# Hurricane Katrina - What Happened?
## The Geology of the Katrina Disaster in New Orleans
## Field Trip Guide


http://www.tulane.edu/~sanelson/Katrina


April 21, 2013


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Photos - Top - looking north from I-10 overpass over Carrollton Ave. Middle - cars and other debris in park on Fleur de Lis near 17th St. Canal breach. Bottom – missing house and Cypress stumps at 17th St. Canal Breach (photos by Stephen Nelson)

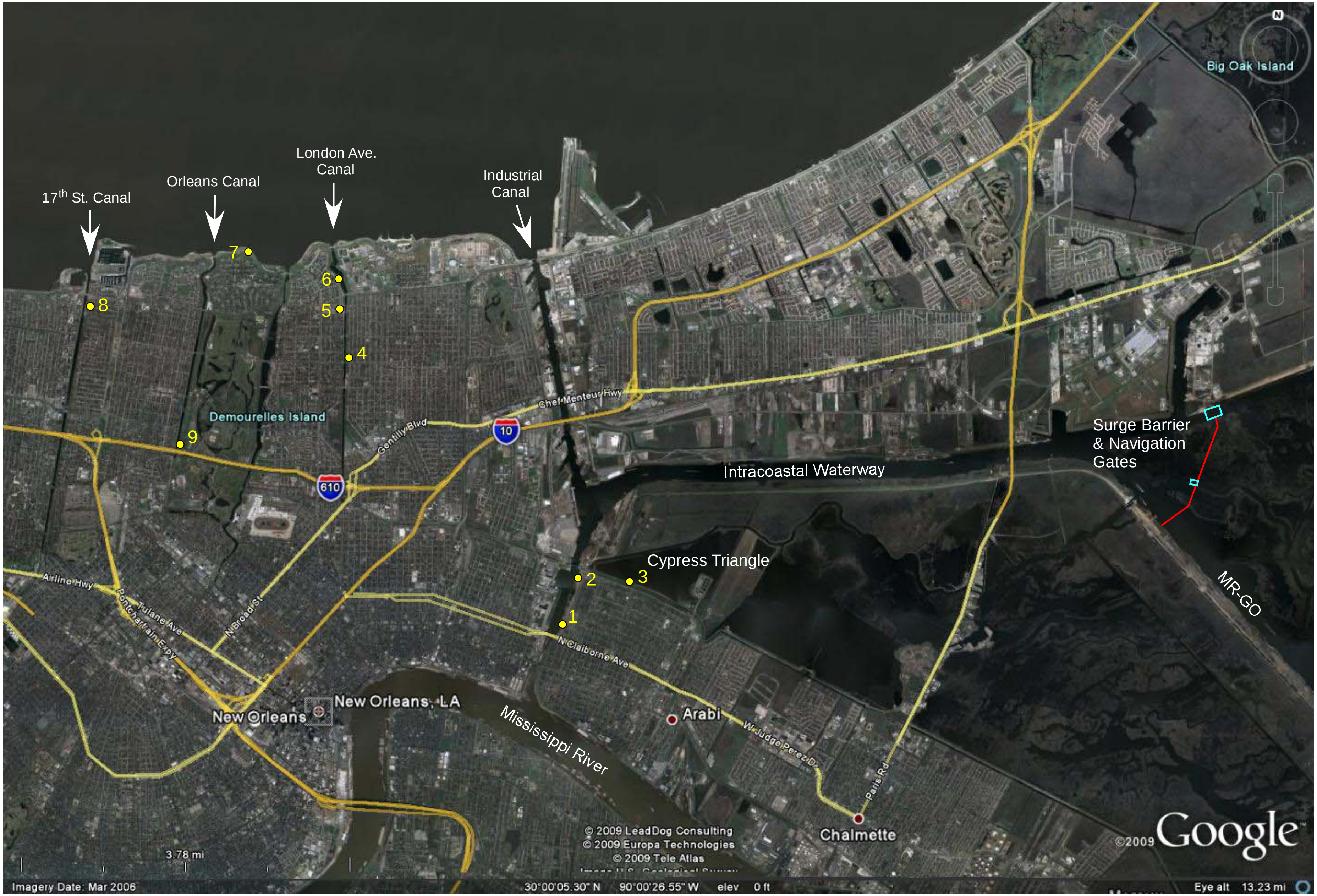


**Figure 1.** Google Earth view of New Orleans showing location of field trip stops and important geographical features, including the surge barrier and navigation gates on the Intracoastal Waterway and Mississippi River – Gulf Outlet (MR-GO) that were completed in 2012.

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This document including its conclusions and interpretations are the sole work of the author, Stephen A. Nelson, who takes full responsibility for the conclusions and interpretations expressed in the document.

## Geologic and Historical Background

Before starting the field trip, it is necessary to provide some background on the geologic history and history of human occupation of the region. The land on which New Orleans is built has origins starting about 5,000 years ago. As sea level was rising after the last glacial maximum, a series of barrier islands was built outward from the coast of Mississippi across what is now the southeastern edge of Lake Ponchartrain (Figure 2). These islands, called the Pine Islands were composed mainly of sand whose source was the Pearl River along the current Mississippi – Louisiana border. At the time the Mississippi River was building its delta out toward the southeast of New Orleans as the Maringouin and Teche lobes of the delta complex (Figure 3). Beginning about 4,300 years ago the Mississippi River began to build the St. Bernard Delta lobe out toward the east. This lobe eventually intersected the Pine Island Barrier Island complex, eventually burying the sands, cutting off the drainage from the north to form Lake Pontchartrain, and building the land on which New Orleans would later be built. The streams forming the delta lobes normally break up into distributary streams due to the fact that they are continually depositing sediment which chokes off some channels requiring the formation of other channels. The distributary channels often flood, and during flood stage they deposit sediment on their banks which eventually builds natural levees along the banks. The natural levees from areas of higher elevation on the delta plain, with the low lying areas in between forming marshes or swamps that accumulate fine-grained organic-rich sediment (organic clays) as illustrated in Figure 4. During the building of the St. Bernard Delta lobe, several such distributary channels crossed through what would later become New Orleans, and the natural levees for these distributaries are now seen as ridges of slightly higher elevation, now known as the Metairie, Gentilly, and Esplanade Ridges (Figure. 5).

Figure 6 shows a geologic and topographic cross-section running approximately North-South through the city. The highest natural elevation in the city is about 17 feet above sea-level in the French Quarter, although the human constructed levees on the Mississippi River rise to about 25 feet above sea-level. Elevation drops to a few feet below sea-level between Interstates 10 and 610, but rise to about 3 feet above sea-level along the Gentilly Ridge. Between Gentilly Ridge and the Lake, elevation again drops, reaching 10 feet below sea level, before rising at the near the shore of Lake Pontchartrain where fill and human constructed levees rise to about 17 feet above sea level. Also shown in Figures 5 and 6 are the near-surface distribution of the buried Pine-Island beach sands. These sands played an important role in levee breaches that occurred during Hurricane Katrina, and will be discussed in more detail at Stop 4 on the field trip.

Although the general geology of the New Orleans area is fairly simple as depicted on the geologic map and cross-section in Figures 5 and 6, a close look at Figure 4 shows that one might expect the details to be quite complex, with interfingering of sands and silts from the distributary channels, natural levees, and crevasse splays with clays and peats of the swamps. Such complexity must be taken into account when designing and building any structure on the soft soils that underlie New Orleans.

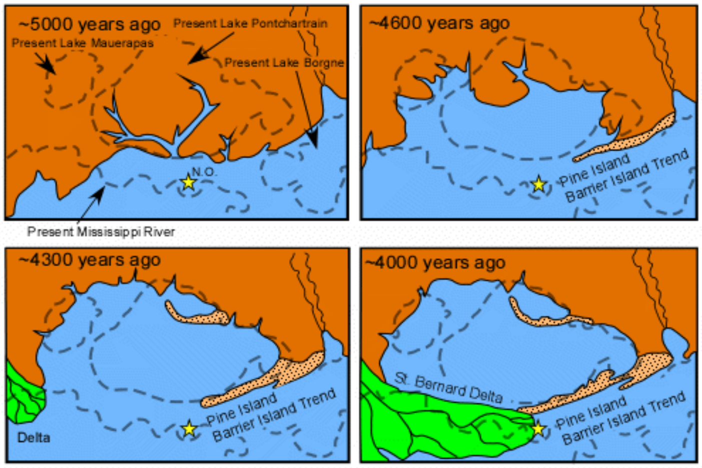



**Figure 2**. Geologic history of southeast Louisiana between about 5,000 and 4,000 years ago showing the development of the Pine Island barrier island trend (modified after Snowden et al., 1980).

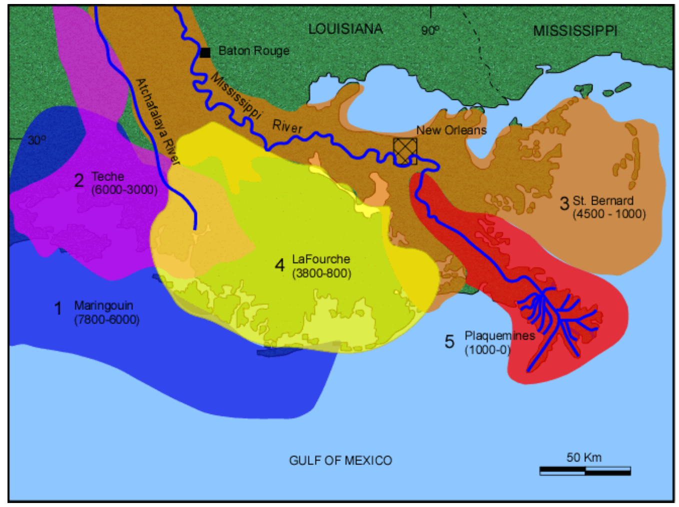



**Figure 3**. Map of the various delta lobes of the Mississippi River (after Saucier [1994] and Frazier [1967]).

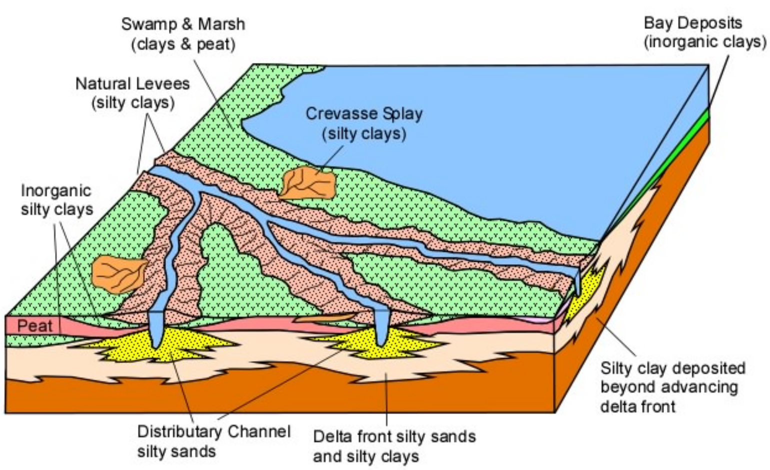



**Figure 4**. Illustration of distributary channels in a delta complex, showing the natural levees and interdistributary swamps and marshes and the complex deposits produced by deltaic sedimentation.

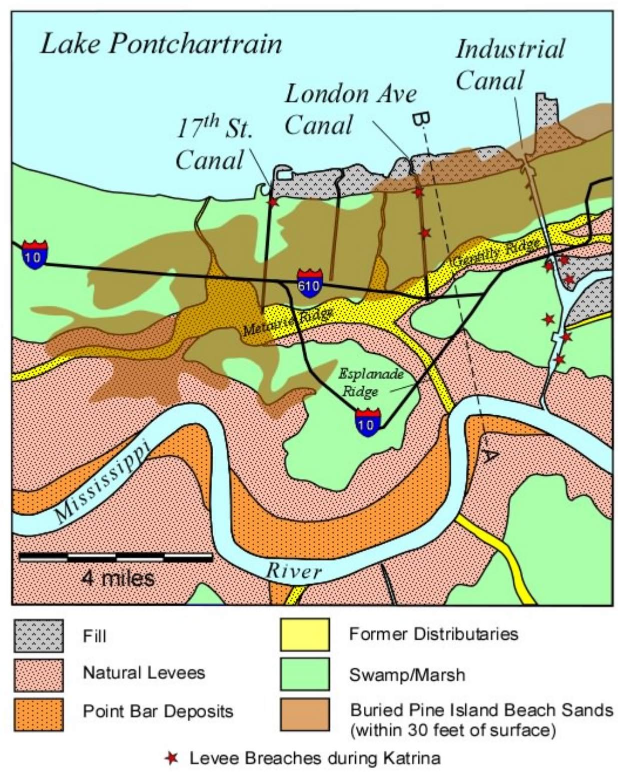



**Figure 5**. Surficial Geology of New Orleans (generalized) showing former distributary channels of the St. Bernard Delta and the buried Pine Island barrier island/beach sands. Line A-B shows the approximate location of the vertical cross-section shown in Figure 6.

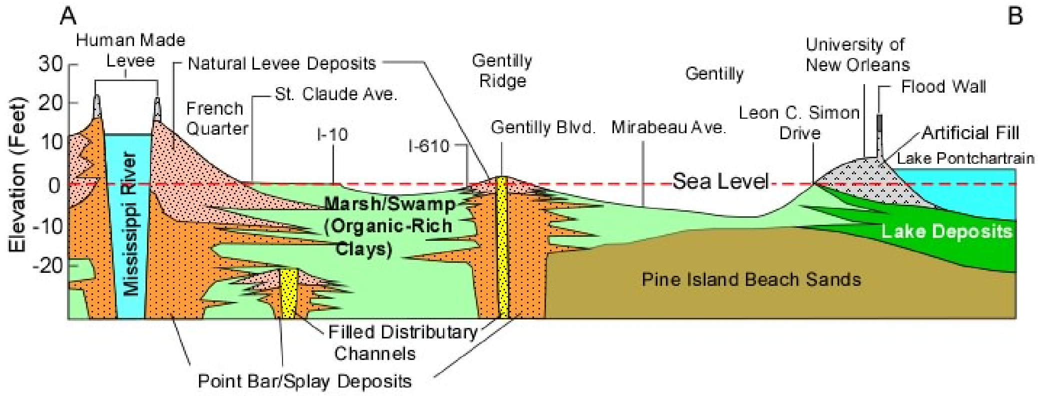



**Figure 6.** – Cross-section from the Mississippi River to Lake Pontchartrain showing Gentilly Ridge (Section approximately along line A-B in Figure 5).

New Orleans was founded in the year 1718 by Jean Baptiste La Moyne, Sieur de Bienville where the first settlement was at the location of the French Quarter. The city grew along the high ground, which included the natural levee of the Mississippi River and the Metairie and Gentilly ridges. Because of its crescent shape along the meander bend of the River, it gained its nickname, The Crescent City. Drainage was a continual problem because of the topography of the region and although Bayou St. John offered a natural drainage from the central part of the crescent to Lake Pontchartrain, it was not enough to drain the often heavy rainfall that occurred. Thus, a drainage system consisting of canals that drained into three outfall canals running from South to North into the Lake was designed and built. Because of the intervening high ground of the Metairie/Gentilly ridges, it was necessary to raise the water at the ridges to get it into the outfall canals. By the mid 1800's this had been accomplished with the main outfall canals from west to east being the Metairie Outfall Canal (now called the $17^{th}$ St. Canal), the Orleans Canal, and the London Ave. Canal. These canals can be seen on the 1878 map of New Orleans shown in Figure 7. Initially water-wheel like machines (called drainage machines) lifted the water about 8 feet at the ridges after which it would flow by gravity through the outfall canals and into the Lake. Still, by the late 1800s the area in the central part of the city and nearly all of the area north of the Metairie and Gentilly ridges was swamp or marsh.

Then, in 1913, Albert Baldwin Wood, a New Orleans Sewerage and Water Board engineer, invented giant screw pumps. These pumps were employed at the ends of the outfall canals to lift the water from the low lying areas to the south of the ridges into the canals. With this improvement in drainage capacity, the swamps north and south of the ridges were drained to provide further habitable land for the growing city. But, it also left the city much more vulnerable to storm surge entering from Lake Pontchartrain, as the outfall canals bounded by low levees, contained water at levels higher than the surrounding land. It was a mistake that would prove critical on the arrival of Hurricane Katrina when levees on the $17^{th}$ St. and London Ave. canals failed and allowed Lake Pontchartrain to essentially drain into the city.

Figures 7 and 8 from the front page of the Times-Picayune newspaper on November 3, 2005, show how the areas that were low lying swamps and marshes in 1878 were the areas flooded as a result of levee breaches on the outfall canals during Hurricane Katrina in 2005. Note that Figure 8 shows estimated flood water depths on Sept. 11, and are not the maximum water depths. The sinuous Metairie and Gentilly ridges are clearly seen as high ground.

A timeline of important events leading up to Hurricane Katrina can be found in Appendix I of this guidebook.

## Flooding of New Orleans During Hurricane Katrina

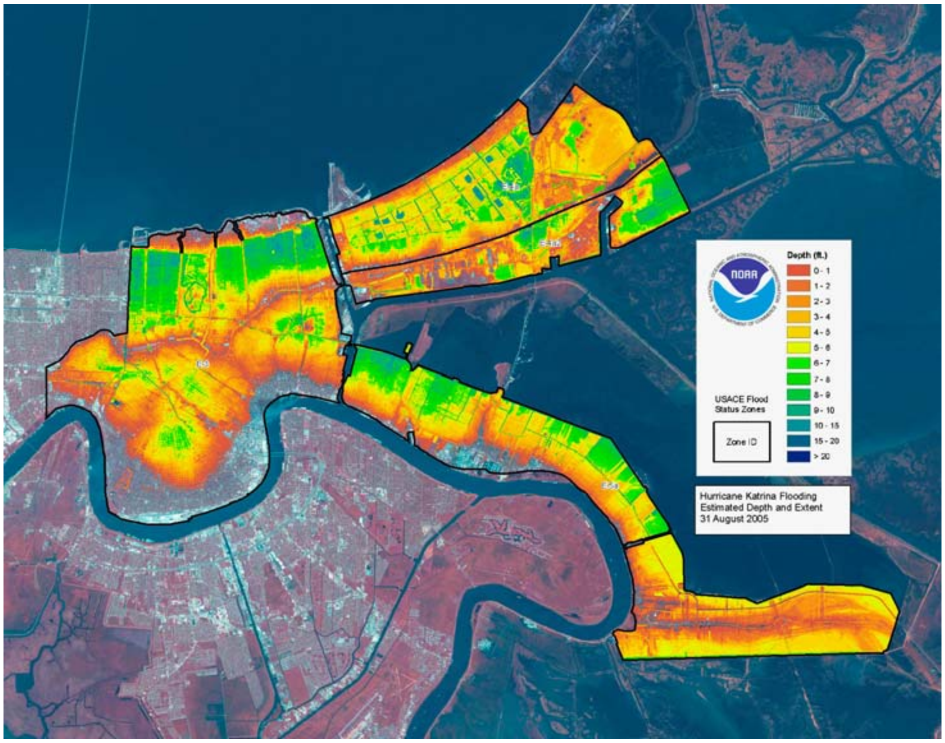
Hurricane Katrina struck the Gulf Coast on August 29, 2005. It first made landfall near the mouth of the Mississippi River, near Buras, LA at 6:10 A.M. Central Daylight Time as a Category 3 Hurricane with wind speeds up to 125 mph and made a second landfall at 10:00 AM near the Mississippi-Louisiana border. One day before, on August 28, Katrina peaked as a Category 5 Storm (Knabb et al. 2005). On August 29, the Mississippi Gulf Coast was subjected to storm surge up to 28 feet above sea level. A 20 foot storm surge was experienced in southeast Louisiana, with 18 feet of surge reaching the eastern margins of Orleans and St. Bernard Parish. Levees were overtopped along the Mississippi River – Gulf Outlet (MR-GO) and along the Intracoastal Waterway, resulting in flooding of much of St. Bernard Parish and

Eastern New Orleans. Catastrophic levee failures occurred along the Industrial Canal (Inner Harbor Navigation Canal) accompanying the overtopping and flooding parts of New Orleans both to the east and west of the canal. Drainage canals in the interior of New Orleans were not overtopped, but 3 levee/floodwall failures (2 on the London Avenue Canal and one on the 17$^{th}$ St. Canal) resulted in further flooding of New Orleans. In all, over 80% of the city was flooded as a result of these levee failures. Two common misconceptions about the flooding in New Orleans are apparently still widely believed. First, at least outside of New Orleans, many people still think that the flooding resulted from breaches on the levees along Lake Pontchartrain or the Mississippi River. None of these levees breached. The levees that failed were all on human made navigation and drainage canals. Second, many people, even some in the New Orleans area, still believe that the breaches occurred the day after Katrina made landfall. This is also not true. All of the breaches and overtoppings occurred early in the morning of August 29, some even before the main pulse of the storm reached the city.

