New Orleans Levee System Performance during Hurricane Katrina: London Avenue and Orleans Canal South

Javier Ubilla, M.ASCE1; Tarek Abdoun, M.ASCE2; Inthuorn Sasanakul, M.ASCE3; Michael Sharp, M.ASCE4; Scott Steedman, M.ASCE5; Wipawi Vanadit-Ellis, M.ASCE6; and Thomas Zimmie, M.ASCE7

Abstract: Hurricane Katrina was one of the worst natural disasters in U.S. history. The effects of the hurricane were particularly devastating in the city of New Orleans. Most of the damage was due to the failure of the levee system that surrounds the city to protect it from flooding. This paper presents the results of centrifuge models conducted at Rensselaer Polytechnic Institute and the U.S. Army Corps of Engineers simulating the behavior of the levees at London Avenue North and South that failed during Hurricane Katrina. Those levees failed without being overtopped by the storm surge. Also included are the results of a centrifuge model of one levee section at Orleans Canal South, which did not fail during the hurricane. The key factor of the failure mechanism of the London Avenue levees was the formation of a gap between the flooded side of the levee and the sheetpile. This gap triggered a reduction of the strength at the foundation of the protected side of the levee. The results are fully consistent with field observations.

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Introduction

On August 29, 2005, a powerful Category 3 hurricane named Katrina hit the southern coast of the United States with catastrophic life and economic consequences. New Orleans was the city most affected during Katrina; the main reason being that the city is located almost entirely below sea level and surrounded by several large bodies of water. Lake Pontchartrain is located to the north of the city, Lake Borgne to the east directly connected to the Gulf of Mexico, and the Mississippi River running through the southern portion of New Orleans. The levee system that surrounds the city protecting it from flooding experienced extensive damage during the hurricane, leaving roughly 80% of the city under water.

Shortly after the hurricane, several multidisciplinary groups were formed with the goal to understand the causes of this disaster, in particular, the failure of the levee system. Many of those independent investigators visited New Orleans shortly after the hurricane to capture as much data and field observations as possible before the levee failure sites were disturbed by ongoing emergency repair activities. The field observations described in this paper were taken from a report published about three months after Katrina and sponsored by the National Science Foundation (Seed et al. 2005).

All of the work reported in this paper was conducted as part of the evaluation performed by the U.S. Army Corps of Engineers (USACE) regarding the hurricane protection system in southeast Louisiana. That effort initiated by the Chief of Engineers for USACE was termed the Interagency Performance Evaluation Taskforce (IPET). Part of that effort was a thorough analysis of the performance of the hurricane protection system. A component of that work was physical modeling of selected locations of the levee system, which is presented herein. The USACE provided critical information for the research presented in this paper, such as the pre-Katrina geometry of the levees and material properties, as well as storm surge water elevations and the general progression of events during Katrina, which was later published in USACE (2006).

This paper presents the results of 50g centrifuge physical models of the performance of two levee sections at London Avenue and one levee section at Orleans Canal. The tests were conducted at the Rensselaer Polytechnic Institute (RPI) in Troy, N.Y., and the USACE, Engineer Research and Development Center (ERDC) in Vicksburg, Miss. Duplicate physical models of the levees reported in this paper were conducted at both facilities to
ensure repeatability of the results and to add some measure of independence to the results. The results of the test conducted at RPI and ERDC are fully consistent with each other and confirm the repeatability of the results presented in this paper. Test descriptions, data analysis, and interpretation as well as a comparison with field observations are described in the following sections.

New Orleans Flood Protection System

Integral to New Orleans is a system of levees intended to provide flood and hurricane protection to the city and surrounding areas. Additionally, there are pumping stations located throughout the region, which maintain the groundwater level at a constant elevation and serve to remove rain water. This water is pumped into canals that then move into Lake Pontchartrain to the north of the city or into the swamps and bayous to the south.

