Overview of New Orleans Levee Failures: Lessons Learned and Their Impact on National Levee Design and Assessment

G. L. Sills, P.E., M.ASCE[1]; N. D. Vroman, P.E.[2]; R. E. Wahl, P.E., M.ASCE[3]; and N. T. Schwanz, P.E.[4]

Abstract: This paper provides an overview of the Southeast Louisiana Flood and Hurricane Protection System that was in place at the time of Hurricane Katrina. Both geography and components of the system are described. A brief description of the development of the storm, the major damage caused, and lessons learned are discussed.

DOI: 10.1061/(ASCE)1090-0241(2008)134:5(556)

CE Database subject headings: Levees; Failures; Risk management; Louisiana.

Hurricane Katrina made landfall on August 29, 2005, just east of New Orleans, and inflicted widespread damage on the Hurricane Protection System (HPS) for southeast Louisiana. The storm surge produced by Hurricane Katrina in some cases overwhelmed the HPS beyond its design, but in other cases levee failures occurred at water levels well below their design due to the combination of misinterpretation of geologic conditions and an unforeseen failure mechanism.

Almost immediately after the realization that various components of the system had failed, the U.S. Army Corps of Engineers (USACE) responded through an intensive mode of emergency operations. Even while rescue operations were ongoing, the entire system was surveyed by air to determine the condition of the system and to assess the extent of the damage. The survey was followed by planning for closure of the breaches and "unwatering" of the flooded areas.

The response to this disaster by USACE also included forming an Interagency Performance Evaluation Taskforce (IPET) to study the response of the system and, among many lines of inquiry, to identify the causes of failure and poor performance of levees and floodwalls. Beginning in September 2005, the IPET gathered forensic evidence and geotechnical data from failed portions of levees and floodwalls. These data were considered perishable and had to be gathered quickly due to levee rebuilding operations.

The performance of the levee and floodwall system provided valuable lessons demonstrating the need for resilience of the HPS, risk-based planning and design, and the deficiency of knowledge in the technology and expertise needed in the hurricane protection system arena. The failure of the HPS also showed the need for the system to move from concept to reality as rapidly as possible as certain parts of the system were not complete at the time of Hurricane Katrina. The rebuilding efforts and future assessments and designs of hurricane protection systems will incorporate these lessons learned.

New Orleans Levee System

History of Hurricane Protection System

Performance of the flood protection measures intended to protect the New Orleans area is a consequence of its storied history, synopsized in this section from several references, including Camillo (C. A. Camillo, personal communication, 2006), Elliott (1932), and Maygarden et al. (1999).

In 1699, two French explorers, Pierre Le Moyne d'Iberville and his younger brother, Jean-Baptiste Le Moyne de Bienville discovered an Indian portage between Lake Pontchartrain and the Mississippi River. Bienville later founded what is now known as the City of New Orleans on this site in 1718. The story that has been handed down through history is that the royal engineer of King Louis XIV, Sieur Blond de la Tour, advised against settling on this area of land because of the terrain. Over thousands of years, the Mississippi River has periodically overflowed its banks and deposited sediment, primarily sand and silt, between its bank and the active floodplain. These deposits formed a ridge paralleling the river channel boundaries and are referred to as "natural levees." Bienville continued his plans for the city and began its development along one of the river's bends. The development

---

[1] Geotechnical Engineer, Geotechnical and Earthquake Engineering Branch (GEEB), Geosciences and Structures Division (GSD), Geotechnical and Structures Laboratory (GSL), U.S. Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC), 3909 Halls Ferry Rd., Vicksburg, MS 39180-6199. E-mail: george.l.sills@erdc.usace.army.mil

[2] Geotechnical Engineer, Geotechnical and Earthquake Engineering Branch (GEEB), Geosciences and Structures Division (GSD), Geotechnical and Structures Laboratory (GSL), U.S. Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC), 3909 Halls Ferry Rd., Vicksburg, MS 39180-6199 (corresponding author). E-mail: noah.d.vroman@erdc.usace.army.mil

[3] Geotechnical Engineer, Airfields and Pavements Branch, Engineering Systems and Materials Division, GSL, USACE ERDC, 3909 Halls Ferry Rd., Vicksburg, MS 39180-6199. E-mail: ronald.e.wahl@erdc.usace.army.mil

[4] Geotechnical Regional Specialist, USACE, St. Paul District, Sibley Square at Mears Park, 190 Fifth St. East, Suite 401, St. Paul, MN 55101-1638. E-mail: neil.t.schwanz@usace.army.mil

Note. Discussion open until October 1, 2008. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on April 14, 2007; approved on January 29, 2008. This paper is part of the ***Journal of Geotechnical and Geoenvironmental Engineering***, Vol. 134, No. 5, May 1, 2008. ©ASCE, ISSN 1090-0241/2008/5-556–565/$25.00.

