Geotechnical Effects of Hurricane Harvey in the Houston, Beaumont, and Port Arthur Areas

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ABSTRACT: *The Geotechnical Extreme Events Reconnaissance (GEER) Association deployed multiple teams of engineers from academia and practicing firms to the coast of Texas in late August and early September 2017 following Hurricane Harvey. This report summarizes the observations and data from the GEER team that focused primarily on the inland effects of Hurricane Harvey in the Houston area with some observations in the Port Arthur / Beaumont area east of Houston. Rain, not storm surge or wind, caused the observed damage in Houston, Beaumont, and Port Arthur by overwhelming stormwater management facilities and creating high flows and flooding in and near area waterways. The major Houston-area flood structures, Addicks and Barker Dams, performed well from a geotechnical perspective. Observed damages included shallow slides along levees, severe erosion along riverways, isolated road and culvert erosion and uplift, and area-wide flood effects in low and poorly drained neighborhoods.*

KEYWORDS: hurricane, flood, erosion, dam, levee, highway, residential

SITE LOCATION: Geo-Database

INTRODUCTION

Hurricane Harvey affected a wide area along the Texas coast with both high wind and unprecedented, for the area, rainfall totals. The damage in the Houston and Beaumont / Port Arthur areas was largely due to the flooding and stream flow that resulted from the rain. The GEER Hurricane Harvey Houston team (GEER Houston) visited Houston area sites that were

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known to be of significance for flood risk reduction or were identified by the media as areas with affected infrastructure. Figure 1 shows the ten areas of significance visited by GEER Houston, followed by a legend listing the site names. Descriptions of observations at each site can be found in later sections of this paper.

This report summarizes the following aspects of the GEER Houston team reconnaissance:

- Description of the Hurricane Harvey rainfall.
- Performance of the two large U.S. Army Corps of Engineers (USACE) flood protection dams, Addicks and Barker Dams.
- Performance of area levees built and maintained by Levee Improvement Districts (LIDs).
- Erosion along area rivers, bayous, and streams.
- Highway damage.
- Residential impacts.

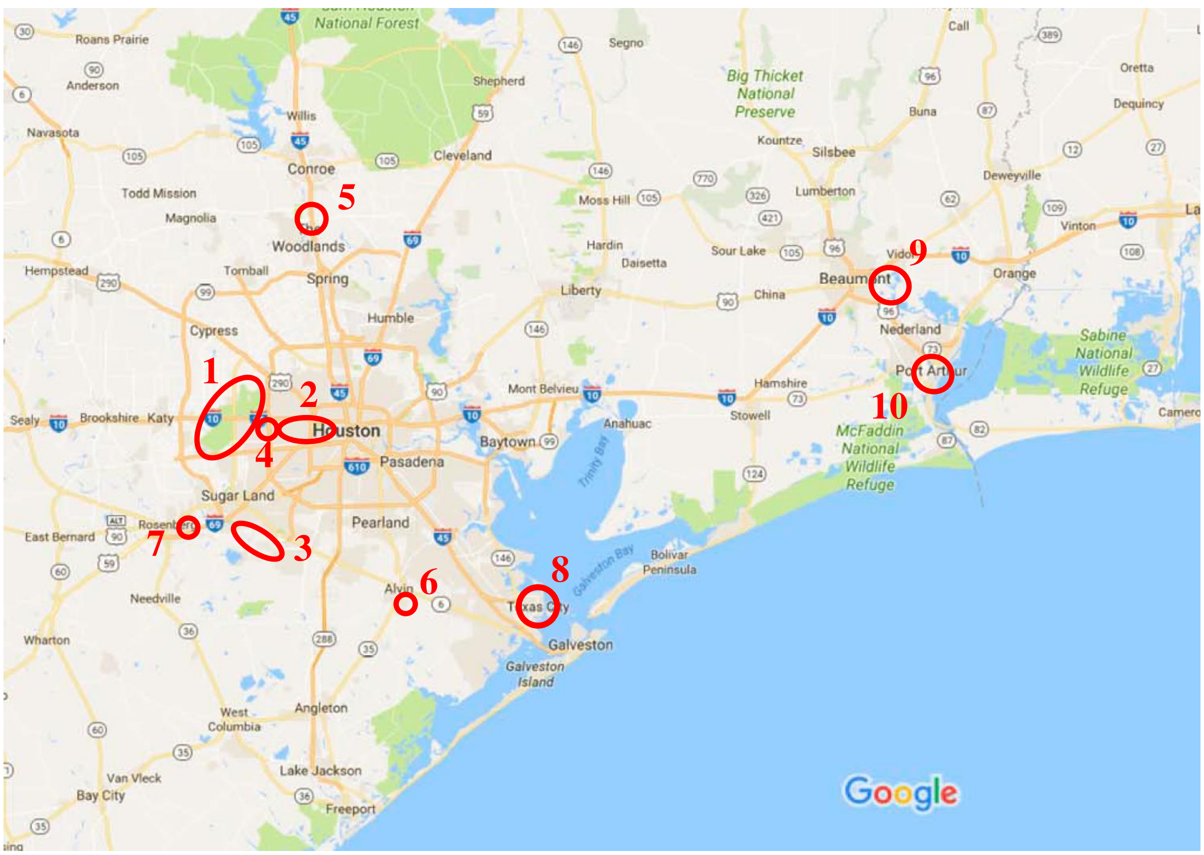

Figure 1. Observation Areas by GEER Hurricane Harvey Houston Team (see following list for site names). 1 – USACE Houston Flood Risk Management Dams – Barker and Addicks Dams, 2 – Buffalo Bayou, 3 – Brazos River Levees, 4 – Beltway 8 Underpass Slab, 5 – San Jacinto River Bridges, 6 – Mustang Bayou Bridge, 7 – FM 762 Road Culvert, 8 – Texas City Levees, 9 – Beaumont, 10 – Port Arthur

HURRICANE HARVEY

Harvey began as a tropical wave off the west coast of Africa on August 13, 2017, moved westward across the Atlantic Ocean and Caribbean Sea, and made landfall on the Texas coast on August 25 as a Category 4 hurricane. The storm continued to the northwest and eventually stalled over Houston on August 26 before changing direction again and heading back southeast.

Harvey made landfall one final time as a tropical strom near Cameron, Louisiana, on August 30. Fig. 2 shows the trajectory of the storm center as well as flood levels in some coastal areas.

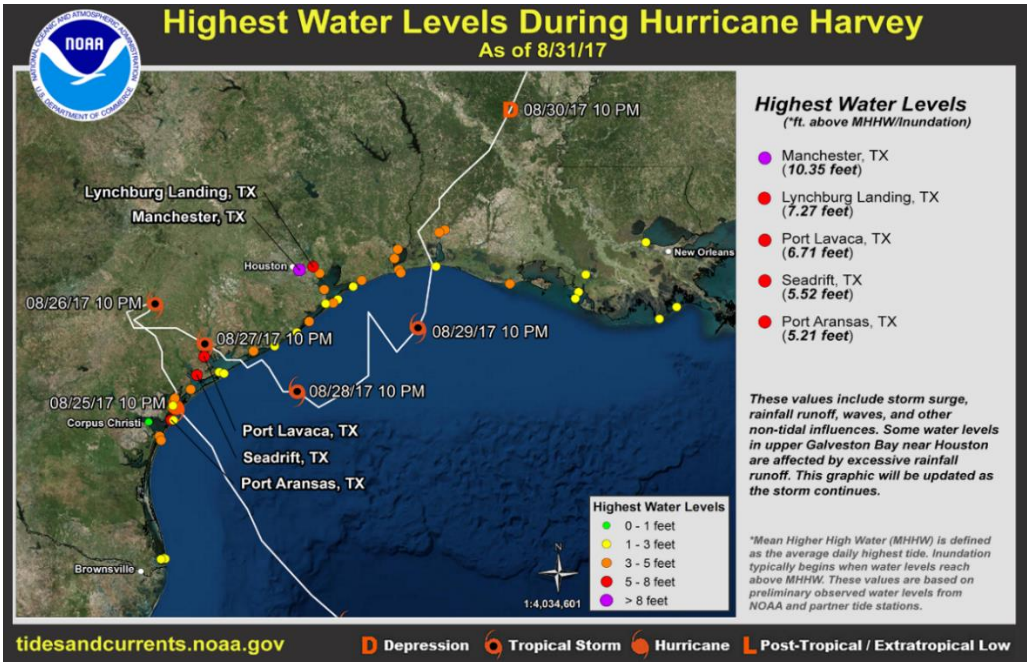

Figure 2. Harvey's path with the highest flood levels (NOAA, 2017).

