent flooding resulted in the loss of crops. With the growth of urban areas adjacent to rivers and coastlines over the past two to three hundred years (the first urban levee in New Orleans was 1718, nearly 300 years ago) the first urban leb, levees have become increasingly important defense mechanisms for industry, vital infrastructure elements such as drinking water, sewage, and electricity transmission, and, most importantly, human life. Little guidance is provided by either the USACE or FEMA design criteria on what are acceptable design standards for high-consequence urbanized areas vs. low-consequence agricultural areas.

The current approach to establishing design standards utilized by the USACE is conducting a cost-benefit analysis. This financial evaluation analyzes the cost of achieving a certain level of protection and compares it with the recognized benefit associated with that level of protection. Unfortunately, the cost/benefit model used by the USACE does not account for the loss of human life, economic losses to cities, counties, and states as a result of a non-operational and non-functional revenue base (businesses shut down due to damage and lack of utilities, lack of a work force to operate businesses, lack of a tax base due to the displaced residents, and lack of tourists).

10.7.1. USACE Risk Management Approach

In response to budget constraints, increased situations requiring cost-sharing, and general public concern for the performance and reliability of completed projects, the USACE has evaluated the use and methodology by which to incorporate risk-based analyses (especially as related to the geotechnical components of these projects). A seminar was convened in 1983 by the USACE in order to "incorporate more information into the safety assessment [of projects] than [traditional] factor of safety methods." A more recent evaluation was undertaken and the results of this effort are presented in Engineering Technical Letter (ETL) 1110-2-556, published on May 28, 1999. This study recognized that there are inherent uncertainties associated with infrastructure problems and the total effect of risk and uncertainty on the project's economic viability should be examined in order for "conscious decisions" to be made reflecting "explicit trade-offs between risk and cost."

According to ETL 1110-2-556, major sources of uncertainty that require evaluation include the following:

- Uncertainty in loadings;
- Uncertainty in engineering analysis parameters;
- Uncertainty in analytical models (model bias);
- Uncertainty in performance;
- Conversion of empirically-derived performance modes;
- Frequency and magnitude of physical changes or failure events; and

- Condition of unseen features.

ETL 1110-2-556 identifies special situations uniquely applicable to geotechnical problems that result in uncertainties with large magnitudes:

- Natural earthen materials generally exhibit high variability in composition and engineering properties;
- Engineering characteristics of soils can exhibit high variability due to composition, deposition, sampling, and field & laboratory testing procedures;
- Engineering analyses can be performed assuming total stress (excluding the effects of groundwater) or effective stress (including the effects of groundwater). As a result, groundwater uncertainties may either be included or excluded in the analyses;
- Consideration of spatial correlation of soil properties is required due to the variability of deposition history; and
- The spatial scale of the project (as much as tens of miles long for levees) requires "sectioning" of the system into subcomponents.

These uncertainty factors can result in very large ranges and broad distributions for parameter bounds. For example, a mean soil shear strength value, determined based on a subsurface field sampling and laboratory testing which is used to evaluate the stability of levee slopes may naturally vary between 50% of the mean value to as much as 150% of the mean value. These broad distributions impact the reliability of the resulting calculated answer.

The report summarized recommended target reliabilities for expected performance levels. These target reliabilities are presented in Table 10.7.

Table 10.7 Target Reliability Indices

Expected Performance Level	Beta (β)	Probability of Unsatisfactory Performance	*Approximate Median Factor of Safety[1] ($F.S._{50}$)*
High	5.0	0.0000003	*2.5*
Good	4.0	0.00003	*2.1*
Above average	3.0	0.001	*1.7*
Below average	2.5	0.006	*1.6*
Poor	2.0	0.023	*1.4*
Unsatisfactory	1.5	0.07	*1.3*
Hazardous	1.0	0.16	*1.2*

The approximate median Factor of Safety associated with the established expected performance levels were added to the target reliability indices presented in ETL 1110-2-556 according to the following formula:

$$F.S._{50} = e\wedge(\beta\sigma_{\ln RS}) \qquad \text{Equation 9.2}$$

In this formulation, β is the safety index, R is the capacity and S is the loading/demand, a coefficient of variation of 30% is assumed in the loading and capacities, and a lognormal distribution for the system is assumed.

10.7.2. Other Risk-Based Approaches

Alternative approaches to establishing design levels exist. A paper was presented in the ASCE *Journal of Geotechnical and Geoenvironmental Engineering* by John T. Christian (2004) that highlighted select approaches to risk management. Christian summarized studies performed by Baecher that back-calculated the annual probability of failure based on failures of actual engineered systems. The lives lost or financial loss associated with the failure were plotted against the back-calculated annual probability of failure. This plot provides a mechanism by which to ascertain the desired level of performance of a given engineered structure, based on historic performance. The resulting plot is presented in Figure 10.45.

In addition to the studies by Baecher, Hong Kong and the Netherlands have risk-based decision making tools (Figure 10.46) as part of their planning process to establish acceptable levels of safety for engineered systems based on the expected number of fatalities (Christian 2004). Failures that impact large populations and may result in fatalities greater than 1,000 are required to have very low annual probabilities of failure.

To convert the annual probability of failure (Pf_{pa}) to an "average return period, (ARP)" such as the 100-year or 1,000-year event, the following correlation can be used:

$$Pf_{pa} \approx (ARP)^{-1} \qquad \text{Equation 9.3}$$

Using the risk management planning tool (Figure 10.46) developed by the Hong Kong Government Planning Department as an example, a proposed engineered system that has the potential to result in 1,000 fatalities would have an acceptable risk (based on an annual frequency of occurrence) of 10^{-8}, the range over which the principle As Low As Reasonably Prudent is recommended varies from Pf_{pa} of 10^{-8} to 10^{-6}, and a risk with a Pf_{pa} of less than 10^{-6} is considered unacceptable.

Table 10.8 Risk Levels for a System with the Potential for 1,000 Fatalities

Risk Level	Pf_{pa}	Annual Return Period (yrs)
Acceptable	$<10^{-8}$	>100,000,000
ALARP	10^{-6} to 10^{-8}	1,000,000 to 100,000,000
Unacceptable	$>10^{-6}$	< 1,000,000

Table 10.8 presents a summary of calculated Annual Return Periods (in years), based on the probability of occurrence limits recommended by the Hong Kong Government Planning Department. This example highlights the sociological decision made in Hong Kong that high consequence events should occur very infrequently, with an annual return period of 1 million years! Although this may not be realistic due to natural and anthropogenic uncertainties, the premise of varying acceptable risk as a function of consequences is feasible.

Another important concept presented by Christian was that of interpretation errors and the inability of the general population to comprehend very low probability events. Figure 10.47 presents an overconfidence bias plot which shows that individuals are able to distinguish the difference between generally high-probability events (i.e. the difference between a 10-year storm (annual probability of 0.1) and a 100 year storm (annual probability of 0.01)). However, individuals were not able to distinguish as easily the difference between very low probability events (for example, the difference between a 1,000 year storm and a 100,000 year storm). This implies that sole “perception-based judgment” may not be a sufficient screening tool for establishing performance levels for systems subjected to low frequency events that have the possibility of resulting in catastrophic failures.

10.8. Conclusions

Hurricane Katrina resulted in the catastrophic flooding of the greater New Orleans area. Although the magnitude of the storm surge that overwhelmed the levee flood defense system was greater than the capacity of the system, the extent of the devastating damage could have been greatly minimized if the system had been robustly designed. There were many miles of earthen levees that were significantly overtopped, but did not breach catastrophically. These levees that did not breach were only overtopped for a few hours’ duration and the quantity of water that did flow over the levees could have been pumped out of the protected area utilizing the existing drainage network and pump infrastructure (see Chapter 4). The levees that were not able to withstand overtopping, breached catastrophically, allowing the full magnitude of the storm surge to overwhelm the protected area.

Design guidelines need to be updated to ensure the design and construction of robust levee systems. All failure mechanisms must be acknowledged and included in the design evaluation. All levees should be designed to withstand overtopping. Material selection and compaction are critical components to ensure adequate performance and appropriate specifications for material selection and compaction should be developed and should be incorporated into the design guidelines.

The current design guidelines sponsored by both the USACE and FEMA assume that overtopping does not occur and does not require safety in the event of overtopping of the levees.

A probabilistic approach should be utilized to determine the appropriate factor of safety for the design of these levee systems. Accounting for uncertainties in demands on the system (height of storm surges, wave impacts, etc.) as well as uncertainties in the capacity of the levee system (erosion resistance, foundation stability, etc.) must be included in the safety evaluation of the levee system.

The current design guidelines sponsored by both the USACE and FEMA are based on deterministic factor of safety levels that do not account for a broad range of uncertainties nor do they account for mechanisms to ensure an appropriate level of safety based on the consequences of failure.

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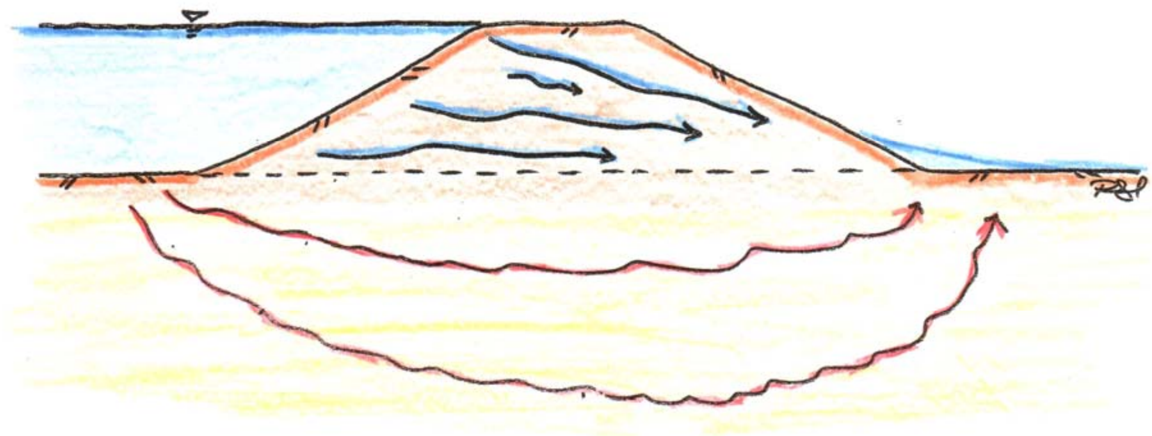


Figure 10.1: Underseepage in highly permeable underlying foundation materials (red lines) can result in the catastrophic failure of the levee in that once the foundation materials have been eroded, the levee (which may be completely undamaged) has no underlying support and falls into the resulting void and essentially washes away.

Internal erosion and piping (blue lines) occurs in levee materials that have high permeabilities (such as sand and gravel) and allow for water to rapidly flow from high pressure areas to low pressure areas. As the water flows through the levee, smaller/finer soil particles are "washed" out of the levee resulting in the internal erosion of the levee. Enough internal erosion of the levee can lead to the collapse and subsequent "wash-out" of the levee.

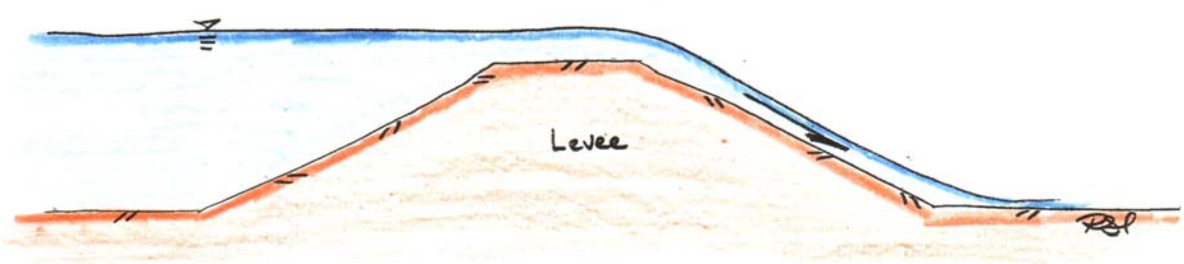


Figure 10.2: Overtopping occurs when the water level on the outboard side of the levee exceeds the crest elevation of the levee. The inboard side of the levee acts as a spillway for the overtopping water and damage is inflicted on the levee as a result of water scour.

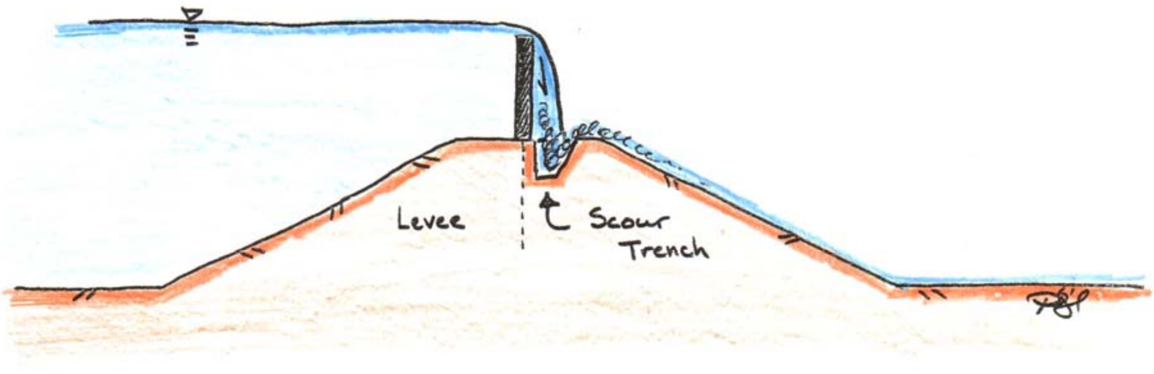


Figure 10.3: Jetting occurs when the water level on the outboard side of the levee exceeds the top of wall elevation for structural walls that are founded within the earthen levee. Unlike overtopping of a conventional earthen levee, the floodwall acts as a weir and water impacts the levee in a concentrated stream that is much more energy intensive than conventional overtopping.

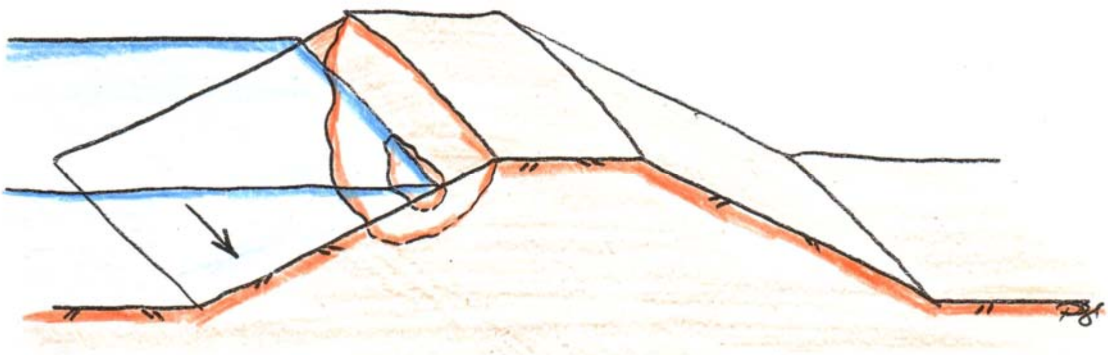


Figure 10.4: Surface erosion generally occurs on the outboard side of the levee and is the result of water flowing past the levee face. If the imposed shear stress from the water abrading against the soil levee face is high enough, soil scour occurs and the integrity of the overall levee is significantly reduced.

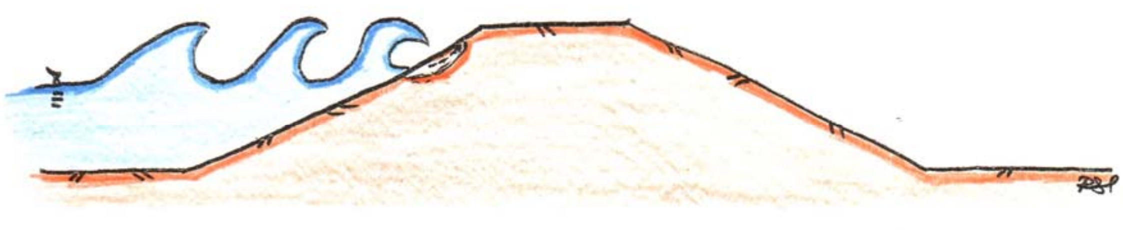
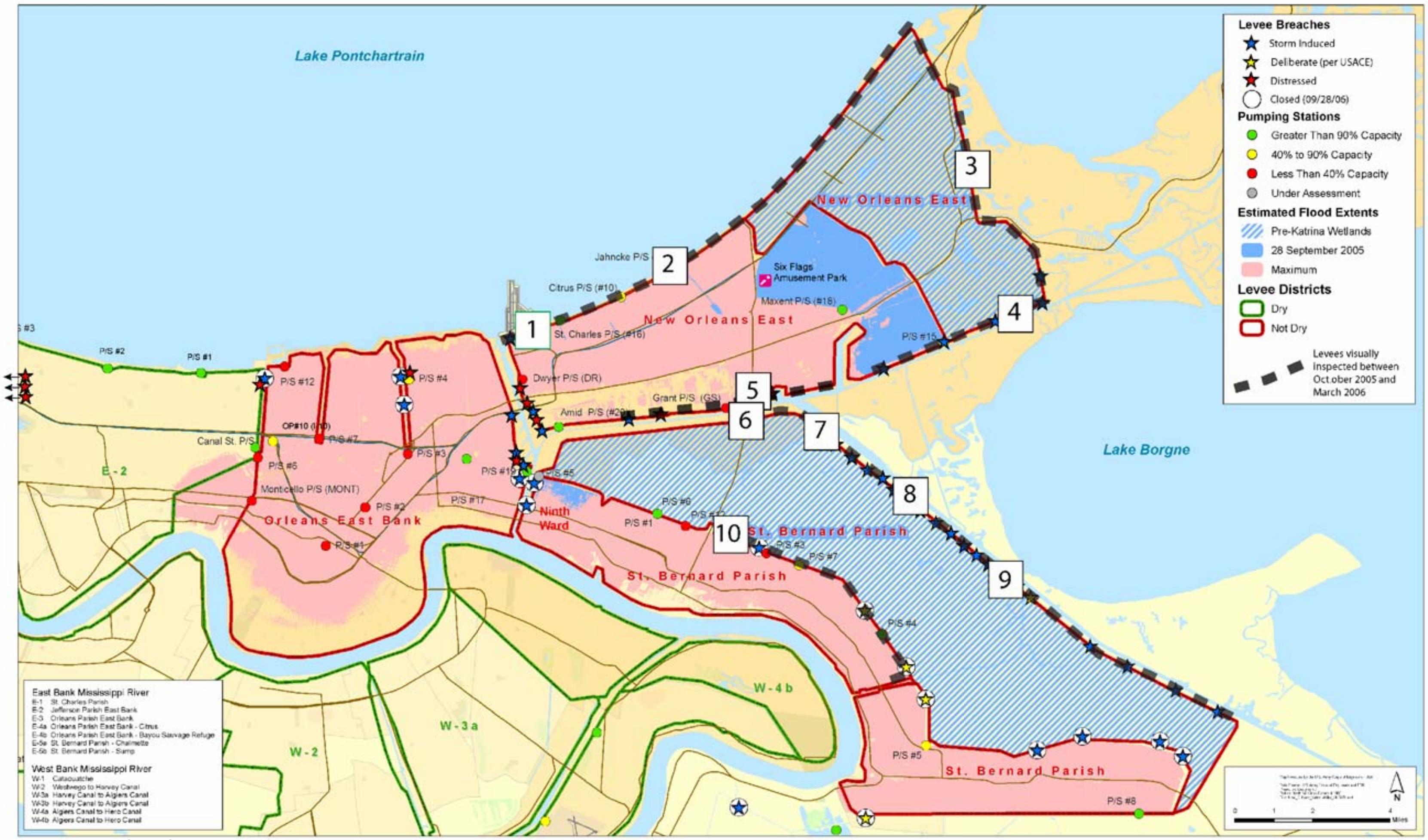


Figure 10.5: Wave impacts can cause significant erosion to levee faces. Wave-induced erosion consists of run-up (sloshing up and down of water as a result of staggered wave arrival) and "mini-jetting" when the crest of the waves breaks on the levee face.



Source: Modified after USACE, 2005

Figure 10.6: Map showing the extents of the visual reconnaissance (dashed black line) of the earthen levee systems performed between October 2005 and March 2006. Locations of notable performance are identified in the numbered boxes.

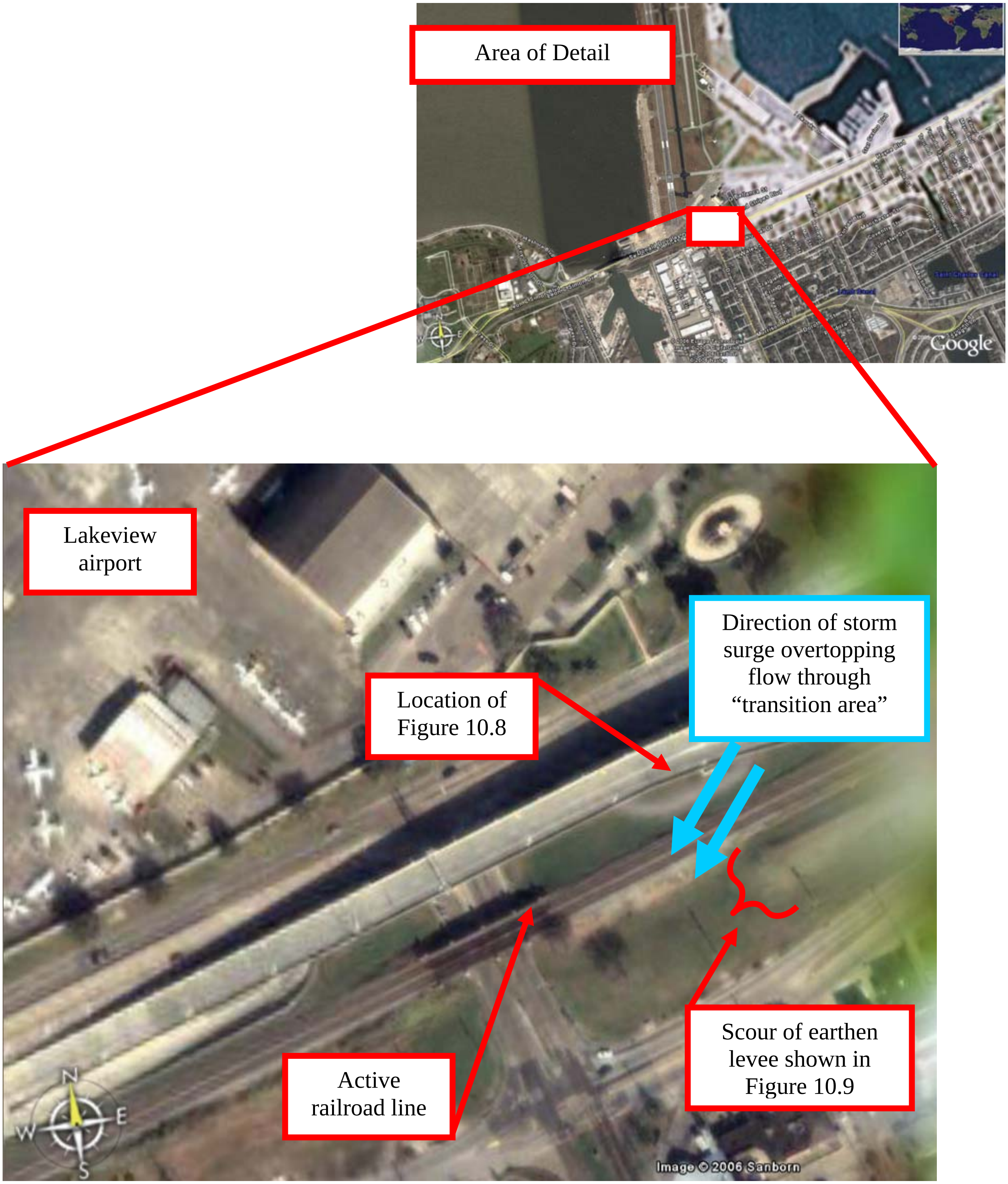
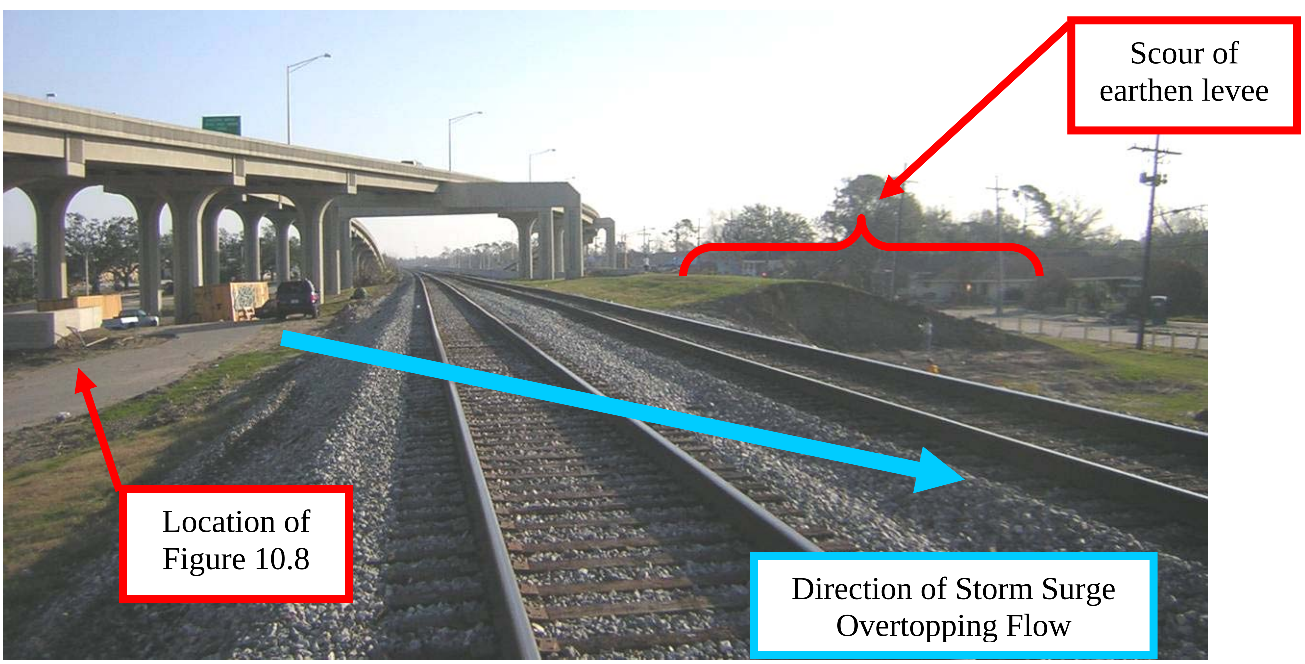


Image from Google Earth, 2006

Figure 10.7: Storm-surge induced overtopping traveled through the granular gravel ballast for the railroad line and eroded the railroad line embankment, which served as a transition levee between the concrete floodwall and the earthen levee shown in Figure 10.8.

Photograph by Rune Storesund

Figure 10.8: Lakefront levee near the Lakefront Airport at location 1 (as indicated on Figure 10.7) where overtopping occurred and significant scour around the floodwall was observed.



Photograph by Rune Storesund

Figure 10.9: Significant erosion was observed on the levee behind the floodwall shown in Figure 10.8. The storm surge overtopped the floodwall and railroad ballast and failed the earthen levee.

Photograph by Rune Storesund

Figure 9.16: Lakefront levee at location 2 (as indicated on Figure 10.6) where minor overtopping occurred. These levees performed well and only minor, surficial damage was observed.

Photograph by Rune Storesund

Figure 9.17: Observed scour at the Jahncke Pump Station outfall structure (location 2 as indicated on Figure 9.12). Scour was limited to areas of soil-structure interfaces.

Photograph by Rune Storesund

Figure 10.12: Condition of levees east of HWY 11 (location 3 on Figure 10.6) in October 2005. These levees performed exceptionally well and were not eroded during Hurricanes Katrina or Rita.

Photograph by Rune Storesund

Figure 10.13: Levee rehabilitation work (near location 3 on Figure 10.6) post Hurricane Katrina included reinforcement and protection of soil-structure interactions with rock-gabion transition zones.

Photograph by Rune Storesund

Figure 10.14: Zones of earthen levees at the southeast corner of the New Orleans East polder (location 4 on Figure 10.6) were washed out during Hurricane Katrina allowing water to rush in.

Photograph by Rune Storesund

Figure 10.15: Levee rehabilitation work (location 4 on Figure 10.6) post Hurricane Katrina. The semicompaction construction approach was employed, utilizing earthmoving equipment to compact the placed material as it transported borrow materials to the construction site. The construction equipment was located one mile west of this picture, which was located at the very southwest corner of the New Orleans East polder.

Photograph courtesy the Entergy Corporation

Figure 10.16: Photographs (location 5 on Figure 10.6) captured by a security camera at the Entergy Michoud Generating Plant beneath Route 47, on the IWW/MRGO show active overtopping during Hurricane Katrina.

Photograph by Rune Storesund

Figure 10.17: Post Hurricane Katrina view of the earthen levee shown in Figure 10.16. Only minor damage on the protected side was observed, with the majority of the damage a result of wave reflection from the bridge abutment at the right-hand side of the picture.

Photograph courtesy ngs.woc.noaa.gov/Katrina/KATRINA0000.HTM

Figure 10.18: The presence of a concrete floodwall beneath the Hwy 47/Parish Road Bridge acted as a weir during the overtopping stages of the storm and "sucked" in nearby barges. Scour can be observed behind the concrete floodwall, but there is only minor scour damage visible at the earthen levee/concrete floodwall transition. Overall, this system performed well (also considering the impact associated with the barges).

Photograph courtesy Lee Wooten

Figure 10.19: Woody debris and steel barges "washed up" on the southern ICWW/MRGO levee just west of Route 47 (location 6 on Figure 10.6). This is a side view from the aerial photograph presented in Figure 9.24.

Photograph courtesy Francisco Silva-Tulla

Figure 10.20: A gas processing barge "washed up" on the southern IWW/MRGO levee just east of Route 47 (location 6 on Figure 10.6). This levee was also overtopped and was not damaged by the barge impact.

Photograph courtesy Les Harder

Figure 10.21: Aerial photograph of the Bayou Bienvenue Control Structure (location 7 on Figure 10.6). The western half of the control structure levee system performed extremely well (withstanding significant impact loads from the steel barge), while the eastern portion suffered severe erosion.

Photograph by Rune Storesund

Figure 10.22: This flood control gate acted like a weir as water overtopped the structure during the storm surge. Significant scour and erosion was observed around the flood control gate structure.

Photograph by Rune Storesund

Figure10.23: By March of 2006, after Hurricane Katrina, splash pads had been installed at this flood control gate to mitigate erosion impacts if any future overtopping of the flood protection system occurs. This photograph was taken at the same location as Figure 10.22.

Photograph by Rune Storesund

Figure 10.24: The northern side of the Bayou Bienvenue control structure has been heavily reinforced with rip-rap transported to New Orleans from Kentukee. This photograph was taken about 6 months after Hurricane Katrina and the barge, which can be seen in Figure 10.21, has been removed.

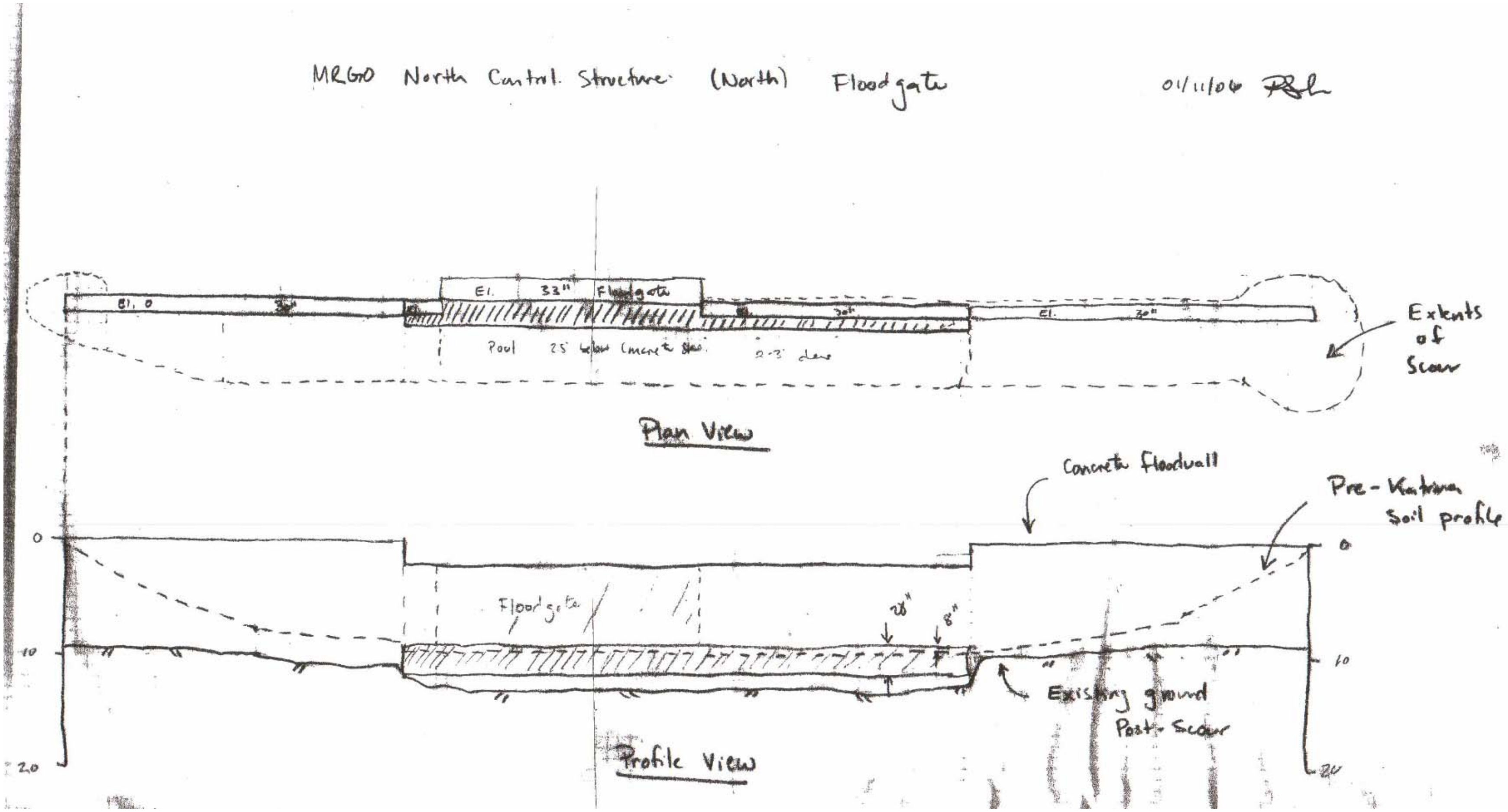
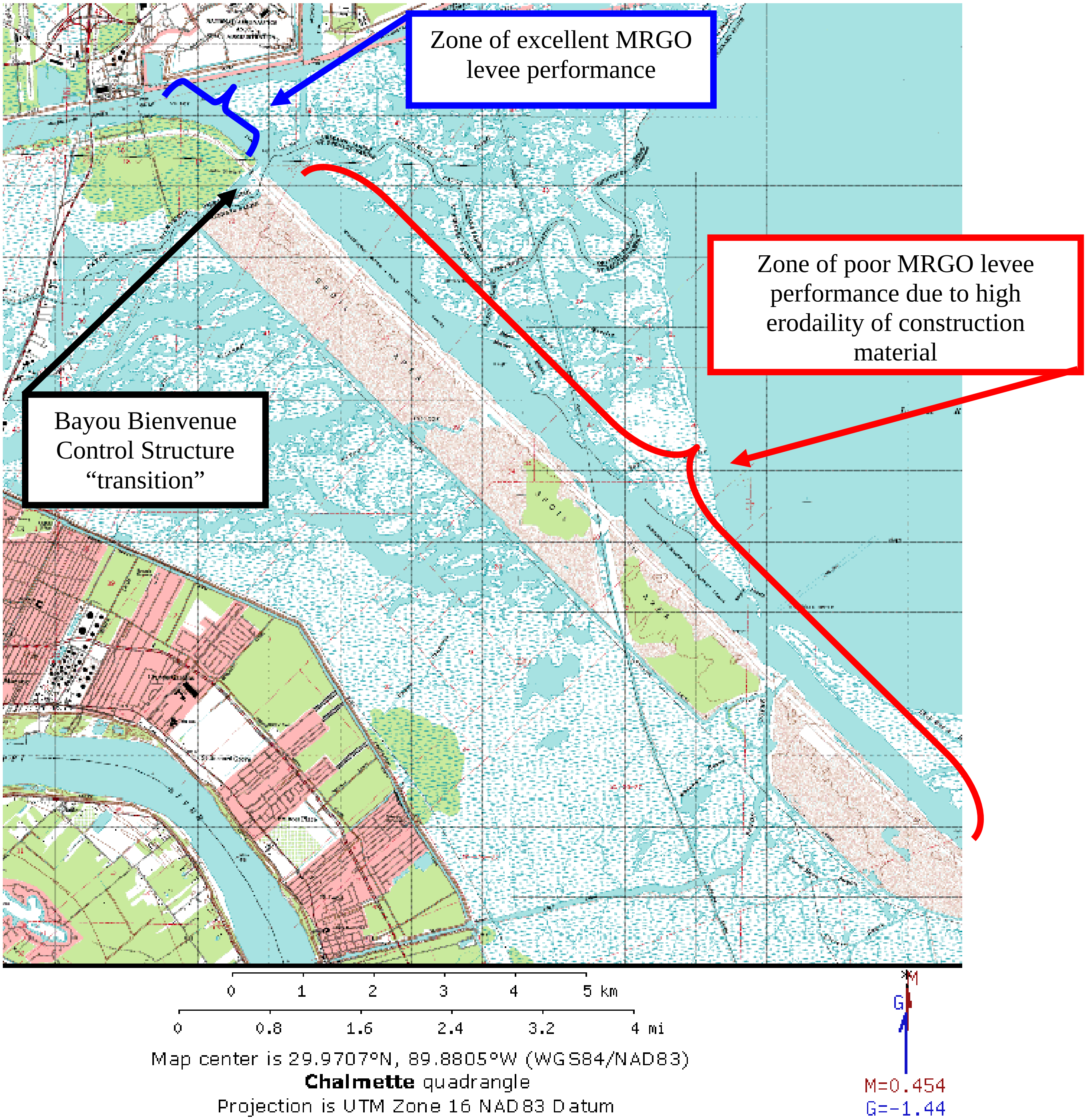


Figure 10.25: Scour pattern behind around the floodgate structure at the Bayou Bienvenue Control Structure shown in Figure 10.22.



Topographic map from Topozone.com

Figure 10.26: A U.S.G.S. topographic map showing the presence of "spoils" along the MRGO. As seen in Figure 10.28, the levee materials to the southeast of the Bayou Bienvenue Control Structure performed poorly.

Photograph courtesy ngs.woc.noaa.gov/Katrina/KATRINA0000.HTM

Figure 10.27: Aerial photograph taken by NOAA in early September 2005 along the MRGO showing severe erosion/breaches of the earthen levee and transport and deposition of large barges over the levee as a result of the storm surge (location 8 on Figure 10.6).

Photograph courtesy Les Harder

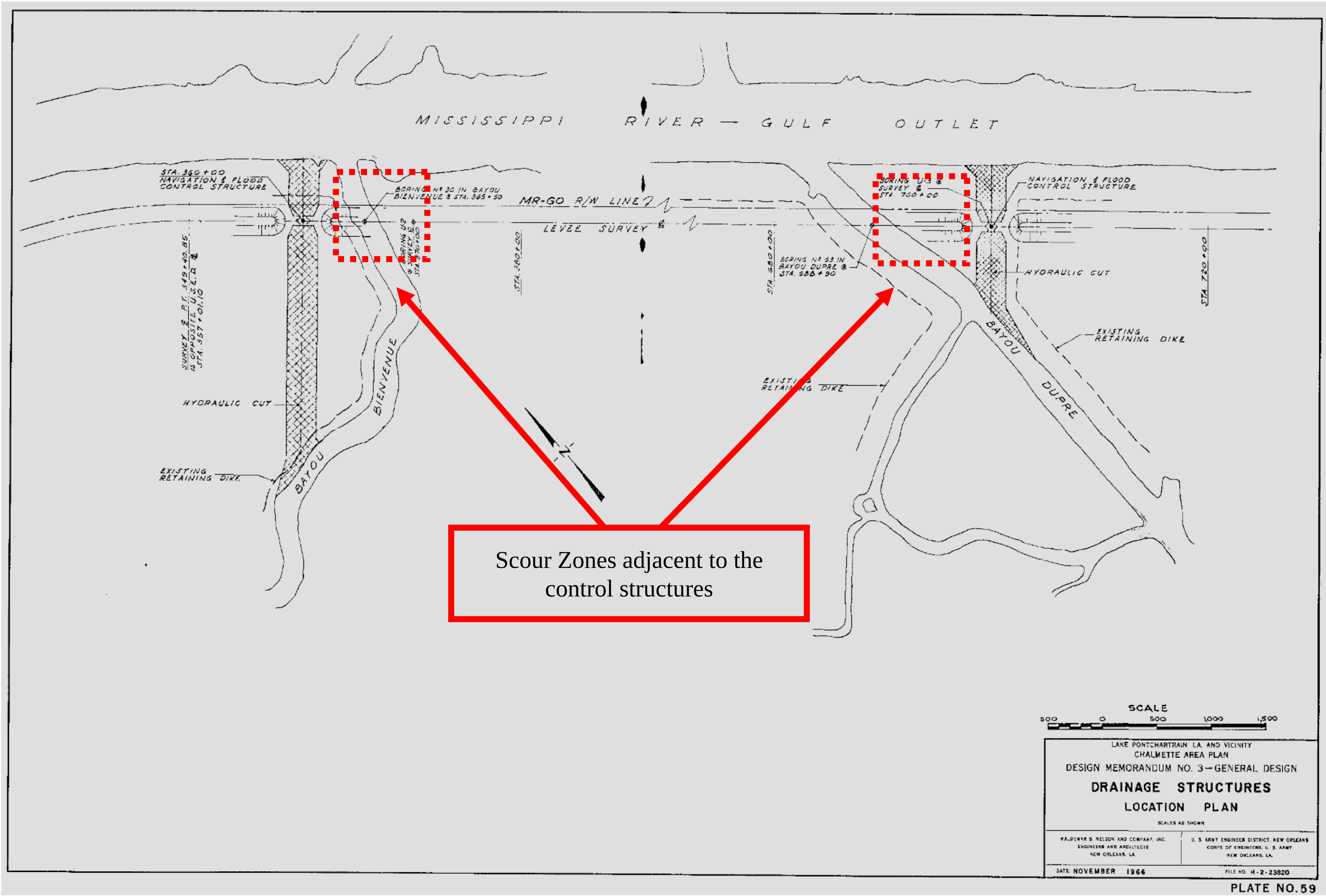
Figure 10.28: Close up aerial photograph of severely eroded MRGO levees at location 8 on Figure 10.6.

Photograph courtesy Les Harder

Figure 10.29: Control structure at Bayou Dupre (location 9 on Figure 10.6) suffered extensive scour and erosion during the storm surge and overtopping conditions associated with Hurricane Katrina.

Photograph courtesy Les Harder

Figure 10.30: Another aerial photograph of the scour and erosion damage to the Bayou Dupre control structure.



Source: USACE (1966)

Figure 10.31: Areas of severe scour and erosion damage to the two control structures appear to correspond to the alignment of the abandoned original channel.

Photograph courtesy Robert Bea

Figure 10.32: Aerial photograph taken of the repair operations at Bayou Dupre in January 2006.

Photograph courtesy Robert Bea

Figure 10.33: Close up aerial photograph showing backfilling operations at Bayou Dupre.

Photograph courtesy Rune Storesund

Figure 10.34: Eastward looking view of the earthen levee (constructed to approximately Elevation +6.0 feetMSL) immediately to the north of the Corinne Canal, east of Paris Road (location 10 on Figure 10.6). This levee was significantly overtopped and did not experience significant damage.

Photograph courtesy Rune Storesund

Figure 10.35: A fishing boat was washed over the levee shown in Figure 10.34 and landed in this Chalmette residential neighborhood within St. Bernard Parish.

Photograph courtesy Rune Storesund

Figure 10.36: The same levee shown in Figure 10.34, where a fishing boat washed over the levee during Hurricane Katrina, has been raised from an elevation of approximately +6 feet MSL to an elevation of approximately +10 feet MSL by March of 2006.

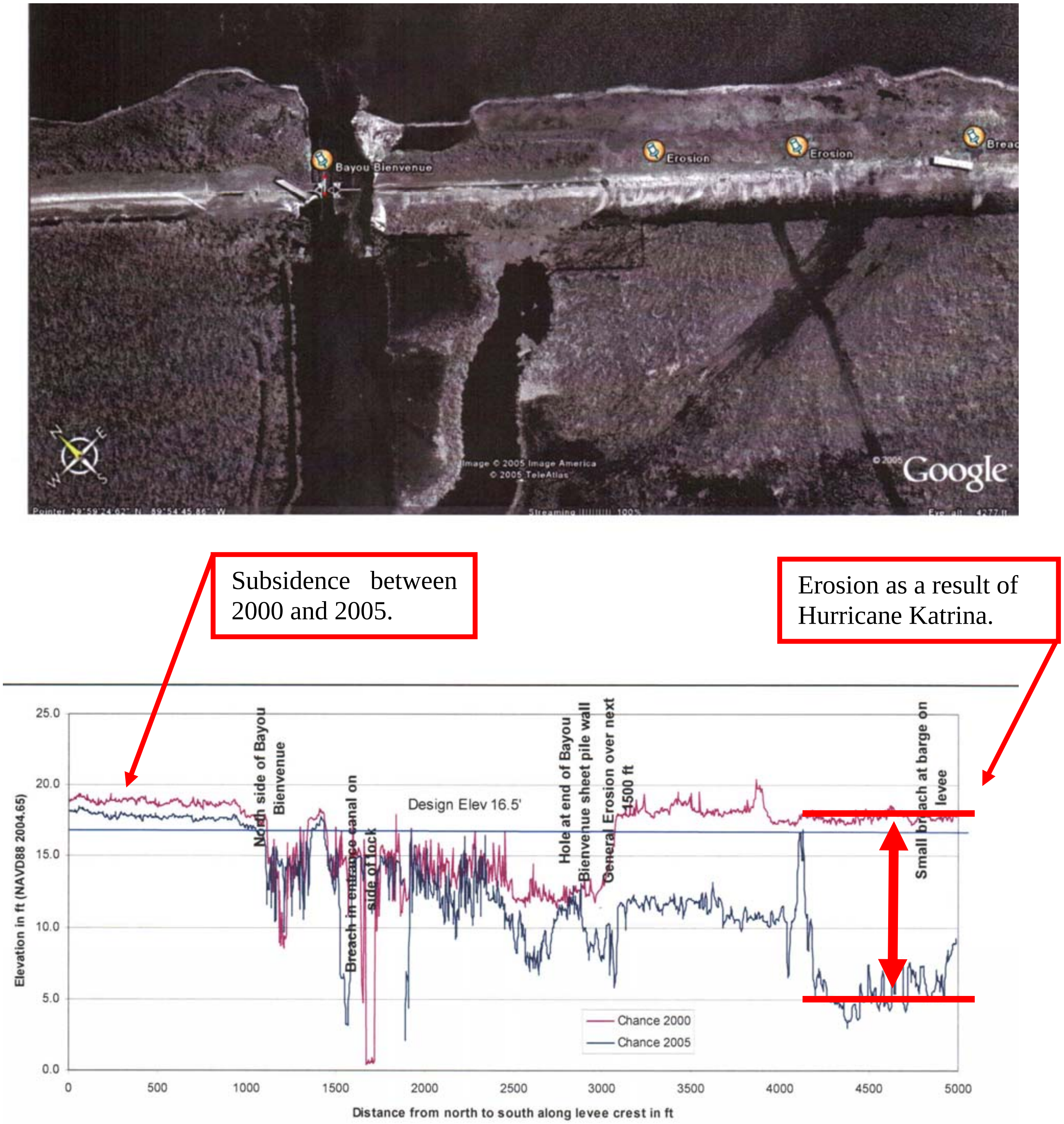


Figure 10.37. This is a comparison of two LiDAR surveys of the MRGO levee system at the Bayou Bienvenue control structure, near the intersection of the GIWW at the northeast corner of St. Bernard Parish. Effects of subsidence can be clearly seen in the elevation differences on the north side of the control structure and the control structure itself between 2000 and immediately following Hurricane Katrina in 2005. The levee on the north side of the Bayou Bienvenue control structure was largely undamaged. The levee on the south side of the control structure was catastrophically damaged. The magnitude of the erosion has been highlighted and white "splotches" of displaced levee materials can be seen in the aerial photograph (USACE 2006).

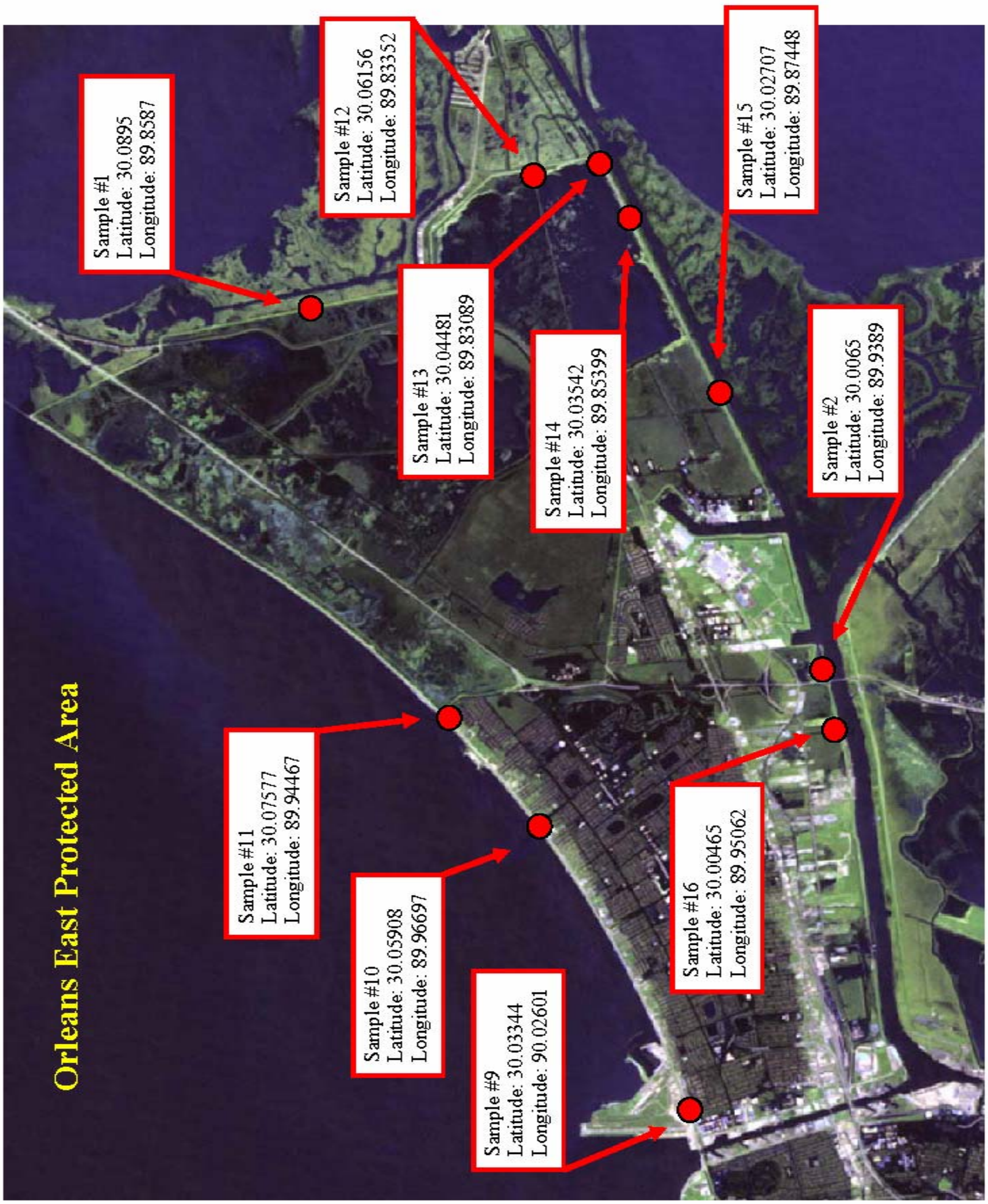


Figure 10.38: Levee sample sites within the Orleans East Protected Area.

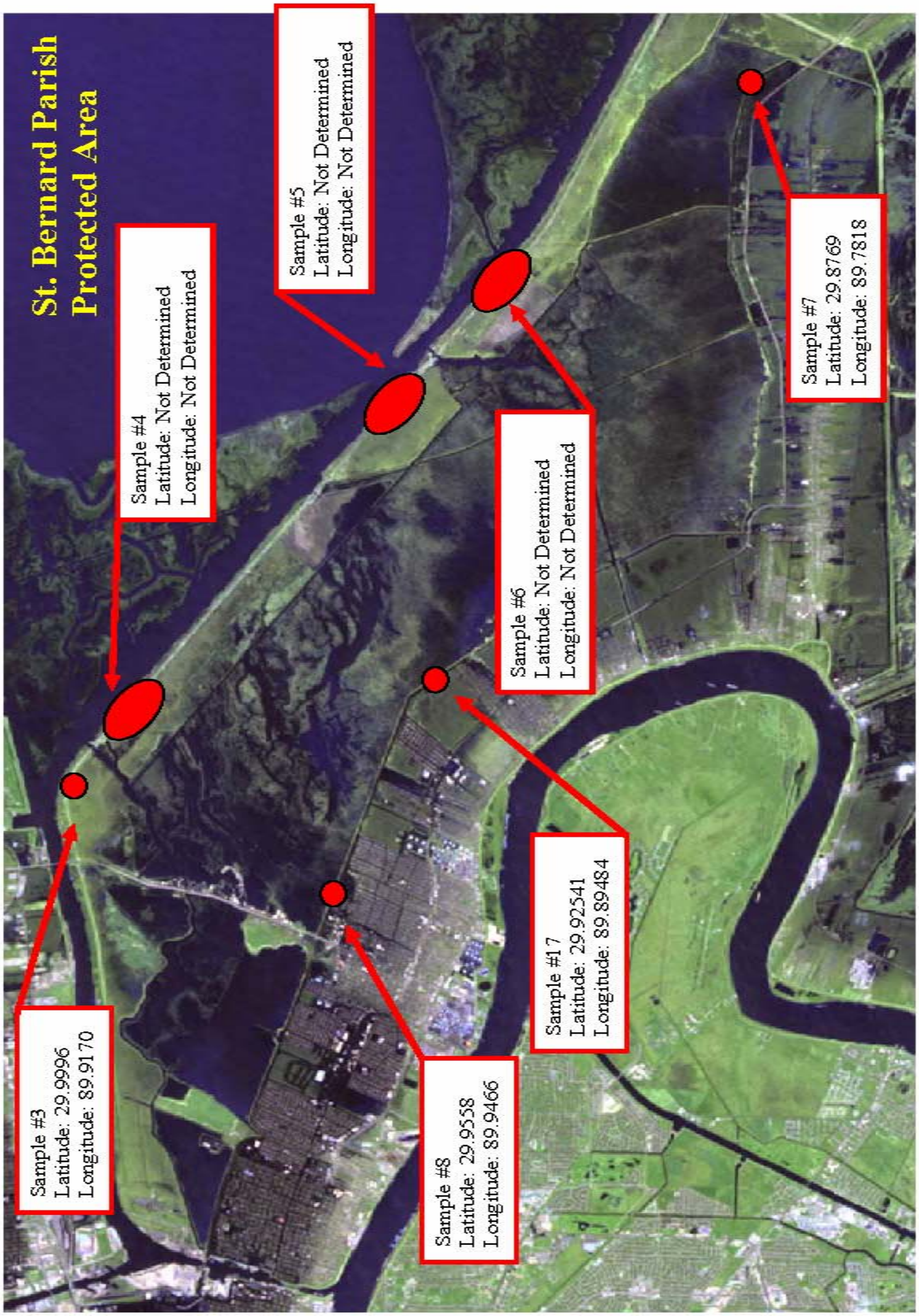


Figure 10.39: Levee sample sites within the St. Bernard Parish Protected Area.

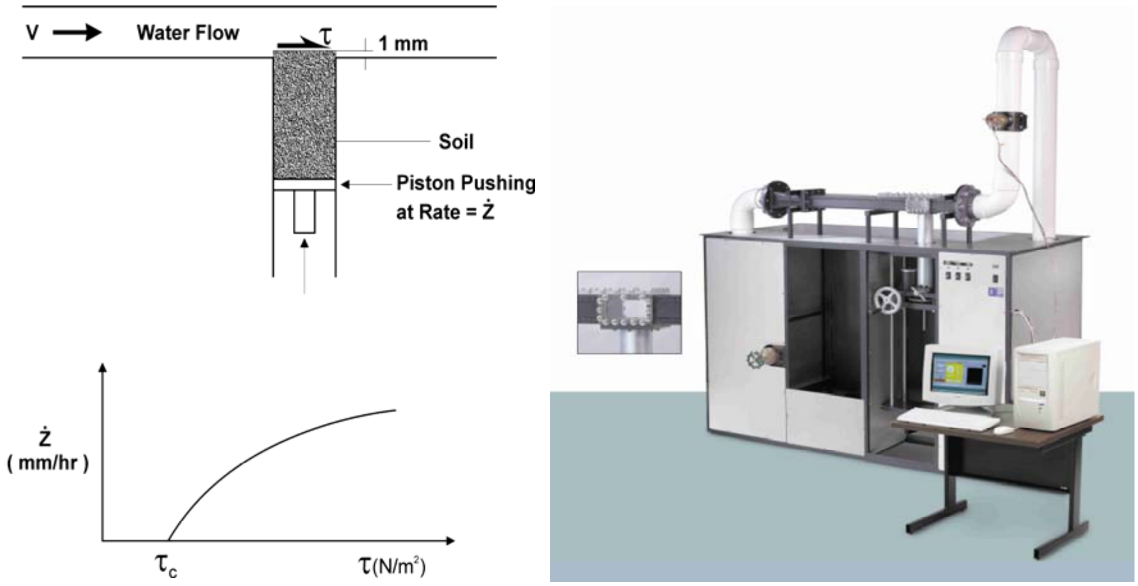


Figure 10.40: The EFA (Erosion Function Apparatus) as developed by Briaud et al. Soil samples are advanced into a rectangular tube of flowing water, creating a shear stress on top of the inserted soil sample. The velocity of the water is increased until the critical shear stress is achieved, where the soil begins to actively erode.

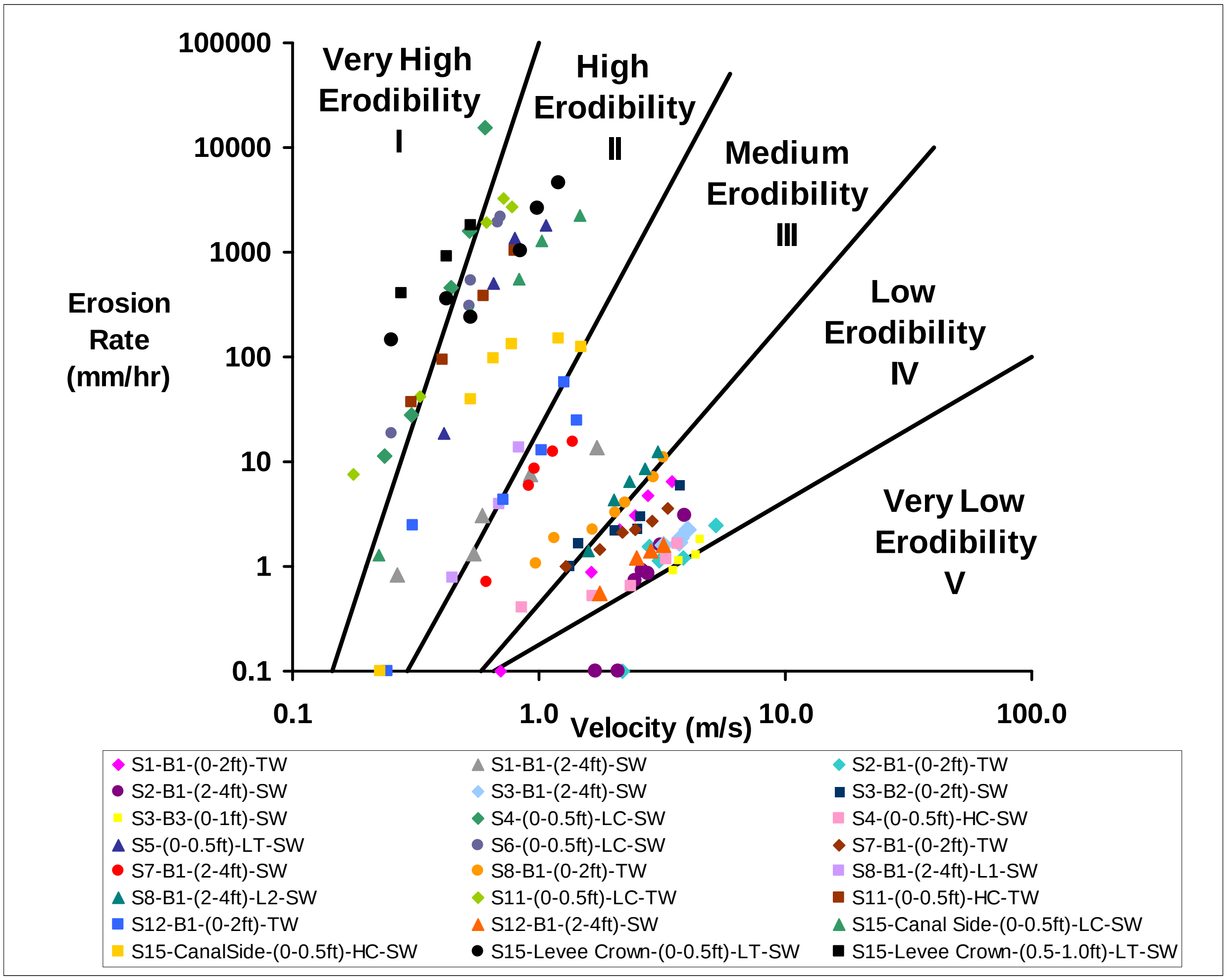
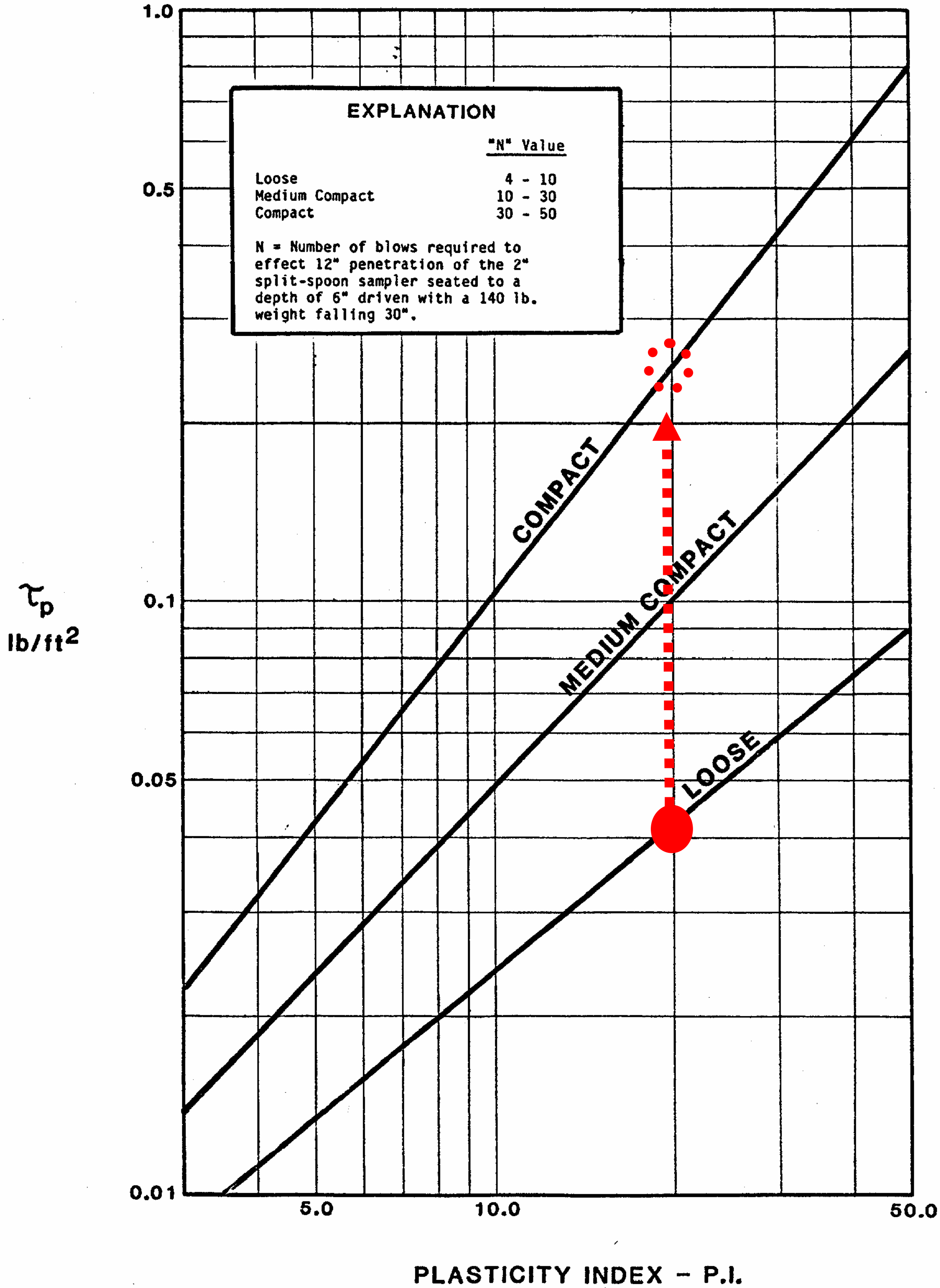


Figure 10.41: Summary of all EFA test results. The test result designations are based on the Site Number, the boring number at the site, the depth interval over which the sample was collected and sample notes. The EFA test results indicate that the materials used in levee construction varied from very high to very low erodibility, which matched the observed performance of these levees.



Graphic after FHWA 1988

Figure 10.42: The effects of compaction are clearly evident in this figure from this FHWA design guideline. For the same material (with a plasticity index of 20) a ten-fold increase in shear stress capacity can be achieved by properly compacting the material.

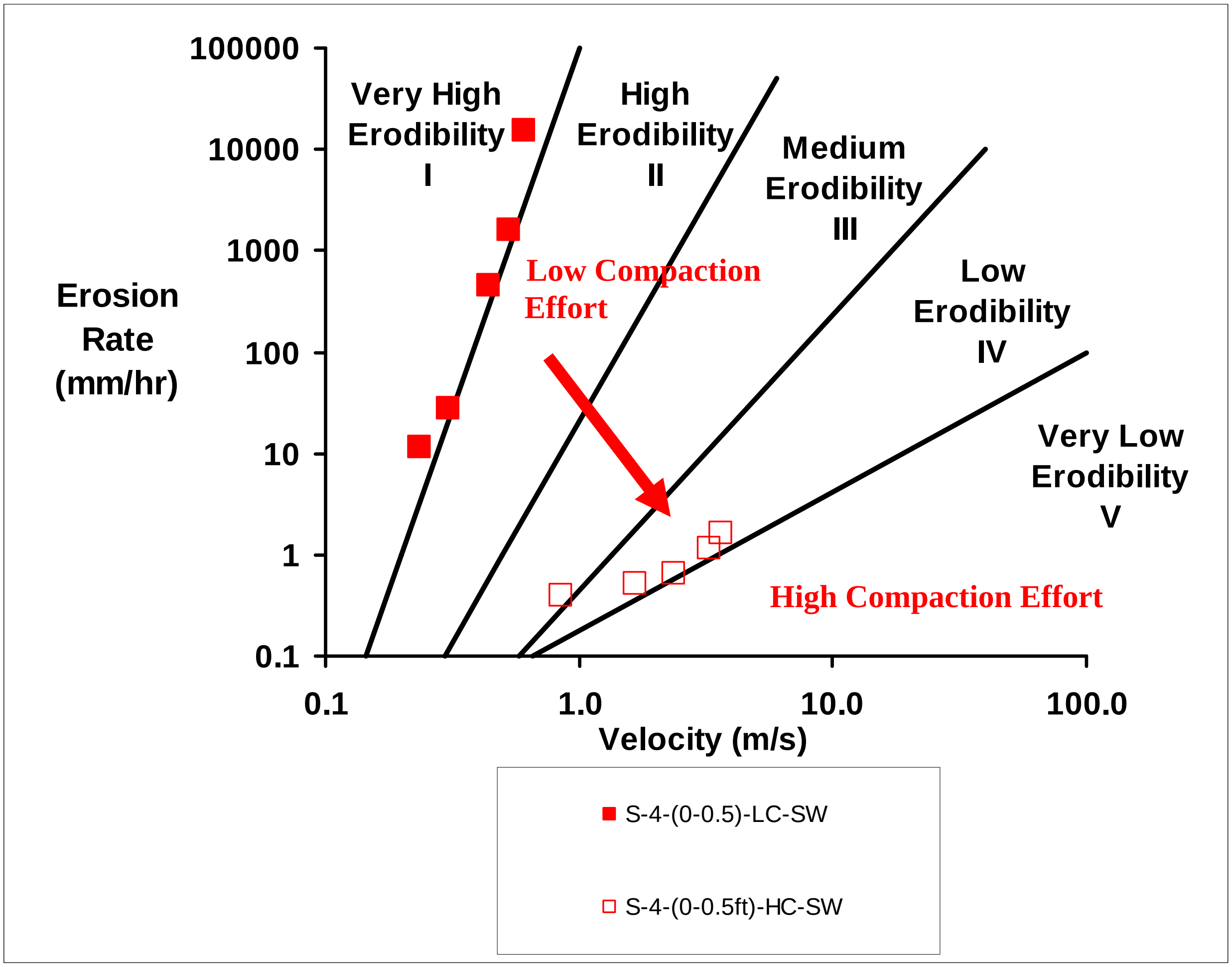


Figure 10.43: Here materials sampled from the MRGO were tested at two levels of compaction. This figure shows the dramatic impact proper compaction has on the erodibility of soils. Materials sampled from the MRGO levee were tested at two compaction levels: low compactive effort and high compaction effort. The corresponding results speak volumes to the importance of compaction in earthen levees. The low-compaction sample was found to be very highly erodible, whereas the high-compaction sample exhibited low erodibility characteristics.

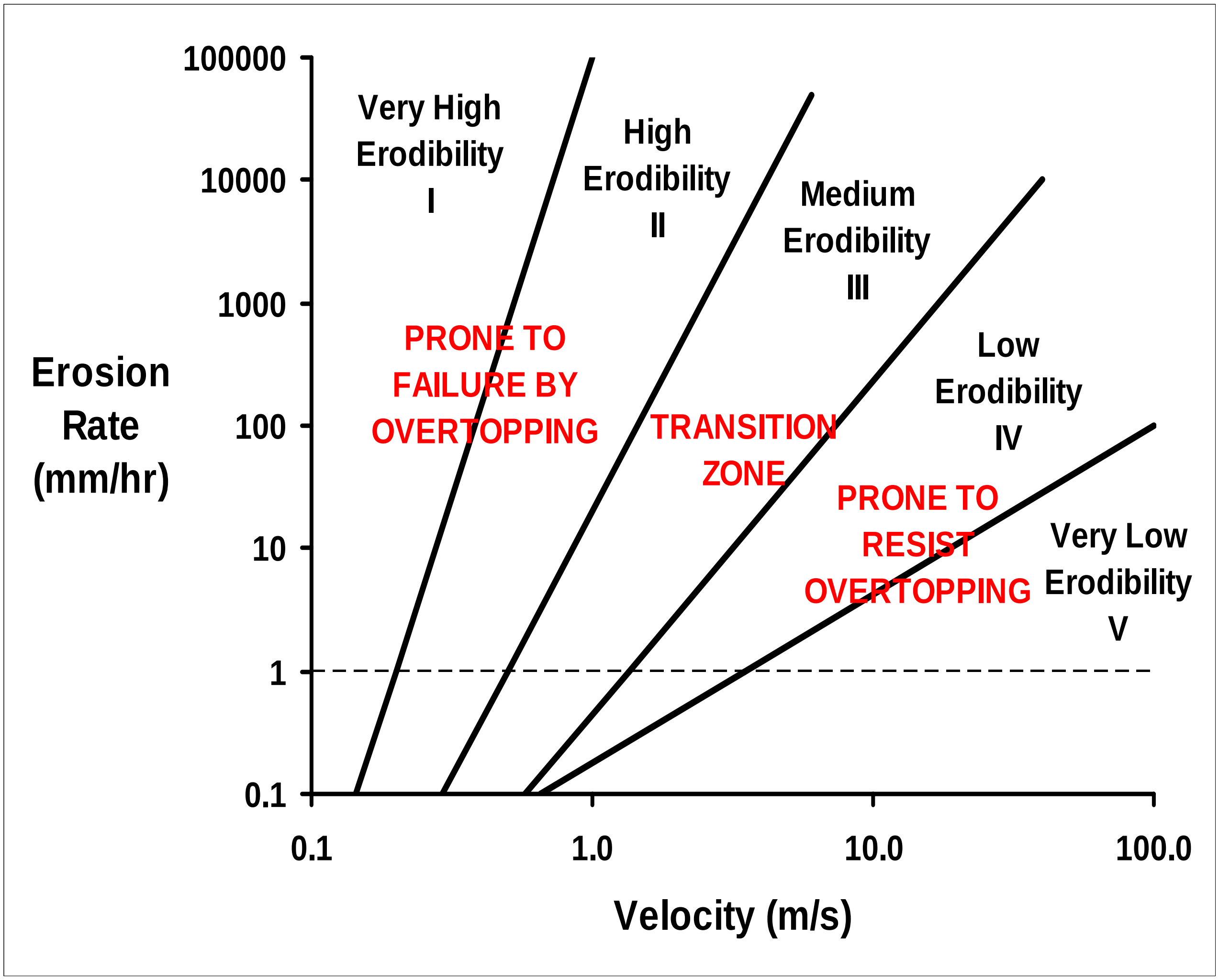


Figure 10.44: Resulting guideline table for evaluating erosion susceptibility of soils used for levee construction developed by Dr. Briaud from Texas A & M University.

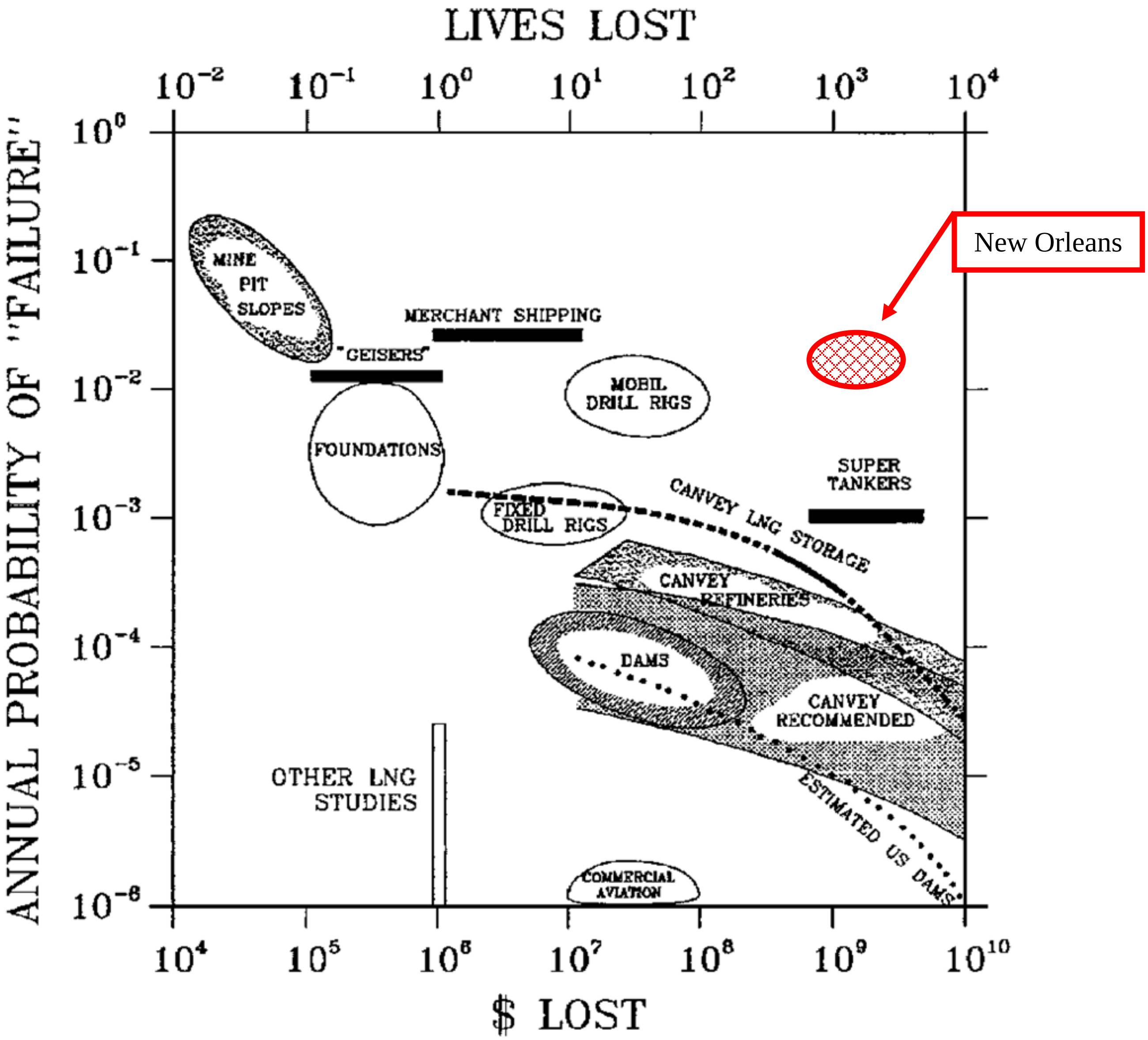


Figure 10.45: A plot of back-calculated annual probability of failure vs. lives lost and $ lost (note that either the "lives lost" or "$ lost" axes are used, they are not intended to be used in conjunction). From Christian, 2004.

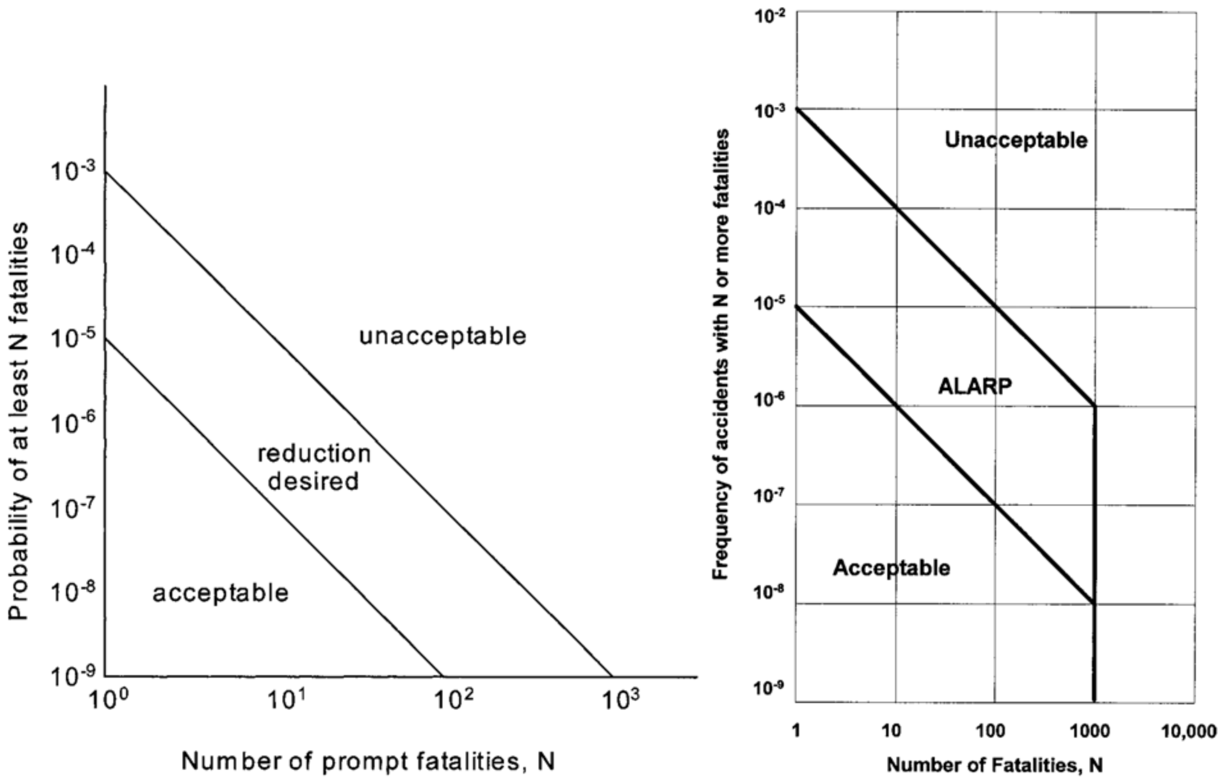


Figure 10.46: F-N diagrams adopted by the Hong Kong Planning Department (left) and F-N diagram as proposed for planning and design use in the Netherlands (right). From Christian, 2004.

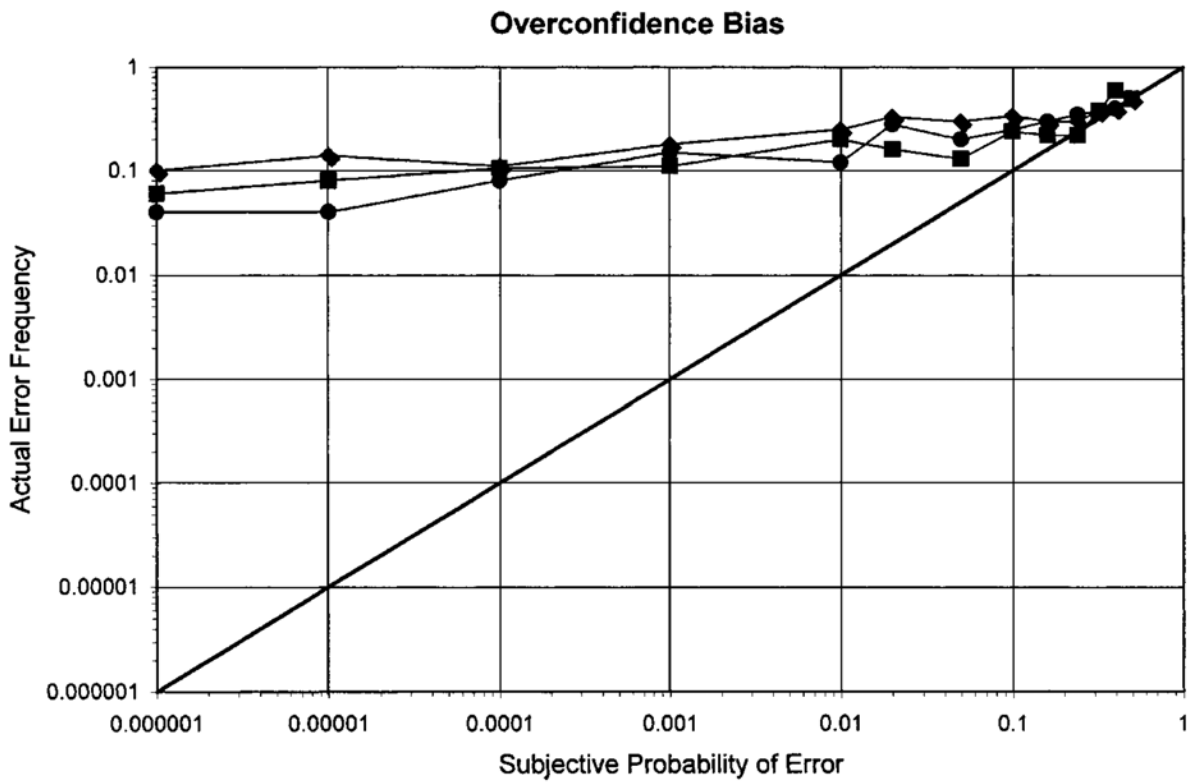


Figure 10.47: An overconfidence bias plot which shows that individuals are generally not able to distinguish the difference between high-probability events and low probability events. This implies that the "100-year" event is perceived as approximately the same level of risk as a "1,000-year" or even "100,000" year event. From Christian, 2004.

CHAPTER TWELVE: ORGANIZED FOR FAILURE

We reflect on the 9/11 Commission's finding that the most important failure was one of imagination. The Select Committee believes Katrina was primarily a failure of initiative. But there is, of course, a nexus between the two. Both imagination and initiative - in other words, leadership - require good information. And a coordinated process for sharing it. And a willingness to use information - however imperfect or incomplete - to fuel action.

Hundreds of miles of levees were constructed to defend metropolitan New Orleans against storm events. These levees were not designed to protect New Orleans from a category 4 or 5 monster hurricane, and all of the key players knew this. The original specifications of the levees offered protection that was limited to withstanding the forces of a moderate hurricane. Once constructed, the levees were turned over to local control, leaving the USACE to make detailed plans to drain New Orleans should it be flooded.

The Local sponsors - a patchwork quilt of levee and water and sewer boards - were responsible only for their own piece of levee. It seems no federal, state, or local entity watched over the integrity of the whole system, which might have mitigated to some degree the effects of the hurricane. When Hurricane Katrina came, some of the levees breached - as many had predicted they would - and most of New Orleans flooded to create untold misery.

A Failure of Initiative

Final Report of the Select Bipartisan Committee

U.S. House of Representatives, 109th Congress (2006)

12.1 Introduction

This chapter summarizes results of studies performed by members of the Independent Levee Investigation Team (ILIT) into the organizational and institutional factors associated with failure of the Flood Defense System for the greater New Orleans area (NOFDS).

Over a period of eight months following failure of the NOFDS on 29 August 2005, the ILIT examined more than 2,800 documents, conducted more than 220 interviews, and reviewed more than 370 inputs from the general public.

During the past 8 months, there have been a large number of extensive investigations into the reasons for the failure of the NOFDS. The ILIT made full use of results from these investigations. These results were combined with results from the ILIT investigations to formulate the primary findings documented in this chapter; organized for failure.

Chapter 13 outlines our thoughts on future organizational developments; *organizing for success*. Chapter 14 summarizes background on engineering a long-term NOFDS and the associated engineering guideline developments; *engineering for success*.

Appendix F presents a synopsis of the history of developments in the NOFDS between 1965 and 2005, summarizes background on understanding failures of engineered systems, and provides key quotations and results from other studies of failure of the NOFDS. Results from studies of the engineering and organizational aspects associated with future developments of a NOFDS are summarized in Appendix G. Appendix H by Dr. Edward Wenk, Jr., documents a study of *How Safe is Safe? - Coping with Mother Nature, Human Nature and Technology's Unintended Consequences*.

12.2 Purposes

The ILIT studies have two purposes:

- to understand how and why the failure of the NOFDS developed, and
- to understand alternatives to reduce the likelihoods and consequences of such future catastrophes.

If we can adequately understand the mistakes of the past, then perhaps we have a chance to avoid making them in the future.

The ILIT approach in this study was to include historical and organizational - institutional issues, political and budgetary considerations, decision making, utilization of technology, and the evolving societal, governmental, and organizational priorities over the life of the NOFDS. One cannot develop an adequate understanding of the failure of the NOFDS without understanding both the engineering and organizational factors that were interwoven in development of this failure.

12.3 Failure of the NOFDS

Of particular importance in this diagnosis is the organizational - institutional *Technology Delivery System (TDS)* that was used to develop the NOFDS. This TDS is comprised of three major components:1) Government (federal, state, local), 2) Industry, and 3) the Public. All of these components and elements are interconnected through a complex series of multiple connections that represent information and communication transmission. Inputs to the system include technical information, human and natural resources, capital, manufactured goods and services and values and preferences. Outputs from these components are represented in the NOFDS including its intended and unintended consequences.

