Preliminary Report on the Performance of the New Orleans Levee Systems in Hurricane Katrina on August 29, 2005

by

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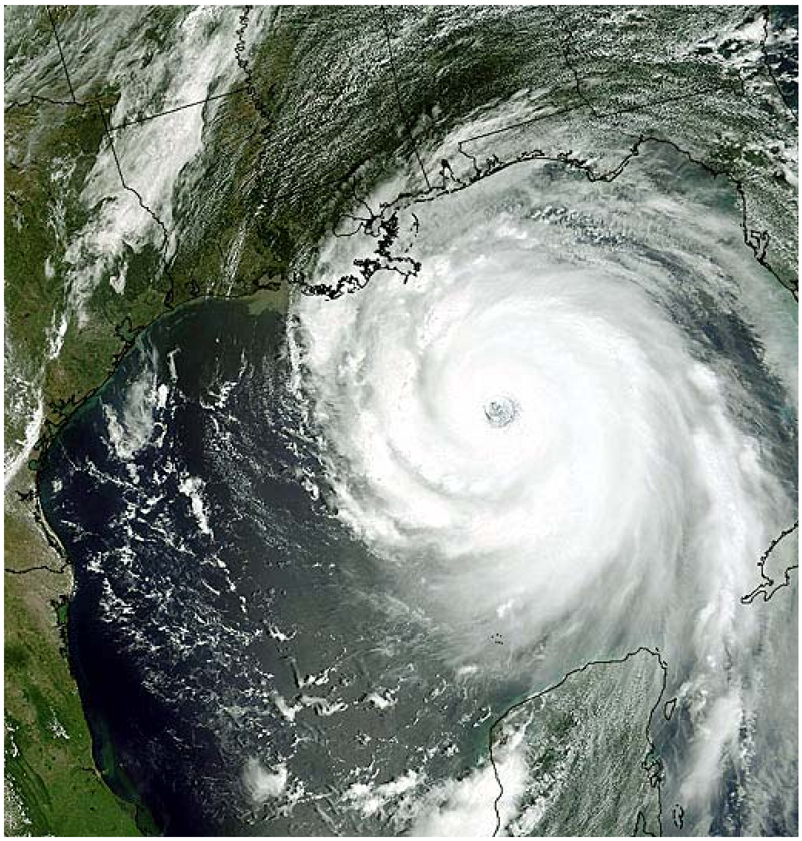

Preliminary findings from field investigations and associated studies performed by teams from the University of California at Berkeley and the American Society of Civil Engineers, as well as a number of cooperating engineers and scientists, shortly after the hurricane.

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expressed in this report are those of the author(s) and do not
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This report contains the observations and findings of a joint investigation between independent teams of professional engineers with a wide array of expertise. The materials contained herein are the observations and professional opinions of these individuals, and does not necessarily reflect the opinions or endorsement of ASCE or any other group or agency.

Ver. 1.2

This report has been slightly modified from its original version, which was issued on November 2, 2005 in response to a deadline for testimony before the U.S. Senate Committee on Homeland Security and Government Oversight. The minor revisions are not substantive in nature, and serve principally to improve the accuracy of the language and the clarity of some of the statements. No significant changes in the technical content or findings have been made in this second iteration.

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Table of Contents

Cover Image from http://www.noaanews.noaa.gov/stories2005/s2506.htm

EXECUTIVE SUMMARY

This report presents the results of field investigations performed by several teams of engineers and scientists in the wake of the passage of Hurricane Katrina to study the performance of the regional flood protection systems in the New Orleans area. The principal focus of these efforts was to capture perishable data and observations related to the performance of flood control systems.

The initial field investigations occurred over a span of approximately two and a half weeks, from September 28 through October 15, 2005. The starting date for these field investigations was determined by balancing the need to gather vital perishable data before it was damaged or obscured by emergency repair operations versus the need to avoid interference with such emergency operations, and issues associated with safe access, logistics, etc. There were numerous occasions when team units arrived and investigated sites only days, or even hours, prior to the covering of vital information by ongoing emergency repair activities.

The storm surges produced by Hurricane Katrina resulted in numerous breaches and consequent flooding of approximately 75% of the metropolitan areas of New Orleans. Most of the levee and floodwall failures were caused by overtopping, as the storm surge rose over the tops of the levees and/or their floodwalls and produced erosion/scour that subsequently led to failures and breaches.

Overtopping was most severe on the east side of the flood protection system, as the waters of Lake Borgne were driven west towards New Orleans, and also farther to the south, along the lower reaches of the Mississippi River. Significant overtopping and erosion produced numerous breaches in these areas. The magnitude of overtopping was less severe along the Inner Harbor Navigation Canal (IHNC) and along the western portion of the Mississippi River Gulf Outlet (MRGO) channel, but this overtopping again produced erosion and caused additional levee failures.

Field observations suggest that little or no overtopping occurred along most of the levees fronting Lake Pontchartrain, but evidence of minor overtopping and/or wave splashover was observed at a number of locations. There was a breach in the levee system at the northwest corner of the New Orleans East protected area, near the Lakeside Airport.

Farther to the west, in the Orleans East Bank Canal District, three levee failures occurred along the banks of the 17th Street and London Avenue Canals. Evidence that we observed indicates that these failures occurred when water levels were below the tops of the floodwalls lining these canals. Based on our observations, we believe that these three levee failures were likely caused by failures in the foundation soils underlying the levees. In addition, we observed lateral displacements, sinkholes, and sand boils indicative of an incipient breach at a fourth distressed levee/floodwall segment on the London Avenue Canal.

This report presents an overview of initial observations and findings regarding the performance of the New Orleans flood protection system, including observations regarding preliminary assessments of likely causes of failures and/or significant damage to levees and floodwalls at many sites. Although most of the failures/breaches that occurred were primarily due to overtopping and subsequent erosion, three major and costly breaches appear to have been the result of stability failures of the foundation soils and/or the earthen levee embankments themselves. In addition, it appears that many of the levees and floodwalls that failed due to overtopping might have performed better if conceptually simple details had been added and/or altered during their original design and construction.

Major repair and rehabilitation efforts are now underway to prepare the New Orleans flood protection system for future high water events. The next hurricane season will begin in June of 2006. Based on our observations, a number of initial comments are warranted concerning the rebuilding and rehabilitation of the levee system, and this preliminary report makes a number of observations and recommendations regarding ongoing flood system repair efforts. Preparing the levees for the next hurricane season should also include a review of how the system performed during Hurricane Katrina, so that key lessons can be learned and then used to improve the performance of the system.

There are ongoing studies of the performance of the flood protection system in this catastrophic event, as well as efforts to improve the levels of reliability and safety of these types of defenses for the future. We hope that the results of these studies will lead to a clear appreciation of what happened in Katrina, and that the lessons learned from this event will lead to improved protection in the future, not just in the New Orleans area, but throughout the nation and around the world.

Chapter One: Introduction and Overview

1.1 Introduction

This report presents the results of field investigations performed by collaborating teams of scientists and engineers in the wake of the passage of Hurricane Katrina to study performance of the regional flood protection systems 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 control systems 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 participating teams were an NSF-sponsored team led by the University of California at Berkeley, a team from the American Society of Civil Engineers (ASCE) organized by its Geo-Institute and 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 Engineering 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.

The initial field investigations occurred over a span of approximately two and a half weeks time. Initial scouts from the USACE/ERDC team and the ASCE G-I team arrived onsite on September 26 and 28, respectively. Four members each from the NSF-sponsored, ASCE G-I and ASCE COPRI teams then worked as a combined 12-person team from October 1 - 8, 2005, and a second group consisting of two more ASCE G-I team members and five more NSF-sponsored team members worked the next week from October 8 - 15, 2005. The NSF and ASCE teams were accompanied in the field, and supported logistically, by members of the USACE/ERDC investigation team. Members of the LSU/HRC team also accompanied the main field teams and provided important insights regarding water levels, storm surge projections, etc.

The starting date for these field investigations was determined by balancing the need to gather vital ephemeral data before it was lost or obscured due to emergency repair and response operations versus the need to avoid interference with such emergency operations and issues associated with safe access, logistics, etc. It was fortunate that the main teams arrived when they did, as there were numerous occasions when team units arrived and investigated sites only days, or even hours, prior to the covering of vital information by ongoing emergency repair activities. At a number of sites, observations made were sufficient to make preliminary determinations of mechanisms of failure, while only a day later the burial of key evidence at these same sites would have rendered even eventual identification of the potential causes of failure highly unlikely. The field investigation teams are very grateful for the unusual opportunity to have been granted free and unobstructed access to all sites in spite of ongoing emergency reconstruction and repair activities.

1.2 Hurricane Katrina

The path of Hurricane Katrina's eye is shown in Figures 1.1 and 1.2. 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 on Monday, August 29, as shown in Figure 1.2. The Hurricane had weakened to a Category 4 level prior to landfall on the morning of August 29.

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.

1.3 Overview of the New Orleans Flood Protection Systems

Figure 1.3 shows the general 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 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 "polders", each protected by its own perimeter levee system, and these are dewatered by pumps. Polder is the Dutch word for a contiguous land unit protected by a perimeter levee system, and it is an appropriate term here.

As shown in Figures 1.4 and 1.5, there are four main polders, or protected areas, that comprise the New Orleans flood protection system. A number of smaller levee-protected units also exist in this area, but the focus of these current studies is the four main protected areas which were largely constructed under the supervision of the U.S. Army Corps of Engineers. Figures 1.4 and 1.5 show the locations of most of the levee breaches and severely distressed (but non-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 additional stars have been added to the map in Figure 1.4 as a result of the field studies reported herein. We understand that the yellow stars correspond to deliberate breaches made to facilitate draining the flooded areas after the storm.

As shown in Figure 1.4, the Orleans East Bank section is one polder. This protected unit contains the downtown district, the French Quarter, and the Garden District. The northern edge of this polder 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 polder, separating the Orleans East Bank polder from New Orleans East (to the northeast) and from the Ninth Ward and St. Bernard Parish (directly to the east.) Three large drainage canals extend into the Orleans East Bank polder 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 polder surrounds and protects New Orleans East, as shown in Figure 1.4. This polder fronts Lake Pontchartrain along its north edge, and the Inner Harbor Navigation Canal 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 (IWW) along this stretch. The eastern portion of this polder is currently largely undeveloped swampland, contained within the protective levee ring. The east flank of this polder is fronted by additional swampland, and Lake Borgne is located slightly to the southeast.

The third main polder contains both the Ninth Ward and St. Bernard Parish, as shown in Figure 1.4. This polder is also fronted by the Inner Harbor Navigational Canal on its west flank, and has the MRGO/IWW channel along its northern edge. At the northeastern corner, the MRGO bends to the south (away from the GIWW channel) and forms the boundary at the northeastern edge. Open swampland occurs to the south and southeast. Lake Borgne occurs to the east, separated from this polder by the MRGO channel and a narrow strip of undeveloped marshland. The main urban areas occur within the southern and western portions of this polder. The fairly densely populated Ninth Ward is located at the west end, and St. Bernard Parish along approximately the southern half of this polder. The northeastern portion of this polder is undeveloped marshy wetland, contained within the protected polder in anticipation of future development. A secondary levee, operated and maintained by local levee boards, separates the undeveloped marshlands of the northeastern portions of this polder from the Ninth Ward and St. Bernard Parish metropolitan areas.

The fourth main polder is a narrow, protected strip along the Mississippi River heading south from St. Bernard Parish to the mouth of the river at the Gulf of Mexico, as shown in Figure 1.5. This protected strip, with levees fronting the Mississippi River and a second side of levees facing away from the river forming a protected strip 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. This levee-protected corridor will be referred to in this report as “the Plaquemines Parish” protected zone, or polder.

The current perimeter levee and floodwall defense systems for these four polders 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. The flood protection improvements typically involved raising existing levee defenses and adding new floodwalls.

1.4 Flood Protection System Performance 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 is intended to represent a scenario roughly "typical" of a rapidly moving Category 3 hurricane passing close to the New Orleans region. 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 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 through the region.

Figure 1.6 shows a plot of peak storm surge levels predicted by the LSU Hurricane Research Center on August 28, 2005, just a day before the arrival of Katrina. The water levels shown in Figure 1.6 were predicted using a numerical model for a point in time when the eye of the hurricane would pass slightly to the east of New Orleans. Predicted and actual storm surge heights varied over time, at different locations, and the water levels shown in Figure 1.6 do not represent predictions of the peak storm surges noted at all locations. Instead, this image shows predicted conditions at a point in time when a large surge was being driven west from Lake Borgne. These types of storm surge modeling calculations are being calibrated and updated based on actual field measurements of high water marks, etc.

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 not yet had time to adequately resolve differences between different datums, so all elevations stated in this preliminary report should be regarded as somewhat approximate, and should be taken as referring approximately to elevation with respect to NAVD 88 or "mean sea level" in the region.

Hurricane Katrina, as expected, produced a large onshore storm surge from the Gulf of Mexico. This produced significant overtopping of levees along the lower Mississippi reaches in the Plaquemines Parish area, and numerous levee breaches occurred in this area, as shown in Figure 1.5. It also raised water levels within Lake Borgne (which is directly connected to the Gulf.)

As the hurricane 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 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 in this area. One lakefront levee breach occurred, near the west end of New Orleans east.

The largest storm surge, however, was produced by waters from Lake Borgne which had been raised by the onshore storm surge from the Gulf. As the storm passed to the west of New Orleans, the lake waters were driven west by the passing storm onto the east flank of the

New Orleans regional flood protection system (as shown in Figure 1.6.) This produced a storm surge estimated at approximately 18 to 25 feet, which rolled by about 5 to 10 feet over the levee protection system along the northeastern edge of the protected basin containing St. Bernard Parish and the Ninth Ward. Studies of timelines for both flooding and water levels are ongoing, and a number of investigating field groups are working at the time of this writing to better define peak water levels and storm surge timings. There is strong evidence for the massive overtopping of the levees along the northeast edge of the St. Bernard Parish/Ninth Ward polder, however, as a gate tender responsible for a lock gate along this frontage remained at his station throughout the storm. He retreated to his crow's nest lookout tower, and debris from the storm surge was recovered from well up this tower. The storm surge at his location rose at least 5 to 10 feet above the top of the levee system, matching well with current numerical modeling of storm surge at this location performed by several modeling groups.

The levees in this area, which were largely earthen levees constructed of relatively poor materials, were simply overwhelmed and were massively eroded. The floodwaters from this severe overtopping then flowed across the open, undeveloped swampland to the southwest and overtopped a lower set of levees separating the developed areas of this Polder from the largely undeveloped wetlands, producing a number of additional erosive breaches on this secondary levee system, as shown in Figure 1.4.

The combined storm surges from several directions produced storm surges along the Inner Harbor Navigation Canal (IHNC) and the MRGO channel, and these storm surges were sufficient to produce overtopping at a number of locations along both of these channels. This overtopping was less severe, however, than that which occurred along the east flank of the St. Bernard Parish polder, and many sections of the levee protection system that were overtopped along the IHNC and the MRGO channel survived without breaching. A number of breaches did occur along both the IHNC and the MRGO channel, however, and large areas of both New Orleans East and the Ninth Ward/St. Bernard Parish polder basins were flooded.

Farther to the west, the storm surge along the Pontchartrain lakefront 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 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 polder (as shown in Figure 1.4)

The consequences of the flooding of major portions of all four levee-protected polders were catastrophic. Figure 1.7 shows inundation of the Ninth Ward adjacent to one of the major breaches in the levee along the IHNC. Numerous areas of greater New Orleans were similarly flooded, as shown in Figures 1.4 and 1.5. Large developed areas within all of the main polders were flooded, and they remained inundated for several weeks before levee breaches could be repaired and the waters pumped out.

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 1.8. 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 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 1.9 shows the devastation immediately inboard from the large breach at the same Ninth Ward site shown previously in Figure 1.7, but in this case 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 1.10 shows another aspect of the flooding. This photograph shows a region within St. Bernard Parish in which numerous homes were floated and transported from their original locations by the floodwaters, and then deposited in new locations. Figure 1.11 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 nearly floated over 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 1.12 and 1.13 show typical devastation 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 this denoted the number of dead bodies found within the building. In most cases, as shown previously in Figure 1.8, this number was "0", but this was not always the case. Figure 1.14 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 1.15 shows the muddy devastation, and a wheelchair, within this flooded structure.

At the time of the writing of this preliminary report, the death toll has risen just past 1,000, with more than 700 of these deaths occurring in the State of Louisiana. Loss projections continue to evolve, but estimates of overall losses have now climbed to the $100 to $ 200 billion range.

1.5 Organization of this Interim Report

The purpose of this interim report is to disseminate as much of the data and observations made during our initial site investigations as possible, for the mutual benefit of all research and investigation teams attempting to further study the performance of flood control systems in this event, and for the benefit of efforts to repair and rebuild the levee protective systems in preparation for the next hurricane season (which will begin in June of 2006.)

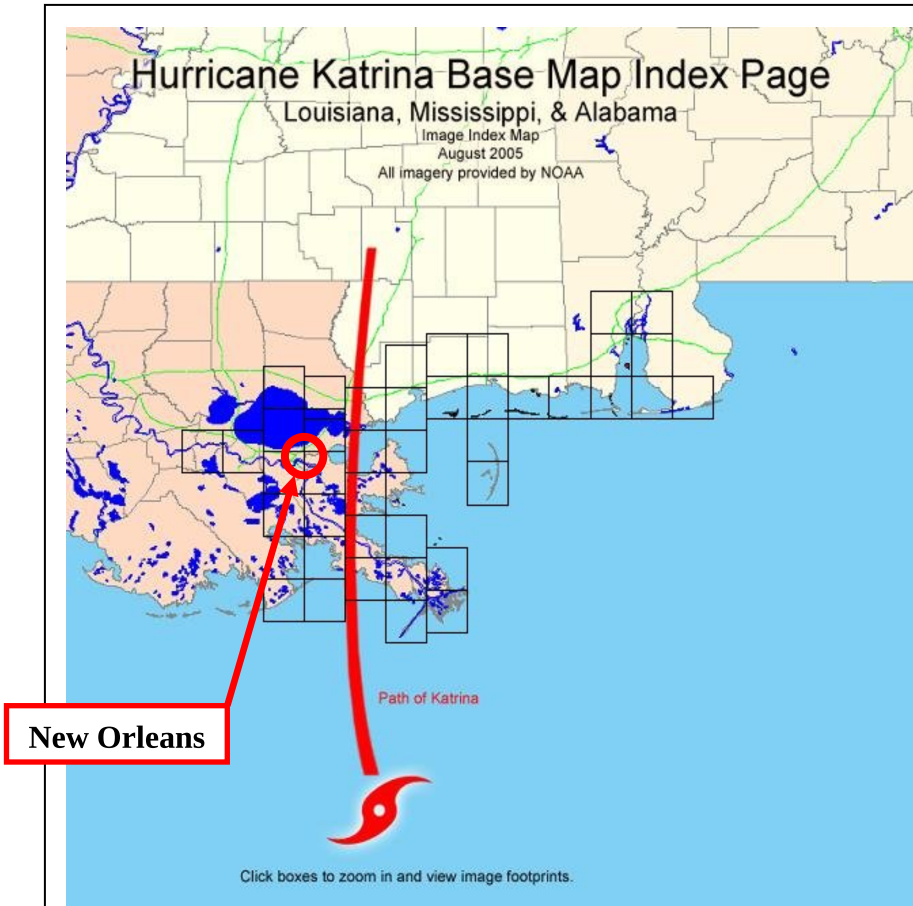
Considerable further studies are planned, and all observations reported should be considered as preliminary in nature, as further field studies, including borings and sampling, CPT probes, etc, as well as laboratory testing are anticipated in the months ahead. Considerable additional field work is also planned to further define high water levels to refine and field-calibrate numerical models of storm surges vs. time throughout the flood protection system. Background documentation, including site investigations, design calculations and design memoranda, as-built drawings, etc. have been requested at many sites of interest, and the U.S. Army Corps of Engineers (USACE) has agreed to provide all of these as quickly as time, and the still ongoing emergency repair operations, permit. As of the issuance of this report, the USACE had initiated posting of data online.

In addition, significant additional site investigations (including CPT probes, borings and sampling, etc.), as well as laboratory testing are already underway under the auspices of the USACE, and the USACE have agreed to openly share all resulting data with the various levee investigation teams currently studying this event.

Chapters 2 through 5 of this report present a summary of observations and preliminary findings to date associated with protective levee system performance in the (2) Orleans East Bank, (3) Ninth Ward/St. Bernard Parish, (4) New Orleans East, and (5) Plaquemines Parish protected areas, respectively. Chapter 6 briefly addresses observations regarding pumping and dewatering systems, and other aspects of the overall regional flood protection system. Chapter 7 describes LIDAR imagery data sets taken to capture three-dimensional representations of detailed ground surface conditions and configurations at a number of key sites. Finally, Chapter 8 summarizes a number of preliminary overall observations and recommendations.

Source: http://flhurricane.com/googlemap

Figure 1.1: Location of New Orleans, and map of the path of the eye of Hurricane Katrina.



Source: http://ngs.woc.noaa.gov/katrina/KATRINA0000.HTM

Figure 1.2: Traced path of the eye of Hurricane Katrina at landfall in the New Orleans area.

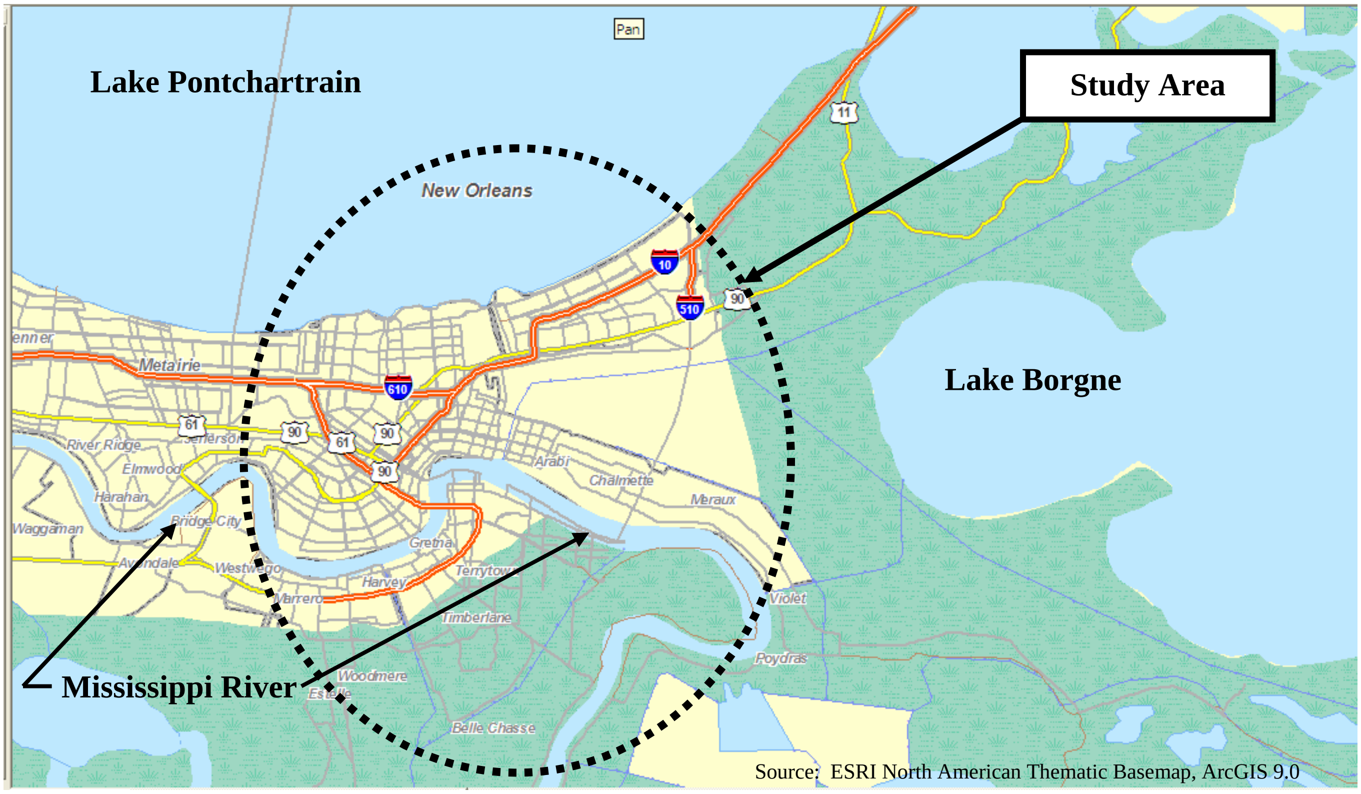


Figure 1.3: The Greater New Orleans Region Levee Performance Study Area.