The stalling of Harvey over the Houston area led to considerable amounts of rainfall, with much of the Houston area receiving at least 102 cm (40 inches) of rainfall (Fig. 3). South Houston received nearly 114 cm (45) inches of rainfall during this event. The largest amount of rainfall was recorded as 154 cm (60.6 inches) near Nederland, Texas. This massive amount of rain caused severe flooding along the area's rivers. Most of the damages from this event were caused by flooding. Early estimates placed the cost of Hurricane Harvey at $70-180 billion (USD).

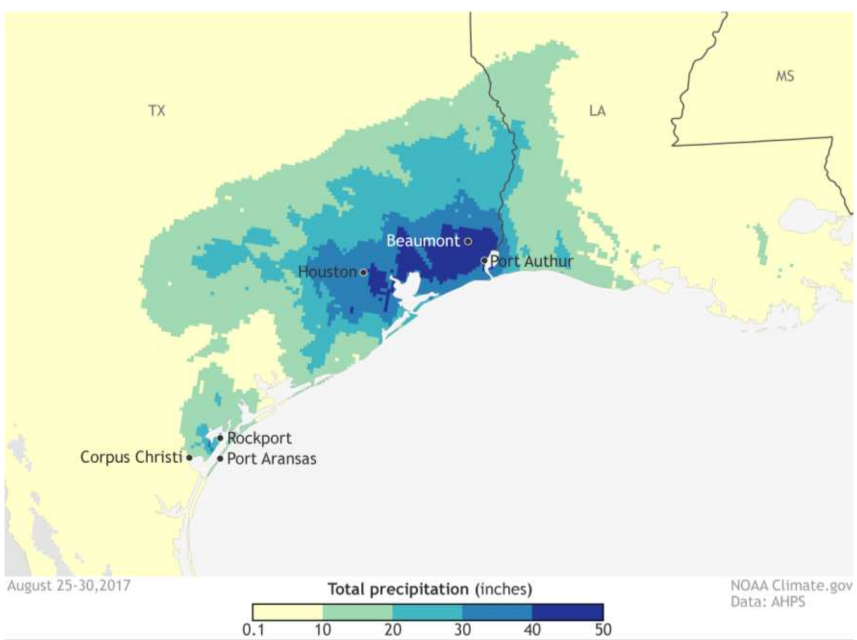

Figure 3. Rainfall totals in Texas from Hurricane Harvey, sourced from the National Weather Service.
(https://www.climate.gov/news-features/event-tracker/reviewing-hurricane-harveys-catastrophic-rain-and-flooding)

ADDICKS AND BARKER DAMS

Descriptions

In 1929 and 1935, major flood events occurred in Houston. The USACE responded to these floods by constructing the Addicks and Barker Dams in a large and mostly undeveloped region west of Houston and east of Katy between 1942 and 1948. The Addicks Dam is located on the north side of Interstate 10, the Barker Dam is on the south side of Interstate 10, and both are flanked by West Sam Houston Parkway on the east and Fry Street on the west (see Fig. 4).

Both dams are long earth embankments, with each dam having one gated outlet structure near mid-length and two auxiliary spillways, one at each end. Key characteristic data for the dams are given below. Note that all elevations in this paper are relative to NAVD 88.

<u>Addicks Dam</u>
Length: 22,200 m (72,900 ft or13.8 miles)
Maximum height: ~11 m (~36 ft)
Crest elevation: 36.9 m (121.0 ft)
Natural ground elevations at ends of auxiliary spillways: north – 32.9 m (108 ft), south – 34.1 m (112 ft)
Maximum storage capacity: 248 million cubic meters (201,000 acre-ft)
North auxiliary spillway length: ~2.595 m (~8,480 ft)
South auxiliary spillway length: ~3,206 m (~10,520 ft)
Previous maximum pool elevation: 31.3 m (102.7 ft) (April 2016)

<u>Barker Dam</u>
Length: 18,800 m (61,666 ft or 11.7 miles)
Maximum height: 15 m (~50 ft)
Crest elevation: 34.5 m (113.1 ft)
Natural ground elevations at ends of auxiliary spillways: 31.7 m (104 ft)
Maximum storage capacity: 258 million cubic meters (209,000 acre-ft)
North auxiliary spillway length: ~887 m (~2,910 ft)
South auxiliary spillway length: ~3,545 m (~11,630 ft)
Previous maximum pool elevation: 29.1 m (95.24 ft) (April 2016)

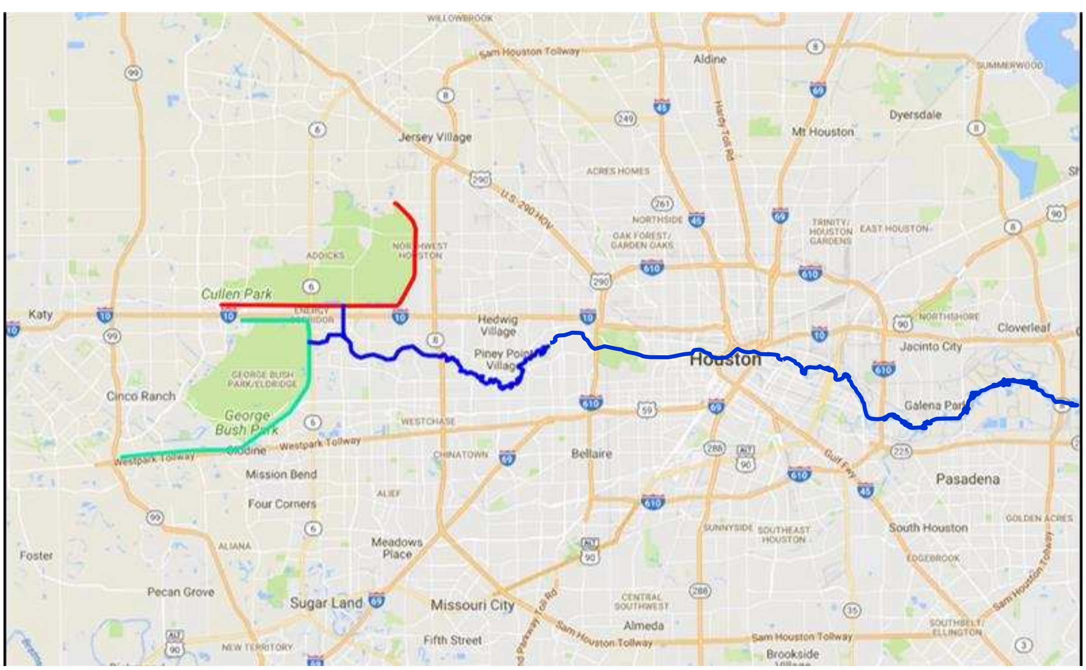

Figure 4. Addicks (red) and Barker (green) Dams and their feed into the Buffalo Bayou (blue) (Google Maps).

Normal reservoir outflows occur through a gate structure and channel at each dam, into east-flowing Buffalo Bayou, through Houston and into the central business district where it joins White Oak Bayou, and continue east to the Houston Ship Channel. Based on personal communications with USACE personnel, the Addicks and Barker Reservoirs are dry about 95% of time, allowing them to host several recreational facilities, which were visited more than 4.4 million times in 2008 (USACE, 2009). Several local roads traverse the dams and reservoirs for use during normal, low water periods. In addition to the gated outlets, both dams also have long auxiliary spillways across the ends of the earth embankments. The auxiliary spillway crests are covered with roller compacted concrete (RCC) for scour protection.

The Addicks and Barker Dams and the property owned by the USACE within the reservoir are abutted by residential and commercial developments. The USACE property within the reservoirs extends to elevations of 31.5 m (103.2 ft) for Addicks and 29.0 m (95.0 ft) for Barker. For reference, the 100-year-flood levels are estimated to be El. 30.6 m (100.5 ft) (Addicks) and El. 29.1 m (95.5 ft) (Barker). The dams are designed to contain floods in excess of the 100-year flood. Residential development extends up to these property lines, and one could stand on the auxiliary spillways, look upstream, and see housing within the reservoir area.

At the time of Harvey's arrival, the USACE was in the middle of remedial construction projects on the dams. These projects included replacing the gate structures for both dams, which required the construction of two cofferdams, construction of slurry trench cutoff walls at the structures and, at a potential seepage location at Barker, filling of voids under the outlet conduits, installation of a seepage controlling granular filter along the conduit, and construction of a parabolic spillway.

Performance

Our primary focus was to document geotechnical aspects of the dams associated with the high-water levels of Hurricane Harvey. Fortunately, during and after the hurricane, the Addicks and Barker Dams were stable and showed no signs of distress from a geotechnical standpoint.

