Design and Construction of the Lake Borgne Surge Barrier in Response to Hurricane Katrina

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ABSTRACT

Following hurricanes Katrina and Rita in 2005, the U.S. Army Corps of Engineers (USACE) began to design and construct the Hurricane and Storm Damage Risk Reduction System (HSDRRS) for Southeast Louisiana. A key feature of the HSDRRS is the Inner Harbor Navigation Canal (IHNC) Lake Borgne Surge Barrier. The surge barrier is part of a larger program designed to provide a 100-year level of defense to a large portion of Orleans and St. Bernard parishes by reducing the effect of storm surge coming from the Gulf of Mexico and Lake Borgne.

The 10,000-foot (3050-meter) long, 26-foot (8-meter) high surge barrier includes three gate structures and a barrier wall. The project is being constructed approximately eight miles (13 kilometers) east of downtown New Orleans, near the confluence of the Gulf Intracoastal Waterway (GIWW) and the Mississippi River Gulf Outlet (MRGO). The entire barrier and all three gates are currently scheduled to be functional by June 2011.

This paper presents a description of challenges encountered by the design-build team, integration of design, procurement, and construction to meet an accelerated schedule and some of the unique methods used to construct the project.

INTRODUCTION

On Tuesday, August 23, 2005, Tropical Depression Twelve formed over the southeastern Bahamas. The storm reached hurricane strength (Hurricane Katrina) shortly before making landfall along the eastern Florida coast on the morning of August 25. After crossing over the southern tip of the Florida Peninsula, the storm entered the Gulf of Mexico and intensified to a Category 5 hurricane. At its peak strength, at approximately 1:00 p.m. on Sunday, August 28, the storm had a sustained wind speed of 175 miles per hour (282 kilometers per hour). Katrina made its second landfall on the morning of Monday, August 29 as a Category 3 hurricane with sustained winds of 125 miles per hour (201 kilometers per hour) near Buras-Triumph, Louisiana. At landfall, hurricane force winds extended outward 120 miles (193 kilometers) from the center. The center of the storm passed approximately 20 miles (32 kilometers) east of downtown New Orleans, traveled northward along the Louisiana/Mississippi border, and was eventually downgraded to a tropical depression as it traveled north near Clarksville, Tennessee (see Figure 1).

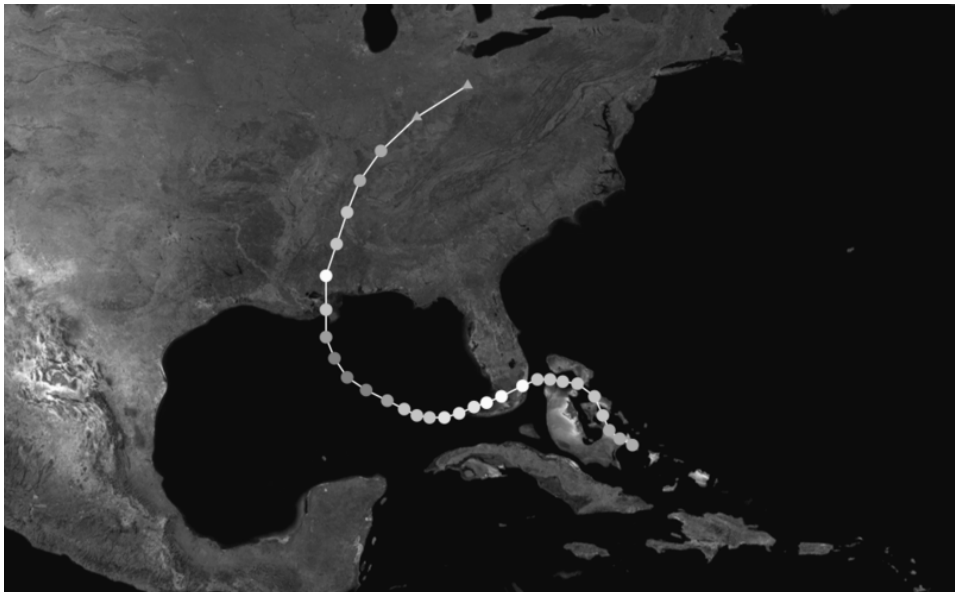

Figure 1. Path of Hurricane Katrina

On September 23, 2005, Hurricane Rita (another Category 5 hurricane) made landfall as a Category 3 hurricane near the Louisiana/Texas border. Rita caused further flooding and delayed cleanup and recovery efforts. The 2005 season was an unusually active year for Atlantic hurricanes (see Table 1).

Table 1. Comparison of "Average" Atlantic Season with 2005

	Tropical Storms	**Hurricanes (category 1 through 5) >74 mph (119 km/h) winds**	**Intense Hurricanes (category 3 through 5) >111 mph (179 km/h) winds**
"Average" Year	11	6	2
2005	28	15	7

Notes:
> greater than
km/h kilometers per hour
mph miles per hour

EFFECTS OF THE STORMS

As Hurricane Katrina passed New Orleans, a 26-foot (8-meter) high storm surge crippled the city's existing hurricane defense system. Levees and floodwalls along the perimeter of Lake Borgne, the IHNC, GIWW, MRGO, Lake Pontchartrain, and several drainage canals were either overtopped or failed, causing widespread flooding throughout the city and surrounding areas. In a span of approximately 5 hours, 80 percent of the city was flooded; some of it to a depth of more than 10 feet (3 meters) (see Figure 2).

