Reconnaissance of the New Orleans Hurricane and Storm Damage Risk Reduction System after Hurricane Gustav

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Cover Photo – Inner Harbor Navigation Canal and flood wall, September 1, 2008 (USACE)

Introduction

On Oct 2 and 3, 2008, a group of civil engineers visited the New Orleans, LA area to assess levee performance during Hurricane Gustav. The team was sponsored by the National Science Foundation (NSF), through the Geoengineering Extreme Events Reconnaissance (GEER) Association. Our team was hosted by the U. S. Army Corps of Engineers, New Orleans District (MVN) and the Mississippi Valley Division (MVD). Specifically, Mr. Ken Klaus with MVD and Mr. Noah Vroman of the Corps' Engineer Research and Development Center (ERDC) handled logistical details. Messrs. Rob Dauenhauer, Tim Ruppert and Rich Varuso, engineers with MVN, served as guides, prepared and distributed handouts and photographs, and answered our many lengthy and detailed questions.

Chapter 1 of our report gives a brief overview of the current Hurricane and Storm Damage Risk Reduction System (HSDRRS) relative to post-Katrina repairs and improvements and of Hurricane Gustav. We included this chapter to brief both ourselves and the reader on the vast scope of changes that have occurred and will occur to the HSDRRS since Katrina.

Chapter 2 presents the observations from our reconnaissance and our understanding of the performance of elements of the HSDRRS that we collected from other sources. We toured nine sites along the Mississippi River Gulf Outlet (MRGO) the Gulf Inter-coastal Waterway (GIWW) and the Inter-Harbor Navigational Canal (IHNC). We visited a distressed non-federal back levee in Plaquemines Parish. We also collected data from the USACE and news sources. Our major observations of the HSDRRS were that:

- There was no evidence of seepage distress occurring at transitions or of significant under-seepage distress such as sand boil cones.
- Flood walls that were loaded with a still water level near the top of the walls did not exhibit any signs of structural distress such as tilting.
- Walls that were overtopped by waves in several locations, and possibly by the still water level at France Road, did not exhibit any signs of erosion on the protected side of the walls.

Chapter 3 lists our conclusions and lessons learned from the reconnaissance observations and inquiries which we summarize below.

<u>Performance of the HSDRRS during Gustav</u> - Our fundamental conclusion was that the HSDRRS around New Orleans performed well under the surge and wave stresses generated by Gustav. We observed no signs of distress in the HSDRRS as a result of Gustav. Reconnaissance of performance of the levees and floodwalls after Hurricane Gustav demonstrated a significant improvement to the system since Katrina.

Future Hurricanes and Overtopping - Gustav imposed lower flood levels and loads on the HSDRRS than did Katrina. Marginally larger hurricanes could result in significant overtopping along the IHNC and the GIWW until the Lake Borgne Barrier is installed and the HSDRRS is raised to the estimated 100-year level of flood protection as planned for 2011.

HSDRRS Improvements - However, we believe that the HSDRRS, even in its current configuration, provides an improved level of both protection and durability that should reduce the potential for breaches if subjected to stresses imposed by higher levels of surge and waves that overtop system elements. We do not know what levels of surge and wave would overstress the system, but the current and future configurations are significantly superior to the pre-Katrina HSDRRS.

Plaquemines Parish Back Levee Performance - The non-federal back levee in Plaquemines Parish was overtopped by Gustav flood levels and was in danger of failure at the location of a shallow slide on the protected side slope. Desiccation cracks on the levee may have contributed to the slide by allowing overtopping water pressures into critical zones.

Lessons - Gustav tested the HSDRRS and offered some lessons for flood protection systems.

- Boats, barges, or any large object (e.g. rail cars, tanks, shipping containers) that floats could impose a risk to floodwalls. The USCG's evacuation of the IHNC and GIWW is critical to protection of the HSDRRS.

- Preparation for a hurricane requires timely action by all responsible parties. Delays by the railroad, salvage yards, boat and barge operators, operators of facilities on the flood side of the HSDRRS in clearing potential hazards could put the HSDRRS at risk.

- The erosion resistance of non-federal local clay levees in Plaquemines Parish (not part of the HSDRRS) during overtopping was noted during Katrina. The clay back levees in Plaquemines Parish resisted erosion during Gustav, but may have demonstrated a potential vulnerability due to desiccation cracks. Improved placement control of water content and compaction, revised material requirements relative to plasticity and organic content, or landscaping measures such as establishment of dense vegetation may be required to prevent desiccation.

- Protection of life in the southern Louisiana area will require continued emphasis on evacuation. Storm surges larger than those created by Gustav and Katrina should be anticipated. Bringing the HSDRRS up to a level appropriate for protection of the New Orleans area will take years if not decades to achieve.

1. Overview

1.1 Background on Katrina Performance and Critical Deficiencies Identified

Hurricane Katrina made landfall in southeast Louisiana on August 29, 2005 as a Category 3 storm. The storm surge generated from record high waves and intensity of the storm while a Category 5 in the Gulf overtopped much of the hurricane protection system levees and floodwalls in the New Orleans metropolitan area, and breached levees and floodwalls at many locations. At three or four locations the floodwalls breached at water levels below the tops of the floodwalls leading to intense scrutiny of design flaws and putting into question the stability of all I-type floodwalls (I-walls).

In the aftermath of Hurricane Katrina and the devastation that ensued, many lessons were learned including identification of a number of technical deficiencies in the Hurricane Protection System in place at the time. Most of these deficiencies have been well documented and disseminated to the public. Some of the most obvious of these (besides design strength and structural response deficiencies) were: lack of overtopping protection, high stick-up heights of floodwall elements, vulnerabilities to erosion at transitions between different components of the system, use of erodible materials for construction of earthen levees, improper design heights for hurricane protection components, and general lack of resiliency and/or redundancy for critical life safety structures. The Interagency Performance Evaluation Task Force (IPET) report noted that the pre-Katrina hurricane protection did not perform as a system because its piecemeal design and development resulted in inconsistent levels of protection.

In particular, the detail of “connections” or “transitions” between different sections (projects, materials, various apertures) was a repeated source of failure during Katrina. A common failure mode was identified for unprotected soil embankments adjacent to concrete I-type floodwalls. Another major failure mode occurred due to scour of soil behind overtopped floodwalls, leading to loss of passive resistance and stability of the floodwalls.

1.2 Post-Katrina Repairs and Improvements

1.2.1 Overview of Repairs and Improvements

The performance of the levees protecting New Orleans is a key to its social, cultural, and historic conditions. - IPET, Executive Summary, 2008

<u>Introduction</u> - The post-Katrina repairs and improvements to the Hurricane and Storm Damage Risk Reduction System (HSDRRS) for the New Orleans area did in fact protect the city during Gustav. The condition of the HSDRRS in September 2008 existed because of the efforts of the U.S. Army Corps of Engineers (USACE) to provide increasing levels of protection to New Orleans in the short period of time since Katrina's devastation. This overview touches briefly on the repairs and improvements, which are still in progress. We provide a slightly expanded description of the current and pending repairs in Appendix A with details about upgrades to (1) the earthen levees, (2) floodwalls, (3) drainage canal closures, (4) pump stations. A more thorough and graphic description of these efforts can be found on the USACE New Orleans District web page (http://www.mvn.usace.army.mil/hps2/index.asp).

As documented by the IPET study, surges associated with events more frequent than the 100-year event (1% annual probability of occurrence) would overtop the pre-Katrina / June 2006 level of protection provided by the HSDRRS. The USACE is now working to raise the HSDRRS to levels that prevent overtopping by estimated 100-year-event water levels. The improved HSDRRS is scheduled for completion in 2011. Fig. 1.2.1-1 shows the HSDRRS status map for June 2008 as provided by the USACE.

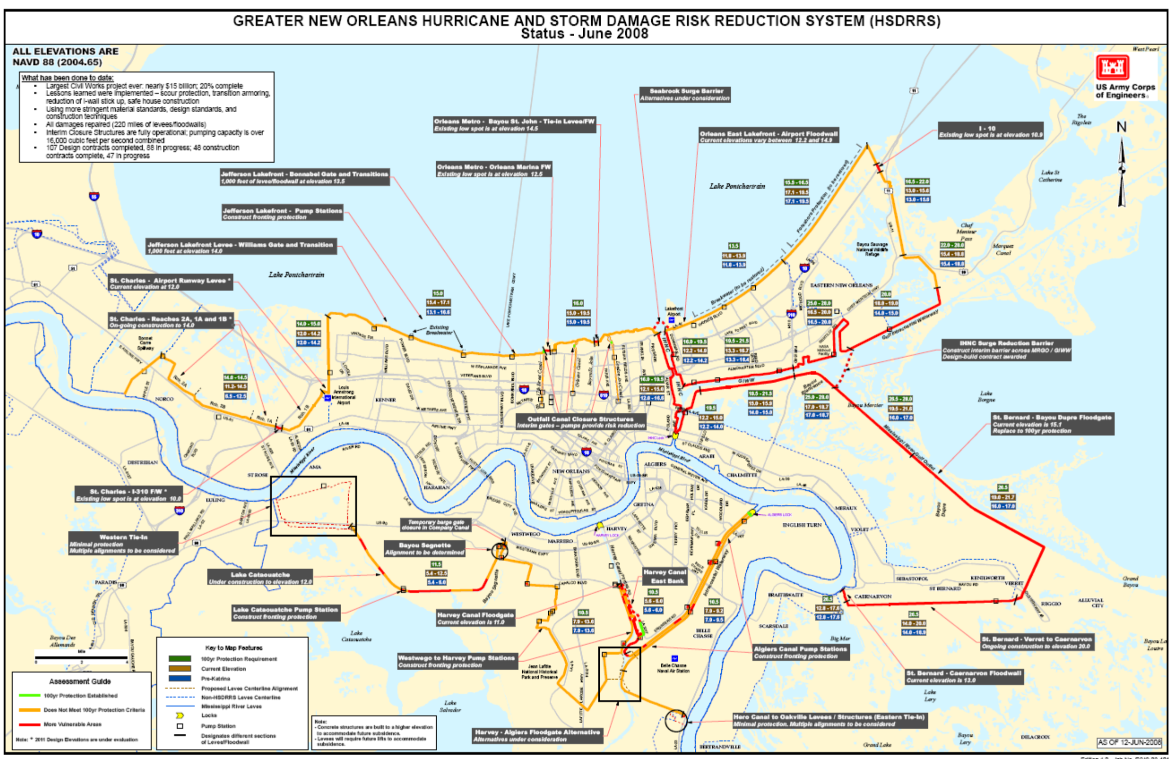


Fig. 1.2.1-1. – HSDRRS Status Plan, June 2008
(http://www.mvn.usace.army.mil/hps/pdf/2008_Storm_Vulnerability_Elev_final.pdf)

In addition to overtopping prevention, HSDRRS improvements have increased the durability of the HSDRRS for events that may overtop the system elements. Specifically, the systems have been designed and constructed to resist erosion if overtopping occurs, to increase existing pump station operability and reliability during storm events, and to maintain pumping capacity in the event high water levels occur at new pump stations.

We describe some of the repairs and improvements to the HSDRRS in the remainder of our overview.

1.2.2 Earthen Levee Reconstruction

The USACE has designed and constructed repairs and improvements to the HSDRRS earth levees with two main purposes – (1) to raise the level of protection so that the likelihood of overtopping is lessened and (2) to improve the capacity of levees to withstand erosion during overtopping. Figure 1.2.2-1 shows an enlarged view from the HSDRRS plan (Figure 1.2.1-1) focusing on the HSDRRS levees along the Mississippi River Gulf Outlet (MRGO), the Gulf Intracoastal Waterway (GIWW) and the Inner Harbor Navigation Canal (IHNC). The elevations given in the boxes are the 100-year level of protection goal for 2011 (top/green), the June 2008 system crests (middle/brown), and the pre-Katrina system crests (bottom/blue). Figure 1.2.2-2 shows the earth levee at the southeast corner of the HSDRRS along the MRGO which is a typical example of the reconstructed earthen levees.

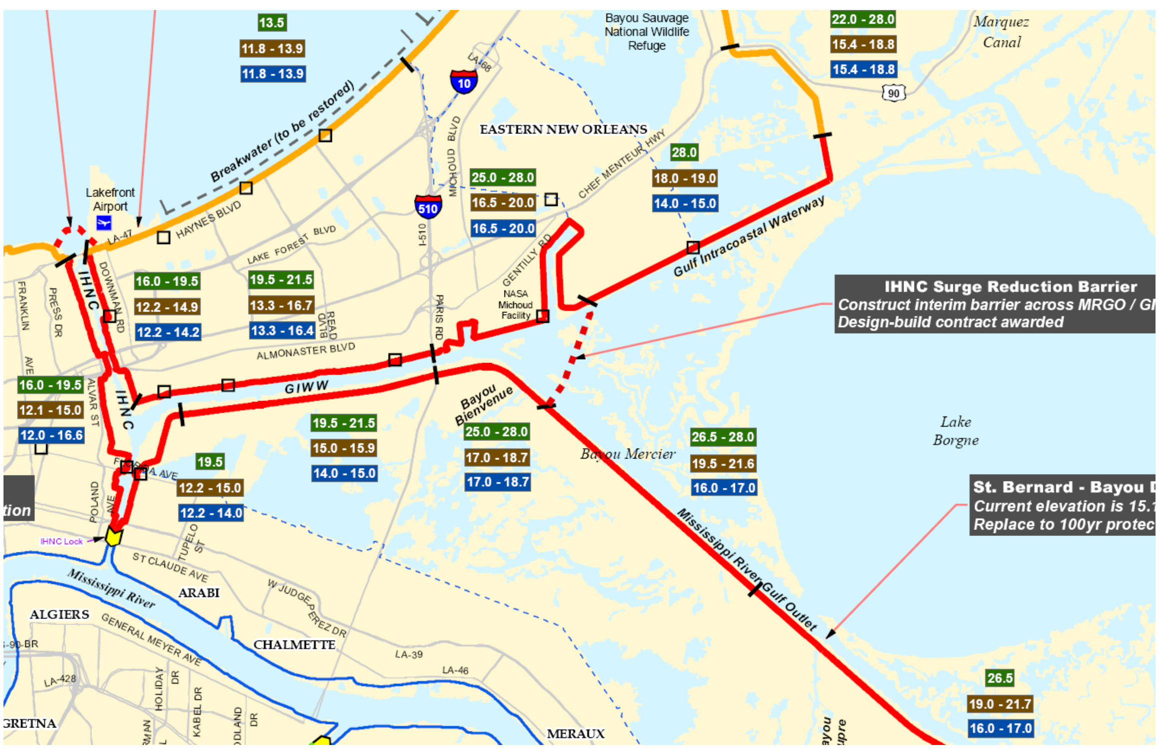
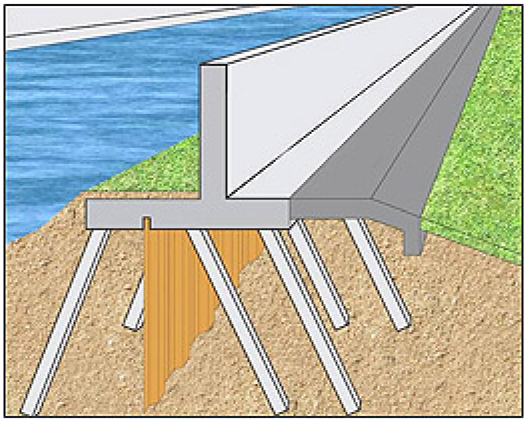


Fig. 1.2.2-1. – Section of HSDRRS plan, East New Orleans and St. Bernard Polders (http://www.mvn.usace.army.mil/hps/pdf/2008_Storm_Vulnerability_Elev_final.pdf)

Fig. 1.2.2-2. Southeast corner of the MRGO levee, flood side (L.Wooten)

1.2.3 Floodwall Improvements

The USACE has improved the HSDRRS floodwall protection by replacing breached and damaged floodwalls, by upgrading existing floodwall stability, and by hardening the protected side of floodwalls and floodwall-levee transitions. In many places, a pre-existing I-wall was replaced with a more robust T-type floodwall (T-wall). Figure 1.2.3-1 & 2 shows a T-wall schematic and a photograph taken during construction of a T-wall. The splash aprons (see gray element in Figure 1.2.3-1) are typically concrete slabs for new walls but have also been constructed using grouted riprap. Figure 1.2.3-3 shows a reinforced concrete splash apron on the protected side of the I-wall and T-wall on the west side of the IHNC along France Road adjacent to the former container terminal.



Figs. 1.2.3-1 & 2. T-wall schematic and T-wall under construction (http://www.mvn.usace.army.mil/hps2/hps_outfall_canals.asp)

Fig. 1.2.3-3. I-wall and splash apron, IHNC west along France Road; New L-wall and splash apron in background (L.Wooten)

1.2.4 Drainage Canal Closures

The USACE has constructed interim floodgates at the Lake Pontchartrain end of the drainage canals to block storm surges from flowing into the canals and overloading the I-walls. Large pumping facilities were installed adjacent to the gates to provide a means of evacuating canal storm drainage around the gates when closed. Figure 1.2.4-1 shows a schematic for the canal closure structures.