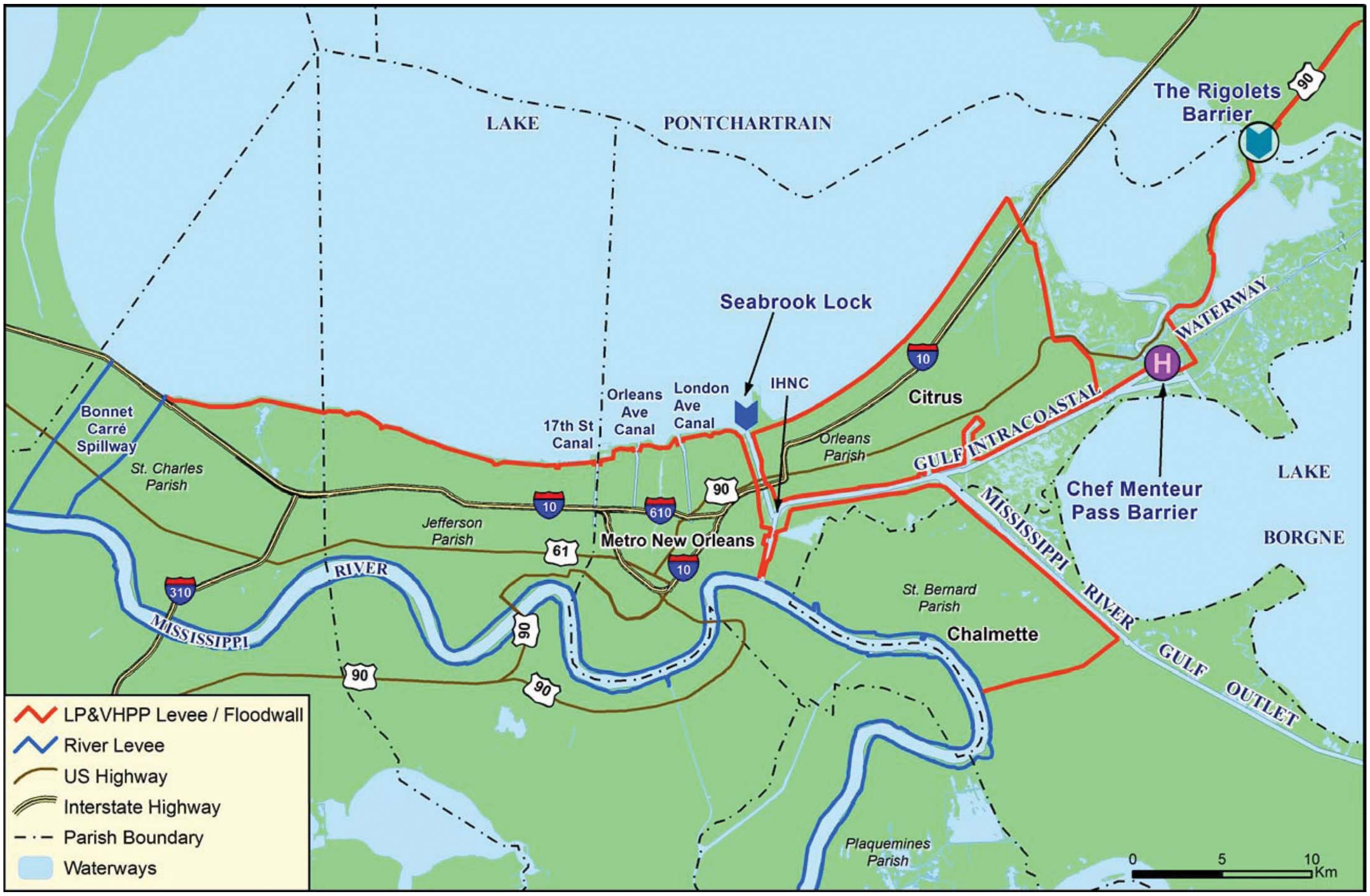

Fig. 1. Map of 1965 "barrier plan" (adapted from Woodley and Shabman 2007)

along this higher ground and within this river bend came to be known as the "Crescent City." The city found itself surrounded by the Mississippi River on one side and swampland, which is below sea level, on the other side. These conditions gave little room for city growth and contributed to frequent flooding of the city.

The problems brought on by flooding from occasional Gulf storms and floods from the Mississippi River convinced the French settlers to construct some private levee systems. These private systems grew and became combined by 1735 into a much larger system, which stretched from approximately 30 mi. above New Orleans to about 12 mi. below the city. The earliest Federal participation in these efforts included establishment of the Mississippi River Commission in 1879 and the Mississippi River and Tributaries (MR&T) Project in 1928 (IPET 2006, Vol. III). The MR&T project helped improve the levees along the Mississippi River. Local interests continued to expand the interior private system and by 1925 the interior system had grown into a system that served 30,000 acres. This system was a network consisting of approximately 560 mi. of canals, drains, and pumping stations. The total pumping capacity of this system was reported to be about 13,000 cfs. As these measures were undertaken, the quality of life was greatly improved and the flood protection system became a model for the protection of low-lying regions worldwide. With the construction of this interior flood protection system the city began to expand outward from the higher ground close to the river into the lower swamp area near Lake Pontchartrain.

The next attempt by the United States Congress to address the flood protection problem in New Orleans was the passing of the Flood Control Act of 1946. This act authorized levees to be constructed along Lake Pontchartrain to protect Jefferson Parish from 30-year frequency storm-induced flooding from the lake.

In March 1964, the USACE submitted a flood protection plan to Congress that later became known as the "barrier plan," which is a plan that consisted of many features but included a number of barrier complexes. This plan served as the basis for the feasibility report for the current hurricane protection project. On September 9, 1965, Hurricane Betsy struck New Orleans and the Louisiana area, causing major flooding, loss of life, and property damage. One month after this storm, Congress then authorized the "barrier plan" within the Flood Control Act of 1965. A map of the 1965 "barrier plan" is shown in Fig. 1. Nevertheless, with the effects of the storm still lingering, the Corps was sued over the authorized hurricane protection plan referred to as the "barrier plan." These lawsuits forced the Corps to change to the so-called "high level plan," which is a plan to provide protection solely by raising and strengthening levees and floodwalls. The "high level" plan was studied with two alternatives. One was to provide gates at the canal entrances at the lake and the other proposed raising the levees/floodwalls along the canals. The second alternative became known as the "parallel protection plan" and was mandated by congress in 1992 for construction.

Another important feature of the "barrier plan" was the construction of gates at the entrances to Lake Pontchartrain. Federal courts had stopped this concept so this plan had been abandoned in favor of the high level plan as presented in the 1984 Re-Evaluation Study by USACE. The entire authorized hurricane protection system was not scheduled for completion until 2015.

Hurricane Katrina Impact

Forty years had elapsed since New Orleans and the surrounding areas had experienced a major storm. For this reason, it seems likely that many residents had become a little complacent about Gulf storms. It is also likely that not many were concerned with the reports of the tropical depression that was forming over the central Bahamas on August 23, 2005. Knabb et al. (2005) wrote a detailed description of the synoptic history of Katrina, and the following is a summary of their report.

By early morning on August 24, a tropical depression became Katrina, the 11th tropical storm of the 2005 Atlantic hurricane season. On August 25, Katrina turned toward southern Florida and reached hurricane status close to midnight. Katrina, now classified as a Category 1 (Saffir–Simpson scale) hurricane, made its first landfall near the border of Miami-Dade County and Broward County. Katrina moved west-southwest overnight and only spent about 6 h over land, mostly the water-laden Everglades. The storm then weakened to a tropical storm. The tropical storm emerged into the southeastern Gulf of Mexico just north of Cape Sable on August 26.

Once back over the water, Katrina quickly regained hurricane status with maximum sustained winds of 65 knots (knots is a unit of velocity equal to 1 nautical mi/h, which is about 1.15 statute mi./h). The intensity of the storm continued during the day, and late on August 26, Katrina first became a Category 2 storm with maximum sustained winds of 83 knots. The storm tracked mostly westward, occasionally decreasing slightly in intensity. On August 27, Katrina became a Category 3 storm with 100 knot winds and was situated 365 nautical mi. southeast of the mouth of the Mississippi River. During the day, the inner wall deteriorated and a new outer eyewall formed and the intensity leveled off. With the deterioration of the inner eyewall the wind force expanded. Katrina nearly doubled in size on August 27 and by the end of the day tropical storm force winds extended up to about 140 nautical mi. from its center. On August 28, Katrina strengthened from a low-end Category 3 hurricane to a Category 5 hurricane in less than 12 h, with winds reaching 145 knots. By late in the day on August 28, the tropical storm winds extended 200 nautical mi. from the center, and hurricane-force winds extended about 90 mi. This made Katrina not only extremely intense but also exceptionally large.

