Hurricane Katrina - What Happened?

Tulane University
Field Trip
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http://www.tulane.edu/~sanelson/Katrina

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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 Cyprus stumps at 17th St. Canal Breach (photos by Stephen Nelson)

Figure 1. Google Earth oblique view of New Orleans showing location of levee breaches and important geographical features.

Levee Breaches in 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. One day before, on August 28, Katrina peaked as a Category 5 Storm (Knabb et al. 2005). The Mississippi Gulf Coast was subjected to storm surge up to 28 feet above sea level. 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, which flooded much of St. Bernard Parish, and along the Intracoastal Waterway to flood Eastern New Orleans and St. Bernard Parish. 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 on one the 17th St. Canal) resulted in further flooding of New Orleans. In all, over 80% of the city was flooded as a result of these levee failure. 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 Lake Front levees or the Mississippi River levee. Neither of these levees breached. Second, many people, even some in the New Orleans area, still believe that the breaches occurred the day after Katrina made landfall. 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. Below is a summary of the breaches, most of which will be visited on the field trip.

2 breaches on the east side of the Industrial Canal - between N. Galvez & N. Roman Streets and at Florida Ave.
Flooded Lower 9th Ward.

2 breaches on the west side of the Industrial Canal near France Road.

2 Breaches on the London Avenue Canal, one near Mirabeau Ave. & Warrington Drive and the other near Robert E. Lee Blvd. & Pratt Drive. These breaches flooded parts of New Orleans near the west side of the Industriall canal.

1 Breach at the 17th St. Canal near Belaire Drive between Stafford Place & 40th Street
Flooded Lakeview, Gentilly, Mid City, Old Metairie, Jefferson, & parts of Uptown

No Lakefront or Mississippi River levees were overtopped, although some minor splash over occurred at some locations along the lakefront levees and more extensive overtopping and erosion of the Lakefront levees occurred in New Orleans East.

The Industrial Canal is about 35 feet deep and provides a shipping channel between the Mississippi River and Lake Ponchartrain and connects with the Intra Coastal Waterway (ICW) and the Mississippi River - Gulf Outlet (MR-GO).

The 17th St., Orleans (Marconi), and London Avenue Canals are about 8 to 18 feet deep and provide drainage to pump rainwater out of New Orleans into Lake Pontchartrain.

Field Trip Itineraries

(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).

Alternate Field Trip Beginning at Industrial Canal/Lower Ninth Ward

Field Trip will leave Tulane driving down river 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 Forstall Street into Lower Ninth Ward (note that nearly all street signs are down in the Lower Ninth ward, so you will have go guess at which street you are on in this area).

About 3 blocks North of Claiborne, turn left and head as close to the Industrial Canal levee breach as possible. This is **Stop A.**

After leaving Stop A and driving through the Lower Ninth Ward, return to N. Claiborne Ave. turn right and heard west back over the Claiborne Avenue Bridge.

Continue West to Elysian Fields Ave, right (North) on Elysian Fields.

Continue North on Elysian Fields to Mirabeau Ave., then left on Mirabeau, heading West.

Continue West on Mirabeau Ave. to just before Warrington Drive and **Stop 1** (See Below)

Field Trip Beginning at London Avenue Canal, South Breach

Field Trip will leave Tulane driving up river on St. Charles Ave. to Broadway – right on Broadway.

Continue on Broadway to Fontainebleau – right on Fontainebleau

Continue on Fontainebleau to S. Broad St. – left on S. Broad.

Continue North on Broad St. to Gentilly Blvd. - right on Gentilly Blvd.

Continue North East on Gentilly Blvd. to Norman Mayer Ave.- left on Norman Mayer Ave.

Continue North on Norman Mayer Ave. curve to right street name changes to St. Anthony Ave.

Continue North on St. Anthony Ave. to Mirabeau, Ave., then left Mirabeau Ave.

Continue West on Mirabeau Ave. to just before Warrington Drive and park at **Stop 1**

Make a U-turn and head East on Mirabeau Ave. to St. Anthony Ave, then left on St. Anthony Ave.

Continue North on St. Anthony Ave. to Leon C. Simon. – Left on Leon C. Simon.

Continue West on Leon C. Simon. to Pratt Drive - Left on Pratt Drive.

Continue South on Pratt Drive to Robert E. Lee Blvd and park at levee breach on London Ave. Canal - **Stop 2**

Continue West on Robert E. Lee Blvd. to Marconi Dr. - right on Marconi Dr.

Continue North to Lakeshore Drive then left to parking lot near Lakeshore Levees - **Stop 3**

Continue on Lakeshore Drive - West, then South to Robert E. Lee Blvd. - right on Robert E. Lee.

Continue 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.. - left on Spencer Ave.. - **Stop 4**

Continue East on Spencer Ave. to Fleur de Lis Drive - left on Fleur de Lis

Continue North on Fleur de Lis to Robert E. Blvd. - right on Robert E. Lee.

Continue East on Robert E. Lee Blvd. to Canal Blvd. - right on Canal Blvd.

Continue South on Canal Blvd. to City Park Ave.

If returning to Tulane, turn left on City Park Ave. and Continue to Carrollton Ave, the right on Carrollton to return to Tulane.

If going to alternate Stop 5, turn right on City Park Ave. - becoming Metairie Road after crossing under I-10.

Continue West on Metairie Road to Friedrichs Ave. - left on Freidrichs Ave.

Continue South on Friedrichs Ave. to Northline St. - left on Northline

Continue East on Northline, 1 block to Orpheum Ave. and 17th St. Canal - **Stop 5**

Continue East across the bridge, jog left then right onto Palmetto and take Palmetto to Carrollton

Take right on Carrollton and head back to Tulane.

Field Trip Guide

The field trip will leave from the front of the Tulane Campus and proceed as per the above itineraries depending on whether one is going first to alternate stop A in the Lower Ninth Ward or directly to Stop 1 in Gentilly. In both cases we start in Uptown New Orleans. Uptown New Orleans, generally south of Freret St. was not affected to any large extent by flooding. As we pass Freret St. It becomes notable that flooding occurred. Water marks on the sides of homes and cars that remain in the areas indicating the level of standing water become clearly visible. Piles of debris along the curb indicate that the homes were flooded. Dead vegetation due to standing water (particularly lawn grass) is also a good indicator of areas where standing water remained for as much as 3 weeks. Note that the water marks (scum marks) indicate the level of standing water and likely not the maximum flood level in all neighborhoods (more discussion of this will ensue when we reach the stops at the levee breaches).

The land on which New Orleans is built has origins that began about 4,000 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). Then, beginning about 4,000 years ago the Mississippi River began to build the St. Bernard Delta complex out toward the east. Some of the distributary channels for this delta lobe ran along what is now the Metairie Ridge and Gentilly Ridge. The natural levee deposits built high areas and the channels eventually filled in with sediment. Between the distributary channels the low areas became swamps, accumulating organic-rich clays and peat (Figure 3).

Figures 4 & 5 from the front page of the Times-Picayune newspaper on November 3, 2005, show some aspects of the topography of the New Orleans “bowl”. Areas that were inhabited in 1878 (Figure 4) were mostly high areas and these high areas (along the Mississippi River, Old Metairie, and Gentilly) are generally areas where water depths were less during the flooding resulting from levee breaches during Hurricane Katrina in 2005 (Figure 5). Note that Figure 5 shows estimated flood water depths on Sept. 11, and are not the maximum water depths.

Prominent on Figures 4 and 5 is the sinuous nature of the Metairie ridge which becomes the Gentilly Ridge in central New Orleans. Currently Metairie Road and City Park Avenue run along the top of the Metairie Ridge and join with the Gentilly Ridge along which runs along Gentilly Boulevard. Esplanade Ave. runs from the River to the Gentilly Ridge. These ridges represent older Mississippi River distributary channels and their associated natural levee systems that were active within the last 4,000 years (Figures 4 and 6).

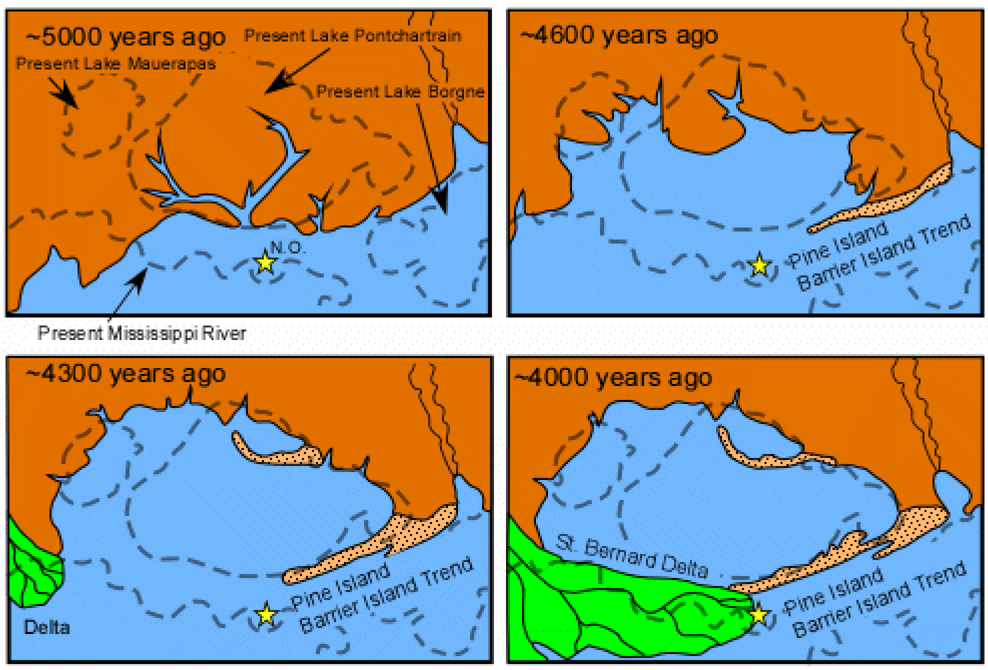

Figure 2. Geologic history of southeast Louisiana between about 5,000 and 4,000 years ago showing the development of the Pine Island barrier island trend (modified after Snowden et al., 1980).

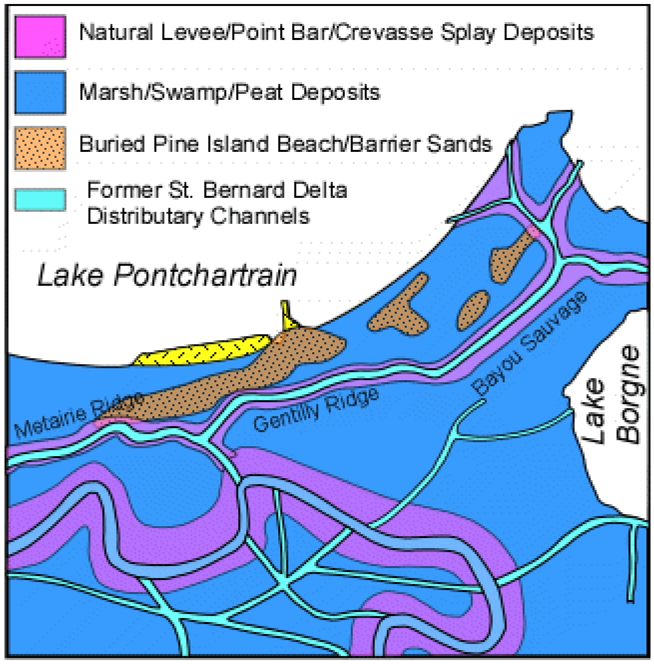

Figure 3. Surficial Geology of New Orleans (generalized) showing former distributary channels of the St. Bernard Delta and the buried Pine Island barrier island/beach sands.

