Hurricane Katrina: Geotechnical Observations in Biloxi, Mississippi

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Hurricane Katrina made land fall along the Louisiana-Mississippi border during the morning of August 29th, 2005. At the time of the landfall, Katrina was a category 4 hurricane. The storm eye traveled a path 73.4 km west of Biloxi, where winds reached sustained speeds of 164 km/hr in Biloxi, with gusts in excess of 200 km/hr. The damage caused by Hurricane Katrina in Biloxi was catastrophic in all single family dwellings within 400 to 600 mm of the waterfront and along the east end of the Biloxi peninsula (Fratta and Santamarina 2006).

The wind load, rain-induced flooding, and the storm surge associated to large hurricanes cause slope failures, internal piping of earth dams, sediment transport along coastal regions and the failure of foundations for slender structures (Wieczorek 1996; Bucknam et al. 2001). Prepared with this information, we visited the Biloxi area twice (11/2005 and 7/2006) to assess the response of near-shore geotechnical systems (both onshore and offshore), including foundations, retaining walls, anchors and scouring next to bridge piers.

Sediment Transport

The storm surge in Biloxi reached 8 m in less than 12 hours (FEMA); for comparison, the normal tidal fluctuation in the area is ~0.5 m (NOAA). Wave action and storm surge eroded the banks and street subbases along the shore in Harrison County, MS. On the other hand, sediment transport and deposition were evident along Beach Boulevard (Highway 90) which was covered with beach sand (uniform, fine silica sand; D_{50}=0.30 mm, C_u=1.9). In some locations, the new sand deposits reached 3 m deep; for example, the first floor of a beachfront condominium under construction was completely buried in sand after the storm.

Erosion behind Retaining Walls

Most shoreline retaining walls extend less than 1.5 m above mean sea level. The most common construction method is based on driven steel sheetpiles. Larger walls end with a concrete beam cast on top of the sheetpiles. Typically, retaining walls are anchored 4 to 6 m back into the sandy backfill at about 1 m below the ground elevation. Limited settlement or erosion of the backfill were observed in retaining walls.

The Broadwater Beach Marina involves the most important retaining wall system in Biloxi. The marina was built to house the President Casino barge on the coastline (The barge became loose during the storm and landed north of Beach Boulevard, 1 km WNW from its original position). The C-shaped retaining wall starts onshore and extends about 450 m into the ocean.

The top of the wall is 2.5 m above mean sea level. The retaining wall normal to the shoreline suffered some erosion and undermining of the concrete road that runs parallel to the wall (up to 0.7 m settlement), however, the wall itself shows no sign of distress. On the other hand, the front wall parallel to the shoreline rotated more than 1m towards the water and there is extensive erosion of the backfill (more than 1 m deep). The reinforced concrete tiebacks are fully exposed, and some have severed (Figure 1). Therefore, the failure mechanism combines the effects of backfill erosion, reduced tieback resistance and seepage forces.

Scour around Bridge Piers

Water flow through cross sections along bridge crossings reached velocities V_{flow}=0.27 m/s, which is more than an order of magnitude higher than during normal tides. To quantify erosion around bridge piers, we ran P-wave reflection imaging along the Highway 90 and I-110 bridges across the Bay of Biloxi, using a subbottom profiler from a small fishing boat (Tritech, dual frequency ~20 kHz and ~200 kHz). The subbottom profiler permits obtaining the bathymetry of water bodies and the stratigraphy of subbottom sediments.

Clear scour is observed at every pile set, as can be seen in Figure 2 for the case of the I-110 bridge. Erosion takes place all around the pier, yet it is more pronounced on the side of the incoming surge.

The sediments in the Bay of Biloxi consist of a plastic green, organic mud with traces of sand. This soft mud traps gas, and it is often found overlaying oyster beds. Trapped gas and shells reduce the penetration depth of the subbottom profiler, and "shadows" appear in the cross section, as can be seen in Figure 2.