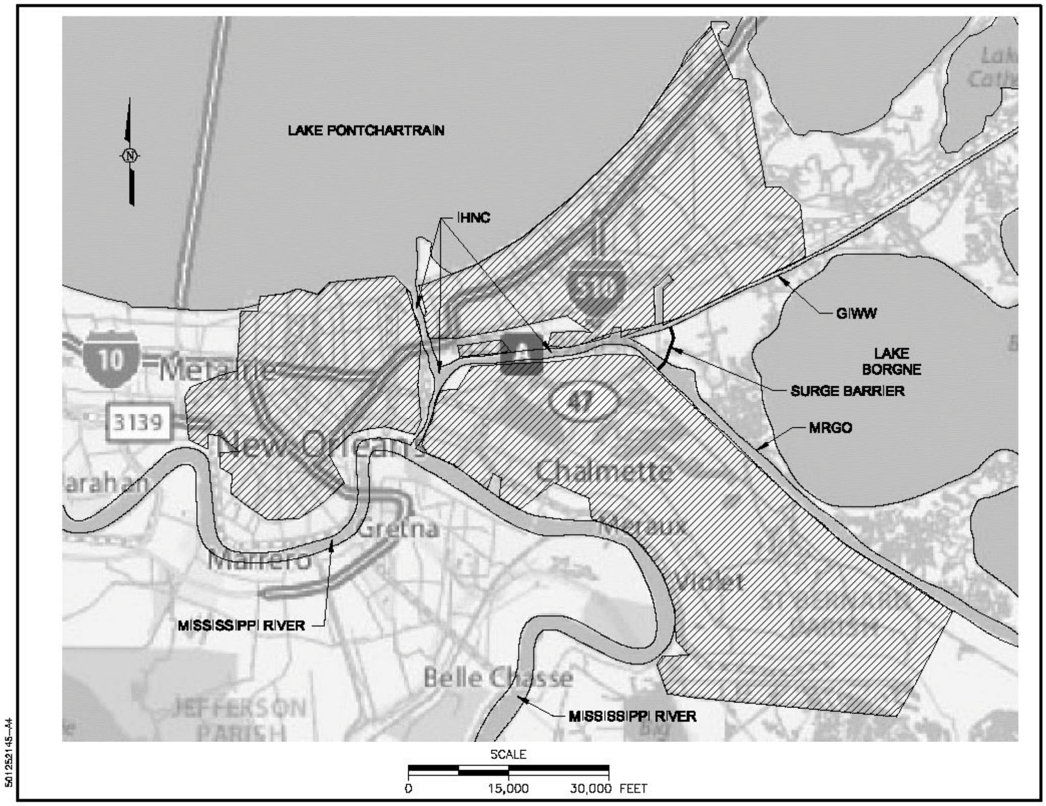

Figure 2. Greater New Orleans Area Showing Approximate Extent of Flooding

The hurricane, and the subsequent flooding, was responsible for approximately 1,850 deaths. Property damage has been estimated at $81 billion, making it the costliest U.S. hurricane on record; more than twice that of Hurricane Andrew. Approximately 1 million people were displaced. A large percentage of these people have not returned to New Orleans nearly six years later.

THE NEW ORLEANS HURRICANE PROTECTION SYSTEM

The New Orleans area is protected from flooding by a complex system of levees, walls, canals, and pumping stations. The system has undergone numerous modifications throughout history. Prior to the 2005 hurricane season the system was built to protect against the flooding caused by Hurricane Andrew in 1992, a Category 3 storm with 12-foot (3.5-meter) tides and 130-mile per hour (209-kilometer per hour) winds. To that end, several walls and levees were constructed to a height of 14 feet (4.3 meters) above mean sea level.

The IHNC, connecting the Mississippi River to Lake Pontchartrain was originally constructed between 1918 and 1923. The IHNC became part of the GIWW, authorized by the U.S. Congress in 1919 and constructed between the late 1930's and 1949. The GIWW is a navigable inland waterway running approximately 1,050 miles (1,700 kilometers) from Carabelle, Florida to Brownsville, Texas. The GIWW provides a protected route for barge transportation along the gulf coast.

The MRGO was a 76-mile (122-kilometer) long channel that extended from the confluence of the IHNC and GIWW southeastward to the Gulf of Mexico. Originally authorized by the U.S. Congress in 1956, the MRGO channel was constructed between 1960 and 1965. The purpose of the MRGO was to provide a deep draft channel for ocean-going ships to travel between New Orleans and the open waters of the gulf, avoiding the winding trip of approximately 80 miles (130 kilometers) along the Mississippi River. The MRGO never carried the traffic that its proponents envisioned, partly because the navigation gates at the junction of the IHNC and the Mississippi River were never enlarged to accommodate newer deep-draft ships.

As Hurricane Katrina passed by New Orleans in August 2005, the resulting storm surge traveled westward across Lake Borgne and entered the GIWW and MRGO. The surge caused extensive damage to levees and walls along the parishes neighboring the GIWW, IHNC, and MRGO. The storm surge also entered Lake Pontchartrain, to the north of New Orleans, and caused extensive flooding along the city's northern shoreline and several drainage canals that connect to the lake.