The Government component is represented by agencies from all three branches (executive, legislative, judicial) at federal, state, and local levels. There are important multiple connections among federal, state, and local (parish, city) agencies. In the case of the NOFDS, the primary agencies are the Corps of Engineers, the Louisiana Department of Transportation and Development, and the parish levee and sewerage and water boards. All of these government agencies are interconnected with a multitude of other federal, state, and local agencies. These parts of the TDS were summarized by the Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina (2006):

> *Several organizations are responsible for building, operating, and maintaining the levees surrounding metropolitan New Orleans. USACE generally contracts to design and build the levees. After construction USACE turns the levees over to a local sponsor. USACE regulations state that once a local sponsor has accepted a project, USACE may no longer expend federal funds on construction or improvements. This prohibition does not include repair after a flood. Federally authorized flood control projects, such as the Lake Ponchartrain project, are eligible for 100 percent federal rehabilitation of damaged by a flood.*
>
> *The local sponsor has a number of responsibilities. In accepting responsibilities for operations, maintenance, repair, and rehabilitation, the local sponsor signs a contract (called Cooperation Agreement) agreeing to meet specific standards of performance. This agreement makes the local sponsor responsible for liability for that levee. For most of the levees surrounding New Orleans, the Louisiana Department of Transportation and Development was the sate entity that originally sponsored the construction. After construction, the state turned over control to local sponsors. These local sponsors accepted completed units of the project from 1977 to 1987, depending on when the specific units were completed. The local sponsors are responsible for operation, maintenance, repair, and rehabilitation of the levees when the construction of the project, or a project unit, is complete.*

In development of the NOFDS, the Corps of Engineers had the primary responsibilities for development of the concepts, design, and construction (Collins 2005; National Academy of Engineering 2006). Once construction was completed, the operations and maintenance were then turned over to the responsible state and parish agencies. At the federal level, the Corps of Engineers had important interfaces with the executive branch (e.g., Department of Defense and White House), the legislative branch (Congress), and the judicial branch. Important interfaces also developed with state, parish, and city government agencies, industry, and with the general public. The Industry component is represented by commercial enterprises that are involved throughout the life-cycle of the system including concept development, design, construction, operation, and maintenance. The Public component is represented by national, state, and local individuals and groups that are concerned with and influenced by the NOFDS.

12.4 Extrinsic Factors

Failure of the NOFDS is firmly rooted in *Extrinsic* factors associated with human and organizational performance (Appendix F; Rasmussen 1997; Svedung and Rasmussen 2002; Bea 2006). Causes of the NOFDS failure spanned the full spectrum of organizational failures: cultures, communications, lack of knowledge, use of existing technology, structure and organization, management, leadership, monitoring and control, and mistakes. Mistakes involved breakdowns in perceptions, interpretations, decisions, discrimination, diagnoses, judgments, and actions. In several notable cases, doing things right and doing the right things apparently were surrendered to getting the job done in an expedient way. These observations were summarized by the Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina (2006):

> *Both USACE and the local sponsors have ongoing responsibility to inspect the levees. Annual inspections are done both independently by USACE and jointly with the local sponsor. In addition, federal regulations require local sponsors to ensure that flood control structures are operating as intended and to continuously patrol the structure to ensure no conditions exist that might endanger it. Records reflect that both USACE and the local sponsors kept up with their responsibilities to inspect the levees. According to USACE, in June 2005, it conducted an inspection of the levee system jointly with the state and local sponsors. In addition, GAO reviewed USACE's inspection reports from 2001 to 2004 for all completed project units of the Lake Ponchartrain project. These reports indicated the levees were inspected each year and had received 'acceptable' ratings.*
>
> *However, both the NSF-funded investigators and USAACE officials cited instances where brush and even trees were growing along the 17th Street and London Avenue canals levees, which is not allowed under the established standards for levee protection. Thus, although the records reflect that inspections were conducted and the levees received acceptable ratings, the records appear to be incomplete or inaccurate. In other words, they failed to reflect the tree growth, and of course, neither USACE nor the local sponsor had taken corrective actions to remove the trees.*

Complex formal and informal organizations developed that involved a multiplicity of federal, state, parish, city, commercial - industrial, and public enterprises. These organizations had vastly different means, methods, and resources that evolved in different ways at different times. Executive, legislative, and judicial forms of government provided a primary framework for interactions with commercial, industrial, public, and private enterprises. Malfunctions within and between these organizational elements provided the primary element responsible for the failure of the NOFDS (Government Accountability Office 2005, Members Scholars of the Center for Progressive Reform 2005, Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina 2006, Townsend 2006, Houck 2006). Ineffective leadership and management were evident before and after failure of the NOFDS. Leonard and Howitt observed (2006):

> *The leadership failures that contributed to the events we witnessed on the Gulf Coast last August and September began long, long before Katrina came ashore. It literally took centuries to make the mistakes that rolled together to make Katrina such a vast natural and human-made calamity. First, for hundreds of years,*

people have been constructing and placing large amounts of previous (human lives) and expensive (infrastructure, homes, communities) value in new Orleans and along the Gulf Coast in the known path of severe storms. Second, for decades, we have been living with inadequately designed, built, or maintained man-made protections (levees, building codes, pumps, and so on), and have pursued policies and interventions that actively contributed to the destruction of the natural buffers (salt marshes, dunes, and other natural barriers) against the hazards created by placing value in harm's way. Third for years - at least since 9/11, but even before that - we have known that we had systems of preparation and response that would prove inadequate against truly large scale disasters. Fourth, in the days and hours before Katrina's landfall, we failed to mobilize as effectively as we might have those systems that we did have in place. And fifth, the days following the impact, we did not execute even the things that we were prepared to do as quickly and smoothly as we should have. How do we not, in the future, find ourselves again with those same regrets? Our work needs to begin with a judicious and honest assessment of threats, followed by investments in prevention and mitigation and by construction of response systems that will be equal to a larger of class of disturbances than we have previously allowed ourselves to contemplate."

In development of the analysis of Extrinsic factors involved in failure of the NOFDS, it is important to recognize that while the Corps of Engineers was primarily responsible for design and construction of the NOFDS and the local state and parish organizations (e.g., Department of Transportation and Development, Levee Boards, Sewerage and Water Boards) were primarily responsible for operations and maintenance, these organizations were subjected to a wide variety of influences and constraints provided by their executive, legislative, judicial and public constituents. The responses of these multiple organizations to provide an adequate NOFDS was clearly lacking. The Senate Committee on Homeland Security and Governmental Affairs report supports this (Leonard and Howitt 2006).

For many years, the Corps of Engineers was severely criticized for delays and cost increases in the Lake Pontchartrain and Vicinity Hurricane Protection Project (Government Accountability Office 1972, 1982, 2005b, 2005c; Carter 2003, 2005a, Carter and Sheikh 2003, Carter et al 2005). Many of these delays and cost increases were reflections of challenges posed by local cost sharing and participation requirements. Local participation and funding requirements introduced additional problems as did interactions with the general public. Additional complexities were added by federal and state legislative, executive, and judicial participation in the developments (lots of 'managers' with different goals, objectives, means, and methods).

At the federal level a long and complex process is required to identify, define, select, and develop projects and secure funding authorizations (Carter and Hughes 2005, Carter 2005d). Historic problems exist with project backlogs, increases in funding requirements, reprogramming actions to manage project funds, and even the fundamental basis for project selection; cost-benefit analyses (Government Accountability Office 1983, 2003, 2005). In short, the Corps must operate in a world that is not of its own making. Outside pressures on the Corps have been negative as well as positive in terms of their effects on performance.

This study indicates that the historic procedures utilized to develop the cost-benefit analyses employed by the Corps of Engineers were and are seriously flawed. These procedures are apparently responsible for some of the seemingly illogical elements in the NOFDS. All costs and all benefits are not incorporated into these analyses (General Accountability Office 2003, Heinzerling and Ackerman 2002). These analyses fail to recognize many important considerations, uncertainties and projected future developments (Government Accountability Office 2003).

Because of the multitude of recognized deficiencies presently incorporated into traditional Corps cost-benefit analyses, flawed information is provided to policy makers to help them make wise decisions regarding provision of financial resources to develop an adequate NOFDS. Within the executive branch, the Office of Management and Budget has the responsibility to ensure the quality of cost-benefit analyses and resource recommendations, yet the deficiencies were not effectively addressed.

This study indicates that many of the flaws that were introduced into the NOFDS came from flawed decision making regarding provision of financial resources by many organizations at many levels, times, and places. The exceedingly complex and flawed organizational system and its decisions regarding provision of resources that evolved during development of the NOFDS was a primary cause of the failure of the NOFDS. The Corps of Engineers does have and use advanced methods to evaluate costs, benefits, and risks for flood damage reduction studies and dam safety (National Research Council 1983; U.S. Army Corps of Engineers 1996; Powers 2005). Application of these advanced methods was not in evidence in the background available on development of the NOFDS. The substantial body of technology developed to assist risk management decision making (e.g., Fischhoff et al. 1981; Wenk 1989; Shapira 1995; Molak 1997; Kammen and Hassenzahl 1999; Spouge 1999; Moteff 2004; Jordan 2005; see Appendix H) should be further developed, codified and applied by the Corps to assist policy makers in decisions regarding development and maintenance of levees and flood protection systems.

For many years, the Corps of Engineers has been subjected to extreme pressures at the federal and state levels to do more with less (Government Accountability Office 1997; Office and Management and Budget 2006); do their projects better, faster, and cheaper; and improve project management (planning, organizing, leading, controlling). The organization's attempt to respond to all of these frequently conflicting pressures has introduced organizational turbulence and diversion of attention and resources that continues the present time. The Corps of Engineers developed a plan to re-engineer itself (U.S. Army Corps of Engineers 2003b). However, it is clearly struggling with all of its constraints to achieve key elements in this plan (Office of Management and Budget 2006). Our study indicates that as in the case of NASA (Appendix F) technical and engineering superiority and oversight was compromised in attempts to respond to all of these constraints and pressures. Adequate quality and reliability in the constructed works has suffered and will continue to suffer until these challenges are successfully addressed.

Evidently the organizations responsible for the various parts of the life-cycle of the NOFDS did not have effective process auditing procedures (Knoll 1986). They did not have incentive systems that discouraged excessive and inordinate risk taking that could lead to less than desirable quality and reliability. Quality standards did not meet or exceed the referent standards required for a high quality and reliable NOFDS. These organizations did not correctly assess the risks associated with given problems or situations; apparently, situational awareness was frequently lost. These organizations lacked strong command and control systems as evidenced with appropriate rules and procedures, effective selection and training of personnel, decisions being made in the rights ways at the right times by the right people, effective redundancy (robustness) to create tolerance to organizational defects, and maintenance of situational awareness for appropriate action. In general, these organizations performed as Low Reliability Organizations (Weick and Sutcliffe 2001). Effective leadership and management was lacking (Townsend 2006; Collins 2005; Government Accountability Office 2006). Such organizational malfunctions were summarized by Irons (2005):

> *The evidence indicates the U.S. Army Corps of Engineers knew about the threat of breaches, as opposed to overtopping, since the early 1980s. Moreover, all concerned agencies, including those at the local, state, and federal levels, knew about the threat of overtopping and consequent flooding in even a Category 3 hurricane.*
>
> *Basic flaws in the design of the levee protection system were first recognized over two decades ago, before the wetlands were so diminished. An outside contractor, Eustis engineering, was the first to express concerns about the levee vulnerability to breaching in the early 1980s. In 1981, the New Orleans Sewerage & Water Board developed a plan to improve street drainage by dredging the 17th Street Canal. The Corps of Engineers issued permits to do the dredging in 1984 and 1992, though the Corps was not a partner in the Project. Eustis Engineering contracted to do a design study for Modjeski and Masters, the consulting engineers on the project, and performed soil investigations on a section of the 17th Street Canal from south of the Veterans Memorial Boulevard bridges to just north of those structures. They found that 'the planned improvements to deepen and enlarge the canal may remove the seal that has apparently developed on the bottom and side slopes, thereby allowing a buildup of such pressures in the sand stratum.' Eustis' concerns about a 'blow-out', or breach, of the levee were strong enough that the company recommended test dredging before the final design.*
>
> *…The most puzzling point about the dredging project is that the Corps of Engineers planned to follow the project by raising the floodwall from 10 feet to 14.5 feet. It is unclear whether the Corps paid attention to the contractor's concerns since most of the documents related to the work remain unavailable to the public. Although the Corps of Engineers was not a direct partner in the dredging, it was aware of the work and knew it would have an impact on its later project. Indeed, contractors working for the Corps on the later project raised their own concerns about the soil and foundations of the levee.*
>
> *Reports indicate that key sections of the levee system's soil and foundation, particularly the floodwall on the 17th Street Canal where much of the serious flooding occurred, posed serious problems for the contractors involved. Court papers from 1998 show that Pittman Construction indicated to the Corps of Engineers as early 1993 that the soil and foundation for the walls were 'not of sufficient strength, rigidity and stability' to build on. The construction company claimed that the Corps of Engineers did not provide it with complete soil data when it developed a bid on the levee project.*
>
> *…Engineers now say the difficulties Pittman Construction faced were early warning signs that the Corps of Engineers ignored. The Corps of Engineers officially disputed the points made by Pittman Construction regarding the soil condition, though it now seems clear that the crucial breaches in New Orleans occurred in levees where the floodwall foundations were not as deep as the canals*

and that the Corps of Engineers was aware of the issue.… Would an organization with processes in place to support ongoing learning, and surprise-avoidance, fail to recognize the legitimacy of the contractor's point rather than argue about purely budgetary issues related to the contract?

Principal knowledge related malfunctions centered inappropriate use of existing technology (unknown knowables) and inadequate measures to disclose unknowns throughout the life-cycle of the NOFDS. Examples include the subsidence and settlements of critical flood protection elements in the NOFDS including those of the floodwalls along the drainage canals (about two feet below intended elevations), the Industrial Canal floodwalls (about three feet below intended elevations), and the levee elevations along the Mississippi River Gulf Outlet (MR-GO) that front the south side of Lake Borgne (about two to three feet below intended elevations) (Interagency Performance Evaluation Task Force, 2006a, 2006b). Concerns for settlements and subsidence were expressed early in the development of the NOFDS, but apparently no effective action was taken to quantify the regional subsidence and settlements and to make appropriate adjustments to the NOFDS. Even though information was developed by the National Geodetic Survey that the reference benchmarks being used in construction of the NOFDS were in excess of one foot low, the decision was made in August 1985 to use the benchmarks "current at the time of construction of the first increment of the project" (1965) (Chatry 1985). The report of the Senate Committee on Homeland Security and Governmental Affairs observed (2006):

In Designing, constructing and maintaining the hurricane-protection system the Corps did not adequately address: (a) the effects of local and regional subsidence of land upon which the protection system was built; and (b) then-current information about the threat posed by storm surges and hurricanes in the region.

Another important example of knowledge development and utilization malfunctions is that of the overtopping and breaching of the levees and flood control structures along the MR-GO. Of particular importance is the stretch of levee that defends St. Bernard Parish between bayou Bienvineu and bayou Dupre flood control structures. This stretch of levee was badly damaged during hurricane Katrina as were sections where the levee joined the flood control structures (Seed et al 2005). The current work of the ILIT indicates that the sections adjacent to the flood control structures breached where the construction had covered the original bayou channels. The design of the junctions between the flood control structures and the earth levee were not sufficient to withstand the surge and wave action developed during hurricane Katrina. In a similar manner, the levee between Dupre and Bienvineu was not able to withstand the waves and surge that developed across lake Borgne; it was severely breached. The ILIT indicates that the wave and surge velocities that preceded the arrival of the peak surge likely were initiating breaching before the levee was overtopped so that when the levee was overtopped, the breaches could be readily expanded and allow large volumes of water to enter the protected areas in St. Bernard parish. In contrast, the performance of the levee north of bayou Bienvineu to its intersection with the ICWW was markedly different. Our studies indicate that this performance resulted from a combination of factors that included superior soils used in construction of this stretch of levee (highly erosion resistant) and natural protection (water velocity reduction) afforded by adjacent wetlands.

The MR-GO is a 76-mile long navigation channel connecting the Gulf of Mexico to the Port of New Orleans Inner Harbor Navigation Canal via the ICWW. The channel bisects the marshes of lower St. Bernard Parish and the shallow waters of Chandeleur Sound. Construction of this canal was authorized by Congress in 1956. Its construction was started in 1958 and completed in 1965. Many people contend that the MR-GO played a prominent role developing the flooding of St. Bernard parish and East New Orleans during hurricane Betsy (1965). Before, during, and after construction of the MR-GO (48 years) many concerns were expressed for the effects of this canal on the adjacent wetlands and on its potential focusing effect on surge propagation into the IHNC. Originally conceived as a way to get deep draft ships to the Port of New Orleans facilities in the IHNC, it failed to realize its commercial justification because of changes in ships (deeper drafts) and because of the need for almost continuous dredging to keep the channel open. The channel also allowed the highly saline waters from the Gulf of Mexico to intrude into the adjacent fresh and brackish water wetlands and marshes destroying many in the process (estimated more than 20,000 acres of marsh have been destroyed). In 1988, the St. Bernard Parish Council unanimously adopted a resolution to close MR-GO because it constituted a threat to public health and safety. In October 2004, the Louisiana Legislature passed a resolution urging closure of the MR-GO and immediate implementation of remedial measures to address the risk posed by the MR-GO.

Available information and soil sampling conducted during this study indicates that the levee between bayous Bievenieu and Dupre originally were constructed from dredge spoil deposited during the construction of the MR-GO (A. Theis, personal communication, January 2006) (see Chapter 9). Additional construction was proposed to increase the height of the levee at the time of hurricane Katrina. While these materials were highly susceptible to scour and erosion, the ILIT study failed to disclose documentation of plans or proposals for armoring this levee prior to hurricane Katrina.

Given the recognized degradation of the protection afforded by wetlands (Hallowell 2001), recognition of the erodability of the levee soils, the lack of provision for protection of the levee soils, recognized deficiencies in the design criteria, the continued challenges of keeping these levees at their authorized elevations (significant subsidence and compaction), and the repeated expressions of concerns for the adequacy of these protective works, the performance of this part of the NOFDS was a "predictable surprise." The Member Scholars of the Center for Progressive Reform (2005) arrived at similar conclusions.

Rejection and misuse of technology are evident in the history of the NOFDS. Interactive risk assessment and management approaches (e.g., Quality Assurance and Quality Control) (Knoll 1986; Loosemore 2000) to help detect, analyze, and correct knowledge related challenges apparently failed for a wide variety of reasons including excessive authority gradients, low task and situational awareness, excessive professional courtesy, cultural-societal morays, excessive beliefs, deficiencies in communications, and deficiencies in resource and task management. Irons observed (2005):

> *The U.S. Army Corps of Engineers is historically an insular agency, known for doing things its own way. It is not possible to say whether surprise-avoidance processes are in place at the Corps of Engineers, until the public receives more access to internal documents. The failure of Corps' staff to recognize and prioritize the challenges of levee upgrades and receding wetlands to the city of New Orleans, and surrounding areas, strongly suggests that surprise-conducive processes characterize its organization. The Corps' organization has over the past few decades outsourced more work, lost many engineers to private industry, and consequently suffered a diminished capacity to attract top-notch engineers.*

> *New Orleans had dodged the bullet many times, with the major force of hurricanes skirting around the area. Nevertheless, most people with a reason to know about it were aware that a Category 3 hurricane posed a severe threat to the New Orleans' levee protection system, and a Category 5 hitting land as a Category 4, as with Katrina, posed a catastrophic threat.*
>
> *The occurrence of a hurricane like Katrina was not unexpected in New Orleans; neither were the complications faced in the aftermath of the storm. Given this understanding, and the neglect in preparing for a hurricane like Katrina, as well as the ineffective response preparations, it seems reasonable to assert that Katrina as well as its aftermath was a predictable surprise. The threats posed by the hurricane, and the likely aftermath, were well known and unsurprising to most who thought about the hurricane threat to New Orleans. Unfortunately, much of the local, state, and federal leadership, especially the U.S. Army Corps of Engineers, appears to have remained complacent about preparing the levees for a catastrophic hurricane.*

All of these Extrinsic factors represent corporate failures in making decisions that involved all components of the TDS, including the public. The right things were traded-off for the wrong things at the wrong times and in the wrong ways. The failure of the NOFDS has all of the same ingredients found in previous catastrophic failures and accidents (Appendix F). It involved many different people and organizations developing a wide variety of malfunctions (e.g., decisions) over a long period of time (40 years). While a majority of these malfunctions were embedded during the concept and design phases, early warnings that indicated ‘all was not well’ as the NOFDS developed were not detected, analyzed, and corrected. When hurricane Katrina tested the flawed, defective, and deficient NOFDS, it failed catastrophically producing the single most catastrophic failure of an engineered system in the history of the United States.

12.5 Intrinsic Factors

Intrinsic factors representing natural variability and analytical modeling uncertainties also played roles in the failure of the NOFDS (Vick 2002; Bea 2006). There are fundamental flaws in basic criteria and guidelines used to design the NOFDS. These flaws include engineering elements that address:

- Design *demands* for the elements of the NOFDS including the Standard Project Hurricane (SPH) conditions (surge heights in the NOFDS, frequency of occurrence, and lack of explicit recognition of effects of more intense hurricanes) (Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina 2006, ASCE 2006a). Even though studies after 1972 indicated the need for increases in the design flood protection elevations due to greater surge and wave heights, these were not reflected in revised design guidelines (Brouwer 2003; Carter 2005a, 2005b).
- Design *capacities* for the elements of the NOFDS including engineering guidelines used to design and construct the levees and floodwalls (e.g., analyses of levee stability, levee stability factors of safety, analyses of floodwall/sheetpile stability, deformation and stresses, floodwall design factors of safety, provision for deformations in the floodwalls during surge loading, provisions for robustness - defect and damage tolerance and fail-safe performance, and provisions for subsidence) (Select Bipartisan Committee to Investigate the Preparation

for and Response to Hurricane Katrina 2006; Vartabedian and Braun 2006; Irons 2005; ASCE 2006b).

- Configuration of the elements that comprise the NOFDS as an *integrated flood defense system* (Seed et al. 2005, ASCE 2006a). Many failures of the NOFDS occurred at a variety of types of interfaces in the physical elements such as interfaces between earth levees and concrete and steel flood protection elements and between the flood control structures and pump station structures (Carter 2005a). Flood discharge pumps were not sufficiently protected from backflow and exacerbated flooding. Many vulnerabilities were found at transitions and interfaces between flood protection elements and / or where other infrastructure are involved (Seed et al. 2005). The NOFDS was not an integrated, coherent system; rather "*it is a jointed series of individual pieces conceived and constructed piecemeal*" (ASCE 2006a).

12.5.1 Standard Project Hurricane

The heart of most Corps of Engineers hurricane protection projects since the 1960s has been the SPH (Carter 2005a, Government Accountability Office 2005a, 2005b). The SPH was developed by the National Weather Service and the Corps of Engineers at the request of Congress in the 1950s "to provide generalized hurricane specifications that are consistent geographically and meteorologically for use in planning, evaluating and establishing hurricane design criteria for hurricane protection works" (Grahan and Nunn 1959). Attempts to describe the SPH in terms of Categories has lead to confusion because the SPH preceded development of the Saffir-Simpson hurricane scale (Categories),. Depending on what characteristic of a hurricane is referenced, the SPH can vary from a Category 2 to a Category 4 storm.

A primary goal of the SPH was to compare hurricane protection standards from region to region (Perdikis 1967). This standardized approach led to disparities within a particular region. The SPH model excluded storms that were deemed to be inordinately severe. For example, the 1979 revision of the SPH removed two particularly severe storms from the data base; hurricane Camille of 1969 and the Labor Day Hurricane of 1935. Experience shows that excluding outlier data is not appropriate in the context of dealing with extreme hazards. In addition, a higher standard of protection was specified for facilities and areas "where high winds, waves and storm surge could pose a threat to the public health and safety from a hurricane-induced accident at a nuclear power plant" (Schwert et al 1979). This shows that the SPH criteria includes an implicit cost-benefit assessment. This implicit assessment prevents policymakers (and the public they represent) from determining whether an extreme event is worth guarding against by excluding the possibility that such an event will or can occur. The following quotations indicate the interpretations that developed through the history of development of the NOFDS regarding what the SPH represented.

- "The Standard Project Hurricane wind field and parameters represent a 'standard' against which the degree of protection finally selected for a hurricane protection project may be judged and compared with protection provided at projects in other localities." (Graham and Nunn 1959).

- "The project is designed to protect against the Standard Project Hurricane moving on the most critical track. Only a combination of hydrologic and meteorological circumstances anomalous to the region could produce higher stages. The probability of such a combination of occurring is, for all practical purposes, nil." (U.S. Army Corps of Engineers 1974).

- "The SPH is a steady state hurricane having a severe combination of values of meteorological parameters that will give high sustained wind speeds reasonably characteristic of a specified coastal location. By reasonably characteristic is meant that only a few hurricanes of record over a large region have had more extreme values of the meteorological parameters." (National Weather Service 1979).

- "The SPH was expected to have a frequency of occurrence of once in about 200 years, and represented the most severe combination of meteorological conditions considered reasonably characteristic for the region." (Government Accountability Office 2005).

As can be seen, over time the SPH went from being a general indicator of threat levels to a guarantee of safety. The methods used to define the SPH were buried, along with their potential flaws and questionable assumptions. Because it became the "gold standard" of flood system performance, the SPH served to prevent up-to-date reanalysis of the true risks of catastrophic flooding of the NOFDS.

Recent work indicates that the probability that any hurricane will pass within 75 miles of New Orleans in any given year is about 12.5 percent, or about once every eight years (URS 2005). The likelihood of a major hurricane (Category 3 and above) are about 3.2 percent per year, or about once every 30 years. These projections do not account for the current period of intensified hurricane activity (Klotzbach and Gray 2006). Thus, the history of development and evolution of the SPH did not provide an adequate basis to understand the risks associated with catastrophic flooding of the NOFDS. The report of the Senate Committee on Homeland Security and Governmental Affairs observed (2006):

> *For several years, the Corps has inaccurately represented to state and local officials and to the public the level of protection that the hurricane system provided. The Corps claimed the system protected against a fast-moving Category 3 storm even though: (a) there was no adequate study or documentation to support this claim; and (b) information known to or provided to the Corps demonstrated that the claim was not accurate.*

Some industries that must deal with hurricane related hazards have developed specific design conditions (e.g., wave or surge height) and associated forces based on specified annual return periods (e.g., 100 years) (Bea 1990, 1998, 2001). These design conditions are chosen based on their potential *effects* (e.g., forces, water surface elevations) *on the structures to be designed*. The design conditions and prescribed forces are supplemented with safety factors (e.g., 2 to 4) that help assure that the resulting system can perform acceptably in much more intense conditions (frequently identified as Ultimate Limit State conditions) (Bea 1990). For important industrial facilities, these Ultimate Limit State conditions have return periods in the range of 1,000 to 10,000 or more years (Vick 2002; Baecher and Christian 2003, U.S. Army Corps of Engineers 1999, Tekie and Ellingwood 2003). For example, typical modern offshore structures in the Gulf of Mexico that are evacuated in advance of hurricanes are able to resist forces from hurricanes that have return periods of more than 1,000 to 5,000 years (Bea 1996). Structures that can not be evacuated are able to resist forces from hurricanes and storms that have return periods in the range of 5,000 to 10,000 years (Spouge 1999). In a similar vein, the Dutch currently provide protection against flooding of the Netherlands for events that represent the worst storm that could be expected to affect the area in the range of 1,000 to 10,000 years (Versteeg 1988, Netherlands Water Partnership 2005).

The SPH evolved to represent the most severe storm the government should guard against when designing hurricane protection projects. The SPH came to represent not only a method for comparative assessment of storm risks between geographic areas, but also a design standard that carried its own assurance of adequate reliability. For a variety of reasons, the concept of storms much more intense than the SPH was not allowed to explicitly enter the engineering process even though the development of the SPH also involved a Probable Maximum Hurricane (PMH) (National Weather Service 1979):

> *The PMH is a hypothetical steady state hurricane having a combination of values of meteorological parameters that will give the highest sustained wind speed that can probably occur at a specified coastal location.* ***One of several possible uses of the values of meteorological parameters is to compute maximum storm surge at coastal points when the hurricane approaches along the most critical track*** [authors emphasis].

Thus, it was clearly recognized that the SPH did not represent a maximum set of conditions for design against hurricane conditions. It is also clear that general public was not informed about the flooding risks that selection of the SPH as a basis for design implied. In many cases, even though very inexpensive defenses could have been provided for the potential for hurricane surges exceeding those of the SPH (e.g., splash-pads behind I-walls and other similar floodwalls sensitive to overtopping erosion), these defenses were not provided.

Another important element of the SPH was that it was not revised as knowledge improved after the 1960s. Authorization constraints and engineering restraints were provided to us as an explanation (bureaucratic engineering). Tremendous strides in the meteorology and oceanography of hurricanes were made during the 1970's and these improvements in technology continue to the present time (Simpson 2003, Interagency Performance Evaluation Task Force 2006a, 2006b). However, the SPH remains essentially the same as it was when it was defined in the 1950s and early 1960s. The natural variability in hurricane conditions and the ability of these conditions to exceed the design norms of the SPH and how these norms were translated in design resulted in many of the failures observed in the NOFDS in the wake of hurricanes Katrina and Rita.

12.5.2 Failure Modes and Safety Factors

A primary obligation of an engineer is to anticipate failure modes in the element, component, or system being engineered and then provide measures to prevent those failure modes from developing or from developing catastrophic results (Petroski 1985, 1994; Harr 1987; Wenk 1989, 1995, 1998; Appendix H). This obligation requires two primary things: 1) anticipation of possible failure modes, and 2) provision of defenses in depth to prevent and/or mitigate those failure modes.

The design demand for a particular component in the NOFDS when combined with a prescribed safety factor and associated analytical models and procedures determines the Ultimate Limit Strength of that element. When combined with an assessment of the intrinsic uncertainties (natural, model, parametric, state), the ratio of the Ultimate Limit Strength to the design demand (factor of safety) reflects the reliability (or probability of failure) associated with that component (Bea 1990; Kulhawy 1996; Duncan 2000; Whitman 2000; Vick 2002; Christian 2004; Lacasse 2004).

For example, a factor of safety of 1.3 was specified by the Corps of Engineers as the minimum acceptable safety factor for drainage canal levee lateral stability (U.S. Army Corps of Engineers 1988, 1989, 1990, 2000). Our examination of the basis for this factor of safety indicates that it was developed in the 1950s for levees used primarily to defend sparsely populated agricultural areas (Wolff 2005). This factor of safety is embodied in current Corps of Engineers guidelines for the design of levees and assessment of slope stability (U.S. Army Corps of Engineers 2000, 2003). In the case of the drainage canal levees and the floodwalls constructed on and in these levees, the design demand was determined by the total lateral force represented by the canal water level determined on the basis of the SPH (U.S. Army Corps of Engineers 1994).

In the 1990s the Corps of Engineers developed very advanced analytical methods to assess the reliability of important flood control components such as levees and dams (U.S. Army Corps of Engineers 1996, 1999, National Research Council 1983). These methods were validated with field and laboratory test data and field performance data (U.S. Army Corps of Engineers 1999; Wolff 1999; Duncan 2000). Application of these methods entailed an assessment of the inherent uncertainties for different failure modes and identification of target reliabilities for these modes (Wolff 1999). Analytical methods were developed for both elements and assemblies of elements that represented flood control components and systems. The issues associated with target or acceptable reliabilities were also addressed. These methods were used to define reliability based design and maintenance factors of safety. Application of these methods for important flood protection facilities defending highly populated areas and the Corps of Engineers levee stability analysis procedures indicated factors of safety that substantially exceeded those used for the levees and associated floodwalls that defended the NOFDS drainage canals. Factors of safety of 2 to 3 and greater were indicated for very important facilities (annual target Safety Indices in the range of 3 to 4). Similar safety factors were identified by other investigators for similar facilities (Bea 1990, Duncan 2000, Whitman 2000, Vick 2002, Christian 2004, Lacasse 2004). Apparently a *technology lag* (breakdown in technology transfer) or rejection of technology (Sowers 1993) developed and persisted in the design guidelines used for levees and floodwalls in the NOFDS.

Following Hurricane Katrina a similar technology lag was identified as the failure at the 17th Street canal. Both the ILIT (Seed et al. 2005) and the Corps of Engineers Interagency Performance Evaluation Task Force analyses (Interagency Performance Evaluation Task Force 2006b) of this failure concluded that a failure mode developed that was not recognized by the designers. This finding lead to the official contention that this was a "design failure." *The information developed by the ILIT clearly indicates that this failure was a result, not a cause.*

The failure mode involved lateral deflection of the concrete floodwall and the sheet piles that supported that floodwall. This deflection resulted in separation between the stiff supporting sheet piling and the soft soil of the levee on the flood side of the wall. Water was then able to enter the gap and exert additional lateral forces on the remaining 'half' of the levee – floodwall. Now the levee only had about 'half' of its width able to transmit the lateral forces to the underlying soils. This combination resulted in lowering the lateral resistance with a commensurate lowering of the factor of safety.

This development was incorrectly reported as "unforeseen and unforeseeable" by the Interagency Performance Evaluation Task Force (Marshall 2006; Seed and Bea 2006). In 1985, the New Orleans district of the Corps of Engineers conducted a full scale instrumented lateral load test of a 200-foot long sheet pile flood wall in the Atachafalaya basin (U.S. Army Corps of

Engineers 1988b). This particular location (south of Morgan City, Louisiana) was chosen because of the close correlation of the soil conditions in the New Orleans area with those at the test location. "The foundation soils are relatively poor, consisting of soft, highly plastic clays, and would be representative of near worst case conditions in the NOD (New Orleans District)." (U.S. Army Corps of Engineers 1988b).

Test data from the highly instrumented sheet pile wall and adjacent supporting soils indicated a gapping behavior (separation of the sheet piles from the soils). The test was designed to take an eight foot height of water (above the supporting ground level) with a factor of safety of 1.25. But, the wall was already in a failure condition (increasing lateral displacements with no increase in loading) when the water level reached only 8 feet instead of the calculated 10 feet. Strain gage readings on the sheet piles indicated that they were well below the steel yield point, thus the yielding had to have been developing in the supporting soils. Two very important pieces of information developed by the E-99 sheet pile tests were that there was potential soil separation from the sheet piles (allowing water to penetrate below the ground surface between the piles and the soils) and that the calculated safety factor was not reached (it was over-estimated due to unanticipated deformations in the soils).

Additional reports and professional papers further developed the experimental information and advanced analytical models that could be used to help capture such behavior (U.S. Army Corps of Engineers Waterways Experiment Station 1989b). Later developments in this work were reported by Oner, Dawkins and Mosher (1997):

> *As the water level rises, the increased loading may produce separation of the soil from the pile on the flooded side (i.e., a "tension crack" develops behind the wall). Intrusion of free water into the tension crack produces additional hydrostatic pressures on the wall side of the crack and equal and opposite pressures on the soil side of the crack. Thus part of the loading is a function of system deformations.*

These developments in technology inexplicably were *not* reflected in the design guidelines used (U.S. Army Corps of Engineers 1988a, 1989a, 1990). We found no evidence that questions regarding the adequacy of the design were raised after the design and construction were completed. Loss of corporate memory, breakdowns in technology transfer, and abilities to keep the design guidelines current with existing knowledge seemed to background these developments.

The second suspect element in this development regarded characterizations of the soils that supported the earth levee and sheet piling in the vicinity of the 17th Street canal breach. The processes used at the time of design to analyze the soil types and engineering characteristics did not capture the unique characteristics of the soils. Higher soil strengths beneath the crest of the levee were used to characterize the strengths of the soils at and beyond the toes of the levees. In addition, the spatial averaging process (vertical and lateral) did not capture the unique soil characteristics in the vicinity. Soils in Southern Louisiana and other parts of the Gulf Coast have very complex histories due to past floods, hurricanes, the rise and fall of sea level, changes in vegetation, and other events. Far from being uniform, they contain complicated and rapidly varying strata of different materials with very different characteristics.

In 1964 - 1965 the Corps ran a full scale levee test in the Atachafalaya basin in which advanced studies were conducted regarding characterizations of the soil strengths and performance – stability characteristics of the levee (U.S. Army Corps of Engineers 1968;

Kaufman and Weaver 1967). The levee test sections were thoroughly instrumented and their performance monitored during and after construction. Various analytical methods were used to evaluate the usefulness and reliability of the various methods. These developments clearly indicated the need to understand the geologic soil depositional processes and the associated variations in soil strengths (horizontal and vertical) in order to understand the performance and stability characteristics of levees. The importance of local soil conditions to performance of the levee was clearly pointed out. Additional reports and professional papers were published that resulted in significant advances to the engineering knowledge (Duncan 1970, Ladd et al. 1972; Edgers et al. 1973; Foott and Ladd 1973, 1977).

In-depth background on the geologic and depositional environment of vital importance to understanding the characteristics of the Mississippi Basin soils were developed in the 1950s and 1960s (Fisk et al. 1952; Kolb and Van Lopek 1958; Krinitzsky and Smith 1969) and the Corps of Engineers lead in development of this background. Of particular importance was recognition that the marsh and swamp deposits were “treacherous” and highly variable. It was repeatedly pointed out that “careful and detailed characterization of the soil properties was required.” Further the studies that the method based on traditional Corps of Engineers soil characterization and stability analyses gave factors of safety that were too large (Foot and Ladd 1977). As in the first instance, these developments in technology inexplicably were not reflected in the design guidelines and practices that were used nor were adequate testing procedures employed.

The safety factors used in design were not sufficient to accommodate the uncertainties inherent in the design procedures and processes and inherent in the environment in which the facility would exist. Important failure modes in the components were not recognized. When the system was tested, it failed because of a confluence of intrinsic and extrinsic uncertainties. *This was not a design failure; this was a failure on the part of the organizations responsible for the design and construction of the flood defense works to effectively use proven technology*.

12.6 Life-Cycle Development of Flaws

Sources of flaws in the NOFDS developed during the life-cycle of the system starting with its concept (e.g., SPH), then during design (e.g., I-wall configurations, strength and stability guidelines, factors of safety), construction (e.g., normalized reports of excavation and forming instabilities and seepage from canals) and operation (e.g., persistent reports of leakage from canals and signs of ground instability), and finally during the maintenance (e.g., in-ground construction, vegetation growth on and adjacent to levee toes) phases (Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina 2006, Irons 2005). Similar life-cycle flaws were developed and propagated in the levee and flood protection structures adjacent to the MR-GO. *Important flaws in the NOFDS were embedded in every stage of the life-cycle.* In many cases, these flaws were allowed to propagate and magnify. Early warning signs that were ignored or ineffective. NOFDS component interface flaws developed throughout the life-cycle of the NOFDS were particularly evident.

When the NOFDS was challenged by hurricane Katrina, these flaws became evident. Had these flaws not been present, it is likely that hurricane Katrina would not have developed into a major catastrophe.

Design challenges not successfully addressed were traced to fundamental flaws that became embedded in engineering design procedures and how these procedures were used. Tests were performed and the results not properly utilized, and in several key cases, not utilized at all (Seed and Bea 2006). Even though procedures for other similar facilities (e.g., dams, coastal and offshore structures) existed and were highly developed, the design (also construction, operation, inspection, maintenance, repair) technology was not integrated into the design of the NOFDS (rejection or misuse). In addition to flaws previously discussed, the design procedures focused on individual components, with insufficient treatment given to the concepts of integrated system performance, defenses in depth, and robustness (damage and defect tolerance). The Member Scholars of the Center for Progressive Reform arrived at similar conclusions in their report titled *An Unnatural Disaster: The Aftermath of Hurricane Katrina* (2005).

12.7 Findings - Looking Back

Failure of the NOFD was not caused by an overwhelming extreme natural event (hurricane wind, waves, currents, surge). While portions of the NOFDS were overtopped by hurricane Katrina's surge and waves, our studies indicate that the majority of the flooding came from unanticipated and unintended breaches in the levees (many adjacent to other structures), failures in the floodwalls, and water entering through gaps (floodgates not in place) or low spots in the NOFDS. The roots of these unanticipated and unintended developments were firmly embedded in Technology Delivery System flaws and malfunctions; failures of organizations - institutions and their resource allocation processes.

ILIT identified eight categories of TDS malfunctions that played primary roles in the failure of the NOFDS. Additional background on each of these TDS malfunctions is provided in Appendix F and H.

Failures of foresight: Catastrophic flooding of the greater New Orleans area due to surge from an intense hurricane was predicted for several decades (Townsend 2006). The consequences observed in the wake of hurricane Katrina were also predicted (Members Scholars of the Center for Progressive Reform 2005). The hazards associated with the NOFDS were not recognized, defensive measures identified and prioritized, and effective action was not mobilized to effectively deal with the hazards (Irons 2005; Senate Committee on Homeland Security and Governmental Affairs 2006).

Failures of organization: The roots of the failure of the NOFDS are firmly embedded in flawed organizational - institutional systems (Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina 2006). The organizational - institutional systems lacked centralized and focused responsibility and authority for providing adequate flood protection (Government Accountability Office 2005a, 2005b; Carter 2005a, 2005b; ASCE 2006a; Senate Committee on Homeland Security and Governmental Affairs 2006). Dramatic and pervasive failures in management existed, exemplified in ineffective and inefficient planning, organizing, leading, and controlling to achieve desirable quality and reliability in the NOFDS (Houck 2006, Braun and Vartabedian 2005). There were extensive and persistent failures to demonstrate initiative, imagination, leadership, cooperation, and management (Leonard and Howitt 2006).

Failures of funding: The failure of the NOFDS resulted from inadequate provision of resources based primarily on recommendations provided by the Corps followed by failure of the federal and state governments to fund badly needed improvements once limitations were recognized (Members Scholars of the Center for Progressive Reform 2005; Houck 2006; Braun and Vartabedian 2005). In several instances, State agencies pressured for 'lower cost' solutions not realizing that these solutions would result in lowering the quality and reliability of the NOFDS (Members Scholars of the Center for Progressive Reform 2005). Important deficiencies existed in the cost-benefit analyses used to justify the levels of protection and their continued improvement as knowledge and technology advanced (Government Accountability Office 2003, 2005; Heinzerling and Ackerman 2002).

Failures of diligence: Forty years after the devastating flooding caused by hurricane Betsy, the flood protection system authorized in 1965 and founded on the Standard Project Hurricane (SPH) was not completed (Government Accountability Office 2005a, 2005b). The concept and application of the SPH was recognized to be seriously flawed, no adjustments were made to the system before Katrina struck (Select Bipartisan Committee to Investigate Preparation for and Response to Hurricane Katrina 2006). Early warning signs of deficiencies and flaws persisted throughout development of the different components that comprised the NOFDS and these signs were not adequately evaluated and acted upon (Houck 2006; Carter 2005a, 2005b).

Failures of trade-offs: A history of flawed decisions and trade-offs proved to be fatal to the ability of the system to perform adequately (Carter 2005a, 2005b). Compromises in the ability of this system to perform adequately started with the decisions regarding the fundamental design criteria for the development of the system, and were propagated through time as alternatives for the system were evaluated and engineered (Houck 2006). Design, construction, operation, and maintenance of the system in a piecemeal fashion allowed the introduction of additional flaws and defects (Collins and Lieberman 2005). Efficiency was traded for quality, reliability, and effectiveness. Superiority in provision of an adequate NOFDS was traded for mediocrity and getting along (Collins 2005; Senate Committee on Homeland Security and Governmental Affairs 2006).

Failures of management: Requirements imposed on the Corps of Engineers by Congress, the White House, State and local agencies, and the general public have changed dramatically during the past three decades. Defense, re-construction, maintenance, waste disposal, recreational, emergency response, and ecological restoration have served to divert attention from flood control (Office of Management and Budget 2006, Vartabedian and Braun 2006). Public and Congressional pressures to reduce backlogs of approved projects, improve project and organizational efficiency (downsizing, outsourcing), address environmental impacts and develop appropriations for projects have served to divert attention from engineering quality and flood control reliability (Carter and Sheikh 2003). Engineering technology leadership, competency, expertise, research, and development capabilities appear to have been sacrificed for improvements in project planning and controlling (Office of Management and Budget 2006; Senate Committee on Homeland Security and Governmental Affairs 2006).

Failures of synthesis: While individual parts of a complex system can be adequate, when these parts are joined together to form an interactive - interdependent - adaptive system, unforseen failure modes can be expected to develop (Rasmussen 1997; Bea 2000). These unforseen, but forseeable, failure modes developed in the NOFDS during hurricane Katrina. It is evident that insufficient attention was given to creation of an integrated series of components to provide a reliable NOFDS (ASCE 2006a). Synthesis was subverted to decomposition. As a result, many failures developed at interfaces or 'joints' in the NOFDS (Committee on New Orleans Regional Hurricane Protection Projects 2006; Seed et al. 2005).

Failures of risk assessment and management: The risks (likelihoods and consequences) associated with hurricane surge and wave induced flooding were seriously underestimated (Carter 2005a, 2005b). There was inadequate recognition of the primary contributors to the likelihoods and consequences of catastrophic flooding. Sufficient defensive measures to counteract and mitigate these uncertainties were not used. Safety factors used in design of the primary elements in the NOFDS were insufficient (ASCE 2006a, 2006b). Quality assurance and control measures invoked during the life of the system failed to disclose critical flaws in the system (Vartabedian and Braun 2006). Inappropriate use was made of existing engineering technology available to design, construct, operate, and maintain a NOFDS that would have acceptable quality and reliability. Deficient risk management methods were used to allocate resources and impel action to properly manage risks (Moteff 2004). Risk management failed to employ continuing improvement, monitoring, assessment, and modifications in means and methods which were discovered to be ineffective (Senate Committee on Homeland Security and Governmental Affairs 2006).

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CHAPTER THIRTEEN: ORGANIZED FOR SUCCESS

The excuse we have heard from some government officials throughout this investigation, that Katrina was an unforeseeable ultra-catastrophe, has not only been demonstrated to have been mistaken, but also misses the point that we need to be ready for the worst that nature or evil men can throw at us. Powerful though it was, the most extraordinary thing about Katrina was our lack of preparedness for a disaster so long predicted.

This is not the first time the devastation of a natural disaster brought about demands for a better, more coordinated government response. In fact, this process truly began after a series of natural disasters in the 1960s and into the 1970s. One of those disasters was Hurricane Betsy, which hit New Orleans in 1965. The similarities with Katrina are striking: levees overtopped and breached, severe flooding, communities destroyed, thousands rescued from rooftops by helicopters, thousands more by boat, and too many lives lost.

Katrina revealed that this kaleidoscope of reorganizations has not improved our disaster management capability during these critical years. Our purpose and our obligation now is to move forward to create a structure that brings immediate improvement and guarantees continual progress. This will not be done by simply renaming agencies or drawing new organizational charts. We are not here to rearrange the deck chairs on a ship that, while perhaps not sinking, certainly is adrift.

This new structure must be based on a clear understanding of the roles and capabilities of all management agencies. It must establish a strong chain of command that encourages, empowers, and trusts frontline decision-making. It must replace ponderous, rigid bureaucracy with discipline, agility, cooperation, and collaboration. It must build a stronger partnership among all levels of government with the responsibilities of each partner clearly defined, and it must hold them accountable when those responsibilities are not met.

Senator Susan Collins
Opening Statement
Committee on Homeland Security and Government Affairs
Hurricane Katrina: Recommendations for Reform
Washington DC, March 8, 2006

We are Doomed to an Unacceptable Future - Unless …

What do the following accidents have in common? Torrey Canyon tanker (1967) and the Exxon Valdez tanker (1989); the U.S.S. Greeneville (2002) and the U.S.S. San Francisco (2005); the Challenger Space Shuttle (1986) and the Columbia Space Shuttle (2003); the Piper Alpha Platform (1988) and the Petrobras P36 Platform (2001), Herald of Free Enterprise (1987) and the Estonia ferry (1994), and failure of the NOFDS in the wake of hurricane Betsy (1965) and hurricane Katrina (2005).

In each case someone, somewhere, understood that organizational and system processes were as much the cause of the accident as were engineering design and maintenance errors (Appendix F). In each case this knowledge failed to prevent a second disaster from happening in the same industry. This record suggests that we are doomed to a future in which increasingly complex organizations and systems of organizations fail causing unnecessary death and injury, large scale economic disruption, political haggling, and years of rebuilding.

We are doomed to this future despite growing evidence that preventing disasters is always cheaper than recovery. We are doomed to this future despite the fact that we know technological failures virtually always occur within the context of management failures and there is a growing body of literature that describes management implementations designed to reduce large scale failure (e.g. Roberts and Bea 2001a; 2001b; Dekker 2002; Weick and Sutcliffe 2001).

As an example of what doesn't happen, the National Incident Management System (NIMS) Integration Center issued this alert (Department of Homeland Security 2006):

> *All federal, state, local, tribal, private sector and non-governmental personnel with a direct role in emergency management and response must be NIMS and ICS trained. This includes all emergency services related disciplines such as EMS, hospitals, public health, fire service, law enforcement, public works/utilities, skilled support personnel, and other emergency management response, support and volunteer personnel….*

In mid March, 2005, Donald Hiett, Jr, Principal, Organizational Strategic Solutions Group, was asked by Louisiana State University (LSU) to develop a NIMS training program directed to the senior executive leadership in New Orleans to take place before June, 2006. On March 28, 2005 he was informed there was no interest by these officials in taking this training program (Hiett, personal communication). We are doomed – unless. This chapter deals with "unless." It first discusses the determination of safety, and the usual engineering response to risk. It then asks that the reader take a new perspective on the USACE and contextual issues it needs to consider. It then discusses preventing the next "Katrina" and offers recommendations.

13.1 How Safe is Safe Enough?

The hurricane Katrina catastrophe exposed a technological failure of inadequate defense against a predictable, risky and potentially lethal event. Recent studies focus on death and destruction from flood waters released by collapse of the NOFDS. Studies of cause acknowledge the extreme forces of nature but also cite human and organizational errors (HOE) that now occur more conspicuously because the engineering parameters are fairly well understood. HOE failures far exceed mechanical sources.

Because protection against human weaknesses is more art than science, the study of their causes and remediation require a context for risk analysis. Non-specialists with policy and management responsibilities should be helped by a perspective that points to the systems based and interdisciplinary requirements for the NOFDS. Such a perspective can help us answer the enigmatic question, “How Safe is Safe?” In other words, what level of risk is acceptable when making decisions about public safety and security?

Risk is usually defined as a condition in which either an action or its absence poses threats of socially adverse and sometimes extreme consequences. Risk happens from acts of nature, from weaknesses of human nature, and from side effects of technology, all situations that mix complex technical parameters with the variables of social behavior. Although each risk event is unique, all display commonalities that permit systemic analysis and management. These recurring properties lead to certain principles.

To begin, the acceptability of risk cannot be extracted from science or mathematics; it is a social judgment. The spectrum of risk thus embraces both the physical world defined by natural laws, and the human world loaded with beliefs instead of facts, values, ambiguities and uncertainties. Among other features, the physical world may be thought of as a mechanism whose behavior follows principles of cause-and-effect. The human world performs more like an organism whose components are not fixed but may grow, be altered by the thrust of events and their interplay with other elements.

Following a notion that what you can’t model you can’t manage, a systems model is needed to represent the processes by which both physical and societal factors are defined, interconnected and interact. Such technology-based human support systems are labeled by their intended social functions: food production, shelter, military and homeland security, etc. In our modern era, these and other functions are enormously strengthened by applications of scientific knowledge, applied through engineering.

It helps to think of technology as more than the hardware of planes, trains and computers. Rather, it is a social system comprising many organizations, synchronized by a web of communications for a common purpose. It is energized by forces of free market demand, of popular demand for security and quality of life, and by forces of scientific discovery and innovation. It is best understood as a *Technological Delivery System* (TDS) that applies scientific knowledge to achieve society’s needs and wants.

Technology then acts like an amplifier of human performance. With water wheel, steam engine and bomb, it amplifies human muscle. With the computer it amplifies the human mind and memory. It also amplifies social activity, mobility, quality and length of life.

A paradox arises when technologies introduced for specific benefits also spawn side effects. These can induce complexity, conflict and even chaos. Most of these are unwanted by some sector of stakeholders, now or in the future. This paradox is dramatized when technologies are introduced to defend against violence of nature or against human and organizational error but themselves spring unintended and possibly dangerous consequences.

The investigation of risk and of measures to contain it within safe limits requires both hindsight and foresight. The past can illuminate failures, their causes and their control as lessons for engaging new ventures and threats. The future commands the exercise of foresight, an imaginative preparation of scenarios stirred by such questions as, "what might happen, if," or "what might happen, unless." Those inquiries should then examine the timing of impacts (immediate or hibernating) and identity of players on the risk horizon who trigger risk, those parties responsible for risk abatement and those adversely affected now or in the future.

Modeling then becomes essential to represent a full cast of stakeholders and their inter-relationships, including both the private and the public sectors. The concept of a technology delivery system (TDS) is simply an attempt to model how the real world works.

The responsibility to manage risk stems from the American Constitution, from custom, and from a growing body of public law. Federal, state, and local governments are heavily involved in all of the technologies previously discussed and many more. With waterways, for example, the Army Corps of Engineers (USACE) has a predominant statutory responsibility. That accords with the historic federal stewardship of national infrastructure, from roads, shipping channels, harbors and canals to airplane routes and the Internet.

That achievement carries significant but subtle implications. For one thing, safety costs money. The federal budget is constantly challenged to meet a rainbow of different demands, the total of which always exceeds Congressional appropriations. The mismatch must then be reconciled through tradeoffs at the highest policy levels stretching all the way to the President of the United States and the Congress.

Often, a focus on power of the Federal Government misses a major premise of democratic governance. As the Declaration of Independence states, *those who govern should do so only with the consent of the governed*; we would say the informed consent. This notion is reflected in such regulatory legislation as the National Environmental Policy Act (NEPA). Section 102(2) c. It requires estimates of harm that could result from technological initiatives, along with alternatives to accomplish the same goals but with less harm. After preparation, these environmental impact statements (EIS) are made available for public comment and possible amendment. The point is that this process makes every citizen a part of government to negotiate the question of how safe is safe and thus provide citizens the levels of safety and security that they desire.

Implied is a prospective national policy that those put in harm's way have a voice in what otherwise could be involuntary exposure to risk. This principle leaves implementation of the concept to the responsible federal agencies, subject to Constitutional safeguards. Despite a tendency to flare the sensational, the media can enrich understanding with a backstory because disasters so agitate a functioning system as to reveal the full cast of stakeholders, their roles in increasing or decreasing risk and their degree of injury.

In this modern era, society demands better protection against threats to life, to peace, justice, health, liberty, .life style, private property and to the natural environment. These challenges are not new, but two things have changed—the increased potency of technology and increased media coverage. Technological factors are more robust in speed of delivery and in potential harm. Media covers events live, 24/7, and worldwide. Events anywhere have repercussions everywhere. The better informed public tends increasingly to be risk averse. Apprehension and fear peak after a calamity with demands for better protection through better governance. Higher expectations are legitimate because so many threats just itemized are due to human and organizational errors either in catering technologies to meet market demand or in guarding against hazards. This current study shows that the Katrina event fits that pattern. Government at all levels failed to provide security to citizens before and during the catastrophic flooding. Victims are justified in asking how this pathology of a mundane levee technology developed. How can that knowledge be applied to prevent a reoccurrence.

13.1.1 The Engineering Response to "How Safe is Safe?"

The engineering profession has long practiced social responsibility by a technique of over-design, to compensate for uncertainties in loading, in materials, in quality of construction and maintenance, etc. This may be accomplished by adopting some multiple of loading as a margin of safety ranging from 1.4 to 5.0 and even greater. How these margins are set and by whose authority is of critical importance, especially where tradeoffs with cost or other compelling factors such as deadlines may compromise the intended reduction of risk.

This method of safety assurance is more applicable to design of mechanisms not subject to human and organizational errors. The term "errors," incidentally, is shorthand for a broad spectrum of individual and societal weaknesses that include ignorance, blunder, folly, mischief, pride, greed and hubris. Protecting structures against violence of nature such as with earthquakes, volcanic eruptions, tsunamis, floods, landslides, hurricanes, pestilence, droughts and disease may utilize the concept of over-design, based on meteorological, hydrological, seismic and geophysical data of past extreme events.

Learning from documented failures is a powerful method for reducing risks of repeated losses. Another method is to learn from close shaves. Many dangerous events fortunately culminate in only an incident rather than an accident, but the repetition of similar incidents can serve as early warnings of danger. Indeed, the logging and analysis of such events on the nation's airways partially accounts for commercial aviation's impressive safety record. A system for reporting close encounters of aircraft was installed decades ago. Anticipating the possibility that perpetrators of high risk events might be reluctant to blow the whistle on themselves, many years ago the Federal Aviation Administration arranged for NASA to collect incident date and to sanitize it to protect privacy of the incident reporter. NASA also screened reports to identify patterns as early warning of dangerous conditions. Similar systems are in place for reporting nuclear power plant incidents.

With the growing recognition of human factors in accidents or in failures to limit damage, a class of situations entailing uncommonly high risks but conspicuously good safety records was examined. In the Navy, for example, high risks are a part of daily operations of submarines and aircraft carriers. Yet accident rates are paradoxically low. Careful analysis of these situations showed that certain qualities of leadership and organizational culture foster integrity, a sense of responsibility among all participants, a tolerance by authority figures for dissent, and consensus on common goals of safe performance. High safety performance is associated with an institutional culture that is bred from the top of the management pyramid. The most critical element of that culture is mutual trust among all parties (e.g., Roberts 1990).

Long experience with military and paramilitary organizations such as first responders proves the value of rehearsals to reduce risks and control damage. Of special virtue is proof of satisfactory communications. Evaluation of dry runs has repeatedly turned up serious problems in communication. So has post-accident analysis of real events when delays or blunders in communication of warnings and rescue operations cost lives.

13.1.2 Insights from Addressing These Issues

To sum up, the context for analyzing the levee failures from Hurricane Katrina illustrates several realities. The most compelling imperative of life is survival. Yet the experience of living teaches that there is no zero risk. Some exposures must be tolerated as "normal," whether in rush hour traffic or coping with nature, with human nature or with unintended consequences of technology. The preceding situation analysis opens a window on a number of issues treated in more detail in subsequent sections and Appendix H:

- The design of precautionary measures requires inspired foresight, to fantasy alternative futures.
- Tradeoffs are inevitable between short- and long-range events and consequences, between safety and cost, between special interests and social interests, between who wins and who loses and who decides.
- All human support systems entail technology, and all technologies project unintended consequences.
- Society embraces a spectrum of values that often conflict, as with the goals of efficiency in the private sector and of sustainability and social justice in the public
- Key decisions regarding citizen safety and security are made by government through public policies to manage risk. These policies dominate the legislative agenda.
- This mandate imposes a heavy burden on the President and on Congress, both bodies requiring access to authentic and immediate information.
- Making decisions and assuring implementation draws on political capital in the structure of authority by the exercise of political power and political will.
- In our democracy, this authority should flow from citizens following the principle that those who govern do so at the informed consent of the governed.
- The quality of risk management can best be judged by the effects on future generations.
- The geography of risk crosses boundaries as between federal, state and local entities, and between the United States and other nations.
- Different cultures have different risk tolerances, including attitudes distinguishing voluntary from involuntary risk.
- Analysis of risk and its control extracts lessons from past failures, although the most catastrophic events are so rare as to frustrate projections.

This portfolio of issues illustrates the anatomy of risk and the complexity of its management. They sound a wake-up call for deeper understanding by those responsible for risk management and by those attentive citizens who are exposed and are entitled to a voice in the decision process.

13.2 Maximizing How Safe is Safe in the U.S. Army Corps of Engineers (Context)

We know a finite number of precursors lead to major disasters. But in order to understand what they are we must place a focal first responder organization into its context. For example, the Corps of Engineers (USACE) is nested within a large number of organizations that should be interdependent with one another. The social science literature addresses this problem by using such concepts as *interstices* (Grabowski and Roberts 1999), "interdependencies" (Heath and Staudenmayer 2000) or the "space between" (Bradbury and Lichtenstein 2000; Buber 1970). Failure to consider the processes that operate both within any one unit and across units is failure to be ready for the next large scale catastrophe. This discussion focuses on context and asks the reader to take a new perspective of the Corps of Engineers.

Hurricane Katrina provided an interesting, if devastated setting for understanding what not to do in a quickly changing potential disaster. The organizational liquefaction that occurred after the Hurricane (the heart of the disaster as opposed to the storm), laid bare the skeletons of the organizations that should have had flesh and muscle to respond. It laid bare for the public to see, not only skeletons, but complete organizational disregard for the interdependences so necessary to a coordinated response. As Houck (2006) observes:

> *So What Do We Do? Here is what we know. It is not just the tire, it's the car. And it's not just the car, it's the driver. Nothing in the system has made a numero uno priority either of protecting New Orleans from hurricanes or to restoring even hanging onto - the Louisiana coast. We have a flood control program, a navigation program, a permitting program, a coastal management program, a flood insurance program, a coastal restoration program - just for openers - and they do not talk to each other. They are riddled with conflicts, basically headless, basically goal-less, weakened by compromises and refuse outright to deal with first causes and first needs.*

The key phrases here are "and they do not talk to each other" and "They are riddled with conflicts, headless, basically goal-less…and refuse outright to deal with first causes…."

In reaction to the organizational liquefaction that developed during hurricane Katrina the Senate Committee on Homeland Security and Governmental Affairs recommended (2006):

> *The Corps and local levee sponsors should immediately clarify and memorialize responsibilities and procedures for the turn-over of projects to local sponsors, and for operations and maintenance, including, but not limited to procedures for the repair or correction of levee conditions that reduce the level of protection below the original design level (due to subsidence or other factors) and also emergency response. It must always be clear - to all parties involved - which entity is ultimately in charge of each state of each project. The Corps should also provide real-time information to the public on the level of protection afforded by the levee system. A mechanism should be included for the public to report potential problems and provide general feedback to the Corps.*

13.2.1 The Office of the President, the Congress, and the Corps

Other things happen at interstices. Figure 13.1 shows the Presidential and Congressional budget requests and Congressional recommendations for Corps of Engineer funding for 1975 through 2005 for the Lake Pontchartrain and vicinity hurricane flood defense projects.

Several hypotheses can be gleaned from this information. First, it appears that while the president was trying to reduce Corps funding Congress was trying to protect Corps funding. With the Lake Pontchartrain projects only about sixty percent complete as of 2005 (40 years after authorization) it may be that Congress, in its wisdom, decided to fund only what it thought needed to be completed. The graph shows other interesting issues about interdependencies. The Corps of Engineers is interdependent with both the Office of the President of the United States and Congress. Congressional members bring pressure to bear on the Corps for new large projects. Faced with these pressures the Corps, then, defers maintenance. For over a decade Congress has funded the Corps at higher levels than recommended by the President. The Corps, then, has to devote time to currying favor with Congress. Currying favor with Congress is not supposed to be the main task of the Corps.

Yet another interesting hypothesis can be derived from these data. When multi year projects are funded annually an interesting dilemma is created for the funded organizations. The funding oscillation level is at one level, but organizations struggling under that oscillation oscillate at a higher frequency. This is hypothesized because it is likely the funded organization operates under a considerable amount of ambiguity and uncertainty. This suggests that the Congressional process creates unintended and negative consequences for its funded agencies. The processes and responses to them are both schizophrenic.

This is almost surely the same as the case for NASA. The Columbia Accident Investigation Board (CAIB) report said (Columbia Accident Investigation Board 2003):

> *The White House and Congress must recognize the role of their decisions in this accident and take responsibility for safety in the future.… Leaders create culture. It is their responsibility to change it.… The past decisions of national leaders – the White House, Congress, and NASA Headquarters – set the Columbia accident in motion by creating resource and schedule strains that compromised the principles of a high risk technology organization.*

Diane Vaughan reports that both economic strain and schedule pressure still exist at NASA. She notes that it is unclear how the conflict between NASA's goals and the constraints upon achieving them will be resolved but that one lesson from Challenger and Columbia is that system effects tend to reproduce (Vaughan 2005). This also happens to military installations every time a Base Reallocation and Closing (BRAC) list is formed. From the day of its publication until the day of decisions installations on this list spend considerable time trying to get off the list, distracting them from their principle tasks.

In the Katrina case will Congress and the Office of the President take a sweeping look at their own behaviors in concert with those of the Corps of Engineers? They probably will not because there is not yet a stated strong incentive for them to do so. One incentive might be that the cost of clean up is always more than the cost of prevention. Money is not limitless. But since we've observed many costly past disasters that were not prevented, and many instances in which they could have been mitigated or prevented, the reality is they probably will do nothing. Thus, the challenge is to find incentives that will encourage emergency response organizations from the President on down, to examine their own organizational skeletons, muscle, and flesh, as well as to look at the "spaces between."

13.2.2 Additional External Interstices for the Corps

Three additional sorts of interfacing between the USACE and its constituents need to be thought about. The first are the interfaces mandated by Emergency Support Function # 3 of the National Response Plan (Department of Homeland Security 2004a).

> *ESF #3 is structured to provide public works and engineering-related support for the changing requirement of domestic incident management to include preparedness, prevention, response, recovery and mitigation actions. Activities within the scope of this function include conducting pre- and post-incident assessments of the public works and infrastructure; executing emergency contract support for life-saving and life-sustaining services; providing technical assistance to include engineering expertise, construction management, and contracting and real estate services; providing emergency repair of damaged infrastructure and critical facilities; and implementing and managing the DHS/Emergency Preparedness and Response/Federal Emergency Management Agency (DHS/EPR/FEMA) Public Assistance Program and other recovery programs.*

To accomplish these goals, USACE can draw on the resources 15 federal government agencies. In addition, state, local and tribal governments are "fully and consistently integrated into EFS #3 activities." (Department of Homeland Security 2004a). All of this occurs, of course, when an incident or potential incident overwhelms state, local, and tribal capabilities.

The NRP concept of operations states that the DOD/USACE is the primary agency for providing ESF #3 technical assistance. It further states that close coordination is to be maintained with federal, state, local, and tribal officials to determine potential need for support. In addition it spells out the organizational structures for providing support, naming the Interagency Incident Management Group (IIMG) as the resource for providing on-call subject-matter experts to support IIMG activities.

Regional and field level mechanisms of support are clearly defined. ESF #3 activities are also spelled out and include such processes as:

> *coordination and support of infrastructure risk and vulnerability assessments, participation in pre-incident activities, such as pre-positioning assessment teams,… participation in post-incident assessments of public works and infrastructures to help determine critical needs and potential workloads, implementation of structural; and non structural mitigation measures, including deploying protective measures to minimize adverse effects or fully protect resources, prior to an incident.*

Additional evidence to the stories published in various national newsmagazines and newspapers is not required to know that neither the USACE nor any other agency rolled out the NRP. If the integration required by this plan is too difficult for agencies to implement it is the duty of the agencies and their oversight agencies (DOD, DHS, HHS, etc.) to indicate this and to develop strategies to revise the NRP to be a workable document. Lee Clarke (1999) discusses at length "fantasy plans" and that looks to be exactly what we have here. Thus, a last word on integration across agencies (Lakoff 2006):

> *From the vantage of preparedness, the failed response to Hurricane Katrina did not undercut the utility of "all-hazards" planning. Rather, it pointed to problems of implementation and coordination. This suggests that in the aftermath of the*

event, we are likely see the redirection and intensification of already-developed preparedness techniques rather than a broad rethinking of security question.

Given our experiences with accident response, without substantial leadership and reorganization it is this team's conclusion that neither comprehensive technical or social reforms will be developed to address future natural or man made catastrophes.

The second set of interfaces that need to be thought about are those created by the Corps needs to outsource. These needs have been imposed by the federal government; specifically through the White House Office of Management and Budget and through Congressional actions. Input from current Corps of Engineers personnel clearly has indicated that through outsourcing and diversion of efforts the USACE has lost "engineering" (Figure 13.2). Core engineering (practicing, research, development) competencies have been sacrificed to pressures to outsource, to improve project management, and to develop environmental restoration and mitigation capabilities.

Partnering has a number of advantages and disadvantages. Some operational benefits accrue from partnering. One can learn new things from partners, perhaps through access to best-of-class processes. Perhaps partnering competitors can learn technology secrets from one another. Where industry benchmarks aren't well known partnering with a competitor can offer insights on a company's productivity, quality, and efficiency.

But there are also obvious disadvantages. Lack of control is a critical disadvantage. The demise of ValuJet, for example, happened because the company outsourced cargo handling to a company it had no control over in terms of quality standards. In another form of outsourcing competitors learn from each others' operations, which may be detrimental to one or more partners. Or a "coopetition" (combination of cooperation and competition) may self destruct before the renewal option dates arrive. A new company board for one of the partners may not approve of the other partner. The strategic aims of partners may change mid-stream, causing failure. These are just some of the reasons for outsourcing failures. (Roberts and Wong 2006). The Corps needs to examine its partner relationships, asking itself if it has lost too much.

One of the Corps sister agencies in time of chaos, FEMA, has also created problems through outsourcing its disaster response efforts (Perrow 2005):

For example, when the Nisqually earthquake struck the Puget Sound area in 2001, homes that had been retrofitted for earthquakes and schools with FEMA funds were protected from high-impact structural hazards. The day of that quake was also the day that the new president, G. W. Bush, chose to announce that Project Impact would be discontinued (Holdeman 2005). Funds for mitigation were cut in half, and those for Louisiana were rejected. Disaster management was being privatized, with the person who was to be promoted to head the agency, Michael Brown, saying at a conference in 2001, "The general idea—that the business of government is not to provide services, but to make sure that they are provided—seems self-evident to me" (Elliston 2004). The administration tried to cut federal contribution for large-scale natural disaster expenditures from 75 percent to 50 percent.

13.2.3 The Corps Internal Interstices

Two other organizational processes also result in lost memory and loss of control. They are downsizing and retirements. Table 13.1 shows that in recent years the USACE has also lost employees. Figure 13.3 shows that the Corps is also losing employees through retirements. Recently, we were told by a high ranking official of the Corps that during the next 5 years, the Corps expects to loose approximately 50% of its civilian workforce through retirements.

In 2002, between 35 and 40 percent of architecture and engineering work was outsourced to private firms while all construction projects were outsourced (U.S. Army Corps of Engineers 2002). The simultaneous operation of the three processes (outsourcing, downsizing and retirement) was and will be disasters for the Corps. Retirements, downsizing, and outsourcing are interdependent in terms of the problems they cause for organizations. Again, the causes are probably buried in not only the Corps activities, but in the Corps' relationship to its external constituencies.

New approaches to looking at organizational failure examine the degree to which organizations are internally stove piped. Figure 13.4 shows that the Corps organizational structure might lend itself to this. It appears regions and districts act pretty autonomously.

In addition Houck (2006) observes:

…restoring coastal Louisiana is a national issue and will require remedies beyond this state. We lie at the receiving end of a large watershed, and some of what we need has been turned off and other stuff that is hurting us has been turned on. The Corps districts need to talk to each other. The EPA has to step up to the plate, upstream states have to change some habits too. If the nation's taxpayers are going to be asked to spend more money than America spent on the Marshall Plan to fix all of post-war Europe, then they have a right to expect a national effort.

McCurdy (1993) discusses how stove piping existed when NASA was created. Today the results of NASA's stove piping are unit independence, specialization and coordination neglect in a situation that should be characterized by just the opposite (Roberts et al. 2005).

All in all, the Corps ability to do its job has been organizationally handicapped. It has lost engineering and research and development muscle and flesh, it has lost its ability to maintain old projects, it fails to be appropriately interdependent with various constituencies, and it fails to act on issues of internal interdependence. AND, IT CANNOT GET WELL ALONE.

13.4 Preventing the Next Katrina

In virtually all human affairs risk is normal. The consequences of neglect may be grave, if not now, in the future. As we indicated in the beginning of this chapter we are skeptical that those with power and resources to prevent the next Katrina will take the steps necessary to do so and we provided evidence for this assertion

From our larger discussion about defining safety and including all stake holders in definition and response, three recommendations emerged:

- Responsibilities for vigilance and decision making at the tip of the authority structure should be clarified and strengthened to enhance management of all modes of risk.

- Additional technical Congressional staff should be appointed to assure adequate revenues to manage risk and to monitor performance of the Executive Branch in its duties of care.
- New processes should be authorized at a local level to foster informed consent and dissent and to function as early warnings in disaster-prone areas and to reflect that citizens at risk are entitled to information regarding their exposure and opportunities to participate in governance.

One central purpose should animate all four of these entities, separately and in tandem. They should address the question, "How Safe is Safe?" That investigation demands foresight in the spirit of the injunction, "Without vision, the people perish."

In addition to this larger purview specific attention needs to be given to the Corps and the organizations with which it is interdependent. We know a great deal about how to fix problems of this nature and there are growing bodies of engineering, legal, public policy, organizational, and other literatures that address such issues. There is also a growing body of experts from different areas who know how to talk about such issues. The problem is that stakeholders have huge incentives not to pay any attention to this. They are no more likely to fix this problem than they were likely to prevent the Challenger problem from becoming the Columbia problem or the Betsy problem from becoming the Katrina problem.

Fixing the problem will require a set of processes affected stakeholders do not want to engage in:

- They must come together to decide exactly what they want (clear and consistent goals) in a politically complex and charged world.
- They must be willing to spend many years addressing such problems in a world in which incentives result in attention spans that run the gamut of minutes and weeks.
- Agencies must work together and trust one another.
- They must recognize the interdisciplinary nature of their problems.
- They must be willing to spend money and make recipients of that money accountable for their spending.
- They must develop oversight positions and agencies with real teeth.

13.5 Re engineering the USACE

Fixing the USACE's technical problems will have only limited impact unless we also fix the organizational problems. The USACE must strive to become a High Reliability Organization (emulating the Rickover Navy, Appendix G). Here are four recommendations that would go a long way toward repairing the Corp's ability to design and build effective flood control projects:

- Rebuild the USACE's engineering and R&D capability,
- Restructure the federal/state relationship in flood control,
- Develop a National Flood Defense Authority,
- Create effective disaster planning.

Three years before Katrina, the National Research Council concluded that the "Corps' more complex planning studies should be subjected to independent review by objective, expert panels." (National Research Council 2002). This is an obvious point – which makes it all the more urgent to implement. Although the need for independent project review has been apparent for several years, none of the past proposals have yet been implemented.

13.5.1 Rebuilding USACE Capacity

The USACE's engineering and R&D capabilities were degraded over the past twenty years as a result of streamlining and budget cuts (downsizing and outsourcing). As a nation, we cannot afford the loss of this expertise. Although outsourcing can be efficient, it cannot be allowed to deplete USACE's own core expertise. As the National Research Council concluded, "Shifting analytical tasks to the private sector, however, has its limits, as core, "in-house" competence is necessary for the Corps to commission, manage, and comprehend the advice of external experts." (National Research Council 2004) The Army Corps of Engineers must be, first and foremost, the nation's premiere expert in flood control engineering. Through no fault of its own, the Corps has been stripped of much of what it needs to perform this role. Congress must adopt a plan and allocate the necessary funds to "put the 'engineers' back in the Corps of Engineers." It must remake the Corps into the organization new "wet behind the ears" civil engineers want to join to sink their teeth into their new profession. It must retain and perform sufficient challenging engineering work to encourage these engineers to develop careers with the USACE. It must define and perform sufficient R&D work to help support the activities of these engineers.

The Working Group for Post-Hurricane Planning for the Louisiana Coast has advanced some complimentary recommendations for Corps staffing in their report *A New Framework for Planning the Future of Coastal Louisiana after the Hurricanes of 2005* (2006):

> *An essential element in enhancing the credibility and soundness of planning and implementation is an agency's internal staff capabilities. The Corps of Engineers is facing a significant loss of staff numbers and capability through retirement, just at the time that the demands for its skills are increasing. Indeed, the integrated planning process will demand a wider array of skills form the engineering, hydrologic, geological, biological and social sciences than is currently available in the agency or in federal or state agencies generally. Also, the effectiveness of the long-term program requires the institutional memory that develops within a permanent and professional staff. Restructuring the Federal/State Relationship in Flood Defense.*

13.5.2 Restructuring the Federal/state Relationship in Flood Defense

USACE's relationship with local flood control entities in Louisiana is dysfunctional. Some of the issues relate to the fragmentation of the local entities, which the state has begun to address. However, the issues are broader.

Often, water planning activities involve not only multiple federal agencies, but also state and local governments. In the blunt words of one observer, "The first consequence is that flood defense has no head . . . . Whatever the merits of this diffusion of authority, it does not produce coherent flood control." (Houck 2006). One useful model may be what has been called "modularity" -- a concept which involves provisional and functional rearrangement of units in terms of alternative configurations of tools, structures and relationships. (Freeman and Farber 2005).

13.5.3 Developing a National Flood Defense Authority

A National Flood Defense Authority (NFDA) might be instituted and charged with oversight over the construction and maintenance of flood control systems. Each state would have an equivalent organization that could foster cooperation and developments between and within the states. The Corps of Engineers, state flood control authorities, and technical advisory boards would work with the NFDA to foster application of the best available technology and help coordinate development and maintenance efforts and planning. Federal and state governments would provide reliable and sustainable funding for the life-cycle (design, construction, operation, maintenance) of specific flood defense systems. To facilitate coherent funding, Congressional authorization and financing would be separated from the traditional Water Resources Development Act process.

The Corps of Engineers, in cooperation with other qualified agencies and industrial partners, would have the responsibility to design and construct, and if directed and authorized, operate and maintain flood defense systems. The NFDA would be based on a continuous and integrated process of flood risk assessment and management for specified flood defense systems with each of these systems being integrated with other allied flood defense systems. Flood risk assessment and management processes would include proactive, reactive, and interactive (adaptive) approaches based on the best available proven technology. Flood defense system planning and development would engage public and industrial stakeholders and responsible federal and state agencies in a cooperative and vigilant Technology Delivery System.

The Interagency Floodplain Management Review Committee in 1994 advanced similar concepts as a result of their in-depth evaluation of the performance of existing floodplain management programs following the disastrous 1993 Midwest flooding. The Working Group for Post-Hurricane Planning for the Louisiana Coast has advanced similar recommendations for organization and funding in their report *A New Framework for Planning the Future of Coastal Louisiana after the Hurricanes of 2005*. This group observed (2006):

> *Organizational and funding barriers that have inhibited the adoption of an integrated planing and adaptive decision making process persist. Both new organization and funding reforms are needed to support coastal planning and project implementation by the Corps and the State.*

This group proposed a model that involves proposals for Federal Intragovernmental Coordination, development of working processes with the new Louisiana Coastal Protection and Restoration Authority, the development of a Coastal Assessment Group and Coastal Engineering and Science Program. This model includes recommendations for programmatic authorization and funding including formation of a new Louisiana Coastal Investment Corporation and major revisions in the Water Resources Development Act appropriations process.

13.5.4 Creating Effective Disaster Planning

Research on organizational learning finds that practices and routines in organizations develop incrementally through feedback from the organization's environment. Organizations generally tend to be inert, adapting less than perfectly to and falling in and out of alignment with their environments (Nelson and Winter 1982).

This stagnation is especially dangerous for organizations that deal with major emergencies such as floods, fires, and other natural and manmade disasters. Organizations that await major failures to adapt tend to enter crisis mode and find learning and response even more difficult (Staw et al 1981; Turner 1976). For example, following the demise of the space shuttle Challenger, NASA faced political pressures, inertia, and resource constraints that expedited some organizational changes but made other structural and cultural adjustments more difficult (McCurdy 1993). Furthermore, in the absence of a significant environmental change or destabilizing event, lessons learned in organizations often tend to be forgotten or misapplied (de Holan and Phillips 2004; March et al 1991).

Even worse, because of the infrequency with which major disasters occur, trial and error organizational learning processes may lead organizational members to forget lessons from past disasters. Levitt and March (1988) argue that in the case of disaster preparedness, trial and error processes lead to "pernicious learning" – organizational leaders conclude that resources designated for disaster preparedness are left idle and should be applied elsewhere. Disaster preparation calls for a different form of learning in which organizations draw on not only their own experiences but also those of other organizations. Such network effects exist for a variety of learning processes (e.g. Argote et al. 1990; Baum and Ingram 1998; Beckman and Haunschild 2002).

Over the past few decades, scholars from many disciplines have advocated relational or systems approaches, as opposed to reductionist approaches that study particular events and entities in isolation (Miller 1972; Wolf 1980; Kastenberg et al. 2003). Taking a relational approach will help us identify and examine learning processes as they affect and are influenced by organizations responding to major catastrophes. The issues we discuss may occur at several different levels in organizations – the interpersonal level, the subunit level, or the inter-organizational level.

Fortunately, we have learned a great deal about how to overcome these organizational barriers. What is needed is to instill "mindfulness" toward risks. We suggest three ways of doing so:

- Create a National Disaster Advisory Office in the White House.
- Create a Catastrophic Risk Office in Congress.
- Make FEMA into a High Reliability Organization (HRO).

13.5.4.1 Creating a National Disaster Advisory Office in the White House

No one in the White House has the job of disaster response. Yet, federal disaster response requires action by many agencies – not just FEMA but also DOD, EPA, CDC, and others. White House coordination of these executive branch activities is crucial. Just as the White House has a National Security Advisor, it needs to have an official charged with national disaster oversight. This official would also be in charge of monitoring organizational problems in the line agencies in charge of disaster response. Moreover, a natural part of the official's portfolio would be disaster prevention efforts, where the aim should be to avoid ever again being taken unawares by a "predictable surprise" like Katrina.

13.5.4.2 Creating a Catastrophic Risk Office in Congress

An integrated approach to catastrophic risk is lacking. One lesson from Katrina is that disasters are not just engineering failures, they are social system failures. Societal and physical infrastructures can collapse. Consequently, disaster prevention cannot be considered in isolation from disaster response, mechanisms for compensation and risk spreading, and reconstruction planning. All of these issues are tightly coupled, yet the linkages receive little attention.

Under the Constitution, Congress bears the primary responsibility for developing national policy and setting national priorities. Congress authorizes and controls FEMA, the Army Corps, flood control projects, the flood insurance program, and other aspects of our nation's response to catastrophic risks. Yet Congress lacks the expertise needed to accomplish these tasks in a systematic way.

13.5.4.3 Making FEMA an HRO

Some organizations cannot afford to fail (Appendix F). Accidents can be disastrous on nuclear submarines, aircraft carriers, in air traffic control, and in hospital emergency rooms. Successful organizations of these kinds have learned to attain high reliability. By studying these organizations, experts have learned the ingredients to creating a High Reliability Organization (HRO). And there is a growing body of research on high reliability organizations (Weick 1987; Roberts 1990; Madsen et al., in press) and on high reliability systems of organizations (Roberts and Grabowski, in press; Roberts et al. 2005). Until organizations representing various aspects of disaster preparedness and disaster management seriously see themselves as systems of organizations they cannot adequately address the problems they face.

13.6 Recommendations – Organizing for Success

The primary requirement for reconstitution of a Technology Delivery System that can and will provide an adequate and acceptable NOFDS is mobilization of the 'will' to provide such a system. If the United States decides that the catastrophe of Katrina will not be repeated, then the necessary leadership, organization, management, resources, and public support must be mobilized to assure such an outcome. One of the primary challenges is time, the clock is ticking until this area of the United States is again confronted with a severe challenge of flooding.

Recommendation 1: Seriously consider defining risk in the framework of federal, state, and local government responsibilities to protect their citizens.

Recommendation 2: Exploit the major and unprecedented role that exists for citizens who should be considered part of governance in the spirit that those who govern do so at the informed consent of the governed. This is the population exposed to catastrophic risks and the people that will be protected by the NOFDS. Authorities for catastrophic risk management should ensure that those vulnerable have sufficient and timely information regarding their condition and a reciprocal ability to respond to requests for their informed consent especially regarding tradeoffs of safety for cost. The public protected by the NOFDS need to be encouraged to actively and intelligently interact with its development.

Recommendation 3: Intensify, focus, and fund Corps of Engineers modernization efforts increasing in-house engineering capabilities and project performance, increasing in-house research and development capabilities, increasing in-house engineering performance of technically challenging projects, developing an organizational culture of high reliability founded on existing cultural values of Duty, Honor, Country, and developing a leadership role and responsibility for technical and management oversight of all phases in development of a NOFDS. Technical superiority must be re-established. Outsourcing must be balanced with in-sourcing to encourage development and maintenance of superior technical leadership and capabilities. This will require close and continuous collaboration of federal legislative, executive, and judicial agencies. This will require that the Corps of Engineers reconceptualize itself as a pivotal part of a modular organization developing partnerships with other federal agencies, state and local governments, enterprise interests, and private stake holders.

Recommendation 4: Restructure federal/state relationships in flood control. One possible model is what has been called “modularity” -- a concept which involves provisional and functional rearrangement of units in terms of alternative configurations of tools, structures and relationships.

Recommendation 5: Develop a National Flood Defense Authority (NFDA) charged with oversight over the design, construction, operation and maintenance of flood control systems. Each state would have an equivalent organization that could foster cooperation and developments between and within the states. The Corps of Engineers, state flood control authorities, and technical advisory boards would work with the NFDA to foster application of the best available technology and help coordinate development and maintenance efforts and planning. In cooperative developments, federal and state governments would provide reliable and sustainable funding for the life-cycle of specific flood defense systems. This development should be accompanied by development of an integrated and coherent Louisiana Flood Defense Authority representing state, regional, local, city, and public stakeholders that can focus and prioritize stakeholder interests and requirements and collaborate with the Corps of Engineers in development of a NOFDS.

Recommendation 6: Because of the importance of emergency response in the NOFDS, FEMA should be developed as a high reliability organization and returned by the executive branch to Cabinet level status. A new Council for Catastrophic Risk Management should be appointed in the White House and given oversight of disaster preparation and response. A similar body should be appointed to Congress. Incentives must be created to encourage all levels of government to seriously deal with potential national, regional, and local catastrophes.

13.7 References

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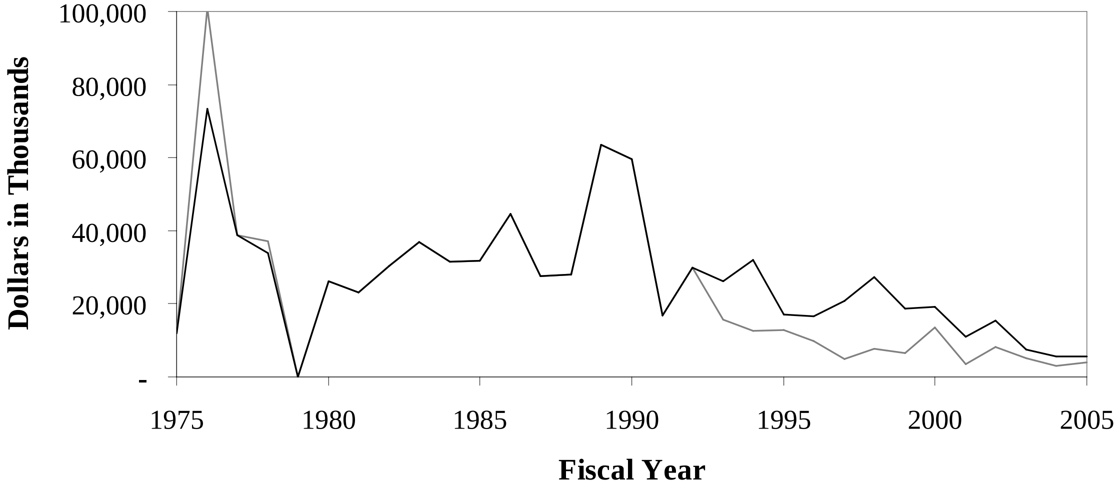

Figure 13.1: Lake Pontchartrain and Vicinity Project Construction Appropriations over the past 30 years [2005 dollars]; President's Budget Request (grey) and the amount recommended by Congress (black).

Figure 13.2: Artwork by Jan Fitzgerald illustrating the debate surrounding President Bush's initative to streamline the federal government (Tate and Halford 2002).

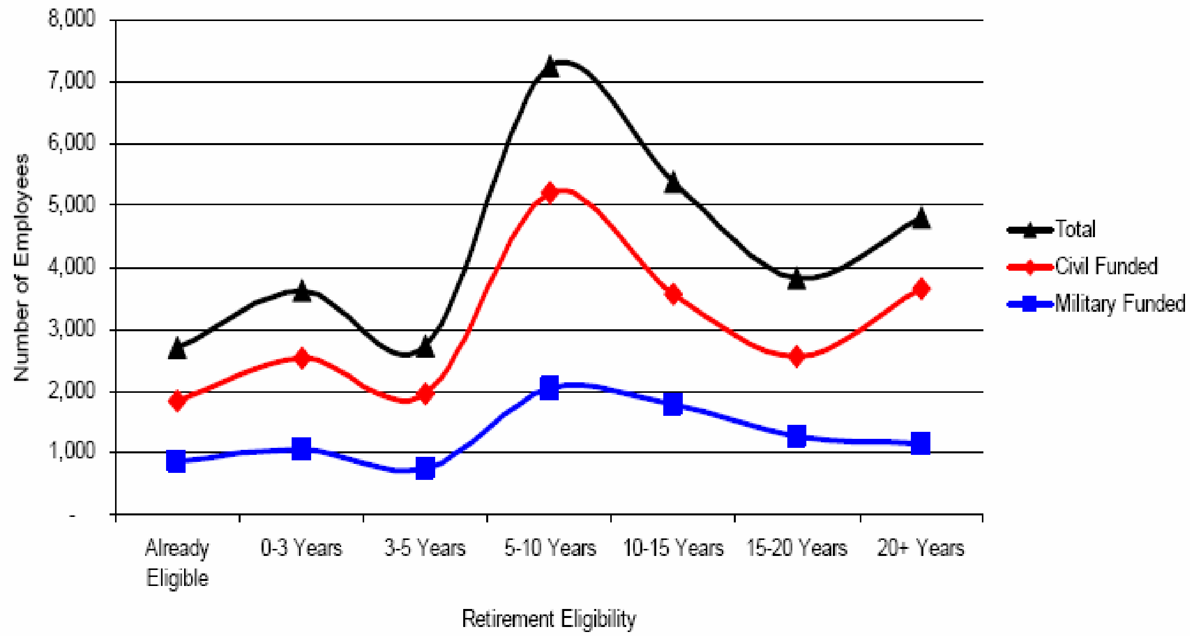

Figure 13.3: Human Capital Planning Projected Retirement (USACE 2002).