Although hydrologic/hydraulic performance of the dams was outside of our purpose and primary expertise, it appeared that Addicks and Barker Dams fulfilled their mission of reducing the impact of flooding for a significant part of the Houston area, specifically along Buffalo Bayou downstream of the dams, including the central business district. During the heaviest rainfall, around 86-89 cm (34-35 inches) of rainfall was recorded in the watershed. Peak reservoir levels occurred on about August 30, 2017 at 33.3 m (109.1 ft) and 31.0 m (101.6 ft) in the Addicks and Barker reservoirs, respectively. The highest elevations of the crest for these two dams are 34.1m (121 ft) and 34.1 m (112 ft), respectively, which provided freeboards of approximately 3.4 m (11 ft) (Addicks) and 3.0 m (10 ft) (Barker) at the peak reservoir levels. The peak reservoir water level in Addicks slightly exceeded the level of the ground at the north end of Addicks north auxiliary spillway (details below). The USACE opened the Addicks outflow gates on August 28, 2017 to reduce risks associated with higher water levels. These outflows peaked around August 30, 2017 at about 200 cubic meters/second (m^3/s) (7,000 cubic ft per second [cfs]) for Addicks and 180 m^3/s (6,300 cfs) for Barker. The USACE noted that Addicks and Barker Dams reduced peak flows in Buffalo Bayou by more than 3,540 m^3/s (125,000 cfs) during the April 2016 flooding, a smaller event than Hurricane Harvey. The April 2016 event, also known as the Tax Day Flood, resulted from about 43 cm (17 inches) of rain, which accumulated over just 12 hours and caused the previous record pools for the dams. During the time of our visit on September 9, 2017, the gates of the dams were opened to allow flows of 170 m^3/s (6,000 cfs) (Addicks) and 110 m^3/s (4,000 cfs) (Barker) for a total flow into the Buffalo Bayou of 280 m^3/s (10,000 cfs) (see Figs. 5 and 6). The USACE gradually reduced outflows from these levels to a total of 110 m^3/s (4,000 cfs) on September 17, 2017.

Figure 5. Addicks outlet releasing ~170 m^3/s (~6000 cfs) (September 9, 2017, 29.79026° N, 95.62378° W).

Figure 6. Barker outlet releasing ~110 m^3/s *(~4000 cfs) (September 9, 2017, 29.76977° N, 95.64629° W).*

The USACE had contracted to construct new outlet structures and cutoff walls at each dam. This construction was in progress at the time of Hurricane Harvey and was suspended until the consequences of and recovery from the flooding could be assessed. At the time of the hurricane, cofferdams were in place and parts of the cutoff walls had been constructed. The cofferdams performed suitably in keeping the water in the reservoir from flooding the construction zone; however, the high backwater from the channel to Buffalo Bayou flooded the Addicks construction zone (see Fig. 7), and rainwater and underseepage pooled in the Barker cofferdammed area.

Figure 7. Interior of Addicks construction cofferdam for new outlet structure, flooded from Buffalo Bayou backwater; note erosion channels on slopes (September 9, 2017, 29.79063° N, 95.62586° W).

High water in the Addicks Reservoir (~33.3 m [~El. 109.1 ft]) exceeded the elevation of the level ground at the end of the north auxiliary spillway RCC (~El. 108), resulting in small outflows (~6 m^3/s [~200 cfs]) that began on August 29, 2017. Figure 8 shows this area on September 7, 2017 when some small spillage was still taking place. These outflows were within the design intent of the dam and the auxiliary spillway, and should not be described as dam overtopping. Overtopping implies that the water levels have risen above the main dam, which is typically a serious condition that can lead to rapid erosion of the dam and a dam failure.

Figure 8. North end of Addicks auxiliary spillway (September 3, 2017, 29.84977° N, 95.58904° W, photo by USACE).

The high-water levels in the Addicks (El. 33.3 m [El. 109.1 ft]) and Barker (El. 31.0 m [El. 101.6 ft]) Reservoirs exceeded not only the April 2016 historic high levels (El. 31.3 m [102.7 ft] at Addicks and El. 29.0 m [95.24 ft] at Barker) but also the elevations at the upstream edge of the USACE property. As noted previously, housing developments extended up to these boundaries and, consequently, were flooded during Harvey (see Figs. 9, 10, and 11). Area subsidence likely contributed to the upstream extent of flooding. Subsidence in the Houston area is due to consolidation of the underlying aquifers resulting from groundwater withdrawal and has resulted in elevation changes as large as 3.0 m (10 ft) (USGS). The 1.2 m (4 ft) difference in elevations between the two emergency spillways at Addicks Dam is due to this subsidence.

Figure 9. Aerial photograph of flooding within the Addicks Reservoir along the south auxiliary spillway (September 3, 2017, 29.79222° N, 95.68830° W, USACE photograph).

Figure 10. Flooded residential area in the southwest corner of the Barker Dam (September 9, 2017, 29.70706° N, 95.72835° W).

Figure 11. High water mark on fences surrounding residential area (September 9, 2017, 29.70706° N, 95.72835° W).

Nearby runoff that is not captured by the dams is managed in drainage ditches or creeks immediately adjacent to the dams' downstream toes. These drainage channels, along with numerous other stormwater / flood management features, are managed by the Harris County Flood Control District. The team observed several slope failures that will require repairs along Turkey Creek near the southeast corner of Addicks Dam (see Figure 12). Contributing factors to the sloughs could have included the steepness of the banks, flow forces acting on trees on the banks or diverted by trees in the waterway, undercutting by flood flows, reduced shear strength in the clay soils, and the drawdown of the creek water level.

Figure 12. Slope failures along Turkey Creek drainage ditch (September 9, 2017, 29.79009° N, 95.59639° W).

LEVEE IMPROVEMENT DISTRICTS (LIDS) LEVEES

Fort Bend County, southwest of Houston, is home to 19 levee improvement districts (LIDs) and municipal utility districts (MUDs) that maintain levee systems along the Brazos River. These districts have constructed and manage about 160 km (100 miles) of levees systems, along with large drainage ditches, outfall structures, pump stations, flood gates, detention/retention ponds, internal drainage systems, and other stormwater management facilities to protect residents in their districts from flooding from both the Brazos and from stormwater internal to the levees. Residents within the districts fund the construction and management of these facilities through property taxes. Figure 13 shows the LIDs (green) and MUDs (purple) with levees (red dashed lines) in Fort Bend County along with the numbered locations of various features that are described herein. The numbering legend is given below in the figure.