The levees are, in general, earthen structures whose primary function is to provide flood protection from seasonal high water. To provide additional protection from storm surges associated with hurricanes, many of the levees had structural components added. Those structural components are in the form of sheetpiles driven through the levees with most having some type of concrete cap. That concrete cap in conjunction with the sheetpile was either a rather simple structure (I-wall) or a more complex structure (T-wall). In some instances, the sheetpile extends above the top of the levee without any type of concrete cap. Most of the levees that had increased hurricane protection added were in the form of I-walls or T-walls. A typical I-wall section is shown in Fig. 1. When the water level rises above the crest of the levee, the concrete cap serves to provide increased protection from flooding.

During Hurricane Katrina several sections of levees and floodwalls around the city failed as a result of the hurricane’s storm surge. Fig. 2 shows a satellite image where it is possible to observe the magnitude of the flood. This is evident in the darker areas lying between Lake Pontchartrain to the north and the Mississippi River to the south. This, of course, was a very heavily populated area.

Much of the damage occurred because the storm surge overtopped the levees. In those instances where the levee failed as a result of this overtopping the failure mechanism was primarily due to erosion. However, there were important exceptions where levees failed without being overtopped, in particular, sections of the levees along the 17th Street Canal and the London Avenue Canal (Fig. 3). Three major breaches, shown with a thick arrow, occurred in this area, one along the 17th Street Canal and two along the London Avenue Canal, producing catastrophic consequences. All three of these failures were on levees that had I-walls. Orleans Canal, lying between the 17th Street and London Avenue Canals had no failures during the storm. The canal has levees with T-walls on the west side and I-walls on the east side. This will be discussed in more detail in subsequent sections.

This paper contains the results of centrifuge models of the two breached zones at London Avenue and one nonbreached section near the southern end of the Orleans Canal. Centrifuge tests were also conducted for the breached zone at the 17th Street Canal and on the nonbreached zone near the north end of the Orleans Canal. Results of these centrifuge models can be found in Sasanakul et al. (2008).

The following sections describe the pre-Katrina geometries, water elevations, and material properties of the levees at London Avenue North, London Avenue South, and Orleans Canal, modeled in this study (USACE 2006). Also included are post-Katrina relevant field observations of the breached sections at these locations (Seed et al. 2005).
London Avenue, North Breach

Fig. 4(a) presents the estimated pre-Katrina configuration and dimensions of the levee, sheetpile, and soil layers for the location of the northern breach at London Avenue while Fig. 4(b) shows the idealized layout of the pre-Katrina levee configuration at the breached zone utilized for the centrifuge modeling. The zero elevation corresponds to the mean sea level. At the bottom there is a thick layer of fine sand, with a relative density of about 60%; this layer extends up to an elevation of around 4 m below the sea level. On top of the sand layer, there is a relatively thin layer of swampy/marsh, with a thickness between 2 and 3 m and undrained shear strength on the order of 10 kN/m² (200 psf). The levee was made of a clayey material, the crest of the flooded side extends up to an elevation of around 0.6 m above sea level, and its shear strength is around 25 kN/m² (500 psf). The top of the floodwall is at an elevation of more than 4 m above sea level and, is driven into the sand layer to an elevation of about 5 m below sea level.

The water elevation in the canal is generally maintained around a level of 1 m above sea level. During hurricane Katrina the maximum water levels in the canal were at an approximate elevation of 3.4–3.7 m, or approximately 1 m below the top of the floodwall [Fig. 4(b)]. All available information indicate that there was no evidence of overtopping producing erosion at the inboard sides of the intact levee floodwalls, anywhere along this canal.

A major breach occurred on the west bank of the London Avenue Canal, near the north end of the canal, as shown in Fig. 5. Based on post-Katrina field observations, the conditions at this site strongly suggest that the breach occurred as a result of the sheetpile being pushed backward by the elevated water pressures on the outboard side, and that support on the inboard side of the sheetpile was reduced as a result of soil failure at or beneath the base of the earthen levee embankment.

