FORENSIC INVESTIGATIONS GET TO THE FACTS

East Side IHNC Flood Wall Breaches during Hurricane Katrina

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Photo courtesy of Peter G . Nicholson.

I served as a geotechnical expert for the U.S. Department of Justice (DOJ) supporting the defense of the U.S. Army Corps of Engineers (USACE) against alleged professional negligence in its design of the flood walls for the Inner Harbor Navigation Canal (IHNC). A group of attorneys representing individuals affected by the levee failures launched a lawsuit, as Plaintiffs, seeking tens of billions of dollars of restitution from the U.S. government. This article briefly describes the case and its outcome, focusing on the different theories of failure for two flood wall breaches and presenting my assessment of the failures based on additional investigations. (Editor's note: The subsequent article by Pat Lucia beginning on p. 42 provides additional background and perspective about the flood wall breaches. Also see "Levee Failure Mechanisms," by Reed Mosher and Mike Duncan, in the January/February 2007 issue of *GEOSTRATA*.)

Figure 1. **Failed flood wall near the Florida Avenue Bridge. (Photo courtesy of U.S. Army Corps of Engineers.)**

The Event

In the early hours of August 29, 2005, Hurricane Katrina slammed New Orleans and overwhelmed its flood protection system. Levees and flood walls failed in many locations, resulting in massive flooding, and more than 1,800 deaths and $150 billion in economic losses. The Lower 9th Ward was hit particularly hard following two separate breaches on the east side of the IHNC flood wall.

The two breaches, referred to herein as the North Breach and South Breach, occurred as the water level in the canal rose to unprecedented levels. The North Breach, located about 150 ft south of Florida Avenue, occurred around 6 am and opened to approximately 210 ft wide (Figure 1). The South Breach, located 870 ft north of North Claiborne Avenue, started around 7-8 am and opened to approximately 820 ft wide (Figure 2). Water flowed through these breaches at very high rates and was responsible for a major portion of the flooding of the Lower 9th Ward. Once the floodwaters started to recede, water slowly flowed out of the Lower 9th Ward through the breaches until the pumping system drew the internal water level below ground. Subsequently, the USACE constructed rockfill dikes to provide temporary closure of these and other breaches.

Prior Investigations

While preparing for trial, the DOJ experts faced conflicting prior opinions regarding the causes of the flood wall failures. The USACE had assembled a team of internal and external experts, referred to the Interagency Performance Evaluation Team (IPET), to characterize and evaluate the failures resulting from Hurricane Katrina. That team assembled information on flood wall configuration, subsurface conditions, and storm water levels in order to assess the performance of the flood walls loaded with high water levels. IPET concluded that sliding through weak foundation soils caused the North Breach, with stability further reduced by relatively low ground levels on the land side of the levee. IPET concluded the South Breach resulted from overtopping of the I-wall that that led to an overturning failure.

The American Society of Civil Engineers (ASCE), at the request of the USACE, assembled an External Review Panel (ERP) of independent experts (ERP) to evaluate the principal failures. ASCE's ERP reached conclusions similar to those of IPET for the two IHNC breaches.

The University of California at Berkeley assembled another team with modest funding from the National Science Foundation and the large effort of many volunteer professionals to investigate the Katrina failures, including the breaches discussed here. This team, referred to as the Independent Levee Investigation Team (ILIT), concluded that both breaches were likely caused by underseepage-induced instability of the land-side levee toe owing to high horizontal permeability of soil beneath the sheet pile wall, and that overtopping and land-side erosion may have contributed.

The U.S. Department of Defense (DOD) commissioned an independent study by the National Research Council (NRC) to consider the work of IPET. Although NRC found the failure mechanisms proposed by IPET to be plausible, back-analyses only matched the observed surge elevation at failure by introducing a full-depth gap and assuming very low shear strength in the clay beyond the toe of the levee. The NRC thus found the documentation and analyses provided for the IHNC breaches to be insufficient for independent review and inadequate to support definitive conclusions on cause of failure.

There were other key questions left unanswered by these prior studies, including:

- Why had the flood wall only failed at these two locations and not others along the east IHNC?
- What had the eyewitness — who claimed to hear a loud explosion and see a hole in the wall — actually heard and seen?
- Why was the concrete portion of the I-wall completely missing in many locations after the failures?