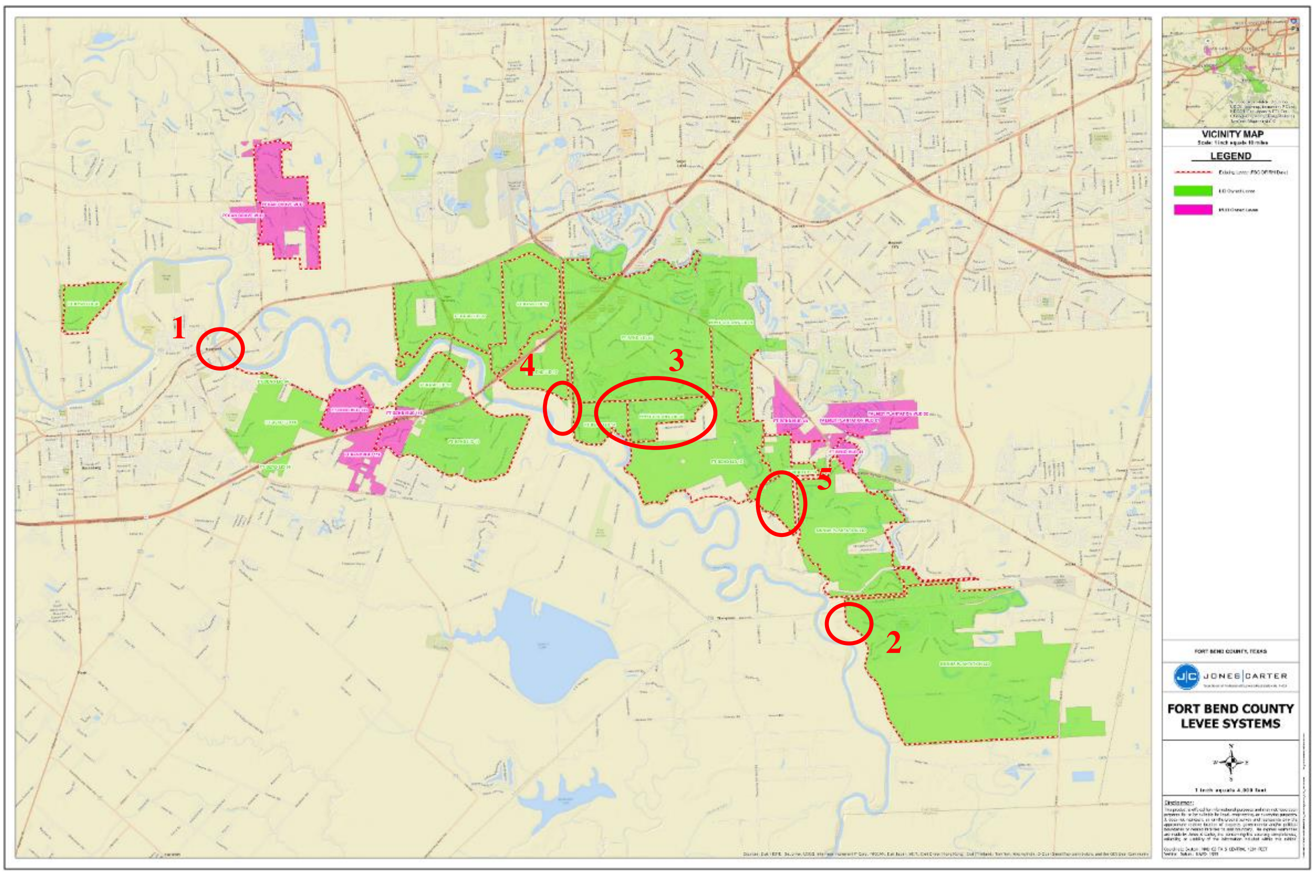

Figure 13. Fort Bend County Levee Systems. See following list for names of labelled systems. Existing levees are shown as red-dashed lines, LIDS in green, and MUDs in purple (from Jones|Carter), 1 – Richmond, Texas, USGS gauge on the Brazos River, 2 – Sienna Plantation Levee Improvement District levee surficial slough, 3 – First Colony LID 2, 4 – Ditch H, 5 – Flat Bank Diversion Channel

During the Hurricane Harvey flooding, the USGS stream gauge for the Brazos River at Richmond, Texas, (see Location 1 on Fig. 13) recorded a peak reading of 16.8 m (55.19 ft) corresponding to about 3,540 m^3/s (125,000 cfs). The gauge also recorded a total of 64 cm (25 inches) of rain between August 25 and August 29, 2017. The previous high-water record at the gauge was 16.7 m (54.74 ft) on June 2, 2016 during the Memorial Day Flood.

Overall, we understand that the Brazos River LID levees performed well, with no major failures, breaches, or overtopping. One incident of a surficial slide on the protected slope of a Sienna Plantation LID levee was reported and photographed by others as shown in Fig. 14 (see Location 2 on Fig. 13). The GEER team visited the First Colony LID 2 (see Location 3 on Fig. 13) and two of the drainage ditches that serve the LIDs (see Locations 4 and 5 on Fig. 13). Despite the good levee performance, flooding occurred within several LIDs due to the issues with storm water removal from the protected side behind the levees to the river side. Some LIDs were even completely cut off due to water surrounding the entirety of the LID.

Figure 14. Aerial photo (right) and Google Earth (left), August 30, 2017, 29.491844° N, 95.541017° W.

First Colony LID 2 (FCLID2)

The levee system in FCLID2 was built in 1988, protects 1,200 homes, which are collectively valued at $430,000,000, and performed well during the Hurricane Harvey event. Major elements of the system include the levees, a pump station with two 83-cubic-meter/minute (22,000-gallon/minute) pumps, a diesel generator for emergency power, and a flood gate structure with two 91-cm (36-inch) discharge outfalls and four 183-cm (72-inch) flood gates. During the event, an emergency pump was brought on site for backup. Due to the record rise of the Brazos River, both pump outlets were discharging under several feet of water but were able to keep up with internal stormwater accumulation. The water height on the river side reached a surveyed maximum elevation of 21.6 m (70.8 ft) along the FCLID2 levee. The levee crest at FCLID2, at elevation 23.8 m (78.1 ft), provided a freeboard of 2.2 m (7.3 ft). The high-water level within the pump station basin on the protected side of the levee is visible in Fig. 15 at about El. 19.8 m (65 ft) on the gauge. Fig. 16 shows the condition of the levee and drainage ditch that conveys water from the protected side of FCLID2 out to the Brazos River. The FCLID2 monitored the levee and pump station system 24 hours a day during the hurricane and high-water levels of the Brazos River. Routine levee maintenance by the FCLID2 included keeping a dense grass cover that is long enough to ensure solid root structures, irrigation for the grass cover and to prevent levee desiccation cracking, and repair of damage caused by rooting and burrowing animals. In FCLID2, wild hogs and fire ants are the main burrowing animal concerns.

Figure 15. FCLID2 drainage outfall / pumping station basin, showing four 1.4 m (60 inch) flood gates, high water line at ~19.8 m (65 ft) gauge height, levee in background (September 10, 2017, 29.55509º N, 95.61779º W).

Figure 16. FCLID2 drainage ditch to Brazos River facing FBLID14 levee. High water line and persistent water lines visible on FBLID14 levee (September 10, 2017, 29.55292º N, 95.61820º W).

Drainage Ditch Slope Slides

The team made observations of slope slides at two large drainage ditches in Fort Bend County: Ditch H and the Flat Bank Diversion Channel. The ditches serve as channels for drainage from and across the LIDs. Ditch H extends due north from the Brazos River, past LIDs 14, 2, and 17, and connects to the Bullhead Bayou and the Oyster Creek watershed in Sugar Land. Flat Bank Diversion Channel runs between Sienna Plantation LID North and LID 19 to connect Oyster Creek to Steep Bank Creek, which then connects to the Brazos River. Fig. 13 shows the locations of both ditches, and Fig. 17 shows a Google Earth aerial of Ditch H during the Harvey flooding.

The observed ditch geometries typically consisted of, from bottom to top, an approximately 20-m- (70-ft-) wide channel bottom, a 15-m- (50-ft-) high, 2.5H:1V channel slope, a small 1-m- (3-ft-) high collector ditch berm, a 1-m- (3-ft-) wide collector ditch, and an 2.4-m- (8-ft-) high levee with a 3H:1V slope. All ditch dimensions and slopes were estimated. The widths of the channels from levee crest to levee crest are about 150 m (500 ft) at Ditch H and 90 m (300 ft) at the Flat Bank Diversion Channel. The flood-side collector ditches at the base of the levees drain down the ditch slope through buried corrugated metal pipes (CMPs) to the channel.

The team observed several slope failures or sloughs along the slopes of Ditch H and numerous feral hog burrows. The east side slopes had some scarps that ranged in height from 15 to 99 cm (6 to 39 inches). Figs. 18 and 19 show two of the sloughs. The slope failures were likely due to softening of the clay soils by the flooding and the subsequent increases in stress on the slope due to drawdown of the flood water. Leakage from either an intact or ruptured CMP could have also contributed to one of the slope failures. The team also observed an erosion gulley below a drainage outfall on the University Avenue bridge (Fig. 20), which could have been prevented with hardened material protection (e.g., riprap, concrete blocks) below the outfall.

Figure 17. A Google Earth image of LID # 14 and Ditch H and its connection to the Brazos River (August 30, 2017).

Figure 18. Ditch H levee, dimensioned slope failure (September 10, 2017, 29.55797°N, 95.63792°W).

