Ruling on IHNC Floodwall Failures during Hurricane Katrina

Timothy D. Stark, Ph.D., P.E., J.D., F.ASCE

Professor, Dept. of Civil and Environmental Engineering, Univ. of Illinois at Urbana-Champaign, 205 N. Mathews Ave., Urbana, IL 61801. E-mail: tstark@illinois.edu; and

N. H. Jafari, S.M.ASCE

Ph.D. Candidate, Dept. of Civil and Environmental Engineering, Univ. of Illinois at Urbana-Champaign, 205 N. Mathews Ave., Urbana, IL 61801 (corresponding author). E-mail: njafari2@illinois.edu

Introduction

On 29 August 2005, Hurricane Katrina came ashore just east of New Orleans with sustained winds exceeding 212 km/h (125 mph), significant rainfall and storm surge, and widespread flooding. The ruling in *Armstrong*, C.A. No. 10-866 on 12 April 2013 by Federal Judge Stanwood R. Duval, Jr. against property owners in the Lower Ninth Ward that were inundated by two breaches of the floodwall along the Inner Harbor Navigation Canal (IHNC) essentially ended litigation against the United States of America. This paper discusses events leading up to and during Hurricane Katrina, IHNC floodwall performance, negligence claim brought by Lower Ninth Ward property owners against the United States and Washington Group, International (WGI), and the United States's defense to the negligence claim with emphasis on the "cause in fact" prong. Recommendations for clarifying the causation issue are presented to help focus the trying and defense of future levee and floodwall negligence claims.

On 12 April 2013, United States District Court Judge Stanwood R. Duval, Jr. (Duval 2013) ruled[1,2] in favor of the United States of America and the Washington Group International (WGI) in a class-action case brought by six named Lower Ninth Ward property owners (Kenneth and Jeannine Armstrong, Fred Holmes, the Succession of Ethel Coats, Alvin Livers, and Clifford Washington) whose properties were rapidly and catastrophically inundated by two floodwall failures during Hurricane Katrina on 29 August 2005. The Court conducted a 15-day bench trial over 3 weeks to determine whether the United States and WGI were negligent before Hurricane Katrina in their environmental restoration activities in the Inner Harbor Navigational Canal (IHNC) that parallels the subject floodwall and Lower Ninth Ward.

This paper discusses the events leading up to and during Hurricane Katrina, the negligence claim brought by property owners, the plaintiffs' problems proving "cause in fact," and why the defendants did not prove the cause of the two floodwall failures but only that the United States and WGI activities were not a substantial factor in either floodwall failure. Because of the many variables and uncertainties surrounding the two floodwall failures (e.g., soil compressibility, floodwall height and alignment; storm surge height and duration; wave heights in the IHNC; duration and height of floodwall overtopping; depth of landside scour and erosion; sheet pile tensile properties, repairs, interlocking, and performance; wind speeds; timing of floodwall failures), proving the exact cause of both floodwall failures with certainty was difficult, if not impossible. In fact, Judge Duval states in his 12 April 2013 ruling[3]:

> "The Court cannot and will not find as a certainty what exactly caused these breaches."

As a result, the plaintiffs only had to show that both failures were caused by WGI's work, i.e., excavations and backfilling performed by WGI on the floodside of the floodwall, under the supervision and approval of the U.S. Army Corps of Engineers (USACE) before Hurricane Katrina. Judge Duval confirms this approach by stating in his ruling[4]:

> "In this procedural posture, the Court is not empowered to find the cause."

Regardless, the plaintiffs' experts focused on what caused both floodwall failures instead of how, if at all, WGI's work caused one or both breaches. As discussed subsequently, the plaintiffs were not able to show that either failure was caused by WGI's work. This paper demonstrates the importance of clarifying the causation issue and not being diverted to more popular or interesting issues, such as the exact cause of each floodwall failure, instead of focusing on the elements that must be proven to prevail or defend the case, i.e., whether WGI's work caused one or both of the failures.

Inner Harbor Navigational Canal and EBIA

The IHNC is located west of the Lower Ninth Ward in Saint Bernard Parish, Louisiana. The IHNC was constructed in 1923 as an intercoastal waterway to rapidly transfer river and seaborne commerce between the Mississippi River and Lake Pontchartrain[5] (IPET 2006). The IHNC was created by dredging a trapezoidal channel with the dredged spoils cast to the sides to raise the ground surface and construct levees on both sides of the canal. The trapezoidal canal dimensions are a minimum depth of 10 m (30 ft), minimum bottom width of 100 m (300 ft), and a minimum channel width of 152 m (500 ft) near the piers and slips, and 200 m (600 ft) adjacent to quays in the IHNC.

The IHNC in Fig. 1 runs essentially north–south with the southern end connecting to the Mississippi River and the northern end connecting with Lake Pontchartrain. The Mississippi River level is higher than the normal level of Lake Pontchartrain, so a lock structure to control flow and water level between the river and lake is located south of the Claiborne Avenue Bridge. During Hurricane Katrina, two failures of the floodwall shown in Fig. 1 occurred between the Florida Avenue Bridge at the north and the Claiborne Avenue Bridge at the south. This section of floodwall parallels the IHNC, is immediately west of the Lower Ninth Ward, and is the focus of this paper.

The ground surface between the IHNC and the floodwall along the Lower Ninth Ward is termed the East Bank Industrial Area (EBIA). The EBIA is approximately 13 ha (32 acres) in size and is subdivided into six properties (Fig. 1) based on historic land use[6] (WGI 2005). Each property consisted of its own structures

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(e.g., piers, docks, buildings, slips) to service the various vessels traversing the IHNC. In 1999, the U.S. Army Corps of Engineers started investigating the replacement of the 1923 IHNC lock south of the Claiborne Avenue Bridge. The USACE wanted to expand the existing lock to relieve shipping congestion and allow expansion of the Port of New Orleans, i.e., increase the size and volume of shipping in the IHNC. In addition to a larger lock, a bypass channel was proposed for the EBIA to allow two-way traffic within the IHNC instead of the current single lane of traffic. The bypass channel was to be located in the area of the EBIA, so before dredging to create the bypass channel could commence, the existing structures and infrastructure had to be removed, in addition to contaminated soil from decades of industrial use.

The six properties in the EBIA are named for former occupants and consist of from the north (Florida Avenue Bridge) to the south (Claiborne Avenue Bridge) (Fig. 1): Boland Marine, McDonough Marine, Indian Towing, Mayer Yacht, Saucer Marine, and International Tank Terminal. The Boland Marine and Saucer Marine sites are the location of the North and South Breaches of the floodwall, respectively, during Hurricane Katrina and are the focus in this paper. Boland Marine was used for ship repairs for nearly 20 years from the 1970s to the 1990s, and Saucer Marine was used for ship building operations for about four decades. The other EBIA property of great importance is McDonough Marine, which is located between the North and South Breaches. The floodwall along this property did not fail during Hurricane Katrina. As a result, this area is referred to as the No Breach area and was the site of a large soil borrow pit that was used to backfill most of the excavations created during the removal of infrastructure and contaminated soil in the EBIA by WGI. The McDonough Marine area was selected for the borrow pit because it contained the least amount of contaminated soil and thus a greater source of uncontaminated organic clay to backfill various WGI excavations created during the EBIA restoration.