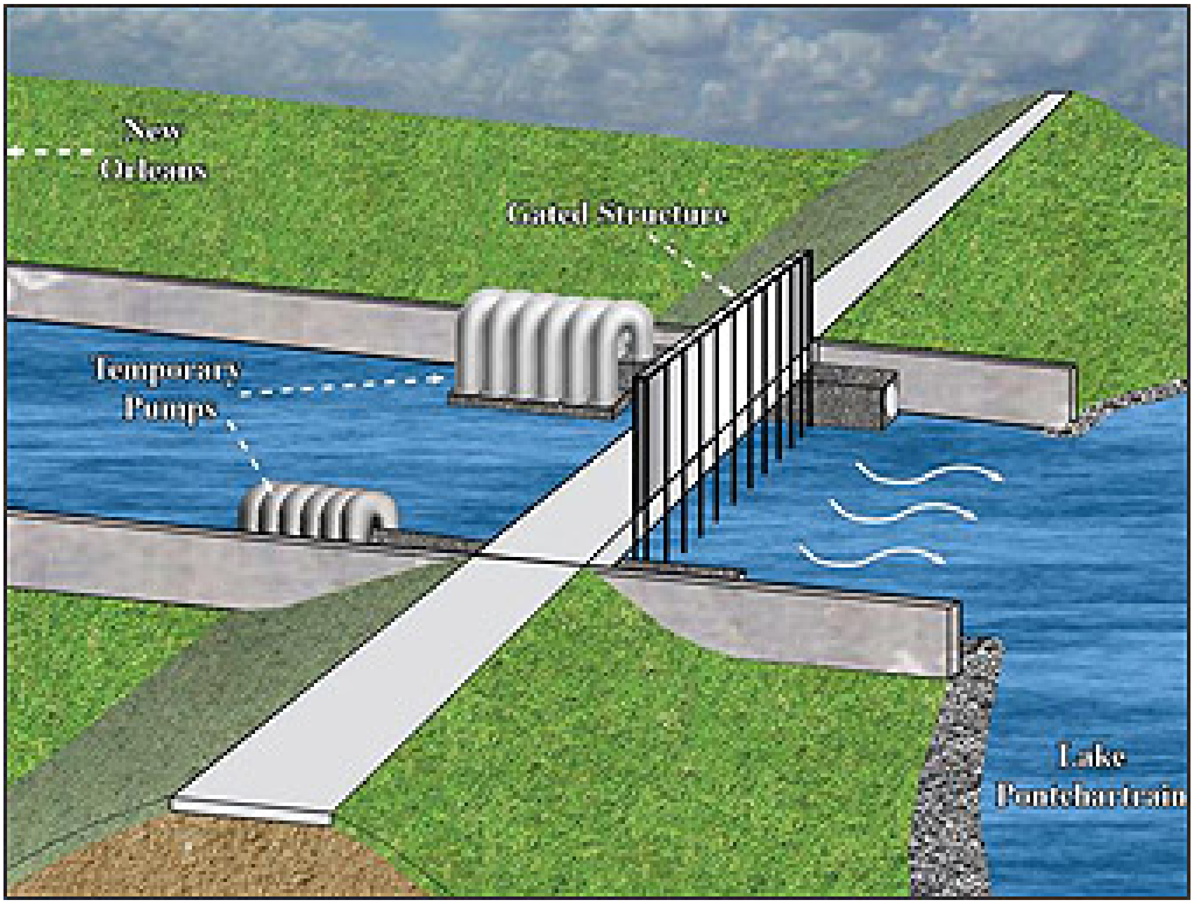


Fig. 1.2.4-1. Canal Closure Facilities Schematic
(http://www.mvn.usace.army.mil/hps2/hps_outfall_canals.asp)

1.2.5 Pump Station Improvements

The USACE is in the process of repairing, modifying, and rebuilding thirty of the seventy-three area pump stations to operate during future storm events by ensuring backup power, strengthening the structures, and storm / flood proofing the facilities and equipment.

1.2.6 Pending Improvements (HSDRRS)

The ongoing task to complete the 100-year HSDRRS protection remains significant. The remaining major elements of the HSDRRS include raising levees, flood walls, and gate structures (see Figures 1.2.1-1 and 1.2.2-1), constructing the Lake Borgne Barrier across the MRGO and GIWW, and resolving / designing / constructing the Lake Pontchartrain side protection for the IHNC. Figure 1.2.6-1 shows a USACE map and photographs of the HSDRRS projects.

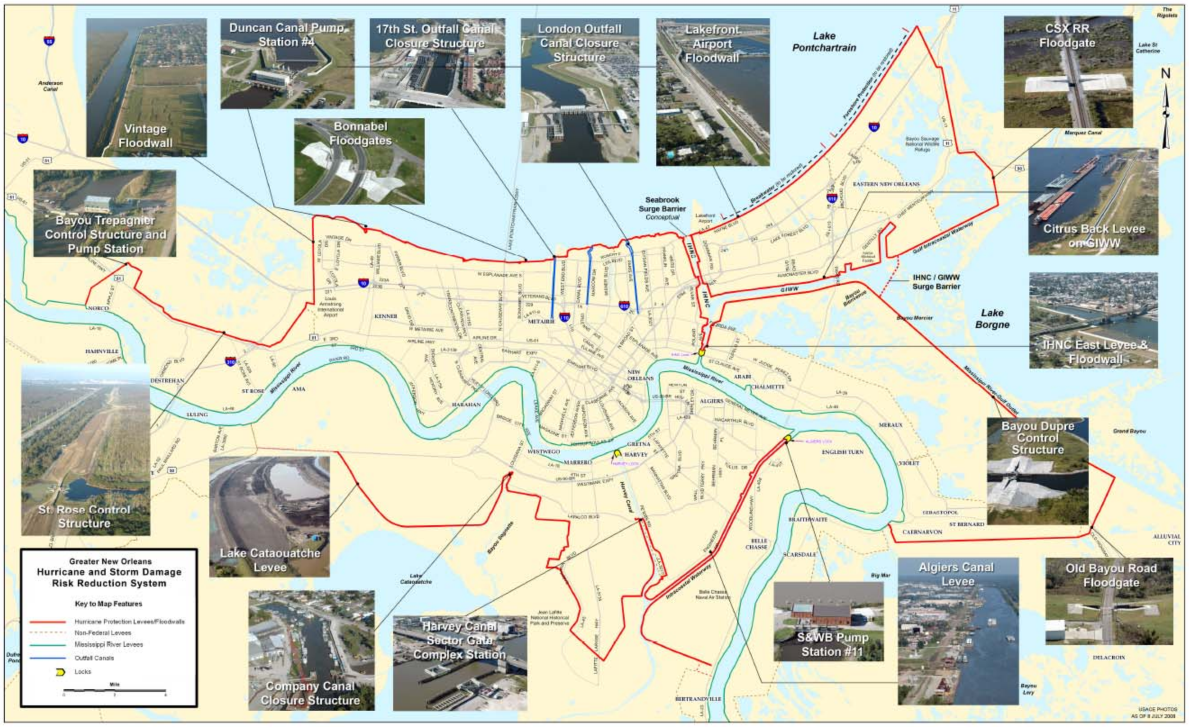


Fig. 1.2.6-1. HSDRRS Map with Photographs of Major Projects (http://www.hq.usace.army.mil/gustav/Visuals/hrsystemmap.pdf)

1.2.7 Planning Beyond the 2011 HSDRRS - LACPR

The USACE, in partnership with the state of Louisiana, is studying a larger range of coastal protection, restoration, planning, and damage reduction options that encompasses all of south Louisiana - the Louisiana Coastal Protection and Restoration (LACPR) Project. The study is evaluating protective measures for events ranging from the 100-year to larger events categorized by the Congressional authorization as “Category 5” protection. The LACPR Final Technical Report is in progress and is scheduled for external independent review by the National Academy of Sciences in 2009.

1.3 Hurricane Gustav

The track for Hurricane Gustav is shown in Fig. 1.3-1. It entered the Gulf of Mexico on August 31, 2008 with maximum sustained winds of 135 mph (Category 4) and a minimum central pressure of 958 millibars. A satellite image of the storm in the Gulf of Mexico is shown in Fig. 1.3-2. It made landfall just west of Grand Isle in Cocodrie, Louisiana at about 9:30 AM on September 1, 2008. At this point, it had maximum sustained winds of about 110 mph (Category 2), a minimum central pressure of 955 millibars, and a Radius of Maximum Wind of 25 nautical miles. Hurricane force winds extended out 70 miles from its center at landfall.

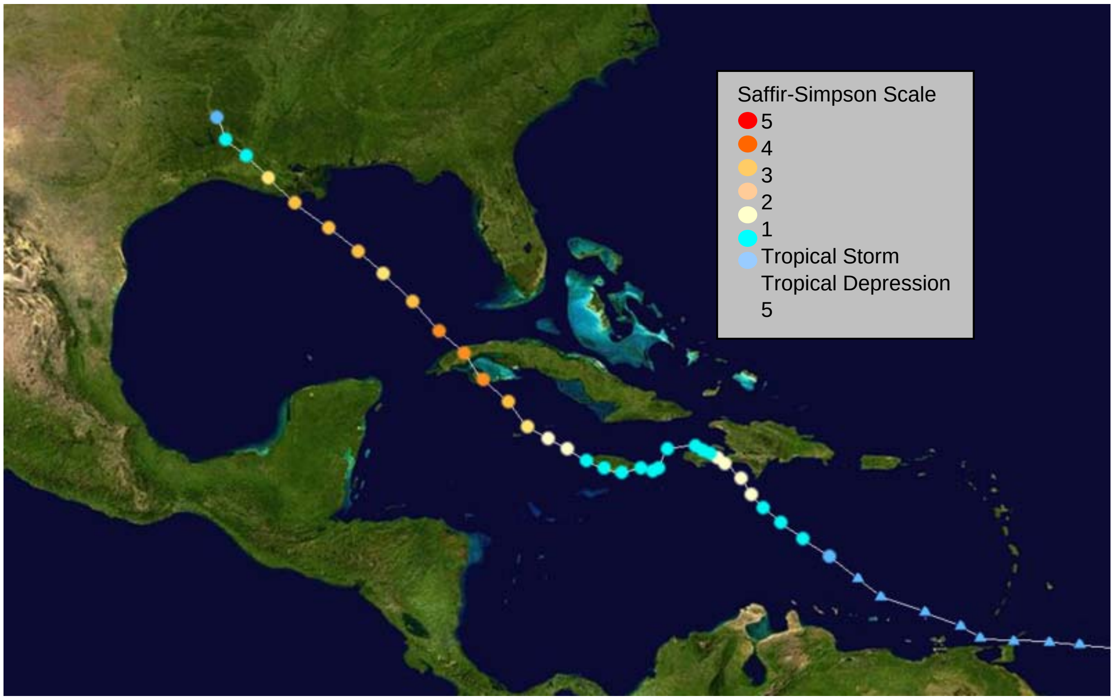


Fig. 1.3-1 Track of Hurricane Gustav. Picture adapted from National Hurricane Center with background from NASA satellite imagery.

Fig. 1.3-2 Satellite image of Hurricane Gustav in Gulf of Mexico, approaching Louisiana coast. Satellite image from NASA.

The storm surge from Hurricane Gustav reached a maximum level, about 14 feet NAVD88, southeast of New Orleans in the marsh bordering Black Bay (Figs. 1.3-3 and 4). Along the New Orleans Hurricane Protection System, the greatest storm surge levels were in the IHNC. At the IHNC Lock, the peak water level reached 11.4 feet (Fig. 4). The peak storm surge levels in the IHNC during Hurricane Katrina were approximately 3 feet higher (IPET 2008). For example, the measured peak water level at the IHNC Lock during Katrina was 14.4 feet.

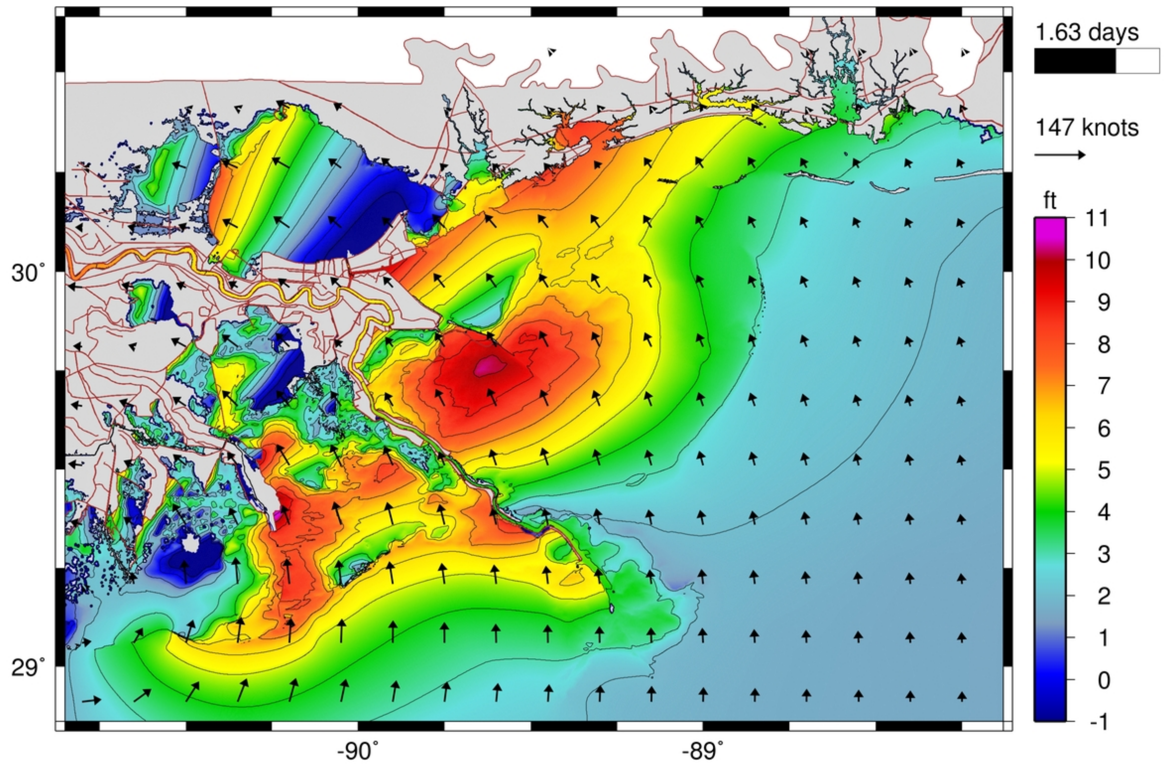


Fig. 1.3-3 Preliminary computer model (ADCIRC) of storm surge at about the time that the surge reached its peak. Water elevations are relative to NAVD88. Graphic provided by Joannes Westerink, University of Notre Dame.

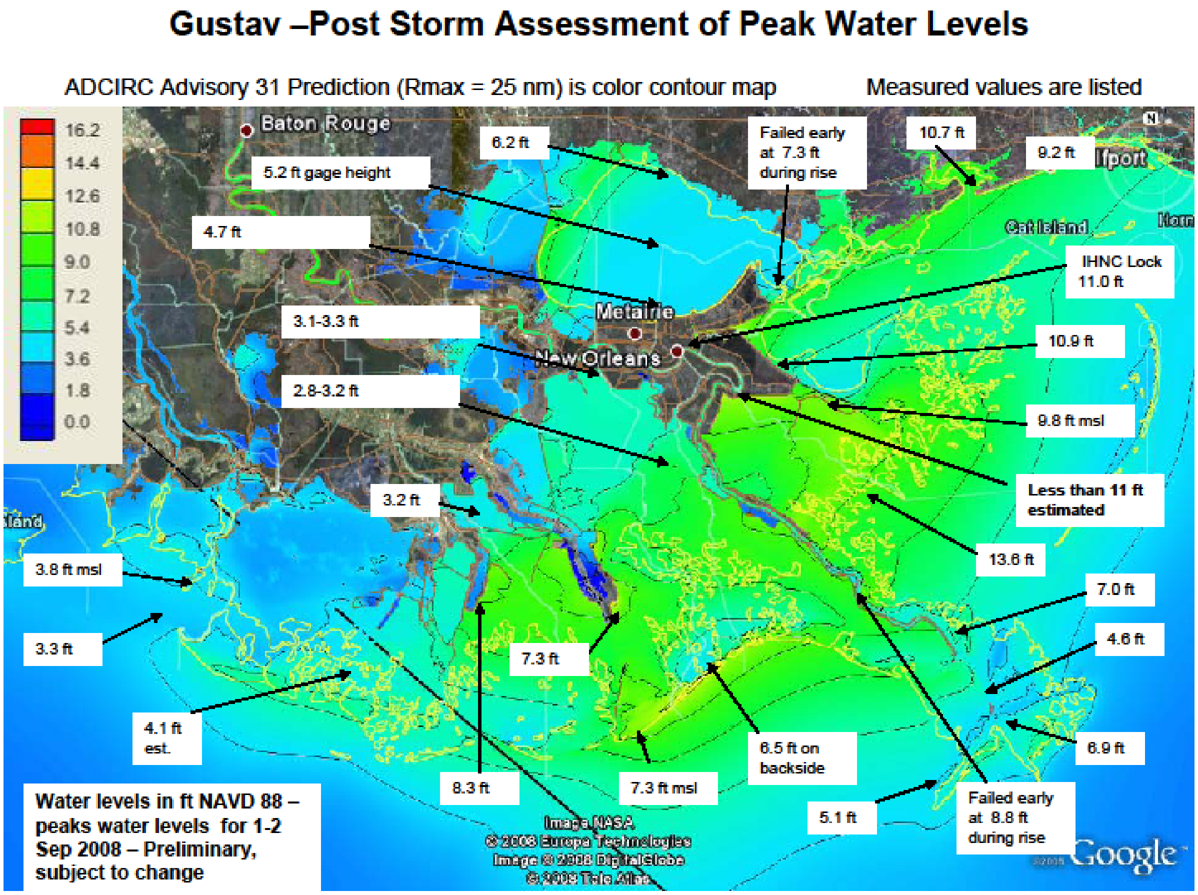


Fig. 1.3-4 Post-storm assessment of peak water levels during Gustav based on measurements and observations. Information is preliminary. Graphic provided by U.S. Army Corps of Engineers, New Orleans District.