On August 28, Katrina turned northward toward the northern Gulf Coast. The hurricane, with winds of about 110 knots, made landfall on August 29 at 6:10 a.m. as an upper end Category 3 storm near Buras, La. Katrina continued northward and made its final landfall near the mouth of the Pearl River at the Mississippi/Louisiana border as a Category 3 hurricane of 105 knots. Katrina remained very large as it weakened. Katrina weakened rapidly after moving inland and became a Category 1 hurricane by approximately 6:00 p.m. on August 29, eventually weakening to a tropical storm just 6 h later just northwest of Meridian, Miss.

During the 12 h period prior to Katrina making its final landfall, the storm had pushed a large volume of water against the Mississippi River delta and the east-facing levees along the Mississippi River. The storm then pushed that volume of water northward with hurricane strength winds toward the Mississippi coast and into Lakes Borgne and Pontchartrain (IPET 2006, Vol. IV). Katrina brought the highest storm surge (28 ft) ⟨http://www.hq.usace.army.mil/history/Hurricane_files/Hurricane.htm⟩ and highest waves (55 ft) ⟨http://www.ndbc.noaa.gov/hurricanes/2005/katrina⟩ ever recorded to hit the North American continent. Details of storm surge and wave height with respect to levee overtopping can be found in IPET Volumes 3 (Geodetic vertical and water level datum) and 8 (Engineering and operational risk and reliability analysis). In addition, levee overtopping amounts and deficiencies in pre-Katrina levee elevations with respect to original design elevations can be found in Woodley and Shabman (2007).

In most cases, Katrina generated surge and waves that greatly exceeded the intended design criteria of the HPS. There were 50 major breaches in the HPS during Katrina; however, all but four were caused by overtopping and erosion. These four breaches, in the outfall canals and Inner Harbor Navigation Canal (IHNC), occurred where I-type floodwalls breached well before water levels reached the top of the wall. In some cases, these breached at water levels below the intended design for wall freeboard.

Shortly after the storm, the Chief of the USACE formed a group to perform an in-depth analysis of the HPS for New Orleans and southwest Louisiana. This group became known as the IPET. The Assistant Secretary of the Army and the Chief of Engineers also charged the IPET to conduct this study in an open environment and to keep the public informed. The IPET consisted of about 150 engineers and scientists who came from the government (primarily the USACE), academia, and the private sector. These engineers and scientists were divided into ten teams that were responsible for: (1) the collection and management of perishable data and information; (2) the study of geodetic vertical and water level datum assessment; (3) hurricane surge and wave analysis; (4) hydrodynamic force analysis; (5) geotechnical structure performance analysis; (6) floodwall and levee performance analysis; (7) pumping station performance analysis; (8) interior drainage and flooding analysis; (9) consequence analysis; and (10) risk and reliability analysis.

While conducting the study, the IPET also was tasked to transfer knowledge and lessons learned to New Orleans so this study could be used to repair and reconstruct the HPS, which was the duty of the USACE task force guardian (TFG). To help with this task, the USACE New Orleans District, Task Force Hope, and TFG all assigned individuals to serve on the IPET. The IPET's work was reviewed on a weekly basis by a panel of specialists from the ASCE to assure technical scrutiny and to evaluate the quality of the engineering analysis. In addition to this review group, the National Research Council (NRC) Committee on New Orleans Regional Hurricane Protection Projects was tasked with strategic oversight and review. The key objectives of IPET were to understand the engineering behavior of the hurricane protection projects and failure mechanisms, and to apply that knowledge to the reconstruction of a more reliable and resilient system.

Overtopping and Breaching Timeline

The following is a summary of the findings of the water level and eyewitness account studies conducted by IPET (IPET 2006, Vol. IV). The primary purpose of these efforts was to aid in the development of a timeline for the overtopping and breaching of the hurricane protection system. With respect to the eyewitness accounts, over 600 people were contacted and over 200 interviews (usually face to face and at the location of eyewitness account) were conducted with people who observed flooding induced by Hurricane Katrina. Other means of establishing the timing of events included documentation of stopped clocks found in residences and the collection of videos and still photos.

As is expected in a study of this magnitude, there are often discrepancies in the data that must be addressed. The most reliable data came from the time-stamped digital photographs and videos where the flooding (locations, elevations, directions of flows, etc.) are clearly evident and documented. The next level of reliability is a log where an individual recorded events and times during the storm. Stopped clock data often provided critical insight into the timing of events, but there was also uncertainty in these data. This study indicated how the hurricane protection system performed as Katrina hit the city. The summary presented in this paper relates to the following five sites only:

1. 17th Street Canal;
2. London Avenue Canal-South;
3. London Avenue Canal-North;
4. IHNC, West; and
5. IHNC East (Lower Ninth Ward and St. Bernard Parish).

17th Street

While there is the expected range of eyewitness times throughout this area, two reliable accounts state that the initial breach was first observed around daybreak (about 6:30 a.m.) on August 29. One account is from a man with a telescope trained on the floodwall area from his home in the Lake Marina Tower high-rise building just north of the breach. He reported that just as dawn broke, he saw one section of the wall (approximately 25 ft long) was breached (or leaned over). Sometime later when he looked, the breach had fully developed.

Based on the above data, it appears that the initial failure occurred early on the morning of August 29 by about 6:30 a.m., and was probably fully developed (probably catastrophically) by about 9:00 a.m. If the initial breach occurred around 6:30 a.m., then according to the constructed Lake Pontchartrain stage hydrograph based on digital pictures and eyewitness accounts, the stage in the canal would only have been at about 7.3 ft. elevation North American vertical datum of 1988 (NAVD88), which would be well below the top of the wall. According to post-Katrina surveys, the top of the 17th Street floodwall is at about 12.5 ft NAVD88 at the floodwall panels adjacent to the breach.

London North

Unfortunately, there were no eyewitnesses found in the immediate vicinity of this breach. However, there were a number of stopped clocks recorded within about a ten-block area near the breach. It appears that the breach on London North occurred in the 7:00–7:30 a.m. timeframe. Assuming that the breach occurred at 7:30 a.m., the corresponding stage in the canal according to the hydrograph would be about 8.9 ft NAVD88, which would be about 4 ft below the top of the wall based on a floodwall height of 12.9 ft NAVD88.

London South

The earliest reported account of flooding was between 7:00 and 8:00 a.m. on Monday morning by an individual who lives right at the breach. Another individual at a second site reported that the water came up really fast from the west at about 8:00 a.m. It appears that the London South Breach occurred between about 7:00 and 8:00 a.m. on Monday morning. Assuming the breach occurred at 8:00 a.m., the corresponding elevation in the canal would have been about 9.5 ft NAVD88, according to the stage hydrograph for London Avenue Canal. The elevation of the floodwall in this vicinity is about 12.9 ft NAVD88.