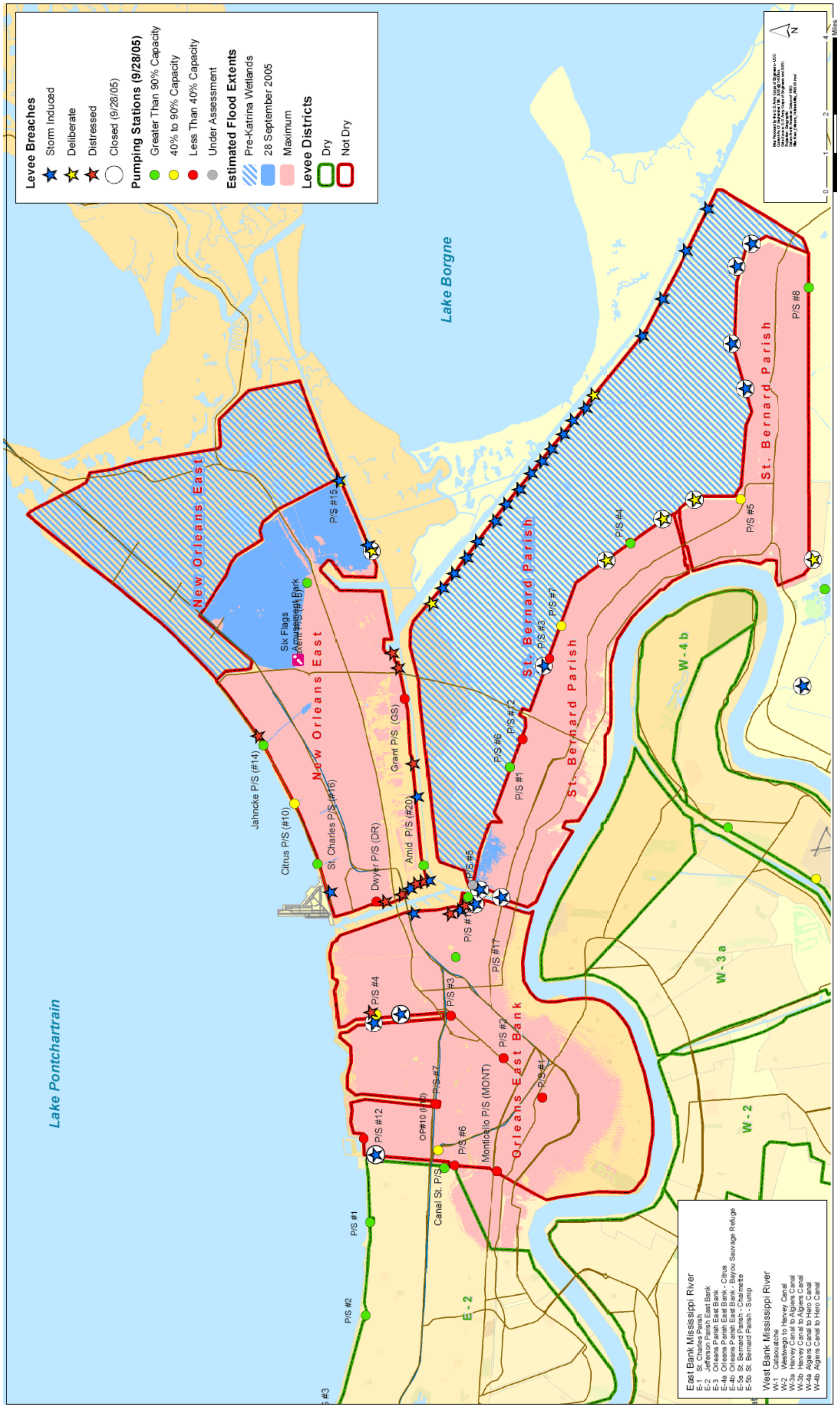


Figure 1.4: Map showing principal features of the main flood protection rings or “polders” in the New Orleans area. [Modified after USACE, 2005]

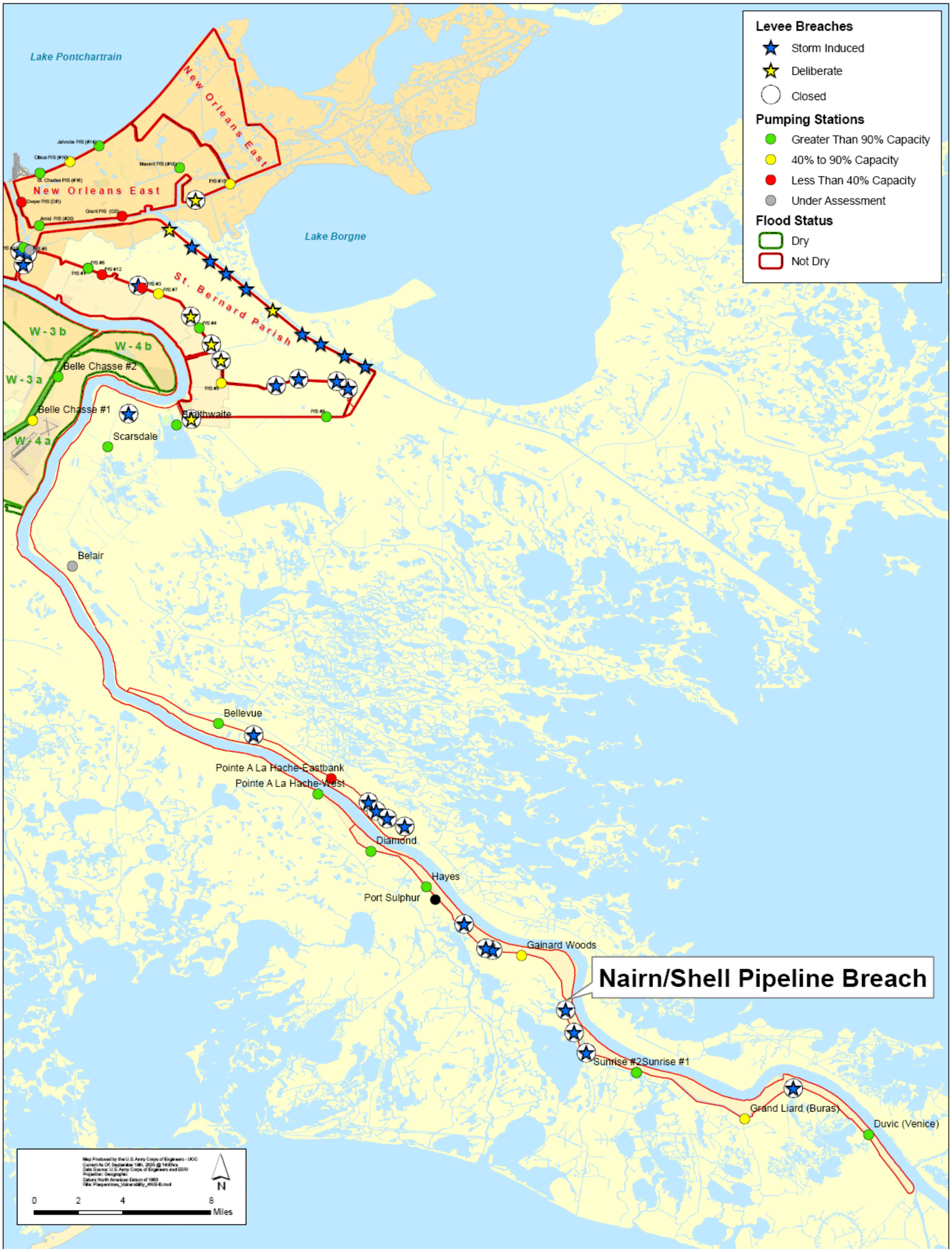
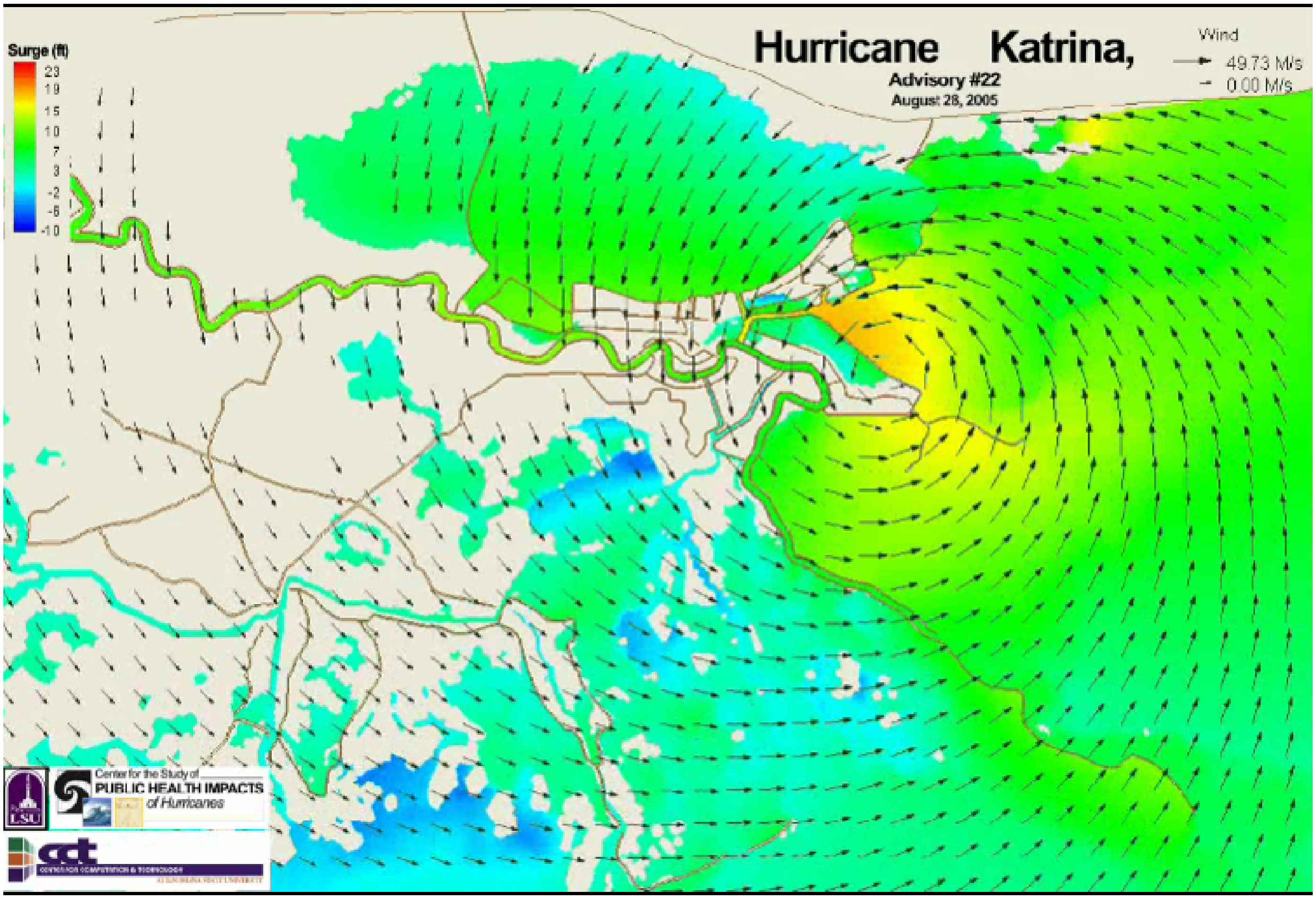


Figure 1.5: Map showing the levee protected areas along the lower reaches of the Mississippi River (in the Plaquemines Parish Area) [USACE, 2005]



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

Figure 1.6: Map of calculated storm surge levels, at time when the eye of the storm passed close to the east of New Orleans. [LSU Hurricane Research Center, 2005]

Figure 1.7: Flooding at the west end of the Ninth Ward, and outflow through levee breach as initial storm surge subsides.

Photograph by Rune Storesund

Figure 1.8: High water marks remain on structures after temporary levee repairs have been completed and flood waters have been pumped out.

Photograph by Les Harder [oct.14, 2005]

Figure 1.9: Oblique view of the (south) levee break at the Inner Harbor Navigation Canal into the lower Ninth Ward.

Photograph by Les Harder

Figure 1.10: Flooded neighborhood in St. Bernard Parish, showing homes floated off their foundations and transported by floodwaters.

Photograph by Les Harder

Figure 1.11: 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 1.12: Damage to a residential neighborhood in the 17th Street Canal area due to flooding.

Photograph by Rune Storesund

Figure 1.13: Another view of flooding damage, this time in the lower Ninth Ward.

Photograph by Les Harder [Oct 10, 2005]

Figure 1.14: Search and rescue team markings on a building in the Ninth Ward where three inhabitants died.

Photograph by Les Harder [Oct. 10, 2005]

Figure 1.15: View inside structure shown previously in Figure 1.14.

Chapter Two: The Orleans East Bank (Downtown) Protected Area

2.1 Overview

The location of the Orleans East Bank protected section, or polder, was shown previously in Figure 1.4. This encompasses the main downtown area of New Orleans, as well as a number of famous historic districts including the French Quarter and the Garden District.

Figure 2.1(a) shows an enlarged view of the principal levees protecting the northern portion of this polder, in the "Canal" district. The small numbers in Figure 2.1(a) indicate the approximate elevations of the tops of the levees along the lakefront, and the tops of the floodwalls at the crests of the earthen levees along the three main drainage canals. As shown in this figure, the tops of the lakefront levees were generally on the order of elevation +17.5 to +18 feet, while the tops of the floodwalls along the sides of the three drainage canals were typically at elevations of about +13 to +15 feet.

The storm surge towards the south from Lake Pontchartrain drove both lake waters and waves against the lakefront levees. Best available field data, and numerical calculations of storm surge, at the time of this writing suggest that the lakefront storm surge in this area rose to about 11 feet, well below the crests of the lakefront levees in this area. No significant sustained overtopping occurred (only wave splashover at a few locations).

These levees were well-constructed earthen embankments, constructed using apparently cohesive soils, and they generally had good erosion protection on their outboard faces (generally consisting of large stone rip-rap.) These lakefront levees performed well, and despite some evidence of minor wave overtopping at a few locations, these lakefront levees safely withstood the storm with only minor evidence of any erosion at the crests and back faces evident after the storm had passed.

The three drainage canals traverse the canal district from south to north, as shown in Figures 1.4 and 2.1. These drainage canals serve as open channels to carry flow from large pumping stations at their southern ends northwards into Lake Pontchartrain. They are used to unwater the southern end of this protected polder. The three drainage canals have a slightly S-shaped entrance configuration at the lake end, so that wind driven waves at the Lake Pontchartrain lakefront will not be fully transmitted southwards into the canals. Accordingly, they also have slightly lower crest heights (at the tops of their floodwalls) than the Pontchartrain lakefront levees.

The levees along all three drainage canals consist of earthen embankments, topped by concrete floodwalls. The concrete floodwalls are mainly "I-walls", with the concrete wall section being cast atop a row of sheetpiles driven through the crest of the earthen embankment, as shown in Figure 2.2(a). These concrete walls get their stability by cantilever action as they and their sheetpiles are supported by the embankment soils. Some of the floodwalls along these canals appeared to be "T-walls", as shown in Figure 2.2(b). These wall sections also cap a sheetpile curtain, but they get additional rotational and lateral stability by nature of their broad concrete base (which forms an inverted "T".) They may also be founded on battered (inclined, reinforced concrete) bearing piles, which can provide significant additional rotational stability.

The three canals did not appear to have equally well-constructed and maintained levee and floodwall protection. The central canal, the Orleans Avenue Canal, generally had visibly wider soil embankment sections, and was also generally better maintained with regard to preventing growth of brush and trees on the land side slope faces.

The other two canals, the 17th Street Canal and the London Avenue Canal, generally had narrower embankments. Brush growth, and even trees, were noted at a number of locations on the land side faces of the levees along both of these canals.

A major breach occurred at the east bank of the 17th Street Canal, near the north end, as shown in Figure 1.4. This produced flooding over a significant area between the 17th Street and Orleans Avenue Canals.

Two additional major breaches occurred on the London Avenue Canal. As shown in Figure 2.1, one of these occurred near the north end of the London Avenue Canal, at the west bank levee, and this breach flooded a significant area between the London Avenue Canal and the Orleans Canal. In addition, significant "distress" occurred directly across the canal from this breach, along the eastern levee embankment and floodwall.

A second major breach occurred farther south along the east bank of the London Avenue Canal, as shown in Figure 1.4. This breach flooded a significant area east of the London Avenue Canal.

2.2 The 17th Street Canal Breach

Figure 2.3(a) shows the major breach at the east side of the 17th Street Canal as it is being "plugged" with large sandbags being delivered by military helicopters in the wake of Hurricane Katrina. This photo is taken looking to the northeast. Figure 2.3(b) shows the same figure, but this time highlighting key features for discussion. The line of grassy soil units in the center of the photo are the inboard half of the southern end of the original levee embankment, and the chain link fence is remnants of the fence that passed along the inboard lip of the crest road, separating the crest from adjacent homeowner's back yards. The southern end of the embankment has translated to the east, traveling laterally up to about 45 feet away from its original position. The northern end of the breached embankment section was largely eroded by scour after the breach opened.

Figure 2.4 shows a second view of some of the details at this site. The relatively intact southern embankment sections translated laterally approximately 45 feet, and without significant rotation, as the trees and chain link fence remained vertical throughout this displacement. The laterally translating wedge of embankment (and possibly also some foundation) soil "plowed" into soft soils at the inboard toe, causing them to bulge upwards, heaving the largely collapsed shed and pushing it into the house.

Figure 2.5 shows a view looking east across the zone through which the principal floodwaters flowed. Clearly evident in this photo are large blocks of peat scoured from the eroding foundation by the floodwaters.

Figure 2.6 shows an approximate plan view of this site, highlighting key locations and objects of interest. The overall breach was 465 feet in width at the end of the flooding and scour, and the intact embankments and floodwalls immediately to the north and south of the breached section were largely undamaged.

Figure 2.7 shows a simplified schematic cross-section through the site, roughly along Section A-A′ in Figure 2.6. This shows the lateral translation of the inboard portion of the embankment, and the compression and heaving produced at the inboard toe by these movements.

Foundation soils at this site were known to consist of a layer of organic, peaty material. The peats were interbedded with occasional thin, soft clayey layers, probably periodic overbank flood deposits, and one such clay layer within the peat unit was exposed at the southern end of the breach opening, as shown in Figures 2.8 and 2.9. A torvane performed in the field during our visit indicated an undrained shear strength of approximately 200 lb/ft^2 for this weak material, which varied in thickness from about 1 to 4 inches over several feet laterally at this location.

Figure 2.10 shows the approximate configuration of the levee, and its sheetpile curtain and concrete floodwall. As shown in Figure 2.10, the sheetpiles do not penetrate very deeply into the poor foundation soils, and they do not provide a full cut-off for underseepage through the pervious foundation soils.

Maximum storm surge water levels within the canal during the Hurricane are not yet known with certainty. There are, however, well-determined water level measurements available from the nearby London Avenue Canal (see Section 2.2), and these match well with current numerical modeling of water levels in this vicinity. These same calculations show peak water levels in the 17th Street Canal to be about 3 to 5 feet below the tops of the floodwalls at this site. In addition, there was no evidence of overtopping-induced scour along unbreached sections of the 17th Street Canal, as shown for example in Figure 2.11, which was taken immediately south of the breach. The bridge crossing the 17th Street Canal at Robert E. Lee bridge, just to the north of the breach site, had not yet had its side walls raised to elevation +14 feet (such raising of these walls had been planned, but not yet implemented), and this bridge thus represented a “low spot” along a canal whose other floodwalls were generally at elevation +13 to + 15 feet. Most of the other bridges along all three canals had already had their side walls raised. There was evidence of minor scour from overtopping at the east end of the bridge, suggesting that minor overtopping occurred at this location, which would have placed water levels at this location at an elevation just a bit above elevation +10 feet. Best available evidence to date thus indicates that the 17th Street Canal levee embankment floodwalls did not overtop during the storm, but instead had a maximum storm surge that caused the canal waters to rise to within about 3 to 5 feet from the tops of the concrete floodwalls.

The mechanism of failure at this site appears to have been a stability failure of the foundation soils beneath the earthen embankment. The embankment was pushed sideways, by about 45 feet, by storm surge induced water pressures acting against the front face of the sheetpile/I-wall vertical barrier. The actual depth at which foundation soil shear failure occurred is not yet known, and this remains to be investigated. Also still to be determined is the actual soil unit or strata that provided the weak sliding plane, and the precise mechanism of weakness that was most critical.

Additional soil borings and sampling are currently being performed at this site, under the supervision of the USACE, and additional CPT probes are planned as well. The USACE is also planning additional laboratory testing of the samples obtained. The USACE has agreed to share all results of these additional field and laboratory studies with the various investigation teams involved.

These investigations will provide a basis for better evaluating the subsurface conditions at this site, and for better evaluation of soil shear strength and underseepage flow characteristics at this site. Additional analyses will, of course, follow once this new data becomes available.

At the time of our field teams' initial visit (October 3, 2005) an embankment fill had been placed over the core of large sandbags and large stone used to effect the initial closure. Additional gravelly fill had been placed at the inboard toe to provide a working mat. The conditions at this time are shown in Figure 2.12. The fill used as a covering veneer was a gap graded sandy gravel known locally to be internally unstable with regard to erosion, and our site team noted four sinkholes at the outboard lip of the crest of the temporary levee section, as shown in Figure 2.13. Three of these could be observed to be curving inward toward the center of the embankment section, and running water could be clearly heard in one of these.

The USACE was notified of the apparently unstable condition, with evidence of ongoing internal erosion of the fill, and the section was covered the next day, initially with a three foot thick layer of open graded stone (6-inch to 24-inch stone), which was then covered at the crest by a five to seven foot (uncompacted) lift of better graded silty sand, as shown in Figure 2.14. Both the open-graded stone, and the covering veneer silty sand fill can be clearly seen in this photo. The silty sand was also pushed down the inboard and outboard faces of the embankment providing a covering veneer of several feet on both sides of the emergency embankment section. The USACE was again notified that this did not appear to represent a hydraulically stable (or well filtered) embankment configuration; and the rapid placement of additional competent fill as an inboard berm, to be quickly followed by installation of a sheetpile cut-off wall, was recommended.

An inboard side toe berm was placed on October 11, 2005. On the morning of October 13, 2005 a longitudinal crack approximately 1/8 inch wide opened along the crest of the embankment. The crack widened slightly the next day, and a second, narrower crack opened along the upper inboard face of the embankment. Additional berming on the inboard side was recommended and immediately implemented, and operations are now underway to install a sheetpile cut-off curtain on the outboard side of the emergency closure section.

2.3 The London Avenue Canal Breaches and Distressed Section

2.3.1 The North Breach and Distressed Sections at Robert E. Lee Blvd.

A major breach occurred on the west bank of the London Avenue Canal, near the north end of the canal, as shown previously in Figure 1.4. In addition, the levee embankment and floodwall section on the east bank, directly across the canal, suffered major distress and is compromised with regard to its ability to safely retain high water levels in future events.

Figure 2.15 shows the breach at the west side of the canal. The scour patterns inboard (to the west) suggest that the embankment may have initially moved laterally to the west, pulling apart at the transitions between the translating central embankment section and the two intact ends to the north and south, and emitting the strongest scouring water forces at the northern end, with a secondary scour stream near the southern end. There is some evidence of possible vertical uplift at the toe, as the playhouse in Figure 2.16 was originally at the level of the ground at the inboard toe and was elevated to its current position as the embankment movements occurred, but this may also have been the result of "heaving" of the soils at the inboard toe as they were "plowed" or compressed by the lateral embankment movements.

Figures 2.15 and 2.17 show how the sheetpile/concrete floodwalls were pushed back by the elevated canal waters on the outboard sides, and by the reduction of earth pressure support on their inboard sides. Figure 2.17 is taken from the south end of the breach, and the gapping between the floodwalls and the soil of the outboard portion of the earthen levee embankment is clearly evident. According to design documents available to date, the sheetpiles were relatively short at this breach site (a design tip elevation of -16 feet), and the floodwalls appear to have toppled backwards away from the canal in a rigid manner ("post-hole toppling failure".)

Significant deposits of sediment occurred inboard of this breach, and these appeared to represent a mix of soils scoured out from the breached embankment section and its foundation soils, as well as sediments from the canal outboard of the failed section (see Figure 2.18.)

Three high water marks, determined to be of high reliability, were found in close proximity to the breach section at this canal by members of our team from COPRI, and these indicate that the maximum water levels at this portion of the canal were at approximately Elev. +11 to +12 feet, or approximately 2 to 3 feet below the tops of the floodwalls at this section. In addition, there was no evidence of overtopping producing erosion at the inboard sides of intact levee floodwalls anywhere along this canal. The sidewalls of the Robert E. Lee bridge had not yet been raised to the elevation of the adjacent I-walls, so the bridge represented a low spot in the system. There was evidence of minor overtopping at one end of the bridge, but this was slight. As the bridge walls were approximately 4 feet lower than the adjacent I-walls, this would further confirm that the maximum water level at this location in the canal was about 3 feet (or so) below the tops of the I-walls. Best available evidence, and current field-calibrated numerical analyses of storm surge levels, thus indicate that the floodwalls along the London Avenue Canal were not overtopped.

Evidence at this site strongly suggests that the breach occurred as a result of the sheetpile/floodwall being pushed backwards by the elevated water pressures on the outboard side, and that support on the inboard side of the sheetpile/floodwall was reduced as a result of soil failure at or beneath the base of the earthen levee embankment. The severe distress of the similar levee and floodwall directly across the canal (on the east bank), and its similar foundation conditions, provide additional evidence here.

Figure 2.19 shows the floodwall of the "distressed" section directly across the canal, on the east bank. This photo shows the outboard side of the floodwall, which has been pushed laterally, opening an extensional crack as wide as approximately 18 to 28 inches at its original outboard side base contact with soil at the levee embankment crest.

Figure 2.20 shows conditions on the inboard side of the east bank distressed section, directly on the other side of the wall shown in Figure 2.19. The wall has been pushed towards the inboard side, and now leans inwards (to the right) by about 5º off vertical in this photo. Figure 2.21 shows a closeup view of part of a line of sinkholes noted at the inboard toe of the wall, along the section shown in Figure 2.20. These appear to have been related to underseepage and resulting erosion and piping. Figure 2.23 shows the "boil" outlet of one erosional "pipe" at the inboard toe of the embankment at this location.

This does not mean that erosion and piping caused the distress at this levee/floodwall section, nor the failure at the breached section across the canal. Instead, the underseepage and erosion appear to be indicative of massive underseepage flows during the period when the water levels in the canal were elevated by the storm surge. The "distressed" embankment section on the east bank translated slightly inboard, as evinced by a partially eroded overthrust feature that occurred at the inboard toe along a short distance just to the south of the swimming pool shown in Figure 2.22, as well as by lateral bulging (and resultant vertical humping) of the ground and the lateral deflection of backyard chain link fences in this same inboard toe area.

The evidence at the "distressed" east bank section, and at the breached west bank section, would both be consistent with similar failure and "distress" mechanisms. Indeed, the east bank section appears to have been in an incipient failure condition, and failure at the east bank may have been prevented by the drawdown of water levels produced by the failure at the west bank, and also by the failure at the second breached section along the canal further to the south.

The foundation soils at these two sites (the east and west banks) consist of a relatively thick deposit of sands, overlain by a relatively thin top layer of marsh and peat deposits. These marsh and peat deposits vary in thickness between 10 to 15 feet. Based on the available data, the poorly graded Holocene beach sands extend to an elevation of approximately -40 to -50 feet. These sands were underlain by less pervious soils.

Evidence at both sites suggests that massive underseepage passed beneath the relatively short sheetpiles, and this may have weakened the foundation soils beneath the inboard sides of the earthen levee embankments. At the same time, elevated water levels in the canal pushed strongly against the outboard sides of the sheetpile/floodwalls. Soil failure appears to have occurred at or below the base of the inboard half of the earthen levee embankment on the west bank, and evidence suggests that an incipient failure of similar nature nearly occurred on the other side of the canal. It is also possible that straightforward erosion and piping led to one or both of these situations.

Significant further investigation is needed to better define the actual failure and "distress" mechanisms here. The actual depth at which foundation soil shear failure occurred is not yet known, and this remains to be investigated. Also still to be determined are the actual soil units or strata that provided the weak sliding planes, and the precise mechanism of weakness that was most critical.

Additional soil borings and sampling are currently being performed at this site, under the supervision of the USACE, and additional CPT probes are planned as well. The USACE is also planning additional laboratory testing of the samples obtained. Most importantly, the USACE has agreed to share all results of these additional field and laboratory studies with the various investigation teams involved.

These investigations will provide a basis for better evaluating the subsurface conditions at this site, and for better evaluation of soil shear strength and underseepage flow characteristics at this site. Additional analyses will, of course, follow once this new data becomes available.

Figure 2.23 shows placement of fill during construction of the emergency repair embankment section at the east-side breach section of the London Avenue Canal (North) site. The progressive evolution of the embankment section at this site closely paralleled that described previously in Section 2.2 at the 17th Street Canal breach site, except that no sinkholes were noted in the temporary embankment section at the time of our teams' site visits. The core of the embankment is, again, large sandbags and stones used to effect the initial emergency closure. Clearly visible in Figure 2.23 are the gap graded sandy gravel fill that covered this irregular core, and the layer of open graded stone that was placed atop the interim crest of the sandy gravel fill. At time of the photo in Figure 2.23, better-graded silty sand fill was being end-pushed without compaction to form the final crest and also to provide a covering veneer on both the inboard and outboard faces of the embankment section. Our field investigation teams formally advised the USACE that this did not represent an internally stable embankment section with regard to internal erosion, and a clayey cap was placed over the silty sand fill and additional inboard side berm fills were rapidly added. In addition, plans are now underway to install a sheetpile cutoff that will extend to a much greater depth (the new sheetpiles design tip elevations are Elevation – 65 feet) than the original sheetpiles of the breached section. The new sheetpiles will have significant lateral overlap with the remaining intact sheetpile curtains at the north and south ends of the repair section.