The long history of industrial use and contamination in the EBIA includes shallow burial of asbestos-related waste at Boland Marine and shallow burial of drums containing hazardous waste at Saucer Marine. At Boland Marine, a number of surficial structures

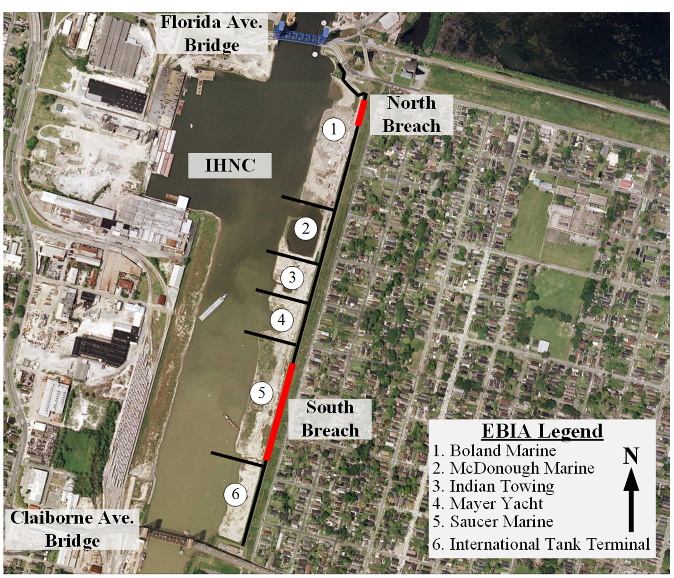

Fig. 1. Overview of IHNC, six EBIA properties, and location of floodwall breaches [background image courtesy of Gulf Coast Aerial Mapping (GCAM), with permission]

and wastes had to be removed, in addition to a shallow buried railroad tank car used for fueling vessels near the IHNC water. As a result, each property and its structures and excavations were removed before dredging of the proposed bypass channel could commence. Thirty-five buildings in various states of disrepair were demolished and their foundations excavated. Twelve shallow sunken barges, a sewer lift station, and 72,000 t of shallow transite (nonfriable) asbestos were excavated and removed from the EBIA by WGI during the environmental restoration project. The USACE contracted with WGI to perform the site characterization, demolition, decontamination, and environmental restoration of the EBIA. WGI began working in the EBIA in January 2001 and completed the project on 19 July 2005, just over 1 month before Hurricane Katrina.

Floodwall History

Heavy flooding of the Lower Ninth Ward in 1965 caused by Hurricane Betsy highlighted the flooding potential from the Gulf of Mexico hurricanes. To address this potential, Congress removed New Orleans flood protection responsibility (i.e., design, construction, and maintenance of levees and floodwalls) from the State of Louisiana and to the USACE through the Flood Control Act of 1965[7] (U.S. 1965).

Before Hurricane Katrina, the Lower Ninth Ward was protected from the IHNC by a levee constructed in 1965 and an I-shaped floodwall completed in 1969 along the east bank of the IHNC. The I-shaped floodwall, also termed an I-wall, consists of a steel sheet pile driven vertically to a desired depth and a concrete cap adhered to the top of the sheet pile to establish the desired floodwall height and resist the flood loading. No landside scour or erosion protection was authorized or constructed east of the I-wall in the case of overtopping. Congressional funding limits resulted in the I-wall along the IHNC being designed for only a Category 3 hurricane with a design floodwall height of elevation +4.1 m (+13.5 ft) NAVD88 datum (North American Vertical Datum 1988; NAVD88 corresponds to the current elevation datum in New Orleans.) This left the Lower Ninth Ward vulnerable to a severe hurricane or slow moving storm[8] (Westerink and Luettich 2003).

The River and Harbor Act of 1956[9] authorized the Mississippi River-Gulf Outlet (MRGO), a navigation channel that was completed in the mid-1960s and runs from the Gulf of Mexico in a north–south direction. The MRGO eventually turns westward, where it joins the Gulf Intercoastal Water Way (GIWW). The MRGO/GIWW system then forms a "T" intersection with the IHNC just north of the Florida Avenue Bridge so commerce can turn right to enter Lake Pontchartrain and turn left for the Mississippi River. At the time of Hurricane Katrina, the MRGO provided a hydrological connection between the IHNC and Gulf of Mexico, which allowed transmission of the Hurricane Katrina storm surge to rapidly reach the IHNC and its floodwalls.

Hurricane Katrina

Hurricane Katrina developed into a Category 5 hurricane as it wandered through the Gulf of Mexico, but it weakened to a Category 3 or 4 hurricane before it landed east of the IHNC on 29 August 2005 with winds greater than 212 km/h (125 mph). However, the slow-moving nature of the storm and the IHNC being on the eastern side of the hurricane caused increased wind speed, unprecedented rainfall 0.2–0.3 m (9–10 in.), and a significant storm surge in the IHNC. During Hurricane Katrina, the storm surge transmitted to the IHNC by the MRGO and GIWW quickly raised the water level in the

IHNC to an elevation of +4.3 m (+14.2 ft) NAVD88 datum[10] (ILIT 2006). During this rapid but short-duration (30 h) storm surge, two floodwall breaches occurred along the east bank of the IHNC primarily because of the landside scour from wave and flood overtopping. The north breach is located south of the Florida Avenue Bridge (http://ngs.woc.noaa.gov/storms/katrina/24426949.jpg; http://ngs.woc.noaa.gov/storms/katrina/24426944.jpg) and the south breach is located north of the Claiborne Avenue Bridge (http://www.cnn.com/2013/08/23/us/hurricane-katrina-statistics-fast-facts/; http://ngs.woc.noaa.gov/storms/katrina/24428010.jpg). The North Breach occurred shortly after 6:00 a.m. on 29 August 2005 and caused a floodwall gap of approximately 61 m (200 ft), whereas the South Breach occurred approximately 2 h later and caused a gap of over 244 m (800 ft) that primarily devastated the Lower Ninth Ward.

The storm surge was at an approximate elevation of +3.5 m (+11.5 ft) at 6:00 a.m. and approximately +4.3 m (+14.0 ft) at 8:00 a.m., which resulted in overtopping from the waves and a storm surge at both breaches before failure. The top of the I-wall was below the design elevation of +4.1 m (+13.5 ft) NAVD88 datum all along the IHNC because of local and regional subsidence of the soft underlying organic clays. The top of the floodwall in the area of the north and south breaches was approximately +3.4 m (+11.3 ft) and +3.7 m (+12.1 ft), respectively[11] (Marr 2012). The economic loss resulting from Hurricane Katrina is estimated to be approximately $147 billion with over 1,800 deaths (WMO 2014), and the litigation damages caused by the IHNC floodwall breaches is an estimated $100 billion.