According to the chronology put together by the Interagency Performance Evaluation Task Force (IPET, 2006) (See Appendix II for a timeline of events during Hurricane Katrina from various sources) the first flooding to occur in New Orleans took place between 4:30 – 5:00 AM along the west side of northern arm of the Industrial Canal (also know as the Inner Harbor Navigational Canal, a shipping channel completed in 1923) where the CSX railroad crosses the canal. Here, the floodgates were not working and sandbags had been used to seal floodwalls (See Figure 9).


**Figure 7**. 1878 Map of New Orleans showing the areas inhabited at the time. This was before most of the drainage projects that were designed to drain the swampy areas near the Lakefront and in what is now Mid City. It is clear from the map where the high areas were (and still are). Areas near the Mississippi River and along the Metairie Ridge – Gentilly Ridge – Esplanade Ridge were inhabited at the time. These ridges are high areas because they were the natural levees on a system of distributary streams that were active when the Mississippi River was depositing the St. Bernard Delta lobe (Figure 3). Compare this with the map in Figure 8 which shows the areas flooded due to levee breaches during Hurricane Katrina. Image from the Times Picayune front page November 3, 2005. The image accompanies the article by Gordon Russell (see references). A detailed 36” print of this map can be purchased at the Historic New Orleans Collection.

**Figure 8.** Image from NOAAshowing depths of flood waters on August 31, 2005 Compare this with the 1878 map of New Orleans in Figure 7. Note that the areas least affected by flooding were areas near the Mississippi River and along the old natural levee system known as the Metairie Ridge, Gentilly Ridge, and Esplanade Ridge. This is not surprising since the high and low areas today are not different from those back in 1878.




By about 6:00 AM the storm surge in Lake Borgne ran up the Mississippi River Gulf Outlet (MR-GO), & Intracoastal Water Way (ICW), and overtopped levees along the southern margin of New Orleans East. By 7:30 AM, surge from the ICW had run up both the both north and south arms of the Industrial Canal and had overtopped levees on both sides of the canal. The MR - GO ship channel is a human made channel (completed in 1965) that helped to funnel water during the hurricane storm surge into St. Bernard Parish and the Industrial Canal (Brown, 2005 and van Heerden, 2005). Levees along the MR-GO were overtopped and eroded sending water into St. Bernard Parish by about 8:00 AM.

Storm Surge in the Industrial Canal reached an elevation of about 15 feet above sea-level and overtopped the floodwalls on the west side near France Road, at about 6:00 AM, eventually causing breaches in two locations by about 7:30 AM. On the east side of the Industrial Canal the floodwalls were also overtopped and two breaches into the Lower 9$^{th}$ Ward occurred at about 7:45 AM.

The storm surge in Lake Pontchartrain, which is connected to the Gulf of Mexico through two narrow passageways on the east, Chef Menteur Pass, and the Rigolets, reached elevations between 17 feet on the east and 11 feet on the west. This pushed water into the three outfall canals. Two breaches on the London Avenue Canal, one near Mirabeau Ave. & Warrington Drive and the other near Robert E. Lee Blvd. & Pratt Drive, occurred between 7:30 and 9:00 AM. These breaches flooded parts of New Orleans near the west side of the Industrial canal and throughout Gentilly. A breach on the 17$^{th}$ St. Canal appears to have started about 6:30 AM and was completed by about 9:00 AM, resulting in flooding in Lakeview, Mid City, Old Metairie, Jefferson, & parts of Uptown.

A summary of the critical errors that led to levee failures as determined by the Independent Levee Investigation Team (ILIT, 2006), can be found in Appendix III and will be discussed further at the various stops on the field trip.

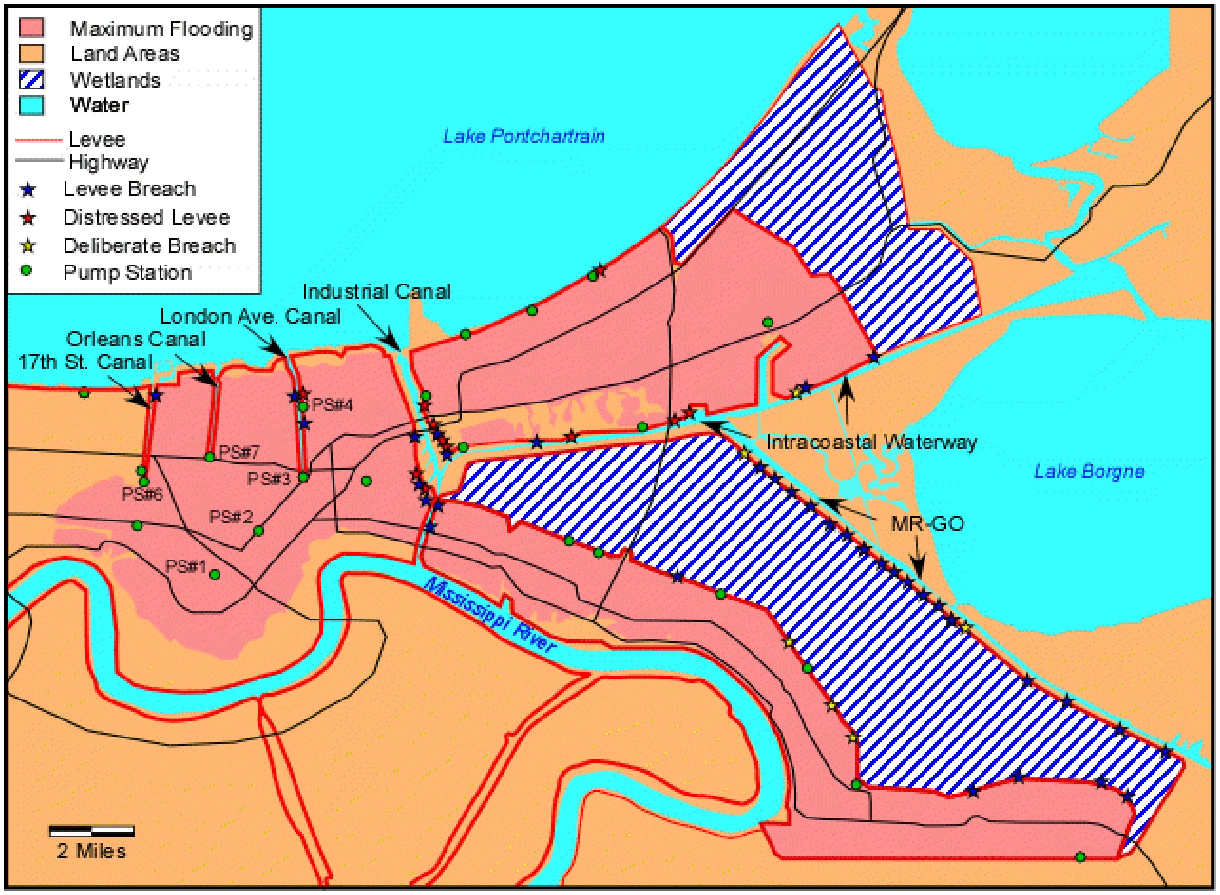



**Figure 9.** Map of maximum extent of flooding during Katrina modified and locations of breached levees after U.S. Army Corps of engineers and Seed et al. (2005)

## Field Trip Itinerary

(Note: due to the ever changing nature of the cleanup, demolition, and restoration in the New Orleans area, you may not be able to follow all routes exactly as they are detailed below. Be prepared to make minor alterations to the routes. It would be useful to bring along a road map of New Orleans). Figure 1 shows the general area that will be visited.

Field Trip will leave Tulane driving down river (east) on St. Charles Ave. to Jefferson Ave. – left on Jefferson.

Continue on Jefferson to Claiborne – right on Claiborne

Continue on Claiborne to Interstate 10 eastbound (stay in left lane on overpass to enter I-10 eastbound.

Continue on Interstate 10 eastbound to the North Claiborne Ave. exit and exit onto N. Claiborne.

North Claiborne becomes North Robertson, continue eastbound over the Claiborne Ave. Bridge over the Industrial Canal.

Turn left (North) on Reynes Street into Lower Ninth Ward

Continue on Reynes St. and turn left at North Prieur St., continuing to Deslonde St. Turn Right at Deslonde and immediately park for **Stop 1.**

After leaving Stop 1, turn left on N. Prieur St. and go one block to Tennessee St, then turn left on Tennessee St. and drive north to Florida Ave. Turn left on Florida Avenue. Before crossing the bridge, turn left through the gate in the chain link fence and park for **Stop 2**.

After leaving Stop 2, return through the gate in the chain link fence and turn right (east) onto Florida Ave. Continue on Florida Avenue to just before Caffin Ave and park. Walk to the north, over the railroad tracks to the platform to view the Cypress Triangle and **Stop 3**.

After leaving Stop 3, turn right (south) on Caffin Ave. and continue to N. Galvez St.. Turn right (west) on N. Glavez and continue to Reynes St. Turn right (north) on Reynes St. and continue back to Florida Ave.

Turn left on Florida Ave. and continue over the blue Florida Ave. Bridge to France Rd. Turn right at France Road and after crossing the railroad tracks turn left and follow the road along the side of the overpass.

Continue North Alvar St. and continue over the overpass and under the underpass, turning left on Chef Menteur Highway (Hwy 90 W). .

Continue West on Chef Menteur Hwy which becomes Gentilly Blvd. after going under the railroad overpass. Continue on Gentilly Blvd to Elysian Fields – turn right onto Elysian Fields.

Continue North on Elysian Fields to Mirabeau Ave. then turn left.

Continue West on Mirabeau Ave. to St. Anthony St. A short stop (**Stop 4a)** can be made in front of the church on the left just past St. Anthony. Then continue to Warrington Drive and turn right on Warrington Drive and **Stop 4**

Continue North on Warrington Dr. and turn right Wickfield Drive. Continue on Wickfield, rounding the corner to the left and on to Filmore Ave.

Turn Left (West) on Filmore, cross the London Ave. Canal, then turn right on Chatham Drive going north.

Continue north on Chatham to Pressburg St. turning right (east) on Pressburg,

Continue east on Pressburg to Pratt Drive and turn left (north) on Pratt Drive.

Continue north on Pratt Drive and park 1 block before Robert E. Lee Blvd and **Stop 5**.

Continue north on Pratt Drive. After crossing Leon C. Simon, continue about ¼ mile and park just past the gate/pump structure on the left for **Stop 6**

Continue north of Pratt Drive to Killdeer Drive and turn right, and continue to Lakeshore Drive and turn left. After crossing the bridge over Bayou St. John, continue about 0.7 miles and park on the right for **Stop 7.**

Continue on Lakeshore Drive – west and after about ¼ mile turn left through the floodgate onto Marconi Ave. Driving south on Marconi, pass the gate/pump structure on the Orleans canal on the right and continue to Robert E. Lee Blvd.

Turn right - west on Robert E. Lee to Fleur de Lis Drive - left on Fleur de Lis

Continue south on Fleur de Lis - 1 block to Hay Place - right on Hay Place.

Continue west on Hay Place to Belaire Dr. - left on Belaire Dr.(17th St. Canal levee breach)

Continue south on Belaire to Spencer Ave. and park for **- Stop 8**

Continue south on Belaire Drive to Harrison Ave. then left (west) on Harrison.

Continue west on Harrison to Marconi (after crossing the Orleans Canal). - right (south) on Marconi.

Continue south on Marconi to just before the I-610 underpass and park for **Stop 9**

Continue south on Marconi (where it becomes Orleans Ave.) to City Park Ave.

If returning to Tulane turn left on Orleans Ave. and continue to Carrollton Ave, then right on Carrollton to return to Tulane.

## The Field Trip

**Stop 1 – Lower 9th Ward**

Stop 1 is in the Lower 9th Ward near the east side of the Industrial Canal. The area is shown in overhead images in Figure 10, before the storm, Figure 11 during the flooding event, and Figure 12 taken in Mid-March, 2006. Figure 13 is a view looking east, into the Lower 9th Ward, taken in the first few days after the storm. Levee/Floodwall failures occurred at two places along the east side of the Industrial Canal. The longer breach (approximately 1,000 feet long) occurred between N. Galvez and N. Roman Streets (Figs. 11, 13, 14 and 15). The shorter breach (about 200 feet-long) occurred just to the south of Florida Avenue (Figs. 11 and 16). Note that Figures 11, 13, and 14 show a barge which came to rest in the Lower 9th Ward, having floated through the breach from the Industrial Canal.

The breaches occurred at about 7:45 AM on August 29, 2005 (although some suggest that the northern breach occurred about an hour earlier), as the storm surge in the canal reached an elevation of about 15 feet above sea level. The top of the floodwall along the canal was supposed to be at an elevation of 14.5 feet above sea level, but due to an error involving the use of the wrong the datum by the U.S. Army Corps of Engineers (discovered in 1985) and to subsidence, the top of the wall was only at an elevation of 12 feet above sea level (ILIT 2006, IPET, June 1, 2006).

All houses and most trees were removed by the incoming water in the areas immediately in front of the breaches (Figs. 11, 12, 13, & 14) and in areas between the breaches the rush of water was forceful enough to lift houses off their foundations and float them around until they collided with other houses and either came to rest or broke apart to form piles of rubble (Fig. 11). The floodwall and underlying sheet pilings were strewn into the first few blocks of the Lower 9th Ward like a ribbon (Figures 14, 15, and 16).

Photographs available on the U.S. Army Corps of Engineers, Interagency Performance Evaluation Task Force (IPET) web site and reproduced in Figure 17, show that along portions of the floodwall that did not fail, water flowing over the top of the floodwall eroded trenches on the protected side of the levee. It is likely that this could have removed enough support on the protected side that the floodwalls and their underlying sheet piling eventually toppled into the protected side of the canal sending a huge surge of water into the Lower 9th Ward.

Figure 18 shows the floodwall between the two breaches on the Industrial Canal where the wall was not breached, but was leaning outward toward the Lower 9th Ward. One can easily see that the top of the levee has dropped down along side of the leaning floodwall. This type of floodwall was an I-wall, one of two designs used in the New Orleans hurricane protection system (Fig. 19).

Although the floodwalls along the Industrial Canal were built in the 1970s, in 1985, the research branch of the Army Corps of Engineers conducted experiments on the I-wall design. They constructed a levee and enclosure in the Atchafalaya Basin (to the southwest of New Orleans) and began filling the area next to the levee and sheet pile floodwall with water. As the water rose against the floodwall, deflections of the floodwall began to occur and a gap opened on the water side of the floodwall which allowed the full hydrostatic force of the water to penetrate to the tip of the sheet piling (Jackson, 1988, Oner and others, 1997). This type of floodwall failure is illustrated in Figure 20. These findings were apparently never communicated to those in the Corps responsible for the design and construction of floodwalls in New Orleans (Marshall, March 14, 2006). The leaning floodwall seen in Figure 18 clearly shows that this also happened on the Industrial Canal floodwall during Hurricane Katrina. The force of the water pushing the wall outward toward the protected side coupled with removal of support by erosion caused by the water pouring over the top of the floodwall was the most likely cause of the catastrophic failures on the east side of the Industrial Canal (Fig. 21).

The Interagency Performance Evaluation Task Force (IPET, 2006) agreed that the main cause of failure here was the result of the surge waters in the Industrial Canal overtopping the floodwall and eroding away the levee on the protected side, but the Independent Levee Investigation Team (ILIT, 2006) suggests another cause. They do agree that erosion of the levee on the protected side could have contributed, but their analysis indicates that the geological conditions present in the subsurface along with the shallow depth to the tip of the sheet pilings resulted in hydraulic piping beneath the sheet pilings which undermined the levee and caused it and the floodwall to collapse. Two layers of highly permeable marsh deposits occur at a shallow depth below the levee (Fig. 21). According to the analysis of ILIT (2006), the added pressure in the canal forced water through these permeable layers and out at the toe of the levee on the protected side, thus removing support for the floodwall and levee.