We found finer sediments near Highway 90 (D_{50}= 0.01; LL=80, PL~25) than around the I-110 bridge (D_{50}= 0.06 mm; LL=34, PL~25). This is reflected in the depth of erosion wells which are deeper for the I-110 bridge (up to 3.5 m) than along the Highway 90 bridge (up to 1.5 m), even though the Highway 90 bridge was more exposed to the storm (the estimated peak flow velocity is very similar in both cases - $V_{flow} \approx 0.27$ m/s). Erosion analyses support this observations (for example, see Graf 1984): spherical particles size D_{50}=0.06 mm (near I-110 bridge) can be eroded when the flow velocity exceeds 0.25 m/s, while particles size D_{50}=0.01 mm (near Highway 90 bridge) require a flow velocity of 0.60 m/s to be eroded.

Bridge Slabs and Foundations

While scour is extensive, it did not cause the observed catastrophic failure of bridges. Instead, structural features can account for these failures. Let's consider the Highway 90 bridge. This is a four lane structure that gradually rises from the bridge abutments to about 20 meters above mean water level above the navigation canal. Slabs were simply supported on 140 pile caps. All slabs sitting lower than ~6 m above the mean sea level fell off the pile caps into the bay toward the NW side of the bridge, while slabs closer to the draw bridge and above the ~6 m elevation remained in place even when the scour was deeper around the corresponding piers. Given the 8 m high storm surge, these observations suggest that the failure mechanism combined flotation and drag forces (Mosqueda et al. 2006; Fratta and Santamarina 2006).

In contrast to the collapse of the Highway 90 bridge, a nearby railway bridge suffered only minor damage and was back in service approximately 45 days after the storm. While the concrete slabs were only 4 m above the mean water level, the pile caps in this bridge have shear keys that prevented the lateral displacement of the slabs (22 out of 93 shear keys needed some minor repairs along the NW side of the bridge after the storm).

The floatation & drag failure mechanism for simple supported concrete slabs is also responsible for the failure of lower floors in oceanfront prefabricated concrete structures, and for the collapse of the remaining simply-supported slabs of the old two-lane Highway 90 bridge that had collapsed during Hurricane Camille in 1969.

Besides scour, there were very limited foundation problems in the Highway 90 bridge. The only pile set that fail -out of 140 pile sets- rotated in the direction of the bridge about a point 8.5 m below the pile cap (2 m below the sediment). The rotation was triggered by the unbalanced lateral force exerted by falling slabs and caused the bending failure of the piles. In addition, one pile cap showed a shear fracture towards the NW corner where the slab sat as it was being pushed off the pile cap and apparently plunged the corner battered pile in the set. In other bridges, piles and slabs suffered damage as they were impacted by loose barges and shrimp boats during the storm.

Other Foundations: Houses, Tanks, Floating Casinos

Floatation & drag forces are also responsible for the failure of many other foundation-structure systems. Only the foundation blocks and concrete mat foundations for wooden homes and small hotels remained within 300 m of the coastline (this is an average distance – local values vary with topography and distance to the eye of the storm). Further inland, many houses were displaced from their foundations sometimes by tens of meters. Structures built on an empty first floor of "concrete stilts" also experienced extensive damage as the surge far exceeded this elevation and sheared off the structure from its base.

Oil tanks that were not sufficiently filled at the time of the store surge were lifted from the foundation shearing anchor bolts, and floated away sometimes above the peripheral embankment designed for spill containment (Figure 3 – see also Godoy et al 2006).

Several casinos were housed on floating barges (typical dimensions: 200 m long, 40 m wide and 5 stories tall). These barges were kept in place with either of two designs. Most barges used slip rings to slide up-and-down steel shafts following the tides. In this case, while the shafts did not fail, rings reached the end of the allowed ~4 m run during the hurricane, and sheared from the barges (Figure 4). The freed barges floated away (more than a 1000 m in the case of the President Casino). The other design, used in the Beau Rivage y Hard Rock casinos consisted of keeping the barge in position with 20 to 30 m long tension piles. The Beau Rivage casino suffered minor damage (no apparent foundation damage), while the Hard Rock casino was destroyed (we have not been able to gather information about the foundation performance).

