GEOTECHNICAL RECONNAISSANCE OF THE 2011 FLOOD ON THE LOWER MISSISSIPPI RIVER

Sand Boil on Protected Side near Old River Lock, June 2, 2011

June 18, 2012

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1. INTRODUCTION

The Spring of 2011 brought heavy rainfall and snowmelt throughout the Midwest, resulting in record flow rates and flood stages on the Lower Mississippi River from Cairo, Illinois to the Gulf of Mexico. In many locations, the flood crested at levels above those from the great floods of 1927 and 1937. A levee was intentionally breached near Cairo to relieve pressure and save the town from catastrophic flooding. The Morganza Spillway in Louisiana was opened for the first time since 1973, flooding nearly 5,000 square miles of rural land. Approximately 25,000 homes were evacuated from Illinois through Louisiana.

While there were fortunately no major failures, the flood protection system of levees, walls, gates and spillways has been loaded to its capacity. The National Science Foundation's Geo-engineering Extreme Event Response (GEER) Association supported a team to perform reconnaissance of the flood protection system at the height of the flood. The team included the following members:

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The team visited the flood protection system on June 2 and June 3, 2011, focusing on the Mississippi River from the Old River Control Structure down to Duncan Point just south of Baton Rouge (Figure 1.1).

The New Orleans District of the U.S. Army Corps of Engineers (USACE) was instrumental in making this reconnaissance happen. They guided the itinerary, provided access to all components of the system, and supplied information and expertise about its performance. The following individuals contributed significantly to this effort:

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This report summarizes the information and findings from the reconnaissance. The report is organized as follows: the flood protection system and the hydrologic event are described, observations from the reconnaissance are presented, and conclusions and recommendations are provided. A detailed itinerary of the reconnaissance activities is included as an appendix. Any opinions, findings, conclusions and recommendations expressed in this report are those of the authors and do not necessarily reflect the views of the associated organizations and funding agencies.

Figure 1.1 Map of major locations along reconnaissance route

2. DESCRIPTION OF FLOOD PROTECTION SYSTEM

The Great Flood of 1927 on the Lower Mississippi River caused significant life loss and property damage. River levees breached at about 150 locations and approximately 30,000 square miles of land was flooded with depths as high as 30 feet. There were 246 fatalities in seven states and over $400 million in damages ($1.5 billion in 2011). A great resource for the history of this event is *Rising Tide: The Great Mississippi Flood of 1927 and How It Changed America* by John Barry.

The 1927 flood prompted the United States to create a more robust and coordinated system of flood protection along the Lower Mississippi River. The Flood Control Act of 1928 authorized development of a project for flood protection from the mouth of the river up to Cape Girardeau, Missouri. The U.S. Army Corps of Engineers developed, designed and constructed a system of levees, walls, gates and spillways to control flooding along the river.

2.1 Levees and Floodwalls

Today, there are about 2,200 miles of levees and floodwalls that protect the Mississippi River Valley below Cape Girardeau, with 1,600 miles of levees and walls on the Mississippi River itself and 600 miles on the southern banks of the Arkansas and Red Rivers and within the Atchafalaya Basin. In the wake of the 1927 flood, many existing levees were raised and their slopes were flattened. Subsequent floods in 1937 and 1973 also led to raised and strengthened levees.

A photograph of a levee is shown in Figure 2.2 and a conceptual cross-section of a typical levee on the Mississippi River is shown in Figure 2.2. These levees have been constructed on natural river levees, and raised and widened multiple times over the past century. The levees are underlain by a blanket layer of Natural Levee deposits, relatively low-permeability clays. The blanket layer is underlain by thick sequences of high-permeability sands and (Fig. 2.1). The levees were typically constructed by compacting fine-grained soils borrowed from the Natural Levee deposits. In the New Orleans vicinity, about 15 miles of floodwalls were built on top of the levees in order to raise the height of flood protection without widening the footprint of the levee.

Over the past century, there have been numerous opportunities to observe how the levees perform in flood events, identify problem areas and then mitigate the problems. Common mitigation measures include relief wells, toe/seepage berms and scour protection (Fig 2.3).

Underseepage is a significant concern in this geologic setting; water pressures in the coarse-grained deposits below the blanket layer generally respond directly to the elevation of the river. These elevated pressures can lead to internal erosion where the blanket layer is ruptured and sand from below the levee is washed out. Although this process tends to arrest itself naturally as soil particles eventually block (or filter) the migration of other soil particles, it does have the potential to undermine the levee if left unchecked. In addition, elevated pressures below the levee can reduce the resistance to sliding under the lateral pressure imposed by the water on the flood side.