According to the chronology put together by the Interagency Performance Evaluation Task Force (IPET, 2006), 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 were used to seal floodwalls (See Figure 7). By about 6:00 AM the storm surge in Lake Borgne ran up 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 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 MRGO were overtopped and eroded sending water into St. Bernard Parish by about 8:00 AM. This could have been responsible for overtopping of levees in St. Bernard Parish and the Industrial Canal,

At about 7:30 AM the levees on the east side of the Industrial Canal bordering the Lower Ninth Ward were breached by surge waters in the Industrial Canal (Figs. 8, 9, & 10). The photographs in Fig. 8 and 10 show the breached levee two days after the storm. Note that at that time, water was running back into the Industrial Canal from the Lower Ninth Ward. Note also that both photos show a barge which came to rest in the Lower Ninth Ward, having presumably floated through the breach from the Industrial Canal.

Photographs available on the U.S. Army Corps of Engineers, Interagency Performance Evaluation Task Force (IPET) web site and reproduced in Figure 11, 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 erosion eventually 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. This occurred at two places along the Industrial Canal levee. The shorter (about 200 foot-long) breach occurred just to the south of Florida Avenue and the longer breach (approximately 1,000 feet long) occurred between N. Galvez and N. Roman Streets (Figures 9 & 10). In both cases, 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. The floodwall and underlying sheet pilings were strewn into the first block of the Lower 9th Ward like a ribbon (Figure 12). Figure 13 shows a possible failure mechanism for the floodwall and levee along the industrial canal.

If the field trip is going to Alternate Stop A, in the Lower 9th Ward, we can see into, but not enter, the breach repair. All of the broken floodwall and most of the remaining floodwall have been removed as of mid-February, 2006, and a new floodwall is being constructed as of mid-March. Most of the streets have been cleared, but many displaced cars, the rubble piles of former homes, and foundations of many homes remain, clearly showing the force of the floodwaters that poured through the breach. The barge that went through the breach was being removed as of March 1, 2006.

It is important to note that levees in St. Bernard Parish, New Orleans East, and along the Industrial Canal failed because the water from the storm surge was high enough to overtop these levees. In short, the levees were just not high enough to offer protection from a storm of this magnitude. Furthermore, along the east side of the Industrial Canal, the fact that the levees were not armored to protect against erosion from water flowing over the top of the floodwall, coupled with the poor design of the floodwall/sheet piling system, led to catastrophic failure of the floodwall and levee.

If the field trip is going directly to Stop 1, as we proceed up Broad St. toward Gentilly, you should notice that as we pass over the Esplanade Ridge (Esplanade Ave) and the Gentilly Ridge (Gentilly Blvd.) (Figure 3) the scum marks and dead grass lines indicate lower flood water depths in these areas.

Also proceeding up Broad St. we will pass three important pumping stations designed to drain rain water from New Orleans. These pump stations are important from a historical point of view. Because the pumping stations are located in the middle of the city, canals, like the 17th St. Canal and London Avenue Canal, into which the pumping stations send water, bring water at a level about 2 feet above sea level (or higher during a hurricane) into the middle of the city. The reasons for this involve the history of the city which started out along the high areas and was only populated in the low areas once the pump stations and canals were in place.

The first pumping station we encounter going north on Broad St. is Pump Station #1 (Fig. 7) which pumps water into the Palmetto Canal which then carries the water to Pump Station #6 where the water is elevated and pumped out to Lake Pontchartrain through the 17th St. Canal (also called the Metairie Outfall Canal).

Next is Pump Station #2 (Fig. 7) which pumps water into the Orleans Canal. Finally near the end of Broad St. in the north, we come to Pump Station #3 which pumps water into the London Ave. Canal and into Lake Pontchartrain.

After traveling North Broad to Gentilly Blvd., then north to Mirabeau Ave. and turning left on Mirabeau, we reach Stop 1 at the levee breach on the east side of the London Ave. Canal. At this stop we will first discuss the sequence of events that occurred during Katrina including the areas flooded in New Orleans East, the Ninth Ward, and St. Bernard Parish.

Figure 4. 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 represent an old levee system. Compare this with the map on the next page which shows the areas flooded due to levee breaches during Hurricane Katrina. Images from the Times Picayune front page November 3, 2005. The images accompany the article by Gordon Russell (see references).

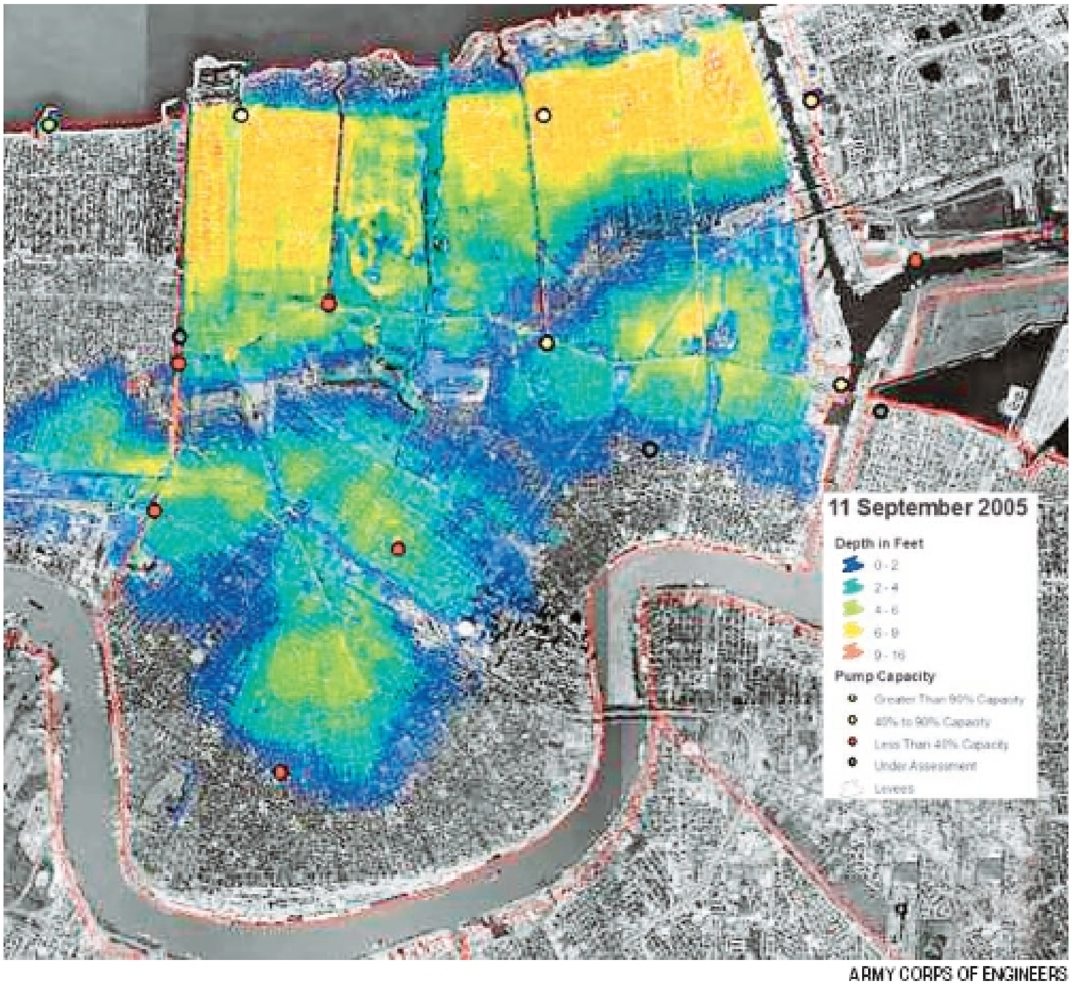

Figure 5. Image from the Times Picayune front page November 3, 2005, showing depths of flood waters on Sept. 11, 2005 from the Army Corps of Engineers. This image accompanies the article by Gordon Russell (see References). Compare this with the 1878 map of New Orleans in figure 2. Note that the areas least affected by flooding were areas near the Mississippi River and along the old 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 much different from those back in 1878.

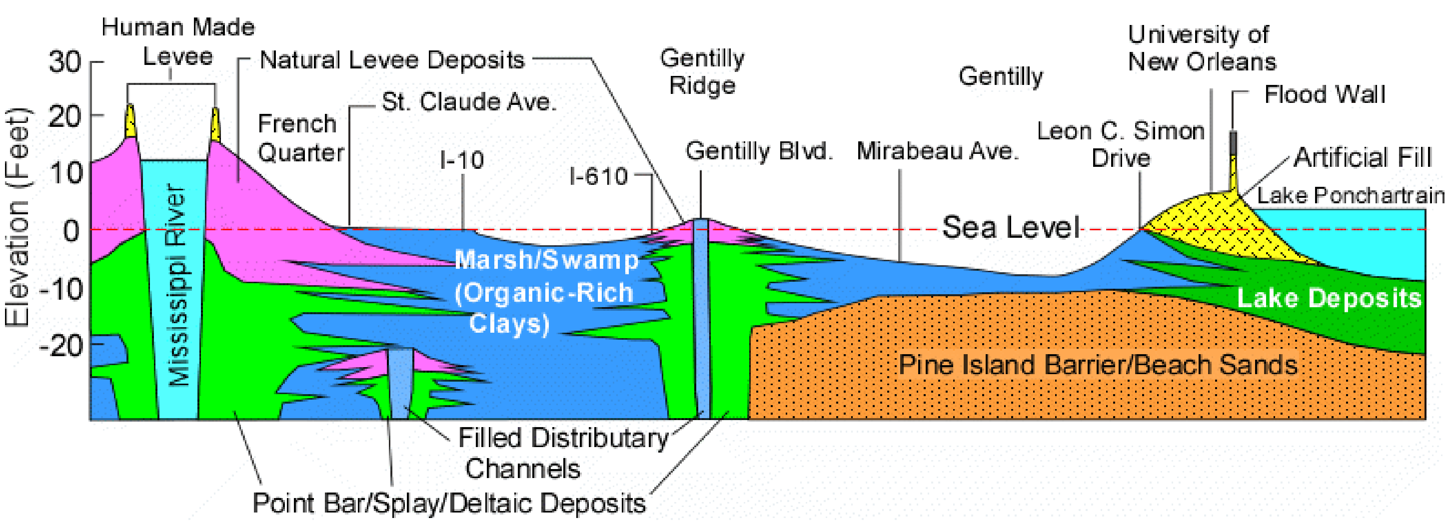

Figure 6. – Cross-section from the Mississippi River to Lake Pontchartrain showing Gentilly Ridge.