Fig. 6 shows the I-wall at the south end of the breach where the sheetpile/concrete floodwalls were pushed landward by the elevated canal waters during Katrina. The floodwall moved in a rigid manner. Fig. 7 shows the distress (excessive tilt) of a similar levee and floodwall system located directly across the canal (on the east bank) of the failed section. This photograph shows the outboard side of the floodwall, which has been pushed laterally. This has resulted in the opening of an extensional crack at the contact between the sheetpile wall and the levee. It is very clear that the distressed east bank section appears to be in an incipient

Fig. 5. Northern breach at London Avenue (adapted from Seed et al. 2005)
failure condition. The evidence at the “distressed” east bank section and at the breached west bank section are indicative of a similar distress and failure mechanisms.

Significant deposits of sediment were observed inboard of the London North breach, and these appeared to represent a mix of soils scoured out from the breached embankment section and its foundation, as well as sediments from the canal outboard of the failed section. Field observations also describe evidence of sinkholes related to underseepage and piping indicative of massive underseepage flows during the period when the water levels in the canal were elevated by the storm surge.

London Avenue, South Breach

A second major breach occurred further to the south, on the east bank of the London Avenue Canal. Fig. 8(a) shows the pre-Katrina cross section at that zone and Fig. 8(b) presents a simplified configuration of this location, which was used for the centrifuge modeling. The London South configuration is very similar to the London North configuration. The soil profile consists of a thick layer of fine sand with a relative density of about 60%. The sand layer extends up to an elevation of around 3 m below sea level. This profile is topped with a thin 1–2 m layer of swampy marsh with an undrained shear strength on the order of 10 kN/m² (200 psf). The levee itself was built out of a clayey material; the crest of the flooded side extends up to an elevation of around 1.5 m above sea level with a shear strength of approximately 25 kN/m² (500 psf). The top of the floodwall is at an elevation of about 4 m and its bottom about 5 m below sea level. The sheetpile was driven about 2 m into the sand layer.

As described previously, the water level in the canal prior to the hurricane was approximately 1 m elevation, while during hurricane Katrina the water level rose to approximately 3.7 m elevation. Fig. 9 shows an aerial view of this breach site, looking to the northeast during some temporary reconstruction work. The sheetpile/I-walls had again toppled inward toward the land side.

Postfailure scour was very extensive at this breach with significant deposits of soils from the embankment, foundation, and canal sediments from just outboard of the breach deposited in the neighborhood on the land side. As with the breach section farther to the north, the sheetpiles supporting the floodwall did not extend to great depth. This would not have provided a full cutoff for underseepage through the pervious sands.

Orleans Canal South

The levee section presented in Fig. 10(a) corresponds with a typical configuration of the southern end of the levees at Orleans Canal while Fig. 10(b) presents the idealized model used for the centrifuge testing. As in the cases of London Avenues North and South, the water level in Orleans Canal was not high enough to overtop the levees, however, contrary to the London Avenue sections, the Orleans Canal did not fail during Katrina’s storm surge.

The configuration and shear strengths of Orleans Canal are consistent with the London North and South configuration and soil strength. There are two main differences in the levee at Orleans Canal compared to London Avenue Canal. One is that the sheetpile is shorter and does not extend through the swampy marsh layer. The second is that the levee is a considerably larger structure, not being confined on its landward side by housing.

Centrifuge Modeling

Principles of Centrifuge Modeling

The ideal method to study the behavior of the levees at New Orleans would be to construct a full-scale model, and reproduce the same characteristics of the storm surge during hurricane Katrina. This obviously would be a very expensive and time-consuming task. Another possibility would be to construct a small-scale model of the levees, for example, a 1/50 scale model. However, the internal confining pressures within the model would be 50 times smaller than the prototype confining pressures in the field and, therefore, the behavior of the soil would not be reproduced accurately considering the fact that the soil stress–strain behavior and strength are highly dependent on the confining stress.

One very attractive and economical solution is the centrifuge modeling. So, a small 1/N model is artificially subjected to centrifugal forces in order to increase the gravitational field N times. In that way, the unit weight of the small-scale model is increased N times and, therefore, the confining stress conditions of the prototype are reproduced inside the centrifuge model. Using a centrifuge, the behavior of the levees at New Orleans or any other geotechnical system can be more accurately modeled.
The tests described in this paper were conducted in the 150g ton, 3-m-radius geotechnical centrifuge at RPI and the 350g ton 6.5-m-radius centrifuge at the ERDC. More information about each research center can be found at www.nees.rpi.edu and www.wes.army.mil/centrifuge.