Figure 2.1 Mississippi River levee at Duncan Point

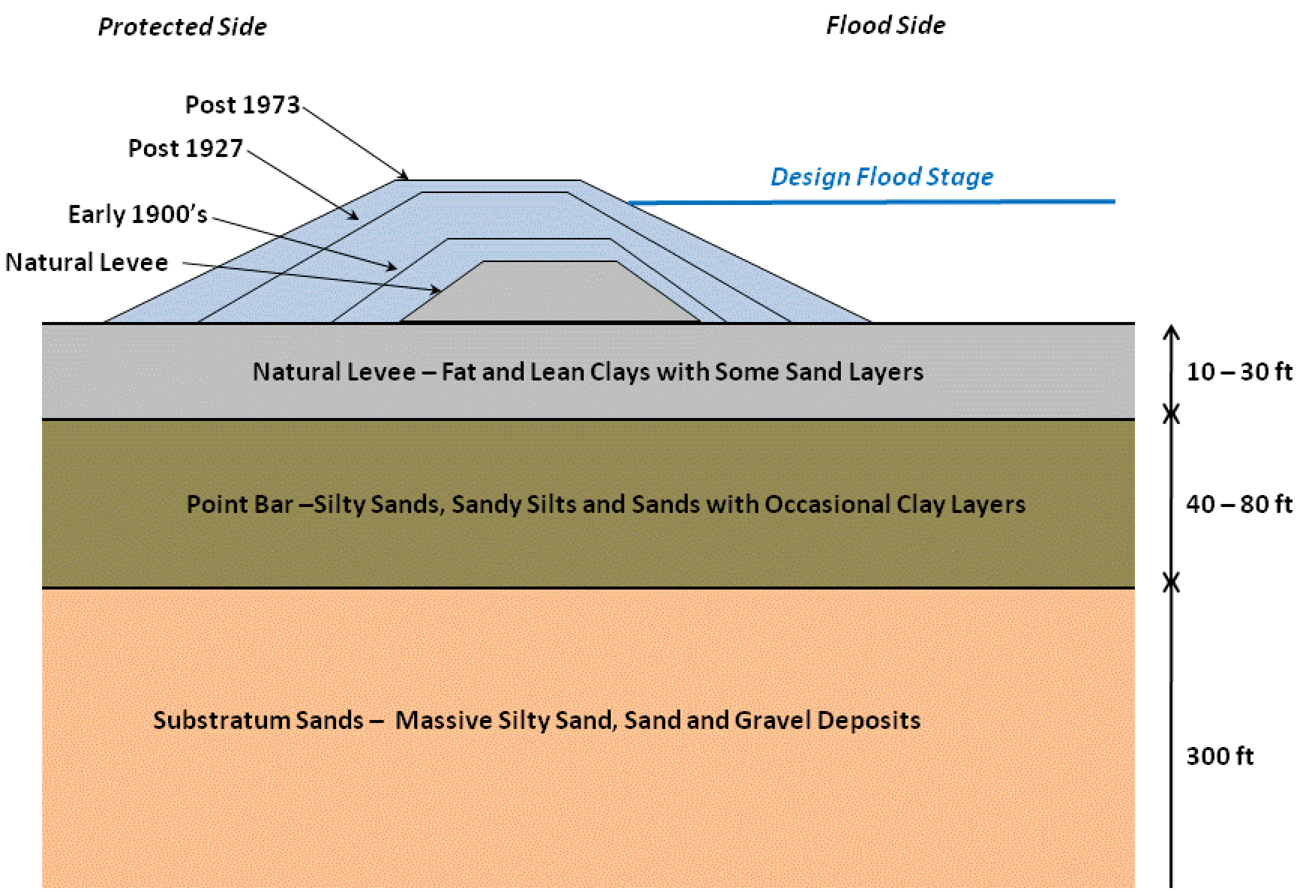


Figure 2.2 Conceptual cross-section of Mississippi River levee

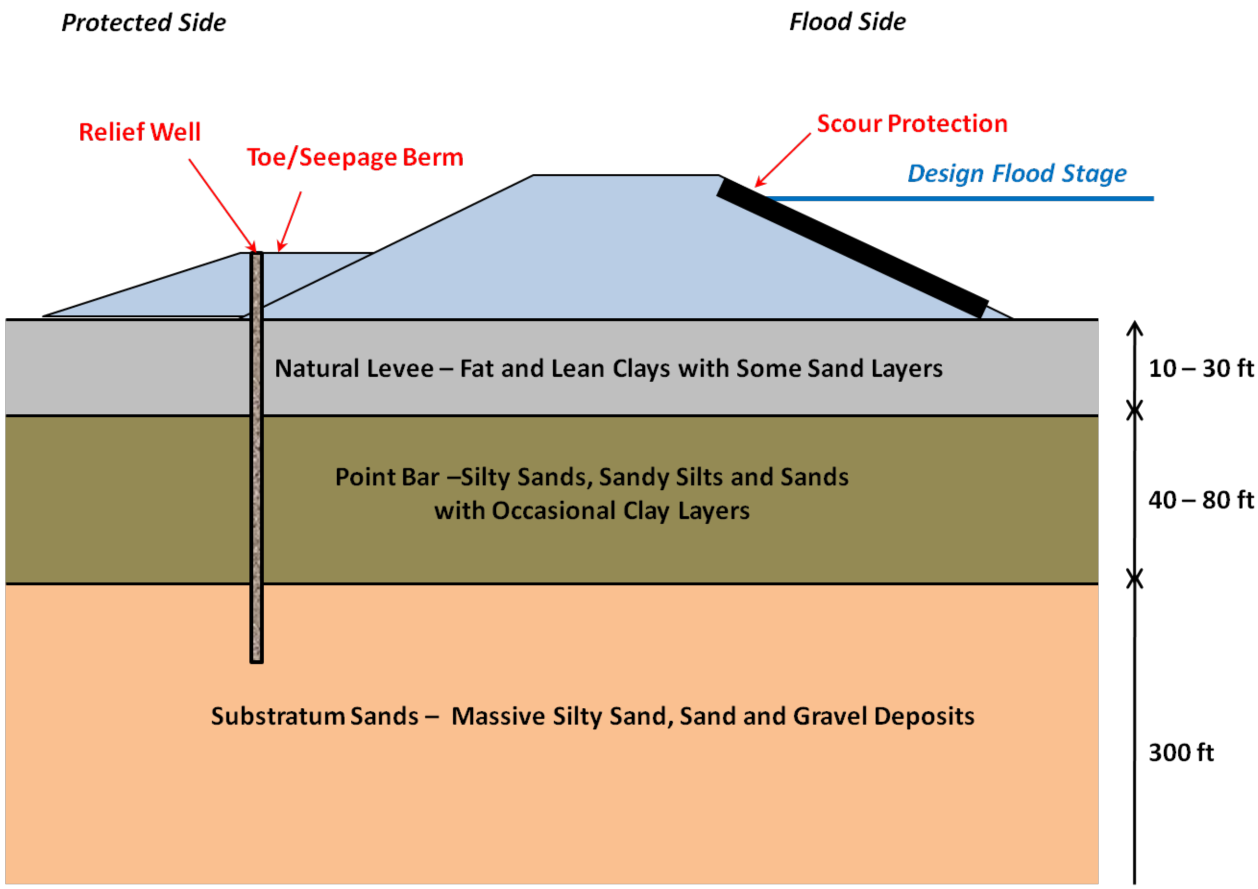


Figure 2.3 Common mitigation measures to improve levee performance

Signs of potential problems due to underseepage include sand boils forming on the protected side and/or high rates of flow exiting near and beyond the toe of the levee on the protected side. In areas where these types of problems have been observed in previous floods, relief wells and/or seepage berms been added. The relief wells typically extend more than 100 feet below the ground surface into the Substratum Sands (Fig. 2.3) and are spaced several hundred feet apart parallel to the levee. A photograph of a relief well producing flow at the surface is shown in Figure 2.4. Toe or seepage berms lengthen the seepage path below the levee, reducing the water pressure near the toe on the protected side (Fig. 2.3). A useful reference for underseepage mitigation on this levee system is “Performance of Relief Well Systems along Mississippi River Levees,” by Mansur, C.I., Postol, G. and Salley, J.R. (*Journal of Geotechnical and Geoenvironmental Engineering*, August 2000, Vol. 126, No. 8, 727-738).

Scour or erosion on the flood side is another potential problem. The high flow rate in the river together with river traffic possibly being closer to the levee during a flood (since the width of the river increases) can erode the flood side of the levee. In areas susceptible to scour, armoring such as large stones or concrete slabs (see Fig. 2.1), have been added on the flood side (Fig 2.3).

Figure 2.4 Relief well producing flow along 415 near Arbroth, Louisiana on June 2, 2011

2.2 Gates and Spillways

In order to control flow on the Lower Mississippi River and to limit flood stage levels in the major metropolitan areas of Baton Rouge and New Orleans, a system of gates and spillways has been constructed. Figure 2.5 shows a schematic of this control system. Within the reconnaissance study area, the two structures of interest are the Old River Control Structure and the Morganza Spillway.

Figure 2.5 Design flow rates for Control Structures, including Old River Control Structure and Morganza Spillway (graphic provided by USACE)

The purpose of the Old River Control Structure is to divide inflow from the Mississippi River and the Red River so that 70 percent of the flow continues on down the main channel of the Mississippi River through Baton Rouge and New Orleans to the Gulf of Mexico while 30 percent of the flow takes the more direct route to the Gulf of Mexico along the Atchafalaya River through Morgan City, Louisiana. It is a critical structure for navigation on the Mississippi River because it prevents the river from changing course down the Atchafalaya channel and bypassing Baton Rouge and New Orleans. A plan view of this structure is shown in Figure 2.6. The primary means for controlling flow is the Low Sill Structure, which is a gate structure (Fig. 2.7) completed in 1963. Due to a very large flow rate and head drop across the Low Sill Structure in the 1973 flood, the river bed was eroded to a depth of 30 feet both upstream and downstream of the gates and the stability of the structure was in question. The Auxiliary Control Structure was added in 1986 to provide better control of the tailwater elevation and flow rate across the Low Sill Structure (Fig. 2.6).

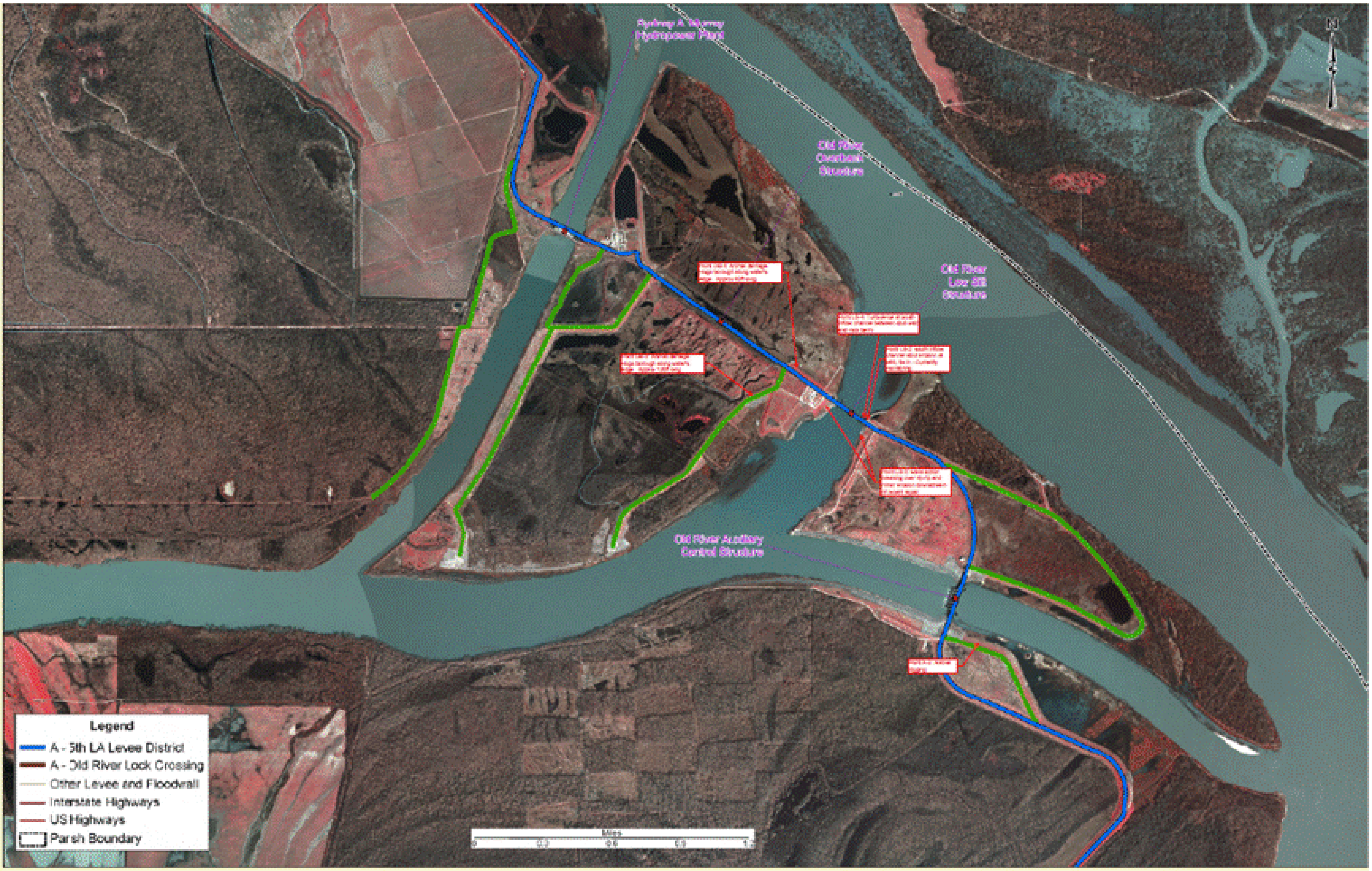


Figure 2.6 Plan view of Old River Control Structure Complex (graphic provided by USACE)

Figure 2.7 Discharge to Atchafalaya Basin through Old River Low Sill Structure, view looking West-Northwest, July 2, 2011

The Morganza Spillway is opened only in extreme flood events. It is a gated structure that was completed in 1954 and has been opened only twice since then, 1973 and 2011 (Fig. 2.8). The spillway directs up to 600,000 cfs off the main channel of the Mississippi River into the Morganza Floodway and ultimately into the Atchafalya River. The Morganza Floodway is a 20-mile long, 5-mile wide area that contains farms and some sparse development. The inhabitants in this floodway are aware that will be flooded periodically and are warned in advance of opening the spillway. Improvements were made to the Morganza Spillway after erosion occurred during the 1973 flood.

The integrity of the Old River Control Structure, the Morganza Spillway and the levees in their vicinity is important beyond limiting flooding along the Mississippi River. These structures prevent the Mississippi River from changing course into the Atchafalaya Basin and bypassing Baton Rouge and New Orleans.