CORPS OF ENGINEERS RESPONSE

Following the hurricane season of 2005, Congress authorized the USACE to design and construct the HSDRRS for Southeast Louisiana. The 350-mile (564-kilometer) system, when completed, will consist of reinforced levees, T-wall floodwalls, surge barriers, pump stations, and floodgates at an estimated cost of more than $14 billion. The goal of the HSDRRS is to defend against the effects of a 100-year level storm by June 2011, thereby providing the greater New Orleans area with the best perimeter flood defense in its history. Figure 3 presents an illustration of the components of the overall system.

The USACE immediately began implementing the HSDRRS and, by June 2006, had accomplished the following repairs and enhancements to the damaged system:

- Pumped 250 billion gallons (9.5 million cubic meters) of water out of the city
- Built 2.3 miles (3.7 kilometers) of new floodwalls
- Built or repaired 22.7 miles (36.5 kilometers) of new levees
- Placed 195.3 miles (314.3 kilometers) of scour repair
- Completed three interim gated closure structures

A key feature of the HDRSS is the Lake Borne Surge Barrier project located near the confluence of the GIWW and MRGO channels east of the city of New Orleans.

During the early planning process, several alternative locations and configurations were considered for the construction of the barrier. Locations built farther to the west would have necessitated a greater amount of levee construction along the eastern perimeter of St. Bernard Parish and the southern shore of New Orleans East. Locations farther to the east would have required a longer barrier built in deeper, less protected waters. The location chosen included a barrier approximately 10,000 feet (3,050 meters) long with two gate complexes to allow for boat traffic. One gate was to be located approximately at midpoint of the barrier wall to allow for local recreational and fishing fleet traffic. The larger gates were to be located near the northern end of the wall to allow for barge commerce along the GIWW.

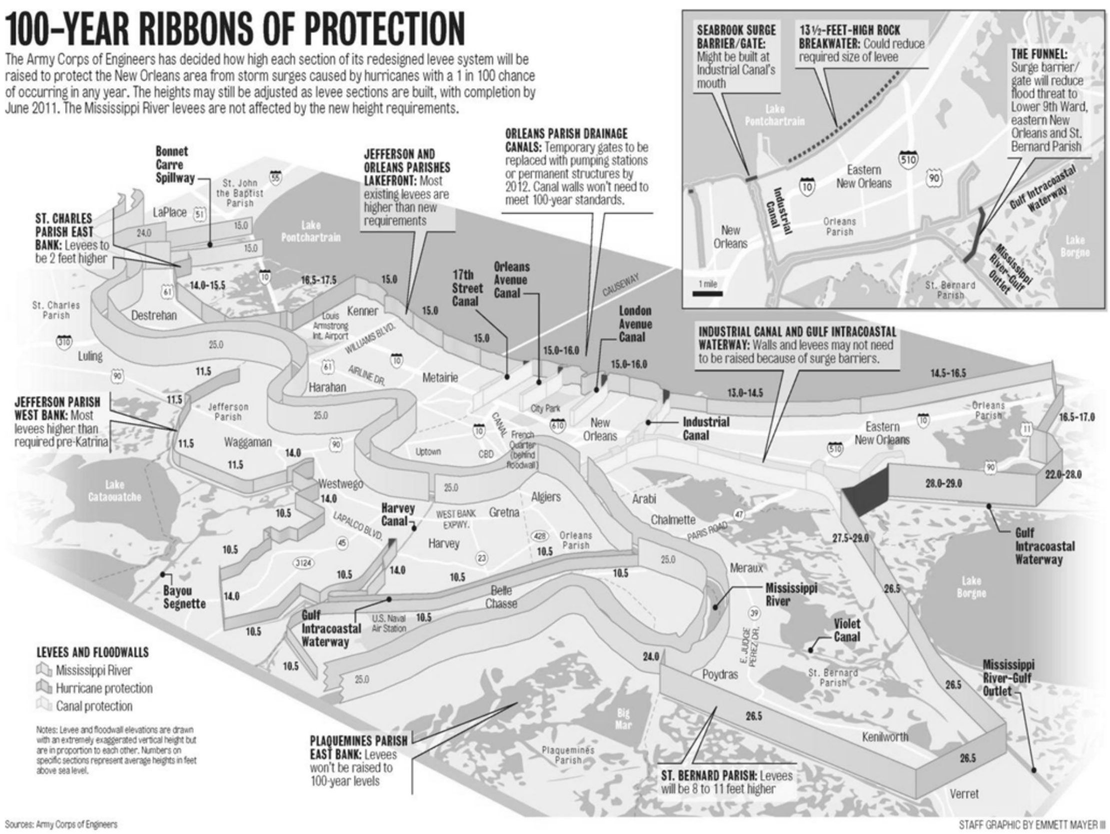

Figure 3. The HSDRRS for Southeast Louisiana

In April 2008, the USACE awarded a design-build contract to Shaw Environmental & Infrastructure Group for the Lake Borgne Surge Barrier, making this project the largest design-build civil works project in USACE history. Until this time, it was highly unusual for a civil works project to be designed and constructed simultaneously. The design-build process was necessary, however, given the very aggressive timeframe to achieve 100-year level of risk reduction in 2011.