2.3.2 The South Breach at Mirabeau Avenue

A second major breach occurred further to the south, on the east bank of the London Avenue Canal at Mirabeau Avenue, as shown in Figure 1.4. Figure 2.24 shows an oblique aerial view of this breach site as it appeared during the construction of the temporary repair berm.

Figure 2.25 shows a view looking to the northeast across at the water side of the breached section, after initial closure and interim repair. The sheetpile/I-walls had again toppled inwards towards the land side. Scour was very extensive at this breach, and the scour hole that had to be filled to effect the emergency closure was very large. Much of the breached embankment was eroded away by the scour, and much of what remained was buried by the large closure section required. Significant deposits of soils from the embankment, the foundation, and the canal sediments from just outboard of the breach were deposited in the neighborhood on the land side, as shown in Figure 2.26.

At the time of our field investigations, relatively little remained to be observed at this site, due to the massive scouring erosion produced by the breach, and the massive quantities of fill required in the initial emergency repairs. Accordingly, it is not yet possible to state with certainty the cause of this breach.

Foundation soil conditions at this site were relatively similar to those at the breach site to the north that was described previously in Section 2.3.1. Cross sections of soil conditions along this section show approximately 5 to 10 feet of artificial fill (embankment material). This artificial fill is underlain by 10 to 13 feet of fat clay marsh deposit. These marsh deposits are underlain by a Holocene poorly graded sand beach deposit. As with the breach section farther to the north, the sheetpiles supporting the floodwall did not extend to great depth, and design drawings available to date indicate that the piles had tip elevations at -26 feet. This would not have provided a full cutoff for underseepage through the pervious sands. Photographic evidence immediately after the failure suggests that lateral movements of the levee embankment may have occurred at this site as well, but significant further studies will be required to develop a firm theory as to the cause of failure at this site.

Additional soil borings and sampling are currently being performed at this site, under the supervision of the USACE, and additional CPT probes are planned as well. The USACE is also planning additional laboratory testing on the samples obtained. Our investigation teams have made a number of recommendations and requests regarding some of the details of these ongoing field and laboratory investigations, including investigations of site conditions immediately to the north and south of the heavily scoured breach section, and also across the canal on the west bank side. Most importantly, the USACE has agreed to share all results of these additional field and laboratory studies with the various investigation teams involved.

These investigations will provide a basis for better evaluating the subsurface conditions at this site, and for better evaluation of soil shear strength and underseepage flow characteristics at this site. Additional analyses will, of course, follow once this new data becomes available.

The construction of the emergency closure embankment and the subsequent temporary closure embankment sections at this site largely paralleled those described previously in Sections 2.2 and 2.3.1 for the 17^{th} Street Canal and London Avenue Canal (North) breach sites. Inboard berms are currently in place, and plans are underway for more permanent closure construction, including a sheetpile cutoff that will, again, extend to significantly greater depth than the original (breached) design section. Considerable water flow is still occurring at the inboard toe of this temporary closure section, but some significant portion of that flow has recently been traced to a broken and flowing water line.

2.4 Performance of the Flood Protection System Along the West Bank of the IHNC

In addition to the three major breaches along the 17th Street and London Avenue Canals, the eastern portion of the Orleans East Bank polder was also subjected to floodwaters as a result of a number of smaller failures along the frontage of the INHC, as shown in Figure 1.4.

The IHNC frontage includes the main Port of New Orleans. Two sets of levees and floodwalls occurred along much of the Port frontage on the west bank of the IHNC, and both were overtopped by storm surges at a number of locations. Multiple failures (breaches) occurred along this frontage, and these will be briefly described in this Section. Best available evidence suggests that storm surges overtopped numerous stretches of levees along this Canal frontage.

Figure 1.4 shows the locations of breaches and major "distressed" sections (or partial breaches) along this west bank of the IHNC. Several different types of distress and/or failure were observed along this section of the flood protection system.

Figure 2.27 shows a breached section of concrete floodwall immediately inboard of the main Port, at Location "A" in Figure 2.1(a). Figure 2.28 shows deep erosion at the inboard toe of the floodwall section immediately (adjacent) to the north of the section shown in Figure 2.27. Our site investigation teams arrived at this site just in time to observe the infilling and then burial of deeply eroded trenches at the inboard toes of the floodwalls adjacent (to the north and south) of this breached floodwall sections. It was apparent that overtopping flows had deeply, and variably, eroded the soils at the inboard sides of the sheetpile/concrete "I-walls", reducing their inboard lateral support and thus also their ability to safely withstand outboard side water pressures associated with the elevated (overtopping) water levels.

The fill being placed to infill the eroded inboard floodwall toes, and then the overlying fill being placed to buttress the inboard sides of the non-breached floodwalls, at the adjacent floodwall sections immediately to the north and south of the breached section were being placed without engineering supervision, and without suitable compaction. Our investigation teams notified the USACE that these fills appeared to be not competent for their apparent intended purpose, and that they should be removed and replaced with a properly engineered fill.

Figure 2.29 shows the results of overtopping erosion at a "transition" from an earthen embankment levee to a concrete "T-wall" just to the south, at Location "B" in Figure 2.1(a). At this location, preferential erosion at the concrete/earthen embankment transition led to a full breach. This represents an example of a common problem noted at numerous locations throughout the regional flood protection system; failure at a "transition" between a structural (concrete) section and an earthen (levee) section. The concrete wall section at this location carried a steel floodgate to permit through passage of traffic from the Port, but which could be closed during periods of high water in the IHNC, as shown in Figure 2.30. The embedment (or overlap) at the transition section (from concrete wall to earthen levee) at the end of the concrete wall was insufficient, and this was exacerbated by the fact that the concrete wall and adjacent earthen levee section had different crest heights. It was common practice in the New Orleans area to build in "structural superiority" wherein structural walls (e.g.: the concrete T-wall and gate structure) had higher crowns than the crests of adjacent earthen levees. This caused overtopping to occur at the earthen levee sections, and produced especially severe overtopping erosion at the "transitions" between the concrete gate wall and earthen levees at each end.

The embankment material at this site was a sandy "shell" fill; a mix of sand and shells widely available in this region. This material, shown in close-up in Figure 2.31, appears to be highly erodeable, and was noted at a number of failed (breached) sections throughout the New Orleans flood protection system.

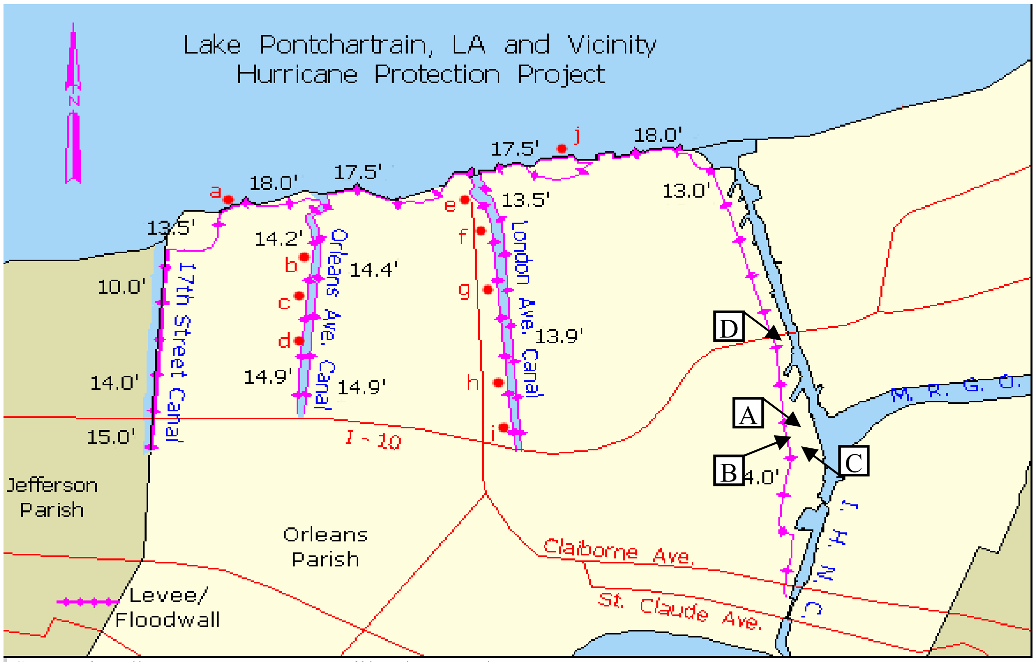
Figure 2.32 shows an additional example of this type of "transition" deficiency between a structural (concrete) wall and adjacent earthen levees, just a bit farther to the east at Location "C" in Figure 2.1(a).

Figure 2.33 shows a view looking to the southwest from the breach at Location "C" in Figure 2.32. Another breach, just 20 yards to the east of the breach section shown on Figure 2.29 also overtopped and eroded and breached. Figure 2.33 shows the inboard side results; massive flooding damage and considerable sediment deposits, including "shells" from the embankment fill.

There was an outboard protective wall and levee in the Port area, and this too was apparently overtopped and breached before the waters then overtopped the inboard levees and walls as discussed above. Our field investigation teams did not have the time to fully investigate all sections of the outboard walls and levees along this section, but there were some important observations and findings in the sections that were examined.

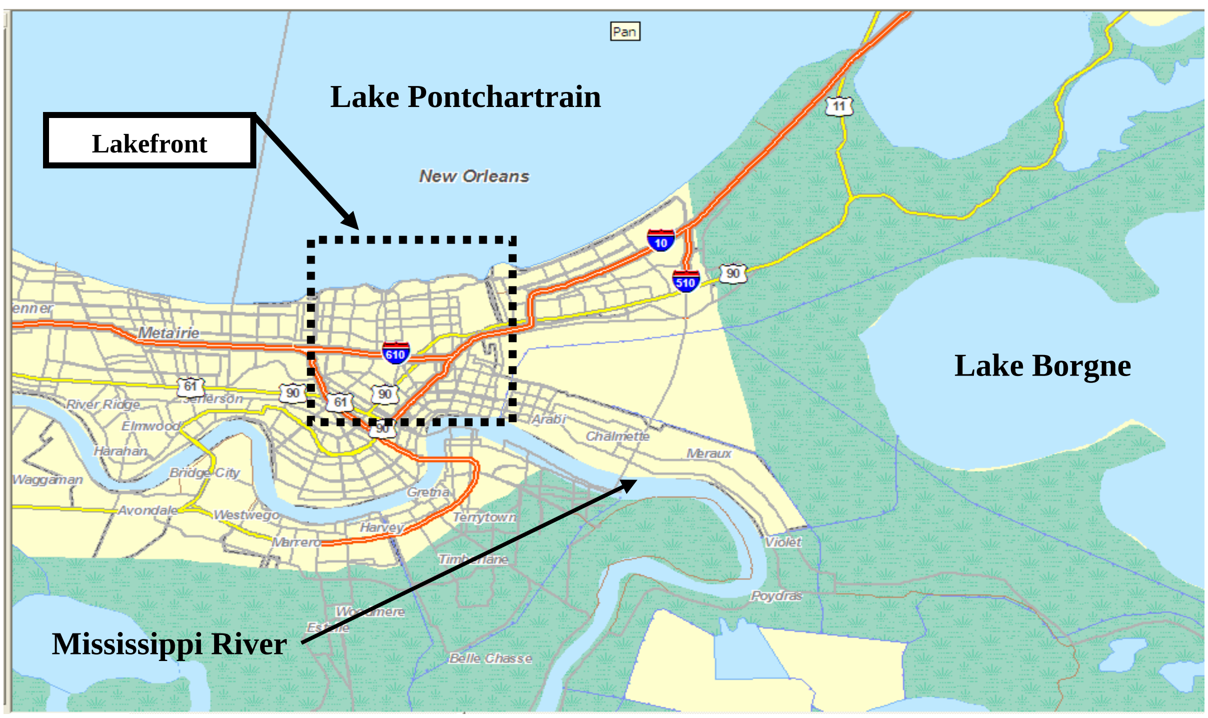
Figure 2.34 shows a complex "transition" at the northern end of the Port region along the west bank of the IHNC, immediately to the south of the Highway I-10 bridge, at Location "D" in Figure 2.1(a). At this location, outboard side levees and floodwalls associated with the Port and industrial operations conjoin with inboard side levees and floodwalls constructed by the USACE. In addition, a roadway embankment crosses through the levees, and a second gap in the "line of protection" for a railway line (crossing the adjacent IHNC) crosses through at this location. This represents a very complex "transition" section, with overlapping users and overlapping authorities and responsible entities. The gate of the railway's floodgate wall had been knocked off by a train derailment several months prior to Hurricane Katrina, and the railway was to have closed the resultant opening with a sandbag levee section within the gated opening. Our understanding is that this sandbag closure was inspected by the Orleans Levee Board. This emergency closure appears to have been unsuccessful, as floodwaters appear to have passed through this opening, and then to have eroded and breached the earthen roadway embankment adjacent and behind this section. Our field investigation teams were unable to track the direct consequences of this, as additional breaches along this same frontage section, as well as the major breach at the east bank of the nearby London Avenue Canal, all apparently contributed to flooding of the neighborhoods immediately inboard of this site.

Overall, multiple breaches and sections of significant distress were noted along the west bank of the IHNC, both along the levees and floodwalls outboard of the Port and industrial facilities, and also along the main USACE-designed levees and floodwalls on the inboard side of these Port and industrial facilities. All of these appeared to be the result of overtopping, and resultant erosion. Some were simply erosional failures of earthen embankments, or of preferential erosion at "transitions" between earthen embankment sections and adjacent structural wall sections. The significant breach at Location "A" appears to have been due to overtopping of the concrete floodwall (the sheetpile/I-wall section), and resultant erosion of soils at the inboard toe of the floodwall which reduced the ability of the sheetpile/floodwall to withstand the lateral water pressures exerted by the elevated water levels on the outboard side.



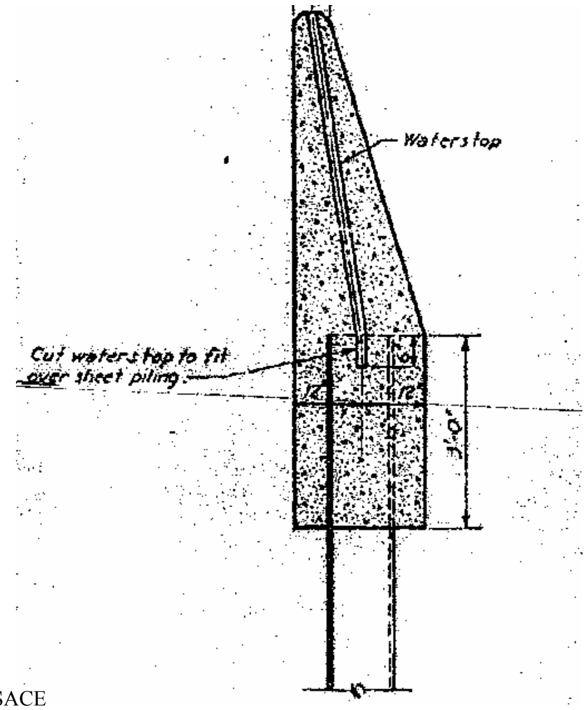
Source: http://www.mvn.usace.army.mil/pao/response/amaps.asp updated July 2003

Figure 2.1(a): Orleans Parish and eastern Jefferson Parish, in the Canal district.



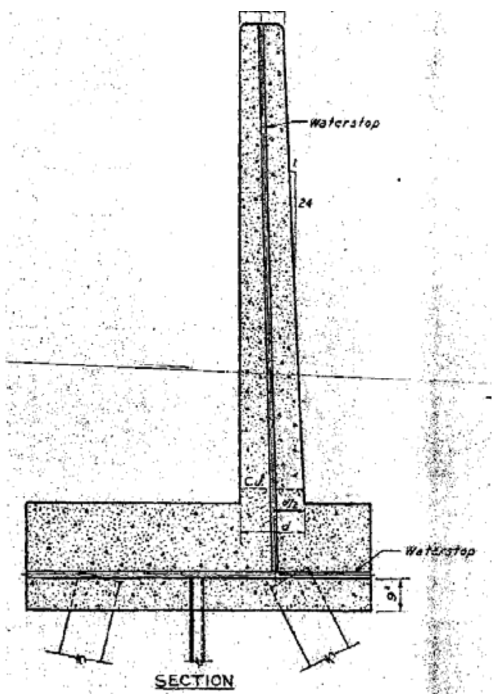
Source: ESRI North American Thematic Basemap, ArcGIS 9.0

Figure 2.1(b): Map showing location of the Downtown protected section, and location of enlarged section shown above in Figure 2.1(a).



Source: USACE

Figure 2.2(a): Typical I-wall section in the New Orleans region.

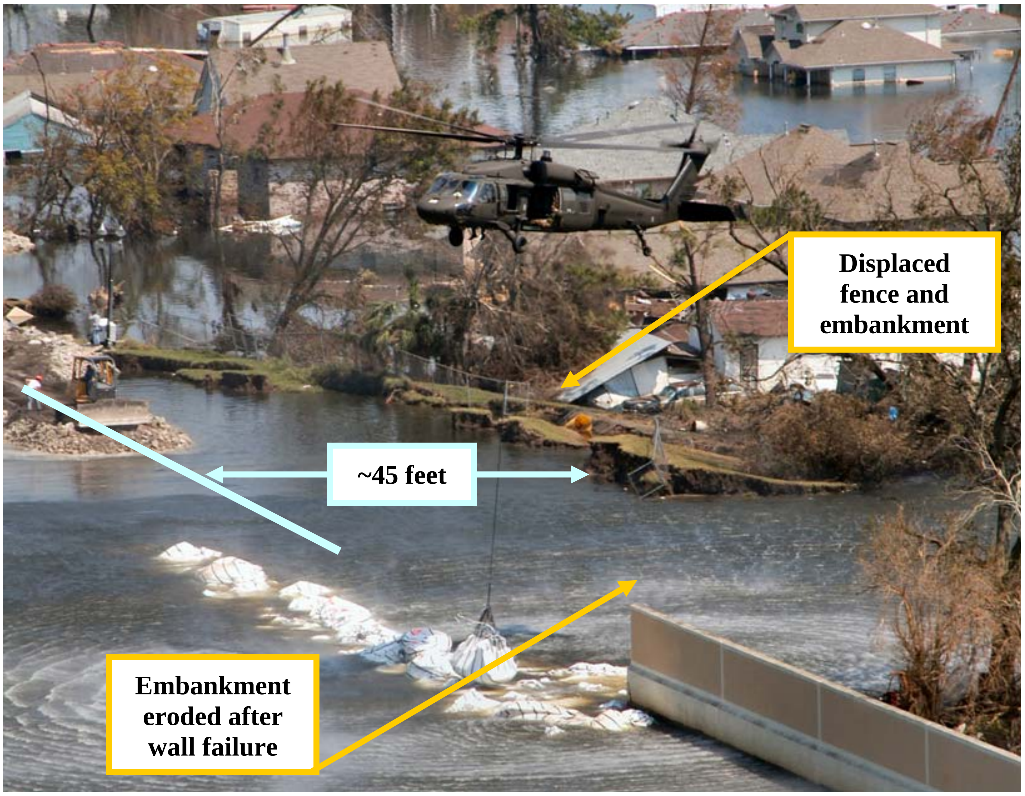


Source: USACE

Figure 2.2(b): Typical T-wall section in the New Orleans region.

Source: http://www.usace.army.mil/katrina-images/NO-A-09-04-05_0072.jpg

Figure 2.3(a): The 17th Street Canal breach during initial breach closure.



Source: http://www.usace.army.mil/katrina-images/NO-A-09-04-05_0072.jpg

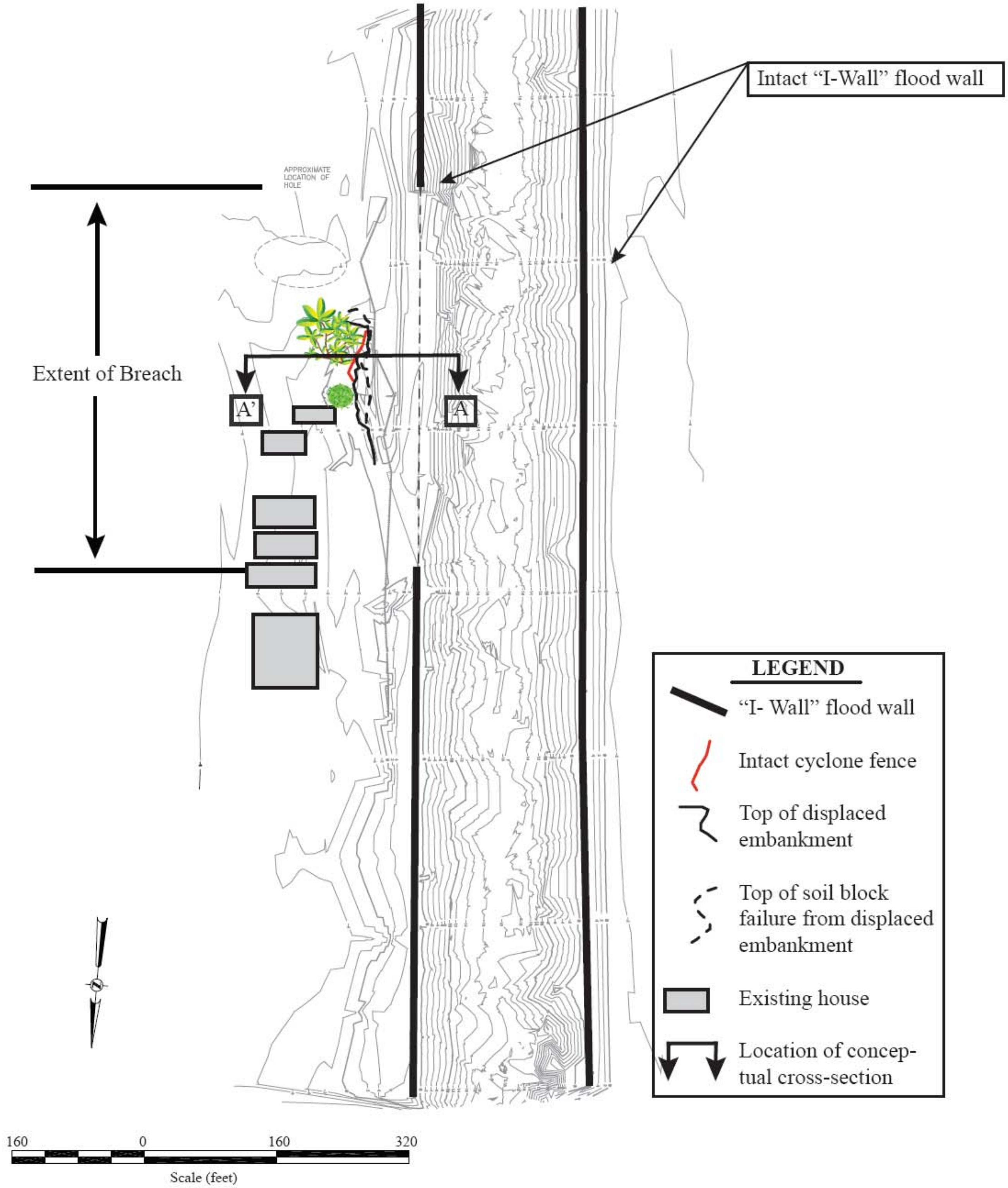
Figure 2.3(b): The 17th Street breach, highlighting key points for discussion

Photograph by Jonathan Bray

Figure 2.4: View of the 17th Street breach section from the south.

Photograph by Jonathan Bray

Figure 2.5: View from crest of emergency embankment closure section at the 17th Street Canal breach, looking south across the floodwater scoured zone.



Source: Plans prepared by Linfield, Hunter & Junius Inc., titled "Lake Pontchartrain and vicinity, 17th Street Canal Floodwall Breach, New Orleans, Louisiana, SURVEY," dated October 6, 2005.

Figure 2.6: Schematic plan view of the 17th Street Canal breach site. Results of LIDAR scan superimposed on base survey.

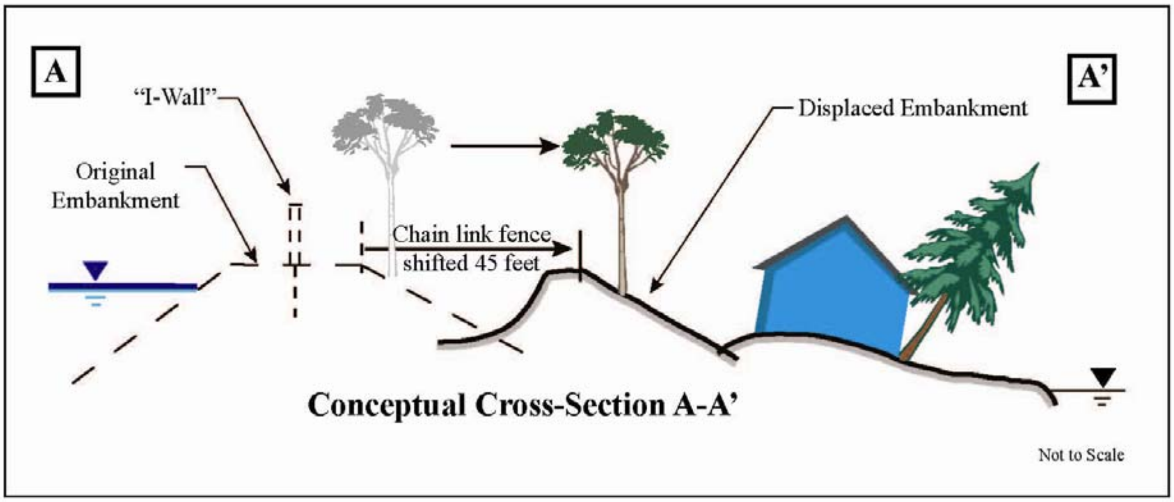


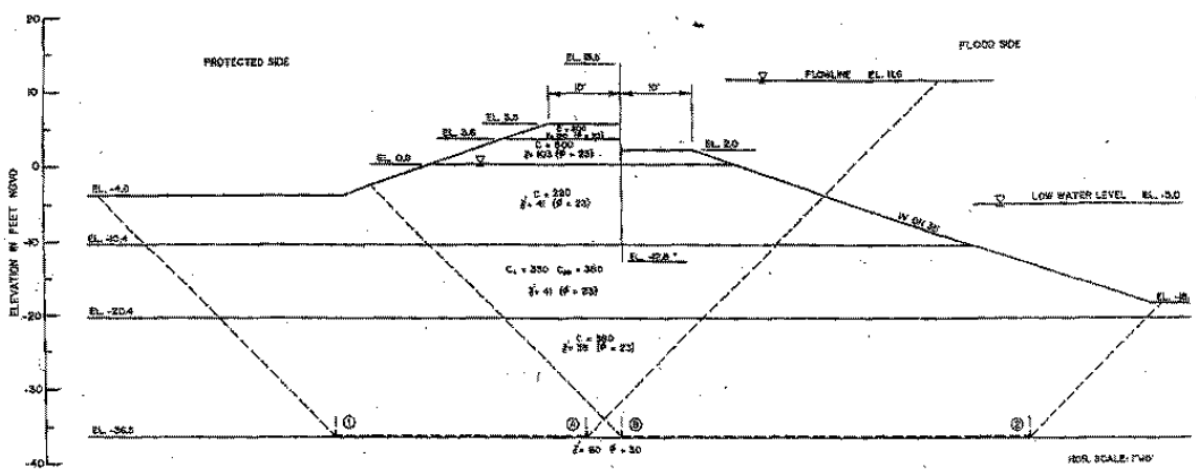
Figure 2.7: Schematic cross section at the 17th Street breach section.