2. Reconnaissance

2.1 Approach

Like most geotechnical engineers we approached this investigation using what we call Terzaghi's "observational method". We think a famous New York Yankee catcher and coach once said "It is amazing what you can see by observing" and if he did not say this; he should have.

Messrs. Ken Klaus (MVD) and Noah Vroman (ERDC) coordinated the logistics of our visit. Messrs. Rob Dauenhauer, Tim Ruppert and Rich Varuso, engineers with USACE New Orleans District, acted as our guides and started our visit with an orientation briefing. They also provided us with a briefing package that contained maps, design drawings, photographs, etc. We have incorporated many of their graphics in this report. We were then given an overview of the performance of the New Orleans Hurricane Protection System during Gustav. Following this orientation we were asked which sites we wanted to visit. After some discussion, sites were selected and the USACE personnel suggested a site order which would minimize travel time.

At each site we were interested in subsurface conditions, design and post-Katrina construction details, geometrical configurations, water elevation during Gustav and where/how that datum was obtained, and the observed levee or wall performance. For comparison purposes, we were also interested in the performance during Katrina of each levee/wall section at sites we visited. New Orleans District engineers who escorted us were knowledgeable, open and free with their knowledge and experience. They answered our questions in a clear concise manner.

We present our observations in the following sections. We have supplemented our observations with information from news sources, USACE materials, and information provided to us by New Orleans District engineers. Our observations focused on just a few areas of the HSDRRS which we understood to have been the most affected by Gustav.

2.2 MRGO

2.2.1 Frontage Levee

The frontage levees along the Mississippi River Gulf Outlet (MRGO) channel are the closest elements of the HSDRRS to the open waters of the Gulf. As such, these earthen embankments experienced the earliest and highest water levels during both Gustav and Katrina. The high water levels during Katrina overwhelmed the MRGO frontage levees with overtopping along the entire stretch of the MRGO and eroded significant lengths of the levee.

Figure 2.2.1-1 shows a section of the MRGO frontage levee and the typical extent of the erosion damage caused by the Katrina overtopping.

Fig. 2.2.1-1 Post-Katrina MRGO Frontage Levee, October 14, 2005. (L. Harder)

Our visit was confined to the southeast sections of the frontage levee up to the Bayou Dupree gate because of time and logistic constraints. We believe that this section of embankment was representative of the frontage levee because of its proximity to Lake Borgne and because, during Katrina, it suffered damage equal and similar to that along more northerly lengths of the levee.

We observed no signs of either erosion or overtopping of the MRGO frontage levee during our visit. Based on the limited debris lines along the levee, the high water levels during Gustav were well below the crest of these rebuilt and elevated earthen embankments. The wave and current actions of Gustav also appeared to have caused no erosion on the earth embankments. Figures 2.2.1-2 and 2.2.1-3 show two typical views of the MRGO frontage levee embankment.

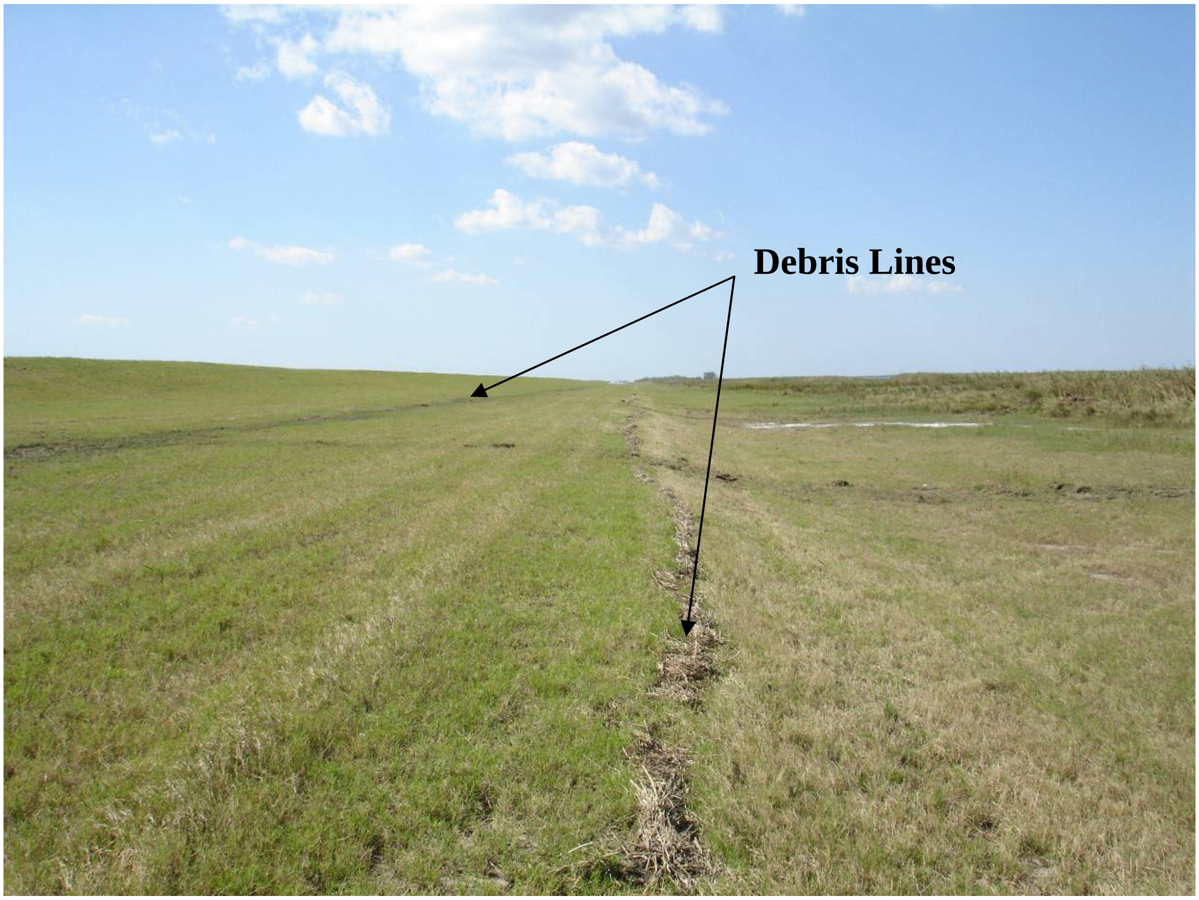


Fig. 2.2.1-2 MRGO Frontage Levee, flood side, looking northwest. Upper debris line, believed to be due to Gustav, was cleared prior to our visit, probably as part of the ongoing efforts to maintain the protective grass cover. The lower debris line may represent the high water level during Ike. (L. Wooten)

Fig. 2.2.1-3 Southeast Corner of MRGO Frontage Levee, looking southeast (L. Wooten)

2.2.2 Bayou Dupree Gate

The Bayou Dupree gate structure suffered several severe breaches during Katrina, which overtopped the entire structure by several feet. Figure 2.2.2-1 is an October 2005 photo of the gate structure following Katrina which shows breaches at the I-wall section and at the transition from the I-wall to the embankment.

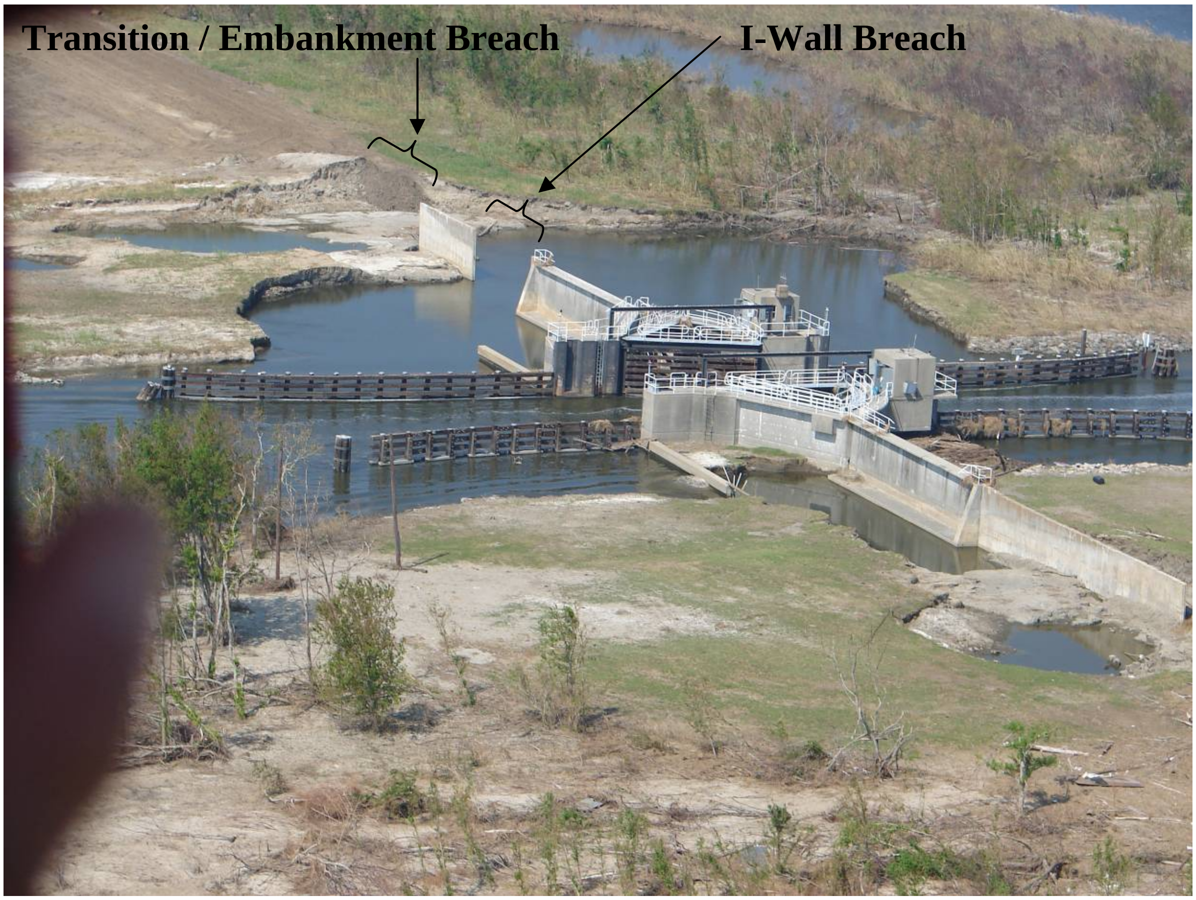


Fig. 2.2.2-1 Bayou Dupree gate, October 14, 2005 (L. Harder)

Figure 2.2.2-2 shows the improvements constructed by the USACE to the same section of gate. The concrete sheetpile I-wall has been replaced with a steel sheetpile cofferdam section, and the transition to the earthen levee has been elevated and covered with grouted riprap. The use of grouted riprap to harden vulnerable areas around the gate has been extensive as illustrated in Fig. 2.2.2-3. Ungrouted riprap has also been placed as erosion protection at the toe areas of grouted riprap.

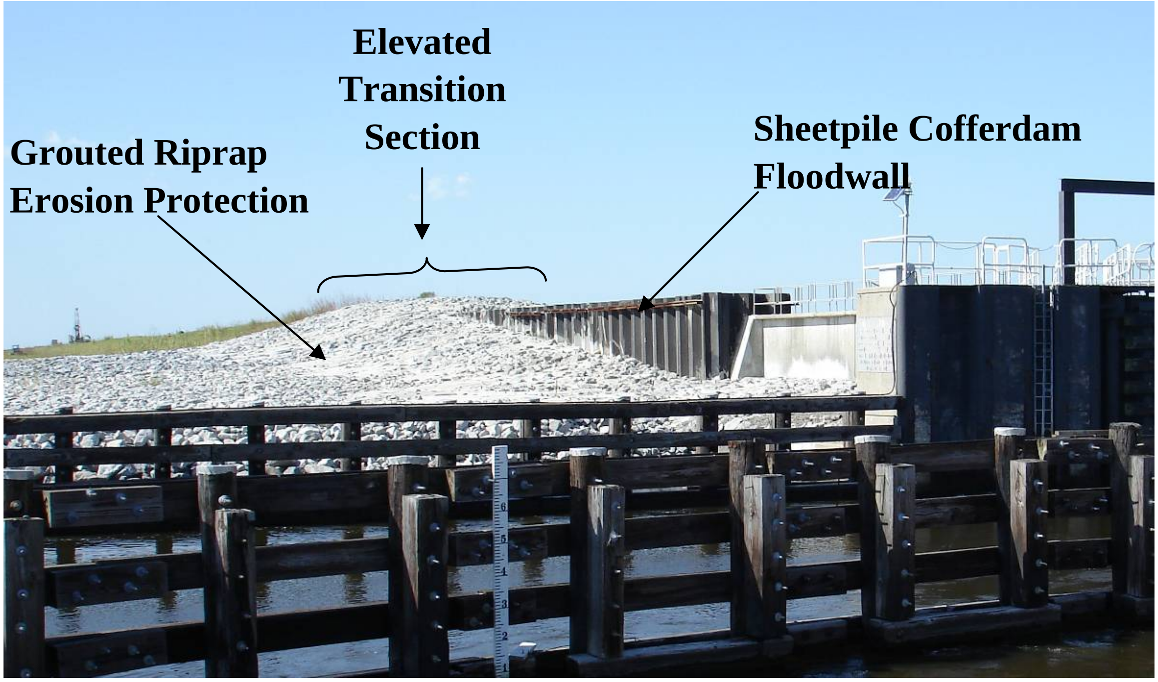


Fig. 2.2.2-2 Bayou Dupree Gate, October 2008, northwest flank, protected side, looking north (L. Wooten)

Fig. 2.2.2-3 Bayou Dupree Gate, October 2008, southeast flank, crest, looking northwest (L. Wooten)

We observed no signs of erosion or damage from Gustav's high water and waves at or near the gate. The limited debris line on the northwest flank appeared to indicate that the highest waters from Gustav were several feet below the crest of any of the gate structure elements (see Fig. 2.2.2-4).

Fig.2.2.2-4 Bayou Dupree Gate, October 2008, northwest flank, MRGO side, looking east. The lower debris line may represent the high water level during Ike. (L. Harder)

2.3 GIWW (as described by USACE)

We did not visit the levees along the GIWW and relied on descriptions provided by USACE representatives. The post-Gustav damage assessments conducted by representatives of MVN and the local sponsors noted no signs of erosion, overtopping, instability or seepage of those levees. Furthermore, the levee/structure transitions were all found to be in good condition. Prior to landfall of Hurricane Gustav, work was being conducted to raise the levees on the south side of the GIWW between IHNC and the GIWW/MRGO confluence. Despite the limited grass growth on the levee, no erosion was observed during the inspection.

2.4 IHNC

The storm surge from Hurricane Gustav in the metro New Orleans area was most dramatic in the Inner Harbor Navigation Channel (IHNC) where several previous floodwall and levee failures resulted in catastrophic damage during Hurricane Katrina. Waves from Gustav overtopped the floodwalls at some locations along the western side of the IHNC. The following sections describe observations of specific areas of the HSDRRS along the IHNC.

2.4.1 IHNC West / France Road

In the middle section of the western side of the IHNC (see Fig. 2.4.1-1), opposite the junction of the IHNC with the GIWW, the flood wall and levee system are located landward of industrial port facilities, up to about 1500 feet from the IHNC. France Road and a railroad parallel much of this part of the HSDRRS. Overtopping surge and waves during Katrina resulted in three breaches in this area – at an I-wall, at a transition between a railroad gate floodwall and the adjacent levee (constructed largely of shell hash compacted fill), and at an earthen levee section. Significant sections of the HSDRRS paralleling France Road also experienced significant distress due to the Katrina water loads and overtopping, exhibited by tilting, a flood side gap, and a protected side scour trench.