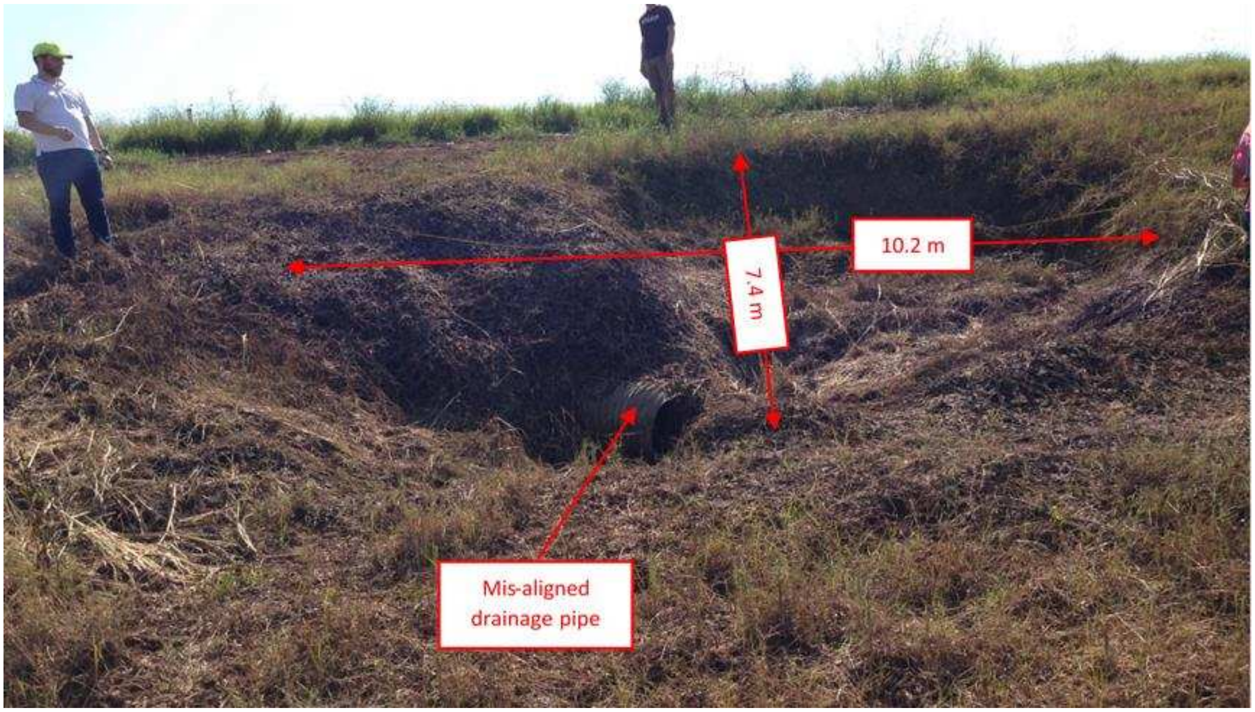

Figure 19. Sour hole at ruptured drainage pipe on Ditch H levee (September 10, 2017, 29.55759°N, 95.63768°W).

Figure 20. Erosion on Ditch H levee under the University Blvd Bridge due to flow impact from bridge drainage outfall (red arrow, September 10, 2017, 29.55902° N, 95.63744° W).

The team observed numerous slope failures along the Flat Bank Diversion Channel (see Fig. 13 for location) between 29.53103° N, 95.56200° W and 29.52572° N, 95.56201° W. Fig. 21 shows the dimensions of one large slide where the team collected a soil sample that was subsequently classified at the Kansas State University laboratory as low plasticity clay (CL) with a 21.3% moisture content. The team noted a drainage CMP outfall on an intact portion of the slope adjacent to this slide and another slide to the south. Figure 22 shows another embankment slough that extended into the base channel.

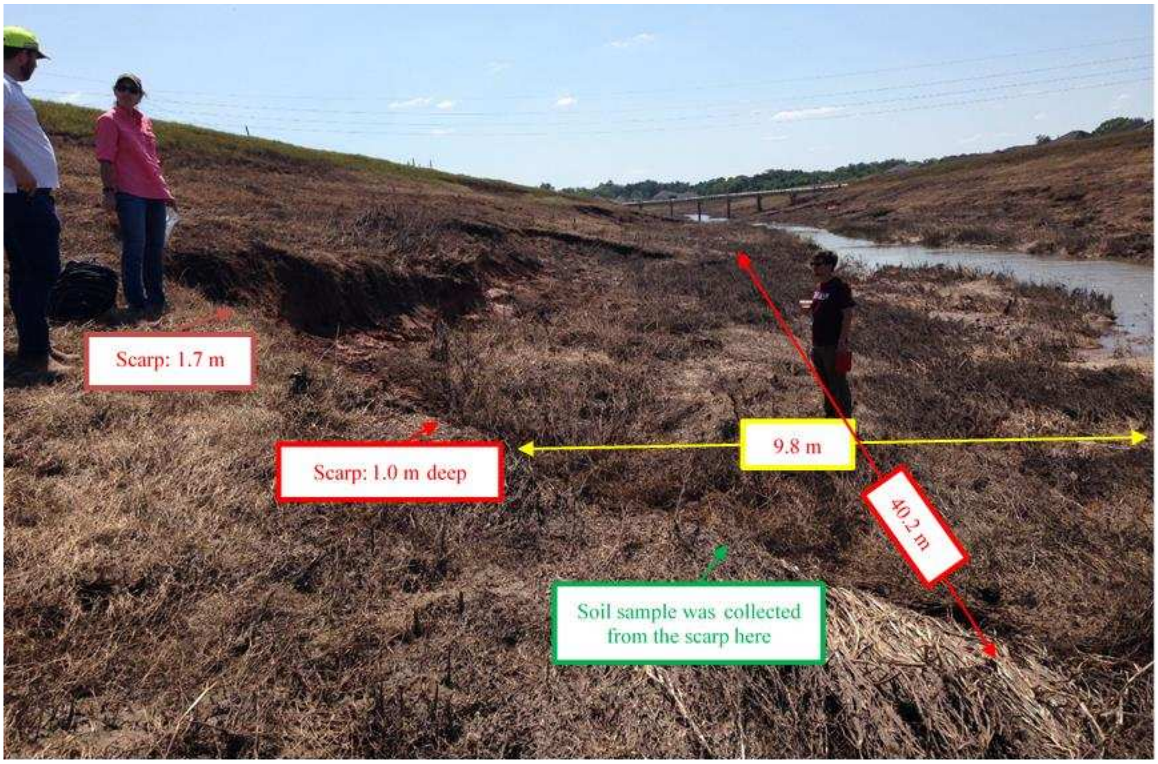

Figure 21. Slope failure north of damaged drainage pipe on the east side of ditch (September 10, 2017, 29.52647°N 95.56194°W),

Figure 22. Earth slumping on the west side embankment (September 10, 2017, 29.53103° N, 95.56200° W).

EROSION ALONG AREA RIVERS, BAYOUS, AND STREAMS

Buffalo Bayou

Buffalo Bayou normally is a slow-flowing waterway that runs from Katy, Texas, 85 km (53 miles) to the east, through much of Houston to the Houston Ship Channel into Galveston Bay. The bayou itself is part of the larger Buffalo Bayou watershed and is a critical part of the Houston flood control system, serving as the downstream channel for both the Barkers and Addicks Reservoirs as shown in Fig. 4. During and after Hurricane Harvey, local stormwater and outflows from the reservoirs into the Buffalo Bayou resulted in significant flooding along the waterway's path as shown in the inundation maps in Fig. 23. Flooding lasted well beyond the hurricane, with significant road closures along the bayou up to the GEER team visit's on September 9, 2017.

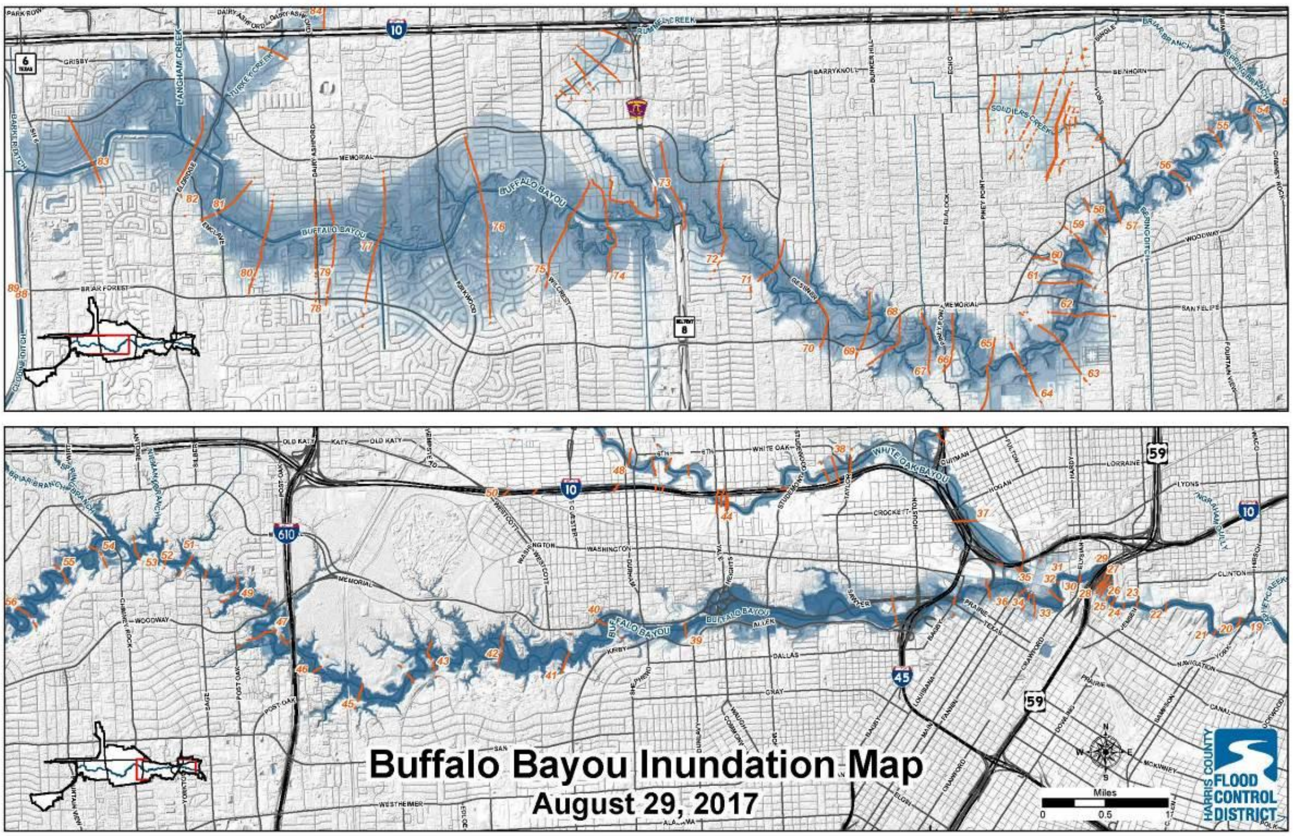

Figure 23. Buffalo Bayou inundation map (courtesy of Harris County Flood District).