IHNC West

There were three breaches in this reach of the system. These include a breach at the railroad crossing near I-10, breaches at the junction of the floodwall and earth levee near pumping plant No. 19, and the failure by the storage yard near France Road. There were not enough data in this area to determine a good timeline; however, it appears that water started entering this area around 5:45 a.m. The water in the canal at this time was about 14 ft NAVD88 and obviously flowing over the top of the wall.

IHNC East (Lower Ninth Ward and St. Bernard Parish)

There were two major failures of the wall within this area. One was located near Florida Avenue and the other approximately 2,700 ft further south. Residents of the Lower Ninth Ward were interviewed by IPET personnel to gather information regarding the timeline of the breaches. One eyewitness reported that shortly after about 4:30 a.m. on August 29 he observed water flowing into his home and that by 5:00 a.m. the water was at his ceiling. Based on the eyewitness accounts and stopped clock data, it appears that water began entering the Lower Ninth Ward prior to 5:30 a.m., and possibly as early as 4:30 a.m.

This early time suggests that the water flowed through one or both of the breaches in the IHNC floodwall. However, the water levels at this time were estimated to be below the top of the floodwall. Research by the IPET determined that a small (200 ft) section of the east side of the IHNC floodwall near Florida Avenue failed between 4:30 and 5:00 a.m. at a water level of about 10.2 ft. NAVD88. The remaining floodwall was overtopped at about 7:30 a.m. Water levels for the Lower Ninth Ward and St. Bernard Parish peaked at about 10.5–11 ft. NAVD88. A larger section of floodwall (600 ft) subsequently breached by 7:30 a.m. presumably due to being overtopped.

Interior Flooding from Breached Levees

An estimate of the interior flooding was prepared by IPET Task Groups II and III. According to their estimates the breaches at the 17th Street Canal, London North and South, and IHNC West all contributed flood waters to the area in Fig. 2 labeled as Orleans East Bank. This flooded area contained approximately 105,000 acre ft of water. Of that total, about 66% came from the breaks, 21% from rainfall, and the remaining 13% from overtopping during the event and the pumps not functioning. The breaches along IHNC East and the overtopping and numerous breaches along the Gulf Intracoastal Waterway (GIWW) and the Mississippi River Gulf Outlet (MRGO) were estimated to have contained 429,000 acre ft of water. This area is shown as St. Bernard Parish in Fig. 2. Of this quantity of water, approximately 63% is believed to be caused from the breaches, 8% from rainfall, and the remaining 29% from overtopping.

Failure Mechanism Analyses

Levees

In the following discussions, levees and floodwalls are differentiated, the former having no concrete or steel components. No levee failures occurred without overtopping. The extent of breaching and overtopping scour was a function of soil type and compaction effort applied to the levee fill material, as well as the

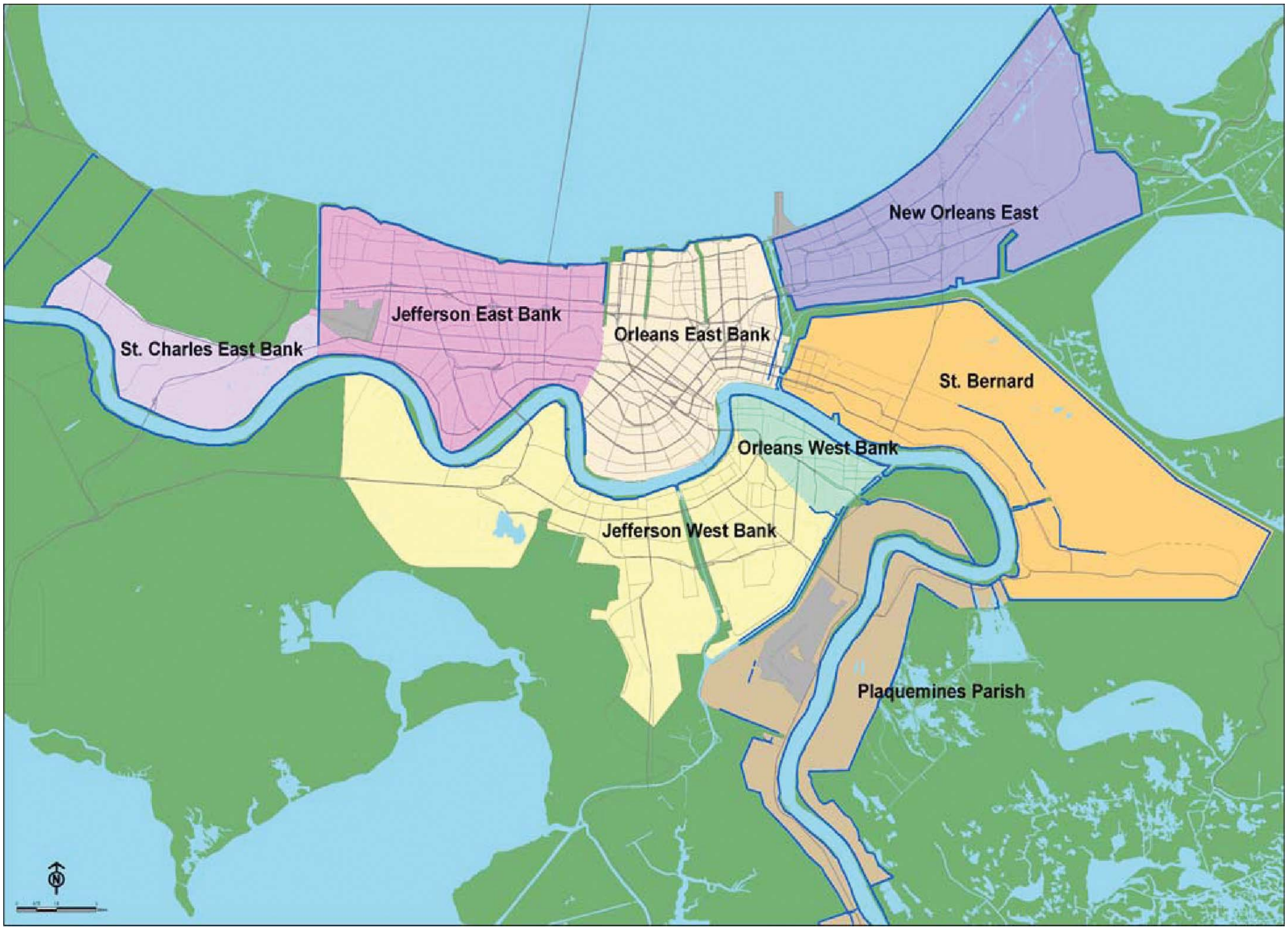

Fig. 2. Basin layout and names [adapted from IPET (2006)]

severity of the surge and wave action. Levees that had been constructed using hydraulic fill and had higher silt and sand content were severely damaged. The levee along the MRGO that fronts Lake Borgne was constructed with hydraulic fill that contained significant amounts of sand and silt; it experienced numerous breaches and total loss of the levee section. On the other hand, rolled fill levees that were constructed of cohesive materials, for the most part, were able to survive overtopping without breaching during this event. The focus of the IPET study was not to address the reasoning for planning or design decisions. Thus, no rationale was given to explain why hydraulic fill was used or why overtopping protection was not used for levees vulnerable to overtopping erosion. A review by the external review panel administered through ASCE on the draft final IPET report concluded that there was too little that could be gathered from all the facts and data collected to determine the "why" for planning and design decisions.