Plaintiffs' Cause of Action

The plaintiffs alleged negligent environmental restoration of the IHNC by WGI and negligent design and oversight by the USACE resulted in the North and South Breaches of the IHNC floodwall. In particular, the plaintiffs alleged WGI's negligent restoration work created and/or exacerbated subsurface pathways so the Hurricane Katrina storm surge could flow under the sheet pile of the I-wall and undermine the floodwall and levee system, as illustrated in Fig. 2. Fig. 2 shows a hypothetical deep excavation piercing the lower organic clay, i.e., the clay layer below the sheet pile tip, and backfilled with high hydraulic conductivity sand. This allegedly allowed the storm surge water to be directly injected to the lower organic clay and transmitted below the tip of the sheet pile to the landside where the resulting landside hydraulic gradients and uplift pressures purportedly destabilized the floodwall and levee system. The weakened I-wall tilted and eventually collapsed under the high forces applied by the storm surge, allowing rapid inundation of the Lower Ninth Ward.

If true, the United States would be liable because negligence is outside the immunity for design and construction deficiencies provided by the Discretionary-Function Exception under the Federal Tort Claim Act.[12] The original design for a Category 3 hurricane with a 4.1 m (13.5 ft) storm surge, i.e., *Standard Project Hurricane*, was set by the Chief of Engineers report and authorized by Congressional spending limits. Therefore, the United States was not liable for the floodwall height not being high enough to resist Hurricane Katrina wave overtopping and storm surge because of Congressional funding constraints.

The plaintiffs complained that high hydraulic gradients, uplift pressures, and accompanying soil erosion and piping caused by alleged storm surge induced underseepage. This could have been prevented had WGI and USACE complied with industry custom and practice, in addition to the myriad of policies and regulations mandating that WGI and/or USACE perform a geotechnical analysis on the seepage effect of EBIA environmental restoration adjacent to the floodwall. The plaintiffs also alleged WGI and USACE should have known (or reasonably should have known) that the IHNC water and soils beneath the floodwall were hydraulically connected so a storm surge would result in enhanced underseepage and rapid transmission of hydraulic gradients and uplift pressures to the landside that could undermine the I-wall and associated levee.

The plaintiffs alleged that WGI excavations formed by removing structures, utilities, pilings, and contaminated soil from the EBIA pierced the lower organic clay and were backfilled with sandy materials (Fig. 2), thus creating a rapid hydraulic connection between the storm surge and lower organic clay underlying the sheet pile that was driven to an elevation of −3.2 m (−10.5 ft) NAVD88. Most of the sandy backfill was used to backfill shallow excavations to remove transite asbestos near the North Breach, as shown in Fig. 3, because the borrow pit supply was exhausted. The closest transite excavation to the floodwall in this area was 26 m (85 ft) from the floodwall, and the typical depth of these excavations was between 0.6 and 1.5 m (2 and 5 ft) (Fig. 3). The alleged underseepage from the floodside to the landside of the floodwall purportedly resulted in excessive hydraulic uplift pressures beneath the I-wall and levee embankment, which reduced its stability and contributed substantially to the North and South Breaches.

I-wall underseepage also was allegedly facilitated by WGI utility removal, e.g., gas and water lines, and extraction of over 1,100 piles that supported various structures in the EBIA. Removal of the utilities did not generate much traction with the Court because the excavations did not extend below the tip of the sheet pile; they

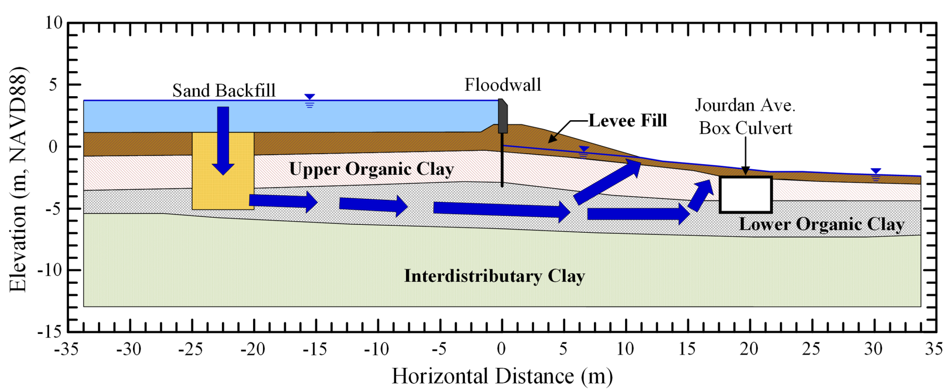

Fig. 2. Cross section of I-wall at North Breach with alleged excavation below sheet pile tip backfilled with sandy backfill material and storm surge–induced seepage depicted below sheet pile undermining the land side of levee and floodwall

Fig. 3. Shallow excavations being backfilled with sandy material resulting from a shortage of clayey soil from borrow pit located on McDonough Marine [image courtesy of Washington Group International (WGI), with permission]

stopped at the sheet pile (i.e., the utility was not removed on the landside of the I-wall); and they were backfilled with clayey material. In addition, a gas pipeline was removed from the area of the soil borrow pit, as discussed subsequently, and failure did not occur at the borrow pit.

However, extraction of the over 1,100 pilings did receive some traction during trial. Fig. 4 shows the resulting vertical hole from the extraction of a pile in the EBIA. Plaintiffs' expert Dr. Jonathan David Rogers of the Missouri University of Science and Technology contended that removal of over 1,100 pilings created numerous hydraulic connections to the lower organic clay below the sheet pile tip that also facilitated underseepage. The pilings were less than 0.3 m (1 ft) in diameter and had lengths of 6.1–21.1 m (20–69 ft). Most of the pilings were removed before 2005, which was well in advance of Hurricane Katrina on 29 August 2005. After substantial testimony about the extracted pilings, the Court concluded in its 12 April 2013 ruling[13]:

> "Nonetheless, it appears to the Court that it is more likely than not that because of the nature of the soils in the EBIA, the holes or cavities left behind from the pile extractions would close in a *matter of days or months* due to the lateral stresses in the soft subsurface clays in the EBIA. (TT of Rogers at 723-24 citing Rogers Dep. II at 190:6-191:1)." (italic emphasis added in this paper)
>
> "The Court was not overly impressed with Dr. Rogers' new found belief which he 'researched' after his deposition that led him to equivocate with respect to his initial deposition testimony. (See TT-Jonathan Rogers at 723-724)."