Upon arrival of the GEER team at sites along Buffalo Bayou on September 9, 2017, the observed flows in the bayou were about 210 m^3/s (7,300 cfs) at the USGS Addicks gauge. Flooding of residential areas had been largely reduced by September 9, though much of the former parks and trails along the bayou were still inundated with water. Signs of the previous flooding could be seen with river debris noted on bridge girder and railings (see Fig. 24). No critical geotechnical failures were noted along the observed portions of Buffalo Bayou, but scour areas and a slope failure were observed (see Figs. 25 and 26).

Figure 24. Buffalo Bayou evidence of bridge overtopping (flood debris:) a) Montrose Bridge (September 9, 2017, 29.76307° N 95.39377° W), and b) Memorial Bridge (September 9, 2017, 29.76219° N 95.38425° W).

Figure 25. Buffalo Bayou evidence of scour a) Bridge abutment, and b) Downstream of Woodway Drive Bridge (September 9, 2017, 29.76457° N 95.45815° W).

Figure 26. Buffalo Bayous slope failures (September 9, 2017, 29.76318° N, 95.45945° W).

Beaumont – Neches River

As shown on Fig. 3, rainfall totals from Hurricane Harvey in the Beaumont / Port Arthur area were between 102 and 127 cm (40 and 50 inches) and were generally greater than those in the Houston area. This extraordinary amount of rain caused interior flooding behind levees and high stream and river flows.

In Beaumont, the team observed significant erosion scour along the Neches River in the downtown area. Riverfront Park, behind City Hall and located on an outside bend of the river, was severely affected with the loss of shoreline and undercutting of many park features. Fig. 1 shows the location of Beaumont within the study area. Fig. 27 shows the location of Riverfront Park along the Neches River. Fig. 28 shows aerial / satellite images from Google Earth of Riverfront Park taken before the Harvey flooding (January 2015) and during the Harvey flooding (September 2015), respectively.

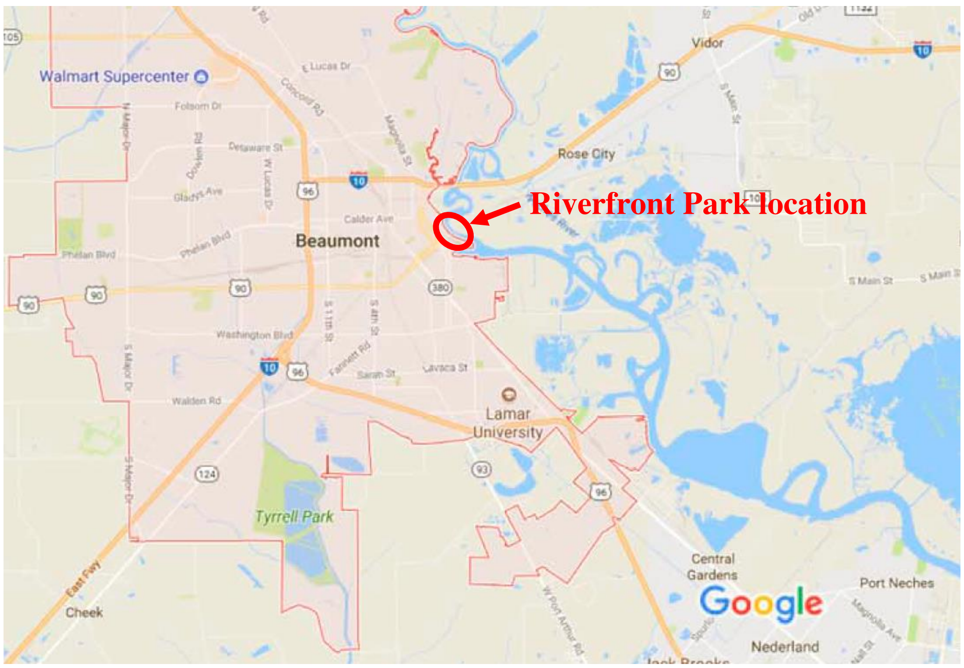

Figure 27. Riverfront Park location (Google Maps for source map).

Figure 28. Aerial images of Beaumont Riverfront Park, January 2015 (left) and September 3, 2017 (right) (Google Earth).

Figs. 29 and 30 show the loss of shoreline and scarps left by the Neches River erosion of the park shoreline, starting from an upstream section protected by riprap and extending through the downriver port area. The pre-hurricane park area shoreline was fronted with a riverwalk/dock (see aerial on Fig. 28), which was largely washed out. Based on pre-hurricane aerials on Google Earth, the shoreline had eroded up to about 15 m (50 ft) from the previous shoreline.

Figure 29. Scour under amphitheater structure. Scarp is estimated to be about 12 m (40 ft) back from previous shoreline (September 11, 2017, 30.08334° N, 94.09441° W).

Figure 30. Downstream end of park. Scarp is estimated to be about 10.7 m (35 ft) back from previous shoreline (September 11, 2017, 30.08184° N, 94.09278° W).

Scarps along the waterfront were up to about 5 m (15 ft) in height, with the highest scarps at the amphitheater. Exposed soils in accessible scarps were stratified, with fill (primarily sand) over stratified silty/clayey (slightly plastic to non-plastic) sand with shells and varying amounts of organic fines. The riprap-covered (30- to 46-cm- [12- to 18-in-] sized rubble concrete) shoreline at the north end of the park was largely intact.

Port Arthur

Port Arthur is located downstream of Beaumont on Sabine Lake, which connects to the Gulf of Mexico via the Sabine Pass. Port Arthur is the historic and current home of several refineries and port facilities. Sabine Lake at the Port Arthur is broad enough that flood flows from upriver have significantly less velocity and height than in Beaumont. However, because of its proximity to the Gulf, Port Arthur is at greater risk from hurricane storm surges and has several levee and floodwall structures to protect it from such surges. Based on our limited observations at several levee locations in Port Arthur and on discussions with local officials, the storm surge from Hurricane Harvey did not overtop or breach the Port Arthur levees. Most of the damage from Hurricane Harvey in Port Arthur occured behind the levees because interior drainage systems had to deal with the 102 to 127 cm (40 to 50 in) of rainfall accumulation.

Texas City

Texas City is located southeast of Houston in the Galveston Bay area (see Fig. 1 for location). It is protected by the Texas City Hurricane-Flood Protection Levee (TCHFPL) system and the nearby Texas City Dike. The TCHFPL is a 27-km- (17-mi-) long levee system that was built by the U.S. Army Corps of Engineers between 1962 and 1982 following Hurricane Carla. When Hurricane Ike hit the area in 2008, the levees, which ranged between 6 m to 7 m (19 to 23 ft) above sea level, managed to hold back the Galveston Bay storm surge with only about 0.6 m (2 ft) of remaining freeboard in some sections. The little damage that occurred was mostly due to erosion (Evans, 2008). The storm surge in this area during Hurricane Harvey was well below that of Hurricane Ike, and no storm damage was visible to the GEER team during their drive along a road built on top of the levee's crest.

ROADWAY / INFRASTRUCTURE DAMAGE

Beltway 8 Underpass Slab Uplift

Flooding caused roadway damage to and closure of a major area artery at the underpass intersection of the Sam Houston Parkway / Beltway 8 and Boheme Drive (see Fig. 1 for location, 29.76736° N, 95.56210° W). The parkway is depressed at this intersection and floods often enough that flood depth sign gauges are posted along the road to warn motorists of the standing water depth (see Fig. 31).

Figure 31. Beltway 8 / Boheme Drive underpass and flood depth signs (September 11, 2017, 29.76694° N, 95.56139° W).