Photograph by Jonathan Bray

Figure 2.8: Location at which clay seam interbedded within the peat at the toe of the translated levee embankment was sampled.

Photograph by Jonathan Bray

Figure 2.9: Clay seam (light gray layer) underlain by darker lean clay, and overlain by fibrous peat.



Source: Eustis Engineering, "Geotechnical Analyses, Metairie Relief Canal (17th Street Canal), OLB Project No. 2043-0222, New Orleans, Louisiana, 31 August, 1988.

Figure 2.10: Design cross-section at the 17th Street breach.

Photograph by Jonathan Bray

Figure 2.11: Typical conditions at the inboard side of floodwalls along the 17th Street Canal showing no scour of soil at the toe of the wall.

Photograph by Rune Storesund

Figure 2.12: Temporary closure section embankment on October 3rd, 2005.

Photograph by Jonathan Bray

Figure 2.13: One of four sinkholes noted at the front lip of the crest of the temporary closure section embankment.

Photograph by Jonathan Bray

Figure 2.14: Placement of silty sand fill at the crest and on both the inboard and outboard faces of the temporary embankment closure section on October 6, 2005.

Figure 2.15: The breach section at the west side of the London Avenue Canal (North).

Photograph by Jonathan Bray

Figure 2.16: Conditions at the inboard toe of the London Avenue Canal (North) breach section.

Photograph by Jonathan Bray

Figure 2.17: The toppled floodwall/sheetpile walls at the London Avenue Canal (North) breach site.

Photograph by Jonathan Bray

Figure 2.18: Sediment from the London Avenue Canal was deposited inboard of the levee break. High water marks (from long-term ponding) are visible on the exteriors of the residential homes.

Photograph by Jonathan Bray

Figure 2.19: Gap at the base of the floodwall on the canal side of the East Bank "distressed" section.

Photograph by Jonathan Bray

Figure 2.20: View of the inboard side of the floodwall and earthen levee embankment.

Photograph by Jonathan Bray

Figure 2.21: Closeup view of sinkholes at the inboard toe of the floodwall, at the location of the engineer wearing a red shirt in Figure 2.20.

Photograph by Jonathan Bray

Figure 2.22: View of conditions at the inboard toe, immediately inboard of the locations shown previously in Figures 2.21 and 2.22. Note the bulged and hummocky ground, the laterally displaced chain link fence, and the piping boil ejecta.

Photograph by Jonathan Bray

Figure 2.23: Photo during construction of the emergency breach repair embankment at the London Avenue Canal (North) breach site.

Photograph by Les Harder

Figure 2.24: Aerial view of the breach section at London Avenue Canal (South).

Photograph by Francisco Silva

Figure 2.25: View of the crest of the temporary embankment closure section at the London Avenue Canal (South) breach.

Photograph by Rune Storesund

Figure 2.26: Significant quantities of sediment were deposited in the residential neighborhoods on the east side of the London Avenue Canal. More than five feet of sediment was deposited around this home.

Photograph by Rune Storesund

Figure 2.27: Breached levee floodwall section at Location "A" along the west side of the INHC.

Photograph by Rune Storesund

Figure 2.28: Erosion at the inboard toe of concrete floodwalls at Location "A" along the west side of the INHC, adjacent to the breached section shown previously in Figure 2.27.

Photograph by Jonathan Bray

Figure 2.29: Erosion at a “transition” between a concrete floodgate wall and the adjacent earthen embankment section.

Photograph by Jonathan Bray

Figure 2.30: View of the structural wall and floodgate structure from Figure 2.29.

Photograph by Rune Storesund

Figure 2.31: Close-up view of sandy "shell" fill at the scoured edge of the breach shown previously in Figure 2.29.

Figure 2.32: Common structural wall (with flood gate) and earthen levee transition problem with erosion at the contact between the earth and concrete sections.

Photograph by Rune Storesund

Figure 2.33: Scour hole and deposits of sediment and shells, inboard of the breach shown previously in Figure 2.32.

Photograph by Rune Storesund

Figure 2.34: A complex “transition” involving several overlapping operations and penetrations through the flood protection levees immediately south of the I-10 bridge across the IHNC.

Photograph by Joe Wartman

Figure 2.35: Rail line crossing through floodgate structure at the west side of the INHC at the complex transition shown in Figure 2.34.

Chapter Three: New Orleans East Protected Area

3.1 Overview

The region known as New Orleans East is bordered by distinctively different hydraulic boundaries: Lake Pontchartrain borders it to the north and east; the Inner Harbor Navigational Canal (IHNC), locally also known as the Industrial Canal, borders it to the west; to the south and southeast is the Intracoastal Waterway (IWW)/Mississippi River Gulf Outlet (MRGO) and Lake Borgne, respectively. The principal flood control for the New Orleans East polder is illustrated with flood elevation protection levels in Figure 3.1

This area was exposed to conditions that exceeded those for which the levee system was designed. Overtopping of the flood control levees and floodwalls was observed to have occurred on most sides of the New Orleans East polder. Overtopping evidence included significant landside scour and debris on the tops of walls and levees. On the north side fronting Lake Pontchartrain, the available field data and numerical calculations of storm surge, at the time of this writing, suggest that the lakefront storm surge in this area stayed below the crests of the lakefront levees except in the area near the Lakefront Airport. No significant sustained overtopping, only "splash over" due to waves generated in the lake, occurred at certain locations along the lakefront. Breaches of the levee system occurred at various other locations with the notable exception of the eastern earthen levee. This levee is fronted by large extents of wetlands between the levee and the actual shoreline, in this case, the easternmost end of Lake Pontchartrain to the northeast. Storm surge water levels along the IWW/MRGO channel were relatively high and significantly exceeded design conditions. This storm surge then propagated westward into the IWW/MRGO channel. Researchers at the LSU hurricane center have postulated that the IWW/MRGO channel area acts as a funnel that causes storm surges as it propagates to the west.

Most of the flood protection fronted by Lake Pontchartrain performed well despite some wave overtopping with a few notable exceptions. Many of the breaches of the levee system in this region could be attributed to one or more "transition" problems characterized by different wall types, material types or adjacent levee crest elevations, or combinations of the above. Transitional issues also occurred where levees crossed from one jurisdiction to another. Each of these transitional issues will be discussed in more detail later. Other sections of the flood control system, particularly along the IWW/MRGO, where storm surge heights were greatest, were overwhelmed by severe overtopping that caused scour on the landsides of floodwalls and earthen levees. These sections will also be discussed.

3.2 Lakefront Airport

The Lakefront Airport is located at the northwest corner of the New Orleans East polder on Lake Pontchartrain near the entrance to the IHNC. Evidence of surge/wave overtopping was observed here along with a breach at a complex transition that combined levee sections of varying floodwall/levee heights and materials. Figure 3.2 shows a panorama of this distressed transitional area. The problems observed here were: 1) a concrete floodwall higher than adjacent roadway over an earthen material adjacent to; 2) railroad tracks laid over highly pervious ballast, with tracks at approximately the same elevation as the top of the floodwall, adjacent to; 3) an earthen embankment levee. The breach that occurred at this location was, in fact, two breaches. One was a scour of the roadway section next to the higher concrete wall, while the other occurred through the embankment levee immediately south of the railroad embankment. It is difficult to assess the role the pervious ballast beneath the tracks played, if any, to the problems observed at this site.

I-wall sections on the lakefront side appeared to have been overtopped, or to have at least experienced significant splash over, as evidenced by scour on the protected side of the walls and debris both on and behind the walls. Inspection of these wall sections showed little to no distress despite the significant scouring at places (Figure 3.3). This was in contrast to many other I-wall sections that had either been severely distressed or failed. It appeared that the construction of the I-wall sections in this area were significantly more robust than those other sections with damage. The walls appeared to be newer than most of the other I-wall observed in New Orleans East, with uniformly thicker and taller concrete sections. The section of floodwall that paralleled the shoreline was exposed to waves generated in Lake Pontchartrain. The scour trenches behind the walls parallel to the shorefront were relatively wide and deep. Interestingly, the scour behind wall sections perpendicular to the shorefront were smaller, an apparent result of the absence of waves reaching those sections.

3.3 Lakefront East from the Airport

Proceeding along the shoreline of Lake Pontchartrain in a northeastward direction beyond the Lakefront Airport we observed earthen levees with and without concrete floodwalls that largely withstood the storm surge and waves. Figure 3.4 shows the beginning stages of scouring along the landside toe of a concrete floodwall most likely due to wave overtopping. Figure 3.5 illustrates both the value of armoring the floodwall toe against scour and the difficulties encountered at the transition points between the armored and non-armored sections. Figure 3.6 shows an apparent low point along the lakefront levee with evidence of erosion from wave overtopping.

Further to the east, beyond Paris Road, the lakefront community of Little Woods located lakeside of the levee was almost completely demolished by the wind and storm waters (Figure 3.7). Figure 3.8 shows debris from the demolished structures left very near the levee crest, indicating a high water level consistent with other water lines we observed in the lakefront area. Debris from the houses was also strewn on the landside of the levee in a pattern that suggested wind transport. Figure 3.9 shows the only surviving structure at Little Woods, which was noticeably elevated on piles. It appears intact except for the absence of stairs to reach the elevated balcony, suggesting that the building industry can construct structures that resist storm forces like the ones experienced during Hurricane Katrina at Little Woods.

3.4 I-wall Failures - Intracoastal Waterway and MRGO

Some sections of the I-walls along the southern boundary of New Orleans East, on the IWW/MRGO, were observed to have failed while others remained standing either in good working order or in various states of distress. Virtually all of the I-walls had been overtopped, and the soil behind them significantly scoured (Figure 3.10). The various states of distress (and failures) appeared to be for the most part related to the loss of passive resistance resulting from the scour (Figure 3.11). Those that were in distress but not failed also showed gapping between the wall and the soil foundation on the waterside (Figure 3.12). This waterside gap would also assist in destabilizing the walls by reducing support of the sheet piles beneath the concrete wall sections. Where there were T-walls we observed no significant distress to the walls. In general, the T-wall sections appeared to be used only adjacent to gate structures and pumping facilities. Figure 3.10 also shows an example of a T-wall adjacent to an I-wall on the IWW/MRGO. The T-wall showed no apparent distress.

There was a failure of embedded sheetpile without concrete caps along the IWW. This case occurred where the top of the sheetpile wall was at a lower elevation than an adjacent concrete wall, thereby drawing the floodwaters over the more vulnerable sheetpile section first (Figure 3.13). Figure 3.14 is an aerial view of the same site portrayed in Figure 3.13 showing the magnitude of scour at the breach.

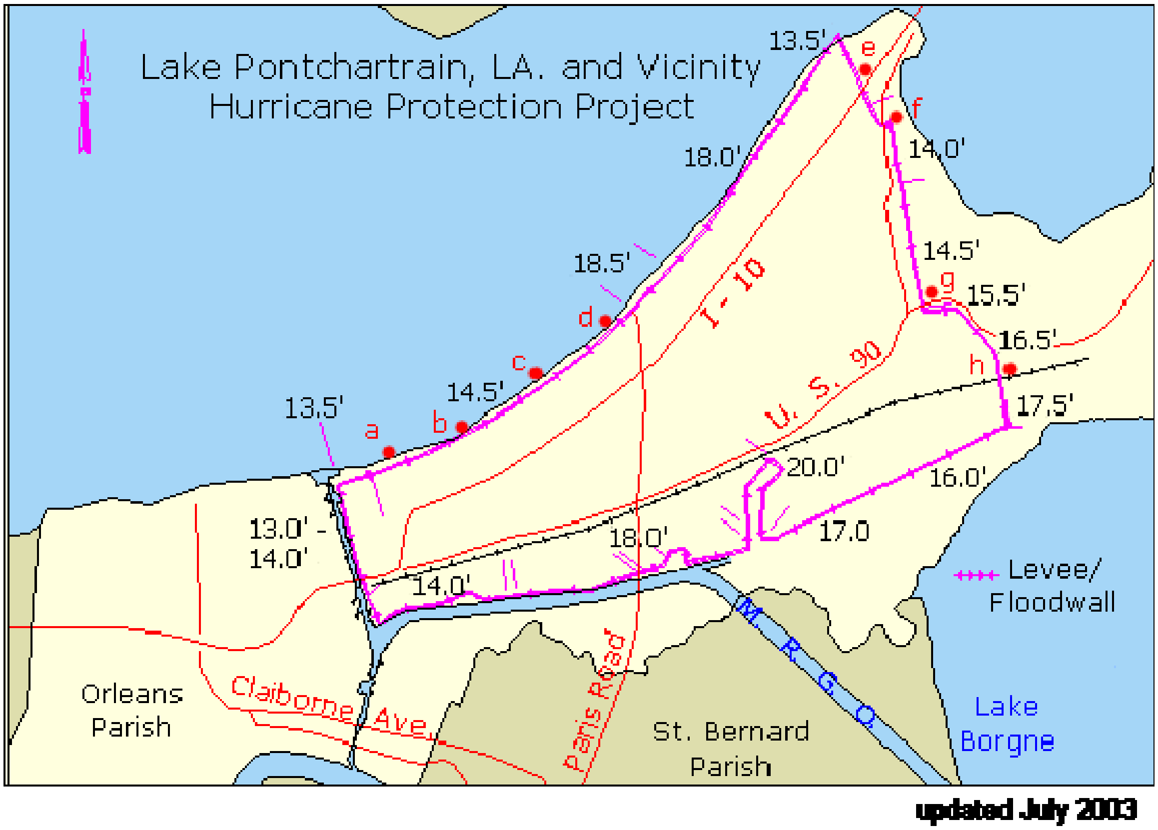
3.5 Earth Embankments – East and South

Many of the earthen embankment levees providing flood protection for New Orleans East performed well. While many of the embankments on the east and south sides of the protected area were overtopped, most of these survived well. At least one embankment section was reported by the USACE to have breached on the southeastern border along the IWW while others only showed signs of erosion and scour (Figures 3.15). Still others came through virtually unscathed (Figure 3.16). The performance of these earthen embankment sections with little to minor damage may be in part due to their construction and the materials of which they were made. This is in stark contrast to some of the numerous breaches of overtopped embankment sections that we observed in other locations, such as along the south eastern side of the MRGO, where easily eroded materials along with higher levels of storm surge and waves, likely led to their poor performance. A significant attribute noted for the performance of both the earthen embankments and I-wall sections was the relationship between orientation of the flood barriers and the assumed direction of the storm surge and associated waves.

The earth levee along the north bank of the Intracoastal Waterway under the Route 47 Bridge stands as an example of satisfactory performance despite hydraulic conditions that far exceeded the design criteria. Figure 3.17 shows the erosion damage on the landside slope of the levee due to the overtopping. Figure 3.18, taken from the Entergy Michoud Generating Plant, shows the area in Figure 3.17 under storm conditions. Given the ferocity of the storm as evidenced in Figure 3.18, the relatively modest damage to the earth levee represents satisfactory performance.

3.6 Additional Transition Problems - IHNC

Aside from the failure of some significant sections of I-walls and sheet pile walls, many portions of the flood control system surrounding New Orleans East performed well under greater than design conditions. The common failures occurred where transitions between differing materials or varying flood protection heights (or both) occurred. A detailed explanation was provided in Section 3.2 of a breach at a complex transition near the Lakeview Airport. This problem was especially prevalent on the western boundary of New Orleans East along the IHNC. A significant number of levee washouts were observed where the weaker of two adjacent materials was at a lower elevation. In this situation, the floodwaters would initially be concentrated or channelized to flow over the weaker material. Water flow and stress concentrations at transitions were likely causes of a number of failures where sheetpile walls transitioned to concrete walls (Figure 3.19). Another common transition problem was observed where differing wall heights, especially between dissimilar materials, were found adjacent to each other. Along the western border of the protected area, the earthen levee was regularly interrupted by a concrete structure supporting a flood control gate for vehicle and rail access to the shipping facilities. At nearly every one of these transitions, the earth had been scoured at each transition around the concrete. Many of these scours had already been filled when the team made its observations so that the extent of the scour holes could not be assessed.



Source: http://www.mvn.usace.army.mil/pao/response/amaps.asp

Figure 3.1 New Orleans East Protected Area

Photo by Lee Wooten

Figure 3.2: Complex transition near Lakefront Airport consisting of various flood protection heights, differing materials and junctures between various jurisdictional organizations. These types of complex transitions were found to be associated with several of the levee flood protection problems.

Photo by Peter Nicholson

Figure 3.3: I-wall adjacent to the Lakefront Airport showing deep back-scour but no evidence of distress to the wall.

Photo by Francisco Silva

Figure 3.4: Beginning of overtopping scour along lakefront flood wall suggests moderate overtopping at this location.

Photo by Francisco Silva

Figure 3.5: Concentrated scour due to presence of concrete apron. Area in the background is a good example of the benefits of armoring the base of the flood walls.

Photo by Francisco Silva

Figure 3.6: Wave overtopping of lakefront earthen levee at low spot in structure did not cause serious damage (N 30° 03’ 47.8”, W 89° 58’ 13.1)

Photo by Francisco Silva

Figure 3.7: The lakefront community of Little Woods destroyed by wind and water (N 30° 04' 70.5", W 89° 56' 44.0")

Photo by Francisco Silva

Figure 3.8: Debris from the Little Woods houses accumulated near the crest of the earth levee indicates the level of the lake waters during the storm. (N 30° 04' 70.5", W 89°, 56' 44.0")

Photo by Francisco Silva

Figure 3.9: The lone surviving structure at Little Woods appears unscathed, except for the lack of stairs.

Photo by Jonathan Bray

Figure 3.10: Undamaged T-wall in foreground and damaged I-wall in background along the IWW/MRGO. Severe scour on the landside and distress of the I-wall (N30.00030 W89.99459).

Photo by Lee Wooten

Figure 3.11: Severely distressed I-wall after overtopping from the water side along the IWW/MRGO.

Photo by Lee Wooten

Figure 3.12: "Gapping" between soil and wall as distressed wall was displaced landward from the IWW/MRGO.

Photo by Peter Nicholson

Figure 3.13 Failure of sheetpile wall adjacent to higher and stronger concrete topped I –wall on the north side of the IWW.

Photo by Les Harder

Figure 3.14: Aerial view of the failed wall section shown in Figure 3.14

Photo by Jonathan Bray

Figure 3.15: Embankment along the IWW/MRGO that survived although somewhat scoured.

Photograph by Jonathan Bray

Figure 3.16: Virtually unscathed earth embankment levee on the eastern edge of the protected area of New Orleans East

Photograph by Francisco Silva

Figure 3.17: Earth levee beneath the north abutment of the Route 47 Bridge over the IWW/MRGO, next to the Entergy Michoud Generating Plant, looking south. Despite considerable damage, the levee performed satisfactorily during and after overtopping.

Photograph courtesy of Entergy Corporation

Figure 3.18: Same view of the overtopped earth embankment as seen in Figure 3.18 taken during the storm surge.

Photo by Lee Wooten

Figure 3.19: Transition between concrete and sheetpile walls at uneven wall height elevations

Chapter Four: Lower Ninth Ward and Adjacent St. Bernard Parish Protected Area

4.1 Overview

The Lower Ninth Ward of New Orleans and the neighboring portion of St. Bernard Parish were some of the hardest hit communities in the New Orleans metropolitan region. These communities had a combined pre-Katrina population of approximately 87,000 people and jointly include a residential area that extends over approximately 27 square miles. The structures in the region consist largely of wood frame or masonry residential units interspersed with larger commercial buildings along major roadways. The Lower Ninth Ward is a historic neighborhood where many of the homes date to the early twentieth century. St. Bernard Parish is a newer, more suburban community that grew significantly in the 1950's and 1960's. Hurricane-related flooding is not unknown in these communities; for example, in 1965, Hurricane Betsy left parts of the Lower Ninth Ward and the nearby town of Chalmette, St. Bernard Parish under as much as 8 feet of water. Parts of the Lower Ninth Ward were also flooded during Hurricane Flossie in 1956.

The Lower Ninth Ward of New Orleans and neighboring St. Bernard Parish together form an 81 square mile polder located across the Inner Harbor Navigational Canal (IHNC) and locally referred to as the Industrial Canal from central New Orleans (see Figure 1.4). Elevations within the polder range from approximately -4 feet to 12 feet, with the higher elevation reaches situated near its southern edge, which is bordered by the Mississippi River. The Gulf Intracoastal Waterway (IWW) and Mississippi River Gulf Outlet Canal (MRGO) are located north of the polder. Figure 4.1 shows the primary levee system surrounding the polder. The primary levee system, which includes earthen levees, I-wall, T-wall, and sheet pile sections, was designed and constructed by the U. S. Army Corps of Engineers (USACE). The polder also includes a secondary or local levee shown in Figure 1.4 that separates the developed portions of the region from the wetlands to the north. The local levee serves two purposes: (1) it acts as a hydraulic boundary for nearby pump stations, which discharge water into the marshlands, and (2) it forms a temporary holding basin that protects the residential areas from flooding in the event of limited overtopping of the primary levees along the north edge of the polder. The Lake Borgne Levee District operates and maintains the local levee system. The performance of the local levee system was not assessed in this study.

While the levee system along the Mississippi River performed well in the region, many portions of the primary levee system located along the western and northern edges of the polder sustained significant damage from the storm surge (Table 4.1). Two of the most significant breaches occurred along the western edge of the polder bordering the IHNC in the Lower Ninth Ward. Widespread damage to the levee system along MRGO was so severe that the local levees presently provide the only flood protection in this area. Portions of the primary levees protecting the area to the northeast, i.e. those along the southeastern banks of the MRGO, are exposed to the water levels in the Gulf of Mexico, via Lake Borgne. These water levels reached significantly higher elevations than those in Lake Pontchartrain and in the outfall canals. This area appears to also be exposed to waves generated in Lake Borgne.

4.2 IHNC, East Side, South Breach, (Lower Ninth Ward)

The flood protection system located north of the Claiborne Avenue Bridge in the Lower Ninth Ward consists of I-walls embedded in the earthen levees. The I-walls at this location consist of approximately 20 feet of sheet pile topped by an 8 foot high concrete floodwall section. The sheet pile extends about 5 feet into the floodwall with a concrete sheet-pile connection. Subsurface conditions in the vicinity generally consist of approximately 10 feet of very soft clays over 5 feet of soft peats underlain by about 25 feet of soft clay. Dense sands are encountered at a depth of approximately 40 feet.

Figures 4.2 and 4.3 show aerial views of an approximately 900 feet long levee breach located 850 feet north of the Claiborne Avenue Bridge. The breach initially resulted from the Hurricane Katrina storm surge in the IHNC. An emergency repair was made shortly after the breach occurred. This repaired portion of the breach was later re-breached on September 24 by a storm surge caused by Hurricane Rita, which flooded the Lower Ninth Ward for a second time. This second flooding incident was reportedly much less severe than that caused by Hurricane Katrina (floodwaters reached a depth of about 3 feet), and as such, it is likely that it caused relatively little, if any, additional damage to the levee system at this location.

In this area, the earthen portion of the levee was almost completely destroyed and the I-wall was overturned toward the landside and dragged inland by as much as 190 feet. As shown in Figure 4.2, the displaced I-wall assumed a sinuous shape that reached its maximum distance along the northern extent of the breach. It is worth noting that the sheet pile remained interlocked, hence the displacement resulted from elongation of the sheet pile portion of the I-wall structure. The unbreached portions of the I-wall system located immediately north and south of the failure were tilted landward, reaching their maximum inclination of approximately 3 degrees near the breach and gradually tapered to close to vertical at further distances from the breach. Scour trenches at the landside toe of the floodwall (protected side) were found along the entire length of the intact I-wall section. The scour trenches were typically about 5 feet wide at the top and extended to depths of approximately 4 feet. The scour trenches were generally wide and U-shaped near the breach and gradually became narrower, V-shaped and incised with at further distances from the breach (Figure 4.4).

Figure 4.5 shows a unique feature of the failure site: a large barge that was drawn through the breach and came to rest on the landside of the levee as floodwaters receded. The barge was reportedly docked in the IHNC and became unmoored during Hurricane Katrina. Note the crushed school bus under the right side of the barge. Review of press photographs indicate that the barge initially came to rest further inland as floodwaters from Hurricane Katrina receded. The barge was later refloated as the Ninth Ward flooded a second time during Hurricane Rita. The barge drifted back toward the breach and came to rest upon the school bus as the Lower Ninth Ward was later unwatered.

It is likely that the breach resulted from overtopping of the levee system along the IHNC, leading to scour and subsequent loss of passive resistance at the base of the wall, which then overturned in response to the high water levels in the canal. This hypothesis is supported by the extensive scour found at the base of the protected side of the levee. As the breach opened, the rushing waters may have eroded what remained of the earthen portion of the levee while carrying the I-wall sections landward. Though it is thought that overtopping may be the principal cause of the levee failure, it is not yet known why the failure occurred at this exact location along the IHNC levee system.

Figure 4.6 shows the emergency repair of the breach, which consists of a core of large sandbags overlain by embankment fill. Additional gravelly fill had been placed along the top of the embankment to serve as a working mat. The sandbags were airlifted into place, while the stone was placed from land. There was no significant seepage noted at the time of site visits on October 4 and during the week of October 9.

4.3 IHNC, East Side, North Breach, (Lower Ninth Ward)

The flood protection system in the vicinity of Florida and Surekote Avenues near the northwest corner of the Lower Ninth Ward consists of I-walls/earthen levees that transition to T-wall sections near an adjacent flood gate (Figure 4.7). The I-walls at this location are the same as those found at the south breach location. Figure 4.8 shows a T-wall levee system at the site. The T-wall system at the site is generally similar to that discussed earlier in Section 2.4. Subsurface conditions at the site are similar to those found at the south breach site, with very soft clays overlying soft peats at shallow depths.

Figure 4.9 shows an aerial view of a 210 foot long levee breach located approximately 500 feet south of Florida Avenue. The breach initially resulted from the Hurricane Katrina storm surge in the IHNC. An emergency repair was made soon after. It is reported that unlike the south breach location, the north breach emergency repair was not overtopped in Hurricane Rita The earthen portion of the I-wall levee system was almost completely destroyed and the I-wall was overturned and dragged inland by as much as 70 feet while remaining fully interlocked. In the most extreme case, the I-wall came to rest upside down, with the concrete portion at the bottom, and the toe of the sheeting pointing upward (Figure 4.10). The sheet pile separated from the concrete wall at the north end of the site by splitting the webbed section rather than tearing the interlock.