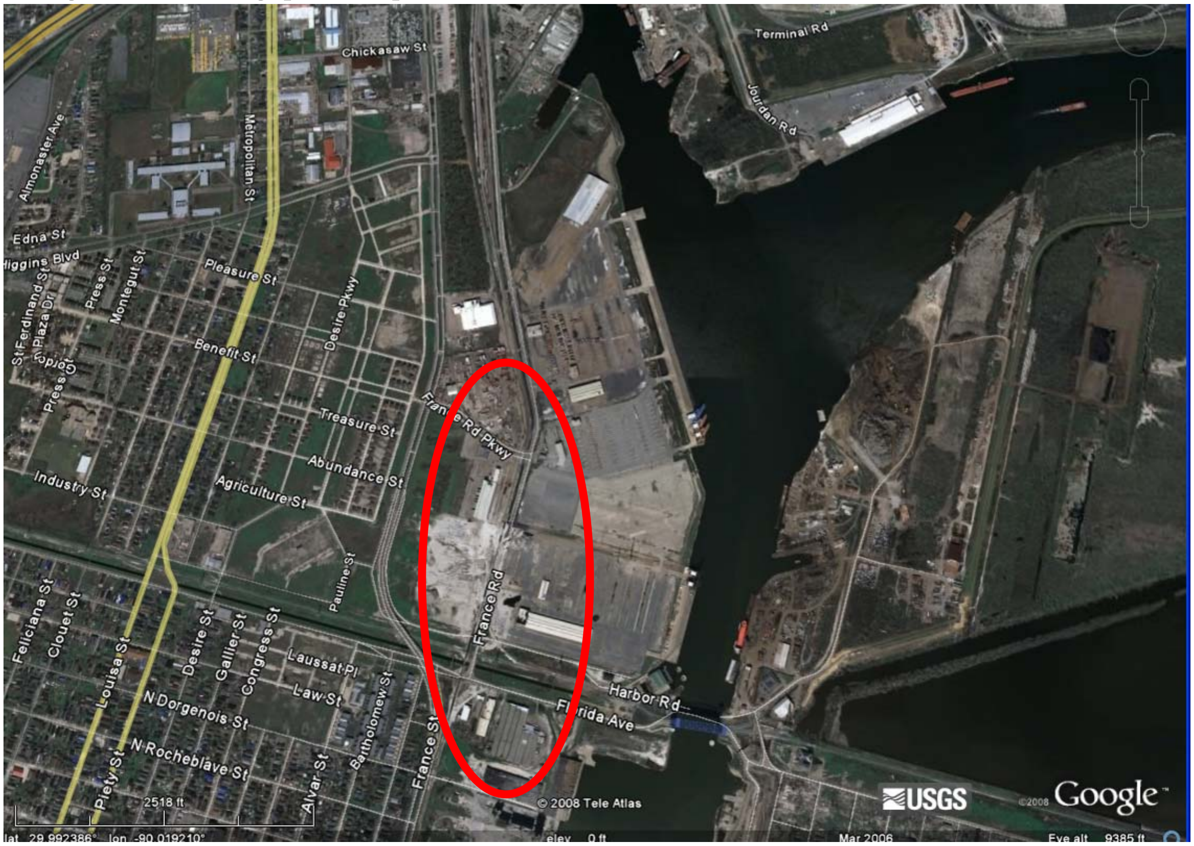


Fig. 2.4.1-1 IHNC West Location Plan (Google Earth / USGS)

Repairs and improvements of these failed and distressed sections included raising and buttressing embankment sections, armoring of embankment-concrete floodwall transitions, replacement of I walls with L-walls (due to space constraints), and buttressing of pre-existing I-wall sections to reduce the stick-up height (the height of wall above finished grade). Figures 2.4.1-2 and 3 show the post-Katrina (October 2005) and post-Gustav (October 2008) conditions at the location of the earth levee breach. Figures 2.4.1-4 and 5 show the post-Katrina and post-Gustav conditions at the railroad gate transition breach location. Figures 2.4.1-6 and 7 show the post-Katrina and post-Gustav conditions at the I-wall breach location.

L-walls were used to replace damaged I-walls instead of T-walls because the L-walls provided suitable stability and because railroad rights of way restricted space for construction.

Fig. 2.4.1-2 IHNC West levee Katrina breach site, October 2005 (Breach had been temporarily repaired. Note scour hole.) (L. Wooten)

Fig. 2.4.1-3 IHNC West new floodwall at location of breach shown in Fig. 2.4.1-2, October 2008 (L. Wooten)

Fig. 2.4.1-4 IHNC West Katrina breach at railroad gate transition, October 2005 (L. Wooten)

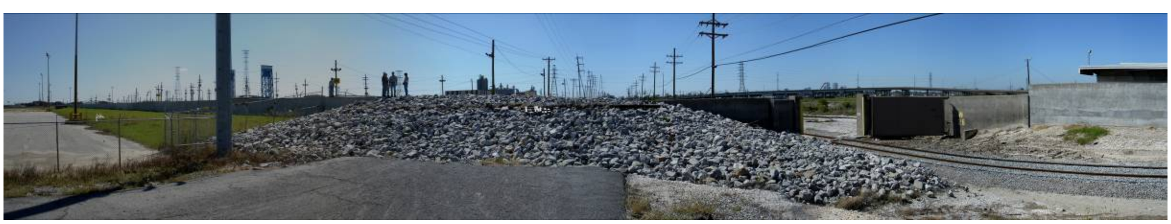


Fig. 2.4.1-5 IHNC West repaired breach at railroad gate transition, October 2008 (L. Wooten)

Fig. 2.4.1-6 IHNC West I-wall Katrina breach site, October 2005 (L. Wooten)

Fig. 2.4.1-7 New L-wall – old I-wall transition near location of Katrina I-wall breach on IHNC West (L. Wooten)

The repairs and improvements of these sections of the hurricane protection appeared to have performed well in light of clear evidence of wave overtopping. Figure 2.4.1-8 shows the debris left by overtopping waves on the protected side of one section of new L-wall along the IHNC West.

Fig. 2.4.1-8 Protected side of new L-wall along IHNC West. Note debris left by overtopping on floodwall and slope protection. October 2008 (L. Wooten)

At the transition between the new L-wall and the old I-wall (Figs. 2.4.1-7 and 1.2.3-3), there was storm debris left on top of and behind the higher L-wall, while the top of the lower I-wall was left clean. It is possible that the still water elevation of the peak storm surge exceeded the top of the old I-wall (elevation of about 14 feet NAVD88) at this location.

2.4.2 IHNC West near Claiborne Ave. Bridge

Strong photographic evidence is available for wave overtopping during Hurricane Gustav of the T-wall located on the west side of the IHNC just north of Claiborne Avenue (Figs. 2.4.2-1 for location, Figs. 2.4.2-2 and -3 during hurricane). This T-wall had previously survived Hurricane Katrina. A concrete splash apron at the toe of the wall on the protected side was added after Katrina to protect from erosion (Fig. 2.4.2-4). The wall performed well during Gustav. During the field reconnaissance, there was no noticeable sign of distress in the wall, including the joints between concrete panels, and in the new concrete splash apron (Fig. 2.4.2-4). There was evidence of minor erosion beyond the splash apron on the protected side.

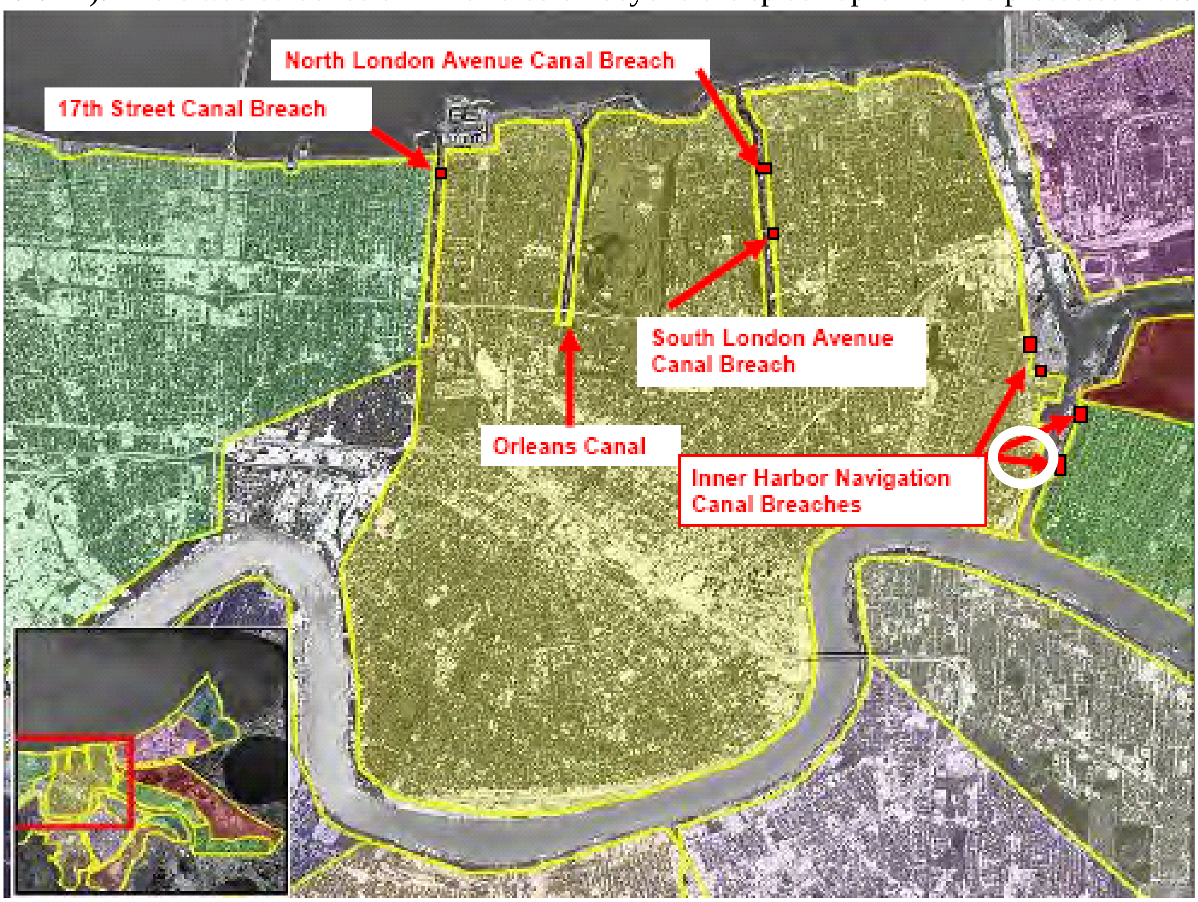


Fig. 2.4.2-1. Plan View of Hurricane Protection System. Circle shows location on west side of IHNC just north of Claiborne Avenue. The T-wall at this location survived Hurricane Katrina in 2005. ("Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System, Volume V: The Performance - Levees and Floodwalls," Final Report of the Interagency Performance Evaluation Task Force, June 2007)

Fig. 2.4.2-2. Photograph from Sept. 1, 2008 of Gustav storm surge. Photograph taken from Claiborne Ave. Bridge looking north. The waves are overtopping the T-wall. (USACE)

Fig. 2.4.2-3. Photograph from Sept. 1, 2008 of Gustav storm surge. Photograph taken from Claiborne Ave. Bridge looking north at T-wall southeast of floodwall shown in Fig. 2.4.2-2. (USACE)

Fig. 2.4.2-4 Photograph from Oct. 2, 2008 of IHNC west side T-wall (same section as shown during Gustav in Fig. 2.4.2-2). Picture taken looking south on the protected side (IHNC is to the left and Claiborne Ave. Bridge is in the background). Waves overtopped this wall based both on the photos during Gustav (Fig. 2.4.2-2) and the debris still there on Oct. 2, 2008 (see above). The concrete splash apron was added here after Katrina to protect from erosion. After Gustav, there was evidence of minor erosion in the ballast of the railroad tracks to the right, but no evidence of distress to the wall itself or to the splash apron. (R. Gilbert)

2.4.3 IHNC Lower 9th Ward

Two breaches occurred during Hurricane Katrina on a stretch of I-wall between Claiborne and Florida Avenues on the east side of the IHNC (Figs. 2.4.3-1 to 2.4.3-4). These breaches led to flooding of the Lower 9th Ward during Katrina. The suspected cause of the southern-most breach was loss of soil support due to overtopping erosion on the protected side of the I-wall (Fig. 2.4.3-2 and Fig. 2.4.3-3), while the suspected cause of the northern-most breach was a stability failure before the surge level reached the top of the wall (Fig. 2.4.3-4). This entire stretch of I-wall, even the section between the two breaches that survived Katrina, was replaced with a T-wall (Figs. 2.4.3-5 and 2.4.3-6). The I-wall section south of Claiborne Avenue that did not breach in Katrina was left in place but was reinforced with a larger earthen berm and a buttressing structural concrete splash apron to strengthen the section, reduce the wall height, and provide overtopping scour protection.

During Hurricane Gustav, both the old I-wall and the new T-wall sections were loaded to near their pre-Katrina design surge level. The peak still water level was near the top of the old I-wall located south of Claiborne Avenue (Fig. 2.4.3-7), and waves apparently overtopped the wall. The top of this wall is at about elevation 13 feet NAVD88. After Gustav, the wall showed no noticeable signs of distress (Fig. 2.4.3-8). Also, there was no visible evidence of underseepage on the protected side.

The peak still water level was several feet below the top of the new T-wall section (Fig. 2.4.3-9). After Gustav, there were no noticeable signs of distress at either the transition between the old I-wall and the new T-wall (Fig. 2.4.3-10) or along the new stretch of T-wall (Fig. 2.4.3-11). Also, there was no visible evidence of underseepage on the protected side. However, a water main leak on the protected side just south of the Florida Avenue Bridge was causing water to pond on the ground surface, making it difficult to see any evidence of underseepage.

One potentially interesting observation is that there is about a 1-inch-deep vertical offset between the pile-supported base of the T-wall and the slab-on-grade concrete splash apron (Fig. 2.4.3-11). This offset, if the splash apron was cast to be flush with the base of the wall in the summer of 2006, may indicate settlement occurring at a rate of about 0.5 inches per year in the upper 70 feet of the soil profile.

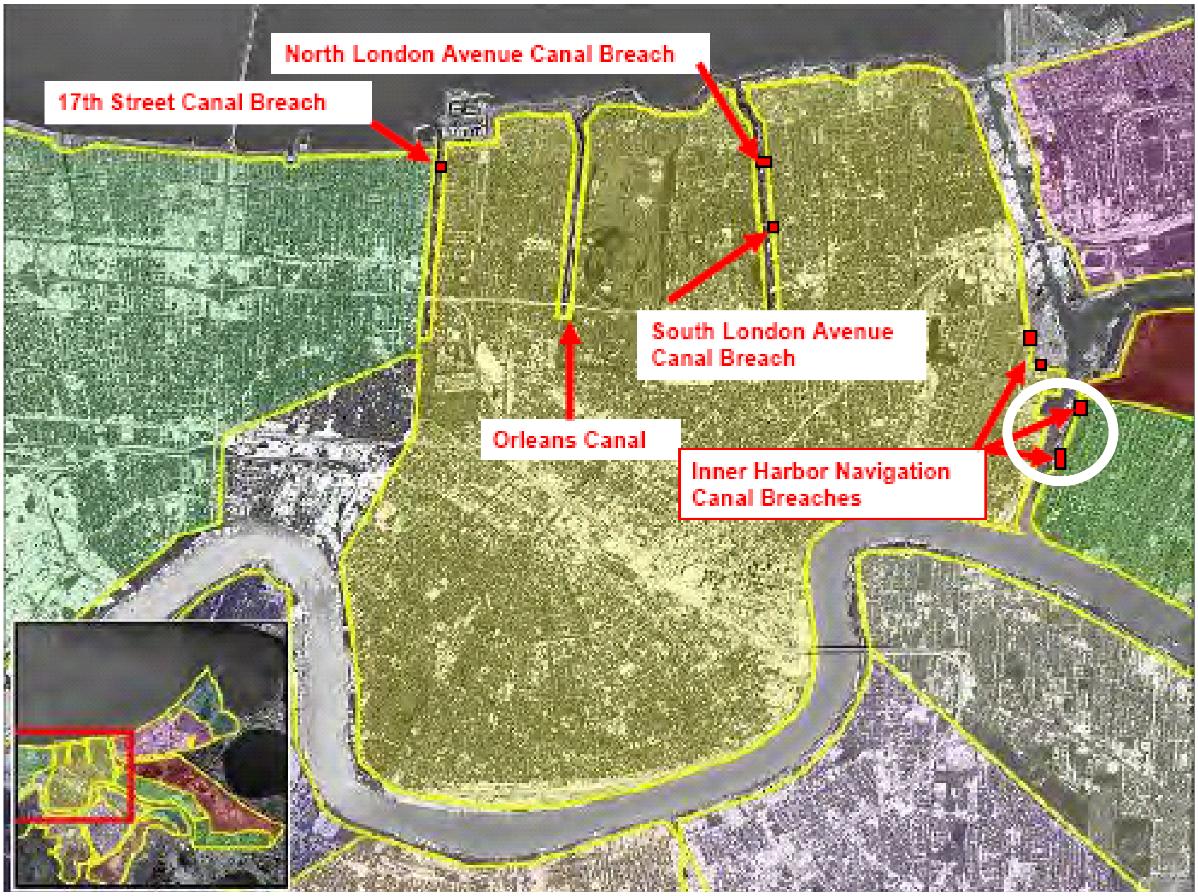


Fig. 2.4.3-1 Plan View of Hurricane Protection System. Circle shows location on east side of IHNC between Claiborne and Florida Avenues, where two breaches occurred in an I-wall during Hurricane Katrina and flooded the Lower 9th Ward. ("Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System, Volume V: The Performance - Levees and Floodwalls," Final Report of the Interagency Performance Evaluation Task Force, June 2007)