ALTERNATIVES ANALYSES

The design-build team initially had to decide on the type of barrier wall and gates to be constructed. Figure 4 presents the evaluation criteria applied to the 12 options considered for the barrier wall. Each option was evaluated against the following criteria:

- Ability to Achieve Schedule: each alternative was rated Excellent, Good or Poor for the ability to achieve the two schedule milestones: Advance Measure Protection by June 1, 2010 and 100-year Protection by June 1, 2011.
- Ability to incorporate advance protection measures into final construction: All alternatives were rated Excellent.
- Cost: Costs for construction, operations and maintenance (O&M) and total lifecycle costs were rated Low, Medium or High for each alternative.
- Each Alternative was rated Excellent, Good or Poor for the "4Rs" criteria of resiliency, redundancy, repairability and reliability.
- Each alternative was rated Excellent, Good or Poor for the ability to be expanded in the future.
- Each alternative was rated Low Medium or High for its impact on the environment.
- Each alternative was rated Low Medium or High for complexity of design.
- Each alternative was rated Excellent, Good or Poor for constructability, local construction expertise and availability of local materials.
- All alternatives were rated to have a similar impact on navigation.

Figure 5 presents a description of the recommendations that were generated by the evaluation process and the alternative that was chosen to proceed into final design. The chosen alternative was a braced concrete pile wall utilizing large diameter cylindrical piles driven vertically at close spacing. The resistance to lateral loads was strengthened by steel batter piles driven on the western (protected side of the wall). The gaps between the vertical cylinder piles were closed by the installation of precast concrete piles into a column of grouted soil (see Figures 8 and 9).

Figure 6 presents the evaluation criteria applied to the seven options considered for the two required navigation gates. Each option was evaluated against the same criteria that were used to evaluate the barrier options. Figure 7 presents a description of the recommendations that were generated by the evaluation process and the alternative that was chosen to proceed into final design. The chosen alternative for the largest gate was for a radial sector gate constructed within a dewatered cofferdam. In order to maintain barge commerce during construction, it was decided to build this primary gate in two segments, with a secondary gate structure adjacent to (and built prior to) the sector gate. This gate was a concrete barge swing gate. After the barge gate was constructed, commercial barge traffic was routed through it and construction of the main sector gate began (see Figure 10).

Barrier System Alternative	Achieve Schedule			Cost				4 Rs Criteria						Team Confidence				
	Advance Measures	**100-Year Level of Flood Protection**	**Incorporation into Advance Measures**	**Construction**	**O&M**	**Lifecycle**	**OMRR&R***	**Resiliency**	**Redundancy**	**Repairability**	**Reliability**	**Expandability**	**Environmental Impact**	**Design Complexity**	**Constructability**	**Local Construction Expertise**	**Local Material Availability**	**Impacts to Navigation**
Braced Concrete Pile Wall	G	E	E	M	L	M	L	E	G	G	G	G	L	M	G	E	E	L
Large (e.g. 56-foot diameter) Caissons	U	G	E	M	L	M	L	E	E	G	E	E	M	H	G	P	P	L
Dumbbell Caisson	U	G	E	M	L	M	L	E	E	G	E	E	M	H	G	P	P	L
Open Cell Sheet Pile	G	G	E	M	M	M	M	G	G	P	G	G	L	M	G	G	E	L
Earthen Levee	P	U	E	H	H	H	H	P	P	E	G	G	H	L	G	E	P	L
Pile-Supporte d Levee	P	U	E	H	H	H	H	P	P	E	G	P	H	L	G	E	P	L
Jet Grout Wall	P	G	E	H	L	M	L	E	G	G	G	G	L	M	G	G	E	L
New T-Wall	P	G	E	H	L	M	L	E	G	G	G	G	L	M	G	E	E	L
Braced Steel Sheet Pile Wall	G	E	E	M	M	M	M	G	G	P	G	G	L	M	G	E	E	L
Earth Levee with Soil Mixing	P	U	E	H	M	H	M	P	G	E	G	P	H	L	G	G	P	L
Hybrid Box Levee with T-Wall	P	G	E	M	M	M	M	G	G	G	G	G	M	M	G	G	G	L
Open Cell Sheet Pile with Earthen Levee	G	G	E	M	H	M	H	P	G	G	G	G	M	M	G	G	G	L

Notes:

**-Operation and Maintenance, Repair, Replacement and Rehabilitation*

E-Excellent, G-Good, P-Poor, H-High, M-Medium, L-Low, U-Unknown

Figure 4. Evaluation Matrix for 12 Barrier Options

Barrier System Alternative	Action/Decision
Braced Concrete Pile Wall	Retain as primary solution. Provides robust system that can be constructed by local resources. Low O&M
Large (e.g. 56-foot diameter) Caissons	Retain as alternate solution. Provides robust system with low O&M
Dumbbell Caisson	Dropped – variant of above. Can be re-evaluated if primary solution is not selected for further design
Open Cell Sheet Pile	Dropped – corrosion concerns with the sheet pile, high costs, and global stability concerns
Earthen Levee	Dropped – high cost for acquiring and placing the clay and high O&M cost for settlement. Also, resilience concerns from overtopping. Work will be significantly impacted by adverse weather
Pile-Supported Levee	Dropped – see above. Savings from smaller levee footprint offset cost for the piles
Jet Grout Wall	Dropped – high cost for jet grouting/deep soil mixing and concrete wall. Also, significant amount of site construction potentially affected by adverse weather
New T-Wall	Dropped – high cost for robust T-wall with piles, slow installation, and significant amount of site construction potentially impacted by adverse weather
Braced Steel Sheet Pile Wall	Dropped – corrosion concerns with the steel sheet piles
Earth Levee with Soil Mixing	Dropped – see "earthen Levee" Savings from smaller levee footprint offset by higher cost for deep soil mixing
Hybrid Box Levee with T-Wall	Dropped – difficult to attain Advance Measures, hybrid box cannot be cost-effectively built to an elevation to attain the Advance Measures so will still need T-wall. See "Earthen Levee" for sol placement concerns and "New T-wall:" for T-wall concerns
Open Cell Sheet Pile with Earthen Levee	Dropped – see "Open Cell Sheet Pile" and "Earthen Levee" for concerns

Figure 5. Evaluation and Decision Among Barrier Options

The gate structure located approximately midway along the length of the barrier was originally designed as a sector gate. However, after a value-engineering reanalysis, it was changed to be a steel vertical lift gate. This gate has a smaller draft requirement and is intended to primarily serve the local recreational and fishing fleet traffic. During construction, traffic was redirected through the recently completed barge gate at the GIWW.

The barrier wall was built in soft sediments resulting from thousands of years of deposition by the Mississippi River. To provide resistance necessary for the required protection against storm surge, the barrier and gates needed to be supported on piles driven deep below the mud line. The primary components of the wall were 1,271 cylindrical, 66-inch (1.7-meter) diameter vertical concrete piles driven to an elevation of -130 feet (-40 meters) below water level and spaced only 6 inches (15 centimerers) apart. The horizontal resistance was provided by 660 36-inch (91-centimeter) diameter steel batter piles driven to an elevation of -190 feet (98 meters) and connected to the vertical piles by precast and poured-in-place caps.

Concurrent with the evaluation of barrier and gate construction options, extensive numerical and physical modeling of navigational impacts was performed.

	Achieve Schedule			Cost				4 Rs Criteria						Team Confidence				
Gate System Alternative	Advance Measures	100-Year Level of Flood Protection	Incorporation into Advance Measures	Construction	O&M	Lifecycle	OMRR&R*	Resiliency	Redundancy	Repairability	Reliability	Expandability	Environmental Impact	Design Complexity	Constructability	Local Construction Expertise	Local Material Availability	Impacts to Navigation
Sector Gate – “Dry” Construction	G	G	E	M	M	M	M	E	G	G	E	G	M	M	E	E	G	M
Vertical Lift Gate	G	G	E	M	H	M	M	G	G	G	E	G	L	M	G	G	G	M
Sector Gate – “Wet” Construction	G	G	G	H	M	M	M	E	G	G	E	G	M	H	G	P	G	L
Steel Swing Gate	G	G	E	M	M	M	H	G	G	G	G	G	M	M	G	G	G	M
Concrete Swing Gate	G	G	E	M	L	M	H	G	G	G	G	G	M	M	G	G	G	M
Buoyant Roller Gate	G	G	E	M	M	M	H	G	G	G	G	G	M	H	G	G	G	M
Visor Gate	G	G	E	H	U	H	H	P	G	U	G	G	M	H	P	P	G	M

Notes:

**-Operation and Maintenance, Repair, Replacement and Rehabilitation*

E-Excellent, G-Good, P-Poor, H-High, M-Medium, L-Low, U-Unknown

Figure 6. Evaluation of Seven Gate Options

Barrier System Alternative	Action/Decision
Sector Gate – “Dry” Construction	Selected as primary solution. Proven design, proven construction, and proven performance
Vertical Lift Gate	Selected as alternate solution. Demonstrated at Olmsted. Concerns with wind loads with gate in up position.
Sector Gate – “Wet” Construction	Dropped – more costly than Dry Construction and local contractors are not proficient with this method
Steel Swing Gate	Dropped – does not meet operating timeframe or maintenance requirements. Concerns with opening under head.
Concrete Swing Gate	Dropped – does not meet operating timeframe. Concerns with opening under head.
Buoyant Roller Gate	Dropped – does not meet operating timeframe. Concerns with opening under head.
Visor Gate	Dropped – current designs are not believed to be resilient and would be difficult to construct.

Figure 7. Evaluation and Decision Among Gate Options

DESIGN-BUILD COORDINATION

Because of the aggressive project schedule, decisions regarding materials procurement and fabrication had to be made early. One of the most challenging decisions was to decide on the length of the large diameter concrete piles that were to be the primary structural component of the barrier. A 66-inch (1.7-meter) diameter spun-cast hollow concrete pile was selected as the primary element. Three locations near the barrier alignment were selected for full-scale pile load tests to gather the data needed to design the lengths of the 1,271 production piles. However, the fabrication and curing time for the piles did not allow for the completion of the pile load tests prior to beginning the pile fabrication. For this reason, the piles were constructed in 16-foot (4.9-meter) segments, and production of the segments commenced well before the pile load tests began in December 2008. As the pile load tests were completed, and design loads finalized, decisions were made regarding the required lengths of the piles (i.e., the number of segments needed). The previously manufactured segments were then joined together using a tendon pre-stressing and grouting system to form the full length piles. The final production length used nine pile segments for a total length of 144 feet (44 meters).