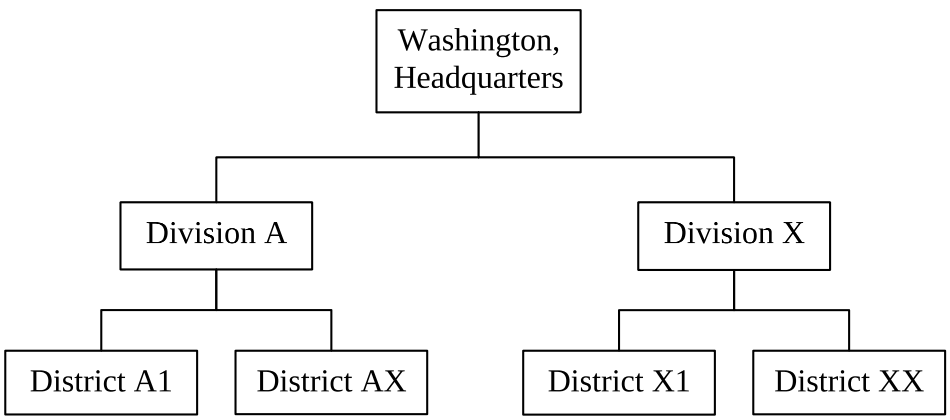

Figure 13.4: Conceptual Organizational Chart of the U.S. Army Corps of Engineers Civil Works Program.[1]

[1] The Corps Civil Works Program is composed of 8 Divisions and 38 subordinate districts. Prime Power, ERDC, Centers, and FOAs are not shown for clarity. In addition, a 9th provisional division with four districts was activated January 25, 2004, to oversee operations in Iraq and Afghanistan. A more complete organizational chart is available in *USACE 2012 – Appendix G, Resource Analysis,* page 1.

CHAPTER FOURTEEN: ENGINEERING FOR SUCCESS

> ***The tragedies of Hurricanes Katrina and Rita in 2005 have revealed to the world the enormous challenge Louisiana now faces. South Louisiana appears to have entered a period when the convergence of two powerful forces is working against its survival. Since the 1950's, the processes driving coastal loss have continued only slightly abated. Since 1990, meteorological and oceanic processes driving tropical systems have more frequently generated category 4 and 5 hurricanes. More destructive hurricanes are predicted for coming decades. ~ South Louisiana's ongoing peril is the continued overlap of weakened hurricane protection with more frequent and intense hurricanes.***
> ***In light of this predicament, how can the coast and culture of south Louisiana survive? The survival of a culture and a region is at stake. Hurricanes Katrina and Rita may have narrowed the field of discussion from what we might want, down to what we absolutely need. There is a growing consensus that what is needed is a pragmatic and effective strategy to integrate both coastal habitat restoration and engineered flood protection, such as levees. This strategy must be established soon and while under duress.***

John Lopez (2006).
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Report to Lake Pontchartrain Basin Foundation, New Orleans.

14.1 Introduction

At the present time, the federal government has a significant effort underway to re-establish the New Orleans Flood Defense System (NOFDS) to "pre-Katrina conditions" by 1 June 2006. The federal government has proposed to further improve the NOFDS to meet "100-year flood conditions" by 2010. Studies are currently underway by the Corps of Engineers to define an expanded and more reliable NOFDS (Appendix G). In this Chapter we explore options for the engineering elements that could be provided in a long-term NOFDS.

The first question addressed in going forward is: "what should we do about providing adequate flood protection for the greater New Orleans area?" To the people who lived and continue to live in this area, this is not a question. These people are in the process of rebuilding their homes and lives. A majority of people who live in this area are committed to re-building and continuing the development of this area. Some have and will decide not to return; they will rebuild elsewhere.

The real question is about the '*we*'. The following thoughts on this question were advanced by former Speaker Newt Gingrich (2006):

> *Shortly after Hurricane Katrina devastated New Orleans, Speaker of the House Dennis Hastert wondered aloud whether the Federal Government should help rebuild a city much of which lies below sea level. The most tough-minded answer to that question demonstrates that rebuilding and protecting New Orleans is in the national interest. Reason: The very same geological forces that created that*

port are what make it vulnerable to Category 5 hurricanes and also what make it indispensable.

If engineering the Mississippi made New Orleans vulnerable, it also created enormous value. New Orleans is the busiest port in the U.S.; 20% of all U.S. exports and 60% of our grain exports, pass through it. Offshore Louisiana oil and gas wells supply 20% of domestic oil production. But to service that industry, canals and pipelines were dug through the land, greatly accelerating the washing away of coastal Louisiana. The state's land loss now totals 1,900 sq. mi. that land once protected the entire region from hurricanes by acting as a sponge to soak up storm surges. If nothing is done, in the foreseeable future an additional 700 sq. mi. will disappear, putting at risk port facilities and all the energy-producing infrastructure in the Gulf.

…Washington also has a moral burden. It was the Federal Government's responsibility to build levees that worked, and its failure to do so ultimately led to New Orleans' being flooded. The White House recognized that responsibility when it proposed an additional $4.2 billion for housing in new Orleans, but the first priority remains flood control. Without it, individuals will hesitate to rebuild, and lenders will decline too invest.

How should flood control be paid for? States get 50% of the tax revenues paid to the Federal Government from oil and gas produced on federally owned land. States justify that by arguing that the energy production puts strains on their infrastructure and environment. Louisiana gets no share of the tax revenue from the oil and gas production on the outer continental shelf. Yet that production puts an infinitely greater burden on it than energy production [from] other federal territory puts on any other state. If we treat Louisiana the same as other states and give it the same share of tax revenue that other states receive, it will need no other help from the government to protect itself. Every day's delay makes it harder to rebuild the city. It is time to act. It is well past time.

For us it is not a question of *if* we go forward to provide an adequate and acceptable NOFDS. It is a question of *how* we go forward. Going forward will demand a lot of all involved including vision, commitment, responsibility, respect, organization, cooperation, leadership, knowledge, resources, preparations, time, and some good luck. While this Chapter examines the engineering aspects of providing long term hurricane flood protection for the greater New Orleans area, it should be clearly understood that a PREREQUISITE to a successful venture must be re-engineering the Technology Delivery System needed to develop such a system. History has clearly shown that without an effective and sustainable TDS, we can expect a deficient and defective long-term NOFDS. History will repeat itself if we let it.

During the next several decades, hurricane seasons are expected to produce greater numbers of more severe storms. Unnecessary delays in embarking on development and realization of a long-term NOFDS only increase our chances of failing. We learned this lesson during the 40 year period between disastrous flood of 1965 (hurricane Betsy) and catastrophic flood of 2005 (hurricane Katrina). Now is the time for careful and deliberate thought followed by effective and timely action. Another disastrous flooding of the greater New Orleans area should not be an option.

14.2 Engineering Considerations

The ILIT addressed two key aspects associated with the engineering considerations of going forward: 1) the NOFDS physical facilities, and 2) the engineering criteria and guidelines for these facilities.

14.2.1 Physical Facilities

Evaluation of the options for NOFDS physical facilities requires a basic understanding of the natural environmental - geological - ecological setting of this area, the commercial - industrial complex established in this area, and unique cultural - social - institutional - political elements. This is a very complex system whose future is shadowed by its past.

A systematic and integrated study needs to be performed of the options for provision of physical facilities so that informed choices can be made about how best to provide long-term flood protection for the greater New Orleans area. The NOFDS is part of an even larger challenge that involves other parts of the Gulf coast and the floodplain of the Mississippi River (Dean 2006). The real threats of increased hurricane activity and intensity, coastal degradation, subsidence, and climate change (rise in sea level, increase in rainfall and flood potential) must be recognized and appropriate and effective preparations put in place to help protect life and property in this area.

The Mississippi River and the Gulf of Mexico have been interacting in this part of the United States for millions of years (Kelman 2003). As a result of sediments transported and deposited by the Mississippi River during the past 10,000 years, a vast complex of delta lobes have developed where a succession of different river channels met the Gulf of Mexico (Coleman 1988). Sixteen of these lobes have been developed and abandoned during the past 20,000 years. The sediments deposited by these delta lobes dominate the geology of this area and the recently deposited sediments reach thicknesses exceeding 500 feet (U.S. Army Corps of Engineers 2004).

The Mississippi Delta is a broad wedge-shaped floodplain whose top is about where the Atchafalaya River branches off from the Mississippi River and whose broad curved base is the Gulf of Mexico coastline (about 150 miles wide) (Sparks 2006). The coastline is delineated with a long line of barrier islands. The shape of this delta is determined by sediment accumulation, compaction, subsidence, growth faulting, changing sea level, and most recently by man's activities. Recent information indicates that since the sea reached its present level (about 6,000 years ago), six major lobes including a developing new one at the mouth of the Atchafalaya River have existed. The modern Birdsfoot Delta that lies to the southeast of New Orleans (Plaquemines parish) has existed for only about the last 1,000 years.

The river has been trying to change its course to the Atachafalaya River (100 miles to the bay) as the length of the Mississippi River to the Gulf of Mexico has increased (now more than 200 miles). In order to maintain New Orleans as a deepwater port in the 1950s, the Corps of Engineers constructed the Old River Control Structure to help divert about 30% of the Mississippi River water down the Atachafalaya and keep the remainder flowing to the Gulf through its present course. In 1973, a flood on the Mississippi River almost caused failure of the Old River control Structure. The Corps completed a new auxiliary structure in 1985 to take some of the pressure off the Old River control Structure. At the present time, the Atachafalaya lobe is actively building toward the Gulf of Mexico and the lobe south of New Orleans is regressing.

A variety of processes have altered the natural process of land building by the Mississippi River and its tributaries (Hallowell 2005; Committee on the Restoration and Protection of Coastal Louisiana 2006; Zinn 2004; 2005a, 2005b). These include building dams and flood control structures (decreased sediment supply), building levees (do not permit sediment transport to adjacent areas), building canals and pipelines (oil and gas exploration and production), and building waterways (e.g., Inter-Coastal Water Way, Mississippi River Gulf Outlet). All have had their effects on replenishing sediments to keep up with subsidence and balance coastal transport processes and on providing nutrients to sustain freshwater wetlands. With population and industrial growth along the Mississippi River and its tributaries (it drains about 40% the United States), an influx of by products and waste products have taken their toll on the wetlands. Exploration for and production (extraction, transport) of hydrocarbons also have taken their toll on wetlands and contributed to land loss. The rise of sea level also has taken its toll. The result is a rapidly degrading and regressing coastline. This coastline is projected to loose about 10 square miles of land per year during the next 50 years (Dean 2006, Sparks 2006). The rapidly regressing coastline has had important effects on the increase in hurricane conditions affecting the NOFDS.

The NOFDS is faced not only with the challenges associated with hurricane surges and waves, but with potential floods from the Mississippi River, with subsidence and compaction, reduction of the buffering provided by coastal barrier islands and wetlands, and with potential water ingress provided by waterways. Oliver Houck (2006) addressed these challenges:

> *So here is the starting point: exactly what we do want the Louisiana coast to look like, to do for us, for say, the next century? …Earth to Louisianans: you really can't have this cake and eat it too. With all due respect, it is not just a matter of doing everything we want 'smarter.' It is a matter of getting straight what we want, and what comes first. What comes next is the hardest step for any American community to take, and all be heresy in South Louisiana. A plan. The mere mention of planning raises blood pressures and brings on cries of Godless Communism. What we have had in the city of new Orleans and along the entire gulf coast is planning by default (local attorney Bill Borah calls it 'planning by surprise'). Planning takes place. It's just that we haven't taken part in it. Where water resources are concerned, it starts with real estate developers, port authorities, levee boards and other outside-the-ballot-box enterprises, their projects facilitated and funded by the Army Corps of Engineers. In their minds, the only question is a technical one: what kind of engineering do we need to get our project done? The system has produced the expected results: more rip-rap here, more drainage there, and levees to the horizon. The goal is - although it is never stated anywhere - to develop as much of the coast as possible. When you add the projects up, they determine the destiny of the city and South Louisiana.*
>
> *What is apparent is that these levees, designed by engineers and approved by Congress, are the basic planning documents for the future of South Louisiana. what is north of these levees will be developed. What is south of them will be anyone's guess, although not for long; the map on global warming shows these coastal marshes gone within a century. De facto, we end up with a wall. Not all that adequate a wall, by the way. Only Category three, if that. Can you imagine the costs of maintaining even a Category three levee system winding back and forth to the Gulf from New Orleans to Texas" Can we imagine what will happen when development piles in behind it, and then gets flooded? Do we already know,*

from Lakeview and New Orleans East, what happens to land elevations behind levees once they are drained and paved?

Our choice is to start this process from the other end. If we do, another range of options open. There are a dozen major towns across the southern tier with thousands of homes and residents, and they deserve protection. But the way to provide it may be with the same kind of ring levee systems that protects (or should) New Orleans and its surrounding parishes, supplemented by flood gates at the mouths of the main canals. Or, it may mean peninsular levee systems down the historic ridges of the bayous, protecting what has always been the high ground. …Problem is, we have lacked the process - we have lacked even the language - for such a discussion. In addition to scientists and engineers, we may need some social workers. In saying this, I am most serious.

The ILIT examined two basic alternatives to develop a long-term NOFDS. The first was constructing levees, floodwalls, and pump stations capable of providing a long term NOFDS. At the present time, efforts are underway to provide "100-year" flood protection. But, the question is why "100-year" protection? Why not 1,000 year or 10,000 year protection (frequently posed as Category 4 or 5 hurricane protection)? Our considerations of economic cost-benefit guidelines, historic and current standards of practice for public facilities in the United States and elsewhere indicated that protection against disastrous flooding of the greater New Orleans area should be for conditions having average return periods much more demanding than the present goal of "100-year" flood protection. This issue was addressed by another very similar area that must defend its population and commercial enterprises at elevations up to 23 feet below sea level - the Netherlands (Netherlands Water Parternership 2005):

Our standards are accepted risks related to the design-criteria of our dikes. Those standards are laid down in the Flood Defense Act. For the economically most important and densely populated part of the country, we design our dikes and dunes to be strong enough to withstand a storm-situation with a probability of 1 to 10,000 a year. That means, that a Dutchman - if he should live a 100 years - has a chance of 1 percent to witness such an event. For our parliament, these odds became the acceptable standard. For the less important coastal areas we calculate the probability of 1 to 4,000 and along the main rivers 1 to 1,250.

This background was developed largely after the Netherlands suffered catastrophic flooding of the country in 1953. This flooding was comparable to the flooding of the greater New Orleans area in the wake of hurricane Katrina (approximately 1,800 dead, 50,000 destroyed homes, 350,000 acres of flooded land). It was also preceded by a history that included a large number of malfunctions that included poor organization, bad maintenance, not heeding warnings, poor communications, underestimation of the danger, negligence, lack of preparedness (Jurjen Battjes, personal communication, Dec. 30, 2005). This history was repeated in the catastrophic failure of the NOFDS.

Following the 1953 catastrophe, the Dutch vowed "never again" and developed a system that is today a model of advanced engineering and water resource management. It also provides a model for the organizational re-engineering required to realize the system they have in place today and that they continue to maintain and improve. This organization is a centralized Rijkswaterstaat which is the national public works department in charge of all flood defense works. This department has direct ties and interfaces with the local agencies responsible for continued development, maintenance, and improvement of flood defense work (including evacuation and disaster recovery). However, the Dutch have learned the sad lessons of trying to overwhelm nature with engineered works. They realized many unintentional consequences from such an approach surfaced as very severe negative environmental and quality of life impacts. And, they learned from these mistakes and gone on to remediate the mistakes and develop new strategies (Netherlands Water Partnership 2005):

Climate changes are increasing the likelihood of flooding and water-related problems. In addition population density continues to increase, as does the potential for economic growth, and consequently, the vulnerability to economic and social disaster. Two undesirable developments that, in terms of safety, exacerbate one another - a grown risk with even larger consequences. As such, the safety risk is growing at an accelerated pace (safety risk - chance multiplied by consequence).

The Netherlands is changing its approach to water. This change involves the idea that the Netherlands will have to make more frequent concessions. We will have to relinquish open space to water, and not take back existing open spaces, in order to curb the growing risk of disaster due to flooding, we will also need to limit water-related problems and be able to store water for expected periods of drought. By this we do not mean space in terms of the height of ever taller levees or depth through continued channel dredging, but space in the sense of flood plains. This approach will require more area, but in return we will increase our safety and limit water related problems. Safety is an aspect that must plan a different role in spatial planning. Only by relinquishing our space can we set things right; if this is not done in a timely manner, water will sooner or later reclaim the space on its own, perhaps [in a] dramatic manner.

The Dutch continue to be challenged by their countrymen not to become conceited or complacent - they are devoted to a culture of continuous improvements in their flood protection. Our consideration of this background indicated that the most attractive option for provision of an acceptable and sustainable NOFDS *is one of re-establishing and enhancing selected natural defenses supplemented with engineered works as necessary to provide long-term flood protection*. Guidelines and many useful insights are provided by John Lopez (2006) in the report *The Multiple Lines of Defense Strategy to Sustain Louisiana's Coast* about how such an option might be developed. Additional background for development of this option is also provided in the reports *Coast 2050: Toward a Sustainable Coastal Louisiana* (Louisiana Coastal Wetlands Conservation and Restoration Task Force 1998), *Ecosystem Restoration Study* (U.S. Army Corps of Engineers 2004), *Drawing Louisiana's New Map* (National Research Council 2006), and *A New Framework for Planning the Future of Coastal Louisiana after the Hurricanes of 2005* (Working Group for Post-Hurricane Planning for the Louisiana Coast 2006). Results contained in these studies provide a coherent and substantial basis for development of a long-term NOFDS. Lopez (2006) proposes eleven *Lines of Defense* (see Figure 14.1):

1st Offshore shelf within the Gulf of Mexico: *The offshore shelf ranges in depth from 300 feet at the shelf edge to zero depth at the gulf shoreline. Its width vanes from a few miles to hundreds of miles. The primary benefit of the shallow shelf is to dramatically reduce wave height and wave energy from an approaching tropical system. A negative aspect of the shelf is that it will promote higher storm surges inland. The variable influences storm surges due to the geometry of the* *shelf needs to be considered for storm surge analysis. Also, dredging activities on the shelf should avoid increasing shoreline erosion by wave refraction around dredge holes. The gulf fisheries and the oil and gas industry are key economic aspects of the shelf. Examples: Narrow shelf at the mouth of Mississippi River & Wide shelf offshore from Cameron Parish*

***2nd Barrier Islands**: The Louisiana barrier island shoreline is characterized by fragmented barriers or shoals with low vertical profiles and low sand content. However, barrier islands provide an important wave barrier for interior sounds and coastal marsh. The primary benefits of barrier islands are the near-complete reduction in wave height and the slight reduction in storm surge further inland. A negative aspect of barrier islands is their ephemeral nature and unpredictable local impacts to them from hurricanes. Barrier islands also have significant recreational aspects such as fishing and birding. Examples: Chandeleur Islands and Grand Isle*

***3rd Sounds**: The primary benefit of the sounds is to provide a relatively shallow water buffer to deep water currents. Sounds do have a negative aspect during storms by allowing waves to re-generate on the sound side of barrier islands. Also, sounds may cause storm surge and wave erosion on the back side of barrier islands.*

***4th Marsh Landbridges**: Marsh landbridges are areas of emergent marsh with relative continuity compared to adjacent bays, sounds or areas of significant marsh/land loss. Ideally, landbridges connect other elevated landforms such as natural ridges. Since some ridges are developed and have adjacent levees, marsh landbridges may also bridge adjacent levee systems and economic corridors. Marsh landbridges compose much of the residual internal framework of the coast which reduces fetch and shoreline erosion of interior marshes and lagoons. Landbridges impede storm surge movement inland and protect other emergent marsh areas that may perform the same function. Some landbridges are threatened themselves by various processes of marsh loss and need to be sustained through restoration and maintenance. The landbridges represent an increasing fraction of the remaining emergent marsh of the coast and provide typical high productivity and fishery benefits typical of coastal wetlands. Examples: East Orleans landbridge, Biloxi Marsh landbridge, Barataria Basin landbridge, Upper Terrebonne Bay landbridge, Grand Lake-White Lake landbridge, Western Marsh Island landbridge, south Calcasieu Lake landbridge*

***5th Natural Ridges**: In southeast and central Louisiana, most natural ridges are the natural levees of abandoned distributary channels. These channels now act as tidal channels and are often colloquially named bayous or rivers. In southwest Louisiana, most natural ridges are chenniers running parallel to the Gulf coastline. Natural ridges may have continuous elevation of several feet and, therefore, will impede overland flow across the ridge and potentially reduce storm surge. Natural ridges often define (at least historically) the hydrologic basins of the coast. Natural ridges are most effective when they have at least 6 feet of elevation and well drained soils to maintain upland forests. Forests will also slow the movement of overland flow and may also provide a wind barrier. Natural ridges tend to be the economic corridors across the coast including* *primary state highways and coastal communities. These highways are also likely to be evacuation routes. Examples: Bayou la Loutre, Bayou Lafourche*

***6th Manmade Soil Foundations**: Manmade soil foundations for transportation may provide incidental benefit to storm surges. Railroads, highways and spoil banks may run parallel to the coast and locally provide a manmade ridge several feet [high]. These foundations may have settled and may need improvement to provide reliable transportation routes without chronic flooding. If highway improvements are contemplated, the effects 011 storm surge may be considered. Examples: Highway 90, Hwy 82*

***7th Flood Gates**: Flood gates are typically designed to withhold flood water and, therefore, remain open under most conditions. Flood gates are generally open so as not to impede navigation or natural ebb and flow of tides and aquatic organisms. Flood gates would be closed during a threat of flooding and to reduce flood tides in channels. Because of the generally low elevation of the coast, the effectiveness of flood gates may depend on the nearby topography or constructed features such as levees or spoil banks. Examples: Bayou Bienvenue, Bayou Dupre*

***8th Flood Protection Levees**: Flood protection levees are designed and constructed for flood protection of municipalities or other coastal infrastructure features. Levees are generally designed to be an absolute barrier defining a flood side and a protected side. The intent is to have zero storm surge flooding on the protected side, but an unintended consequence may be to increase water levels on the flood side. Levees are generally not designed to be overtopped or to withstand significant wave erosion. Exceptions include "potato levees" or other low relief levees designed to reduce flooding from non-storm tides. Typical hurricane protection levees protect limited portions of the coast with intense economic development. Examples: St. Bernard levee, Jefferson and Orleans Parish levees on Lake Pontchartrain*

***9th Flood protection pumping:** Pumping stations are generally within leveed areas and are used to reduce flood risk from rainfall and are not designed to pump out flood water in the case of a levee breach. Most pumping stations are not prepared with fuel, staff or other requirements to be effective to pump out flood water from a significant levee breach. Generally, these are large capacity pumps which displace water vertically above the water level on the flood side of the levee. Pumping stations are generally to protect areas of intense development. Examples: Orleans and Jefferson Parish's pumping stations.*

***10th: Elevated Homes and Businesses:** All homes and businesses in south Louisiana are subject to being flooded if they are not elevated above the normal land elevation. Even those behind levees are not 100% safe. Hurricanes Katrina and Rita made this painfully clear. All attempts to reduce storm surge height or its extent are limited by the intensity and attributes of particular storm events. Since there will always be the potential of a storm exceeding the limits of protection from storm surges, immovable assets such as homes and businesses should be elevated to the appropriate flood elevation risk. This is the last line of defense for immovable assets. Elevated homes also provide important side benefits such as improved protection from termites and more economic capacity to re-level or raise the houses due to settlement or increased flood risk. Example:*

pre-1940 housing in New Orleans, LUMCON, Marina del Ray in Madisonville

11th Evacuation*: Evacuation routes are typically highways, but could also include other means of transportation such as railroads, air transportation, etc. Evacuation routes are the last line of defense for people or moveable assets. Evacuation routes and procedures should be established for the coast. Ideally, evacuation routes may also serve as re-entry routes for first responders and as routes to re-populate after a storm event. Evacuation routes are generally selected based capacity to move a large number of people to safer areas as a storm approaches the coast. Some routes may be subject to flooding quickly and need to be improved. Examples: Regional contra-flow evacuation plan for southeast Louisiana.*

The Corps of Engineers and other organizations are continuing work to develop an advanced and more reliable NOFDS that is more compatible with the natural, industrial and social environments of southern Louisiana. The Working Group for Post-Hurricane Planning for the Louisiana Coast recently concluded (2006):

In the long term, hurricane protection for larger population centers, including the New Orleans region, can only be secured with a combination of levees and a sustainable coastal landscape. This will require adapting to changing conditions by re-establishing the constructive processes associated with distributing Mississippi River water and sediments across the coastal landscape, as well as alleviating the other destructive effects of past or future human activities.

With presently observed subsidence rates and anticipated acceleration of sea-level rise, most - although not all - of the coastal landscape could be maintained through the 21st century. And with efficient management of the river's resources, this landscape could be expanded in some places. However, this result can only be achieved with very aggressive, strategic, and well-informed restoration efforts, varying in size and objective but integrated within a landscape management plan.

The challenges associated with rehabilitation and improvement of the NOFDS need to be addressed in an integrated way combining public and social, organizational and institutional, natural and environmental, and commercial and industrial considerations. This is a “systems problem” that has many parts which are interactive, interdependent, and highly adaptive. We need to understand potential impacts, positive and negative, on the parts of this system so that wise choices and informed decisions can be made on how best to proceed. This is a different kind of “engineering problem” in which the Technology Delivery System used to address that problem is of utmost importance. Gerald Galloway (2006) summarized these issues:

Since 1983, when the Water Resources Council was effectively abolished, there has been no central direction to or coordination of federal water efforts, among the many departments that deal with water issues. Congress remains locked in a turf-conscious committee system that does not encourage coordination. Except for enforcing water quality standards there is little federal guidance, other than budgetary or ad hoc initiatives, on other water issues.

Given the present policy vacuum and the reluctance on the part of Congress and the administration to support comprehensive planning, New Orleans and coastal Louisiana will have to develop, in coordination with federal agencies, their own *vision for the future and move ahead in a way that brings together solutions to the many water challenges facing the region. this comprehensive plan must address all aspects of coastal Louisiana's water challenges.*

Each of the alternatives for development of a long-term NOFDS has its pluses and minuses, costs and benefits. It is clear that these alternatives need to be continually examined in an integrated and systematic way. The fundamental technology exists to develop an adequate long-term NOFDS. The question is not “can we do it?” The question is “will we do it?”

14.3 Engineering Criteria and Guidelines

The basic technology exists to develop an effective and efficient NOFDS. A major challenge is timely and proper application of this technology. The following recommendations are made to facilitate such application.

Recommendation 1: Develop an integrated and coherent Flood Defense System for the greater New Orleans area (NOFDS) to provide desirable and acceptable levels of flood protection throughout its life-cycle. Particular attention must be paid to interfaces and interdependencies in this system. The NOFDS should be balanced, complete, cohesive, clear, consistent, and have controls and continuity. The NOFDS should be based on the best available and safest technology and most up-to-date legal standards. Risks should be properly identified, contained and compartmentalized. The system must recognize the unique natural environmental setting including its geology, meteorology, oceanography, the Mississippi River floodplains, deltas and wetlands, subsidence, and the rise in sea level and frequency and intensity of hurricanes. The system must also recognize and accommodate the unique societal and cultural environments of this area.

Recommendation 2: Develop a NOFDS based on enhancing natural defenses supplemented with engineered defenses that incorporate concepts of defenses in depth, robustness or resilience, and fail-safe performance. Selective re-establishment of natural coastal defenses and wetlands and restored floodplains to provide for river floods should be supplemented with engineering works that together have the capabilities of providing desirable and acceptable levels of flood protection. Coastal management must be focused on providing safety from flooding and environmental protection. Water should be given space. Some areas will have to be returned to nature and judicious and wise decisions must be reached on which areas will be populated and developed and the levels of protection that will be provided to these areas. Engineering works should include raising, strengthening and defending levees, providing floodgates and storm surge barriers, positioning and defending modern pump stations. Engineering must also address compartmentation to limit potential flooding and adequate and effective evacuation measures to help limit effects on people and their possessions. A robust NOFDS will require a combination of appropriate configuration of engineered elements and components, ductility or an ability to deform and stretch and not loose important performance characteristics, excess capacity so that if some elements or components are overloaded or do not perform desirably, desirable protection can be maintained, and appropriate correlation or mutual relationships so that desirable protection is realized. Fail safe characteristics should be provided in all of the important elements of the NOFDS so that when the design and ultimate performance conditions are exceeded, the performance characteristics are not appreciably compromised.

Recommendation 3: Develop a NOFDS founded on advanced Risk Assessment and Management principles for all phases in the life-cycle including concept development, design, construction, operation, and maintenance. These principles should address natural, analytical modeling, human and organizational performance, and knowledge acquisition and utilization uncertainties and be based on proactive, reactive, and interactive risk assessment and management approaches. These approaches should be based on reductions in likelihoods of failure, reduction in the consequences associated with potential failures, and increases in detection and correction of developments that can lead to failures. Advanced Risk Assessment and Management approaches should be used to provide decision makers with information to define what levels of protection should be provided for which areas to be protected and how much can and should be spent for those purposes.

Recommendation 4: Develop updated engineering guidelines and procedures for all elements and components to be incorporated in the FDS for all life-cycle phases based on proven state-of-practice and state-of-art technology. Where technology gaps are identified, substantial development programs should be implemented to fill them with existing research results. Where technology gaps can not be filled with existing research results, research should be undertaken or sponsored to enable their timely filling.

Recommendation 5: Develop, implement, and enforce advanced Quality Assurance and Quality Control methods and procedures for all life-cycle phases of the NOFDS. Quality Assurance (proactive) and Quality Control (interactive) measures are of particular importance to help disclose 'predictable surprises' and variances in the desirable quality characteristics of the elements and components in the NOFDS. These methods and procedures should be used in all life-cycle phases of the NOFDS including concept development, design, construction, operation, maintenance, and continued improvement. These procedures and measures need to assure that the best available and safest technology is used and used properly.

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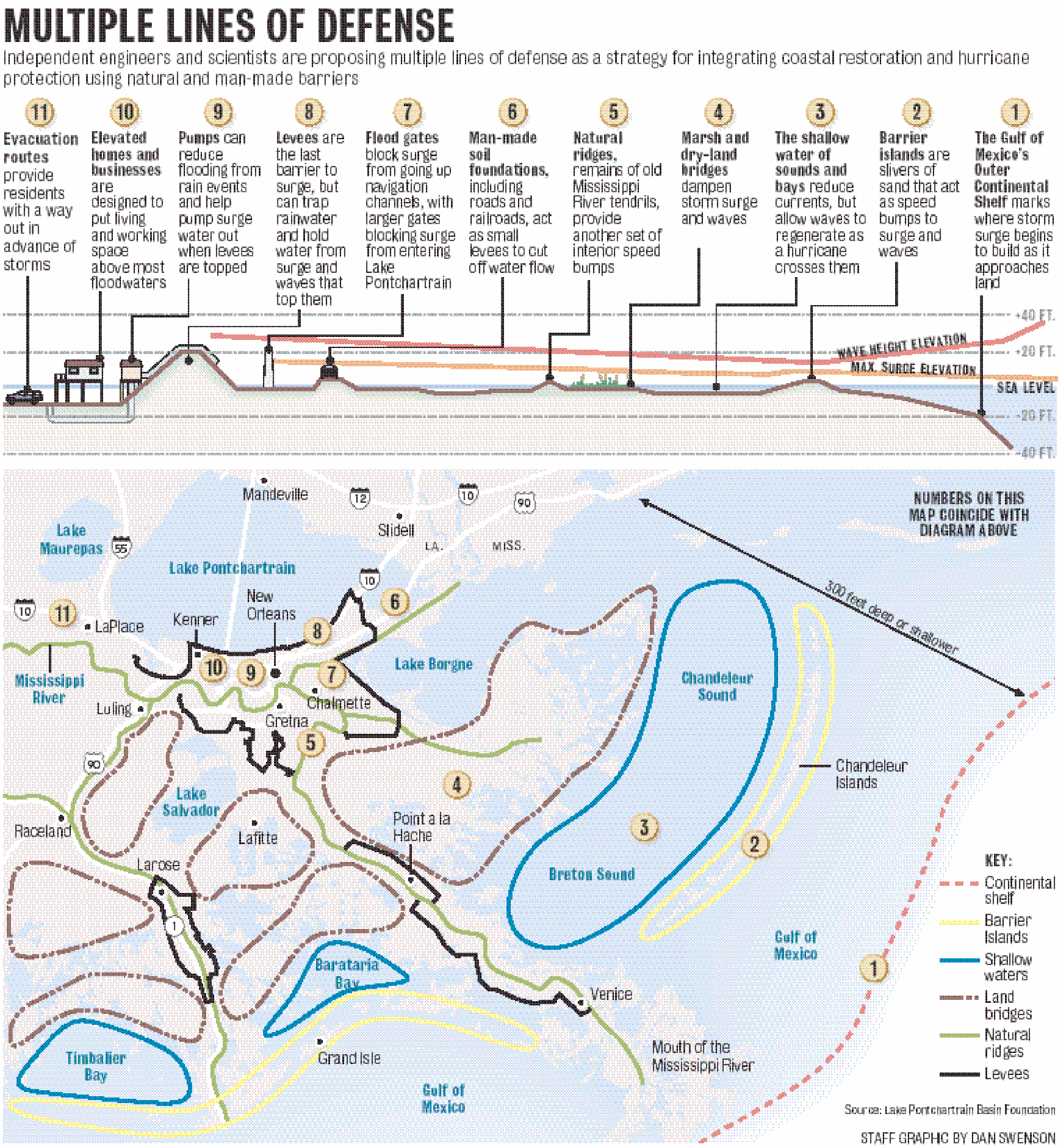

Figure 14.1: Eleven Lines of Defense (Lopez, 2006; graphic provided by the New Orleans Times Picayune)

CHAPTER FIFTEEN: FINDINGS AND RECOMMENDATIONS

15.1 Overview

This report presents the results of an investigation of the performance of the New Orleans regional flood protection system during and after Hurricane Katrina, which struck the New Orleans region on August 29, 2005. This event resulted in the single most costly catastrophic failure of an engineered system in history. Current damage estimates at the time of this writing are on the order of $100 to $150 billion in the greater New Orleans area, and the official death count in New Orleans and southern Louisiana at the time of this writing stands at 1,293, with an additional 306 deaths in nearby southern Mississippi. An additional Approximately 400 additional people are currently still listed as "missing", and the death toll is expected to continue to rise a bit further. More than 450,000 people were initially displaced by this catastrophe, and at the time of this writing more than 200,000 residents of the greater New Orleans metropolitan area continue to be displaced from their homes by the floodwater damages from this storm event.

This investigation has targeted three main questions as follow: (1) What happened?, (2) Why?, and (3) What types of changes are necessary to prevent recurrence of a disaster of this scale again in the future?

In the end, it is concluded that many things went wrong with the New Orleans flood protection system during Hurricane Katrina, and that the resulting catastrophe had it roots in three main causes: (1) a major natural disaster (the Hurricane itself), (2) the poor performance of the flood protection system, due to localized engineering failures, questionable judgments, errors, etc. involved in the detailed design, construction, operation and maintenance of the system, and (3) more global "organizational" and institutional problems associated with the governmental and local organizations responsible for the design, construction, operation, maintenance and funding of the overall flood protection system.

15.2 Performance of the Regional Flood Defense System During Hurricane Katrina

As Hurricane Katrina initially approached the coast, the resulting storm surge and waves rose over the levees protecting much of a narrow strip of land on both sides of the lower Mississippi River extending from the southern edge of New Orleans to the Gulf of Mexico. Most of this narrow protected zone, Plaquemines Parish, was massively inundated by the waters of the Gulf.

The eye of the storm next proceeded to the north, on a path that would take it just slightly to the east of New Orleans.

Hurricane Katrina has been widely reported to have overwhelmed the eastern side of the New Orleans flood protection system with storm surge and wave loading that exceeded the levels used for design of the system in that area. That is a true statement, but it is also an incomplete view. The storm surge and wave loading at the eastern flank of the New Orleans flood protection system was not vastly greater than design levels, and the carnage that resulted owed much to the inadequacies of the system as it existed at the time of Katrina's arrival. Some overtopping of levees along the eastern flank of the system (along the northeastern frontage of the St. Bernard and Ninth Ward protected basin, and at the southeast corner of the New Orleans East protected basin), and also in central areas (along the GIWW channel and the IHNC channel) was inevitable given the design levels authorized by Congress and the surge levels produced in these areas by the actual storm. It does not follow, however, that this overtopping had to result in catastrophic failures and breaching of major portions of the levees protecting these areas, nor the ensuing catastrophic flooding of these populous areas.

The northeast flank of the St. Bernard/Ninth Ward basin's protecting "ring" of levees and floodwalls was incomplete at the time of Katrina's arrival. The critical 11 mile long levee section fronting "Lake" Borgne (which is actually a Bay, connected directly to the Gulf of Mexico) was being constructed in stages, and funding appropriation for the final stage had long been requested by the U.S. Army Corps of Engineers (USACE), but this did not arrive before Katrina struck. As a result, large portions of this critical levee frontage were several feet below final design grade. In addition, an unfortunate decision had been made to use local dredge spoils from the excavation of the adjacent MRGO channel for construction of major portions of the levees along this frontage. The result was that major portions of these levees were comprised of highly erodible sand and lightweight shell sand fill.

When the storm surge arrived, massive portions of these levees eroded catastrophically and the storm surge passed through this frontage while still on the rise, crossed an open swamp area that should have safely absorbed most of the overtopping flow from the outer levees (if they had not catastrophically eroded), and it then crossed easily over a secondary levee of lesser height that had not been intended to face a storm surge largely undiminished by the minimal interference of the too rapidly eroded outer levees fronting Lake Borgne. The resulting carnage in St. Bernard Parish was devastating, as the storm surge rapidly filled the protected basin to an elevation of approximately +12 feet above sea level; deeply inundating even neighborhoods with ground elevations well above sea level in this area.

The storm surge swelled waters of Lake Borgne also passed over and then through a length of levees at the southeast corner of the New Orleans East protected basin. Here too, the levees fronting Lake Borgne had been constructed primarily using materials dredged from the excavation of an adjacent channel (the GIWW channel), and these levees also contained major volumes of highly erodible sands and lightweight shell sands. These levees also massively eroded, and produced the principal source of flooding that eventually inundated the New Orleans East protected area. Here again, there was an area of undeveloped swampland behind the outer levees that might have absorbed the brunt of any overtopping flow, and a secondary levee of lesser height was in place behind this swampland that might then have prevented catastrophic flooding of the populous areas of New Orleans East. This secondary levee was not able to resist the massive flows resulting from the catastrophic erosion of the highly erodible section of the Lake Borgne frontage levee, however, and the floodwaters passed over the secondary levee and began the filling of the New Orleans East protected basin.

The catastrophic erosion of these two critical levee frontages need not have occurred. These frontages could instead have been constructed using well compacted clay fill with good resistance to erosion, and they could have been further armored in anticipation of the storm surge and wave loading from Lake Borgne. The levee at the northeast edge of St. Bernard Parish could have been completed in a more timely manner. The result would have been some overtopping, but not catastrophic erosion and uncontrolled breaching of these critical frontages. Some flooding and damage would have been expected, but it need not have been catastrophic.

The storm surge swollen waters of Lake Borgne next passed laterally along the east-west trending GIWW/MRGO channel to its intersection at a "T" with the north-south oriented IHNC channel, overtopping levees along both banks to a limited degree. This produced an additional breach of a composite earthen levee and concrete floodwall section along the southern edge of New Orleans East, adding additional uncontrolled inflow to this protected basin. This failure could have been prevented at little incremental cost if erosion protection (e.g. a concrete splash pad, or similar) had been emplaced along the back side of the concrete floodwall at the levee crest, but the USACE felt that this was precluded by Federal rules and regulations regarding authorized levels of protection.

The surge next raised the water levels within the IHNC channel, and produced a number of failures on both the east and west banks. Two major failures occurred on the east side of the IHNC, at the west edge of the Ninth Ward. Overtopping occurred at both of these locations, but this was not the principal cause of either of these failures. Both failures were principally due to underseepage flows that passed beneath the sheetpile curtains supporting the concrete floodwalls at the crests of the levees. Like many sections of the flood protection system, these sheetpiles were too shallow to adequately cut off, and thus reduce, these underseepage flows. The result was two massive breaches that devastated the adjacent Ninth Ward neighborhood, and then pushed east to meet with the floodwaters already rapidly approaching from the east from St. Bernard Parish as a result of the earlier catastrophic erosion of the Lake Borgne frontage levees.

Several additional breaches also occurred farther north on the east side of the IHNC fronting the west side of New Orleans East, but these were relatively small features and they just added further to the uncontrolled flows that were now progressively filling this protected basin. These breaches occurred mainly at junctures between adjoining, dissimilar levee and floodwall sections, and represented good examples of widespread failure to adequately engineer these "transitions" between sections of the regional flood protection system.

Several breaches occurred on the west side of the IHNC, and these represented the first failures to admit uncontrolled floodwaters into the main metropolitan (downtown) protected area of New Orleans. These features did not scour and erode a path below sea level, however, so they admitted floodwaters for a number of hours and then these inflows ceased as the storm surge in the IHNC eventually subsided. Only 10% to 20% of the floodwaters that eventually inundated a majority of the main (downtown) New Orleans protected basin entered through these features.

These failures and breaches on the west side of the IHNC all appear to have been preventable. One failure was the result of overtopping of an I-wall, with the overtopping flow then eroding a trench in the earthen levee crest at the inboard side of the floodwall. This removal of lateral support unbraced the floodwall, and it was pushed over laterally by the water pressures from the storm surge on the outboard side. Here again the installation of erosional protection (e.g. concrete splash pads or similar) might have prevented the failure.

The other failures in this area occurred at "transitions" between disparate levee and floodwall sections, and/or at sections where unsuitable and highly erodible lightweight shell sand fills had been used to construct levee embankments. Here, again, these failures were as much the result of design choices and/or engineering and oversight issues as the storm surge itself.

As the eye of the hurricane next passed to the northeast of New Orleans, the counterclockwise swirl of the storm winds produced a storm surge against the southern edge of Lake Pontchartrain. This produced additional temporary overtopping of a long section of levee and floodwall at the west end of the lakefront levees of New Orleans east, behind the old airport, adding further to the flows that were progressively filling this protected basin.

The surge against the southern edge of Lake Pontchartrain also elevated the water levels within three drainage canals at the northern edge of the main metropolitan (downtown) New Orleans protected basin, and this would produce the final, and most damaging, failures and flooding of the overall event.

The three drainage canals should not have been accessible to the storm surge. The USACE had tried for many years to obtain authorization to install floodgates at the north ends of the three drainage canals that could be closed to prevent storm surges from raising the water levels within the canals. That would have been the superior technical solution. Dysfunctional interaction between the local Levee Board (who were responsible for levees and floodwalls, etc.) and the local Water and Sewerage Board (who were responsible for pumping water from the city via the drainage canals) prevented the installation of these gates, however, and as a result many miles of the sides of these three canals had instead to be lined with levees and floodwalls.

The lining of these canals with levees topped with concrete floodwalls was rendered very challenging due to (a) the difficult local geology of the foundation soils, and (b) the narrow right of way (or available "footprint") for these levees. As a result of the decision not to install the floodgates, the three canals represented potentially vulnerable "daggers" pointed at the heart of the main metropolitan New Orleans protected basin. Three major breaches would occur on these canals; two on the London Avenue Canal and one on the 17th Street Canal. All three of these breaches eroded and scoured rapidly to well below sea level, and these three major breaches were the source of approximately 80% of the floodwaters that then flowed into the main (downtown) protected basin over the next three days, finally equilibrating with the still slightly elevated waters of Lake Pontchartrain on Thursday, September 1.

The central canal of the three, the Orleans Canal, did not suffer breaching, but a section of floodwall topping the earthen levee approximately 200 feet in length near the south end of the canal had been left incomplete, again as a result of dysfunctional interaction between the local levee board and the water and sewerage board. This effectively reduced the level of protection for this canal from about +12 to +13 feet above sea level (the height of the tops of the floodwalls lining the many miles of the canal) to an elevation of about +6 to +7 feet above sea level (the height of the earthen levee crest along the 200 foot length where the floodwall that should have topped this levee was omitted). As a result of the missing floodwall section, flow passed through this "hole" and began flowing into the heart of the main New Orleans protected basin. This flow eventually ceased as the storm surge subsided, and so was locally damaging but not catastrophic.

The three breaches on the 17th Street and London Avenue canals were catastrophic. None of these failures were the result of overtopping; surge levels in all three drainage canals were well below the design levels, and well below the tops of the floodwalls. Two of these breaches were the result of stability failures of the foundation soils underlying the earthen levees and their floodwalls, and the third was the result of underseepage passing beneath the sheetpile curtain and resultant catastrophic erosion near the inboard toe of the levee that eventually undermined the levee and floodwall.

A large number of engineering errors and poor judgments contributed to these three catastrophic design failures, as detailed in Chapter 8. In addition, a number of these same problems appear to be somewhat pervasive, and call into question the integrity and reliability of other sections of the flood protection system that did not fail during this event. Indeed, additional levee and floodwall sections appear to have been potentially heading towards failure when they were "saved" by the occurrence of the three large breaches (which rapidly drew down the canal water levels and thus reduced the loading on nearby levee and floodwall sections.)

15.3 Engineering Issues

The New Orleans regional flood protection system failed at many locations during Hurricane Katrina, and by many different modes and mechanisms. This unacceptable performance can in many cases be traced to engineering lapses, poor judgments, and efforts to reduce costs at the expense of system reliability. These, in turn, was to a large degree the result of more global underlying "organizational" and institutional problems associated with the governmental and local organizations jointly responsible for the design, construction, operation, and maintenance of the flood protection system, including provision of timely funding and other critical resources.

Our findings to date indicate that no one group or organization had a monopoly on responsibility for the catastrophic failure of this regional flood protection system. Many groups, organizations and even individuals had a hand in the numerous failures and shortcomings that proved so catastrophic on August 29th. It is a complex situation, without simple answers.

It is not without answers and potential solutions, however, just not simple ones. There is a need to change the process by which these types of large and critical protective systems are created and maintained. It will not be feasible to provide an assured level of protection for this large metropolitan region without first making significant changes in the organizational structure and interactions of the national and more local governmental bodies and agencies jointly responsible for this effort. Significant changes are also needed in the engineering approaches and procedures used for many aspects of this work, for the standards used in such design, in the conceptual approaches considered, and in the conceptualization and treatment of potential modes of failure and poor performance during design and operation. There is also a need for interactive and independent expert technical oversight and review as well. In numerous cases, it appears that such review would have likely caught and challenged errors and poor judgments (both in engineering and in policy and funding) that led to failures during Hurricane Katrina.

There are many detailed engineering lessons developed within this report, but a number of overarching engineering issues have been identified, and a number of the most important of these are presented below. These are a somewhat urgent set of issues, as the USACE and the IPET investigation are currently working to assess the level of risk associated with the now largely reconstructed system, and these issues impact that assessment.

1. Overall levels of safety and reliability targeted during engineering design and analysis were inappropriately low for a critical system protecting a major metropolitan area. Factors of safety and analysis methods and procedures used in design calculations for the "transient" loading conditions associated with hurricane-induced storm surge, coupled with the design surge elevations employed, provided levels of risk that were on the order two to three orders of magnitude higher than the standards generally used in U.S. dam practice where similarly large populations are at potential risk. This left little room for error, uncertainties, or surprises.

2. The difficult and complex geology of the region posed design challenges that were not adequately addressed. Insufficient site investigation and characterization of foundation soil conditions at many sites produced minor short-term project savings, but these pale against the massive losses that ensued. More attention needs to be paid to the geology, and more detailed site investigation and site characterization is clearly warranted given the potential consequences of failures.

3. There was a persistent pattern of attempts to reduce costs of constructed works, at the price of corollary reduction in safety and reliability. This represented a policy that has now been shown to be "penny wise and pound foolish".

4. A pattern of optimistic assessment with regard to a number of potential sources of risk and of potential modes of failure was endemic to the detailed design of a number of major system elements. This included:

(a) The risks associated with underseepage flows during "transient" storm surges were systematically underestimated. This led to the use of sheetpile curtains that were extended to inadequate depths at a number of locations, and it led directly to a number of the major failures and breaches during hurricane Katrina. Appropriate consideration and analysis of underseepage issues (including potential embankment instability due to pore pressure induced strength reduction, and potential erosion and piping) for transient storm surge conditions was routinely missing, and the overall system should now be re-evaluated with regard to these potential modes of failure.

(b) The use of highly erodible sand and even lightweight shell sand fills in levee sections also figured prominently at numerous locations of breaching and catastrophic erosion. Use of such materials should henceforth be disallowed in this system that protects a major metropolitan region. Here again, the overall system should be re-evaluated for their presence, and the levels of risk posed by the presence of these unsuitable materials, both in levee embankments and at shallow depths within the underlying foundation soils. This risk should be mitigated.

(c) Similarly, design procedures did not include consideration of the potential failure mode that involves formation of a 'gap' at the outboard side of the floodwalls, between the outboard section of the earthen levee embankment ant the sheetpile curtains supporting the floodwalls. Formation of such gaps occurred at a number of sites as pressure increased on the outboard sides of the foodwalls, and water then intruded into the gaps and greatly increased the lateral "push" of the storm surge (water) against the sheetpile/floodwalls. A number of failures occurred as a result. In the future, such gapping should be "assumed" during analysis and design. Many of the "I-wall" type concrete floodwalls are currently being removed and replaced by the more robust "T-wall" type floodwalls (which have additional battered piles to help then resist overturning and lateral displacement.) These T-wall systems will have somewhat increased capacity, but they too will need to be analyzed with regard to this potential failure mode. It cannot simply be assumed that "T-walls" are intrinsically completely safe.

5. Design review was generally inadequate, and there was an institutional failure to catch and challenge unconservative design assumptions and interpretations of data. Instigation of interactive consultation and review by consulting panels of leading <u>outside</u> experts is common practice in dam engineering. It should be common practice in levee engineering as well, when the levee systems protect significant populations. In addition, it would be wise for local interests (e.g. the State and/or the City) to mount an additional unbiased expert review panel (again including leading experts) to provide a second check and opinion. At many failure sites it appears likely that suitable expert review would have caught and challenged errors and questionable judgments that contributed to the failures observed.

6. Improved advantage needs to be taken of ongoing technical advances related to the engineering, design and construction of these types of regional flood defense systems. Engineering design concepts and analysis approaches employed at many locations were sorely "dated" at the time of their use, and there was a lack of movement towards embracing new and improved methods and tools. "This is how we have always done it" is a potentially dangerous concept here, and inertia in terms of embracing technical advances was a troubling issue. Failure to embrace their own full-scale field testing and research led the Corps to neglect the "water-filled gap" as a potential failure mode to be addressed during design. And it is time to relegate the "Method of Planes" to its place in history and to adopt more modern and more flexible stability analysis methods capable of addressing a wider range of potential failure modes.

7. The USACE is the lead oversight agency with regard to engineering and construction of the regional flood defense system. The Corps needs to be allocated adequate funding and support, given the ability to perform research, and granted adequate freedom to facilitate the continuing professional development of highly qualified engineers within the Corps in order to ensure an adequate in-house supply of engineering expertise for their critical role.

15.4 Looking Back - Organized for Failure

The ILIT mandate at the outset of this investigation study was to include study of historical and organizational - institutional issues, political and budgetary considerations, decision making, utilization of technology, and the evolving societal, governmental, and organizational priorities over the life of the Flood Defense System for the Greater New Orleans Area (NOFDS). One cannot understand the failure of the NOFDS without understanding both the underlying engineering and organizational mechanics that were interwoven in the evolution of this failure.

ILIT's view of the importance of these *organizational, institutional, resource and technology delivery* factors increased during the course of this study. These factors are grouped into what is termed a *Technology Delivery System* (TDS). A TDS can be represented as system that has organizational components, inputs, outputs, and information linkages that are interactive, inter-dependent, and adaptive. Three primary organizational components comprise a TDS for a system such as the NOFDS. These are: (1) society (the public), (2) government (federal, state, local), and (3) enterprise (commercial, industrial, private). These components are embedded in and interact with their natural and cultural environments. Inputs comprise knowledge plus human, natural, and fiscal resources. Outputs include desired goods or services and undesired outcomes or unintended consequences.

Eight principal categories of TDS malfunctions were identified that played major roles in the catastrophic failure of the NOFDS, and these are as follow:

Failures of foresight: Catastrophic flooding of the greater New Orleans area due to surge from an intense hurricane was predicted for several decades. The consequences observed in the wake of hurricane Katrina were also predicted. The hazards associated with the NOFDS were not recognized, defensive measures identified and prioritized, and effective action was not mobilized to effectively deal with the hazards.

Failures of organization: The roots of the failure of the NOFDS are firmly embedded in flawed organizational - institutional systems. The organizational - institutional systems lacked centralized and focused responsibility and authority for providing adequate flood protection. There were dramatic and pervasive failures in management represented in ineffective and inefficient planning, organizing, leading, and controlling to achieve desirable quality and reliability in the NOFDS. There were extensive and persistent failures to demonstrate initiative, imagination, leadership, cooperation, and management.

Failures of resource allocation: Contributing to the failure of the NOFDS was provision of inadequate resources based primarily on recommendations provided by the Corps of Engineers. This was followed by failure of the federal and state governments to fund badly needed improvements once limitations were recognized. In several instances, State agencies pressured for 'lower cost' solutions not realizing that these solutions would result in lowering the quality and reliability of the NOFDS. There were important deficiencies in the cost - benefit analyses used to justify the levels of protection (and reliability) provided, and also the continued improvement in these levels of protection (and reliability) as knowledge and technology advanced.

Failures of diligence: Forty years after the devastating flooding caused by hurricane Betsy, the flood protection system authorized in 1965 and founded on the Standard Project Hurricane (SPH) was not completed when hurricane Katrina arrived. The concept and application of the SPH was recognized to be seriously flawed, yet there were no adjustments made to the system before Katrina struck. Early warning signs of deficiencies and flaws persisted throughout development of the different components that comprised the NOFDS, and these signs were not adequately evaluated and acted upon.

Failures of decision making: The history of this system was marked by a series of flawed decisions and trade-offs that proved to be fatal to the ability of the system to perform adequately. Compromises in the ability of this system to perform adequately started with the decisions regarding the fundamental design criteria for the development of the system, then were propagated through time as alternatives for the system were evaluated and engineered. Design, construction, operation, and maintenance of the system in a piecemeal fashion allowed the introduction of additional flaws and defects. Efficiency was traded for effectiveness. Superiority in provision of an adequate NOFDS was traded for mediocrity, lower expenditures, and getting along.

Failures of management: Requirements imposed on the Corps of Engineers by Congress, the White House, State and local agencies, and the general public have changed dramatically during the past three decades. Defense, re-construction, maintenance, waste disposal, recreational development, emergency response, and ecological restoration have served to divert attention from flood control. Public and Congressional pressures to (1) reduce backlogs of approved projects, (2) improve project and organizational efficiency (e.g.: down-sizing, out-sourcing, etc.), (3) address environmental impacts, and (4) develop appropriations for projects have served to divert attention from engineering quality and reliability of flood control. Engineering technology leadership, competency, expertise, research, and development capabilities appear to have been sacrificed for improvements in project planning and controlling.

Failures of synthesis: While individual parts of a complex system can be adequate, when these parts are joined together to form an interactive - interdependent - adaptive system, unforseen failure modes can be expected to develop. These unforseen, but forseeable, failure modes did develop in the NOFDS during hurricane Katrina. It is evident that insufficient attention was given to creation of an integrated series of components to provide a reliable overall NOFDS. Synthesis was subverted to decomposition, as projects were engineered and constructed in piecemeal fashion to conform to incremental appropriations. As a result, many failures developed at interfaces or 'transitions' in the NOFDS.

Failures of risk assessment and management: The risks (likelihoods and consequences) associated with hurricane surge and wave induced flooding were seriously underestimated. There was inadequate recognition of the primary contributors to the likelihoods and consequences of catastrophic flooding. Sufficient defensive measures to counteract and mitigate these uncertainties were not employed. Factors of safety used in design of the primary elements in the NOFDS were not sufficient; and represented implicit levels of system reliability that were inappropriately low for a system protecting a major metropolitan region. Quality assurance and control measures invoked during the life of the system failed to disclose critical flaws in the system. Inappropriate use was made of existing engineering technology available to design, construct, operate, and maintain a NOFDS that would have acceptable quality and reliability. Deficient risk management methods were used to allocate resources and impel action to properly manage risks. Risk management failed to employ continuing improvement, monitoring, assessment, and modifications in means and methods which were discovered to be ineffective.

15.5 Looking Forward - Organizing for Success

The following recommendations are offered for consideration in developing a NOFDS that will have desirable and acceptable quality and reliability. These recommendations are divided into two categories: engineering developments and organizational developments. It will take both working together to realize the desired goals of an NOFDS. The primary challenge is timely mobilization of inspired and inspiring leadership, adequate resources, existing technology, and high reliability organizations.

15.5.1 Strategic and Engineering System Issues:

The technology exists that can be used to develop a NOFDS that will be effective and efficient. A major challenge is timely and proper application of this technology.

Recommendation 1: Develop an integrated and coherent Flood Defense System for the greater New Orleans area (NOFDS) that will provide desirable and acceptable levels of flood protection throughout its life-cycle. Particular attention must be paid to interfaces and interdependencies in this system. The NOFDS should be balanced, complete, cohesive, clear, consistent, and have controls and continuity. The NOFDS should be based on the best available and safest technology and most up-to-date legal standards. Risks should be properly identified, contained and compartmentalized. The system must recognize the unique natural environmental setting including its geology, meteorology, oceanography, the Mississippi River floodplains, deltas and wetlands, subsidence, and the rise in sea level and frequency and intensity of hurricanes. The system must also recognize and accommodate the unique societal and cultural environments of this area.

Recommendation 2: Develop a NOFDS based on enhancing natural defenses supplemented with engineered defenses that incorporate concepts of defenses in depth, robustness or resilience, and fail-safe performance. Selective re-establishment of natural coastal defenses and wetlands, and restored floodplains to provide for river floods should be supplemented with engineering works that together will have the capabilities of providing desirable and acceptable levels of flood protection. Coastal management must be focused on providing safety from flooding and environmental protection. Water should be given space. Some areas will have to be returned to nature and judicious and wise decisions reached on which areas will be populated and developed and the levels of protection that will be provided to these areas. Engineering works should include: (1) raising, strengthening and improvement of the erosion resistance of levees, (2) provision of floodgates, and storm surge barriers, (3) improved positioning and defense of modern pump stations, (4) compartmentation to limit potential flooding consequences, and (5) adequate and effective evacuation measures to help limit effects on people and their possessions. A robust NOFDS will require a combination of appropriate configuration of engineered elements and components, ductility or an ability to deform and stretch and not loose important performance characteristics (e.g. the ability to overtop for some limited period of time without catastrophic breaching), and provision of excess capacity so that if some elements or components are overloaded or do not perform desirably then desirable protection can be maintained. Fail safe characteristics should be provided in all of the important elements of the NOFDS so that when the design and ultimate performance conditions are exceeded, the performance characteristics are not excessively compromised.

Recommendation 3: Develop a NOFDS founded on advanced Risk Assessment and Management principles for all phases in the life-cycle including concept development, design, construction, operation, and maintenance. These principles should address natural, analytical modeling, human and organizational performance, and knowledge acquisition and utilization uncertainties and be based on proactive, reactive, and interactive risk assessment and management approaches. These approaches should be based on reductions in likelihoods of failure, reduction in the consequences associated with potential failures, and improvements in detection and correction of developments that can lead to failures. Advanced Risk Assessment and Management approaches should be used to provide decision makers with information to define what levels of protection should be provided for which areas, and how much can and should be spent for those purposes.

Recommendation 4: Develop updated engineering guidelines and procedures for all elements and components to be incorporated in the FDS for all life-cycle phases based on proven state-of-practice and state-of-art technology. Where technology gaps are identified, then substantial development programs should be implemented to fill these gaps with existing research results. Where technology gaps cannot be filled with existing research results, then research should be undertaken or sponsored to enable timely filling of the technology gaps. Upgrading the technical capabilities of the engineers responsible for oversight and design, and the use of interactive boards of consultants as well as expert external review boards, would likely greatly improve the ability to deliver reliable flood protection.

Recommendation 5: Develop, implement, and enforce advanced Quality Assurance and Quality Control methods and procedures for all life-cycle phases of the NOFDS. Quality Assurance (proactive) and Quality Control (interactive) measures are of particular importance to help disclose 'predictable surprises' and variances in the desirable quality characteristics of the elements and components in the NOFDS. These methods and procedures should be used in all life-cycle phases of the NOFDS including concept development, design, construction, operation, maintenance, and continued improvement. These procedures and measures need to assure that the best available and safest technology is being used and used properly.

15.5.2 Technology Delivery System Developments - Organizing for Success

It will not be feasible to create an adequately reliable regional Flood Defense System without addressing the organizational, institutional, political and resources issues that adversely affect the current process. Simply changing engineering procedures, design manuals, and the review process will not suffice.

The primary requirement for reconstitution of a Technology Delivery System that can and will provide an adequate and acceptably reliable NOFDS is mobilization of the 'will' to provide such a system. If the United States decides that the catastrophe of Katrina will not be repeated, then the necessary leadership, organization, management, resources, and public support must be mobilized to assure such an outcome. One of the primary challenges is time, the clock is ticking until this area of the United States is again confronted with a severe challenge of flooding.

Recommendation 1: Seriously consider defining risk in the framework of federal, state, and local government responsibilities to protect their citizens.

Recommendation 2: Exploit the major and unprecedented role that exists for citizens who should be considered part of governance in the spirit that those who govern do so at the informed consent of the governed. This is the population exposed to catastrophic risks and the people that will be protected by the NOFDS. Authorities for catastrophic risk management should ensure that those vulnerable have sufficient and timely information regarding their condition, and a reciprocal ability to respond to requests for their informed consent especially regarding tradeoffs of safety for cost. The public protected by the NOFDS need to be encouraged to actively and intelligently interact with its development.

Recommendation 3: Intensify, focus, and fund Corps of Engineers reorganization and modernization efforts directed toward (1) increasing and maintaining in-house engineering capabilities and project performance, (2) increasing in-house research and development capabilities, (3) increasing in-house engineering performance on technically challenging projects, (4) developing an organizational culture of high reliability founded on existing cultural values of Duty, Honor, Country, and (5) developing a leadership role and responsibility for technical and management oversight of all phases in development of a NOFDS. Technical superiority must be re-established. Outsourcing must be balanced with in-sourcing to encourage development and maintenance of superior technical leadership and capabilities within the USACE. This will require close and continuous collaboration of federal legislative, executive, and judicial agencies. This will require that the USACE reconceptualize itself as a pivotal part of a modular organization developing partnerships with other federal agencies, state and local governments, enterprise interests, and private stake holders. This will require additional funding; in the end the nation will get only what it is willing to invest and pay for.

Recommendation 4: Restructure federal/state relationships in flood control. One possible model is what has been called “modularity” -- a concept which involves provisional and functional rearrangement of units in terms of alternative configurations of tools, structures and relationships.

Recommendation 5: Develop a National Flood Defense Authority (NFDA) charged with oversight over the design, construction, operation and maintenance of flood control systems. Each state would have an equivalent organization that could foster cooperation and developments between and within the states. The Corps of Engineers, state flood control authorities, and technical advisory boards would work with the NFDA to foster application of the best available technology and help coordinate development and maintenance efforts and planning. In cooperative developments, federal and state governments would provide reliable and sustainable funding for the life-cycle of specific flood defense systems. This development should be accompanied by development of an integrated and coherent Louisiana Flood Defense Authority representing state, regional, local, city, and public stakeholders that can focus and prioritize stakeholder interests and requirements and collaborate with the Corps of Engineers in development of a NOFDS.

Recommendation 6: Because of the importance of emergency response in the NOFDS, FEMA should be developed as a high reliability organization and returned by the executive branch to Cabinet level status. A new Council for Catastrophic Risk Management should be appointed in the White House and given oversight of disaster preparation and response. A similar body should be appointed to Congress. Incentives must be created to encourage all levels of government to responsibly deal with potential national, regional, and local catastrophes.

15.6 Conclusion

The performance of the New Orleans regional flood protection system during hurricane Katrina was unacceptable. Detailed study has now led to understanding of the physical causes and mechanisms of most of the many failures and breaches, and this in turn provides a basis for development of improved conceptual and engineering design methods, as well as improved review and overview paradigms.

Simply addressing engineering design methods, standards and procedures is unlikely to be sufficient to provide a suitably reliable level of protection, however. There is also a need to resolve difficult issues intrinsic in the operations and relationships between (1) Federal and more local government as they serve as decision-making, policy and funding sources, (2) the Federal and local agencies responsible for the actual design, construction and maintenance of such flood protection systems, and (3) private enterprise that must assist in construction. Some of these groups need to enhance their technical capabilities; a long-term expense that would clearly represent a prudent investment at both the national and local level, given the stakes as demonstrated by the losses in this recent event. Steady commitment and reliable and sustainable funding, shorter design and construction timeframes, clear lines of authority and responsibility, and improved overall coordination of disparate system elements and functions are all needed as well.

The overall philosophy and basis for design of these types of expensive and vital systems warrants reconsideration. Improvements such as (1) conceptual design strategies that involve working in conjunction with natural barriers and other favorable features, (2) system-based risk assessment, analysis and design, (3) allocation of appropriate resources, (4) embracing research and appropriate technological advances, and (5) maintenance of a deliberate culture of diligence in seeking overall system reliability would all represent significant steps forward.

And there is some urgency to all of this. The greater New Orleans regional flood protection system was significantly upgraded in response to flooding produced by Hurricane Betsy in 1965. The improved flood protection system was intended to be completed in 2017, fully 52 years after Betsy's calamitous passage. The system was incomplete when Katrina arrived. As a nation, we must manage to dedicate the resources necessary to complete projects with such clear and obvious ramifications for public safety in a more timely manner.

New Orleans has now been flooded by hurricanes six times over the past century; in 1915, 1940, 1947, 1965, 1969 and 2005. It should not be allowed to happen again.

APPENDIX F: LOOKING BACK

We must expect more catastrophes like Hurricane Katrina - and possibly even worse. In fact, we will have compounded the tragedy if we fail to learn the lessons - good and bad - it has taught us and strengthen our system of preparedness and response. We cannot undo the mistakes of the past, but there is much we can do to learn from them and to be better prepared for the future. This is our duty.

Frances Gragos Townsend
Assistant to the President for Homeland Security and Counterterrorism
The Federal Response to Hurricane Katrina, Lessons Learned
Report to the President of the United States, February 2006

F.1 Synopsis of History of the New Orleans Flood Defense System 1965 - 2005

This synopsis of the history of the NOFDS starts in 1965 in the period following hurricane Betsy. This is only the most recent phase in a history of the NOFDS that dates back 300 hundred years.

September 1965: Hurricane Betsy sweeps over New Orleans with winds exceeding 100 miles per hour and tides up to 16 feet above mean sea level. Betsy was the most destructive hurricane on record to strike the Louisiana coast. It inundated an area of some 4,800 square miles, killed 81 persons within the state, caused about 250,000 people to be evacuated and disrupted transportation, communication, and utility service throughout the eastern coastal area of Louisiana for many months. East New Orleans, St. Bernard Parish, and the Lower Ninth Ward were particularly hard hit. Residents blamed flooding on the Mississippi River Gulf Outlet (MR-GO, completed 1961) and its connection to the Inter-Coastal Water Way (ICWW) and the Industrial Canal (Inner Harbor Navigation Canal, IHNC). Earlier in the year, the Orleans Levee Board began driving sheet pilings on the 17th Street canal and other drainage canal levees that had been raised following flooding caused by a hurricane in 1947. Maintenance dredging was initiated by the Corps of Engineers on the MR-GO.

October 1965: Congress authorized the Corps of Engineers plan to strengthen the NOFDS to protect from flooding caused by a storm surge or rainfall associated with a Standard Project Hurricane (SPH, estimated to have a 200 to 300 year return period), which is roughly the same as what is now classified as a fast moving Category 3 hurricane. The Corps proposed massive floodgates and barriers on the far end of Lake Pontchartrain to stop hurricane surges from the Gulf of Mexico (Barrier Plan). Also included were additional protection to areas around the lake in the parishes of Orleans, Jefferson, St. Bernard, and St. Charles. This protection included a series of levees along the lakefront and concrete floodwalls along the Inner Harbor Navigation Canal. This plan was selected over another alternative, known as the High Level Plan which excluded the barriers and flood gates and instead employed higher levees. The Barrier Plan was favored because it was believed to be much less expensive and quicker to construct. Although federally authorized, it was a joint federal, state, and local effort with the federal government paying 70 percent of the costs and the state and local agencies paying 30 percent. *The Corps was responsible for project design and construction. State and local interests were responsible for operations and maintenance of the flood controls.* The project was forecast to take about 13 years to complete (1978) and cost about $85 million.

October 1968: The Corps of Engineers performed field tests of levee construction in the Atchafalaya Basin. These test sections were built in 1964 and 1965 to investigate the performance of new levee designs. The sections were instrumented and their performance monitored during and after construction. Important information was developed regarding characterizations of the soil properties and how these should be used in analyzing levee stability factors of safety. Definitive differences were found between soil strengths near the centers and at the toes of the levee test sections. Differences in factors of safety due to different analysis methods were analyzed and it was noted that the method used by the Corps of Engineers tended to over-predict the factors of safety.

August 1969: Construction of floodwalls along the Inner Harbor Navigation Canal started in 1966 was almost completed as was an earthen levee elevated to 12 feet along Lakeshore Drive from West End Boulevard to the Inner Harbor Navigation Canal when hurricane Camille surge conditions produced similar surge conditions to those of hurricane Betsy. Temporary sheet piling had been driven by the Orleans Levee Board to increase their effective height. *Only minor flooding occurred in the project area.* Hurricane Betsy (Category 5 hurricane) crossed the Mississippi coast at Pass Christian and devastated the coastal communities along the Mississippi coast to Biloxi Alabama.

November 1969: Corps of Engineers issues report on Standard Project Hurricane surge and wave conditions for St. Bernard Parish. Effects of MR-GO and its adjacent levee are incorporated into these conditions.

December 1973: In order to accelerate construction, the Orleans Levee board financed and constructed portions of the floodwalls along the Inner Harbor Navigation Canal and these were virtually completed at this time.

August 1976: Corps of Engineers estimate the cost of the improved NOFDS had risen to $352 million and its completion delayed to 1991. In a review of progress, the Comptroller General's Report to the Congress (1976) observed: "…its (Corps of Engineers) own belated completion of design, plans, and specifications, has contributed to the delays." The Citrus Back Levee, Michoud Slip Levee, New Orleans East Back Levee, New Orleans East South Point to Gulf Intercoastal Water Ways were substantially completed as was the flood protection structure at Bayou Bienvenue.

December 1977: In reaction to a suit brought by a coalition of local fishermen and the Save Our Wetlands environmental group in 1976, the Fifth Federal District Court ruled the Environmental Impact Statement for the Corp's Barrier Plan was inadequate and enjoined construction of the entire project. The Court ordered the Corps of Engineers to produce an environmental impact report on the proposed Barrier Plan. The injunction was subsequently modified to permit construction of the levee and floodwall elements of the hurricane protection plan.

September 1979: NOAA issues official revisions to Standard Project Hurricane guidelines first issued during 1959 and used as a basis for the authorization of the Lake Pontchartrain and Vicinity congressional authorization. These revised SPH guidelines increased the sustained and maximum wind speeds, and modified the hurricane radius to the maximum winds and forward speeds. These changes resulted in increases in the surge and wave heights over those in the original SPH. *These changes were not reflected in later design guidelines for the flood protection system.*

April 1980: Flooding overtops east side of the London Avenue canal south of Robert E Lee, where 200 feet of sheet piling had been removed at a point where the levee was eroding.

January 1981: Stability analysis performed by consulting engineers Modjeski and Masters shows that proposed higher levees for the 17th Street canal would fail in high water. Factors of safety less than 1.3 and as low as 0.8 were found for substantial portions of the canal. Additional studies were recommended.

September 1981: Corps of Engineers issues a design memorandum and revised environmental impact statement in which it is observed: "There is an unresolved issue with regards to the three main outfall canals in New Orleans which empty into Lake Pontchartrain along the reach known as the New Orleans Lakefront. Return levees flank these gravity drainage canals for a considerable distance inland from the lake, typing into lift pump stations at the head of the canals. *Since the time of project authorization, it has been determined that the return levees are inadequate in terms of both grade and stability*." Work was underway to raise the lakefront levees to a height of 16 feet.

August 1982: At this time, only about half of the improved NOFDS project had been completed. Costs were estimated to have grown to $757 million, not including any work along the drainage canals, and project completion had slipped to 2008. The General Accounting Office (1982) observed: "We believe that improved planning is needed by the Corps to resolve certain environmental, technical, and financial issues. Environmental concerns have remained unresolved for almost 5 years after a court injunction prohibited the Corps from constructing certain parts of the projects. The Corps is considering a change in its solution of providing protection from constructing barrier structures at the entrance to the lake and the raising of some levee heights (Barrier Plan) to constructing much higher levees with no barriers (High Level Plan)." The report observed: "Costly project work at the drainage canals has not been reported to the Congress, and technical and financial concerns which may impede project completion remain unresolved." Further this report observed: "*Subsequent to project authorization and based on the Weather Bureau's new data pertaining to hurricane severity (NOAA 1979), the Corps determined that the levees along the three main drainage canals, which drain major portions of New Orleans and empty into Lake Pontchartrain, were not high enough since they are subject to overflow by hurricane surges.*"

A report issued to Modjeski and Masters by Eustis Engineering notes following installation of piezometers to determine water pressures on both sides of the canal (17th Street) "*..the planned improvements to deepen and enlarge the canal may remove the seal that has apparently developed on the bottom and side slopes, thereby allowing a buildup of such pressures in the sand stratum (under the levee).*" Further, it was noted "*computations indicate the possibility of a blow-out during* *extreme high water in the canal. Unless more definitive information can be developed regarding the potential hydrostatic uplift pressure at the levee to through this reach, measures should be taken to prevent a blow-out during extreme high water conditions*." Additional correspondence addressed preventative measures including a 65-foot long (deep) sheet pile cutoff wall and a concrete lining for the canal.

November 1984: The Corps of Engineers encounter project delays and cost increases due to design changes caused by technical issues, environmental concerns, legal challenges, and local opposition to various aspects of the project. Foundation problems were encountered during construction of levees and floodwalls which increased construction time; delays were also encountered in obtaining rights-of-ways. The Corps of Engineers presents an alternative to the Barrier Plan identified as the High Level Plan. The Corps of Engineers propose to build floodgates on the canals, but local officials want to construct floodwalls on the levees.

December 1984: Report issued to St. Bernard Parish, NOAA and the Louisiana Department of Natural Resources on the MR-GO bank stabilization. The history of construction, ship traffic, channel dredging, and erosion were documented together with recommendations for protective measures to help prevent further erosion and destruction of wetlands.

July 1985: The Corps of Engineers reach agreements with state and local agencies to proceed with the High Level Plan based on construction of floodwalls on the levees. The Corps of Engineers make a decision to continue use of 1983 benchmark elevations even though National Geodetic Survey information indicates that these elevations are one or more feet low: "Hurricane protection projects which are partially complete will use the NGS benchmarks current at the time of construction of the first increment of the project" (1965).

July 1987: Construction was virtually completed on the lakefront levees and floodwalls raising these defenses to an elevation of approximately 18 feet in accordance with the Corps of Engineers' High Level Plan.

June 1988: The Corps of Engineers issues a technical report documenting results from a full-scale field load test performed on a PZ-27 sheet pile wall located in the Atchafalaya Basin south of Morgan City. Flood loading was simulated by ponding water against the wall which was founded in soft clays similar to those underlying the New Orleans area. *The wall was designed to carry an 8 foot head of water with a factor of safety of 1.25. The wall 'failed' (rapidly increasing wall displacements) when the water head reached 8 feet. A gap developed between the loaded sheet pile and the supporting soil on the water side (indicated by slope indicators located in the soils and on the piles).* The Corps of Engineers Waterways Experiment Station (WES) was contracted to perform additional analyses of the data.

August 1988: The Corps of Engineers issues Design Memorandum 19 for the Orleans Avenue outfall canal work. *Issues were raised regarding the factors of safety for use in design of the flood walls and evaluation of the levee stability (specified to be a minimum of 1.3), quality control problems with reporting the soil characteristics, how soil shear strengths are averaged and selected for the foundation layers, the presence of very low shear strength layers, challenges associated with dredging the canal so that the embankment stability would not be threatened, and concerns for seepage from the canal to the protected sides. Changes in the SPH developed in 1979 were not reflected in changes in the flood protection design elevations*.

December 1988: The Corps of Engineers Waterways Experiment Station issues a report that proposes a new method for soil-structure interaction analysis of floodwalls. The report shows that under loading of a floodwall the deformations and strains in the sheet piling are controlled by the movements of the soil supporting the sheet piling. *It was noted that as the water level rises, the increased loading may produce separation of the soil from the pile on the flood side (a tension crack develops behind the wall). Intrusion of free water into the tension crack produces additional hydrostatic pressures on the wall side of the crack and equal and opposite pressures on the soil side of the crack. This part of the loading was noted to be a function of the levee soil - sheet pile system deformations.*

January 1989: The Corps of Engineers issues Design Memorandum 19A for the London Avenue outfall canal work. *Issues are raised concerning how the levee stability analyses are performed (including the shapes of the failure surfaces) and how the soil shear strengths are treated in the analyses. Concerns for differences in soil shear strengths along and at the toes of the levees are raised.*

September 1989: The Waterways Experiment Station issues a report on analyses of sheet pile walls based on the E99 tests performed in 1985. The work indicates that deep-seated movements in the levee foundation control the magnitude of the sheet-pile deflection with the result that the height of water loading that can be sustained by a particular I wall is controlled by the stability of foundation as determined by a slope stability analysis. *It was concluded that conventionally determined deflections of the sheet piling were a poor criterion for design because movements were caused by deformations in the foundation and not the cantilever action of the sheet piles.*

March 1990: The Corps of Engineers issues Design Memorandum 20 for the 17th Street outfall canal work. *There are discussions concerning analysis of the soil shear strengths, the shapes of the failure surfaces for stability analyses and factors of safety for evaluation of the levees and sheet pile walls.*

August 1990: The Orleans Levee Board initiates work on the 17th Street canal levee. The levee board elected to take the lead to achieve savings because the New Orleans Sewerage and Water Board planned to deepen and widen the canal to meet their drainage needs. The Corps of Engineers issued permits to the New Orleans Sewerage and Water Board in 1984 and 1992. The work required modifications to the existing levees and floodwalls. After the dredging, the bottom was 18.5 feet below sea level (below the bottom of the sheet piling), and the canal side levee on the Orleans side had been shaved so narrow, water now touched the wall. Concerns were again raised on details associated with how the levee stability analyses were being performed including concerns about factors of safety, analysis of soil shear strengths, and shape of the slope stability analyses geometries.

October 1990: Congress orders the Corps of Engineers to begin raising the levees on the London and Orleans avenues drainage canals.

September 1997: Two technical papers published in the Electronic Journal of Geotechnical Engineering (www.ejge.com) summarize results from the E99 sheet pile load tests performed in 1985 and the subsequent research conducted at the Corps of Engineers Waterways Experiment Station. Advanced analytical methods developed during the period 1982 - 1989 for determining the deformations developed in levees and the interaction of sheet pile floodwalls with the levees were summarized. In the first paper (Oner et al, 1997a) in the section on Incremental Loading (p 10) it was noted "*The rising water produces several loading effects on a flood wall system. Most apparent is the hydrostatic pressure on the exposed wall above the ground surface. This part of the loading is independent of system deformations. …As the water level rises, the increased loading may produce separation of the sol from the pile on the flood side (i.e., a "tension crack" develops behind the wall). Intrusion of free water into the tension crack produces additional hydrostatic pressure on the wall side of the crack and equal and opposite pressures on the soil side of the crack. This part of the loading is a function of system deformations*."

February 1998: Decision reached by administrative judge, member, Corps of Engineers Board of Contract Appeals regarding a construction claim filed by the Pittman Construction Company for difficulties encountered while constructing a section of the floodwall on the 17th Street canal (in vicinity of breach). It was Pittman's contention that the lack of structural integrity of the existing sheet pile around which the concrete was poured and the weakness of the soils resulted in difficulties in pouring the concrete walls to the required tolerances. Pittman's expert witness, *Dr. Herbert Roussel concluded that the soils is so weak and may have been further weakened by the additional driving of the sheet pile that increasing the penetration can not get the deflection within tolerance*. Questions were also raised concerning the reasonableness of the specified tolerances for the concrete flood walls (0.25 inches in 10 feet). The claim was rejected by the Corps of Engineers Board of Contract Appeals.

September 1998: Hurricane Georges was headed directly for New Orleans but turned and made landfall at Biloxi, Mississippi. Storm tides reached 2 to 3 feet in Lake Pontchartrain and flooded the New Orleans Lakefront Airport. Only minor flooding occurred in the greater New Orleans area.

May 2005: The estimated cost of construction for the completed enhanced NOFDS was estimated to be $738 million with an estimated completion date of 2015. A Corps of Engineers report on the High Level Plan indicated that construction work on the project was 60 - 90 percent complete in different areas. Work on bridge replacement and floodproofing was underway along Orleans Avenue and London Avenue canals and on the Hammond Highway bridge over the 17th Street canal. During the last 10 years (1996-2005), federal appropriations generally declined from about $15-20 million annually in the earlier years to about $5-$7 million in the last three years. The Corps of Engineers noted that the appropriated amount for 2005 was insufficient to fund new construction contracts. The Corps of Engineers also noted it could spend $20 million in 2006 on raising levees that had settled and needed to be raised to provide the design-level of protection.

August 2005: Hurricane Katrina strikes the NOFDS with winds that exceeded 140 miles per hour and a surge that ranged from approximately 11 feet (Lake Pontchartrain) to 14 to 18 feet (Lake Borgne) flooding more than 85% of the city. The NOFDS failed catastrophically. More than 1,500 people died as a result of the flooding (about 500 more are currently missing). Failure of the NOFDS constitutes the single most catastrophic and costly failure of a civil engineered system in the history of the United States.

F.2 Learning from Failures

Detailed studies have been made of more than 600 well documented major failures and accidents involving engineered systems (Turner 1978; Whittow 1979; Petroski 1985; 1994; Allison 1993; Roberts 1993; Sowers 1993; Groeneweg 1994; Lancaster 1996; Dorner 1996; Dumas 1999; Perrow 1999; Bea 2000; Chiles 2002). These studies include recent accidents including the Challenger and Columbia space shuttles (Vaughn 1996, 1997; Columbia Accident Investigation Board 2003), the collapse of the World Trade Center towers, the failures of the Three Mile Island and Chernobyl nuclear power plants , the Teton dam collapse, the Union Carbide Bhopal chemical plant catastrophe, failures of the offshore platforms Occidental Piper Alpha and Petrobras P36 and the groundings of the oil tankers Torry Canyon, Amoco Cadiz, Exxon Valdez and Braer. Sufficient reliable documentation is available about these failures and accidents to understand the roles of the various components that comprised the systems during their life-cycle phases leading to the accident or failure. In many cases, personnel who participated in the events were interviewed to gain additional insights about how and why the accidents and failures developed. Extensive care was exercised to neutralize biases in this work (e.g., triangulation of multiple reliable sources, use of different assessors with different backgrounds) (Hale et al. 1997; Center for Chemical Process Safety 1994; Rasmussen et al. 1987).

Background from these detailed studies (conducted over a 15-year period) provided important analysis templates that helped development of understanding of the failure of the NOFDS. Results from these studies are summarized in this Chapter. In addition, because it has particular relevance to this investigation, a summary will be presented of results from the investigation of the NASA Columbia accident. This summary will be preceded by introduction of the primary concepts associated with high and low reliability organizations.

F.2.1 Engineered Systems

The studies indicated that the *system* involved in development of failures needed to be carefully defined and evaluated (Bea 2006). Seven primary interactive, inter-related, and highly adaptive components were defined to help characterize engineered systems: 1) structure (provides support for facilities and operations), 2) hardware (facilities, control systems, life support), 3) procedures (formal, informal, written, computer software), 4) environments (external, internal, social), 5) operators (those who interface directly with the system), 6) organizations (institutional - organizational frameworks in which operations are conducted), and 7) interfaces among the foregoing.

The studies clearly identified the importance of system interfaces in the development of failures. Breakdowns in communications and other actions frequently developed at the interfaces between the operators and the organizations that controlled resources, means, and methods. Communication malfunctions at organization-to-organization interfaces, information filtering, distortion, and 'stove-piping' communication barriers in large bureaucratic organizations were even more prevalent.

An important part of this system is the Technology Delivery System (TDS) involved in development, operation, and maintenance of the engineered system. Technology is a social process by which specialized knowledge from science and experience is employed to deliver a system to meet specific needs of a society. The TDS is an ensemble of institutions involving the public, government, and enterprise (industry) which are linked by webs of information channels. Inputs to the TDS consist of technical knowledge, natural resources, capital, human talents, and value preferences. Outputs are the intended goods and services to provided by the engineered system, including unintended and unwelcome consequences. The basic elements of a TDS are further developed in Appendix H.

The studies showed it was essential to identify how the system developed throughout its life-cycle to the point of failure including development of concepts, design, construction, operation, and maintenance. The history (heritage) of a system generally had much to do with development of failures. The studies indicated that in a very large number of cases, the seeds for failure were sown very early in the life of a system; preceding and during the concept development and design phases. These seeds were allowed to flourish during the construction, operation and maintenance phases, and with the system in a weakened flawed and defective condition, when severely challenged, it failed.

F.2.2 Causes of Failures

Uncertainties that were primary contributors to the accidents and failures were organized into four major categories: 1) natural variability (information insensitive), 2) analytical modeling uncertainties (information sensitive), 3) human and organizational performance uncertainties, and 4) knowledge related uncertainties. This organization of uncertainties was developed to permit definition of means and measures that could be used to help manage the causes and effects of the uncertainties.

The studies showed that the causative factors most often (80 % or more) involved human, organizational and knowledge related uncertainties (Reason 1990, 1997; Perrow 1999; Bea 2000, 2006). These were identified as *Extrinsic Factors (not belonging to the essential nature of the system)*. Frequently, these factors are identified as *human errors.* The remaining 20% of the factors involved natural and analytical model related uncertainties. These were identified as *Intrinsic Factors (belonging to the essential nature of the system)* (Vick 2002).

Of the Extrinsic Factors, about 80% of these developed and became evident during operations and maintenance activities; frequently, the maintenance activities interacted with the operations activities in an undesirable way. Of the failures that occurred during operations and maintenance, more than half were traced to seriously flawed engineering concept development and design. The physical system may have been designed according to accepted standards and yet was seriously flawed due to limitations and imperfections embedded in the standards and/or in how they were used. Frequently, engineered systems were designed that could not be built, operated, and maintained as originally intended. Changes (work-arounds) were made during the construction process to allow the construction to proceed; flaws were introduced by these changes or flaws were introduced by the construction process itself. After the structure was placed in operation, modifications were made in an attempt to make it workable or to facilitate operations, and in the process additional flaws were introduced. Thus, during operations and maintenance phases, operations personnel were faced with a seriously deficient or defective system that could not be operated and maintained as intended.

A useful analogy to describe the Extrinsic Factors was that of a 'spear' (Reason 1997) The *pointed end* of the spear represented the operators (operating teams) who are responsible for performing the activities during the life-cycle development of the system. The *blunt end* or shaft of the spear represented the organizations that controlled means, methods, and resources. The activity at the pointed end of the spear was largely determined by what happened along the shaft of the spear; the TDS.

The 20% of the causation factors that involved natural and model related uncertainties represented residual risks that developed from exceedances of the criteria and conditions used to design, construct, operate, and maintain the system. These could identified as '*acts of god'* (Bernstein 1996; Molak 1996; Prigogine 1997).