Fig. 4. Vertical hole resulting from extraction of piling, some of which was not backfilled [image courtesy of Washington Group International (WGI), with permission]

Negligence Cause of Action

The focus of this paper is the defense of the United States to the plaintiffs' negligence claim, which indirectly includes WGI because its defense is encompassed in the United States's defense. Under the Federal Tort Claim Act,[14] the United States is liable only if, under the law of the place where the alleged act or omission occurred, a private party would be held liable under like circumstances. Therefore, to prevail, the plaintiffs had to prove by a preponderance of evidence the following five prongs of a negligence claim against the United States[15]:

1. The United States had a Duty of Care or duty to conform to a specific standard of care to protect the property owners of the Lower Ninth Ward;
2. The United States's conduct failed to conform to the standard of care for levees and floodwalls at the time of the project;
3. The United States's substandard conduct was a cause in fact, i.e., a substantial factor, of the plaintiffs' injuries;
4. The United States's substandard conduct was the legal or proximate cause of the plaintiffs' injuries, i.e., the result of the failure was foreseeable; and
5. Actual and quantifiable damages occurred.

A negative answer to any of the inquiries of the duty-risk analysis would result in a determination of no liability against the United States.[16]

Through its previous flood protection activities, e.g., improved flood protection after Hurricane Betsy, it probably would be found that the United States had some kind of duty, possibly a Duty of Care, to homeowners in the Lower Ninth Ward. The United States owed a duty not to make the situation worse, even though residents lived on reclaimed swampland that was settling as a result of groundwater pumping used to maintain the area dry. It was foreseeable that property owners would be inundated and devastated if the I-wall failed because the Lower Ninth Ward is located approximately 2.4–2.9 m (8–10 ft) below sea level, which resulted in actual damages incurred by the plaintiffs.

The plaintiffs presented expert testimony that the USACE failed to conform to the Standard of Care for levees and floodwalls at the time of the project by not complying with industry custom and practice, in addition to the myriad of policies and regulations requiring a geotechnical seepage analysis of the environmental restoration project adjacent to the EBIA floodwall. Judge Duval seemed predisposed on the Standard of Care prong based on his negligence ruling against the United States in a previous Hurricane Katrina case related to the MRGO,[17] so the United States focused its defense on the remaining prong, i.e., the "Cause in Fact" prong, because the other four prongs were easily or likely to be proven. (All Hurricane Katrina–related litigation was consolidated under Judge Duval to facilitate resolution so he would be the Trier of Fact in the IHNC case.) The United States sought to avoid the estimated $100 billion of liability by showing that WGI's excavations and backfilling were not a "substantial factor"[18] in either the North or South Breach, which helped Judge Duval conclude that the plaintiffs failed to prove that WGI's activities caused either breach. Even though desirable for residents to know the cause of these failures, neither the United States nor WGI had to prove what caused the North or South floodwall breaches to avoid liability under a negligence claim. The plaintiffs had the burden of proof. However, the United States helped Judge Duval conclude that the plaintiffs failed to prove that WGI's activities caused either breach by showing why underseepage and WGI's activities were not a "substantial factor"[19] in either breach.

Subsurface Investigation

An extensive subsurface investigation was conducted to better define the soil stratigraphy and relevant engineering properties (e.g., hydraulic conductivity, soil compressibility, shear strength) along the IHNC floodwall to investigate the North and South Breaches for this litigation. This subsurface investigation started in June 2011 and was completed in early November 2011 to accommodate an April 2012 trial schedule. The field investigation consisted of 40 high-quality borings, 50 piezo-cone penetration tests (CPTUs) using a track-mounted rig, and 25 vane shear borings in which vane shear tests (VSTs) were performed at various depths. This field investigation was approximately equally distributed on the floodside and landside of the I-wall. Some of the floodside investigation locations required a marsh buggy because of shallow water or soft soils. Otherwise, a typical truck-mounted drill rig was used for both floodside and landside borings. The borings were drilled using the wet-rotary method to increase the removal of cuttings and clean-out of the boring, and to reduce the potential for borehole caving. High-quality soil samples were obtained in 1.3-m (4-ft) intervals to the boring completion depths by hydraulically pushing a 125-mm (5-in.) diameter, 1.4-m (4.5-ft) long thin-walled tube using piston sampling techniques in accordance with *Standard Practice for Thin-Walled Tube Sampling of Soils* [ASTM D1587 (ASTM 2010b)].[20] Forty open standpipe piezometers and 16 vibrating wire piezometers in six different borings were installed to measure groundwater fluctuations for calibrating and performing seepage and stability analyses. Finally, four pump wells and 48 pump test observation wells were installed to conduct four continuous field pump tests to measure in situ hydraulic conductivity and compressibility of the upper and lower organic clays underlying the I-wall.

In addition to the field investigation and testing, extensive laboratory testing was performed on specimens from the thin-walled sample tubes for soil index properties [ASTM D4318 (ASTM 2010d)],[21] hydraulic conductivity, and shear strength of the various soil layers. Ninety-three consolidation and 84 hydraulic conductivity tests were performed on high-quality specimens to assess the vertical and horizontal hydraulic conductivity and shear strength of the upper and lower organic clays along and immediately below the sheet pile to evaluate underseepage and stability, respectively, during Hurricane Katrina. Based on this subsurface investigation, the main soil stratigraphic units below the EBIA and I-wall are from top to bottom as follows:

- Levee embankment and EBIA fill—compacted organic clays dredged during IHNC construction;
- Upper organic clay—water content <100% and indicative of a swamp deposit with significant fine-grained material as a result of frequent Mississippi River flooding with sediment laden water;
- Lower organic clay—water content >100% and indicative of a marsh deposit with higher organic content than a swamp deposit but still primarily fine-grained material; and
- Interdistributary clay—a uniform fine-grained clay layer created in a deltaic environment.

Dunbar and Britsch (2008)[22] provide additional details on site geology and formation of these soil stratigraphic units along the IHNC. Fig. 2 shows a generalized cross section for the IHNC I-wall with these clay layers. The upper and lower organic clays were deposited in swamp and marsh environments, respectively, and are classified as an organic clay according to the Unified Soil Classification System using ASTM D2216[23] (ASTM 2010c), D2487[24] (ASTM 2011a), D2974[25], and D4427[26]. These clay layers do not classify as a fibrous peat using ASTM D2974 (ASTM 2012b) and D4427 (ASTM 2010a), because the organic content is less than 75% and a large percentage of gray fine-grained material is present as a result of the frequent flooding and deposition of clay material. The plaintiff experts opined that these clay layers were peat deposits in an attempt to prove the existence of a high hydraulic conductivity layer below the sheet pile tip that could rapidly transmit underseepage as a result of the storm surge.