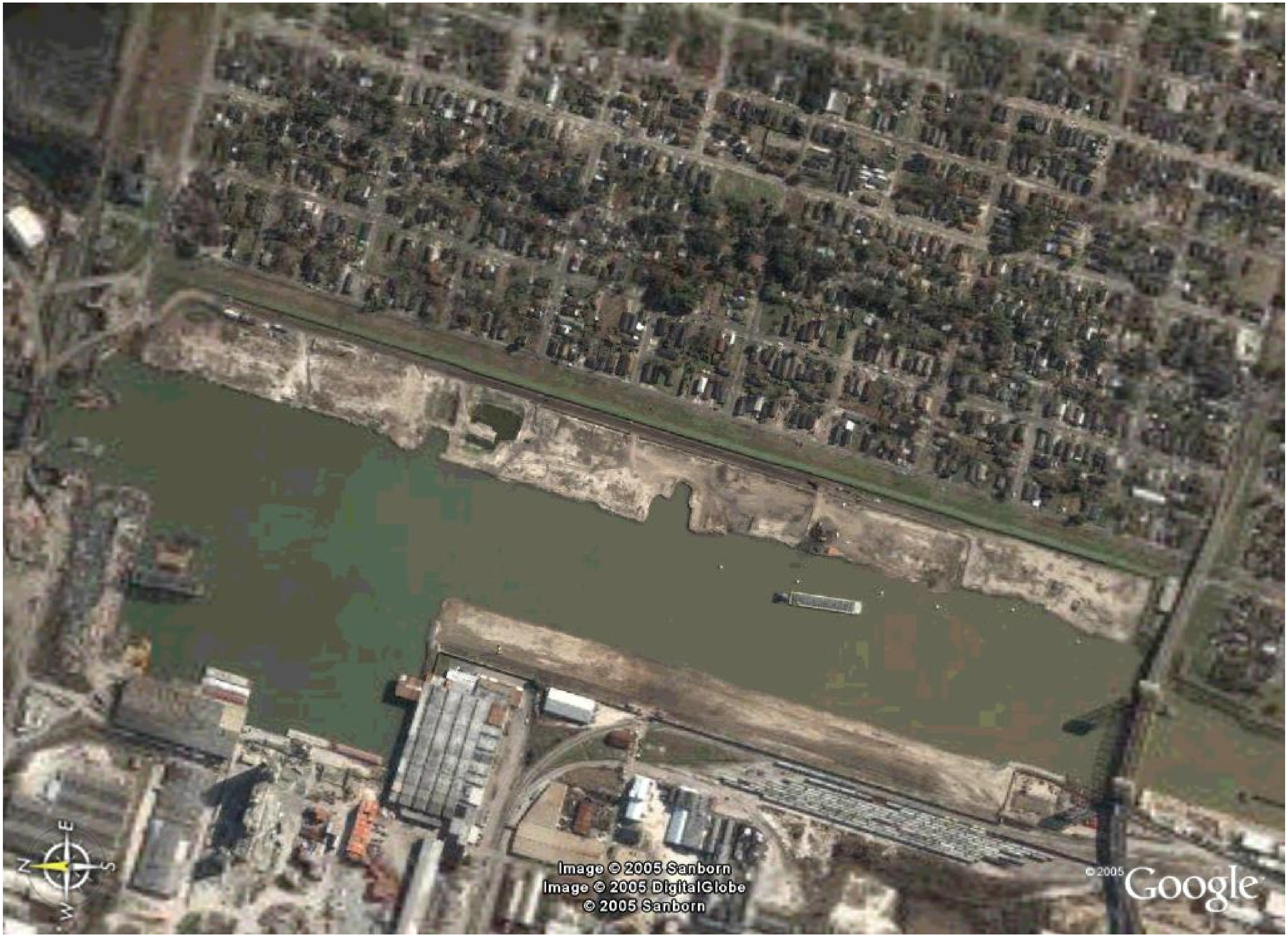



**Figure 10.** Satellite image of the area along the Industrial Canal where the levee was later breached during Hurricane Katrina. (Source - Google Earth)

**Figure 11.** Air photograph of the area where the Industrial Canal Levee was breached to flood the Lower Ninth Ward. Image acquired Sept. 3, 2005 Source: National Oceanic and Atmospheric Administration's National Geodetic Survey, Katrina Images - http://ngs.woc.noaa.gov/katrina/

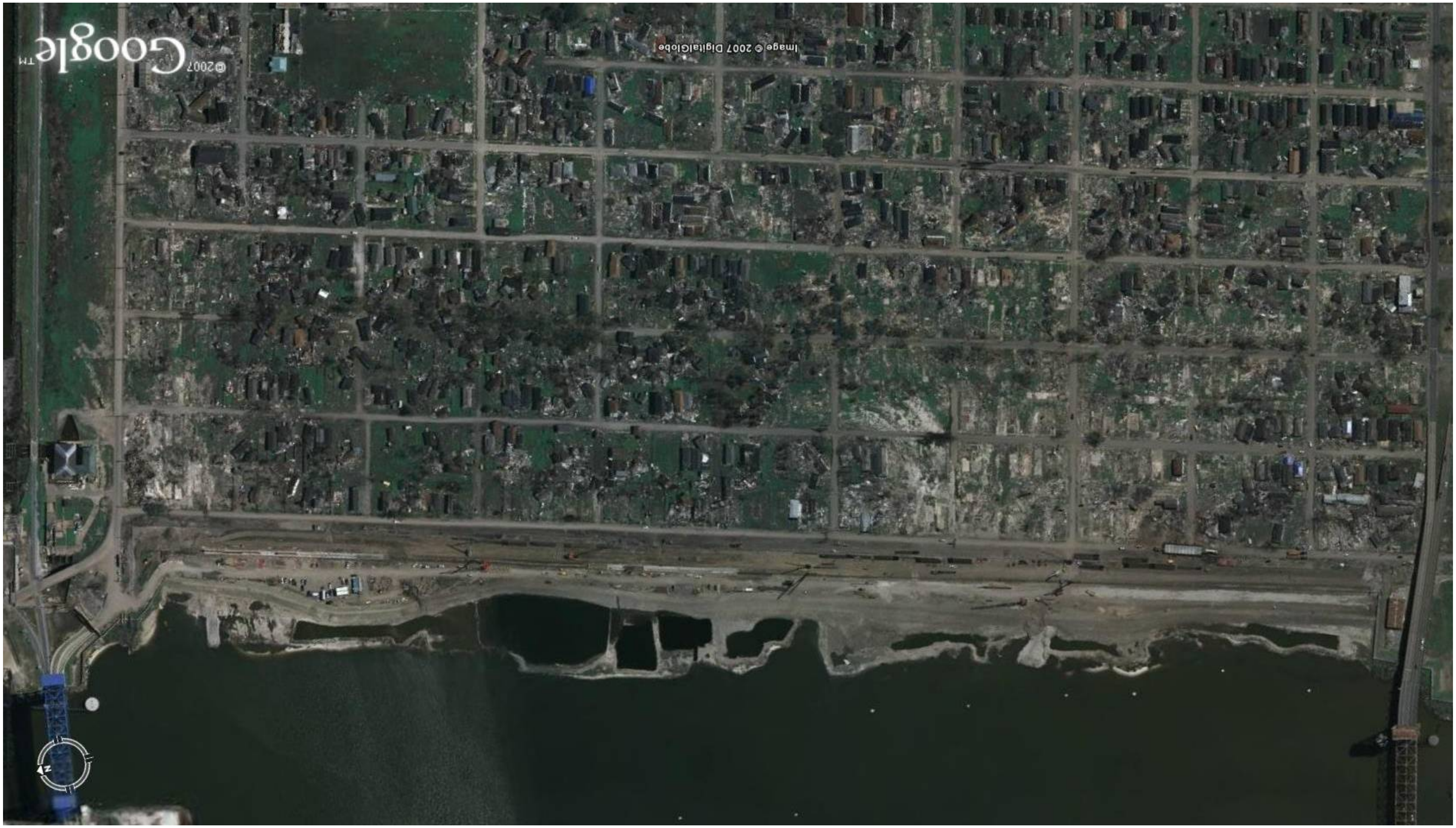



**Figure 12.** Google Earth image of the area where the Industrial Canal Levee was breached to flood the Lower Ninth Ward. Image acquired around mid-March, 2006.

**Figure 13.** The large breach in the Industrial canal that flooded the Lower Ninth Ward could have been caused by a barge crashing through the floodwall during Katrina. Alternatively the barge could have floated in after the levee and floodwall were breached. Note the barge in the photo above. Note also that at the time of this photo water was running out of the Lower Ninth Ward back into the Industrial Canal. (Source - Vincent Laforet, AFP/Getty Images)

**Figure 14.** View of southern breach on the Industrial Canal, looking South. Note the floodwall and sheet piling (brown) strewn through the Lower Ninth Ward neighborhood where all houses were removed by the force of water coming through the breach. Gray deposits on right are breach repair gravels. Note barge near in the center near the top of the photo. Photo by L. Harder - Independent Levee Investigation Team Final Report (2006).

**Figure 15.** Floodwall and sheet piling strewn into Lower 9th Ward at the southern (larger) breach on the Industrial Canal. Photo from U.S. Army Corps of Engineers IPET web site.

**Figure 16.** Aerial view of the north breach on Industrial Canal. Photo by L. Harder - Independent Levee Investigation Team Final Report (2006).

**Figure 17.** Looking North along the floodwall of the Industrial Canal levee showing trenches eroded by water from the Industrial Canal that overtopped the floodwall. Breached section is just beyond the barge and barely discernable in this view. Florida Avenue Bridge (blue) in upper center. Photo from U.S. Army Corps of Engineers IPET web site, taken October 4, 2005.

**Figure 18.** Looking South along the floodwall of the Industrial Canal on the inside of the floodwall between the two breaches showing the floodwall leaning toward the left (east) with a block of the levee next to the floodwall dropped down (near center of picture). Claiborne Ave. Bridge in right center. Photo from U.S. Army Corps of Engineers IPET web site, taken October 4, 2005.

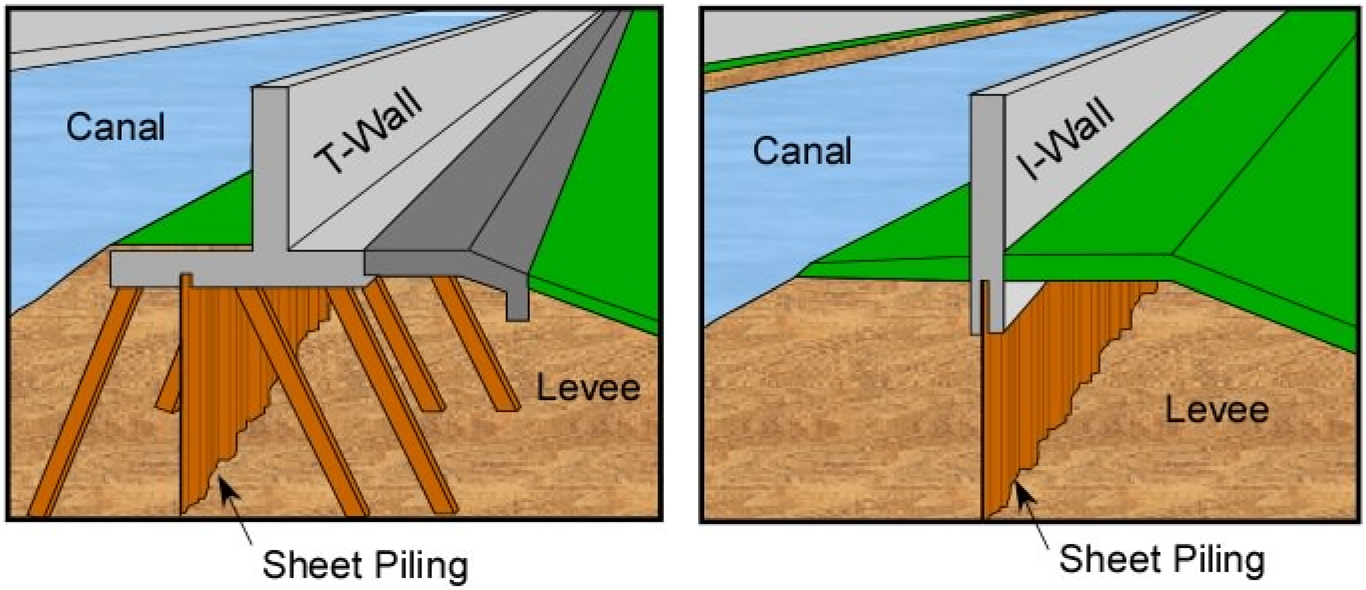



**Figure 19.** Most pre-Katrina floodwalls in New Orleans were built with the I-wall design (right). In repairing failed floodwall sections after Katrina, the T-wall design (left) was used.

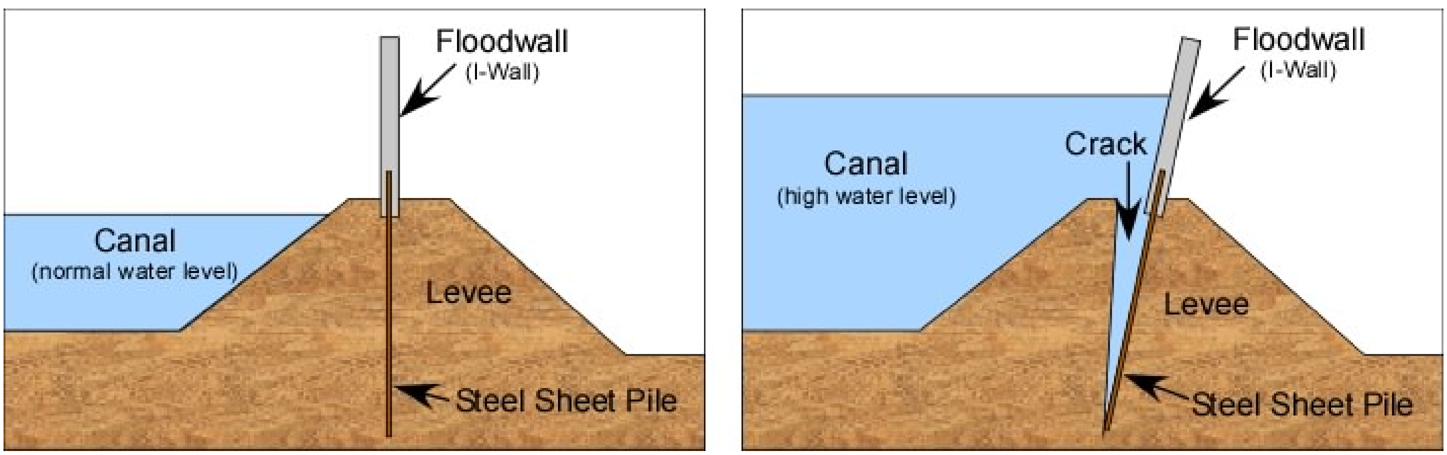



**Figure 20.** Illustration of crack development as water in a canal rises on the floodwall and pushes outward on the floodwall as observed in 1985 experiments by U.S. Army Corps of Engineers.

At Stop 1 in the Lower 9th Ward, one now sees that the entire floodwall between the two bridges (Claiborne to the south and Florida Avenue to the North – the blue colored bridge) has been replaced with a T-wall with a top elevation at 14.5 feet above sea level, the level it was supposed to have attained prior to Katrina. This new floodwall was completed in mid-June, 2006. The original I-wall is still present along the other side of the Industrial Canal as well as to the south and north of the new T-wall. The only improvement made to the levees where the I-walls still exist is concrete armoring has been added to the base of the I-wall to prevent the erosion of the levee should water come over the top of the wall again.

As of April, 2013, 7.5 years after Katrina, rebuilding progress has been very slow in the Lower 9th ward in front of the breaches. Most of the rubble piles have been cleared, all of the damaged cars and trees have been removed, but a few heavily damaged houses and the remains of foundations still can be found throughout the neighborhood. Figure 22 shows a ground view of the Lower 9th Ward destruction as it appeared in December of 2005. The barge that went through the breach was removed near the beginning of March, 2006.

Some of the new construction in the Lower 9th Ward is part of the Make it Right Foundation project, led by actor Brad Pitt (http://www.makeitrightnola.org/). The homes being built by this project are the colorful homes raised well above street level, with odd shaped roofs. The homes are energy efficient and have solar panels for generation and storage of electricity. In order to most efficiently collect the solar energy, the roofs of these homes are tilted at odd angles giving them a distinctive look. So far, about 90 of the 150 planned homes have been constructed in the Lower 9th Ward.

From Stop 1, we will proceed to the north passing through the part of the Lower Ninth Ward between the two levee breaches. Note that in general, homes built on slab foundations were not moved by the force of the flood waters in this part of the neighborhood. Homes built on pier foundations, however, were, in almost all cases lifted off their foundations and floated around the neighborhood. It was notable shortly after the flooding event that debris deposited on the roofs of single story homes indicated that the maximum of depth of the flood water was in excess of the roof line. This contrasts with the standing water line left on the houses, which was at a much lower elevation. At the northern end of the neighborhood, near Florida Avenue, note that nearly all structures were removed from the area to the east of the northern breach.

At Florida Ave., turn left (West) to the floodwall on the Industrial Canal and Stop 2.

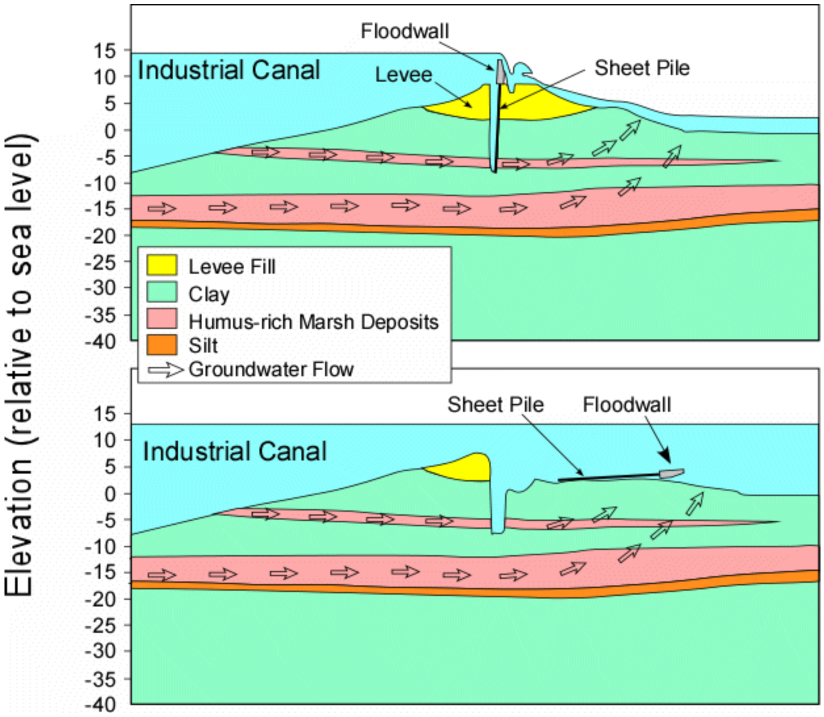



**Figure 21.** Possible failure mechanism at the Industrial Canal Levee breach in near the Lower 9th Ward


**Figure 22.** View of Lower Ninth Ward looking East as it appeared in December, 2005.

**Stop 2 Inside the Industrial Canal Flood Wall**

At Stop 2 we walk through the gate in the chain link fence and over the levee into the Industrial Canal. This is the area of the breach shown in Figure 16. Note the original floodwall, the yellow wall on the canal side of the road is at a lower elevation than the new T-wall floodwall that extends from here to the south toward the white Claiborne Ave. Bridge. Note also that the floodwall on the other side of the canal is still the same I-wall that was present before Katrina and is still at an elevation about 2.5 feet lower than the new T-wall. All of these low spots on the flood protection system are now potential areas where water from the Industrial Canal can enter the city on both sides of the canal, just as it did during Hurricanes Betsy in 1965 and Katrina in 2005.