The unbreached portions of the I-wall system located immediately south of the failure were tilted inward (landward). The tilted I-walls reached their maximum inclination of approximately 3 degrees near the breach and gradually tapered to close to vertical at further distances to the south. Scour trenches at the landside toe of the floodwall (protected side) were found along the entire length of the intact I-wall section. The scour trenches were typically about 5 feet wide at the top and extended to depths of approximately 3 to 4 feet. As with the south breach, the scour trenches were wide and u-shaped near the breached area and gradually became narrower, v-shaped and incised at greater distances. Scour was also noted along the landside of the T-wall levee sections (Figure 4.8).

It is likely that the breach occurred in a manner similar to that described for the south breach location (i.e. overtopping of the levee, leading to scour and loss of passive resistance at the base of the wall, resulting in overturning). The scour-related failure hypothesis is again supported by extensive erosion found at the base of the protected side of the levee. While it is thought that overtopping may be the principal cause of the levee failure, it is not yet known why the failure occurred at this location along the IHNC levee system.

Figures 4.9 and 4.11 show the emergency repair, consisting of a core of large sandbags overlain by embankment fill. The sandbags were airlifted into place, while the stone was placed from land. Owing to the presence of standing water on the landside during a visit on October 4, it was not possible to determine if seepage was occurring through the repaired section.

4.4 IWW/MRGO Bayou Bienvenue Gate and West

The flood protection system at the Bayou Bienvenue gate site is a complex levee-gate transition involving several different levee sections located as shown in Figure 4.12. These include (from northwest to southeast) an earthen levee, transitioning to an I-wall, transitioning to a gate structure, transition to a sheet pile section, which finally transitions again to an earthen levee along the MRGO.

Figure 4.13 shows an approximately 80 feet long levee breach in the sheet pile section located immediately southeast of the gate structure. The earthen portion of the levee was completely obliterated and the sheet pile wall appears to have been torn from its connection southeast to the Bayou Bienvenue gate structure, and overturned. Representatives of the Orleans Levee District indicated that the gates were closed during Hurricane Katrina, and later reopened manually, due to the lack of electric power, after the storm had passed. Many of the sheet pile breach features were obscured by water at the site, and hence it was not apparent if the breach occurred due to a structural failure at the sheet pile gate connection, a result of overtopping, leading to scour and subsequent loss of passive resistance, or some combination of these factors. At the time of the last visit to the site on October 5, no repairs had been made to the breach.

Visible in Figure 4.12 is a large barge that struck and then overran the I-wall section northwest of the gate. The barge eventually came to rest directly upon the I-wall, which was locally damaged by the impact of the barge. Scour was found immediately adjacent to the I-wall damage as a result of concentrated water flow at this location (Figure 4.14). Despite the combined effects of the scour, impact damage, and the vertical load imposed by the barge, the I-wall at this location survived relatively intact and performed remarkably well. As shown in Figure 4.15, minor scour was also noted at the transition between the earthen levee and I-wall section located northwest of the barge.

Figure 4.16 shows the levee and floodwall along the south bank of the IWW, looking west from the Highway 47 Bridge. The concrete floodwall survived with only minor damage despite the impact of several barges shown in the photograph grounded against the levee. Also evident in Figure 4.16 is the characteristic scouring from floodwall overtopping. The levee did experience a breach at the transition between the concrete gate structure and the earth embankment. Flood-transported debris partially plugged the breach.

Crest road erosion damage was also noted at several locations along the earthen levee between the Bayou Bienvenue Gate and the northwest corner of the Lower Ninth Ward. This suggests that the earthen levees were overtopped at these locations; nevertheless, no breaches were found and the overall performance of the levee system was very good at these locations. These earth levees (west of Bayou Bienvenue) show a clear debris line at the crest level as shown in Figure 4.17. The result of the overtopping appears to have been limited to occasional moderate erosion of surface soils. Figure 4.18 shows one of the various types of barges that made contact with the earth embankment without any significant consequences.

4.5 MRGO, Bayou Dupree and Northeast St. Bernard Parish

Figure 4.19 presents a plan view of MRGO and indicates the numerous breaches caused by Hurricane Katrina along the southwest bank of the waterway. This section covers the levee sections located southeast of Bayou Bienvenue. The field evidence, including numerous sections of earth levees obliterated by the storm waters, indicates that the flood protection barriers were overtopped along the MRGO.

The map in Figure 4.19 shows that the storm barriers along the MRGO suffered damage at many locations. Figures 4.20 and 4.21 capture the failure of earth levees with steel pile sheeting between Bayou Bienvenue and Bayou Dupree. At some locations, the canal side of the earth embankment was completely eroded away and the erosion from overtopping left only remnants of the landside portion of the levee. The section where pipelines cross the steel sheeting (Figure 4.21) show scour on both sides of the sheets and deflections in both directions possibly as result of wave action and outflows.

Figures 4.22 and 4.23 show that the gate structure at Bayou Dupree suffered a failure similar to the one observed at Bayou Bienvenue. While the concrete structures remain largely intact, except for a section of concrete sheet piles to the right of those shown in the figures, the soils at the transition section were eroded by the storm waters resulting in a breached barrier.

Figures 4.24 and 4.25 show that overtopping obliterated the earth levees along the southwestern bank of MRGO near Bayou Dupree. Not only were the sandy soils in the embankment material completely removed in some sections (e.g. Figure 4.25), but the more cohesive soils at the foundation level suffered deep scouring. The only erosion protection on soil embankment levees that was visible for much of this area was grass. Figure 4.26 shows an aerial view of a section of these levees that survived the storm, albeit with erosion damage.

Members of the team observed a breach repair immediately north of Bayou Dupree on 12 October 2005. It is not known if this was a temporary or permanent repair. Saturated soils in scour areas were being filled over with local materials; new embankment was tied into existing embankment without shaping or removal of loose, disturbed fill; and compaction was accomplished by tracking fill with a small dozer. These repairs, if permanent, will likely be more vulnerable to problems than adjacent levees that survived Katrina intact. Construction supervision was not observed onsite. However, the team only observed a brief snapshot of construction activity, and we were later informed by the USACE Public Information Officer that a request had gone out to recruit over 100 additional personnel, apparently for purposes of inspection and contract administration.

The performance of much of the storm barrier along the section of the MRGO in St. Bernard Parish appears to have been influenced by the following factors:

- Severe overtopping of the storm barrier;
- Use of unarmored highly erodable sandy soils for construction of the earth portions of the levees which could not resist the effects of overtopping;
- Accelerated erosion of soils at the transition between soil and concrete structures; and
- Lack of capping on sheet piles.

The storm surge levels in this area were on the order of 18 to 25 feet, which significantly exceeded original design conditions and the +17.5 feet levee crest elevation. It is no surprise, therefore, that the levees were damaged as much as was observed. Large segments of the levees along the St. Bernard Parish bank of the MRGO were completely destroyed by the storm. Studies at Louisiana State University (LSU) suggest that the MRGO and East New Orleans levees form a funnel-like structure which intensifies a wave sent into the funnel. During hurricane Katrina, the St. Bernard Parish levees bore the brunt of the storm surge. Advanced Circulation (Model ADCIRC) analyses examined by coastal engineers from the NSF/ASCE team suggest that the higher surge along the MRGO levees was due in part to the northeasterly winds as the hurricane approached and the long straight section of levees perpendicular to the wind direction, rather than a funneling effect. This storm surge was then transmitted into the MRGO and the IWW.

Table 4.1: Summary of Damage to Primary Levee System in the Lower Ninth Ward/St. Bernard Parish Polder

Location [Figure 4.1 Designation]	*Levee Type*	*Damage Summary*	*Length of Breach or Damaged Section*	*Notes*
IHNC, East Side, South Breach, (Lower Ninth Ward) [1]	I-wall	Breach	930 ft	Significant scour found at the toe of adjacent levee sections Emergency repair was overtopped in Hurricane Rita
IHNC, East Side, North Breach, (Lower Ninth Ward) [2]	I-wall	Breach	210 ft	Significant scour found at the toe of adjacent levee sections
Intracoastal Waterway/ MRGO, Bayou Bienvenue Gate Site [3]	Sheet Pile	Breach	~ 80 ft	Located at transition to concrete gate structure Earthen levee located west of site was overtopped; however, no significant damage occurred.
MRGO, Southwest Bank [4]	Earthen and Sheet Pile Sections	Multiple Breaches		Extensive damage to wide stretches of levee
Bayou Dupree Gate Site [5]	Earthen and concrete sheet pile sections	Multiple breaches		Complete washouts of earthen and concrete sheet pile sections

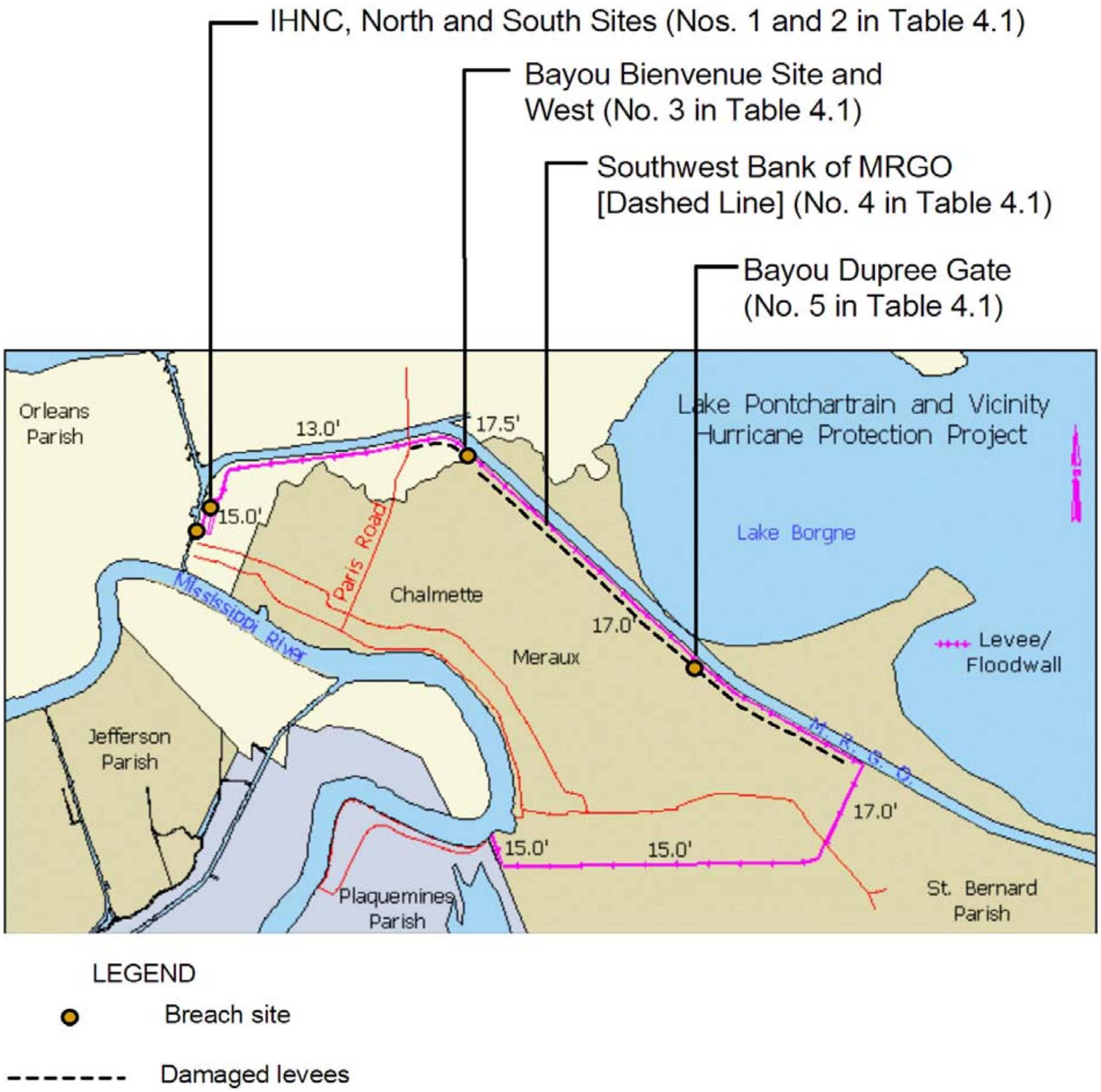


Figure 4.1: Overview map of the Lower Ninth Ward/St. Bernard Parish Polder showing the locations of damage to the primary levee system. Sites nos. 1 through 4 are summarized in Table 4.1. The elevations shown correspond to the top of the levee system at each location (after USACE).

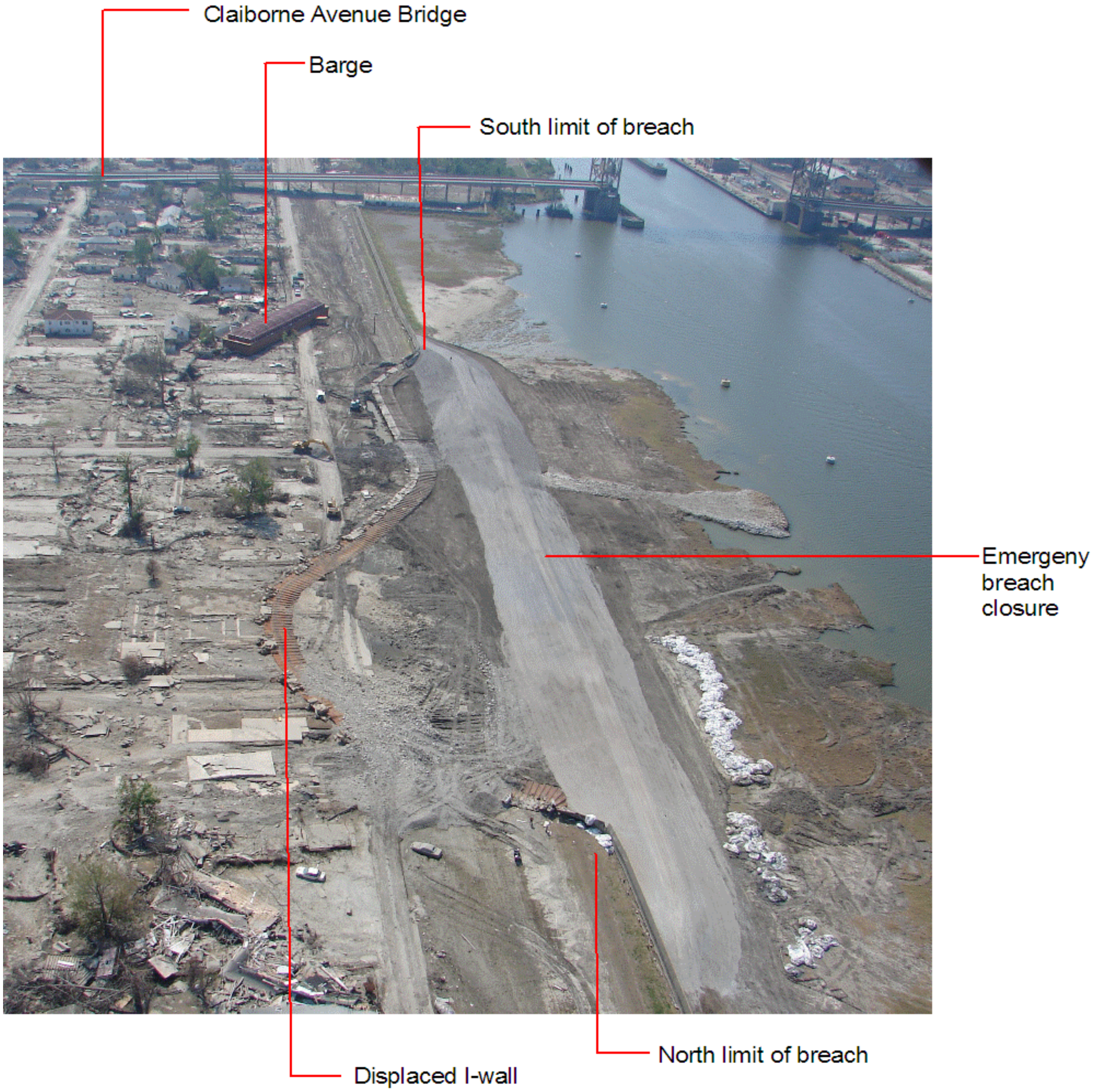


Figure 4.2: Aerial view of the south breach at the Lower Ninth Ward (L. Harder, October 14, 2005).

Figure 4.3: Airborne digital imagery of the south breach at the Lower Ninth Ward. Water is shown flowing back into the IHNC (courtesy NOAA, August 31, 2005).

Figure 4.4: North view from the end of the south breach of Lower Ninth Ward. Note how the scour trench becomes progressively wider as it approaches the breach (J. Wartman, October 4, 2005).

Figure 4.5: A barge was drawn through the south breach of the Lower Ninth Ward (J. Wartman, October 4, 2005).

Figure 4.6: South view of the south breach repair at the Lower Ninth Ward (J. Wartman, October 4, 2005).

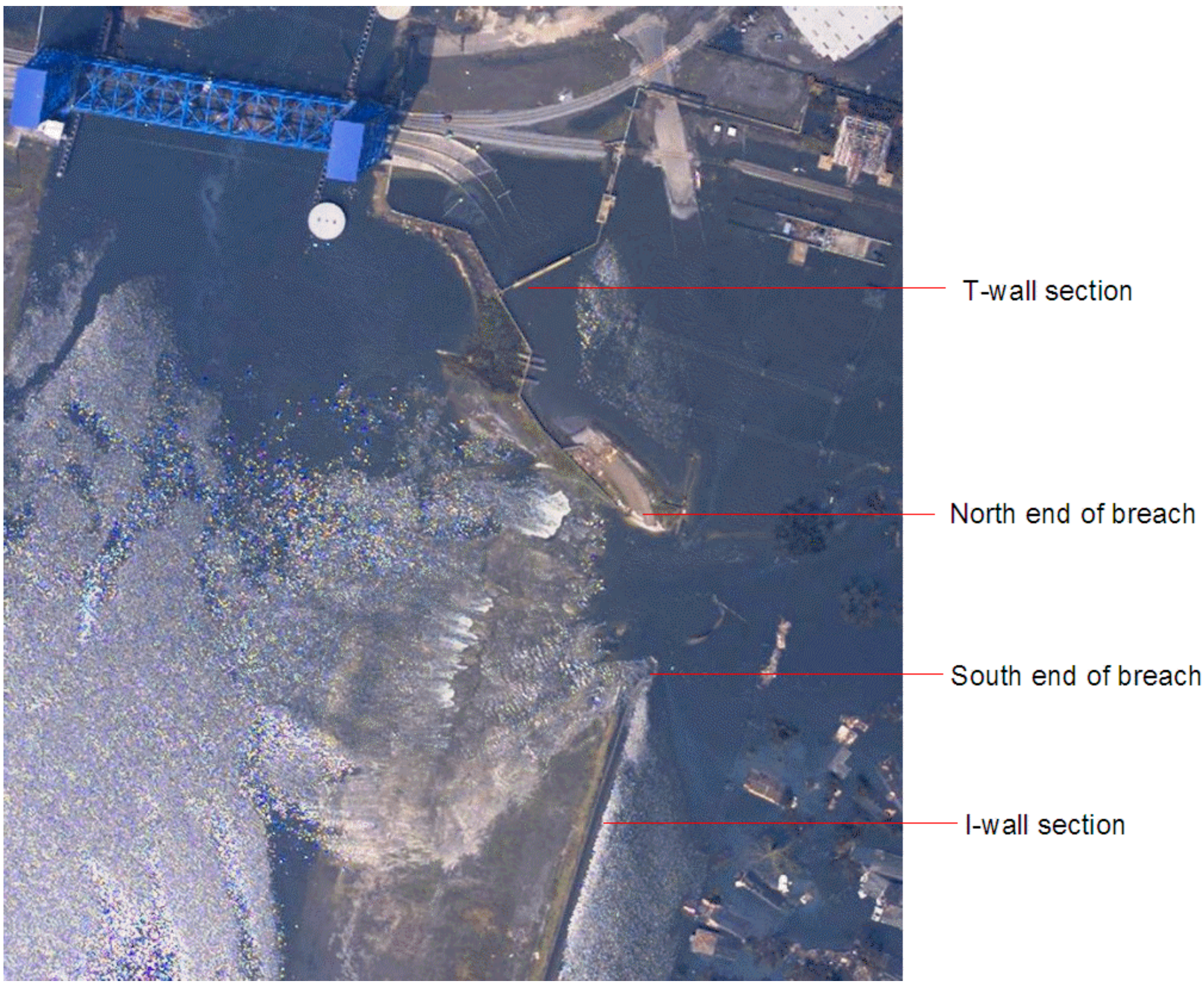


Figure 4.7: Airborne digital imagery of the north breach at the Lower Ninth Ward. Water is shown flowing back into the IHNC (courtesy NOAA, August 31, 2005).

Figure 4.8: A scoured, but nevertheless well-performing "T-wall" levee section located near the north breach of the Lower Ninth Ward (J. Wartman, October 4, 2005).

Figure 4.9: Aerial view of the north breach of the Lower Ninth Ward (L. Harder, October 14, 2005).

Figure 4.10: Overturned I-wall system at north breach of Lower Ninth Ward (J. Wartman, October 4, 2005).

Figure 4.11: Looking south along the north breach repair at the Lower Ninth Ward (J. Wartman, October 4, 2005).

Figure 4.12: Northwest facing aerial view of the Bayou Bienvenue Gate structure (L. Harder, October 14, 2005).

Figure 4.13: Sheet pile breach at the Bayou Bienvenue Gate (J. Wartman, October 5, 2005).

Figure 4.14: Scour near barge damage at the Bayou Bienvenue Gate site (J. Wartman, October 5, 2005).

Figure 4.15: Scour near Bayou Bienvenue Gate site (L. Wooten, October 5, 2005).

Figure 4.16: View of levee along the south bank of the Intracoastal Waterway from the Rt. 47 Bridge (Lee Wooten, October 6, 2005).

Figure 4.17: Debris line near levee crest just west of the Rt. 47 Bridge south abutment (L. Wooten, October 5, 2005).

Figure 4.18: Various barges and other floating structures made contact with the earth levees without causing significant damage. Photo shows a gas processing barge (F. Silva, October 1, 2005).

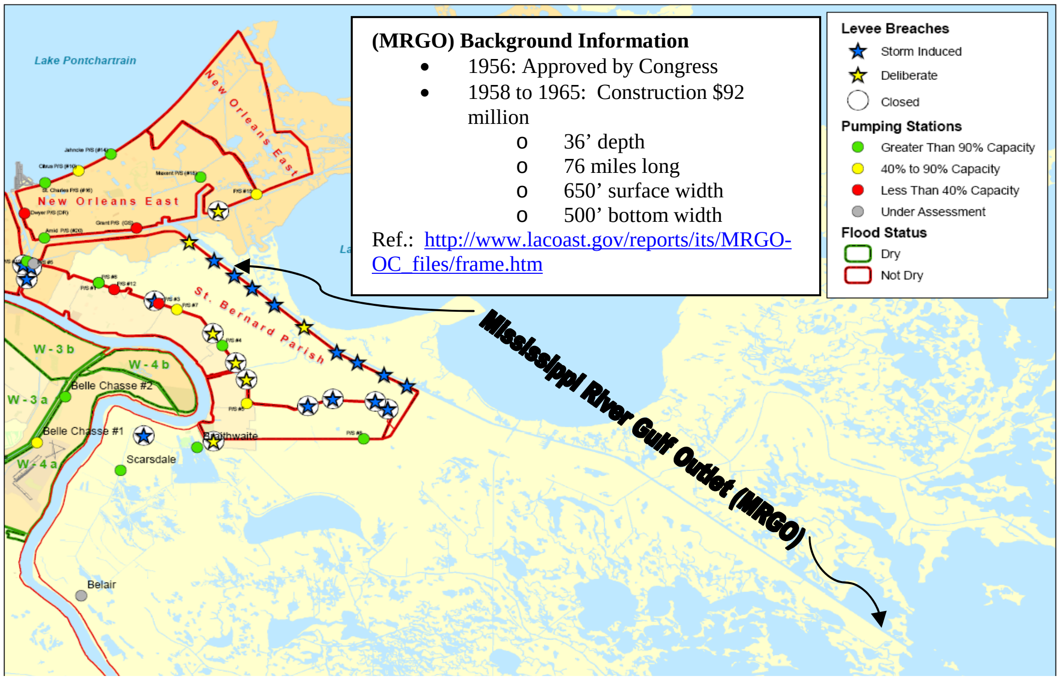


Figure 4.19: Mississippi River Gulf Outlet [MRGO] (USACE). The two yellow stars (i.e., deliberate breaches) along MRGO seem to correspond to locations of gate structures where storm-induced breaches occurred. These yellow stars markers are likely errors in the original map that should have been designated using blue star markers.

Figure 4.20: Failure of earth levee with steel sheetpile barrier on the southeast bank of the MRGO. Note severe erosion and scour (L. Wooten, October 6, 2005).

Figure 4.21: Levee failure on southwestern bank of MRGO between Bayou Bienvenue (where barge is aground on I-wall) and Bayou Dupree. Note severe erosion and scouring (L. Harder, October 14, 2005).

Figure 4.22: Levee failure on southwestern bank of MRGO at Bayou Dupree. Note concrete sheetpile and levee transition washouts (L. Harder, October 14, 2005).

Figure 4.23: Ground perspective of Bayou Dupree gate abutment failure (L. Wooten, October 6, 2005).

Figure 4.24: Failure of earth levee on southwest bank of MRGO adjacent to the Bayou Dupree gate (L. Wooten, October 6, 2005).

Figure 4.25: Overtopping obliterated earth levee along southwestern bank of MRGO, within two miles southeast of Bayou Dupree. Note deep scour at the levee foundation level (L. Harder, October 14, 2005).

Figure 4.26: Aerial view of MRGO looking towards the city of New Orleans (L. Harder, October 14, 2005).

Chapter Five: Plaquemines Parish

5.1 Overview

Plaquemines Parish is the area where the last portion of the Mississippi River flows into the Gulf of Mexico (see Figure 1.5). Extending southeast from New Orleans, Plaquemines Parish straddles the banks of the Mississippi River for about 70 miles out to the river's mouth in the Gulf. It is an area that is sparsely populated, with only about 27,000 people in the entire parish (see Plaquemines Parish Government Website: http://www.plaqueminesparish.com/). Most of the residents 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. For many of the communities lying along the Mississippi River levees, hurricane or back levees were also constructed behind them to protect them from hurricane surges coming from the Gulf. 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.

Hurricanes Katrina and Rita devastated many of the Plaquemines Parish communities. Hurricane Katrina was reported to have induced storm surges up to 20 feet in this region, which overtopped and damaged many portions of the hurricane levees. Both the United States Army Corps of Engineers (see Figure 1.5) and the Plaquemines Parish Government website report numerous breaches of the hurricane levees and widespread deep flooding and destruction (see Figures 5.1 through 5.3).

5.2 Pointe a la Hache

Pointe 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 5.4 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 breach to facilitate access and repairs.