Figure 2.8 Discharge through Morganza Spillway into the Morganza Floodway, view looking South-Southwest, July 2, 2011

2.3 Flood Fights

When a major flood like 2011 occurs, the USACE activates a formal set of operating procedures termed a Flood Fight. In the New Orleans District, Phase I of a Flood Fight is activated when the Mississippi River reaches 11 feet in New Orleans. At this point, an Emergency Operation Center is activated and coordinated with local and state officials. In addition, the frequency of levee inspections is increased and initial preparations are made to operate gates and spillways. Phase II of a Flood Fight is activated when the Mississippi River is forecast to rise above 15 feet in New Orleans. Phase II involves increasing the frequency of inspections to daily and holding daily meetings with Engineering Division personnel to review concerns and provide recommendations. Example actions during a flood fight include confining sand boils with water ponded within sand bags or drums to decrease the exit gradient, increasing the levee height in low spots resulting from subsidence by adding sand bags or Hesco® baskets, creating emergency toe/seepage berms with sand bags, and closing and opening gates to control flow rates and water elevations. Flood fights continue beyond the crest of the flood until the river stages recede to near normal conditions since slope failures on the flood side of levees as the water recedes.

3. Hydrology of 2011 Flood

The 2011 Flood produced record flood stages along the Lower Mississippi River at numerous locations (Table 3.1), including the stretch that was the focus of this reconnaissance, from Red River Landing to Baton Rouge, Louisiana.

Table 3.1 Summary of Flood Stages on Lower Mississippi River during 2011 Flood (table provided by USACE)

Mississippi & Atchafalaya STAGES – 6 June 2011 – 0600 CDT

Station	Flood Stage	Current Stage	Actual/Forecasted Crest Stage	Date	Record Stage	Year
Cairo, IL	40.0	41.18	61.72****	2 May	59.51	1937
New Madrid, MO	34.0	31.55	48.35	6 May	47.97	1937
Caruthersville, MO	32.0	32.43	47.61	7 May	46.00	1937
Memphis, TN	34.0	29.63	47.87	10 May	48.70	1937
Helena, AR	44.0	40.83	56.59	12 May	60.21	1937
Arkansas City, AR	37.0	40.39	53.14	16 May	59.20	1927
Greenville, MS	48.0	52.55	64.22	17 May	65.4*****	1927
Vicksburg, MS	43.0	49.56	57.1	19 May	56.20*	1927
Natchez, MS	48.0	56.38	61.95	19 May	58.04	1937
Red River Lndg, LA	48.0	59.41	65.5*** (63.09***)	21 May	61.61	1997
Baton Rouge, LA	35.0	41.46	47.5*** (45.01***)	18 May	47.28	1927
New Orleans, LA	17.0**	16.00	19.5*** (17.0***)	14 May	21.27	1922
Simmesport, LA	47.0	40.07	44.94	23 May	59.13	1927
Butte LaRose, LA	25.0	20.80	23.15	26 May	27.28	1973
Morgan City, LA	4.0	9.19	9.5*** [10.35***]	30 May	10.53	1973

*62.2' If Levees Held New Record Stage Exceeding Current Record Stage

**Levees Protect New Orleans to 20.0' Stage ***w/o Morganza Operation ***w/Morganza Operation

****NWS Crest of 63.0' on 5 May w/o BPNM Operation – Actual Stage of 59.7' on 5 May w/BPNM Operation

*****Adjusted to Current Gage Location - Prior to 1940 stages were taken at City Front or Warfield Point

Note: With Morganza Operation, Baton Rouge to N. Orleans crests will occur before upstream locations and will remain steady during the floodway operations.

The flood stages below the Old River Control Structure were successfully limited by opening gates at the Old River Low Sill Structure and the Morganza Spillway. A summary of historical discharges during floods in comparison to 2011 is provided in Table 3.2, and a schematic of the peak discharges through the Old River Control Structure and the Morganza Spillway during the 2011 Flood is shown in Figure 3.1. Both the Old River Low Sill Structure and the Morganza Spillway performed well in diverting floodwater and controlling the flow rates and stage levels in the Mississippi River during the 2011 Flood. There was no evidence of scour at the Old River Sill, where a 30-foot deep scour hole developed during the 1973 flood.

Table 3.2 Summary of Discharges on Lower Mississippi River during 2011 Flood (table provided by USACE)

Historical Discharges

Station	2011	1927	1937	1973	PDF[7/]
Cairo, IL	1,936,000 [C/6/]	1,626,000 [1/]	2,010,000 [5/]	1,536,000	2,360,000
Memphis, TN	2,136,000 [C]	1,744,000 [2/]	2,020,000	1,633,000	2,410.000
Helena, AR	2,130,000 [C]	1,756,000	1,968,000	1,627,000	2,490,000
Arkansas City, AR	2,293,000 [C]	1,712,000	2,159,000	1,879,000	2,890,000
Vicksburg, MS	2,272,000 [C]	1,806,000 [3/]	2,060,000	1,962,000	2,710,000
Natchez, MS	2,227,000 [C]	N/A	2,046,000	2,024,000	2,720,000
Red River Landing, LA	1,641,000 [C]	1,461,000 [4/]	1,467,000	1,498,000	2,100,000

C = Discharge Crest , Provisional
1/ About 1,765,000 cfs if flow had been confined between levees
2/ If there had been no crevasses
3/ About 2,278,000 cfs if flow had been confined between levees
4/ About 1,779,000 cfs if flow had been confined between levees
5/ Includes flow though the Birds Point New Madrid floodway
6/ Approximate mile 950.8 at 1400 CDT 5/02/2011
7/ Project Design Flood (PDF) provides design flows for MR&T project - Currently estimated to be complete in 2032 at the average rate of funding over the last 10 years

Revised 1 June 11, 1700 CDT

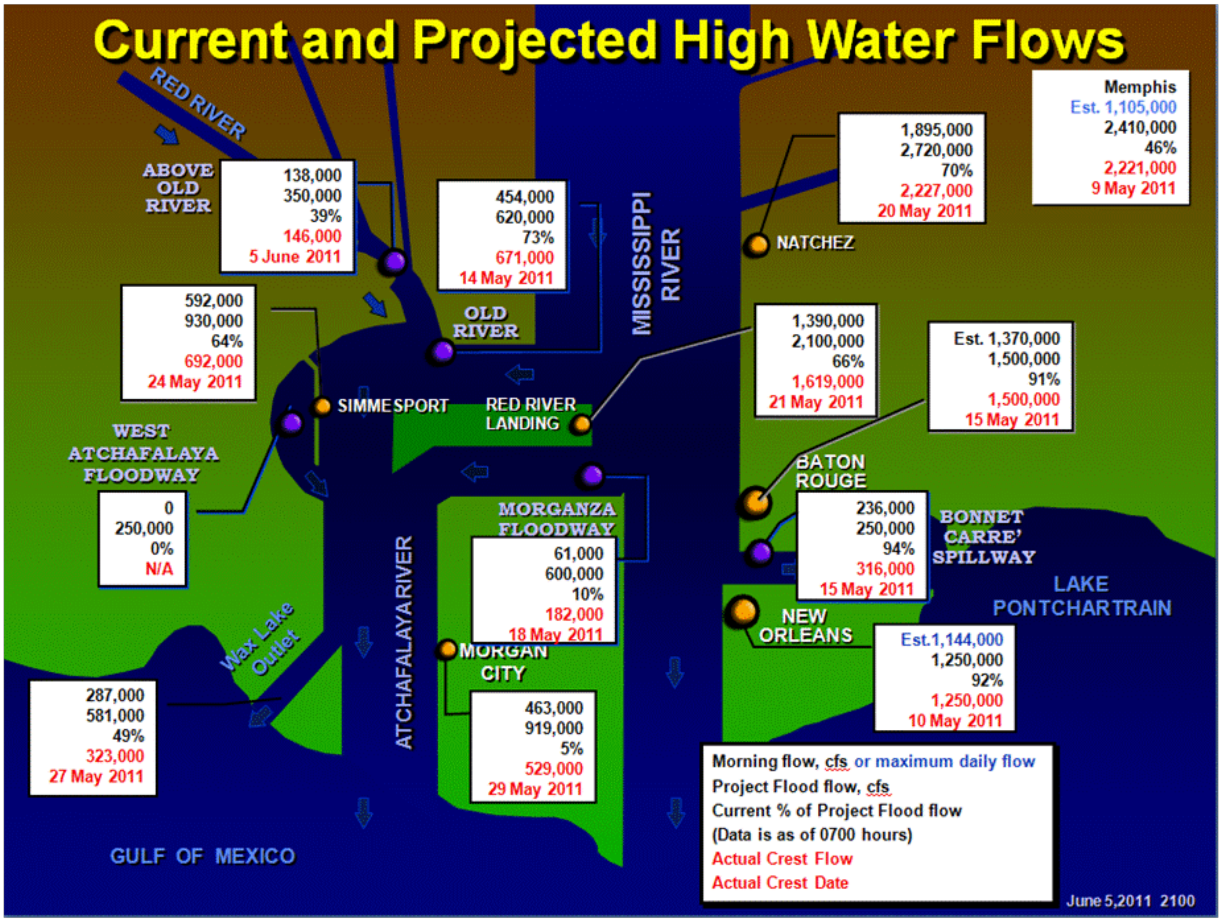


Figure 3.1 Schematic showing crest flows along Mississippi and Atchafalaya Rivers during 2011 Flood (provided by USACE)

4. GEOTECHNICAL OBSERVATIONS ON LEVEE PERFORMANCE

4.1 Overall Performance

At the time of the GEER Team visit on June 2 and 3, 2011, the Mississippi River level was within three feet of the top of most levees which is the design freeboard. Even though the levees were being severely challenged by the design flood level for the past three weeks, all of the levees were performing well and no levee breaches were observed or reported. Some levee and foundation seepage was observed as well as some seepage anomalies (discussed below) but none of these phenomena threatened the stability of the levee. As a result, the Flood Fight of 2011 was being successfully managed by the U.S. Army Corps of Engineers (USACE) and it was expected that the flood water would begin receding in about two weeks. This means at the time of the GEER Team visit, the Flood Fight of 2011 was in its final stages and the levees were still performing well even though this was the most extreme flooding since 1973 when the Morganza Spillway was last opened to control Mississippi River flooding.