F.2.3 Magnitudes of Failures

An important discriminating difference between major (catastrophic) and not-so-major failures involved the *magnitude of consequences* developed during and after the failures. Not-so-major failures generally involved only a few people, a few malfunctions or breakdowns, and small magnitude consequences. Major or catastrophic failures involved of many people and their organizations, a multitude of malfunctions or breakdowns developed over long periods of time, and very large magnitudes of consequences (direct, indirect, on-site, off-site, short-term, long-term). Frequently, organizations construct barriers to prevent failure causation to be traced in this direction. In addition, until recently, the legal process focused on the proximate causes of failures (*human errors*). There have been some recent major exceptions to this focus; the important roles of organizational and institutional malfunctions in accident causation have been recognized in court and in public. Not-so-major accidents, if repeated very frequently, can lead to major losses and it is obvious that it is important to develop approaches and strategies to address both categories of accidents.

F.2.4 Breaching Defenses

Most failures involved never to be exactly repeated sequences of events and multiple breakdowns or malfunctions in the components that comprise a system. Failures resulted from breaching multiple defenses that were put in place to prevent them. These events are frequently dubbed incredible or impossible. After many of these failures, it was observed that if only one of the barriers had not been breached, the accident or failure would not have occurred. Experience adequately showed that it was extremely difficult, if not impossible, to recreate accurately the time sequence of the event that actually took place during the period leading to failure. Unknowable complexities generally pervade this process because detailed information on failure development is not available, is withheld, or is distorted by memory. Hindsight and confirmational biases are common as are distorted recollections. Stories told from a variety of viewpoints involved in the development of a failure are the best way to capture the richness of the factors, elements, and processes that unfold in the development of a failure.

Defenses against breaching could be organized into *proactive, interactive, and reactive* categories (Bea 2000). These categories represented the timeframes in which activities were conducted to defend the system against failure. Reason (1997) suggested the analogy of Swiss Cheeze; failures could develop when 'holes' in these three defenses aligned. The larger the number and sizes of the holes, then the more likely they were to align and allow a failure to develop. While generally a lot of attention was given to proactive measures, insufficient attention was given to interactive and reactive defenses.

Development of effective reactive defenses often degraded because of an unwillingness or inability to recognize the 'truth', measures employed to depress development of accurate facts, and deficiencies introduced because of a wide variety of unrecognized biases (e.g., recall, hindsight, rational, control, wishful thinking, small samples, knowledge, correlation, perception, belief, confirmational, reductive). Searches were often conducted to assign blame and distribute pain. Often, once the facts and truth were known, there were efforts to restrain communications or put a 'spin' on the information so it would not appear as unfavorable as it was. In general, there were very numerous and large holes in reactive defenses.

Development of ineffective interactive defenses often developed because their importance was not recognized (Klein 1999). A key example of interactive defenses was quality control (quality assurance is a proactive measure). Often the wrong things were inspected by the wrong people at the wrong times using the wrong things and for the wrong reasons. Proper detection, analysis and correction of potential flaws was inhibited by a variety of problems (Sasou and Reason 1997). In many cases, even though very thorough proactive quality assurance procedures and processes were developed, they were not followed (violations). Often insufficient resources were allocated to implementation of interactive defenses. In general, there were very numerous and large holes in the reactive defenses (Weick and Sutcliffe 2001).

F.2.5 Knowledge Challenges

One sobering observation concerning many accidents and failures is that their occurrence is directly related to knowledge (information) access and development. Information access and development challenges were organized into two general categories: *unknown knowables*, and *unknown unknowables*. The first category represents information access and understanding challenges (Weick 1995; Klein 1999). The information exists but is either ignored, not used, not accessed, or improperly used. This category is identified as rejection - misuse of technology. Others identify this category as *'predictable surprises'* (Bazerman and Watkins 2004).

The second category - *unknown unknowables* - represents limitations in knowability or knowledge. There are significant limitations in abilities to project system developments or characteristics very far in space or time. Human abilities to know all the things that are potentially important to the future success of systems is limited. Often, there are major limitations in knowledge concerning new or innovative systems and the environments in which these systems will be developed and exist. There is ample history of accidents and failures due to both of these categories of challenges to knowledge. They appear to be most important during the early phases of constructing and operating engineered systems; *burn-in' failures*. Things develop that one did not know or could not know in advance. They also appear to be most important during the late life-cycle phases; *wear-out failures*. In this case, the quality characteristics of the system have degraded due to the effects of time and operations (frequently exacerbated by improper or ignored maintenance) and the hazards posed by unknown knowables and unknown unknowables interact in undesirable ways. This recognition poses a particularly important limitation on proactive risk analyses that are conducted before systems are constructed and put in service; in a predictive sense, one can only analyze what one understands or knows. The most effective approach identified during these studies is *interactive* risk *assessment and management* (National Academy of Engineering 2004; Klein 1998; Weick and Sutcliffe 2001). Interactive risk assessment and management can be facilitated through a variety of people and system enhancements which promote abilities to detect, analyze, and correct challenges to quality and reliability before they are allowed to propagate to failures (Loosemore 2000).

F.2.6 Organizational Malfunctions

Analysis of the history of failures of engineered systems provides many examples in which organizational and institutional malfunctions were primarily responsible for the failures (Wenk 1986, 1998; Dorner 1997; Hopkins 1999, 2000; Reason 1997; Vaughn 1996; Columbia Accident Investigation Board 2003). Organization malfunction is defined as a departure from acceptable or desirable practice on the part of a group or groups of individuals that results in unacceptable or undesirable results (Roberts and Bea 2001a, 2001b). Frequently, the organization develops high incentives for maintaining and increasing production; meanwhile hoping for quality and reliability (*rewarding 'A' while hoping for 'B')* (Roberts 1993; Roberts and Libuster 1993). The formal and informal rewards and incentives provided by an organization have a major influence on the performance of operators and on the quality and reliability of engineered systems. In a very major way, the performance of people is influenced by the incentives, rewards, resources, and disincentives provided by the organization. Many of these aspects are embodied in the organization's culture (shared beliefs, artifacts). This culture largely results from the organization's history (development and evolution). For many successful organizations, success breeds arrogance that can lead to failure (lethal arrogance). Cultures are extremely resistant to change.

Several major organizational malfunctions developed because of down-sizing and out-sourcing practices adopted in response to pressures to increase organizational efficiency. Loss of corporate memories (leading to repetition of errors), inadequate core competencies in the organization, creation of more difficult and intricate communications and organization interfaces, degradation in morale, unwarranted reliance on the expertise of outside contractors, cut-backs in quality assurance and control, and provision of conflicting incentives (e.g. cut costs, yet maintain quality) are examples of activities that lead to substantial compromises in the intended quality of systems. Much of the down-sizing ('right-sizing'), outsourcing ('hopeful thinking'), and repeated cost-cutting ('remove the fat until there is no muscle or bone') seems to have its source in modern 'business consulting.' While some of this thinking can help promote 'increased efficiency' and maybe even lower CapEx (Capital Expenditures), the robustness (damage and defect tolerance) of the organization and the systems its creates are greatly reduced. Higher OpEX (Operating Expenditures), more 'accidents', and unexpected compromises in desired quality and reliability can be expected; particularly over the long-run.

Experience indicates that one of the major factors in malfunctions is the organization's culture (Reason 1997; Merry 1998; Meshkati 1995). Organizational culture is reflected in how action, change, and innovation are viewed; the degree of external focus as contrasted with internal focus; incentives provided for risk taking; the degree of lateral and vertical integration of the organization; the effectiveness and honesty of communications; attention to the potentials for failures; diligence in the use of information; particularly bad or unwelcome news (lethal arrogance); autonomy, responsibility, authority and decision making; rewards and incentives; and orientation toward the quality of performance contrasted with the quantity of production. One of the major culture elements is how managers in the organization react to suggestions for change in management and the organization. Given the extreme importance of quality and reliability, it is essential that these managers see suggestions for change (criticism?) in a positive manner. This is extremely difficult for some managers because they do not want to relinquish or change the strategies and processes that helped make them managers.

F.2.7 Engineering Challenges

New technologies compound problems of latent system flaws (structural pathogens) (Reason 1997). Excessively complex design, close coupling (failure of one component leads to failure of other components) and severe performance demands on systems increase the difficulty in controlling the impact of human malfunctions even in well operated systems. The field of ergonomics (people-hardware interfacing) has much to offer in helping create 'people friendly' engineered systems. Such systems are designed for what people will and can do, not what they should do. Such systems facilitate construction (constructability), operations (operability), and maintenance (maintainability, reparability).

It is becoming painfully clear that the majority of engineering design codes and guidelines do not provide sufficient direction for creating robust – damage – defect tolerant systems. Thinking about sufficient damage tolerance and inherent stability needs rethinking. Thinking about designing for the 'maximum incredible' events needs more development. While two engineered systems can both be designed to 'resist the 100-year conditions' with exactly the same probabilities of failure, the two structures can have very different robustness characteristics. The minimum CapEx system will not have a configuration, excess capacity, ductility , or appropriate correlation to allow it to weather the inevitable defects and damage that should be expected to develop during its life. Sufficient damage tolerance almost invariably results in increases in CapEx; the expectation and the frequent reality is that OpEx will be lowered. But, one must have a long-term view for this to be realized.

Robustness (defect and damage tolerance) can be developed through a combination of four key elements. The first is appropriate configuration of the elements that comprise the system. The second is excess capacity built into the system elements that will allow 'overloads' to be carried without compromising the basic quality and reliability characteristics of the system. The third is ductility or an ability to stretch without breaking so that overloads can be shifted to other under-loaded elements. The fourth is appropriate correlation of the elements; for series (weak link) type systems, high degrees of correlation are needed to reduce the likelihood of weak links; for parallel (redundant) type systems, low degrees of correlation are needed to help insure independence in performance.

Other strategies to achieve robust systems include those of fail-safe and inherently-safe design. In fail-safe design the system is configured and proportioned so that when its 'capacities' are exceeded the system fails in a way that does not compromise basic safety requirements. In design of intrinsically safe systems, the system is configured so that there are fewer inherent hazards, there is a reduced probability of unwanted events, there is reduced inventory and damage potential (reduced severity), there are fewer people exposed, there is reduced scope for smaller incidents to escalate and overwhelm the facilities, and there is a clear focus on simplicity, reliability and longevity to reduce exposure.

This work has clearly shown that the foregoing statements about structure and hardware robustness apply equally well to organizations and operating teams; frequently, this is termed organizational redundancy. Proper configuration, excess capacity, ductility, and appropriate correlation play out in organizations and teams in the same way they do in a structure and hardware. When the organization or operating team encounters defects and damage – and is under serious stress, the benefits of robustness become evident. A robust organization or operating team is not a repeatedly downsized (lean and mean), out-sourced, and financially strangled organization. A robust organization is a *High Reliability Organization (HR0)* (Roberts 1989, 1990, 1993; Weick and Sutcliffe 2001; Columbia Accident Investigation Board 2003).

Software and engineering guideline errors in which incorrect and inaccurate algorithms were coded into computer programs or written into engineering guidelines have been at the root cause of several recent failures of engineered systems. Extensive software and guidelines testing and validation is required to assure that the desired performance and results are realized. Of particular importance is the provision of qualified independent checking processes and people using those process who can be used to validate the results from analyses and engineering work. High quality procedures need to be verifiable based on first principles, results from testing, and field experience.

Given the rapid pace at which significant industrial and technical developments are taking place, there is a tendency to make design guidelines, construction specifications, and operating manuals more and more complex. Such a tendency is apparent in many current guidelines used for designing engineered systems. In many cases, poor organization and documentation of software and procedures has exacerbated the tendencies for humans to make errors. Simplicity, clarity, completeness, accuracy, and good organization are desirable attributes in procedures developed for the design, construction, maintenance, and operation of engineered systems.

F.2.8 Initiating, Contributing, Compounding Events

These studies illustrate the failure development process as organized into three categories of events or stages: *1) initiating, 2) contributing, and 3) propagating*. The dominant initiating events were developed by operators (e.g. design engineers, construction, maintenance personnel) performing erroneous acts of commission; what is carried out has unanticipated and undesirable outcomes. The other initiating events are acts or developments involving omissions (something important left out, often intentional short-cuts and violations). Communications breakdowns (withheld, incomplete, untrue, not timely) were a dominant category of the initiating events. Various categories of violations (intentional, unintentional) were also very prevalent and were highly correlated with organizational and social cultures.

The dominant contributing events were organizational malfunctions (about 80%); these contributors acted directly to encourage or trigger the initiating events. Communication malfunctions, interface failures (organization to operations), culture malfunctions (excessive cost cutting, down-sizing, outsourcing, and production pressures), unrealistic planning and preparations, and violations (intentional departures from acceptable practices) were dominant categories of these organizational malfunctions.

The dominant propagating events also were found to be organizational malfunctions (about 80%); these propagators were responsible for allowing the initiating events to unfold into a failure or accident. With some important additions, the dominant types of malfunctions were the same as the contributing events. The important additions concerned inappropriate selection and training of operating personnel, failures in quality assurance and quality control (QA/QC), brittle structures and hardware (damage and defect intolerant), and ineffective planning and preparations.

F.3 High and Low Reliability Organizations: The NASA Columbia Accident Investigation

The organizational causes of this accident are rooted in the Space Shuttle Program's history and culture, including the original compromises that were required to gain approval for the Shuttle Program, subsequent years of resource constraints, fluctuating priorities, schedule pressures, mischaracterizations of the Shuttle as operational rather than developmental, and lack of an agreed national vision. Cultural traits and organizational practices detrimental to safety and reliability were allowed to develop, including: reliance on past success as a substitute for sound engineering practices (such as testing to understand why systems were not performing in accordance with requirements/specifications); organizational barriers which prevented effective communication of critical safety information and stifled professional differences of opinion; lack of integrated management across program elements; and the evolution of an informal chain of command and decision-making processes that operated outside the organization's rules.

Columbia Accident Investigation Board (2003)

The findings documented in the Columbia Accident Investigation Board (CAIB) Report (2003) have particular relevance to development of insights about how technology can have *unintended consequences* or *revenge effects* when an organizational - institutional culture of low reliability is allowed to develop. After introducing the concepts of High and Low Reliability Organizations, findings of the CAIB regarding the organizational - institutional issues will be sumarized .

F.3.1 High Reliability Organizations

Studies of HRO (High Reliability Organizations) has shed some light on the factors that contribute to errors made by organizations and risk mitigation in HRO. HRO are those organizations that have operated relatively error free over long periods of time making consistently good decisions resulting in high quality and reliability operations. A variety of HRO ranging from the U. S. Navy nuclear aircraft carriers to the Federal Aviation Administration Air Traffic Control System have been studied.

The HRO research has been directed to define what these organizations do to reduce the probabilities of serious errors (Roberts, 1989). Reduction in error occurrence is accomplished by the following:

- Command by exception or negation,
- Redundancy,
- Procedures and rules,
- Training,
- Appropriate rewards and punishment

- Ability of management to "see the big picture".

Command by exception (management by exception) refers to management activity in which authority is pushed to the lower levels of the organization by managers who constantly monitor the behavior of their subordinates. Decision making responsibility is allowed to migrate to the persons with the most expertise to make the decision when unfamiliar situations arise (employee empowerment).

Redundancy involves people, procedures, and hardware. It involves numerous individuals who serve as redundant decision makers. There are multiple hardware components that will permit the system to function when one of the components fails.

Procedures that are correct, accurate, complete, well organized, well documented, and are not excessively complex are an important part of HRO. Adherence to the rules is emphasized as a way to prevent errors, unless the rules themselves contribute to error.

HRO develop constant and high quality programs of training. Training in the conduct of normal and abnormal activities is mandatory to avoid errors. Establishment of appropriate rewards and punishment that are consistent with the organizational goals is critical.

Lastly, Roberts defines an HRO organizational structure as one that allows key decision makers to understand the big picture. These decision makers with the big picture perceive the important developing situations, properly integrate them, and then develop high reliability responses.

In recent organizational research reported by Roberts and Libuser (1993), they analyzed five prominent failures including the Chernobyl nuclear power plant, the grounding of the Exxon Valdez, the Bhopal chemical plant gas leak, the mis-grinding of the Hubble Telescope mirror, and the explosion of the space shuttle Challenger. These failures were evaluated in the context of five hypotheses that defined "risk mitigating" organizations. The failures provided support for the following five hypotheses.

- Risk mitigating organizations will have extensive process auditing procedures. Process auditing is an established system for ongoing checks designed to spot expected as well as unexpected safety problems. Safety drills would be included in this category as would be equipment testing. Follow ups on problems revealed in prior audits are a critical part of this function.
- Risk mitigating organizations will have reward systems that encourage risk mitigating behavior on the part of the organization, its members, and constituents. The reward system is the payoff that an individual or organization gets for behaving one way or another. It is concerned with reducing risky behavior.
- Risk mitigating organizations will have quality standards that meet or exceed the referent standard of quality in the industry.
- Risk mitigating organizations will correctly assess the risk associated with the given problem or situation. Two elements of risk perception are involved. One is whether or not there was any knowledge that risk existed at all. The second is if there was knowledge that risk existed, the extent to which it was acknowledged appropriately or minimized.

- Risk mitigating organizations will have a strong command and control system consisting of five elements: a) migrating decision making, b) redundancy, c) rules and procedures, d) training, and e) senior management has the big picture.

Weick, Sutcliffe, and Obstfeld (1998) have extended these concepts to characterize *how* organizations can organize for high reliability. Their extensive review of the literature and studies of HRO indicate that organizing in effective HRO's is characterized by:

- Preoccupation with failure – any and all failures are regarded as insights on the health of a system, thorough analyses of near-failures, generalize (not localize) failures, encourage self-reporting of errors, and understand the liabilities of successes.
- Reluctance to simplify interpretations – regard simplifications as potentially dangerous because they limit both the precautions people take and the number of undesired consequences they envision, respect what they do not know, match external complexities with internal complexities (requisite variety), diverse checks and balances, encourage a divergence in analytical perspectives among members of an organization (it is the divergence, not the commonalties, that hold the key to detecting anomalies).
- Sensitivity to operations – construct and maintain a cognitive map that allows them to integrate diverse inputs into a single picture of the overall situation and status (situational awareness, 'having the bubble'), people act thinkingly and with heed, redundancy involving cross checks, doubts that precautions are sufficient, and wariness about claimed levels of competence, exhibit extraordinary sensitivity to the incipient overloading of any one of it members, sensemaking.
- Commitment to resilience – capacity to cope with unanticipated dangers after they have become manifest, continuous management of fluctuations, prepare for inevitable surprises by expanding the general knowledge, technical facility, and command over resources, formal support for improvisation (capability to recombine actions in repertoire into novel successful combinations), and simultaneously believe and doubt their past experience.
- Under-specification of structures – avoid the adoption of orderly procedures to reduce error that often spreads them around, avoid higher level errors that tend to pick up and combine with lower level errors that make them harder to comprehend and more interactively complex, gain flexibility by enacting moments of organized anarchy, loosen specification of who is the important decision maker in order to allow decision making to migrate along with problems (migrating decision making), move in the direction of a garbage can structure in which problems, solutions, decision makers, and choice opportunities are independent streams flowing through a system that become linked by their arrival and departure times and by any structural constraints that affect which problems, solutions and decision makers have access to which opportunities.

F.3.2 Low Reliability Organizations

Weick, Sutcliffe, and Obstfeld (1998) observe that low reliability organizations (LROs) are characterized by a focus on success rather than failure, and efficiency rather than reliability. In these organizations the cognitive infrastructure is underdeveloped, failures are localized rather than generalized, and highly specified structures and processes are put in place that develop inertial blind spots that allow failures to cumulate and produce catastrophic outcomes. Efficient organizations practice stable activity patterns and when they encounter unusual cognitive processes these often result in errors. They do the same things in the face of changing events, these changes go undetected because people are rushed, distracted, careless, or ignorant.

LROs are characterized by expensive and inefficient learning. Diversity in problem solving is not welcomed. Information, particularly ‘bad’ or ‘useless’ information is not actively sought, failures are not taken as learning lessons, and new ideas are rejected; lethal arrogance. Communications are regarded as wasteful and hence the sharing of information and interpretations between individuals is stymied. Divergent views are discouraged, so that there is a narrow set of assumptions that sensitize it to a narrow variety of inputs.

Success breeds confidence and fantasy, managers attribute success to themselves, rather than to luck, and they trust procedures to keep them appraised of developing problems. Under the assumption that success demonstrates competence, LROs drift into complacency, inattention, and habituated routines which they often justify with the argument that they are eliminating unnecessary effort and redundancy. Down-sizing and out-sourcing are used to further the drives of efficiency. Insensitivity is developed to overloading and its effects on judgement and performance. Redundancy (robustness) is eliminated or reduced in the same drive resulting in elimination of cross checks, assumption that precautions and existing levels of training and experience are sufficient, and dependence on claimed levels of competence. With outsourcing, it is now the supplier, not the buyer, that must become preoccupied with failure. But, the supplier is preoccupied with success, not failure, and because of low-bid contracting, often is concerned with the lowest possible cost success. The buyer now becomes more mindless and if novel forms of failure are possible, the loss of a preoccupation with failure makes the buyer more vulnerable to failure. LROs tend to lean toward anticipation of expected surprises, risk aversion, and planned defenses against foreseeable accidents and risks; unforeseeable accidents and risks are not recognized or believed.

F.3.3 Columbia Accident Investigation Board Findings

The following quotations from the Columbia Accident Investigation Board (CAIB) Report provide important insights into how NASA in the span of three decades developed into a LRO.

> ***Accident Theories****: To develop a thorough understanding of accident causes and risk, and to better interpret the chain of events that led to the Columbia accident, the Board turned to the contemporary social science literature on accidents and risk and sought insight from experts in High Reliability, Normal Accident and Organizational Theory. High Reliability Theory argues that organizations operating high-risk technologies, if properly designed and managed, can compensate for inevitable human shortcomings, and therefore avoid mistakes that under other circumstances would head to catastrophic failures. Normal Accident Theory, on the other hand, has a more pessimistic view of the ability of organizations and their members to manage high-risk technology. Normal Accident Theory holds that organizational and technological complexity contributes to failures. Organizations that aspire to failure-free performance are inevitably doomed to fail because of the inherent risks in the technology they operate. Normal Accident models also emphasize systems approaches and systems thinking, while the High Reliability*

model works from the bottom up: if each component is highly reliable, then the system will be highly reliable and safe.

Though neither High Reliability Theory nor Normal Accident Theory is entire appropriate for understanding this accident, insights from each figured prominently in the Board's deliberation. Fundamental to each theory is the importance of strong organizational culture and commitment to building successful safety strategies.

***What Went Wrong**: The Board believes the following considerations are critical to understand what went wrong during STS-107.*

1) *Commitment to a Safety Culture: NASA's safety culture has become reactive, complacent, and dominated by unjustified optimism. Over time, slowly and unintentionally, independent checks and balances intended to increase safety have been eroded in favor of detailed processes that produce massive amounts of data and unwarranted consensus, but little effective communication. Organizations that successfully deal with high-risk technologies create and sustain a disciplined safety system capable of identifying, analyzing, and controlling hazards throughout a technology's life cycle.*
2) *Ability to Operate in Both a centralized and Decentralized Manner: The ability to operate in a centralized manner when appropriate, and to operate in a decentralized manner when appropriate, is the hallmark of a high-reliability organization.*
3) *Importance of Communication: At every juncture of STS-107, the Shuttle Program's structure and processes, and therefore the managers in charge, resisted new information.*
4) *Avoiding Oversimplification: The Columbia accident is an unfortunate illustration of how NASA's strong cultural bias and its optimistic organizational thinking undermined effective decision-making.*
5) *Conditioned by Success: Even when it was clear from the launch videos that foam had struck the Orbiter in a manner never before seen, the Space Shuttle Program managers were not unduly alarmed. They could not imagine why anyone would want a photo of something that could be fixed after landing. More importantly, learned attitudes about foam strikes diminished management's wariness of their danger. The Shuttle Program turned the experience of failure into the memory of success.*
6) *Significance of Redundancy: The Human Space Flight Program has compromised the many redundant processes, checks, and balances that should identify and correct small errors. Redundant systems essential to every high-risk enterprise have fallen victim to bureaucratic efficiency. Years of workforce reductions and outsourcing have culled from NASA's workforce the layers of experience and hands-on systems knowledge that once provided a capacity for safety oversight. Safety and Mission Assurance personnel have been eliminated, careers in safety have lost organizational prestige, and the Program now decides on its own how much safety and engineering oversight it needs.*

Organizational Development: *The Board's investigation into the Columbia accident revealed two major causes with which NASA has to contend: one technical, the other organizational. The Board studied the two dominant theories on complex organizations and accidents involving high-risk technologies. These schools of thought were influential in shaping the Board's organizational recommendations, primarily because each takes a different approach to understanding accidents and risk.*

The Board determined that high-reliability theory is extremely useful in describing the culture that should exist in the human space flight organization. NASA and the Space Shuttle Program must be committed to a strong safety culture, a view that serious accidents can be prevented, a willingness to learn from mistakes, from technology and from others, and a realistic training program that empowers employees to know when to decentralize or centralize problem-solving.

The Board believes normal accident theory has a key role in human space flight as well. Complex organizations need specific mechanisms to maintain their commitment to safety and assist their understanding of how complex interactions can make organizations accident-prone. Organizations can not put blind faith into redundant warning systems because they inherently create more complexity, and this complexity in turn often produces unintended system interactions that can lead to failure.

The Shuttle Program's complex structure erected barriers to effective communication and its safety culture no longer asks enough hard questions about risk. Safety culture refers to an organization's characteristics and attitudes - promoted by its leaders and internalized by its members - that serve to make safety the top priority.

By their very nature, high-risk technologies are exceptionally difficult to manage. Complex and intricate, they consist of numerous interrelated parts. Standing alone, components may function adequately, and failure modes may be anticipated. Yet when components are integrated into a total system and work in concert, unanticipated interactions can occur that can lead to catastrophic outcomes. the risks inherent in these technical systems are heightened when they are produced and operated by complex organizations that can also break down in unanticipated ways.

Despite periodic attempts to emphasize safety, NASA's frequent reorganizations in the drive to become more efficient reduced the budget for safety, sending employees conflicting messages and creating conditions more conducive to the development of a conventional bureaucracy than to the maintenance of a safety-conscious research-and-development organization. Over time, a pattern of ineffective communication has resulted, leaving risks improperly defined, problems unreported, and concerns unexpressed. The question, is why?

The Shuttle Independent Assessment Team's report documented these changes, noting that the size and complexity of the Shuttle system and of the NASA /

contractor relationships place extreme importance on understanding, communication, and information handling. among other findings, the Shuttle Independent Assessment Team observed that: The current Shuttle program culture is too insular. There is a potential for conflicts between contractual and programmatic goals; There are deficiencies in problem and waiver-tracking systems; the exchange of communication across the shuttle program hierarchy is structurally limited, both upward and downward.

The Board believes that deficiencies in communication, including those spelled out by the shuttle Independent Assessment Team, were a foundation for the Columbia accident. These deficiencies are byproducts of a cumbersome, bureaucratic, and highly complex Shuttle Program structure and the absence of authority in two key program areas that are responsible for integrating information across all programs and elements in the Shuttle Program.

Principles of Organizational Change: *The Board consistently searched for causal principles that would explain both the technical and organizational system failures. The Board's analysis of organizational causes supports the following principles that should govern the changes in the agency's organizational system.*

Leaders create culture. It is their responsibility to change it. Top administrators must take responsibility for risk, failure, and safety by remaining alert to the effects their decisions have on the system. Leaders are responsible for establishing the conditions that lead to their subordinates' successes or failures. The past decisions of national leaders - the White House, Congress, and NASA Headquarters - set the Columbia accident in motion by creating resource and schedule strains that compromised the principles of a high-risk technology organization. The measure of NASA's success became how much costs were reduced and how efficiently the schedule was met."

Changes in organizational structure should be made only with careful consideration of their effect on the system and their possible unintended consequences. Changes that make the organization more complex may create new ways that it can fail. When changes are put in place, the risk of error initially increases, as old ways of doing things compete with new. Institutional memory is lost as personnel and records are moved and replaced. Changing the structure of organizations is complicated by external political and budgetary constraints, the inability of leaders to conceive of the full ramifications of their actions, the vested interests of insiders, and the failure to learn from the past."

Strategies must increase the clarity, strength, and presence of signals that challenge assumptions about risk. Twice in NASA history, the agency embarked on a slippery slope that resulted in catastrophe. Each decision, taken by itself, seemed correct, routine, and indeed, insignificant and unremarkable. Yet in retrospect, the cumulative effect was stunning. In both pre-accident (Challenger, Columbia) periods, events unfolded over a long time and in small increments rather than in sudden and dramatic occurrences. NASA's challenge is to design systems that maximize the clarity of signals, amplify weak signals so they can be tracked, and *account for missing signals. A safety team must have equal and independent representation so that managers are not again lulled into complacency by shifting definitions of risk. It is obvious but worth acknowledging that people who are marginal and powerless in organizations may have useful information or opinions that they don't express. Even when these people are encouraged to speak, the find it intimidating to contradict a leader's strategy or a group consensus. Extra effort must be made to contribute all relevant information to discussion of risk. Because ill-structured problems are less visible and therefore invite the normalization of deviance, they may be the most risky of all.*

F.3.4 Summary

The history of major accidents involving engineered systems clearly shows that the vast majority of these accidents have their roots firmly embedded in human and organizational malfunctions or breakdowns. While the majority of these accidents develop during the operations and maintenance phases, the studies also clearly show that the majority of the flaws in the system are developed during the concept development and design phases.

A key signature of major accidents is that they generally develop over long periods of time, involve large numbers of people and different organizations, and involve a multitude of breakdowns or malfunctions; there is no such thing as a 'root cause' to explain these accidents. These major accidents are focused in organizational - institutional breakdowns; malfunctions of the Technology Delivery System that is used to develop, operate, and maintain the engineered systems. What is frequently indicated as an 'engineering failure' (or 'pilot error') is in fact a failure of the Technology Delivery System.

Breakdowns in Technology Delivery Systems are most often present in Low Reliability Organizations (LROs) and interfaces between such organizations. LROs are characterized by a focus on success rather than failure, and efficiency rather than reliability. The cognitive infrastructure is underdeveloped, failures are localized rather than generalized, and highly specified structures and processes are put in place that develop inertial blind spots that allow failures to cumulate and produce catastrophic outcomes. They do the same things in the face of changing events, these changes go undetected because people are rushed, distracted, careless, or ignorant. LROs are characterized by expensive and inefficient learning. Diversity in problem solving is not welcomed. Information, particularly 'bad' or 'useless' information is not actively sought, failures are not taken as learning lessons, and new ideas are rejected; lethal arrogance. Divergent views are discouraged, so that there is a narrow set of assumptions that sensitize the LRO to a narrow variety of inputs. Under the assumption that success demonstrates competence, LROs drift into complacency, inattention, and habituated routines. Down-sizing and out-sourcing are used to further the drives of efficiency. Insensitivity is developed to overloading and its effects on judgement and performance. Robustness (damage and defect tolerance) is eliminated or reduced in the same drive resulting in elimination of cross checks, assumption that precautions and existing levels of training and experience are sufficient, and dependence on claimed levels of competence. With outsourcing, it is now the supplier, not the buyer, that must become preoccupied with failure. But, the supplier is preoccupied with success, not failure, and because of low-bid contracting, often is concerned with the lowest possible cost success. The buyer now becomes more mindless and if novel forms of failure are possible, the loss of a preoccupation with failure makes the buyer more vulnerable to failure. LROs tend to lean toward anticipation of expected surprises, risk aversion, and planned defenses against foreseeable accidents and risks; unforeseeable accidents and risks are not recognized or believed.

F.4 Quotations from Key Reports and Papers

F.4.1 Townsend, F. F. (2006). *The Federal Response to Hurricane Katrina, Lessons Learned*, Report to the President of the United States, The White House, Washington, DC, February.

Yet Katrina creates an opportunity - indeed an imperative - for a national dialogue about true national preparedness, especially as it pertains to catastrophic events. We are not as prepared as we need to be at all levels within the country: Federal State, local, and individual. Hurricane Katrina obligates us to re-examine how we are organized and resourced to address the full range of catastrophic events - both natural and man-made. The storm and its aftermath provide us with the mandate to design and build such a system.

The magnitude of Hurricane Katrina does not excuse our inadequate preparedness and response, but rather it must serve as a catalyst for far-reaching reform and transformation to do this, we must understand Hurricane Katrina in its proper context.

The storm surge, extreme amounts of rain, and high winds stressed the city's complex 350 mile levee system to its breaking point. Several of the levees and flood walls were overtopped, and some were breached through the day of landfall. It was these overtoppings and breaches of the levee system that lead to the catastrophic flooding of New Orleans. In addition to the levee and floodwall breaches, many of the pumping stations - which would have otherwise removed water from the city and prevented some of the flooding - stopped working due to power outages and flooded pumping equipment.

Some overtopping of the levees was expected due to the intensity of the storm, which would result in localized flooding. However, such overtopping would not have lead to the catastrophic events that occurred due to the levee and flood wall breaches. Further, the New Orleans Flood and Hurricane Protection System is designed so that individual breaches will not lead to catastrophic flooding. The compartmented design, with four main basins, is intended to minimize the threat of flood to the entire system. Thus, had only one basin experienced serious overtopping or a breach, it would have been possible to avoid the catastrophic flooding New Orleans experienced.

New Orleans flooded as the levees and flood walls gave way and the pumpi9ng stations stopped operating; at its height, approximately 80 percent of New Orleans was filled with water up to twenty feet deep. this unprecedented flooding transformed Hurricane Katrina into a "Catastrophe within a catastrophe" as the storm shattered the lives of countless residents and presented State and local officials with challenges far exceeding their capabilities.

We must expect more catastrophes like Hurricane Katrina - and possibly even worse. In fact, we will have compounded the tragedy if we fail to learn the lessons - good and bad - it has taught us and strengthen our system of preparedness and response. We cannot undo the mistakes of the past, but there is much we can do to learn from them and to be better prepared for the future. This is our duty.

F.4.2 Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina, 2006. *A Failure of Initiative*, U.S. Government Printing Office, Washington, DC.

The preparation for and response to Hurricane Katrina show we are still an analog government in a digital age. We must recognize that we are woefully incapable of storing , moving, and accessing information - especially in times of crisis. Many of the problems we have identified can be categorized as 'information gaps' - or at least problems with information-related implications, or failures to act decisively because information was sketchy at best. Better information would have been an optimal weapon against Katrina. Information sent to the right people at the right place at the right time.

We reflect on the 9/11 Commission's finding that 'the most important failure was one of imagination.' the Select Committee believes Katrina was primarily a failure of initiative. But there is, of course, a nexus between the two. Both imagination and initiative - in other words, *leadership* - require good information. And a coordinated process for sharing it. And a willingness to use information - however imperfect or incomplete - to fuel action.

The levees protecting New Orleans were not built to survive the most severe hurricanes. It was a well-known and repeatedly documented fact that a severe hurricane could lead to overtopping or breaching of the levees and flooding of the metropolitan area. In fact, for years the U.S. Army Corps of Engineers (USACE) has had a written plan for unwatering (i.e. draining) New Orleans in such a contingency.

Once construction of the levees was completed by USACE, the responsibilities for operating and maintaining the levees were split among many local organizations, which is the standard cooperation agreement for carrying out flood control projects nationwide. The costs of constructing these projects are shared, with operation and maintenance being a 100 percent local responsibility. these include levee boards in each parish, as well as separate water and sewer boards. The number of organizations involved, and disagreements among them, makes accountably diffuse and creates potential gaps and weaknesses in parts of the flood protection system. In one case, improvements to levee strength which may have mitigated or prevented some of the critical breaches that flooded downtown New Orleans were rejected by the competing local organizations. There also appear to have been lapses in both maintenance and inspections of selected levees, including those that breached. Also, prior to Hurricane Katrina, residents along these same levees reported they were leaking, another potential lapse in maintenance.

Despite the well-known importance of the levees, and the consequences of failure, the local levee boards responsible for maintaining and operating the levees did not have any warning system in place. While federal regulations require that they monitor levees during periods of potential flooding, the requirement is impractical to implement during a hurricane. In addition to no warning system, the loss of communications and situational awareness, and only sporadic reports of flooding from a variety of sources, made it difficult to confirm that there were breaches in the levees and then to assess the damage. These factors, as well as physical difficulties of getting to the breach sites, combined to delay repair of the levee breaches.

…hurricanes threaten the Gulf coast every year, and New Orleans is particularly vulnerable because of its location and topography. The majority of the metropolitan area is below sea level.

Over the years, the city has continued to sink, due to drainage, subsidence, and compaction of the soils. As an example of previous damage, Hurricane Betsy brought extensive destruction to New Orleans when it made landfall in Louisiana in September 1965. Unfortunately, many of the descriptions and photos from Hurricane Betsy sound and look familiar to our nation as it considers the damage from Hurricane Katrina, forty years later.

After Hurricane Betsy in 1965, federal and state governments proposed a number of flood control projects to deal with the threat of hurricanes and the flooding they might cause in New Orleans. These included a series of control structures, concrete floodwalls, and levees along Lake Ponchartrain and several other waterways. One of the major projects is formally called the Lake Ponchartrain and Vicinity, Louisiana Hurricane Protection Project. This project included levees along the Lake Ponchartarain lakefront, the 17th Street Canal, the London Avenue Canal, the Orleans Avenue Canal, the Intercoastal waterway, the Industrial Canal, The Mississippi River Gulf Outlet, and other areas. Although the project was federally authorized, it was a joint federal, state, and local effort with shared costs.

“The levees protecting New Orleans were not designed to withstand the most severe hurricanes. According to USACE’s plans for unwatering New Orleans, ‘the hurricane protection system is not designed for the largest storms and as a result, the metropolitan area is vulnerable to flooding from hurricane storm surges.’ USACE originally designed the levees around New Orleans to protect against a hurricane intensity that might occur once every 200-300 years.

According to USACE, the ‘standard project hurricane’ was used to design the New Orleans levees and is roughly equivalent to a fast moving, or moderate category 3 hurricane. However, there is no direct comparison of the standard project hurricane to a specific category on the Saffir-Simpson Hurricane Scale - which did not exist when the levees were designed. As shown in the table below, the standard project hurricane is equivalent to a hurricane with category 2 winds, category 3 storm surge, and category 4 barometric pressure.

In addition, there is no ‘standard’ hurricane - the actual forces that levees need to withstand are a function of several factors. According to the preliminary NSF study, ‘the actual wind, wave, and storm surge loadings imposed at any location within the overall flood protection system are a function of location relative to the storm, wind speed and direction, orientation of levees, local bodies of water, channel configurations, offshore contours, vegetative cover, etc.. They also vary over time as the storm moves through the region.’ Similarly, USACE documents indicate that overtopping will depend upon the intensity of the storm, the track that the center or eye of the storm follows and the speed at which it travels along the track.

Although the Lake Ponchartrain project is named a hurricane protection project, a number of factors other than saving lives and property are included in the design of such projects. For example, in addition to protection urban and community lives and health, the design of such projects must include environmental and economic effects, and ensure that benefits of the completed project outweigh its cost of construction. In discussing the design of the Lake Ponchartrain project in a 1978 hearing, USACE District Commander for New Orleans, Colonel Early Rush, stated ‘Even Though economists may, and in this case did, favor protection to a lower scale to produce a higher ratio of benefits to costs, the threat of loss of human life mandated using the standard project hurricane.

Even with its hurricane protection system, it was common knowledge that New Orleans was susceptible to hurricane-caused flooding. the risks of a major hurricane and flooding in New Orleans had been covered in the general media - by Scientific American (October 2001) and National Geographic (October 2004) - as well as in emergency management literature. A recent article in the Natural Hazards Observer stated: 'When Hurricane Katrina came ashore on August 29, she ended decades of anticipation. There were few hazards in the United States more studied by scientists and engineers and there was ample warning that a strong storm could cause the City of New Orleans to flood.

Because of the well-known potential for flooding, USACE has had a plan for several years for draining New Orleans - *Unwater Plan, Greater Metropolitan Area, New Orleans, Louisiana*, dated August 18, 2000. this plan provides details on the hurricane protection system and describes methods to get the water out after catastrophic flooding from a hurricane. The premise of the plan is that a category 4 or 5 hurricane may produce storm surge water levels of sufficient height to overtop the existing protection system. The plan lays out a series of scenarios that could occur and suggests appropriate emergency responses to unwater the area. For example, in one case…'There is catastrophic flooding due to complete overtopping of the levees and floodwalls and inundation of the protected area. There will be extensive and severe erosion of levees and perhaps complete breaches. Due to the high water levels, all of the pumping stations will probably be flooded with major damages….The levee districts and drainage departments may be dysfunctional to some degree.

In more recent years, well before Hurricane Katrina, questions were raised about the ability of the Lake Ponchartrain project to withstand more powerful hurricanes than the 'standard project hurricane,' such as a category 4 or 5 hurricane. USACE had discussed undertaking a study of modifications needed to increase the strength of the exiting levees, but no formal study was undertaken.

Several organizations are responsible for building, operating, and maintaining the levees surrounding metropolitan New Orleans. USACE generally contracts to design and build the levees. After construction USACE turns the levees over to a local sponsor. USACE regulations state that once a local sponsor has accepted a project, USACE may no longer expend federal funds on construction or improvements. this prohibition does not include repair after a flood. Federally authorized flood control projects, such as the Lake Ponchartrain project, are eligible for 100 percent federal rehabilitation of damaged by a flood.

The local sponsor has a number of responsibilities. In accepting responsibilities for operations, maintenance, repair, and rehabilitation, the local sponsor signs a contract (called Cooperation Agreement) agreeing to meet specific standards of performance. this agreement makes the local sponsor responsible for liability for that levee. For most of the levees surrounding New Orleans, the Louisiana Department of Transportation and Development was the sate entity that originally sponsored the construction. After construction, the state turned over control to local sponsors. These local sponsors accepted completed units of the project from 1977 to 1987, depending on when the specific units were completed. The local sponsors are responsible for operation, maintenance, repair, and rehabilitation of the levees when the construction of the project, or a project unit, is complete.

The local sponsors include a variety of separate local organizations. For example, different parts of the Lake Ponchartrain and Vicinity Louisiana Hurricane Protection Project, were turned over to four different local sponsors - to include the Orleans, East Jefferson, Lake Borgne, and Ponchartrain levee districts. In addition ,there are separate water and sever districts that are responsible for maintaining pumping stations.

The different local organizations involved had the effect of diffusing responsibility and creating potential weaknesses. For example, levee breaches and distress were repeatedly noted at transition sections, where different organizations were responsible for different pieces and thus two different levee or wall systems joined together. According to USACE, 'at sections where infrastructure elements were designed and maintained by multiple authorities, and their multiple protection elements came together, the weakest 9or lowest0 segment or element controlled the overall performance.

Both USACE and the local sponsors have ongoing responsibility to inspect the levees. Annual inspections are done both independently by USACE and jointly with the local sponsor. In addition, federal regulations require local sponsors to ensure that flood control structures are operating as intended and to continuously patrol the structure to ensure no conditions exist that might endanger it.

Records reflect that both USACE and the local sponsors kept up with their responsibilities to inspect the levees. According to USACE, in June 2005, it conducted an inspection of the levee system jointly with the state and local sponsors. In addition, GAO reviewed USACE's inspection reports from 2001 to 2004 for all completed project units of the Lake Ponchartrain project. These reports indicated the levees were inspected each year and had received 'acceptable' ratings.

However, both the NSF-funded investigators and USAACE officials cited instances where brush and even trees were growing along the 17th Street and London Avenue canals levees, which is not allowed under the established standards for levee protection. Thus, although the records reflect that inspections were conducted and the levees received acceptable ratings, the records appear to be incomplete or inaccurate. In other words, they failed to reflect the tree growth, and of course, neither USACE nor the local sponsor had taken corrective actions to remove the trees.

In addition, there was apparently seepage from one canal before Hurricane Katrina, indicating problems had developed in the levee after construction. Specifically, residents of New Orleans who live along the 17th Street Canal said water was leaking from the canal and seeping into their yards months before Hurricane Katrina caused the levee system to collapse. The leaks, they said, occurred within several hundred feet of the levee that later failed.

Because the eye of Katrina passed just slightly to the east of New Orleans, the hurricane threw unusually severe wind loads and storm surges on the flood pr9otection systems. the surge overtopped large sections of the levees during the morning of August 29 east of New Orleans, in Orleans and St. Bernard Parish, and it also pushed water up the Intercoastal waterway and into the Industrial Canal. the water rise in Lake Ponchartrain strained the floodwalls along the canals adjacent to its southern shore, including the 17th Street Canal and the London Avenue Canal. Breaches along all of these canals led to flooding of 80 percent of New Orleans to depths up to 20 feet. the flooding of central New Orleans led to the most widespread and costly damage of the hurricane. It also lead to the difficulties encountered by emergency responders that are documented elsewhere in this report.

Despite the well-known importance of the levees, and the consequences of failure, the local levee boards responsible for maintaining and operating the levees do not have any warning system in place. Federal regulations require local sponsors to ensure that flood control structures are operating as intended and to continuously patrol the structure during flood periods to ensure that no conditions exist that might endanger it. However, it would be impractical to monitor the levees during a hurricane.

There were also physical barriers that made assessments and repair difficult. Specifically, emergency repair operations to close some of the breaches were seriously hampered by lack of access roads. USACE regulations generally require access roads on top of levees to allow for inspections, maintenance, and flood-fighting operations, and most USACE levees built in the United States meet this requirement. However, in New Orleans, exceptions were made to these regulations because of its highly urban nature. Access roads were foregone when it was decided to use I-walls in the levee crowns to minimize right-of-ways into surrounding neighborhoods. When Hurricane Katrina led to the breaches in the levees, the lack of access roads atop the levees resulted in very significant increases in time and cost to repair the damaged areas.

Hundreds of miles of levees were constructed to defend metropolitan New Orleans against storm events. These levees were not designed to protect New Orleans from a category 4 or 5 monster hurricane, and all of the key players knew this. The original specifications of the levees offered protection that was limited to withstanding the forces of a moderate hurricane. Once constructed, the levees were turned over to local control, leaving the USACE to make detailed plans to drain New Orleans should it be flooded.

The Local sponsors - a patchwork quilt of levee and water and sewer boards - were responsible only for their own piece of levee. It seems no federal, state, or local entity watched over the integrity of the whole system, which might have mitigated to some degree the effects of the hurricane. When Hurricane Katrina came, some of the levees breached - as many had predicted they would - and most of New Orleans flooded to create untold misery.

The forces that destroyed the levees also destroyed the ability to quickly access damage and make repairs. The reasons for the levee failures appear to be some combination of nature’s wrath (the storm was just too large) and man’s folly (an assumption that the design, construction, and maintenance of the levees would be flawless). While there was not failure to predict the inevitability and consequences of a monster hurricane - Katrina in this case - there was a *failure of initiative* to get beyond design and organizational compromises to improve the level of protection afforded.

F.4.3 Report of the Committee on Homeland Security and Governmental Affairs. *Hurricane Katrina, A Nation Still Unprepared,* United States Senate, Washington, DC, May 2006.

The Contribution of the Mississippi River Gulf Outlet to Damage from Hurricane Katrina

Congress authorized construction of the Mississippi River Gulf Outlet (MRGO) in 1956 to facilitate commercial shipping access to the Port of New Orleans from the Gulf of Mexico. Upon its completion in 1965, the MRGO provided a route 40 miles shorter than the alternative up the Mississippi River. The MRGO also provides a connection from the Gulf of Mexico to the Gulf

Intracoastal Waterway (GIWW), which is a recreational and commercial waterway running east-west from Texas to Florida. Though the MRGO produced commercial benefits, those benefits came at a cost to the environment. The Corps estimates that the construction of the channel led to substantial loss of wetlands, which, as noted above, help slow and decrease the power of storms before they hit populated areas.

The MRGO also contributed to a potential "funnel" for storm surges emerging from Lake Borgne and the Gulf into the New Orleans area. The "funnel" was created by the intersection of the MRGO from the southeast and the GIWW from the northwest into the confined channel, referred to as the GIWW/MRGO that separates New Orleans East and the Ninth Ward/St. Bernard Parish. The levees on the south side of the MRGO and the levees on the north side of the GIWW converge from being about 10 miles apart where they straddle Lake Borgne to a few hundred yards apart where the MRGO merges into the GIVY'W. The western part of the "funnel" is a 6 mile-long section of the combined GIWW/MRGO which was enlarged by a factor of three when the MRGO was built in order to expand from a barge channel to accommodate oceangoing vessels.

Prior to Hurricane Katrina, many warned that the potential funnel would accelerate and intensify storm surges emerging from Lake Borgne and the Gulf into the downtown New Orleans area. The funnel had been described as a "superhighway" for storm surges or the "Crescent City's Trojan Horse" that had the potential to "amplify storm surges by 20 to 40 percent," according to some storm modeling. [33] Researchers at LSU believed that in creating this funnel, "the US Army Corps of Engineers had inadvertently designed an excellent storm surge delivery system - nothing less - to bring this mass of water with simply tremendous 'load' - potential energy - right into the middle of New Orleans.

The extent to which MRGO, and the funnel it helped create actually contributed to the hurricane's damage is still being investigated, but there have been some preliminary findings. A recent report issued by the Corps' IPET concluded that the portion of MRGO running from the GIWW to the Gulf (called "Reach 2") did not significantly impact the height of Katrina's storm surge, not because the "funnel" effect was nonexistent, but because the storm was so great it nullified the impact of either the wetlands or the [35] intersection of the MRGO and the GIWW - the funnel - at the height of the surge.

The building of MRGO and the combined GIWW/MRGO resulted in substantial environmental damage, including a significant loss of wetlands that had once formed a natural barrier against hurricanes threatening New Orleans from the east. MRGO and the GIWW/MRGO provided a connection between Lake Borgne and Lake Pontchartrain that allowed the much greater surge from Lake Borgne to flow into both New Orleans and Lake Pontchartrain. These channels further increased the speed and flow of the Katrina surge into New Orleans East and the Ninth Ward/St. Bernard Parish, increasing the destructive force against adjacent levees and contributing to their failure. As a result, MRGO and the combined GIWW/MRGO resulted in increased flooding and greater damage from hurricane Katrina.

The Roles and Responsibilities of the U.S. Army Corps of Engineers, the Louisiana Department of Transportation and Development and the Orleans Levee District

The U.S. Army Corps of Engineers

Levee systems of the size needed to protect the New Orleans area are often collaborative efforts between federal and local governments. The federal role in such projects is carried out by the Corps, an agency within the Department of Defense (DOD) charged with both military and civilian missions. Military missions are assigned within the military command structure, while civilian flood control projects are authorized by Congress in legislation.

Flood-control projects usually begin when a community feels a need for protection and contacts the Corps. If the Corps does not already have the statutory authority to respond, then Congress may grant it. After initial studies, the Corps may enter into a project cooperation or assurance agreement with a local sponsor acting on behalf of the community. The assurance agreements for projects generally set forth roles of the parties, including payment obligations, design and construction responsibilities, and operations and maintenance (O&M) duties before and after the project is complete.

The levee system that protects most of New Orleans, including areas that experienced major breaches and flooding during Katrina - such as the 17th Street and London Avenue Canals, New Orleans East, and most of St. Bernard Parish - is a Corps project called the Lake Pontchartrain and Vicinity Hurricane Protection Project (Lake Pontchartrain Project). There are several other federal cost-shared projects that protect other parts of southeastern Louisiana. The Corps' involvement in these projects was mostly through its New Orleans District, one of the Corps' largest with more than 1,200 employees and part of the Corps' Mississippi Valley Division headquartered in Vicksburg, Mississippi. When Katrina made landfall, the New Orleans District was under the command of Colonel Richard P. Wagenaar, who had assumed control only six weeks before.

The assurance agreements for the Lake Pontchartrain Project made the Corps responsible for designing and constructing the project. Local sponsors provided the land for levee construction and rights-of-way, and agreed to share the cost. The Corps was to turn the completed project over to the local sponsors for O&M consistent with the Corps' standards, i.e., making sure the flood-control system actually works on a day-to-day basis and protects those living inside the system. [10] To help the local sponsor do this, the Corps is required by its rules and regulations to provide the local sponsor with an operations manual" and then conduct annual inspections to be sure the local sponsor is doing what it is supposed to do.

In addition to its authority to build flood-control projects, the Corps also has statutory authority in federal cost-share flood-control projects like the Lake Pontchartrain Project to act in anticipation of, or response to, flood emergencies. In this role, the Corps may help the local sponsors deal with the flood threat to the levee system, and aid state and local governments trying to prevent flood damage. This "flood-fighting" authority is authorized by Public Law 84-99, also known as the "Flood Act." In the days following Katrina, the Corps used its Flood Act authority to close off the levee breaches at the 17th Street and London Avenue Canals, which were filling the city with water, and to make other emergency repairs.

The Orleans Levee District

One of the local sponsors for the Lake Pontchartrain Project was the Orleans Levee District, one of the first five levee districts created by the state in 1879. The levee districts, which were established to be a funding source for and to ensure local involvement in levee construction and operation, all had the same general duty: to do what was necessary to "insure the thorough and adequate protection of the lands of the district from damage by flood ... for the adequate drainage control of the district."

Like the Corps under the Flood Act, the levee districts have broad statutory obligations in addition to their obligations under their assurance agreements on individual levee projects. For example, regardless whether a project was being designed and constructed by the Corps or had been turned over for O&M to the local sponsor, state law charged the levee districts with adopting rules and regulations for maintaining a "comprehensive levee system." State law authorized them to obtain engineering assistance from the Louisiana Department of Transportation and Development (LA DOTD) in Baton Rouge if they needed additional technical expertise.' State law also required levee-district board members to attend once during their term in office an educational program on how to care for and inspect levees.

To carry out their primary duty of flood control, state law not only authorized the levee districts to serve as local sponsors for federal cost-share projects, but also to raise money pursuant to taxing and bonding authorities. In the unique case of the Orleans Levee District, it was also authorized to engage in various business enterprises, 20 making the Orleans Levee District a unique entity with some governmental qualities (taxing and bonding authority) and some corporate qualities: the authority to engage in for-profit businesses like operating the Lakefront Airport, running two marinas along Lake Pontchartrain, and leasing dock space to a riverboat casino.

The revenues the Orleans Levee District earned from the businesses and its taxing and bonding authority were substantial. The Orleans Levee District financial statements for the fiscal year ending June 30, 2005, show it collected more than $24 million from property taxes and $14 million from its business-type activities in the previous 12 months. The same report said the district had $21 million in unallocated general funds and $13 million in a "special levee improvement fund. The levee improvement fund, according to the levee district's former president, Jim Huey, could "only be used for flood protection projects and/or flood-related projects.

Although the levee district's primary responsibility was flood protection it spent large amounts on non-flood related activities (e.g., the licensing of a casino or the operation of an airport and. marinas or the leasing of space to a karate club, beautician schools or restaurants) rather than apply the money to flood protection or emergency preparedness. 25 For example, the Orleans Levee District's Emergency Operations Center (EOC) sat outside the protection of the levee system at the Lakefront Airport, vulnerableto the very hurricanes the levee system was designed to protect against. For years the district had, studied moving its EOC inside the flood protection system, but never did. The levee district's Chief Engineer, Stevan Spencer, described the situation as a "very bad joke" that dated back to at least 1998, when Hurricane Georges flooded the airport. Spencer said "there was never funding" to move the EOC. Yet in 2003, the Orleans Levee District spent $2.4 million to repair the "Mardi Gras Fountain" in a park near Lake Pontchartrain. When Katrina made landfall, Orleans Levee District staff had to be rescued, mostly by boat, from the flooded EOC at the airport before they could survey damage or assist with repair efforts at the 17th Street and London Avenue Canals.

The Orleans Levee District was also aware of a levee in New Orleans East that was considered to be three feet below its design height. Levee-district board minutes and conversations with Corps personnel suggest that paying for repairs to this low levee was considered to be the Corps' responsibility. Federal funding was unavailable, but instead of paying for the repairs itself and asking for reimbursement from the Corps, as it had with previous projects, the levee district merely sent letters to its Congressional delegation asking for federal funding.

Pressed to explain how the Orleans Levee District made spending decisions, Huey offered no direct explanation, but focused on the district's multiple obligations - not only was the district responsible for flood control, but it also had statutory requirements to maintain recreational space and was authorized by state law to engage in non-flood related business ventures. A review of the levee-district board minutes of recent years revealed that the board and its various committees spent more time discussing its business operations than it did the flood-control system it was responsible for operating and maintaining.

The Louisiana Department of Transportation and Development (LA DOTD)

Though not a party to the assurance agreements for the Lake Pontchartrain Project, LA DOM and its Office of Public Works (OPW) have statutory responsibilities to assist and oversee certain levee district functions. State law tasks LA DOM with approving any activity that might compromise the levees, and with administering training sessions to levee-district board members and their inspectors on caring for and inspecting levees.

To the extent training sessions were held, they were organized by the Association of Levee Boards of Louisiana, an organization that lists Edmund Preau as its Secretary Treasurer. Preau is an Assistant Secretary in LA DOTD and leads the OPW within the Department, which is responsible for LA DOTD's levee-related activities.

When Huey, who served on the levee district's board for more than 13 years (nine as president), was read the section of state law describing the training requirement, he said it was the first he had heard of it. Huey explained: "You know what that is? That's going up to a workshop for a weekend and having a crawfish boil up here and hear a couple people talk about some things and they get a little piece of paper and they honored the law Huey was then asked whether the Association sessions addressed how to inspect levees. He responded, "No, nothing. LA DOTD also had the statutory responsibility to "review" each levee district's emergency-operations manual every two years . According to Preau, this review entailed checking whether relevant contact information had been updated and whether the levee district had included any new flood-control systems within its jurisdiction in its planning. The review entailed no assessment of whether the levee district had stockpiled materials or had the personnel necessary to assess an emergency and respond accordingly. Preau said he assumed any more elaborate review would have been done by the Louisiana Office of Homeland Security and Emergency Preparedness (LOHSEP).

Louisiana's Emergency Operations Plan (EOP) made the LA DOTI) the primary state agency overseeing Emergency Support Function (ESF-3), Public Works and Engineering. ESF-3 encompassed critical infrastructure in the state, including the "construction, maintenance and repair of state flood control works. ESF-3 also dictated that, "When an emergency is imminent, the ESF 3 Coordinator [who is to be designated by LA DOTI) Secretary Johnny Bradberry] will assess the potential impact of the threat on the state's infrastructure and work with other authorities to ensure that any necessary immediate repairs or arrangements for critical structures and facilities are initiated. ESF-3 also said, "As the emergency progresses, the coordinator will monitor the status of the infrastructure and effect emergency repairs where needed and feasible."

The LA DOTD did not acknowledge or accept its responsibility under ESF-3. Preau told Committee investigators that he didn't think the provision applied to LA DOM "I'm not sure what that means, because we don't have any state flood control works. State doesn't own any flood control works. By Preau's reading, a levee project was covered only if it was owned by the state, not simply if it was in the state. As Preau read it, LA DOTD had no responsibility to coordinate with levee districts on critical facilities like the Lake Pontchartrain Project. This response is problematic: the responsibilities articulated under ESF-3 are specifically delegated to the LA DOTD, and the plain language employed by the State's Emergency Operations Plan cannot be unilaterally dismissed as meaningless by the people it covers.

The result was that neither LA DOTI) nor any state agency made sure that the state's levee districts were integrated into the state's emergency-planning process, much less genuinely prepared for an emergency. As a result, when Katrina made landfall, no Orleans Levee District personnel were located at, or in contact with, emergency managers in Baton Rouge; nor was any mechanism in place to request additional support from the state. Notwithstanding Preau's insistence that the LA DOTD had no responsibilities under ESF-3 for the levee system, LA DOTD ultimately played an active role in efforts to close levee breaches in New Orleans in the aftermath of Katrina.

Design and Construction of the Lake Pontchartrain Project

During Katrina, levees and floodwalls were overwhelmed throughout the New Orleans area, and in several places were breached. Some of these failures occurred in parts of the Lake Pontchartrain Project. Understanding the link between the breaches and the nature and organization of the Lake Pontchartrain Project requires some background. Congress authorized the Lake Pontchartrain Project in the Flood Control Act of 1965 to provide hurricane protection to areas around Lake Pontchartrain in Orleans, Jefferson, St. Bernard, and St. Charles Parishes. 52 The project called for design and construction of about 125 miles of levees and floodwalls to be completed by 1978 at a cost of $85 million. The project was still not complete when Katrina hit, and its cost had grown to more than $750 million as of 2005 .

As authorized by Congress, the project was to protect the area from what the Corps called the "Standard Project Hurricane" (SPH), a model storm "based on the most severe combination of meteorological conditions considered reasonably characteristic of that region."54 The SPH was developed in 1959 by what was then called the United States Weather Bureau, which updated the SPH after the devastating impact of Hurricane Betsy in 1965. The SPH was revised again in 1970, 1977, and 1979 by the Weather Bureau's successor, the National Oceanic and Atmospheric Administration (NOAA). 55 There is no evidence that design parameters of the Lake Pontchartrain Project were modified in light of NOAA's changes to the reference-model storm.

Nevertheless, the Corps has repeatedly maintained that the SPH was the equivalent of a fast-moving Category 3 storm on the Saffir-Simpson scale - a measurement scale that rates the strength of hurricanes on a scale of Category I to Category 5, with Category 5 being the most intense. For example, at a press conferences immediately after the storm, Lieutenant General Carl Strock, the Commander of the Corps and its Chief of Engineers, explicitly said that the Corps "knew" that the levee system "would protect from a Category 3 hurricane,' and the page on the Lake Pontchartrain Project on the Corps' website after Katrina said, "The SPH is equivalent to a fast-moving Category 3 hurricane.

This claim is misleading: the Saffir-Simpson scale was not adopted until 1977, 12 years after the Lake Pontchartrain Project was authorized. Al Naomi, the Corps' Senior Project Manager for the project, acknowledged that the Corps never conducted a formal study comparing the SPH to the Saffir-Simpson scale, so the claim that the Lake Pontchartrain Project provided Category 3 protection was at best a rough estimate, and at worst, simply inaccurate:

> *SPH has ... wind speed, central pressure, and surge. You go in and say what is my wind speed for an SPH? You look at it. It's a very high Category 2 storm on the Saffir-Simpson Scale. I look at my central pressure for SPH. I go to the Saffir-Simpson Scale, it's a mid-range Cat 4. 1 say what is my surge? SPH surge in the lake at I I and a half [feet] on the Saffir-Simpson that is a Category 3 range. What am I going to tell the Rotary Club? What do I have? Generally in talking to the hydrologist, you can say it's about equivalent to a fast moving Cat 3. It's not really that, but for their understanding that is what you can say. That is what we say. What happens is the press gets this and it says we have Cat 3 protection. That is not really true. It's SPH protection which may be equivalent to a fast moving Cat 3 storm.*

However, the view that the hurricane protection system could protect the greater New Orleans region from a moderate and/or fast-moving Category 3 storm was widely held within the Corps' New Orleans District. Prior to Hurricane Katrina, the New Orleans District issued numerous news releases to the general public (some of which are referenced below), stating that the hurricane protection system provided some level of Category 3 protection:

- *December 19, 200 1, N. 0. hurricane bridge contract awarded, Corps, Levee Board will flood proof two bridges in Gentilly: "The bridge floodproofing will protect neighborhoods along the London Avenue, Orleans Avenue and 17th Street canals from storm surges from Lake Pontchartrain. The system of levees, floodwalls and bridges is designed to protect against fast-moving Category 3 hurricanes."*

- *May 27, 2003, Cross Bayou Drainage Structure to reduceflooding in St. Charles*

Parish: "The structure is part of the Lake Pontchartrain Hurricane Protection Project and is the second of five such structures to be built in St. Charles Parish These contracts, to be completed in 2004, will result in a levee system that provides protection from a Category 3 storm for St. Charles Parish"

- *August 21, 2003, Filmore Bridge in Gentilly will reopen on Friday, Aug. 22. Mirabeau Bridge is closing Wednesday, Aug. 27for hurricane floodproofing: "The systems of levees, floodwalls and bridges is designed to protect against fast moving Category 3 hurricanes. This view was also held by the Corps' New Orleans District Commander (Col. Wagenaar 63) and the District's Emergency Manager (Michael Lowe 64). Further, the same representations were made in more substantive Corps written materials.*

Moreover, the Lake Pontchartrain Project, as it stood in the path of Katrina, was still not complete as designed. Some portions were still under construction, and soil subsidence (sinking) had left portions of the project with less elevation above sea level than intended. In other words, some elements of the project were not even high enough to protect against the Standard Project Hurricane, let alone a genuine Category 3 hurricane.

The Corps was well aware of this fact. As Jerry Colletti, the New Orleans District's Manager for Completed Works explained, the Corps never tried "to provide full-level protection on an annual basis.... we just can't raise everything to the design height for each storm that would come through.

Meanwhile, the National Weather Service (NWS) concluded from a new model of projected storm surges that the Lake Pontchartrain Project would be more vulnerable to hurricanes than previously thought - that more Category 3 and even certain Category 2 hurricanes would overtop parts of the levee system and produce flooding. Dr. Wilson Shaffer, who studies storm surges at NWS, said this discovery was shared with the Corps, perhaps as early as 2003, but certainly by 2004. The findings were also shared with LOHSEP and with state and local emergency managers at the Louisiana Emergency Preparedness Association's June conferences in 2004 and 2005 . At a minimum, this information should have prompted a fresh look at the adequacy of the Lake Pontchartrain Project, but like the NOAA updates to the Standard Project Hurricane in the 1970s, it does not appear that either the state or the Corps took any action to respond to the new information.

Effect of Subsidence on the Level of Protection

As noted earlier, the level of protection provided by the levee system was affected not only by its design, but also by a geologic subsidence, or soil sinking. The entire coastal region of Louisiana had been subsiding for millions of years, as the enormous weight of the sediments continually deposited by the Mississippi River enters the Gulf of Mexico, pushing down on the earth's crust. Human activities like extracting oil and natural gas, pumping water, raising buildings, and even adding to levees and floodwalls all accelerate subsidence. (See Chapter 9.) As the entire region subsides, the effective height of the levees above sea level, and thus the level of protection they provide, decreases. A recent report concluded that a section of levee that was overtopped and failed during Katrina was nearly three feet below its design height.

All of these factors should have persuaded the Corps to reconsider its public claims that the Lake Pontchartrain Project provided Category 3 level protection.

Operation and Maintenance (O&M)

Maintaining a flood control system is essential, but is complicated in southeast Louisiana by the recurring need to rebuild levees to compensate for subsidence. The Corps is not supposed to turn over a project until it is complete; until then, the Corps is responsible for O&M.71 Once a project is turned over, the local sponsor must conduct O&M to Corp standards "to obtain maximum benefits. This includes checking for "undue settlement" of the levee, water seeping through or under it, and growth of damaging brush, and taking immediate action to address potential emergencies.

Because the Lake Pontchartrain Project was not complete, according to the Corps' Senior Project Manager for the project, none of it had been formally turned over to the local sponsor, but remained in an "interim" status:

> *There are still pieces that have to be done. We are not going to turn over a piece of the project until every piece in that ring of protection is completed. If there is one little thing left to do I think by regulation - I could be wrong. I think we have to have the entire system 100 percent comFlete so we turn over the entire segment that is protected, a certain area of the City.*

Nonetheless, the Corps did nominally turn over parts of the project to local sponsors to maintain when it determined that construction on that particular part or "reach" was complete. The Corps sent letters to the Orleans Levee District and others to this effect, informing each district that it now had O&M responsibility for that unit. Personnel within the Corps' New Orleans District referred to these letters as "turnover letters" even though they were not the "official total project completion turnover" letters. The Orleans Levee District did not respond to these letters or even acknowledge their receipt .

When the Committee asked for copies of the de-facto turnover letters, it received only a limited response. The letters submitted did not cover the entire project, and some were pre- 1965, before the project was even authorized. In short, the exact legal status of the project segments and the degree to which the Corps and local sponsors like the Orleans Levee District were truly responsible for maintenance is at best uncertain.

Other conflicting and irregular procedures in the turnover process went beyond the turnover letters. The Corps was supposed to require local sponsors to report semiannually to its District

Engineer on inspection and O&M for the flood-control system. Colletti, the Corps' Operations Manager for Completed Works, explained that the Corps unilaterally decided not to require the Orleans Levee District to provide the report. In addition, for each completed work, the Corps is required to give the local sponsor an 82 operations manual . Colletti said his office gave no such manual to the Orleans Levee District for levees and floodwalls, but merely provided a one-page set of guidelines similar to a part of the Code of Federal Regulations that detailed obligations of local sponsors.

The Corps' observance of rules and regulations for completed projects took the form of a required annual inspection conducted around June I - the start of hurricane season - by representatives from the Corps, the Orleans Levee District, the LA DOTD, and other interested parties (e.g., the City and the Port of New Orleans). These inspections appear to have taken about four hours, covered at least a hundred miles of levees and floodwalls, and would usually involve a motorcade that would stop at pre-determined spots to allow the group to look over an area and discuss issues. The purpose of the inspections, according to the Corps, was to ensure O&M compliance by the local sponsor, but not to test the system's actual structural integrity or measure whether it was at design height. Perhaps the most colorful explanation of the annual inspection was offered by former Orleans Levee District president Huey, who suggested that the event was more of a social occasion than a genuine technical inspection:

> *They normally meet and get some beignets [pastries] and coffee in the morning and get to the buses. And the colonel and the brass are all dressed up. You have corrunissioners, they have some news cameras following you around and you have your little beignets and then you have a nice lunch somewhere or whatever. And that's what the inspections are about.*

Ineffective Inspection Regime

The weaknesses of this inspection approach can be seen in the last pre-Katrina annual inspection of the Lake Pontchartrain Project in May 2005. It apparently did not address some known vulnerabilities. The W-30 Floodgate along the Inner Harbor Navigation Canal had been destroyed by a train accident in 2004 by the New Orleans Public Belt Railroad . This gate was intended to close off the levee at a point where the railroad track passed through it. The railroad had provided money for repairs, but the floodgate was still broken when Katrina struck, even though Huey, then board president, told an April 5, 2005, levee-district board meeting that he considered the broken gate to be an "emergency." Under state law, Huey had the authority to address such emergencies without going through the standard contracting process. 92 Asked why he did not use his emergency authority to repair the gate before hurricane season, Hue simply said, "I do ,Y not know. My bottom line straightforward answer: I don't know."

Another problem apparently not dealt with in the annual inspection was a levee in New Orleans East that was three feet short of its design height. Like the W-30 floodgate, the problem remained unaddressed when Katrina made landfall, even though Naomi, the Corps' Senior Project Manager, considered repair "vital" to protecting the city. In addition, Corps rules and regulations for completed works require local sponsors, like the Orleans Levee District, to fix defects promptly. Finally, the Corps' rules on levees require local sponsors to ensure that "No trees exist, the roots of which might extend under the wall and offer accelerated seepage paths." However, one of the forensic teams investigating the levees' failure, and Corps officials, found trees growing along the

17th Street and London Avenue Canals. In spite of the major defects requiring repairs, the Orleans Levee District's Chief Engineer said he expected the district to get "an outstanding review in regards to the maintenance of the levees" from the 2005 inspection.

The Committee learned during its investigation that the 17th Street and London Avenue Canal floodwalls weren't part of the 2005 inspection because they were inaccessible by car. It appears likely that they were never inspected by the Corps after construction was finished in the early 1990s, partially because the floodwalls abutted private property which made them difficult, but certainly not impossible, to access. It seems likely that the only physical inspections they received would have been conducted by Orleans Levee District personnel mowing the grass, making visual inspections, and identifying problems like holes dug by wild animals, significant erosion, etc. The personnel responsible for this work received no specialized training on care or inspection of levees and floodwalls, and supporting documentation of these inspections comprised nothing more than worker timesheets indicating the work conducted, such as mowing the grass, the location of the work, and the hours spent doing the job.

When asked who was responsible for fixing problems once they were identified, Orleans Levee District leadership explained that there was an undocumented understanding that "major" problems would be brought to the attention of the Corps and "minor" problems would remain the responsibility of levee district personnel . However, and as noted by the Orleans Levee District Chief Engineer, Stevan Spencer, the district's total in-house, engineering expertise amounted to three engineers , a level of expertise not on par with the challenges posed by the hurricane protection system within the jurisdiction of the Orleans Levee District.

The only other inspection the Orleans Levee District claims to have made of the levees was a field survey of floodwall heights every two to three years to check for subsidence. 105 If the Orleans Levee District did, in fact, conduct these surveys, they did not identify the severity of the subsidence along the 17th Street and London Avenue Canals documented by the Corps' forensic team. The Orleans Levee District certainly did not conduct any structural analysis of the floodwalls; nevertheless, when asked by the Committee about the quality of the Orleans Levee District's operations and maintenance regime over the years, Colletti said that the Corps "felt that they've done an outstanding job. 9107

The Orleans Levee District's O&M practices and the passive oversight by the Corps did not meet what experts consider to be the standard of care for a flood control system like the Lake Pontchartrain Project. For example, in a letter to the Committee, Dr. Ernst G. Frankel of the Massachusetts Institute of Technology explained that visual surveys are not sufficient because potentially catastrophic voids can occur well below the surface of the levees. To expose internal degradation, holes must be drilled in the levees to retrieve core samples for analysis. Acoustic equipment can be used to scan the density of material layers at various depths. No entity conducted such an analysis of the New Orleans flood-control structures, 109 nor were efforts made by the Levee District to obtain equipment to improve its inspection regime. Professor Frankel added that inspection of levees below the waterline was also necessary to detect hidden threats to their integrity. The Orleans Levee District's simple visual inspections failed in this respect as well.

Lack of Coordination with the Sewerage and Water Board of New Orleans

Because New Orleans and surrounding parishes are below sea level and ringed by levees, rain and flood waters that enter must be pumped out. The Sewerage and Water Board of New Orleans (the Water Board) has the responsibility for maintaining a system of pumps and canals for this purpose. (The Water Board also runs the municipal water and sewer systems.) Floodwalls along two of these drainage, or outfall, canals sustained major breaches - the 17th Street and London Avenue Canals. However, the Orleans Levee District and the Corps, at least to the extent the Corps had not turned over the entire project to the local sponsor, are responsible for the floodwalls that line these canals.

In the aftermath of Katrina, the New Orleans Times-Picayune newspaper reported that six months before Katrina, several residents near the 17th Street Canal reported to the Water Board that they had found water in their yards. A similar report was carried by National Public Radio. Following the Times Picayune report, the Water Board conducted an inquiry into these allegations and concluded that the water reported by these property owners was coming from a water-service line and not from the canal. This conclusion was documented in a letter from the Water Board to the Times-Picayune and provided to the Committee. The 17th Street Canal floodwall broke within several hundred feet of where the water seepage was reported. The Committee was not able to independently confirm either the news reports or the Water Board's explanation. However, it is clear that the Water Board had no plan in place or arrangement with either the Corps or the Orleans Levee District to address this sort of situation. The Water Board's Executive Director, Marcia St. Martin, explained how her organization dealt with such situations:

> *What we do is if a person says that there's water that's ponding in front of my house, we look to see whether or not a Board asset, which is the water meter, has a defect or a leak. If we determine it has a defect or a leak, we repair it. If we determine it's not coming from the Board's asset, we say to the customer, "It has to be a private property leak and you need to seek the services of a plumber*. 91114

The Corps has relied on local residents to inform it about these types of problems, but had no public outreach program to urge residents to do so. When the Corps did receive reports of seepage or other issues, it had no process to formally document and address the issues. 116 Likewise, the Orleans Levee District had no plan to reach out or communicate with residents to encourage the identification or the sharing of reports of leakage or other problems."

Subsidence in the Metropolitan New Orleans Area

In addition to design and construction issues, soil subsidence - "the lowering or sinking of [the] earth's surface" - has impaired the protection offered by the New Orleans levee system. In the New Orleans area, subsidence is caused primarily by the cumulative weight of millions of years of soil and silt deposits left by the Mississippi River as it enters the Gulf of Mexico. The sediment literally presses down on the earth's crust, causing the land to sink. As a result, the water level rises, gradually increasing its vulnerability to tides and storms. The levees themselves can also subside because of their own weight pressing down on the swampy soils upon which they are built.

As a result, it appears that the level of protection actually provided by the levee system in the New Orleans region, at the time of Katrina, was significantly less than intended: 44many sections of the levees and floodwalls were substantially below their original design elevations, an effective loss of protection. For example, the structures associated with the Inner Harbor Navigation

Canal were originally constructed to an elevation of 15 feet (relative to mean sea level) but are now just over 12 feet, a typical loss of approximately 2.7 feet in elevation over the lifetime of the project." The report noted that "subsidence is occurring at a rate of up to one inch every three years" in the New Orleans region.

Subsidence routinely creates problems for those trying to construct levees and other structures at known heights above sea level. As stated in one MET report, due to the complex and variable subsidence in Southeast Louisiana, "establishing an accurate vertical reference for measurements has been a constant challenge." Unfortunately, until the October 2005 release (by [the U.S. Department of Commerce's National Oceanic and Atmospheric Administration's (NOAA)] National Geodetic Survey) of 85 benchmarks located in southern Louisiana, which showed heights (elevations) accurate to between 2 and 5 centimeters (roughly I to 2 inches), surveyors, engineers, and the U.S. Army Corps of Engineers in New Orleans evaluated the levees and structures built and in use with vertical heights that had not been calibrated nor checked for several years.

As a result, it appears that the levees were not built and maintained at the proper level above sea level. Since the level of protection that the levees provide is so closely related to their height above sea level, and thus their ability to block increased water levels driven by hurricanes, the failure to build and maintain the levees at the proper elevation diminished the level of protection they would provide.

F.4.4 American Society of Civil Engineers External Review Panel (ERP), Letter to LTG Carl Strock, Chief of U.S. Army Corps of Engineers, February 20, 2006.

Four critical areas warrant urgent and thorough examination.

Organizational issues: No one person or organization is in charge of the New Orleans hurricane protection system. Local levee districts are responsible for maintaining the levees. Local parishes are responsible for operating pump stations (and even for deciding whether they will be operated during a hurricane). Numerous penetrations affecting such infrastructure as rail lines, bridges, and roadways have been made below the tops of levees and floodwalls under various jurisdictions. Construction contracts are awarded piecemeal, sometimes resulting in abrupt discontinuities in the elevations of floodwalls or levees. Even within the U.S. Army Corps of engineers differing levels of responsibility exist at the district, division, and headquarters levels. the City of New Orleans, the state of Louisiana, and perhaps other entities also are involved in hurricane protection for New Orleans.

The ERP sees clearly that organizational complexities and the ways in which decisions are made are among the most important factors that influenced the performance of the hurricane protection system. Organizational effectiveness has been and will continue to be questioned, with justification. It is impossible for the ERP to conceive a mechanism through which the levee system can be rebuilt and operated effectively and efficiently with such organizational discontinuities and chaos. The ERP recommends that organizational issues be assessed critically and thoroughly as soon as possible.

System issues: The hurricane protection system of New Orleans evolved over a long period of time. The system is not an integrated, well-thought-out system; rather, it is a joined series of individual pieces conceived and constructed piecemeal. Examples include the following: (1) the canals, which evolved over a period of decades to accommodate the pumping technologies available at the time and the continuing land reclamation northward toward Lake Pontchartrain (even though the logic of having many miles of exposed levee and floodwalls along the canals as opposed to closing off the mouths of the canals with a gate or short section of levee, is weak at best); (2) the connections between rigid structures and earthen levees, which experienced numerous failurs during Katrina; (K3) discontinuities and differences in crest elevations of levees and floodwalls; and (4) the pumps, which were designed to remove rainwater and infiltrating groundwater but, when not turned on, are not protected from backflow and exacerbate flooding during a hurricane.

A logical hurricane protection system for New Orleans would integrate components and the management of components, would be robust and resilient, and would contain a level of redundancy sufficient that, if a levee failed, all would not be lost. A system wide strategy would also ensure that critical structures - for example, pumping stations, hospitals, places of refuge, and electrical generation and distribution nodes - were protected. The lack of a broader, system-oriented strategy exerted a major deleterious influence on the performance of the system and deserves serious consideration.

System development: It is obvious that the hurricane protection system for New Orleans failed miserably during Katrina. that the system was so clearly overwhelmed and failed so catastrophically demonstrates to the ERP that fundamental flaws were part of how the system was conceived and developed. For example, what was the basis for selecting the standard project hurricane and, hence, the authorized level of protection? What process was in place to review the safety of the design as new knowledge evolved over time? How safe and redundant was the system intended to be upon design? Was adequate funding in place to ensure that satisfactory design standards could be implemented? How were safety margins for design established, and are they appropriate in light of new knowledge and the risks involved? How was the potential for loss of life factored into decision making?

Overtopping of levees: A fundamental flaw in the floodwalls and levees is that they include no means of accommodating overtopping that does not inflict major damage or destruction. Once the levees were overtopped during Katrina, rushing water eroded away many sections of levee and in other cases undermined floodwalls. Most of the 350 miles of levees in New Orleans are unprotected from devastating damage and potentially total destruction if overtopped. No mater how high the levees are built, a possibility always remains of a hurricane causing a surge elevation that is even higher than the one for which the levees were designed.

One of the lessons of Katrina that is already obvious is that once the levees were overtopped, destruction was catastrophic. In addition to the tragic loss of life, there were at least two other critical results: extensive and catastrophic flooding and an enormous destruction of capital investment. The question is not whether the levees will again be overtopped but when and by how much they will be overtopped. The levees need to be protected from catastrophic failure resulting from overtopping.

On multiple occasions, statements by top Corps officials have assured the public that the levee system will be adequately safe, and its risks sufficiently low for displaced residents to return to the city by June 1. These statements have seriously compromised task 10 (risk assessment) efforts by introducing a motivational bias that predetermines the outcome of its risk determinations.

This undermines the credibility of task 10 and ultimately of the Corps itself. The lesson to be learned is that task 10 will not produce technically sound risk estimates unless there is full support and cooperation from the Corps at the highest levels for unbiased outcomes free of any appearance of manipulation of predetermined conclusions.

F.4.5 Committee on New Orleans Regional Hurricane Protection Projects, National Academy of Engineering and the National Research Council, 2006. Report to The Honorable John Paul Woodley, Assistant Secretary of the Army, Civil Works, Washington, DC, February.

The New Orleans and southeastern Louisiana hurricane protection system includes many engineering, geologic, hydraulic and hydrologic, administrative, and economic and cultural features that interact in complex ways. the levees, floodwalls, and other protective structures in New Orleans and southeast Louisiana have been constructed in a region of active alluvial deposition, subsidence, and fluvial dynamics. The Mississippi River delta, for example, has changed location several times in the past 5,000 years. the region is underlain by deep deposits of recent sediments with high clay content and by sites with varying rates of geologic subsidence - conditions that pose many stringent engineering challenges.

In addition to geologic and engineering considerations, there is a long history of piecemeal construction and maintenance of the system. Construction of levees and floodwalls in the New Orleans area dates to early stages of urban development in the area. An important event in this history was Hurricane Betsy in 1965. Betsy was responsible for 75 deaths and billions of dollars of property damage, prompting efforts to create a regional program of hurricane protection. In the aftermath of Betsy, Congress authorized construction of a hurricane protection system to protect areas in the vicinity of Lake Pontchartrain and surrounding parishes from storm surges. The various projects that make up this system are paid for with a combination of federal state, and local funds. The decision-making and investment processes that have lead to the development of the system have involved numerous stakeholders for more than 50 years.

Primary responsibility for design and construction of hurricane protection projects has been assigned to the U.S. Army Corps of Engineers. Actual project construction has been contracted to numerous private sector firms. Once projects are constructed and fully completed, responsibility for their maintenance is often assigned to local authorities. Since 1965, approximately 125 miles of levees, concrete floodwalls, and other structures have been built in the New Orleans region. Not all projects authorized for construction by the U.S. Congress, however, had been completed as of August, 1005. The hurricane protection structures that existed in New Orleans and the surrounding area in August 2005 were not a single system constructed as part of a unified plan; rather, the system had been added to and repaired by different administrative units - federal, state, and local - operating with different mandates, levels of resources, and staff backgrounds and capacities. No single entity has been fully “in charge” of constructing and maintaining all hurricane protection structures, complicating efforts at systematic repair and construction and efforts to retrieve and assess data on historical decisions and pre-existing conditions.

F.4.6 U.S. Government Accountability Office, Army Corps of Engineers History of the Lake Pontchartrain and Vicinity Hurricane Protection Project, Statement of Anu Mittal, Director Natural Resources and Environment, Testimony Before the Committee on Environment and Public Works, U.S. Senate, November 9, 2005; also Testimony Before the Subcommittee on Energy and Water Development, Committee on Appropriations, House of Representatives, September 28, 2005.

What GAO Found

Congress first authorized the Lake Pontchartrain and Vicinity, Louisiana Hurricane Protection Project in the Flood Control Act of 1965. The project was to construct a series of control structures, concrete floodwalls, and levees to provide hurricane protection to areas around Lake Pontchartrain. the project, wen designed, was expected to take about 13 years to complete and cost about $85 million. Although federally authorized, it was a joint federal, state, and local effort.

The original project designs were developed based on the equivalent of what is now called a fast-moving Category 3 hurricane that might strike the coastal Louisiana region once in 200-300 years. As GAO reported in 1976 and 1982, since the beginning of the project the Corps has encountered project delays and cost increases due to design changes caused by technical issues, environmental concerns, legal challenges, and local opposition to portions of the project. As a result, in 1982, project costs had grown to $757 million and the expected completion date had slipped to 2008. None of the changes made to the project, however, are believed to have had any role in the levee breaches recently experienced as the alternative design selected was expected to provide the same level of protection. In fact, Corps officials believe that flooding would have been worse if the original proposed design had been built. When Hurricane Katrina struck, the project, including about 125 miles of levees, was estimated to be from 60-90 percent complete in different areas with an estimated completion date for the whole project of 2015. The floodwalls along the drainage canals that were breached were complete when the hurricane hit.

The current estimated cost of construction for the completed project is $738 million with the federal share being $528 million and the local share $210 million. Federal allocations for the project were $458 million as of the enactment of the fiscal year 2005 federal appropriation. This represents 87 percent of the federal government's responsibility of $528 million with about $70 million remaining to complete the project. Over the last 10 fiscal years (19965-2005), federal appropriations have totaled about $128.6 million and Corps reprogramming actions resulted in another $13 million being made available to the project. During that time, appropriations have generally declined from about $15 - 20 million annually in the earlier years to about $5-7 million in the last three fiscal years. while this may not be unusual given the state of completion of the project, the Corps' project fact sheet from May 2005 noted that the President's budget request for fiscal years 2005 and 2006, and the appropriated amount for fiscal year 2005 were insufficient to fund new construction contracts. The Corps had also stated that it could spend $20 million in fiscal year 2006 on the project if the funds were available. The Corps noted that several levees had settled and needed to be raised to provide the level of protection intended by the design.

During the first 17 years of construction on the barrier plan, the Corps continued to face project delays and cost increases due to design changes caused by technical issues, environmental concerns, legal challenges, and local opposition to various aspects of the project. For example, foundation problems were encountered during construction of levees and floodwalls which increased construction time; delays were also encountered in obtaining rights-of-ways from local interests who did not agree with all portions of the plan. By 1981, cost estimates had grown to $757 million for the barrier plan, not including the cost of any needed work along the drainage canals, and project completion had slipped to 2008. At that time, about $171 million had been made available to the project and the project was considered about 50 percent complete, mostly for the lakefront levees which were at least partially constructed in all areas and capable of providing some flood protection although from a smaller hurricane than that envisioned in the plan.

More importantly, during the 1970s, some features of the barrier plan were facing significant opposition from environmentalists and local groups who were concerned about environmental damages to the lake as well as inadequate protection from some aspects of the project. The threat of litigation by environmentalists delayed the project and local opposition to building the control complexes at Rigolets and Chef Menteur had the potential to seriously reduce the overall protection provided by the project. This opposition culminated in a December 1977 court decision that enjoined the Corps from constructing the barrier complexes, and certain other parts of the project until a revised environmental impact statement was prepared and accepted. After the court order, the Corps decided to change course and completed a project reevaluation report and prepared a draft revised Environmental Impact Statement in the mid-1980s that recommended abandoning the barrier plan and shifting to the high-level plan originally considered in the early 1960s.

In recent years, questions have been raised about the ability of the project to withstand larger hurricanes than it was designed for, such as a Category 4 or 5, or even a slow-moving Category 3 hurricane that lingered over the area and produced higher levels of rainfall. Along this line, the Corps completed in 2002 a reconnaissance or pre-feasibility study on whether to strengthen hurricane protection along the Louisiana coast. A full feasibility study was estimated to take at least five years to complete and cost about $8 million. In March 2005, the Corps reported that it was allocating $79,000 to complete a management plan for the feasibility study and a cost-share agreement with local sponsors. The President's fiscal year 2006 budget request did not include any funds for the feasibility project.

F.4.7 U.S. General Accounting Office, Improved Planning Needed by the Corps of Engineers to Resolve Environmental, Technical, and Financial Issues on the Lake Pontchartrain Hurricane Protection Project, Report to the Secretary of the Army, August 17, 1982.

Although the Corps' District Office in New Orleans considers this $924 million project a high priority, its completion date has slipped from 1978 to 2008. In the 17 years since congressional authorization in 1965, only about one-half of the project has been completed.