There is a set of well-established scaling laws related to centrifuge modeling (Taylor 1995). In general, this scaling is related to the physical units of the property that is being scaled. In this case, the centrifuge tests were conducted at 50g, which means that the physical dimensions of the models were 50 times smaller than their equivalent prototype.

The materials used in this study to create the levee models were Nevada Sand #120 for the sand layer (Arulmoli et al. 1992), aluminum plates for the sheetpile, and Kaolin clay for the levees and undisturbed swampy marsh, taken directly from New Orleans. Details of the properties of the materials used in these centrifuge models as well as the characteristics and dimensions of the container utilized can be found in the companion paper Sasankul et al. (2008).

The generic model configuration is shown in Fig. 11. The three studied models (London Avenue North, London Avenue South, and Orleans Canal) have the same general setup and are different only in the geometry of the levee, the thickness of the swampy marsh layer, and the height and depth of the sheetpile. The sequence of model construction proceeded as follows. The Nevada sand layer is rained in dry with instrumentation placed at the appropriate location [Fig. 12(a)]. In this layer the instrumentation consisted of pore pressure transducers (PPT) and markers along the Plexiglas, which allowed observing any soil movement. As the sand was being rained into the model it was also densified with a small compacting device to reach a final relative density of approximately 60%. The model was then sealed, vacuumed, and the sand layer saturated. At the conclusion of this process, the sheetpile was positioned [Fig. 12(b)] making sure that there was a tight fit between the sheetpile and the container. A rubber gasket and vacuum grease were placed in the contact between the sheetpile and the box to prevent leaking through this contact and also allow free movement of the sheetpile. Then, the undisturbed layer of swampy marsh was sliced into segments of the appropriate

**Material Properties, Model Preparation, and Setup**

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thickness and placed on top of the sand [Fig. 12(c)]. Prior to placement of the layer, both penetrometer and moisture contents were obtained. The average shear strength values obtained using a pocket penetrometer were about 20 kN/m$^2$ (400 psf) and the moisture contents were 357%. Pore pressure transducers were inserted in the layer in the location corresponding to the footprint of the levee.

The model was then placed on the centrifuge with a small amount of gravel having a footprint and total weight equivalent to the weight of the levee that eventually would be placed on top of the swampy marsh layer [Fig. 12(d)]. The model was spun up to 50g and allowed to fully consolidate. Consolidation using the gravel was intended to simulate the natural process of consolidation that would occur in the foundation from the weight of the levee over time. During the consolidation process there was constant monitoring of the PPTs in the swampy marsh layer and displacement transducers on the surface. The consolidation was considered finished when the pore water pressure and the surface displacement readings reached stability. The consolidation process took around 4–5 h. This was a critical process in the model construction to ensure that the strength profile across the section would be correct.

At the conclusion of the consolidation process with the gravel, the gravel material was removed and the completed levee sections were placed on top of the swampy marsh layer. Again, in the contact between the levees and the lateral walls of the box a layer of vacuum grease was placed to avoid water leaking through these boundaries. The levee was made of kaolin clay that had been consolidated in order to reach the appropriate shear strength and then trimmed into the correct levee geometry [Fig. 12(e)]. The shear strength of the clay deduced from penetration measurements after consolidation averaged 17 kN/m$^2$ (360 psf) and the moisture contents averaged 61%. The levee consisted of upstream and downstream sections that were placed against the sheetpile on top of the peat [Fig. 12(f)]. Instrumentation that consisted of PPTs and displacement markers was added to the levee sections.

Figs. 13(a–c) present the prototype dimensions and sensor setup for the models of the London Avenue North breach, London Avenue South breach, and Orleans Canal, respectively. The sensors were placed at the centerline of the model in the $Y$ direction. In all the models two laser displacement sensors at different heights were placed along the sheetpile in order to measure the wall displacement and rotation. Several video cameras were installed as well, for viewing the levee from different angles.