Hurricane Gustav in September of 2008 showed just how vulnerable this area is to storm surge. Gustav made landfall as a Category 2 hurricane about 65 miles southwest of here. Nevertheless, it produced storm surge in the Industrial Canal that reached near the top of the old floodwall,(Fig. 23) and television news coverage showed waves overtopping the floodwall on the west side near the Claiborne Avenue Bridge. Debris strand lines from this event can still be observed between the top of levee here and the new T-wall.

This illustrates the still present vulnerability that exists all along the Industrial Canal so long as storm surge can enter the canal from the Mississippi Gulf Outlet, Intracoastal Waterway, and Lake Pontchartrain (Figs. 1 & 9). To reduce the vulnerability, the U. S. Army Corps of Engineers has recently finished building a barrier wall with navigation flood gates (that will close during an approaching hurricane) as shown in Figures 1 and 24. The navigation gates are installed on the Intracoastal Waterway and Bayou Bienvenue to allow ship and boat traffic through, and the barrier across the marsh and is built to an elevation of 24 to 26 feet above sea-level and is designed to protect against storm surge from a storm that has a 1% chance of occurring each year (the so-called 100 year storm).The cost of this project was about $1.3 billion, and is part of the $14.5 billion project to protect against the 1% event. In addition a navigation gate structure has been completed at the entrance to the Industrial Canal at Lake Pontchartrain (Fig. 1).

**Figure 23.** View of the Industrial Canal from the Claiborne Ave. Bridge looking North toward Stop 7 with the Florida Ave. Bridge (blue bridge) on the horizon. Photo as taken on the morning of Sept. 1, 2008 during the passage of Hurricane Gustav. Note the elevation drop from the post-Katrina floodwall (on the right) to the original floodwall to the left. Photo from U.S. Army Corps of Engineers.

From here will travel back on Florida Avenue going East and stop a few blocks down for Stop 3 at the intersection of Florida Ave. and Caffin Ave.

**Stop 3 The Cypress Triangle**

After climbing stairs to a small platform built over the top a sheet pile floodwall, one has a view of the Cypress Triangle. This area was once a thriving Cypress forest and swamp, but it is now completely flooded and only shows a few Cypress stumps. At the northern edge of the Triangle is Bayou Bienvenue, one of the many bayous that provided early settlers access to New Orleans from the Gulf of Mexico. The swamp and forest, once thriving with wild life, began to decline in the early 1960s as the Army Corps of Engineers, with the strong backing of business leaders and the Port of New Orleans, excavated the Mississippi River – Gulf Outlet (MR-GO) as a shortcut for ship traffic from the Gulf of Mexico into the Industrial Canal and the Port of New Orleans. The MR-GO also provided a more direct path for salt water to reach the freshwater swamp resulting in the death of the cypress forest and extensive erosion. This was exacerbated in 1965 when Hurricane Betsy, a Category 3 hurricane passed by to the west and pushed storm surge from the Gulf into the swamp.

**Figure 24**. The surge barrier and navigation gates across the Intracoastal Waterway and MR-GO (see location in Figure 1), designed to prevent storm surge from entering the Industrial Canal.

Such destruction of Cypress swamps has been common all along the Louisiana Coast as canals were dredged for both oil exploration and navigation. While not the only cause of coastal erosion (natural subsidence, natural faulting, and lack of sediment input form the now leveed Mississippi River are substantial contributors as well), the contribution from canal excavation is certainly evident here.

Current plans call for restoration of the Cypress Triangle by adding sediment dredged from the Mississippi River, adding fresh water from treated sewage, planting marsh-building plants, and replanting the cypress forest. The proposed gate structure on the Intracoastal Waterway and MR-GO will also aid in the rebuilding process by keeping storm surge from future hurricanes out of the Cypress Triangle.

We will next proceed back along Florida Ave, heading west and cross the Industrial canal on the Florida Avenue bridge. After crossing the bridge, note the concrete armoring that has been added to the top of the levee to prevent erosion should the old I-wall be overtopped in the future.

Before reaching the underpass, turn right on France Road and then left after crossing the railroad tracks. Along here (point A in Figure 1), look off to the right to view deposits of white shells that were emplaced during the breach of a levee constructed mostly of shells on the west side of the Industrial Canal (one of two breaches on this side). Figure 25 is a Google Earth Image of these deposits.

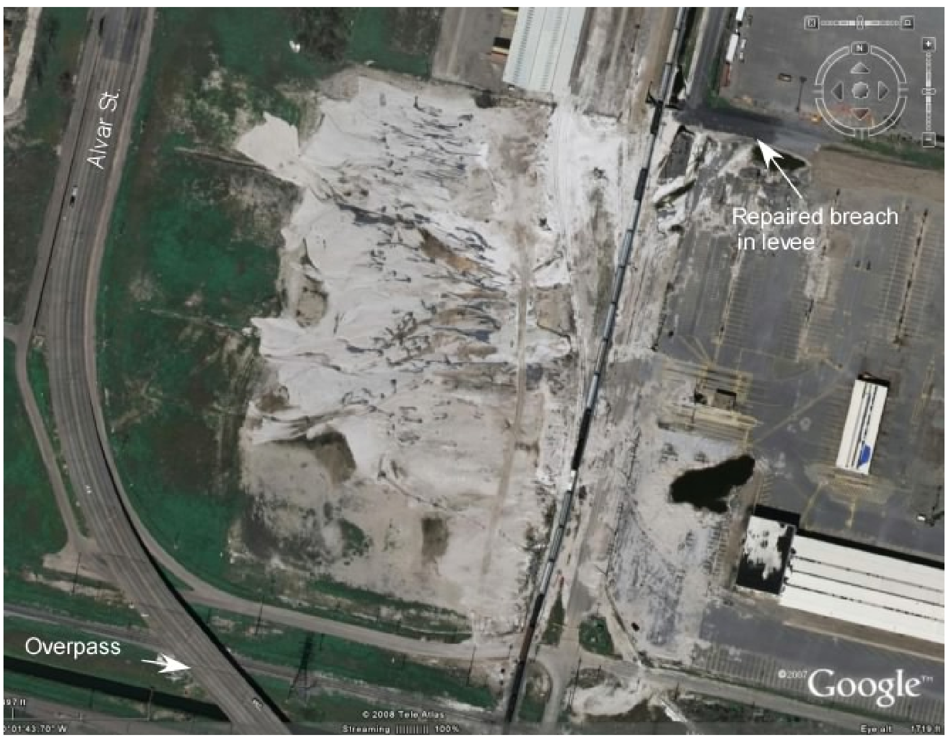



**Figure 25.** Google Earth Image (acquired around May, 2006) of area near overpass to Alvar St. (point A in Figure 1) showing location of breached levee and deposits of shells (white material in center of image) that resulted from the breach. Industrial Canal is off the image to the right (east).

Continue on the road curving to the right merging onto Alvar St. Continue on Alvar St. passing under the High Rise Bridge and turn left on Chef Menteur Hwy (Hwy 90, West). Chef Menteur Hwy becomes Gentilly Blvd. after passing beneath the railroad underpass.

Gentilly Blvd. runs along the Gentilly Ridge, one of the distributary channels of the St. Bernard Delta complex (Figs. 5 & 6). Despite the fact that the Gentilly Ridge is a higher area of the City, water did cover the ridge during Katrina's flood event. Still, the homes along Gentilly Blvd. were built high enough that most did not flood. The floodwaters killed most lawn grasses in New Orleans, thus, shortly after the storm one could see a line separating dead lawn grass (covered by floodwaters) from healthy lawn grasses that remained above the water.

Continue west along Gentilly Blvd. to Elysian Fields Ave. and turn right (north) on Elysian Fields. As we continue to the north the elevation again drops and you will note the standing water line, where it is still present, rises as we continue to the north.

Upon reaching Mirabeau Ave., turn left and head west. At the corner of Mirabeau and St. Anthony St., the church to right (northwest corner) shows the standing water line on the wall facing St. Anthony St. and on the windows facing Mirabeau Ave. The metal church steeple also is rusted below this water line. The water line is about 7 feet above the level of the parking lot (Fig. 26). Again this water line is at an elevation of about 3 feet above sea-level. Ahead you can see the bridge over the London Ave. Canal, one of the three drainage canals that drain this part of New Orleans. Just before the bridge we will turn right onto Warrington Drive, and proceed northward, stopping in the second block north of Mirabeau were we will park for Stop 4.


**Figure 26**. Church at the corner of St. Anthony and Mirabeau showing the standing water line and rusted church steeple.

**Stop 4 – Southern Breach London Ave. Canal**

The London Avenue canal, along with the 17$^{th}$ St. Canal and Orleans Canal (Figs. 1, 5, & 9), are drainage canals that have existed since the mid 1800s. Their purpose is to drain rainwater out of the low lying areas of New Orleans. Unlike other drainage canals throughout the New Orleans area which are below street level, these three canals contain water at the level of Lake Pontchartrain (1 – 2 feet above sea level). Note that the three canals begin near the Metairie and Gentilly Ridges at the their southern end, where pump stations lift the water from lower areas to the south where the drainage is through canals below street level or underground drainage pipes. Note that the canals are shown on the 1878 map of New Orleans (Figure 7). In the 1915, A. Baldwin Wood invented giant screw pumps that were installed at the southern ends of these canals. Similar pumps were later installed along the sides of the canals so that swampy areas could be drained to become habitable land.

After Hurricane Betsy (1965) when plans for the hurricane protection system were being made, the Army Corps of Engineers proposed that movable gates be placed near Lake Pontchartrain to keep storm surge from the Lake from entering into the canals. This would also have required that the pumps be moved to the Lake so that rainwater could still be pumped out of the city during a hurricane if the gates were closed. The New Orleans Levee and Sewerage and Water Boards objected to these plans because they would not have control over flooding scenarios (Braun and Vartabedian, 2005). After these boards successfully lobbied Congress against the floodgate plan, the Corps developed a plan to raise the levees on the drainage canals. Simply raising the levees was deemed impossible because raising levees also requires widening them. Because of right-away concerns along the canal levees, the plan became one of increasing their height by adding floodwalls. This change in plans obviously became a fatal mistake, but one that cannot be blamed entirely on the Corps of Engineers.

Stop 4 is at Mirabeau Avenue and the London Avenue Canal. According to the IPET Final Report (IPET, 2006), the breach at this site occurred between 7:00 and 8:00 AM on August 29, when winds were blowing out of the northeast pushing water from Lake Pontchartrain into the drainage canals. Figure 25 shows the area of the breach before Katrina and Figure 26 shows approximately the same view on August 31, 2005 when the breach was still active. A house in the center of the breach was moved out onto Warrington Drive (this house was demolished on about March 10, 2006). In Figure 26, natural gas can be seen bubbling up through the flood waters at the location of the now displaced house. The breach here is about 200 feet wide and has now been replaced by a T-wall. (Construction of the T-wall was completed in October, 2006).

Also noticeable by comparison of Figures 27 and 28 is that before Katrina a tree stood at the toe of the levee adjacent to the part that breached. That tree is laying on its side in the image taken on August 31, 2005 (Fig. 28). It is notable that many trees in the New Orleans area were blown over by the hurricane force winds on the morning of August 29 and when they are blown over they bring up a large root ball leaving a large hole in the ground. If this tree was one of those that were blown over, it is entirely possible that because of its location at the toe of the levee, it could have destabilized the levee and been responsible for the breach. Unfortunately, there were no eye-witnesses to the levee breach at this location, so it is not known if the tree was blown over prior to the breach or if it was simply knocked down during the breach.

After the flood waters were pumped out, large deposits of sand were seen throughout the neighborhood. As of March 1, 2006 most of the sand had been removed from in front of the houses, and the back yards were cleared by January, 2007. Fig. 29 shows the sand deposits as they appeared before removal.

The sand in these deposits did not originate from the canal water or lake water that was pushed into the canal during Katrina. Instead, it originated from beneath the levee. A geologic cross-section constructed from data on soil borings (done in 1986) (U.S. Army Corps of Engineers, 1989) from the banks of the London Avenue Canal is shown Figure 30. The cross-sections clearly show the presence of sand at a depth beginning between 10 and 15 feet below sea level. This sand is the same Pine Island beach sand that was deposited in the area between 4,000 and 5,000 years ago as shown in Figures. 2, 5 and 6.

Sand is a highly permeable material. This means that water can easily be transported between the sand grains, especially when the weight of the overlying water is increased due to the added height of the water column during a storm surge. This increases the pressure and could force the water through the pore spaces in the sand and back up to the surface on the other side of the levee. If enough flow takes place, the sand will be picked up by the flowing groundwater and eventually form an underground channel. This would undermine the levee and cause it to collapse. The principle is illustrated in Figure 31 with a simple thought experiment. The underflow (called seepage or siphoning) is the apparent cause of the collapse at this section of the London Ave. Canal levee and floodwall. The "as built" design specifications indicate that the sheet pilings (which should form an impermeable barrier to pressure induced flow in the sand) were placed to a depth of 14 feet below sea level (U.S. Army Corps of Engineers, 1994), one can see from the cross section in Fig. 32, that the water still has a path back to the surface if it flows as groundwater beneath the sheet pilings. Note that in order to prevent such siphoning, the sheet pilings would need to be driven to a depth of about 50 feet below sea-level where they would penetrate a layer of clay. Clay, because the individual mineral grains stick together and thus reduce pore space and interconnection between pores, is much less permeable than is sand.

There is no evidence that the water in the canal overtopped the floodwall built at the top of the levee in this area. Evidence to be discussed at Stops 5 and 7 show that the maximum level of water during the surge was about 3 feet below the top of the floodwall. The floodwall in this area is about 12.5 feet above sea-level, although it was supposed to have been at 14.5 feet elevation.

At stop 4 we will be able to walk up Warrington onto the levee and view the new T-wall built to replace the I-wall that failed on August 29, 2005. In some places we can still observe the sand deposits and cross bedding within the sand. Sand filled many of the houses, as well as the cars that were deposited here along with the sand (most was removed as of mid-May, 2006).

Figure 33 shows our map of the extent of the sand that was scoured from the bottom of the London Ave. Canal and the blowout hole beneath the levee to be deposited throughout the neighborhood. The distribution and thickness of the actual deposit was controlled by current velocity and barriers such as houses, fences, and hedges. For more information on the sand deposits at this locality, see Nelson and Leclair (2006).

Our estimate of the volume of sand deposited in the neighborhood is about 932,000 $ft^3$. Such a volume would cover a football field, from end to end (including the end zones) with over 16 feet of sand. Engineers working on the breach repair reported that they had to dig to a depth of 30 feet below sea level to completely remove gravel and sand bags used to plug the breach in the first few days after Katrina. A conservative estimate of the volume of this hole is about 500,000 $ft^3$. This only accounts for about 50% of the volume of sand found in the neighborhood, and implies that the canal bottom, both upstream and downstream from the breach, was scoured to an unknown depth. This raises questions about the stability of the levee/floodwall system outside the breach area if the canal bottom is now in permeable sand in these areas.

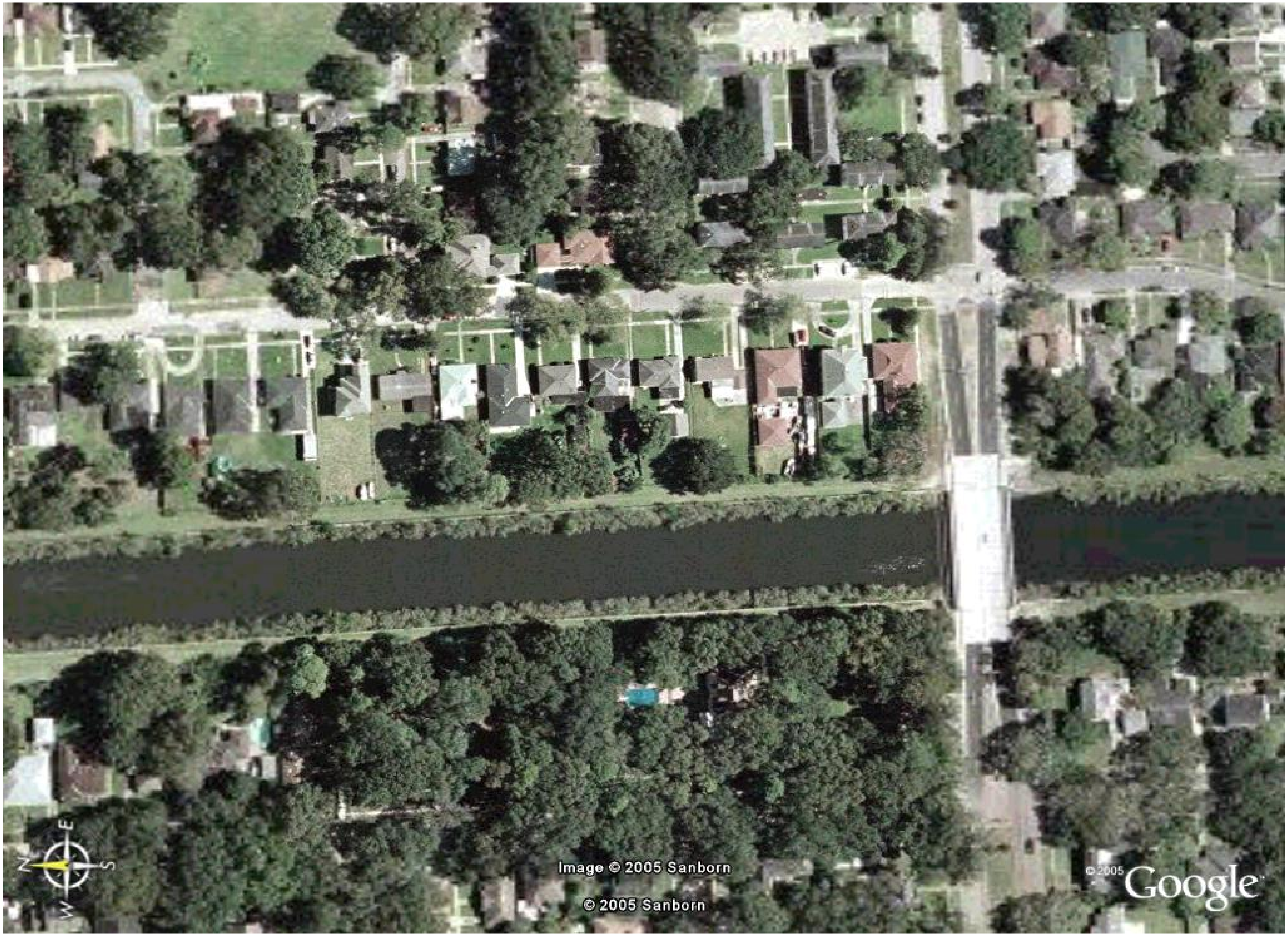



**Figure 27.** Satellite image of the area along the London Avenue Canal near Mirabeau Ave. and Warrington Drive (Stop 4), where the levee was later breached during Hurricane Katrina. (Source - Google Earth)

**Figure 28.** Air photograph of the area where the London Avenue Canal levee was breached near Mirabeau Ave. and Warrington Drive (Stop 4). Image acquired Aug. 31, 2005. Source: National Oceanic and Atmospheric Administration's National Geodetic Survey, Katrina Images - http://ngs.woc.noaa.gov/katrina/


a b c **d**

**Figure 29**. Sand deposits near the south breach of the London Avenue canal. (a) sand ridges deposited in the wake of houses as the currents flowed down the driveways between the houses. (b) Sand deposits that buried two cars in front of house on Warrington Drive. (c) Ridges of sand filling the back yards of houses along Warrington Drive, just north of the breach. As of March 1, 2006, most of the sand in the front yards had been removed and as of mid January, 2007 most of the sand in the backyards had been removed.(d) one of the cars buried by sand in (b) during excavation.