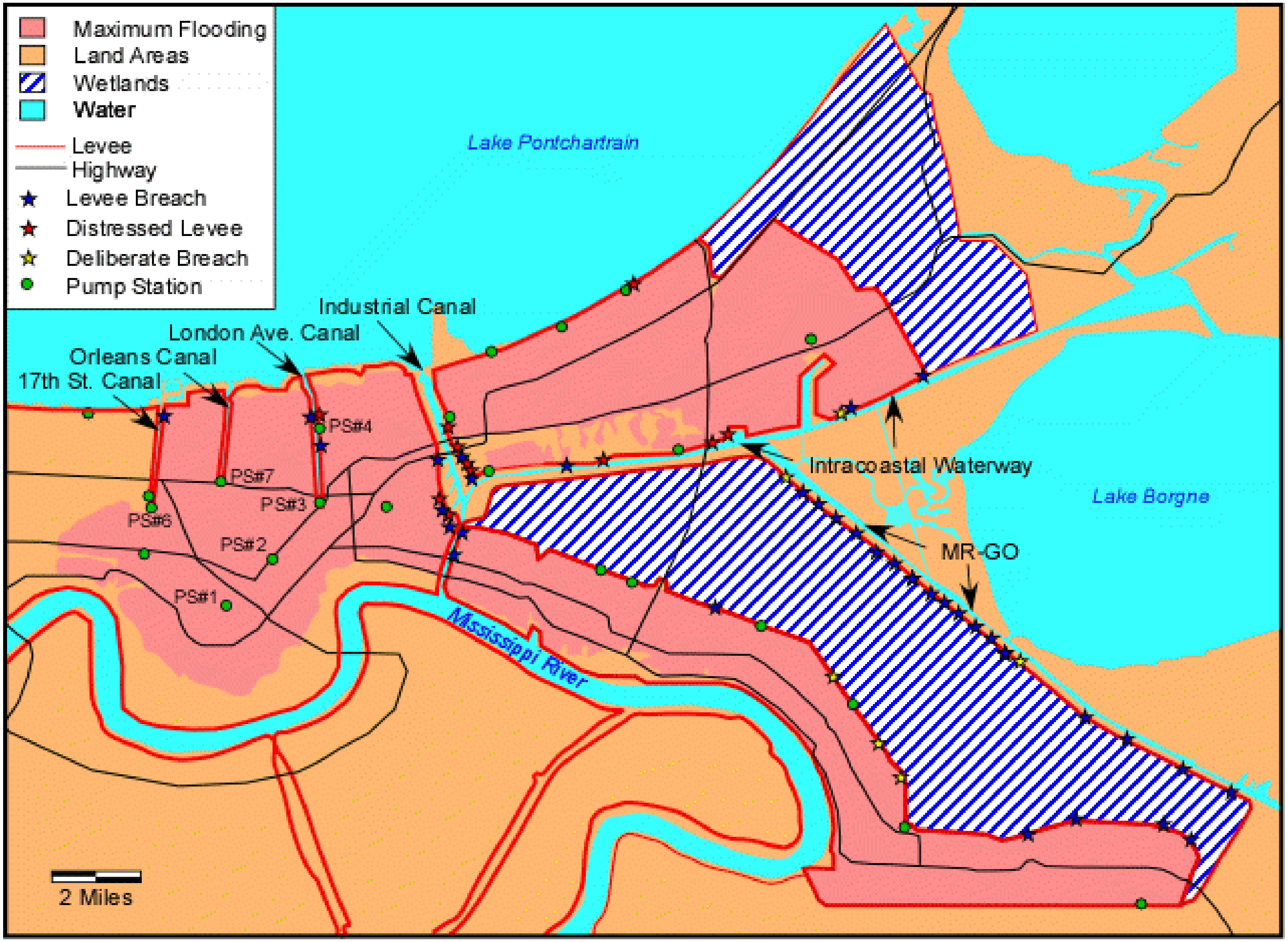

Figure 7. Map of maximum extent of floodwaters during Katrina modified and locations of breached levees after U.S. Army Corps of engineers- http://www.hq.usace.army.mil/cepa/katrina/pumps/pumps.html#New%20Orleans%20Pump%20Status and Seed et al. (2005).

Figure 8. 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)

Stop 1 is at Mirabeau Avenue and the London Avenue Canal. According second preliminary IPET report (IPET 2006), the breach at this site occurred between 7:00 and 8:00 AM on August 29. winds were blowing out of the northeast pushing water from Lake Pontchartrain into the drainage canals. Figure 14 shows the area of the breach before Katrina and Figure 15 shows approximately the same view on August 31 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 15, 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 is currently under repair. At the present time seepage is still occurring through the sand bag and gravel fill that was used to repair the breach, although this could also be due to broken city water mains in the breach area.

Notice the large deposits of sand that occur throughout the neighborhood. As of March 1, 2006 most of the sand has been removed from in front of the houses, but much remains in their back yards. 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 appears to have 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 16. 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 and 3.

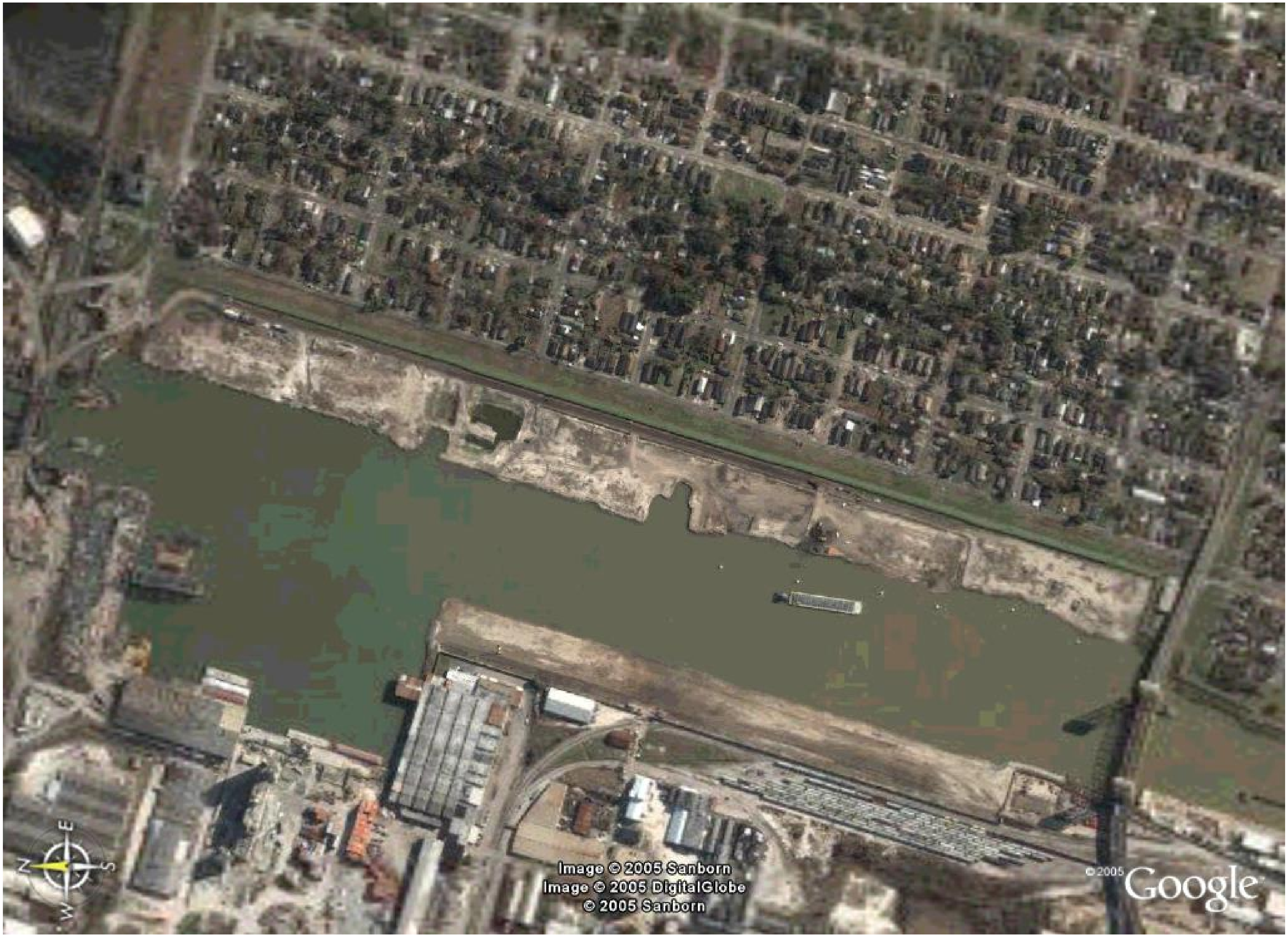

Figure 9. Satellite image of the area along the Industrial Canal where the levee was later breached during Hurricane Katrina. (Source - Google Earth)

Figure 10. 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 11. Looking North along the floodwall of the Industrial Canal levee showing trenches eroded by water from the Industrial Canal that overtopped the floodwall. Photo from U.S. Army Corps of Engineers IPET web site, taken October 4, 2005.

Figure 12. 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, taken October 4, 2005.

Sand is a highly permeable material. This means that water can easily be transported between the sand grains, especially when the weight due to 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 could undermine the levee and cause it to collapse. The principle is illustrated in Figure 17 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. 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 and IPET web site), one can see from the cross section in Figure 18, 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 placed to a depth of about 50 feet below sea-level where they would penetrate a layer of clay.

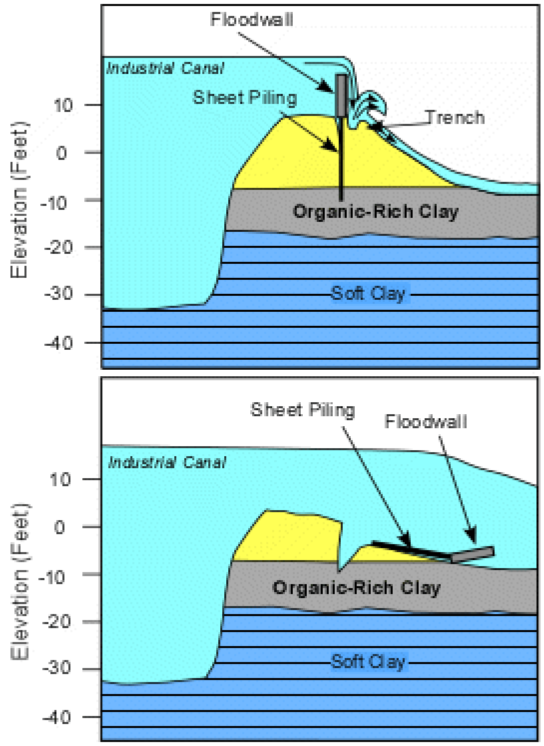

Figure 13. Possible failure mechanism at the Industrial Canal Levee breach in near the Lower 9th Ward.