We believe that improved planning is needed by the Corps to resolve certain environmental, technical and financial issues. Environmental concerns have remained unresolved for almost 5 years after a court injunction prohibited the Corps from constructing certain parts of the project. The Corps is considering a change in its solution of providing protection from constructing barrier structures at the entrance to the lake and the raising of some levee heights (the barrier plan) to constructing much higher levees with no barriers (the high-level plan).

Various problems and conditions have caused delays in the project. Specifically: Engineering and environmental concerns have caused delays in project completion. Costly project work at the drainage canals has not been reported to the Congress, and technical and financial concerns which may impeded project completion remain unresolved. Current project financing by the local sponsors has not been assured because of limited resources. Project cost estimates are understated, and a project plan has not been formally adopted.

The local sponsors agreed with information in a draft of this report, but were concerned over their financial capability to meet their share of project costs. They believed the project construction could be pursued more expeditiously. One sponsor believed that Corps standards may be too high to obtain adequate, affordable, and speedy protection.

F.4.8 Houck, O. (2006). "Can We Save New Orleans?", Tulane Environmental Law Journal, Vol 19, Issue 1, 1-68, New Orleans, Louisiana.

On the other hand, for the City That Care Forgot to call anything 'fantasy' is a bit bold, and everything about the run-up to the Katrina disaster had fantasy written all of it: on slab development, on fill development, subdivisions in wetlands (protected by wooden fences), condos on beaches (protected by nothing), canals as senseless as the Mississippi River Gulf Outlet (MRGO), oil and gas channels by the thousands, coastal mitigation programs that failed to work (failed even to materialize), disappearing levee money, tinker-toy levee plans, what-the-hell levee construction, drive-by-and-when's-lunch levee inspections – and we haven't even gotten to FEMA yet. Detailed reporting in local papers, science colloquiums, National Geographic, NOVA and government planning sessions predicting this very storm in this very way with these very results were tossed away like so many Mardi Gras beads. So there is plenty of fantasy to go around.

We know a couple of things more, going in. For openers, we are short on land building materials. We live on a sinking delta, and the silts and plant mass that created it and offset its natural rate of subsidence are down to a fraction of their volumes a century ago. We have a lot less to work with than Mother Nature did. Even within the city, we are sinking. Post-Katrina surveys are finding many buildings about a half a foot lower than they were thought to be, and down by two feet in the East. Which is not good.

We also know that we are terribly late to the restoration game, about 1,900 square miles late, what is left is largely sick, and what we've managed to recoup over the past few years couldn't stand up to the latest storms. The newly restored marshes of the $80 million Canaervon diversion project ended on the rooftops in St. Bernard.

We know, worse, news, that hurricanes are coming more frequently now and with greater anger, that our levees are subpart, and – although it still seems to escape the grasp of the President and the Louisiana congressional delegation in Washington, D.C. – that the seas are rising and that global warming will raise them by more than a foot within the lifetimes of our children.

You would think that flood control and the protection of the City of New Orleans would be job one for the U.S. Army Corps of Engineers. And you would be wrong. It isn't, and it never was. ...The Army's field engineers were the only government entity around with the ability to blow things up and move dirt around, and so this became their job, to maintain navigation on the navigable waters of the United States. Navigation was interstate commerce, the means of interstate commerce, and it made money for people. Flood control, by contrast, was seen as a form of land use, a local affair, cemented in place when the federal government ceded lands to local levee boards in the 1850's, in part to persuade them to stay loyal to the Union. That part didn't work so well, but it set a mold for local levee boards that we have yet to change. It also further cemented the mindset that navigation comes first.

The Flood Control Act of 1936 opened a huge candy store, something like the discovery of gold at Sutters Mill, only this time the miners ere in Washington and wearing suits. Ostensibly authorizing the Corps of pursue projects for 'flood control and related purposes,' the other purposes quickly took over and by the 1960s the country was being dammed, drained, pumped, and leveed by hundreds of Corps projects feeding real estate development, energy production, soybean crops and right on down to reacreational lakes with wave machines and the McCurtin County Catfish Farm. The Act's one caveat, that the benefits of these projects 'to whomsoever they may accrue,' was turned into a weapon of destruction, with the Corps discovering benefits so chimeric that they became legend in the fields of government and political science, the object of ridicule in the press that the government should participate in thse projects 'if the benefits to whomever they may accrue are in excess of the estimated costs,' and recurrent calls for Corps Reform. Not to worry; the Corps had the ally that mattered, the Congress of the United States.

The rise of the water project bonanza has had several large consequences for flood control in south Louisiana. Basically, it eclipsed it. The first consequence is that flood control has no head. Unlike every other federal activity in the country, this one is overseen and directed by the Corps, members of Congress, local levee districts and lobbyists among which are found some of Louisiana's most illustrious power brokers: Bob Livingston, Bennet Johnston, John Breaux, Jimmy Hayes, just to start the list. Congress determines budgets, and promotion from Colonel to General. For Colonels heading the New Orleans District, it has been a trial by fire that has made and ended careers. It also produces conformity. When project funding for hurricane protection along Lake Pontchartrain dwindled in the early 1990s, nobody squawked out loud: a former director of the Corps Waterways Experiment Center in Vicksburg explained to the New York Times, 'I don't think it was culturally in the system for the corps to say this is crazy.' Whatever the merits of this diffusion of authority, it does not produce coherent flood control.

All of which works as long as there are no floods. Then, they become somebody else's fault. The didn't fund me. Well, you didn't ask. So it goes, and so it went after Katrina.

The second impact is that the program is not based on the completion of a few major projects but, rather, on spreading construction money and benefits around as many projects and about-to-be-made-happy constituencies as possible. This is true at the national level, where water resources bills are passed in omnibus fashion, meaning that they are approved in one big lump with something inside for everyone's district. Those brave or fiscally minded souls who object to a particularly sad entry end up ostracized or worse; one year the leadership announced the Pinocchio award for members who stuck their noses into other member's water resources projects.

So it is at the Louisiana level as well. Every cycle there is something in there for everyone, your new port, my new waterway, their pumps and drainage upstream. In this mix, New Orleans is just one more open beak among the chicks. It is not in the Corps' political interest and it is not in the Congress's political interest to satisfy one beak at the expense of others. The political objective is to spread the food around as widely as possible, and if that takes more time it also keeps more contractors working in more parts of the state. Inviolate Rule of Politics: More happy people is better than fewer happy people. Inevitable Effect of Rune: Short change for hurricane protection for the City of New Orleans.

Case in point: Louisiana has received nearly $2 billion for Corps water projects over the past 5 years. It has for time immemorial received the lion's share of water resources funding, with California, Texas, Illinois and Florida distant seconds (around $1.2 billion each over the last 5 years), and no one else even close. It's not a question of getting money down here. It's where it goes. In 2002, the Bush Administration rejected a Corps request for $27 million for additional hurricane protection along Lake Ponchartrain of which the Congress only restored $5.7 million in its appropriations. Meanwhile, Congress was boosting funding for the $780 million Industrial Canal Lock (the most expensive on record), a $194 million dredging project for the New Iberia, and tens of millions more on canals like the MRGO.

A third consequence of the game is that flood control for developed urban areas comes in last. The sad fact is, it doesn't make money for anyone. By leveeing off wetlands for new development makes lots of money in real estate (set aside the fact that the homes and streets will subside and begin to flood from spring rains). Floating boats also produces identifiable payouts (albeit they are calculated by asking shippers if they would like to use the canal once it is built, which is a little like using Monopoly money; very few Corps waterways live up to their traffic predictions, and some are ludicrously underused). Even converting cypress swamps to soybeans has a market price. By contrast, lives saved by levees don't receive economic benefits in the decisions that justify Corps projects and determine their funding priorities. Nor do they attract powerful lobbyists. The Industrial Canal lobby can afford to put ex-senators, congressmen and entire law firms on its payroll. The City of New Orleans, on the other hand is broke, and one doubts that St. Bernard and Plaquemine even field full-time representatives in Washington. Money talks.

A final most perverse effect of the water resources game is that it produces projects that not only conflict with flood control for money and fame, but cause floods as well. Big ones. The role of the MRGO in the Katrina and Rita flooding is by now undeniable. What remains impressive, however, is the tenacity with which the Corps and the Louisiana congressional delegation hung on to this project – indeed, continue to hang onto it – against the pleas of the St. Bernard Police Jury, the Lake Pontchartrain Basin Foundation, and coastal scientists who have been complaining that it had destroyed 20,000 acres of the Parish, was killing much of the lakeshore, and was going to bring major hurricanes right into the city. These claims were never rebutted. They were simply ignored.

What we have here, then, is a game that is not focused on flood control, and never has been. It has been focused on making money first for people with boats and then for as many people as possible, even when that has meant increasing hurricane risks and putting other people right into harm/s way. It has been denial about its impacts, and remains largely in denial. And it as been accompanied by a similar series of body blows to the coastal zone from another sources which is even more powerful and difficult to turn around: the oil and gas industry.

The impact of oil and gas extraction on the natural systems of the Louisiana coast is hard to exaggerate. The initial space of the access canals is relatively minor. It's what happens next that matters. The canals erode, exacerbated by wave wash from passing boats. In 10 years the widths have doubled; then they double again. While intact, the spoil banks cut off the natural drainage for hundreds of yards around, impounding half of the marsh and drowning the other half. Up the canal comes saltwater from the gulf. The grasses go belly up, the root masses die, the soils are released, the whole thing falls apart. Recent studies by the United States Geological survey discover a related phenomenon. The industry has excavated billions of gallons of brines, salts, and minerals from under the wetlands, much of it close to the surface, following which - surprise! - they caved in. Marsh erosion or subsurface extraction: pick your weapon, they both kill.

About 70 years ago, Louisiana made a deal with the oil and gas industry. the industry would get what it wanted; the state would get a piece of the take. In Plaquemines Parish the industry took nearly everything, save what it paid back to Leander Perez. The state's near slavish defense of the industry since that time is a matter of legend; Bennett Johnston was commonly referred to as the Senator from Oil, and his successor was one of the three Democratic votes to open the arctic wildlife refuge to oil and gas and to remove the rights of states to decide on drilling off their coasts. It's in the genes. As Louisiana moved forward on its coastal restoration plan, it would ask the federal government for massive amounts of money. Part of the rationale, no small part, was to protect the oil and gas industry's pipelines and infrastructure through the coastal zone. Nowhere, however, did the state ask the industry to pay a penny for the restoration that would save its base. Over 10,000 miles of canals are now eroding and the marshes are caving in and somebody big is walking away from the table.

There is something special about Louisianans when it comes to flood control. We could call it courage. We could call it denial. Or we could call it anything in between and probably all of them and not be wrong. but Louisianans settled a state that flooded regularly from the north and from the south, from rivers and the Gulf, and some of its most gripping stories - Lanterns on the Levee, Last Island - are scenes of tragedy from high winds and waters that no book or film could fully capture. and yet we built, and built again. For a long while, we tended to build elevated homes, on ridges, and kept the boats handy for what we knew would come. Then we raised levees. when they didn't work we got the federal government to raise levees and built out back into the swamps and put in pumps. Before long we were building on slab. and still we flooded. We lead the nation in flood losses. No reason not to. The federal government pays us for it.

And so we had a cozy game of build-flood-and-get-paid going until coastal erosion weighed in, and the onset of an awesome and unanticipated season of hurricanes that, apparently, has only just begun. Louisiana towns that used to sit well inland were finding themselves on the front line with the Gulf of Mexico, which has been coming north at about 10 to 30 meters a year. A 1990 report by the National Academy of Sciences recommended mapping the erosion zones and moving new construction away from them through the flood insurance program. there were no takers. Five years later, FEMA recommended that the government at least chart the zones. No takers either. Nor on its almost annual pleas to raise the flood insurance rates to something close to real life. Louisiana knows a good thing when it sees it.

The northeast gets its railroad subsidies, the far west gets grazing and timber subsidies; this one is ours." "The hurricanes came. They have, of course, always come, and when Betsy and Camille came ashore in the late 1960s the nation gasped. There were record storms, record damages, record loss of life, we must do something. What we did was go back on the same beaches and vulnerable strips of coastal wetlands and build the same stuff, only more expensive. there was a lull while it all came together - the casinos, the high rises, a building boom on Grand Isle, ditto Holly Beach, ditto a boomlette that was just starting down in the marshes of St Bernard, ditto all around Lake Pontchartrain - all subsidized by people who don't enjoy houses on the shore. No longer quaint low-end bungalows. Some very expensive housing for our wealthiest fellow citizens who get below cost flood insurance and income tax deductions for their second home mortgages. Another hayride.

Global temperatures rise and fall over geologic time. As they rise and fall, they produce sea changes in life history, species go extinct, civilizations advance and disappear. There is a normal range of variation. but the current climate is warming at a rate without precedent for the last several hundred thousand years.

So what? Here in Louisiana we will be warmer in summer (think, maybe, 103 degrees at Jazz fest), warmer in winter, and considerably drier (think about sugar, soybeans, rice and other wet-soil crops). Without winter freezes we'll have a lot more insects - mosquitoes, termite and cockroach numbers soared between 1990 and 1995 when there were no killing frosts - and the bayous will be blanketed with alge blooms. We're tough. We can handle that. Pass the pesticides.

What will be a little harder to handle is sea level rise. A heated ocean expands, and - according to the most definitive international panel on climate change yet assembled - the oceans will rise from a half a foot to three feet, absolute. that's before we get to subsidence in places like Louisiana, where the relative rise could go to four feet. And that's before adding increasing snowmelt and the run from polar glaciers. For which we add another half a foot. It's already happening. Rocky Mountain peaks are going dry. The famed snows of Kilimanjaro have about disappeared. Temperatures around the North Pole are rising so rapidly that a new sea route is opening between the oceans, expected to be clear even for unarmored ships within the next 30 years. Native Inuit report seeing warm weather birds, beyond anything in the legends of their people.

Four feet is a killer for South Louisiana. On a landscape as flat as the coastal zone, and where building elevations are in the single digits, relative sea rise of only a few inches covers an enormous amount of ground. Worse for New Orleans, which is buffered by coastal systems, for coastal towns that fish, trap and work their natural resources, and even for the oil and gas industry whose wells and pipelines lie increasingly exposed in open water above sinking bottoms, a few inches of relative sea rise will be enormously hard to match with coastal restoration programs. The game is not static. It's like trying to score touchdowns but they keep moving the goalposts back. Way back. Think about trying to devise a way to rebuild 1,000 square miles of Louisiana wetlands already lost and another 20 to 30 each year, against the relentless pressure of the Gulf of Mexico. Now add this: you will have to build and maintain the whole thing several more feet into the air.

And now we add this. an increasing body of data shows a strong correlation between warmer seas and violet hurricanes. And more frequent ones. It makes sense: warm waters are hurricane food, which is why the season comes at the end of the summer. The doubters have since weighed in with their list of unprovens - which is the way science works, healthy science anyway - and the case is not ironclad. But there seems to be good evidence that global warming is not only destroying Louisiana's defenses, it is also fueling what could be, any year, its ultimate storms.

Are We Serious Yet? Because we certainly haven't been serious up to this point at all. Katrina and Rita have to be the most well predicted and publicized disasters in history, and we did next to nothing to stave them off or to prepare for the hits. In August 2005, a couple of weeks before the storms, a Homeland Security brochure came in the mail on hurricane preparedness. It consisted of a map marking evacuation routes out of town, with major revelations like the existence of I-10 and I-59.

Meanwhile, we continued to treat flood control as the stepchild of navigation projects that were in large part boondoggles, and in full measure drained monies and attention away from the hurricane protection needs of the Crescent City. We treated the whole water resources effort more like a re-election machine than a serious program, run by local interests, lobbyists, congressmen and ex-congressmen who are glued to the status quo. We let the largest party in coastal destruction walk away from the table without paying, while we in turn pay no end of public subsidies for people to build and live in the hurricane hit zone. We turn our back on the pall of jeopardy that global warming and rising seas throw over the future of the region; worse, we advocate against doing anything about it. And that's just in Washington.

Back home, the scene is little more encouraging. We have a dysfunctional system for building levees, and even more dysfunctional one for maintaining them, aggravated by a Byzantine arrangement of levee boards, port authorities, and other bodies that so fragment the process that it seems primarily directed towards maintaining political alliances and local perks. Post-Katrina down here has been like the Wizard of Oz. When the curtain is finally pulled back, there are a couple of flood control guys in suits and uniforms and they haven't a clue. If they are not protected by sovereign immunity, they are facing the largest negligence verdict in history.

Hurricane Betsy brought a rude awakening to New Orleans and the Army Corps of Engineers. for more than a century they had been putting bigger and better locks on the front door, against the high spring floods of the Mississippi River. Now it was plain that the big one would come in the back door, with the capricious, violet, and increasingly frequent hurricanes of late summer and fall. And so, in 1965, Congress authorized the Corps to proceed with a plan to protect the city and the region from the east and south: the Lake Pontchartrain and Vicinity Hurricane Protection Project. It would defend against a Betsy-type storm, winds up to 100 mph, waves at maybe ten feet. It would take about 13 years to complete, with an estimated price tag of $85 million.

The Corps had two basic options, a high-level plan relying on levees fronting Pontchartrain along New Orleans and Jefferson Parish, or a lower set of levees, fronted by barriers 40 miles out at the inlets to Lake Pontchartrain across the Rigolets and the Chef Menteur pass. Initially, the barriers prevailed. They were seen as less costly, quicker to build (higher levees would require more time for the fill to settle), and - what many considered to be the driving factor at the time - they would allow for the drainage and development of wetlands in St. Charles Parish and New Orleans East where in the Corp's words 'protection would not be incrementally justified.' Indeed, some 79% of benefits came from protecting new wetland development; protection New Orleans came in a distant second.

Developing the wetlands was in high swing at the time. New Orleans itself had just finished expanding over marshes and swamps to the edge of the lake. (The streets and houses hadn't started to crack open yet.) President Lyndon Johnson was partner (with his wife and Dallas Cowboys owner Clint Murchison) in a project to develop new Orleans East (a Lenin's tomb-like monument along I-10 still bears the name), and had managed to finesse federal highway regulations to build three interchanges for the venture. A similar venture along the St Charles lakefront advertised scenes of upland development complete with contented dairy cows so obviously deceptive that it was shut down after protest by the Louisiana Attorney General. What these developers wanted, of course, was exactly what environmentalists feared. The barrier plan looked like a stalking horse for wetland development, New Orleans piggybacking the scheme.

The plan had another problem. It would block off most of the Rigolets and Chef passes, which were the migration corridors for the aquatic life of the interior lakes. Lake Pontchartrain had been the seafood market for the city, and crabbing along its banks was in the family memory of thousands of local families. Commercial fishers were worried as well and, despite Corps statements that gates in the barriers would maintain necessary flows, a groundswell of opposition grew on both sides of the lake. A poll by Congressman Bob Livingston showed his constituents doubting the barriers, causing him to express reservations as well. an Environmental lawsuit challenged the impact statement on the plan, which the Corps later admitted was a cursory job. Like so many such lawsuits at the time, the court found the statement inadequate and required the Corps to write a new one. Most of the time the Corps did just that, and then proceed with its original plan. In this case, though, the Corps changed its mind.

In 1982, its review completed, the Corps announced for the high levee option. It would turn out to be less expensive after all, they found, less harmful to the environment and more 0protecteditve as well. (Among other things it would guard against waves kicked up by hurricane-force winds across the lake itself). And so the project marched forward, its costs ballooning to an estimated $757 million, towards a pre-Katrina estimated completion date of 2015. At that point the Corps had thrown up 125 miles of levees around the city, in various stages of readiness. The all-important interior canal walls - the ones that failed - were parts of the project declared to be complete. Appropriations for the project were declining, however, from some $15-20 million annually in the early years to about $5-7 million in recent years. The monies were going elsewhere.

So when Katrina and Rita hit the fan, it was little surprising that two former Corps employees, high level ones at that, told the *L.A. Times* that environmentalists had drowned the city with their lawsuit. The Wall Street Journal, ever eager for news like that, and a pack of right wing blogs picked up the cry, which carried to Washington DC and the House Resources Committee. The Committee, in turn, ever eager for news like that, held hearings on it, absent the benefit of witnesses who had participated either in the project or the case. The United States Justice Department, ever eager for news like that, even asked its field offices to report any and all environmental cases that had obstructed Corps flood projects. None were ever disclosed.

In the end, the story flopped. The Chief of Engineers and the Government Accounting Office, which had been bird-dogging the project for years, both testified before other committees that the barrier plan would not have protected New Orleans any better than functioning levees, and in fact could have worsened the flooding by trapping the storm surge against the city. As serious investigations proceeded, it became clear that the problem was not the high levee plan. Category 3 levees would have kept the city dry. Instead, the city got tinker toys and they fell apart.

F.4.9 Member Scholars of the Center for Progressive Reform (2005). *An Unnatural Disaster: The Aftermath of Hurricane Katrina*, Center for Progressive Reform Publication, CPR Publication #512, September.

Hurricane Katrina tragedy is not a ‘wake-up call,’ as some have described it; rather, it is a consequence of past wake-up calls unheeded. By any reasonable measure, government failed the people of New Orleans. Hurricane Katrina was a natural disaster of enormous proportion, but its tragic consequences have been made even worse by an unnatural disaster - the failure of our government adequately to anticipate, prepare for, and respond to the devastation that the hurricane brought. One very powerful message of the ideology that now dominates both the executive and legislative branches of the federal government is that actions have consequences. The Katrina tragedy has demonstrated that inaction also has serious consequences.

New Orleans sat in the path of Katrina like a stretch of road with too little banking and with no one having taken responsibility for its repair. In this case, the government failures that preceded Katrina and made it worse seem to span a wide range of environmental, natural resource, disaster-planning, and emergency-response functions for which we rely upon government. Identifying those systematic and programmatic contributors to the Katrina disaster will give us the information we need to demand that government do better.

The proper response to Hurricane Katrina is action at every level of public life to restore the critical protections and safety nets that only government can provide for the people.

Today, government must again play an active role in protecting its citizens from the visibly power forces of nature and from the less visible, but equally powerful forces of policy-making that is sometimes slanted away from protecting and serving the public and toward protecting profit margins.

In addition, we strongly recommend that Congress create an independent commission to pursue these questions, in an atmosphere free of the bitter partisan strife that seems to swamp both houses in anticipation of the 2006 mid-term elections. The notion of a bipartisan, objective congressional investigation, promoted by the President, does not seem possible or desirable given the rancor of recent days.

The failure of New Orleans' levees was preceded by a failure of environmental protection and planning. Louisiana's coastal plain contains one of the largest expanses of coastal wetlands in the contiguous United States, but it is being lost at a rate of 6,600 acres per year. the main culprit in wetlands loss in the area is the vast network of levees, navigational channels, and oil-and-gas infrastructure. Important though the network is to safety and commerce, it accelerates coastal land loss by reducing the natural flow of a river's freshwater and sediment to wetland areas where lost land would then naturally be replenished. In addition, the area's major navigational channels pose their own special threat to flood control by sometimes acting as 'hurricane highways,' allowing storms to sweep inland, past marshland, like liquid bulldozers.

Broken Levees: Predictions that Came True. Over a period of many years, scientists had predicted that a strong storm could breach the levees, and some had predicted what appears to be the precise sequence of breaches that flooded the city. The failure to protect New Orleans resulted from inadequate planning by the Army Corps of Engineers (Corps), and from the failure of the federal government to fund badly needed improvements once those limitations were recognized. Neither the Corps nor Congress adequately accounted for the loss of life and property that would occur if a catastrophic hurricane hit New Orleans.

"Moreover, although the Mississippi River-Gulf Outlet (MRGO) canal was a primary cause of the flooding, it is seldom used and heavily subsidized by taxpayers. Less than three percent of the New Orleans port's cargo traffic uses the MRGO, less than a ship a day. Although New Orleans' vulnerability was widely predicted, the Corps declined to move forward with enhancements to the levee and flood wall system because 'no clear bureaucratic mandate exists for reassessing the blueprints once levees are built.' Moreover, when Congress has appropriated money to protect New Orleans better, the Corps has not been in a hurry to get the job done. Finally, the Bush Administration and its predecessors have failed to fund Corps requests.

Why the City Flooded. The water that flooded New Orleans did not flow over the levees situated between the lake and the city. Instead, it appears that the surge flowed up the 17th Street and London Avenue canals and caused one breach of the floodwall along the 17th Street canal and two breaches of the floodwall along the London Avenue canal. In other words, the water moved to the path of least resistance - the floodwalls along the canals.

The city also flooded because the levee system did not protect it from the 'end around' exposure that occurred during Hurricane Katrina. The hurricane surge entered Lake Borgne from the Gulf of Mexico and proceeded up the MRGO canal to the Industrial canal in the heart of New Orleans. Hurricane Katrina appears to have destroyed as much as 90 percent of the levees and flood walls along the MRGO canal in St. Bernard Parish as it pushed up the narrowing canal from Lake Borgne to the conjunction of the MRGO canal with the Industrial canal. Colonel Richard Wagenaar, the Corps head engineer for the New Orleans district, reported that the eastern levees were 'literally leveled in places'. That same surge probably caused the breaches in the floodwalls along the Industrial canal.

We Knew This Would Happen. Not long after the levees broke and water from Lake Pontchartrain on the north and Lake Borgne on the east began to fill New Orleans, President Bush told television correspondent Diane Sawyer that no one could have foreseen the breach of those levees. In fact, over a period of many years, scientists had predicted that a strong storm could also breach the levees. Scientists especially feared that even a relatively weak storm coming from the right direction would push a wall of water into the heart of New Orleans from Lake Borgne through the funnel-shaped MRGO canal and into the Industrial canal, destroying the levees along the canal and flooding much of St. Bernard Parish and the Lower Ninth Ward. It now appears that this is exactly what happened.

Moreover, the risks posed by the MRGO canal were evident. In 2002, the Corps of Engineers acknowledged that 'the MRGO levee is more likely to be affected than the area on the lake itself.' Proponents of closing the canal pointed out that, with the erosion of the wetlands in the unleveed stretches south and east of the city, it had 'evolved into a shotgun pointed straight at New Orleans'.

The Failure to Protect: Bad Planning, Skewed Priorities. The failure to protect New Orleans resulted from inadequate planning by the Corps to save the city, and from the failure of federal government to fund badly needed improvements once those limitations were recognized. Neither the Corps nor Congress adequately accounted for the loss of life and property that would occur if a catastrophic hurricane hit New Orleans.

The hurricane protection plan that was implemented after 1985 by the Corps was designed to protect the city against the 'standard project' hurricane that roughly corresponds to a fast-moving Category 3 storm. Scientists had for years prior to the storm predicted that the levee system woulc not withstand a Category 4 or Category 5 storm. Hurricane Katrina struck the Louisiana / Mississippi coast as a Category 4 storm.

Moreover, although the MRGO canal was a primary cause of the flooding, it is seldom used and heavily subsidized by taxpayers. The canal, which was completed in 1968, is a deep draft seaway channel that extends for approximately 76 miles east and southeast of New Orleans into Brenton Sound and the Gulf of Mexico. It was designed to shorten the distance for ships from the eastern shipping lanes of the gulf to New Orleans, but it has never lived up to its predicted economic expectations. Less than three percent of the New Orleans port's cargo traffic uses the MRGO; this amounts to less than one ship per day. According to one estimate, the government spends $7 to 8 million dollars per year (about $10,000 for every large vessel that uses the canal) just to maintain the canal.

Although the vulnerability of New Orleans to a catastrophe was well known and widely predicted, the Corps has floundered in its efforts enhance the protection of New Orleans from Lake Pontchartrain. In an award winning series of articles on the levee system, The Times-Picayune concluded that the Corps of Engineers has declined to move forward with enhancements to the levee and floodwall system because 'no clear bureaucratic mandate exists for reassessing the blueprints once levees are bu9ilt.' For example, an attempt in 1996 to reevaluate the Lake Pontchartrain levees broke down in disputes over modeling and other bureaucratic disagreements. When Congress has appropriated money to protect New Orleans better, the Corps has not been in a hurry to get the job done. For example, the Congress in 1999 appropriated money for a $12 million study to determine how much it would cost to protect new Orleans from a Category 5 hurricane, but the study had not even been launched as of September 2005.

In addition, the Bush Administration has failed to fund Corps requests. Mike Parker, a former Republican Congressman from Mississippi who was until 2002 the chief of the Corps, was forced to resign when he publicly sated to the Senate Budget Committee that the national interest was being harmed by President Bush's proposal to cut over $2 billion from the Corps' $6 billion budget. The Bush Administration rejected an Corps request for $27 million to pay for hurricane protection projects along Lake Pontchartrain and proposed a budget of only $3.7 million for the projects, but the Corps still had to delay seven levee improvement contracts. After Hurricane Katrina struck, Mr. Parker stated that President Bush had not adequately funded improvements to the very levees in New Orleans that had been breached; indeed, Mr. Parker stated that had full funding been authorized 'there would be less flooding than you have.' an official Corps memo dated May 2005, long after Parker left the agency, seemed to corroborate this possibility. It stated that the bush Administration funding levels for fiscal years 2005 and 2006 were not enough to pay for new construction on the New Orleans levees.

There are now strong indications that the critical floodwalls along the outlet canals did not breach because the water surged over them and eroded their support but because they were not capable of withstanding even the surge of a Category 3 hurricane. Whether this failure of the floodwalls was attributable to poor design or poor construction and maintenance remains to be seen, but in either case the Corps and the local levee authorities bore the responsibility for ensuring that the floodwalls were adequately designed, built, and maintained.

Although it is tempting to blame the current administration for the failure to fund critical levee improvement projects, the truth is that improving the Lake Pontchartrain levees has been a low priority for many administrations, Democratic and Republican, and for Congress. The Bush Administration and Congress have had other priorities over a longer period of time than the last four years. In fact, it seems clear that even the Louisiana congressional delegation has on occasion insisted that the Corps direct its resources to projects like a $194 million project for deepening the Port of Iberia and replacing the lock on the Industrial canal.

The Bush Administration and Congress are influential in setting budget priorities because the Corps is very reluctant to participate in the process of setting priorities for its projects. Moreover, once the Corps has determined that the benefits of a proposed project exceed its costs, the Corps leaves it to Congress to decide through the appropriations process which projects receive funding and which do not. Congress is ordinarily willing to consider passing appropriations for large public works projects, however, only in the wake of major disasters or after years and years of study.

The reasons why New Orleans and its vulnerable citizens were not better protected are clear. The levee system was not designed to protect the city from more than a Category 3 hurricane system and there was little administration or congressional support for making improvements in the levee system despite the fact that its limitations were widely recognized.

According to the Government Accountability Office (GAO), the Corps' guidance (Engineer Regulation 1105-2-100) directs analysts to address the issue of prevention of loss of life when evaluating alternative plans, but they are not required to formally estimate the number of lives saved or lost as a potential effect of a project.

F.4.10 Braun, S. and Vartabedian, R. (2005). "The Politics of Flood Control," Los Angeles Times, December 25.

NEW ORLEANS -- When the U.S. Army Corps of Engineers and New Orleans levee officials joined forces in July 1985 to protect the city from a long-feared hurricane, the two agencies could not agree on how to proceed. It was the beginning of a dysfunctional partnership that ushered in two decades of chronic government mismanagement.

Corps engineers wanted to install gates in front of the city's three main internal canals to protect against violent storm surges from Lake Pontchartrain. The Orleans Levee District, the city's flood protection agency, preferred to build higher flood walls for miles along the canals. For five years, neither side yielded.

But in October 1990, a deft behind-the-scenes maneuver by the levee board forced the corps to accept higher flood walls. As Senate and House negotiators gathered to craft the Water Resources Development Act of 1990, Louisiana's congressional delegation quietly inserted a lobbyist's phrasing ordering the corps to raise the levee walls. It was stealth; legislative trickery," recalled New Orleans lawyer Bruce Feingerts, who lobbied for the levee board. "We had to push every button at our disposal.

The gambit was a crucial victory over the corps by the Orleans district, the most powerful and well-financed among 18 Louisiana boards that supervise more than 340 miles of storm levees across the hurricane-prone southern half of the state. The corps had to abandon its floodgate plan and shoulder 70% of the project's costs while allowing the Orleans board to hire its own consultants to design the strengthened levees.

But their fractious partnership proved disastrous. While the corps and the Orleans board settled into an acrimonious 15-year relationship, spending $95 million to buttress the city's canal levees, their shared supervision failed to detect crucial weaknesses inside the flood walls before Hurricane Katrina struck. No one felt the urgency, none of us," said Lambert C. Boissiere Jr., a former Orleans levee commissioner. "The corps and our own engineers told us the levees were strong enough. They were all dead wrong.

Structural inspections were cursory. Maintenance was minimal. A confusing regulatory patchwork of ownership over the levees and canals blurred the lines of authority -- all shortcomings cited by independent engineering teams analyzing the levees' collapse.

Although the corps and federal officials kept a tight leash on funding, the Orleans board spent money lavishly, diverting resources to high-stakes investments such as casinos and marinas. The levee board's unusual authority to hire its own consultants allowed its officials to select firms that regularly gave campaign contributions to politicians with influence over levee board business.

Left unchecked because of repeated failures by the Louisiana Legislature to reform the levee board system, critics say, the Orleans district operated its own patronage system. The New Orleans board had the reputation of being one of the worst -- by worst, I mean more political than professional," said former Louisiana Gov. Charles E. "Buddy" Roemer III, a Republican whose Orleans board appointees launched the 1990 power play in Congress.

When Katrina hit in late August, floodwater from Lake Pontchartrain burst through the walls of the 17th Street and London Avenue levees, where steel foundations gave way in porous soil. Storm water also flowed through a 200-foot gap in the Orleans Avenue levee, a section left unfinished due to Bush administration funding cuts.

Last week, the corps announced plans to seal off the three broken canals with permanent barriers and relocate New Orleans' pump houses from inside the city to the lakeshore -- at a cost of $3.1 billion. The corps' move to abandon the old flood-control system it built with the Orleans board came as a bitter coda to a 20-year relationship.

Least Cost' Project. Money was the most pressing concern in July 1985, when Orleans levee officials signed "assurances" -- an official commitment -- to join the corps in buttressing New Orleans' hurricane protection system. The corps' traditional preference for a "least cost" project made floodgates a far more attractive option -- at $20 million -- than the $60-million estimate for raising the levees. We were caught between the [Reagan] administration saying keep the cost down, and Congress and New Orleans officials saying spend more," said Fred H. Bayley III, then the corps' director of engineering for the Lower Mississippi Valley Division.

But the Corps' proposed "butterfly-valve gate" -- a concrete-and-steel barrier that would open to let out water and close to seal off storm surges -- was untested in high storm conditions. The corps' plan also clashed with the city's practice of using its system of antiquated pump stations -- two miles inside the city -- to force floodwater out into the lake through the canals. Officials with the New Orleans Sewerage and Water Board who supervised the canals feared that in a major hurricane, the gates would jam with debris and canals would back up, submerging the city.

Corps engineers had been fixated on floodgates since the 1970s, when the agency proposed using towering gates to block off surges at the far eastern end of the lake. That plan was the corps' response to Hurricane Betsy, a storm that hit New Orleans in 1965, swamping the city's Lower 9th Ward, killing at least 75 people and causing more than $1 billion in property damage.

Louisiana's congressional delegation, led by Democratic Sens. Russell Long and J. Bennett Johnston, won legislative approval for the barrier plan. But by the early 1980s, the project was shelved, scuttled by a judge's order, opposition by environmental and business groups, and bickering levee boards.

The corps, convinced that raising levees was risky, shifted its plans, proposing to build gates at the lakeshore. Higher flood walls required deep sheet piles -- heavy-gauge steel foundations -- sunk into the soft coastal soil to brace against water pressure. To raise the levees properly, corps engineers warned that houses along the 17th Street and London Avenue levees might have to be razed. But the corps refused to absorb the costs, and the levee board shied from taking on neighborhood groups -- a pivotal early error.

Eager to show off their prototype, corps engineers herded city officials into the Army's cavernous Hydraulics Lab in Vicksburg, Miss. The hinged doors opened and closed easily. But city sewerage officials peppered the engineers with doubting questions. Indeed, according to a November 1987 corps report, the "original design did not perform as intended." Only when corps engineers altered the model, "the gate design performed satisfactorily."

Despite the skepticism, corps officials moved firmly to clear a path for the floodgate plan. The corps ruled that it would not pay for raising the levees because the city's canals were used for local drainage, not navigation -- beyond the scope of the corps' authority over river and waterway projects.

The decision forced Orleans levee officials to gamble. Although the corps refused to pay for raising the levees, the Lake Pontchartrain, La., and Vicinity High-Level Plan was still in its planning stages. Under the drawn-out design process, levee officials still had the ability to research their own alternative -- at the board's cost. They aimed to keep the levee-raising option alive by hiring their own design consultants, then using political leverage to win their levee-raising plan later.

Involving Politics. From the Orleans levee office on Stars and Stripes Boulevard to the governor's mansion in Baton Rouge, Louisiana's political veterans knew the unstated rules of the levee-building game. There were scores of qualified civil engineers in New Orleans, all angling to score lucrative public contracts. Many firms boasted former corps engineers who knew how the corps worked and had friends still in the service.

The corps had these relationships with the levee boards," Roemer recalled acidly. "In their conversations, the levee board would ask the corps: 'What do we need to do to have safety and economic development?' And the corps would give unofficial answers. Then the levee board would hire a consulting engineer and go to the window the corps had opened. It was sweet.

Normally, the corps used its own contractors to design and build flood-control projects. But with the corps' approval, levee boards could hire consultants as a way to pay their 30% local share of a project's cost. In hindsight, said the corps' commander, Lt. Gen. Carl A. Strock, the decision to let the Orleans board hire its own contractors was "an unusual practice for us." Some corps veterans worried about the intrusion of local politics and budget complications. "Generally, when there were more layers involved, it got more difficult," Bayley said.

The political lines stretched to Louisiana's governors, who chose the majority of commissioners on local levee boards. In 1985, the power in Baton Rouge was Roemer's predecessor, Democratic Gov. Edwin Edwards, who had installed New Orleans lawyer Emile Schneider as levee board president. Schneider moved quickly. The board issued $50 million in bonds, then began hiring private engineers. The consultants were chosen on their qualifications. But politics and hiring sometimes mixed, said former commissioners.

All three engineering consultants who were selected by the Orleans board to design the levees contributed to the political campaigns of officials with sway over the board. Burk-Kleinpeter Inc., the engineering firm that designed the raised London Avenue flood wall, gave $5,000 to Edwards in 1991 before he won the 1992 governor's race. Walter Baudier also donated during the period that his firm, Design Engineering Inc., planned the Orleans Avenue levee. Baudier gave $2,200 to Roemer in 1987 and $3,000 to Edwards in 1991. "Everybody gave to everybody," Baudier said. "That neutralized any advantage.

Baudier's firm was also awarded a separate contract with the Orleans district, coordinating other levee board projects. Louisiana's legislative analyst criticized the arrangement in 1992, warning of potential conflicts between the firm's dual roles. Baudier insists his firm dealt only with financing and did not "review other people's designs. Levee board contractors also frequently gave campaign money to Francis C. Heitmeier, a powerful state legislator from New Orleans who has long wielded influence over Orleans levee district affairs. Among Heitmeier's donors from 1996 through 2002 were Baudier ($5,000), Burk-Kleinpeter ($10,000), and Modjeski and Masters Inc., an engineering firm that designed the 17th Street levee ($750). Officials with Burk-Kleinpeter and Modjeski and Masters did not return calls seeking comment.

For years, former Orleans levee officials say, Heitmeier, who headed the state Senate's public works committee and now its Finance Committee, was influential in levee board decisions on hiring, policy and contracts. Roemer was stymied by Heitmeier when he tried to reform the levee board system and wrest contracts away from local authorities. His "biggest battles," Roemer said, were with Heitmeier. Just last month, Heitmeier again played obstructionist, helping to snuff out a post-Katrina attempt by reformers to create a unified state levee board. Critics howled. Heitmeier shrugged. They can say what they want," he said.

Questions About Depth. By 1990, faced with spiraling costs for its gates at the 17th Street canal, the corps agreed to pay for raised levees there. But the corps still insisted on gates at Orleans and London avenues. Even before the corps made its concession, the board had acted on its own, hiring a construction firm to drive sheet piles at 17th Street.

The Orleans board's impatience with the corps was shared by neighboring levee agencies. In recent years, Plaquemines Levee District President Benny Rousselle twice ordered crews to raise levees along a local highway despite formal corps orders to desist. And earlier this year, the East Jefferson Levee District bolstered its side of the 17th Street levee by a foot and a half without the corps' approval. "When you deal with the corps, it takes years of studies," Rousselle said.

Corps engineers were openly peeved in 1990 when they learned about the Orleans board's decision. The move posed "an undesirable situation for this office and the corps," Bayley wrote to the corps' district commander. Bayley also warned that work crews were not driving the steel foundations deep enough. It was the first alarm about shallow sheet piles under the levee.

Despite the corps' recent insistence that 17th Street's foundations were properly designed at 17 feet below sea level, a National Science Foundation team of engineering experts has described the pile depths as inadequate.

By autumn of 1990, the Orleans board had also quietly hired Bruce Feingerts, a former aide to Russell Long, to lobby in Washington for levee expansion. Feingerts had discovered that the levees of Orleans and London avenues might win federal funding if he could persuade Congress to expand the coverage of the post-Betsy hurricane plan passed in 1965. Sens. Johnston and John B. Breaux agreed to help, Feingerts said, as did most of the state delegation. When Senate and House versions of the 1990 Water Resources bill neared passage in October, Feingerts went into action. Johnston recalled that former Louisiana Rep. Jimmy Hayes was the "point man" as a House manager for conference negotiations.

Now a Washington lobbyist, Hayes did not respond to interview requests. But a former aide, Rhod Shaw, said he often aided New Orleans projects and "would have been carrying whatever the delegation wanted. The military engineers were "asleep at the wheel," Feingerts said. "If they had seen it coming, they would have blown a gasket." The final bill passed with his language intact: "The conferees direct the corps to treat the outfall canals as part of the overall hurricane project.

As new levee construction projects geared up at Orleans and London avenues, work crews at the 17th Street canal were struggling with construction obstacles. Unable to operate from the land side of the canal because property lines backed tightly up against the levee, construction crews had to maneuver by barge up the canal with a 300-foot crane to drive steel piles and raise the concrete wall.

Lakeview resident Bud Thaller stormed outside one day when his house began to shake violently. A levee crew driving foundations at 17th Street with a vibrating hammer had just struck a sandbar. The foreman shrugged when Thaller approached. He told me they were having a hard time getting the piles in, Thaller recalled.

Boh Brothers, a Louisiana construction firm, was the first of three companies to drive sheet piles under the levee walls. They were joined by concrete specialists, some working for the Orleans board, others hired by the corps and the sewerage board. A parade of inspectors and engineers also crowded over the site, so many that "it could get confusing," recalled Boh Vice President Dale Biggers, then a crew foreman.

The Corps was always the final authority -- even overseeing the number of hammer blows used to drive in the sheet piles. But on any given day, crews also had to coordinate with state and city officials and inspectors for Modjeski and Masters, the levee board's design consultant. The question of who performed the inspections is crucial because engineering experts have had difficulty learning how on-site decisions were made.

No one was in charge," said Raymond Seed, a UC Berkeley engineering professor leading a National Science Foundation inquiry. Seed's team has heard allegations that piles were deliberately shortchanged. The Justice Department is investigating.

Structural engineer Herbert J. Roussel Jr., who testified for a construction firm that sued the corps during one dispute, recalled Army engineers as dismissive: "The corps had an attitude problem. It was: 'We're the Army Corps of Engineers. We know what we're doing and you don't.' "

Levee board officials complained about excessive corps delays. They were slow. We'd come up with a design, and the corps would always send them back," Boissiere said.

Army engineers raised their own complaints. Baudier's firm was removed as Orleans Avenue designer in 1992, accused by the corps of missing deadlines. As sections of the flood walls were finished piece by piece through the mid-1990s, the levee board's emphasis turned to the mundane chores of grass-cutting and maintenance. That left ample time for board business that had little to do with flood protection.

Outside Interests. When lawyer Robert Harvey was installed as the Orleans district's president in 1992, the levee board was a recreation powerhouse. A year after Mississippi River floods swamped New Orleans in 1927, Louisiana political legend Huey Long had prodded the state Legislature to allow the Orleans board to expand its influence into parks, beaches and other "places of amusement.

By the late 1980s, the board operated an airport, two marinas and lakeshore rental properties, but the agency was hemorrhaging money. Leases went unfilled at the airport, and its South Shore Marina had too many vacant boat slips. Instead of scaling back, Harvey accelerated the board's outside interests. The tough-talking lawyer won his post after contributing $5,000 to the 1991 campaign of Gov. Edwards, an old friend. "It's a plum job," Harvey recalled. "Your connection with the governor is close. You have 300 employees, lots of contracts.

When Edwards pushed for state gambling -- a position that led to his federal corruption conviction in 2001 -- Harvey wooed the Bally's gambling empire to locate a casino boat at a dock owned by the levee board. The boat brought in millions in gambling taxes, but other Harvey projects fell flat. A flirtation with film studios went nowhere. A series of probes by the state auditor found cases of financial mismanagement, conflicts of interest and risky investments. At one point, six attorneys were working for the board without formal contracts. And Harvey was accused by the New Orleans Metropolitan Crime Commission of padding the levee board payroll with old friends. The controversies took their toll. Harvey resigned in 1995, followed by an FBI probe of his levee board tenure. "They didn't find anything," Harvey said.

His successor, James P. Huey, waded into his own controversies. Huey's board hired his wife's first cousin, George Carmouche, as a lobbyist in Baton Rouge. After Katrina struck, the board sublet a Baton Rouge office from Carmouche. And Huey pocketed nearly $100,000 in back pay, failing to first obtain permission from state lawyers. He returned the money after resigning under pressure. Huey, who did not respond to interview requests, is under investigation by state and federal authorities.

At the same time, the newly raised flood walls received haphazard scrutiny. Harvey recalls staring jealously at East Jefferson Levee District's well-trimmed border of the 17th Street canal, then at untamed foliage and trees massed along the Orleans levee wall. "I'd look at the Orleans side and get depressed," he said.

Neither the corps nor the Orleans board had a rigorous program for scanning for structural defects. Instead, the two agencies joined twice a year for five-hour-long inspection tours. A caravan of officials would make random stops along the floodwalls. Sometimes corps officials issued citations. Then they would head out for long lunches. "That was always on the agenda," said former Orleans commissioner Peggy Wilson.

On one tour, Wilson was joined by only one other levee board official. When they stopped briefly at the levees, corps officials seemed in a rush. “I kept asking them what I was supposed to look for, puddles of water?” she said. They said, ‘Oh, don’t worry.’ The agencies relied largely on maintenance crews and neighbors to flag levee problems. “If something structural came up, we’d tell the corps,” said retired Orleans levee board crewman Ed Robbins.”

But at 17th Street, corps engineers were a rare sight, recalled Eric Moskau, a commercial real estate agent who has lived near the flood wall since 2001. I’d just see them driving out near the walls,” Moskau said. “I always wondered exactly what they did out there.

17th Street. When Katrina’s swells blew out huge chunks of 17th Street’s cement wall on the morning of Aug. 30, Harvey was prepared for disaster. Years of interagency spats with the corps and his own engineers had left him a skeptic. He bought an inflatable rubber boat and stored it in the attic of his house near the 17th Street levee. When floodwaters rose, Harvey dragged down his boat and began rescuing neighbors. “Nobody wanted to go into a starvation mode and pay for real protection in the halls of Congress,” he said afterward.

Since 2001, the Bush administration had repeatedly turned down requests from the levee board and the Louisiana delegation for more flood protection. When Katrina struck, Orleans Avenue’s levee walls held firm. But when Walter Baudier, the levee’s original designer, drove out with another engineer to the canal weeks later, he was stunned to find a 200-foot gap between the levee wall and the pump station. The wall was left unfinished because of the government’s refusal to fund the project, according to the corps and levee officials. The gap allowed floodwater to flow freely into the city.

Near the breach at 17th Street, an 18-foot section of levee wall ended up in Moskau’s living room. Displaced to Idaho, Moskau returned weeks later to survey the damage. He hiked over hardened mud, gaping at the two-block-long rupture. Crowds of red-shirted corps engineers swarmed nearby, directing repairs. There were more engineers, he realized, than he had seen in the four years he had lived near the levee. The government was just like everybody who lived near the levee,” Moskau said later. “They took those walls for granted.

F.4.11 Vartabedian, R. and Braun, S. (2006). “Fatal Flaws: Why the Walls Tumbled in New Orleans,” Los Angeles Times, January 17.

NEW ORLEANS -- In the frantic days after Hurricane Katrina, the Army Corps of Engineers scrambled to plug a breach on the 17th Street levee, dropping massive sandbags from a fleet of helicopters. But the engineers were baffled: The sandbags kept disappearing into the watery breach. The pit eventually swallowed 2,000 sandbags, each weighing between 3,000 and 20,000 pounds. It was an early sign that the hurricane had opened an extraordinarily deep hole in the foundation of the storm wall, pointing to a fundamental breakdown in the engineering of the city’s levee system.

Investigators recently told The Times that the 17th Street levee failed because its engineers made a series of crucial mistakes, one of which was to base the levee design on the average strength of the soil rather than on the strength of its weakest layer. The errors may reflect a loss of expertise during the 1990s, when the corps sharply downsized its soil laboratories. The faulty soil analysis is one of many defects or flaws in concept, design, construction and maintenance that left many of the levees in New Orleans especially vulnerable to Katrina. Environmental miscalculations, including the loss of natural protection from marshes, added to the problems. The errors might have been offset had the corps required larger safety margins, and that raises questions about the corps' internal culture.

Although the levees' shortcomings became apparent shortly after the hurricane hit, experts are only now pinpointing the underlying causes of the collapses. What they find will determine who bears the political and legal responsibility for the flood and provide a technical basis for any future levee system to protect New Orleans from a monster storm. The levee failures were among the most costly engineering errors in the United States, measured by lives lost, people displaced and property destroyed, said half a dozen historians and disaster experts.

Katrina flooded New Orleans with about 250 billion gallons of water and killed more than 1,000 people. "I don't think there is anything comparable in recent American history," said retired engineering professor Edward Wenk Jr., a science advisor to three presidents and investigator of the Exxon Valdez accident.

Early blame for the levee failures has fallen largely on the Army Corps of Engineers, the principal architect of a 40-year project to protect New Orleans from hurricanes. Corps officials say they will accept responsibility for the failures if investigations prove that their supervision of the system was deficient. "What I don't think we understand yet is the forces that caused those failures," said Lt. Gen. Carl Strock, corps commander and its chief of engineers. "A failure is really where a design does not perform as intended. If forces we designed for were exceeded, there may not be a design failure.

However, a preliminary report funded by the National Science Foundation has found evidence of design flaws in the city's concrete storm walls, where at least six catastrophic failures caused half of the flooding. A handful of technical, civil and criminal investigations are underway, including an effort by the Justice Department to look for possible criminal negligence. The corps is conducting the federal government's official investigation, despite widespread concern that only an independent board of investigators is likely to be impartial.

The corps was slow to make public all of its engineering paperwork on the levees and has still not produced a full record of the internal correspondence that occurred during the last 15 years. Moreover, it is not examining what role its organization and culture played in technical lapses, which, Wenk said, typically are at the root of engineering disasters. The corps says it has addressed those concerns by recruiting outside experts to participate in its investigation. The agency is expected to make its final report in June.

The corps is attempting to temporarily repair 50 miles of damaged levees before the hurricane season next June. The Bush administration announced last month it would spend $3.1 billion for temporary levee repairs and limited upgrades in the next several years. However, many local leaders believe the levee system must be strengthened to withstand the strongest possible hurricane -- a Category 5 -- to restore full confidence in the city. Katrina, a Category 5 storm over the Gulf of Mexico, weakened to a Category 3 by the time it hit New Orleans.

Making his ninth visit to New Orleans since Katrina struck, President Bush last week praised the $3.1-billion initiative but said nothing about Category 5-level protection. And, according to the corps, even the temporary repairs and limited upgrades will not protect the city from another

Category 3 storm, which has winds up to 130 mph and storm surges as high as 12 feet above normal.

Meanwhile, more than four months after the hurricane, investigators are still coming to grips with the levee system's technical failures and shortcomings that paved the way for Katrina's destruction.

Weak, Slippery Soil. No levee failure was more dramatic than the breach at the 17th Street Canal, where a 465-foot section of concrete wall gave way Aug. 29, flooding the affluent Lakeview section of New Orleans. Floodwaters were 3 to 5 feet below the top of the levee wall when it collapsed. The soil under the levee, composed of layers of loose clay and softer organic peat, was too weak to handle the weight of the water pushing against the levee walls.

The earthen base of the levee slid backward by about 45 feet, taking the concrete storm wall along for the ride. The whole system relied in part on heavy-gauge steel beams, called sheet piling, driven into the soil for reinforcement. But they only went to a depth of 17 feet below sea level, not deep enough to provide a strong foundation, National Science Foundation investigators say.

In rebuilding the damaged sections of the canal levees, the corps is sinking sheet piling 45 feet, and in some areas is using heavier gauge piling up to 70 feet deep. The corps says the deeper piles are needed because soil in the damaged areas is even weaker than before Katrina.

The levee design was overseen by the corps but assigned to two firms: Eustis Engineering, which analyzed the soil under the levee; and Modjeski and Masters Consulting Engineers, which did the structural design. (Neither firm returned phone calls seeking comment.). The levee design depended on crucial soil measurements along the canal that began in 1981. Technicians drilled for soil samples 300 to 500 feet apart to measure the strength of the soil.

The soil tests provided accurate and complete data about the weak soils, but government and private design engineers made three crucial errors analyzing the information, said Bob Bea, a UC Berkeley engineering professor who is part of the National Science Foundation investigating team. First, engineers determined the overall strength of the soil by averaging different layers and different sections along the banks of the canal. But it was the weakest layers of soil that would determine the overall strength, and using the average gave the engineers a false confidence, Bea said.

Second, the levee design failed to account for the fact that the soil would weaken significantly once the canals were full of water and the soil became saturated, Bea said. Soil tests conducted before the levees were built showed the soil's shear strength was about four times greater than after Katrina. The engineers incorrectly believed that sediment in the canals would prevent water from intruding through foundations, but dredging and other activity disturbed that natural seal, he said.

Finally, the engineers miscalculated how the levee foundation could slide, if it did fail. They assumed the greatest risk of failure was in one of the stronger layers of soil, whereas it failed in a weaker layer.

Since Katrina, the corps has proposed installing storm gates that would seal off the 17th Street Canal, along with the city's two other major drainage canals. Once the canals were sealed off from Lake Pontchartrain, hurricane surges would no longer be able to travel through them into the heart of the city.

Not long after construction started on the levee, signs of trouble popped up. The company that built the 17th Street storm wall, Pittman Construction, warned the corps in the early 1990s that the pilings were unstable and had caused problems during construction. The company filed a claim for more money but lost its case. Pittman told the corps he was concerned about the weak soils," said Herbert Roussel, a consulting engineer hired by the company's owner, A.E. Pittman. "The corps acted as though it was his problem.

Loss of Expertise. As questions about the soils were being raised, the corps shut down its soils lab in the New Orleans district and curtailed its geotechnical research lab in Vicksburg, Miss. The labs had long performed crucial soil analysis and research for projects around the country, but the corps' leadership wanted staff engineers to oversee outside contractors, said Bill Marcuson, the former director of the New Orleans soils lab and president-elect of the American Society of Civil Engineers.

That trend leads to less in-house capability and competence," Marcuson said. "If the corps is not physically doing research, it is hard to evaluate the quality of others' research." Strock said the moves were part of a larger federal government trend to save money by turning over work to the private sector. He conceded that the practice "eroded our technical capability," but said the damage was limited.

But Bea countered that the agency lost significant technical capability, particularly in its large civilian workforce. "They don't have the number of people or the quality of people that they used to," said Bea, who began his engineering career with the corps.

Levees Without Armor. Along many levee sections, particularly those on the waterway known as the Industrial Canal, water poured over the tops of storm walls and cascaded down the backside, scouring and weakening the foundations. Eventually, the walls collapsed. If they had remained standing, they would have acted as a buffer and slowed the pace of flooding.

The levees could have survived the overtopping if the backs of the walls had had concrete or heavy stone pads at their base, a protection known as "armoring." Some of the storm walls in New Orleans were built with armored foundations and significantly stronger sheet piling, known as T-walls. Those levees did not fail and incurred far less damage during Katrina.

The corps generally assumed that hurricane flood waters would not rise high enough to spill over the levees. But most outside experts say that assumption was a mistake. "There are only two kinds of levees: those that have been overtopped and those that will be overtopped some day," said Gerald Galloway, a levee expert at the University of Maryland. He added that armoring "is not cheap or simple.

The corps is replacing some failed sections of levees with T-walls. Brig. Gen. Robert Crear, the corps' district engineer in New Orleans, said the agency was preparing to armor many levees under the $3.1-billion rebuilding program. The armoring will include placing beds of rock or concrete at the base of the walls to prevent erosion in future storms.

Thin Safety Margins. Doubts about the corps' oversight have also flared over the low margin for error designed into the canal floodwalls. Engineers design structures to withstand forces far greater than the maximum anticipated loads to compensate for uncertainties in their own understanding and for possible defects in construction.

According to Wenk, the engineering expert, public structures typically have safety margins as high as four, meaning they are four times as strong as it is anticipated they will need to be. Corps documents indicate that engineers approved a margin of 1.3 for the floodwalls. That meant the walls were designed to be 30% stronger than the maximum stress expected from a hurricane flood surge. Wenk said he was astounded by such a low factor, particularly for a system that protected such a large urban area.

Strock agreed that the issue needed close attention. “I was not aware before this event that the factor was 1.3,” he said. Critics have questioned whether the corps devoted sufficient attention to safety, and Strock acknowledged that the low safety margins “may get back to the cultural issue.”

Overgrown Trees, Brush. Years of neglected maintenance in southern Louisiana may have contributed to the heavy flooding, engineering experts said. The growth of large trees near the 17th Street Canal levee may have helped undermine the floodwall. Katrina’s strong winds blew down a massive oak near the levee breach and investigators believe the roots of the tree pulled out a large plug of soil from the embankment.

The Orleans Levee District is responsible for maintenance and employs work crews to trim grass along the levee slope. But trees and bushes sprouted from the yards of private homes near the breach site and were left untrimmed for years because of opposition from homeowners and the failure of levee officials to move aggressively. The Orleans Levee District could have taken action, critics say. Just across the 17th Street Canal, the levee wall owned by the neighboring East Jefferson Levee District is regularly shorn of trees and heavy brush. “It is a major concern,” said Jim Baker, superintendent of operations for the East Jefferson Levee District. “If you have a tree blow over, it can open up a good size hole. I don’t like trees growing on our levees.”

Lost Wetlands Barrier. Closer to the Gulf of Mexico, a different kind of environmental miscalculation also contributed to the disaster. Environmentalists, political leaders and engineers warn that decades of neglect and corps-sponsored dredging led to the disappearance of vital wetlands, allowing hurricane storm surges to threaten New Orleans.

When Hurricane Katrina roared up the Gulf of Mexico, it spawned a storm surge toward New Orleans through a navigation channel known as the Mississippi River Gulf Outlet, or MRGO. The outlet was built from marsh and wetlands by the corps in the early 1960s to allow large ships quicker access to the Port of New Orleans. Originally designed as a 300-foot-wide channel, the outlet has widened to more than 3,000 feet, the result of repeated dredging by the corps and of ships’ wakes.

You can put more surge through a wider body,” said Thomas Sands, a retired corps general who headed the New Orleans district. “When I was district engineer, the erosion along the MRGO was horrible.” The project also allowed salt water to penetrate and destroy hundreds of square miles of wetlands that acted as a natural flood barrier.

Henry “Junior” Rodriguez, president of St. Bernard Parish, said that the heavy flooding that topped his community’s levees during Katrina was far worse than during Hurricane Betsy in 1965. “Listen, we didn’t even have levees during Hurricane Betsy and the flooding wasn’t as bad,” Rodriguez said.

After Katrina, the corps has pledged to halt dredging of the MRGO for at least a year and is considering proposals to scale it back. The agency is also proposing to channel sediments and freshwater into the marshes to reduce future wetlands losses, though the National Research Council recently termed the current proposals inadequate.

We will never be able to rebuild the coast we had 50 years ago, but the wetlands still out there can be preserved," said Carlton Dufrechou, executive director of the Lake Pontchartrain Basin Foundation, a leading environmental group in the region. "If we do nothing, the gulf will be lapping at the edges of New Orleans in future decades," Dufrechou said. "And if the MRGO stays open, you might as well put a bull's-eye on the city and tell everybody to clear out on June 1 when the hurricane season starts.

F.4.12 Irons, L. (2005). "Hurricane Katrina as a Predictable Surprise," Homeland Security Affairs, Vol. I, Issue 2, Article 7, http://hsaj.org/hs a.

How can a surprise be predictable? Paradoxically, many people think low-probability events are just that: low probability; not impossible but very unlikely. People find it difficult to sustain a high level of preparedness for events that are unlikely to happen on any given day, especially if the preparation requires spending scarce time and resources. As Max Bazerman and Michael Watrkins observe in their recent book, Predictable Surprises: The Disasters You Should Have Seen Coming, And How To Prevent Them, 'We don't want to invest in preventing a problem that we have not experienced and cannot imagine with great specificity.

Bazerman and Watkins outline four major characteristic traits of predictable surprises.

1. Leaders know problems exist and will not solve themselves.
2. Organizational members realize a problem is getting worse.
3. Fixing the problem requires significant cost in the present with no immediate benefit (rewards for avoiding the costs of prevention are uncertain but potentially larger than incurring the costs).
4. Humans tend to maintain the status quo if it functions (minorities protect their own interests, subverting efforts by leaders to implement change.

One basic lesson to learn from Hurricane Katrina is that organizations managing preparedness for flood control and hurricanes, such as the U.S. Army Corps of Engineers, as well as organizations managing responses to disasters, such as FEMA, can benefit from developing learning organizational processes. Those same processes make it more likely that staff will avoid surprises by recognizing them, prioritizing the challenges, and mobilizing resources to prevent them from developing.

A basic step in preparing an organization to use the affect of its people to enhance their efficiency and effectiveness is for its leadership to admit that it is not perfect, that operations require continuous improvement. Professional criticisms of operational performance must flow up the organization as well as down, with the organization encouraging such contributions. Indeed, a learning organization does the following:

- defines a clear mission, designed to inspire workers to do their best;

- creates a culture that emphasizes professionalism;
- provides top-notch technical training;
- provides leadership development for managers;
- pushes responsibility down the ranks so employees in the field are authorized to act quickly; and
- advocates continuous improvement.

Learning organizations are challenges to promote a level of awareness sufficient to enable surprise-avoidance capability from their members. Indeed, the structure of large and complex organizations increases the difficulty leaders' face in anticipating predictable surprises. As the complexity of organizations, or even project teams, increases, the way expertise is coordinated tends to develop into silos. Organizational silos often disperse responsibility as well as information. In other words, organizational silos encourage staff to 'let someone else' deal with recognized problems, essentially supporting surprise-conducive processes.

Leadership is a key point of interest when considering the way organizations attempt to avoid, or mitigate the impact of, predictable surprises. There is little dispute of the point that local, state, and federal leaders knew about the vulnerability of the New Orleans' levee protection system and the threats it posed to the city. Although some officials initially claimed that non one expected the levees and flood walls in New Orleans to collapse, most experts knew about the vulnerability for many years.

The evidence indicates the U.S. Army Corps of Engineers knew about the threat of breaches, as opposed to overtopping, since the early 1980s. Moreover, all concerned agencies, including those at the local, state, and federal levels, knew about the threat of overtopping and consequent flooding in even a Category 3 hurricane.

Improving the levee and floodwall system in New Orleans was a recognized challenge for decades, as was the challenge of a receding delta providing less protection to the New Orleans area from storm surges resulting from a hurricane. The Breaux Act of 1990 created a task force involving several federal agencies and gave it the mission of restoring wetlands. The task force received only forty million dollars per year to stop the erosion of the delta. A University of New Orleans study estimated the effort averted only about two percent of the overall loss, leaving an erosion rate of twenty-five square miles of delta per year.

Basic flaws in the design of the levee protection system were first recognized over two decades ago, before the wetlands were so diminished. An outside contractor, Eustis engineering, was the first to express concerns about the levee vulnerability to breaching in the early 1980s. In 1981, the New Orleans Sewerage & Water Board developed a plan to improve street drainage by dredging the 17th Street Canal. The Corps of Engineers issued permits to do the dredging in 1984 and 1992, though the Corps was not a partner in the Project. Eustis Engineering contracted to do a design study for Modjeski and Masters, the consulting engineers on the project, and performed soil investigations on a section of the 17th Street Canal from south of the Veterans Memorial Boulevard bridges to just north of those structures. They found that 'the planned improvements to deepen and enlarge the canal may remove the seal that has apparently developed on the bottom and side slopes, thereby allowing a buildup of such pressures in the sand stratum.' Eustis' concerns about a 'blow-out', or breach, of the levee were strong enough that the company recommended test dredging before the final design. the company recommended that, without test dredging, the bottom of the canal needed sealing with a concrete liner or building a seepage cutoff wall, like sheet pilings, to a depth of 65 feet below sea level versus the existing 12 feet. Engineers studying the levee breaches consider the report by Eustis significant because the stretch of canal the firm studied is widely considered to exhibit stronger soil layers than those that breached during Hurricane Katrina.

The most puzzling point about the dredging project is that the Corps of Engineers planned to follow the project by raising the floodwall from 10 feet to 14.5 feet. It is unclear whether the Corps paid attention to the contractor's concerns since most of the documents related to the work remain unavailable to the public. Although the Corps of Engineers was not a direct partner in the dredging, it was aware of the work and knew it would have an impact on its later project. Indeed, contractors working for the Corps on the later project raised their own concerns about the soil and foundations of the levee.

Reports indicate that key sections of the levee system's soil and foundation, particularly the floodwall on the 17th Street Canal where much of the serious flooding occurred, posed serious problems for the contractors involved. Court papers from 1998 show that Pittman Construction indicated to the Corps of Engineers as early 1993 that the soil and foundation for the walls were 'not of sufficient strength, rigidity and stability' to build on. The construction company claimed that the Corps of Engineers did not provide it with complete soil data when it developed a bid on the levee project.

Though the construction company lost its suit against the Corps of Engineers, the gist of their complaints about the condition of the soil and existing foundation was not disproven. Engineers now say the difficulties Pittman Construction faced were early warning signs that the Corps of Engineers ignored.

The Corps of Engineers officially disputed the points made by Pittman Construction regarding the soil condition, though it now seems clear that the crucial breaches in New Orleans occurred in levees where the floodwall foundations were not as deep as the canals and that the Corps of Engineers was aware of the issue. The soil then allowed water to percolate under the levee and floodwalls, weakening the structure so that the storm surges from Hurricane Katrina moved it entirely, or breached it. Would an organization with processes in place to support ongoing learning, and surprise-avoidance, fail to recognize the legitimacy of the contractor's point rather than argue about purely budgetary issues related to the contract?

The U.S. Army Corps of Engineers is historically an insular agency, known for doing things its own way. It is not possible to say whether surprise-avoidance processes are in place at the Corps of Engineers, until the public receives more access to internal documents. The failure of Corps' staff to recognize and prioritize the challenges of levee upgrades and receding wetlands to the city of New Orleans, and surrounding areas, strongly suggests that surprise-conducive processes characterize its organization. the Corps' organization has over the past few decades outsourced more work, lost many engineers to private industry, and consequently suffered a diminished capacity to attract top-notch engineers.

Bazerman and Watkins note that predictable surprises play out over long time frames, sometimes longer than the typical tenure of organizational leaders. They contend 'this creates a variation on the free-rider problem. Why, a leader might ask, should I be the one to grapple with this problem and take all the heat when nothing is likely to go wrong during my watch? In other words, members of the U.S. Army Corps of Engineers, conceivably, made a collective bet that the unlikely occurrences that, in fact, did end up happening, were not worth the expense, form a professional or organizational initiative point of view. …The sheer magnitude of the problems faced in the New Orleans levee protection system probably appeared overwhelming to members of an organization enduring ongoing budget concerns and staff turnover.

Consider the scale of the plans offered to fix the levee challenges: a plan floated in early 2001 involved two to three billion dollars proposed to divert sediment from the Mississippi River back into the delta, rather than allow the sediment to wash down the levee system and dump into deep water. The project was compared to the four billion dollar resstoration initiative for the Florida Everglades. However, these projects are typically funded through matching grants in which the state has to match a federal dollar with one of its own. Louisiana was only able to match each dollar with fifteen to twenty-five cents. Facing the scale of such a challenge, and the state's limited ability to pay for its share of the costs, the response of most people was to maintain the status quo. the result was a catastrophic disaster that cost many times the few billion dollars needed to initiate a full-scale rebuilding program for the levee protection system and the surrounding wetlands. Essentially, those responsible for the levee protection system in New Orleans saved money in the short term only to permit one of the largest disasters in American history to occur over the long haul.

The U.S. Army Corps of Engineers currently finds its authority questioned by many, not because of the competence of its engineers' expertise, but rather due to concerns about its organizational processes that allowed such basic design flaws to go without sustained questioning by engineers exercising professional judgement.

New Orleans had dodged the bullet many times, with the major force of hurricanes skirting around the area. Nevertheless, most people with a reason to know about it were aware that a Category 3 hurricane posed a severe threat to the New Orleans' levee protection system, and a Category 5 hitting land as a Category 4, as with Katrina, posed a catastrophic threat.

The occurrence of a hurricane like Katrina was not unexpected in New Orleans; neither were the complications faced in the aftermath of the storm. Given this understanding, and the neglect in preparing for a hurricane like Katrina, as well as the ineffective response preparations, it seems reasonable to assert that Katrina as well as its aftermath was a predictable surprise. The threats posed by the hurricane, and the likely aftermath, were well known and unsurprising to most who thought about the hurricane threat to New Orleans. Unfortunately, much of the local, state, and federal leadership, especially the U.S. Army Corps of Engineers, appears to have remained complacent about preparing the levees for a catastrophic hurricane.

F.4.13 Congressional Research Service Report for Congress (2005). *Protecting New Orleans: From Hurricane Barriers to Floodwalls*, N. T. Carter, Washington DC, December.

Understanding why New Orleans' hurricane protection system failed is essential for moving beyond simply making repairs to damaged levees and floodwalls. Knowing why the floodwalls failed is central to assessing the city's vulnerability to storm surge flooding and deciding on how to most effectively combine approaches for managing flood risk during rebuilding efforts (.e.g, investing in coastal wetlands loss and hurricane protection infrastructure, requiring flood-proofing in certain areas, and mapping areas for the federal flood insurance program.

The original design of the Lake Pontchartrain project was sent to Congress in July 1965. The project was designed to protect the city from a standard hurricane for the region, which was roughly equivalent to a Category 3 hurricane on the Saffir-Simpson Scale. The standard hurricane was defined as high sustained wind speeds reasonably characteristic for a specified coastal location. Reasonably characteristic was defined as only a few hurricanes on record over the general region had been recorded to have more extreme wind and other meteorological characteristics. The standard hurricane was determined by the U.S. Weather Service.

Two months later in September 1965, Hurricane Betsy, a Category 3 hurricane, struck Louisiana's coast, causing damage in New Orleans. Congress authorized construction of the Lake Pontchartrain project in the Flood Control Act of 1965, enacted in October 1965. Modifications to the authorization have been made in subsequent legislation. Since that original design, there have been two major developments in the project relevant to current investigations into the floodwall failures: (1) the shift from the barriers at the inlets to Lake Pontchartrain to higher levees along the lake; and (2) the shift from floodgates at the mouth of the city's storm water outfall canals that drain into Lake Pontchartrain to higher floodwalls along the length of the canals.

The original July 1965 Lake Pontchartrain project design consisted of the Barrier Plan for constructing inlet barriers at Lake Pontchartrain's three main tidal entrances as well as levees and floodwalls for surge protection. The barriers generally would remain open and allow for navigation, and would close during coastal storms to reduce storm surges from entering the lake. Based on updated weather data and experience learned during the city's flooding in September 1965 by Hurricane Betsy, changes in project were sought before construction began. For almost two decades, technical issues, environmental concerns, legal challenges, and local opposition to various components slowed construction.

The design that the Corps eventually chose was the High-Level Plan which consists of higher levees and floodwalls, instead of the originally planned inlet barriers and lower levees and floodwalls. The change from the Barrier Plan to the High-Level Plan was approved by the Corps chief of Engineers in February 1985; both the barrier and the high-level plans were designed to protect from the rough equivalent of a fast-moving Category 3 hurricane. The Chief's decision to adopt the High Level Plan was based on a 1984 project reevaluation study conducted by the agency in response to a 1977 court injunction on the construction of inlet barriers until an adequate Environmental Impact Statement (pursuant to the National Environmental Policy Act of 1969 P.L. 91-190) was completed. the reevaluation study recommended the change because 'the High level Plan has greater net benefits, is less damaging to the environment, and is more acceptable to the public' than the Barrier Plan.

To drain the city of stormwater (i.e., accumulated rainfall), the city pumps water into three outfall canas - the 17th Street canal, the Orleans Avenue canal, and the London Avenue canal - that flow into Lake Pontchartrain. The pumps are located at the southern ends of the canals, away from the lake. To protect the city from rising water in Lake Pontchartrain during hurricanes, levees were built along the length of the canals. The levees along the outfall canals were considered adequate when the Corps developed the original design for the Lake Pontchartrain project that was sent to Congress in July 1965.

Subsequent to the U.S. Weather Bureau's adoption of a more severe standard hurricane for the region, the Corps determined that the levees along the outfall canals were inadequate in their height and stability to protect the city from the standard hurricane. The Corps eventually integrated hurricane protection for the canals into its Lake Pontchartrain project. The Corps considered improved canal protection necessary regardless of the selection of the Barrier or High-Level Plan. The two basic canal options evaluated were: 'butterfly' floodgates at the mouths of the outfall canals that would close when water levels in Lake Pontchartrain exceeded levels in the canals (known as fronting protection); and higher and stronger levees and floodwalls along the canals (known as parallel protection).

The Orleans Levee District and the Sewerage and Water Board of New Orleans favored parallel protection over floodgates; they were concerned that the operation of the butterfly floodgates would reduce the ability to pump storm water out of the city during storms. The Corps analyzed the options and recommended parallel protection for the 17th Street Canal; in contrast, the Corps recommended butterfly flood gates for the Orleans and London Avenue canals. The Corps concluded that the butterfly floodgate plan for the London Avenue canal 'fully satisfies the project's mandate to provide protection against the hurricane generated tidal surges and yet provides the maximum latitude for operation of local interest interior drainage (i.e., storm water removal). The butterfly control valve plan has been shown to be the least costly fully responsive plan. When compared to the parallel protection plan it is approximately three times less costly'.

The conclusion for the Orleans Avenue canal was similar; the Corps found the butterfly gates to fully satisfy the project purpose of hurricane storm surge protection and to be one-fifth the cost of parallel protection.

Rather than having the Corps proceed with construction of the butterfly floodgates, the Orleans Levee District decided to construct on its own most elements of the parallel protection on the Orleans and London Avenue canals. this local construction was designed in accordance with Corps criteria, so that the parallel protection would be incorporated into the larger Lake Pontchartrain project. The Corps recommended that the federal cost-share contribution for the parallel protection of the two canals be capped at 70% of the less-costly butterfly floodgates design. In H. Rept. 101-966, the Conference Report for the Water Resources Development Act (WRDA) of 1990 (P.L. 101-640), Congress directed the Corps to consider favorably parallel protection for the two canals and for the federal government to bear part of the costs, but did not specify what percentage of the cost. This report was followed by the Energy and Water Development Appropriations Act of 1992 (P.L. 102-104) in which Congress stated: 'The Secretary of the Army is authorized and directed to provide parallel hurricane protection along the entire lengths of the outfall canals and other pertinent work necessary to complete an entire parallel protection system, to be cost shared as an authorized project feature, The Federal cost participation in which shall be 70 percent of the total cost of the entire parallel protection system, and the local cost participation in which shall be 30 percent of the total cost of such entire parallel protection system'.

Concerns about levee and floodwall reliability are compounded by concerns about the level of protection provided by the existing infrastructure given New Orleans' increasing vulnerability to hurricane storm surge. Land in the city has subsided; barrier islands and wetlands have been disappearing; and sea levels have risen. These factors have raised concerns about the ability of the city's infrastructure to provide Category 3 protection. According to the project justification sheet included in the Administration's Corps FY 2006 budge request, 'the project was initially designed in the 1960s, and a reanalysis was performed for part of the project in the mid-1980s. Continuing coastal land loss and settlement of land in the project may have impacted the ability of the project to withstand the design storm.' The challenge of protecting New Orleans could become even greater. According to some scientists, higher sea surface temperatures may result in increased hurricane intensity. Climate change concerns and other factors have raised questions about whether both estimates of the likelihood of hurricanes of various strengths and past infrastructure investment decisions based on these estimates need to be reevaluated.

Hurricane Katrina has resulted in some questioning why a Category 4 or 5 hurricane protection system was not in place for New Orleans, and whether it should be part of the rebuilding effort. The Corps currently only as congressional authorization for a Category 3 system; additional congressional authorization would be necessary to build a more protective system Discussions of Category 4 or 5 protection for the city often include the extent to which coastal wetlands restoration may play a role in reducing the city's vulnerability to storm surge and whether some of the regional navigation improvements may increase storm surge vulnerability. these discussions raise broader policy issues related to the appropriate level of investment to protect against low probability-high consequence events; to protect against loss of life and economic disruption; and whether structural storm and flood control measures provide a false sense of security in vulnerable areas like New Orleans. The corps cost estimates are $1.6 billion to return coastal Louisiana's federal levees and floodwalls to pre-Katrina conditions by June 2006, and an additional $3.5 billion to increase protection for New Orleans from Category 3 to Category 5. State officials have estimated the cost of Category 5 protection and wetlands restoration for all of coastal Louisiana as high as $32 billion. Most local stakeholders argue for the inclusion of coastal wetlands restoration in any plan to improve hurricane protection.

Understanding why the hurricane protection system failed in New Orleans is essential to moving beyond simply making repairs, to identifying and reducing vulnerabilities in the system, addressing coastal wetlands loss, and rebuilding the city. Nonetheless, the Corps is having to proceed with available information in order to perform repairs to the failed floodwalls and other breaches to meet the June 2006 deadline, which marks the start of the hurricane season. Consequently, congressional oversight of New Orleans' hurricane protection is likely to continue as the nation grapples with decisions on what type and level of hurricane protection to provide New Orleans and other coastal areas around the nation, and who should bear responsibility and costs for protection in coastal, floodplain, and other hazard-prone areas.

F.4.14 Congressional Research Service Report for Congress (2005). *Flood Risk Management: Federal Role in Infrastructure*, N. T. Carter, October, Washington DC.

The U.S. Army Corps of Engineers is responsible for much of the federal investment in flood control and storm protection infrastructure. Corps involvement in flood control construction is predicated on the project being in the national interest, which is determined by the likelihood of widespread and general benefits, a shortfall in the local ability to solve the water resources problem, the national savings achieved, and precedent and law.

The 100-year flood standard was established at the recommendation of a group of experts in the late 1960s. 'It was selected because it was already being used by some agencies, and it was thought that a flood of that magnitude and frequency represented a reasonable probability of occurrence and loss worth protection against and an intermediate level that would alert planners and property owners to the effects of even greater floods. The adoption of the 100-year flood standard in many respects guides perceptions of what is an acceptable level of vulnerability. The 100-year flood standard is a vulnerability standard, and not a risk standard. Thus, the question of does the 100-year flood standard combined with threat and consequence information result in an acceptable level of risk remains largely unaddressed; this question is especially relevant for low probability, high consequence events such as a Category 4 hurricane hitting a major urban center.

Attempting to provide at least 100-year flood protection largely drives local floodplain management and infrastructure investments, resulting in a measure of equity within and across communities. That equity in vulnerability, however, results in uneven levels of risk because flooding of different communities has different consequences, such as differences in the potential loss of life, social disruption, structures damaged, and economic impact because of variations in land use and development patterns.

The residual flood risk behind levees or downstream of dams remains largely unaccounted for in the National Flood Insurance Plan and often is not incorporated into individual, local, and state decision-making. Residual risk is the portion of risk that remains after flood control structures have been built. Risk remains because of the likelihood of the measures' design being surpassed by floods' intensity and of structural failure of the measures. Often when the designs of flood control structures are surpassed or when structures fail for other reasons, the resulting flood is catastrophic, as shown by the floodwall breaches in New Orleans (LA) with Hurricane Katrina. The consequences of floods increase as development occurs behind levees and below dams; ironically, this development may occur because of the flood protection provided. The nation's risk of low-probability events (e.g., 150-year flood, or Category 4 hurricane) having high-consequences in terms of lives lost, economic disruption, and property damage is increased by overconfidence in the level and reliability of structural flood protection for events that are less probability than the 100-year flood.

The risk posed by low-probability events may be underestimated by the current methods for analyzing flood control investments. The benefit-cost analyses compiled to support federal decision-making for water resources projects focus on the 'national economic development benefits' of investments; regional, social, and environmental benefits may be analyzed but often are largely excluded from the decision-making. Moreover, the Corps generally limits its benefit-cost analyses of the consequences of flooding to damages. That is, estimated benefits from flood control infrastructure investments are primarily the avoided losses to existing structures and land uses.

The Corps' benefit-cost analysis of a project may result in a recommended plan for flood control infrastructure providing for protection greater than or less than the 100-year flood. Local project sponsors can request that a 'locally preferred alternative' be built, instead of the plan identified by the benefit-cost analysis. The National Flood Insurance Plan creates incentives for communities to support flood control alternatives providing at least the 100-year level of protection, but the program provides few incentives for more protection. For some local leaders and communities, the financial capital required to cost-share a Corps flood control project may represent a barrier to pursuing greater protection.

The Corps' benefit-cost analysis does not constitute a comprehensive risk analysis, because the consequences considered are largely limited to property damage, leaving out other potential consequences, such as loss of life, public heath problems, and economic and social disruption.

..Although potential loss of life is noted in Corps feasibility reports, there are no Corps regulations or guidelines for how to incorporate loss of life into the agency's benefit-cost analyses. …Therefore, although preventing loss of life is a goal of federal flood control policy, current practice results in property damage being the primary consequence metric used for making Corps flood control investment decisions. A related benefit-cost analysis issue commonly debated is whether there is a bias toward lower levels of flood protection for low-income communities due to their lower property values. another commonly debated issue is whether there is a bias toward structural flood control measures over nonstructural options (e.g. buyouts of structures in flood-prone areas).

Because the Corps' benefit-cost analyses are focused on damages, the Corps projects funded in the Administration's FY 2006 request are those that reduce the most damages per dollar spent, which may not be the projects most efficient at reducing risk more broadly. Also, the remaining benefits to remaining costs (RB/RC) metric is used for multiple types of Corps water resources projects - navigation, flood control, and storm protection. Because the Corps benefit-cost procedures vary by project type, comparisons of the RB/RC ratio of navigation projects, flood control, and storm protection projects may be misleading, especially if significant benefits derived from projects, such as the potential benefits of lives saved, are not quantified. In other words, benefit-cost analyses as applied by the Corps are tools for informing decisions on individual projects but were not performed with the intent to determine the most cost-effective projects. Metrics that include consequences in addition to damages could be combined and weighted to produce a risk-ranking for flood control projects; however, attempts to prioritize the Corps budget across multiple types of water resources projects continues to be a challenge because of the varying and inter-related types of benefits and costs of ecosystem restoration, flood control, navigation, and multi-purpose projects.

A fundamental question being raised in the aftermath of Hurricanes Katrina and Rita is: do current federal policy, programs, practices result in an acceptable level of aggregate risk for the nation? Risk management is being increasingly viewed as a method for setting priorities for managing some hazards in the United States. Because floodplain and coastal development are largely managed by local governments, some aspects of national flood risk management likely would be unwelcome and infeasible, and could be perceived as resulting in an inequitable distribution of flood protection. For example, if floods in large urban concentrations are perceived as representing a greater risk for the nation, federal resources may be directed away from protecting smaller communities and less-populated states. Two of the concerns raised in discussions of greater emphasis on risk analysis in the development and design of specific projects are that risk analysis may result in lower levels of protection being implemented in some areas, and that information and knowledge are insufficient to perform an adequate analysis. However, an argument can be made that the federal government has an interest in reducing risks resulting in national consequences, and in prioritizing federal involvement and appropriations accordingly.

"actors complicating the determination of the nation's flood risk include changing conditions and incomplete information. For example, many flood control projects were built decades ago using the available data and scientific knowledge of the period that may have underestimated flood hazards for particular areas. Similarly, there are issues with changes in risk over time due to processes such as land loss, subsidence, sea-level rise, reduced natural buffers, urban development, and infrastructure aging. For existing dams, there is some information on consequences of failure as measured by loss of life, economic loss, environmental loss, and disruption of lifeline infrastructure (such as bridges and power grids); however, the database with this information only tracks the amount and type of losses, not the likelihood of failure.

A risk-reduction approach for organizing federal flood-related investments likely would incorporate many structural and nonstructural flood management measures already being considered and implemented, but change their priority and mix. Options considered in a risk-centered approach may include shifting federal policy toward wise use of flood-prone areas (e.g. rules or incentives to limit some types of development in floodplains), incorporating residual risk and differences in riverine and coastal flood risk into federal programs (e.g. residual risk premiums as part of the National Flood Insurance Program), creating a national inventory and inspection program for levees, promoting greater flood mitigation and damage mitigation investments, re-evaluating operations of flood control reservoirs for climate variability and uncertainty, and investing in technology and science for improved understanding of the flooding threats.

Hurricanes Katrina and Rita have focused the nation's attention once again on issues that flood experts have debated for decades. The disasters have renewed public concerns about reliability of the nation's aging flood control levees and dams. The debate over what is an acceptable level of risk - especially for low-probability, high-consequence events - and who should bear that risk is taking place not only in the states affected by the hurricanes, but nationally. The concerns being raised range widely, including interest in providing more protection for concentrated urban populations, risk to the nation's public and private economic infrastructure, support for reducing vulnerability by investing in natural buffers, and equity in protection for low-income and minority populations.

The response to Hurricanes Katrina and rita have included discussions of expanding mitigation activities (such as floodproofing structures and buyouts of structures on the most flood-prone lands), investing in efforts to restore natural flood and storm surge attenuation, and assuring vigilant mantenance of existing flood control structures, as well as interest in new and augmented structural flood protection measures. Although major flood events, such as the Midwest Flood of 1993, generally spur these discussions, the policy changes implemented often are incremental. The 109th Congress, like previous Congresses, faces a challenge in reaching consensus on how to proceed on anything other than incremental change because of the wealth of constituencies and communities affected by federal flood policy. Another practical challenge is the division of congressional committee jurisdictions over the federal agencies and programs involved in flood mitigation, protection, and response.

For example, Senate Committees that would likely have jurisdiction over elements of any comprehensive change in federal flood policy would include Banking, Housing, and Urban Affairs; Environment and Public Works; and Homeland Security and Government Affairs.

F.4.15 Office of Management and Budget (2006). *Agency Scorecards*, Washington, DC.

Good intentions and good beginnings are not the measure of success. What matters in the end is completion: performance and results. Not just making promises, but making good promises.

The scorecard employs a simple 'traffic light' grading system common today in well-run businesses: green for success, yellow for mixed results, and red for unsatisfactory. Scores are based on five standards for success defined by the President's Management Council and discussed with experts throughout government and academe, including individual fellows from the National Academy of Public Administration.

The Corps of Engineers ratings: Human Capital - yellow, Competitive Sourcing - Red, Financial Performance - Red, Enhancing E-Government - Red, and Budget Performance and Integration - Red

Reducing the Construction Backlog. Between 2000 and 2005, funding for the Corps construction program increased by 30 percent in nominal terms. Much of this increase was for work on projects with relatively low benefits or outside of the Corps' three main mission areas: 1) facilitating commercial navigation; 2) reducing damages caused by floods and storms; and 3) restoring aquatic ecosystems. During the same period, the Corps construction workload grew at an unmanageable rate and more projects faced construction delays, as additional projects were authorized without funding for timely completion. This growth trend has resulted in a $50 billion cost to complete authorized projects, of which only $15 billion is for projects that are both within the Corps' main mission areas and meet current economic and environmental performance standards. Funding new projects further stresses the Corps' workload as these projects inevitably compete for funding with ongoing projects that offer much greater benefits, relative to their costs. As a result, some projects cost more than they need to, and most projects are completed many months - and sometimes years - later than they could.

F.4.16 Senator Susan Collins and Senator Joseph Liberman, Senate Homeland Security Committee Holds Hurricane Katrina Hearing to Examine Levees in New Orleans, Press Release, November 2, 2005.

Examining why the levees in New Orleans failed following Hurricane Katrina is a crucial part of our committee's investigation. While some of the flood walls and levees were overtopped, something much more catastrophic happened that was not anticipated. Some of the levees and flood walls failed outright, leaving gaping holes through which water rushed uncontrollably into the neighborhoods of New Orleans.

This flooding caused enormous destruction and tragic loss of life that would not have occurred if the levees had held. The people of New Orleans put their faith in the levee system and unless the cause of this failure is investigated and addressed, New Orleans will remain a city in jeopardy.