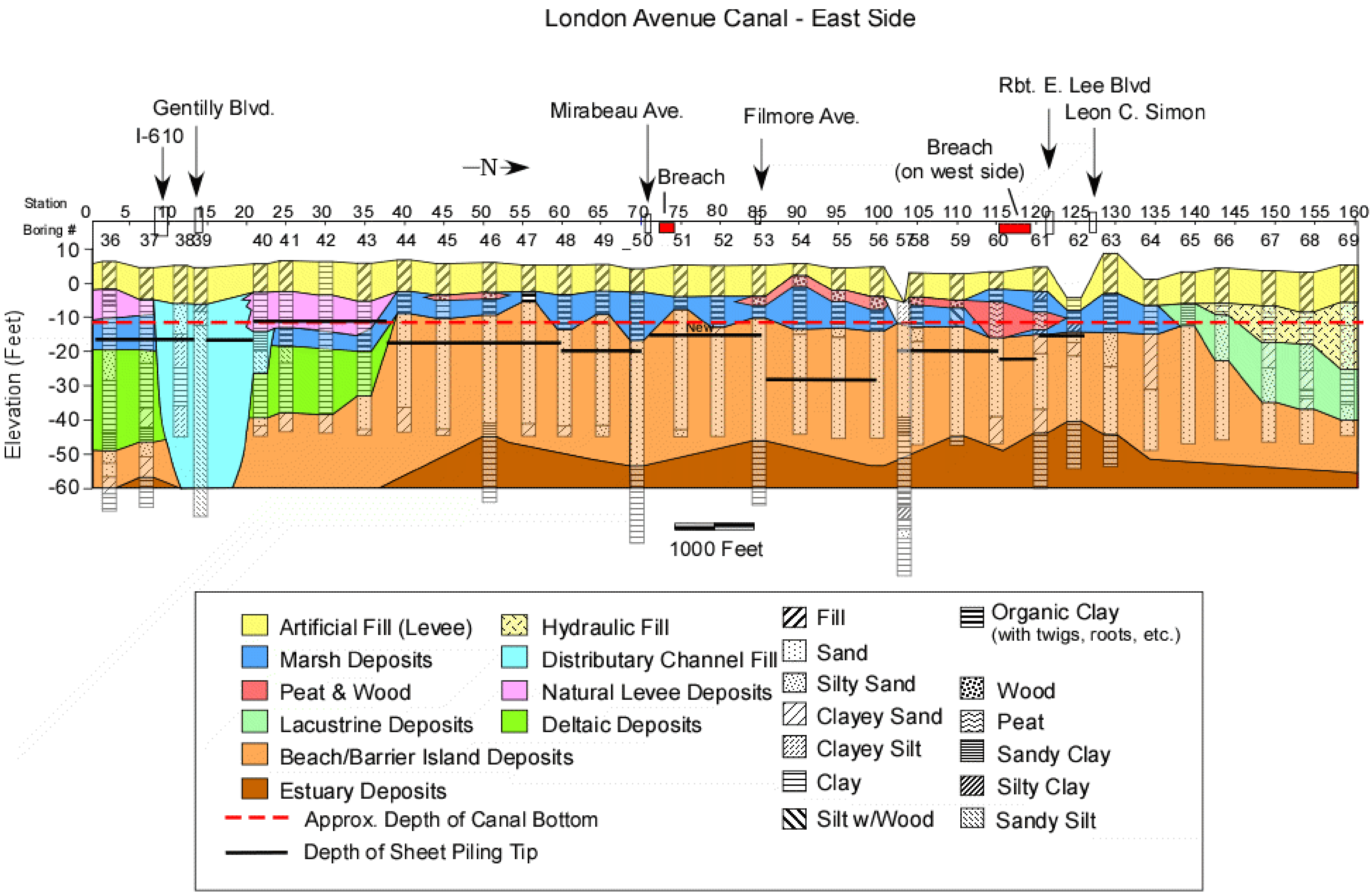



**Figure 30**. Geological cross-section along the east side of the London Avenue Canal constructed from data in U.S. Army Corps of Engineers (1989).

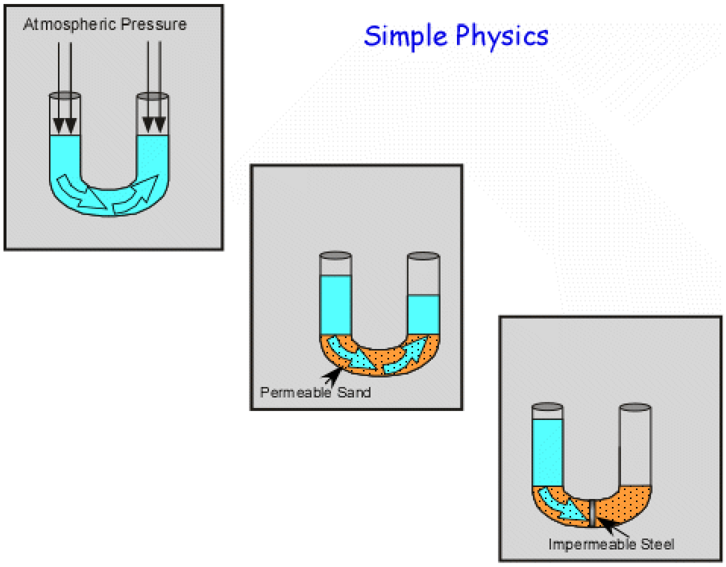



**Figure 31.** A simple thought experiment illustrates the principle of hydrostatic pressure by imagining a U-shaped glass tube. The water levels in each side of the tube rise to the same level because both sides of the tube are subject to the same pressure (atmospheric pressure). If a permeable material like sand is placed in the bottom of the tube and water is poured into one side, the water will find its way through the intricate pathways between the sand grains and will eventually, although not instantaneously rise to the same level on the other side of the tube. If an impermeable barrier is placed in the sand in the bottom of the tube, then the water will not get from one side to the other.

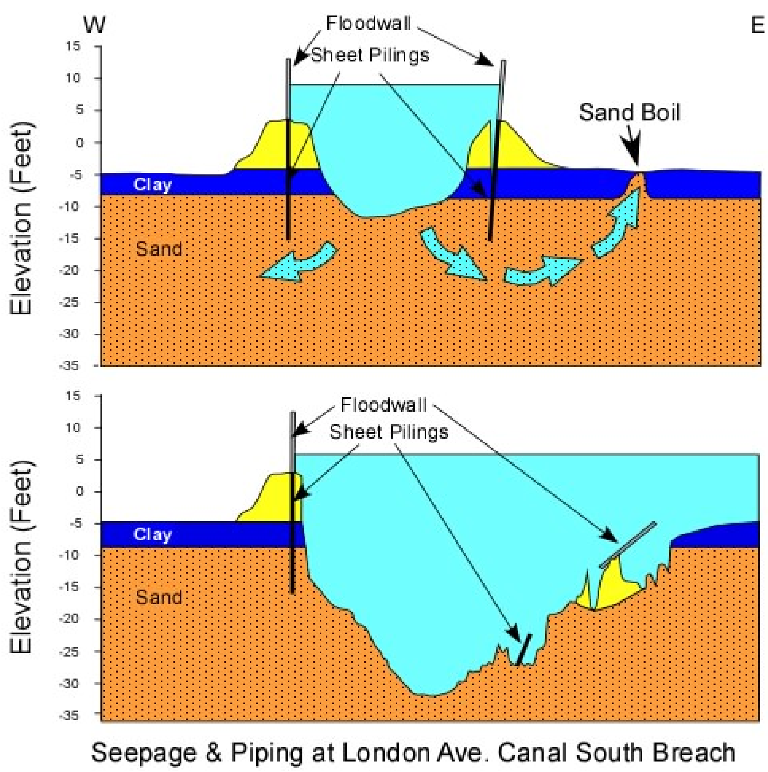



**Figure 32**. Geological cross section across the London Ave. Canal based on borings 16 and 51 (Figs. 29 and 36), shown at time of estimated high water during Katrina's storm surge. The sands form a permeable layer through which groundwater originating in the canal can penetrate and move below the sheet pilings and up to the surface (top diagram), eventually undermining the levee and causing a blowout completely removing a section of levee and carrying sand into the neighborhood. The shape of the canal bottom is based on depth soundings undertaken by the U.S. Army Corps of Engineers on September 5, 2005.

The repair operation has only been done in the area of the breach. The operation involved digging out the material used in the initial emergency repair, filling it with clay and construction a T-wall to replace the missing I-wall. Fortunately, the Corps of Engineers has now completed removable floodgates near the mouths of the London Ave, Orleans, and 17$^{th}$ St. canals near Lake Pontchartrain. These floodgates are closed in the event of a hurricane and prevent storm surge from reaching onto the floodwalls in the canals. If the gates are closed, however, the pumps at the southern end of the canals cannot be used to pump rainwater out of the city. Thus, the Corps has built pumping stations at the Lake (where they should have been built in the first place), but full pumping capacity is not yet available Still rainwater flooding is better than having Lake Pontchartrain drain into the city.

After leaving Stop 4, we will then wind our way around Gentilly looking at the damage and water marks eventually ending up at Stop 5 on Robert E. Lee Blvd. and the London Avenue Canal at Pratt Drive.


**Figure 33.** Preliminary map of sand deposits (by S. A. Nelson) from the Mirabeau Ave. breach on the London Ave. Canal. Underlying image is a composite from Google Earth.

## Stop 5 – Northern Breach London Ave. Canal

Stop 5 is on Pratt Drive near the intersection with Robert E. Lee Blvd. where the London Avenue Canal levee was breached on the west side of the canal. The estimated chronology determined by IPET (2006) suggests that this breach occurred sometime before 9:00 AM on August 29, 2005. Figure 34 shows an image of this area before Katrina. Figure 35 shows approximately the same area in an image taken on August 31, 2005 after the breach occurred and before the floodwaters had been pumped out.

No houses on Pratt Drive were removed by the breach, although the ones immediately in front of the breach were highly eroded and filled with sand. Most have been demolished in the years since the storm. The section of the I-wall that failed here was about 450 feet long and has been completely replaced with a new T-wall. On the east side of the canal immediately across from here, the I-wall was in a state of incipient failure, leaning by about 5$^{o}$ away from the canal. It did not fail during Katrina, but it too has been replaced by a T-wall.

A geologic cross section of the west side of the levee is shown in Figure 36. Note that the conditions beneath the surface are similar to those at the Mirabeau Ave. breach, with a sand layer about 12 feet below sea-level. Here a peat layer is also observed. Peat is organic matter (vegetation that is in the process of decay). It represents material accumulated in swampy areas and indicates that this area was a swamp in the not too distant past. Peat is very porous and has the additional property that it shrinks when it is dried out and expands when water is added. The presence of peat can make for very unstable soil conditions.

Note in Figures 34 and 35 that there is abundant vegetation along the banks of the canal inside the floodwalls. During the surge event in the canal, this vegetation trapped debris flowing in the canal and the height of this trapped debris in the vegetation could be used to estimate water level. Such evidence observed shortly after the storm indicates that the water level in the canal was no higher than about 3 feet from the top of the floodwall. Note also in Figure 35 how the vegetation along the bank of the failed floodwall shows a distinct edge marking the pre-failure position of the floodwall. During the failure, the floodwall slid away to the west as a result of the water pressure against the floodwall and sheet pilings.

Although the "as built" design documents (U.S. Army Corps of Engineers, 1994) show that the depth of the sheet pilings were at 14 feet below sea-level, water still had access to the peat layer and thus the peat layer could have played a role in the collapse of the levee. Another phenomenon that was observed here was that of ground heave in the area of collapse. Water, and perhaps expanding peat, apparently pushed up the levee and land surface on the west side of the canal prior to collapse of the levee. This is illustrated in Figures 37 and 38. Although the clubhouse shown in Figure 37 has been removed during the repair of the levee, the house (with the mispositioned air conditioner compressor) is the 5$^{th}$ house south of Robert E. Lee Blvd. on Pratt Drive (this house was demolished in early November, 2006).

After the water was drained from the area, deposits of sand along with blocks of peat were observed to have filled the street and the backyards of houses along Pratt Drive (Figs. 39 and 40). The sand deposits were similar to the ones observed at the Mirabeau Ave. breach, but also contain blocks of peat as expected from the geologic cross section shown in Figure 36. The sand was not as extensive as the deposits at the southern Mirabeau breach, only reaching a thickness of about 3 feet, and only filling the street in front of the breach, but not extending into the back yards of houses on the other side of the street.

From here we will walk up onto the levee and observe the newly constructed T-wall, then walk along the top of the levee going north toward Robert E. Lee Blvd. Keep an eye on the height of the floodwall. Just before reaching the bridge, notice that the height of the floodwall drops by about 2 feet to the bridge abutment and bridge. This drop in elevation of the floodwall height is clearly a problem, as it provides a hole in the flood protection system. Prior to Katrina, the bridge and abutment where scheduled to be raised to form a sealed bridge. This illustrates how the hurricane protection system, began in 1966, after Hurricane Betsy, had not yet been completed in the 29 years since the project began.

Looking across the canal one can see where the distressed floodwall has also been replaced by T-wall. Interesting here, is the fact the low bridge abutment on the other side was replaced in order to tie in the new T-wall, but it was replaced at the same elevation as the pre-existing bridge abutment that was too low to begin with!

Note that the levee to the north of the bridge does not have a floodwall. Although some parts of that levee did have a pre-Katrina elevation nearly as high as the floodwall to the south, the section immediately next to the bridge was at an elevation equal the bottom of the bridge. Although the levee has been raised in the years since Katrina, it is still lower than the top of the floodwall to the south. Despite the fact that the bridge, and bridge abutments, and the levee north of the bridge are low here, there was no evidence that floodwaters even came over the top of the bridge, thus further emphasizing the point that the floodwalls along the London Avenue canal were not overtopped, but failed well before reaching the load they were supposedly designed to hold back.

From the south side of the bridge, if one looks down to the right elevation markings can be seen painted on the old floodwall. An Army Corps of Engineers study, post-Katrina, determined that the "safe water level" in this canal is 5 feet above sea-level. That elevation is barely on the floodwall, indicating that the Corps does not put much trust in the stability of the original floodwalls. To mitigate this problem, the Corps has recently driven sheet pile along the inner banks of the canal next to the floodwall on both sides of the canal.

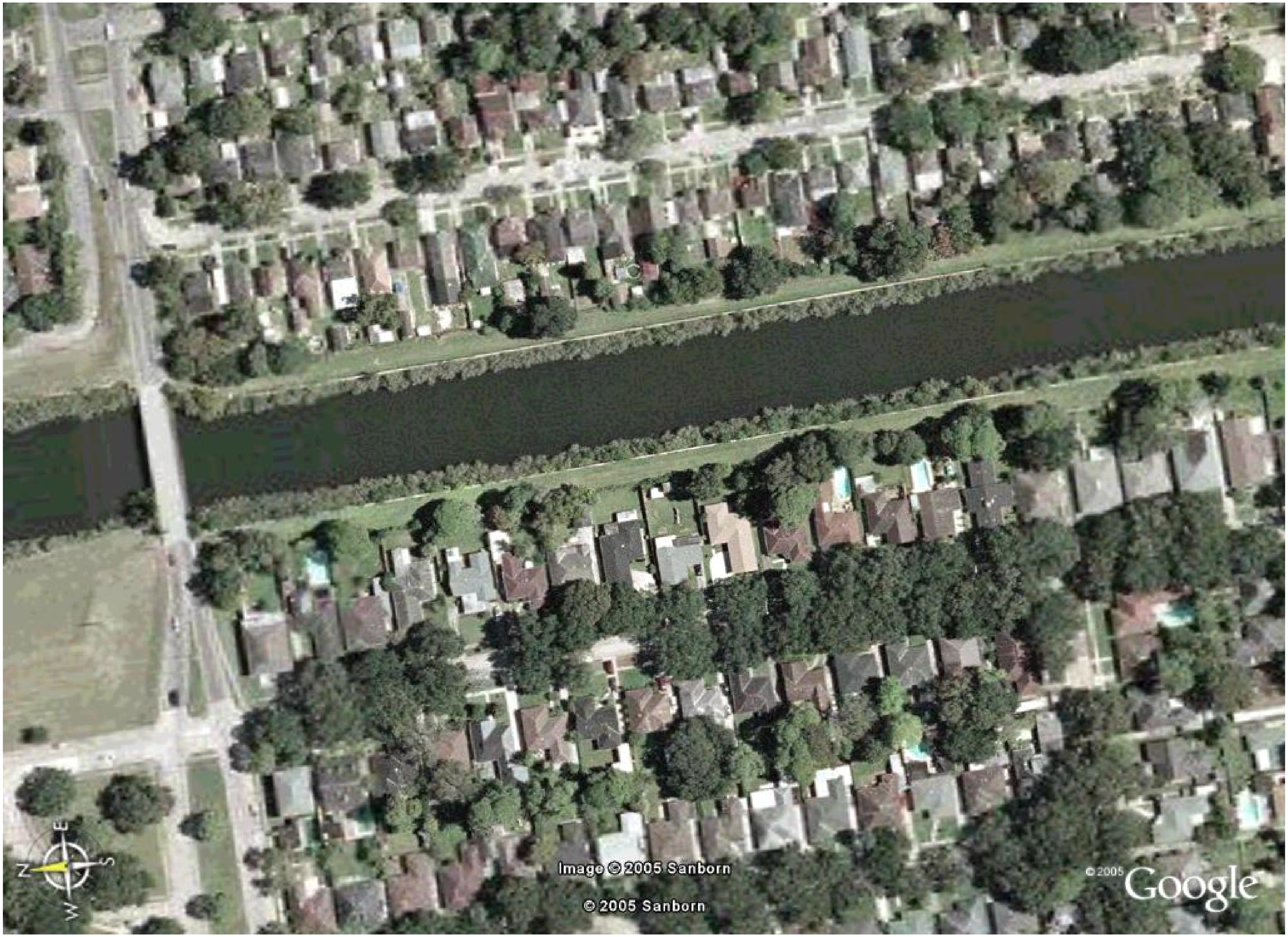



**Figure 34.** Satellite image of the area along the London Avenue Canal near Robert E. Lee Blvd. and Pratt Drive (Stop 5), where the levee was later breached during Hurricane Katrina. (Source - Google Earth)