The roadway damage consisted of an uplifted road slab (or slabs) on Beltway 8 and a washout of the adjacent access road, West Sam Houston Parkway N, which is supported about 6.7 m (22 ft) above the parkway by a cantilevered retaining wall consisting of precast panels, which are supported by H-pile reinforced concrete piers. It appears that flood water from the area west of the parkway flooded the access road, drained down behind the retaining wall, and uplifted the Beltway 8 slabs. These flows then washed out soil behind the wall and under the access road and adjacent sidewalk, leaving a 5 m- (17 ft) deep hole. Fig. 32 photographs show the state of the damaged roadway during and after the flooding event. Fig. 33 shows repair work conducted on the uplifted slabs.

Figure 32. Damage of the walkway slab on Beltway 8 (left photo courtesy Brian Klein, a resident in the area, August 27, 2017, and right photo courtesy of a construction worker on site, 29.76735° N, 95.56219° W).

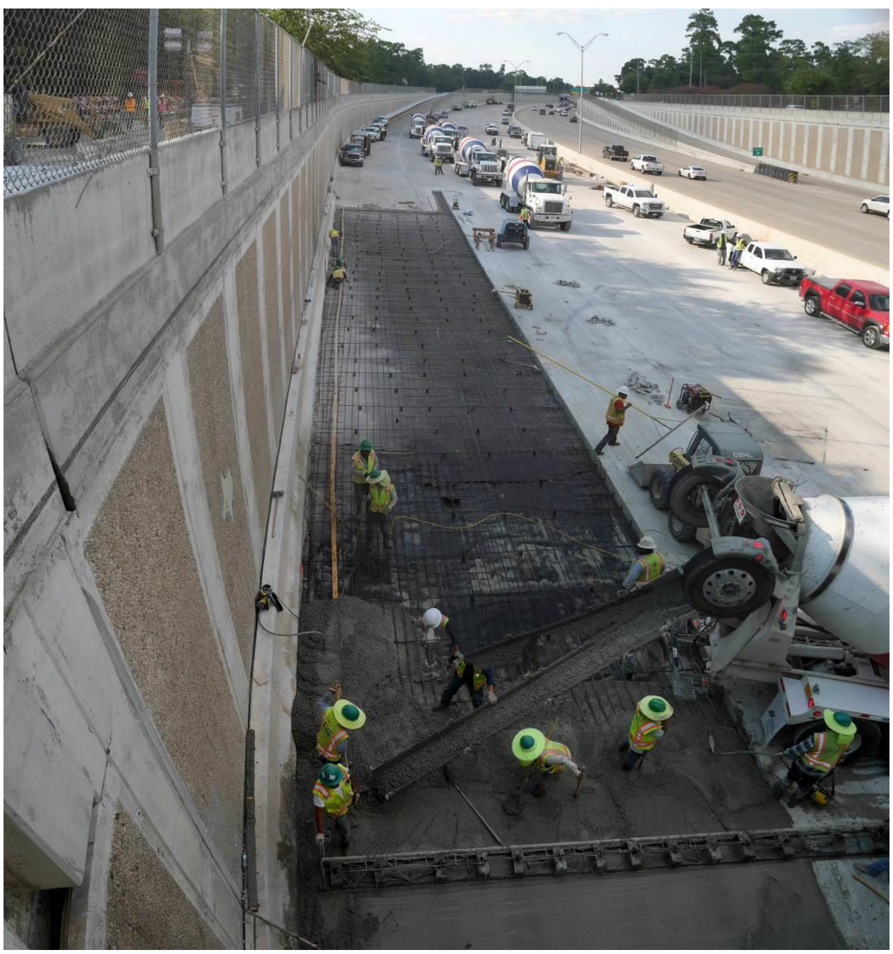

Figure 33. Road pavement repair in progress on Beltway 8 (September 10, 2017, 29.76736° N, 95.56208° W).

San Jacinto River I-45 & Missouri Pacific Railroad Bridges

The GEER team visited the bridge foundations and supports of Interstate 45 (I-45) and the Missouri Pacific Railroad over the West Fork San Jacinto River south of Conroe, Texas, approximately 16 km (10 mi) downstream of the Lake Conroe Dam on September 11, 2017 (see Fig. 1 for location, Fig. 34 for aerial). The USGS river gauge 08068000 on the West Fork San Jacinto River, downstream of the Lake Conroe Dam, measured maximum water levels of approximately 38.7 m (127 ft) on August 29, which the USGS correlates with 3,230 m^3/s (114,000 cfs) (statistic daily mean 13.5 m^3/s [477 cfs] prior to regulation by Lake Conroe).

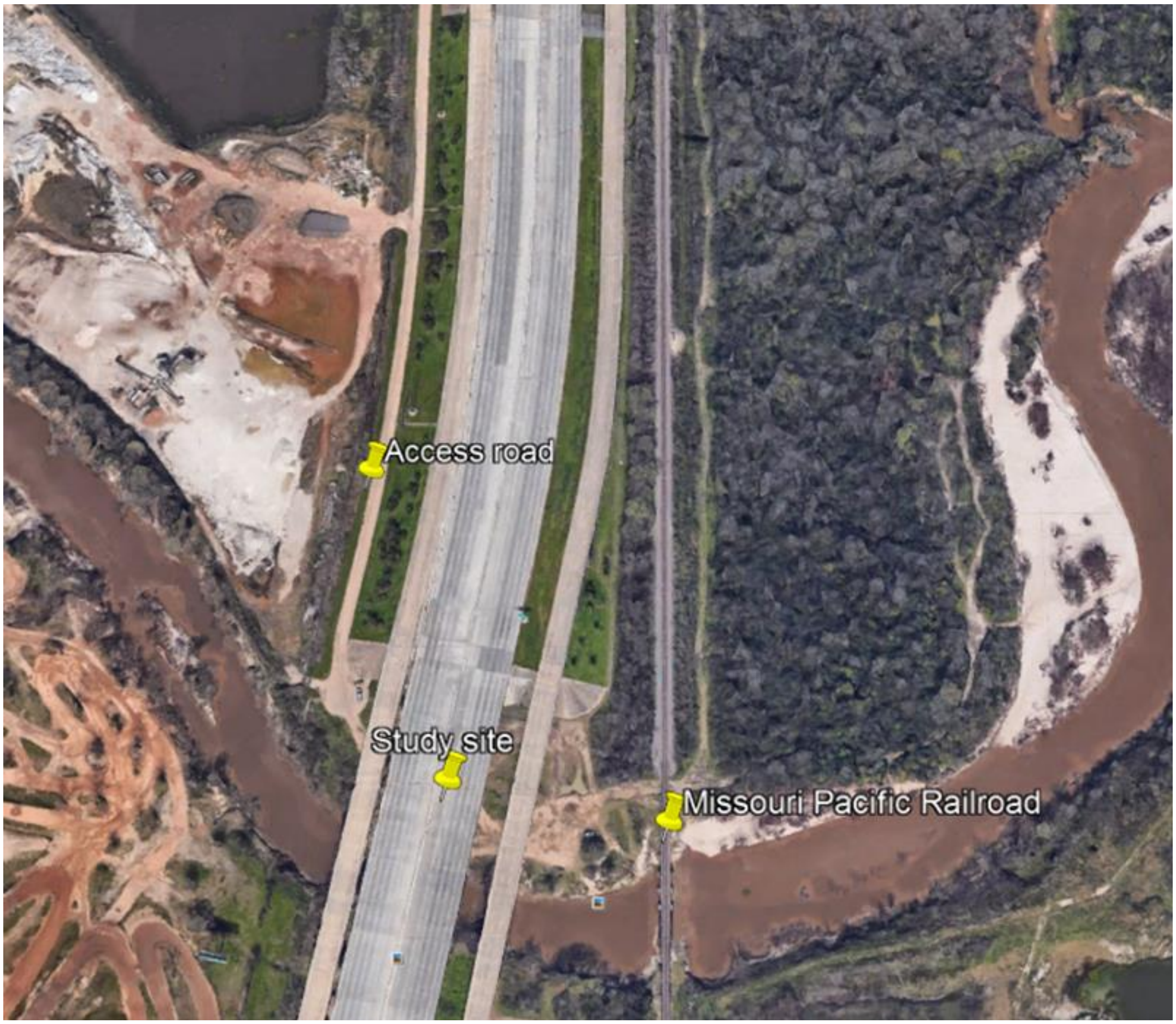

Figure 34. San Jacinto River Area observation locations (Google Earth image for April 2017, 30.24599° N, 95.45722° W).

As expected, bridge columns with no erosion control had variable amounts of accumulated debris (see Fig. 35) and scour (see Figs. 36 & 37). No measurable scour was observed around columns with erosion control (see Fig. 38), which included riprap and polymeric reinforcement. Fig. 40 shows the bank of the San Jacinto River from the north side, facing south. The riprap along the banks likely reduced the erosion of the fine, sandy soil. Fig. 41 shows an observed 2.4-m- (8-ft-) diameter scour hole in the sandy bank material. Despite the observed scour, no geotechnical or structural failures were observed on the I-45 Bridge over the San Jacinto River.