A lot of the flooding of New Orleans should not have happened, and would not have happened if not for human error and the 0possibility of malfeasance suggested by one of our witnesses in the design and construction of the city's levees.

Today's testimony about the inadequacy of the levees to protect the people of New Orleans is as disheartening, as heartbreaking, as infuriating, and ultimately as embarrassing as the scenes of degradation and despair that we saw in the immediate aftermath of Hurricane Katrina.

Both Senators expressed their concern by the fact that the levees were constructed to withstand a Category 3 hurricane. But while Katrina was only a Category 1 when it hit parts of New Orleans, the levees still failed, causing 80 percent of the city to flood, more than twice as much as would have occurred had the levees held.

F.4.17 Senator Susan Collins (2005). "Hurricane Katrina: Who's In Charge of the New Orleans Levees?" Hearing Statement Before Homeland Security and Governmental Affairs Committee, December 15, Washington, DC.

While the levees were absolutely critical to the survival of the city, our November 2nd hearing demonstrated that this last line of defense was fatally flawed in design, construction, or maintenance. The people of New Orleans and surrounding parishes depended on the levees to protect them. It now appears their faith had little foundation. Even though the hurricane caused extensive damage, it was the flooding from the levee breaches that actually destroyed the City of New Orleans.

The Army Corps of Engineers, the Orleans Levee District, and the Louisiana Department of Transportation and Development are the key players. But they each played their parts in a system fragmented by overlapping obligations and inexplicable past practices. Once the levees were constructed the Army Corps of engineers is expected to: turn over completed sections to the Orleans Levee District; perform an annual inspection with the District; and review the semi-annual reports filed by the District.

The Orleans Levee District is charged by law with: operating and maintaining the levees; conducting a quarterly inspection of the levees at least once every 90 days; and filing a semi-annual report with the Army Corps. The Louisiana Department of Transportation is obligated by state law to: approve the soundness of the engineering practice and the feasibility of the plans and specifications submitted by the Orleans Levee District; conduct training of the District's commissioners; and review the District's emergency plans.

Today we will hear about the reality, about the confusion on issues as fundamental as control, the misunderstandings, and what appear to be outright abdications of responsibility." "the uncertainty about control, combined with overlapping responsibility for emergency management, affected the repair efforts at one of the breach sites after Hurricane Katrina. In a staff interview, the Commander of the New Orleans District of the Army Corps of Engineers described the confusion: 'Who is in charge? Where's the Parish President? Where is the Mayor? And then the State?…Who is in charge?

F.4.18 Herman Leonard and Arnold Howitt (2006). "Katrina as Prelude: Preparing for and Responding to Future Katrina-Class Disturbances in the United States," Testimony U.S. Senate Homeland Security and Governmental Affairs Committee, Washington DC, March 8.

The inescapable reality is that the United States - its governmental units and its society as a whole - is not now and never has been prepared adequately to deal with a disaster the scale of Hurricane Katrina. … but while there were individual failures involved, the story is not principally a story of individual failures - it is, instead, a story of failures of systems and of failures to construct systems in advance that would have permitted and helped to produce better performance and outcomes.

The leadership failures that contributed to the events we witnessed on the Gulf Coast last August and September began long, long before Katrina came ashore. It literally took centuries to make the mistakes that rolled together to make Katrina such a vast natural and human-made calamity. First, for hundreds of years, people have been constructing and placing large amounts of previous (human lives) and expensive (infrastructure, homes, communities) value in new Orleans and along the Gulf Coast in the known path of severe storms. Second, for decades, we have been living with inadequately designed, built, or maintained man-made protections (levees, building codes, pumps, and so on), and have pursued policies and interventions that actively contributed to the destruction of the natural buffers (salt marshes, dunes, and other natural barriers) against the hazards created by placing value in harm's way. Third for years - at least since 9/11, but even before that - we have known that we had systems of preparation and response that would prove inadequate against truly large scale disasters. Fourth, in the days and hours before Katrina's landfall, we failed to mobilize as effectively as we might have those systems that we did have in place. And fifth, the days following the impact, we did not execute even the things that we were prepared to do as quickly and smoothly as we should have.

How do we not, in the future, find ourselves again with those same regrets? Our work needs to begin with a judicious and honest assessment of threats, followed by investments in prevention and mitigation and by construction of response systems that will be equal to a larger of class of disturbances than we have previously allowed ourselves to contemplate.

F.4.19 Congressional Research Service (2003). *Army Corps of Engineers Civil Works Program: Issues for Congress*, Issue Brief for Congress, N. Carter and P. Sheikh, Washington DC, May 21.

The Corps is a unique federal agency located in the Department of Defense with military and civilian responsibilities; it is staffed predominantly by civilians. Through its military program, the Corps provides engineering, construction, and environmental management services to the Army, Air Force, government agencies, and foreign governments. the Corps military program is currently active in restoring the capability for oil production, oil refining, and gas processing as well as other activities in Iraq.

At the direction of Congress, the Corps plans, builds, operates, and maintains a wide range of water resources facilities under its civil works program. The Corps' oldest civil responsibilities are creating navigable channels and controlling floods. during the last decade, Congress has increased Corps responsibilities in the areas of ecosystem restoration, environmental infrastructure, and other non-traditional activities such as disaster relief and remediation of formerly used nuclear sites. The economic and environmental impacts of Corps projects can be significant locally and regionally, and at times are quite controversial.

The civil works budget of the Corps consists primarily of funding for the planning, construction, and maintenance of specific projects; appropriations are made as part of the Energy and Water Development Appropriations bills. Funding for Corps civil works has often been a contentious issue between the Administration and Congress, with appropriations typically providing more funding than the Administration has requested, regardless of which political party controls the white House and Congress.

Congress typically authorizes Corps projects as part of a biennial consideration of a Water Resources Development Act (WRDA). The trend in the last decade has been to authorize projects earlier in the development and review process than in the past. Congress might authorize a project following a review by the Assistant Secretary of the Army for Civil Works and the Executive Office of the President, Office of Management and Budget (OMB) and a favorable Chief of Engineers report; on the basis of a favorable Chief's report without senior administrative review; or contingent on a favorable Chief's report being completed within a year. Most projects authorized since WRDA 1996 have not undergone senior administrative or OMB review prior to receiving congressional authorization.

Contingent authorization, authorization prior to OMB review, and another practice - authorization in appropriations bills - have been criticized by some Members of Congress and Corps critics. The critics contend that contingent authorization rushes projects through critical stages of the development process and that congressional decisions are made without basic project information. They also argue that authorizations prior to senior review by the Administration result in insufficient review from a national perspective.

There also has been criticism regarding the type of projects authorized in recent WRDAs. Local sponsors of navigation and flood control projects fear that the Corps' growing involvement in ecosystem restoration and other new responsibilities detracts from the agency's more traditional missions.

Criticism of Corps project development has been raised for decades, particularly since the growth of the environmental opposition to large water resources development projects in the 1970s. Although Congress passed greater local cost-sharing requirements in 19865, it has enacted few changes to how the Corps develops and evaluates projects.

In response to two events in 2000, support for changing how the Corps undertakes and reviews projects has gained some momentum. First, the Washington Post published a series of articles raising questions about the integrity of the Corps planning process. Second, a Corps economist when public as a whistleblower contending that Corps officials manipulated a benefit-cost analysis to support expensive lock improvements on the Upper Mississippi River-Illinois Waterway.

The Bush Administration has generally approached reform as a fiscal issue linked primarily to the agency's growing construction backlog. Over the longer term, many more projects have received authorization than appropriations, resulting in a backlog consisting of over 500 'active' authorized projects with a federal cost of approximately $44 billion. To reduce the construction backlog, the President's FY 2004 budget request focuses the agency's civil works activities on specific projects within the agency's water resources missions of navigation, flood control, and environmental restoration. during the 1990s, Congress continued biennial authorizations of navigation and flood control projects and began authorizing more environmental activities and non-traditional projects.

In contrast, legislative proposals during the 107th and 106th Congresses consisted less of fiscal reforms and more of improved project development processes and review procedures. In 2003, Corps officials testified on how the agency is 'transforming' itself in response to the criticism levied against its practices. Corps officials defended the integrity of the agency's review processes and detailed recent efforts to further strengthen it.

There are currently two initiatives to change the operation of the Corps civil works program: the government-wide President's Management Agenda and an Army initiative referred to as the Third Wave. Neither initiative specifically targets the Corps, but both encompass Corps activities. The President's Management Agenda was undertaken by the Bush Administration as part of a movement toward more entrepreneurial government; one of the five components of the President's Management Agenda is a competitive sourcing initiative. The President's Management Agenda directed executive agencies to competitively source commercial activities in order to produce quality services at a reasonable cost through efficient and effective competition between public and private sources. The administration mandated for FY 2002 and FY 2003 the competition of 5% and 10%, respectively, of the positions performing commercial activities at agencies, including the Corps.

The Army's Third Wave initiative is broader than the President's Management Agenda. The Third Wave is a search for ways to improve the Army's operations by focusing its energies on its core war-fighting competencies. This includes a review of all positions and functions (i.e., entire areas of responsibilities and missions, such as wetlands regulation) that are not part of the Army's core military competencies. Actions that can be considered under the Third Wave for non-core functions and positions include competitive sourcing, privatization, transfer of responsibilities to other agencies, and divestiture. A significant portion of the Corps workforce was included in the first phase of the third Wave because much of the water resources work performed by the Corps is not considered essential to the Army's war fighting competencies.

F.4.20 U.S. General Accounting Office (2003). Corps of Engineers Improved Analysis of Costs and Benefits Needed for Sacramento Flood Protection Project, Report to Congressional Requesters, GAO-04-30, Washington DC, October.

The Corps did not fully analyze likely cost increases for the Common Features Project or report them to Congress in a timely manner. Corps guidance generally directs the Corps to seek new spending authority from Congress if it determines, before issuing the first construction contract, that it cannot complete the project without exceeding its spending limit. A severe storm in January 1997 demonstrated vulnerabilities in the American River levees and alerted the Corps of the need to do additional work to close the gaps in the cut-off walls at bridges and other areas and extend the depth of some cut-off walls from about 20 feet to about 60 feet. Although these design changes were likely to increase project costs significantly, the Corps did not use cost risk analysis, or any other analysis, to determine the potential extent of the increases. the Corps then began constructing the redesigned American River levee improvements without communicating to Congress the project's potential exposure to substantial cost overruns. In 2002, when the Corps finally updated project costs, it had already completed or contracted at a much higher cost for most of the American River levee improvements that were authorized in 1996. Because of the reporting delay, Congress did not have the opportunity to determine whether, at these higher costs, building these levee improvements was an efficient and effective use of public funds. by 2003, the corps had committed most of the funding authorized for the entire Common Features Project to the 1996 American River work, thereby leaving the 1999 work and the Natomas Basin improvements without funding.

In response to the criticism that the Corps had failed to design the levee protection to account for seepage that caused failure of some of the levees in the 1997 flooding, the Corps replied to the GAO: "The Army stated that the levee improvements were not originally designed to withstand the destructive effect of seepage and that this design was not an error. Rather, an unknown condition (i.e., the potential for destructive seepage under the levees) resulted in design changes and increased costs.

The Corps made several mistakes in estimating the economic benefits for the American River levee improvements. First, in 1996, the Corps incorrectly calculated the economic benefits by over-counting the residential properties that the levees would protect. The actual number of protected residential properties was about 20 percent less than the number that the Corps estimated. although the Corps updated its benefit estimate in 2002, it again made mistakes in estimating benefits because it incorrectly determined that the levee improvements authorized in 1999 would protect a larger area from flooding that they will and used an inappropriate methodology to determine the amount of flood damages the levee improvements would prevent. However, it is also important to recognize that the levee improvements may reduce the loss of human lives in the event of a flood, which is a benefit that is not included in the Corps' analysis. Second, although the Corps' policy calls for reporting a range of benefits from the levee improvements and the likelihood of realizing them, in 2002 the Corps reported only a single estimate of benefits. The Corps did not provide a range of benefits to Congress because it did not use the most current version available of its computer software, which could have performed the analysis. Finally, although the Corps has a three-tiered quality control process to ensure that it prepares economic analyses accurately and appropriately, this process did not identify the mistakes we found, which raises questions about the effectiveness of the Corps quality control process.

It is important to remember that, in addition to the economic benefits from preventing property damage, levee improvements may reduce the risk of loss of human lives, which is a benefit that is not included in the Corps' calculations. According to the Corps, about 305,000 people live within the American River floodplain and the number of lives lost because of levee failure would depend on a variety of factors, such as the size of the flood, warning time, time of day, and availability of evacuation routes. Because of the many factors involved and the lack of historical data, the Corps was not able to estimate the number of lives that would be lost as a result of levee failure and flooding in the Sacramento area.

The Corps' guidance (Engineer Regulation 1105-2-100) directs the Corps to address the issue of prevention of loss of life when evaluating alternative plans - which the Corps did. However, the Corps is not required to formally estimate the number of lives saved or lost as a potential effect of a project. In situations where historical data exist, the Corps has the option to estimate the number of persons potentially affected by a project, and include this number as an additional factor for the consideration of decision makers.

It is critical that decision making and priority setting be informed by accurate information and credible analysis. Reliable information form the Corps about costs and benefits for the American River component of the Common Features Project has not been present to this point. the analysis on which Congress has relied contained significant mistakes. and of most relevance today, the analyses for the remaining work do not provide a reliable economic basis upon which to make decisions concerning the American River levee improvements authorized in the WRDA of 1999. To provide a reliable economic basis for determining whether these improvements are a sound investment, the Corps' analysis needs to adequately account for the risk that project costs could increase substantially, correctly count and value the properties the project would protect, and include information on the range of potential project costs and benefits.

F.4.21 Heinzerling, L. and Ackerman, F. (2002). "Pricing the Priceless: Cost-Benefit Analysis of Environmental Protection," Georgetown Environmental Law and Policy Institute, Georgetown University Law Center.

Proponents of cost-benefit analysis make two basic arguments in its favor. First, use of cost-benefit analysis ostensibly leads to more efficient allocation of society's resources by better identifying which potential regulatory actions are worth undertaking and in what fashion. advocates of cost-benefit analysis also contend that this method produces more objective and more transparent government decision-making by making more explicit the assumptions and methods underlying regulatory actions.

In fact, cost-benefit analysis is incapable of delivering what it promises. First cost-benefit analysis cannot produce more efficient decisions because the process of reducing life, health, and the natural world to monetary values is inherently flawed. Efforts to value life illustrate the basic problems. Cost-benefit analysis implicitly equates the risk of death with death itself, when in fact they are quite different and should be accounted for separately in considering the benefits of regulatory actions. Cost-benefit analysis also ignores the fact that citizens are concerned about risks to their families and others as well as themselves, ignores the fact that market decisions are generally very different from political decisions, and ignores the incomparability of many different types of risks to human life. the kinds of problems which arise in attempting to define the value of human life in monetary terms also arise in evaluating the benefits of protecting human health and the environment in general.

Second, the use of discounting systematically and improperly downgrades the importance of environmental regulation. While discounting makes sense in comparing alternative financial investments, it cannot reasonably be used to make a choice between preventing noneconomic harms to present generations and preventing similar harms to future generations. Nor can discounting reasonably be used to even make a choice between harms to the current generation; the choice between preventing an automobile fatality and a cancer death should not turn on prevailing rates of return on financial investments. In addition, discounting tends to trivialize long-term environmental risks, minimizing the very real threat our society faces from potential catastrophes and irreversible environmental harms, such as those posed by global warming and nuclear waste.

Third, cost-benefit analysis ignores the question of who suffers as a result of environmental problems and, therefore, threatens to reinforce existing patterns of economic and social inequality. Cost-benefit analysis treats questions about equity as, at best, side issues, contradicting the widely shared view that equity should count in public policy. Poor countries, communities, and individuals are likely to express less willingness to pay to avoid environmental harms simply because they have fewer resources. Therefore, cost-benefit analysis would justify imposing greater environmental burdens on them than on their wealthier counterparts. With this kind of analysis, the poor get poorer.

Finally, cost-benefit analysis fails to produce the greater objectivity and transparency promised by its proponents. For the reasons described above, cost-benefit analysis rests on a series of assumptions and value judgements that cannot remotely be described as objective. Moreover, the highly complex, resource-intensive, and expert-driven nature of this method makes it extremely difficult for the public to understand and participate in the process. Thus, in practice, cost-benefit analysis is anything but transparent.

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APPENDIX G: LOOK FORWARD

The inescapable reality is that the United States - its governmental units and its society as a whole - is not now and never has been prepared adequately to deal with a disaster the scale of Hurricane Katrina. … but while there were individual failures involved, the story is not principally a story of individual failures - it is, instead, a story of failures of systems and of failures to construct systems in advance that would have permitted and helped to produce better performance and outcomes. The leadership failures that contributed to the events we witnessed on the Gulf Coast last August and September began long, long before Katrina came ashore. It literally took centuries to make the mistakes that rolled together to make Katrina such a vast natural and human-made calamity.

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How do we not, in the future, find ourselves again with those same regrets? Our work needs to begin with a judicious and honest assessment of threats, followed by investments in prevention and mitigation and by construction of response systems that will be equal to a larger of class of disturbances than we have previously allowed ourselves to contemplate.

Herman Leonard and Arnold Howitt (2006)
Preparing for and Responding to Future Katrina-Class Disturbances in the United States
Testimony U.S. Senate Homeland Security and Governmental Affairs Committee
Washington DC, March 8.

G.1 High Reliability Organization: The USN Nuclear Propulsion Program

A high reliability organization (HRO) is one that successfully works with extremely complex, potentially hazardous technologies by operating at extremely high levels of reliability and safety. We can extend this definition to include organizations that operate at extremely high levels of quality. Quality is defined as freedom from unanticipated defects and the ability to satisfy the serviceability, safety, compatibility, and durability requirements of those that own, operate, design, construct, regulate, and are affected by the engineered system.

Research has shown that serious accidents involving hazardous systems can be prevented through intelligent organizational design and management. HROs are thus organizations that must operate in a challenging environment requiring the use of advanced engineering methods in which the cost of failure is so great that it needs to be avoided all together. High reliability theory does not take the naive stance that *people* have the ability to behave with perfect rationality. However the theory does assert that *organizations* can compensate for human frailties and can therefore be significantly more rational and effective than individuals.

Over the years, high reliability theorists have identified four critical causal factors that constitute a HRO (Sagan 1993):

> *…the prioritization of safety and reliability as a goal by political elites and the organization's leadership; high levels of redundancy in personnel and technical safety measures; the development of a "high reliability culture" in decentralized and continually practiced operations; and sophisticated forms of trial and error organizational learning.*

While the exact mix of strategies appropriate in a given case depends on the nature of a particular problem, the catastrophe-aversion strategy outlined above should be applicable to virtually any risky technology (Marone and Woodhouse 1986). In this section, we will briefly look at some of the characteristics of the United States Navy's Nuclear Reactor Program under Hyman G. Rickover's leadership that made it a HRO.

G.1.1 The USN Nuclear Propulsion Program

> *... the Naval Nuclear Propulsion Program embodies unsurpassed engineering and sustained excellence that few technical programs in or out of government can claim. In every area of performance, standards, safety, and environmental care, the Naval Nuclear Propulsion Program has excelled. ...*

Former President Bill Clinton

The Naval Nuclear Propulsion Program is a joint Department of Defense / Energy program formed between 1947 and 1948 following WWII under the direction of then Captain Hyman G. Rickover. Its goal was to utilize the new knowledge developed during the war to research, design, construct, operate, and maintain all nuclear-powered submarines. Later the organization's scope was broadened to include all U.S. nuclear-powered warships (i.e., aircraft carriers). Previous studies have shown that the Naval Reactors (NR) program is an archetypal HRO and has all four critical elements identified by high reliability theory (Columbia Accident Investigation Board 2003). NR has over 900 reactor-years of experience with nuclear technology with an unblemished safety record. As a result, many important observations regarding public high reliability organizations can be drawn from looking at the NR program under Rickover's command including:

- People are the most important element to an organization. An extraordinary amount of time and resources are needed to ensure proper selection, education, and training of the personnel.
- Complex jobs cannot be designed reliably with transient personnel.
- Scientist or engineers should not make assumptions if they truly do not understand the environment of the problem.

HRO should be actively involved in organizations that have an influence on their operations as a means to control the external environment they must operate in (closed rational system). When a HRO must interact or rely upon other organizations to complete its clear and agreed upon goals, the personnel of the HRO should be at least as equally knowledgeable as the other organizations staff in the area you are working with them. HROs should be actively involved in organizations that have an influence on their operations as a means to control the external environment they must operate in.

One characteristic of a HRO is that it fits into what W. Richard Scott has called "closed rational systems" approach in organization theory. The HRO is *rational* in the sense that they setup highly formalized structures that are oriented toward the achievement of clear and consistent goals. They are *closed* in the sense that great effort is put into minimizing the effects the environment outside the organization has on the achievement of its objectives.

In this respect, the Naval Reactors program was intentionally formed under both the US Navy Bureau of Ships (BuShips) and the Department of Energy's Atomic Energy Commission (AEC). The BuShips has the authority to design, build, and maintain all US naval ships. NR's association with BuShips gave the agency the legal authority to sign contracts, spend money, and approve ship design features. The 1946 Atomic Energy Act on the other hand states that the responsibility and authority for anything atomic is in the AEC's hands. This includes atomic fuel procurement, fabrication, reprocess, reactor safety inspections & evaluations. Therefore Rickover intentionally established the NR program to be in the AEC to give it the legal authority to sign contracts and make arrangements to deal with atomic materials and secrets. This "dual citizenship" of sorts served to give the NR program the legal authority to do its job with a minimum degree of outside interference.

Within Naval Reactors, strong, clear, and open communications is paramount to the organization's success. Rickover continually made the point to the media that he had no organizational structure. In 1980, with a total of 359 engineering, financial, naval, and clerical personnel in his Washington office, he solemnly issued an elaborate organization chart to the media. Only the title, date, and signature were in English; the numerous squares bore Chinese characters (Duncan 1990). Rickover was attempting to communicate, albeit sarcastically, that NR has as little communication barriers as possible in the organization to enable people to communicate with whomever they felt was the most capable of answering their question. This quality is crucial in ensuring the future safety and reliability of the program. Regardless of how well trained and educated "a channel to communicate information to the highest levels of the organization management without barriers" is often needed.

It is worth mentioning while the NR program seeks to minimize the degree of outside interference other organizations had on its ability to design, construct, and operate nuclear submarines, NR is dependent on private contractors and institutions in both the public and private sector in fulfilling its mission. This does not only apply to public organizations, but private corporations as we move to a more global economy where outsourcing is the norm rather than the exception. NR addresses this challenge by seeking that their personnel be at least as knowledgeable as the outsourcer's staff. This allows NR to perform reliable oversight of outsourcing activities by decreasing the likelihood of being misled, and internally provides the capability of leading outsourced duties at the desired level of quality if the outsourcer is unable. Rickover for example had an extensive amount of knowledge about industry and the level of quality they can achieve after the war if appropriately encouraged. This allowed him to outsource work to private contractors and still maintain a high quality engineering product. This further highlights the importance of recruiting and maintaining a highly qualified engineering workforce even if the agency continues to expand its outsourcing efforts in the hope of improving efficiency.

As the nation begins to consider how it might 're-engineer' the Army Corps of Engineer's Civil Works program in light of Katrina, it is important that the Corps relationships with other private and public organizations that might enhance or diminish the quality of water resource projects also be evaluated. This includes relationships with the White House, Congress, local and state governments, and private contractors.

G.1.2 Personnel Recruitment and Retention

complex jobs cannot be accomplished effectively with transients.

Extensive historical investigations of engineered systems where quality was compromised and led to a catastrophic consequence (i.e., human life or financial) performed by the authors concluded that 80% of them were due to human or organizational factors. Of these HOF failures in engineering systems, most occur during their operation or maintenance as a result of errors in design or construction. Therefore, to effectively build and maintain an organization that reliably designs and constructs large-scale complex engineering systems, a lot of time and care must be put into its personnel. Rickover shared this belief and in 1979 testified before the subcommittee on energy research and production of the House Committee on Science and Technology following the Three-Mile Island incident (Rickover 1979):

> *Properly running a sophisticated technical program requires a fundamental understanding of and commitment to the technical aspects of the job and a willingness to pay infinite attention to the technical details. I might add, infinite personal attention. This can only be done by one who understands the details and their implications. The phrase, "The Devil is in the details" is especially true for technical work. If you ignore those details and attempt to rely on management techniques or gimmicks you will surely end up with a system that is unmanageable, and programs will be immensely more difficult to solve. At Naval Reactors, I take individuals who are good engineers and make them into managers. They do not manage by gimmicks but rather by knowledge, logic, common sense, and hard work and experience.*

The challenging and exciting projects at the NR program have allowed the agency to recruit, select and maintain a highly qualified personnel workforce. At the time of its founding, the US Navy Nuclear Reactors program was one of the most premier engineering organizations a young person could hope to work for. The organization was leading the world in advancing science and technology with respect to reactor design. The excitement of working on cutting-edge projects allowed the organization to successfully recruit from the cream of the Navy Engineering Duty Officer (EDO) community, National Laboratories, and the submarine force (Krahn, unpublished manuscript, 1992).

From this pool, the NR program's senior leadership (Rickover included) spent a significant amount of time evaluating and selecting prospective NR engineering personnel. As noted earlier in this investigation, approximately 80% of engineering system failures are caused by human errors (Bea 2006). In order to effectively reduce the probability of failure, it is critical that the performance of the men and women that directly interface with its design, construction, operation, and maintenance be improved. One way to effectively improve personnel performance is to spend more time selecting individuals who have "right stuff" and less time trying to "train" individuals who don't. The right stuff in the NR program was identified to be a combination of desirable technical and behavioral traits. Often times, especially in engineering, employees are selected almost exclusively on practical technical competence. In addition to this, the NR program also assesses the behavioral traits through personal interviews. In addition to other traits this interview serves to understand an engineer's ethics when exposed to anything from normal to high levels of pressure/stress. Rickover highlighted the objective of this part of the selection process in the NR program (Rockwell 1992):

> *…what I'm trying to find out is how they will behave under pressure. Will they lie, or bluff, or panic, or wilt? Or will they continue to function with some modicum of competence and integrity? I can't find that out with routine questions. I've got to shake 'em up. That's the only way I'll know….*

Engineering organizations charged with designing, constructing, operating, or maintaining complex engineering systems can not do so successfully with low personnel retention. When an engineering organization has a large turnover, one can expect low morale and dedication amongst personnel as well as high error rates. Although the effect of turnover level on organizational performance depends critically on the nature of the system in which the turnover occurs, generally an organization can expect disruption of social and communication structures, increased training and assimilation costs, and decreased cohesion and commitment of members who stay (Arthur 1994). Additionally, the organization can expect lower levels of organizational memory and learning.

The NR program shared the belief that complex jobs cannot be accomplished effectively with transients. To minimize the agency's turnover rate, the NR program required that all prospective engineering personnel be volunteers. Furthermore, the personnel were continually offered the kind of challenges and rewards in their work where they could overlook the shortcomings of their monetary compensation typical in many public-sector organizations. This allows the organization to benefit fully from their knowledge, experience, and corporate memory (Rockwell 1992). This includes the reporting of near-misses, as we will see later is a crucial element to managing risk in a complex system (i.e., organizational learning).

Former director of the Naval Nuclear Propulsion program, Admiral "Skip" Bowman, discussed some of the program's issues with respect to retention following a decrease in submarine orders after the Cold War:

> *Although the build rate had changed dramatically, the importance of maintaining tight controls didn't change, and the demographics of the organization became an issue. Were we going to wake up six years from now and find that the old guard had tuned gray and gone away and that we hadn't watched closely enough the professional development of the youngsters who need to be stepping in as section heads? We looked at the retention pattern at Naval Reactors, and it wasn't good. So we dramatically changed the opportunities for professional development and worked at making young engineers feel more and more a part of this organization – to create a niche where they could feel comfortable supporting their own desires, aspirations, and families.*

The Naval Reactor program would not survive very long if the personnel were not clearly dedicated to their jobs. For this reason the NR program can be said to follow what human resource researchers have called a *commitment* versus a *control* human resource system. Commitment human resource systems focus on developing committed employees who can be trusted to use their discretion to carry out job tasks in ways that are consistent with organizational goals (e.g., quality). In contrast, control human resource system's objective is to improve efficiency by enforcing employee compliance with specified rules and procedures and basing rewards on some measurable output criteria. Generally, organizations that adopt this strategy have a much higher percentage of non-dedicated personnel that are hence more likely to violate the formal and informal procedures in the organization and less inclined to adopt management's leadership in creating a quality culture within the organization (Arthur 1994).

G.1.3 Engineering Assumptions

A critical aspect to life-cycle engineering is the treatment of uncertainties. In design and construction, many traditional engineering approaches are deterministic and thus require "conservative" assumptions of random variables. These variables can include anything from the price of steel to the compressive strength of concrete. The industry has notably established a variety of inspection and testing activities that improve our ability to predict the performance of our systems.

In designing the first nuclear powered submarine, many engineers who have never been on a submarine were asked to make very important design decisions. Rickover felt it was critical that any engineer or scientist not make assumptions if they truly did not understand the environment the submarine must operate in. This includes the internal (e.g., temperature), external (e.g., squalls or blast loads), and social (e.g., training/knowledge of crew or variable operational stress climates). Rickover used videos to help impress upon engineers the nature of the problem they are being asked to design. Furthermore, the organization went to great lengths to minimize communication barriers so that information could be transferred freely directly to the people who need it.

G.1.4 Conclusion

> *... Particularly noteworthy are the conservative rugged designs, standardized plants, thorough testing, comprehensive plant maintenance, emphasis on correcting small problems before they can grow, and the high degree of selection, training, and qualification of officers and enlisted personnel who operate the plants. These high standards and achievements continue to be reflected in the quality and competence of the Naval Reactors Headquarters and field organizations, including their dedicated laboratories, shipyards, manufacturing activities, and training facilities. ...*

Chairman, U.S. Nuclear Regulatory Commission, Shirley Jackson

Failure was never an acceptable option for Rickover. While this was largely due to the fact the Navy was looking for 'any' reason to get rid of Rickover and the program, but also because the consequences of a nuclear reactor failure are incredibly high. The flooding of New Orleans has made it abundantly clear that the consequences of a poorly designed, constructed, and maintained water resource infrastructure are also far too high for our country to sustain.

Many of the organizations responsible for building and maintaining flood protection in New Orleans, including the U.S. Army Corps of Engineers and the local levee districts, can learn a lot from High Reliability Theory and the example the Naval Nuclear Propulsion Program continues to set. The fluid organizational structure, vibrant exchange of ideas (coupled with developed communication skills), and coherent training programs are to be desired by many organizations. The structure of the organization allowed anyone to do whatever it is they saw that needed to be done and seek the necessary resources to do it. People were limited only by their own abilities and not by formal titles and organizational charts. The Corps leadership along with Congress and the White House must recognize the important role technical people have within the Civil Works program and take major steps to create an environment that stresses quality and reliability to its personnel and that can clearly be seen throughout the organization.

G.2 Findings from Other Studies: Organizing for Success

G.2.1 Report of the Committee on Homeland Security and Governmental Affairs (2006). Hurricane Katrina, A Nation Still Unprepared, United States Senate, Washington, DC, May.

A vital part of the Hurricane Katrina story lies in nearly two centuries of natural and manmade changes to the Louisiana coastline. When New Orleans was settled in 1718 the primary flood threat was the Mississippi River, not the Gulf of Mexico, which was separated from the city by an expansive coastal landscape that served as a buffer from storms emerging from the Gulf.

That protective landscape no longer exists. The ever changing and disappearing coastline left New Orleans more susceptible to hurricanes and contributed to the damage inflicted by Katrina. Should this trend continue, New Orleans and the rest of coastal Louisiana will become even more vulnerable to damage from future storms, and efforts to protect the city with levees and floodwalls will be undetermined.

While a comprehensive analysis of coastal Louisiana's environmental challenges and potential remedies is beyond the scope of this report, this section briefly examines some of the potential impacts of Louisiana's altered landscape on hurricane protection.

Louisiana's Changing Coastal Landscape is Increasing Hurricane Vulnerability

The Louisiana coastline is changing more rapidly than any other part of the country and, as a result, becoming more vulnerable to hurricanes. Over the last 70 years, Louisiana has lost over 1,900 square miles of coastal land - an area roughly the size of Delaware. At the peak of the trend in the 1960s and 1970s, Louisiana was losing 40 square miles of coastal land per year. This loss has slowed in recent years, primarily because the most vulnerable lands have already disappeared, but Louisiana is still losing 10 square miles of coastal land per year. As a civil-engineering magazine put it, "in southeastern Louisiana a football field worth of wetlands sinks into the sea every 30 minutes .

These coastal lands primarily consist of wetlands, including extensive cypress swamps and grass marshes. But Louisiana's barrier islands (an elongated chain of islands running parallel to the coast and serving as a barrier against waves) and even many higher ridges, which were formed by large amounts of sediment piling up along past banks of the Mississippi River, are also disappearing. The U.S. Geological Survey (USGS) projects that an additional 700 square miles could be lost by 2050 if no further actions are taken to halt or reverse current processes.

The Mississippi River is the single most important factor in sustaining coastal Louisiana. The river brings water, sediments, and nutrients from 41 percent of the land area of the contiguous U.S. to the coast of Louisiana. Prior to the extensive building of levees and dams along the Mississippi, the river carried nearly 400 million tons of sediment to the Louisiana Coast every year - enough to cover 250 square miles one-foot deep in sediment. The growing wetlands fed by the accumulating sediments, nutrients, and fresh water of the Mississippi have added 9,600 square miles of land to the Louisiana coastline over the last 6,000 years - a rate of 1.25 square miles per year. At its peak, this land, known as the Mississippi deltaic plane, accounted for nearly 20 percent of the land area of present-day Louisiana, including New Orleans.

Major causes of land loss in Louisiana have been identified. [10] Dams and diversions along the Mississippi River and its tributaries have greatly reduced the amount of sediment that reaches coastal Louisiana, and levees force the remaining sediment so far offshore that it falls directly onto the outer continental shelf and beyond, where it no longer contributes to sustaining or building coastal lands. By blocking natural flooding cycles, levees prevent fresh water and nutrients from the Mississippi River from nourishing and sustaining wetlands. Ten major navigation canals and more than 9,000 miles of pipelines servicing approximately 50,000 oil and gas production facilities in coastal Louisiana result in a large direct loss of land and also contribute to wetland loss from saltwater intrusion and dredging.

The Louisiana deltaic plane is essentially sinking, in a process known as subsidence, which occurs naturally as sediments deposited by the Mississippi are compacted over time. Oil and gas production further contribute to subsidence, potentially causing local subsidence three times greater than the highest natural subsidence rates. Finally, sea level is rising, primarily as a result of global warming.

The deterioration of Louisiana's coastal landscape of barrier islands, wetlands and higher ridges, and the effects of subsidence have made coastal communities more vulnerable to hurricane flooding. [17] New Orleans, in particular, is widely considered to be more vulnerable to hurricanes both because land in the city has subsided and because much of the barrier islands and wetlands that once surrounded the city have disappeared.

Many of the mechanisms by which barrier islands, shoals, marshes, forested wetlands, and other features of the coastal landscape protect against hurricanes are well-known. Geologic features such as barrier islands or the land mass associated with wetlands can block or channel flow, slow water velocities, and reduce the speed at which storm surge propagates. These effects can significantly restrict the volume of water available to inundate the mainland.

Forested wetlands can greatly diminish wind penetration, reducing surface waves and storm surge. Shallow water depths weaken waves via bottom friction and breaking, while vegetation provides additional frictional drag and further limits wave buildup. Where wetlands and shallow waters are in front of levees, they absorb wave energy and reduce the destructiveness of storm waves on the levees.

Depending on the rate of relative sea-level rise, healthy coastal wetlands can maintain a near sea-level landscape by trapping sediments or accumulating organic material, thus helping to counter subsidence and global sea-level rise. In contrast, when Louisiana's coastal wetlands deteriorate and disappear, the land held in place by the wetlands undergoes wave erosion, eventually washing away and leaving behind open water 10 to 12 feet deep.

On the other hand, the quantitative impact of wetlands and other coastal features on hurricane protection is poorly known. Anecdotal data accumulated after Hurricane Andrew suggests a storm-surge reduction along the Louisiana coast of about three inches per mile of marsh. During Hurricane Katrina, bottom friction and breaking reduced the average height of the highest one-third of waves from 55 feet in deep water (with peak waves above 80 feet), to 18 feet in shallower water outside of the barrier island east of New Orleans, to a fraction of that height in protected areas.

Researchers at the Louisiana State University (LSU) Hurricane Center found that, during Hurricane Katrina, levees protected by wetlands had a much higher survival rate than those bordering open water. For example, large sections of the Mississippi River Gulf Outlet (MRGO) levees that had little or no wetlands separating them from Lake Borgne disintegrated, while the nearby 20-Arpent Canal levee, protected by a buffer of marsh and wooded wetlands, remained standing. According to LSU researchers, an area about the size of a football field with the tree density equal to that found in most Louisiana swamps would reduce wave energy in a storm by 90 percent. These researchers further found that friction from marsh grasses and shrubs reduced water speed from Hurricane Katrina in some places from seven feet per second to three feet per second.

Subsidence is also contributing substantially to hurricane vulnerability. Subsidence occurs across the entire region, and therefore impacts not only natural features such as wetlands and barrier islands, but also man-made structures such as buildings and levees. According to a recent report by the U.S. Army Corps of Engineers (Corps) Interagency Performance Evaluation Task Force (IPET), which examines the hurricane protection levee system, the average rate of subsidence across the area is 0.6 feet over a decade. The rate of subsidence is frequently greater under cities and towns than under natural features: when areas are drained in order to prepare them for buildings, organic material in the soil decomposes and leads to further subsidence. In addition, the levees themselves further subside due to their own weight pressing down on the unstable soils of the New Orleans area. As a result, the effectiveness of the levee system deteriorates over time as both the levees and the region subside. The IPET report concluded that some portions of the hurricane protection system around New Orleans are almost two feet below their original elevations, further increasing their own vulnerability, and that of the areas they are designed to protect, to the power of hurricanes.

The changes to Louisiana's coastline have serious implications for the long-term sustainability of the region. Land subsidence and predicted global sea-level rise during the next 100 years mean that areas of New Orleans and vicinity now 5 to 10 feet below mean sea level will likely be 8 to 13 feet or more below mean sea level by 2100. At the same time, the loss of wetlands, barrier islands, and other natural features could eliminate protection from waves and allow for higher and faster moving storm surges. According to the National Academy of Sciences, these trends will make much of Louisiana's southern delta uninhabitable without substantial new engineering projects. In the long-term, New Orleans and other regions of the Louisiana deltaic plane cannot be protected without taking proper account of the tremendous change that is continuing to occur to Louisiana's coastal landscape.

G.2.2 Senator Susan Collins (2006). "Opening Statement", Committee on Homeland Security and Government Affairs, Hurricane Katrina: Recommendations for Reform," Washington DC, March 8.

The excuse we have heard from some government officials throughout this investigation, that Katrina was an unforeseeable ultra-catastrophe, has not only been demonstrated to have been mistaken, but also misses the point that we need to be ready for the worst that nature or evil men can throw at us. Powerful though it was, the most extraordinary thing about Katrina was our lack of preparedness for a disaster so long predicted.

This is not the first time the devastation of a natural disaster brought about demands for a better, more coordinated government response. In fact, this process truly began after a series of natural disasters in the 1960s and into the 1970s. One of those disasters was Hurricane Betsy, which hit New Orleans in 1965. The similarities with Katrina are striking: levees overtopped and breached, severe flooding, communities destroyed, thousands rescued from rooftops by helicopters, thousands more by boat, and too many lives lost.

Katrina revealed that this kaleidoscope of reorganizations has not improved our disaster management capability during these critical years. Our purpose and our obligation now is to move forward to create a structure that brings immediate improvement and guarantees continual progress. This will not be done by simply renaming agencies or drawing new organizational charts. We are not here to rearrange the deck chairs on a ship that, while perhaps not sinking, certainly is adrift.

This new structure must be based on a clear understanding of the roles and capabilities of all management agencies. It must establish a strong chain of command that encourages, empowers, and trusts frontline decision-making. It must replace ponderous, rigid bureaucracy with discipline, agility, cooperation, and collaboration. It must build a stronger partnership among all levels of government with the responsibilities of each partner clearly defined, and it must hold them accountable when those responsibilities are not met.

G.2.3 Newt Gingrich (2006). "Why New Orleans Needs Saving," *Time Magazine*, March 6.

Shortly after Hurricane Katrina devastated New Orleans, Speaker of the House Dennis Hastert wondered aloud whether the Federal Government should help rebuild a city much of which lies below sea level. The most tough-minded answer to that question demonstrates that rebuilding and protecting new Orleans is in the national interest. Reason: The very same geological forces that created that port are what make it vulnerable to Category 5 hurricanes and also what make it indispensable.

If engineering the Mississippi made New Orleans vulnerable, it also created enormous value. New Orleans is the busiest port in the U.S.; 20% of all U.S. exports and 60% of our grain exports, pass through it. Offshore Louisiana oil and gas wells supply 20% of domestic oil production. but to service that industry, canals and pipelines were dug through the land, greatly accelerating the washing away of coastal Louisiana. The state's land loss now totals 1,900 sq. mi. that land once protected the entire region from hurricanes by acting as a sponge to soak up storm surges. If nothing is done, in the foreseeable future an additional 700 sq. mi. will disappear, putting at risk port facilities and all the energy-producing infrastructure in the Gulf.

There is no debate about the reality of that land loss and its impact. On that the energy industry and environmentalists agree. There is also no doubt about the solution, Chip Groat, a former director of the U.S. Geological Survey, says, "This land loss can be managed, and New Orleans can be protected, even with project sea-level rise." Category 5 hurricane protection for the region, including coastal restoration, storm-surge barriers and improved levees, would cost about $40 billion - over 30 years. Compare that with the cost to the economy of less international competitiveness (the result of increased freight charges stemming from loss of the efficiencies of the port of new Orleans), higher energy prices and more vulnerable energy supplies. Compare that with the cost of rebuilding the energy and port infrastructure elsewhere. Compare that with the fact that in the past two years, we have spent more to rebuild Iraq's wetlands than Louisiana's. National interest requires this restoration. Our energy needs alone require it. Yet the White Houses proposes spending only $100 million for coastal restoration.

Washington also has a moral burden. It was the Federal Government's responsibility to build levees that worked, and its failure to do so ultimately led to New Orleans' being flooded.

The White House recognized that responsibility when it proposed an additional $4.2 billion for housing in new Orleans, but the first priority remains flood control. Without it, individuals will hesitate to rebuild, and lenders will decline too invest.

How should flood control be paid for? States get 50% of the tax revenues paid to the Federal Government from oil and gas produced on federally owned land. States justify that by arguing that the energy production puts strains on their infrastructure and environment. Louisiana gets no share of the tax revenue from the oil and gas production on the outer continental shelf. Yet that production puts an infinitely greater burden on 8it than energy production form other federal territory puts on any other state. If we treat Louisiana the same as other states and give it the same share of tax revenue that other states receive, it will need no other help from the government to protect itself. Every day's delay makes it harder to rebuild the city. It is time to act. It is well past time.

G.2.4 Houck, O. (2006). "Can We Save New Orleans?", Tulane Environmental Law Journal, Vol 19, Issue 1, 1-68, New Orleans, Louisiana.

So What Do We Do? Here is what we know. It is not just the tire, it's the car. And it's not just the car, it's the driver. Nothing in the system has made a numero uno priority either of protecting New Orleans from hurricanes or to restoring even hanging onto - the Louisiana coast. We have a flood control program, a navigation program, a permitting program, a coastal management program, a flood insurance program, a coastal restoration program - just for openers - and they do not talk to each other. They are riddled with conflicts, basically headless, basically goal-less, weakened by compromises and refuse outright to deal with first causes and first needs. So, this is a tall order.

We also know this. As they came ashore, there were really two Katrinas. One blew through the levees into New Orleans and St. Bernard, and topped the ones further south. The other smashed into coast-front development in a wide swath from Alabama to Texas, wiping out the first half-mile or so of Pass Christian, Waveland, Gulfport, Biloxi, half of Grand Isle, and all the way over to Holly Beach. Same set of storms, but the run-up for one was negligence, and the run-up for the other was arrogance. Building behind levees is one thing; you have some reason to think they'll hold up. Building on the edge of the gulf and thumbing your nose at it is another.

The vision for New Orleans is relatively clean. the city is a given, fixed in its history, architecture, economy and culture and these contributions call for maintaining it, as is, for as long as we can. Nobody needs to reinvent new Orleans: we simply need to get it back. Its protection will cost a fortune, and will take more than anyone wants to concede (and no small amount of luck, as we race the clock against the near-term hurricane seasons). But at least we know what we are driving at. Whether we succeed will depend on levees, flood gates, rational storm water management within the city walls, conservative building elevations, levees and one thing more: a viable coastal zone to buffer them, without which the system will not hold over time.

So here is the starting point: exactly what we do want the Louisiana coast to look like, to do for us, for say, the next century? …Earth to Louisianans: you really can't have this cake and eat it too. With all due respect, it is not just a matter of doing everything we want 'smarter.' It is a matter of getting straight what we want, and what comes first." … what comes next is the hardest step for any American community to take, and all be heresy in South Louisiana. A plan. The mere mention of planning raises blood pressures and brings on cries of Godless Communism.

…What we have had in the city of new Orleans and along the entire gulf coast is planning by default (local attorney Bill Borah calls it 'planning by surprise'). Planning takes place. It's just that we haven't taken part in it. Where water resources are concerned, it starts with real estate developers, port authorities, levee boards and other outside-the-ballot-box enterprises, their projects facilitated and funded by the Army Corps of Engineers. In their minds, the only question is a technical one: what kind of engineering do we need to get our project done? The system has produced the expected results: more rip-rap here, more drainage there, and levees to the horizon. The goal is - although it is never stated anywhere - to develop as much of the coast as possible. When you add the projects up, they determine the destiny of the city and South Louisiana.

What is apparent is that these levees, designed by engineers and approved by Congress, are the basic planning documents for the future of South Louisiana. what is north of these levees will be developed. What is south of them will be anyone's guess, although not for long; the map on global warming shows these coastal marshes gone within a century. De facto, we end up with a wall. Not all that adequate a wall, by the way. Only Category three, if that. Can you imagine the costs of maintaining even a Category three levee system winding back and forth to the Gulf from New Orleans to Texas" Can we imagine what will happen when development piles in behind it, and then gets flooded? Do we already know, from Lakeview and New Orleans East, what happens to land elevations behind levees once they are drained and paved?

Our choice is to start this process from the other end. If we do, another range of options open. There are a dozen major towns across the southern tier with thousands of homes and residents, and they deserve protection. But the way to provide it may be with the same kind of ring levee systems that protects (or should) New Orleans and its surrounding parishes, supplemented by flood gates at the mouths of the main canals. Or, it may mean peninsular levee systems down the historic ridges of the bayous, protecting what has always been the high ground. …Problem is, we have lacked the process - we have lacked even the language - for such a discussion. In addition to scientists and engineers, we may need some social workers. In saying this, I am most serious.

The Dutch have been fighting the North Sea for a thousand years, and their historic methods - dikes, drainage canals and pumps - look quite familiar, as does their continuing and accelerated rate of subsidence. Parts of the coast are now 23 feet below the level of the sea. the temporary successes of this engineering look familiar too, always followed by greater, catastrophic losses. finally, in 1953 a major hurricane blew in and left 1,800 bodies in its wake, 50,000 destroyed homes and 350,00 acres of flooded land. In a country half the size of Louisiana.

Vowing 'Never Again,' the country devised a new plan. Back in 1932, they had dikes off the Zuiderzee, an estuary twice the size of Lake Pontchartrain, with a barrier more than 20 miles long. Their new Delta Plan would apply that same strategy to the entire Atlantic Coast. They dammed every one of their major rivers, some of them multiple times. They diked off their estuaries, diked off entire seas, and reduced their coastline by more than two-thirds. The water is the enemy, explained a professor of engineering. 'You don't let the enemy, before the fight starts, penetrate your territory.'

They won. At a cost of about $18 billion over some 40 years, they completed their first rounds of the Delta plan and they haven't flooded since. They predict their strategy to hold for the next 500 years. At the same time they moved aggressively to fill lands behind their coastal barriers, 'polders' created literally from the sea. the polders produced fruit and vegetables. So far, it was all win-win.

Then another bill came in. Over half the estuaries disappeared, and those remaining were in trouble. Coastal fisheries were hammered. at the mouth of two of Europe's major rivers, the Meuse and the Rhine, the Grevelingen was the largest and most productive estuary on the Atlantic coast. Within two weeks of completing the barrier across it the mussels and shellfish were dead. the government tried to turn what is now a lake behind the barrier to tourism, but the water was, and remains, so contaminated that it is unfit for human contact. It is covered with toxic algae and more than 5 billion feet of polluted sludge has settled on the bottom. They had made a dead zone. ….Interfering with natural processes and natural systems is always a bad thing, says one. 'Mother nature is the best engineer'.

There is also a question of commitment. The Netherlands is a small country, and it has dedicated itself to fighting the sea. It cannot afford not to. Sixty percent of its land is below sea level. Louisiana, as valuable as it is to the nation and to those of us who live here, is only one piece of America, and America's attention span for this or any other endeavor is limited. so will be federal funding, and we are still in the heyday of a petroleum economy that cannot and will not, last. Unless Louisiana goes in a direction that is more self-sustaining over the long term, it could (end) up with a large white elephant on its hands.

Perhaps the most important lesson from the Netherlands experience is how it has since evolved. As noted, Dutch engineers have tried to retrofit their structures to accommodate natural processes, to recreate natural processes, with mixed success. Easier to do that from the start. As a matter of engineering strategy, they have now explicitly rejected big-levee and big-drainage solutions as unworkable. They have instead come to rely on multiple layers of defense, redundant in the safety they provide, and none designed to provide full protection on their own. Most significantly, they have changed their philosophy from 'flood control' to 'water management,' and are tiptoeing to the next logical, indeed the only logical step: people management. It is rather remarkable.

Meanwhile, it is most recent report, under the title Lessons Learned, the Netherlands Water Partnership says: The Netherlands is changing its approach to water. The country will have to make more frequent concessions. the report explains, we will have to relinquish open space to water, and not take back existing open spaces, in order to curb the growing risk of disaster due to flooding. Giving space does not mean the height of ever taller levees or depth by channel dredging. Rather, space in the sense of flood plains. …Only by relinquishing our space can we set things right; if this is not done in a timely manner, water will sooner or later reclaim the space on its own, perhaps in a dramatic manner.

If a sustainable coast is the goal, we need a map of what we can sustain. That map, in turn, should drive what we do for restoration and for human development, and for its protections. …If on the other hand, we start from the position of maintaining as much of the coastal zone and its natural storm barriers as we can, we meet a different set of possibilities. We interfere with natural processes as little as possible, remove barriers to them, and over time move to the traditional places Louisianans have always lived, the ridges of the natural bayous and distributaries leading to the gulf. We protect those zones. We also protect critical infrastructure for oil and gas, fisheries and essential navigation canals. For the rest, we let nature have the space it needs to rebuild and it will protect us in turn.

We also need new mapmakers. We have always thought of coastal management in terms of engineering, and engineering agencies are well funded at every level from the Corps to local levee districts, politically supported from top to bottom, and largely autonomous. …The nice thing about engineering is that it seems so certain. It may be faulty and the building may fall over, but responds to numbers and rules of physics. We are comforted by it. Usually, it works, or we would never take an airplane ride. and so we like engineering solutions. among other things, they made living in this part of the world possible. They also look impressive, big dams and canals. And, down inside, they allow us to move dirt and water around which we have all done and enjoyed from early childhood. Hard structure engineering has a great deal of history, money, and human nature going for it. Which is why we have lots of engineering maps.

Coast 2100, We can now put the puzzle together. In a post-Katrina world of greater urgency, funding and public awareness of the plight of New Orleans and the Louisiana coastal zone, we have the opportunity to go beyond Coast 2050, take it off the leash and see where we can really go: Coast 2100. Before suggesting a few principles for that new plan, let us reach two understandings.

The first is that restoring coastal Louisiana is a national issue and will require remedies beyond this state. We lie at the receiving end of a large watershed, and some of what we need has been turned off and other stuff that is hurting us has been turned on. The Corps districts need to talk to each other, The EPA has to step up to the plate, upstream states have to change some habits too. If the nation's taxpayers are going to be asked to spend more money than America spent on the Marshall Plan to fix all of post-war Europe, then they have a right to expect a national effort.

The second is the funding. When it comes to restoring the city of New Orleans itself, the funding should be federal. Not just restoring the levees, the city. However you look at it, and with plenty of supporting actors, the Corps of Engineers drowned new Orleans and the sight of individual homeowners trying to rip out, detoxify and rebuild their homes is one of the most unjust features of a post-Katrina world. New Orleans is a federal responsibility. You flood somebody, you pay.

Conventional wisdom holds that the Corps is immune from liability for its role in the levee failures, and case law supports that conclusion. United States v. James, 478 U.S. 597, 612 (1986). On the other hand, it seems a far stretch to say that 1929 statute dealing exclusively with Corps works on the Mississippi River should minimize the Corps for activities in a different location, of a different nature, at a later time. Whatever the legal merits, the federal government's moral obligation to repair the catastrophic damaged caused by its own agents seems clear. The obligation is not simply to provide better flood control; it is to repair the harm.

With these understandings, here are ten criteria for a coastal plan with the maximum long-term chance of success:

1. Draw the maps. Not just a flood protection plan. …To be sure, we need to know what the engineering possibilities are. But they beg the question, engineering to do what? Right now, we have the cart before the horse.

2. Review the bidding. the Corps and other agencies have projects pending that could seriously compromise an all-out effort to restore the coastal zone. …That Congress has already authorized them is not persuasive. Like MRGO, they were authorized in a very different day under very different circumstances. Katrina changed the equation. They need to be looked at again, new restoration map in hand. They should be consistent with the future, not the past.

3. Free the upstream sediments. The Mississippi today at the latitude of New Orleans carries about 80 million tons of sediment a year. An impressive figure, until we realize that a century and half ago it carried about 400 million….The point is that most of those silts today lie behind dams on the upper watershed. We need them, and the Mississippi is their natural conveyor belt. The bumper sticker should read: Free the Mississippi 400 Million.

4. Free the rivers. Which, until today, we have tiptoed around with a few, very expensive freshwater diversion structures whose efficacy has been further compromised by their capacity and politics….We can cut sills in the levees to replicate natural crevasses, and let the river do its thing.

5. Cut upstream fertilizers. …The upstream states are in denial, so is Louisiana for that matter, and EPA is in hiding. It is time to insist. A less polluted river is not a matter of aesthetics. It is a matter of survival.

6. Heal the marsh. Which is hemorrhaging from the inside out. Push in the spoil banks. Crevasse the ones that remain. Plat grass. Pretend we're farmers. We can build wetlands, if necessary, by hand. Not fully - manmade marshes still come out looking a little weird - but we need to rebuild a base for natural processes to then improve upon. A coast fully ceded to open water will be harder to restore.

7. Stop the bleeding. We will have to make historic commitments to hold onto even the base of coastal wetlands we currently enjoy, an order of magnitude beyond the ambition of Coast 2050. Meanwhile, we continue to permit dredging and filling of the same wetlands for access canals, waste dumps, new subdivisions and the like. Every acre of the coast we allow to be destroyed is certain loss. ..An ounce of prevention is worth a ton of restoration.

8. Make space for natural processes. Elevate roads and railroads. Open new floodways. Move oyster leases, consolidate energy, port and navigation facilities, zone development within protected areas and let the rest rebuild. We shouldn't try to storm-proof the coastal zone, and the more we try to storm-proof the more we will loose.

9. Dare to think retreat. …People and structures in the most vulnerable areas should be offered the opportunity to relocate in protected areas, at full and fair compensation. The costs of such a program will be more than offset by the savings in the attempt to protect these same residences forever, and in reduced looses to future storms. the more we delay this process, the harder it will be.

10. Face global warming. It is real. And it makes everything else we do to save the coast infinitely more difficult, if not impossible."

Senator Landrieu inserted an $800 million appropriation into the 2005-06 budget, directing the Corps to conduct such a study for both New Orleans and all of South Louisiana on a very tight schedule; a scant six months for a draft plan. It may seem curious to some that, for these purposes, we would go back to the very agency that built failing levees in the first place and has shown historic resistance to thinking outside the box. Such is the abiding faith of the congressional delegation in its historic water resources partner. It is what Congress knows. The output of such a process is likely to be the maximum development model. It is what the Corps Knows. An alternative model is not yet on the table.

The technical decisions here, form the outset, call for a broader base than that of the Corps. The Corps is qualified to make engineering and technical decisions. But as history shows, decisions of this magnitude should be reviewed by an entity that is truly independent, also expert, and with the authority to remand an unsupported conclusion. It could be the National Academy of Sciences, although the Academy is not structured to provide long-term services. It could be an empowered state agency. What ever the vehicle, well-qualified and indepe3ndent review seems essential.

As the Katrina relief debacle illustrated, shared responsibilities are necessary, but joint command is fatal. …but, our job calls for a new command with a single, unfragmented mandate - to save the Louisiana coastal zone - and the capacity to ensure that all other players are working towards that goal. This authority's first job is to prepare the maps that guide all that follows. Its second job is to review ongoing projects, flood-control and otherwise, that could affect the success of their plans. Its third job is to integrate restoration, development and flood control initiatives - in that order - to achieve long term sustainability. An agency with less autonomy, or with a different set of priorities, will not succeed.

Can We Save New Orleans? Here is our choice. We can live with nature next time around, or we can fight it for all the turf we can take and spend fortunes trying to defend it. When it comes to floods and hurricanes, a little space goes a long way. ….more problematically, we are likely to propose large outer barriers to protect the city as well, a second ring across the Rigolets and to the south. We are likely to extend these barriers, leaky or otherwise, across the entire Louisiana coast, for as far as the money will go. That is what we have always done, it is what the Corps of Engineers knows how to do, it avoids the need to plan, it sets up killings in real estate, and it is the easy path for politicians. Of course, it will be increasingly hard to maintain for even this century, the costs in trying will be enormous, and when there are failures more people will die. But those consequences are for another day. We are living now.

The point of this Essay is that we have a choice. Rather than start with the premise that we are going to protect as much of the Louisiana coast as we can from hurricanes and then graft on some restoration measures, we can start with the premise that we are going to restore as much of the Louisiana coast as we can and then see what we need to do, within that context, to protect people from hurricanes. The approaches are not the same, and they will lead to two very different futures. We are entitled to see the second one, before we are handed the first as a fait accompli. The first one is being prepared, by the Corps, on an unrealistically hasty schedule, as we speak.

There is another engineering outfit on the scene, however. Mother Nature. The best way to restore coastal Louisiana and to provide long-term safety for New Orleans and other coastal residents is to help nature get back in the game, and then stand back. Not very far back. Just far enough for it to work for us: a natural, self-sustaining, horizontal, first and major line of defense spinning off renewable resource dividends for generations to come. We can have a coast and live and work in it safely for a very long time. Just not everywhere, and doing every damn thing we want. Can we save New Orleans? It'll be a journey. Will we? Depends on no rain in the morning, and the path we choose.

G.2.5 Netherlands Water Partnership (2005). *Dutch Expertise, Water Management & Flood Control*, Delft, The Netherlands, November.

Climate changes are increasing the likelihood of flooding and water-related problems. In addition population density continues to increase, as does the potential for economic growth, and consequently, the vulnerability to economic and social disaster. two undesirable developments that, in terms of safety, exacerbate one another - a grown risk with even larger consequences. As such, the safety risk is growing at a n accelerated pace (safety risk - chance multiplied by consequence).

The Netherlands is changing its approach to water. This change involves the idea that the Netherlands will have to make more frequent concessions. We will have to relinquish open space to water, and not take back existing open spaces, in order to curb the growing risk of disaster due to flooding, we will also need to limit water-related problems and be able to store water for expected periods of drought. By this we do not mean space in terms of the height of ever taller levees or depth through continued channel dredging, but space in the sense of flood plains. This approach will require more area, but in return we will increase our safety and limit water related problems. Safety is an aspect that must plan a different role in spatial planning. Only by relinquishing our space can we set things right; if this is not done in a timely manner, water will sooner or later reclaim the space on its own, perhaps [in a] dramatic manner.

We are developing a new risk management approach that includes determining how far the government can and should go in providing protection against high water levels and how much it can and should spend for that purpose. We will base the approach on factors including the 'safe Netherlands roadmap.' In that project, the Ministry has joined forces with provincial governments and water boards to gauge the likelihood and consequences of flooding in each levee 'ring' (an area that is completely surrounded by levees).

The consequences of flooding are also taken into account in the Dutch risk management approach. Human and economic values also determine risk standards. Which means that no just technical expertise on dealing with flood management is needed, but also socio-economic experience. We support the decision-making process by providing scenarios, alternatives and public relations advice.

The Netherlands is divided into compartments with different risk levels of flooding. High density areas with greater human and economic interest, like Rotterdam and Amsterdam, are surrounded with stronger levees than rural areas and therefore have a lower risk level from flooding than others. One of the most difficult policy decisions in the Dutch in the next decade is to decide what level of protection is necessary, acceptable and cost-effective for each compartment.

Our standards are accepted risks related to the design-criteria of our dikes. Those standards are laid down in the Flood Defense Act. For the economically most important and densely populated part of the country, we design our dikes and dunes to be strong enough to withstand a storm-situation with a probability of 1 to 10,000 a year. That means, that a Dutchman - if he should live a 100 years - has a chance of 1 percent to witness such an event. For our parliament, these odds became the acceptable standard. For the less important coastal areas we calculate the probability of 1 to 4,000 and along the main rivers 1 to 1,250.

G.2.6 Interagency Floodplain Management Review Committee (1994). ***Sharing the Challenge: Floodplain Management into the 21st Century,*** **Report to Administration Floodplain Management Task Force, Washington DC, June.**

Over the last 30 years the nation has learned that effective floodplain management can reduce vulnerability to damages and create a balance among natural and human uses of floodplains and their related watersheds to meet both social and environmental goals. The nation, however, has not taken full advantage of this knowledge. The United States simply has lacked the focus and incentive to engage itself seriously in floodplain management. The 1993 flood has managed to focus attention on the floodplain and has provided the incentive for action.

The Interagency Floodplain Management Review Committee proposes a better way to manage the floodplains. It begins by establishing that all levels of government, all businesses and all citizens have a stake in properly managing the floodplain. All of those who support risk behavior, either directly or indirectly, must share in floodplain management and in the costs of reducing that risk. The federal government can lead by example; but state and local governments must manage their own floodplains. Individual citizens must adjust their actions to the risk they face and bear a greater share of the economic costs.

While development of the region has produced significant benefits, it has not always been conducted in a wise manner. As a result, today the nation faces three major problems:

First, as the Midwest Flood of 1993 has shown, people and property remain at risk, not only in the floodplains of the upper Mississippi River Basin, but also throughout the nation. Many of those at risk do not fully understand the nature and the potential consequences of that risk; nor do they share fully in the fiscal implications of bearing that risk.

Second, only in recent years has the nation come to appreciate fully the significance of the fragile ecosystems of the upper Mississippi River Basin. Given the tremendous loss of habitat over the last two centuries, many suggest that the nation now faces severe ecological consequences.

Third, the division of responsibilities for floodplain management among federal, state, tribal and local governments needs clear definition. Currently, attention to floodplain management varies widely among and within federal, state, tribal and local governments.

Now is the time to:

Share responsibility and accountability for accomplishing floodplain management among all levels government and with all citizens of the nation. The federal government cannot go it alone nor should it take a dominant role in the process.

Establish, as goals for the future, the reduction of the vulnerability of the nation to the dangers and damages that result from floods and the concurrent and integrated preservation and enhancement of the natural resources and functions of floodplains. Such an approach seeks to avoid unwise use of the floodplain, to minimize vulnerability when floodplains must be used, and to mitigate damages when they do occur.

Organize federal programs to provide the support and the tools necessary for all levels of government to carry out and participate in effective floodplain management.

G.2.7 Input from citizens of the greater New Orleans area Levees.Org

We the citizens of Levees.Org are pleased to submit the issues that we believe are critical to the future of New Orleans and southern Louisiana.

Mission. Flood protection must be the primary mission of the entity in charge of design and construction of the flood protection system. The US Army Corps of Engineers views their mission as not rocking the boat and following Congress' authorization. We feel that is the wrong mission.

Cost/Benefit. The Dutch have developed sophisticated and rigorous cost benefit analysis focused on protecting property and lives. This has guided hard decisions about what to protect and what to give back to nature. Decisions must be based upon sound cost benefit analysis and not politics.

Peer Review. There must be real-time independent peer review of the Corps' projects and practices to assure that the right projects are being done right. This review can be done both at the state level via the local levee boards and via private groups formed by local business and environmental interest. The review must be done concurrently so as not to delay time-sensitive projects.

Outrage. Finally, we at Levees.Org wonder: Where is the outrage? Over a thousand have died, a hundred thousand homes have been destroyed, and a historic American city lies in ruins. This was not a natural disaster. This was a manmade disaster caused by deeply ingrained institutional problems of the US Army Corps of Engineers and Congress. Every American should be outraged.

It is our hope that, through the expert opinion revealed in the National Science Foundation report that the nation and Congress will come to a better understanding of the issues concerning August 29, 2005. Hopefully, finally, we can all agree on what caused the Greater New Orleans Flood and begin the process of rebuilding New Orleans and southern Louisiana and making its citizens whole.

Respectfully submitted by
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G.2.8 Congressional Research Service (2005). *Aging Infrastructure: Dam Safety*, Report for Congress, K Powers, Washington DC, September 29.

While dams have multiple benefits, they also represent a risk to public safety and economic infrastructure. This risk stems from two sources: the likelihood of a dam failure and the damage it would cause. While dam failures are infrequent, age, construction deficiencies, inadequate maintenance, and seismic or weather events contribute to the likelihood. To reduce the risk, regular inspections are necessary to identify deficiencies and then corrective action must be taken.

To identify deficiencies that could cause dam failures, the federal government established inspection requirements for the nation's federal dams. Once deficiencies are identified, most agencies finance repairs through their operation and maintenance accounts. Funding mechanisms vary for larger rehabilitation activities. At the Bureau of reclamation, for example, most larger repairs are conducted with annual appropriations to its dam safety program. At some other agencies, dam rehabilitation must compete with other construction projects for funding.

At non-federal dams, safety is generally a state responsibility, though some federal assistance has been provided. Funding through the National Dam Safety Program, which is authorized through FY 2006, helps states improve their dam safety programs and train inspectors. In addition, the Federal Energy Regulatory Commission and the Department of

Labor, Mine Safety and Health Administration require regular inspections at the non-federal dams within their jurisdiction. Even so, there are concerns that most state dam safety programs have inadequate staff and funds to effectively inspect or monitor all of the dams for which they are responsible. Further, there are concerns that states, local governments, and other non-federal dam owners may not have the financial resources to maintain and rehabilitate their dams.

Following the failure of the levee at Lake Pontchartrain in 2005, it is likely that there will be increased scrutiny of flood control infrastructure and the structural stability of high hazard-potential dams. Further, there has been periodic pressure for Congress to pass legislation authorizing federal support for rehabilitation work at non-federal dams. Demand for such assistance is likely to increase, but there is currently no federal policy that describes the conditions under which federal funding is appropriate, nor has congress established criteria for prioritizing funding among non-federal projects.

G.2.9 Sparks, R. E. (2006). "Rethinking, Then Rebuilding New Orleans," Issues in Science and Technology, National Academy Press, Winter 2006, p 33-39, Washington DC.

New Orleans will certainly be rebuilt. But looking at the recent flooding as a problem that can be fixed by simply strengthening levees will squander the enormous economic investment required and, worse, put people back in harm's way. Rather, planners should look to science to guide the rebuilding, and scientists now advise that the most sensible strategy is to work with the forces of nature rather than trying to overpower them. This approach will mean letting the Mississippi River shift most of its flow to a route that the river really wants to take; protecting the highest parts of the city from flooding and hurricane-generated storm surges while retreating from the lowest parts; and building a new port city on higher ground that the Mississippi is already forming through natural processes. The long-term benefits - economically and in terms of human lives - may well be considerable.

To understand the risks that New Orleans faces, three sources need to be considered. They are the Atlantic Ocean, where hurricanes form that eventually batter coastal areas with high winds, heavy rains, and storm surge; the gulf of Mexico, which provides the water vapor that periodically turns to devastatingly heavy rain over the Mississippi basin; and the Mississippi River, which carries a massive quantity of water from the center of the continent and can be a source of destruction when the water overflows its banks. It also is necessary to understand the geologic region in which the city is located: the Mississippi Delta.

If Hurricane Katrina, which in 2005 pounded New Orleans and the delta with surge and heavy rainfall, had followed the same path over the Gulf 50 years ago, the damage would have been less, because more barrier islands and coastal marshes were available then to buffer the city. Early settlers on the barrier islands offshore of the Delta built their homes well back from the beach, and they allowed driftwood to accumulate where it would be covered by sand and beach grasses, forming protective dunes. The beach grasses were essential because they helped stabilize the shores against wind and waves and continued to grow up through additional layers of sand. In contrast to a cement wall, the grasses would recolonize and repair a breach in the dune. Vegetation offers resistance to the flow of water, so the more vegetation a surge encounters before it reaches a city, the greater the damping effect on surge height. The greatest resistance is offered by tall trees intergrown with shrubs; next are shorter trees intergrown with shrubs; then shrubs; followed by supple seedlings or grasses; and finally, mud, sand, gravel, or rock with no vegetation.

Of Course, the vegetation has its limits: Hurricanes uproot trees and the surge of salt or brackish water can kill salt-intolerant vegetation. Barrier islands, dunes, and shorelines can all be leveled or completely washed away by waves and currents, leaving no place for vegetation to grow. the canals cut into the Delta for navigation and to float oil-drilling platforms out to the gulf disrupted the native vegetation by enabling salt or brackish water to penetrate deep into freshwater marshes. The initial cuts have widened as vegetation dies back and shorelines erode without the plant roots to hold the soil and plant leaves to dampen wind- or boat-generated waves.

The ecological and geological sciences can help determine to what extent the natural system can be put back together, perhaps by selective filling of some of the canals and by controlled flooding and sediment deposition on portions of the Delta through gates inserted in the levees.

If New Orleans is to be protected against both hurricane-generated storm surges from the sea and flooding from the Mississippi river, are there alternative cost-effective approaches other than just building levees higher, diverting floods around New Orleans, and continuing the struggle to keep the Mississippi River from taking its preferred course to the sea? Yes, as people in other parts of the world have demonstrated.

Could the same approach be taken in the Delta, in the new Atchafalaya lobe? Advocates for rebuilding New Orleans in its current location point to the 1,000+ year levees and storm surge gates that the Dutch have built. But the Netherlands is one of the most densely populated countries in Europe, with 1,000 people per square mile, so the enormous cost of building such levees is proportional to the value of the dense infrastructure and human population there. The same is not true in Louisiana, where there are approximately 100 people per square mile, concentrated in relatively small parcels of the Delta. This low population density provides the luxury of using Delta lands as a buffer for the relatively small areas that must be protected.

However, the Dutch should be imitated in several regards. First, planners addressing the future of New Orleans should take a less on from the long-term deliberate planning and project construction undertaken by the Dutch after their disastrous flood of 1953. These efforts have provided new lands and increased flood protection along their coasts and restored floodplains along the major rivers. Some of these projects are just now being realized, so the planning horizon was at least 50 years.

Planners focusing on New Orleans also would be wise to emulate Dutch efforts to understand and work with nature. Specifically, they should seek and adopt ways to speed the natural growth and increase the elevation of the new Atchafalaya lobe and to redirect sediment onto the Delta south of New Orleans to provide protection from storm waves and surges. A key question for the Federal Emergency Management Agency (FEMA), the FEMA equivalents at the state level, planners and zoning officials, banks and insurance companies, and the Corps of Engineers is whether it is more sustainable to rebuild the entire city and a higher levee system in the original locations or to build a 'new' New Orleans somewhere else, perhaps on the Atchafalaya lobe.

Under this natural option, old New Orleans would remain a national historic and cultural treasure, and continue to be a tourist destination and convention city. Its highest grounds would continue to be protected by a series of strengthened levees and other flood-control measures. City planner sand the government agencies (including FEMA) that provide funding for rebuilding must ensure that not all of the high ground is simply usurped for developments with the highest revenue return, such as convention centers, hotels, and casinos. the high ground also should include housing for the service workers and their families, so they are not consigned again to the lowest-lying, flood-prone areas. The flood-prone areas below sea level should be converted to parks and planted with flood-tolerant vegetation. If necessary, these areas would be allowed to flood temporarily during storms.

At the same time, the Corps, in consultation with state officials, should guide and accelerate sediment deposition in the new Atchafalaya lobe, under a 50- to 100-year plan to provide a permanent foundation for a new commercial and port city. If old New Orleans did not need to be maintained as a deepwater port, then more of the water and sediment in the Mississippi could be allowed to flow down the Atchafalaya, further accelerating the land-building. The new city could be developed in stages, much as the Dutch have gradually increased their polders. The port would have access to the Mississippi River via an exiting lock (constructed in 1963) that connects the Atchafalaya and the Mississippi, just downstream of the Old River Control Structure.

This plan will no longer force the Mississippi River to go down a channel it wants to abandon. The shorter, steeper path to the sea via the Atchafalaya might require less dredging that the Mississippi route, because the current would tend to keep the channel scoured. Because the Mississippi route is now artificially long and much less steep, accumulating sediments must be constantly dredged, at substantial cost. Traditional river engineering techniques that maintain the capacity of the Atchafalaya to bypass floodwater that would otherwise inundate New Orleans also might be needed to maintain depths required for navigation. These techniques include bank stabilization with revetments and wing dikes that keep the main flow in the center of the channel where it will scour sediment.

Action to capitalize on the natural option should begin immediately. The attention of the public and policymakers will be focused on New Orleans and the other Gulf cities for a few more months. The window of opportunity to plan a safer, more sustainable New Orleans, as well as better flood management policy for the Mississippi and its tributaries, is briefly open. Without action, a new New Orleans - a combination of an old city that retains many of its historic charms and a new city better suited to serve as a major international port - will go unrealized. And the people who would return to New Orleans rebuilt as before, but with higher levees and certain other conventional flood control works, will remain unduly subjected to the wrath of hurricanes and devastating floods. No one in the Big Easy should rest easy with this future.

G.2.10 Curole, W. (2005). *Comprehensive Hurricane Protection Plan Guidelines*, General Manager, South Lafourche Levee District Presentation to French Quarter Citizens Group, November 2005.

Wendell Curole provided the following concepts for provision of a comprehensive hurricane protection plan for populated areas of southern Louisiana that included:

- *Protection of evacuation routes with a hurricane levee system or flood proofing.*
- *Plan for freshwater and sediment diversion projects to regain natural protection from storm surges.*
- *Coordinate on-going flood studies by the Corps of Engineers and others. State and local officials should decide when and where the flood protection should be directed.*

- *Keep the public informed of the threat a hurricane poses to them and their property.*
- *Increase level of already constructed hurricane protection levees to Category 4 or 5 standards.*
- *Plan for internal drainage from the upper reaches of the drainage basin to the barrier islands: a) Gravity drainage through water control structures in the hurricane levee, b) Interior drainage levees, c) Pump systems, d) Channel improvements.*
- *Protection of infrastructure (highways, navigation channels).*
- *Stress elevation in construction of bu9ildings through education not regulation.*

Curole stressed that "the most dependable way to protect from all types of flooding (river, rainfall, or hurricane) is constructing buildings with as high an elevation as possible."

G.2.11 Lopez, J. (2005). *The Multiple Lines of Defense Strategy to Sustain Louisiana's Coast.* Report to Lake Pontchartrain Basin Foundation, New Orleans.

The tragedies of Hurricanes Katrina and Rita in 2005 have revealed to the world the enormous challenge Louisiana now faces. South Louisiana appears to have entered a period when the convergence of two powerful forces is working against its survival. Since the *1950's*, the processes driving coastal loss have continued only slightly abated. Since 1990, meteorological and oceanic processes driving tropical systems have more frequently generated Category 4 and 5 hurricanes. More destructive hurricanes are predicted for coming decades. South Louisiana's ongoing peril is the continued overlap of weakened hurricane protection with more frequent and intense hurricanes.

In light of this predicament, how can the coast and culture of south Louisiana survive? The survival of a culture and a region is at stake. Hurricanes Katrina and Rita may have narrowed the field of discussion from what we might want, down to what we absolutely need. There is a growing consensus that what is needed is a pragmatic and effective strategy to integrate both coastal habitat restoration and engineered flood protection, such as levees. This strategy must be established soon and while under duress. The next hurricane season will always be just 180 days away.

Ibis is a plan of how to merge coastal habitat restoration and engineered flood protection. When both are achieved, the ecology and economy of the region can continue and together they will save and sustain Louisiana's Coast for future generations. Ihis can be achieved and this is how it may be done.

The examples shown and areas discussed in this report focus on the delta portion of the Louisiana coast; however, the same principles are applied to the entire coast of Louisiana. Maps of the chennier plain in southwestem Louisiana are under development.

The Multiple Lines of Defense Strategy proposes that two key elements of the coast be managed and perpetuated that will together sustain the coast. The two planning elements are:

1) Utilizing natural and manmade features which directly impede storm surge or reduce storm damage (Lines of Defenses),

2) Establishing and sustaining the wetland habitat goals (Target Habitat Types).

Ibis two, when integrated, can sustain the coast. This strategy is not a new restoration technology; rather, it is a new strategy to coordinate and prioritize conventional restoration methods and projects for coastal habitats.

This coastal management vision acknowledges the reality that environmental habitat restoration and engineered flood protection are not separable goals. It is unlikely that sufficient flood protection in south Louisiana can be accomplished by a "levees only" strategy. It is also true that adequate flood protection cannot be accomplished by simply restoring coastal habitats. Both habitat restoration and engineered flood protection must proceed in a coordinated plan which maximizes regional benefits and minimizes costs. Because there are substantial costs associated with both coastal habitat restoration and engineered flood protection, their financial justifications are codependent on a sustainable coastal economy.

The Lines of Defense include the Gulf of Mexico shelf, the barrier islands, the sounds, marsh landbridges, natural ridges, manmade ridges, flood gates, flood levees, pump stations, home & building elevations, and evacuation routes. Identification of these Lines of Defense on a map allows hydrologists, levee district managers, emergency personnel, etc. to ah share a common landscape template to evaluate, abate, and monitor flood risk or other storm impacts.

The Target Habitat Types include swamp, fresh marsh, intermediate marsh, brackish marsh and salt marsh. Maintaining the target salinity regime and then optimally managing the habitat types, puts ah the natural resources and resource managers on the same page with a unified biological and natural resource vision. Since each habitat has a differing profile of vegetation, fisheries, soils, hydrology, waterfowl, etc., it is imperative that geographic areas of each habitat be identified to optimize restoration and management for the needs for each habitat type. The establishment and maintenance of the Target Habitat Types requires a corresponding salinity gradient goal. This salinity gradient would be maintained by controlled river reintroductions and, if needed, hydrologic restoration.

Types for coastal planning are useful separately to articulate and develop projects. However, additional value is gained by overlaying of these elements on a single map. This integrated map becomes the central coastal management planning tool since it depicts a unifying landscape vision for the coast, embracing environmental habitat restoration and engineered flood protection. The Lines of Defense define priority areas for coastal habitat restoration; that is, the "where" of restoration. The target habitats types define potential restoration methods or limitations of coastal habitat restoration; that is, the "how" of restoration. This complimentary relationship together focuses restoration finding on priority areas and guides the type of restoration possible or required. Coastal habitat restoration using traditional restoration techniques may proceed while producing ecologic benefits and enhancing flood protection to the coastal infrastructure. The integrated map may satisfy the National Research Council recommendation to include an explicit map of the desired future condition or goals for the coast.

At least two important results of the Multiple Lines of Defense Strategy should be noted. One is that a natural ridge's ecologic function is recognized as generally being a hydrologic barrier. This makes their ecologic function compatible with using them as economic corridors. Natural ridges such as Bayou Lafourche may be leveed and still retain its ecologic function, which opens an economic corridor with flood protection. A second result is that restoration is generally focused on remaining marsh, and avoids large areas where previous heavy wetland loss has occurred. This may avoid areas with chronic causes for wetland loss that may be ongoing, such as subsidence.

In summary, the proposal described here is a unified vision for the coast which embraces environmental habitat restoration as well as engineered flood protection. Goals can be clearly articulated through maps of the Target Habitat Types and Lines of Defense. The Multiple Lines of Defense Strategy should be evaluated quickly for the entire Louisiana coast to begin implementation if it is deemed to be warranted.

The eleven Lines of Defense are:

1st: Offshore shelf within the Gulf of Mexico. The offshore shelf ranges in depth from 300 feet at the shelf edge to zero depth at the gulf shoreline. Its width vanes from a few miles to hundreds of miles. The primary benefit of the shallow shelf is to dramatically reduce wave height and wave energy from an approaching tropical system. A negative aspect of the shelf is that it will promote higher storm surges inland. The variable influences 011 storm surges due to the geometry of the shelf needs to be considered for storm surge analysis. Also, dredging activities 011 the shelf should avoid increasing shoreline erosion by wave refraction around dredge holes. The gulf fisheries and the oil and gas industry are key economic aspects of the shelf. Examples: Narrow shelf at the mouth of Mississippi River & Wide shelf offshore from Cameron Parish

2nd: Barrier Islands. The Louisiana barrier island shoreline is characterized by fragmented barriers or shoals with low vertical profiles and low sand content. However, barrier islands provide an important wave barrier for interior sounds and coastal marsh. Ihe primary benefits of barrier islands are the near-complete reduction in wave height and the slight reduction in storm surge further inland. A negative aspect of barrier islands is their ephemeral nature and unpredictable local impacts to them from hurricanes. Barrier islands also have significant recreational aspects such as fishing and birding. Examples: Chandeleur Islands and Grand Isle

3rd: Sounds. The primary benefit of the sounds is to provide a relatively shallow water buffer to deep water currents. Sounds do have a negative aspect during storms by allowing waves to re-generate on the on the sound side of barrier islands. Also, sounds may cause storm surge and wave erosion on the back side of barrier islands.

4th: Marsh Landbridges. Marsh landbridges are areas of emergent marsh with relative continuity compared to adjacent bays, sounds or areas of significant marsh/land loss. Ideally, landbridges connect other elevated landforms such as natural ridges. Since some ridges are developed and have adjacent levees, marsh landbridges may also bridge adjacent levee systems and economic corridors. Marsh landbridges compose much of the residual internal framework of the coast which reduces fetch and shoreline erosion of interior marshes and lagoons. Landbridges impede storm surge movement inland and protect other emergent marsh areas that may perform the same function. Some landbridges are threatened themselves by various processes of marsh loss and need to be sustained through restoration and maintenance. Ihe landbridges represent an increasing fraction of the remaining emergent marsh of the coast and provide typical high productivity and fishery benefits typical of coastal wetlands. Examples: East Orleans landbridge, Biloxi Marsh landbridge, Barataria Basin landbridge, Upper Terrebonne Bay landbridge, Grand Lake-White Lake landbridge, Western Marsh Island landbridge, south Calcasieu Lake landbridge

5th: Natural Ridges. In southeast and central Louisiana, most natural ridges are the natural levees of abandoned distributary channels. These channels 110W act as tidal channels and are often colloquially named bayous or rivers. In southwest Louisiana, most natural ridges are chenniers running parallel to the Gulf coastline. Natural ridges may have continuous elevation of several feet and, therefore, will impede overland flow across the ridge and potentially reduce storm surge. Natural ridges often define (at least historically) the hydrologic basins of the coast. Natural ridges are most effective when they have at least 6 feet of elevation and well drained soils to maintain upland forests. Forests will also slow the movement of overland flow and may also provide a wind barrier. Natural ridges tend to be the economic corridors across the coast including primary state highways and coastal communities. These highways are also likely to be evacuation routes. Examples: Bayou la Loutre, Bayou Lafourche

6th: Manmade Soil Foundations. Manmade soil foundations for transportation may provide incidental benefit to storm surges. Railroads, highways and spoil banks may run parallel to the coast and locally provide a manmade ridge several feet in height. These foundations may have settled and may need improvement to provide reliable transportation routes without chronic flooding. If highway improvements are contemplated, the effects 011 storm surge may be considered. Examples: Highway 90, Hwy 82.

7th: Flood Gates. Flood gates are typically designed to withhold flood water and, therefore, remain open under most conditions. Flood gates are generally open so as not to impede navigation or natural ebb and flow of tides and aquatic organisms. Flood gates would be closed during a threat of flooding and to reduce flood tides in channels. Because of the generally low elevation of the coast, the effectiveness of flood gates may depend on the nearby topography or constructed features such as levees or spoil banks. Examples: Bayou Bienvenue, Bayou Dupre

8th: Flood protection levees. Flood protection levees are designed and constructed for flood protection of municipalities or other coastal infrastructure features. Levees are generally designed to be an absolute barrier defining a flood side and a protected side. The intent is to have zero storm surge flooding on the protected side, but an unintended consequence may be to increase water levels on the flood side. Levees are generally not designed to be overtopped or to withstand significant wave erosion. Exceptions include "potato levees" or other low relief levees designed to reduce flooding from non-storm tides. Typical hurricane protection levees protect limited portions of the coast with intense economic development. Examples: St. Bernard levee, Jefferson and Orleans Parish levees 011 Lake Pontchartrain

9th: Flood protection pumping. Pumping stations are generally within leveed areas and are used to reduce flood risk from rainfall and are not designed to pump out flood water from a significant levee breach. Most pumping stations are not prepared with fuel, staff or other requirements to be effective to pump out flood water from a significant levee breach. Generally, these are large capacity pumps which displace water vertically above the water level on the flood side of the levee. Pumping stations are generally to protect areas of intense development. Examples: Orleans and Jefferson Parish's pumping stations

10th: Elevated homes and businesses. All homes and businesses in south Louisiana are subject to being flooded if they are not elevated above the normal land elevation. Even those behind levees are not 100% safe. Hurricanes Katrina and Rita made this painfully clear. Ah attempts to reduce storm surge height or its extent are limited by the intensity and attributes of particular storm events. Since there will always be the potential of a storm exceeding the limits of protection from storm surges, immovable assets such as homes and businesses should be elevated to the appropriate flood elevation risk. This is the last line of defense for immovable assets. Elevated homes also provide important side benefits such as improved protection from termites and more economic capacity to re-level or raise the houses due to settlement or increased flood risk. Example: pre-1940 housing in New Orleans, LUMCON, Marina del Ray in Madisonville

11th: Evacuation. Evacuation routes are typically highways, but could also include other means of transportation such as railroads, air transportation, etc. Evacuation routes are the last line of defense for people or moveable assets. Evacuation routes and procedures should be established for the coast. Ideally, evacuation routes may also serve as re-entry routes for first responders and as routes to re-populate after a storm event. Evacuation routes are generally selected based on capacity to move a large number of people to safer areas as a storm approaches the coast. Some routes may be subject to flooding quickly and need to be improved. Examples: Regional contra-flow evacuation plan for southeast Louisiana."

G.2.12 Committee on the Restoration and Protection of Coastal Louisiana (2006). *Drawing Louisiana's New Map*, Ocean Studies Board, National Research Council, The National Academies Press, Washington DC.

Coastal wetlands develop within a fine balance of many geomorphologic and coastal ocean processes. Relative sea level rise, wave action, tidal exchange, river discharges, hurricanes and coastal storms, and the rates of sediment accretion due to sediment deposition and accumulation of organic material play particularly important roles. The interplay of these processes and the wetland's resilience to natural or anthropogenic perturbations determine its sustainability. Some of the processes of land loss and gain in the Louisiana coastal area are natural and have occurred for centuries. Others are the result of human activities in the wetlands and the watershed of the Mississippi River system.

Annual land loss rates in coastal Louisiana have varied over the last 50 years, declining from a maximum of 100 square kilometers (km^2) per yr (39 square miles [mi^2] per yr) for the period 1956—1978. Cumulative loss during this 50-year period in Louisiana represents 80 percent of the coastal land loss in the entire United States. Initial efforts to prevent catastrophic land loss were implemented under the federal Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) in partnership with Louisiana's efforts through Act 6 (L.A.R.S. 49:213 et *seq.).* Passed in 1990, CWPPRA called for the development of a comprehensive Louisiana Coastal Wetlands Restoration Plan (P.L. 101-646 §303.b). The first such plan was completed in 1993 and has been in use since that time. In addition, the Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority prepared a plan for the coast in 1998 entitled *Coast 2050: Toward a Sustainable Coastal Louisiana* (Coast 2050).