Floodwalls

Overtopped I-type floodwalls experienced varying amounts of erosion and scour. The extent of erosion was similar to that of levees where the soil type and degree of compaction of the material being attacked by the overtopping waters dictated the degree of erosion. The south breach at the IHNC, which catastrophically flooded the Lower 9th Ward, is an example of this type of failure. The waters flowing over the top of the wall attacked the soil that provided the passive resistance the floodwall needed for its stability. After this passive resistance was removed, the wall was no longer stable and it breached.

The four breaches that were not caused by overtopping and erosion were I-type floodwalls that failed due to instability in the foundation soils. The stability and performance of the I-wall system was greatly impacted by a gap developing on the water side of the floodwall as the canal water level rose. A diagram depicting the I-wall gap is shown in Fig. 3. These failures were at the 17th Street Canal, London Avenue Canal (two breaches), and IHNC East Bank (near the Florida Avenue pump station). Below is a brief synopsis of how the geotechnical forensic data, engineering analysis, and physical modeling were pieces of the puzzle that explained the failure mechanisms involved.

17th Street Canal Breach Area

Limit equilibrium analysis, finite-element analysis, and centrifuge model tests were conducted to evaluate the 17th Street Canal failure. All three methods clearly show that translational sliding occurred in weak foundation soils, and that the failure surface started at the sheet-pile tip in the clay layer and extended under the levee toward the protected side until outside the toe of the

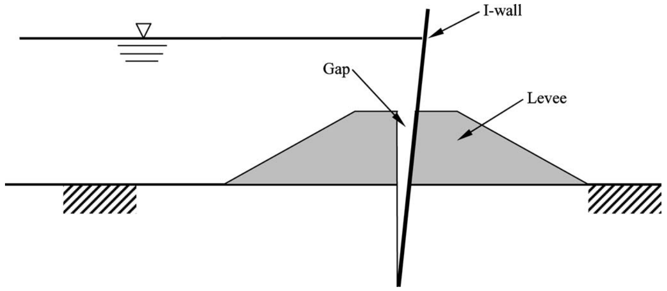

Fig. 3. Diagram of I-wall gap

levee, where it exited through the marsh layer. In addition, all three methods show that the formation of a gap between the sheet-pile wall and the canal-side portion of the levee was an essential element in the development of the failure. Results of all three methods are consistent with the observations made during field investigations soon after the storm (IPET 2006, Vol. 5).

London Avenue Canal Breaches

The levees and I-walls at the London Avenue Canal were constructed on a marsh layer overlying a beach sand layer. The postfailure field investigations revealed significant quantities of sand in the neighborhoods adjacent to the two breaches (north and south breaches) along the London Avenue Canal. Significantly larger amounts of sand were found in the vicinity of the southern breach. This sand was geotechnically identical with the beach sand in the foundation that was beneath the marsh layer. Heaving and sand boils were found at the protected side toe of the levee opposite the north breach.

Seepage and slope stability analyses, finite-element analyses, and centrifuge tests were performed on representative sections of these two breach areas to determine if erosion and piping and/or sliding instability were the causes of failures at these two locations. For the south breach of London Avenue Canal, seepage and piping were the most likely cause of instability. Instability of the levee and I-wall occurred after significant volumes of sand and marsh were removed by seepage and piping. This failure mechanism was also observed in centrifuge test simulations of the South London cross section.

For the north breach, the most likely cause of failure was sliding instability in the sand layer caused by high uplift pressures acting against the base of the marsh/clay layer. The scenario was likely even though seepage analysis of this area indicated that conditions for seepage and piping were present. High pore pressures in the sand would reduce the passive resistance sufficiently to cause sliding without significantly altering the main features of the cross section. The results of analyses of seepage and slope stability and the finite-element soil-structure analysis performed on the north breach area are consistent with this interpretation of the likely failure mechanism. The details of these analyses can be found in Volume 5 of the IPET report.

For both the north and south breaches, the formation of a gap between the canal side levee and the floodwall likely had a major impact on the performance of the I-wall and levee during Katrina. At the London Avenue Canal, the formation of a gap down to the sand resulted in another consequence that destabilized the levee by providing a path for water to flow down into the sand layer. This contributed to high pore-water pressures and led to instability of the levee/sheet-pile wall. Other factors that likely contributed to high pore-water pressures and instability were storm surge scour of fine grained sediments lining the canal that isolated the beach sands from direct hydraulic contact with the canal water, and the use of cold-rolled sheet piles at the south breach that possibility lost interlock while driving in the dense beach sand layer.

IHNC East Bank (near Florida Avenue Pump Station)

During the postfailure field investigations, a gap on the floodside of the wall was observed along the I-walls near the breach. Significant wall movement near the breach indicated that deep-seated movements occurred in the foundation. A timeline of events pieced together from data from hydrographs and eyewitness accounts provided evidence that this breach occurred before canal waters reached the top of the floodwall. Slope stability analysis was performed on a representative section of the north breach of IHNC. The slope stability analysis indicated that a foundation failure was likely. This foundation failure resulted from differences between the actual conditions and assumptions used as the basis for the design. Those differences are: (1) the ground surface beyond the toe of the levee at the north breach location was lower than the landside ground surface in the design cross section; and (2) the design analyses did not consider the possibility of a gap forming behind the wall as shown in Fig. 3, allowing water to fill the gap and increasing the load on the wall.

Lessons Learned

Failures of the HPS were devastating to the area. The lessons learned from the failures and successes of the HPS are vital to all flood control systems and hurricane protection systems across the United States.

Need for Resilience of HPS

The HPS was authorized to provide protection for a standard project hurricane (SPH) design hurricane. Hurricane Betsy that hit New Orleans in 1965 had much of the same characteristics of the SPH design hurricane in terms of wind speed and central pressure (Woodley and Shabman 2007). Hurricane Betsy was a Category 3 hurricane when it hit New Orleans and the probability of a storm greater than a storm similar to Hurricane Betsy, which would test the HPS, was expected to be very low. In the case of Katrina, the storm was downgraded from a Category 5 to a Category 3 as it passed through the New Orleans area, but the storm surge that tested the system was greater than a Category 3 level in most cases. The inability of the HPS to withstand forces and conditions beyond its height or design proved to be catastrophic.