The key underseepage layer is the lower organic clay because it lies below the sheet pile tip (Fig. 2), and any Katrina storm surge-induced underseepage had to flow through this layer. The next section discusses the horizontal and vertical hydraulic conductivity of the lower organic clay because of its importance to underseepage evaluation.

Lower Organic Clay Hydraulic Conductivity

The depth or elevation of the sheet pile tip was a key piece of evidence in the trial because the short duration of the storm surge rendered the amount of seepage through the sheet pile and sheet pile interlocks negligible. In other words, the sheet pile was effective in cutting off most of the short-duration storm surge–induced seepage through the levee embankment and upper organic clay layer but not the lower organic clay. Therefore, detrimental underseepage had to pass under the sheet pile to reach the landside of the floodwall. The depth or elevation of the sheet pile tip (Fig. 2) was a key piece of evidence because it delineated the length of seepage path from floodside to landside. Judge Duval concluded[27]:

> "Using current datum NAVD88, this resulted in a bottom elevation of −10.5. (Expert Report of Timothy Stark at 14)"

As a result, the depth of WGI's excavation and sand backfill relative to an elevation of −3.2 m (−10.5 ft), NAVD88 was important and the horizontal and vertical hydraulic conductivity and coefficient of volume compressibility of the lower organic clay were primary input parameters for the underseepage analyses. The underseepage analyses were used to investigate whether WGI's excavations and sand backfilling were a "substantial factor"[28] in either the North or South Breach by allowing detrimental underseepage and hydraulic gradients to occur on the landside of the I-wall.

To measure the horizontal and vertical hydraulic conductivity and coefficient of volume compressibility of the lower organic clay, flexible wall hydraulic conductivity tests [ASTM D5084 (ASTM 2010e)],[29] incremental stress (IS) [ASTM D2435 (ASTM 2011b)],[30] and constant rate of strain (CRS) [ASTM D4186 (ASTM 2012a)][31] consolidation tests were conducted on high-quality specimens trimmed at horizontal and vertical orientations with specimen diameters of 71–127 mm (2.8–5 in.). In addition, pore pressure dissipation tests during piezo-cone penetration tests, field falling head and rising head slug tests in open standpipe piezometers, and four field pumping tests were conducted. Based on this extensive field and laboratory testing, the most likely values of these parameters for the lower organic clay are summarized below:

- Horizontal hydraulic conductivity $\sim 1 \times 10^{-5}$ cm/s;
- Vertical hydraulic conductivity $\sim 6.3 \times 10^{-6}$ cm/s;

- Ratio of horizontal to vertical hydraulic conductivity ∼1.6; and
- Coefficient of volume compressibility $\sim 1.5 \times 10^{-3}$ 1/kPa (7.3×10^{-5} 1/psf).

Judge Duval relied on a video of flow rate during a field pump test (i.e., 4 teaspoons in 1 min) near the South Breach to establish the critical horizontal hydraulic conductivity or permeability of the lower organic clay of approximately 1×10^{-5} cm/s as follows[32]:

> "Dr. Stark presented compelling evidence which the Court accepts that the site specific permeability of the organic clay soil at the EBIA would result in it taking *one minute to generate four teaspoons of water to flow through that clay* (TT of Stark at 3414). With this inexorable fact confronting Plaintiffs' experts, a shift in causation from *water seepage to pressure* as the primary cause of the uplift pressure and de-stabilization of the floodwall occurred." (italic emphasis added in this paper)

Underseepage Analysis

The United States retained the following experts in alphabetical order to present various aspects of their defense: Professor Thomas L. Brandon of Virginia Tech, Mr. Joseph Dunbar and Lee Guillory of the USACE, Dr. Patrick C. Lucia and Thomas A. Naymik of GeoSyntec Consultants, Dr. W. Allen Marr of Geocomp Corporation, and Professor Timothy D. Stark of the University of Illinois at Urbana-Champaign. Dr. Stark was tasked with investigating whether the plaintiffs' theory of underseepage and landside hydraulic gradients and uplifts pressures was a "substantial factor"[33] in either floodwall breach. Dr. Stark accomplished this by researching the various WGI excavations and backfill material, seepage parameters of the soils underlying the floodwall and levee embankment, and amount of seepage and uplift pressure that could be transmitted from the floodside to the landside during the 30-h storm surge.

Stark (2012) performed two-dimensional (2D) and three-dimensional (3D) transient seepage analyses that accurately modeled the geometry and depth of all of the WGI excavations near the North and South Breaches, concrete and steel sheet pile portions of the I-wall, unsaturated and saturated levee embankment and upper organic clay materials, and saturated lower organic and interdistributary clays underlying the floodwall and levee (Fig. 2 cross section) using site-specific data. These underseepage analyses showed negligible underseepage (i.e., approximately 4 teaspoons in 1 min) and negligible hydraulic uplift pressures developed on the landside of the floodwall during Hurricane Katrina. This indicates that WGI's excavations were not a "substantial factor"[34] in either floodwall breach. Of course, these analyses were contradicted by the plaintiffs' experts seepage analyses that showed significant underseepage and uplift pressures on the landside of the floodwall, which they used to opine were a "substantial factor"[35] in both floodwall breaches. The plaintiffs primarily relied on 4 days of expert testimony by Dr. Robert G. Bea of the University of California at Berkeley to prove WGI's excavations and backfilling and USACE's activities were a "substantial factor"[36] in both the North and South Breaches. The reason why Dr. Bea's seepage analyses showed significant underseepage and uplift pressures on the landside of the floodwall was his use of unrealistically low values of coefficient of volume compressibility (m_v; hereafter referred to as soil compressibility) for the lower organic clay and levee materials (Stark et al. 2014).[37] An unrealistically low value of soil compressibility converts the transient or time-dependent water seepage problem to a "pressure transmission" problem as noted previously by Judge Duval.[38]

Eq. (1) presents the equation for 3D transient flow through a saturated anisotropic porous medium from Freeze and Cherry (1979)[39]

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h_t}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial h_t}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial h_t}{\partial z}\right) = \gamma_w \times m_v \frac{\partial h_t}{\partial t} \quad (1)$$

where k = hydraulic conductivity in the x, y, and z directions; h_t = total hydraulic head; t = time; and γ_w = unit weight of water. The time for changes in total hydraulic head and thus seepage is introduced in the water seepage analysis through the right-hand side (RHS) of Eq. (1). For a unit decline in total hydraulic head with time, the RHS is directly related to the magnitude of m_v. If an unrealistically low value of m_v is used, e.g., assuming 1×10^{-8} kPa^{-1} indicates the soil is incompressible like rock, the RHS approaches zero and converts the analysis to a steady-state seepage condition as shown in Eq. (2). Consequently, the steady-state seepage analysis becomes independent of time and generates significant landside hydraulic gradients and uplift pressures by only decreasing one parameter, i.e., m_v. This converts the problem to a pressure transmission problem instead of the appropriate water seepage problem as noted previously by Judge Duval.[40] This essentially results in the hurricane having an infinite duration instead of only 30 h

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h_t}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial h_t}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial h_t}{\partial z}\right) = 0 \quad (2)$$

The plaintiffs' expert analogized this pressure transmission during the storm surge to levitating the floodwall and levee embankment, which allowed the lateral forces of the storm surge to push the floodwall into the Lower Ninth Ward. The expert compared this process to a car brake system in which significant pressure is transmitted to the wheels to stop the car without substantial flow[41]:

> "Simply put, Plaintiffs have not proven that it is more probable than not that the United States' and WGI's remediation, excavations and backfill methods created a 'hydrologically charged' condition such that uplift pressures were transmitted through clay soil without any appreciable flow of water to destabilize the floodwall causing its demise."