In the New Orleans District of the USACE, the Corps is responsible for approximately 512 miles of levees/floodwalls along the Mississippi River and 450 miles of levees along the Atchafalaya River Basin. Before high water, the Corps identified, classified and documented 432 “Inspection Hot Spots” or areas of interest where more frequent monitoring was being performed. The observed deficiency and the number of occurrences at these Inspection Hot Spots are summarized in Table 4.1.

Table 4.1 Inspection Hot Spots as of July 2, 2011

Concern (alphabetical order)	Number of Occurrences
Armor needed (erosion)	3
Damage from burrowing animals	26
Cracking (desiccation)	21
Debris -	2
Depression –	2
Encroachment	5
Erosion	8
Excavations	3
Slough slide	2
Distress (undetermined)	0
Leaking	13
Obstructions	1
Other	8
Poor sod cover	5
Rutting	5
Sand boils	19
Scouring	7
Seepage	292
Settling (levee elevation)	1
Sliding	7
Slope stability issues	2

Of these 432 Inspection Hot Spots, one was classified as “High Priority,” four as “Medium Priority” and 427 as “Low Priority.” The High and Medium Priority Hot Spots are detailed in Table 1.

Table 4.2 High and Medium Levee Inspection Hot Spots[1]

Priority	**Deficiency**	**Location**	**USACE Designation**
High	Seepage	Duncan Point	PONT11-March 25-001
Medium	Sliding	near Concordia	UWMS11-May 10-002
Medium	Slope pavement cracking	Riverwalk at USS Kid near Baton Rouge, LA	PONT11-April 1-003
Medium	Failure (slope)	near Ascension	PONT11-May 31-001
Medium	Other	near Plaquemines	LCST11-May31-003

[1]Classifications were made prior to high water based on performance during previous flood events.

The GEER Team visited the Duncan Point area so additional details about this Hot Spot are presented below. The Corps identified 24 Inspection Hot Spots on the map in Figure 4.1 where some remedial or preventive action, such as sand bags to ring a sand boil, sand bags or Hesco® baskets to raise levee height, or sand bags to augment a dry side seepage berm, were implemented. Of these Hot Spots, none were considered to threaten the integrity of the associated levee.

Because of the height and duration of flooding, the vast majority of levee embankments were exposed to elevated piezometric pressures and some experienced seepage on the protected side slope and toe area. However, all levees performed well with little or no damage or distress. Many of the sites with distress had been already under observation and/or undergone repair efforts at the time of the reconnaissance, thus limiting our assessments of original pre-flood conditions and possible distress/damage mechanisms. Some of the different manifestations of seepage, e.g., sheet and emerging seepage, sand boils, and piezometer flow, and levee field performance, e.g., settlement, animal burrows, and wave erosion, observed during the trip are described in the following sections.

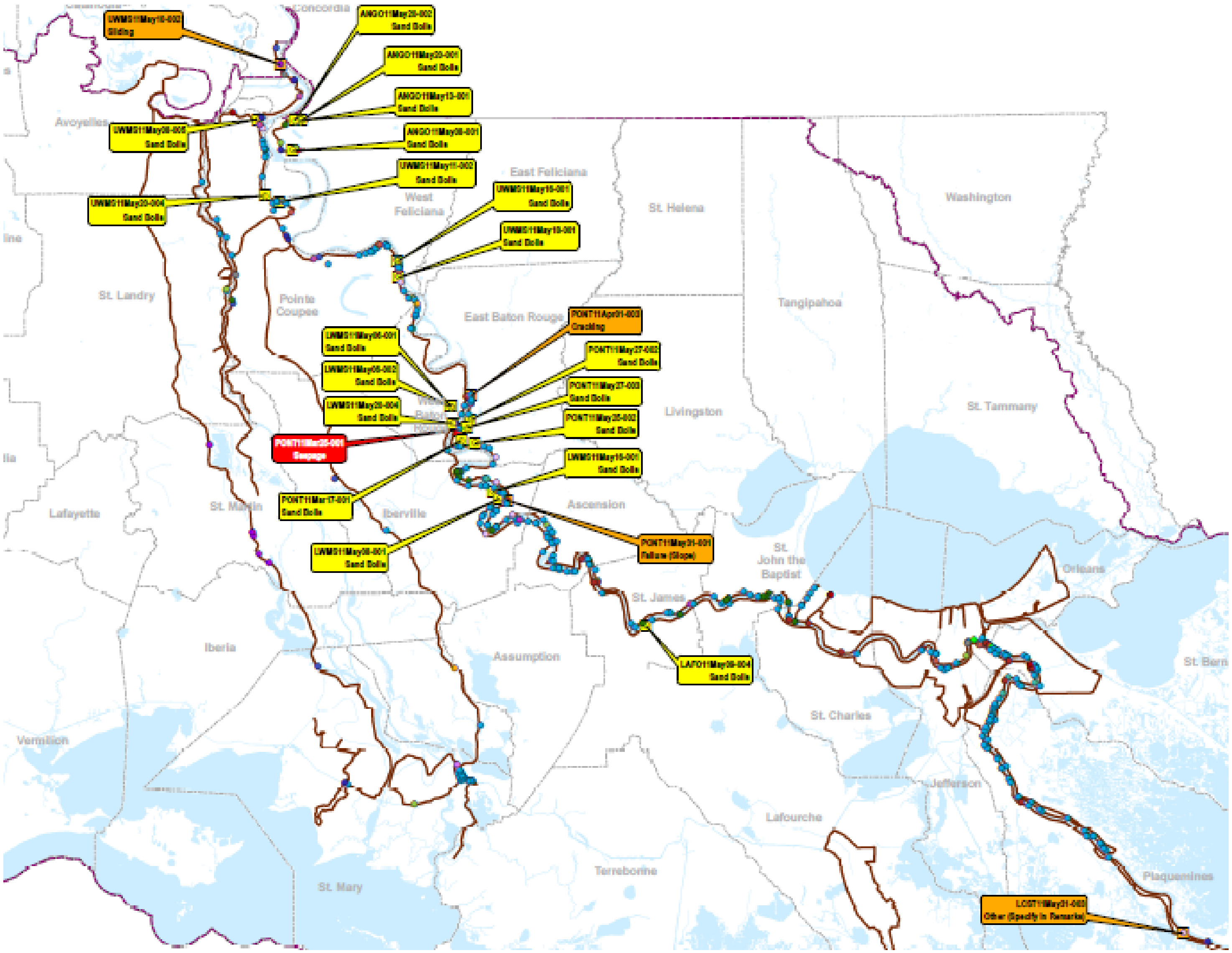


Figure 4.1 Map of New Orleans District Inspection Hot Spots (provided by USACE)

4.2 Sheet Seepage

At a levee north of Baton Rouge, Louisiana (N 30° 50’ 12.42” W 91° 38’ 03.72” and see Figure 4. 1 for location), “sheet” seepage was observed. The observed sheet seepage is shown in Figure 4.2 and corresponds to seepage over a larger area than a sand boil. Sheet seepage occurs at a low gradient over a large area with relatively uniform soil conditions because seepage is evident but sand boils are not developing. The sheet seepage corresponds to underseepage and not seepage through the levee because water is observed in the ditch at the toe of the levee and across the road from the levee but no seepage was observed on the dry side slope of the levee. The river level at this location was about six feet below the levee crest.

(a)

(b)

(c)

(d)

Figure 4.2 (a) Overview of sheet seepage from levee crest (note: no repair deemed necessary), (b) close-up of sheet seepage from levee crest, (c) drainage ditch at levee toe filled with water and sheet seepage visible on opposite side of road on Mississippi River Right Levee at River Mile 290 (N 30° 50′ 12.42″ W 91° 38′ 03.72″, 2 June, 2011 at 12:00 pm), and (d) Mississippi River level at this location

4.3 Emerging Seepage

Even though the Mississippi River had been elevated for only about three weeks, two levee locations exhibited seepage on the protected-side face. These two locations are the levee under the John James Audubon Bridge and at Duncan Point near Baton Rouge, Louisiana. The Duncan Point levee is discussed below in regards to piezometer indications and filter berm performance. The levee under the Audubon Bridge is discussed in detail here to illustrate emerging seepage. The John James Audubon Bridge was recently opened to traffic on May 5, 2011 to retire the New Roads/St. Francisville ferry service which usually closed during high water events. This bridge is the longest cable-stayed bridge in the Western hemisphere. The John James Audubon Bridge connects the Pointe Coupee and West Feliciana parishes in south central Louisiana. The bridge is the only bridge structure on the Mississippi River between Natchez, Mississippi and Baton Rouge, Louisiana (approximately 90 river miles) and is a 2.44 mile long four-lane elevated bridge structure.

This example of emerging seepage is interesting because the presence of a concrete apron on the dry side of the levee made the emerging seepage readily visible and its location easily recordable. Thus, this location is suitable for investigating partially saturated seepage through levees and in particular, how quickly the wetting front migrates through a partially saturated levee. The emerging seepage exited the levee and migrated through a small crack in the concrete apron (see Figures 4.3 (c) and (d)).

(c) (d)

Figure 4.3 (a) Overview of Mississippi River level under the John James Audubon Bridge, (b) close-up of Mississippi River side showing river level had dropped about two feet from its high water mark on the concrete apron (see double-sided arrow), (c) overview of emerging seepage from downstream side of levee, and (d) close-up of emerging seepage through concrete apron (see tape measure for scale) on Mississippi River Right Levee at River Mile 262 (N 30° 43’ 05.04” W 91° 21’ 31.14”, 2 June, 2011 at 17:00 – 17:20)

4.4 Sand Boils at Levee Toe

At a levee just downstream of the Old River Navigation Lock near Torras, Louisiana (N 30° 59’ 57.66” W 91° 40’ 43.14” and see Figure 4.1 for location), two sand boils were observed at the protected side toe of the levee. The sand boils are shown in Figure 4 and one of the boils had already been stabilized with sand bags. In addition, a steel drum had been installed on top of the sand boil to reduce the hydraulic gradient at the exit point. Shortly after then GEER Team’s visit, a ring of sand bags was placed around the other sand boil to prevent the erosion of foundation materials. The two sand boils are located directly in line with some nearby utility poles and may be the location of prior utility poles or where the effectiveness of the natural fine-grained blanket was reduced by some other means.