Once the model was completed and all instrumentation connected and zeroed, the package was slowly spun up to 50g at a rate of 0.25g/min. This spin up occurred over the course of several hours to prevent any prefailures associated with sudden increases in pore pressure. Water was maintained in the canal at a depth of approximately 1 m until 50g was reached. At 50g, the model is properly scaled having the correct weight and pressure at

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**Fig. 10.** (a) Orleans Canal South pre-Katrina configuration (adapted from USACE 2006). (b) Configuration of the 50g centrifuge idealized Orleans Canal South model in prototype units.
all points in the model, consistent with the field prototype. The water level in the canal was increased to normal canal operation level. The model was then allowed to stabilize at 50g with the correct canal water elevation prior to addition of flood load.

**Pre-Katrina Hydraulic Conditions**

Seepage in the sand layer was driven by a differential head between the water in the canal and the ground water table on the landward side. Over time in the field, a steady-state flow net will develop governing the excess water pressure or head at different locations under the levee. Figs. 14(a–c) show steady-state flow nets calculated using the software SEEP-W (Geo-Slope 2004) compared to piezometric head levels measured by pore pressure transducers in the sand for the London North, London South, and Orleans Canal configurations, respectively.

Based on the pre-Katrina flow nets, it is possible to observe that for both London Avenue North and South configurations there is a very small influence of the sheetpile on the flow net in the sand. In the case of Orleans Canal, there is no interaction between the flow net and the sheetpile.

**Crack Formation**

In the field and in all the centrifuge model tests, a crack or gap was observed to form on the canal side of the wall once water had reached certain elevations above the crest of the levee. The gap permitted a full hydrostatic head of water to develop to the bottom of the crack, which in the case of the London South and North profiles, provided a hydraulic connection between the underlying sand layer and the canal above the center of the levee. The effect of the crack opening in the pore water pressure within the sand layer is further analyzed in the following section of this paper.

The formation of the crack followed the rise in water level on the canal side. As the water level rose against the levee, the flood wall did not experience any increase in lateral load. However, once the water reached the flood wall, a hydrostatic force started to build up on the wall pushing it landward. The flood walls included in this study worked as cantilever beams and therefore, the rising water on the flood wall was reacted by a small rotation of the wall, resisted by the embedment of the sheetpile wall and the passive resistance of the levee material on the landward side of the flood wall. Any rotation of the wall landward will mobilize...
passive resistance against the flood condition and immediately open a water-filled crack on the canal side.

Evidence for the formation of the crack is clearly seen for the London South model in the video imagery from the model tests, seen here in Fig. 15, which shows the early stage of the levee failure, where the arrows indicate the initial and displaced position of the sheetpile. This is consistent with field observations as presented earlier in this paper. The same behavior was observed in the London North model.

Model tests carried out on a cross-sectional representation of the Orleans canal where the sheetpile is relatively shallow, not reaching the underlying sand layer, showed very small movements of the wall at flood levels up to Katrina. Beyond the Katrina flood level (over 1 m higher) movement of the wall was observed indicative of crack formation. This is clearly seen in the video image, Fig. 16.

**Rotation of the Wall**

In the London North and London South centrifuge models, where the toe of the sheetpile wall penetrated into the sand, the opening of the crack on the canal side of the flood wall was followed by a rotation of the wall landward. Laser displacement sensors on the wall and video images recorded the horizontal movement, as shown in Fig. 17 for the London South model. Fig. 17 presents the time history of the rotation of the wall with the canal elevation and the pore water pressure below the swampy marsh layer around the wall. The values of the pore pressures are in meter column of water, so it is comparable with the canal elevation. The prototype time was normalized by the wall failure time defining parameter \( \tau = \text{prototype time/wall failure time} \).

In all of the centrifuge models where the sheetpile reached the sand layer the sheetpile showed gross movements indicative of wall failure. The rotational movement was accompanied by a translational sliding of the landward part of the levee with the underlying swampy marsh layer, on top of the deeper sand layer.