Fig. 2.4.3-2 Photograph from 2005 of southern-most breach that occurred in the I-wall on the east side of the IHNC during Katrina. Photograph is looking south, with the IHNC on the right and the Lower 9th Ward of the left. The breach was 850 feet long and located about 100 yards north of the Claiborne Avenue Bridge (seen in background). The suspected cause of this breach was erosion of the toe on the protected side due to water pouring over the top of the wall when the surge level exceeded the top of the wall. ("Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System, Volume V: The Performance - Levees and Floodwalls," Final Report of the Interagency Performance Evaluation Task Force, June 2007)

Fig. 2.4.3-3 Photograph from 2005 of southern-most breach and the scour behind the adjacent I-wall on east side of IHNC during Katrina. Photograph is looking north, from the Claiborne Avenue Bridge. (L. Harder)

Fig. 2.4.3-4 Photograph from 2005 of northern-most breach that occurred in the I-wall on east side of the IHNC during Katrina. Photograph is looking north, with the IHNC on the left and the Lower 9th Ward of the right. The breach was 250 feet long and located just south of Florida Avenue. The suspected cause of this breach was a stability failure when the surge level was near the top of the water. (L. Wooten)

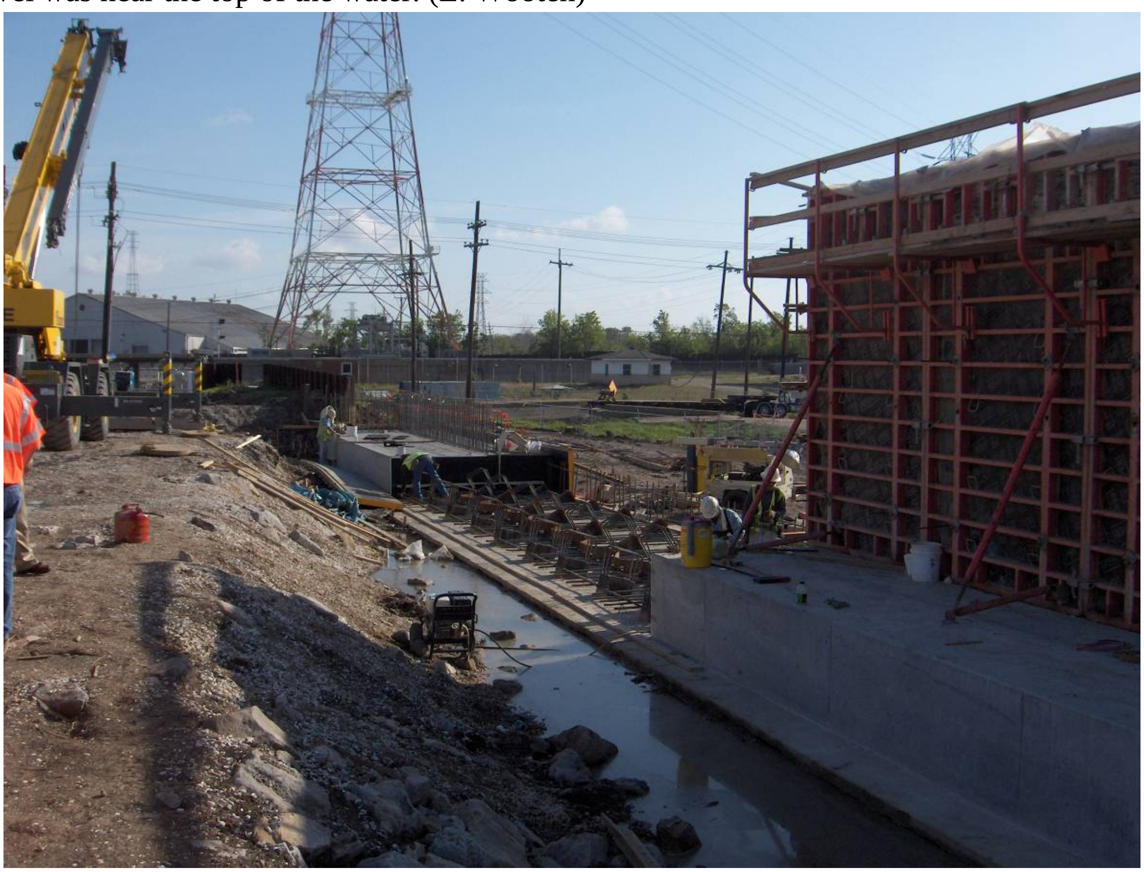
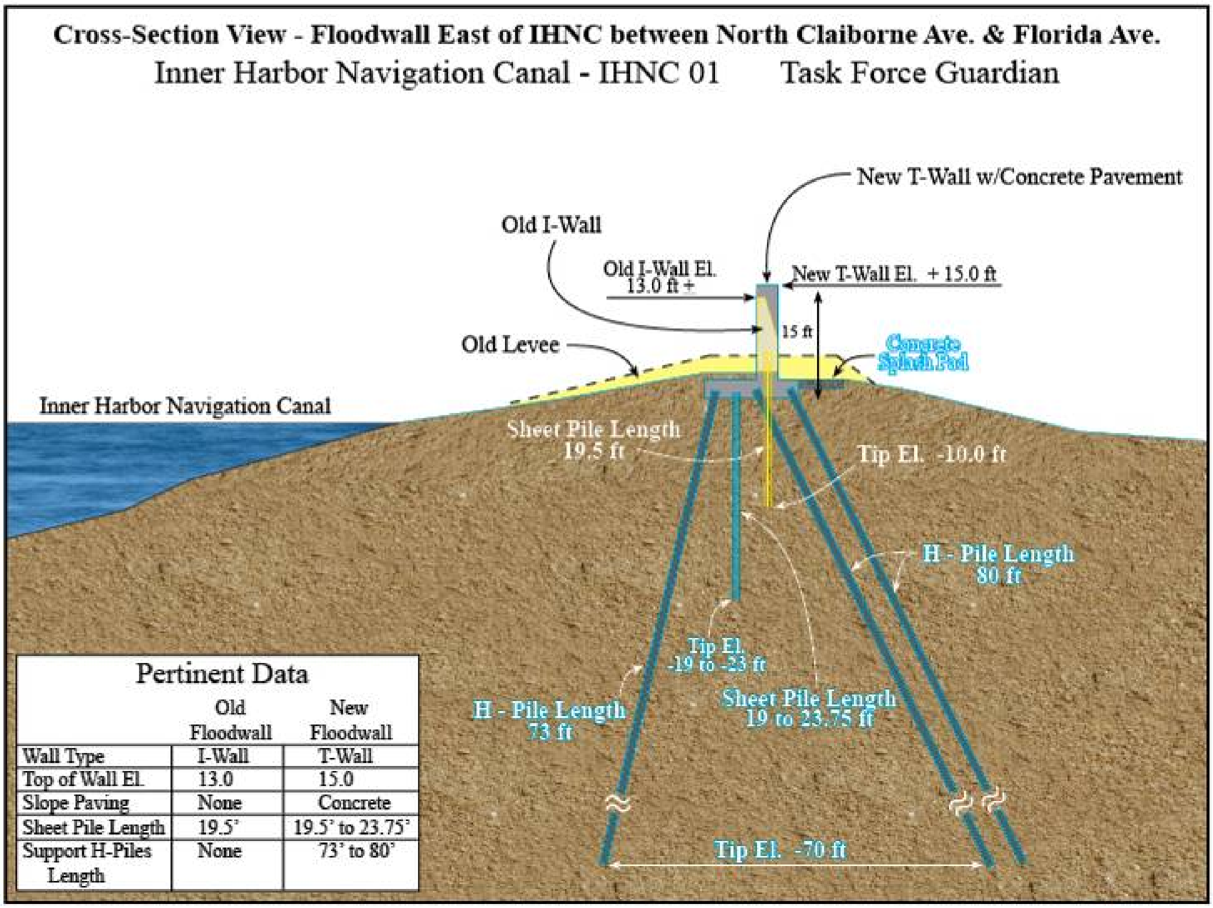


Fig. 2.4.3-5 Photograph from 2006 of T-wall being constructed to replace the I-wall that breached in two locations on the east side of the IHNC during Katrina. Photograph taken looking north at about the same location as the northern-most breach near Florida Ave. (see Fig. 2.4.3-4). (ASCE External Review Panel, May 2006)



* All elevations are NAVD88

Fig. 2.4.3-6 Cross-section showing the new T-wall constructed to replace the I-wall that failed during Katrina between Claiborne and Florida Avenues. (USACE)

Fig. 2.4.3-7 Photograph from Sept. 1, 2008 of Gustav storm surge. Photograph taken just south of Claiborne Avenue, looking south, south-west. The storm surge is within about 1 foot of the top of the wall. The wall at this location is an I-wall that was overtopped but did not breach during Katrina. The protected side of the wall has been built up to improve stability and covered with a concrete to protect against erosion. The I-wall stick-up on the protected side is just under 4 feet, while that on the canal side is just under 6 feet. (USACE)

Fig. 2.4.3-8 Photograph from Oct. 2, 2008 of I-wall shown during Gustav above in Fig. 2.4.3-6. Photograph taken looking north on protected side (IHNC is to the left and Lower 9th Ward to the right); location shown in Fig. 2.4.3-7 is circled. This wall was loaded with the surge within about 1 foot of the top of the wall (Fig. 2.4.3-7), and apparently had waves that overtopped it based on the debris line (circled in photo). After Gustav, there were no noticeable signs of distress here, including movement of the wall due to the surge load or erosion at the toe due to waves overtopping the wall. (R. Gilbert)

Fig. 2.4.3-9 Picture from Sept. 1, 2008 of Gustav storm surge. Picture taken from the Claiborne Avenue Bridge, looking north toward Florida Ave Bridge (seen in background) from perspective similar to Fig. 2.4.3-3. This location is where the old I-wall section shown in Figs. 2.4.3-7 and 2.4.3-8 transitions to the new T-wall section shown being constructed in Figs. 2.4.3-5 and 6. The storm surge is close to the top of the I-wall and several feet below the top of the T-wall. (USACE)

Fig. 2.4.3-10 Photograph from Oct. 2, 2008 of transition between old I-wall and new T-wall (shown in Fig. 2.4.3-3 post-Katrina and Fig. 2.4.3-9 during Gustav). Picture taken looking north from the protected side (same orientation as Fig. 2.4.3-3 and Fig. 2.4.3-9). After Gustav, there were no noticeable signs of distress at this transition. (R. Gilbert)

Fig. 2.4.3-11 Photograph from Oct. 2, 2008 of new T-wall section between Claiborne and Florida Avenues (shown in Fig. 2.4.3-9 during Gustav). After Gustav, there were no noticeable signs of distress in this wall. One potentially interesting feature here is the approximately 1-inch-deep vertical offset between the pile-supported base of the wall (to the left of the caulked joint) down to the concrete slab-on-grade splash apron (to the right of the caulked joint). If this splash apron was cast to be flush with the base of the wall, then this offset is possibly an indication of differential settlement between the pile-supported wall and the surrounding ground. If it is settlement, the rate is approximately 1 inch over two years, or 0.5 inches per year, and is likely occurring in the upper 70-feet of the profile (because the piles tip is approximately 70 feet below the ground surface – see Fig. 2.4.3-6). (R. Gilbert)

2.4.4 IHNC East Morrison Road

We visited the section of the HSDRRS near East Morrison Road in New Orleans East to investigate the USACE preliminary reports of damage to the relief wells and of soil moving through the wells. Much of the HSDRRS in this section of New Orleans East along the northeast section of the IHNC consists of I-walls set on earthen embankments with regularly spaced relief wells located at the toe of the embankment (see Figs. 2.4.4-1 & -2). These features were in place at the time of Katrina. Since Katrina, the USACE has added a grouted riprap splash apron on the protected side of the I-walls.

Fig. 2.4.4-1 IHNC Floodwall near East Morrison Road. Note splash apron (center) and relief wells (left). (L. Wooten)

Fig. 2.4.4-2 Relief Well Cover, October 2008 with inset taken from USACE Hurricane Gustav Damage Assessment Team SITREP 05 Sep 08 (L. Wooten)

We observed no signs of damage to the HSDRRS near East Morrison Road due to Gustav. The corrugated metal protective casings over the relief well outlets were in various states of deterioration. We did not see evidence of extensive sand migration out of the wells, although our observations were more than a month after Gustav, and we did not inspect all wells. The inset photo to Fig. 2.4.4-2 was taken from the USACE SITREP dated September 5, 2008 which shows a damaged outlet casing and sand that appears to have discharged from the well.

2.4.5 IHNC West Temporary Bin Wall

Immediately prior to Gustav, the USACE constructed an 1800-foot-long temporary bin wall using HESCO baskets to protect one length of I-wall along the northwest side of the IHNC that did not meet required stability criteria. Figure 2.4.5-1 shows the temporary bin wall under construction by the USACE, and Figure 2.4.5-2 shows the bin wall immediately after Gustav.

Fig. 2.4.5-1. Temporary Bin Wall under construction, IHNC northwest along France Road (http://www.mvn.usace.army.mil/HPS/Status%20Report%20Newsletters/Sept_9_2008.pdf)

Fig. 2.4.5-2. Post-Gustav Photograph of End of Temporary Bin Wall at Tie-in to I-Wall (http://www.mvn.usace.army.mil/HPS/Status%20Report%20Newsletters/Sept_9_2008.pdf)

The majority of the bin wall was constructed about 50 feet outboard of and parallel to the I-wall, with two tiers of baskets. The lower tier was four baskets wide and the upper tier was two baskets wide. The top of the bin wall was about 2 to 3 feet lower than the top of the adjacent flood wall. Surge and waves from Gustav left debris on the first tier (3-foot-height) of the bin wall but not on the top of the second tier. The bin wall appears to have protected this section of floodwall from any loading during Gustav. If Gustav had generated a storm surge higher than the bin wall, the existing I-wall would have been loaded, but to a lesser degree because of the bin wall. Specifically, the bin wall would have (1) reduced the period of loading, (2) mitigated wave loading, and (3) lengthened the seepage path during pre-overtopping periods. The permanent configuration of this section of the IHNC floodwall has not been determined. Figure 2.4.5-3 shows an overhead view of the I-wall and the post-Katrina installed grouted riprap splash apron on the protected side of the wall.

Fig. 2.4.5-3. IHNC I-wall and grouted riprap splash apron (L. Wooten)

2.4.6 IHNC Bridges, Ships, Boats, Barges

The empty barge that floated into the Lower 9th Ward following Katrina and Rita has been well-documented (see Fig. 2.4.6-1). There has been speculation that this barge or another barge could have contributed to the failure of the Lower 9th Ward I-wall. The high winds of a hurricane can easily push an empty vessel with enough force to break mooring lines and force the vessel into structures in the IHNC. Such was the case during Hurricane Gustav. The U.S. Coast Guard (USCG) has jurisdiction over the ships and barges in the IHNC.

Fig. 2.4.6-2 shows how ships and barges were pushed during Gustav against the dolphins protecting the railroad bridge that crosses the IHNC. This railroad bridge was in the down position and underwater during periods of high water. The Florida Avenue Bridge to the south of these barges and ships was in a slightly raised position to be out of the water but low enough to keep wind loads from having leverage on the support towers. In these positions, both bridges would have confined the ships and barges to the central part of the canal.

For the subsequent hurricane, Ike, the USCG ordered all ships and barges removed from the IHNC.

Fig. 2.4.6-1. Barge in the Lower 9th Ward, October 2005 (L. Wooten)

Fig. 2.4.6-2. Ships and barges pushed against railroad bridge after Gustav, September 1, 2008 (Eric Gay, Associated Press)

2.5 Lake Pontchartrain

2.5.1 Interior Drainage Canals

The performance of the HSDRRS along the interior drainage canals (London Avenue, Orleans Avenue, and 17th Street Canals) is critical to the protection of New Orleans, especially in light of the three major breaches that occurred during the Katrina storm surge. Failures of the 17th Street Canal and London Avenue Canal floodwalls were responsible for a significant portion of the flooding in New Orleans because those breaches extended below sea level and continued to flow after the Katrina storm surge receded.

As described in Section 1.2.4, the USACE has constructed canal closure gates and pumping systems at the north ends of each of the three interior drainage canals. A safe water elevation (SWE) was established for each canal. The gates at the 17th Street Canal and at the London Avenue Canal were closed on the evening of September 1, 2008 when water levels came within one foot of the SWE (El. 5 for 17th Street and El. 6 for London Avenue). The pumping systems at these two structures were also activated to allow the Sewerage and Water Board of New Orleans to continue operation of their storm water system pumps which dumped into the canals. All systems performed well and canal levels were kept between El. 2.0 and 2.5. The gates and pumps on the Orleans Avenue Canal were not operated because storm surge levels did not approach the SWE (El. 8) for that canal.