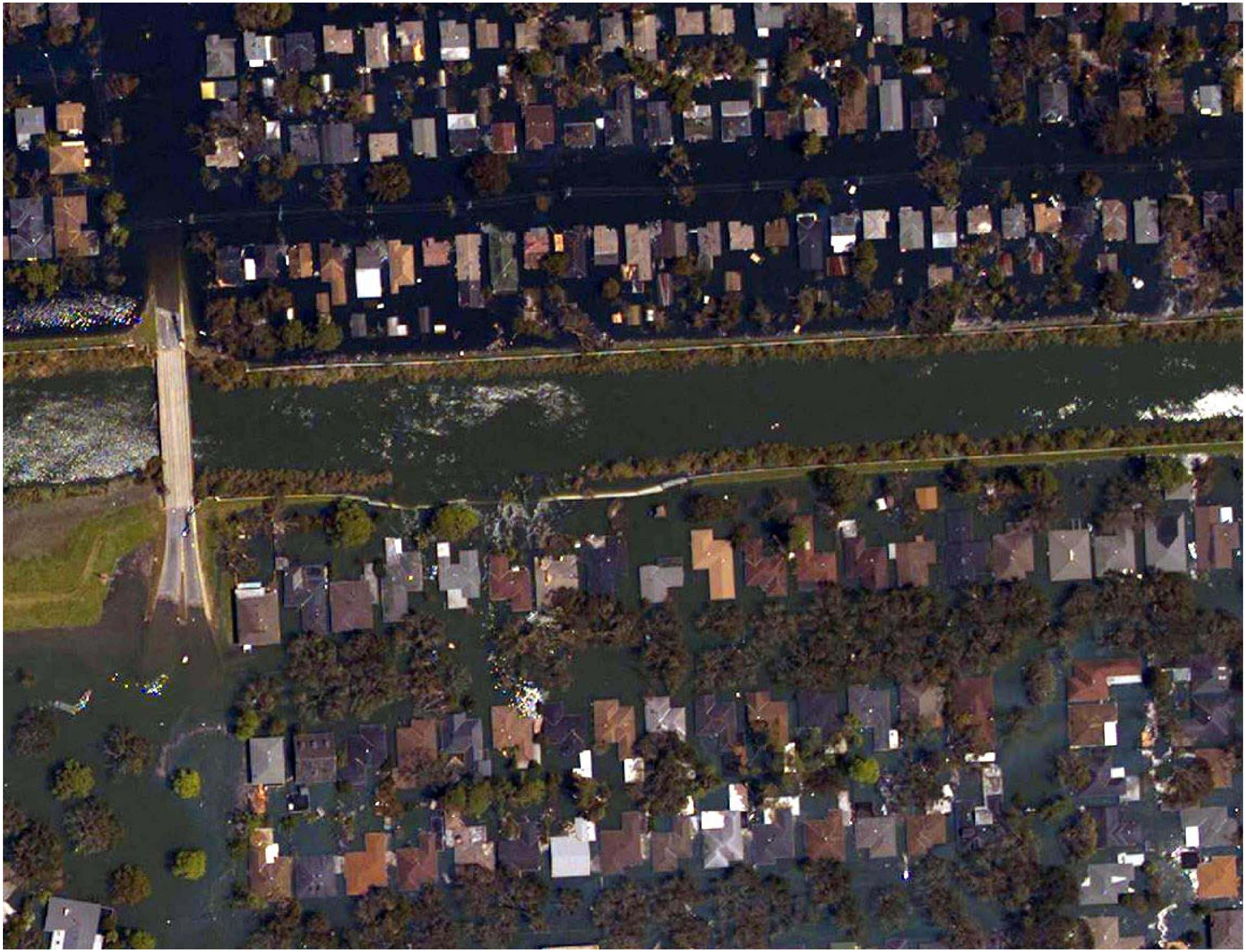


**Figure 35.** Air photograph of the area where the London Avenue Canal levee was breached near Robert E. Lee Ave. and Pratt Drive (Stop 5). Drive. Image acquired Aug. 31, 2005. Source: National Oceanic and Atmospheric Administration's National Geodetic Survey, Katrina Images - http://ngs.woc.noaa.gov/katrina/

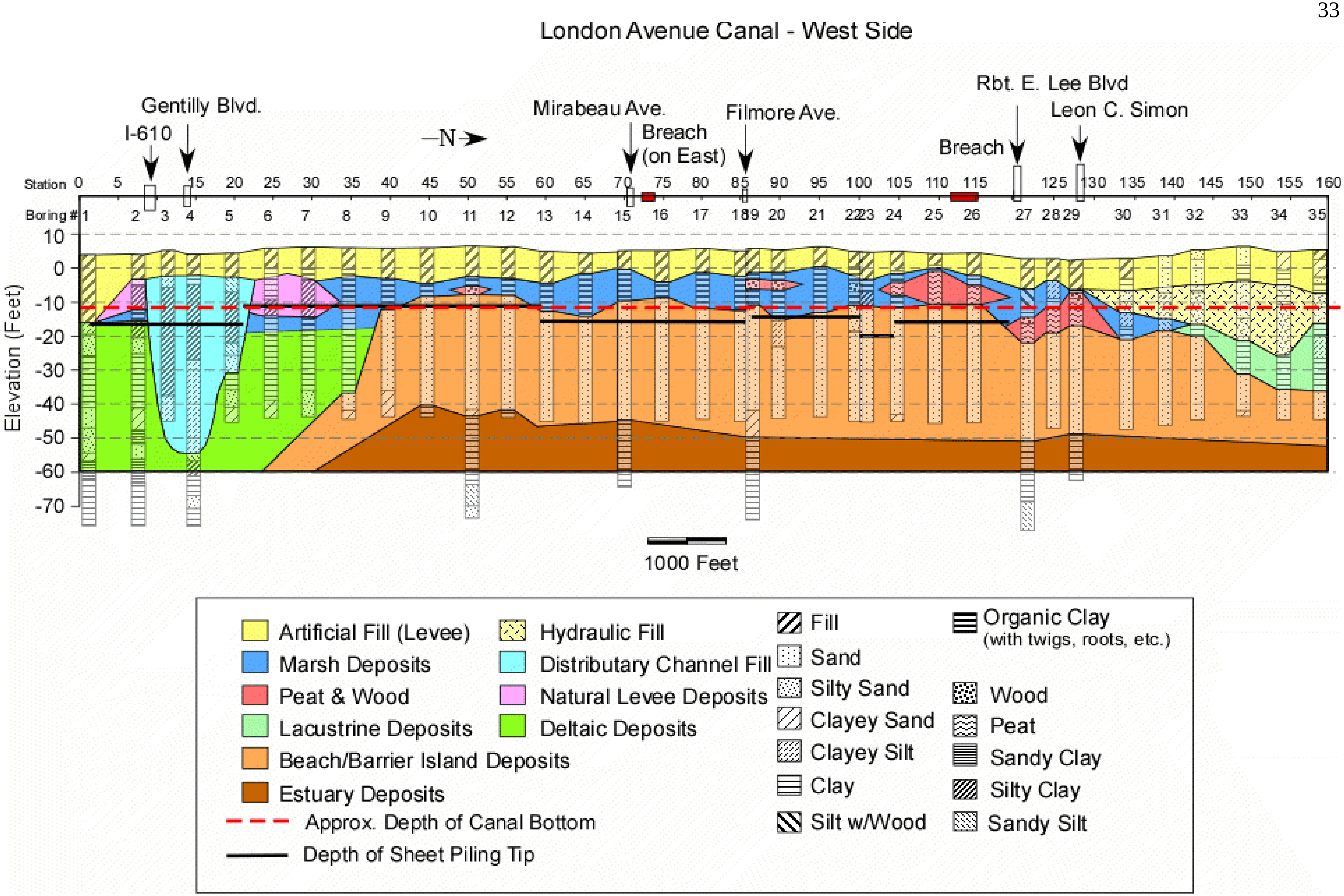



**Figure 36**. Geological cross-section along the west side of the London Avenue Canal constructed from data in U.S. Army Corps of Engineers (1989).

**Figure 37.** Child's clubhouse behind the Cantrell home on Pratt Drive uplifted along the west side of the London Avenue Canal near the breach (Stop 5). Note the fractures beneath and in front of (right side in photo) the clubhouse. Gray material at base of tree is gravel used in the repair of the breach. Source: Times-Picayune Tuesday, October 4, 2005. See reference to article by John McQuaid, same date

**Figure 38.** Water in the canal at the north breach of the London Ave. Canal puts lateral pressure on the floodwall and sheet piling along with water driven through sand under the sheet pilings (and possibly through peat, depending on the depth to which the sheet pilings actually were driven) pushes up the ground outside of the canal in a phenomenon known as heave. This would eventually provide a flow path for water which would undermine the levee and cause its collapse. This may have been responsible for the eventual collapse of the floodwall on the west side of the canal resulting in the breach. The floodwall on the east side of the canal was leaning, but did not fail to create a breach.

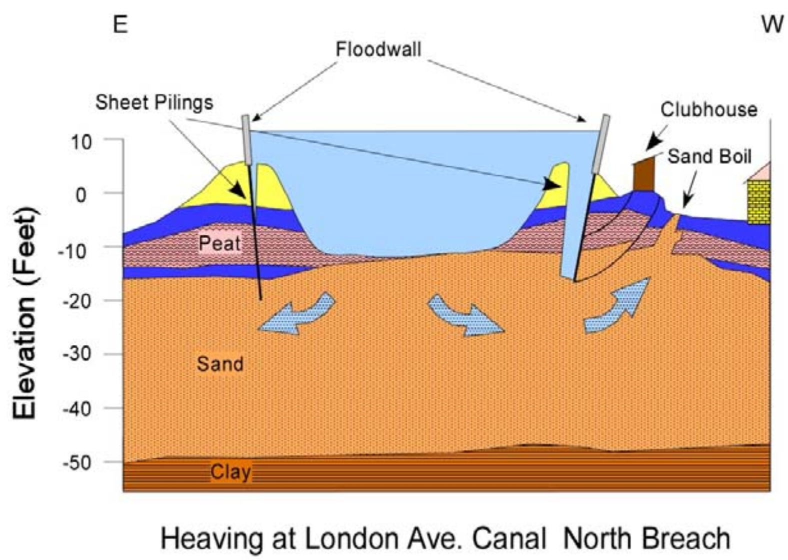




**Figure 39**. Sand deposits and peat blocks (black) behind homes on Pratt Drive at the North breach of the London Ave. Canal. Note the sand boil on the right. Gray material in the foreground is gravel used in the repair of the breach.


**Figure 40**. Sand deposits in front of houses on Pratt Drive at the North breach of the London Ave. Canal.

Walking out on the bridge and looking to the north, one can see the gray structure that crosses the canal. This is the moveable temporary flood gate structure that was built in 2006. The gates are designed to be closed if a hurricane is approaching New Orleans, and, if they work, should prevent storm surge from entering the canal and causing another disaster.

**Stop 6 – London Avenue Canal Gate and Pumps**

Here is a close up view of the interim gates and pumps near the Lake end of the London Avenue Canal (See Figure 41). This structure was built in 2006 to prevent storm surge from Lake Pontchartrain from entering the canal. Similar structures were also built on the Orleans and 17th Street Canals. The gray structures across the canal are the gates which are closed prior to a hurricane. Platforms on the both sides of the canal behind the gates house pumps and generators to drive the pumps. The pumps take water out of the canal and pump it around the gates where the water comes out through the black pipes on either side of the gates. The gate/pumps have been used successfully to keep storm surge out of the canals and water drained from the city during hurricanes Gustav in 2008 and Isaac in 2012.

When the gates/pumps where constructed in 2006, they were estimated to have a useful life of 5 years. They are thus scheduled to be replaced by similar more robust facilities as part of the 100-year protection plan and construction should start soon.

Although these structures will probably adequately protect the canal from storm surge, it does require coordination of pumping between the pumps at the south ends of the canals and the pumps at the gates. A safer plan would be to do away with the gates altogether by continuing the Lakefront levees across the mouths of the canals and moving the pump stations to pump over the levees directly in the Lake. This is how it works on the more recently constructed drainage canals in Jefferson Parish and Eastern New Orleans. The Corps of Engineers, however, has decided that this safer plan is too expensive.


**Figure 41**. Gate and pumps near the Lake end of the London Avenue Canal (Stop 6).

From here we will proceed north to Lakeshore Drive and turn left (East) toward Stop 7
.

**Stop 7 – Lakeshore Drive – Lake Pontchartrain**

Stop 7 is at the Lakefront. With the exception of the levees in New Orleans East on the east side of the Industrial Canal, the levees along the Lakefront were not overtopped by the storm surge from Lake Pontchartrain. Some minor splash-over did occur, but the levees with tops at an elevation 17 to 18 foot above sea level held up quite well and none were breached in this part of Orleans Parish (or in Jefferson Parish). There were substantial amounts of water in the area between the Lake and the levees and significant amounts of erosion occurred behind the seawall right along the Lake. Debris lines on the levee observed shortly after the storm indicate that the water level came within a few feet of overtopping the levees. Some wave splash-over was also noted along here, but the levees did not fail and were not eroded to any degree. To the east of the Industrial Canal, however, the storm surge did overtop the levees and floodwalls, and did create an erosion trench at the base of sections of floodwall near the Lake Front Airport (see the field trip website, images section for photos). Minor erosion did occur on the top the Lakefront Levees and thus storm surge from the Lake was one of the causes of flooding in Eastern New Orleans.

Lake Pontchartrain is a brackish water estuary that is connected to the Gulf of Mexico through two narrow passageways to the east, the Chef Menteur Pass (visible on Figure 9 on the right) and the Rigolets (not visible in Figure 9). The Lake has an average depth of about 12 feet and is normally at 1 to 2 feet above sea level. As part of the Hurricane Protection

System, the Corps of Engineers originally developed a plan, called the Barrier Plan, to put moveable gates at these two entranceways to the Lake. An organization called Save Our Wetlands, filed a lawsuit objecting to the 4 page environmental impact study presented by the Corps, and a judge in 1977 ruled that the environmental impact statement was inadequate (Schwartz, 1977). The Corps, rather than issue an acceptable environmental impact statement, decided against the construction of the gates. This was another critical mistake. Construction of the flood gates might have prevented the storm surge from entering Lake Pontchartrain during Katrina and thus could have prevented the flooding due to breaches on the drainage canals.

The absence of flood gates that would prevent storm surge from entering Lake Pontchartrain proved costly during Hurricane Isaac on August 29, 2012. Isaac was a slow moving Category 1 storm that stalled the southwest of New Orleans. Storm surge entered Lake Pontchartrain and resulted in destructive flooding on the north shore of the Lake and in LaPlace on the western shore. The New Orleans area protected by the recently completed 100 year storm protection system, however, did not flood.

From here we will head eastward to Marconi Ave. turning right (south) onto Marconi. Along Marconi we encounter the new floodgates and pumps on the Orleans Canal. The structure is similar to ones built on the Lake Ponchartrain ends of the London Avenue (Stop 6) and 17$^{th}$ St. Canals.

We will then go back to Robert E. Lee Blvd, heading west and turn left into the area of the 17$^{th}$ St. Canal breach.

**Stop 8 – 17$^{th}$ St. Canal Breach**

Stop 8 is in the area of the breach on the 17$^{th}$ St. Canal (also called the Metairie Outfall Canal). According to data presented by IPET (2006) this breach started at about 6:30 AM and was completely open by about 9:00 AM on August 29, 2005 It was reported to WWL radio by the New Orleans Fire Department at 11:00 AM. The breach occurred along a ~500 ft. section of the levee on the Orleans Parish side of the canal. Figure 41 shows an aerial view of the breach area before Katrina and Figure 42 shows approximately the same area on August 31, 2005 as water was still flowing through the breach into Lakeview.

Note that the breach occurred along Belaire Drive where, like the along the London Avenue Canal, houses are backed up against the levee. (All houses bordering the breach area on the west side of Belaire Drive were demolished by the Corps of Engineers in July, 2006). Here, the main part of the breach occurred in a recently cleared empty lot. A tree in that empty lot, close to the levee toe (Fig. 41) can be seen to be toppled in the August 31 image (Fig. 42). Just as at the Mirabeau breach, no eyewitness are available to tell us if the tree toppled due to the hurricane force winds on August 29 or as a result of the levee breach. Without such observations, we note that it is entirely possible that if the tree was toppled by the winds it could have been responsible for the breach at this locality. A house to the south of the main part of the breach, built on a chain wall foundation, was completely removed (see also the photo in the lower right of Figure 51). Natural gas from a line that fed the house can be seen bubbling up through the floodwater in Figure 42. Another house to the north of the empty lot was built on a slab and was also removed by the rushing floodwaters. The natural gas line that fed that house can also be seen bubbling up natural gas, just to the right of the yellow spot (roof of a school bus) in Figure 42.

Also visible in Figure 42 is a section of the levee that was displaced eastward by about 45 feet. Figures 43 and 44 are oblique aerial views of this displaced levee and floodwall. The area in front of the displaced levee was pushed horizontally outward near the position of the yellow school bus. This can also be seen in Figure 45 where the toe of the slide block is seen as an abrupt change in slope of the ground surface.

Before the debris was completely removed, large blocks of peat were present throughout the neighborhood, some of which could be found a block away to the east near Fleur de Lis Blvd. Examples of the peat blocks before their removal can be seen in Figure 46and the upper right photograph in Figure 51.

Although most houses built on slabs received little structural damage except where rapid water currents ran through them or another house collided with them, houses built on piers were picked up by the floodwaters and moved along with the current until they ran into trees or another house. Notable examples of displaced wood-frame houses that were built on piers and floated away were seen on nearly every street leading away from Belaire Drive and the levee breach.

Figure 47 shows a geological cross section along the levee of the 17th street canal. The most notable feature of the cross section is the peat layer observed at depths between about 8 and 15 feet below sea level in the area of and to the south of the breach.

A series of articles in the Times Picayune, by John McQuaid, Bob Marshall, Mark Schleifstein, and Sheila Grissett (see references section) discuss the role of the peat layer, the possible design flaws, and the possible mistakes made during the construction of the 17th St. Canal levee and floodwall system. Figure 48 summarizes the possible cause of failure. Although the "as built plans" made available on the IPET web site and seismic tests performed on the sheet pilings suggested that they were only driven to a depth of 10 feet below sea level (Marshall, November 9, 2005; Olson Engineering, 2005), when sheet piles immediately adjacent to the breach were pulled they were shown to be at the design specification of 17 feet below sea level (Schleifstein, December 13, 2005); Schleifstein and Marshall, December 14, 2005; Marshall, December 19, 2005). Even at this depth, the sheet pilings would not have been deep enough to prevent failure (Marshall, November 30, 2005 & December 30, 2005), and were not even as deep as the bottom of the canal.

In years prior to Katrina, seepage through the levee was noted by residents along the 17th St. Canal, a clear sign of potential problems, but was never pursued (Marshall, November 18, 2005). Furthermore, the annual inspection of the levees is now seen to have been a ceremonial gathering rather than a detailed inspection (Marshall, December 5, 2005).