The need to limit on-site exposure to inclement weather conditions posed additional scheduling challenges. With construction continuing through the 2009 and 2010 hurricane seasons, the decision was made to store project components at the onshore fabrication facilities and transport them by barge to the project site on a very closely controlled delivery schedule. The subcontractors were required to continually update their contingency plans for demobilizing equipment and materials to "safe haven" sites in advance of upcoming storms.

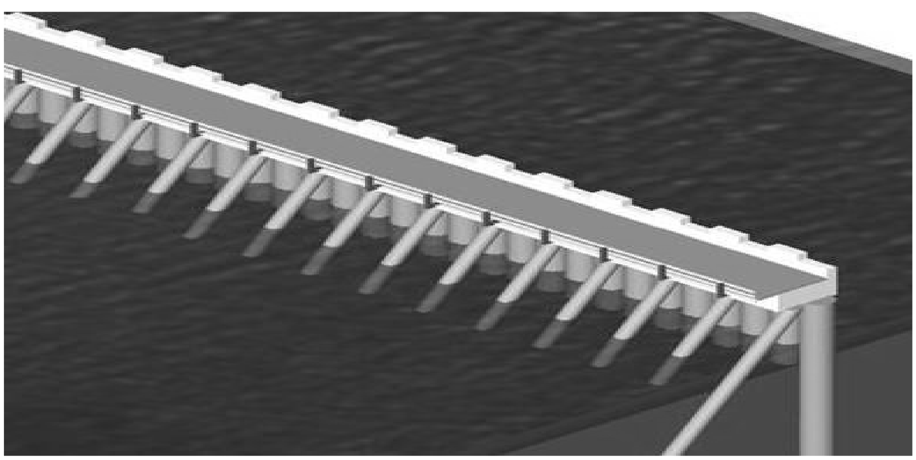

Figure 8. Illustration of Barrier Wall System. Flood Side of Barrier is Located to the Right Side of Illustration