Floodwall and levee repairs and improvements at the 17th Street and London Avenue Canals to close and upgrade the breached sections showed no effects from the modest loads imposed by Gustav prior to and after gate closure. T-walls replacements at the breached I-wall locations were not distressed, nor were the walls subjected to significant loads, due to the protection provided by the canal gates and pumps. The additional wave energy and overtopping protection which has been added at the entrances of the interior drainage canals and at transitions provided a higher level of resiliency that was not taxed by Gustav.

Gustav did not generate storm surges at levels experienced during Katrina. However, this less severe test did allow for evaluation and operation of the improved elements of the HSDRRS, which, for Gustav, provided suitable protection for New Orleans.

2.5.2 Lake Front Levees and Floodwalls

The USACE reported no signs of erosion, overtopping, instability or seepage distress from Gustav along the lakefront levees and floodwalls. Our limited observations were consistent with the USACE reports. High water levels only reached about El. 4.7 on the lakefront in New Orleans.

2.6 Plaquemines Parish Non-Federal Local Levee

Plaquemines Parish consists of the small communities along the narrow Mississippi River delta south of St. Bernard Parish. These communities are protected from the Mississippi River by the USACE constructed levee and along their Gulf facing sides by back levees which, in places, are non-federal. We visited one length of non-federal back levee which was constructed and maintained by Plaquemines Parish and which is not considered part of the New Orleans area HSDRRS.

Members of our team were escorted along parts of the Plaquemines Parish Back Levee by Messrs. Ken Klaus and Noah Vroman as part of our Gustav reconnaissance. Sections of the back levee near Braithwaite and Scarsdale, on the east bank of the Mississippi, were described as having been overtopped and in distress during Gustav and Ike. Our team observed about half of the northeastern-most back levee of the Parish located as shown in Figure 2.6-1.

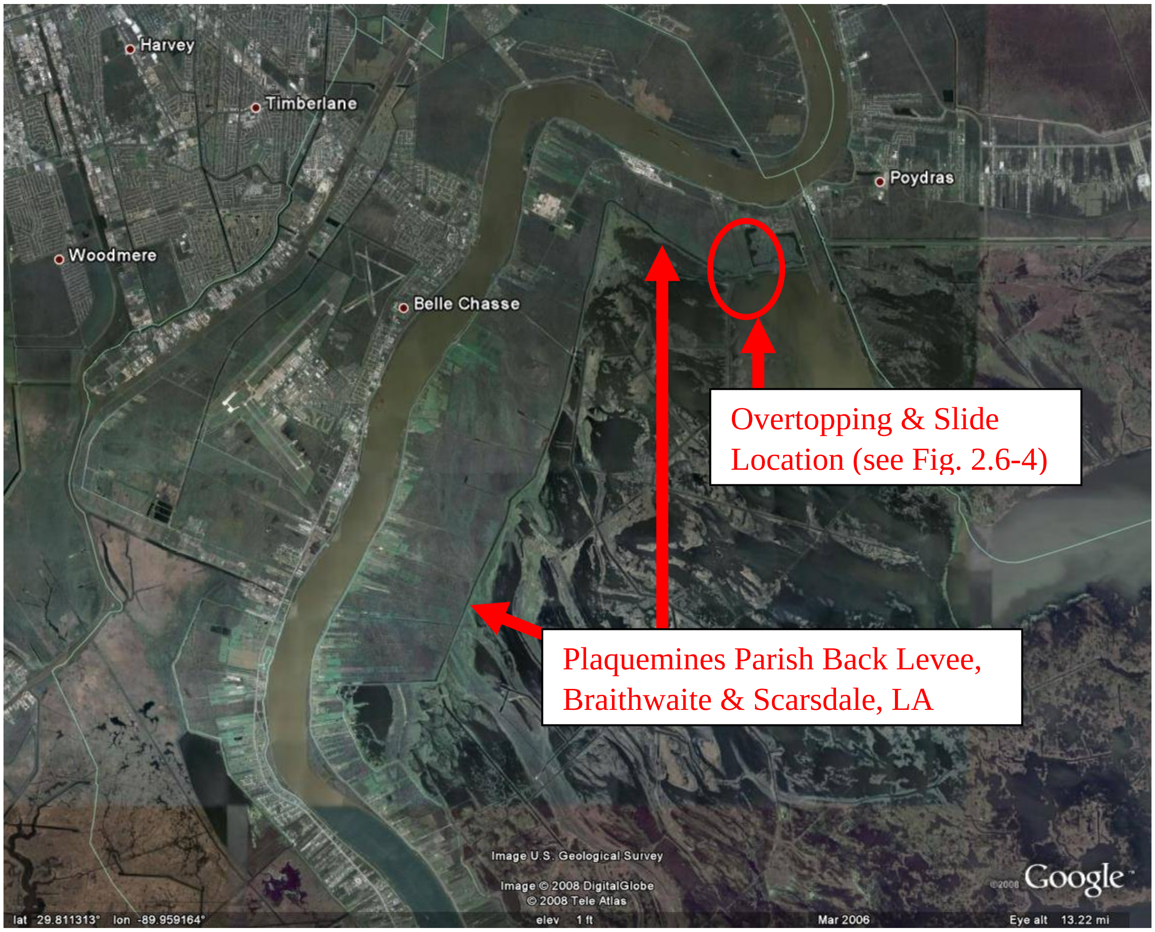


Fig. 2.6-1. Plaquemines Parish Back Levee near Braithwaite and Scarsdale, LA (Google Earth / USGS Imagery)

Plaquemines Parish workers and emergency workers from St. Bernard and Orleans Parishes and the USACE were reported to have responded during Gustav to help prevent a breach of the levee. The Caernarvon Mississippi River Diversion gates were also reported to have been opened in an effort to drain high flood waters in the Clearwater Canal, which abuts the northeastern edge of the back levee, to the lower level of the Mississippi River (see Figure 2.6-2) (Vanacore, Andrew (2008)).

Fig. 2.6-2. Plaquemines Parish Back Levee (Google Earth / USGS Imagery)

At the time of our visit, multiple sections of the levee crest were still covered with a slit-film woven geotextile held in place with a continuous sand bag berm on the flood side and by intermittent sand bags on the protected side of the crest (see Figure 2.6-3). Based on our observations and on interviews with a pump station operator, it appears that much of the back levee was overtopped and that a slope failure or slide had occurred on the protected side of the levee along one 300-foot-long levee section located as shown in Figures 2.6-1 and 2.6-2. Figures 2.6-4 and 2.6-5 show the slide on the back levee and the slide scarp of a little over 1 foot. We also observed that desiccation cracks were prevalent along parts of the levee (Figures 2.6-6 and 2.6-7). The desiccation cracks may have contributed to the slide by allowing overtopping water pressures into embankment zones critical to slope stability. The placement water content, compaction, and organic content of the back levee soils were not known and may be factors in the susceptibility of the levee soils to desiccation cracks and erosion.

Fig. 2.6-3. Plaquemines Parish Back Levee sand bags and geotextile crest cover (L. Wooten)

Fig. 2.6-4. Protected side slope of Plaquemines Parish back levee and slide (L. Wooten)

Fig. 2.6-5. Scarp above slide on Plaquemines back levee (L. Wooten)

Figs. 2.6-6 and 2.6-7. Desiccation cracks on Plaquemines Parish back levee (L. Wooten)

Along more southerly sections of the levee, we observed signs of overtopping with less dramatic effects. Debris and erosion gullies, often covered with sand bags, were prevalent along sections of the levee (Figures 2.6-8, 2.6-9, and 2.6-10). We did not visit other sections of the various Plaquemines Parish back levees south of the locations shown on Figure 2.6-1.

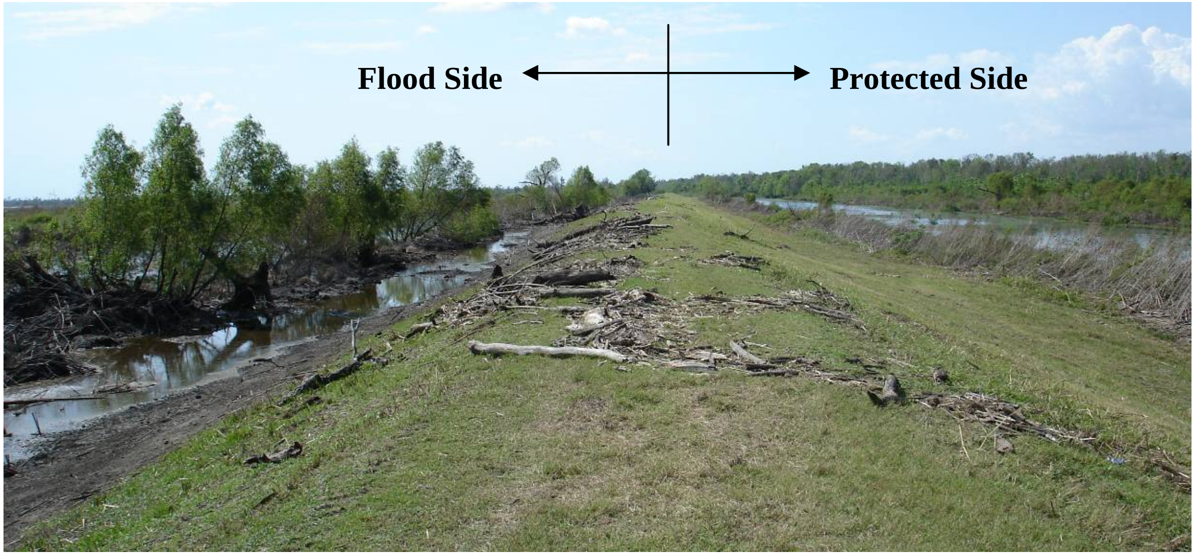


Fig. 2.6-8. Debris left by hurricane surge and waves on Plaquemines Parish back levee (L. Wooten)

Figs. 2.6-9 and 2.6-10. Overtopping erosion gullies on Plaquemines Parish back levee, protected side (L. Wooten)

3. Conclusions and Lessons Learned

Performance of the HSDRRS during Gustav - Our fundamental conclusion was that the HSDRRS around New Orleans performed well under the surge and wave stresses generated by Gustav. We observed no signs of distress in the HSDRRS as a result of Gustav. Performance of the levees and floodwalls after Hurricane Gustav demonstrated a significant improvement of the system since Katrina. Many of the most serious deficiencies identified after Katrina have been (and continue to be) addressed. Where storm surge waters and waves reached or exceeded the heights of levees and floodwalls along the IHNC, the flood protection showed an improved durability. Increased heights of a number of levee sections provided protection higher than that provided by the HSDRRS prior to Katrina, and some amount of breaching and damage may have been averted due to these improvements.

Future Hurricanes and Overtopping - Gustav imposed lower water levels and loads on the HSDRRS than did Katrina. A Katrina-like or larger storm can be expected to occur in the future, and the performance during Gustav may not provide an accurate representation of the level of protection (or damage) that could occur during such an event. Marginally larger hurricanes could result in significant overtopping along the IHNC and the GIWW until the Lake Borgne Barrier is installed and the HSDRRS is raised to the estimated 100-year flood levels.

HSDRRS Improvements - However, we believe that the HSDRRS, even in its current configuration, provides a level of both protection and durability that should reduce the potential for breaches if subjected to stresses imposed by higher levels of surge and waves that overtop system elements. Improvements, upgrades, and replaced sections of flood protection levees and floodwalls appeared to have significantly increased the capacity, durability and resiliency of various components of the system. Of particular note was the armoring provided to resist overtopping scour behind floodwalls, the hardening /armoring of critical transitions between disparate components, reconstruction, heightening and reduced slopes (some with buttresses) of earth embankments with compacted and less erodible materials, and addition of hurricane barrier gates and pump stations at the entrance of the interior drainage canals. We do not know what levels of surge and wave would overstress the system, but the current and future configurations are significantly superior to the pre-Katrina HSDRRS. The proposed improvements to the HSDRRS planned for 2011 will further increase the level of protection and system durability.

Plaquemines Parish Back Non-Federal Local Levee Performance – The non-federal local back levee in Plaquemines Parish was overtopped by Gustav flood levels and was in danger of failure at the location of the slope slide. Desiccation cracks on the levee may have contributed to the slide by allowing overtopping water pressures into embankment zones critical to slope stability. The placement water content, compaction, and organic content of the back levee soils were not known and may be factors in the susceptibility of the levee soils to desiccation cracks and erosion.

Lessons - Gustav tested the HSDRRS and offered some lessons for flood protection systems.

- Boats, barges, or other large objects (e.g. rail cars, tanks, shipping containers) that float could impose a risk to floodwalls. The USCG's evacuation of the IHNC and GIWW is critical to protection of the HSDRRS.

- Preparation for a hurricane requires timely action by all responsible parties. Delays by the railroad, salvage yards, boat and barge operators, operators of facilities on the flood side of the HSDRRS in clearing potential hazards could put the HSDRRS at risk.

- The erosion resistance of non-federal local clay levees in Plaquemines Parish (not part of the HSDRRS) during overtopping was noted during Katrina. The clay back levees in Plaquemines Parish resisted erosion during Gustav, but may have demonstrated a potential vulnerability due to desiccation cracks. Improved control of placement water content and compaction, revised material requirements relative to plasticity and organic content, or landscaping measures such as establishment of dense vegetation may be required to prevent desiccation.

- Protection of life in the southern Louisiana area will require continued emphasis on evacuation. Storm surges larger than those created by Gustav and Katrina should be anticipated. Bringing the HSDRRS up to a level appropriate for protection of the New Orleans area will take years if not decades to achieve.

Acknowledgements

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The research teams wish to acknowledge the gracious logistical support and technical interaction provided by the U. S. Army Corps of Engineers who acted as hosts for our visit. Messer's Rob Dauenhauer, Tim Ruppert and Rich Varuso of the New Orleans District, Mr. Ken Klaus of the Mississippi Valley Division, and Mr. Noah Vroman of the Engineer Research and Development Center handled logistical details, served as guides, prepared and distributed handouts and photos included herein, and answered our many lengthy and detailed questions. The Corps personnel were familiar with many important details and reinforced our confidence in the post-Katrina work of the Corps.

The Geoengineering Extreme Events Reconnaissance (GEER) Association is made possible by the vision and support of the NSF Geotechnical Engineering Program Directors: Dr. Richard Fragaszy and the late Dr. Cliff Astill. GEER members also donate their time, talent, and resources to collect time-sensitive field observations of the geotechnical effects of extreme events. The GEER Association web site, which contains additional information, may be found at: http://www.geerassociation.org/

Finally, we thank Prof. Jonathan D. Bray, PhD, PE, University of California at Berkeley, in his capacity as Chair of GEER, for logistical support, direction, and encouragement for the reconnaissance effort.

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Appendix A – Current and Ongoing Improvements of the HSDRRS

A.1 Overview of Repairs and Improvements

Introduction - The post-Katrina repairs and improvements to the Hurricane and Storm Damage Risk Reduction System (HSDRRS) for the New Orleans area did in fact protect the city during Gustav. The condition of the HSDRRS in September 2008 existed because of the efforts on the part of the U.S. Army Corps of Engineers (USACE) to provide increasing levels of protection to New Orleans in the short period of time since Katrina's devastation. This overview briefly describes some of the repairs and improvements, which are still in progress. A more thorough and graphic description of these efforts can be found on the USACE New Orleans District web page (http://www.mvn.usace.army.mil/hps2/index.asp).

Task Force Guardian - Immediately following Katrina, the USACE established Task Force Guardian with the primary mission to repair the HSDRRS to the pre-Katrina level of protection before the 2006 hurricane season. Task Force Guardian accomplished this mission along with other significant recovery and emergency response tasks such as debris removal and distribution of recovery supplies.

2011 Hurricane and Storm Damage Risk Reduction System - As documented by the IPET study, surges associated with events more frequent than the 100-year event (1% annual probability of exceedance) would overtop the pre-Katrina / June 2006 level of protection provided by the HSDRRS. Subsequent to Task Force Guardian, the USACE has worked and planned for raising the HSDRRS to levels that prevent overtopping by the 100-year-event water levels. The improved HSDRRS is scheduled for completion in 2011. Fig. A.1-1 shows the HSDRRS status map for June 2008 as provided by the USACE.