Clay, because the individual mineral grains stick together and thus reduce pore space and interconnection between pores, is much more impermeable 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 2 and 4 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 be at elevation of 14.5 feet.

At stop 1 we will be able to walk up Warrington Drive and observe the levee breach which is currently under repair. We can observe the sand deposits, and cross bedding within the sand. Sand fills many of the houses, as well as the cars that were deposited here along with the sand (most have been removed as of mid-May, 2006).

Figure 19 is a view looking down Warrington Drive before the sand deposits were removed in mid-February, 2006. Figure 20 shows my preliminary map of the extent of the sand that was likely scoured out of the bottom of the London Ave. Canal and deposited throughout the neighborhood. My preliminary 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. The volume is apparently larger than the hole produced by the breach, and thus scour must have occurred on the bottom of the canal, both upstream and downstream from the breach. The distribution and thickness of the actual deposit was controlled by current velocity and barriers such as houses, fences, and hedges.

After leaving Stop 1, we will then wind our way around Gentilly looking at the damage and water marks eventually ending up at Stop 2 on Robert E. Lee Blvd. and the London Avenue Canal at Pratt Drive.

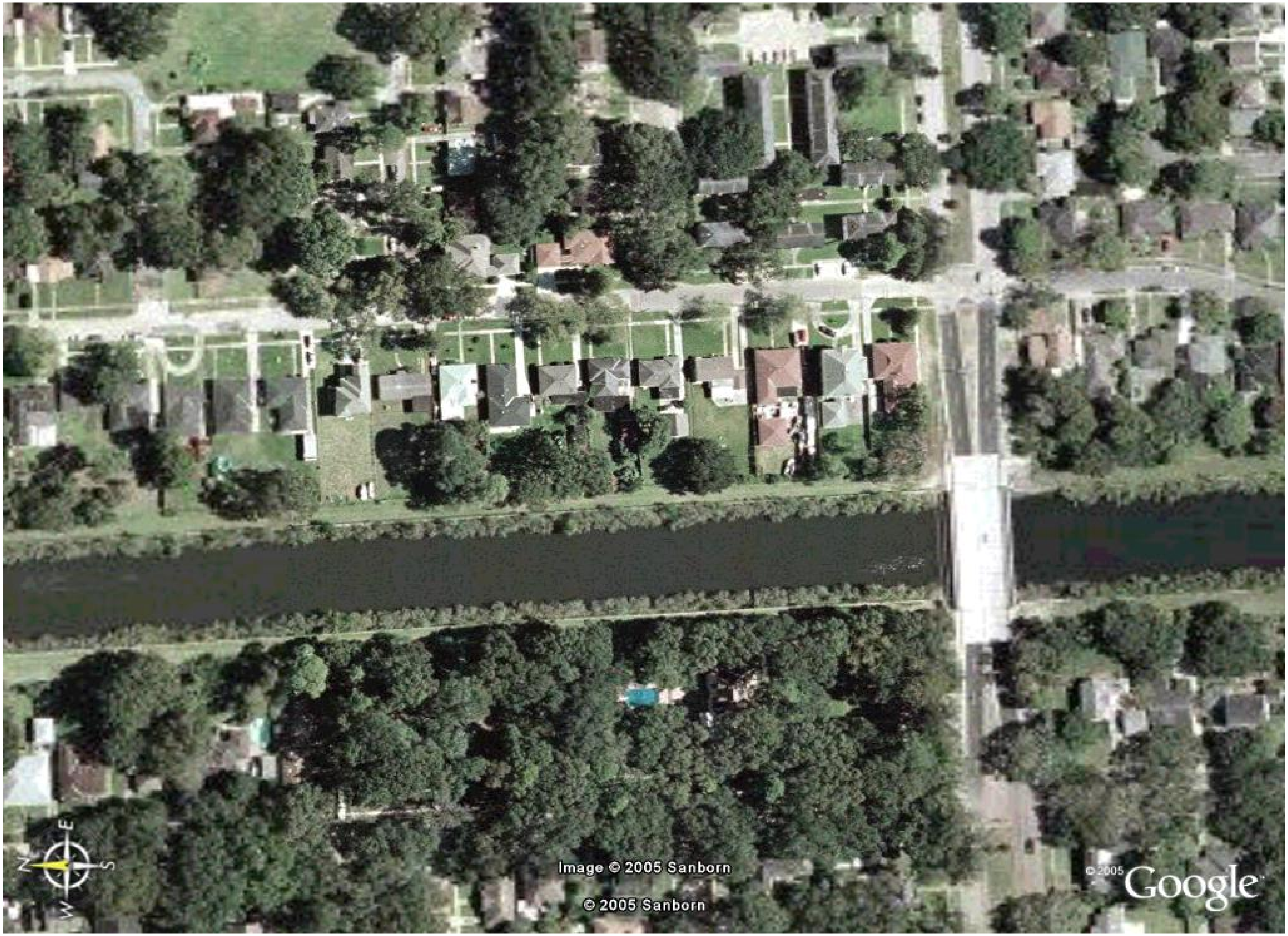

Figure 14. Satellite image of the area along the London Avenue Canal near Mirabeau Ave. and Warrington Drive (Stop 1), where the levee was later breached during Hurricane Katrina. (Source - Google Earth)

Figure 15. Air photograph of the area where the London Avenue Canal levee was breached near Mirabeau Ave. and Warrington Drive (Stop 1). Image acquired Aug. 31, 2005. Source: National Oceanic and Atmospheric Administration's National Geodetic Survey, Katrina Images - http://ngs.woc.noaa.gov/katrina/

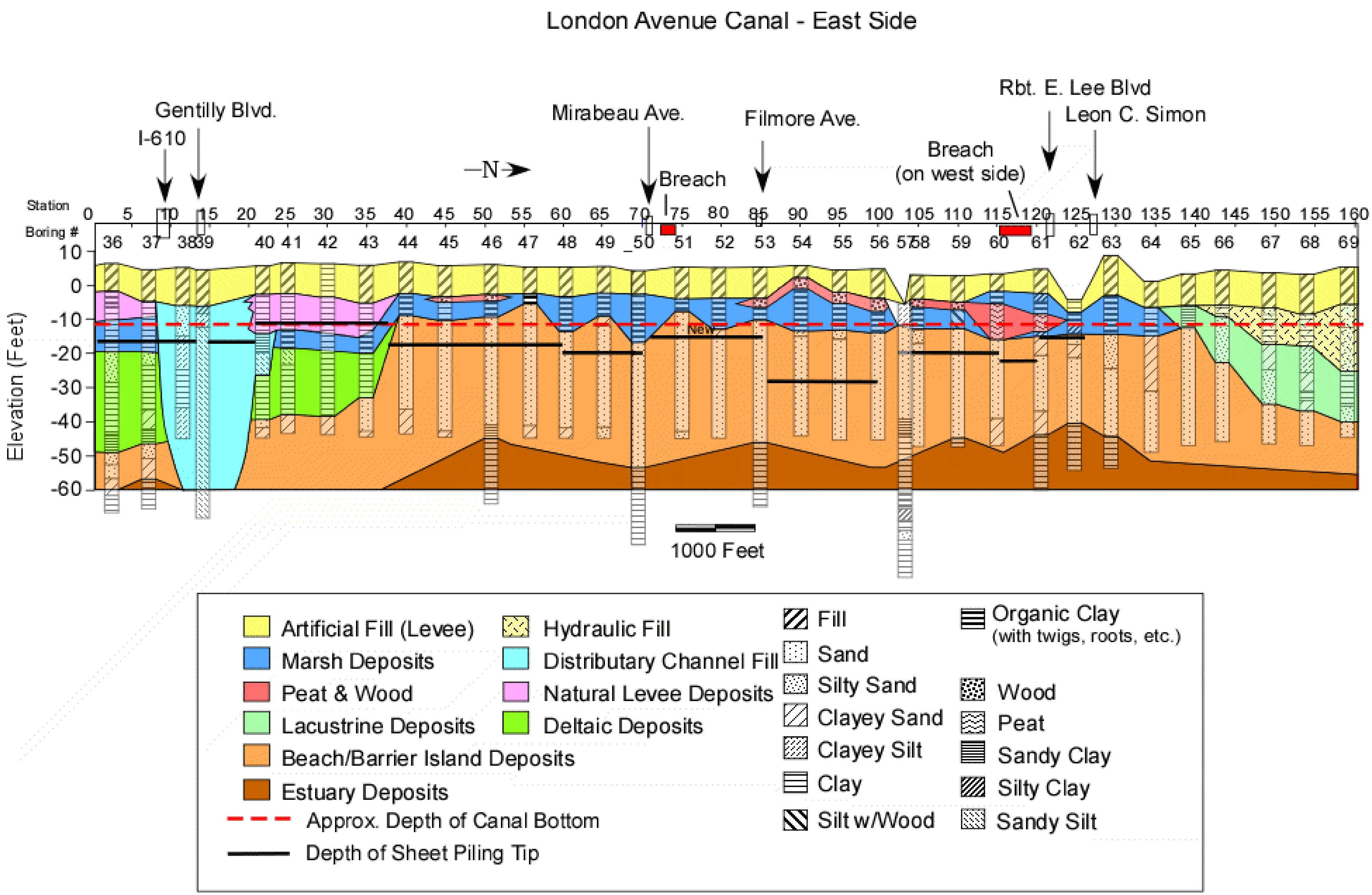

Figure 16. Geological cross-section along the east side of the London Avenue Canal constructed from data in U.S. Army Corps of Engineers (1989).