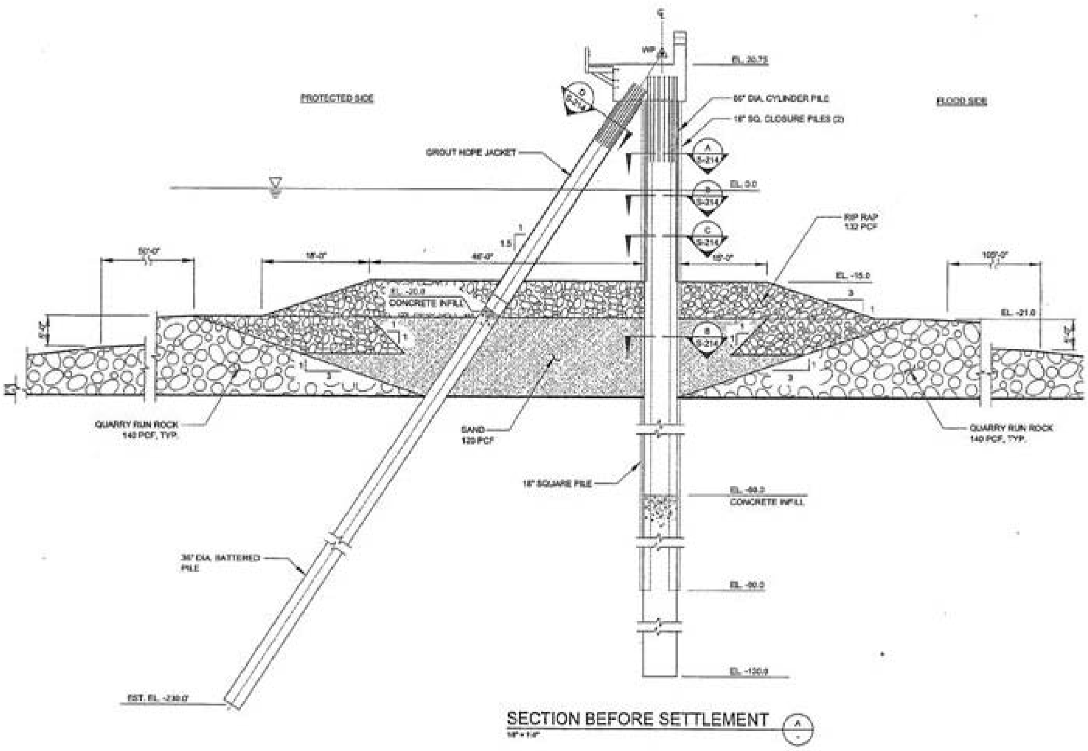

Figure 9. Cross-Section of Barrier Wall

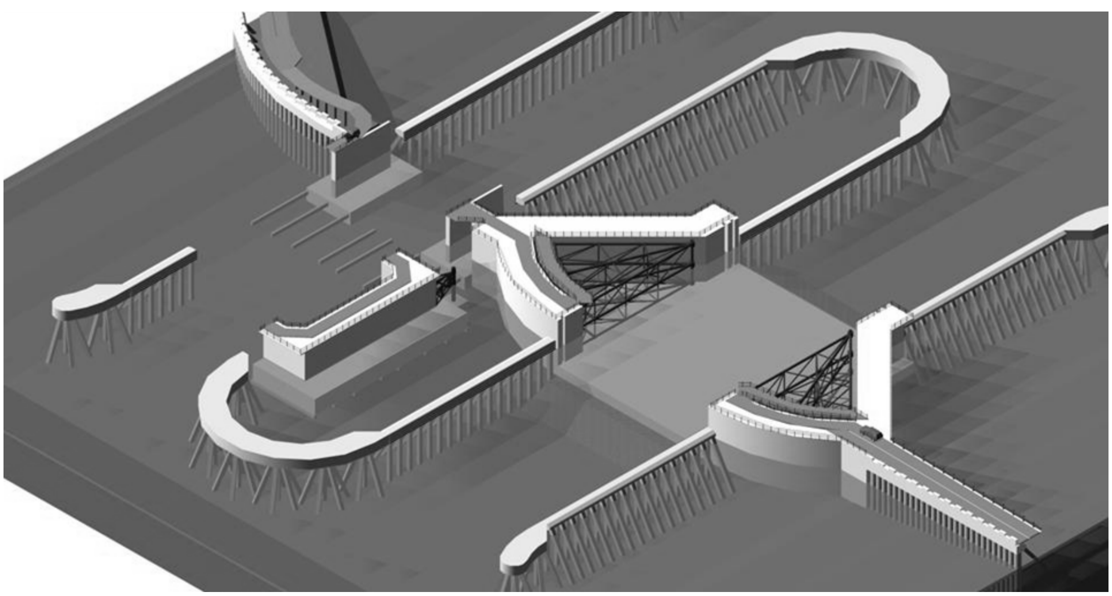

Figure 10. Illustration of Gate Structures at the GIWW (Each Gate is 150 Feet (46 Meters) Wide)

CONSTRUCTION SEQUENCING

In order to meet the demanding project schedule, multiple subcontractors and suppliers were used to build portions of the project concurrently on an around-the-clock schedule. The first production pile was installed on May 9, 2009. The surge barrier was complete and the gate structures were substantially complete by the start of the hurricane season on June 1, 2011.

Multiple marine subcontractors worked dual shifts at multiple locations within the project to complete the majority of the barrier wall in less than 12 months. The construction progressed in an "Assembly Line" fashion, with the construction equipment following each other in the following sequence:

- Dredging of the barrier alignment to allow for the construction to be performed with floating equipment. The dredge spoils were used to enhance nearby marsh areas.
- Closure of the MRGO. Congress de-authorized the MRGO for navigation and closed it to all traffic in April of 2009. Sand berms were built across the channel to provide for a stable construction site for the barrier wall to cross the former channel.
- Drive 66-inch (1.7-meter) diameter hollow concrete piles at close spacing along the barrier alignment. 1,271 piles were installed between May 9, 2009 and October 21, 2009. Each pile weighed 96 tons (87,000 kilograms) and was driven to 130 feet (40 meters) below the mud line.
- Install 12-inch (30-centimeter) concrete closure piles on both sides of the gap between the vertical piles. The piles were placed in pairs into jet-grouted columns of cement-treated soil (see Figures 11 and 12).
- Drive 36-inch (90-centimeter) diameter steel pipe piles at a 1:1.5 (H:V) batter on the "protected" side of the barrier. These piles were 240 feet (73 meters) long. They were installed in two segments, requiring field welding of each pile at the midpoint of driving.
- Clean out and fill concrete piles with steel reinforcing and concrete
- High-density Polyethylene sleeves were placed over the steel batter piles from the mud line to the top of the wall to protect against corrosion and to provide added protection in the event of a collision. The annulus between the piles and the sleeves was filled with cement grout.
- Clean out and place grout in the area between the main concrete piles and the closure piles to form a solid wall.
- Place precast concrete sections on top of the wall. Individual cap sections weighed 100 tons (91,000 kilograms) each and were grouted in place.
- Cast-In-Place cap closure sections were poured between precast cap sections.
- Construct parapet wall above the concrete pad.
- Install expansion joints, railing and finish details.