Closing Comments

Hurricane Katrina caused very limited wind damage in most large structures in the Biloxi area. In fact, there were very few failures of water tanks or large bill boards even though these structures experienced large wind forces. Instead, most of the devastation that Hurricane Katrina produced is related to the storm surge and the combined effects of floatation & drag forces.

Geotechnical systems performed well in most cases. Future design considerations must properly account for higher storm surges, floatation and lateral water forces, and incorporate adequate design and construction details to prevent the detachment of the superstructure from the foundation and the erosion of backfills.

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Figure 1: Retaining wall failure in the Broadwater Beach Marina. (a) The 450-m long east retaining wall suffered no damage; however, the fill under the pavement eroded and the pavement settled about 0.7 m. (b) The 240-m south retaining wall rotated more than 1.0 m towards the Gulf of Mexico. (c) The backfill for the south wall eroded, the pavement settled and the tie backs failed.

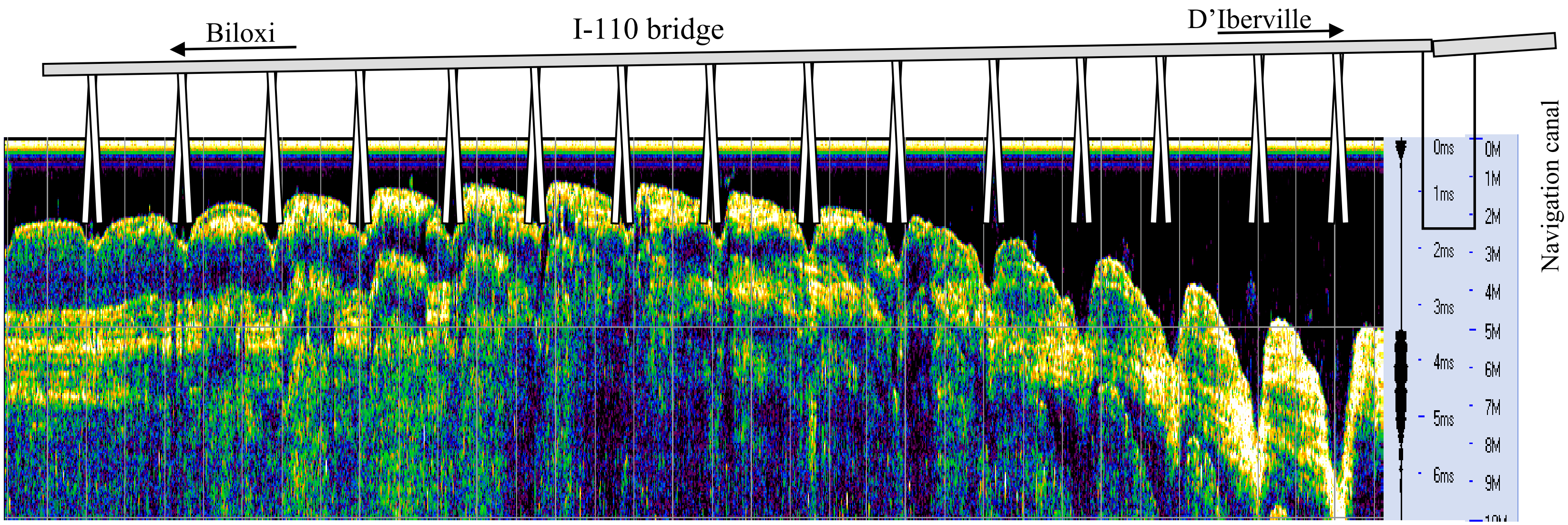

Figure 2: 20 kHz subbottom profiles of Bay of Biloxi Bridges. (a) Collapsed Highway 90 bridge. The profile was run approximately 1.5 m from the SE edge of the pile sets, the average separation between pile sets is 16 m. (b) I-110 Bridge. The profile was run approximately 1.5 m from the E edge of the pile sets, the average separation between pile sets is 30 m. Horizontal scales are different.

Figure 3: Displaced oil tanks at the Munro MP Terminal in Biloxi. Some tanks were displaced more than 40 m and even crossed the spill controlled embankment built around the tanks.

Figure 4: Anchor system and failed slip rings of the Grand Casino barge.