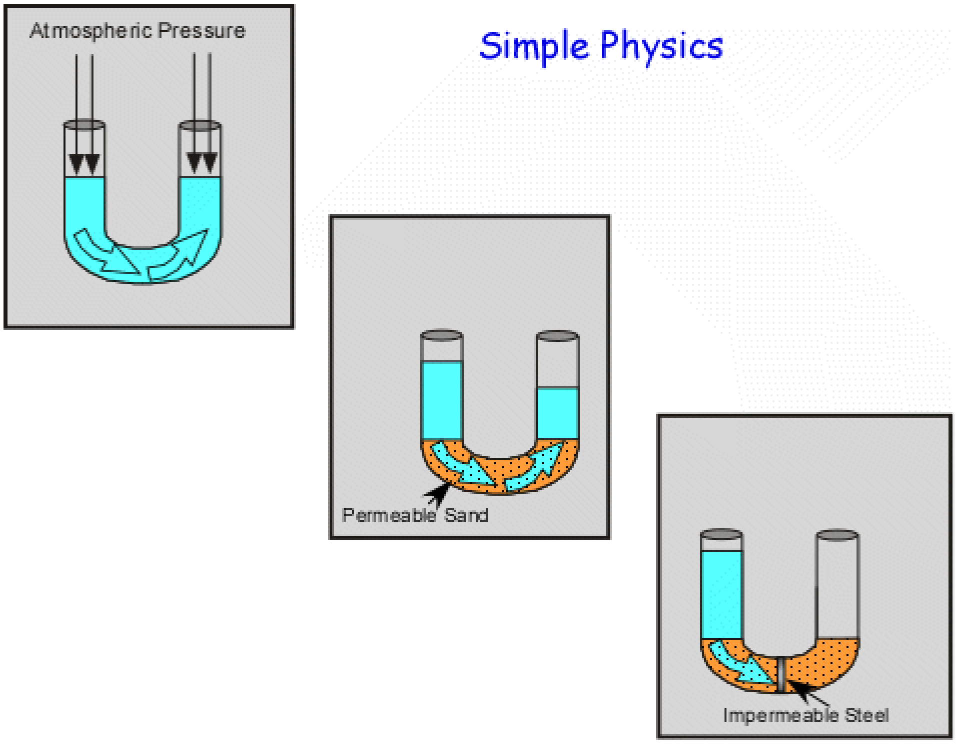

Figure 17. A simple thought experiment illustrates the principle of hydrostatic pressure by imagining a U-shaped glass tube. The water levels in each side of the tube rise to the same level because both sides of the tube are subject to the same pressure (atmospheric pressure). If a permeable material 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.

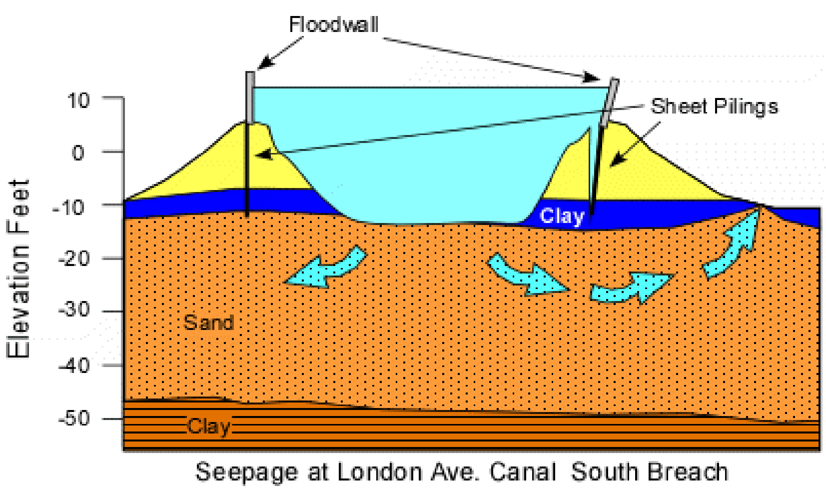

Figure 18. Geological cross section across the London Ave. Canal based on borings 16 and 51 (Figs. 15 and 22), shown at time of estimated high water during Katrina's storm surge. The sands form a permeable layer through which groundwater originating in the canal can penetrate and move below the sheet pilings and up to the surface, eventually undermining the levee and leading to its collapse.

Figure 19. Sand deposits on Warrington drive showing deposition in the wake of houses as the currents flowed down the driveways between the houses. As of March 1, 2006, most of the sands deposits have been removed.

Figure 20. 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 2 is near the intersection of Pratt Drive and Robert E. Lee Blvd. where the London Avenue Canal levee was breached on the west side of the canal. The estimated chronology suggested by IPET (2006) suggests that this breach also occurred sometime before 9:00 AM on August 29. Figure 21 shows an image of this area before Katrina. Figure 22 shows approximately the same area in an image taken on August 31 after the breach occurred and before the floodwaters had been pumped out.

We will first walk onto the levee on the west side of the canal, north of Robert E. Lee Blvd. Note that there is no flood wall on the levee north of Robert E. Lee and although the top of the earthen levee is higher here than south of Robert E. Lee Blvd., the top of the levee has an elevation well below the floodwall to the south of Robert E. Lee Blvd. Although this earthen levee has had some rock material added since Katrina, it is not substantially higher than it was pre-Katrina. Still there is no evidence that this earthen levee was topped and eroded by floodwaters coming out of the canal. Thus, the maximum water level in the canal would have not been higher than the top of the floodwall on the section of the levee to the south.

Further evidence of water level can be obtained within the canal itself. Note that there is abundant vegetation along the walls of the canal inside the floodwalls. This vegetation traps debris flowing in the canal and the height of this trapped debris in the vegetation can 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.

From this position on the levee north of Robert E. Lee Blvd., one can also observe the “distressed” floodwall on the east side of the canal. The floodwall is leaning away from the canal, but did not breach, probably because the west side breached and relieved the pressure on the east side (As of early May, 2006, the distressed floodwall has been removed and replaced by sheet piling..

Due to changes in construction activity at the breach, we may or may not be able to walk into the breach. The breach is about 400 feet wide. A geologic cross section of the west side of the levee is shown in Figure 23. 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.

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 24 and 25. Although the clubhouse shown in figure 24 has been removed during the repair of the levee, the house (with the mispositioned air conditioner compressor) is the 5th house south of Robert E. Lee Blvd. on Pratt Drive.

A short walk down Pratt Drive or along the levee breach reveals the presence of thick bodies of sand scoured from the bottom of the canal. These deposits are similar to the ones observed at the Mirabeau Ave. breach, but also contain blocks of peat as expected from the geologic cross sections shown in figure 23.

From here we will proceed west on Robert E. Lee Boulevard to Marconi Ave, then north to the Lakefront and Stop 3.

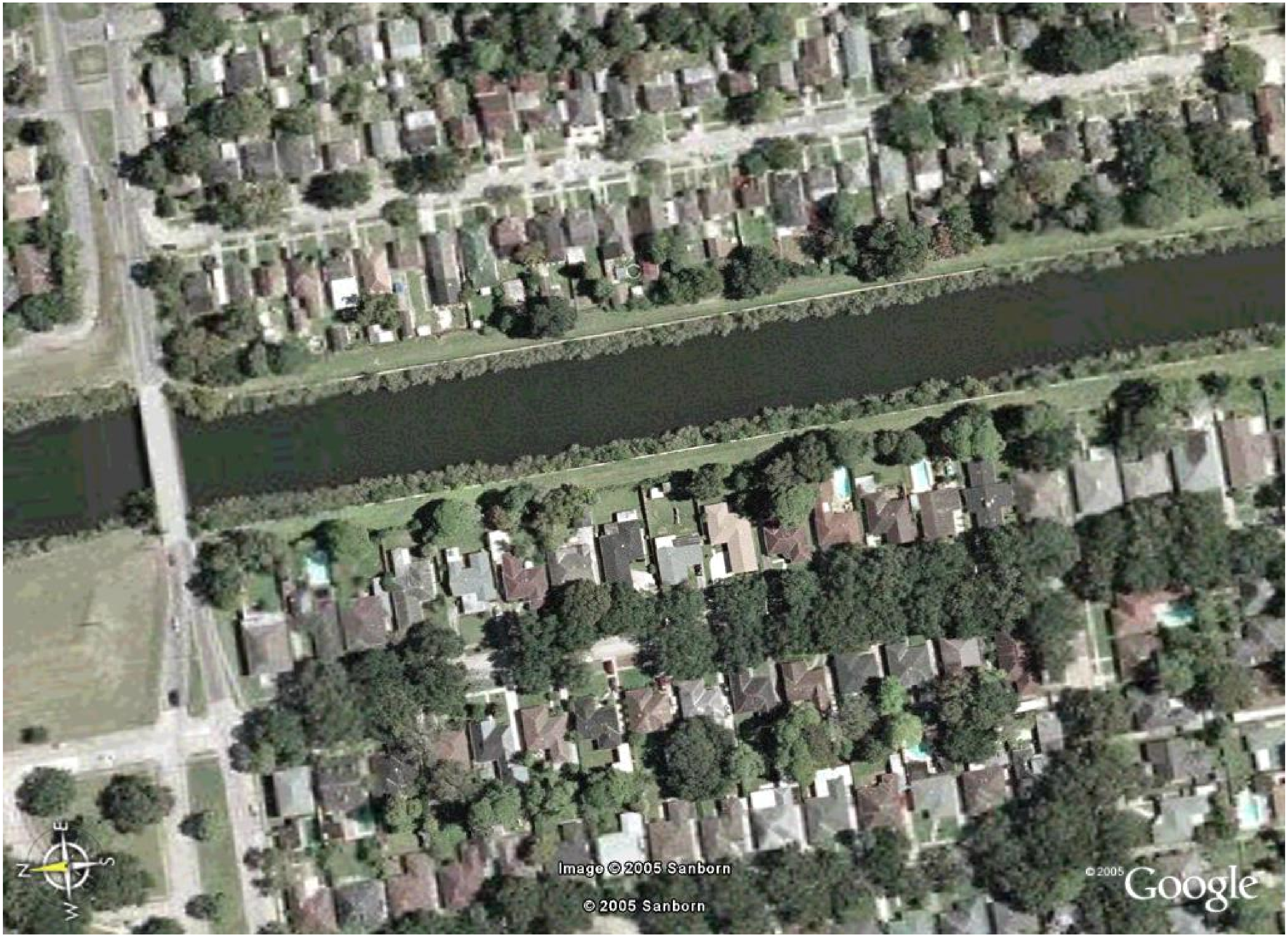

Figure 21. Satellite image of the area along the London Avenue Canal near Robert E. Lee Blvd. and Pratt Drive (Stop 2), where the levee was later breached during Hurricane Katrina. (Source - Google Earth)