Other factors that could have contributed to the levee failure include the clearing of the empty lot at the site of the breach, wave action in the canals (Schleifstein, November 29, 2005), trees along the levee being uprooted by the strong winds accompanying the hurricane (IPET, 2006, ILIT 2006), dredging of the canal on the Orleans Parish side that would have deepened the canal and removed the less permeable clays that had accumulated over the years on the canal bottom (Marshall and Grissett, December 9, 2005), and political factors that went into decisions about the construction of the floodwall/levee system (Marshall, November 19, 2005; McQuaid, December 18, 2005; Braun and Vartabedian, 2005).

The most recent information from the Interagency Performance Evaluation Task Force (IPET) [2006] suggests that the floodwall and levee failed at the 17th St. Canal as a result of the water level rising to an elevation of about 8 feet above sea level in the canal. The floodwalls were designed to have tops at an elevation of 14 feet above sea level, but IPET data indicate that by the time of Katrina the tops of the floodwalls on the 17th Street Canal were about 12.5 feet above sea level. Thus, IPET estimates that water levels in the canal were still 4 feet below the tops. IPET has collected eyewitness accounts and scoured the neighborhood for clocks that were stopped as a result of the flooding in order to determine the time of the breach. One eyewitness account suggests that the floodwall at the breach area was leaning to the protected side at about 6:30 AM on August 29 and other accounts suggest that the breach was open by about 9:00 AM. This, along with levee breach experiments conducted on scale models in a large centrifuge led IPET to suggest that as water levels rose in the canal, the floodwall and sheet piling was pushed outward toward the land side, opening a gap between the levee and the floodwall on the canal side. This gap allowed water to seep down along the sheet piling and eventually push the levee on the protected side outward away from the canal. Based on sections of the breached levee observed in the breach area, IPET suggests that the failure did not occur along the peat layer, but along a layer of weak clay at the base of the peat. This clay layer was thrust over and through the peat as illustrated in Figure 48.

A photograph of the end result of IPET's scale model centrifuge experiment is shown in Figure 49. The canal side (on the left in the photograph) next to the sheet piling is seen to have dropped down as a result of the floodwall moving toward the right (toward the protected side). Indeed in the end result of the experiment, the levee, peat layer, and upper part of the underlying clay layer all have moved to the protected side. Viewing the complete video of the experimental run (https://ipet.wes.army.mil/), however, shows that the initial failure occurred either in the peat layer or at the peat – clay interface, and only when the sheet pile started to move to the right, away from the canal, did the upper part of the clay layer also move. Furthermore, the only part of the clay layer that moved was the part immediately in front of the tip of the sheet pile, and it only moved because it was being pushed along by the sheet pile.

When the Corps of Engineers announced that they had discovered the cause of the levee/floodwall failure at the 17th Street Canal, they implied that it was a different mechanism than had been observed before, that the peat had little to do with it, and that this failure mechanism could not have been foreseen (Marshall, March 11, 2006). Two days later it was pointed out that the Army Corps of Engineers had indeed seen this exact failure mechanism in an experiment they conducted on experimental levees in the Atchafalaya basin in 1985 (Marshall, March 14, 2006)(See Fig. 20). This was before the design and construction of the canal levee/floodwall system in New Orleans. On April 5, 2006, General Strock of the Army Corps of Engineers admitted before Congress that there were failures in the design of the levee/floodwall system in New Orleans (Walsh, 2006).

In coming up with acceptable designs for any structure, engineers must determine whether or not the structure is strong enough for any expected forces. Stability is based on the factor of safety (FS), defined as the strength divided by the expected forces acting. For FS < 1, the strength of the system is less than the expected forces acting and this would result in failure of the system. For FS >1, the strength of the system is greater than the expected forces and the system should be stable. For the levees in New Orleans, the Corps of Engineers used an FS value of 1.3. In other words, they allowed for a 30% error. An FS value of 1.3 is considered low by most engineering standards because failure can lead to catastrophe. The value used by Corps for levees, was determined many years ago, when most levees were built to protect pastures and livestock, not to protect hundreds of thousands of humans.

In order to calculate the FS for the floodwall/levee system, one would need to know the strengths of all components, including the floodwall, sheet pile, and all of the soils in and beneath the levee that would be acted on by the forces. One of the basic principles that all of us can understand is that something will break where it has the lowest strength, Thus levee components of low strength are the ones that should be considered, as these are the components most likely to fail.

Figure 50 shows graphs of shear strength and wet density versus depth as obtained on samples from soil borings (done before 1990) along an 1800 foot section of the 17$^{th}$ St. Canal, which includes the area of the breach. Red lines have been added for emphasis, one showing the depth to the tip of the sheet piling within the breach zone (17.5 feet below sea level) and the other highlighting the characteristic strengths used by the designers to determine the stability of the floodwall. Between the two graphs are lines separating the different kinds of soils. Note that all soils above about -37 feet are shown as CH soils, which are clays with high plasticity. If one looks at the geologic cross-section in Figure 47, there is an interval between about -10 and -18 shown as peaty clays (the same peat that came to the surface as a result of the levee breach). Peats have low density and thus the wet density data in Figure 50 clearly shows a zone of low density material in the depth range between 0 and -20. The strengths in this zone show a range, but the designers chose to use an average value. What is even more troubling, however is that in the depth range between about -15 and -37, the nearly all of the measured strengths fall below the characteristic strength line used in calculations of FS. This is the critical zone, where all investigators think the failure occurred during Katrina. If the strengths were overestimated by 30%, then the true FS value would fall below 1.0 and the structure would be unstable (just as it was during Katrina).

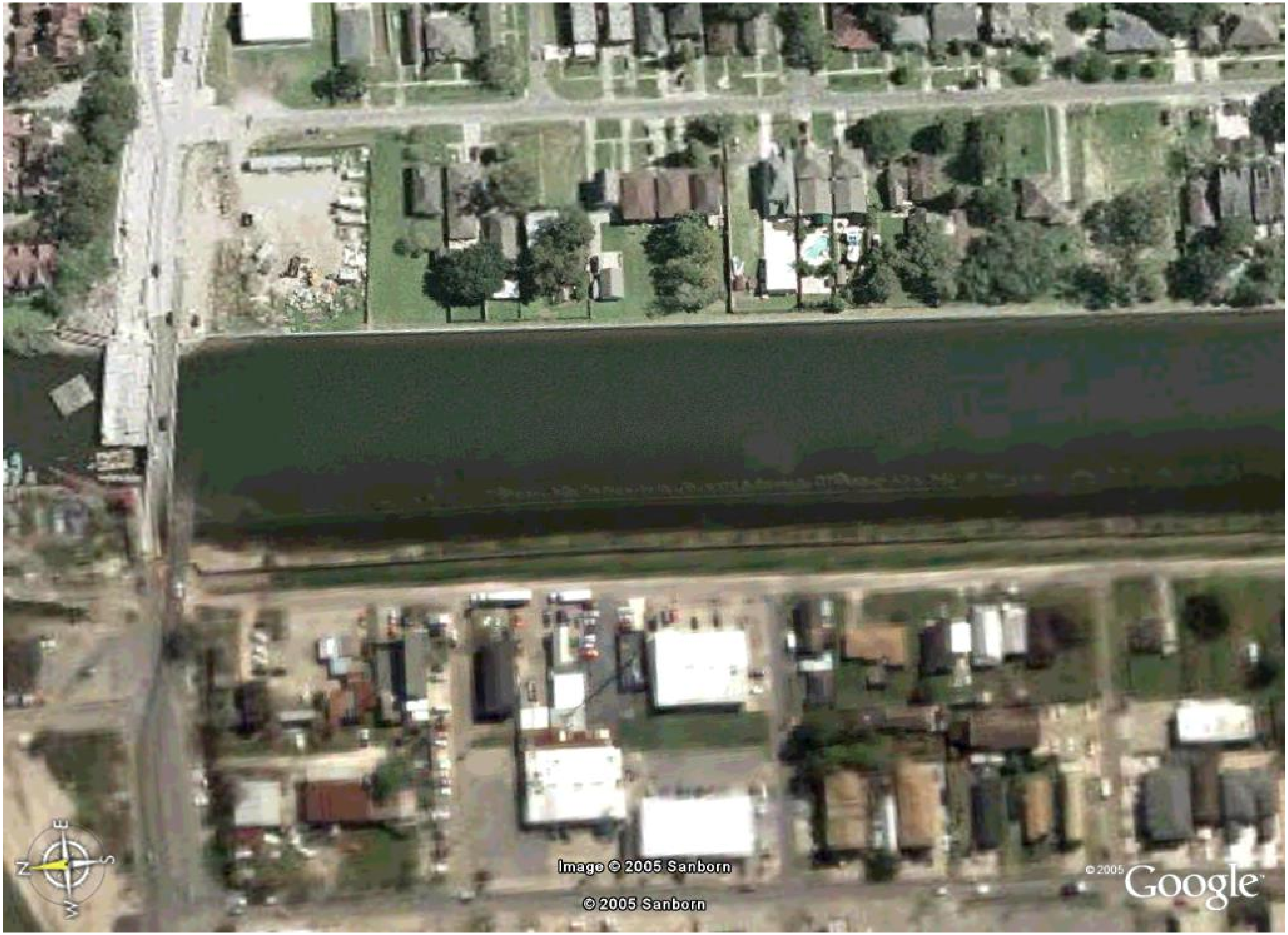



**Figure 41.** Satellite image of the area along the 17th Street Canal near the Old Hammond Highway Bridge (under construction), where the levee was later breached during Hurricane Katrina (Stop 8). (Source - Google Earth)

**Figure 42.** Air photograph of the area where the 17th Street Canal Levee was breached near Belaire Drive (Stop 8). Image acquired Aug. 31, 2005. Source: National Oceanic and Atmospheric Administration's National Geodetic Survey, Katrina Images - http://ngs.woc.noaa.gov/katrina/

**Figure 43**. View of 17th St. Canal breach looking toward south. Note displaced floodwall and levee just below the missing section of the levee. Photo from IPET Report .

**Figure 44**. View of 17th St. Canal breach looking toward east. Note fractures in the displaced part of the levee. Photo by J. Augustino FEMA.


**Figure 45.** . Slide toe (at abrupt change in slope in front of school bus) where levee and neighborhood were displaced about 45 feet toward the viewer.


**Figure 46.** Blocks of Peat along Belaire Drive near the 17th St. Canal levee breach

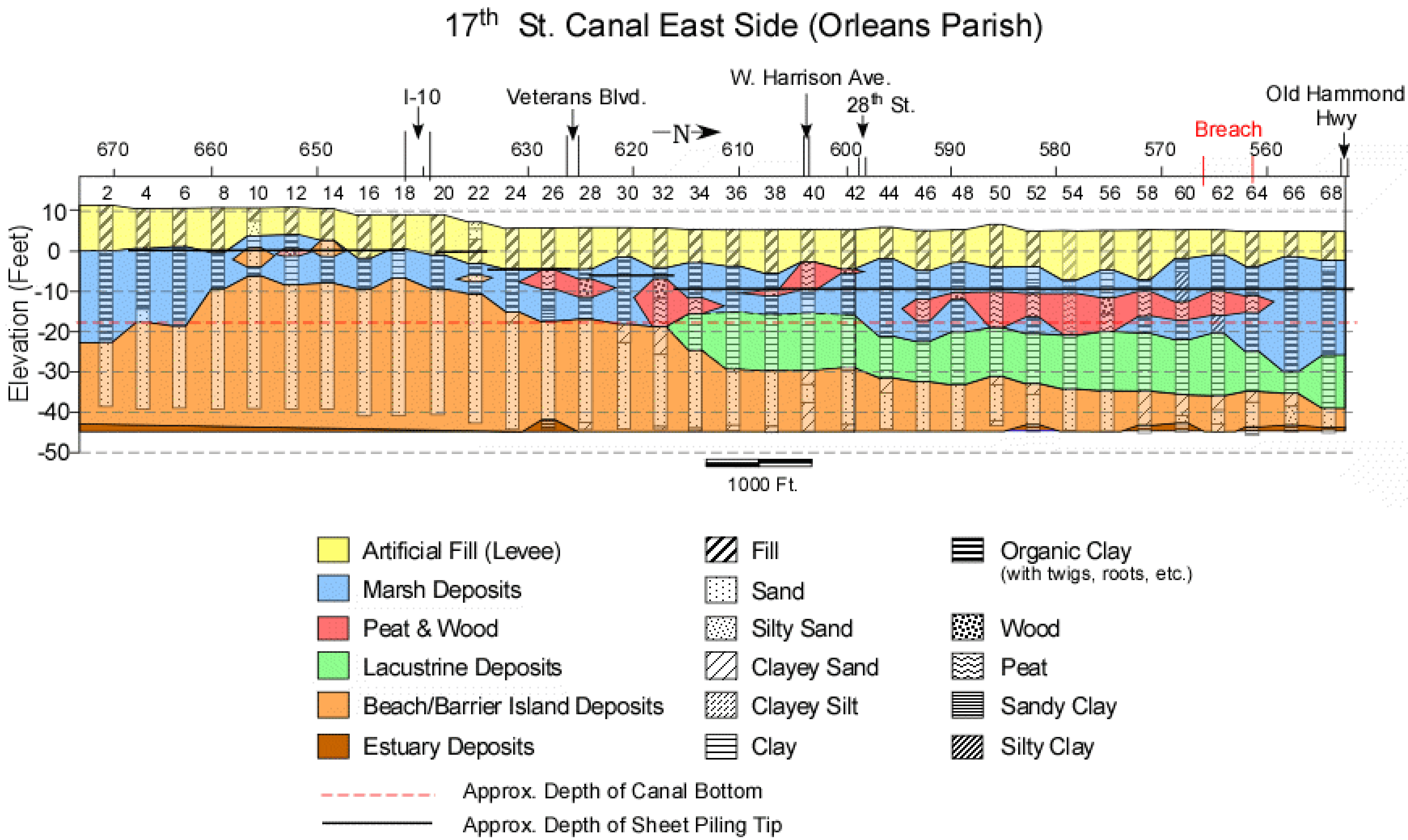



**Figure 47**. Geological cross-section along the eastern side of the 17th St. Canal (based on data in the U.S. Army Corps of Engineers design documents (1990). Notable in the cross-section is the peat layer that occurs in the area of the breach. Depth to sheet piling tips is highly uncertain due to inconsistent information available from the U.S. Army Corps of Engineers. The set of as built available on the IPET web site plans (from which the sheet piling depths in this figure were used), show a depth of 10 feet in the area of the breach, yet the Corps claimed and later confirmed by pulling a sheet pile near the breach, that the sheet piles actually extended to 17.5 ft. below sea-level.

Although throughout the field trip we have seen the water line (scum line) left by standing water, this line does not represent the maximum flood depth. As seen in Figure 51, comparison of the photos on the left, taken when the water level was near its maximum with the water line left on the same structures (photos on the right) indicate that the maximum flood depth was about 1.5 to 2 feet higher than the line left by standing water.

It is notable that the same peat layer and the same levee design and construction are present on the Jefferson Parish side of the canal, which by luck or the path of the storm, did not breach on August 29, 2005. Figure 52 shows a geological cross section of the west bank (Jefferson Parish side) of the 17th St. Canal constructed from data provided on the Army Corps of Engineers IPET web site where it can be seen that the same geologic materials are present beneath the Jefferson Parish side as are found on the Orleans Parish side (compare with Figure 47). One major difference on the Jefferson Parish side is that a street occupies the area next to the levee and there are no trees, houses or swimming pools abutting the levee on that side.

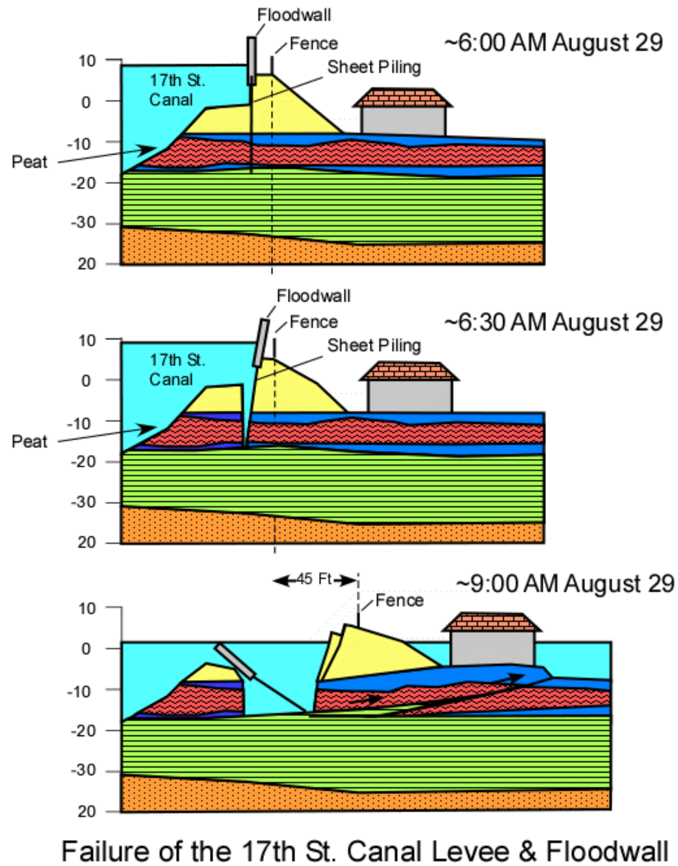



**Figure 48**. Diagrammatic cross sections across the 17th St. Canal in the vicinity of the breach. Based partially on a sketch in Seed and others (2005), ILIT (2006) and IPET (2006).

**Figure 49.** Photograph of failed levee and floodwall in IPET's scale model centrifuge experiment representing the 17th St. Canal. The white at the top is clay and represents the levee. This overlies the dark peat layer, which in turn overlies another white clay layer meant to represent the estuary deposits beneath the peaty marsh deposits. Small rectangles were initially laid out in a rectangular grid and can be used to determine how much deformation has occurred during the experiment. (IPET, 2006).