Figure 35. Observed debris on first column in flow direction. Debris pile is 1.24 m (49 inches) tall around the 1-m- (3-ft-) diameter bridge column (September 11, 2017, Time 10:04 CDT, 30.24688° N, 95.45796° W).

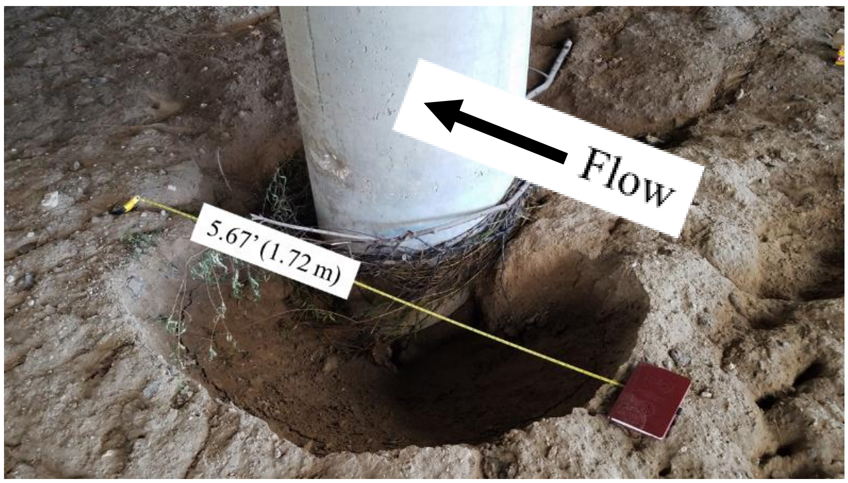

Figure 36. Bridge column scour (September 11, 2017, Time 10:06 CDT, 30.24688° N, 95.45796° W).

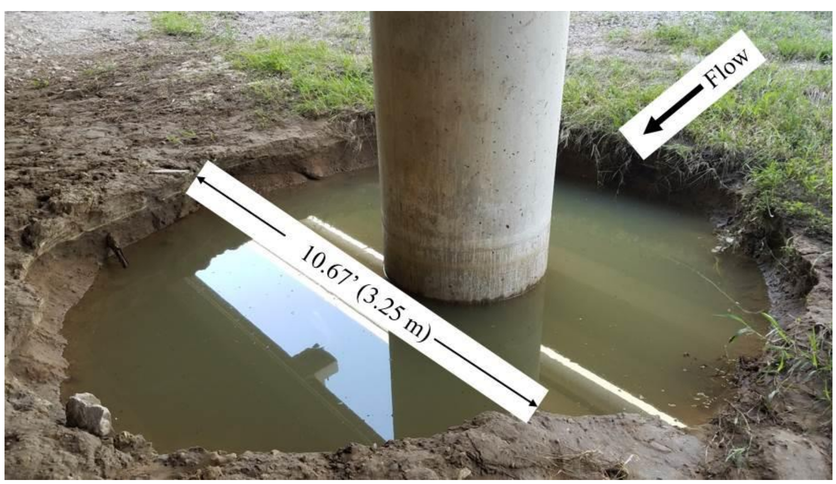

Figure 37. Scour hole on column closer to river. The hole was 3.7 m (12.3 ft) long in the flow direction and 3.25 m (10.67 ft) perpendicular to flow. The depth of the scour hole was 0.8 m (2.75 ft) from the existing ground (September 11, 2017, Time 10:23 CDT, 30.25071° N, 95.45703° W).

Figure 38. Erosion control riprap, including polymeric reinforcement, with minimal observed scour (September 11, 2017, Time 10:19 CDT, 30.24688° N, 95.45796° W).

Figure 39. Riprap along south bank of San Jacinto River (September 11, 2017, Time 10:56 CDT, 30.24574° N, 95.45761° W).

Figure 40. Scour around columns on San Jacinto Banks (sandy soil). The scour hole was approximately 2.4 m (8 ft) across and 0.6 m (2 ft) deep (September 11, 2017, Time 10:59 CDT, 30.243364°N, 95.46452°W).

Figs. 41 and 42 show the Missouri Pacific Rail Road Bridge downstream of I-45. Bank erosion was noted on the south bank of the San Jacinto River downstream of the railroad bridge. Fig. 42 shows debris on top of the pile caps and at the top of the bents on the railroad bridge. These high debris levels were consistent with the maximum measured gauge height during Harvey of approximately 10 m (33 ft) above average gauge height.

Figure 41. Bank erosion on the San Jacinto River downstream of I-45 and a railroad bridge parallel to the highway (September 11, 2017, Time 11:05 CDT, 30.24688° N, 95.45796° W).

Figure 42. Debris on railroad bridge indicating flow levels and scour around pile caps below current flow levels (September 11, 2017, Time 11:10 CDT, 30.24688° N, 95.45796° W).

FM 762 Road Culvert Washout

The culvert failure and subsequent washout of the 3900 Block of 762 in Rosenberg, Texas, southwest of Houston (see Fig. 1 for the general site location), was heavily featured on news coverage at the time of our visit. The replacement flow structure observed by the team was a set of three concrete ~1-m- (~3-ft-) diameter culverts running beneath the FM 762 highway, carrying flows from the adjacent railroad and shopping center culverts to the south into a creek that empties into the Brazos River. The failure of the road culverts was first reported on August 27, 2017, and resulted in a road closure through the time of our September 10, 2017 visit.

Erosion of the road progressed from the downstream side (see Fig. 43) until the entire width of the road washed out, stopping within 18 m (60 ft) of the adjacent railroad tracks. Repair construction was underway at the time of our visit. Possible erosion mechanisms could have included overtopping flow, culvert leakage or failure, or embankment seepage.

Figure 43. FM 762 Washout on August 27, 2017
(Courtesy of the Rosenberg Police Department, 29.5442° N, 95.7434° W).

Mustang Bayou Bridge

The erosion at the State Highway 35 Bypass bridge and pipe crossing over Mustang Bayou in the city of Alvin (see Fig. 1 for location) was typical for small waterways with high flow. Two shallow soil slump failures with slip depths of about 0.3 to 0.6 m (1 to 2 ft) were noted along the north bank of the bayou, one of which was beside and under a pipeline pile cap (Fig. 44).

Figure 44. Shallow soil failure along the north bank of Mustang Bayou, adjacent to pipe-support foundation (September 4, 2017, Time 12:48 CDT, 29.40889° N, 95.23234° W).

RESIDENTIAL IMPACTS

Area residents, especially in low-lying areas, suffered significant damage to their homes and businesses, but generally were able to return to start clean-up and repairs soon after the storm (see Figs. 45 and 46 for photos of typical flood damage debris on curbs). Area subsidence probably contributed to flood vulnerability and resulting residential damage, especially within the Addicks Reservoir. While many homeowners and businesses suffered greatly because of the damage, we hope and expect that the combination of rapid restoration of infrastructure and businesses, along with a robust local economy, has allowed for a quick recovery for the area.

Figure 45. Residential flood damage debris, Houston.

Figure 46. Residential flood damage debris, Port Arthur.

SUMMARY

Rain, not storm surge or wind, caused the observed damage in Houston, Beaumont, and Port Arthur by overwhelming stormwater management facilities and creating high flows in area waterways. The dams and levees that the GEER team visited performed well from a geotechnical perspective, although we understand that fifteen private, non-regulated dams did fail or suffered significant damage. The USACE dams, Addicks and Barker, showed no signs of structural distress and served their primary function of reducing flood damage to large areas of Houston, including the central business district. The USACE made controlled releases of water from the dams to Buffalo Bayou to reduce risks associated with high reservoir water levels. The high flows in Buffalo Bayou from area runoff and these releases were what flooded low elevation residences and businesses along the bayou. Area levees built and maintained by LIDs protected their districts from riverside flooding. However, interior flooding occurred within several LIDs where rainfall accumulation and pumping against high riverside pressures overwhelmed LID stormwater management facilities.

The team observed numerous shallow slide failures along drainage channels associated with the LIDs. Slopes constructed in area clays are very susceptible to these shallow slides, most likely due to infiltration of water into desiccation cracks, softening of the clay, and increased loading when water levels in adjacent channels drop. High river, bayou, and stream flows eroded the soil around and under constructed facilities, as one would expect. The most pronounced observed damage occurred to the Riverfront Park along the Neches River in Beaumont. Some limited damage to transportation structures occurred along flooded waterways and at a major highway underpass. The observed damage to transportation facilities was either repaired or under repair, and traffic had returned to normal dense levels at the time of our observations.

The team prepared a GEER report with additional details about observations, which, like all GEER reports, is available on the GEER website at http://www.geerassociation.org/.

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