Realizing that (1) a "battle of the experts" would develop over the highly technical underseepage analyses and value of soil compressibility, i.e., m_v, and (2) Judge Duval had issued a favorable ruling in a previous Hurricane Katrina case[42] based on the testimony of Dr. Robert G. Bea (Duval 2009), a more understandable and hopefully more compelling means to convince Judge Duval that underseepage and hydraulic uplift pressures on the landside of the I-wall were not a "substantial factor"[43] in either floodwall breach was sought. This was paramount to defend the cause because of the huge damages, public resentment, and the judge's previous ruling against the United States and apparent trust of Dr. Bea. This effort focused on the large unfilled excavation created for the soil borrow pit on the McDonough Marine property, in between the North and South Breaches.

Borrow Pit Excavation

Early in the environmental restoration project, WGI and USACE sought a large source of uncontaminated clayey material to backfill the numerous excavations that would be created when removing existing structures, infrastructure, utilities, pilings, and contaminated soils. Initially, WGI proposed to locate the borrow pit on the International Tank property which is located south of the South Breach, i.e., near the Claiborne Avenue Bridge (Fig. 1). However, the organic clays in this property were found to be highly contaminated so the borrow pit was relocated to the McDonough Marine property, which is located about halfway between the North and South Breaches. This location is extremely significant because the floodwall between the North and South Breaches did not fail during Hurricane Katrina, but did show some landslide movement (IPET Rep., Vol. 5, The Performance—Levees and Floodwalls, Appendix 11, Fig. 11-7: http://biotech.law.lsu.edu/katrina/ipet/FINAL%20Vol%20V%20The%20Performance%20-%20Levees%20and%20Floodwalls%20-%20appendices%2011-15.pdf). As a result, plaintiffs' expert referred to this area as "near breach" even though it was not close to failure. The borrow pit excavation became the focus of the United States's defense. The borrow pit should have had a greater effect on underseepage than WGI's excavations because of its size, depth, and being only 23 m (75 ft) from the floodwall, the organic clays being similar to the North and South Breach, and the excavation being backfilled with water, which is more permeable than sand. Therefore, if a direct hydraulic connection and instantaneous pressure transmission existed between the IHNC and the lower organic clay underlying the floodwall, it should have manifested itself at the borrow pit location before or at the same time as the North and South Breaches.

Fig. 5 shows an aerial view of the water-filled borrow pit before Hurricane Katrina, and Fig. 6 shows "Cross Section A-A" through the borrow pit at the location shown in Fig. 5. Fig. 6 illustrates the depth of the borrow pit excavation, its close proximity to the

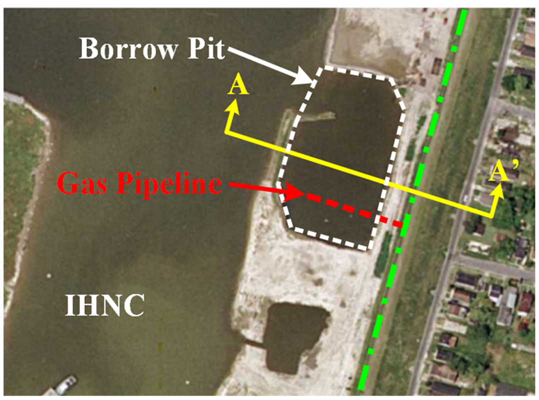

Fig. 5. Aerial photograph of large water-filled soil borrow pit excavation within 23 m of the floodwall (see diagonal dashed line) before Hurricane Katrina between the North and South Breaches (29°58′41.50″N, 90°01′14.14″W) [background image courtesy of Gulf Coast Aerial Mapping (GCAM), with permission]

floodwall, the upper (swamp) and lower (marsh) organic clays underlying the floodwall, and cypress stumps and other organic materials (Fig. 7) that the plaintiffs' experts opined increased the hydraulic conductivity of the lower organic clay. Some of the other facts about the borrow pit for proving that landside underseepage and hydraulic uplift pressures were not a "substantial factor"[44] in either floodwall breach are as follows:

- Large [approximately 9,300 m^2 (100,000 ft^2)] excavation area;
- Excavation has a 3H:1V sideslope on the floodwall side of the excavation (Fig. 7);
- Similar subsurface conditions, including upper (swamp) and lower (marsh) organic clays and cypress stumps and other organic material (Fig. 7), as below the North and South Breaches;
- Excavation pierced the lower organic clay so there was direct hydraulic connection below the sheet pile tip before Hurricane Katrina;
- Closest (23 m; 75 ft) large excavation to the floodwall;
- A utility, i.e., gas pipeline, was removed and backfilled in the borrow pit area and did not result in floodwall failure (Fig. 5);
- Filled with ponded water instead of sandy backfill by WGI (Fig. 2) before Hurricane Katrina; and
- Excavation extended 0.3 m (1 ft) near the floodwall to 2.1 m (7 ft) below the sheet pile tip, which was an important issue at trial.

The fact that the floodwall did not fail immediately east of the borrow pit resonated with Judge Duval, as presented in the following excerpts from his ruling (Duval 2013)[45] that confirm some of the facts listed. For example, the plaintiffs' expert claimed the borrow pit did not extend below the sheet pile tip (i.e., did not pierce the lower organic clay), so significant hydraulic pressures were not developed on the landside of the borrow pit during the storm surge; therefore this section of the floodwall did not fail. Judge Duval concluded that the borrow pit did pierce the lower organic clay and the WGI excavations did not impose a worse condition than the borrow pit by stating[46]:

> "However, it is clear that the *borrow pit pierced the lower organic clay* lens and reached the lower organic clay level. (TT of Stark at 3428-29). Nonetheless, with an open, un-backfilled, un-tamped large pit, no breach occurred at the EBIA in its vicinity." (italic emphasis added in this paper)

Realizing that Judge Duval had a serious interest in the performance of the borrow pit, the plaintiffs' expert presented rebuttal testimony that claimed the borrow pit did not pierce the lower organic clay below the sheet pile tip, so significant hydraulic pressures were not developed on the landside of the borrow pit.