Coast 2050 was developed under a number of federal and state legislative mandates and is the result of recognition by federal, state, and local agencies that a single plan and coordinated strategy were needed. Coast 2050 was then appended to the 1999 U.S. Army Corps of Engineers 905(b) reconnaissance report. In October 2003, a draft comprehensive study *(Louisiana Coastal Area, LA—Ecosystem Restoration: Comprehensive Coastwide Ecosystem Restoration Study* [draft LCA Comprehensive Study]) for implementing coastal restoration was released. After reviewing the draft LCA Comprehensive Study, the U.S. Office of Management and Budget re-quested a near-term approach to focus the scope of work and maintain restoration momentum. The resulting final version of *Louisiana Coastal Area (LCA), Louisiana—Ecosystem Restoration Study* (LCA Study) was released by USACE in November 2004. As plans for completion of the LCA Study were being finalized, Louisiana's Office of the Governor requested that the National Academies review the LCA Study's effectiveness for long-term, comprehensive restoration development and implementation.

The LCA Study and its envisioned successors are unique in many respects, including geographic scope, pervasiveness of the destructive processes involved, complexity of potential impacts to stakeholders, success of preceding efforts to achieve stakeholder consensus, and documentation of earlier planning and restoration efforts. Indeed, the environmental and social challenges confronting coastal Louisiana in the near and distant future are without precedent in North America. Clearly, execution of the LCA Study alone will not achieve its stated goal "to reverse the current trend of degradation of the coastal ecosystem," although successful completion of some of the projects outlined in the LCA Study will reduce this trend, thereby representing an important step toward the goal of sustaining or expanding wetlands in some local areas. By definition, the activities proposed in the LCA Study were intended to provide a foundation for successful future restoration and protection efforts, including those developed and implemented in response to hurricanes like Katrina and Rita.

Taken individually, the majority of the projects proposed in the LCA Study are based on commonly accepted, sound scientific and engineering analyses. It is not clear, however, that in the aggregate, whether or not these projects represent a scientifically sound strategy for addressing coastal erosion at the scale of the affected area. Thus, at foreseeable rates of land loss, the level of effort described by the LCA Study will likely decrease land loss only in areas adjacent to the specific proposed projects. As stated in numerous USACE policy statements and recommended in past NRC reports, planning and implementation of water resources projects (including those involving environmental restoration) should be undertaken within the context of the larger system. A group of projects within a given watershed or coastal system may interact at a variety of scales to produce either beneficial or deleterious effects. Cost-effectiveness analyses discussed in the LCA Study and in supporting documents reflect an effort to identify least-cost alternatives but do not appear to reflect a system-wide effort to maximize beneficial synergies among various projects. The selection of any suite of individual projects in future efforts to restore coastal Louisiana should include a clear effort to maximize the beneficial, synergistic effects of individual projects to minimize or reverse future land loss. Further, because there is a finite availability of water flow and sediment and many of the proposed projects must function for decades to deliver maximum benefit, care should be taken to ensure that implementation of an individual project does not preclude other strategies or elements that are being considered for the future. To achieve this, the development of an explicit map of the expected future landscape of coastal Louisiana should be a priority as the implementation of the LCA Study moves ahead.

The approaches advanced in the LCA Study focus largely on proven engineering and other methods to address land loss at the local scale. In general, individual projects appear to be based on commonly accepted, sound scientific and engineering analyses. The emplacement of 61 kilometers [kin]) (38 miles [mu) of revetment along the banks of MRGO as one of the five major wetland restoration projects proposed in the LCA Study, however, does not appear to be consistent with the study's stated goals. Despite an estimated cost of $108.3 million,1 this project is expected to reduce land loss by only 0.5 km2 per yr (0.2 mi2 per yr) over the next 50 years. (Louisiana is projected to lose an average of 26.7 km2 per yr [10.3 im2 per yr] over the next 50 years.) Although the location of the land loss may make it more significant, the need for and potential value of this project are directly related to the outcome of a study being conducted by USACE, scheduled for completion in FY 2005, to evaluate the potential decommissioning of MRGO for deep draft navigation. In addition to questions regarding the appropriateness of this particular project, its selection casts doubt on the rigor of the ranking and selection process. The selection of the restoration efforts of MRGO as one of the five major projects to be carried out as part of the LCA Study should be reconsidered in light of the limitations of expected benefits and the results of ongoing studies on the decommissioning of MRGO for deep draft navigation. If a decision is made to decommission MRGO, various options could be considered, including complete closure, that would significantly reduce the need to strengthen the levees along its route. If partial closure is chosen, perhaps maintaining MRGO for shallow draft vessels, some of the work along the outlet may still be required. Restoration efforts requiring planning would be more fully informed once a final decision has been made.

"Conflicting stakeholder interests represent one of the greatest barriers to robust coastal restoration efforts in Louisiana. A dominant human-related component of land loss is the constraint on the river system imposed by spoil banks and levees, but these features also provide benefits to a range of stakeholders. By minimizing the cost of dredging and reducing uncontrolled flooding in inhabited and agricultural areas, these features support important local economic activities. Many of Louisiana's inhabited areas are located on natural levees formed by deposition on the floodplain during major floods. Valuable agricultural land was originally maintained at an elevation above water level through flood-derived sedimentation but is now protected by levees, which preclude new sediment introduction. Obviously, the prospects are low that sediment-rich water will be intentionally allowed to flood broad expanses of urban and agricultural land to maintain elevation with the pace of relative sea level rise.

As discussed above, locating individual projects in an effort to maximize positive synergistic effects will tend to concentrate efforts into selected areas within coastal Louisiana. Although distributing individual projects, and the benefits associated with them, across the entire region may be less contentious, such an approach will either drive up the total cost or reduce the likelihood of success for a given amount of effort and expenditure. Successfully implementing a project selection strategy that maximizes synergistic effects of individual projects will require greater popular support for a comprehensive plan both from within the state and at the national level. Such support will likely come about only through greater public involvement in the decision-making process of a comprehensive plan. Louisiana's restoration goals should be better defined and more clearly communicated to the public. This means that maps of the region and projected land-use patterns with and without various restoration projects should be circulated. Without a clarified definition of the temporal and spatial dimensions of "restoration," unrealistic expectations and disappointments are likely. The projections can be revised as additional data become available and a better understanding is developed through the adaptive management program and the science plan.

Although some inhabited areas will require relocation in order to carry out some proposed wetland restoration efforts, it will be difficult to persuade those affected by local relative sea level rise to abandon their property without a program of financial compensation and a social plan to maintain the cultural integrity of the affected communities. It is important that decisions involving relocation and compensation following Hurricanes Katrmna and Rita, or in response to future events, be made in such a manner as to minimize the likelihood of additional relocation or disruption in response to future restoration efforts. The appropriate decisions and responses after major storms have to reflect a broad consensus about the future nature of coastal Louisiana and may have to include managed retreat. Managed retreat and various restoration strategies should include early and active stakeholder participation and concurrence. Relocation could occur either gradually with a few families at a time or at a much higher rate in areas severely affected by Katrina and Rita or future events. This is not intended to preclude reoccupation of the many areas affected by the recent hurricanes or similar events in the future. Rather, this approach is intended to minimize the potential for disrupting lives and property a second time as efforts to protect and restore Louisiana unfold in coming years.

Finally, the LCA Study calls for a long-term study of the possibility of establishing a new lobe of active delta development through a diversion near Donaldsonville, Louisiana. Termed the Third Delta, this proposed restoration feature was among a group of possible features2 that was shown to yield limited benefits at a substantially higher cost than the projects identified for funding in the LCA Study. An alternative scenario for retention of sand and silt now lost beyond the shelf break would involve diverting the main flow of the Mississippi River toward the west of its present main channel somewhere between New Orleans and Head of Passes. An intermediate- and long-term consequence of this action would be the abandonment of the active Birdsfoot Delta by the Mississippi River. A clear benefit would be the nourishment of eroding coastal reaches to the west. Although this alternative has been widely acknowledged as possible, its feasibility, for various reasons, has not been considered seriously by USACE. Therefore, it is not yet possible to assess the potential advantages and disadvantages of Birdsfoot Delta abandonment at this time. Obviously, implementation of such a strategy would have to be accompanied by the creation of a deep navigation access channel somewhere downstream of New Orleans but upstream of Head of Passes. Though the size of the area it would impact would still make it controversial, some consideration should be given to an alternative or companion to the planned Third Delta, such as a larger-scale diversion closer to the Gulf of Mexico, that would capture and deliver greater quantities of coarse and fine sediments for wetland and barrier island development and maintenance.

The LCA Study states that "execution of the LCA [Study] would make significant progress towards achieving and sustaining a coastal ecosystem that can support and protect the environment, economy, and culture of southern Louisiana and thus contribute to the economy and well-being of the nation." The economic analysis provided within the LCA Study and its supporting documents, however, includes only cost-benefit analyses of alternative approaches to meet ecosystem restoration objectives, as is consistent with USAGE policy for evaluating projects proposed as National Environmental Restoration efforts. Evaluating the benefits of restoring coastal Louisiana in terms of national economic interests, as implied by the statement of task, would have required USAGE planners to carry out analyses more consistent with proposing the effort as a National Economic Development project. USAGE officials appeared to view the efforts described within the LCA Study as falling under National Environmental Restoration as opposed to National Economic Development and, thus, did not attempt to identify and meaningfully quantify the contribution to the economy of the nation. Since the information necessary to evaluate proposed coastal Louisiana efforts in terms of the national economy is not provided in the LCA Study, there is insufficient information available for the committee to comment credibly. Carrying out such an analysis would require significant effort and resources beyond those available to the committee in the 10 months following the release of the LCA Study in November 2004. This said, some components of such an analysis can be articulated.

The LCA Study presents sufficient information about the importance of some components of the natural and built environment in coastal Louisiana (e.g., system of deep water ports, oil and gas receiving and transmission facilities, complex and extensive urban landscape, robust commercial fishery) to demonstrate that substantial economic interests are at stake in coastal Louisiana and that these interests have national significance. The immediate impacts of Katrina underscore the importance of New Orleans, and adjacent areas of the Gulf Coast, to the national economy. Establishing the true, national economic significance of efforts to restore coastal wetlands in Louisiana as proposed in the LCA Study, however, must go beyond simply identifying and characterizing these components and should include an analysis of how specific restoration efforts will preserve or enhance the value of these components (i.e., some restoration efforts may have little influence on the vulnerabilities of specific components of the natural and built environment in coastal Louisiana) and should determine how the national economy would respond to the loss or degradation of components (e.g., what is the capacity for similar components in other regions to compensate for the loss and on what time scales?). If, as implied by the statement of task, greater emphasis is to be placed on the national economic benefits of restoring and protecting coastal Louisiana, future planning efforts should incorporate meaningful measures of the economic significance of these projects to the nation consistent with procedures normally employed to determine the value of a project or a suite of projects for National Economic Development. As a greater understanding of the short- and long-term economic impacts of Katrina and Rita becomes available, a more meaningful effort to evaluate the national economic significance of protecting the natural and built environment in coastal Louisiana will be possible. Such information would provide an important context for decision making; however, it will still be important to understand the role wetlands play in protecting specific components of the overall system and to determine how specific restoration efforts can enhance that protection. While wetlands and adjacent barrier islands and levees are known to reduce impacts from waves, their more complex role in reducing storm surge is less well known. Surges contain multiple components, including barometric tide effects, wind stress-induced setup, wave-induced setup, and Coriolis forces. As was pointed out repeatedly in the public media during Katrina and Rita, in the northern hemisphere the eastern side of a hurricane tends to drive water northward in a counterclockwise manner. If a storm stalls off a coast for a significant period of time, it will continue to drive water onshore for a prolonged period, regardless of the nature of any intervening wetland or barrier island. Thus, the potential for reducing risk due to storm surge from a particular storm is more difficult to predict.

Conversely, the significance of the coastal Louisiana wetlands to the nation in terms of both their inherent uniqueness and the ecosystem services they provide is more thoroughly documented in the LCA Study, its predecessor reports, and the scientific literature. Although efforts to restore and protect Louisiana's wetlands will likely provide some unknown but potentially significant protection against coastal storms and hurricanes, those efforts should not be evaluated primarily on their significance for National Economic Development.

The two major components of the LCA Study, a series of restoration and demonstration projects designed to be implemented over a 10-year time frame and the development of a robust intellectual infrastructure to inform future project design and implementation, are at the heart of the phased approach referred to in the statement of task. This approach has decided advantages and disadvantages. As is clear from the LCA Study, simply keeping pace with land loss in Louisiana will require an ongoing effort. Any substantial gains in the next few decades will require a robust effort, an effort that needs to be well informed by a thorough understanding of both the natural physical and ecological processes involved and the viability of various restoration techniques to address land loss at a massive scale. Establishing methods that allow projects to evolve in the face of increased understanding is prudent. Conversely, limiting project selection to those features where construction can be initiated in 5—10 years presents a significant handicap for laying the groundwork for a comprehensive, multidecadal effort.

For example, the 10-year implementation criterion resulted in the selection of projects that already existed in the USAGE and the CWPPRA planning process. This time constraint precluded consideration of projects with solid potential for long-term benefits that had not yet been fully designed (precluding the initiation of construction in 5—10 years). Similarly, this criterion and the need to demonstrate solid near-term success likely precluded large-scale and innovative projects that (1) affect significant sediment delivery to the system (such as abandonment of the Birdsfoot Delta), (2) maximize synergistic effects for reducing land loss over longer time scales by the selection of strategically located or larger-scale projects, or (3) address some of the difficult issues associated with stakeholder response. While the efforts preceding the LCA Study have achieved a laudable degree of unanimity among stakeholders on the conceptual restoration plan, this unanimity will be tested by the difficult decisions associated with implementation of the larger-scale projects designed to achieve a more effective delivery of sediment, water, and nutrients over a larger area. The project selection procedure requires more explicit accounting of the synergistic effects of various projects and improved transparency of project selection to sustain stakeholder support. Furthermore, beneficial, synergistic interaction among projects cannot be assumed but should be demonstrated through preconstruction analysis.

It is important to note that, by definition, the activities proposed within the LCA Study are intended to lay a foundation for more effective and robust efforts to preserve and protect coastal Louisiana. By its own analysis, the LCA Study points out that constructing the five restoration features it proposes would reduce land loss by about 20 percent (from 26.7 km2 per yr [10.3 mi2 per yr] to 22.3 km2 per yr [8.6 mi2 per yr]) at an estimated total cost of roughly $864 million (or $39,400 per hectare [$15,900 per acre]) over the 50-year life of the projects, not including maintenance and operational costs.

Actual land building will be experienced only in areas adjacent to the implemented projects. The significant investment represented by these projects and the efforts to develop the tools and understanding necessary to support future restoration and protection efforts will yield a substantial return of benefits only if future projects are carried out in a comprehensive manner. The funding required to carry out the activities described in the LCA Study should be recognized as the first of a funding continuum that will be required if substantial progress is to be made. A comprehensive plan to produce a more clearly articulated future distribution of land in coastal Louisiana is needed. Such a plan should identify clearly defined milestones to be achieved through a series of synergistic projects at a variety of scales. (While a comprehensive plan is needed, this does not necessarily imply endorsement of the draft LCA Comprehensive Study, which was not formally released or reviewed as part of this study.) The review detailed in this report found no instance where the proposed activities, if initiated, would preclude development and implementation of a more comprehensive approach. Conversely, many examples were identified where implementing the proposed activities would support a more comprehensive approach. Thus, the efforts proposed in the LCA Study should be implemented, except where specific recommendations for change have been made in this report and only in conjunction with the development of a comprehensive plan.

As the State of Louisiana and the nation begin to recover from Katrina and Rita, efforts to restore wetlands in Louisiana will likely compete with reconstruction and levee maintenance or enhancement efforts. As this report and numerous other NRC reports have pointed out, efforts to design and implement water resource projects (including environmental restoration and flood control projects) should be carried out within a watershed and coastal system context. Ongoing discussion of long-term response to Katrina and Rita underscores the need to consider restoration and reconstruction as a seamless process that should be informed by a coherent, comprehensive plan that addresses the issues raised in this report. Therefore, efforts to rebuild the Gulf Coast and reduce coastal hazards in the area should be integral components of an effective and comprehensive strategy to restore and protect coastal Louisiana wetlands.

G.2.13 Working Group for Post-Hurricane Planning for the Louisiana Coast, A New Framework for Planning the Future of Coastal Louisiana after the Hurricanes of 2005, University of Maryland Center for Environmental Science, Cambridge, January 26, 2006.

The principal messages abstracted from our report are the following:

1. The large-scale deterioration of coastal landscapes, particularly during the past fifty years, threatens the sustainability (viability over this century) of both human habitation and the rich natural resource base of coastal Louisiana. Storm events such as hurricanes have both negative and positive effects on wetlands that dominate these landscapes, but deterioration of these wetlands is mostly caused by human activities that both disrupt natural processes building the coastal landscape (river inputs, sedimentation, tidal fluctuation, etc.) and accelerate destructive processes (altered hydrology, subsidence, etc.). **In the long term, hurricane protection for larger population centers, including the New Orleans region, can only be secured with a combination of levees and a sustainable coastal landscape.** This will require adapting to changing conditions by re-establishing the constructive processes associated with distributing Mississippi River water and sediments across the coastal landscape, as well as alleviating the other destructive effects of past or future human activities.

2. The sustainable coastal landscape must include extensive marshes and swamps and the bayous, coastal barriers and ridges that characterize the Mississippi deltaic plain and the Chenier plain in the southwest. If natural processes are not interrupted, coastal wetlands are able to sustain themselves over hundreds of years even where the land is subsiding or the sea level is rising. **With presently observed subsidence rates and anticipated acceleration of sea-level rise, most-although not all-of the coastal landscape could be maintained through the 21't century. And with efficient management of the river's resources, this landscape could be expanded in some places.** However, this result can only be achieved with very aggressive, strategic, and well-informed restoration efforts, varying in size and objective but integrated within a landscape management plan.

3. Hurricanes Katrina and Rita provide poignant evidence that no longer can coastal ecosystem management and restoration, flood protection, and navigation be planned, executed and maintained independently. **We must integrate planning, investment and management decisions under a new framework in order to secure these multiple purposes, while recognizing: the forces of nature; the imperative to protect life, property and communities; the value of natural resources and ecosystem services; the environmental and economic sustainability of the solutions; and financial constraints.** Furthermore, planning to support this integrated decision making must be an adaptive process that creates and uses new knowledge about this "working coast." Integrated management requires that coastal landscape restoration alternatives be screened through a "storm damage reduction filter" (e.g., how might they reduce risks and how quickly might the result be realized?). Conversely, hurricane storm damage reduction or navigation alternatives should be screened through an "environmental consequences filter" (e.g., how might the elements affect ecosystem services and the sustainability of the landscape?). This does not mean that restoration features are justified only because they significantly reduce storm damages-many are required to sustain environmental resources or build landscapes away from population

centers. It does mean that priorities must be determined by multiple benefits more than has been the case in past planning.

4. **The near-term critical restoration features selected by Louisiana Coastal Area Ecosystem Restoration Study should be reexamined and prioritized to assure that they provide environmentally and economically sustainable approaches that advance both ecosystem restoration goals and support storm damage reduction.** While a truly integrated planning process has not yet been developed, there is sufficient understanding to prioritize near-term restoration features based on their likely contribution to the effectiveness of existing and intended storm damage reduction efforts, as well as advancing ecosystem restoration. Furthermore, long-term restoration strategies for the four geographic subprovinces should be refined by incorporating integrated objectives and framed around critical foundation features.

5. **Federal and State governments should engage scientists, economists, engineers, government officials, communities and stakeholders to develop a spatially explicit vision of a future coastal Louisiana that incorporates long-term challenges, opportunities and overarching goals.** As recently stressed by the National Research Council, such a vision should guide integrated, multiobjective management within geomorphic subprovinces and along the entire coast throughout the planning and project implementation process. Stakeholders should participate in formulating and evaluating alternatives that recognize the opportunities and limitations associated with maintaining the status quo under the perilous, urgent and changing circumstances. The vision should anticipate ftiture changes that may affect options, for example energy scarcity, climate change and demographic shifts. As adaptations occur and new projects are realized, the vision for the coast can be revised in light of changing landscape and socioeconomic conditions, knowledge of the system, and social preferences.

6. The President and Congress have mandated studies of potential supplements to the existing but strengthened storm protection works. Particular attention is being given to a continuous peripheral coastal defense (a hurricane barrier) similar to that used in the Netherlands. Although the systematic approach of the Dutch is commendable, substantial differences between the Netherlands and south Louisiana limit the applicability of their model, including contrasts in human settlement patterns, land uses, geology, hydrodynamics and coastal ecology. Maintaining functioning estuarine ecosystems and self-sustaining wetlands inside and adjacent to such peripheral defenses would be extremely difficult, if not impossible, because extended levees and floodgates would obstruct key hydrological processes that maintain the coastal landscape. The relatively dispersed populations and low intensity of land use may make investment in such a barrier difficult to justify. Rather than simply adopting the Dutch approach, the plan for Louisiana should recognize the different Louisiana setting and take advantage of its characteristic coastal landscape. **Storm damage reduction should be achieved through a combination of stronger inner defenses around larger population centers; broader, self-sustaining wetland landscapes that reduce storm surge and wave fetch; restrictions along artificial channels to limit storm surge propagation; and maintaining barrier islands along selected areas of the coast.** This may include lower elevation, semi-porous barriers placed between the levees protecting population centers and the open coast that attenuate storm surge but allow tidal exchange. However, any such barriers should be compatible with sustainable coastal landscapes. To the extent possible, extensive wetland areas should not be enclosed by levee systems.

7. Navigation channels that cut across the coastal gradient have resulted in substantial degradation of wetland habitats, thus increasing hurricane surge vulnerability. **Future integrated planning and decision making should recognize, account for and mitigate the disruption of coastal landscape dynamics when formulating and evaluating navigation channel expansion, maintenance or abandonment.** One of these channels, the Mississippi River Gulf Outlet (MRGO), is likely to be decommissioned as a deep-draft navigation channel as a result of the risks it poses and its weak economic contribution. However, even if mostly closed it will remain a feature on the coastal landscape that has to be integrated into a coastal restoration and storm damage reduction strategy for the vulnerable east side of Greater New Orleans.

8. A new management framework requires improved organizational arrangements for coordinating and integrating planning, decision making, implementation and evaluation. **A joint Federal-State body should be given the responsibility and organizational and fiscal support for guiding the program.** The Corps, or another appropriate agency, would continue to have the responsibility to design, construct and, if authorized, operate and maintain projects. An integrated assessment group and an engineering and science program focused on reducing decision-relevant uncertainties (scientific and otherwise) would support decision making in an adaptive management process.

9. **Authorization and financing should be separated from the Water Resources Development Act process.** The integrated planning process, engineering and science program and smaller investment projects should be supported by a programmatic authorization and a more reliable appropriation stream. Funding for larger projects should be provided through a Congressionally-chartered coastal investment corporation.

10. **Project planning should rely on innovative decision-support analyses that engage stakeholders and responsible agencies in resolution of conflicts and in identifying and synergies among projects.** The analyses would formulate and evaluate project alternatives using performance measures derived from the policies, goals and objectives of the Nation and the region. Significant areas of risk and uncertainty will be highlighted for decision making, as well as for establishing monitoring and research priorities for the adaptive management program."

Expanded Hurricane Protection

As made clear by the President's announcement, initial efforts to improve hurricane protection will focus on strengthening existing levees and floodwalls protecting urban areas. An in-depth analysis of the feasibility and environmental consequences of expanded hurricane protection (EHP) is beyond the scope of the framework developed here. The Corps of Engineers is currently assessing the feasibility of such an expanded and enhanced protection system, the details of which are not yet in the public domain. Based on general information made available to the working group we discuss four possible protection strategies and their implications for restoration and conservation of coastal ecosystems:

Strategy 1: Protect only New Orleans and larger population centers by strengthening existing protection systems without providing additional flood protection farther out in the coastal zone. Restoration would focus on the same activities that were being planned before the hurricanes, but with more attention to the coastal landscapes adjacent to urban areas.

Strategy 2: Construct storm surge barriers along the inner coastal zone between population centers and the outer coast. Openings in the system for water management could provide potential opportunities for restoration and conservation but altered hydrologic conditions inside the barrier could also have potential negative impacts (e.g., changes in salinity and tidal regimes and reductions in soil accretion due to sediment starvation) that should be considered. Opportunities would still exist for restoration outside the barrier system.

Strategy 3: Establish a first line of defense along the existing coastline, e.g. by maintaining barrier islands, to dampen storm surges. This would potentially minimize the destructive impacts of hurricanes, but modeling should be conducted to quantify the likely benefits. These "speed bumps" would be far from the urban areas with extensive open water and wetlands behind them and, when overtopped, may not adequately reduce the storm surge to prevent extensive damage farther inland. A benefit of outer speed bumps is that they could provide opportunities for landward restoration and continue to allow for sediment deposition during storms. However, these barriers would be highly erosive features requiring long-term maintenance.

Strategy 4: Combine elements of strategies 2 and 3. This would provide the greatest opportunity for both protection of populations and conservation of coastal landscapes. The outer ring of speed bumps limits hydrologic impacts to existing wetlands and also provides opportunities for additional restoration in areas behind the features. The inner series of partial barriers (scenario 2) would provide the same opportunities as described above but synergy between the two protection systems would potentially allow for additional restoration opportunities outside of the inner ring of barriers."

Organization and Funding

The existing plans for strengthening storm damage reduction, initiating the LCA ecosystem restoration, and maintaining and improving navigation infrastructure provide a foundation for planning, but cannot be the only basis for future investments. As we have repeatedly stressed, future decisions on projects and their operations must be informed by an integrated assessment of contributions of these and other projects to the multiple economic, environmental, social and cultural objectives. Such integrated assessment will identify conflicts, synergies and opportunities for securing multiple purposes. The value of, and possibilities for, integrated assessment are illustrated by the preliminary analysis and evaluation included above. Importantly, a future integrated planning process should be structured and supported as an adaptive management program that recognizes and reduces uncertainties to improve the effectiveness of future decision making. Some of those decision-critical uncertainties have been highlighted earlier in this report.

A complex of state and federal agencies already exists with missions, budgets and authorities affecting planning, investment and implementation. However, improvements to the existing organizational, funding and planning structures will be needed to meet planning needs and expedite project implementation by the Corps and the State.

The organizational and funding barriers that have inhibited the adoption of an integrated planning and adaptive decision making process persist . Both new organization and funding reforms are needed to support coastal planning and project implementation by the Corps and the state. We recognize that there are many ways in which the government can organize to carry out integrated planning and decision making as long as the organization, funding and analytical needs for such a new process are served. To better illustrate these concepts, and organizational possibilities, the Working Group offers one such approach.

Maritime Transportation Planning

While the President and Congress have mandated the Corps to take actions and develop investment plans for hurricane protection and ecosystem restoration, they were silent on planning maritime transportation investments. Similarly, the scope of the Coastal Protection and Restoration Authority (CPRA) recently created by the Louisiana Legislature does not seem to encompass maritime transportation. However, a marine transportation network that will continue to be maintained and upgraded over time characterizes the Louisiana coast. Marine transportation interests are primarily concerned with: (1) the availability of a system of reliable channels; (2) transit time from to and from port to deep water; and (3) a minimization of cargo handling costs. These goals will continue to be advanced through new project proposals and maintenance of existing projects. As discussed earlier, some elements of the navigation network can be detrimental to hurricane protection and coastal landscapes. Moreover, innovatively conceived navigation realignments and utilization of existing channels could enhance sediment dispersal through the coastal wetlands or reduce storm damages. Therefore, consideration of plan formulation and evaluation for marine transportation investments should be incorporated into the more comprehensive study authorities and re-organization plans, such as those proposed below.

A New Framework for Coastal Louisiana

Federal Intragovernmental Coordination

At present, the Federal program for coastal planning is led by the Corps of Engineers, but it is not clear how the responsibilities of the other federal agencies will be represented going forward. The new integrated management framework would require tradeoffs that impact agency responsibilities and the streamlining of NEPA and other reviews. It requires the Federal government to speak with one voice. The Comprehensive Everglades Restoration Program (CERP) has been working to overcome interagency coordination barriers and may offer useful experiences, if not a model. The Corps is the lead agency for CERP, but there is extensive involvement by other federal agencies. The federal agencies have joined a Memorandum of Understanding (MOU) specifying a dispute resolution process and a time line for resolution. An interagency MOU, similar to that prepared for the CERP, should be signed by the federal agencies with significant participation in coastal Louisiana planning.

The Corps itself is organized along "business lines" including (a) navigation, (b) flood and storm and flood hazard management and (c) ecosystem restoration. The business line organization can create organizational barriers to integrated planning and evaluation. These organization barriers exist both at the districts and headquarters. Also, Corps planning and funding mechanisms are currently not well structured to meet the challenge of integrated and adaptive management. The Corps headquarters should create a unit, led by a Senior Executive, charged with fostering innovations in the planning and assessment approaches required for the integrated management of the Louisiana coastal area, as well as for CERP, Missouri, Upper Mississippi, the Columbia River and other areas where the multiple missions of the Corps can be best achieved through more integrated management.

Coastal Louisiana Authority

The Corps and the state, as well as partner federal agencies, have developed working relationships through the LCA, the CWPPRA, and as cost-share partners on local navigation and storm damage reduction projects. However, differences persist in viewpoint, ranging from cost-sharing responsibilities to project priorities. For example, project selection through the

CWPPRA Task Force sometimes led to individual agency advocacy and agreements that accommodated the different agencies demands, rather than true integration.

Louisiana has created a new Coastal Protection and Restoration Authority (CPRA) to centralize and integrate its coastal efforts and the Legislature will shortly be considering additional legislation for consolidation of the numerous levee districts. However, there is still a need in coastal Louisiana to clarify the federal-state responsibilities for planning, to make and implement joint decisions, and in so doing to expedite outcomes and ensure coordination with water resource and other activities of the federal and state governments. A Federal-State body, which we will for convenience refer to as the "Coastal Louisiana Authority" (it could alternately be a "board" or 64 commission"), should be established to fulfill this role. The CLA would be comprised of a small number of members with appointments made by the President and the Governor of Louisiana. The group would have a small administrative staff and an executive director, as necessary to execute its functions. Its authorization should be subject to periodic review and renewal by the Congress and the state. The CLA could report to the President and Governor or operate under the administrative jurisdiction and support of an appropriate federal agency to ensure coordination with the water resources and other activities of the federal government.

The CLA's responsibilities and powers would be limited to three areas. First, it would be responsible for leading the development of joint federal-state policies that govern an integrated investment and management program (discussed later in this section) and for revising those policies over time as new knowledge emerges, and social, economic and environmental conditions change. Second, the CLA would review and approve the use of the programmatic funds (see discussion of authorization and funding, below) allocated for adaptive management and the science and technology program, as well as other uses discussed below. Third, the CLA would direct, receive and use analyses of its Coastal Assessment Group (CAG) and, based on those analyses, stakeholder input and coordination with the Mississippi River Commission and the Louisiana CPRA, would make funding recommendations for significant investments (those that exceed a defined threshold). The recommendations of the CLA would be an affirmation that the proposed project has been formulated and evaluated in full consideration of the agreed policies. Based on such recommendations the Corps, or another appropriate agency, would have the responsibility to design, construct and, if authorized, operate and maintain the recommended project.

Coastal Assessment Group

The CLA would base its advice on analyses conducted under the direction of a Coastal Assessment Group (CAG). The CAG should have a professional staff with a full range of skills and perspectives (multiple purposes and multiple disciplines including natural science, social science, economics, and engineering). However, the staff would remain small, but could be expanded to address specific tasks with personnel from the state and federal agencies on temporary assignment.

The CAG would have two roles. First, the CAG would be responsible for executing the integrated assessment to assure that each proposed project investment in storm protection, navigation and coastal restoration takes advantage of synergies and avoids and mitigates conflicts among purposes. Also the CAG would report whether and to what extent different economic, environmental and social objectives are served. The integrated planning process would be led by the CAG, however detailed project design, basic data acquisition and modeling, and other tasks contributing to project execution would be done in the existing agencies, principally the Corps and the state. Second, the CAG would be responsible for the direction and oversight of the Coastal Engineering and Science Program (CESP) in order to assure that the work of that program is targeted to the decision making needs of the CLA.

Coastal Engineering and Science Program

A Coastal Engineering and Science Program office would build on the concepts developed for the LCA Science and Technology Program ' but would be broadened to address storm damage reduction and maritime transportation, encompassing the natural science, engineering, social science and economics applications deemed relevant to the integrated management framework. In particular, it would be responsible and accountable for supporting adaptive management, including participatory decision making, and ensuring rigorous, independent peer review. A key responsibility of the managers of the CESP is to respond to the oversight of the CAG and assure that the scientific uncertainties deemed relevant to decision making are addressed through the program. The CESP would rely on scientists and engineers in agencies, universities and the private sector to perform most of the required research, modeling, and monitoring. Consequently, the office staff would remain small.

Programmatic Authorization and Funding

While the total composition and costs of the integrated planning and investment program can not be determined at present, it is necessary for the Administration and the Congress to make a significant and certain up-front commitment of funds and establish new procedures for expeditiously funding this program over time.

No less than two hundred million dollars per year, for a 10year period, should be authorized by the Congress to support the CLA and the CAG. Appropriations should follow that authorization. The agencies receiving the appropriations would manage those funds consistent with the guidance of the CLA for: (a) the integrated systems planning program; (b) the CESP research on decision-critical technical uncertainties, including funding pilot projects to test project design concepts; and (c) comprehensive post-implementation monitoring and assessment. Also, the CLA would be authorized to allocate funds for projects costing less than some threshold, e.g. $25 million, with project execution being the responsibility of the Corps and the State. In the future, consideration should be given to administering the existing CWPPRA program through the CLA some time after the efficacy of the CLA has been established.

Programmatic funding would loosen the restrictions on adaptive management costs as a percentage of total project costs, as well as the requirements for separate authorization for each component project. With a certain funding stream there could be a continuity of programs and staff, an adequately funded and reasonably managed engineering and science support program, and accelerated planning for implementation of smaller projects.

Louisiana Coastal Investment Corporation. The CLA could recommend authorization and appropriations for Corps projects that exceed the thresholds in the programmatic authority, or for project maintenance, through the existing WRDA and appropriations processes. However, reliance on authorization through the uncertain WRDA process (the last WRDA was passed in 2000) seriously risks delay and programmatic incoherence. A more predictable and flexible alternative approach would be to legislatively create an entity, for convenience referred to as the Louisiana Coastal Investment Corporation 60 (LCIC), as an independent funding authority for new projects and their maintenance. The LCIC would receive recommendations from the CLA and would fund projects meeting investment criteria established by Congress when it authorizes the LCIC policies. The corporation would be given the authorization to issue bonds with maturities of up to 50 years to finance investment projects to meet the three purposes of storm protection, marine transportation and coastal landscape restoration. An initial bonding authority of $5- 10 billion appears to be justified by the extensive storm protection, navigation and restoration needs of the region.

The long-term bonding authority aligns the financing of the new investments with the long-term benefits they provide. The federal government would guarantee the bonds. In addition the Congress could set a financial limit on the bonding authority when the corporation is chartered. The Congress could review the LCIC on a five-year basis, could dissolve the corporation at those times or choose to raise or lower the bonding authority. The bonds could be repaid with a combination of funding sources that may include, but would not be limited to: future federal appropriations; fees on port, waterway or pipeline users; wetlands permitting fees; receipts from Outer Continental Shelf (OCS) mineral revenues; and non-federal cost sharing payments. Intergovernmental cost-sharing requirements would be established by a Congressional formula and a legally binding agreement to make payments that contribute to retiring the bonds would be required before issuing any bond.

Professional Staffing

An essential element in enhancing the credibility and soundness of planning and implementation is an agency's internal staff capabilities. The Corps of Engineers is facing a significant loss of staff numbers and capability through retirement, just at the time that the demands for its skills are increasing. Indeed, the integrated planning process will demand a wider array of skills from the engineering, hydrologic, geological, biological and social sciences than is currently available in the agency or in federal or state agencies generally. Also, the effectiveness of the long-term program requires the institutional memory that develops within a permanent and professional staff. This is not to suggest that all the work needs to be done by agency staff. However, if much of the work is done by contract, agency professionalism and competence are essential for comprehending advice from outside experts and translating it into useful information to support decision making. The Corps and the bodies recommended here must have the ability to recruit and the ability to retain talented personnel.

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APPENDIX H: HOW SAFE IS SAFE?

Coping with Mother Nature, Human Nature and Technology's Unintended Consequences

by

Dr. Edward Wenk, Jr.

H.1 Preface

This treatise on risk was prepared a backdrop for the analysis of the cause and cure of massive flooding of New Orleans associated with the hurricane Katrina. I do not regard myself as a theorist in the field of risk management. Instead, I have led a professional life of exposure to elevated risks, of managing risks to which others were exposed, and of advising public officials at the highest levels of government on strategies of risk abatement. From extended observations at ringside, I have down-loaded and sorted memories so as to share experiences that define fundamental properties of all risk environments created by acts of nature, from human frailty and from unintended consequences of technology.

The product is not an encyclopedia of risky situations, nor a how-to handbook on risk management. It is not a post-crisis analysis of Katrina nor of its calamity twins. It is not a check off list of **what** parameters to think about in the risk equation, but rather a tool on **how** to think about the quintessential questions of "How safe is safe" and of the exercise of social responsibility to limit harm.

This treatise has been prepared for readers ranging from professionals in risk management to non-specialists with heavy portfolios to adopt and implement policies to shield citizens from threats of bodily harm or of property damage. Finally, it is directed toward citizens exposed to involuntary risks who feel responsible for participating in civil decisions that affect their safety and security and that of the community.

This survey, suggested methodologies of assessment, and conclusions related to Katrina are based on case studies starting with the wreck of the *Exxon Valdez* where the author was directly involved with the post-mortem analysis. Other cases include the spacecraft *Challenger*, the eruption of Mt. St Helens volcano, the Bhopal, India, chemical spill, the air attack on the twin towers, 9/11, the failure of intelligence for opening the war on Iraq, and about 100 artificial cases prepared over two decades by graduate students in the Program for Social Management of Technology at the University of Washington. The perspective for analysis is systems based and interdisciplinary, elaborated in *Tradeoffs: Imperatives of Choice in a High Tech World* (1986).

The contributions of others with whom I studied and worked deserves emphatic acknowledgement. Indeed, virtually all my bosses over a lifetime deserve accolades as teachers. To the point of this treatise, I want to thank those who read the manuscript and followed my entreaty for robust criticism: Profesors Robert Bea, Naj Meshkati, Robb Moss, Mary Raum, and Karlene Roberts, Dr. Anita Auerbach, George Lindamood, Flo Broussard and Kofi Inkabi.

I especially want to thank Naomi Pascal for her gifted editing that raised the stature of the essay to the highest professional standards, and Professor Robert Bea for inviting my participation in the Katrina project. It has been an exciting experience.

H.2 Introduction

H.2.1. How Safe is Safe?

The Katrina Hurricane disaster in 2005 exposed a technological failure of inadequate defense against a predictable, risky and potentially lethal event. Recent studies, including this latest one from the University of California at Berkeley, focus on death and destruction from flood waters that were released by collapse of levees. Studies of cause acknowledge the extreme forces of nature but also cite the human and organizational errors (HOE) that now occur more conspicuously because the engineering of physical parameters has been refined. HOE failures now exceed mechanical sources.

Because protection against human weaknesses is more art than science, the study of cause and of remediation requires a context for risk analysis. As systems based and interdisciplinary, that depiction should be of help to non-specialists with policy and management responsibilities so as to understand the enigmatic question of "How safe is safe?" In other words, what level of risk is acceptable when making decisions on public safety and security.

Risk is usually defined as a condition where either an action or its absence poses threats of socially adverse consequences, sometimes extreme. Risk happens from acts of nature, from weaknesses of human nature, and from side effects of technology, all situations that mix complex technical parameters with the variables of social behavior. Although each risk event is unique, all display commonalities that permit systemic analysis and management. These recurring properties lead to certain principles.

To begin, the acceptability of risk cannot be extracted from science or mathematics; it is a social judgment. The spectrum of risk thus embraces both the physical world defined by natural laws, and the human world loaded with beliefs instead of facts, values, ambiguities and uncertainties. Among other features, the physical world may be thought of as a mechanism whose behavior follows principles of cause-and-effect because each internal element has fixed properties regardless of which function it is expected to perform. On the other hand, the human world performs more like an organism whose components are not fixed but may grow, be altered by the thrust of external events and by interplay with other internal elements.

Following a notion that what you can't model you can't manage, a systems model is needed to represent the processes by which both physical and societal factors are defined, interconnected and interact. Such technology-based human support systems are labeled by their intended social functions-----food production, shelter, military and homeland security, communications, transportation, health care, energy production, conservation of natural resources, water supply and sanitation, education and even entertainment. In our modern era, all these functions have been enormously strengthened by applications of scientific knowledge, then applied through engineering.

It helps to think of technology as more than the hardware of planes, trains and computers. Rather, it is a social system comprising many organizations, synchronized by a web of communications for a common purpose. It is energized by forces of free market demand, of popular demand for security and quality of life, and by forces of scientific discovery and innovation. It is best understood as a technological delivery system (TDS) that applies scientific knowledge to achieve society's needs and wants

Technology then acts like an amplifier of human performance. With water wheel, steam engine and bomb, it amplifies human muscle. With the computer it amplifies the human mind and memory. It also amplifies social activity, mobility, quality and length of life.

A paradox arises when technologies introduced for specific benefits also spawn side effects. These can induce complexity, conflict and even chaos. Most of these are unwanted by some sector of stakeholders, now or in the future. This paradox is dramatized when technologies are introduced to defend against violence of nature or against human and organizational error but themselves spring unintended and possibly dangerous consequences.

The investigation of risk and of measures to contain it within safe limits requires both hindsight and foresight. The past can illuminate failures, their causes and their control as lessons for engaging new ventures and threats. The future commands the exercise of foresight, an imaginative preparation of scenarios stirred by such questions as, "what might happen, if," or "what might happen, unless." Those inquiries should then examine the timing of impacts (immediate or hibernating) and identity of players on the risk horizon who trigger risk, those parties responsible for risk abatement and those adversely affected now or in the future.

Modeling then becomes essential to represent a full cast of stakeholders and their inter-relationships, including both the private and the public sectors. The concept of a technology delivery system (TDS) discussed later is simply an attempt to model how the real world works.

The responsibility to manage risk stems from the American Constitution, from custom , and from a growing body of public law. Federal, state, and local governments are heavily involved in all of the technologies itemized previously, contrary to popular belief that technology is private industry's territory. With waterways, for example, the Army Corps of Engineers (USACE) has a predominant statutory responsibility. That accords with the historic federal stewardship of national infrastructure, from roads, shipping channels, harbors and canals to airplane routes and the Internet.

That achievement carries significant but subtle implications. For one thing, safety costs money. The federal budget is constantly challenged to meet a rainbow of different demands, the total of which always exceeds Congressional appropriations. The mismatch must then be reconciled through tradeoffs at the highest policy levels stretching all the way to the President of the United States and the Congress.

Indeed, the President becomes the nation's systems manager because all agencies responsible for citizen security report to the Chief Executive, because he is arbiter of budget priorities and author of annual budget requests. He is held to account for quality of performance and for design of public policies if authority or performance is lacking. Serious threats of nature also require the mustering of resources that are available only through the armed services of which the President is Commander-in-Chief.

Often, a focus on power of the Federal Government misses a major premise of democratic governance. As the Declaration of Independence states, those who govern should do so only with the consent of the governed; we would say the informed consent.

This notion is reflected in such regulatory legislation as the National Environmental Policy Act (NEPA). Section 102(2)c. It requires estimates of harm that could result from technological initiatives, along with alternatives to accomplish the same goals but with less harm. After preparation, these environmental impact statements (EIS) are made available for public comment and possible amendment. The point is that this process makes every citizen a part of government to negotiate the question of how safe is safe and thus provide citizens the levels of safety and security that they desire.

Implied is a prospective national policy that those put in harm's way have a voice in what otherwise could be involuntary exposure to risk. This principle leaves implementation of the concept to the responsible federal agencies, subject to Constitutional safeguards. That doctrine of anticipation was the policy spine of NEPA and the 1972 legislation to create Congress's Office of Technology Assessment (OTA).

That agency functioned as radar for the ship of state to estimate future effects of today's decisions. It was killed in an overnight action by House Speaker Newt Gingrich in 1995. In one sense, OTA served as a risk manager for the Congress and the agency's production of unbiased reports gained commendation, sufficient to WARRANT its rehabilitation in a new policy venue sharply focused on risk management.

Managing risk demands attention to operational details. For example, *informed* consent assumes that every citizen has access to the facts, all the facts. And it assumes they are readily understood by individuals without specialized training. Here the print and electronic media become conveyers of raw information to help citizens judge their exposure, but also to serve as watchdogs through investigatory journalism as an independent check on truth. This condition places a burden of responsibility on both the media and citizens to grasp the risk equation sufficiently to better understand their own risk exposure and their risk tolerance, thus to frame their informed consent.

Despite a tendency to flare the sensational, the media can enrich understanding with a backstory because disasters so agitate a functioning system as to reveal the full cast of stakeholders, their roles in increasing or decreasing risk and their degree of injury. Managing editors require that the subject "have legs" to justify time and space of repeated coverage.

Even if this process works perfectly, the outcomes would not be free of conflict. An individual's judgment on matters that threaten lives, property and the natural world is heavily colored by their portfolio of values. Moreover, different stakeholders have different interests to guard. In deciding how safe is safe, disparate views may require bargaining so as to reach a consensus.

A serious problem then surfaces when all parties argue from their short-term self interest. Little attention is accorded the longer term. Left out of the bargaining process is our progeny, the future generations. It can then be argued that the federal government should not simply act as umpire but try to balance long- with short-term effects using foresight, to compare options that do not penalize children by harm or bankruptcy.

The engineering profession has long practiced social responsibility by a technique of over-design, to compensate for uncertainties in loading, in materials, in quality of construction and maintenance, etc. This may be accomplished by adopting some multiple of loading as a margin of safety ranging from 1.4 to 5.0. How these margins are set and by whose authority is of critical importance, especially where tradeoffs with cost or other compelling factors such as deadlines may compromise the intended reduction of risk.

This method of safety assurance is more applicable to design of mechanisms not subject to human and organizational errors. The term "errors," incidentally, is shorthand for a broad spectrum of individual and societal weaknesses that include ignorance, blunder, folly, mischief, pride, greed and hubris.

Protecting structures against violence of nature such as with earthquakes, volcanic eruptions, tsunamis, floods, landslides, hurricanes, pestilence, droughts and disease may utilize the concept of over-design, based on meteorological, hydrological, seismic and geophysical data of past extreme events; e.g. the highest flood or most severe seismic event in a century. Equally pertinent is the scale of losses. Beside the previous techniques of safety enhancement is one of redundancy where, for example, commercial airliners are required to have at least two engines, one of which may suffice to assure a soft landing.

Protecting structures against violence of terrorists entails additional practices of a customized precautionary principle. This intervention may be adopted as a preventative measure or one of damage control.

Learning from documented failures is a powerful method for reducing risks of repeated losses. Another is to learn from close shaves. Many dangerous events fortunately culminate in only an incident rather than an accident, but the repetition of similar incidents can serve as early warning of danger. Indeed, the logging and analysis of such events on the nation's airways partially accounts for their impressive safety record. A system for reporting close encounters was installed decades ago. Anticipating the possibility that perpetrators of high risk events might be reluctant to blow the whistle on themselves, the Federal Aviation Administration that has cognizance arranged for NASA to collect incident date and to sanitize it to protect privacy of the incident reporter. NASA also screens reports to identify patterns as early warning of a dangerous condition. Similar systems are in place for reporting incidents with nuclear power plants.

With the growing recognition of human factors in accidents or in failures to limit damage, a class of situations has been uncovered entailing uncommonly high risks but conspicuously good safety records. In the Navy, for example, high risks attend the crew on submarines and on carrier based aircraft. Yet accident rates are paradoxically low.

Careful analysis has shown that certain qualities of leadership and organizational culture foster integrity, a sense of responsibility among all participants, a tolerance by authority figures for dissent, and consensus on common goals of safe performance.. Especially has high safety performance been correlated with an institutional culture that was bred from the top of the management pyramid. The most critical element of that culture was mutual trust among all parties in a technological delivery system.

Long experience with military and paramilitary organizations such as first responders proves the value of rehearsals to reduce risks and control damage. Of special virtue is proof of satisfactory communications. Evaluation of dry runs has repeatedly turned up serious problems in communication. So has post-accident analysis of real events when delays or blunders in communication of warnings and rescue operations cost lives.

This leads to recognition that successful management of risk depends ultimately on the prudent exercise of political power by leaders at every level. Deficiencies may still remain in political will, in fiscal resources, in vigilance, and in ethics. Hard to define and to measure, these elements may sadly define themselves in emergencies by their absence.

To sum up, the context for analyzing the levee failures from Hurricane Katrina illustrates several realities. The most compelling imperative of life is survival. Yet the experience of living teaches that there is no zero risk. Some exposures must be tolerated as "normal," whether in rush hour traffic or coping with nature, with human nature or with unintended consequences of technology.

In this modern era, society has demanded better protection against threats to life, to peace, justice, health, liberty, .life style, private property and to the natural environment. These challenges are not new, but two things have changed—the increased potency of technology and increased coverage by media. Technological factors are more robust in speed of delivery and in potential harm. Media covers events live, 24/7, and worldwide. Events anywhere have repercussions everywhere. The better informed public tends increasingly to be risk averse. Apprehension and fear peak after a calamity with demands for better protection through better governance. Higher expectations are legitimate because so many threats just itemized are due to human and organizational errors either in catering technologies to meet market demand or in guarding against hazards. This current study shows that the Katrina event fits that pattern. Government at all levels failed to provide security to citizens before and during the catastrophic flooding. Victims are justified in asking how did this pathology of a mundane levee technology develop? How can that knowledge be applied to prevent a reoccurrence? Then there is the quintessential question of "How safe is safe?"

As said earlier, answers cannot be found only from natural laws of science. Safety is a social judgment. Those exposed to risk have a right to information about their exposure to danger and about the strategic issues of protection.

Ultimately, these decisions are made by government, and that process entails wrestling for power. In that matrix of conflicting interests, in our democracy, this authority should flow from citizens taking responsibility to become informed on their exposure to risk and to assure the opportunity to express an informed consent.

At the federal level, both the President and the Congress need objective, expert advice and counsel to fulfill their responsibilities under the Constitution. They also need to increase their respect for independent analysis of risks in order to restore citizen trust.

The preceding situation analysis opens a window on a number of issues treated in more detail in subsequent sections:

- The design of precautionary measures requires inspired foresight, to fantasy alternative futures:
- Tradeoffs are inevitable between short- and long-range events and consequences, between safety and cost, between special interests and social interests, between who wins and who loses and who decides.
- All human support systems entail technology, and all technologies project unintended consequences.
- Society embraces a spectrum of values that often conflict, as with the goals of efficiency in the private sector and of sustainability and social justice in the public
- Key decisions regarding citizen safety and security are made by government through public policies to manage risk. These policies dominate the legislative agenda.

- This mandate imposes a heavy burden on the President and on the Congress, both bodies requiring access to authentic and immediate information.
- Making decisions and assuring implementation draws on political capital in the structure of authority by the exercise of political power and political will.
- In our democracy, this authority should flow from citizens following the principle that those who govern do so at the informed consent of the governed.
- The quality of risk management can best be judged by the effects on future generations.
- The geography of risk crosses boundaries as between federal, state and local entities, and between the United States and other nations.
- Different cultures have different risk tolerances, including attitudes distinguishing voluntary from involuntary risk.
- Analysis of risk and its control extracts lessons from past failures, although the most catastrophic events are so rare as to frustrate projections.

This portfolio of issues illustrates the anatomy of risk and the complexity of its management. They sound a wake-up call for deeper understanding by those responsible for risk management and by those attentive citizens who are exposed and are entitled to a voice in the decision process.

H.2.2. Risk Analysis as a Survival Skill

Humans have always lived at risk. From early times, we experienced threats of hunger, natural disasters and extremes of weather, dangers of accident and violence at the hands of other people. Brutality wasn't just physical. Some threats were psychological and emotional as by deprivation of human rights, freedom and dignity, of equitable access to resources and of opportunities for self-expression. Only a tiny elite lived with reasonable security; others were dominated, exploited and enslaved.

A big bang of change occurred with a twin enlightenment of democracy and of modern technologies. People live longer. Quality of life is higher and more widely and evenly spread. Everywhere, citizens expect government to provide overarching security.

With progress, however, have come new risks. Nuclear, biological and chemical weapons expose every human to extinction, and weapon delivery systems can be so distributed and hidden as to make total safety pure fantasy.. On the other hand, arms control treaties of 1963 on non-proliferation and limits to testing demonstrated how nations can negotiate risk reduction for common survival, even in a hot atmosphere of a cold war. That same ingenuity is required to manage twenty-first century risks.

Periodically, philosophers and theologians have peered into that future, some with lenses colored by optimism, others by the obverse. By the 1930s, a literature emerged of pure speculation and conjecture. Some promised only entertainment; some was serious and usually pessimistic. By the 1960s, risks were being charted by scientists and engineers..

In 1962, for example, Rachel Carson wrote in *Silent Spring* about the loss of bird song because DDT sprayed to wipe out malaria laden mosquitoes had side effects. Egg shells of birds were thinned enough to halt reproduction. That wigwag captured public attention that echoed in the chambers of policy making. In 1970, the United States adopted the National Environmental

Policy Act to protect the environment broadly. It required analysis of ecological, economic, and social impacts triggered by technological initiatives. It also required their publication and opportunities for citizen reaction.

This achievement challenged the public process as to whether society was prepared to deal with the new information on which to form judgments of safety.

In 1972, two related events occurred. First, the United States Congress awakened to the unintended consequences of technology and founded a new advisory agency, the Office of Technology Assessment, the OTA. It was mandated to look ahead and unpeel the ubiquitous side effects of almost every technology. The Act brought the future into the decision process in a vigorous spirit of early warning.

Second, a group of European corporate executives (called the Club of Rome) took time away from their internal management to study and publicize extreme pathological trends in the world at large. Interactions were examined among spiraling population, rising insults to the environment, limits on food production, on such natural resources as energy, and on effects of urbanization. The study, *Limits to Growth,* sounded an alarm that in perhaps 75 years, dangerous trends would become irreversible. Although the study's methodology was questioned, its warnings attracted world wide, policy level attention.

As the public became aware of the two faces of technology, the future was probed not only of physical limits to the carrying capacity of the planet, but limits to human knowledge, ingenuity, judgment, objectivity, and mastery of problem solving. My contribution to the inquiry was to test a portfolio of dangers from unintended consequences of technology against two measures of risk reduction. One lay in defensive technology. The other lay in the muscular practice of politics!

Table H.1 summarizes conclusions reached in 1977, almost 30 years ago and published in *Margins for Survival,* 1979. The different forms of menace have all happened at one or another scale, including terrorists with weapons of mass destruction (WMD) in Japan. The most effective pre-crisis intervention still seems to be through politics, not new techniques. The poorest guesses were on imminence. Perhaps the author was spooked by total immersion in doomsday subject matter of that era and a close shave with the Cuban missile crisis.

These projections are interesting but not as important as planning a risk analysis strategy for survival. While government has that responsibility, a post-mortem of *Katrina* may reveal endemic malfunctioning and the need for broader awareness and involvement of citizens.

Lessons From Disasters and Close Shaves

Engineers remember that until two centuries ago, they learned mostly from failures, Occasionally, they still do. Katrina and 9/11 have been cruel teachers.. With a global span of high-speed communications, we can study catastrophes at great distances. We can construct a rich case book to extract patterns of risk that are universal because natural phenomena are global and new technologies no longer have geographical, national, economic or cultural boundaries. Even our humanitarian concerns encompass people everywhere.

The short compendium that follows is not intended to be comprehensive. It is only a sample of events selected from a swarm of news stories where media editors and TV producers thought them important enough to earn repeated headlines. As the media jargon goes, "the stories had legs." The initial story had many sequels. That publicity was justified by the scale of impact in lives or property lost, by the surprise lack of early warning, by the likelihood of the pattern being repeated so as to deserve hyper vigilance, and by effectiveness or its failure with damage control.

Table H.1: Menaces, Outcomes, Probabilities, and Interventions

Menace	Worst Case Casualties (millions)	Worst Case Imminence (years)	Probabilities and Trends		Pre-Crisis Intervention		
					Minimum Time (years)	Successful Means (scale 1 - 10)	
						Technical	Political
WMD, Terrorism	30	0	High	⇑	10	8	2
Famine, Natural Disasters	1,000	10	High	⇑	15	8	5
Environmental Accidents	2,000	25	Medium	⇑	15	8	7
Climate Change	1,500	75	Low	⇑	50	3	7
Urban Chaos	500	15	High	⇑	30	5	3
Resource Depletion	1,500	30	High	⇑	20	7	4
Economic Collapse	1,000	15	Medium	⇑	15	6	5
Institutional Collapse	500	15	Medium	⇑	25	5	5
Decline in Values	2,000	25	Medium	⇒	20	7	3

Consider these large scale disasters, perceived threats, or close shaves:

1) Hostile Military or Diplomatic Actions

A-Bombing Hiroshima and Nagasaki, 1945
Soviet Space Shot, 1957
Cuban Missile Crisis, 1962
Capture of U.S. naval vessel in Tonkin Gulf, 1967

Actions by Terrorists

Truck bomb damages New York's World Trade Center, 1992
Bombing of Oklahoma City federal building, 1995
Bombing of U.S. Marine Barracks in Lebanon, 1983
Bombing of U.S. embassy in Kuwait, 1983
Bombing of U.S. naval vessel in Yemen, 2000
PanAm #103 exploded over Scotland, 1988
Airplanes crash into World Trade Center and Pentagon, 9/11/2001

Violations of the Environment

Torrey Canyon tanker spill, 1967
Exxon Valdez tanker spill, 1989
Gas emissions damaging the atmosphere's ozone layer
Greenhouse Gas emissions triggering global warming

DDT and PCBs distributed in waters, worldwide

Technology-related Disasters

Rash of steamboat boiler explosions, 1830s
Explosion of chemical plant in Bhopal, India, 1984
Nuclear power accident at Chernobyl, Ukraine, 1986
Challenger spacecraft failed on reentry, 1986
Infrastructure lags behind urban growth
Long outages of electricity, phones, water and waste disposal
Failure of whole systems
One thousand Savings and Loan Bankruptcies, 1980s
Health care fraud and lack of coverage
Continued shrinkage of passenger railroads in U.S.

Acts of Nature

Tsunami in Indonesia, 2005
Earthquake in Kashmir, 2005
Katrina Hurricane on U.S. Gulf Coast, 2005
Global flu epidemic, 1918
Drought and famine, Africa
Evolution of Avian Flu to threaten humans, 2005

Resource Depletion

Increase in energy demand not matched by new supplies
Depletion of ground water resources

Pathological Violence by People

Holocaust, Germany and occupied Europe 1939
Genocide, Sudan, 2001
Genocide, Uganda, 1985
Genocide, Iraq, 1996
Suicide bombers in Israel
Loss of freedom by concentration and control of media

All these threats share common elements: hazards potentially affecting greater numbers of people than ever before, risks extended geographically and through the future. All involve technology and require human intervention in both prevention and mitigation. In most cases, this depends on government, through legislation, specifically tighter regulation.

Each threat has three back stories: the history and immediate context for the main event, the event and its effects, and the post event consequences and application of lessons learned.. Present at every stage are challenges to decision making, mainly by public officials. The political stage is tense: anxiety, frustration and stress rise over lack of crisis prevention and of damage control plans, over weak communication networks, over conflicts among parties at interest, over threats to the status of the decision makers themselves. Spotlights focus on first responders, but ultimately on the nation's Commander in Chief. The President is functionally the nation's system manager!

This inventory demonstrates the close bond between technology and government, the centerpiece of a book by this author, *The Double Helix: Technology and Democracy in the American Future*. As these examples are tweaked in the following sections, the reader should focus on a particular class of technologies, those installed to deal with extreme violence of nature or of terrorists, either to prevent disasters or to limit and ameliorate damage.

H.2.3. Tradeoffs Between Risks, Cost of Mitigation and Performance

Safety costs money. That unwelcome truth creates dilemmas in the social management of all technologies as demonstrated in trends of safety measures for automobiles. Here is a sketch of that evolution

Looking back, during World War II, the production lines of cars gave way to production of armaments; fuel was strictly rationed. With peace, the pent-up consumer demand exploded. One unintended consequence was a sharp rise in highway fatalities. As a creature of auto manufacturers, the National Safety Council opened a publicity campaign to reduce accidents, pointed at "the nut behind the steering wheel." The industry blamed crashes entirely on driver error. Up until then, the most significant improvement in auto safety had been a requirement for brake lights. The public bought that rationale and began training drivers in high schools but ignored safety measures for vehicles themselves.

As fatalities continued to rise, newspapers featured weekend carnage, for example on Route 1 between Baltimore and Washington, D.C. The public became agitated but it lacked mechanisms for protest other than the AAA. Even insurance companies were silent. Safety advocacy then grew following Ralph Nader's model of credible documentation. Things happened.

State and federal governments mandated turn signals, shatter proof windshields, rear view mirrors, tubeless tires, winter treads, emission controls, seat belts, and stiff penalties for DWI. In most cases, the industry resisted initiatives on grounds that improving safety would boost cost and, following elementary economics, would shrink the customer base. Battling the industry were national leaders in engineering, in public health and in consumer rights. The era of citizen activists and responsive government was just dawning and industry had to be dragged, screaming and kicking, toward safer cars.

Albeit not with mathematical equations, the public asserted how safe is safe. Their tolerance for fatalities in the U.S. hovered around 50,000 per year. Beyond that mortality rate, drivers demanded improvements and were willing to pay the added costs.

This story echoes earlier advances in railroad safety and then air transportation. It is also a model of what has happened over the last century regarding citizen protection by immunization, requirements for pure food and drugs, and by preservation of such common property as air and fresh water. Apart from these tangible measures, similar interventions by government were demanded for the less visible harm of monopoly pricing, security trading fraud, etc.

Before elaborating further on the concept of tradeoffs, it is useful to extract further lessons from the case of transportation. Here are some:

First, the public began to say "how safe is safe." Until after World War II, the cast of inventors, entrepreneurs and manufacturers soft-pedaled the issue of auto safety and targeted most research on fatigue failure of axles. Protection was expected by regulatory processes of government, but in the contest between sources of risk and victims, the most vigorous lobbying came from industry, not drivers.

That changed dramatically by the 1960s. For one thing, the love affair with cars made imperative more and safer highways. Federal support of farm-to-market roads underwent a quantum leap with1956 legislation to build a national network of superhighways that had been sketched first in 1923 by General Pershing. The breakthrough was intense public support, inflamed by advocacy of the Hearst newspaper empire. The Public Roads Administration set higher standards for states to follow in highway design and construction, on sight distance by limits on grades, curvature, width, lane separation and freedom from intersections.

The public had found its voice for safer roadbeds to be funded through taxes, and that imperative of risk management slowly leaked over to the cars themselves.

A second lesson was that with safety awareness and education, the public would pay higher car prices for greater safety. Note that the issue was pressed not by car companies or by government but by the public, media and public-interest associations. Then insurance companies reacted to the suits for negligence brought successfully against manufacturers, highlighted by evidence that risks were known to the companies but not mitigated voluntarily. That pattern improved with legislation mandating recalls. Today, safety sells cars. What a switch!

A third lesson lies in how the growth in public appetite for technology required growth in public services to manage risk. A corollary is that government stepped in only after the fact, practically never in the spirit of preventive medicine. That stance of reaction rather than proaction as a doctrine of anticipation stems from historical American antipathy to big government, and partly from the power of lobbies to influence political leadership. As elaborated later, technology has become more political and politics more technological. Sometimes, that reality stings..

A fourth lesson is that the government's role in modern life has greatly increased simply to manage risk. Most of the recent (and not just reorganized) agencies of government were created for the troublesome purpose of regulation. That theme harmonizes with the Constitutional mandate, among others, "to promote the general welfare."

One problem is that each risk is managed by different criteria and different agencies with different cultures, vertically through federal, state and local bodies, and horizontally within each layer. The first broad attempt to improve the risk management process was Section 102(2)c of the National Environmental Policy Act of 1970 requiring environmental impact statements. With a ground swell of popular support, it capped the 1968 presidential election with all candidates driven by public sentiment to stand for environmental protection. The courts later stretched the scope of the act to encompass social and economic dimensions of the human environment and not just those to preserve nature.

That breadth was sharpened by 1972 legislation to create the Office of Technology Assessment (OTA). Its purpose was to provide radar for the ship of state, an early warning system for Congress that required every technological initiative of the federal government to postpone implementation until an assessment was completed focused on questions of, "what might happen, if, or what might happen, unless." This gave public advocates a handle to dig out potentially harmful consequences and through the political process gain mitigation. OTA was killed in 1995. A similar provision for foresight was mandated in the 1976 mandate creating the White House Office of Science and Technology Policy; it has been ignored.

The preceding brief that was concerned with tradeoffs between safety and cost used auto safety as an example. Similar patterns are present in other modes of transportation, by sea, by air and by railroad. A second mode of tradeoff is present when independent parameters of design performance interact with both safety and cost. The most compelling example is with combat submarines.

As context for this case study, recall that submarine hulls must be designed to withstand the intense hydrostatic pressure of surrounding sea water when submerged to operating depth. Given the catastrophic nature of hull failure and the exposure of crew to such risks, precautions are taken to compensate for uncertainties in design theories, in materials, workmanship, aging, or from operating error. This additional strength usually entails additional weight and that poses a dilemma..

Submarines operate close to neutral buoyancy. This affords diving simply by admitting sea water to external ballast tanks. Surfacing then entails blowing the ballast tanks with compressed air carried on board. With such a delicate balance of weights between the sub's hull, propulsion, weapons, life-support functions, crew and sustenance. the incentive for adding strength to reduce risk to crew and sub itself carries a serious penalty. The weight for additional strength must be traded with weights of other components required for combat.

The design process requires serial trial-and-error calculations, varying the safety margin. For civil construction, the building codes dictate a factor of four. For special boilers, it may be as small as three. For submarines, that high a margin would prejudice war fighting characteristics, and practice for naval subs has been as small as 1.7. For research subs, it has been set as low as 1.4. For sightseeing subs, it has been set at 4. The 1.7 level means that for a sub designed to operate safely at 700 feet, its crushing strength would be about 1100 feet.

The risk of such a small margin is accepted because for each new class of subs, complex calculations are refined, confirmed by tests of small scale models in a pressure tank, then warranted by a heavily instrumented deep submergence trial of the first one operating. Other assurances lie in superior workmanship in hull assembly with x-ray examination of welds and close tolerances on shape. Operation at sea assumes high competence of crew.

In other ways, similar margins are introduced in all technologies as an act of social responsibility. The public exposed to risk is seldom consulted, and this raises a major issue in risk management that is epitomized by the familiar notion of "Informed Consent."

H.2.4. Voluntary versus Involuntary Risk

Exposure to risk may be voluntary or involuntary. The two types differ in definition in the acceptable levels of risk and in the degree to which the public expects government to regulate safety. When citizens believe they are in danger with limited options to escape, and when a large number of people is simultaneously exposed, the public demands greater protection. Here are some examples.

When planes became more numerous and larger, there were more crashes and more passengers lost. The public demanded more stringent regulation and enforcement.. Commercial airlines were regarded as common carriers in which people lose control over costs, comfort, privacy, schedules, routes, intermediate stops, destinations and risk.. Except for short flights, other modes could not compete in speed so that the primary tradeoff was in cost of tickets. As in all common carriers, by air, rail or sea, people felt at involuntary risk and demanded more protection. With encouragement by members of Congress, most of whom fly home every weekend, intense oversight has been mandated regarding equipment, pilot training, traffic rules, maintenance, etc. The annual death rate peaked at about 200 per year and is now much lower, far lower than for travel by car.

In contrast, passengers in private planes--termed "general aviation,"--enjoy all the previous options but at a higher transportation cost To keep that within bounds, this class of passenger tacitly accepts higher risks revealed by more fatalities per million passenger- miles compared to commercial aviation. Because these passengers usually have options to fly by safer commercial aircraft, FAA risk analysis deems the higher risk acceptable because general aviation risk is voluntary rather than involuntary.

A more mundane example lies in skiing. Cable lifts are regulated by local authorities as common carriers because the clientele are regarded as at involuntary risk in having no options to gain the top and no options to exit at intermediate elevations. Lift safety is carefully regulated. Coming down, however, skiers are on their own, at voluntary risk. If the number of accidents going up were as numerous as those coming down, there would be hell to pay from public complaints and from lift operators hit with higher insurance premiums and possibly more liability suits.

This question of voluntary versus involuntary risk gets blurred in consumer protection, especially with pharmaceuticals and medical apparatus. Both in liability jurisprudence and in safety standards, a major issue arises on which type of risk is present, and for each type, how does the public decide on acceptable limits.

That enigma is further strengthened because of a growing public distrust of manufacturers. Statistics from drug trials have been faulty (Merck) and short circuits in heart rejuvenators have been concealed (Guidant). This malfeasance injects another uncertainty in the calculus of risk---- the pressures of the health industry on Congress to let free market forces control safety with a minimum of government interference. That could work only if the public is literate on drug therapy; that is unrealistic.

The situation is further tangled by paradoxes in health affairs on the virtues and penalties of single payer health delivery and by advances in technology teasing consumers to believe there is a cure for every ailment, at diminishing risk.

Regulation of safety for miners at involuntary risk under ground began 100 years ago after annual fatalities exceeded 2,000. Occupational safety is now broadly regulated by OSHA

H.2.5. Coping with Threats to Life, Liberty, Property and the Environment

Restated for emphasis, the most compelling imperative of life is survival. For most humans, that condition is more than biological. It means being both alive and free. Toward that end, living teaches that there is no zero risk, that some exposures must be tolerated as "normal." In the last two technological centuries, however, society has demanded that threats to life, to peace, justice, health, property, liberty, life style, sustainability and the natural environment be minimized. Such stewardship was anticipated in a preface to the Constitution whereby founders of the nation committed our fedewral government to assume responsibility to tame these risks.

Life also teaches that threats to survival are episodic, that citizen and media sensitivity to both threats and appropriate response waxes and wanes. Apprehension and fear peak immediately after a calamity, then subside to a stable level that depends on pain of the consequences and proximity to the event, chronological and geographic. The size and continuity of news headlines mirrors and often arouses public awareness. With Hurricane Katrina, chagrin was triggered over impacts of a natural and recurring phenomenon that exposed failure of government at all levels to take precautionary steps for safety and security. The loss of life and property and the subsequent neglect of victims then led to outrage. People ask, Why did a tragedy on this grand scale occur? How can it be prevented from happening again?

This essay is not a post-crisis analysis of Katrina or of its disaster kin. For one thing, critical data are still being evaluated. However, it is clear from a number of interim reports already issued by other bodies that the failure can be attributed to human and organizational error. This source of calamity has also been found in a wide spectrum of disasters,: the nuclear accident at Chernobyl, the oil spill by the *Exxon Valdez* discussed later, Human factors lie behind the failure of intelligence and initiation of the Iraq war, sinking of the *Titanic*, terrorists crashing planes into New York's twin towers , 9/11, loss of the spacecraft *Challenger,* and the chemical spill at Bhopal, India. This source, incidentally, includes failure to anticipate potential disasters, make damage control plans, take accident avoidance measures, or make prudent choices as between safety and cost.

It is worth reiterating that the answer to "How safe is safe" cannot be deduced from natural laws of science and mathematics. It is a social judgment. Assuming people comprehend that there is no zero risk, what level do citizens accept or at least tolerate?

This inquiry is most often left to experts because the public thinks risk analysis is accessible only to professionals. Yet, individuals make many decisions each day without consulting authority. Ponder the close shaves in highway traffic, the choices of home remedies for illness, the strenuous avoidance by those allergic to nuts, the tradeoffs in investments between return and risk. Albeit in new forms, modern risks have antecedents.

Always, there have been accidents from ignorance, error, blunder, folly, greed and hubris.

One new reality is that powerful technologies add to the risk portfolio. The public and policy makers need to understand that technology is more than a technique, more than palpable hardware. It is a social system of organizations interconnected and animated for all life support functions.. Clearly, technology has a huge effect on all human affairs, not only for what it can do **for** us, but also what technology can do **to** us.

Every technology, however, has unintended consequences. Many increase complexity, conflict, personal stress and socio-economic strains. To the point of this discourse, technology such as in health care can ameliorate risks but it can also trigger risks. With many medical procedures the patient must sign "informed consent" acknowledging awareness of threats to life and function. Parenthetically, that practice deserves refinement because simply listing potential injuries does not illuminate the probabilities.

Because of modern information technology, events anywhere have effects everywhere and immediately. The village has morphed into an inhabited planet. While technology has historically driven weapons development of the spear and chariot, nuclear devices now spin a risk of mass extermination. Perpetrators may not be nations but anonymous and ubiquitous terrorists. We have also advanced the risk of a slow tsunami by global warming that melts the ice cap so that the oceans flood low lying habitation in coastal wetlands and alter agricultural seasons.

As context to the strategic issues in risk management, consider these features:

- Dangers can be grouped according to origin, from natural causes, from human behavior, and from unintended consequences of technology such as environmental damage from mining runoff.
- The design of precautionary measures requires inspired and vigorous foresight—to fantasy what might happen, if, or unless, and a comparison of options to identify those that minimize harm.
- Foresight mandates tradeoffs as between short and long range events and consequences, as between safety and cost, between special interests and social interests, between who wins and who loses and who decides.
- Technology can best be understood as a "Technological Delivery System," that applies scientific knowledge to achieve society's needs and wants. A TDS models reality with inputs of knowledge, fiscal, natural and human resources synchronized by a network of communications. Outputs are both intended and unintended. The system is driven and steered by three operating instructions---market place economics, public policies, and social norms.
- Technology lies at the core of all human support systems.
- Conflicts arise from different values in the private sector as compared with the public. Strategies to achieve desired goals contrast efficiency against sustainability and social justice
- All technologies trigger side effects; most are harmful to some community of specified or accidental stakeholders, now or in the future.
- Key decisions regarding technology in terms of outcomes are not made by scientists or engineers, or by executives in the private sector. Rather they are made through the public policy process, in the U.S. as defined by the Constitution, the President, the Congress and the Courts.
- The decision process inevitably entails wrestling for power; its intensity depends upon what is at stake as between winners and losers.
- The most compelling decisions are negotiated as "politics," here defined as the legitimate process by which stakeholders negotiate their individual interests against collective interest within a structure of authority.
- In our democracy, this authority should flow from citizens following the doctrine that those who govern do so with the informed consent of the governed.
- Decisions in this class can be judged by their impacts on future generations.
- Technology has also shrunk time and distance so that isolation is no longer dictated by geography. We live in "one world."
- The management of risk should be based on lessons from failures. However, data may be sparse with rare events of catastrophic scale.
- Different cultures have different risk tolerances. Moreover, there are significant distinctions as between voluntary and involuntary risk.
- Once there is agreement on "how safe is safe," tension is likely to continue between the sources of risk and those harmed. In the interest of social and economic justice, all three branches of government play pivotal roles.

- Since enactment of the National Environmental Policy Act in 1970, a process of impact analysis has been required of all federal technology initiatives. It applies to other classes of threat extended by legislation in 1972 that created the Office of Technology Assessment to serve Congress as a system of early warning of dangers from new technological initiatives.
- The media plays a critically important role as a source of information to all citizens and parties at interest about threats and public safety, about failures of institutions responsible for precautions, and as an editorial source of advocacy for citizens marginalized in the power structure.

H.3 Government's Responsibility for Security

H.3.1. Risk Management: Our Constitution, Public Policy, and our Culture

Restated, the TDS is a symbolic network assembled for a specific purpose with socially desirable outcomes. It incorporates customized organizational components, internally differentiated, hierarchically interrelated, and interconnected by a lacework of communications. While this production function is generally the territory of private enterprise, all elements of the system influence decisions by business management; the most powerful signals link government to the enterprise managers. .In eight different ways, public policies hammered through government shape strategic decisions in the private sector as much as the market place of all citizens. Consider these categories:

- **Providing an umbrella of security for citizens** as set forth in the preamble to the Constitution. Translated to "normal risks," providing security is the core of managed risk It is exemplified by preparing for the common defense. That priority for federal funding in 2005 exceeded support for all other federal functions, combined. Beyond threats from organized national states and from terrorists, security also relates to domestic tranquility, social and economic justice, and especially promotion of the general welfare when life, health and property are threatened by natural calamities. Civic responsibilities now include preserving health of the environment and natural species.
- **Purchasing technology** for national defense that also generates full employment and technology spin-off whereby military innovations cater to the civilian market, e.g., satellite assisted global positioning devices (GPSS).
- **Directing economic assistance to private enterprise** has been accepted as a tradition to foster prosperity and social satisfaction, not to mention economic vitality to assure a healthy tax base. In 1845, the government granted railroads a ribbon of land for trans-continental service. Wider than needed for track, these grants let rail lines profit from sales of excess land to track-side factories. The Corps of Engineers surveyed most of the mountain route at no cost to the companies, following a maritime subsidy of charting coastal waters for safety of commercial shipping Other subventions include a rainbow of tax breaks, import quotas and market guarantees.
- **Providing indirect economic assistance to private enterprise** through support for higher education, for most of the nation's basic and applied research, for such services as the Export-Import bank, launching of commercial communications satellites, weather forecasting, and guidance for American companies doing business overseas. In short, government funds our social overhead.

- **Influencing the capital market** by deficit borrowing, fiscal and tax policies, by manipulation of interest rates, balance of payments and facilitation of venture capital for new starts and ability to meet foreign competition.
- **Functioning as steward of common property resources** such as fresh water, forests, fisheries minerals and pasture on federal property that includes petroleum reserves on the outer continental shelf, and the radio frequency spectrum.
- **Building or financing infrastructure** such as of shipping channels, highways, airways, Amtrak, intangibles of the radio frequency spectrum, and the Internet.
- **Regulating** private technological activities that may be inimical to the public interest. These interventions range from anti-trust legislation, abolition of child labor, safety of transportation and mining, to purity of food, air and water, occupational health, effectiveness and safety of drugs, toxic waste disposal and other measures attending hazards of powerful new technologies.

These functions led to growth in government size and scope, the unintended consequences of greater dependence on high technology. All trigger conflicts, especially on the issue of the appropriate role of government in a society that considers itself a capitalist democracy. History teaches that regulatory legislation was consistent with Constitutional law and later of custom. The courts expect government to make the most fundamental and influential decisions contributing to security. Beyond “national security” that justified our attack on Iraq, government regulates by ranking social priorities, allocating resources, helping to organize economic, social and political activity, and tries to resolve conflicts among contending parties. That menu carries no warranty, however, on performance.

Some conflicts arise, incidentally, from ideology: when those asserting conservative doctrine believe that the best government is the least government. Some conflict arises from the concept of federalism, the cyclic tension between state and federal governments. Some arises because claims on the public purse are not matched to resources so that losers perceive themselves as victims of a game for winners.

Persistent conflict arises because most hardware of technology is produced by the private sector and its Wall Street performance balances only direct costs against profit but not the indirect costs, the externalities, the unintended consequences. Because citizens have only limited opportunities to voice the pain of side effects, government is expected to act as a surrogate. Even when represented by public interest bodies, remedies can only be enforced by government operating under legislative mandates. That damage control, however, is not guaranteed..

The act of governing begins with identification of issues, dramatized by political actors to focus political energies on the choices ahead. Often that process sounds exclusively like wrestling by special interests for influence on the outcome. At some point, differences are negotiated for a consensus on public policies as to become laws..

In other words, public policies are what governments do or what they may not do. They are the primary guidance signals by which a pluralistic society sets the course for the future. These policies should also set the ground rules, for example, of opportunities to express a collective judgment on “How safe is safe.”

Public policies deal with both ends and means. Two legislative steps are required, of authorization and of appropriations. Ultimately, all policies require the President's signature, making the incumbent the nation's uncertified systems manager.

Evidence is clear that government has grown because of technology, and technology blossomed because of government. As uncomfortable as is this trend for some, especially around April 15, one way to look at the new or growing functions is to test their content against a concept of "enhancing security by managing risk."

H.3.2. Resolution by Political Power and Political Will

The word, "Politics," suffers from erosion of its high status in Greek culture, 2500 years ago. It was meant to define a social process by which individuals with differing opinions could argue and try to persuade contrarians of their preferred course of action. This was the grist of democracy, the honorable steps to generate consensus.

Now, the word, politics, is often modified by a second one, "dirty." That derogation implies that tactics of argument violate social norms of truth and fair play. Indeed, the phrase has been stretched to imply that all political actions are contaminated, either by distortions of content or by foul play.

In the political arena when stakes are high, there are many temptations to stray from a moral ideal. However, the historic definition still works. Simply put, politics is the mechanism by which the parties at risk with divergent opinions reach agreement on what risk level is acceptable. The political process, however, goes beyond argumentation. It offers a structure of power to resolve differences, then to enforce an action plan to achieve the goals about which there was debate. In the United States, while that power lies in the three branches of government, from earlier disclosures and discussion, in the present era, the President and Executive Branch dominate the stage.

Presumably, voices of different constituencies have been heard and the Chief Executive has determined the degree of popular support essential for success of a particular course. Penalties are assessed for having to use political capital to win a preferred alternative. Since a president's political capital ebbs and flows, each decision event imposes a political risk. As with risks to security, in politics there is hardly ever zero risk.

Indeed, all the stakeholders are at political risk before, during and after a quest for consensus. Each must choose how much existing political capital they can risk. That strategic reality colors the entire context of risk management because the outcome can seldom be settled on rational grounds alone. Risk managers understand distinctions between the desirable against the feasible.

At policy levels, all players have access to varying amounts of power. The party with the most may not prevail, however, unless there is a conscious decision to exercise political will as well as power.

In a democracy, the media have a major role similar to that in the economic operations of the free market. For it to work best, there is a tacit assumption that all parties have ready access to the same base of information. That assumption also applies in political warfare.

In the theater of risk, that principle may not hold. Parties at risk seldom have the same information as those managing risk. We also must distinguish between voluntary and involuntary risk because social judgments for these two cases are vastly different. It is one thing if the parties at risk are advised in advance which mode they are subject to. It is another thing to be subject to involuntary risk surreptitiously.

In an age when small disturbances can have disproportionate effects, integrity of all negotiating parties may be more important to risk management than technical virtuosity. .

Human nature, however, may shatter this ambition. As suggested earlier, the term politics snaps the mind to electoral politics. Included are the strategies and tactics of ethical lobbying, electioneering, and legislative horse-trading, Still, the politics of public life, as the TDS suggests, is more than about governmental structure and process. Indeed, deciding how safe is safe is what democracy is all about.

Democracy is not a spectator sport. Citizens should regard themselves as part of government. This role requires civic literacy and commitment to shared values. Civic discourse should avoid intense partisanship and hidden influences of campaign funding. Values, unobtrusive and subtle, lie at the heart of political process,. thus connecting more and more dots on the TDS.

This focus on ethics applies to other venues---corporate board rooms, academia's cloistered walls, and religious institutions. They differ greatly with regard to what is at stake, to measures of integrity, to an organization's culture, its ethical standards and its style of conflict resolution, the degrees of coercion exerted by management's power to control its environment.

In the interest of earning public esteem or minimizing exposure to liability claims, organizations and individuals must balance temptations to conceal, distort, exaggerate or lie about facts against the harm they may do. The public interest is all too often sacrificed for private benefit, tempered only by the self-conscious exercise of social responsibility.

Building trust takes time, especially in an electronic era when participants in a transaction may be strangers. Personal contact to test integrity by intuition may be squeezed out.

The issue of trust has always been with us, but recent polls uncloak a new low in public confidence in all our institutions. This is not surprising. Innumerable business executives have been indicted or jailed for misbehavior, for which the 2006 Enron trials serve as a poster child. Simultaneously, charges have been brought against Abramoff, the best known of Washington's lobbyists. Several members of Congress face felony charges, have left office, resigned or are awaiting trial. In both public business and private business, many display an inordinate appetite for wealth as well as power.

Although not subject to proof, the public seems to demand higher ethical standards in public service than in commerce. There may be a danger, however, that the distinctions have been blurred. Social indicators as well as economic indicators suggest a weakening of all the nation's vital signs. The future for children is less promising than for their parents.

This theme has been examined by a growing chorus of public interest bodies such as Common Cause, Move On, ACLU, Natural Resources Defense Council, Interfaith Alliance, etc. Over a broad spectrum of predicaments that seed new or more threatening risks, there is neglect of harmful long term costs balanced against short term benefits. The fault lies in limits to foresight blended with inflated political and corporate ambitions, hubris and greed.

H.3.3. The President and the Congress: Needs for Advice and Counsel

Given society's encounter with different and more threatening risks over the last half century, the burden of responsibilities on the Chief Executive and the Legislature has grown enormously. Risk management is not a function that can be outsourced. At the same time, it is difficult to shoehorn all risk-related functions into a single aunit. Consolidation of homeland security functions into a megasize cabinet-level agency still requires coordination with such other departments as State, Defense, Commerce, Interior, Labor and so on. Only the President and Vice President have the Constitutional authority and the operational centrality to effect a seamless integration of bureaucratic resources each exposure to danger requires.

The problem is that both the President and the Congress are suffocating under workloads that drain energy because new threats arise without relief from earlier ones, and because the technical management of risk requires expertise that is in short supply. Especially lacking is an independent staff for both branches of government to provide advice and counsel in a *modus operandi* committed to a doctrine of anticipation.

To be sure, both branches have sensed a need for professional expertise related to other complex, even arcane, functions. Both branches have responded by creation of specialty staff arms. The Executive Office of the President was created in 1939 and has added numerous special subdivisions as circumstances dictated. These include the National Security ouncil, the CIA, the Office of Management and Budget, the Council on Environmental Quality, the Office of Science and Technology Policy, even FEMA at one time. Congress has created for itself the General Accountability Office, the Congressional Budget Office and the Congressional Research Service. These latter three have earned a high reputation for integrity, non partisanship and insulation from political pressures to tweak facts to fit ideology.

This issue of staffing to deal with catastrophic risk is raised here to alert the reader to arguments arising from substantive issues that may suggest a review of staff capabilities to match the challenge of security in a more dangerous and complex world.

As detailed elsewhere, a small staff could follow methods of impact analysis developed over 25 years of experience with the National Environmental Policy Act and be available in a dire emergency to keep the President well informed. Experience of the Congressional Office of Technology Assessment could also be resuscitated..

H.4 Technology and Its Side Effects

H.4.1. Beyond Technique, Technology as Social Process

The term, "technology" has a rainbow of definitions and deserves clarification on usage here. Very simply, technology is considered a social process by which specialized knowledge from science and empirical experience is employed through engineering to deliver a system to meet specific human needs and wants. But not just through engineering. Other fields of knowledge such as economics, social and political science, psychology and even philosophy must be tapped and synthesized with technique.

This concept carries virtues and problems. One virtue is the distinction thus drawn between the notions of "engineering" and "technology." Confusion arises because institutions of higher learning have used both words as equivalents in their titles [MIT, CIT, GIT, RPI, etc.]

The problem triggered by technology's broader definition is the mixture of disciplines that are not familiar to engineering practitioners. I have joked with colleagues about engineers treating the world as though it were uninhabited except by Newton's laws and their kin. Students in Civil Engineering learn how to design bridges for specified traffic over a specified span, but are generally unable to answer questions of why build the bridge at all, and if so, why there?

In 1970, I clarified the definition with a mental model of a delivery system, a "Technological Delivery System." As shown in Figure H.1, the TDS meets a standard definition of a "system" in having inputs, outputs, organizational components and information linkages. The inputs comprise knowledge plus human, natural, and fiscal resources. The outputs are of two kinds, the desired goods or services plus unintended consequences, most of which are harmful to some people or to the natural environment, immediately or in the future.

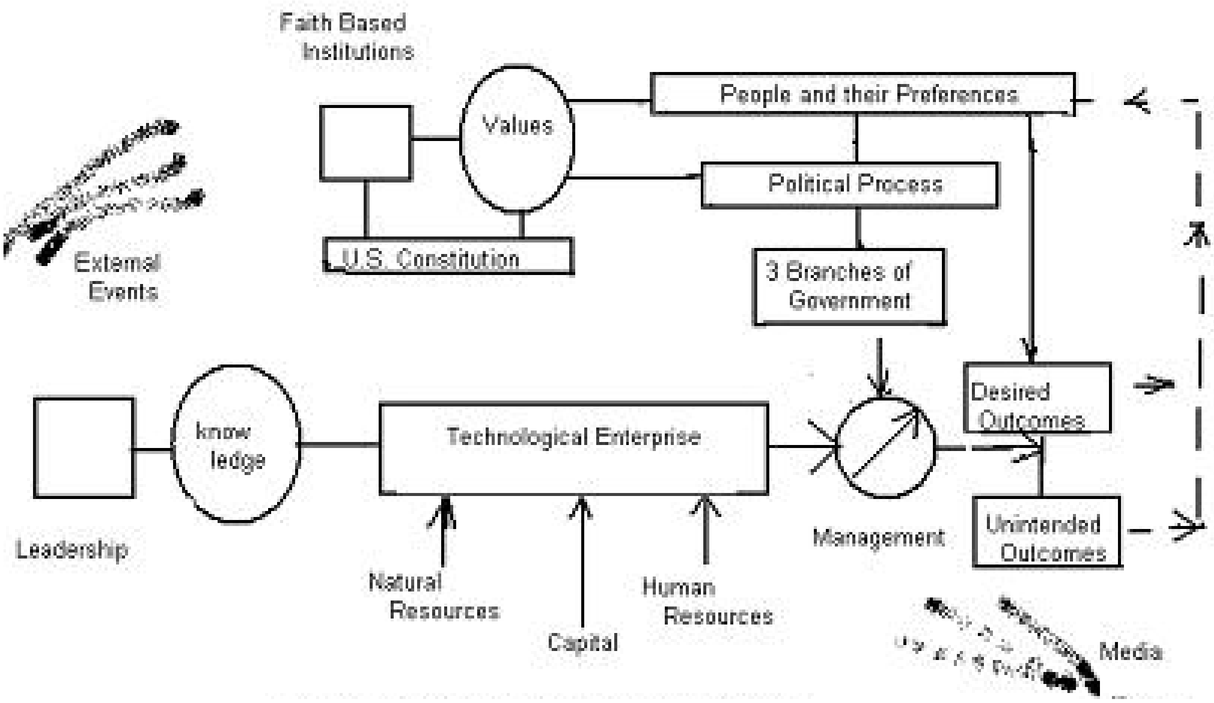

Figure H.1: Technology Delivery System

To tour the diagram, we start with technological enterprise, what the economist, John Kenneth Galbraith termed a "technostructure." It is assembled by entrepreneurial leadership, motivated by the push of innovation or by the pull of external market demand. Under resourceful management, the enterprise feeds on capital, human resources, natural resources including energy and on knowledge. These are inputs.