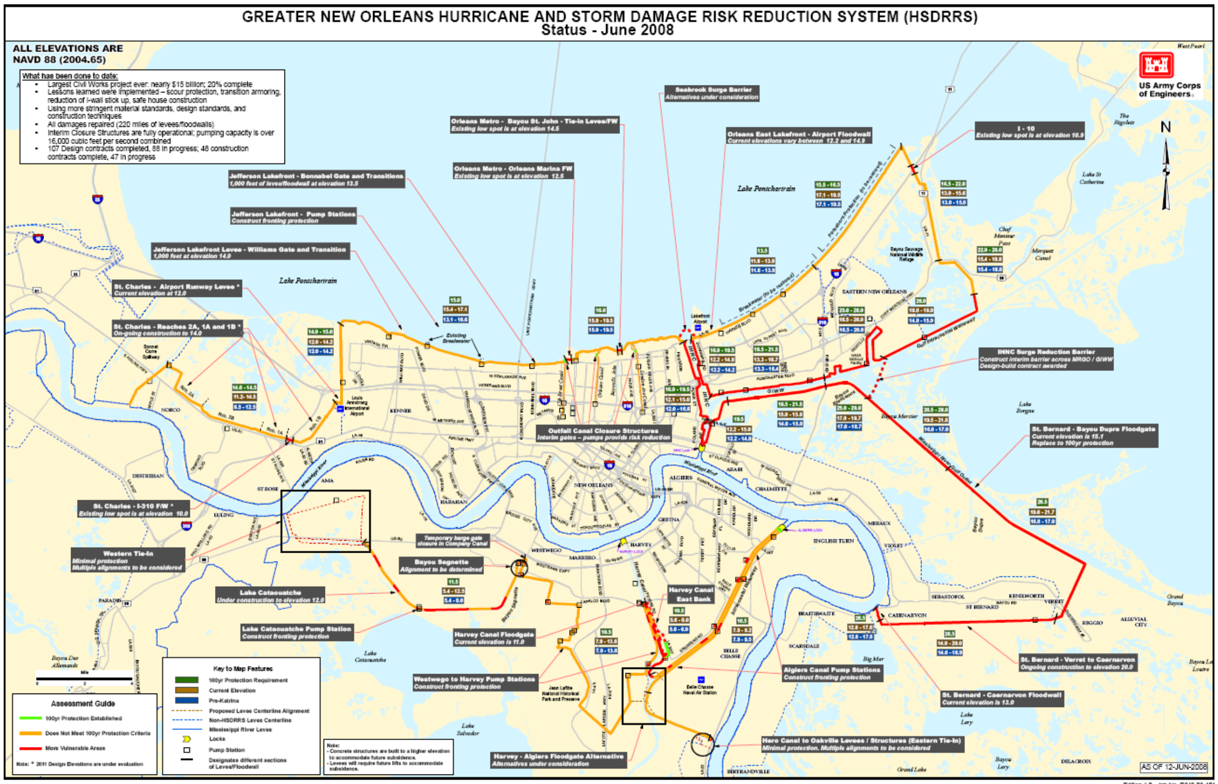


Fig. A.1-1. – HSDRRS Status Plan, June 2008
(http://www.mvn.usace.army.mil/hps/pdf/2008_Storm_Vulnerability_Elev_final.pdf)

<u>Durability</u> - In addition to overtopping protection, both Task Force Guardian and the current 100-year HSDRRS plans have increased the durability of the HSDRRS for events that may overtop the system elements. Specifically, the systems have been designed and constructed to resist erosion if overtopping occurs and to maintain pumping capacity in the event high water levels occur at pump stations.

<u>Louisiana Coastal Protection and Restoration</u> - The USACE, in partnership with the state of Louisiana, is studying a larger range of coastal protection, restoration, planning, and damage reduction options that encompasses all of south Louisiana - the Louisiana Coastal Protection and Restoration (LACPR) Project. The study is evaluating protective measures for events ranging from the 1% annual exceedance probability (100-year) event to larger events categorized by the Congressional authorization as “Category 5” protection. The LACPR Final Technical Report is in progress and is scheduled for external independent review by the National Academy of Sciences in 2009.

We describe some of the specific HSDRRS repairs, improvements, and plans in the remainder of this appendix.

A.2 Earthen Levee Reconstruction

Katrina severely overtopped many of the pre-Katrina earth levees, particularly in the southeast areas of the hurricane protection system around the St. Bernard Parish and New Orleans East polders. The Katrina overtopping resulted in numerous breaches where earth levees were eroded by the overtopping flows, particularly where the levees were constructed with hydraulic fill. Levees constructed of compacted clay, in most cases, eroded at rates that were low enough to withstand the Katrina overtopping surge. We note that erosion is dependent on numerous factors (overtopping forces, overtopping durations, soil type, organic or sand content, compaction effort, etc.) besides the levee material. Several levee sections constructed of hydraulic fill did withstand Katrina overtopping, and levee sections constructed of clay fill eroded where erosion forces were high such as behind overtopped floodwalls. The repairs and improvements to the HSDRRS earth levees have been designed and constructed with two main purposes – (1) to raise the level of protection so that the likelihood of overtopping is lessened and (2) to improve the capacity of levees to withstand erosion during overtopping.

Figure A.2-1 shows an enlarged view from the HSDRRS plan (Figure A.1-1) focusing on the HSDRRS levees along the Mississippi River Gulf Outlet (MRGO), the Gulf Intracoastal Waterway (GIWW) and the Inner Harbor Navigation Canal (IHNC). The elevations given in the boxes are the 100-year-event level of protection goal for 2011 (top/green), the June 2008 system crests (middle/brown), and the pre-Katrina system crests (bottom/blue).

Major system improvements to earth levees have been constructed along the GIWW and the MRGO east of the proposed IHNC Surge Reduction Barrier. The USACE has rebuilt these levees to current crest levels of about El. 18.0 to El. 21.7 as of June 2008 compared to either the pre-Katrina levels of El. 14.0 to 17.0 or to the 100-year-event level goal of El. 26.5 to 28.5. We understand that elevations given in this report are referenced to the North American Vertical Datum 1988 (NAVD88). Earth levees along the GIWW to the west of the proposed IHNC Surge Reduction Barrier have been repaired only to pre-Katrina levels because of the higher level of protection that will be provided once the surge barrier is in place.

Fig. A.2-1. – Section of HSDRRS plan, East New Orleans and St. Bernard Polders (http://www.mvn.usace.army.mil/hps/pdf/2008_Storm_Vulnerability_Elev_final.pdf)

Figures A.2-2 and A.2-3 shows the earth levee at the southeast corner of the HSDRRS along the MRGO. The current reconstructed levee features include:

- Compacted clay fill construction for erosion resistance – The MRGO levees have been raised using compacted clay fill to create higher, broader levees which have increased resistance to erosion because of the use of the clay on the upper layers of the embankment crown and slopes.

- Grass cover, also for erosion resistance – Establishing and maintaining the grass cover has required a significant effort during periods of dry weather because of the lack of fresh water in the immediate vicinity of the MRGO levee.

- 3H:1V and 4H:1V slopes with stability berms - The geometry of the rebuilt MRGO levee is dictated by USACE stability criteria and typically includes slopes of between 4H:1V and 3H:1V, 100-foot wide stability berms on both flood and protected sides, and crest widths of about 10 feet or more.

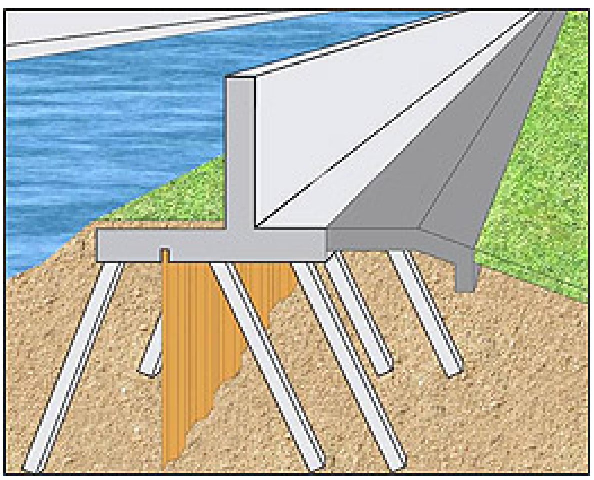
Fig. A.2-2. Southeast corner of the MRGO levee, flood side (L.Wooten)

Fig. A.2-3. MRGO levee crest and protected side slope (L.Wooten)

A.3 Floodwall Improvements

The USACE has improved the HSDRRS floodwall protection by replacing breached and damaged floodwalls, by upgrading existing floodwall stability, and by hardening the protected side of floodwalls and floodwall-levee transitions.

Replacement T-Walls & L-Walls - Katrina surges and overtopping breached, displaced, and damaged I-wall type floodwalls in numerous locations. The USACE has typically replaced these damaged I-walls with T-walls and abutting splash aprons. Figure A.3-1 & 2 shows a T-wall schematic and a photograph taken during construction of a T-wall. In a few locations with constrained alignments, L-walls with splash aprons have been installed. The T-walls and L-walls provide enhanced resistance to tilting, a problem that probably contributed to several of the Katrina I-wall breaches. The extended base of the T-walls and L-walls with the added splash aprons provides erosion protection in the event of overtopping, another likely cause of Katrina I-wall breaches. The splash aprons (see gray element in Figure A.3-1) are typically concrete slabs for new walls but have also been constructed using grouted riprap.



Figs. A.3-1 & 2. T-wall schematic and T-wall under construction (http://www.mvn.usace.army.mil/hps2/hps_outfall_canals.asp)

I-Walls Repairs and Upgrades - The HSDRRS currently depends on many of the I-walls that were in place before Katrina. These I-walls have been repaired, where necessary, by filling scour trenches on the protected side, and enhanced with splash aprons. The USACE has established criteria for retaining I-walls calling for a maximum protected side stick-up height of 4-foot, and a maximum flood-side:protected-side stick-up differential height of 2-feet. Allowable stick-up heights for new T-walls and L-walls are significantly higher. Splash aprons, typically extending at least 7 feet from the I-wall, have been constructed for all I-walls using either reinforced concrete or grouted riprap. Figure A.3-3 shows a reinforced concrete splash apron on the protected side of the I-wall and T-wall on the west side of the IHNC along France Road adjacent to the former container terminal.

Fig. A.3-3. I-wall and splash apron, IHNC west along France Road; new T-wall and splash apron in background (L.Wooten)

<u>Temporary Bin Wall</u> - The USACE determined that one 1800-foot length of I-wall along the northwest side of the IHNC did not meet the required stability criteria. To protect this length of I-wall, two weeks prior to Gustav, the USACE constructed a temporary 6-foot-high cage and geotextile bin (HESCO baskets) fill wall on the flood side. The temporary bin wall was constructed with two levels of 3-foot baskets configured with a four- and two-basket width on the first and second levels respectively. Figure A.3-4 is a photograph of the bin wall.

Fig. A.3-4. Temporary Bin Wall, IHNC northwest along France Road (L. Wooten)

Transition Hardening - Katrina overtopping caused significant erosion at transitions between many of the numerous earth levees and floodwalls in the hurricane protection system. The USACE has modified these transitions by placing erosion protection, typically grouted riprap, and, in some cases, by modifying the transition profiles. Figure A.3-5 shows the transition between the Bayou Dupree floodwall and the MRGO earth levee. At this transition, the USACE has elevated the earth levee at the transition and covered it with grouted riprap.

Fig. A.3-5. Transition Protection and Modification, Flood Side of Bayou Dupree Flood Wall (L. Wooten)

A.4 Drainage Canal Closures

The Katrina breaches of the I-walls along the London Avenue and 17th Street Canals were well documented and represented some of the most critical weaknesses in the HSDRRS because of the extent of similar I-walls along those canals and along the Orleans Avenue Canal. The USACE elected to construct interim floodgates at the Lake Pontchartrain end of the canals so that storm surges do not flow into the canals and overload the I-walls. Large pumping facilities were installed adjacent to the gates to provide a means of evacuating canal storm drainage around the gates when closed. Figure A.4-1 shows a schematic for the canal closure structures. Figures A.4-2, 3, and 4 are photographs of the 17th Street, Orleans Avenue, and London Avenue Canal closure facilities.

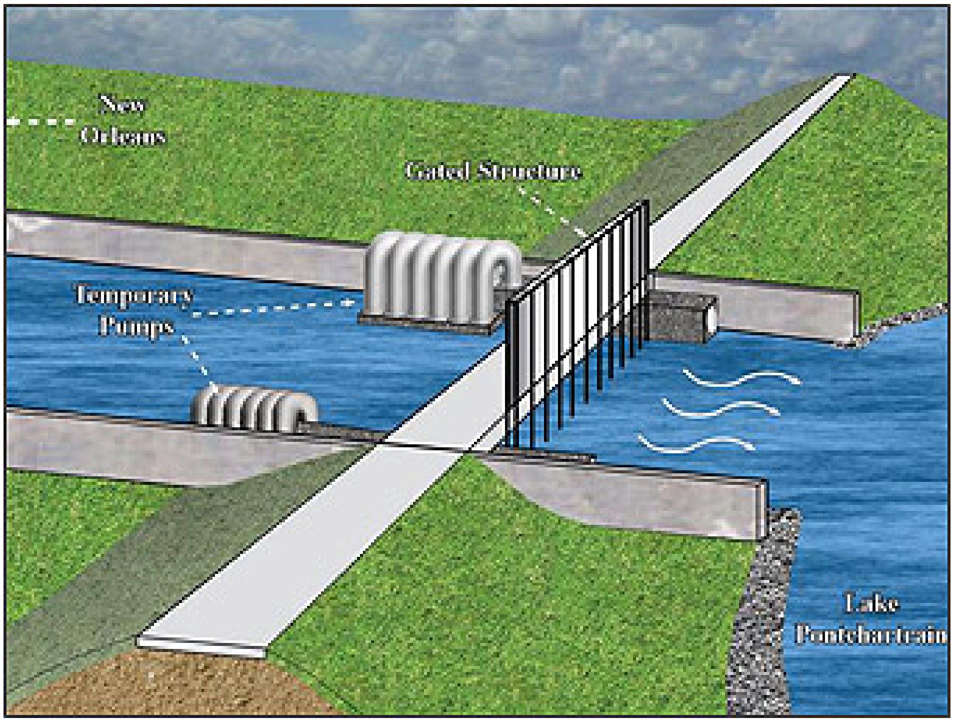


Fig. A.4-1. Canal Closure Facilities Schematic
(http://www.mvn.usace.army.mil/hps2/hps_outfall_canals.asp)

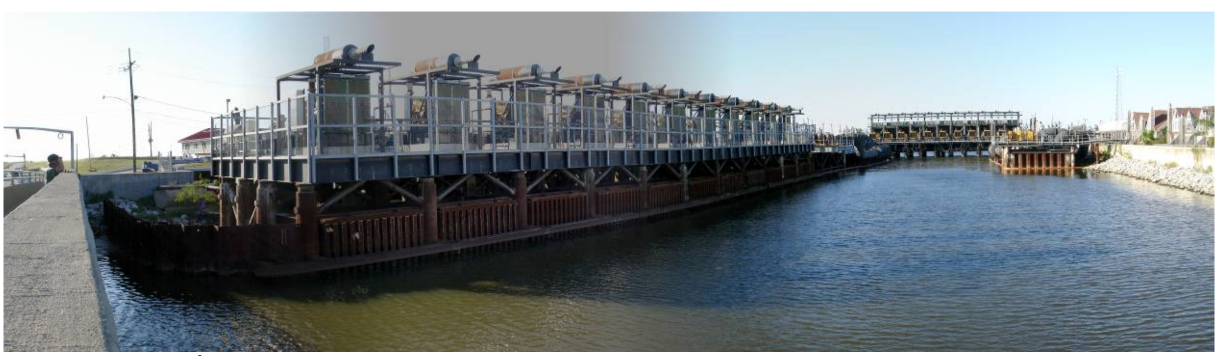


Fig. A.4-2. 17th Street Canal Outfall Closure Structure & Pumps, Protected Side
(L. Wooten)

Fig. A.4-3. Orleans Avenue East Closure Structure East Side Discharge and Gates (L. Wooten)

Fig. A.4-4. London Avenue Canal Closure Structure, Flood Side (L. Wooten)

A.5 Pump Station Improvements

The numerous pump stations in the New Orleans area did not function during Katrina. Almost all pump stations were designed, constructed, operated and maintained by local agencies. They were designed only to remove rainfall runoff, while the HSDRRS was designed to reduce damages from storm surge and waves. The USACE is in the process of repairing, modifying, and rebuilding thirty of the seventy-three area pump stations to operate during future storm events by ensuring backup power, strengthening the structures, and storm / flood-proofing the facilities and equipment. Specific storm proofing measures include providing safe rooms for operators and raising vulnerable pumping equipment. Figure A.5-1 shows the locations of the pump stations.