(a) (b) (c)

Figure 4.4 (a) Overview of sand boil and remediated sand boil at toe of levee just down river from Old River Navigation Lock sheet seepage from levee crest, (b) closeup of unremediated 12 inch sand boil, and (c) closeup of remediated sand boil with sand bag ring and metal drum to reduce uplift pressure and erosion of foundation soils at levee toe on Mississippi River Right Levee at River Mile 304 (N 30° 59’ 57.66” W 91° 40’ 43.14”, 2 June, 2011 at 12:41 pm)

4.5 Levee Settling and Freeboard

At the time of the GEER Team visit, the Mississippi River level was within three feet of the top of most levees which is the design freeboard. However, in a few locations, the levee height was less than the design freeboard of three feet due to levee settlement or the area had not been raised to provide three feet of free board. In these areas, sand bags or Hesco® baskets were placed to increase the freeboard as shown in Figure 5. Hesco® baskets are about three feet high so the baskets are used in areas where levee height has to be increased significantly. Figure 4.5(a) shows Hesco baskets covered with plastic sheeting being used to increase levee height near the north end of the Morganza Flood Control Structure. Hesco® baskets were also used on the south end of the Morganza Flood Control Structure to increase the levee freeboard. Figure 4.5(b) shows a row of Hesco® baskets being filled by National Guard troops in Louisiana.

Figure 4.5 (a) Hesco baskets used to increase levee height near the north end of the Morganza Flood Control Structure on Mississippi River Right Levee near River Mile 280 (N 30° 46' 33.30" W 91° 37' 09.42", 2 June, 2011 at 11:42 am) and (b) Hesco baskets being filled (photo from communities.washingtontimes.com)

4.6 Burrowing Animals and Wave Action

In a number of locations, burrowing and rooting animals and erosion due to river wave action caused damage to a levee. The Corps identified twenty-six (26) Inspection Hot Spots for burrowing animals and eight (8) locations for levee erosion. Sand bags were commonly used to temporarily protect the flood side of the levee in these areas as shown in Figure 4.6.

Figure 4.6 Sand bags being used to control damage due to wave action along the levee approaching the northern end of the Morganza Flood Control Structure on Mississippi River Right Levee near River Mile 280 (N 30° 46′ 33.30″ W 91° 37′ 09.42″, 2 June, 2011 at 11:44 am)

4.7 Piezometer Observations and Performance

The GEER Team visited the Duncan Point area on 3 June 2011 which is a High Priority Inspection Hot Spot (see Table 4.2). Duncan Point is an area of recurring sand boils and seepage during previous Mississippi River high water events, and 2011 was no exception. As a result, this area is extensively monitored during each flood event.

In 2010 an interim stabilization berm was constructed along about 1000 feet at the protected side levee toe. However, due to observed seepage during the 2011 flood, this berm was extended using sand bags as described below. In addition to the sand bags, the Pontchartrain Levee District excavated several seepage relief trenches on the protected side slope of the levee to relieve some of the seepage pressures.

Figure 4.7 shows an aerial map of the Duncan Point area and several sites visited by the GEER Team. The site described in this section is labeled "Levee Piezometers" in Figure 4.7. Other sites visited by the GEER Team and described subsequently are LSU Farms, Farr Park, and Sun Plus Road.

Because Duncan Point is an area of recurring seepage and sand boils, the Corps has heavily investigated this area and also installed piezometers with tip elevations of -5, -35, -80, -150, and -300 feet referenced to the NAVD88 datum. All of the piezometers, except the one with a tip elevation of -300 ft, fluctuate with the Mississippi River level. Figure 4.8 presents a generalized cross-section of the levee and foundation soils at the Duncan Point location. Seepage reoccurs here because the "natural levee" (see Figure 4.8), i.e., the natural fine-grained blanket, is thinner at this location which results in a higher exit gradient and increases the chance for sand boils. The piezometric measurements show a head drop of six to twelve ft across the fine-grained blanket. This head drop is based on a maximum river elevation of 44 ft (levee crest and toe elevations are about 52 and 25 ft as shown in Figure 4.8). The piezometers in Figure 4.9 had to be extended during this flood event from elevation 32 ft to 38 ft because water was pouring out the piezometers onto the levee toe. Extending the piezometers from elevation 32 ft to 38 ft ceased the flow of water indicating that the piezometric level at the downstream toe is between 32 ft and 38 ft, or seven to 13 feet above the levee toe.

Figure 4.7 Aerial view of Duncan Point area near Baton Rouge, Louisiana on Mississippi River Right Levee near River Mile 225 (Imagery ©2012 TerraMetrics, Map Data ©2012 Google)

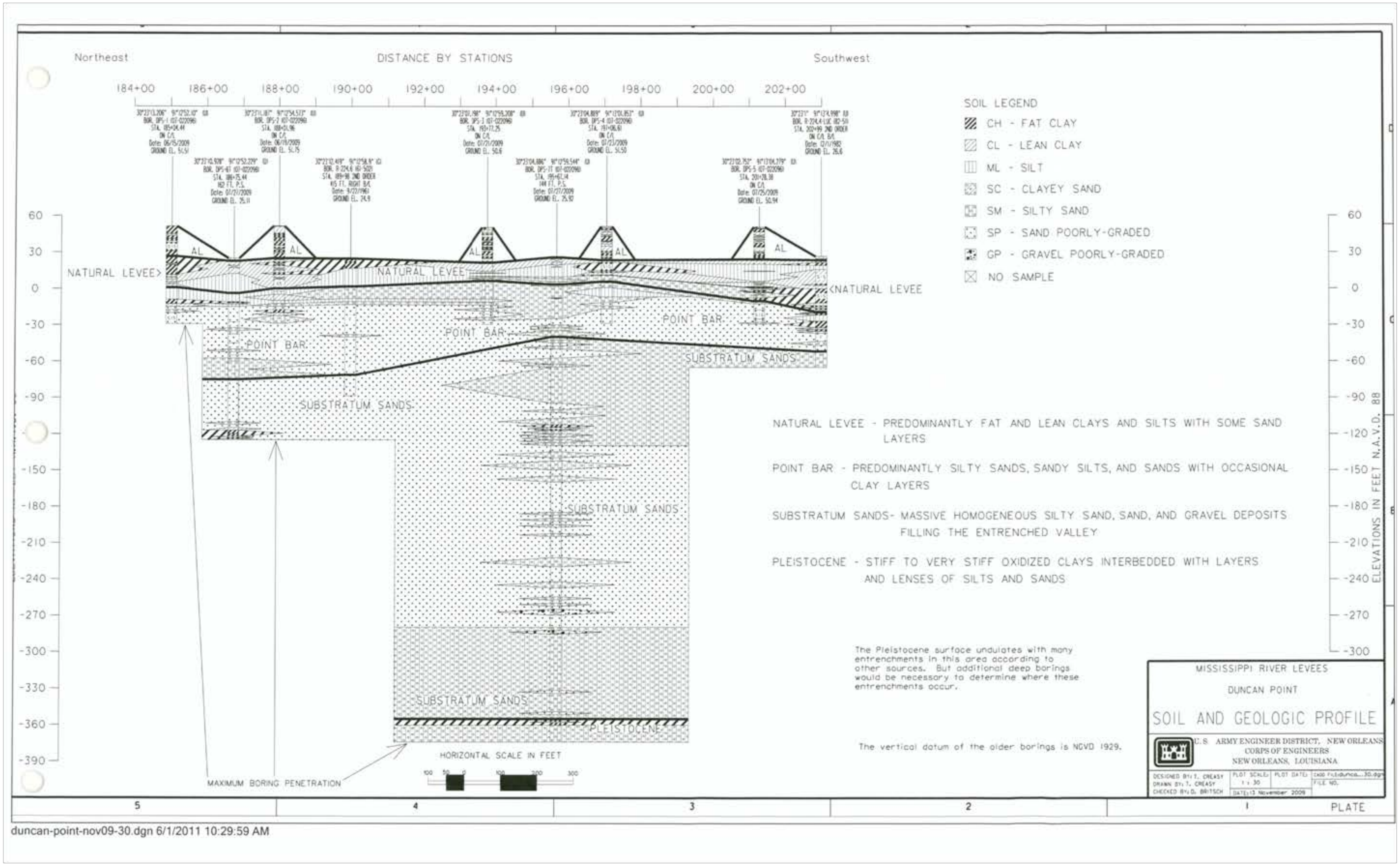


Figure 4.8 Typical cross-section through Duncan Point Levee near Baton Rouge, Louisiana on Mississippi River Left Levee at River Mile 225 (provided by USACE)