Figure 5.5 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 effect 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 with the equipment in use at the time of the team's visit. It is not known how the contractor resolved this situation.

Residences in Pointe a la Hache were commonly inundated to depths of 12 to 15 feet (see Figure 5.6). Flooding was so great that water flowed across the community from the east towards the Mississippi River, and even overtopped the Mississippi River levee by several feet. Based on debris found on tractor equipment left on the levee crown along the Mississippi River, overflows of up to 4 feet were estimated. For the areas visited by the teams, no significant damage was observed on the Mississippi River levee, possibly because the river sides of the levees viewed by the team were paved with concrete slope protection (see Figure 1.11).

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 flood waters flowing into the Mississippi River (see Figures 5.7 through 5.9).

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

Figure 5.1: Aerial photograph of inundated portion of Myrtle Grove along western side of the Mississippi River (September 25, 2005)

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

Figure 5.2: Aerial photograph of levee breach of hurricane (back) levee along western side of the Mississippi River near the community of Sunrise (September 25, 2005)

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

Figure 5.3: Aerial photograph of levee breach of hurricane (back) levee at levee transition near Hayes Pump Station (September 25, 2005)

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

Figure 5.4: Aerial photograph of levee breach of hurricane (back) levee east of Pointe a la Hache (September 25, 2005)

Photograph by Les Harder

Figure 5.5: Photograph of sheetpile cutoff being placed into levee breach of hurricane (back) levee east of Pointe a la Hache (October 12, 2005)

Photograph by Les Harder

Figure 5.6: Photograph of flood elevation on trees landward of hurricane levee east of Pointe a la Hache – illustrating that flood water remained to large depths for extended periods (October 12, 2005)

Photograph by Les Harder

Figure 5.7: Photograph of Pointe a la Hache home deposited on Mississippi River levee crown after storm surges overtopped this levee from the east (left) towards the river – which is to the right in this photograph (October 12, 2005)

Photograph by Les Harder

Figure 5.8: 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 5.9: Photograph of Pointe a la Hache home site where wooden home was floated off of its cinderblock piers – note concrete stairs and black plastic sheet in tree illustrating the depth of flooding (October 12, 2005)

Chapter 6 – The New Orleans Flood Defense System

The physical components of the New Orleans Flood Defense System (NOFDS) include levees and flood walls, flood gates and adjacent structures, canals, and pump stations.

During this initial phase of field work, primary attention was focused on the levees and flood walls. As the work proceeded, it became apparent that the other elements that comprise the NOFDS play equally important roles in defending the city against potential flooding. In addition, it was readily apparent that the organizational components of the NOFDS played roles that had very important effects on the performance of the NOFDS during hurricanes Katrina and Rita.

The USACE has been primarily responsible for overseeing the design and construction of many of the elements in the NOFDS. After commissioning of the completed flood protection elements, they are transferred to other organizations to be operated and maintained. These other organizations include not only local public agencies (e.g.: the New Orleans Levee Board, and the New Orleans Sewage and Water Board) but also private agencies and in some cases private property owners. (e.g.: Department of Transportation roadways and highways, railways, private shipping companies, etc.). The USACE does not maintain direct control and supervision of the flood protection elements over the life of the elements.

In our surveys of the NOFDS it was not always clear which agency had responsibilities for what part or parts of the system. In many instances, it was clear that flooding and breaching of the NOFDS had developed because of breakdowns within the multiplicity of organizations or at their interfaces.

An example of system vulnerabilities associated with the multiplicity of organizations was found on the east side of the IHNC at the lake front adjacent to the railroad bridge that crosses this canal near the Lakefront Airport (Figure 6.1). Inspections of this area clearly indicated that large amounts of water had entered through a railway opening in the adjacent concrete flood wall and soil levee (Figure 6.2). The inspection did not disclose the presence of a flood gate that had closed the railway opening, even though immediately adjacent to this opening was a securely closed flood gate and concrete flood control structure maintained by the USACE (this gate and the adjacent flood control structure had not been breached and showed no signs of overtopping). The low spot in this complex interchange was the base of the railroad ballast, and it was here that the water had flowed through. Attempts had been made to place sandbags prior to the arrival of hurricane Katrina; the attempts had not been successful and water had poured through the opening flooding the areas immediately south and west of the opening.

Another example of system vulnerabilities associated with the multiplicity of organizations occurred in the same area, near the lake front airport (Figure 6.3). The earth levee that paralleled the lake front defending the neighborhood to the south of the Lakefront airport had experienced some overtopping, but water had breached a section between the adjacent flood control structure (concrete, flood gate closed) and the earth levee (Figure 6.4). The earth levee was at an elevation that was lower than the flood control structure. Massive scour had developed in the earth levee due to the surge waters. This water was then conducted into the adjacent neighborhood through the road underpass. There were no flood defenses provided for the road underpass.

We visited one of the key pumping stations that are responsible for pumping water collected from within the city into the drainage canals, and thence into Lake Pontchartrain (Figure 6.5). These pump stations were put in service in the early 1900's, and many of the electrically driven pumps bore manufacturing identification plates that bore testimony to their age (Figure 6.6). The pumps were very old, and were obviously kept in service by tender loving care. While we were there, work was underway to dry out the pumps and associated electrical control equipment that had been submerged during the flooding - including the banks of stand-by batteries that are shown in Figure 6.7. Discussions with the pump station operators that had been present at the time of the hurricane disclosed how, as the water rose in the pump station, a decision was made to shut-down the pumps and evacuate the operating personnel by walking out on the adjacent 'elevated' railway. At this point in the storm, there was no hope of being able to pump water from the rapidly flooding city.

After touring the pump station, we surveyed the area immediately outside of the pump station to determine how the flood walls and other parts of the levee system had performed. We found that it had performed very well, with little signs of overtopping. However, as we toured the area we found that there were 5 different elevations of different parts of the levee system in a small area (Figure 6.8). A significant example of this occurs on the east bank where the floodwall on the earthen levee abruptly ends at a considerable distance (some 300 feet) before the levee reaches the pumping station, leaving a long, low gap where there should have been a contiguous, closed perimeter flood defense. A similar situation occurs on the west side where the floodwall transitions into a short stretch of sheet pile with a considerably lower elevation. Note that these gaps provide access of floodwater into the surrounding residential areas at a water level well below the flood protection system design level. Some overtopping had in fact occurred in both places, as reported by the pump station operator, who was onsite during Hurricane Katrina. Other variations in the elevations of the flood defense elements were correlated with the agencies that had responsibilities for various parts of this part of the system, (e.g. highway department determining the heights under the road overpass immediately adjacent and upstream of the pump station, Figure 6.9)).

At the end of this data and information gathering process, it was apparent that vulnerabilities had been embedded in the physical aspects of this system. These vulnerabilities were often found at transitions between flood protection elements and/or where other infrastructure was involved. In many cases, multiple organizations were involved, and the system was such that any imperfections in the merging of the different elements resulted in vulnerabilities in the overall system. These weak links needed much more coordination, review, and oversight to prevent the failures that occurred, and which could occur again if not remediated.

Photograph by Robert Bea

Figure 6.1: A railroad bridge adjacent to the Lake Pontchartrain frontage road.

Photograph by Robert Bea

Figure 6.2: Lack of a floodgate at the railroad line crossing resulted in scour around the railroad tracks. No overtopping was observed the floodgate across the adjacent roadway.

Photograph by Rune Storesund

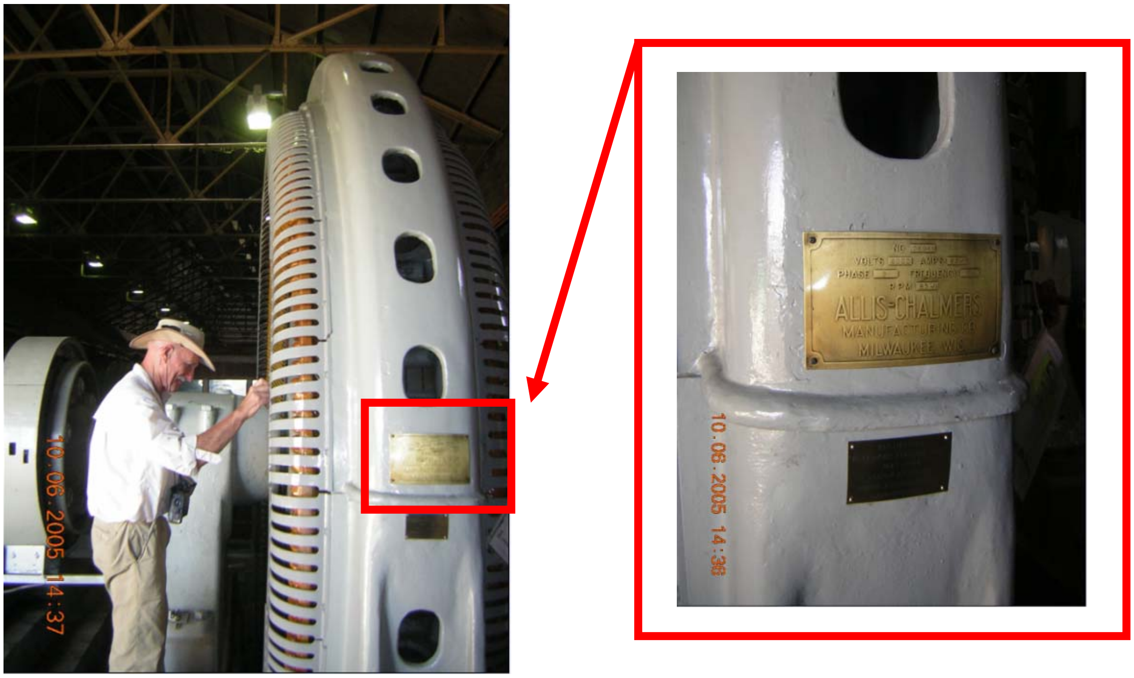
Figure 6.3: Lack of a flood gate beneath the railroad over-crossing facilitated the flooding of residential neighborhoods.

Photograph by Rune Storesund

Figure 6.4: This flood protection levee was overtopped and scoured, resulting in flooding of this lakefront residential area.

Photograph by Rune Storesund

Figure 6.5: Side view of the Orleans Canal pumping station.



Photograph by Rune Storesund

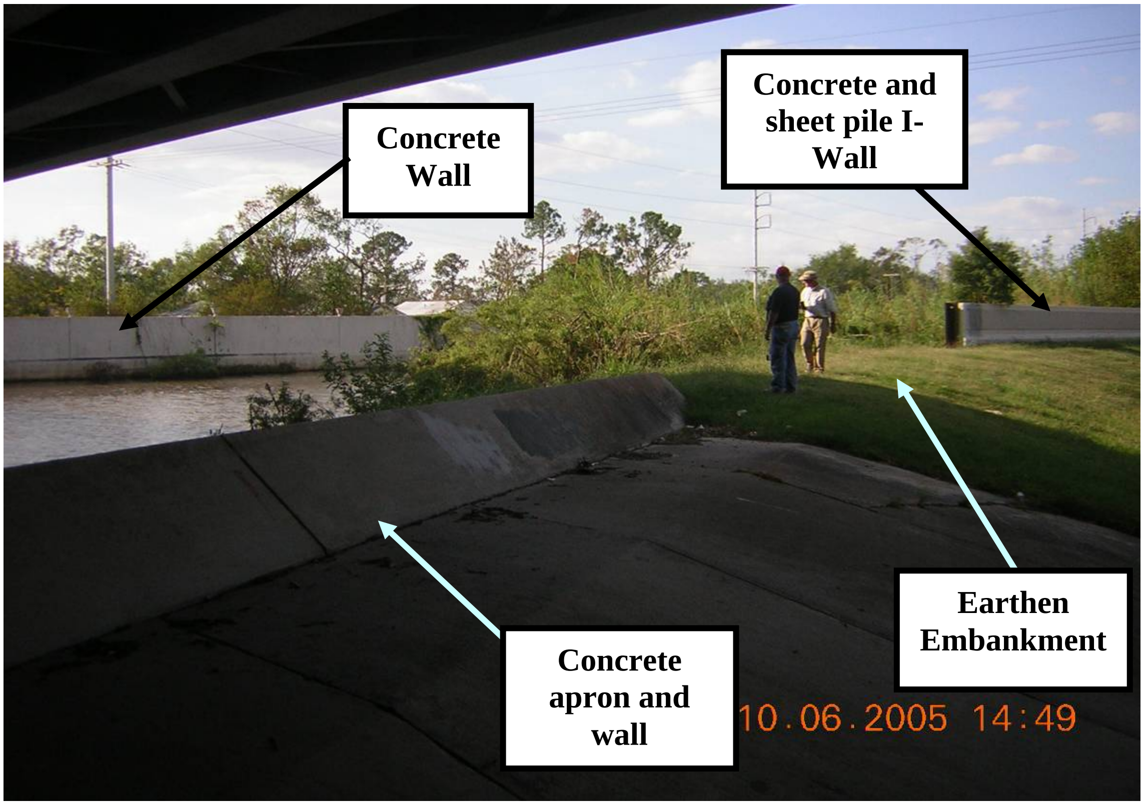
Figure 6.6: Original pump equipment at the Orleans Pumping Station from the early 1900s.

Photograph by Rune Storesund

Figure 6.7: A battery bank in the pump station used for “emergency” power.

Photograph by Rune Storesund

Figure 6.8: Area outside (to the north of) the Orleans pump station.



Photograph by Rune Storesund

Figure 6.9: At the Orleans Canal pump station, the flood protection system consisted of different components, each with a different "top of wall" elevation.

Chapter Seven: Terrestrial LIDAR Imagery of New Orleans Levees Affected by Hurricane Katrina

7.1 Introduction

Preservation of information regarding the magnitude and geometry of structural and geotechnical deformations is paramount for the analysis of levee failure modes. This chapter describes the areas of focus and methodology used in laser mapping of surface evidence of levee deformation and distress at ten areas within the greater New Orleans area. The area of focus extends from the 17th Street Canal in the Orleans East Bank area, to the Entergy power plant in the New Orleans East area. The NSF-sponsored investigation team included two researchers from the United States Geological Survey (USGS) who brought to the field area a terrestrial laser mapping tool to perform laser scanning or LIDAR (LIght Detection And Ranging) data collection. The laser mapping effort was conducted over 5 days from October 9-14, 2005. The objective of the laser scanning effort was to obtain precise measurements of the ground surface to map soil displacements at each levee site, the non-uniformity of levee height freeboard, depth of erosion where scour occurred, and distress in structures at incipient failure. Toward that end, ten sites were visited for LIDAR scanning (Figure 7.1). The sites, along with their global position coordinates (WGS84 Datum) and the number of individual scans collected at each site are outlined in Table 7.1. Because several of the sites are less than one kilometer apart (i.e. Sites 2 & 3, Sites 4 & 5, and Sites 6 & 7), individual scans from each of these site pairs were collected and developed as a single LIDAR model and are listed jointly.

7.2 Methodology

The terrestrial LIDAR method, a 3D laser scanning technique, consists of sending and collecting laser pulses from surface objects to build a point file of three-dimensional coordinates. The time of travel for a single pulse return from a surface is measured along a known trajectory such that the distance from the laser and consequently the exact location can be computed. In addition, visual data on points located within and outside of the laser range can be obtained through the use of a CCD color sensor. A unique aspect of the LIDAR method is the rapid rate of data collection. The USGS laser scanning system can measure the location of up to 8,000 surface points in one second. Thus within a few minutes, an entire surface, be it a structure or levee, can be imaged efficiently with a point file that contains several million position points. The point files from collected scans are typically transformed into three-dimensional surfaces so that cross-sections can be generated and volumetric calculations can be performed between consecutively scanned surfaces.

The LIDAR technique has been successfully utilized by members of the reconnaissance team in a wide range of environments, most recently, for studies involving coastal bluff change along the California coast (Collins and Sitar, 2004, 2005), and in earthquake reconnaissance studies (Kayen et al., 2004, Kayen et al., in press). Complete details of the laser scanning process can be found in these references.

In the study of damage to the levee systems protecting the New Orleans area, the USGS scanning laser, a Riegl Z210 scanner (Riegl, 2005), was utilized as a tripod mounted survey instrument (Figure 7.2). To improve the imagery and increase the efficient transportation of the sensor between scans, the tripod was elevated to a fixed platform on the roof of the field vehicle. Elevating the scanner to approximately 4 meters above the ground reduced shadow zones and extended coverage of each scan. The laser was set up over existing survey benchmarks where available, to tie the data into georeferenced coordinates. However, for the most part, a separate, local coordinate system was utilized for each site. Each laser scan collected approximately 2.3 million data points, scanning an azimuthal range up to 336 degrees and an elevation range of positive 40 degrees to negative 40 degrees measured from the horizontal.

Multiple scans were collected to fill in "shadow zones" of locations not directly in the line of sight of the laser and to expand the range and density of the point data. Processing of the data was performed using the I-SiTE software program (I-SiTE, 2005) specifically designed to handle laser data. Specific details of the processing procedures used at each site are provided with each location's summary.

The range of radial target distances for natural targets is approximately 2 m - 400 m and at these distances the point measurement accuracy is 0.8-2.5 cm, depending on specific laser settings. Time required for scanning at fine-scale density of points (e.g., 2.3 million targeted points) is 4 minutes. In New Orleans, the fine-scale resolution was used to scan the levee sections in most cases. At the highest resolution, the angular separation of the vertical line scans is 0.01°. Thus, the near-field point separation is less than 1 mm and the separation of the farthest data at 400 m can be about 7 cm.

The angular position of the laser-pulse leaving the scanner is controlled by precise stepper-motors within the unit. The scanner makes millions of individual x, y, z position measurements that together form a "point cloud" data set of information about the solid objects that return reflected pulses. The USGS scanner has an optical sensor that records reflective color and intensity. With the addition of a color channel, the natural appearance of the surface can be draped on to the three dimensional surface model. Several useful applications of the color and intensity channels are to (1) extract non-topographic textural information about the target; (2) identify color-based lithologic changes in the target; and (3) enhance and identify georeference reflectors that send back the strongest reflected signal. On some occasions (less than 10 scans) during the team's reconnaissance mission, schedules necessitated night-time data collection such that real-color scans were not collected. This only affected the color imagery of the data, not the positional accuracy or resolution of the point files.

In most cases, after arriving at a site, the scanner was mounted on a tripod on the roof of the field vehicle. In other configurations, the laser was placed on a tripod on the ground, or on its side, for example on the top of an I-wall section to scan downwards into toe scour (Figure 7.3). Typically, the scanner is set upright and leveled, with the unit rotating horizontally.

3-D laser scanners cannot see behind objects, therefore the first surface encountered casts a shadow over areas blocked from the view of the scanner. For example, it can be seen in a scan of the levee at the east side, north breach of the Inner Harbor Navigational Canal (IHNC), locally referred to as the Industrial Canal (Figure 7.4) that shadows are cast by near-field objects like the exhumed sheet pile foundation over the debris behind it. As the incident-angle of the laser point decreases, proportionally larger shadows are cast on the ground behind the target. Therefore, to minimize shadow zones and get full coverage of the target surface using terrestrial LIDAR, the scanner is moved to a number of locations surrounding the target zone (Figure 7.5). The levee scans involved 13 to 29 scanner set-ups to cover the entire feature and surrounding area and to minimize the number of shadow areas. Using multiple setups provided both a convenient way to limit the number of shadow zones while also increasing the resolution of the data collected and the boundaries of the scanned area.

7.3 Data Coverage: LIDAR scan sites at Levee Breaks within the New Orleans Area

Figures 7.6 through 7.12 define the approximate bounds of highly detailed continuous LIDAR data. Considerable data exist outside of these bounds, though they are not continuous and may have shadow effects. In general, point to point spacing of individual LIDAR data points within the outlined areas is on the order of 25 mm providing an extremely dense coverage of all objects within each site. However, typical surfaces generated from the data are typically filtered to a minimum point separation of 10 to 50 cm when greater accuracy is not required.

7.4 Processing of LIDAR Imagery

At each levee site, the topographical surroundings were imaged on thirteen or more individual scans, together consisting of many millions of data points. The investigation team utilized the I-SiTE surface modeling software package, to both collect the scan point-cloud data and allow for post processing of multiple scans into geo-referenced solid surfaces.

After data are acquired, there is a suite of standard processing steps needed to produce a surface model. First, the multiple scans are either locally or absolutely geo-referenced to one-another. A least squares “best-fit” match is made between scans, augmented by precise survey measurements made with a total station or differential global positioning satellite (e.g., real time kinematic RTK-GPS, or Omnistar HP-differential GPS). Filters are then used to eliminate unwanted data. For example, typically filters are applied to remove vegetation-related data points so as to observe the “bare” earth. Finally, the filtered data serves as the working digital terrain model (DTM) that is used to render a solid surface of the object (ground). Again, different surface modeling schemes can be used to fuse and render a surface from multiple scans. The surface model represents a highly accurate virtual representation of the ground that can be used for documentation and change detection of volumes, areas, and distances.

7.5 Analysis Examples of Levee Deformation Using LIDAR Data

Laser mapping allows for highly accurate computation of rotation, length, area, and volume. Rotational displacement was common at areas of levee I-wall distress. For example, the east side of the London Canal immediately south of Robert E. Lee Boulevard suffered distress and lateral deformation associated with incipient failure of the levee. This movement is along a section of wall diagonally northeast of the west side breach across the canal. In Figure 7.13, an oblique image of the distressed wall can be seen from the south. The wall, preserved in incipient failure, leans toward the levee maintenance road and landside portion of the levee. In the right-hand background, is the bridge abutment on Robert E. Lee Blvd for reference.

Considerable vegetation grows along the banks of the canal side of the levee that are less maintained for growth than the landside neighborhood-side of the levee wall. Thin slices of the point-cloud data orthogonal to the alignment of the levee wall (Figure 7.14) display highly accurate cross sections of the distressed I-wall at London Canal. Segment (a) is toward the south (left) of Figure 7.13 and has a modest 1.9 degree rotational deformation. Near a position of maximum distress, the I-wall has 5.0 degrees of rotational deformation toward the landside of the levee.

The London Canal levee failure (west side) and distressed wall (east side) are both immediately south of the bridge crossing at Robert E. Lee Boulevard. A significant gap in height between the lower un-walled bridge abutment and I-wall prevents water from overtopping these levees. The height gap differs slightly between the walls located north and south of the bridge, due either to differing design heights or differential settlement following construction. At the distressed I-wall section on the southeast corner of the bridge, LIDAR surveys and visual inspection indicated the gap at this location was approximately 1.7 meters (5.6 feet). Therefore, water rising in the canal would overtop the bridge abutment and begin to flood the surrounding community when the water level was 1.7 meters (5.6 feet) below the top of the I-wall. Figure 7.15 shows this considerable wall gap, as well as moderate scour at the southeast edge of the bridge abutment (Figure 7.15a). On the northeast corner of the bridge abutment near the north levee wall, LIDAR surveys indicate the gap at this location to be approximately 1.51 meters (5.0 feet). Figure 7.16 and 7.17 show this gap, as well as a scour trench at the base of the northeast abutment (Figure 7.17a).

There was no evidence of overtopping of the levee walls or erosion scour anywhere along this section of the canal except at the gap at the bridge. The LIDAR and scour evidence therefore indicate that the floodwalls along the London Canal section, south of the Robert E. Lee Boulevard Bridge were not overtopped prior to failure of the levee wall.

Measurement of displacement along the 17th Street Canal breach can be made by identifying the blocks of ground formerly within the intact levee that slid eastward toward the landside of the levee. Figure 7.18 is an overview image of a portion of the 17th Street point cloud data set consisting of 11 individual scans. In this image, the bridge crossing over the canal at Robert E. Lee Blvd. (also called the Hammond Highway.) is toward the upper left (north). A dense cluster of points is visible at the levee breach in the center of the image as are the houses in the affected area. Close in to the levee breach in Figure 7.19, the remaining I-wall can be seen in alignment with the crest of the replacement structure. Here, a total breach repair width of 142 meters (466 feet) as measured between intact I-wall sections has been calculated directly from the LIDAR data set. A cross section taken through this area is shown in Figure 7.20. A multi-section view is shown, consisting of a section of the intact southern I-wall overlain over the failed section of the levee. The geometry of the emergency repair embankment is clearly visible. The sections also show the magnitude of the displacement of several earth blocks that moved away from the levee break during failure. While forensic work on the original positions of the earth blocks is still ongoing, the LIDAR data shows that blocks translated approximately 14 meters (46 feet) as measured from the existing alignment of the cyclone fence line to its new position within the displaced blocks. From the perspective shown in Figure 7.20, it can also be seen that the width of the 17th St. Canal has been reduced about 6 meters (20 feet) by the placement of the earthen embankment.

A final example of the use of the LIDAR data is shown in Figure 7.21. Here, the dimensions of the scour trench in the vicinity of the east side IHNC – south breach are outlined. This view shows the depth of scour adjacent to the I-wall and into the embankment so that a direct comparison of the scour depth to sheet pile embedment can be made.

7.6 Summary

The LIDAR data presented herein present the scope of available data coverage of the failed sections of the New Orleans levee system following Hurricane Katrina. The methodology for processing the data has been outlined to provide important background information for maps, section views and calculations developed from the data and presented elsewhere in this report. Examples of specific applications of the utility of the data have also been presented to provide information on how the data sets may be utilized in ongoing and future investigations of the performance of the levee systems.