The system then spins two kinds of output, the intended goods and services and the unintended and often unwelcome.. Such powerful processes fuse technical, economic, social, political and cultural factors.

There are two instruments of these influences, (1)the institutions of government reflecting structure and processes specified in the Constitution, and (2)faith based institutions following a wide range of value-oriented doctrines.

All of these functions and their vehicles are portrayed in the TDS diagram. Their communication linkages are portrayed by solid lines. There are, however, other powerful influences that cannot be encapsulated because their influences are spread throughout the system. These are impacts of external events and messages from the media.

Metaphorically speaking, the TDS is like a wiring diagram for a stereo set. The system not static, however, but is animated. The TDS equivalent to music coming through a stereo is the communication traffic leading to public policy..

The message content is shaped and steered by three operating instructions, the invisible hand of the free market place, public policy, and values embedded in the culture that ignite moral vision and mold conduct.

Validity of this analytical model was tested over two decades by graduate students who applied it to nearly 100 different technologies. The purpose over many years was to capture commonalities, that is, patterns of performance. They are condensed to 12 axioms, some mentioned previously:

- Technology empowers all life support systems---food production, transportation, communications, military security, shelter, urban infrastructure, health affairs, environmental management, energy production, banking, criminal justice, education, entertainment, even religious institutions.
- While manifest as hardware--planes, trains and automobiles--technology is best understood as just described, as a purposeful arrangement of public and private organizations synchronized by information networks.
- Most hardware is conceived, designed, produced, and marketed by private enterprise in a capitalist industrial economy under a mantra of “efficiency.”
- All technologies spawn surprise side effects, most unwanted by some sector now or in the future..
- All technologies pose risks from accidents triggered by human or organizational error with unprecedented scale and geographical distribution. .Accident prevention must thus be integrated with engineering design.
- Technology generates wealth and enhances living standards, but it also fosters materialism, concentrates rewards, and increases appetites for both..
- Major decisions about technology are not made by scientists, engineers or business executives. The most salient are in the design of public policies.

Technology thus tends to concentrate political power, just as power tends to concentrate technologies as corporate structures.

- We enjoy what technology does *for* us, ignoring what it can do *to* us. One counter trend is shifting from “Can we do it?” to “Ought we do it?” and “Can we afford it?”
- These cultural impacts appear as paradoxes: more communications but less sense of community, more information but less understanding, more machines for living but less leisure. Technology distorts perceptions of time and tends to focus on the short run at the expense of longer term costs and benefits. It also distorts perceptions of space because the entire planet is wired,
- Technology tends to weaken human relationships and to foster self-indulgence and isolation.

- In an age glorifying information, we neglect its transformation into knowledge and then into understanding. These steps require time for cogitation and for preparing the mind.
- Despite its material benefits, technology induces anxieties and stress because the pace of change seems to exceed natural human rhythms, and because of greater complexity, multiple information feedback loops, and uncertainties about the future.

H.4.2. Technology's Unintended Consequences

One of the three classes of risk deals with unintended consequences of technology. As with hurricane Katrina, there may be combinations of forces by nature, by human error and by technology's side effects. This drama entails machines whose function is valued for its benefits, but which spontaneously also birth serious disadvantages.. To define this phenomenon more emphatically, I argue that all technologies have unintended consequences, most but not all of which pose surprise costs on innocent victims, to the extreme of lethality. Even when catastrophes are foreseen, they may not be preventable because intervention is too impracticable, too costly or too unpopular.

Once I thought the technology of immunization was an exception because the number of lives saved far exceeds the tiny number of people injured by this prophylaxis. Then I was reminded that this benefit partly accounts for the planet's overpopulation and hunger. Even life-saving measures have malignant side effects. Incidentally, the technology of prevention is more than a needle or a spray; it includes all elements of a TDS, especially many layers of government..

Economists call these subsidiary features "externalities," a characterization of costs that implies a studied neglect in the calculus of economic performance by shifting the burden to other actors beyond the boundary of a particular organization...

Another euphemism reborn during the recent Iraqi wars is "collateral damage." Whatever the term, risk analysis carries a premise that every technology plays "Jekyll and Hyde." So we must learn to live with ubiquitous risk. Risk happens.

Consider these concrete examples. Nuclear weapons at the pinnacle of national defense left hazardous waste at the manufacturing plants, with long radioactive half lives. At the Hanford, Washington, weapons plant, leakage of single shell underground tanks is migrating toward the Columbia River to threaten drinking water down stream. Civilian nuclear power has dangerous byproducts that, 30 years after pledges of safe disposal at Yucca Flats, Nevada, continue to fuel debate.

Automobile transportation discussed earlier for its evolution of safety has had enormous consequences besides people killed or maimed. There are air pollution, noise, stress, lost time and wasted fuel from dense traffic, superhighways puncturing urban centers, disruption of rural life by housing developments, and an insatiable thirst for fuel that shapes geopolitics with oil producing states. The American system for health care entails costs of 16 percent of the nation's GDP, or in other terms, $1,500 per GM vehicle, almost ten percent of the sticker price..

As we struggle with these relentless gremlins of high-tech society, the public that ordains how safe is safe has become more sensitive to involuntary exposure to risk and seeks protection from the perpetrators through political action.. Citizens demand governmental action.

The management of risk is perhaps the greatest challenge of the modern world-- risks of terrorist nuclear bombs, risks of global warming, risks of corporate or national bankruptcy, indeed risks across the portfolio catered earlier. The dilemmas are intensified because society looks neither sideways nor ahead. At best, vision stretches to Monday morning.

That cost of being nearsighted is widely understood. The commercial world took precautions against losses of ships and cargo through insurance companies hundreds of years ago. When these costs mounted, reinsurance was invented to share risks. Now, we seek protection against the full repertoire of hazards, partly out of greater literacy about risk through the media, , partly because we have become a litigious society, partly because the insurance business can be quite profitable.

Government is a reluctant partner of the private sector in dealing with risk by a wide range of instruments. Farmers depend on price supports for their products in the face of crop uncertainties and on tariffs to blunt foreign competition. Flood insurance was offered when corporate America chose not to indemnify the vulnerable. The nuclear power industry was protected by a powerful cap on liability, and a swarm of federal and state measures have been proposed or enacted to cap liability with suits on medical malpractice.

For all parties in technological delivery systems, consciousness has risen on the imperative of foresight. Now a different question arises: If all technologies trigger side effects, why? Was this always true?

Consider the TDS of farming 150 years ago. The family farmer took title to some land, planted and reaped with steam propelled tractors, chewed fingernails when weather turned hostile with drought or freezing or a late, wet spring. At harvest time, farmers took produce directly to market and often sold directly to the local consumer without any middle men. The farmer took all the risks of crop failure. The TDS was a primitive combination of only three entities, the land owner, the farmer and the customer.

In 1878, the Hatch Act created the Department of Agriculture with the objective of producing more food of superior quality at lower cost. With federal assistance, science and technology began to replace tradition and folk lore. Government funded an education system of agriculture colleges and research laboratories, and extension services translate academic findings for field hands. Then with the 1930s depression, government sponsored numerous subventions to hedge against soil blowing away and creating a dust bowl and against other disabilities..

With these advances, the private sector found new and profitable enterprises, manufacturing farm machinery and trucks, distilling fuel and chemicals, contracting to build farm-to-market roads, harvesting seed, selling pumps for artificial irrigation. And the private sector lent farmers money to buy seed and fertilizer for the next season, and to expand acreage as machinery made larger plots amenable to management. In a perspective of the economy, the Ag-business blossomed as organizational size and heft offered efficiencies not available to the family farmer. Their demise as a side effect has become a topic for concern.

In recent decades, transportation by sea, land and air made possible the sale and consumption of food far from the producer, and at reasonable cost. That condition had a downside also in turning the entire planet into a single market place. Try to trace where the tuna fish were caught that you find locally in cans.

This story is dramatized by comparing the simple TDS of 1900 with that today. The increase in number of components in the TDS, information circuits, speed of transportation, sophistication and complexity of modern farming, the need to follow world prices, supply and demand, spread of blight and disease, the cost of money, and possible climate change adds to complexity and challenge. These influences also add to risk, especially as the system engages a highly decentralized cast of uncontrollable characters. Each element of a TDS introduces some market advantage but also some additional risk of uncertainty depending on which political force is strongest and has access to the policy apparatus.

In the calculus of risk, the most compelling requirement in a TDS is a viable information system. That technology is necessary but not sufficient. To produce desired outcomes, information must be transformed to knowledge, then to understanding, and finally to the exercise of foresight so as to minimize unintended consequences.. That motivation and capability to look ahead may be more important in managing risk than new scientific discoveries and technological techniques.

Parenthetically, humans have always been curious about the future, especially regarding the role of fate. The Hebrew Bible tells a story of rewards for forecasting years of famine and years of plenty. Astrological calendars to read portents from the planets and stars dates back 5,000 years and is still found in today's newspapers. Individuals who claimed to divine the future held honored posts in many societies. Some still inhabit stock brokerages. Games of GO, checkers and chess are won by plotting several moves ahead.

Looking ahead assumes greater significance in modern cultures that treasure speed. Progress in computer science hinges on speed of chips, modems and services.. Autos are rated by the shortest time to reach 60 miles per hour. Failing to look ahead more attentively has higher costs. A clean windshield and an unimpaired driver may be the metaphor for safety. In atmospheric fog, we slow down. In social fog, we complain.

That conditioning has its rewards and we need to seek this kind of analogy when dealing with other situations to probe ahead so that glittering benefits do not blind us to their dangers.

In that respect, society shifted gears in the 1960s regarding insults to the environment. The public acted through the political process to look ahead through environmental impact analysis at what might happen, if, and the tradeoffs for perceived long term benefits against costs, and for finding the optimum delivery system.

This concern for the future of our children was broadened by the concept of technology assessment in the Congressional Research Service in 1964 that systemized a doctrine of anticipation. It has nine steps:

- Define the technology delivery system in terms of purpose (ends) and content (means) of hardware and operating systems.
- Define the economic, political, ecological and social context, and the institutions comprising the TDS and their behaviors.
- Establish a base of facts, uncertainties and conditional consequences.
- Forecast what is foreseeable with awareness of how the hardware and software advance, how public attitudes change and how management learns.
- Imagine action alternatives to mitigate risk and trace impacts of side effects
- Identify impacted parties, including future generations

- For each option, compare positive and negative impacts
- Design a policy and implementation plan that has the best promise of reconciling achievement of goals with satisfactions of different stakeholders.
- Monitor and report post-implementation performance

The Congress deserves praise for adopting this legislative remedy to near sightwedness and tunnel vision. It is unfortunate that the Congress didn't peer ahead at what the longer term penalties could be for zeroing out the OTA

H.4.3. What You Can't Model You Can't Manage

This section's title is an aphorism that states, unless you can build a mental model to represent reality attempts to manage will fail. On the principle of linkage between cause and effect, it may be possible to examine an event and describe *what* happened, but not *why*. Measures to reduce risk may end in futility.

Toward using the TDS as that generic model to conduct analyses, managing risk entails mapping the interaction of people, politics and technology. Across a spectrum of multiple stakeholders with different cultures and conflicting purposes, the universal goal is to achieve socially satisfactory outcomes. The TDS architecture combines seventeen components diagrammed on page 26. That static map can be switched on by discerning system dynamics.

To explain, for each life support system, a TDS is assembled by entrepreneurial leadership in response to market demand or to the opportunity created by invention and innovation. Aware of requisite inputs of human, natural, capital and information resources to spin out the desired outcomes, management acts. In the investors' expectation of profit, the free market mechanism spins to do its thing.

Citizens also use the market mechanism to signal their displeasure with unintentional and undesirable outcomes. For over a century, however, experience has taught that market forces don't suffice. Government is obliged *post facto* to enter the arena with a pallet of regulations for reward and punishment. The TDS shows these dual avenues for people to express their preferences, one by purchases directly in a mall and one by public policies hosted by political process All three branches of government participate.

In our democracy, the political process serves as a steering system. Thus the earlier appellation of the President as the nation's system manager.

From analysis of decisions generated in the TDS case studies, we observe that both society and its political apparatus are strongly shaped by values of society as a whole and of key individuals in the decision chain. In a sense, the primary sources of values are the U.S. Constitution and indelible influences of early education in a variety of faith based institutions.

Two other conditions drive policy design, external circumstances and the media. . Consider this sequence of events: the Great Depression of the 1930s, the attack on Pearl Harbor, the Marshall Plan, the Soviet space shot in 1957, assassinations of President Kennedy, Robert Kennedy and Martin Luther King, the resignation of Richard M. Nixon, the multiple bombings by terrorists and the Iraqi war. All left scars on individual citizens and the national psyche.

As to the media, a revolution has occurred in techniques within information technology. Both the geographic span and the speed of communications grew rapidly in text and graphics, in both print and electronic media. Within the technology of electoral politics, in campaigning since the 1960 election, the purchase of TV time has become imperative. As Marshall McLuhan predicted, the medium has become the message

Yet another recent development is the concentration of media ownership. Objectivity became vulnerable to manipulation by lies and misuse of news as propaganda. On the positive side, however, the press continues as the "fourth branch " of government. From the birth of the nation with the Declaration of Independence the backbone of power is said to lie with "we, the people." That social process is exercised only if "those who govern do so at the consent of the governed." That famous expression should be modified to say "informed consent of the governed," informed by the media that can also double as advocates for citizen rights.

Beyond aiding political literacy of the electorate, the media facilitate all internal elements in the TDS having access to the same base of information. That faculty is crucial to synchronizing all elements of the TDS to achieve outcomes that have been negotiated by bargaining among stakeholders. Given society's fractionation by geography, by wealth and income, by urban vs. rural, native vs. immigrant, white collar vs. blue, by religious faith and tradition, by aesthetic preferences, etc., without a free and talented press, there is no way the TDS could perform as intended

This reservoir of constantly changing information is now widely available, 24 hours every day. Stock prices change daily. However, public policies take longer to germinate, a trial of patience but also a salvation against impetuosity, secret deals and hysteria. Social norms change more slowly, usually no faster than in one generation. The sociologist Margaret Meade argued that, in her time, it took three.

Again, the media portray the instant situation, but with few exceptions, the client is expected to place current events in historical perspective, a process noted more for its absence than its presence.

The two TDS elements of external events and media content are in a constant state of turmoil. This is what animates the system of otherwise relatively fixed components.

In short, coping with risks from acts of Nature, of Human Nature and from unintended influences of technology requires understanding of the statics and the dynamics of the socio-technical process. With an operating model and assuming a consensus on goals and implementation processes, all of the stakeholders can separately contribute to the system design to deliver satisfactory life support systems.

Risk analysis starts with mapping the enterprises introduced either to further human progress or to shield it from harm.

H.4.4. Over-Design as a Safety Margin

Engineers learn from failures. By post-mortems, most are found due to inadequate knowledge of variables: the service loading, the service life, properties of materials, quality of materials, metal fatigue, quality control in fabrication, vulnerability to deterioration, operator error, poor maintenance, application of design theory beyond known limits, even human mischief. Beyond uncertainties with novel designs, we must acknowledge human and organizational error.

Several empirical techniques have been adopted to enhance safety. One is the principle of redundancy. Hospitals and high rise buildings typically have independent backup electrical systems if primary sources power fail.

The second mode of risk management in engineering is to practice over-design. The simplest examples can be found with buildings where structures intended to carry a certain floor , wind or earthquake loading are designed instead with some multiple like four as mandated by a local building code.

That multiplier is termed the "safety margin." Its size is arbitrary, a matter of judgment in order to exercise social responsibility by groups of professionals who act as surrogates for the public.

When I was with the U.S. Navy and responsible for strength design of submarine hulls, I learned that the safety margin for decades had been a low 1.7, with no structural weaknesses The submarines *Thresher* and *Scorpion* have been lost subsequently but not believed from hull collapse. This margin was in the same range as that for aircraft and for the same reason, to minimize weight of the hull. Otherwise, in a delicate balance with buoyancy, equipment to meet specified ship performance of speed, endurance, armament, etc. might have to be limited and thus penalize war fighting capability. The design solution, however, generates a paradox. Operating submerged is highly dangerous because of vulnerability to enemy action and the tendency of structural failure to be instantaneous, catastrophic, and without early warning. To reduce that risk to crew, the margins should be high. That desideratum has a cost, however. Inordinate safety is at the sacrifice of function.

I also recognized that the prospect of nuclear propulsion required a step increase in hull diameter. That raised doubts as to whether past structural design methods were valid with the larger boats.. A further growth in diameter was anticipated as subs became missile launching platforms. Past design methods thus warranted reevaluation by both theoretical and experimental techniques. Research involved complex mathematical analysis of ring stiffened cylinders, and the theoretical strength compared with structural response of models in a pressure chamber to simulate hydrostatic loading when submerged. The research was extended beyond contemporary requirements. Traditional design methods were found inadequate and thus were upgraded.

The low safety margin was also reviewed and was deemed valid because of these considerations: high confidence in quality control during fabrication: in materials being carefully screened to meet specifications; in the X-rays of all welds; in careful control of tolerances for out-of-roundness; and in inspections for deterioration after extended service at sea. There was also high confidence in responsible operators, especially confidence that they would not dive below the approved maximum depth for each class..

With these precautions, there was a history of submarine structures never failing from design errors. The 1.7 margin was continued. Subsequently I raised questions on validity of my analysis because nuclear propulsion promised higher speed and unprecedented frequency of dives. With the sea pressure then fluctuating more often, hull components were subject to metal fatigue, especially those experiencing unprecedented tension rather than compression. Precautions to limit risk were adopted, in effect increasing the safety margin.

A somewhat different issue arose in the design of nuclear boilers, here subject to constant internal rather than fluctuating external pressure. The universally adopted boiler code of the American Society of Mechanical Engineers called for a design with a margin of 5 over the operating pressure. The thick shell selected to enhance safety could, paradoxically, have an opposite effect. Radiation from nuclear fuel tends to weaken steel with extended exposure. Thicker would not necessarily be stronger. The safety margin for nuclear service was first reduced to 4, then to 3, expecting special care in fabrication and operation as with.

There are other ways to over-design. In civil engineering, dams must sustain hydrostatic pressure on the upstream face corresponding to the height of water impounded. With severe storms, stream runoff could increase the water level above that of the spillway and raise hydrostatic pressure substantially. Strength design of dams thus requires an assumption as to the height of water above the spillway, and this is selected on the basis of stream flow statistics measured over an arbitrary period of time. The longer the interval selected for severe storms, the greater the height of runoff and thus the greater the pressure used in the design calculations. The pressure assumed with the "perfect storm" is further increased by a safety margin to accommodate all of the uncertainties mentioned earlier for metal structures.

Of passing interest may be historical learning from failure. Early Gothic cathedrals with the airy flying buttresses fell down after a few years and led to pragmatic studies of cause. Mostly, it was due to uneven settlement of the foundation soil under the weight of the rock walls. Cracks in masonry followed, then total collapse. The solution was not to make the structure stronger and degrade its aesthetic appeal but to pile building materials on the site for gravity to compact the soil before construction began..

There is a further example of learning in the emerging age of science. In the 1820's when steam propulsion began to replace sails, boiler explosions on Mississippi River vessels began to take a large toll of human life. Skippers would race each other. The reckless and ruthless ones, bribed by gamblers to try and win, extracted additional propulsion by disabling safety valves. Explosions followed killing scores. Outraged by these losses, citizens demanded that government intervene.

The first research on boiler strength was sponsored in 1830 by the federal government at Franklin Institute, Philadelphia. No doubt, the investigation extended the engineering of boilers to employ safety margins sufficient to accommodate material deficiencies and also consequences of human blunder and folly.

That risky practice of pushing the performance envelope continues to this day, often in tradeoffs of safety for cost. Consider this personal experience of a tradeoff for hubris. Immediately after a sub completed its deep submergence trial, I watched in astonishment as the skipper took over command and ordered a crash dive at about 30 degrees. Here was the background. Two identical vessels had been built in different shipyards and both were instrumented for their deep dives so as to compare dive-induced stresses as indicators of comparative construction quality. The skipper had my permission for the second, crash dive, except on this one he deliberately skidded below the certified maximum depth. Why? So he could boast at diving the deepest of all subs in the fleet.

Skippers of Mississippi River boats and hot combat pilots and submarine skippers have juvenile counterparts on the nation's highways. Managing these risks goes beyond the control of any engineering designer. Additional precautions are demanded by challenges beyond the laws of nature, the laws of human nature. These concern the ethics of safety.

In a high tech world the complexity of technological delivery systems denies to those exposed to risk the opportunity to participate in decisions as to what levels are acceptable. Initial decisions are made by engineers at the design stage, where practice is guided by law, by licensing and by professional codes of practice.

Such protocols have been published, for example, by the National Society of Professional Engineers and the American Society of Mechanical Engineer. Consider these interpretations:

- Hold paramount the safety, health and welfare of the public.
- Uphold the law, beginning with the Constitution.
- Be honest; serve the public, customers, clientele and staff with fidelity.
- Be vigilant of malfeasance and corruption; do not punish dissent and legitimate whistle-blowing.
- Recall that all technologies have unintended consequences, many harmful, so make a practice of looking ahead to anticipate and prevent loss in human life, health, property, intended function or the natural environment.
- In daily operations, demonstrate from the highest levels of internal management respect for truth, openness and equity in benefits when making tradeoffs.
- Counter one-way communication and loss of personal relationships by the growing reliance on electronic apparatus.

Sadly, these principles sound like a farce when one tracks the trends from media reports of indictments and jail of corporate executives convicted of felonies. Elected members of Congress are not totally immune to charges of corruption, of lying, and of fraud. Decisions on involuntary risk must earn trust of all exposed.

H.5 Bed Rock Values in Public Policy

H.5.1. The Rainbow of Stakeholders

Some readers may be discombobulated by a discourse on values in a treatise about risk. At the least, it may seem inappropriate. In defense, I draw on experience in the policy milieu, with both the Congress and the White House. As a science and technology advisor, I endeavored to collect and analyze facts and report their role in the design of policy.. My clients, however, based their decisions on more than the facts. Directly or unselfconsciously, they listened to values of their constituents and their own.

Consider these two loaded questions---"what role, if any, should philosophy of life play in risk assessment?" and "Whose values dictate choice?" These values may be as stark as that of human life, or as subtle as truth, the whole truth. I would argue that the dominant issues of our times are harshly ethical and beyond guidance by science, market place economics, by public law or their combination. Unintended consequences of technologically rich activities threaten innocent victims with repercussions more intense, more far reaching, more swiftly injected and potentially irreversible than in the past. Hard edged and hard wired innovations seduce us with clear benefits, but their side effects often stretch the risk horizon beyond accessible technological fixes.

The disaster in New Orleans spawned by hurricane Katrina is a case in point. The technology of levee protection is reported to have failed because in design a safety margin of 1.3

did not accommodate the uncertain integrity of underlying layers of soil. The resulting flood wiped out people and property.

So with dangers that result from choice and not chance, we seek protection by doctrines of anticipation, of foresight to deal with the reality of uncertainty. The point is that these choices are not just choices of technique. They are tough moral choices that require moral vision. How many lives must be lost at a dangerous intersection before costly traffic signals are installed? How do we decide?

Basic principles lie in lessons from history, from philosophy, from Shakespeare and from spiritual values of sacred texts. People must decide how safe is safe, and establish social norms on degrees of tolerance for risk, This process is especially vital if lives, liberty or the pursuit of happiness are threatened and if risks have human origins, escalate because of human failings with extreme consequences.

Two scales of consequences need review, those which occur immediately and those which may hibernate and explode decades later as a bitter legacy for our children. Leakage of radioactive waste stored since the 1940s at the nuclear weapons factory at Hanford, Washington is a poster child of negligence. Indeed, how actions or inactions threaten our children can be a yardstick of successful risk management.

Introducing this longer term perspective exposes limits in the process of risk management. At policy levels, acceptable risk is usually negotiated by opposing parties. Often, both argue from their estimates of short term self interest. Surrogates for children are not present at the bargaining table except when society mandates the government to play that surrogate role and not simply be an umpire.

Dimensions of the future shine in the National Environmental Policy Act of 1970 and the Technology Assessment Act creating the OTA in 1972. A blanket policy with global reach was drafted in 1980 as a Bill of Rights for Future Generations by Jacques Yves Cousteau and has been considered by the United Nations. Beyond an abstraction, this concept would require impact assessments beyond cost/benefit analyses, to test risk-centered choice by imperatives of social responsibility. This ingredient of public policy was punched into public awareness with a paradigm shift in the 1970s. In what was a vigorous technology-driven culture, the question, “Can we do it?” was balanced with “Ought we?”

Questions of moral vision pivot on the exercise of foresight. This does not mean claiming to predict the future as does astrology. As a vehicle of early warning, it means asking, “What, if?” This powerful tool exposes a surprise.

Whoever controls technology controls the future. That axiom has a twin. Whoever controls technology in effect raises our children. Perhaps that is already happening. The media, electronic games and cell phones, popular musicians, advertisers and their agencies may have more influence on our children than do parents or religious faith.

If this situation accurately maps reality, and society really does care about its progeny, then risk management must balance the short and long term interests by more than commercial values. Without abandoning rights of private property and canons of capitalism, decisions must be tested by norms of social and economic justice.

While American society may commit to high ethical standards, an objective survey of print media of record reveals the frequency of breaches not only of ethics but also of law. Powerful members of Congress have been indicted and sentenced for a wide range of transgressions. So have corporate officers as with the Savings and Loan scandals of the 1980s and extending to trials of Enron executives in 2006.

Part of the problem is bare faced corruption. But another part of the problem lies in our heterogeneous population. We don't have one public but many different publics, and when polled on their preference as to acceptable levels of risk they show major variations. These may be differentiated by wealth, by proximity to the source of danger, by social, religious, and political ideology, by urban vs. rural, by regional cultures, parental counseling and by ethnic origins, The point is that reconciling diversity in risk tolerance challenges the mustering of consensus.

On that issue, we in a democracy have rich experience from practicing the thesis that those who govern do so by the consent of the governed. Implied is "informed " consent. Then the question rises as to who does the informing; is the source objective and do citizens have minds prepared to interpret information they receive, for example to understand the critical tradeoffs of safety for cost.

Polls on citizen perceptions of comparative risks are not encouraging. One overarching conclusion to the medley of issues raised is the intense complexity of our technological delivery systems.

The reader might now be convinced that the design of technological systems must meet the social needs and safety preferences of a broad spectrum of stakeholders. That achievement is a political act. Once again, we must look to the nation's systems manager, the President, to muster credibility, coherence and consensus.

H.5.2. Conflict Management to Balance Benefits and Costs

Three premises condition this analysis. All the support systems of our society have a core of technology that we depend on, first, to the degree that we are totally dependent on it as the Zeitgeist of modern life. Second, technology blends technical systems with social systems. Third, benefits and costs may not be balanced. We applaud mounting living standards but overlook technology's cultural impacts greater than those of religion, philosophy, ethnic traditions, social mores and a growing body of law..

Technology sows complexity not just in hardware but also in delivery systems. In less than two centuries what began as small, orderly and predictable systems and at a human scale have become large, remote and incomprehensible, sometimes hazardous and even catastrophic. In that vulnerability, social performance demands virtuoso intelligence (both kinds) and striking leadership. Modern communications facilitate achievement but a convenient capability can overload human resources by more transmissions, more invisible actors, and more actions, reactions and overreactions.

Decision making at all levels suffers from ambiguity of facts, commercial pressures from muscular lobbies, a noisy public forum for serial conflicts and personal idiosyncrasies. Add duplicity, lying, fraud and other crimes to recognize that the key issues are ethical and both business and government suffer from gross violations of trust. Moreover, familiar relationships of cause and effect yield to confusion and incoherence. As said before, we cheer what technology does *for* us while neglecting what it does *to* us. The challenge to the engineer *cum* problem solver is reconciling direct benefits against hidden surprises of unwanted impacts.

Achieving a compromise between benefits and penalties entails reconciling goals, values and organizational cultures as between business and government, and within both sectors.

In essence, risk management requires a social strategy of foresight that does not come naturally either to individuals or to society. Parsing the concept, foresight entails strategic vision, pre-crisis planning, contingency resources, fixing what is broken and entrepreneurship to explore new opportunities. Finally, there must be political will to do the people's business and not solely that of vested interests and political supporters. And there must be respect for high integrity.

Neither market economics nor public law suffices to frame protection for future generations. Both societal steering and propulsion depend on the human psyche, on courage, integrity, resilience, ingenuity, free will, self-sacrifice and hope for a better future for all people. These constitute humanity's survival kit in a technological world.

In short, user-friendly technology with its harmful gremlins must be visualized as a social rather than technical enterprise. It acts like an amplifier. With lever and wheel, and the bomb, it amplifies human muscle. With the computer, it amplifies the human mind, its memory and speed of calculation. Technology is also a social amplifier. With modern banking, communications and transportation, catastrophes anywhere have effects everywhere. Two minutes after President Reagan was shot in 1981, the gold market in Zurich began to twitch. In 2005, the Katrina hurricane induced a similar shock to the price of crude oil.

This reality of an interconnected world—what columnist, Thomas Friedman, deems a flattening of a world with metaphoric mountain ranges stems from the gift of electronic communications, what we identify as information technology, IT. Telegraph wires morphed to telephony, vacuum tubes in radios and television to silicon chips. Add satellites and fiber optics. With such innovations, it became feasible to assemble highly complex TDSs to meet more strenuous demands.

In short, information constitutes the TDS's nervous system. As visualized in the earlier diagram, information channels are crucial to synchronize all of the 17 normal components of every TDS. The information age displays a ballooning of traffic over greater distances and moving faster. Security is enhanced by early warnings of tsunamis, hurricanes or degraded by mischief by spam artists and terrorists.

There are, however, unintended side effects. Every morning on bringing up Windows, many people suffer an information explosion, or perhaps implosion. Beyond junk and spam, the volume suffocates priority messages. The firehose of bytes lacks any warranty as to truth. Paradoxically, wider access to information is not necessarily accompanied by deeper understanding. Technologies introduced to reduce risk can inadvertently increase them.

For example, information overload induces stress, especially when making decisions. Outcomes may be uncertain and errors threaten punishment. We have the luxury of more choices but less time to choose. In a frantic search for truth, facts may be elusive or laden with the mists of probability. The social context and preferences shift unpredictably. When the technological delivery system engages competing players, each with a self-interested economic or political agenda, no actor has the comfort of ever being in control.

That shock is dramatized when adding to the TDS diagram a suit of feedback loops that exist in the social process. My own research efforts to accommodate that reality and explore repercussions totally failed.

Suffice it so say that the culture of modern society is the 800 pound gorilla in the room; our culture has not spawned a guidance system to harmonize with technology propelled change. Since it is unproductive to speculate on where the culture may be going, we must focus instead on how to cope with the role of culture in designing technologies with concern for costs as well as benefits but measured by parameters well beyond the narrow incentive of economic self-interest.

Confusion engendered by complexity and interdependence makes all the more relevant the earlier aphorism on modeling.

H.5.3. Tensions Between Industry and Government

Two major components of technological delivery systems, industry and government, have a paradoxical relationship. Neither can get along without the other, yet their relationship is marked by enduring tension. Government depends on a vigorous, healthy industry to drive the economy, from which to create jobs and extract a tax base. Industry thus depends on government to create a favorable economic climate, including direct financial assistance. That congenial partnership, however, is accompanied by an adversarial stance with government's obligation to serve as regulator. Industry, in its boisterous role as innovator and entrepreneur, acts in its profit-driven self interest which often collides with social interest. Corporations are expected to turn a profit, but in this era equal emphasis is placed by Wall Street on the creation of wealth. The so-called free market fails by various distortions and excesses that violate norms of economic justice or have severely harmful consequences. With government mandated to protect citizens from harm--physical, economic and psychological--we observe a muscular wrestling match.

Merging corporate and public purposes to nourish a vigorous economy is strained when industry fails to get its way. Government is accused of blocking "free enterprise." Industry then adopts defensive measure to weaken or block the legislative process or administration of laws already passed. It has been so since the nation's birth.

Tired of pressures to ease constraints, Congress invented special regulatory bodies to act on its behalf and set the rules and penalties for violations. Thus were created agencies to regulate the economic life of railroads, buses and trucks, merchant shipping and airlines, and later regulation for passenger safety. Soon other independent agencies were founded to deal with safety of food, drugs, water and air, of the mining industry, of the workplace, and with preservation of the environment. Private enterprise countered by seeking to corrupt regulatory bodies by urging appointments of individuals known to be favorably disposed to their interests, thus undermining the regulatory process from within. Headlines single out the FCC, FDA, EPA, NRA, FTC and others.

In recent years, industry has adopted two other tactics. In this television age, the influence of that medium on public opinion is essential to political campaigning. Candidates for election and reelection raise funds to purchase broadcast time. Industry found a potent avenue to grease access to policy makers.

A second tactic is for lobbyists to be present at what used to be off limits to outsiders, closed sessions when members of Congress negotiate final wording in a bill or final agreement on budgets. Midnight conferences are opportunities to insert clever loopholes or pork barrel bridges to nowhere to benefit a community and facilitate reelection. Today, there are 34,000 registered lobbyists in the nation's capital, roughly sixty-five for each member of Congress.

This phenomenon caught the public's ear for the first time with President Eisenhower's complaint in his farewell address about the self serving greed of the military industrial complex. That was almost a half century ago. The iron triangles of industry, a government agency and senior members of Congress on appropriations committees are today even more powerful. Perpetuation of what President Dwight Eisenhower called the war machine, the "military industrial complex," regained public attention in the 2006 movie, "Why We Fight."

The central problem is clear. Industry cannot regulate itself. Self interest always trumps public interest. In the context of risk management, this history is important because the avalanche of new technologies has opened more risks from side effects. When industry fails in exercising social responsibility, conscientious government is obliged to intervene.

That condition complicates the management of risk. A contest erupts between the sources of risk and those who are the victims. Thus is exposed a cultural contradiction of capitalism in that it works best under an umbrella of social norms.

Contrary to popular belief that government is too zealous a regulator, the reality is that it has been diffident. Very rarely does it act in anticipation of harm; almost always government reacts when the severity of impacts has aroused public opinion to a boiling point that political leaders cannot ignore. Even then, industry fumes at fiscal and social accountability and seeks new avenues to get its way, fair or foul. Take the case of Boeing aircraft now challenged by government charges ranging from theft of a competitor's papers to complicity in hiring a former government contract officer.

In many respects, the tension between government and industry is a sign of health of both. Too much friction can distract both parties from their optimum performance. On the other hand, too little tension could lead to or be a signature of a corporate state.

In the context of risk management, such an evolution of governance would trigger two problems. Business and government have vastly different values. Commerce measures success by short-run profit, growth in size and market share, and respect by Wall Street brokers. Its legal concerns center on protection of property rights and against accountability. Its culture is strongly task oriented and its management style that of an independent CEO with a tame board of directors. Government, on the other hand, is concerned with freedom and human rights, social and economic justice, including concern for future generations. The structure of government mandates principles of building consensus and of accountability.

The second problem arises from a tendency of technology to concentrate wealth and power. In just the recent decade, acquisitions to morph into mega-corporations have been conspicuous in military-space technology, in petroleum operations, in both print and electronic media, in air transportation, and other areas with questionable benefits to all but shareholders. Violations of corporate ethics have earned serial headlines.

Government is not immune to sleazy and even illegal activities. Members of Congress from both major parties have been indicted and jailed. Others have resigned. A major fuss has been raised because White House officials are alleged to have leaked the identity of a CIA agent in a crude attempt to intimidate the role of the agent's spouse in contradicting President Bush's assertion that Saddam Hussein sought nuclear weapons.

While this unhealthy situation may seem foreign to risk management, the effective functioning of democracy and of technological delivery systems depends not only on the discipline of law but on mutual trust. Citizens cannot be expected to master all of the facts and analysis dealing with complex technical issues. In the main, citizens must depend on government to provide protection against the ultra-violet rays of the sun, from the exaggerated claims of pharmaceuticals, from terrorists bent on torching a calamity or from their holding a nation hostage with threats to detonate a nuclear device.

It is in this situation that we observe a confluence of science and engineering with disciplines of public administration, business administration, economics, psychology, sociology, history, communications, law and even theology.

H.6 The Ethics of Informed Consent

H.6.1. The Role of Media in Exposing Risks

On the earlier sketch of a standard TDS, the media were shown as a blurred image. That representation is intended to reflect the ubiquity of media as a source of vital information to all TDS constituents. For those potentially exposed to risk, this capacity serves either as early warning for slowly evolving events or as instruction from another's harmful experience on how to offer informed consent when it is invited.

This critical role carries a burden of social responsibility for the media... Information should obviously be accurate, based on authoritative sources, even handed, timely and accessible to non-technical stakeholders. The year 2005 is overloaded with natural disasters that could not be prevented, where vulnerability was not heeded, and where media played a crucial role. With the tsunami in Indonesia and the earthquake in Pakistan, the number of deaths and injuries and extent of property losses exemplify inept emergency preparedness. The situation along the Gulf coast with hurricane Katrina reveals in post-mortems similar painful deficiencies, but there is also evidence of miscalculation by government stewards who had a mandate to protect lives and property under recurring circumstances.

Earlier we noted that government's style is more one of reacting to a threat in some proportion to public demands for protection. Silence gives consent. The authority responsible for designing and building levees to contain the New Orleans' flood waters, the Army Corps of Engineers, balanced their estimates of safety versus cost. Because of limitations on appropriations by the Congress in the final moments of bargaining over pork barrel allotments to competing claimants, they took precautions for a hurricane of intensity 3 rather than 4 or 5. Still to be determined is the fine detail of negotiations in Appropriation Committees of both Houses, as to whether information was available on the relationship of costs to the degree of flood protection.

Consultation with the public through levee boards was apparently not effective in the power structure. In that chain of political activity, citizens and local officials seemed unaware of the tradeoffs that put the city's safety at risk.

It can be argued that those at risk should have a say in decisions vital to their safety. Because of secrecy surrounding funding decisions, the consequences are unlikely to be known in advance except by zealous probing of reporters. Even that expectation may not be met where news organizations or reporters have cozy relationships with decision authorities in both government and commerce. Both parties thrive on leaks.

There are other challenges to investigative journalism. Probing too aggressively may violate cannons of national security or personal privacy. The pace of information may exceed the human capacity for information processing. Objectivity may be subverted by news organs with self interest threatened. Mega-corporations that own the broadcast networks also own subsidiaries that may be the subject of unwanted publicity over their failures to protect citizens adequately.

That dilemma of self- versus public interest also applies with individual stakeholders. Copper smelters in the Puget Sound area emitted smokestack fumes of arsenic and lead that poisoned nearby soils in which children played. The plant's owner asked affected citizens to choose between continued emissions versus correction so costly as to jeopardize the plant and sacrifice jobs. Jobs won the contest until the plant was shut down by bankruptcy. By themselves, accurate information and positing options did not alone lead to a socially responsible outcome.

Often, stakeholders face information overload that includes unreliable sources. Moreover, transmission speeds overtake a natural cadences in human affairs, Add frustration when an inquiry is funneled through a chain of telephone button pushing, perhaps to lead to an ominous and anonymous, "The computer is down." When a voice is reached, its artificiality drains away any sense of communication with another resident of the planet. Some prefer to be safely uninvolved even at the expense of losing control to an invisible authority structure. Squeezed out by information technology (IT) is a dialectic process wherein after each conversation, live participants may change.

A similar effect occurs with emotionally loaded information as, for example, live TV reporting of battles in Iraq or of destruction of New Orleans. Pictures have greater punch than prose. Intense images brand our minds, injecting content without context. Revised patterns of belief structures alter our perception of reality, even our sense of time. The medium has become the message.

Even the content suffers mutation because of techniques exploiting volume and speed of transmission. Side effects are shorter attention spans and subversion of purpose from education to persuasion, to market a brand of politics or of faith like a soap product.

If the premise is adopted that safety is a social judgment, society must have both timely information and objective analysis to convert that bundle to a state of knowledge. The treasured jewel of understanding emerges amidst a further stage of discourse and debate and mulling where individuals hear many sides of an argument, consult their memory and critical thinking, then make up their mind and join with others of like mind.

That stage occurs last when public preferences reach decision authority, a member of Congress for example. Voices of we, the people, may best be heard if an individual finds and helps fund a public interest organization to serve as collective advocate. On the TDS, that process can be visualized as a lump in the box of citizen preferences.

As footnotes, we have to understand that information flowing in a TDS is both substantive *in* the process, and administrative *about* the process. That is, participants need a mental model of the particular case to learn the cast of actors on the political stage, their culture, interests they guard, avenues of access, and the timetable of action.

Whatever the dynamics of a particular issue, seldom does it gain attention in isolation. Environmental policy interacts with fiscal policy. Farm policy is affected by foreign policy, and U.S. policies have to be weighed in the context of free trade, globalization and outsourcing, and now the uncertainties of terrorism.

There are further complications. Incoming information must pierce a garment of emotion. What I may say is not necessarily what you hear. As a metaphor, assume that every one wears a helmet. This is a screen of past learning, biases, attitudes about change, conflict, and especially experiences that leave scars. In penetrating the helmet, the new information is distorted, attenuated, or filtered out completely. This is especially dangerous in political leaders.

Most pathologies of information processing have counterparts in the media itself, the merchant communicators of common information. Given that the media is an intelligence function serving business, citizens and government officials equally they are often considered a fourth branch of government. The integrity of the press is thus at least as critical as that of public institutions. Confidence in that process can be shaken with revelations of media on corporate or government payrolls. One wonders what Orwell had in mind as the precursor to the central control of information in his metaphoric “1984.”.

Now the media encounter new stresses of deadlines with 24/7 reporting, of penalties they pay if found in error or, worse, treating handouts as news. They are trapped by an appetite for leaks while facing the risk of spilling classified beans.

Business depends on the media regarding equity markets, indicators of future profits or losses, shifts in tax and fiscal policies, investor confidence, threats to oil supplies, and stability of foreign governments. What happens in Washington must be followed carefully

Even elected leaders sift the news, polls, editorial feedback on political performance. President Bush seems to be an exception, proud to receive news only through trusted staff messengers.. Scholars who follow world and domestic affairs feast on media reports, perhaps alone in subjecting them to close scrutiny for accuracy, objectivity and balance. Several privately financed foundations engage in the same watchdog function.

Of all the organs of a TDS, the press has the most seminal responsibility for facts and their understanding so as to what is at stake and in time to practice democracy. In a complex, confusing and noisy world, that’s a high expectation.

As newspaper advertising shrinks, more daily papers feel threatened and seek defensive measures to stay alive. TV as increasingly the media of choice forces producers and anchors to mix in entertainment at the expense of analysis in depth. Text is dumbed down, and the flash card style of ads causes viewers to be numbed down.

Most telling about the media is its strategic influence in every TDS. It is the prime source of facts and their future implications; they play a legitimate role as a Greek Chorus of early warning about a rainbow of threats and loss of a shared vision; through editorials, they can serve as advocates for victims, as did the New Orleans *Times Picayune*,. Sometimes that zealousness is overdone. Coverage of Clinton’s sexual encounter with an intern played to a prurient interest in body fluids and DNA confirmation. In a feeding frenzy led by Republicans in Congress, the media were willing partners in this American tragedy.

McLuhan had it right four decades ago. The medium not only morphs the message; it morphs the messenger. The lesson to be learned again and again is that democracy depends on truth. In his fictional 1948 account, Orwell projected a nation’s slide toward being a corporate state. It happened when partners in business and government gained control of the media. Perhaps his scenario was a metaphor, accurate except with regard to timing.

In this author’s view, there is no more critical role for media than reporting the facts on national security, the validity of perceived threat and response, the compromise of truth in the interest of political victory, and the tradeoffs of national treasure and honor negotiated out of sight.

H.6.2. The Power of Informed Consent

First, reader, take time for a deep breath.. Some who have progressed this far may feel frustrated in not finding a handbook on risk management. The author promised none but apologizes if he inadvertently raised such expectations. This exploration focuses on the context, not on *what* to think about but *how* to think about "how safe is safe."

That question triggers as many as 20 issues that characterize operations of a standard technological delivery system. With each having 17 major components, I focus here on information networks that connect organizations and function as their nervous system to detect the external world and to synchronize the internal parts.

One role is to assure that the tacit consent of those at risk is an informed consent. People cannot feel safe if they are left in the dark. From very early childhood, humans want to know, and it is the obligation both of sources of risk and the security conscious government (which can also double as a source of risk) to assure that satisfaction.

That process, however, has several impediments. As explained before, history teaches that all technologies have side effect, many harmful. And it teaches that the vendors of technology are not always forthcoming about the unwanted and possibly lethal consequences. To counter that secrecy, for example, the FDA requires pharmaceutical houses to embroider their advertising with cautions about abstaining with some existing health conditions, and about physiological effects of hyper sensitivity. Parenthetically, these catalogues of possible risks are silent on the frequency with which products pose particular threats. If very rare, the risks are ignored. There are no warnings on peanut butter because those who are ultra sensitive are assumed to have had close shaves and practice risk avoidance.

This example illustrates how potential victims need to face risk with a prepared mind. Otherwise, they might not understand a label that warns that, even though a food product contains no peanuts, it was processed in a plant that also handled peanut confections. This act of social responsibility by the vendor reflects on the ubiquity of threats and also the heightened awareness in our culture that risks of human origin could and should be minimized.

That scenario is played out in news headlines almost daily. Consider the wrangle over proposed wind farms in Nantucket Sound off Cape Cod. Assessment of environmental impact mandates that all side effects be publicized and evaluated by the public and by a government agency. These side effects constitute hazards to navigation where traffic is dense, disruption of fisheries, and visual pollution of waterfront property. These costs are weighed against benefits of generating non-polluting energy, even if more costly. Public commentary at hearings will be considered before a policy is set.

One problem is that individual stakeholders do not often attend these sessions. Some who do attend often fail to do their homework to explain concerns and also fail to consider tradeoffs that require compromise. Others, however, may be effectively represented by public interest organizations that buttress their arguments with facts and importance of transforming information to knowledge and then to understanding.

Converting information to knowledge requires assessing the credibility of source, the consistency with other sources, an explanation of contradictions, and finally an enrichment of initial basic information with vital context. A final stage of understanding occurs when knowledge is squeezed to identify implications for the issue at hand. Content is merged with context. For example, recognizing that a particular technology can be harmful is elaborated by identifying the full rainbow of parties at risk, including the virtual stakeholders, the future generations.

In a next step, all elements of risk analysis are mustered, especially the distillation from history of past failures, of the frequency of the threat (probability) and the scale of consequences if not prevented or damage controlled.. That history is especially important to rank interventions by degrees of their success and the tradeoffs entailed, especially of benefits versus cost. A further challenge arises in converting all benefits and all costs to a common currency because both have intangible as well as tangible elements. Both have a combination of immediate versus long term effects.

Illumination of context requires description of the political process by which the threat and response is mediated. The TDS can serve as a generic model to identify organizational participants, from perpetrators of risk to its amelioration.

All the desired information may not be readily available. In the political theater, complexities of the facts and the confetti of ethics leads participants to put a premium on confidence in the authority and objectivity of the information source.

Consider these realities. First, in the frenetic atmosphere of policy making, those responsible for decisions rely more on verbal rather than written material, especially if it is boiled down. Who talks to whom is highly significant. Lobbyists know that members of Congress cogitate over an upcoming vote as they walk from their office building to the Capitol. On that trek, advocates would like to be the escort and have the last word.

These intricacies are of great importance. Recall the two-year, continuing investigation by a special counsel of who leaked the name of a female CIA operative to intimidate her spouse who was charging administration malfeasance. In political maneuvering, most information is tainted by self interest of the source. This is rare but not unknown in the technical community as well. Congress has access to such credible facts and analysis in the Government Accountability Office, the Congressional Budget Office and the Congressional Research Service.

In his Executive Office, the president also has access to presumably objective information, but such support may be distorted by incompetent appointees.

In short, the paramount role of information in risk assessment is to help those exposed to risk understand their predicament and have an opportunity to express their consent or dissent. That critical comprehension demands a preparation of mind so as to distill information effectively to knowledge and then to understanding.

I was involved with risks of oil spills by tankers from a 1971 filing of omissions in the Environmental Impact Statement regarding the marine extension of the pipeline to the 1989 investigation of the *Exxon Valdez* disaster. In 2006, there are still repercussions from boisterous complaints of fishermen and indigenous peoples whose livelihood was hurt. They won a legislative provision for government supported citizen watchdogs to reduce future risks. That safety measure is relevant to the study of Katrina.

H.7 Lessons From The Past

H.7.1. The *Exxon Valdez as* a Metaphor for System Failure

The 2005 hurricane Katrina and its melancholy aftermath of death and economic havoc have been reported in American media in great detail, sufficient to illuminate the imperative of foresight and damage control measures to prevent a nightmare recurrence. Similar data were generated by a massive tsunami in Indonesia and Sri Lanka and an earthquake in Pakistan. All three were extremes of rare natural phenomena that could not have been prevented but deserved better emergency preparedness. History records similar disasters caused by human or organizational error.(HOE) that could have been prevented and the adversity minimized. In what follows, the oil spill of the tanker *Exxon Valdez* in Prince William Sound, Alaska, is summarized as a metaphor for system failure, of an accident waiting to happen.

On March 24, 1989, the tanker loaded with 50 million gallons of Alaskan crude fetched up on Bligh Reef in Prince William Sound and spilled 11 million. Oil leaked for four hours at a rate of 1,000 gallons per second! With the slick staining a spectacular wilderness, damaging habitat, fishing and tourism, blame was immediately focused on blunders by the ship's operators. Given the calm sea and clear night, how could this have happened? Were there no lessons on safety measures from the first supertanker spill off Land's End, England in 1967 and others worldwide.

The spill animated intense media coverage focused both on the harm to the environment and wildlife and on the frenzied efforts to contain and cleanup the oil. Less photogenic but equally vital were revelations of almost total system failure in terms of accident prevention and emergency preparedness.

As with every shock to routine human affairs, the curtain was opened on the stakeholders impacted by the accident and others responsible for cause, for prevention or for limiting damage. Investigations were mounted by several federal agencies as well as by Exxon, and by a citizens' commission appointed by Alaska Governor Steve Cowper, which included the author of this treatise.

That probe attacked questions of what happened and why, and how to keep such a calamity from recurring. The commission's report issued in January 1990 told some alarming stories. In applying the TDS concept to map the oil delivery system, we find almost every entity contributed to the disaster.

Obviously, the ship operators were the immediate cause of the accident. The master was in his cabin; a mate was steering; and a lookout presumably at the bow who should have spotted a navigation light on the wrong side of the ship except that she was at the pilot house chatting. By their negligence, many others contributed to the disaster.

For example, to limit first costs, the Exxon Corporation chose to build the largest possible ship with the thinnest permissible plating, the least compartmentation, and single hull rather than double hull construction except under the engine room. There was no redundancy in propulsion or steering. None of these steps to enhance safety would have prevented the accident but a double hull could have reduced the volume of spill.

Human error was obvious. Exxon had retained a master with a history of alcohol abuse, ran the ship with the smallest possible crew (reduced twice with Coast Guard approval) on the assumption of an uneventful voyage and immunity to sleep deprivation. Both these corporate policies reveal a classical tradeoff of safety for profit.

The Commission also faulted Alyeska, the operator of the Valdez loading terminal and responsible for spill prevention and emergency response. Exposed were apathy, incompetence, and carelessness. That company proved incapable of reacting during the short window of opportunity for containment before the spill spread widely and irretrievably. The U.S. Coast Guard was also faulted for reducing power of their radar monitoring the inlet in order to cut expenses, such that their human operator did not provide continuous surveillance. Moreover, the Coast Guard had approved the disembarking of a pilot short of Bligh Reef where the accident occurred. After the spill, the agency found that its containment and cleanup fund was depleted and not refreshed from penalty fines so that contractors couldn't be hired on the spot to limit damage.

The State of Alaska had anticipated the possibility of the *Exxon Valdez* type of accident but their environmental watchdogs neither barked nor bit. An accident of this scale had not happened during the 12 years of shipping oil, complacency had set in, and legislators under pressure from Alyeska had eased contingency safety requirements.

From this snapshot, several lessons emerge. When serious consequences follow acts of nature or of human failures, the mind becomes aware of the large number of constituents and stakeholders in the TDS and their complex linkages. Paradoxically, many functions were installed for redundancy in navigation to prevent such grounding. .

This leads to the surprise concept of "organizational error," a pathology identified by Sociologist Charles Perrow in 1985. He characterized oil delivery systems as error-inducing rather than safety-promoting. This idiosyncrasy accompanies organizational cultures that implicitly accept untoward levels of risk in conscious tradeoffs. Such organizations are not the direct source of accident but they set the stage for human error to occur at lower levels. Indeed, 80 percent of accidents are found due to human factors, most attributed to organizational culture. Research confirms that the imperative of safety begins at an organization's top management with explicit or implicit penalties of reward and punishment for subordinates.

Even when top management signals priority for safety, other subtle influences undermine the delivery system. TDS's entail so many components that functional coherence is destroyed by complexity. Moreover, in the chain of command, each level is expected to make choices that unfortunately may prove to be parochial and short term, indifferent to conflicts with a master policy or plan, and focused on shielding higher authority. Financial considerations rule, and public relations are used to minimize corporate liability rather than risk to the public. In 1989, the oil transportation industry suffered more than most delivery systems from all these deficiencies.

The Alaska Commission filed 58 recommendations to reduce risks of a spill and enhance containment and cleanup response. The 15 most relevant are summarized below:

- Prevention of oil spills must be the keystone policy of all in oil shipping.
- Because many individuals and communities are at risk, citizens should be involved in oversight. This echoes the notions that safety is a social judgment, that those exposed to risk should have a say on protection.
- The nation and states need strong, alert and fully funded regulatory authorities.

- Top management of private oil transportation must be committed to safety
- Citizens in a democracy have a role in all aspects of risk management.
- Federal technical standards and safety requirements should not preclude more stringent measurers by states for prevention and spill response..
- Double hulls and other advances in tanker design should be required at an accelerated time table.
- Traffic control systems should be mandatory, not voluntary
- Crew levels should reflect the need to avoid fatigue and additional crew required by emergency conditions.
- The role of insurance companies to reduce risk should be revisited
- Corporations transporting hazardous materials should be required by the SEC to file safety reports along with the fiscal data of quarterly reports.
- A report should be prepared annually by federal authorities to track progress
- The state should empower itself to take over response to a spill in the absence of swift and effective federal action (again, redundancy)
- An available funding mechanism is needed to facilitate immediate response
- The state should fund a system of emergency economic assistance to fill holes in citizen safety nets

Some of these recommendations were swiftly adopted, especially those aimed at state responsibility. Based on the Commission report, the State of Alaska instituted stricter safety measures, including the requirement for each loaded tanker to be escorted by two large tugs, thus providing more assured redundancy in navigation and power to intercept a disabled tanker swiftly.

Similar recommendations were made by the author in a 1982 study of tanker safety in Puget Sound and were initially ignored. In 1990, however, the the federal government acted; but under pressure from the oil industry, Congress extended the date to replace single hull tankers with double hulls. Some companies, however, acted immediately, especially with the success of liability suits against Exxon by native populations whose businesses were injured by the spill.

Corporate response has been spotty, with litigation over damages on the order of one billion dollars long in the courts. Other observations can be sifted from the Commission report. With engineering improvements in machinery and electronics, the proportion of accidents attributed to human factors has increased; the Norwegian safety authority for shipping states up to 80 percent of the total. The Intergovernmental Maritime Organization of the U.N. emphasizes that corporate commitment to safety begins at the top. Accidents often expose corporate cultures that bond staff and management to a common set of values that conflict with those of society as a whole. Implications are treated later on social responsibility of the firm

This anatomy of an accident illustrates in a modern, interconnected society that an error by a single individual led to damages of over $3 billion. Other examples have been widely cited such as the failure of a chemical plant in Bhopal, India, and the nuclear power station at

Chernobyl. In retrospect, most long-term and persistent dangers arise from weaknesses in people and in their institutions.

On a personal note, for this author being appointed to the *Exxon Valdez* Commission was a depressing irony. In a sense, I was there at the beginning. In 1967, I was in England when the *Torry Canyon* went on the rocks at Land's End as a result of human error. It was the first major spill by a supertanker. On return to my post at the White House, I instituted an Executive Order for President Johnson of a national contingency plan of containment and cleanup.

When I moved to Seattle in 1970, I witnessed the vulnerability of Puget Sound that would serve as a port for oil to be shipped by pipeline and tanker from the Prudhoe Bay, Alaska. Although an environmental impact statement had been required for safety of the pipeline, the filing ignored the hazards of spills along both the Alaskan and Washington coasts. At a hearing in Washington, D.C., I delivered a risk analysis to amend the EIS. The second version nodded at maritime hazards but was weak enough to justify publication of a second alarm, this time in a journal of the ASCE. In 1975, I chaired a study committee for the state legislature that led to federal regulations for Puget Sound requiring a tug escort and limits to tanker size. In 1982, a comprehensive report on navigation safety was published with additional analysis of risks with tanker traffic and the need to strengthen Coast Guard surveillance.

With the appointment to the Alaska Commission, I felt like the fabled tar baby, stuck forever to studies of tanker accidents.

H.7.2. Deficits of Foresight, Vigilance, Contingency Resources, Political Will, and Trust

Contemplating their survival leads most citizens to feel secure when risks are known and convincingly held to acceptable limits. While that accomplishment may be an impossible dream, the human family has advanced in comprehending that threats to survival are not inescapable whims of fate. While many believe, like the ancient Greeks and Romans, that the gods punish human transgressions with disasters, society presently believes risks can and must be controlled.

This protection is especially demanded with risks of human origin. Thus, society has boot-strapped its understanding of cause-and-effect so as to prevent many malignant consequences or at least to act defensively to contain the degree of harm.

Within that abstraction is a chain of understandings, some with ancient roots. The time is long past for people anywhere to achieve the desired security as individuals. For better or worse, each of us is imbedded in a distinctive culture and subculture on which we must depend to be alive and free. The most critical element of that society is trust.

The problem with trust is its undependability, notwithstanding its prominent role in a democracy. Connections between trust, lying and ethics earned attention as far back as Aristotle. The subject has gained distinguished analysis ever since, recently in the book on "Lying" by Sissela Bok and sermons by Solzhenitzen. Consider the following headlines in the New York Times for a single day, January 4, 2006:

- Lobbyist Abramoff Accepts Plea Deal in a Corruption Case
- Bribery Investigation to Reach into Congress(Rep. Nye and others)
- The National Security Agency(NSA) first Acted on its Own to Broaden Spying
- on the Subject of Leaks (on domestic spying)

- U.S. not Told of 2 Deaths during Study of Heart Drug (Johnson and Johnson)
- 6 Ex-Putnam Officials Accused of Fraud
- Judge Orders Ex-HealthSouth Chief to Repay $48 Million
- Windows Patch not Ready (Microsoft vulnerability)

That same day, a tragedy unfolded in West Virginia with the deaths of 12 men in a mine that had been cited with over 200 safety violations in the last two years. The coal company bears responsibility, but so does the federal government which discovered the violations but failed to act. Pressures on members of Congress and the Bush White House led to reduced budgets for mine inspectors and to allow dangerous mines to remain open.

A week earlier, the headlines exposed fraud in scientific results announced by a stem-cell scientist in South Korea. In four books published between 1979 and 1999, I listed similar breeches with examples of Boeing (Bribing contract officials), General Motors hiding dangers of the rear engine *Corvair*, Ford concealing a vulnerable fuel tank on the *Pinto,* the unresolved super scandals of ENRON and World Com currently in the courts.

These observations lead to the melancholy conclusion, that key organizations are as lacking in moral principles as are individuals whose human nature has uncorrected flaws. Compared with that of individuals, however the scale of corporate malfeasance is far greater.

Experience reveals that it takes a spectacular accident or crisis to so agitate a quietly humming TDS as to expose the institutions involved, their communications networks as well as their life style.

Some organizations demonstrate solid integrity, revealed by a concern for safety, doctrinal foresight, a tolerance for dissent, alacrity in damage control, self discipline and acceptance of responsibility. Many do not. They engage in cover-ups, deflection of blame and substitution of public relations for problem solving.

The pathologies of ethics are not limited to the private sector. We still remember the Watergate and Iran-Contra scandals germinating in the White House. Much more recently, these negative and positive aspects were conspicuous in reports of Katrina-related flooding and its aftermath of system failures..

Public and private organizations differ, however, regarding their attitudes toward ethical lapses. The public expects a high level of moral vision in public servants, and so feels more justified in publicizing their weaknesses as in the case of President Clinton and Monica Lewinsky than with private enterprise.

The public cherishes privacy and, given the corporations' legal status in protection of its officers from liability, is more inclined to accept the secret life of corporate officers and boards. Compared to fifty years ago, consider how obscure names of corporate officers have become.

To explain, organizations have personalities, cultural attributes and values similar to those of individuals. When public safety is at stake, the public has a right to expect the same standards of values for corporate officers as they do for officials of government. These personal qualities include intelligence, integrity, respect for the law, common sense and compassion, capacity to listen and learn, emotional stability under stress and deep understanding of the social contract of America.

President Calvin Coolidge tried to epitomize that focus with the statement, "The business of America is business." In terms of function, a more appropriate term would be, "The business of America is technology." If technology was defined as the social process mapped by the TDS, the significance of values would be clear in their shaping ethical qualities of all system components.

The earlier headlines make clear that our society has serious gaps in the practice of ethics. It follows that every brand of risk is intensified where integrity is compromised; instead, it should be the keystone of every organization's culture.

Not all news is bad. There are striking examples of courageous integrity. After completion of New York's City Service skyscraper, design engineers found that the specifications for strength of structural steel were in error and not reported until after completion. Apart from bruised pride, the admission opened the hazard of powerful lawsuits. Yet the social responsibility to protect the public prevailed; additional structural elements were installed. There is heroic power in doing the right thing.

Attention to ethics has not been sufficiently emphasized in our schools of business, and this is reflected in the behavior of graduates. Most believe that evidence of sound management lies in external rewards through rise in stock prices, and internal kudos for maintaining tight control. Here is where fault lines appear in our basic values.

Missing is an awareness that human organizations are organisms and not mechanisms. With mechanisms, cause and effect are coupled predictably. Not so with organisms. Their behaviors are less certain, cause and effect blurred. External influences such as terrorism, intense global competition, or occulted fate undermine certainty,

One thing, however, is fairly certain----whoever controls technology controls the future. No wonder Orwell's speculations regarding the corporate state have been resurrected. That reality would be less likely in a society that honors diversity rather than central control. Diversity works only with a shared set of values that nurture trust. Without trust, the system of governance works only by coercion.

The nation's founders surely recognized that truth but did not incorporate their moral vision in the Constitution. Some elements were added by amendments, the Bill of Rights.. History reveals, however a strong moral climate was suffused in the population through religious doctrines. They may have assumed that such discipline would be permanent despite acknowledging that democracy was an unproven experiment.

In the aftermath of Katrina, it was clear that systemic shortages other than in ethics were present and these are being dissected by the media. Shortfalls include the effects of human and organizational errors, of shortages in foresight, in vigilance to detect early warnings of danger, in contingency resources to limit damage and then to repair what's broken, and finally a shortage of political will to exercise the leverage of power to get the right things done and done urgently, and then to do these things right. Today, most failures do not involve hard-edged technology but rather human ware.

Here lies another contradiction. In our democracy that underlines egalitarianism, power is thought of as suspect and even malign. There are, however, benign purposes for the exercise of power, and these need honoring in the human ambition for survival.

To be emphasized is the imperative role of citizens as a part of government. They should be part of the power structure as suggested in the TDS. Only then will those who govern do so with the informed consent of the governed. This was the perspective of the nation's founders and it could be lost amidst the buzz of intricate social processes, especially cases of unprincipled advocacy by society's powerful economic interests. The antidote to the disproportionate influence by special interests starts with more transparency of policy affairs.

One way to understand the web of influences on risk management is to think of our high-tech society as steered by three sets of IT operating instructions. One set is the free hand of the economic market place. A second is public policy, much of it regulation to manage risk. The third set is values that animate the moral parameters of the other two. . Underpinning these arguments is an implicit assumption that citizens realize government is not the only machinery of governance. We, the people, have a critical role. Most urgent is to meet the deficiencies exposed by the case studies---the lack of foresight, vigilance, contingency resources, time, political will and trust.

Most essential is foresight. Government officials and citizens can then focus on emerging issues of security, seek the facts, compare remedial alternatives, and unintended consequences of each. With information and trust, citizens could make their views known on acceptable levels of risk in the spirit of catastrophe avoidance. Officials should recognize this citizen role in a participatory democracy and welcome an informed and concerned electorate.

H.8 Thinking About The Future

H.8.1. Evaluating Social Choice by Outcomes for the Children

For many centuries, philosophers have taught that the quality of a civilization can be judged by how it treats its children. With that rationale, the quality of decisions made today for managing risk can be judged by consequences observed tomorrow as outcomes for our children. In other words, today's decisions on acceptable risk can best be judged by results observed 10 to 20 years hence. These results become legacies for future generations-- social, political, economic and ecological. With such criteria for success, those responsible for risk assessment must look ahead in order to make operational the questions, "What might happen, if, or What might happen, unless?"

Imaginative analysts might nominate answers, but trouble may still occur when the issue requires a policy decision that spins winners and losers. Assuming that all stakeholders are represented at a bargaining session, it is likely that compromises are reached among different advocates. Almost all will argue from their short term advantage, with no advocate for hypothetical children. The short term triumphs because society chooses to lock its barn door too late.

This vulnerability in public policy was sketched for the U.S. Congress in 1965 by its CRS Science Policy Research group, leading to creation of the Office of Technology Assessment in 1972. Requests from members and committees led to roughly 50 reports a year until the agency was zero budgeted by House speaker Newt Gingrich in 1995. The OTA left a valuable library of risk assessments that permit comparison of different methodologies. All were endowed with a futures perspective.

That resource also demonstrates the importance of values in every society.. For example, studies reveal a paradigm shift in the 1970's regarding technology's wrenching of social norms. The question about potent innovation and asked with pride, "Can we do it? shifted to the questions of “Should we?” In simple terms, this requires a look at the medical mandate to “do no harm.”

If my earlier contention is true that whoever controls technology controls the future, and if we judge the acceptability of a technological development (or its misguided absence) by the effects on the children, we can conclude that whoever controls technology in effect is raising our children. That shocking characterization of shifts in our values may already be happening..

That prospect can be a useful wedge to understand the impact of values on today’s decisions and thus on the future for our progeny. This leads to an inescapable question on which values dominate our culture and that of the deciders who extract from our circumstances answers to “How safe is safe?”

In America’s diverse population, one size answer doesn’t fit us all. Each brand of risk and its stadium of different interests is likely to generate a different outcome. Therein lies another level of perplexity in dealing with risk. There is no standard pattern. Today’s solutions are unlikely to be suitable tomorrow. Living with risk isn’t easy.

H.8.2. Foresight as an Imperative in Risk Management

Safety and security depend on fantasy, on imagining what might happen and then how to prevent harm or at least minimize the event’s impact. Risk management demands a mind set of looking ahead, practicing a doctrine of anticipation. That notion can be sampled in a series of books on Science Policy by the most frequent citations in the indices. It is also possible to track changes in what one author (Wenk) emphasized as important over a span of 22 years, 1979 to 1999, in connecting technology and the future to people and to politics:

*Margins for Survival: Overcoming Political Limits in Steering Technology, 1979

*Tradeoffs: Imperatives of Choice in a High-Tech World---1986

*Making Waves: Engineering, Politics and the Social Management of Technology---1995

*The Double Helix: Technology and Democracy in the American Future---1999

For each book, the most often cited index terms were:

<u>Margins for Survival, 1979</u>: Anticipation, [Foresight, Early Warning, Future, Long-term,] Behavior of political leaders, Cultural values, Decision processes, Government, Information, Nuclear hazards, Technology and Society, Threat and response, Time.

<u>Tradeoffs, 1986:</u> Citizen Participation, Congress, Decision processes, Ethics, Foresight [Anticipation, Future, Long range,] Government, Industry, Information, Media, Political processes, Risk assessment, Technology

<u>Making Waves, 1995</u> Accidents, Business, Coordination, Economics, Engineering, Ethics, Foresight, Government [Congress, President, Policy,] Organizational behavior, Risk, Technology, Values

<u>The Double Helix,1999:</u>: Business, Economics, Ethics, Foresight, Government, Information, Media, Safety and Risk, Technology, Time

A fast scan of these citations unlocks two paradoxes. The featured topics sound more like books in the behavioral sciences than in engineering. That slant was rationalized in a 1995 paper, “Teaching Engineering as a Social Science.” published by the American Society for Engineering

Education. Its thesis was simple, that everything engineers do is to meet needs and wants of people. That suggests learning about human nature as well as laws of nature.

The second enigma was the power of some topics to command attention over a long period when the interaction of technology and society was in flux. The concept of *foresight* deserves special attention.

Many people meet this concept as children when taught to pass a football to where the receiver is perceived to be when the ball arrives. Boy Scouts are engraved with the motto, "Be Prepared." Many young people encounter the future pragmatically in the quest for a college scholarship that depends heavily on high school grades and recognition of leadership earned years before. . Those studies, incidentally, seldom focused on the way ahead; History and English Lit necessarily looked backward. Students met futurist Jules Verne through their vicarious curiosity to explore both the geographical and the scientific frontiers. Beginning in 1933, a series of world's fairs were held in North America, speculating on the future in exhibits and programs: in Chicago, Cleveland, New York, Seattle, Montreal, Spokane and Vancouver. Not until the October 4, 1957 Soviet space spectacular did the entire nation engage the future as the meshing of technology with society and public policy for safety and survival.

It bears repeating that the importance of foresight follows from a reality that all technologies have unintended consequences, some potentially lethal. Shrinking these risks is the core of social responsibility of professional engineers. Practice entailed two different strategies. One is to coral information as to what might happen (in the future), if, or unless. Skillful probing should then lead to stages of care in design to reduce risks. The second strategy was to take precautions against a range of uncertainties by over-design, the use of safety margins.

Both strategies, however, encounter potholes, tradeoffs with other design parameters such as cost, reliability, weight or delivery schedules, and thus with performance. Both strategies stumble for yet another reason. By our culture and possibly by our genes, modern humans have difficulty looking ahead. Anthropologists assert that humans are the only mammals even capable of imagining the future. Seasonal migrations of birds and animals seem spun by instinct, not fantasy. Moreover, early humans were compelled to satisfy immediate needs of food, water and safety so that the longer range perspectives were irrelevant.

Modern humans still suffer from pathologies of the short run. The monograph, *Margins for Survival*, lists sixteen, all dealing with human behavior. That discovery should teach that managing risk crashes into a type of sound barrier that challenges a way of thinking beyond equations and number crunching. Practicing foresight depends on individual and group behavior, what we call social process. Only with this far horizon can risk managers accommodate and compensate for individual and organizational error and its siblings. The three operating instructions for the process were mentioned earlier. Foresight has one other critical product. It instructs us on how to achieve our greatest challenge, making the world a better and safer place for our progeny. Indeed, how a society treats its children is a measure of civilization. In policy terms, that idea stretches back to drafting of the American Constitution.

With the dilemmas of our time, it would be tempting to draft a cook book on foresight, a universal method of forecasting what might happen, if. That quest is fruitless because every case is different. Some dangers, however, repeat themselves such that projections of the future follow trajectories of the past. We learn from failures.

That aphorism puts a premium on history, not just a chronology of key events but also an understanding of different layers of individual and organizational functions, responsibilities, leadership patterns, institutional cultures, communications, resources available, etc.

The past can be prologue.

H.8.3. Pathologies of the Short Run

All risks and measures to enhance safety embody dimensions of time. These intervals range from nanoseconds in computer chips to decades of human longevity, to centuries of tectonic movements. In the context of risk management, the most crucial interval lies ahead, in the immediate future and the distant. Survival is the imperative of the future, both short and long term. Common sense dictates looking ahead, but we are so conditioned to seek immediate gratification that short term goals and strategies trump the longer term, regardless of how much more significant they are. The culture seems indifferent to future penalties of current choice.

This exercise of foresight should be distinguished from prediction, the attempt to satisfy human curiosity about tomorrow's weather, the longevity of a family member, the performance of the stock market. Daily newspapers still carry horoscopes and astrologers still practice an ancient art that extends back to pre-Biblical times. The sagacity of foresight lies in asking questions about alternative, conditional futures--- what might happen, if or unless in relation to acts of nature or acts of people.

There are many pathologies of the short run. Consider the reward structure in commerce. In their narrow self-interest, CEO's are torn between boosting long-term performance of a firm against winning the Wall Street beauty contest next Monday. Shareholders lack patience; so do money managers of mutual funds. Executives also lack incentives for long term strategies because they expect to move on and prudent foresight may bring credit to their successors.

The reward structure in politics is similar. Incumbents sense what earns voter esteem and promise rewards in the next election. Shorter term issues, especially if paraded in headlines, are more rewarding. Seldom are elected officials bold enough to inform an electorate of the distinction between the long and the short run consequences.

To be sure, the future is clouded with uncertainty. In our technological era, we are confounded with complexity of both machines and social processes. Linkages of effect with cause are frustrated because human systems do not have the fixed properties of mechanisms. They are organisms.

In smaller communities of the past, everyone shared information about how their local TDS worked. The social contract was more transparent. Now in large and complex communities, early warnings may be weak. Fretting over the unknown carries emotional burdens eased by ignoring the future. That pattern can explain the unwitting storage of radioactive waste 50 years ago at a weapons factory where it is leaking. Residents knew of the danger since it began, but good jobs drowned out a faint and sporadic protest until very recently.

In general, the public seems indifferent to these longer term issues, partly out of feelings of incompetence and powerlessness. The perceived loss in control leads to weary acceptance of political decisions that are "piecemeal, provisional, parochial, uncoordinated, insubstantial and lacking in prophetic moral vision."

Organizations are known for their resistance to change, for their aging in such a way as to lose alacrity in response to threats (as in New Orleans with Katrina). Energies are directed to self preservation by combating forces uncongenial to well entrenched beliefs. Change can be threatening When dilemmas lack clear solutions, it is more comfortable to avoid action or change in direction. Leaders find bliss by selective ignorance. Such escapes are irresponsible but they are especially attractive when the queue of problems is relentless and new ones erupt before earlier ones have been resolved. Avoiding the future also reduces the risk that a look ahead may uncover mistakes of the past.

In this inventory of pathologies, there is also a perceived shortage of time. That seems anomalous in an era when technology promised to save time and permit mulling over options in the decision theater. Yet the tyranny of a backlog and the frenetic atmosphere of policy making blocks both rational choice and conflict resolution.

Caught in the crossfire, leaders get nervous and either seek immediate relief by impetuosity or are paralyzed by a commitment to the past. Under stress, once again the short term wins. Society leans to a conservative stance because it has lost confidence in itself to manage technology.

This catalogue of pathologies should sound familiar. It exposes how inimical they are to democratic process. Nominating and comparing options takes time, as does an honest debate on who wins and who loses. With unsettled issues accumulating, none receive adequate attention in the policy theater, even less in the media to help inform citizenry to do their duty. When these issues are covered, the media demand instant accountability, live on TV, leaving no time to deal with complexity and context.

When debates are held, advocates argue from their parochial, short term perspectives. No one in the decision pyramid has the patience or energy to look through the mists ahead to practice prophylaxis or take collision avoidance action.

Add problems of information overload, stress of uncertainty, imperatives of reelection, new crises world wide, many beyond remediation. Loss in virtues of foresight and character can lead to exhaustion of stamina and to impetuous judgment.

The operating directions I proposed almost a half century ago came from an innovative concept of technology assessment. Simply put, TA is a method for looking ahead. The OTA’s organic legislation spelled out these paraphrased details:

- Define the TDS, its purposes, its stakeholders, its organizational components and information links.
- Define the technical, social, economic, political and ecological context and the estimated behavior of different system participants.
- Establish a base of hard facts and of uncertainties.
- Forecast what is foreseeable about impacts and about evolution of hardware, software and social ware.
- Generate alternatives of policy and implementation plans including doing nothing, and trace consequences, both desired and unwanted.
- Identify impacted parties, including future generations and effects on each.

- by asking, "What might happen, if, to whom, and when?" Incidentally, this methodology has a mirror image in environmental impact analysis.

Imagine the prize of successful performance of public policies if all initiatives were subject to this mode of analysis.

H.8.4. Early Warning of Close Encounters.

Early risk management drew on common sense, imagination, familiarity with human nature and with contemporary cultures rather than science. Now it also draws on science and engineering, and on learning from failure. For threats that recur frequently, impact statistics are a great help. For threats that occur rarely and especially those with extreme consequences, data are too sparse to extract probabilities for numerical risk analysis as defined previously. That condition springs a paradox.

Admitting there are limits to available information, foresight is still essential. Beyond infrequent accidents or natural catastrophes, we learn from incidents, "close encounters." These events would be similar in patterns of cause and effect to those having severe impact, but in these cases the trajectory to tragedy was arrested either by the lucky tapering of circumstances or by timely and effective accident avoidance maneuvers..

Everyone lives with dangers. Repeated close shaves, however, serve as early warning of a hazardous environment, a hazardous situation or our own impaired judgment. Projected to the future, this store of experience is a survival tool. It doesn't work with slow learners or fools. It does work, however, on an institutional basis where data on close shaves are collected and analyzed in real time in the spirit of prevention or damage control.

The collective benefit of that monitoring is dramatically illustrated by the case of airline safety. For several decades, the FAA has required operating personnel to report close shaves. Analysis of events that were often repeated served as early warning of danger. Participants included pilots, traffic controllers, maintenance inspectors and occasionally passengers.

Because the FAA has authority to punish violators of rules, it was aware that those committing errors might be reluctant to report themselves. As a precaution, FAA contracted with a neutral government agency, NASA, to collect and analyze data, preserving their anonymity but reporting the "hot spot" patterns that deserve immediate risk reduction measures. As a result, accidents on the nation's airways have been conspicuously limited over a period when air traffic sharply increased.

The same reporting system was proposed by the author in a 1982 report on navigation safety in Puget Sound where newly operating tankers carrying crude oil posed a serious environmental hazard.. The Department of Transportation adopted the proposal, issued reporting rules and forms, and selected its laboratory in Cambridge, Massachusetts as the neutral, data collection agent rather than the U.S. Coast Guard which has regulatory authority. Communication of this risk management technique to ship operators was so poor, however, that few reports were filed and the DOT abandoned the system.

The virtue of close encounter reporting remains and has been adopted in other risky situations. Operators of nuclear power plants are required by the Nuclear Regulatory Commission to file such reports, even using telephony to warn operators of similar plants of similar vulnerabilities.

The public is well aware of product recalls mandated by various agencies where intervention is based on the frequency of identical hazards, some creating accidents, some only incidents, the close shaves. Broader applications are obvious.

H.9 The Anatomy of Risk - A Summary

In virtually all human affairs, some risk is normal. The consequences of neglect may be grave, if not now then in the future. There follows a distillation of points raised earlier on how to think about the risk situation as a prelude to risk management.

- Risk is a highly complex condition, especially challenging because it combines abstruse technical factors with diverse and uncertain elements of societal behavior; and because the consequences may cause great harm.
- Three frontiers of risk pose threats, extremes of nature, weaknesses in human nature, and the unintended consequences of technology
- All technologies spawn side effects, most unwanted by some sector of the population, now or in the future
- .Each risk condition is unique, but two theorems for analysis have found wide application to facilitate understanding
- The first is based on the notion that what you can’t model you can’t manage.
- This leads to a generic framework to structure intertwined laws of nature and of human nature, what is termed a Technological Delivery System, a TDS.
- The second tool is based on the notion that risk does not yield to rigorous technical analysis because acceptable risk is a social judgment.
- Risk analysis using a TDS depends on three premises of governance.
- The first is that those exposed to involuntary risk should have a say in their intensity of risk exposure.
- The second is that when economics of the free market, existing laws and local governments fail to meet that level of safety, the federal government is charged to assume responsibility to lower the threshold of threat to levels that citizens demand.
- That achievement, however, has both direct and indirect costs, so that significant tradeoffs are necessary between safety and expense.
- Because of cultural diversity in America, achieving consensus on acceptable risk releases a fog of conflict and uncertainty
- .Bargaining develops among stakeholders; lobbying becomes endemic.
- Typically, each argues from their immediate, short-term self-interest such that little attention is paid to long-term effects, including on future generations.
- The third precept is that the federal government not just serve as umpire, but balance long- with short-term factors, thus serving as a surrogate for progeny

- In this chain of argument, a question arises as to whether the public that is to be consulted as to risk tolerance has adequate factual information and grasp of the risk equation so as to render not just consent but informed consent.
- Two TDS elements help with that illumination, the print and electronic media, and past or recent events. Those so agitate a TDS that the full cast of stakeholders is revealed, their roles in posing a threat, in preventing or limiting the damage or in their capture as victims.
- Study of past and recent events offers a rich opportunity to learn from failure. Most of these failures can be traced to human and organizational errors.
- Those lessons should tutor emergency preparedness through the self-conscious exercise of foresight, to limit impacts to choice and not chance
- Potent levers of foresight are the questions, "What, if or unless; when and to whom." This is the spine of technology assessment that was institutionalized in 1972 for Congress as radar for the ship of state. That capability was lost in 1995. Perhaps it needs rethinking for both branches of government.
- Engineering practice treats uncertainties by over-design with safety margins
- How these are set and by whom are critical.
- The role and performance of the federal government can be evaluated to ascertain effectiveness of regulation for risk reduction and damage control
- Dissection of these events should reveal the strength and weaknesses of existing legislative authority, the match between appropriations and need, the identification of leadership to integrate and activate emergency preparedness and crisis response among federal and lower authorities.
- A customized TDS should help illuminate who is responsible for what among organizational components, but a critical element is the quality of communications to assure that basic information is shared and that otherwise piecemeal actions are synchronized to assure systemic functioning..
- As to federal involvement, the President becomes the nation's uncertified systems manager because all agencies responsible for citizen safety and security report to the Chief Executive, because he is held to account for their satisfactory performance and must initiate new public policies if authority or performance is weak, because many dangerous natural phenomena entail common property of air, land or water, and because in extreme cases the military arm of which he is Commander in Chief must be mustered.
- Ultimately, the President is responsible for protection from terrorism, extremes of nature, from dangers of technology's side effects and from human frailties of ignorance, error, blunder, folly, mischief, greed and hubris.
- This burden must be processed with foresight to exercise political power and political will, especially to meet shortages of vigilance, resources and trust.
- Government is both mandated and constrained by public policies, and these are rooted in values that differ widely among stakeholders.
- One source of conflict arises between industry and government because there are sharp differences between these entities in goals and in tactics based on their internal values.

Industry honors efficiency and measures success by profit and generation of wealth. Government honors sustainability and measures success by economic and social justice.

- Some tension between these two power centers is healthy but excessive tension can be corrosive
- The quality of social and political choice is revealed by the heritage each generation leaves its children
- Citizens need to realize that government is "We, the People!" that democracy is not a spectator sport and that each citizen has responsibility for risk management through public policies and citizen watchdogs.
- The risk management process depends critically on mutual trust of all parties.

H.9.1. Applying These Concepts to Katrina

This treatise was prepared for this study of the Katrina disaster. The diagnosis of causes for the calamity demanded a sifting of the foregoing issues for steps to meet the federal government's responsibilities and accountability to anticipate threats and to prevent and to mitigate losses of life and property.

Three measures emerged from the most salient lessons and the most potent interventions to avert a repetition of the flooding disaster.

- To enhance the management of all modes of risk, the responsibilities for vigilance and decision making at the tip of the authority structure should be clarified and strengthened, perhaps with a new unit in the Executive Office of the President.
- To buttress the legislative responsibilities of the Congress, additional technical staff should be appointed to assure adequate revenues to manage risk and to monitor performance of the Executive Branch in its duties of care.
- To reflect that citizens at risk are entitled to information regarding their exposure and opportunities to participate in governance, new processes should be authorized at a local level to foster informed consent and dissent and to function early warning in disaster-prone areas.

Such measures have great promise in the spirit of preventing another lethal flood in New Orleans. They present opportunities to deal with a much broader array of threats—to life, peace, justice, health, liberty, private and common property

These cardinal recommendations arise from Constitutional law and from a history of public policies that establish the Federal Government as the most senior authority for providing safety and security. Moreover, the technological engines of the last century have added to natural causes a new class of dangers arising from human and organizational errors and from unintended consequences of technologies switched on for their benefits.

This double helix of technology and governance leads to awareness that the President is the nation's uncertified systems manager. Responsibilities accrue from the President being the Chief Executive supervising all federal departments and agencies and responsible for their disaster preparedness, their exercise of foresight and for adequacy of their funding. As Commander in Chief of the armed services, he has direct and immediate access to potent physical and human resources both to prepare for emergencies and to offer rescue and salvage assistance after a disaster.

.The age of electronic communications has heavily affected the functioning of the White House in its connections to the outside world. Events anywhere have repercussions everywhere. Message traffic is more complex, demands faster analysis and response, and entails a denser web of possibly differing participants.

One psychological effect is to force attention to immediate issues rather than the important. Pressures to deal with the unremitting queue of short-term dilemmas squeezes out attention to longer-term challenges. The future is neglected, thus seeding an enormous penalty for future generations, including the burden of public debt.

Decision making in every White House has other impediments. Apart from the standard approach of framing issues and options, the incumbent has to assess the impact of choice on political power and political will. Each quandary imposes stresses on political capital. With a press intent on not becoming a sycophant and losing their role as the fourth estate, that Greek chorus is noisy and distracting, and in a democracy, not centrally controlled. So the President must be aware of the public perception of issues at hand and their intertwining with unresolved preceding issues.

That latter condition is reflected in a new reality of government organization. There was a time when the missions and roles of individual departments were highly specialized and compartmented. Today, issues leak well beyond the province of single agency. This imposes a more intense requirement at the top for coordination and integration of functions of several agencies. Only the President and the Vice President have the authority of being elected and occupy a central position of leadership of all departments and agencies.

In a nutshell, the President needs help of a special cadre of advisors experienced in and focused on catastrophic risks of all kinds. Organizationally, they should not become a layer between him and agency heads. This staff should be mandated to look ahead, to think in the future tense, to adopt a stance of being proactive in the sense of preventative medicine rather than reactive, to balance long- with short-range factors free of partisan politics.

The staff director should have direct access to the President at all times to offer early warnings such as intelligence agencies do for military security, to share urgent information without its filtering in the White House chain of command. In addition, the director should have the authority to convene emergency sessions of appropriate cabinet officers to gain their inputs and cooperation when circumstances demand immediate collaboration and to serve as a monitor of disparate and incoherent responses.

This new capability could be a Council for Catastrophic Risk Management in the Executive Office of the President The interim Council on Marine Resources and Engineering Development, PL89-454, could be a model.

The Congress needs a symmetrical capability, especially in its orientation to the future. Such a resource existed between 1973 and 1995 in its Office of Technology Assessment. That organic legislation should be revisited to see if its engines need restarting but with a more specific focus on risk management. The procedural methodology is sketched on pages 30 and 31.

Finally, there is a major and unprecedented role for citizens who should be considered part of governance in the spirit that those who govern do so at the informed consent of the governed. This is the population exposed to risk. Authorities for risk management should make sure that those vulnerable have information regarding their condition and a reciprocal ability to respond to requests for their informed consent especially regarding tradeoffs, say safety for cost.

In addition they could function as watchdogs to serve as early warning on the ground of disasters waiting to happen as well as monitors of agencies charged with prevention, containment and remediation. This function was deemed essential to help protect Prince William Sound from another disastrous oil spill.

One central purpose should animate all three of these entities, separately and in tandem. They should address the question, "How Safe is Safe?" That investigation demands foresight in the spirit of the injunction, "Without vision, the people perish."