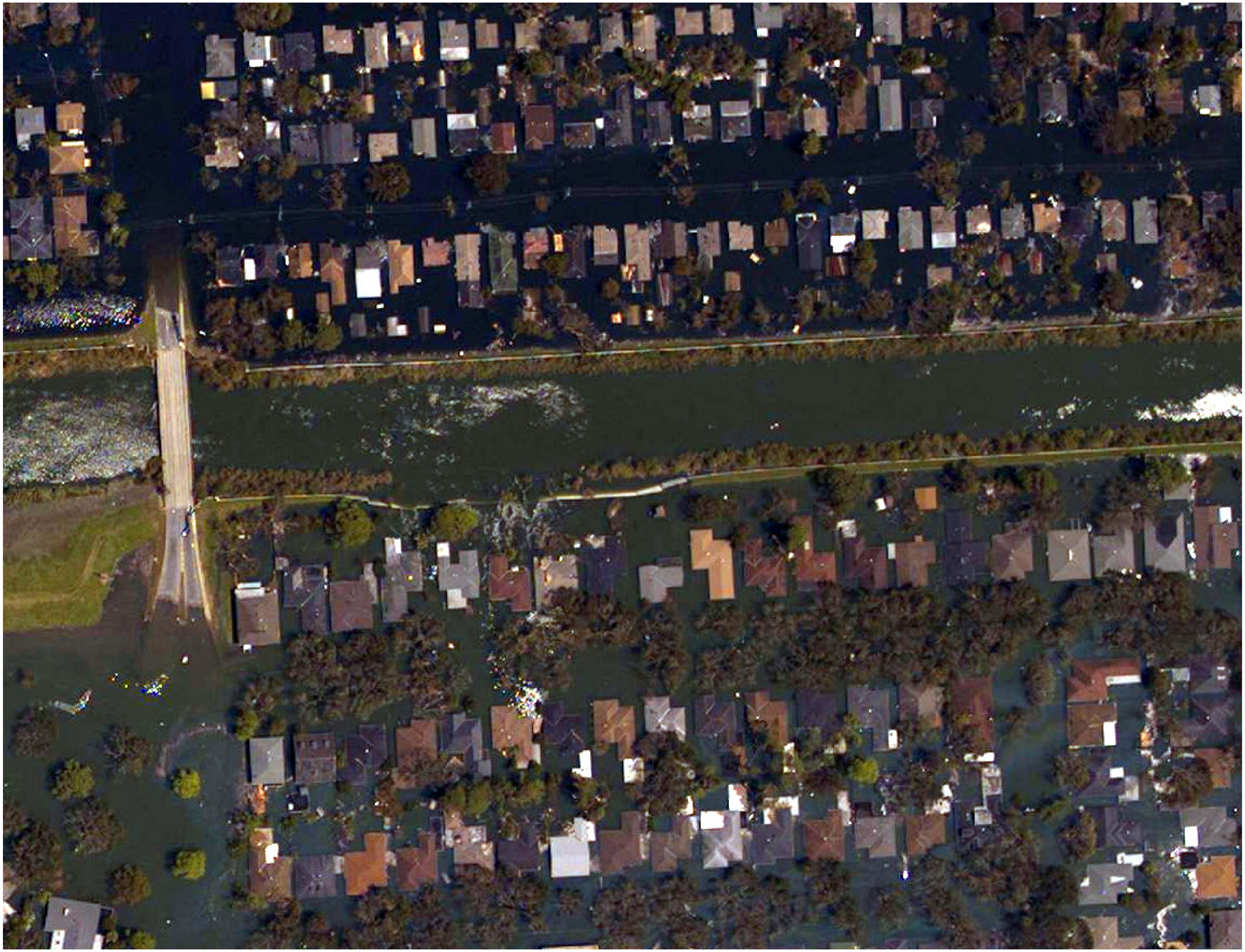

Figure 22. Air photograph of the area where the London Avenue Canal levee was breached near Robert E. Lee Ave. and Pratt Drive (Stop 2). Drive. Image acquired Aug. 31, 2005. Source: National Oceanic and Atmospheric Administration's National Geodetic Survey, Katrina Images - http://ngs.woc.noaa.gov/katrina/

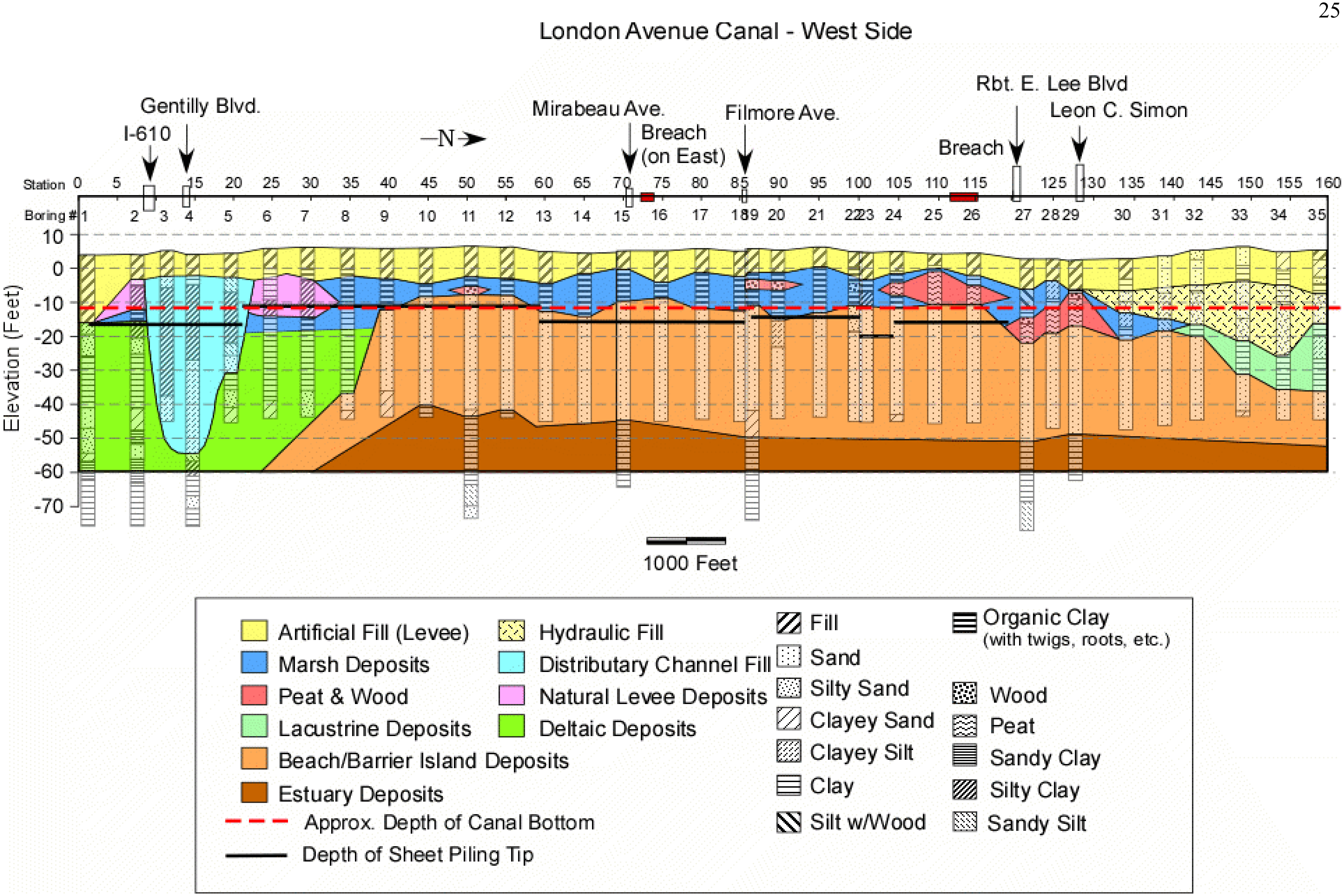

Figure 23. Geological cross-section along the west side of the London Avenue Canal constructed from data in U.S. Army Corps of Engineers (1989).

Figure 24. Child's clubhouse behind the Cantrell home on Pratt Drive uplifted along the west side of the London Avenue Canal near the breach (Stop 2). Source: Times-Picayune Tuesday, October 4, 2005. See reference to article by John McQuaid, same date

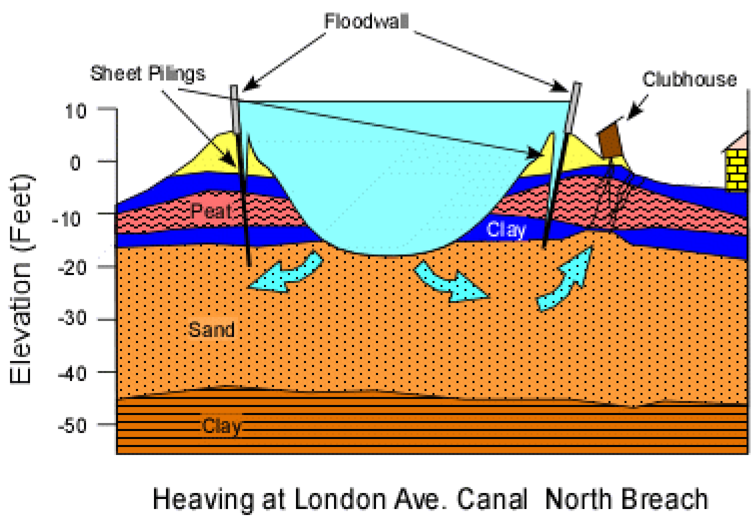

Figure 25. Water driven through sand under the sheet pilings (and possibly through peat, depending on the depth to which the sheet pilings actually were driven) pushes up the ground outside of the canal in a phenomenon known as heave. Thus could eventually provide a flow path for water which would undermine the levee and cause its collapse. This may have responsible for the eventual collapse of the floodwall resulting in the breach.

Stop 3 is at the Lakefront opposite Mardi Gras Fountain. 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 17 to 18 foot tall levees 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.

From here we will continue westward toward the Marina A short stop will be made to observe the burned out Southern Yacht Club (now torn down), the destruction of the Lighthouse, and boats still broken and strewn about the New Orleans Marina. We will then proceed back to Robert E. Lee Blvd, heading west and turn left into the area of the 17th St. Canal breach and Stop 4.

Stop 4 is in the area of the breach on the 17th 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. It was reported to WWL radio by the New Orleans Fire Department at 11:00 AM. The breach occurred along a 200 ft. section of the levee on the Orleans Parish side of the canal. Figure 26 shows an aerial view of the breach area before Katrina and Figure 27 shows approximately the same area on August 31 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. Here, the main part of the breach occurred in a recently cleared empty lot. A house to the south of the main part of the breach, built on a chain wall foundation, was completely removed. Natural gas from a line that fed the house can be seen bubbling up through the floodwater. Another house to the north of the empty lot was built on a slab. The house was destroyed, but the slab remains.

Also visible in Figure 27 is a section of the levee that was displaced eastward by about 45 feet. Although the floodwall that once crowned this levee is either buried or has been removed during the emergency repair work, the chain-link fence that sat atop the levee is still visible. The area in front of the displaced levee was pushed horizontally outward near the position of the yellow school bus. The toe of the slide is still visible and numerous blocks of peat can still be found in the area of the slide.

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 are seen on nearly every street leading away from Belaire Drive and the levee breach.