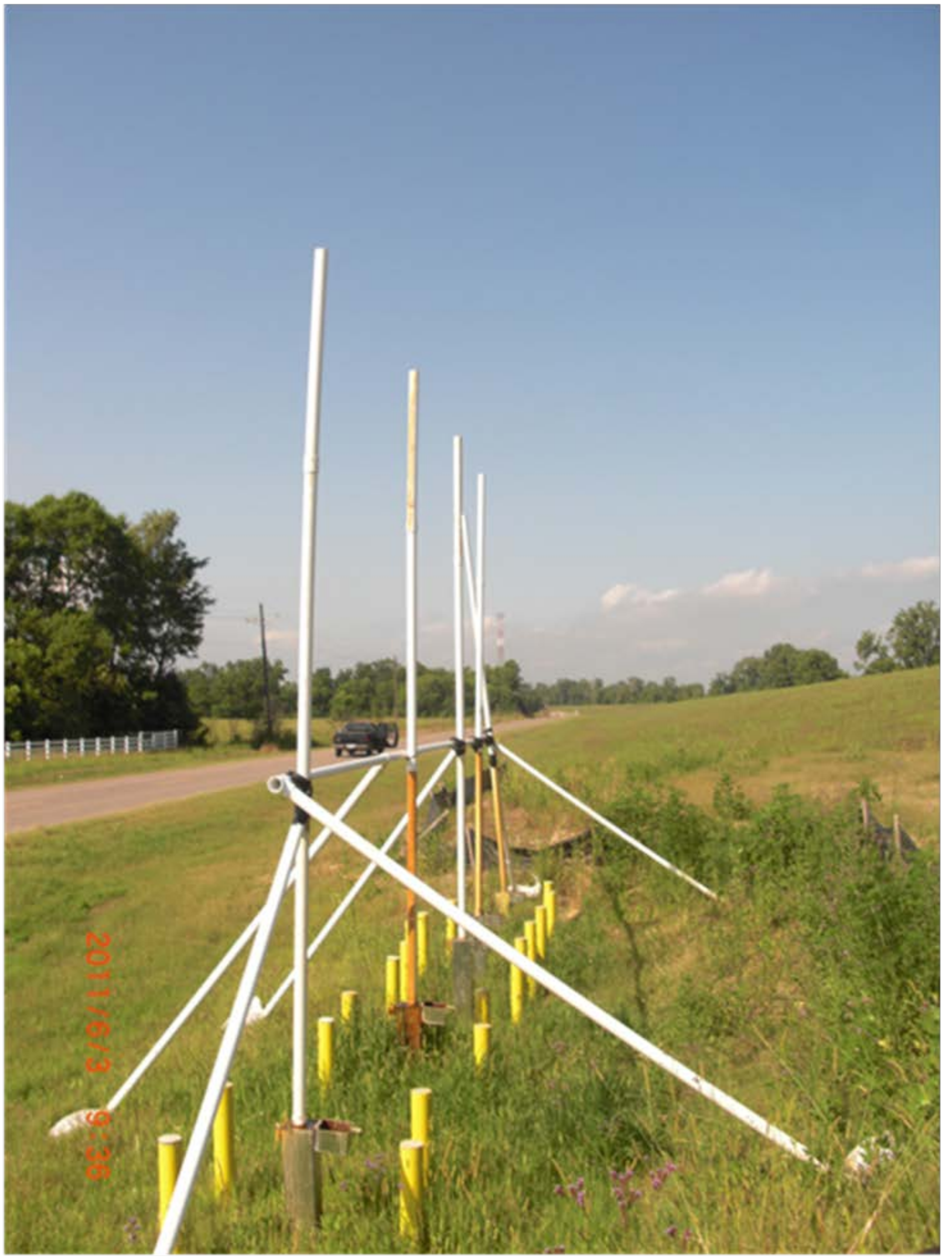


Figure 4.9 (a) Overview of five piezometers installed at Duncan Point and temporary standpipe extensions to estimate piezometric head at levee toe on Mississippi River Left Levee at River Mile 225 (N 30° 23’ 09.84” W 91° 12’ 53.76”, 3 June, 2011 at 09:36)

4.8 Seepage Control Measures

In areas where significant and recurring piezometric heads have been measured, the New Orleans District has implemented permanent seepage control measures, such as relief wells and filter berms. The GEER Team had the opportunity to inspect and observe the performance of both of these control measures. In the case of Duncan Point, the excess piezometric heads at the protected side toe appear to range from a few feet to possibly 12 feet.

Relief Wells

The GEER Team visited two locations where relief wells were installed by the USACE New Orleans District to reduce piezometric heads at the dry side toe to reduce the potential for erosion. At both locations the relief wells were flowing rapidly with no sign of fines in the water. Figure 4.10 presents an overview of one of the flowing relief wells and a close-up that illustrates the active seepage condition.

(a) (b)

Figure 4.10 (a) Overview of flowing relief well and (b) close-up of flowing relief well under Mississippi River flood stage on Mississippi River Right Levee at River Mile 250 (N 30° 56' 94.61" W 91° 31' 83.33", June 2, 2011 at 17:58 – 18:05)

Seepage Berms

The Duncan Point area is a High Priority Inspection Hot Spot because it is an area of recurring seepage and sand boils. In 2010 an interim stabilization berm was constructed because of continued seepage issues during high water events. A more robust berm is planned to be constructed in the near future. This new seepage berm will be about ten feet higher than the interim berm and extend across the current roadway which is shown in Figure 4.11(a). The roadway will be relocated on top of the higher seepage berm.

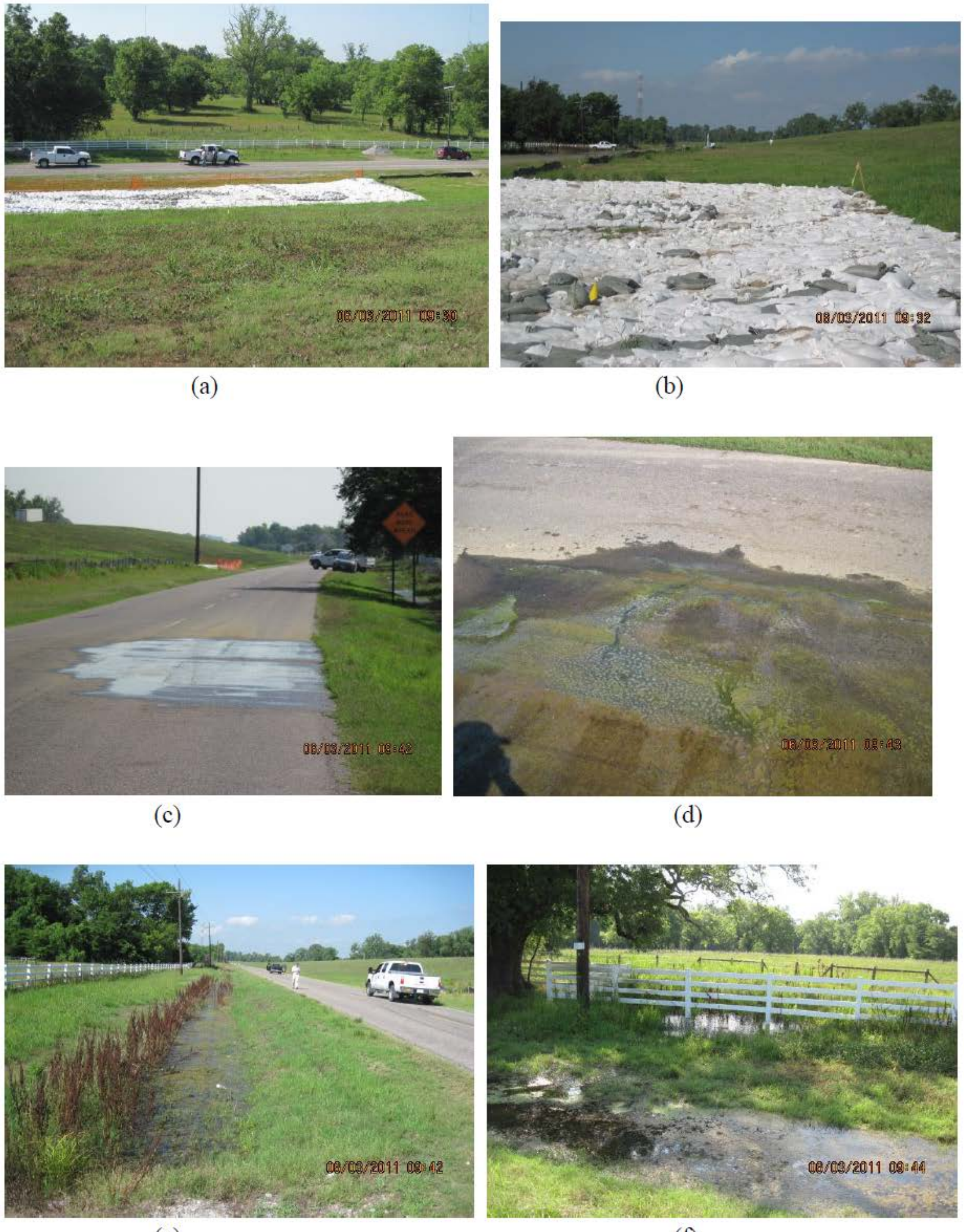


Figure 4.11 (a) Overview of seepage berm, (b) close-up of recently placed sand bags to increase the length of the seepage berm because of underseepage on the protected side of the levee, (c) isolated seepage exiting on to roadway pavement through cracks in pavement, (d) close-up of seepage existing through pavement cracks, (e) seepage occurring in ditch on opposite side of roadway from levee, (f) close-up of seepage in adjacent field with roadway ditch at Mississippi River Left Levee at River Mile 225 (N 30° 23′ 09.84” W 91° 12’ 53.76”, 3 June, 2011 at 08:42)