- Why was there a long tear and a failed joint on adjacent sheet pile sections recovered from the North Breach?

Work by DOJ Experts

The DOJ expert team organized a field and laboratory investigation program to further define the strength and permeability characteristics of the foundation soils in the vicinity of the two failures, as well as at non-failed areas. This involved extensive field and laboratory tests to measure the stress history and shear strength of the foundation soils below the levee for use in global stability analyses and finite-element modeling of deformations versus flood level. This team was joined by experts from Washington Group International, which, as a contractor already performing work on the IHNC, was a co-defendant with the USACE.

A key ILIT premise was that the levee foundation soils contained a layer of high-horizontal-permeability soil that allowed water pressure to transmit to the protected side of the flood wall in a matter of minutes. This premise was critical to the conclusion that the two IHNC breaches resulted from instability of the land-side levee due to high pore pressure from the flood side of the wall. Because the Plaintiffs in the case retained some of the authors of the ILIT report as experts, DOJ anticipated this failure mechanism would be one basis for its claim that the USACE was negligent in its design of the flood wall.

Plaintiff and Defendant teams agreed to work together in a joint program to measure the in-situ permeability of the soft peat layers that ILIT had concluded had high-horizontal permeability. Field pump tests and laboratory tests demonstrated that the peat layer was a compressible soil with low permeability, on the order of 10^{-6} cm/sec; thus, it would not have been possible to transmit water pressure to the land side of the flood wall within minutes.

During the field investigation, the DOJ team located two failed sheet pile sections retrieved from the North Breach and observed a 12-ft tear at the top of one section and a torn connection at the bottom of the other. These sheets, and others from both breach locations, had been stretched horizontally. These observations clearly indicated that the sheet piles had been plastically deformed along their horizontal axis.

The DOJ experts also investigated the condition of the I-wall prior to the failures, particularly regarding the top of the wall elevations. We expected the wall had settled differentially along its length; but all prior investigations assumed that the top of the east IHNC wall was at El. +12.5 ft along its entire 4,000-ft length. We found survey data taken by the local Water and Sewer Board on several occasions prior to the failures. These measurements showed that the top of the wall likely varied from a low of El. +11.3 ft at the North Breach, to another local low of El. +12.1 ft at the South Breach, to a high of El. +12.8 ft along the approximate 4,000-ft length between the south and north corners. The North and South breaches therefore occurred at local low spots along the top of the wall.

The North Breach

After studying the old and new data and the results of many analyses, I concluded that a structural failure in the I-wall concrete and steel sheet piling at the transition between the wall's construction in 1969 and 1980 initiated the North Breach. Several more inches of horizontal translation of the flood wall section to the south of this transition compared to the north section caused the sheet pile to stretch along its horizontal axis. The section to the north had longer sheet piles and more soil mass on the land side; thus, it was inherently stiffer than the section to the south. The weak soils and relatively low ground level on the land side of the flood wall produced a relatively low factor of safety (FOS) against global stability, which resulted in greater relative lateral displacement.

The differential horizontal movements of the two sections of flood wall caused tensile forces to build up in the I-wall

Figure 2. **Photo at South Breach of IHNC. (Photo courtesy of USACE.)**

Figure 3. **Rotated I-wall. (Photo courtesy of USACE.)**

elements, to the point that the two sections of sheet piling just south of the 1969-1980 intersection deformed plastically along their horizontal axis by a substantial amount. These sections were recovered and the plastic deformations measured.

As the sheet piles started to elongate along their horizontal axis, they stretched the concrete wall sitting atop the sheeting laterally along the wall axis in ways it was not designed to resist. Portions of the concrete wall then failed in tension and fell off the wall, creating a gap several feet wide in the wall through which water gushed. Simultaneously, excessive tensile forces caused one of the sheets to tear, starting at the location where a previous tear had been poorly welded during prior construction. When the tensile forces transferred to the bottom of the sheeting, a connection with a third sheet failed from bottom-up, completely separating the southern and northern wall sections.