7.7 References

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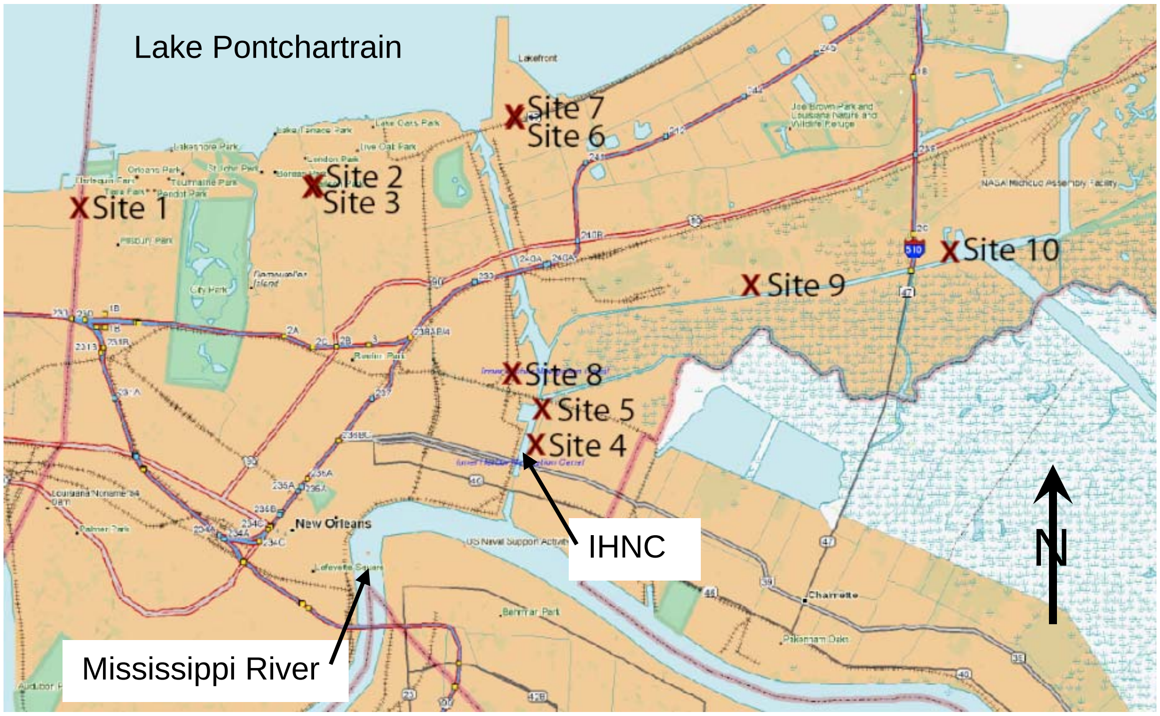
Table 7.1 LIDAR Site Description Summary

LIDAR Site Number	Location	Latitude	Longitude	Number of LIDAR scans	Related Chapter in this Report
1	17th Street Canal	N30.0172°	W90.1214°	20	2
2	London Ave. Canal, North on east side	N30.0210°	W90.0704°	29 with Site 3	2
3	London Ave. Canal, North on west side	N30.0206°	W90.0708°	29 with Site 2	2
4	IHNC East Side, South Breach 9th Ward	N29.97243°	W90.02194°	13	4
5	IHNC East Side, North Breach 9th Ward	N29.97873°	W90.02042°	14	4
6	Lakefront Airport Levee Transition Breach	N30.03367°	W90.02622°	14 with Site 7	3
7	Lakefront Airport Levee I-Wall	N30.03436°	W90.02641°	14 with Site 6	3
8	Structural Distressed I-Wall at Container Wharf	N29.98614°	W90.0272°	20	2
9	Incipient Earth Levee Failure	N30.00200°	W89.97500°	14	3
10	Entergy Plant I-Wall Scour	N30.00900°	W89.93171°	20	3



Source: Delorme TopoUSA

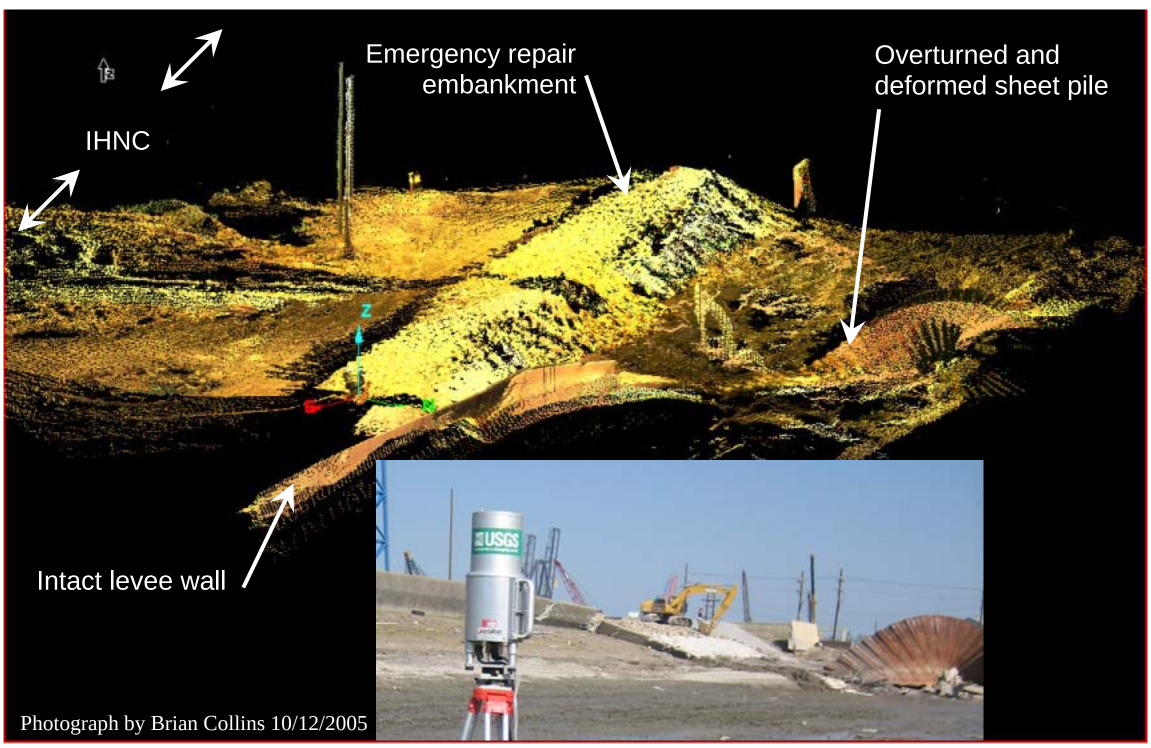
Figure 7.1: The ten sites investigated by the laser mapping method reside within the boundary of Orleans Parish.

Photograph by Robert Kayen 10/13/2005

Figure 7.2: Entergy Plant I-Wall scanned using the USGS Coastal and Marine Geology Team terrestrial LIDAR unit and tripod mounted to the roof of our field vehicle. The fixed roof base allowed for the leveling of the tripod and LIDAR instrument on sloping ground.

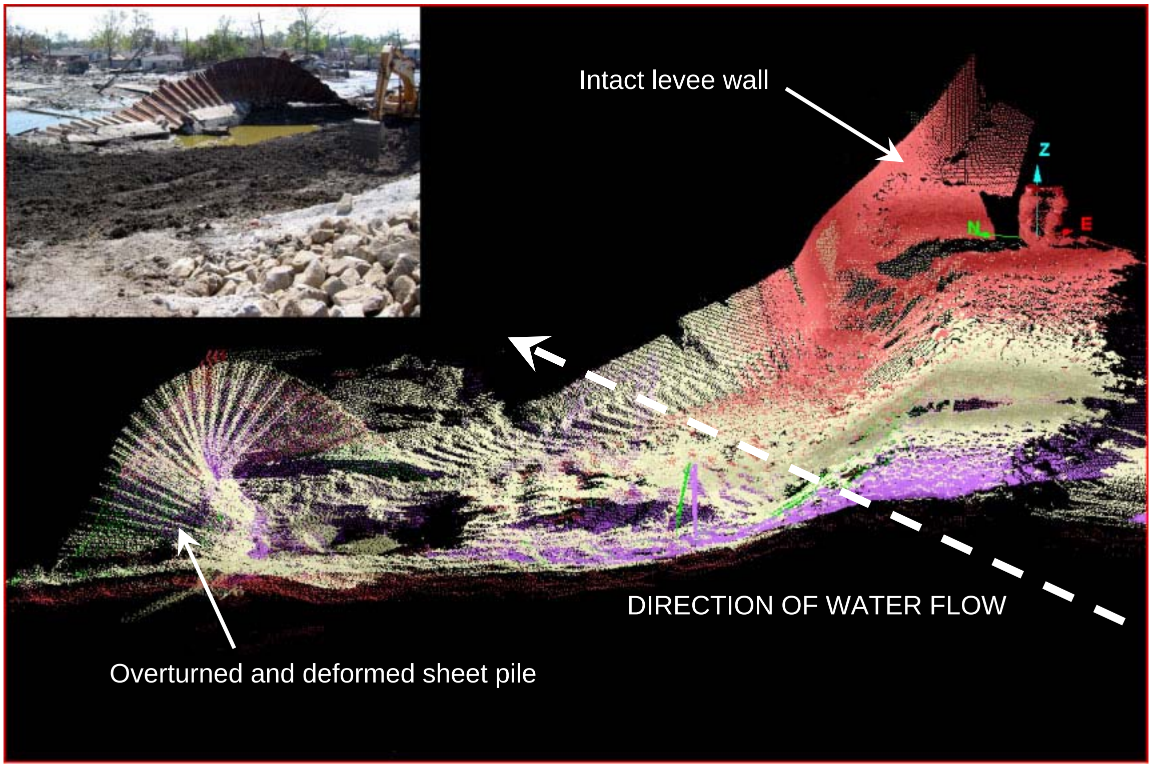
Photograph by Robert Kayen 10/10/2005

Figure 7.3: LIDAR scan system on top of the east I-wall at the London Avenue Canal. Scans of the canal side translational gap were made by placing the LIDAR on its side so the axis of rotation was horizontal.



Photograph by Brian Collins 10/12/2005

Figure 7.4. For complete coverage of the IHNC-North levee breach the laser was moved around objects that cast shadows. The sheet pile foundation and levee were imaged from both sides to complete the 3-D model.



Photograph by Robert Kayen 10/11/2005

Figure 7.5: From another perspective, four separate LIDAR scans can be seen in the merged data file, each colored separately to differentiate them (red; white, purple, green). At the IHNC - North Site, 14 scans were merged into a single composite file.

Source: Modified from http://ngs.woc.noa7.gov/storms/katrina/24425575.jpg

Figure 7.6. Site 1, 17th Street Canal: (N30.0172° W90.1214°)

Source: modified from Google maps

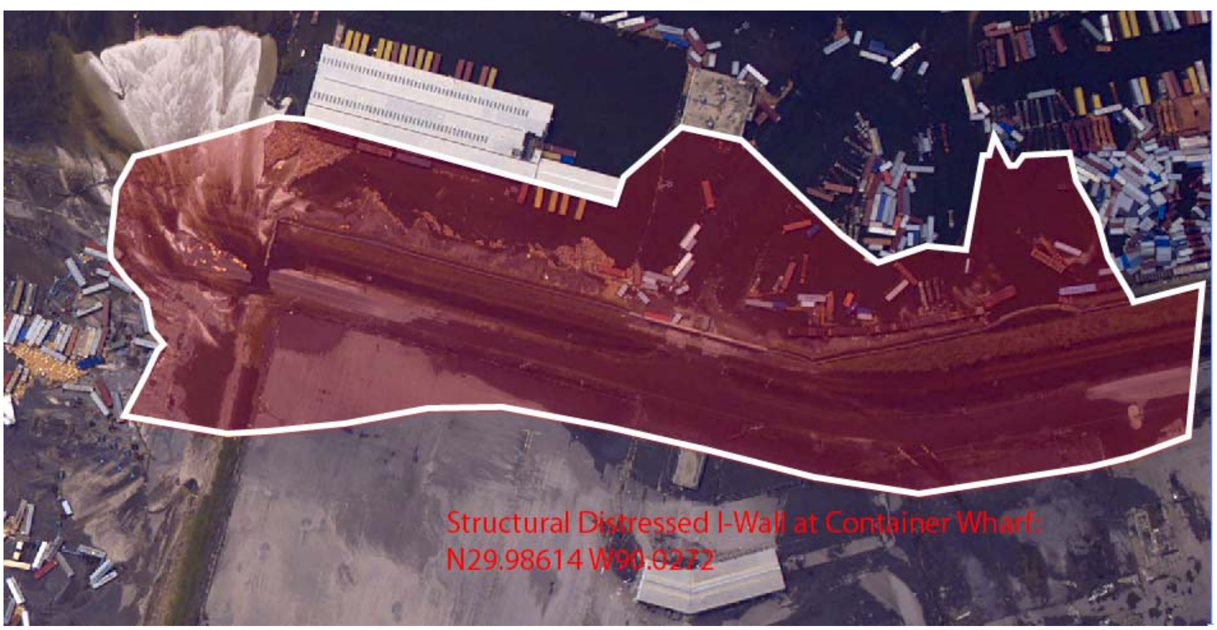
Figure 7.7: Sites 2 & 3, London Ave. Canal, North
on east side: (N30.0210° W90.0704°)
and west side: (N30.0206° W90.0708°).

Source: modified from http://www.digitalglobe.com/images/katrina/new_orleans_surekote_levee_aug31_2005_dg.jpg

Figure 7.8: Sites 4 & 5, IHNC – South Breach: N29.97243° W90.02194° IHNC North Breach: N29.97873° W90.02042°.

Source: Modified from http://ngs.woc.noaa.gov/storms/katrina/

Figure 7.9: Sites 6 & 7, Lakefront Airport Levee Transition Breach: (N30.03367° W90.02622°) and airport Levee I-Wall: (N30.03436°

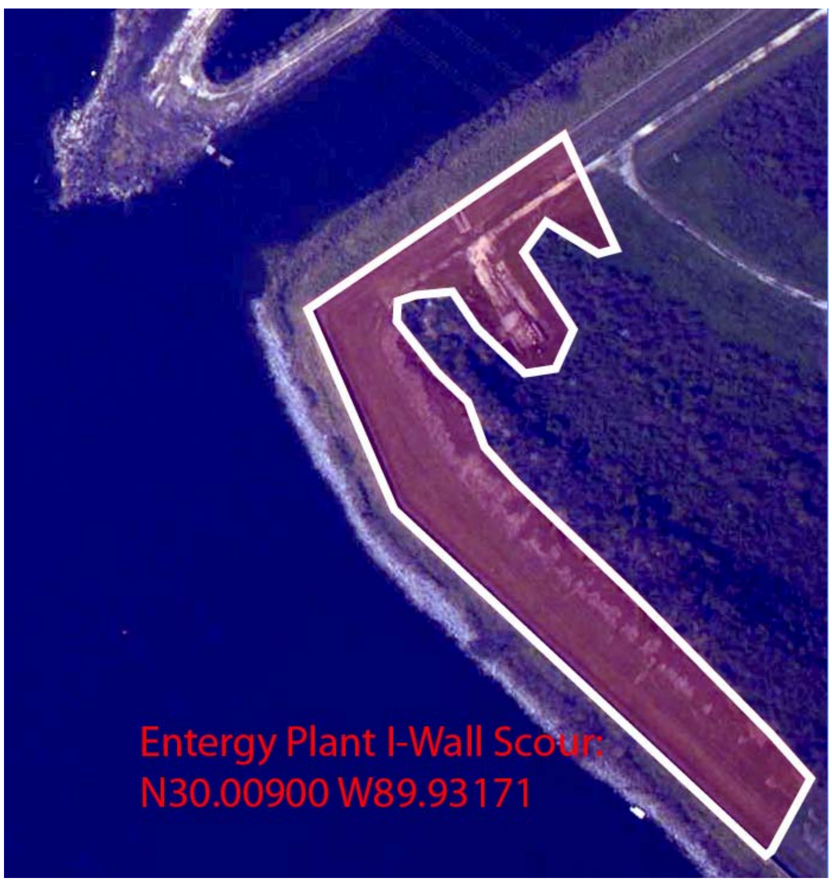


Source: Modified from http://ngs.woc.noa7.gov/storms/katrina/

Figure 7.10: Site 8, Structural Distressed I-Wall at Container Wharf: (N29.98614° W90.0272°)

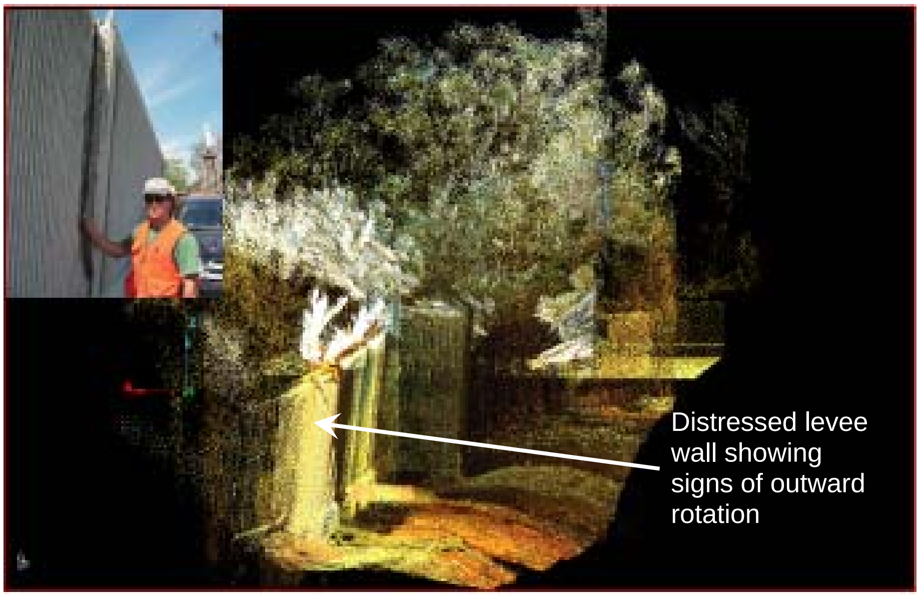
Source: Modified from http://ngs.woc.noaa.gov/storms/katrina/

Figure 7.11. Incipient Earth Levee Failure at N30.00200°, W89.97500°



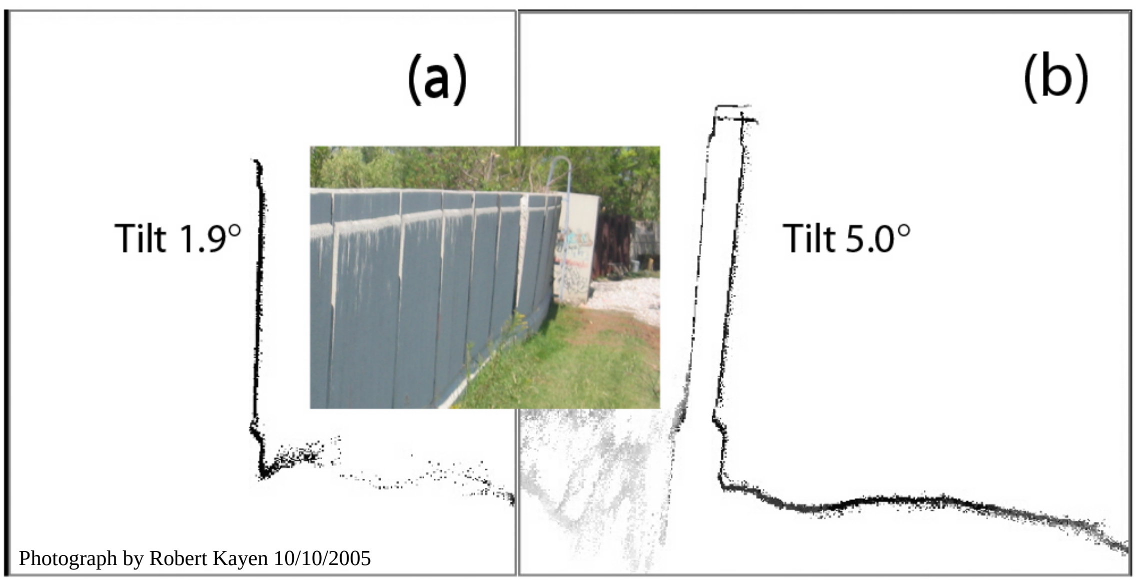
Source: Modified from http://ngs.woc.noaa.gov/storms/katrina/

Figure 7.12. Entergy Plant I-Wall Scour at N30.00900°, W89.93171°



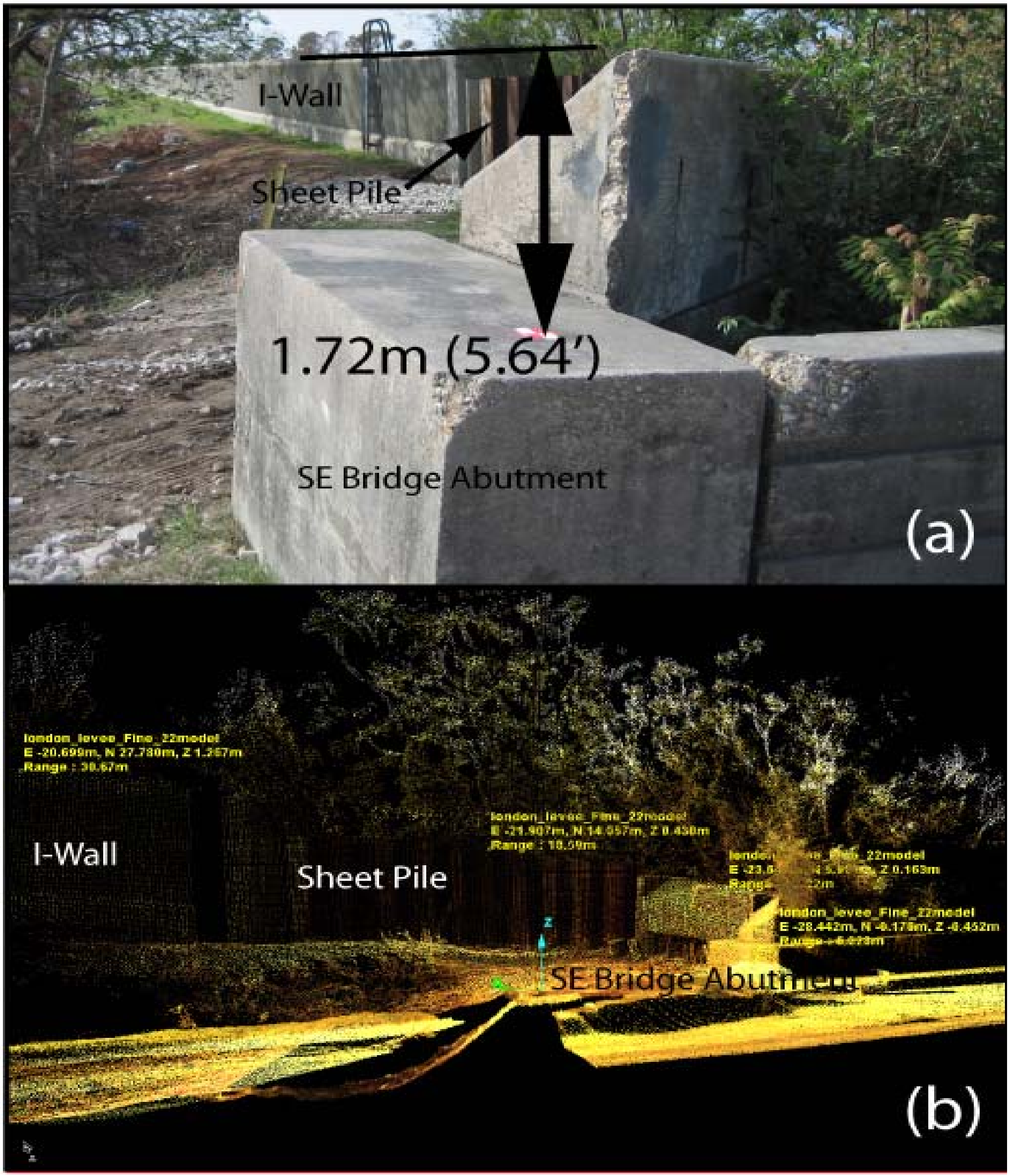
Photograph by Robert Kayen 10/10/2005

Figure 7.13: Leaning I-wall of a distressed portion of the London Avenue Canal. The wall leans toward the levee maintenance road and landside portion of the levee. In the right-most background is the abutment of the bridge on Robert E. Lee Blvd. along with vegetation on the canal side of the levee.



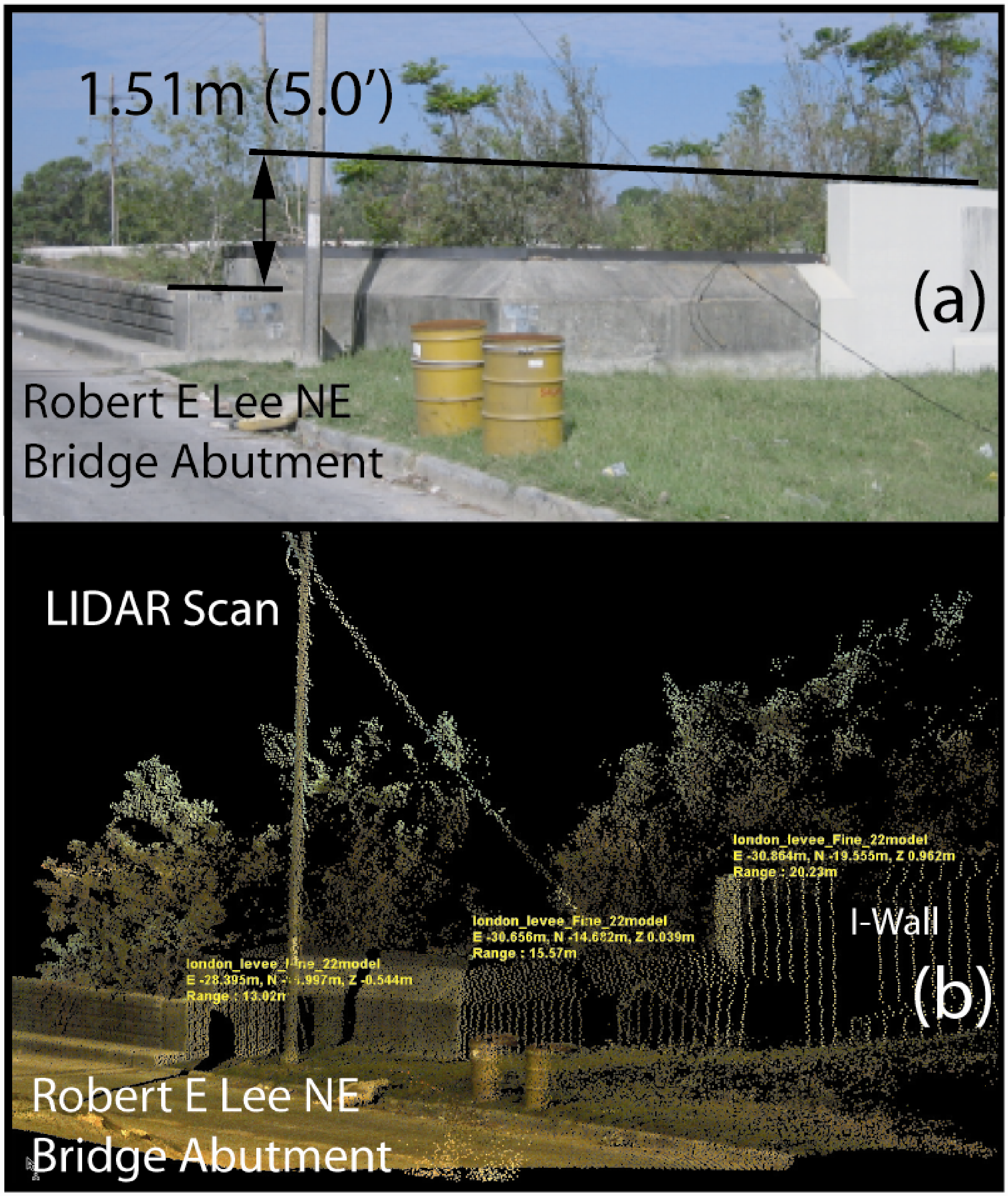
Photograph by Robert Kayen 10/10/2005

Figure 7.14: Cross sections through two segments of distressed I-wall at London Avenue Canal. Segment (a) is toward the south (left) of Figure 7.13 and has a modest 1.9 degree rotational deformation toward the landside of the levee. Near a position of maximum distress, the I-wall has 5.0 degrees of rotational deformation.