4.9 Seepage Anomalies

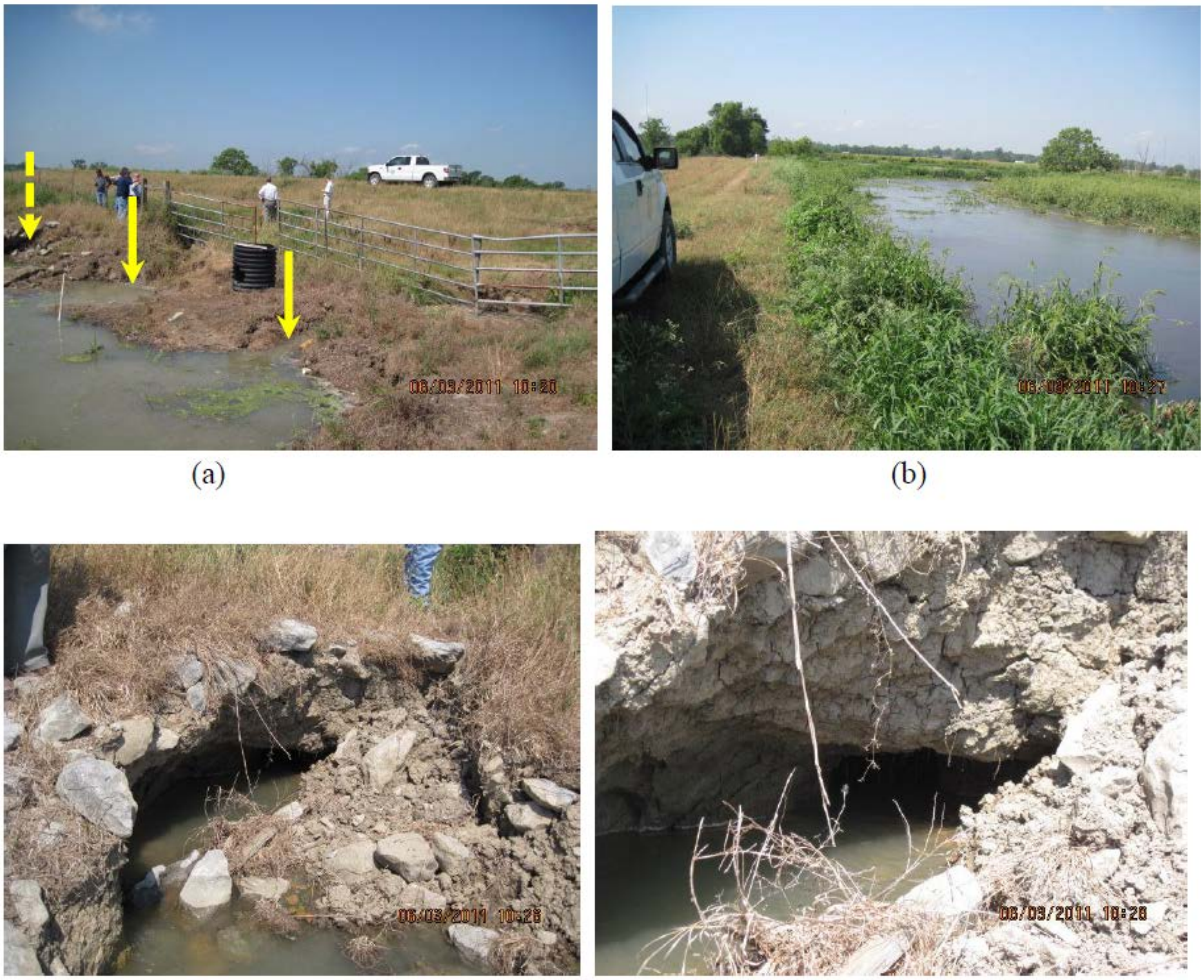
Some of the seepage issues observed in the field reconnaissance could be considered unusual in that normal design procedures often fail to predict their occurrence. This section presents details about some of these seepage anomalies observed during the GEER Team reconnaissance.

Distant Sand Boils

One of the more interesting seepage anomalies observed during the reconnaissance was the presence of sand boils at a large distance from the Mississippi River. Some of these sand boils have diameters up to six feet and are located thousands of feet from the levees along the Mississippi River. These sand boils reflect that that little head loss is occurring as the water seeps over a several 1,000-ft lateral distance and that the water is then exiting at a probable weakness or defect in the overlying fine-grained blanket. This observation has important implications for construction along the Mississippi River levee system because even relatively small piezometric heads at the toe of the levees can still cause seepage problems, such as in excavations, basements or below roads, thousands of feet away from the toes of the levees during a flood event. As a result, seepage control measures have been implemented for excavations and basement walls as shown below for the Louisiana State University (LSU) Veterinary Medicine Building.

Figure 4.7 presents an aerial map of the Duncan Point area and the sites labeled LSU Farms, Farr Park, and Sun Plus Road are locations of distant sand boils that were visited by the GEER Team. The following paragraphs provide a brief description of each site and the observed distant sand boils.

The first distant sand boil location discussed is at the LSU Farms. This site is located about 2,800 from the Mississippi River Levee (MRL). There are five or six well defined sand boils located in the bank of the LSU drainage canal that were flowing clear. Figure 4.12(a) gives an overview of the three largest sand boils. The flow from these sand boils appears to be clear but the cloudy water of the drainage channel makes it difficult to assess the seepage. In addition, there are several small boils in the bottom of the canal that are flowing cloudy water.
An employee of LSU Farm indicated that sand boils have appeared at this site since 2008. The site does not appear to be a threat to the MRL because it is nearly 3,000 feet from the levee. However, at least one of the sand boils had resulted in considerable erosion (see dashed arrow in Figure 4.12(a)) which could undermine the levee for the adjacent LSU oxidation pond which is about 60 ft away (see Figure (b)). The truck shown in Figure 4.12(a) is parked on the crest of the oxidation pond levee. The LSU employee also indicated that the level of the pond had not changed significantly since the sand boils started flowing in 2011 so the seepage is probably due to the Mississippi River and not leakage from the oxidation pond.



(a) (b)

(c) (d)

Figure 4.12 (a) Overview of three large sand boils in a drainage canal at the LSU Farm site with the dashed arrow indicating the sand boil used for the close up photographs in Figures 12 (c) and (d), (b) close-up of LSU oxidation pond upslope of the drainage canal which gives an indication of pond level, (c) close-up of large sand boil in Figure 12(a), and (d) close-up of sand boil in Figure 12(c) eroding and undermining fine-grained blanket which will eventually collapse into the drainage ditch at Mississippi River Left Levee at River Mile 227 (N 30° 24' 13.68" W 91° 11' 28.14", 3 June, 2011 at 10:20 – 10:27)

The second distant sand boil location discussed is behind the Farr Park horse training facility near LSU Farms. This site is located about 2,500 from the MRL and numerous flowing sand boils were observed in a drainage ditch behind an adjacent housing development. The largest sand boil is shown in Figure 4.13(a) and appears to be the prior location of a large tree. Many other sand boils were observed flowing in the adjacent drainage channel, some of which are identified in Figure 4.13(b).

(a) (b)

Figure 4.13 (a) Overview of large sand boil at Farr Park and (b) close-up of various sand boils in adjacent drainage channel at Mississippi River Left Levee at River Mile 225 (N 30° 23' 0.0702" W 91° 12' 28.4472", 3 June, 2011 at 09:59)

The third and most interesting distant sand boil location observed is on Sun Plus Road, which is located in a farm field nearly 2 miles from the Mississippi River Levee and about 1,500 feet from the spur of a navigation canal (Figure 4.7). At this location, there is a six-foot diameter sand boil eroding fine sand from below the fine-grained blanket which is supporting the farming operation (Figure 4.14). In addition, water was observed existing about 3 inches below the crest of the gravel road in Figure 4.14(a), which is above the level of the sand boil in the foreground. It is possible that the gravel embankment for the road extends below the natural fine-grained blanket and provides a vertical conduit for the underseepage to rise to within three inches of the roadway crest.

(a) (b)

Figure 4.14 (a) Overview of large sand boil and (b) closeup of one of large sand boils at Sun Plus Road at Mississippi River Right Levee at River Mile 228 (N 30° 25’ 45.18” W 91° 14’ 05.64”, 2 June, 2011 at 18:50)

One notable feature of the sand boils is how their locations compare to those in earlier floods on the Lower Mississippi River, such as 1973. In many instances, sand boils developed in areas where they had developed in earlier floods. However, there were areas where sand boils did not develop even though they had in earlier floods. Lastly, sand boils also developed in new areas where they had not developed in earlier floods.

Relief Wells for Permanent Seepage Control

The GEER Team also visited Veterinary Medicine Building on the LSU Campus (see Figure 4.15). This is a non-typical use of relief wells in terms of levees because the relief wells were installed to relieve water pressures on the basement walls of the Veterinary Medicine Building. The Veterinary Medicine Building required a basement that placed its foundation below the natural levee, i.e., fine-grained blanket, so underseepage would be directly impacting the basement walls. To reduce the piezometric pressures and the likelihood of water entering the basement which is being used for the care of large animals, permanent relief were placed around the building. The flow from the well shown in Figure 4.15 is used to create the presence of a creek flowing through the garden area in front of the building and under the entrance sidewalk resulting in a pleasant entrance to the building. At the relief well shown in Figure 4.15(b), steady seepage was occurring with no sign of fines in the flowing water.

(a) (b)

Figure 4.15 (a) Overview of LSU Veterinary Medicine Building and relief well adjacent to building and (b) close-up of relief well in Figure 15(a) in front of LSU Veterinary Medicine Building at Mississippi River Left Levee at River Mile 228 (N 30° 24' 47.77”, W 91° 11' 38.29", 3 June, 2011 at 10:57)

5. CONCULSIONS AND RECOMMENDATIONS

The following conclusions are drawn based on this reconnaissance:

- The 2011 Flood on the Lower Mississippi River produced very high flow rates and stage levels, exceeding those from the 1927 and 1973 floods in many locations. Therefore, this flood represents the highest load ever placed on much of system.
- Both the Old River Control Structure (specifically the Old River Low Sill) and the Morganza Spillway performed well in diverting floodwater and controlling the flow rates and stage levels in the Mississippi River. There was no evidence of scour at the Old River Sill where a 30-foot deep scour hole developed during the 1973 flood.
- The levee system along the Lower Mississippi River performed well with no failures and no major damage occurring at any point during the flood, including the rise, peak and fall of the floodwaters.
- There was widespread evidence of seepage under and through levees, including through seepage exiting through the protected side slope of the levee, underseepage exiting over a large area beyond the toe of the levee as sheet seepage, and underseepage exiting through sand boils at and beyond the levee toe.
- Natural and man-made heterogeneities play an important on seepage and internal erosion. Sand boils developed thousands of feet from the toe of the levee due to apparently natural features, such as natural thin spots or weaknesses in the fine-grained blanket, as well as man-made features, such as foundations and excavations in the fine-grained blanket. Sand boils developed in some areas where they had developed in earlier floods, they did not develop in other areas where they had developed in earlier floods, and they developed in new areas where they had not developed in earlier floods.
- The condition of the levees during a flood is dynamic. About 450 locations along the levee system were identified for increased inspection and monitoring during the flood, mostly due to seepage. Low areas along the levees caused by settlement were temporarily raised with sand bags, erosion from waves and holes dug by burrowing animals were temporarily repaired with sand bags, and sand boils near the levee toe were ringed and confined with water to reduce the exit gradient.