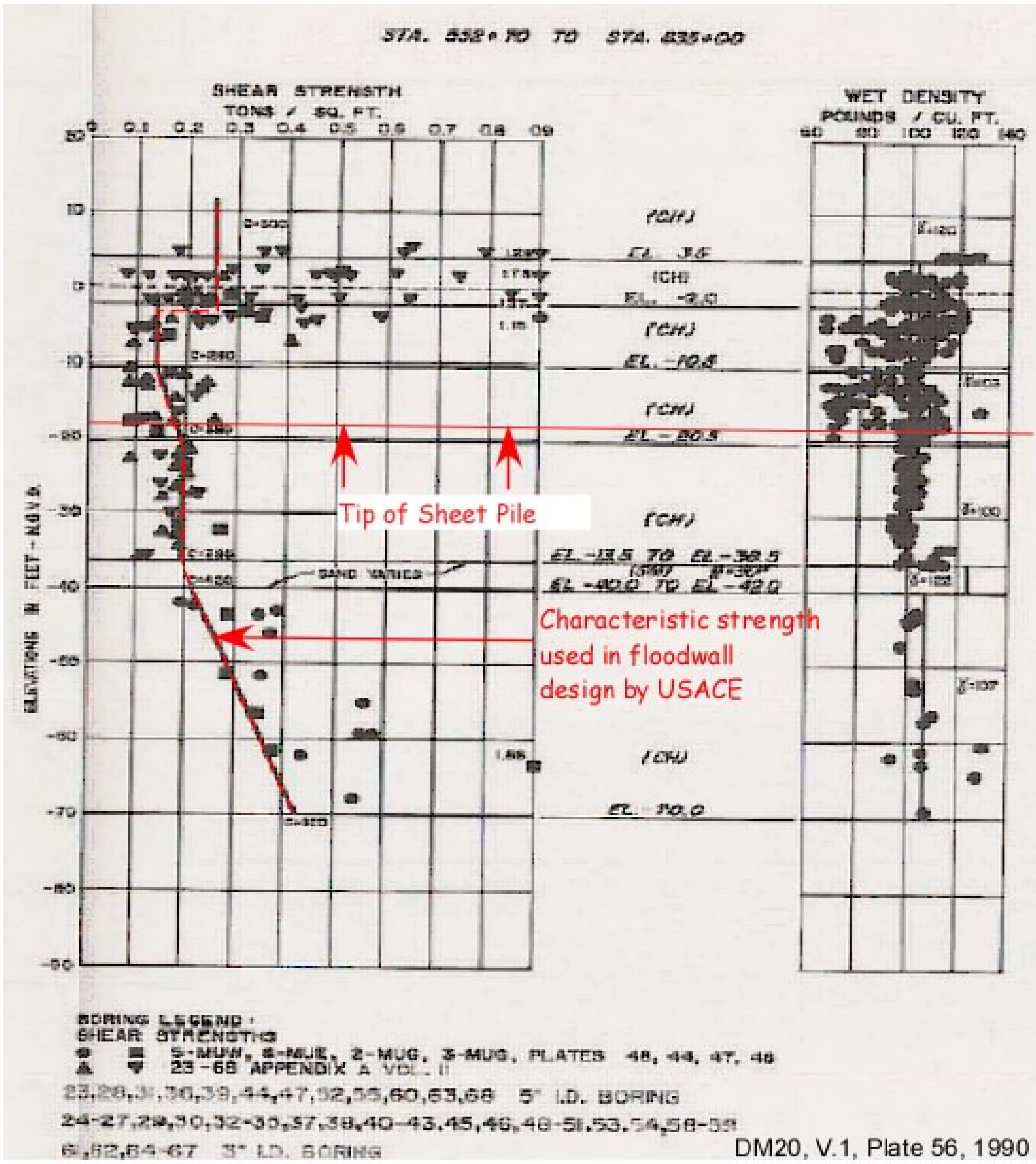



**Figure 50.** Shear strength and wet density versus depth along an 1800 foot section of the 17th St. Canal which includes the area of the breach (from U.S. Army Corps of Engineers, 1990, the Design documents for the 17th St. Canal floodwall). The author has added the red lines and red labeling showing the depth to the tip of the sheet piles in the breach zone and the characteristic strength values as a function of depth that the Corps used to determine the stability of the floodwall system.

After exploring the area of the breach and noting the abundance of globs of peat scattered throughout the breach area, we will proceed back to Robert E. Lee Blvd. and head east to Canal Blvd. then head south. The water line is prominent all along Canal Blvd. At Harrison Ave. we will turn left and drive east toward City Park. Eventually we cross the Orleans Canal, the third drainage canal in this part of the city. Levees and floodwalls along the Orleans Canal did not fail during Hurricane Katrina. As we cross the Orleans canal, note that unlike the other drainage canals, the west side of the canal is separated from the residential area by a street (Orleans Ave.) and that the east side is bounded by City Park. Thus there were no trees and houses abutting the levee on the Orleans Canal. According to IPET (2006), the levees on the east side of the Orleans Canal are also wider than those on the other drainage canals. Furthermore, because of the street on the west side, the floodwalls on that side were T-walls rather than I-walls. While these may be reasons that the levees did not fail on the Orleans Canal, another reason will be explored at our next stop. Upon reaching Marconi Ave. in City Park, turn right and continue south to the I-610 overpass. To avoid the mud along the right hand side of Marconi Ave. pull into the side street to the left, just before the overpass.


**Figure 51.** Comparison of water levels on Sept.1, 2005 (photos on left by Kevin Himmel), with water lines on same structures indicate lines left by standing water are about 1.5 to 2 feet lower than the maximum water level. Note large block of peat in photo at the upper right. In photo at lower right, note the chainwall foundation of a house that was removed by the burst of water when the levee was breached and the cypress stump from a tree that was probably cut down 100 years ago when this Lakeview neighborhood was reclaimed from the cypress swamp.

**Stop 9 – Orleans Canal**

Stop 9 is at the levee of the Orleans Canal just under the I-610 overpass. As we walk up to the levee, note that the floodwall on the top of the levee abruptly ends about 40 yards north of the overpass (Fig. 53). An approximately 100 yard gap thus exists in the flood protection on the canal between the end of the floodwall and Pump Station Number 7 to south on the other side of the overpass. A smaller gap exists on the other side of the canal as well. During Katrina, water from the Orleans Canal was flowing freely through this gap as evidenced by the erosion that occurred around the support structures for the freeway overpass (Figure 54). Fresh concrete has since been poured around the support structures and the levee has been raised about 2 feet from its pre-Katrina level in an attempt to fix the problem. Why was such an obvious gap in the flood protection system allowed to remain? The Independent Levee Investigation Team (2006) offers the following explanation. Apparently, the Orleans Sewerage and Water Board, who run the pump station, objected to the Corps of Engineers plan to build the floodwall right up to the wall of the pump station. They argued that the wall of the pump station was not strong enough to withstand the force of the water if it backed up in the canal, and would fail with the result that the city would flood when the wall failed. Of course the net result was that the city flooded as the water poured through the gap. Nevertheless, the relief of pressure in the canal may have prevented the floodwalls and levees elsewhere on the canal from failing.

After leaving Stop 9, proceed South on Marconi to City Park Ave which is on the Metairie Ridge. Turn left on City Park Avenue to Carrollton Ave and return to Tulane.

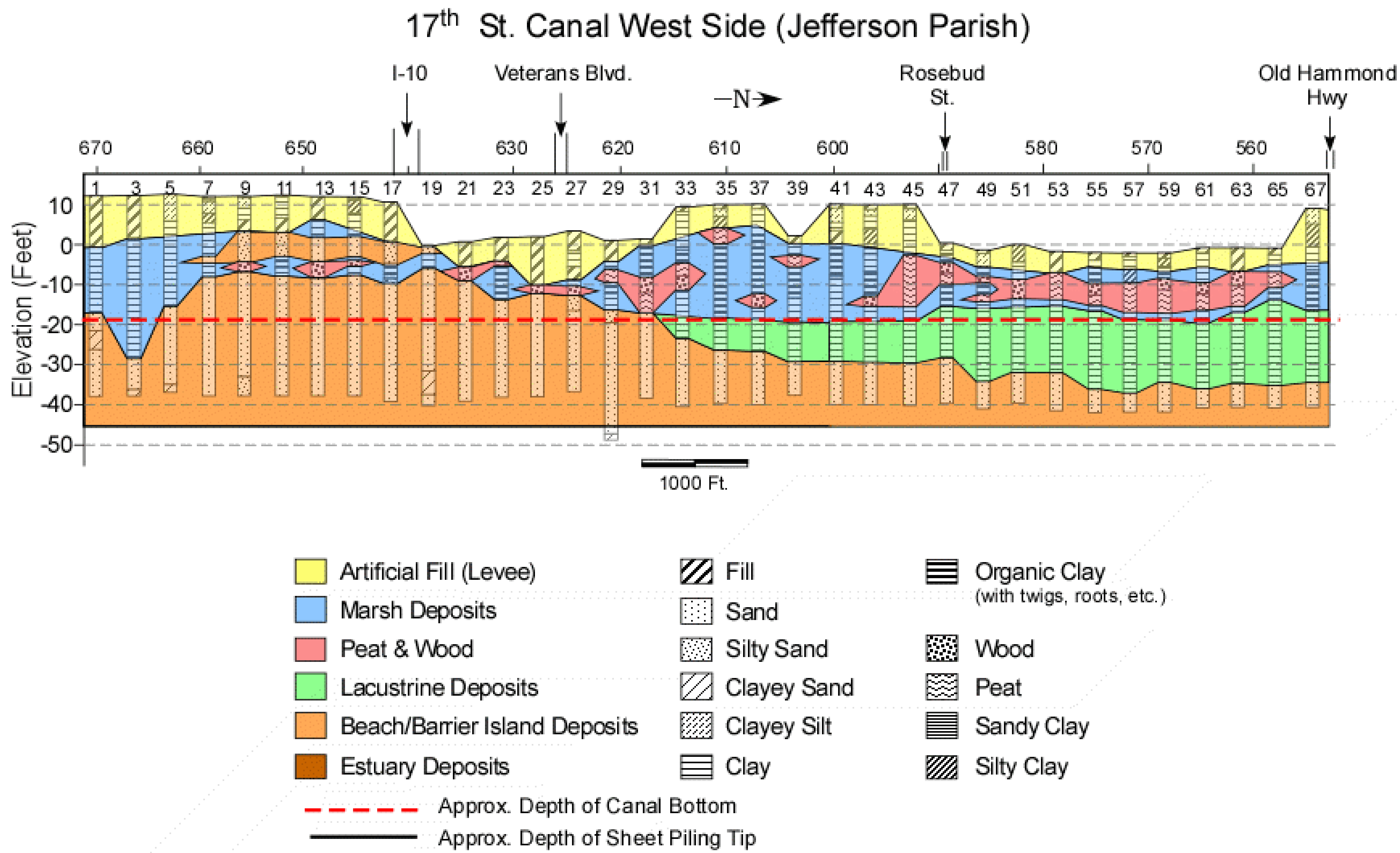



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**Figure 52.** Geologic cross section of the west bank of the 17th St. Canal constructed from data provided to the U.S. Army Corps of Engineers (1990). Note that levee heights appear inconsistent because some of the borings were taken at the toe of the levee rather than on the levee crest. Depth to the tip of the sheet pilings is currently not available for the west side of the 17th St. Canal, although Grissett (April 14, 2007) has information that the sheet pile tips extend only to about 4 feet below sea-level at southern end of the canal (south of Veterans Blvd.).


**Figure 53.** End of floodwall on Orleans Canal just north of I-610 overpass near Marconi Ave. (Stop 9)


**Figure 54**. Erosion around the support structures for I-610 near Orleans Canal on Marconi Ave (Stop 9).

**Appendix I**

**Time Line of Important Events Leading up to Hurricane Katrina***

| | |
|---|---|
| 5000–4500 BP | Deposition of Pine Island Trend Barrier Island/Beach Sands |
| 4500–1000 BP | Deposition of St. Bernard Delta Lobe & formation of Metairie/Gentilly/Esplanade Distributary channels |
| ~1000 BP | Current Mississippi River course established |
| 1718 | Founding of New Orleans |
| 1722 | Hurricane destroyed New Orleans |
| Aug. 9, 1812 | Great Louisiana Hurricane, struck - flooded areas north of city along Lake Pontchartrain |
| 1821 | Easterly winds forced water from Lake Pontchartrain up Bayou St. John to flood northern edge of city. |
| Aug. 16,1831 | “Great Barbados Hurricane” Mississippi River levee broke and flooded French Quarter. |
| 1833-34 | Orleans Canal mostly excavated |
| 1854-58 | Upperline Canal ($17^{th}$ St. Canal) excavated |
| 1860 | 3 Hurricanes struck New Orleans area. One on October 2, caused storm surge in Lake to destroy lake front villages and flood areas north of French Quarter. |
| 1860s | Lower London Avenue Canal excavated |
| 1871 | 3 hurricanes create storm surge in Lake that causes localized flooding in New Orleans |
| 1871 | City Surveyor W. H. Bell warns of storms moving up drainage canals – suggests moving pumps to lakefront. |
| 1873-1878 | Upper London Avenue Canal excavated |
| 1895? | Lake Ponchartrain hurricane protection levee (6 ft. above lake level) |
| 1915 | Hurricane floods city through drainage canals. 275 deaths |
| 1915 | Baldwin Wood invents high capacity screw pump - allows swamps to be drained for habitation. |
| 1923 | Industrial Canal completed |
| 1940s | Inner Coastal Waterway completed |
| Sept. 19, 1947 | Hurricane floods part of city along Industrial Canal and drainage canals. 51 deaths |
| 1960 | Corps proposes plan for movable gates at the Lake end of drainage canals |
| 1961 | Corps proposal for gates at Rigolets and Chef Menteur Pass the “Barrier Plan” |
| 1964 | MR-GO completed |
| Sept. 9, 1965 | Hurricane Betsy floods on both sides of Industrial Canal |
| 1965 | Lake Pontchartrain and Vicinity Hurricane Protection Plan authorized by Congress |
| Aug. 17, 1969 | Hurricane Camille (Cat. 5) hits Mississippi Coast, New Orleans spared from flooding |
| 1970s | Floodwall built on Industrial Canal |
| 1977 | Courts rule against “Barrier Plan”, Corps adopts “High Level Plan” |
| 1984 | Corps modifies Lake Pontchartrain & Vicinity plan to include floodgates at mouths of canals |
| 1992 | Water Resources Development Act gives Corps responsibility for hurricane protection on Canals (previously the responsibility of the Orleans Levee district) after Levee District lobbyists successfully have language inserted into the bill. |
| 1993-1999 | Floodwalls built on drainage canals, but bridges still in progress in 2005. |
| 1998 | Hurricane Georges approaches New Orleans – first time evacuation of city is called for. |
| 2004 | Hurricane Ivan approaches New Orleans, - second evacuation – first time for Contraflow |
| Aug. 29 2005 | Hurricane Katrina |
| Aug. 2006 | Completion of closeable gates and pumps on the 3 drainage canals, |
| Sept. 1, 2008 | Hurricane Gustav strikes, city evacuated, floodwalls on Industrial Canal overtopped by waves. |
| June 1, 2012 | Near completion of the 100 year flood protection system, designed to protect the New Orleans area from a flood that has a 1% chance of occurring each year. |
| Aug. 29, 2012 | Hurricane Isaac a slow moving Category 1 hurricane comes ashore southwest of New Orleans. The new Hurricane Protection system protects New Orleans, but storm surge from Lake Pontchartrain causes extensive damage to LaPlace (west of New Orleans) and the northshore of the Lake. |

*Based on ILIT (2006), Braun & Varabedian (2005), and Schleifstein (Nov. 1, 2005)

## Appendix II
## Hurricane Katrina Timeline
## Levee Breaches and Overtoppings
## All on August 29, 2005 (except where noted)

| | Times Picayune* | IPET (2006) | ILIT (2006) |
|---|---|---|---|
| CSX Railroad floodgate on Industrial Canal | 4:30 AM | | 4:45 AM |
| New Orleans East | 6:30 AM | 6:00 AM | 5:00 AM (southeast)<br>6:15 -7:00 AM (ICWW) |
| Lake Front Airport | 8:30 AM | | |
| MR-GO | 5:00 AM | 5:30 AM | 6 -7:00 AM |
| St. Bernard Parish flooding | 8:30 AM | 8:20 AM | 7:30 – 8:00 AM |
| Plaquemine Parish | 6:10 AM (landfall) | | 7:00 AM - flooded |
| West side Industrial Canal | 6:50 AM (overtopping)<br>7:30 AM (breach) | 5:45 AM | 7:00 – 8:30 AM |
| Lower 9th North Breach | 6:50 AM (overtopping)<br>7:45 AM (breach) | 4:30 AM | 7:45 AM |
| Lower 9th South Breach | 7:45 AM | 7:45 AM | 7:45 AM |
| London Ave. Canal South Breach | 9:30 AM | 7:00 – 8:00 AM | 7:00 – 8:00 AM |
| London Ave. Canal North Breach | 10:30 AM | 7:00 – 7:30 AM | 7:30 – 8:30 AM |
| Orleans South end | 9:00 AM | | |
| 17th St. Canal floodwall tipped | 6:30 AM | 6:00 AM | |
| 17th St. Canal breached | 9:45 AM | <9:00 AM | 9:00 – 9:15 AM |
| Equalization of Lake and floodwaters | Sept. 1 Mid-day | | |

*Marshall (May 14, 2006)

## Appendix III
## Critical Errors (summarized from ILIT [2006])

1. Decision not to install floodgates at the mouths of the drainage canals

2. Decision not to purchase right of ways along canals so that levees could be raised and widened.

3. Failure to inspect and restrict development at the toe of levees (keep trees & swimming pools away from levee toes).

4. Designers failed to use information from research levee experiments conducted in the Atchafalaya basin.

5. Failure to take into accounts the stress histories and effect of overburden stresses on levees.

6. Used estimates that were too optimistic in terms of underseepage flow and thus used sheet pilings that were too short to cut off such flow.

7. Failure to more thoroughly investigate soil conditions (too few borings, borings too widely spaced, not enough at both levee crest and levee toes.

8. Inadequate design review.

9. Used factor of safety far too low for protection of urban environment and didn't consider variability and uncertainty in soil conditions

10. Inadequate funding, uncertainties of funding, and pace of funding affected decision making process and forced corps to take shortcuts or not complete projects in a timely manner.

11. Lack of cooperation, oversight, and discussion among various bodies (levee boards, Sewerage & Water Board, Corps of Engineers, etc.

## References

(Note: All of the of the web links in the following reference list worked as of April 18, 2013, although some of the newspaper web sites continually change their policy on older news items). This list of references includes all that are discussed in the text above, as well as many others that are not explicitly referenced.) Many documents were on the U.S. Army Corps of Engineers Interagency Performance Evaluation Task Force (IPET) web site (https://ipet.wes.army.mil/), but as of 4/18/2013 this link no longer works. The author has digital copies of these documents, and will provide copies upon request. The same goes for newspaper articles that are no longer easily available on the internet. I can provide hard copy of these articles, if necessary.

American Society of Civil Engineers. External Review Panel letter to U.S. Army Corps of Engineers, March 23, 2006. http://media.nola.com/hurricane_katrina/other/032406_leveeletter.pdf

American Society of Civil Engineers. Hurricane Katrina One Year Later – What Must We Do Next? August 25, 2006.

Braun, Stephen and Vartabedian, Ralph. Levees Weakened as New Orleans Board, Federal Engineers Feuded. Los Angeles Times. December 25, 2005. http://articles.latimes.com/2005/dec/25/nation/na-levee25

Burke & Associates, Inc. Geotechnical Investigation, London Avenue Outfall Canal. OLB Project No. 2049-6269 New Orleans, LA Volumes 1 &2, March 4, 1986.

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