Overtopping Scour Protection

IPET (2006, Vol. 5) states that overtopping alone would have caused only one third of the flooding that occurred. If flooding occurred from only overtopping of the HPS (no breaches), the recovery efforts would have been greatly reduced. The recovery was negatively impacted by the breaches because more time and expense were needed to remove the additional volume of water and to repair the breaches. A storm surge from a Category 3 or greater hurricane would have a high probability of overtopping the New Orleans HPS; unfortunately, overtopping scour protection was not incorporated in the HPS. Given the documented subsidence in the area, settlement of sections of levee below the intended design elevation due to soft soil foundations, and incomplete portions of the authorized HPS, overtopping was inevitable for a Category 3 or greater hurricane. Of the approximately 50

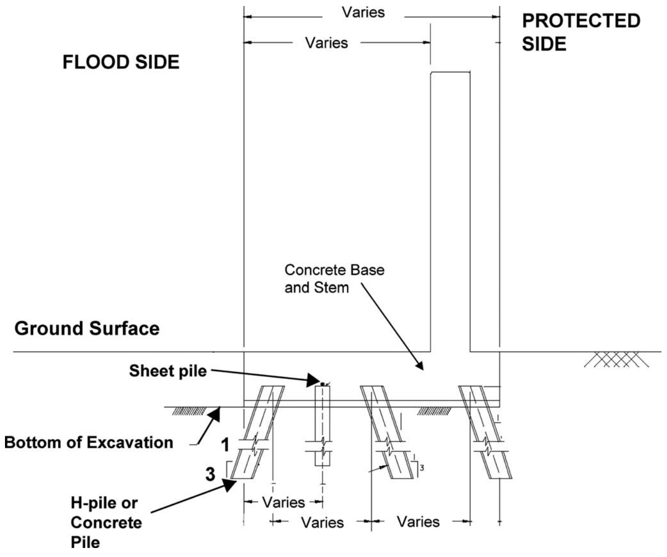

Fig. 4. Typical T-wall cross section

levee and floodwall failures that occurred due to Katrina, the majority of the failures resulted from overtopping and subsequent erosion or erosion-induced instability of I-type floodwalls (IPET, 2006, Vol. 5).

Post-Katrina field surveys showed that rolled compacted clay fill levees performed well with minor erosion occurring even when overtopped. However, hydraulic filled levees with significant amounts of silt and sand performed very poorly. Areas with T-walls performed very well and were very resilient to overtopping. The T-wall sections did not experience extensive erosion and scour even when extensive overtopping did occur except in those areas where there was a transition from a T-wall section to an embankment section. These walls are pile founded with loads transferred deeper into the foundation and were constructed with concrete base slabs that prevented erosion due to splashing near the wall. A typical T-wall cross section is found in Fig. 4. However, I-walls (such as at the south breach of the IHNC East Bank) subjected to overtopping performed poorly. Importantly, the stability of I-walls relies on the passive resistance acting on the wall, which is attacked by overtopping waters.

The ability of the HPS to survive overtopping can be greatly improved for levees and I-type floodwalls by providing erosion protection and by using erosion resistant materials for levee fill.

Conservatism in Designs

The formation of gaps behind the floodwalls with hydrostatic pressures acting along the full depth was unforeseen and not accounted for in the original designs of the I-wall systems. For the outfall canal failures, very little allowance was given for any uncertainties in the I-wall design. The stability analysis performed by the IPET (2006) demonstrated that the gap reduced the factor of safety by approximately 25% for clay foundations. The factor of safety in the original design of the 17th Street Canal floodwall in the area of the breach was 1.30, which was the minimum allowable. Thus, at the 17th Street Canal breach the combined effect of the knowledge deficiency of the gap formation and a design error caused by the application of centerline strengths to the toe caused the I-wall breach to occur before the design water level was reached. The IHNC floodwall near the Florida Avenue pump station had a design factor of safety of 1.25, which was also minimal. Thus, similar to the case for the 17th Street breach, the impact of the knowledge deficiency in the gap formation caused premature breaching and left little or no margin for error in dealing with uncertainties arising from other factors affecting stability such as soil strength.

In the design of the London Avenue Canal, it was assumed that fine-grained sediments at the bottom of the canal would insulate the beach sand layer from the canal waters. Piezometric data acquired during the design phase along with the short duration that the canal waters would be at the high water level led to a decision that the piezometric level at the toe of the levee would not rise above the ground surface. The stability analyses were performed using this design condition in which the sediments represented the first and only line of defense against high pore pressures and uplift in the foundation sands. An opportunity to provide a reliable second line of defense was missed because the sheet piles were not driven to fully penetrate through the beach sand layer. As it turns out, the sheet piles only penetrated about 10 ft into the 35 ft thick beach sands. As a result, without this additional protection, the loss of sediment at the canal bottom and/or the formation of the gap exposed foundation sands directly to the canal water, which induced high pore pressures and instability. The performance of the London Avenue I-walls at the north and south breaches demonstrates the consequences and dangers of designing a system without consideration of including redundant protection systems.

Need for Risk-Based Planning and Design Approach

The New Orleans HPS was designed using a traditional approach that is component-performance based where standards are used to define performance and uncertainty is accounted for through the factors of safety. However, a better measure of the performance of a component is related to the performance of the system combined with the consequences of that performance. Thus, a risk-based approach allows for explanation of where the uncertainty lies and assessment of the system of integrated components.

A risk-based approach is an excellent way to identify and communicate to decision makers the vulnerable areas of the system, nature of the consequences, and the source of the vulnerability. This approach also provides a tool where attention can be focused on certain areas and to design data gathering in order to reduce the risk. A good example would be the 17th Street Canal failure. The original design documents did not address shear strengths of the foundation soils beneath the protected side toe of the levee and beyond. In addition, the slope stability analysis at the breach area used shear strength values determined and derived from data from centerline borings. The same shear strengths applied for the centerline location were applied to the levee toe and beyond. This had an unfortunate result of overestimating the soil strengths at the levee toe and beyond, which contributed to a design with a low factor of safety. In the area of the breach, residential property boundaries extended up the protected side slope to the crest of the levee. The difficulty of accessing the toe of the levee and beyond may have led to the limited geotechnical exploration. However, there is no documentation to explain why geotechnical exploration was limited but the expense to the project design was critical. In a risk-based approach, engineers can communicate to the decision makers and to the public the risk and increased uncertainty of missing shear strength data under the toe.