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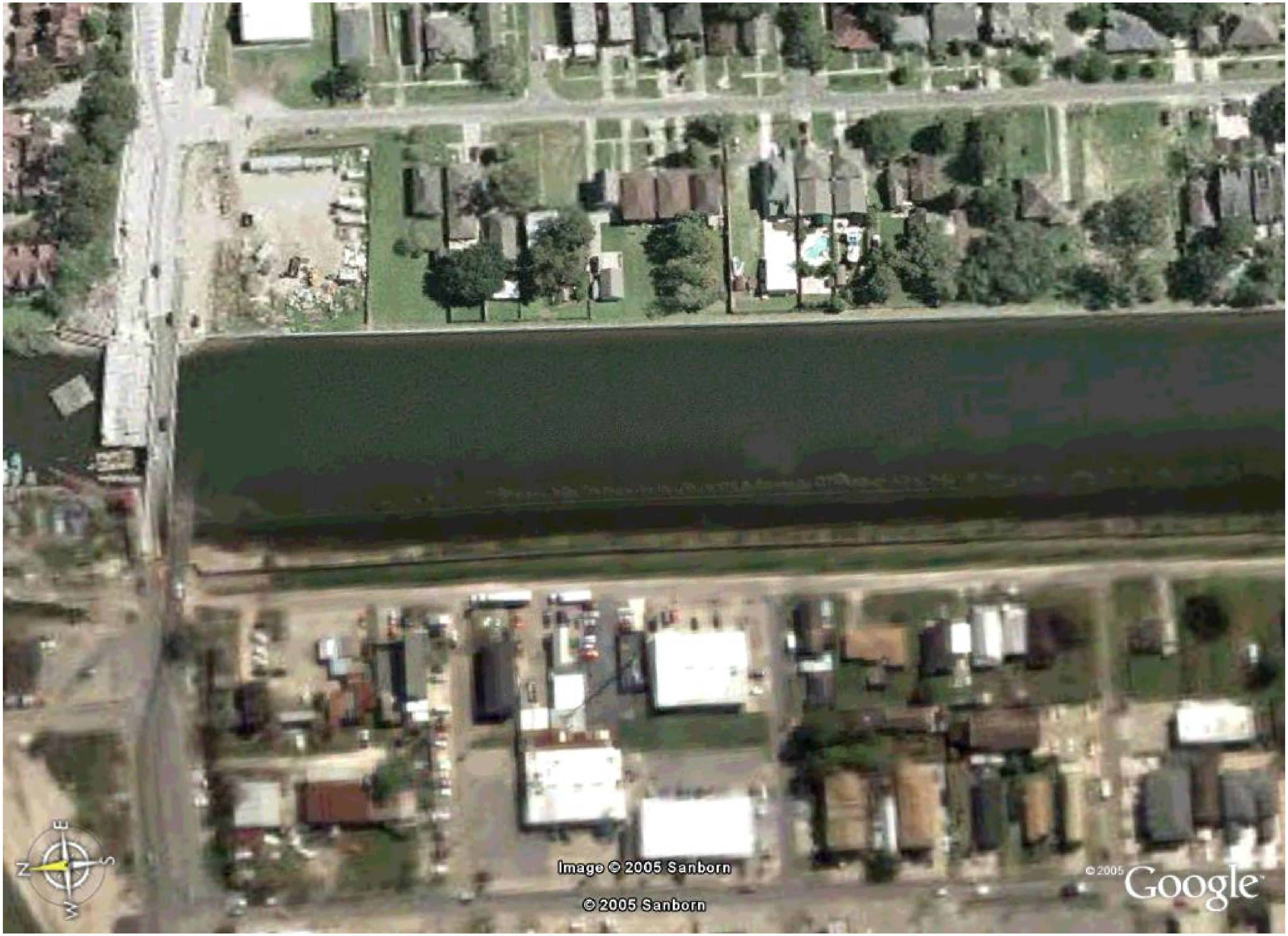

Figure 26. Satellite image of the area along the 17th Street Canal near the Old Hammond Highway Bridge (under construction), where the levee was later breached during Hurricane Katrina (stop 4). (Source - Google Earth)

Figure 27. Air photograph of the area where the 17th Street Canal Levee was breached near Belaire 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/

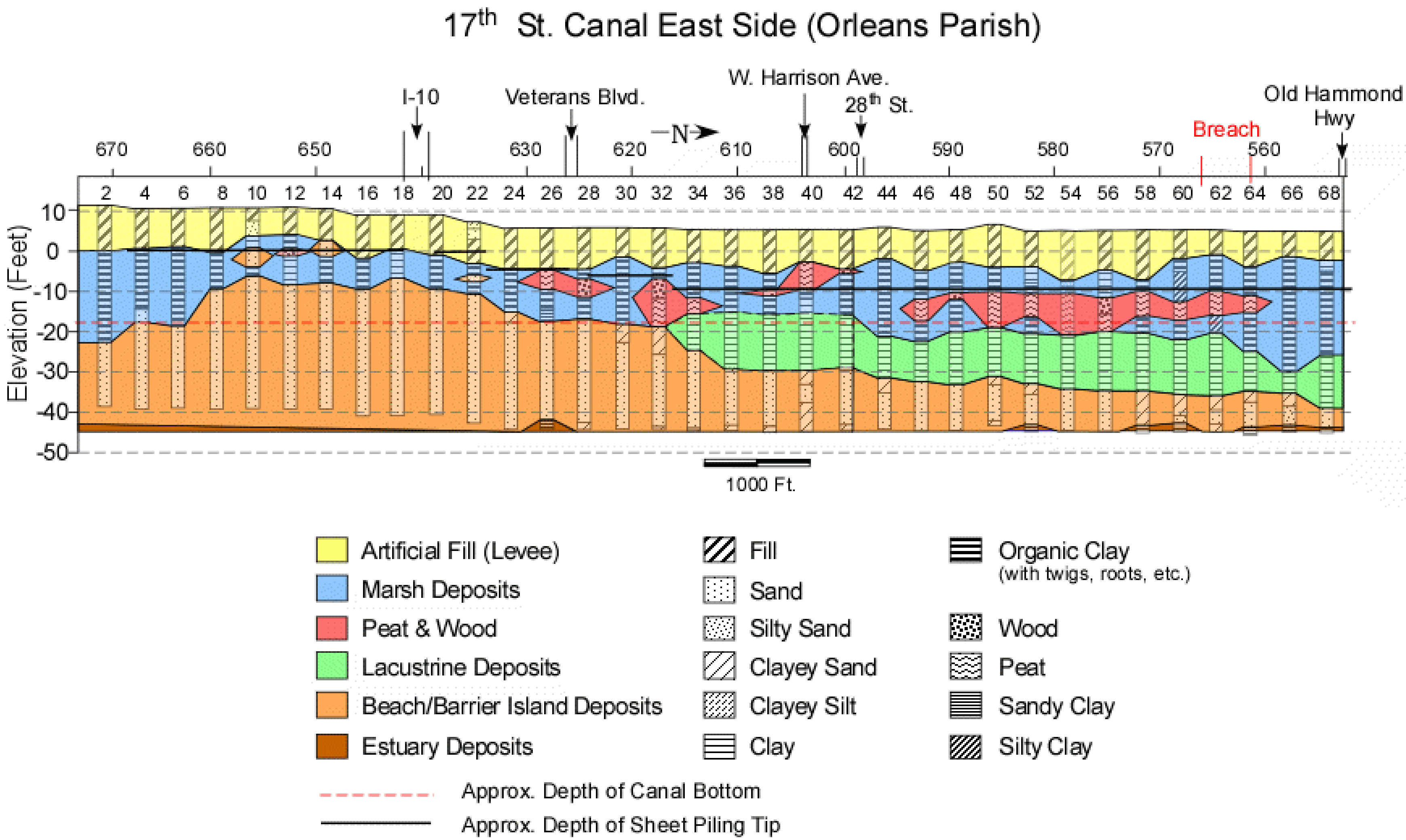

Figure 28. Geological cross-section along the eastern side of the 17th St. Canal (based on data in the U.S. Army Corps of Engineers design documents (1990). Notable in the cross-section is the peat layer that occurs in the area of the breach.

Figure 28 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, and Mark Schleifstein, and Shiela 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 28 summarizes the possible cause of failure. Although initial 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 inspections 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 (U.S. Army Corps of Engineers, IPET, 2005), 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 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 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 29.

A photograph of the end result of IPET's scale model centrifuge experiment is shown in Figure 30. 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.

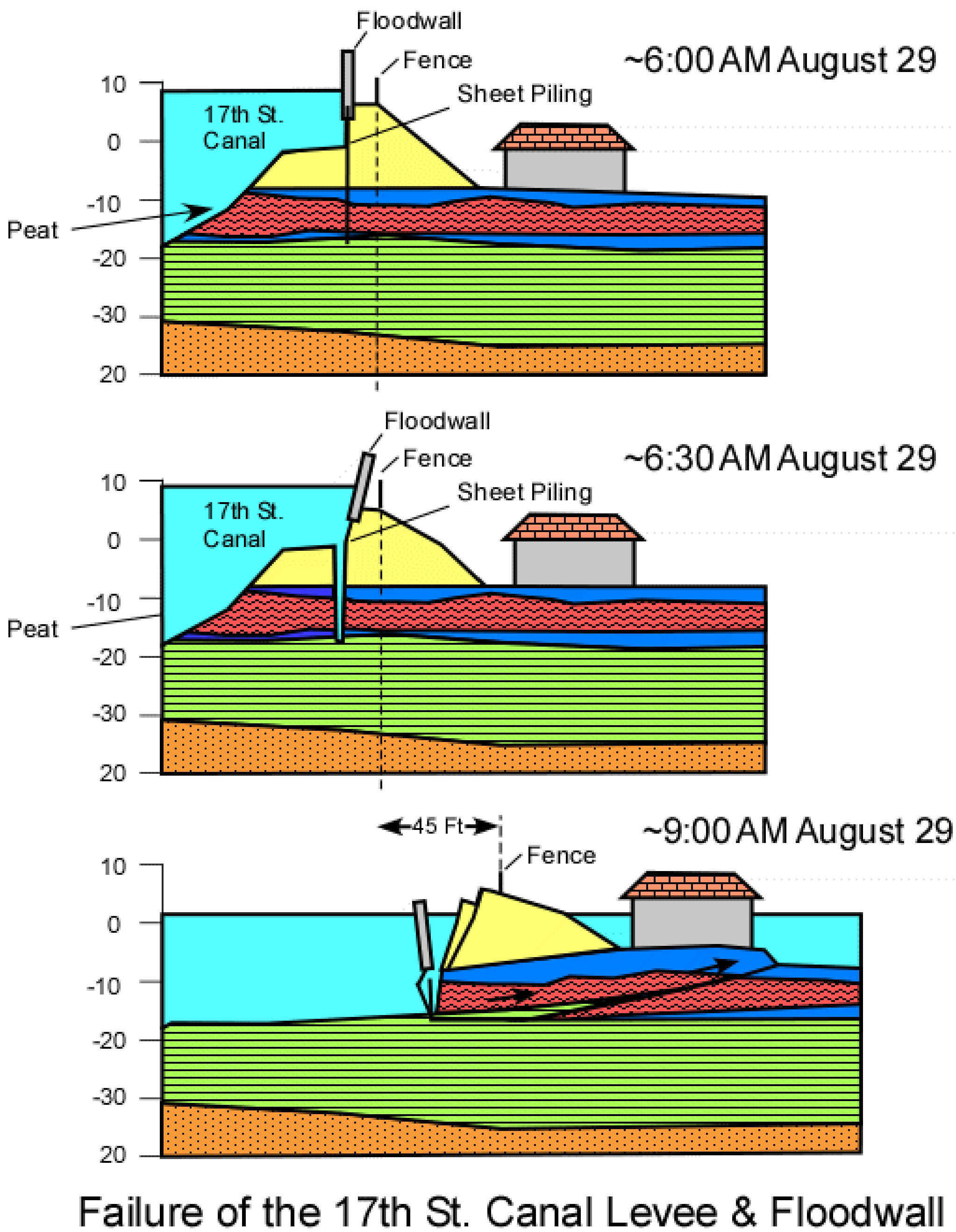

Figure 29. Diagrammatic cross sections across the 17 the Canal in the vicinity of the breach (based partially on a sketch in Seed and others [2005] and IPET (2006).