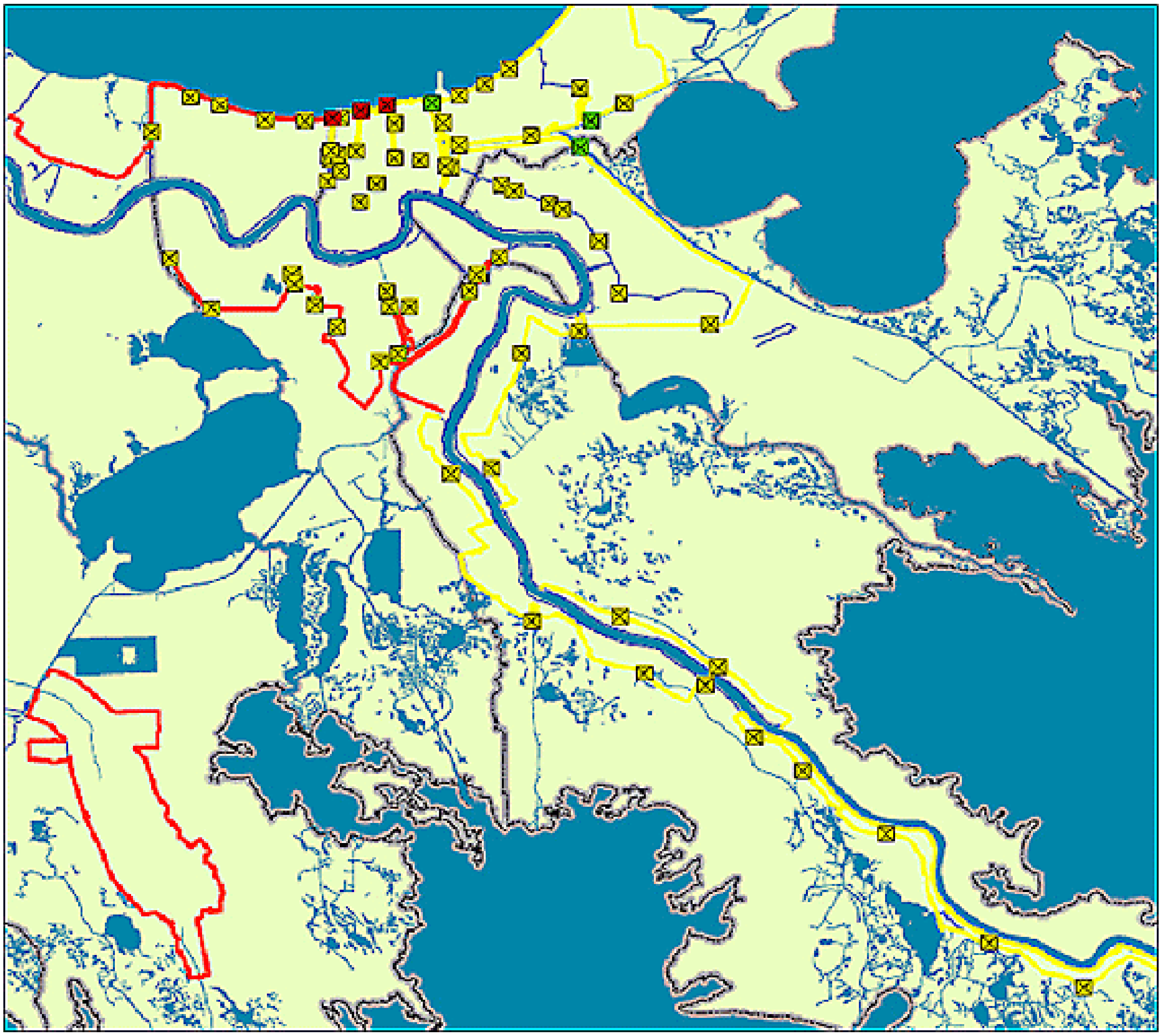


Fig. A.5-1. Pump Station Locations
(http://www.mvn.usace.army.mil/hps2/hps_existing_pump_repairs.asp)

A.6 Pending Improvements (HSDRRS)

The ongoing task to complete the 100-year HSDRRS protection remains significant. The remaining major elements of the HSDRRS include raising levees, floodwalls, and gate structures (see Figure A.1-1 and A.2-1 elevations), constructing the Lake Borgne Barrier across the MRGO and GIWW, and resolving / designing / constructing the Lake Pontchartrain side protection for the IHNC. Figure A.6-1 shows a map and photographs of the HSDRRS projects provided by the USACE.

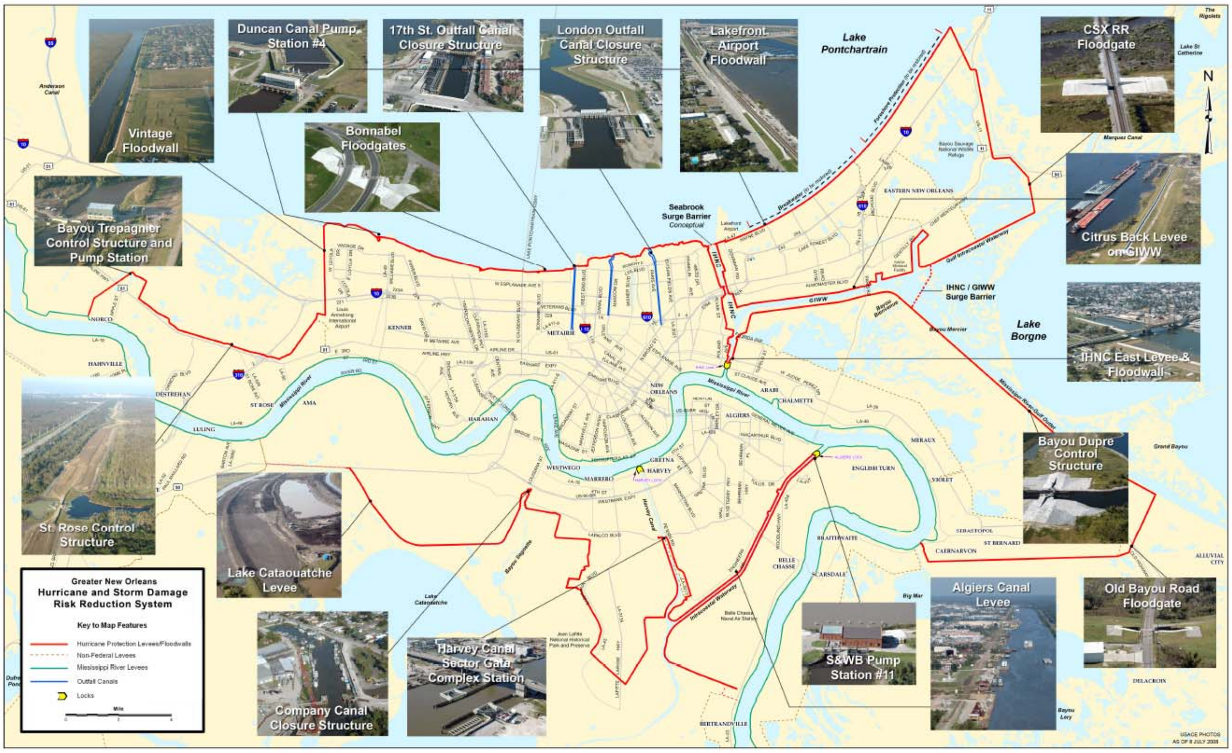


Fig. A.6-1. HSDRRS Map with Photographs of Major Projects (http://www.hq.usace.army.mil/gustav/Visuals/hrsystemmap.pdf)

Raising Levees, Floodwalls, and Gates - Most of the existing levees, floodwalls, and gates of the HSDRRS are being raised from pre-Katrina configurations to the 100-year flood elevation. The biggest levee raises will be in the areas where predicted and past storm surges have been the highest – along the MRGO and GIWW, where current crest and 100-year flood levels are about El. 19 and El. 28 respectively. Refer to Figures A.1-1 and A.2-1 and to the USACE source link (http://www.mvn.usace.army.mil/hps/pdf/2008_Storm_Vulnerability_Elev_final.pdf) for elevation differences at specific locations.

Lake Borgne Barrier and MRGO Closure – Much of the storm surge from Katrina that overtopped and breached the IHNC floodwalls flowed from Lake Borgne to the IHNC via the GIWW and the MRGO. The planned Lake Borgne Barrier will be a closure and gate structure across the MRGO and the GIWW at their confluence (see Figure A.6-2). The barrier will provide protection from future Lake Borgne storm surges, up to the 100-year event level, for the levees and floodwalls along the GIWW west of the barrier and along the IHNC. The USACE has selected the alignment shown in Figure A.6-3 from five alternatives. The proposed alignment will consist of a 1.4-mile concrete wall with navigable gates that would be the largest design/build civil works project in Corps history. Refer to Final Individual Environmental Report (http://www.nolaenvironmental.gov/nola_public_data/projects/usace_levee/docs/original/FinalIER11_21Oct08.pdf) for details.

Fig. A.6-3. MRGO – GIWW Confluence looking east toward the Paris Road Bridge, Michoud Slip, and the New Orleans skyline (http://www.mvn.usace.army.mil/hps/Status%20Report%20Newsletters/Special_Issue_April_17_2008.pdf)

In addition to the Lake Borgne Barrier, the USACE has recommended construction of a closure structure across the MRGO south of the St. Bernard Parish HSDRRS levees, near Hopedale, LA, as part of the de-authorization of the MRGO. Congress mandated the closure of the MRGO in the Water Resources Development Act of 2007, ending almost 50 years of use of the channel for deep-draft shipping. The USACE expects to complete the closure structure before the 2009 hurricane season.

<u>Seabrook Floodgate</u> - Construction of the Lake Borgne Barrier will protect the IHNC from Lake Borgne surges but will not mitigate the smaller surges from Lake Pontchartrain that would enter the IHNC in its current configuration. The USACE is currently evaluating the need for and conceptual configuration of the Seabrook Floodgate at the north end of the IHNC.

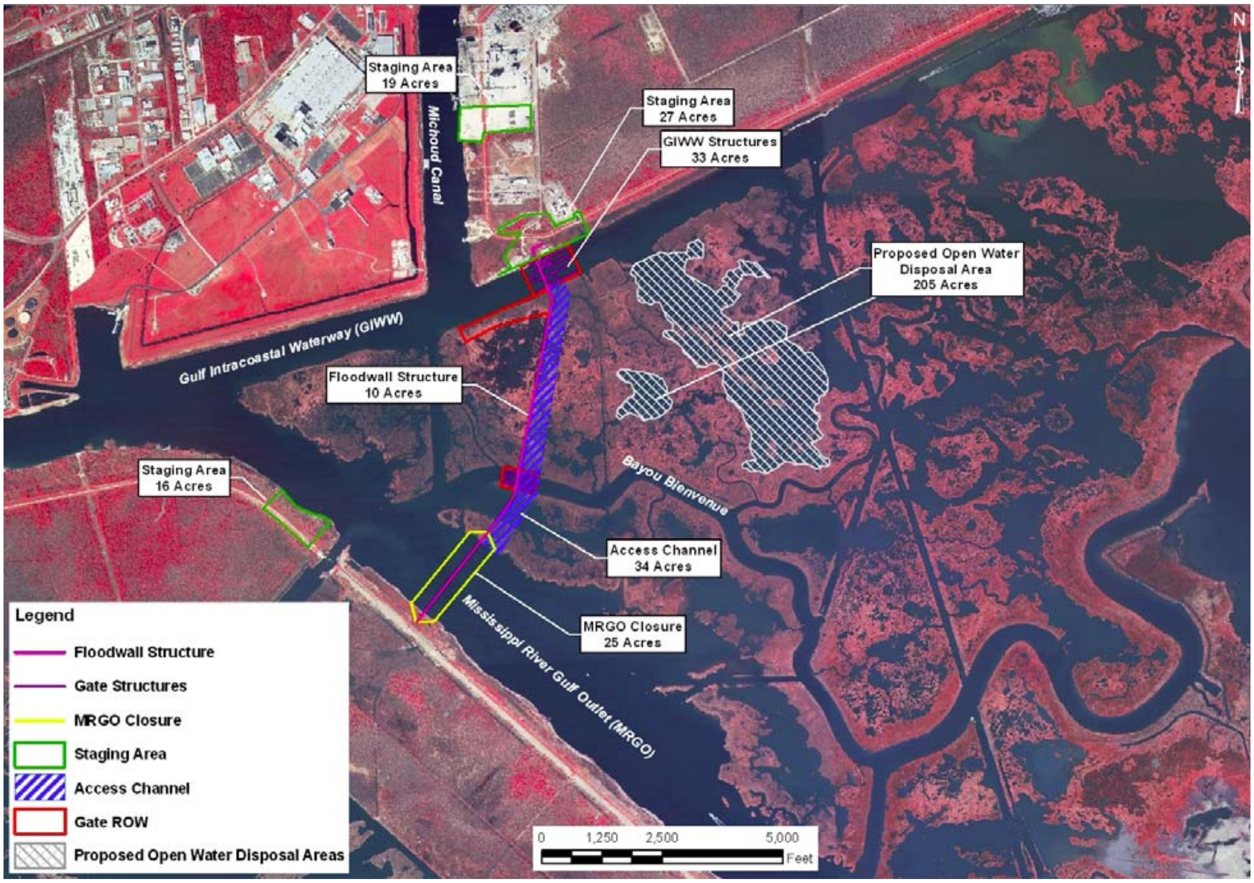


Fig. A.6-4. Lake Borgne Barrier Planned Alignment (http://www.nolaenvironmental.gov/nola_public_data/projects/usace_levee/docs/original/FinalIER11_21Oct08.pdf)

A.7 Planning Beyond the 2011 HSDRRS - LACPR

Congress and the Louisiana Legislature directed that the LACPR be established to investigate and create the first plan in Louisiana's history designed to fully integrate hurricane risk reduction for coastal communities and industries with the restoration of the State's rapidly deteriorating coastal wetlands. The Energy and Water Development Appropriation Act directed that

…, the Secretary of the Army, acting through the Chief of Engineers, is directed to conduct a comprehensive hurricane protection analysis and design at full federal expense to develop and present a full range of flood control, coastal restoration, and hurricane protection measures exclusive of normal policy considerations for South Louisiana and the Secretary shall submit a preliminary technical report for comprehensive Category 5 protection within 6 months of enactment of this Act and a final technical report for Category 5 protection within 24 months of enactment of this Act: Provided further, That the Secretary shall consider providing protection for a storm surge equivalent to a Category 5 hurricane within the project area and may submit reports on component areas of the larger protection program for authorization as soon as practicable: Provided further, That the analysis shall be conducted in close coordination with the State of Louisiana and its appropriate agencies.

The February 2008 Draft Louisiana Coastal Protection and Restoration Technical Report (http://lacpr.usace.army.mil/default.aspx?p=LACPR_Draft_Technical_Report) describes the LACPR efforts to meet this directive. The LACPR the planning objectives are to help solve the problems associated with catastrophic hurricane by developing “the full range of flood damage reduction, coastal restoration, and hurricane risk reduction measures”. Figure A.7-1 shows an example comprehensive plan that the Draft LACPR Report presents to illustrate how various planning alternatives are combined in one area of the study. The risk reduction measures shown include both structural (levees) and voluntary nonstructural (raising structures, buyouts) actions. LACPR Final Technical Report is in progress and is scheduled for external independent review by the National Academy of Sciences in 2009.

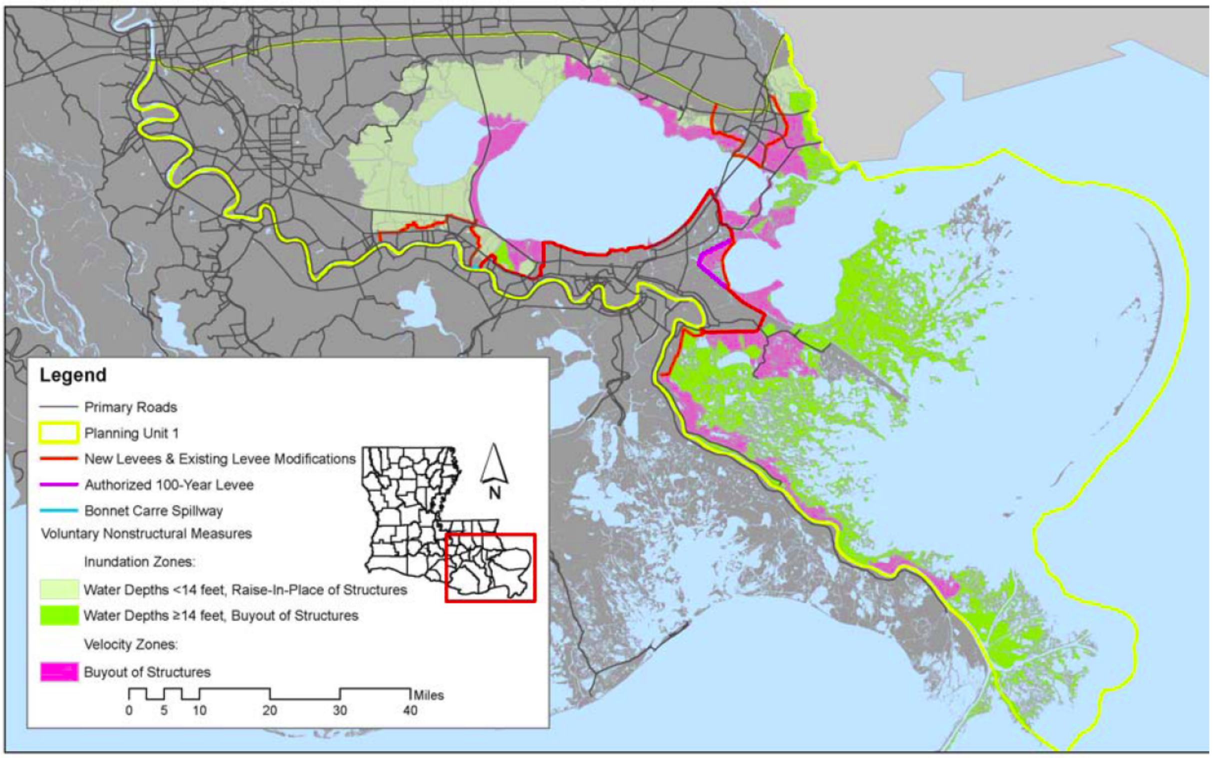


Fig. A.7-1. LaCPR Example Comprehensive Plan, Planning Unit 1 (http://lacpr.usace.army.mil/default.aspx?p=LACPR_Draft_Technical_Report)