Deficiency in Knowledge, Technology, Expertise in Hurricane Protection Systems

The events of Katrina have brought attention to the lack of knowledge that existed on the behavior of I-type floodwalls. An em-

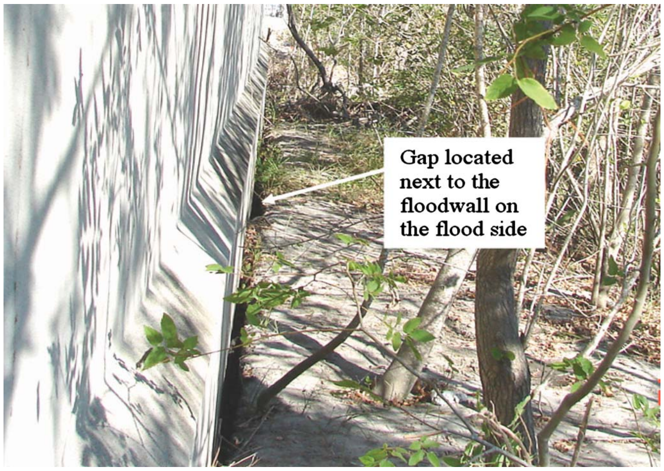

Fig. 5. Gap found near north London Avenue Canal breach

phasis is needed in new knowledge, technology, and technical expertise. The driving factor in the foundation instability of I-walls was the increased loads induced by a gap forming on the floodside of the wall. Fig. 5 shows a photograph of a gap observed from the post-Katrina field investigations. This failure mechanism was not anticipated and was unknown to the designer. Some information on the performance of I-walls had developed over time, but this information was not put together to detect this failure mode. For example, in 1985, the E-99 test section, a field load test of a sheet-pile wall similar in design to those of the I-wall canal failures, was performed by the Lower Mississippi Valley Division (LMVD) of the USACE in conjunction with the UASCE New Orleans District (USACE 1988).

The purpose of the field load test was to obtain full-scale performance data to validate the design methods used for optimizing the depth of sheet-pile penetration. The E-99 test wall was founded in a berm on the toe of an existing levee section and was loaded by pumping water between the test wall and the levee. Piezometric data in the foundation and wall movements and strains were recorded as the water rose from behind the wall. The data showed significant wall deflections. Back-analysis showed that the observed wall deflections did not match those predicted using the design methods. Thus, the LMVD recommended that finite-element analysis be performed to help understand the wall movements. Leavell et al. (1989) performed a finite-element analysis and calibrated their model using data from the E-99 load test. Their analysis showed that deep-seated foundation movement controlled the magnitude of the deflections. They recommended that a limit-equilibrium slope stability analysis should be used to address foundation and levee stability in the design of a sheet-pile-levee system.

After Katrina, the data presented in the E-99 report were reviewed to determine if the data showed the development of a gap between the sheet pile and soil on the flooded side due to the water loadings. A lone reliable reading of a piezometer located 4 ft from the wall on the flood side just above the sheet-pile tip matched the test water levels. However, the piezometric data and the wall displacements provide inconclusive evidence in relation to gap formation. The piezometric level at any point in the clay foundation on the flooded side should be expected to measure the load imposed by the weight of the water behind the floodwall whether or not a gap has formed. Also, the displacements by themselves cannot explain the presence of a gap without a visual observation. The E-99 report did not mention any record of a visual observation of gap after the water was pumped out at the end of the experiment. During the field load test a dark plastic tarp that was place over the wall to prevent leakage through the joints likely prevented any visual observation of a gap if one was present.

The E-99 full-scale field load test provided a false sense of security for I-type floodwalls. More research in I-type floodwall behavior and effects on global stability was needed. Modern technology (such as centrifuge modeling) would have helped shed some light on this behavior. At the outfall canal failures, visual observations of gaps on the flooded side of the floodwall (as shown in the Fig. 5) were important forensic evidence that the gap formation did occur. Thus, the gap represents an example of a knowledge deficiency that had a disastrous impact on the performance of the I-wall systems of the HPS.

Impacts of Lessons Learned on Rebuilding of HPS

The HPS will be reconstructed in several stages. Initially, TFG completed the immediate need of repairing the breached areas to pre-Katrina levels. Between the years of 2007 and 2011, USACE is tasked with rebuilding the HPS to the 100 year or to the authorized level of protection. Finally, studies are being performed to evaluate the effort needed to provide a Category 5 level of protection for the whole south Louisiana area. Knowledge gained from the Katrina experience has brought to light new criteria and design needs.

TFG Repairs

Repair of the damaged HPS began as soon as possible following Katrina. Levees overtopped by the storm surge required an estimated 3.82 million m^3 (5 million $yards^3$) of fill to reestablish the protection. As discussed previously, levees constructed of granular fill did not perform as well as those constructed of clay material. Unfortunately, using good clay material often required long haul distances that slowed construction progress. To prepare quickly for the 2006 hurricane season, local near-site borrow material was used where it met fill requirements. In anticipation of potential overtopping, sandier materials were excluded from the borrow and the embankment was capped using the most erosion-resistant material.

Driving temporary steel sheet piling and placing earth fill on the landward side closed the breaches along the outfall canals until concrete T-walls could be built. Knowing that performance problems existed with the composite levee/I-wall barriers, TFG chose to replace the failed wall sections using T-walls supported on deep piled foundations with sheet-pile seepage cutoff. Repairs could not wait until forensic studies were completed so conservative measures were made to reestablish protection. Sheet-pile lengths were selected to cut off any underlying sand strata that might have a hydraulic connection to the canal. Additionally, designers felt that T-walls offered good protection because of their resiliency and good performance during Katrina.

Although breached areas were closed in the canals, many miles of I-wall protection remained. It was not feasible to remove and reconstruct all existing I-walls along the interior drainage canals, so a design decision was made to construct closure structures at the entrances to the outfall canals. During hurricanes, the canals will be closed and pumping plants will maintain low water levels within the canals. This decision created the need to restrict the maximum canal water levels to safe conditions while maintaining adequate pumping capacity.

After Katrina, inspections identified the importance of the protected-side concrete footings of T-wall type flood barriers because they resisted erosion from overtopping. Splash protection was added to the land side of many walls to inhibit potential instability from erosion. Erosion was also evident at transition points between walls and levees. When walls were at higher elevations than the levee top, flow was concentrated around the end of the wall and resulted in higher water velocities and increased erosion. Fill was placed atop the levees to minimize this effect.

Hurricane Protection Office (HPO) and Project Recovery Office (PRO) Repairs

The role of TFG was essentially complete by June 2006. The next step in recovery was to reestablish protection to the authorized level or to the 100 year level of protection. Changes to the definition of sea level, actual subsidence at a local and regional scale, settlement, and datum-related issues caused the top of barriers to be lower than authorized project levels at some locations. Thus, elevation concerns highlighted the problem of overtopping. TFG concluded that structures should be designed to higher factors of safety under these extreme load conditions. These concerns are being addressed by reevaluating the HPS in its entirety. USACE engineers from New Orleans and throughout the nation are leading this reevaluation, which includes reassessment of soil strengths and levee/floodwall designs. Independent technical review is required for each levee reach by both Corps and non-Corps reviewers.