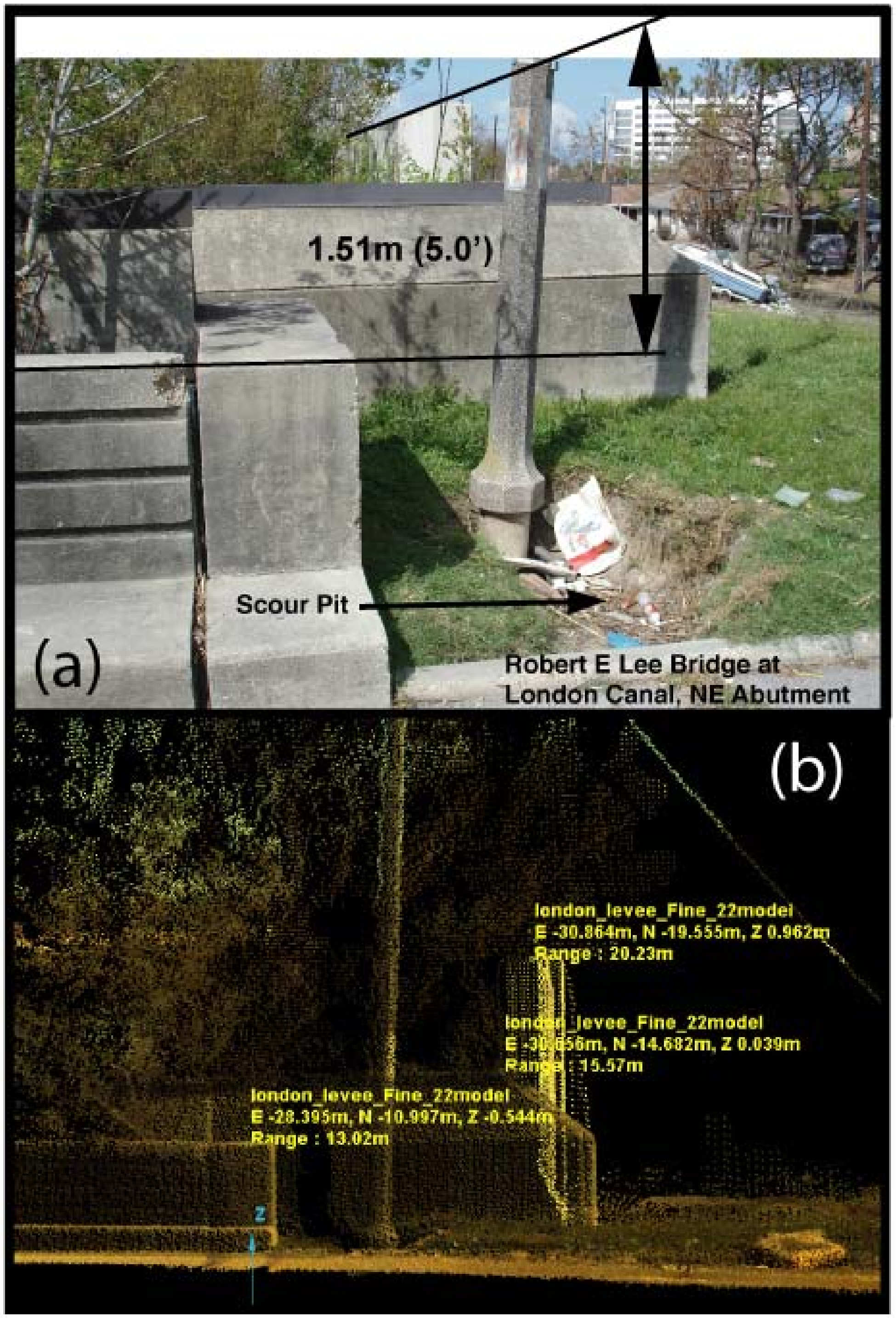
Photograph by Brian Collins 10/11/2005

Figure 7.15: Photograph of the southeast abutment of the London Avenue Canal bridge at Robert E. Lee Blvd (a), and LIDAR scan of the same location (b). New soil and rock apparently fills scour and sink hole erosion beneath the abutment. The relative height gap between the bridge abutment and the flood wall is 1.72 meters (5.6 feet).



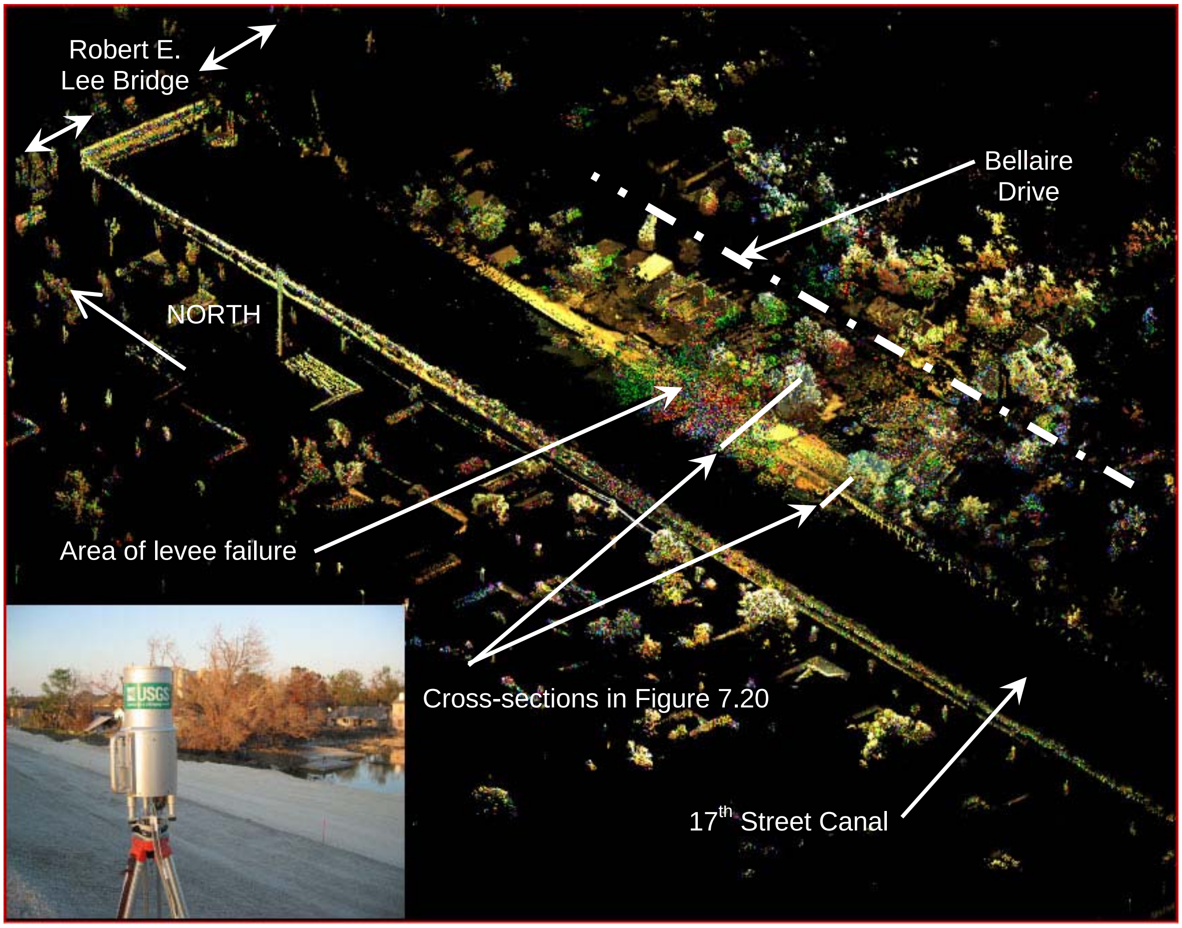
Photograph by Brian Collins 10/11/2005

Figure 7.16: The northeast abutment of the London Avenue Canal bridge on Robert E. Lee Blvd. in photograph taken from the lower portion of the bridge approach-fill embankment (a), and corresponding LIDAR scan (b). The wall gap here is 1.51 meters (5.0 feet).



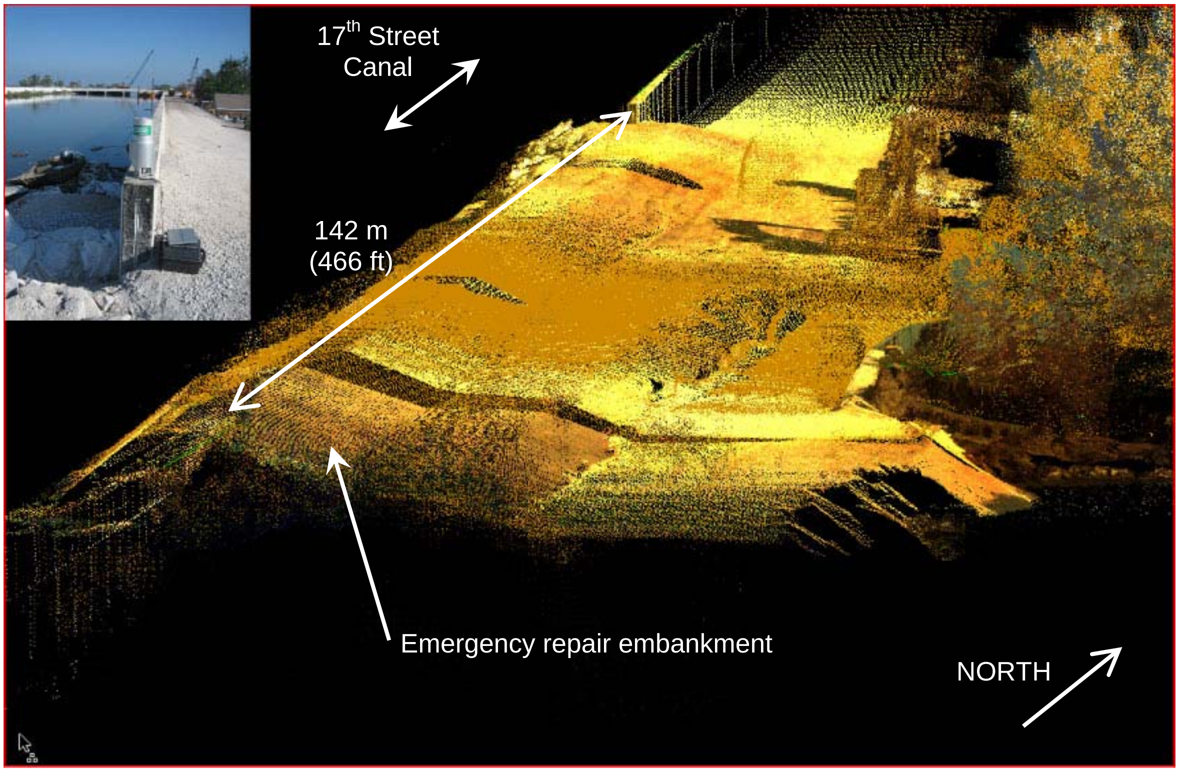
Photograph by Lee Wooten

Figure 7.17: Photograph taken directly south and adjacent to the northeast abutment of the Robert E. Lee Bridge (a), and corresponding LIDAR scan of the same location (b). A scour trench is clearly visible beneath the abutment. The wall gap here is 1.51 meters (5.0 feet).



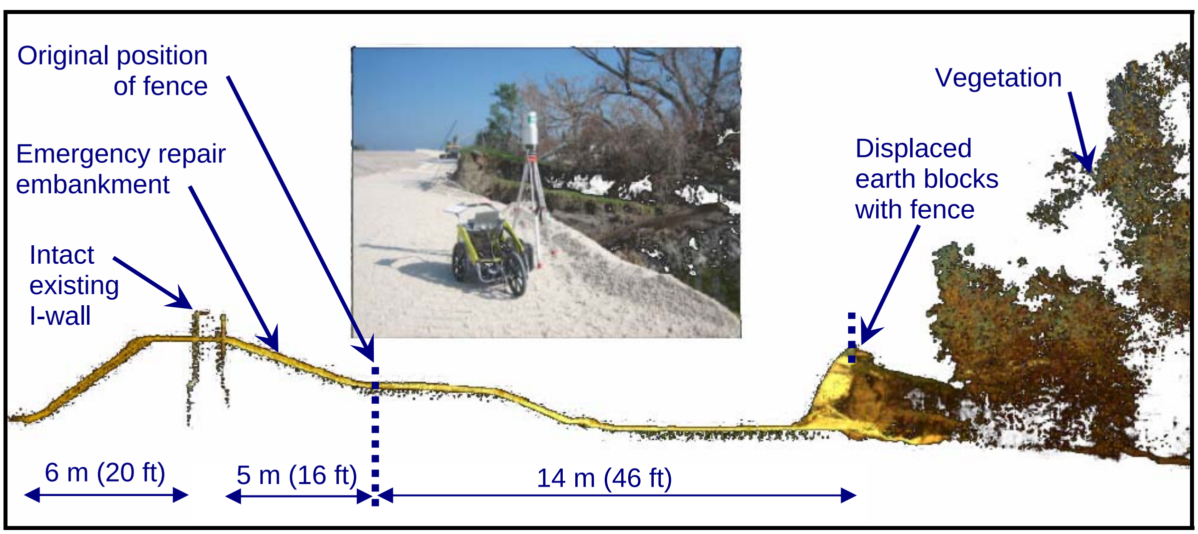
Photograph by Robert Kayen 10/9/2005

Figure 7.18: Overview oblique image of the 17th Street Canal area in the vicinity of the breach. The Robert E. Lee Blvd. Bridge is to the north (upper left) and the breach area is to the upper right (east). Houses within the neighborhood breach area and the scour pond were imaged from the new levee and Bellaire Drive.



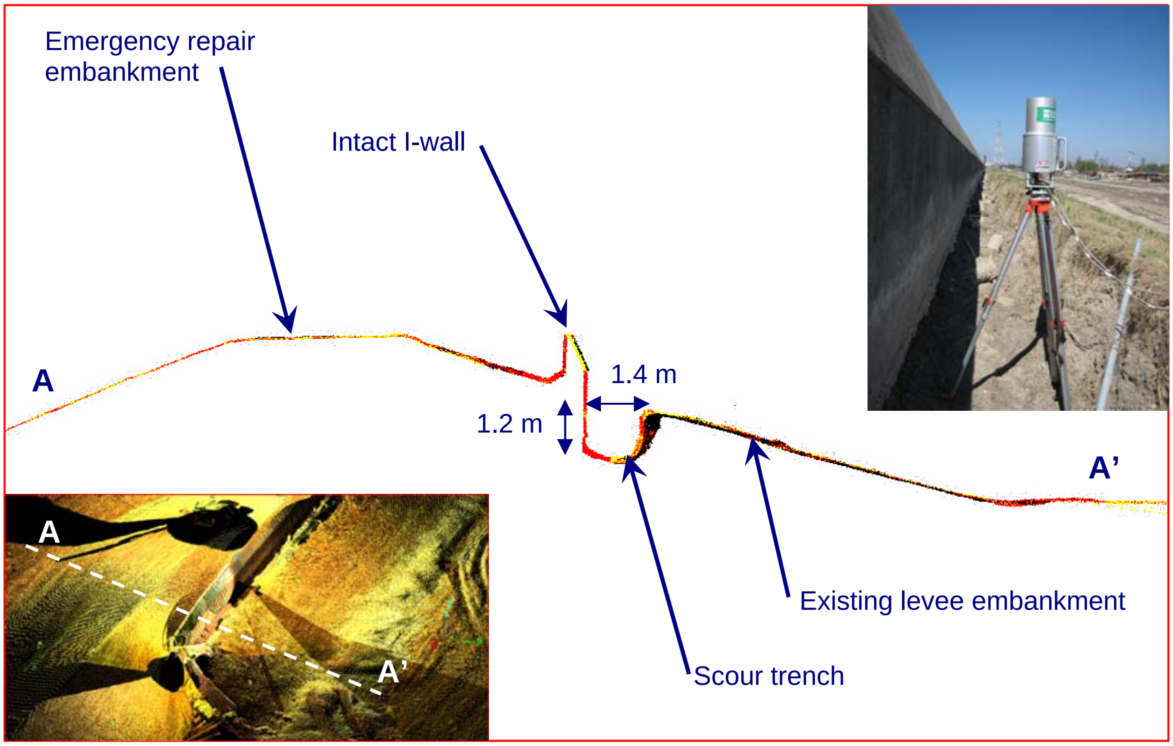
Photograph by Brian Collins 10/10/2005

Figure 7.19. An oblique close-in image of the as built replacement levee at the 17th Street Canal breach from the south. The remaining I-wall is visible on either side of the earthen embankment.



Photograph by Brian Collins 10/10/2005

Figure 7.20 Cross-section of the 17th Street Canal breach looking northward. Measurement of the lateral translation of the landside soil levee from its original position is approximately 14 meters (46 ft). The I-wall in this image is offset (out of the page) from the slide block.



Photograph by Brian Collins 10/11/2005

Figure 7.21: Measurement of scour trench dimensions at the IHNC – South site.

Chapter Eight: Summary of Observations and Findings

8.1 Summary and Findings

The storm surges produced by Hurricane Katrina resulted in numerous breaches and consequent flooding of approximately 75% of the metropolitan areas of New Orleans. Most of the levee and floodwall failures were caused by overtopping, as the storm surge rose over the tops of the levees and/or their floodwalls and produced erosion that subsequently led to failures and breaches.

Overtopping was most severe on the east side of the flood protection system, as the waters of Lake Borgne (which is directly connected to the Gulf of Mexico) were driven west producing a storm surge on the order of 18 to 25 feet that massively overtopped levees immediately to the west of this lake. A second very severe storm surge occurred farther to the south, along the lower reaches of the Mississippi River, and significant overtopping produced additional breaches in this region as well.

Overtopping was less severe along the Inner Harbor Navigation Canal and along the western portion of the Mississippi River Gulf Outlet/Gulf Intracoastal Waterway, but overtopping along these channels again produced erosion and caused additional levee failures.

Field observations suggest that little or no overtopping occurred along most of the levees fronting Lake Pontchartrain, but evidence of minor overtopping and/or wave splashover was observed at a few locations. One breach occurred in the lakefront levee system at the northwest corner of the New Orleans East protected area, near the Lakefront Airport.

Farther to the west, in the Orleans East Bank Canal District, three levee failures occurred along the banks of the 17th Street and London Avenue Canals, and these failures occurred at water levels below the tops of the floodwalls lining these canals. These three levee failures were likely caused by failures in the foundation soils underlying the levees, and a fourth "distressed" levee/floodwall segment on the London Avenue Canal shows signs of having neared the occurrence of a similar failure prior to the water levels having receded.

One common mode of both failure and damage was the erosion of soils at the land side toes of floodwalls as water cascaded over the tops of the concrete floodwalls atop the earthen levees. This was a problem at many I-walls, but was not a problem at most T-walls where the concrete base stems of the inverted T-wall sections acted to deflect the overtopping waters. T-walls also were constructed with more substantial and robust foundations. At a number of I-walls, the waters overtopped and then cascaded down the inboard side, producing very sharply etched erosional trenches, of varying depths, in the soils at the land side toes of the walls. That erosion reduced the lateral soil support otherwise offered at the land side sides of the walls, and reduced the walls' ability to withstand the elevated lateral forces exerted by the storm surge on their water sides.

A second issue noted at a number of both failed and distressed levee sites was an inconsistency in crest heights when multiple flood protection system elements came together. Often there were differences in crest heights between earthen embankment sections and adjacent concrete structural sections. Sometimes two adjacent concrete wall sections differed significantly in height.

Considerable erosional distress, and a number of failures, were noted at transitions between earthen levee and concrete structural segments. Many of these areas of erosion appeared likely to have been related to inadequate transition details (e.g. insufficient overlap, etc.), but these were also commonly exacerbated by inconsistencies in crest heights that tended to concentrate overtopping flows at vulnerable transition locations.

Another repeated issue noted in these field investigations was the potential hazard posed by penetrations through the perimeter flood protection systems required in order to permit through passage of trains or other surface transit (e.g. roads, port vehicles, etc.) These penetrations produced additional transitions between disparate sections, and also created the potential for overlapping or disjoint responsibilities among the authorities/agencies/owners at adjoining perimeter flood protection elements. At sections where infrastructure elements were designed and maintained by multiple authorities, and where their multiple protection elements came together, the weakest (or the lowest) segment or element controlled the overall performance.

Finally, three major breaches, and at least one significantly "distressed" levee/floodwall section, occurred at sites along the 17^{th} Street and London Avenue Canals where the levees and floodwalls were clearly not overtopped. Currently available evidence suggests that the flood surge at these sites was on the order of 2 to 5 feet short of overtopping the floodwalls at these locations. Observations made at the sites of the 17^{th} Street Canal breach and the north breach on the London Avenue Canal suggest that these failures were likely the result of stability failures within the embankment or foundation soils at or below the bases of the earthen levees. This would be consistent with instability due to underseepage flow, and resultant hydrostatic uplift and reduction of shear strength at the bases of the inboard sides of the earthen levee embankments, as well as the lateral "push" exerted against the sheetpile/floodwall diaphragms by the elevated waters on the canal sides of these wall systems. Evidence of piping erosion at the London Avenue Canal (north) breach, and at the distressed section directly across from this breach on the east bank, serves to illustrate the severity of the underseepage at high water stages. Another possibility that also needs to be investigated, however, is the potential presence of a weak stratum or soil unit (either within the lower embankment, or in the underlying foundation soils) with sufficiently low shear strength that it might have failed even without weakening due to underseepage flows. A third possibility at the north breach on the London Avenue Canal is that piping and internal erosion may have directly been the cause of failure, and this also needs to be investigated.

The third breach site (London Avenue Canal, south breach) was massively eroded, leaving relatively little evidence to examine, and it is less clear what the failure mechanism was at this location. Instability of the inboard side of the earthen levee embankment, again possibly associated with underseepage and the lateral push of the outboard side canal water levels, or with seepage erosion and piping, would be consistent with the data and observations made at this site, however, and with photos taken shortly after the failure.

Additional studies will be performed at most of the breached and distressed locations. These supplemental studies will enable better definition of embankment and foundation soil conditions and appropriate seepage flow and shear strength characteristics. The precise soil strata and most critical mechanisms that led to the observed failures at a number of sites remain to be conclusively determined.

Significant additional field investigations (including CPT probes, borings and sampling, etc.) as well as laboratory testing are already underway under the auspices of the USACE at many of the key sites, and the USACE has agreed to openly share the results of these field and laboratory studies with our investigation teams.

Similarly, the ASCE and NSF-sponsored investigation teams have met a number of times with the USACE levee investigation team from ERDC, as well as with representatives from the New Orleans District of the USACE, and have jointly developed lists of requested background documents including site investigation reports and boring logs, laboratory test data, design memoranda (including original design calculations and analyses), as-built section specifications and details, maintenance and field inspection records, etc. for many of the breached and heavily distressed levee and/or floodwall sections, and the USACE has promised to provide these as quickly as practicable.

8.2 Comments on Future Reconstruction

Major repair and rehabilitation efforts are underway to prepare the New Orleans Flood Protection System for future high water events. The next hurricane season will begin in June of 2006. Preparing the levees for the next hurricane season, however, should also include a review of how the system performed during Hurricane Katrina, so that key lessons can be learned and then used to improve the performance of the system.

Based on our observations, a number of initial comments are warranted concerning the rebuilding and rehabilitation of the levee system.

Although it is somewhat customary to expect levee failures when overtopping occurs, the performance of many of the levees and floodwalls could have been significantly improved, and some of the failures likely prevented, with relatively inexpensive modifications of the levee and floodwall system details. The addition of overtopping erosion protection at the land sides of the floodwalls through the provision of rip-rap, concrete splash slabs, or even paving of the ground surface at the inboard faces of the levee crest floodwalls might have been effective in reducing this erosion, and might have prevented some of the failures observed.

As the New Orleans regional flood protection system is now being repaired and rebuilt, it would appear advantageous to plan crest heights in a systematic and deliberate way, so that if and when overtopping does occur, it occurs preferentially at the desired locations along any given section of levee/floodwall frontage. Sections designed to better resist overtopping and erosion should take the larger share of the overtopping flows. Similarly, the transitions between disparate levee/floodwall sections (e.g.: transitions between earthen levees, sheetpiles, and/or concrete wall sections) should be more robustly designed and constructed (e.g. with more pronounced overlap, or embedment, of transitional sheetpile walls within adjacent earthen levee sections, etc.), so that such transitions do not represent locations of potential weakness in otherwise contiguous perimeter flood protection system.

Regardless of the modes or causes of the various failures, it should be also be noted that emergency operations to close some of the breaches were seriously hampered by the difficult access to the breach sites. The USACE's EM 1110-2-1913, "Design and Construction of Levees," Section 8-9, specifically addresses access roads on levees, and their need for "the general purpose of inspection, maintenance and flood-fighting operations." The majority of the levee miles constructed by the USACE in the United States meet these requirements.

In the case of New Orleans, which likely had one of the most developed urban areas behind any USACE levee system, most capability for high-level access at many locations had been foregone when it was decided to put the I-walls in the existing levee crowns without widening the crowns for vehicle access. Such widening would probably have required additional right-of-way in many of the developed areas. When the need for emergency operations arose, many years later, these decisions resulted in very significant increases in time and cost to effect the needed closures and repairs.

Areas in which piping erosion occurred, including reported instances of piping along the MRGO frontage, suggest that there are areas of foundation that were weakened to a state worse than "pre-Katrina" conditions. Similarly, there may be additional sections like the west bank across from the North breach on the east side of the London Avenue Canal that were distressed (but did not fully breach) and are in need of remedial work. It is important, as part of the current repair operations, to remember to thoroughly inspect, and to repair as necessary, levee sections that may have been damaged but that did not fail.

Levees are "series" systems, where the failure of one component (levee segment) equates to failure of the system. They have less redundancy than many other engineered systems. In the case of the canal levees, the three "weakest links" failed, and the "fourth weakest link" (near the north end of the London Avenue Canal, on the east bank) experienced a near failure. Should these and any other damaged sections be repaired, the fact remains that the "next weakest link" (and so on) has not yet been tested to its design water height. The failure of these levees at less than their design water height warrants an overall review of the design of the system.

In the short-term, as interim levee repairs continue, consideration should be given to retaining the use of sheetpiles placed against the bridges at the north ends of the 17th Street and London Avenue Canals to control storm and tidal surges. Until the levees in these canals are more fully repaired and/or more permanent canal surge check structures are emplaced, having the ability to rapidly prevent storm surges down these canals is still needed.

The USACE, like many public agencies, uses Independent Boards of Consultants to review the adequacy of the design and construction (and remediation) of major water resources, including major dams. The levee system in New Orleans is critical to the public health, safety and welfare of its residents, and actually protects more life and property than most major dams in the United States. We recommend that the Corps should retain an

Independent Board of Consultants to review the adequacy of the interim and permanent levee repairs being carried out in the aftermath of Hurricane Katrina.

The ASCE and NSF-sponsored levee assessment teams have already been instrumental in providing insights and recommendations for mitigating potentially serious deficiencies in the temporary/emergency repairs at a number of breached sections. It is anticipated that additional potentially important lessons will be learned in the months ahead as these investigations continue, and that some of these lessons are also likely to be useful in moving forward with the ongoing repair and long-term rebuilding of the New Orleans regional flood protection systems. As much of the population is currently being permitted to re-occupy portions of the New Orleans area, doing everything possible to ensure the safety of these people and their neighborhoods must continue to be the highest priority.

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