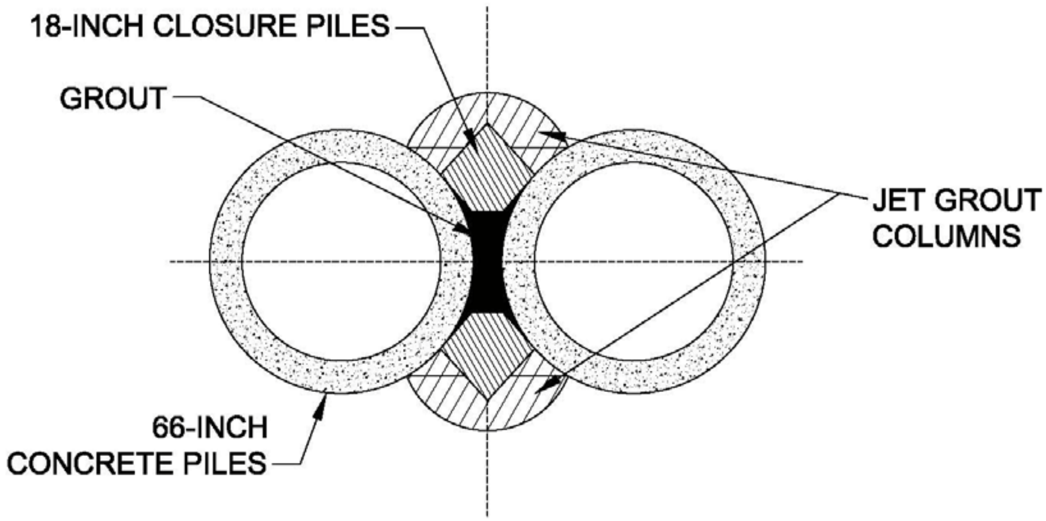

Figure 11. Plan View Detail of Closure Pile System

Concurrent with the construction of the barrier wall, work proceeded on the navigation gates. The foundations of the gates were constructed by driving hundreds of vertical piles through the water and below the mud line. After pile driving at each gate was complete, a steel sheet pile cofferdam was constructed around the perimeter of the gate structure and a thick concrete base slab was poured around the pile heads using tremie methods. The tremie slab was structurally connected to the foundation piles to resist the buoyancy uplift. The interior of the cofferdams was dewatered and the construction of the gate structures was completed “in the dry.” The gates themselves were fabricated offsite and barged to the project site to be installed.

The barrier wall was connected with the adjoining levees on the north and south ends by a pair of pile-supported cast-in-place concrete transition walls. Control buildings for operation of the gate structures were built on top of the barrier wall adjacent to the gate structures.

The barrier and gates were constructed with minimal interruption to normal shipping operations, and with minimal impact to the surrounding wetlands environment.

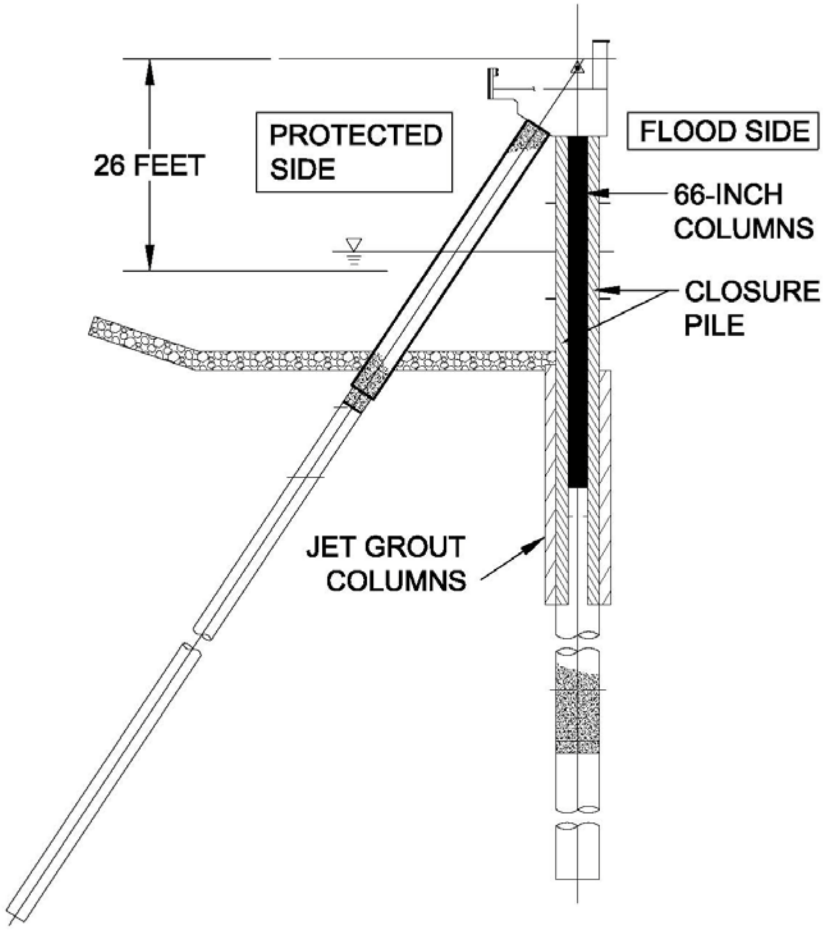

Figure 12. Profile View of Closure Pile System

The following statistics provide a summary of the overall construction of the Lake Borgne Surge Barrier System:

- Over 10,000 foot (3,050 meters) long project alignment
- Largest design-build project ever contracted by the U.S. Army Corps of Engineers
- Over 200,000 cubic yards (153,000 cubic meters) of concrete
- Over 100 linear miles (161 kilometers) of piles driven
- Over 27,000 tons (24,000 metric tons) of reinforcing bar used (enough to build eight Eiffel Towers)
- Approximately 700,000 tons (635,000 metric tons) of rock used as rip rap and scour protection
- Peak work force of 350 workers onsite
- Total work force of over 2,000 field and office personnel
- 17 barge-mounted cranes
- Over 2,000,000 work hours with 4 lost work days due to injuries
- 6 design subcontractors, 10 construction subcontractors, 55 small business subcontractors