New design criteria were established based on the Katrina experience. Personnel from USACE headquarters, the Engineer Research and Development Center, Divisions, and Districts were involved in the process to develop design criteria for continued support of the reconstruction effort. These criteria were reviewed by external technical experts and finalized in April 2006. From a geotechnical perspective, the effect of the flood side gap on composite floodwall/levee systems was included in analyses of global stability, seepage, and the design and reevaluation of any I-walls. Shear strength in fine-grained material was higher beneath the centerline of existing levees than at the levee toe because the consolidation pressures are higher due to the weight of the embankment. The 17th Street Canal breach illustrated the importance of obtaining data at the levee toe. Currently, shear-strength data are being obtained from undisturbed samples, cone penetration test (CPT) methods, and field and laboratory vane shear testing. A combination of approaches will be used until the best methods are determined. Independent technical reviewers of this process will monitor the collection of data to ensure the method meets accepted and published standards (ASTM), and also the data are consistent with soil mechanics theory and practice.

National Perspective

Recognizing the significance of the flood side gap design issue, and the consequence this had on the performance of the I-walls in the New Orleans HPS, HQ alerted the Corps of Engineers community of the concern and began the process of developing criteria for other areas around the Nation. Extending the design conditions from New Orleans geology to the rest of the United States will involve significant research and development that requires time and funding. The I-wall criteria and guidance will be developed and implemented in three phases. USACE has completed Phase 1, which includes the process of cataloging I-walls designed or constructed by USACE. Phase 2 (currently underway) consists of performing preliminary evaluations on those walls, using interim guidance prepared from the knowledge gained from Katrina. These evaluations will be used to help identify projects at risk of poor performance as well as focusing research to address critical areas of concern.

Phase 3 will consist of research and development followed by detailed evaluations. When Phase 3 is complete, it is anticipated that I-wall design guidance will be summarized in an Engineer circular for the USACE and will address the gap development issue and its role on global stability and seepage effects for designing I-walls. Guidance on overtopping erosion protection and transition areas of walls to levees will be considered in relation to design level of protection. Additionally, it is expected that criteria will be related as to how well foundation conditions are known or understood.

Impacts on Lessons Learned for Future Levee Design and Assessments

Katrina has made significant impacts on USACE policy. In August 2006, the Chief of Engineers issued a memorandum listing 12 action items to be immediately incorporated into Corps projects. The 12 action items are listed in the Appendix of this paper. One of these items deals with incorporating "risk-based" concepts into designs. The *USACE Levee Design Manual*, EM 1110-2-1913, is currently under review for revision, and some of the more important possible revisions will include new design factors of safety that are based on risk. If risk is low and the amount of available geotechnical information is limited, the required factor of safety would be higher than that for a similar situation with more geotechnical information. In areas of high risk and inadequate geotechnical data, the new recommendation would be "not to build until adequate information is obtained." External technical experts will review this manual and the manual will be available through USACE's publication Web site. Another action item listed by the Chief deals with the periodic inspection and thorough reassessment of Corps projects.

Shewbridge et al. (2006) reported that currently, the National Levee Safety Program Act, H.R. 4650, is working its way through Congress. This Act will establish a National Levee Safety Program with several goals, including: ensuring the safety of new and existing levees; promotion of acceptable engineering policies and procedures; establishment and implementation of state levee safety programs and standards; support of public education about levees; development of technical assistance materials for federal and state governments; technical assistance to nonfederal entities; and improving the security of levees. Additionally, USACE has established a National Levee Safety Group to develop a methodology to allow the Corps of Engineers to achieve these goals. Details of the National Levee Safety Program are available on the Corps Web site ⟨www.hq.usace.army.mil⟩.

Conclusions

The devastation of Hurricane Katrina is having a significant impact on USACE. Successful performance of flood barriers reinforced the application of adequate design procedures. Unsuccessful performance has brought to light project deficiencies and has underscored USACE's need to better understand project failure modes and the foundation conditions on which the projects are built.

USACE is a learning organization and is continuing to put into practice the lessons learned from Katrina. Coordination between designers and researchers continues as knowledge is gathered on why project components performed as they did. Design criteria and methods have changed, and will likely continue to change, as the lessons learned are applied to field conditions and details are discussed and studied.

Acknowledgments

Permission to publish this paper was granted by Director, Geotechnical and Structures Laboratory.

Appendix. General Strock's 12 Action Items

The "12 actions for change" fall within three overarching themes: Effectively implement a comprehensive systems approach; communication; and reliable public service professionalism. The actions are grouped as follows:

Effectively Implement Comprehensive Systems Approach

Comprehensively design, construct, maintain and update engineered systems to be more robust, with full stakeholder participation:

1. Employ integrated, comprehensive and systems-based approach;
2. Employ risk-based concepts in planning, design, construction, operations, and major maintenance;
3. Continuously reassess and update policy for program development, planning guidance, design, and construction standards;
4. Employ dynamic independent review;
5. Employ adaptive planning and engineering systems;
6. Focus on sustainability;
7. Review and inspect completed works; and
8. Assess and modify organizational behavior.

Communication

Effective and transparent communication with the public, and within the Corps, about risk and reliability:

9. Effectively communicate risk; and
10. Establish public involvement risk reduction strategies.

Reliable Public Service Professionalism

Improve the state of the art and the Corps' dedication to a competent, capable workforce on a continuing basis. Make the commitment to being a "learning organization" a reality:

11. Manage and enhance technical expertise and professionalism; and
12. Invest in research.

References

Elliott, D. O. (1932). *Improvement of the lower Mississippi River for flood control and navigation*, U.S. Waterways Experiment Station, Vicksburg, Miss., 5–6.

Interagency Performance Evaluation Taskforce (IPET). (2006). "Performance evaluation of the New Orleans and southeast Louisiana hurricane protection system." *Draft Final Rep.*, U.S. Army Corps of Engineers.

Knabb, R. D., Rhome, J. R., and Brown, D. P. (2005). "Tropical storm report Hurricane Katrina 23–30 August 2005." *Rep. Prepared for National Hurricane Center*.

Leavell, D. A., Peters, J. F., Edris, E. V., and Holmes, T. L. (1989). "Development of finite-element-based design procedure for sheet-pile walls." *Technical Rep. No. GL-89-14*, U.S. Army Corps of Engineers.

Maygarden, B. D., Yakubik, J.-K., Weiss, C., Peyronnin, C., and Jones, K. R. (1999). *National Register evaluation of New Orleans drainage system, Orleans Parish, Louisiana*, Chap. 4, U.S. Army Corps of Engineers, New Orleans.

Shewbridge, S., Costa, R., Hess, J., and Sills, G. (2006). "The evolving approach to levees in California." *J. Dam Saf.*

U.S. Army Corps of Engineers (USACE). (1988). "E-99 sheet-pile wall field test report." *Technical Rep. No. 1*, Lower Mississippi Valley Division.

Woodley, D., and Shabman, L. (2007). "Decision-making chronology for the Lake Pontchartrain & vicinity hurricane protection project." *Draft Final Rep. Submitted to the Institute for Water Resources of the US Army Corps of Engineers*.