In Fig. 17 it is possible to identify clearly the different stages involved in the failure of the wall. At the beginning the canal level is at the normal operational level in the pre-Katrina condition, then the canal level starts to increase due to the storm surge and the pore pressures (PPT A and PPT B) next to the bottom of the sheetpile follow the tendency. Around \( \tau = 0.45 \), there is a change in the slope in the pore pressure measured with PPT A; this change is associated with the opening of a small crack between the upstream half of the levee and the sheetpile (at this point the wall rotation is negligible). The opening of this crack is consistent with the field observations in the early stages of the failure, as shown in Fig. 7.

Once the crack is open the canal water level keeps increasing. There is a point around \( \tau = 0.75 \) where the wall starts rotating and the pore pressure measured with PPT A increases sharply because the flow through the crack is increasing. This situation occurs until the wall failure stage is reached and there is full hydraulic connection between the sand and the canal through the crack (\( \tau = 1 \)). After this point it is possible to observe that pore pressure

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**Fig. 13. Centrifuge tests sensors setup (dimensions in prototype units)**
PPT A and the canal level have the same slope over time. The same was observed in the field, as shown in Fig. 6, where the wall was tilted due to the water pressure in the canal side.

The opening of the initial crack in the London North and South breaches where the sheetpile goes through the swampy marsh had the effect of producing a hydraulic connection between the canal and the sand next to the sheetpile in the upstream side. This produced a rearrangement of the flow net in the sand layer, as shown in Fig. 18, for different stages during the failure at London South. The change in the flow nets lead to increase in the pore pressures below the levee. Fig. 18 also shows the pore pressure head compared with the total vertical stress. This stress is a product of the weight of the swampy marsh and the levee calculated at the top of the sand layer measured in meters of the water column, so it is comparable with the water pressure head.

Fig. 18 clearly shows the reduction in effective stress on the protected side of the levee due to the increase in pore water pressure associated with the rearrangement of the flow net. The figure shows that even before Katrina the water pressure was very similar to the vertical total stress below the swampy/marsh at the toe of the levee of the protected side. Furthermore, during Katrina the water pressure became much greater than the vertical total pressure, meaning that the effective stress at that level was zero. This explains two more field observations: one is the soil failure below the protected side of the levee and the other is the presence of sinkholes in the protected side in zones where the levee did not reach full failure.

The reduction in vertical effective stress has two effects: the
first is to increase the likelihood of uplift of the swampy marsh layer (as the increasing water pressure in the foundation balances the weight of the levee and peat layer above) and the second is to reduce the stiffness of the sand surrounding the toe of the sheet-pile wall, reducing the passive resistance against the movement of the wall. Fig. 19 presents a schematic summarizing failure progress for the London North and South levees: (a) canal water rise; (b) crack formation; (c) development of full lateral hydrostatic pressure on the wall and increase in pore pressure under the levee (uplift) weakening of the levee foundation; and (d) failure of the levee system.

No Failure Condition

Scale model tests were also carried out on levee sections simulating the typical configuration of the southern portion of Orleans Avenue Canal. This section did not fail, and the objective of this test was to better understand the failure mechanism of the London Avenue sections. The southern portion of the Orleans Avenue levees has soil foundation conditions similar to the sections at London Avenue. The major difference in the levee configurations is the penetration of the flood wall (the toe of the wall is at the base of the levee top of the swampy marsh layer) and the levee geometry (Fig. 10).

As previously mentioned, the approximate elevation of the canal level during Katrina’s storm surge was between 3.4 and 3.7 m above the main sea level. This water elevation corresponds roughly to 0.8 m water height above the crest of clay levee on the canal side [Fig. 10(b)]. This is much less than the approximate 2.6 and 2.3 m water heights above the crest of the clay levee on the canal side of the London North Levee [Fig. 4(b)] and the London South levee [Fig. 8(b)], respectively. In order to fully examine the response of the southern portion of the New Orleans levees, the centrifuge model was conducted in two stages: During the first stage the water elevation was set at 0.8 m above the crest of the levee.