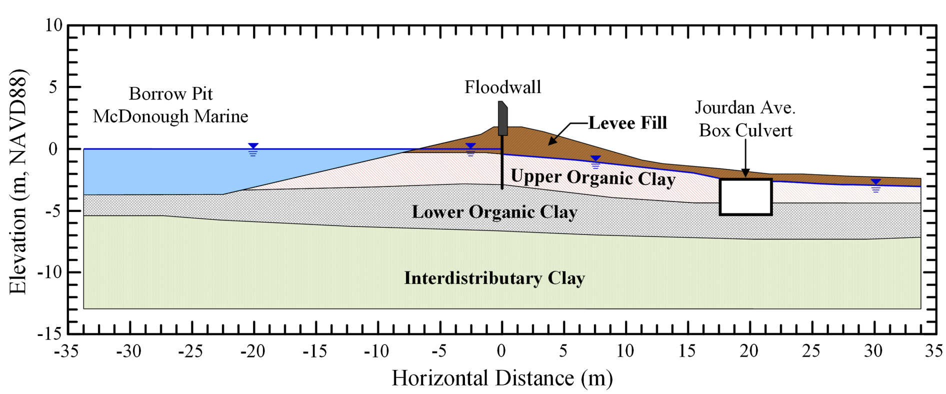

Fig. 6. Floodwall cross section through borrow pit used for transient seepage analyses

Fig. 7. Excavation of soil borrow pit near floodwall and 3.5 m deep showing organic clays that underlie the floodwall [image courtesy of Washington Group International (WGI), with permission]

Judge Duval responded to this rebuttal testimony by concluding that the borrow pit did extend into the lower organic clay[47]:

> "It is clear that that layer was pierced in reality. (Trial Testimony of Stark at 3428). Thus, the Court finds that Plaintiffs have not provided the Court with any reliable data to demonstrate the difference that these excavations made; Plaintiffs ask the Court to make a leap of faith in this regard and the Court is not prepared to do so.
>
> "The basis for Bea's contention that the Near Breach serves as a 'control' because those excavations did not pierce that 'swampy-marsh' layer *is inaccurate*. It is clear that the *layer was pierced in reality*. (TT of Stark at 3428; of Bea at 4131-32, 4134-35)." (italic emphasis added in this paper)

The plaintiffs' expert also tried to convince Judge Duval that the bottom of the borrow pit was lined with low hydraulic conductivity clay after borrow pit excavation was complete, which prevented seepage occurring from the excavation under the sheet pile and to the landside. Judge Duval also responded unfavorably to this rebuttal testimony by concluding[48]:

> "In addition, Dr. Bea's initial contention concerning a clay layer having been added to the borrow pit was ill-founded and any assumptions based on that belief are likewise lacking merit."

Therefore, the Court concluded that none of the plaintiffs' seepage models could explain why the floodwall did not fail in the vicinity of the borrow pit if underseepage was the cause of the North and South Breaches. This resulted in Judge Duval concluding[49]:

> "Thus, the Court finds that Plaintiffs 'proof' of a hydraulic connection and the resulting 'uplift pressure' as a substantial cause of the North and South Breaches is unavailing. The Court found Dr. Bea's testimony not direct and quite circular. The North, South and Near Breach models presented were unconvincing. Moreover, the Court is not persuaded that the use of values in the SEEP/W modeling for compressibility that bear no relation to the field conditions constitutes a valid scientific method."

The main reason why the floodwall did not fail in the vicinity of the borrow pit is probably because the floodwall had a top elevation of approximately +3.9 m (+12.9 ft), which is approximately 0.3 m above the North and South Breaches. The difference in floodwall elevation resulted in less overtopping and landside scour (Marr 2012).[50] IPET Volume V Appendix 11 (Fig. 11-7) shows evidence of landside scour and tilting of the floodwall at the borrow pit, but not failure. It is possible that failure could have occurred with continued overtopping and scour, but the storm surge started to recede shortly after the South Breach. Regardless, the adequate performance of the floodwall along the borrow pit excavation precluded underseepage from being a "substantial factor"[51] in either floodwall failure because of the numerous and compelling factors about the borrow pit excavation, such as it being backfilled with water instead of soil, the excavation extending below the sheet pile tip, being the closest large excavation to the floodwall, and the lower organic clay being present along the entire length of the IHNC floodwall.

Ruling

As is typical in negligence lawsuits, the plaintiffs had to prove by a preponderance of the evidence: (1) duty of care; (2) breach of the duty; (3) the substandard conduct was a cause in fact of either the North or South Floodwall Breach; (4) the substandard conduct was the legal or proximate cause of the breaches; and (5) actual damages were incurred by the plaintiffs. Because all of the prongs were evident or likely to be proven, the plaintiffs only had to prove Prong (3), i.e., underseepage was the cause in fact, a "substantial factor"[52], in the North and South Beaches. The defendants' expert focused on explaining why underseepage, i.e., WGI's work, did not cause failure in the vicinity of the borrow pit and discrediting plaintiffs' experts failure analyses by presenting competing failure mechanisms and anlayses.

Realizing that other experts were trying to determine the actual cause of failure of the North and South Breach, the authors focused solely on underseepage and explaining why the floodwall near the borrow pit did not fail. This lack of failure was explained by the low horizontal hydraulic conductivity of the lower organic clay ($\sim 1 \times 10^{-5}$ cm/s), length of the sheet pile preventing the short storm surge from being rapidly transmitted from the floodside to the landside, the unsaturated floodside and landside material slowing flow, and the short duration of the storm surge (i.e., transient loading).

In summary, the United States avoided the estimated $100 billion of liability by simply showing that the borrow pit subsurface conditions were similar to the North and South Breach and only a small amount of underseepage could occur during the short duration of the hurricane (4 teaspoons per min). Therefore, WGI's excavations and backfilling with some sandy material could not have been a "substantial factor"[53] in either the North or South Breach. This is reinforced with Judge Duval's following statement[54]:

> "Thus, the Court finds that Plaintiffs 'proof' of a hydraulic connection and the resulting 'uplift pressure' as a substantial cause of the North and South Breaches *is unavailing*. The Court found Dr. Bea's testimony not direct and quite circular." (italic emphasis added in this paper)

Judge Duval also confirmed that proving the actual cause of the North and South Breaches (e.g., different sheet pile depths, overtopping, embankment stability) was not necessary to prove or defend this negligence claim by stating[55]:

> "The Court *cannot and will not find as a certainty what exactly caused* these breaches. Clearly, it was not the Ingram Barge. Likewise, it is clear it was not the result of the subject excavations performed by WGI under the complete supervision of the Corps." (italic emphasis added in this paper)