When IPET 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 real levees in the Atchafalya basin in 1985 (Marshall, March 14, 2006). 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).

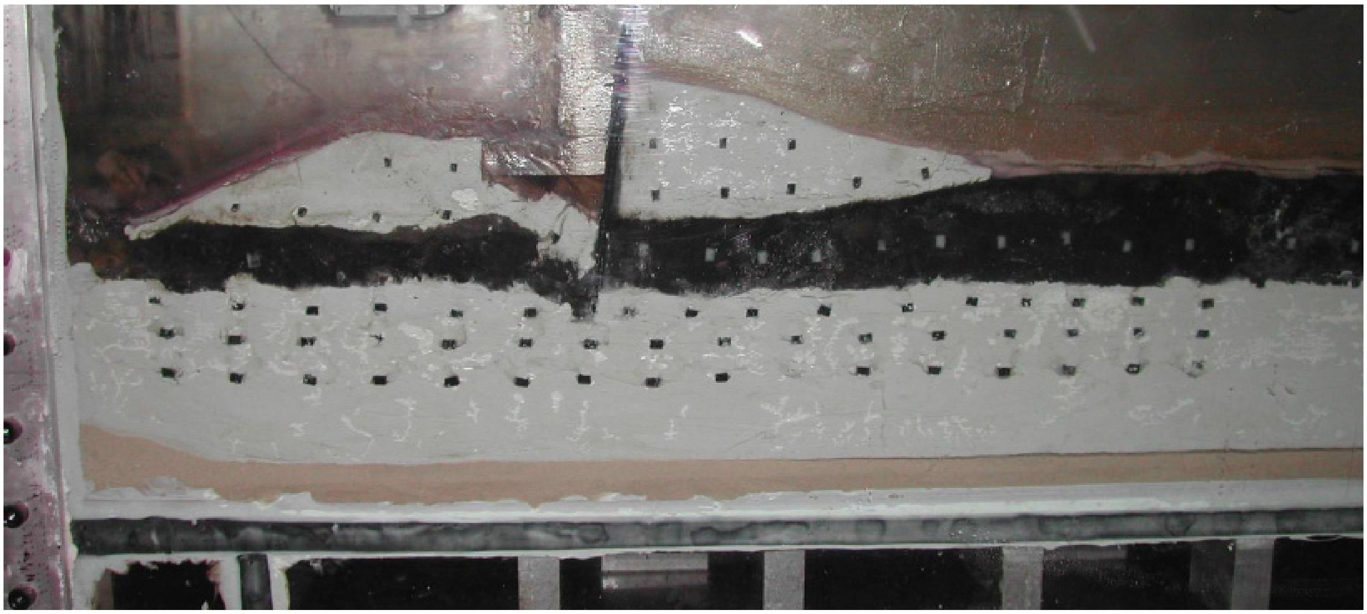

Figure 30. Phtograph of failed levee and floodwall in IPET's scale model centrifuge experiment representing the 17th St. Canal. The white at the top is clay and represents the levee. This overlies the dark peat layer, which in turn overlies another white clay layer meant to represent the estuary deposits beneath the peaty marsh deposits. Small rectangles were initially layed out in a rectangular grid and can be used to determine how much deformation has occurred during the experiment. (IPET, 2006).

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 31, 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 left) indicate that the maximum flood depth was about 1.5 to 2 feet higher than the line left by standing water.

Figure 31. 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.

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
Figures 32 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 - https://ipet.wes.army.mil/ 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 28).

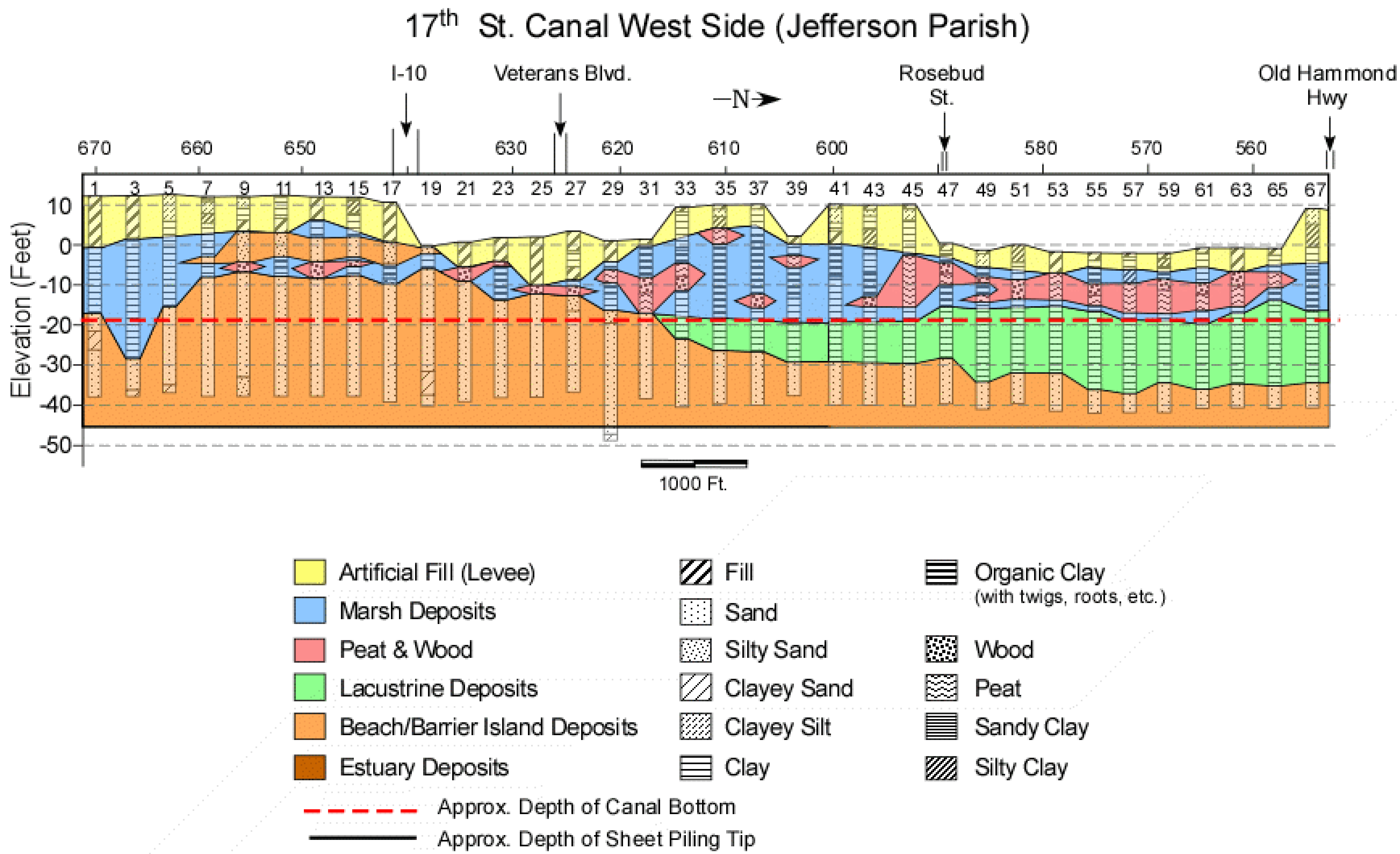

Figure 32 Geologic cross section of the west bank of the 17th St. Canal constructed from data provided to the U.S. Army Corps of Engineers (1990).

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 along the entire drive toward City Park Avenue, but as we approach City Park Ave., on the Metairie Ridge, notice that the depth indicated by the scum line becomes much more shallow. If going back to Tulane, we turn left on City Park Avenue and head east to Carrollton Avenue, turning right on Carrollton to go back to Tulane. If continuing on to Stop 5, we turn right on City Park Avenue where it becomes Metairie Road and head into Old Metairie and Stop 5.

Stop 5 is that the corner of Orpheum Avenue and Northline Street. It is through this area and along Airline Drive south of here, that flood waters from the levee breaches in Orleans Parish reached into Jefferson Parish. The flooding occurred south of the Metairie Road (on the Metairie Ridge) and extended west to Causeway Blvd. and south to near the River. Figure 33 is a Google Earth image of the area at the junction of the Palmeto canal and the 17th St. canal before Katrina and Figure 34 shows approximately the same area on August 31. This area is at the southern end of the 17th St. Canal where the Palmetto Canal brings water from Pump Station #1 on Broad Street (Figure 7) into the 17th St. Canal where it is lifted by Pump Station #6 about 8 feet in elevation and pumped out to the Lake (or through the breach in the 17th St. Canal). The Palmetto Canal has a short floodwall (about 3 feet higher than the roadway). Note in Figure 33, how the floodwalls on the Palmetto Canal are completely covered by water. The two bridges over the 17th St. Canal are barely above water, but it is clear that water flowed over and around these bridges into Old Metairie. It is also clear that Airline Drive, to the south, was a conduit for water to enter Jefferson Parish.

Within a few days after the August 31 image was taken, Jefferson Parish constructed temporary rock and sandbag levees over these two bridges, across Airline Drive, and across Claiborne Ave./Jefferson Highway, and at the Jefferson/Orleans Parish boundary. These temporary levees were apparently constructed to prevent more flood water originating at the levee breaches in Orleans Parish from further flooding Jefferson Parish. Although the levee breaches in Orleans Parish were mostly stopped by the time the temporary levees at the Parish line were constructed, the damage had already been done. There are, however, reports that once these temporary levees were built, Jefferson Parish started pumping water out of Jefferson and back into Orleans Parish. If true, this would have increased the amount of water over that already standing in Orleans Parish while the levee breaches were being patched and before the pumps in Orleans parish could be started to remove the water from the severely flooded areas.

Figure 33. Satellite image of the area near the southern end of the 17th Street Canal near Old Metairie where water would enter Jefferson Parish from levee breaches in Orleans Parish during Hurricane Katrina (stop 5). (Source - Google Earth)

Figure 34. Air photograph of the area where the water from the 17th Street Canal Levee Breach ran back into Old Metairie, near Orpheum and Palm (stop 5). Image acquired Aug. 31, 2005. Source: National Oceanic and Atmospheric Administration's National Geodetic Survey, Katrina Images - http://ngs.woc.noaa.gov/katrina/

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