Failure of the concrete, tearing of the sheeting, and rupture of the connection likely occurred very rapidly, possibly creating the explosive sound heard by an eyewitness situated at a nearby pump station. I concluded that water gushing through the wall gaps rapidly eroded soil in front of the wall, allowing a segment to rotate outward and pull away from the transition. The eyewitness observed these events as described in his deposition. The steel object he described was likely the tops of three steel sheets he saw occasionally through the gushing water. As the canal water level continued to rise, land-side scour of the flood wall embankment caused the failure to propagate southward until the water levels on each side of the embankment equalized.

Stability analyses showed that the flood wall likely had a low FOS against global instability, which may have led to lateral wall deformations, but apparently did not result in the failure. No team found any evidence to indicate the occurrence of a global instability within the foundation soils at the North Breach.

The South Breach

I concluded that overtopping of the flood wall caused the South Breach. The overflowing water scoured away the soil on the land side and removed the soil resistance that held the I-wall in place against the pressure of the rising water in the canal. My evaluation determined that the top of the wall was lower than previously thought (El. 12.1 ft versus El. 12.5 ft) at this location. This meant that overtopping and scour started earlier than previously thought. It also explains why the South Breach failure occurred where it did — at a low section at the top of the wall. Photographs of unfailed sections of the I-wall show that significant scour occurred, and some sections of the wall were rotated outward in the early phases of failure (Figure 3). Analyses show that sufficient scour depths could occur to cause the wall to fail by the top rotating outward and developing into an overturning failure. Aerial photographs show the progression of rotation from both ends of the South Breach. Remarkably, the sheeting remained connected despite being rotated from vertical to horizontal and stretched to 944 ft over the 820-ft length of the failed zone. Most of the concrete I-wall constructed on top of the sheeting had completely failed and fallen off. This was most likely the result of horizontal stretching of the sheeting as described for the North Breach.

Stability analyses showed that the flood wall at the South Breach could not have failed by global instability because the FOS against global instability likely never fell below 1.3. In fact, as the water level on the land side of the wall began to rise, the FOS against global instability increased. No team found any evidence to indicate the occurrence of a global instability within the foundation soils at the South Breach.

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Flow Analyses

Using updated permeability data from the additional field and laboratory work, our flow analyses showed that the duration of high head differential was too short for water to flow through the foundation soil from the canal to the land side. As such, little change in pore water pressure could have occurred in the soils on the land side due to the rising water level in the canal. Therefore, ILIT's conclusions and the Plaintiff Expert's premise that both breaches were likely caused by underseepage-induced instability of the land-side levee toe was not plausible given the new evidence and facts.

Failure Mechanisms

Work by the DOJ Team revealed a failure mechanism for the North Breach that was fully consistent with witness observations, known facts, and measured data, e.g., a structural failure of the flood wall. No prior investigation identified this failure mechanism. We concluded that the South Breach failed by overtopping, as determined by IPET and the ASCE ERP. The additional tests, analyses, and studies showed that the ILIT and Plaintiff expert's failure mechanism of rapidly increasing pore pressures in the land-side earthen dike due to high permeability of the foundation soil was not plausible.

After many days of expert testimony, Judge Stanwood R. Duval, Jr., U.S. District Court in New Orleans, ruled in favor of the United States and its co-defendant, Washington Group International. In his written opinion, Judge Duval indicated that he had been persuaded by the testimony of the Defendants' experts on causation. He also found the expert testimony of the Plaintiff's experts to have unscientific data, erroneous analyses, and unconvincing arguments.

Some Observations

Failure investigations need to consider and incorporate all of the relevant facts and observations about the failure. In this case, prior investigations did not explain the eyewitness observations of an explosive sound and a gap in the I-wall, nor did they give due weight to the many photos of rotating segments of the I-wall, torn sheet piles, and cracked and missing concrete segments from the top of the I-walls.

Failure investigations need comprehensive and reliable data on material properties. Much of the IPET and ILIT geotechnical investigations and studies focused on the 17th Avenue and London Avenue failures, with far less attention given to the IHNC failures. The extent of their investigations and analyses did not adequately define the subsurface characteristics, resulting in assumptions and speculations that didn't hold up to subsequent study.

Comprehensive failure investigations take time and money. Both ILIT and IPET were responding to pressures to get their reports completed and findings made public. NRC identified weaknesses in these reports, but there was no follow-up work to address its findings. A huge opportunity was missed to learn more from these failures and possibly improve geotechnical practice.

Acknowledgements

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