Therefore, when trying or defending a case, it is important to understand the prongs or elements that need to be proven or defended and not pursue extraneous issues. For example, defendants do not have to prove actual cause of an infrastructure or construction failure (plaintiffs have the burden of proof), but can show their activities were not a substantial factor in the failure to assist the judge with deciding the case. Instead, the focus should be on one or more prongs that must be proven to prevail or defend a case of the required prongs. In this case, that prong or element was prong (3) "cause in fact" or that underseepage was not a "substantial factor"[56] in either the North or South Breach because the floodwall did not fail at the borrow pit. As a result, on 12 April 2013, Judge Duval ordered that judgment be entered in favor of the United States and WGI as shown below[57]:

> "*IT IS ORDERED*, *ADJUDGED AND DECREED* that judgment be *entered in favor of United States* and the Washington Group International and against Kenneth and Jeannine Armstrong, Fred Holmes, the Succession of Ethel Coats, Alvin Livers, and Clifford Washington, with each party to bear its/his/her own costs." (italic emphasis added in this paper)

Repair

The North and South Breaches of the IHNC floodwalls were repaired using an inverted T-wall system instead of an I-wall system to provide a 100-year level of risk reduction. The top of the T-wall is at elevation +4.5 m (+15 ft) NAVD88 or 0.8 m (2.5 ft) higher than the previous I-wall. In addition to a higher floodwall that can reduce overtopping, a T-wall provides greater stability than an I-wall because of a wider and reinforced base. The base of the inverted T-wall is 3.7 m (12 ft) wide and is supported by three rows of steel H-piles. The three rows of batter steel H-piles resist landside movement or tilting, which can cause additional overtopping and progressive loss of support. One row of batter H-piles is located on the floodside of the vertical steel sheet pile, and two rows of batter H-piles are located on the landside of the sheet pile. The floodside batter piles resist landside titling and formation of a floodside gap along the sheet pile, whereas the landside batter piles resist overturning and scour by supporting the landside concrete apron. To increase the underseepage path, the sheet pile was driven to elevation −7.0 m (−23 ft) or 3.8 m (12.5 ft) deeper than the previous sheet pile, which was driven to an elevation of only −3.2 m (−10.5 ft).

This repair involved demolition and replacement of 1,231 m (4,038 linear ft) of floodwall damaged by Hurricanes Katrina and Rita. To complete the T-wall system, the following components were installed: approximately 1,220 m (4,000 ft) of earthen levee, 2,250 batter steel H-piles with lengths of 22.3 m and 24.4 m (73 and 80 ft), 1,231 m (4,038 linear ft) of sheet pile driven to an elevation of −7.0 m (−23 ft), and a landslide concrete apron along the floodwall to resist landside scour and erosion resulting from overtopping.

Summary

This paper discusses the negligence claim brought by six Lower Ninth Ward property owners against the United States and WGI for the environmental restoration activities that were performed before Hurricane Katrina in the IHNC. Under the Federal Tort Claim Act, plaintiffs have to prove by a preponderance of the evidence: (1) Duty of care; (2) breach of the duty; (3) the substandard conduct was a cause in fact of either the North of South Floodwall Breach; (4) the substandard conduct was the legal or proximate cause of the breaches; and (5) actual damages were incurred by the plaintiffs. Through its previous flood protection activities, it probably would be found that the United States had a duty of some kind to Lower Ninth Ward property owners because the United States improved flood protection after Hurricane Betsy in 1965 even though Lower Ninth Ward residents live on reclaimed swampland that is approximately 2.75 m (9 ft) below the Mississippi River level and settling as a result of consolidation, secondary compression, and groundwater pumping used to keep the area habitable. Similarly, public perception seemed to be that the USACE breached their duty, and actual damages were incurred by the plaintiffs given the massive flooding and destruction. This is reflected in some "judicial license" exercised by Judge Duval in his ruling[58]:

> "I feel obligated to note that the bureaucratic behemoth that is the Army Corps of Engineers is virtually unaccountable to the citizens it protects despite the Federal Tort Claims Act. The public fisc will very possibly be more jeopardized by a lack of accountability than a rare judgment granting relief."

As a result, all of the prongs were evident or likely to be proven so the plaintiffs only had to prove underseepage was the cause in fact, i.e., a "substantial factor"[59], in either North and South Beaches. For obvious reasons, the plaintiffs' expert focused on discrediting other experts and their causes of failure in addition to trying to explain how underseepage caused the North and South Breaches or did not cause breach at the borrow pit excavation.

Conversely, the defendants realized that they only had to show underseepage was not a "substantial factor"[60] in either the North or South Beaches and actually showed that underseepage was not factor at all in either breach. This case was facilitated by the floodwall in the vicinity of the borrow pit excavation not failing even though it was (1) larger than any other WGI excavation; (2) the closest large excavation to the floodwall; (3) deeper than most of the WGI excavations and the sheet pile tip; (4) subject to removal of structures, infrastructure, pilings, and a gas pipeline during the environmental restoration; and (5) backfilled with water. These conditions resulted in an active seepage condition before Hurricane Katrina.

Because the plaintiffs had the burden of proof on the cause of each failure, the defendants only had to show that WGI's work did not contribute significantly to floodwall underseepage at the borrow pit (e.g., 4 teaspoons in 1 min) to help Judge Duval conclude the plaintiffs did not meet their burden of proof. In other words, if underseepage was not a "substantial factor"[61] at the borrow pit, i.e., the most favorable location for detrimental underseepage, it could not have been a "substantial factor"[62] at the North and South Breaches because the subsurface conditions are similar and the excavation was backfilled with water, not sand. Because of the importance of this case, the United States and WGI also provided testimony on actual cause to give Judge Duval plausible explanations for the failures to facilitate his dismissing underseepage as a contributory factor in either failure. The United States felt that not providing a plausible explanation for the failures would be risky because the judge could simply endorse underseepage if there was no other plausible failure mechanism. The United States felt this approach was warranted because the decision maker was not a geotechnical specialist and might not be able to evaluate the validity or invalidity of the plaintiffs' experts in science and failure mechanism.

Even though it may be interesting and desirable to identify and present the actual cause of failures in construction litigation, each party should focus on the prongs or elements that must be proven to prevail. In this case, residents of New Orleans are probably interested in the cause of each failure. However, Judge Duval concluded that the Court cannot and does not have to determine the actual cause(s) of the North and South breaches (e.g., different sheet pile depths, overtopping, embankment stability) to decide the case. The Court only had to determine whether the WGI excavations and backfilling under the supervision of the USACE contributed significantly to the either breach. On this issue, the Court was conclusive that the WGI excavations did not cause either breach because of results of 2D and 3D transient seepage analyses that show negligible underseepage (i.e., 4 teaspoons in 1 min) and performance of the floodwall in the vicinity of the larger and unbackfilled borrow pit excavation (Stark 2012). This simple approach enabled the United States to avoid over $100 billion of liability caused by the IHNC floodwall breaches.

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