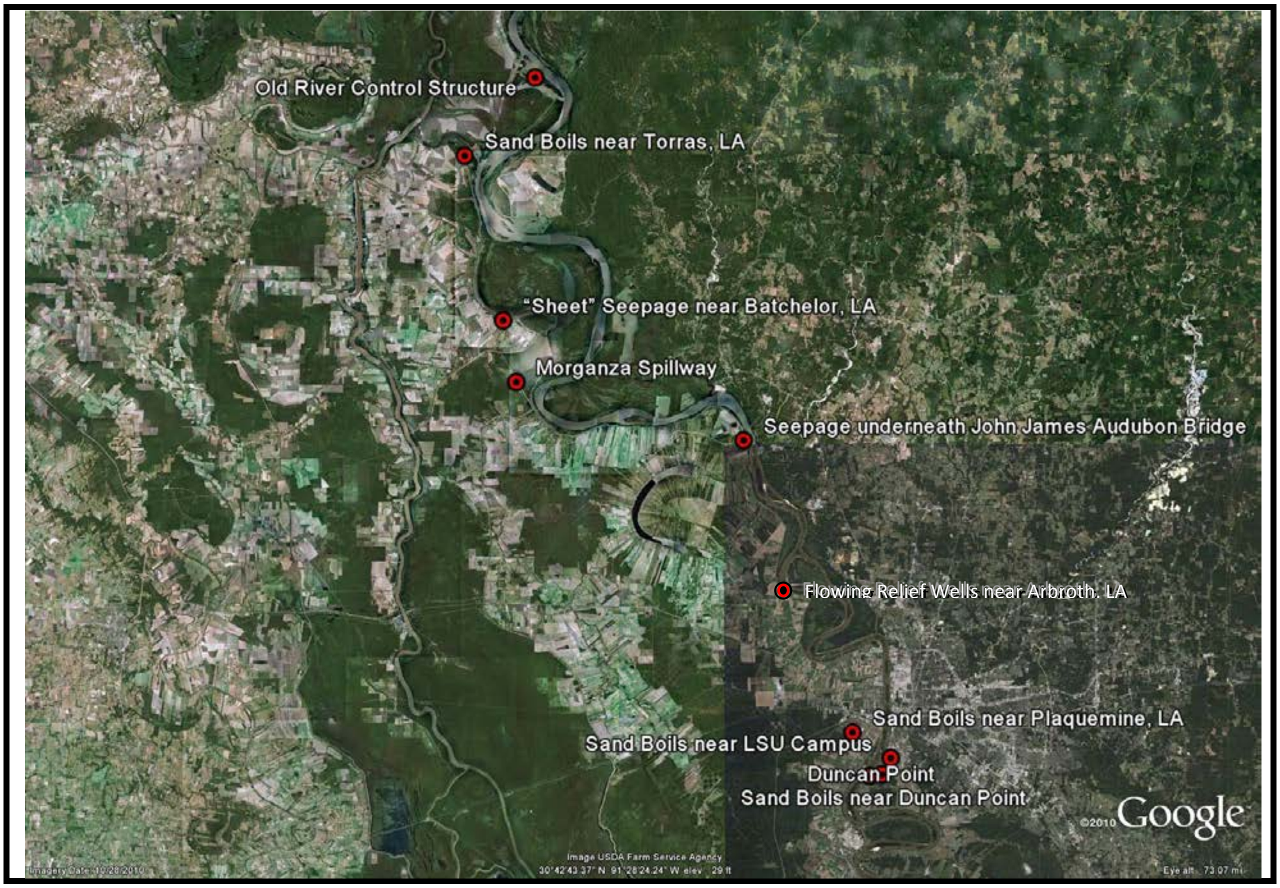
The following recommendations are offered based on this reconnaissance:

- The dynamic nature of a flood and of the levee system underscore the need for the Observational Method, in which the performance of the levees is consistently monitored and potential weaknesses are mitigated as they are identified. Therefore, the design and construction of new levee systems should, to the extent possible, accommodate the potential need for future mitigation measures such as crest raising, scour protection, toe berms and relief wells.
- Each major flood event provides a wealth of information about the performance and condition of the levee system. Therefore, it would be extremely valuable to systematically document all of the information and data about how the levees performed, including piezometric measurements and seepage observations, and to analyze these data to improve understanding of the system and of levees in general.

APPENDIX

RECONNAISSANCE TRIP ITINERARY

June 2 and 3, 2011



Site	Site Visit Date	Location	Latitude & Longitude	Observations
Morganza Spillway	Thursday, June 2, 2011	• The Morganza Spillway is situated approximately 2.6-mi NW of the intersection of LA. St. Hwy. 1 (Gayden Road) and LA. St. Hwy. 10 (Fordoche Bayou Road). • The Mississippi River flows on the eastern side of the Spillway, and the Atchafalaya Floodway is on the western side of the Spillway.	N 30° 46’ 33.30” W 91° 37’ 09.42”	• 9 of 125 flood-gates were open at the Morganza Spillway on June 2, 2011. • A maximum of 17 flood-gates were opened in 2011.
“Sheet” Seepage near Batchelor, LA	Thursday, June 2, 2011	• Evidence of sheet seepage noticed about 1,600-ft east of the intersection of LA. St. Hwy. 419 (Lake Road) and Normandy Lane. • The Mississippi River is directly north of LA. St. Hwy. 419, and a large acreage of crop fields is situated south of La. St. Hwy. 419.	N 30° 50’ 12.42” W 91° 38’ 03.72”	• Large areas of standing water in crop fields and drainage ditches along LA. St. Hwy. 419.

Sand Boils near Torras, LA	Thursday, June 2, 2011	• Sand boils noticed about 3,500-ft NE of the intersection of LA. St. Hwy. 418 and LA. St. Hwy. 15. A lock-structure controlling flow between the Atchafalaya River and the Mississippi River is approximately 2,000-ft NE of the site.	N 30° 59' 57.66" W 91° 40' 43.14"	• Two (2) isolated sand boils near the protected-side toe of the Mississippi River (MSR) levee.
Old River Control Structure – Low Sill Control Structure	Thursday, June 2, 2011	• The Old River Control Structure (ORCS) is located in Avoyelles Parish, Louisiana. The ORCS is about 5-mi north of the east-to-west state border which separates Louisiana and Mississippi.	N 31° 04’ 35.76” W 91° 35’ 51.18”	• The Low Sill Control Structure (LSCS) is one of four flood-control structures which collectively function as the ORCS. • The flow capacity of the LSCS was reached one (1) week prior to the GEER Team site visit.
Old River Control Structure – Auxiliary Structure	Thursday, June 2, 2011		N 31° 03’ 54.96” W 91° 35’ 23.22”	

Seepage underneath John James Audubon Bridge	Thursday, June 2, 2011	• Signs of seepage through MSR levee along LA. St. Hwy. 981 (Cajun II Road) underneath the John James Audubon Bridge. • The John James Audubon Bridge provides vehicular access across the Mississippi River near the town of New Roads, LA.	N 30° 43’ 05.04” W 91° 21’ 31.14”	• Evidence of seepage though concrete slope-paving along protected-side slope of MSR levee. • Seepage of water through levee resulted in accumulation of water in drainage ditch near toe of levee.
Flowing Relief Wells near Arbroth, LA	Thursday, June 2, 2011	• Located on west bank of river on River Road, about 12 miles south of the John James Audubon Bridge	N 30° 56’ 94.61” W 91° 31’ 83.33”	• Water flowing out of relief wells into drainage ditch along road
Sand Boils near Plaquemine, LA	Thursday, June 2, 2011	• Several sand boils observed about 1-mile NW of the intersection of LA.St. Hwy. 1 and Sun Plus Pkwy. • Sand boils were in the general vicinity of Sun Plus Pkwy and south of Sun Plus Pkwy. • Crop fields occupied the land south of Sun Plus Pkwy.	N 30° 25’ 45.18” W 91° 14’ 05.64”	• An array of approximately 10-12 sand boils was detected about 1.5 to 2 miles west of MSR levee. • Sand boils arose in crops fields and adjacent drainage/irrigation channels. • A segment of Sun Plus Pkwy was compromised due to the sand boils.

Duncan Point	Friday, June 3, 2011	• Seepage area was approximately ¾-mile SW of the intersection of LA. St. Hwy. 327 (River Road) and Brightside Drive. • Area was about 2-miles SW of Louisiana State University Campus.	N 30° 23' 09.84" W 91° 12' 53.76"	• Sand bags were placed on top of a protected-side stability berm to prevent seepage through the berm. • Seepage through the centerline of LA. St. Hwy. 327 ("River Road"). • Several areas of localized flooding in green fields and drainage ditches along LA. St. Hwy. 327. • Extra lengths of PVC pipe were added to stand-pipe piezometers at the site as a result of water pressures developing in pervious layers underneath the MSR levee. • The elevation of the top of the stand-pipe piezometers was about 13-ft lower than the elevation of the MSR levee crown.
Sand Boils near Duncan Point	Friday, June 3, 2011	• Approximately 3,500-ft east of	N 30° 23' 15.36"	• Sand boils occurred

		MSR levee in a heavily wooded area. • Residential communities situated immediately north and east of the sand boils.	W 91° 12’ 03.72”	about 3,500-ft east of centerline of MSR levee.
Sand Boils near LSU Campus	Friday, June 3, 2011	• Along a drainage canal about 3,000-ft east of Mississippi River. • Signs of seepage along drainage canal were located about 600-ft to 700-ft SSW of the intersection of the drainage canal and Gourrier Ave.	N 30° 24’ 13.68” W 91° 11’ 28.14”	• Evidence of sand boils approximately 2,800-ft from centerline of MSR levee.