**Fig. 16.** Crack opens for Orleans Canal model

**Fig. 17.** Failure stages for London Avenue models
levee, simulating Katrina’s conditions. During the second stage the water elevation was raised to about 2 m above the crest of the levee (the maximum water elevation without overtopping the floodwall), which is comparable to the 2.3–2.6 m water elevation estimated for the London Avenue levees.

During Stage 1 simulating the hydrostatic loads during Katrina’s storm surge, the floodwall of Orleans Canal did not show any significant movement [Fig. 16(a)]. After maintaining Katrina’s storm surge elevation for an extended period and reaching stability of all the measurements, the canal water level was increased to the top of the wall [Fig. 16(b)]. This water level is roughly 1.2 m above Katrina’s water level or 2 m above the crest of the canal side of the levee, which is comparable to the London North and South cases. At this stage the formation of the water-filled crack was observed to open reaching the toe of the flood wall and was associated with small movements of the flood wall landward, as shown in Fig. 16(b). Unlike the London levee models, this crack did not develop into a full failure condition and no unstable movement of the flood wall was observed afterward, despite the water level reaching the top of the flood wall. It was clear from the measured pore pressures under the levee that there was no increase in the water uplift pressure associated with the small movement of the sheetpile (formation of the crack). In this case, as the sheetpile did not penetrate through the swampy marsh, the flow of water through the formed crack was significantly reduced by the presence of the relatively impermeable swampy marsh. This is very different from what was measured in the London Avenue levee models, where the formation of the crack seems to provide full flow passage from the water in the canal directly to the permeable sand in the foundation. These measured results indicate that the penetration of the sheetpile through the swampy marsh layer into the sand seems to be a key factor triggering high uplift pressure and reduction of the effective stress on the protected side of the levee, producing the failure of the levees during Katrina.

**Conclusions**

This paper presents the results of centrifuge models conducted at RPI and ERDC studying the behavior of three levee sections in New Orleans during Hurricane Katrina: London North, London South, and Orleans Canal. In all cases studied the hurricane’s
storm surge was not high enough to overtop the levees. London North and South correspond to two breached sections along the London Avenue Canal, with catastrophic consequences. The levee along the southern portion of Orleans Canal is located nearby and has similar soil conditions but did not fail.

The key point of the failure mechanism is the formation of a crack between the flooded side of the levee and the sheetpile. This triggered an increase of water pressure below the protected side of the levee and, therefore, a reduction of the effective stress at the foundation of that section of the levee, reducing the foundation strength as the load on the sheetpile was increasing. This situation produced the failure of the London North and London South sections.

In the case of Orleans Canal, during Katrina’s storm surge the floodwall was subjected to less hydrostatic loads than those of London Avenue. Also, in this case the sheetpile did not cut through the peat layer. Negligible movement of the sheetpile was observed under these conditions. When the canal water level was elevated above Katrina’s level, in such a way that the load over the floodwall was comparable to the London Avenue sections, the water pressure opened a crack between the levee and the sheetpile on the canal side, but did not trigger a reduction in the effective stress below the protected side of the levee and cause failure of the levee system.

The very good agreement between the field observations and forensic investigations conducted shortly after Hurricane Katrina and the centrifuge tests, once again confirms the effectiveness of the centrifuge tool to model complex problems of soil–structure systems. The measured and visual data collected during the centrifuge model tests provided crucial information for understanding the response of the New Orleans levee system during Hurricane Katrina. The data obtained from the centrifuge tests presented in this paper and the companion paper (Sasanakul et al. 2008) are valuable for the validation and calibration of numerical models.

In terms of recommendations for future design, the critical event that triggered the failure of the levees was the fact that, after the opening of the gap, water from the canal reached the base of the sheetpile, reducing the effective stress of the foundation at the London North and London South levees. One way to avoid this situation for future design would be to drive the sheetpile much deeper into the sand below the peat layer, in such a way to significantly increase the lateral support of the sheetpile and, at the same time, reduce the flow of water below the sheetpile. More research would be needed to determine the minimum depth at which the tip of the sheetpile should be installed.

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References


