Coastal Bridge Performance during Hurricane Katrina

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ABSTRACT: The storm surge associated with Hurricane Katrina caused tremendous damage along the Gulf Coast in Louisiana, Mississippi and Alabama. Similar damage was observed subsequent to the Indian Ocean Tsunami of December 26, 2004. In order to gain a better understanding of the performance of engineered structures subjected to coastal inundation due to tsunami or hurricane storm surge, the authors surveyed damage to bridges, buildings and other coastal infrastructure subsequent to Hurricane Katrina. A number of coastal bridges experienced significant structural damage due to storm surge and wave action. Bridge decks submerged during the inundation were subjected to hydrodynamic uplift forces due to wave action and hydrostatic uplift forces due to buoyancy, enhanced by air trapped below the bridge deck. Inadequate performance of the deck-to-pier connections resulted in complete loss of all deck segments on a number of low level coastal bridges. Extensive scour was also observed around approach roadways and abutment foundation systems due to a combination of shear- and liquefaction-induced sediment transport.

1 INTRODUCTION

Hurricane Katrina is likely to be the most expensive natural disaster in US history. It developed as a category-5 storm in the Gulf of Mexico before making landfall on the border between Louisiana and Mississippi as a category-3 storm (FEMA, 2006). As expected from a storm of this magnitude, there was considerable wind and rain damage. However, the primary cause of damage to coastal infrastructure along the entire Mississippi coastline, and portions of the Louisiana and Alabama coastlines, was the inundation due to storm surge and wave action. This damage far outweighed the wind-induced damage and far exceeded the storm surge damage caused by any prior hurricane or tsunami impacting the US coastline. Similar damage was observed along coastlines affected by the Indian Ocean Tsunami of December 26, 2004 (CAEE, 2005).

The peak storm surge caused by Hurricane Katrina exceeded 7.5 m above sea level, and occurred between Pass Christian and Gulfport, Mississippi. This level of surge is considerably greater than experienced during other recent hurricanes of similar intensity, primarily because of the shallow coastal bathymetry and the shape of the coastline and man-made levees around the Mississippi River Delta (FEMA, 2006). The extent of storm surge damage to engineered infrastructure along the Gulf coast was greater than might have been anticipated.

The Indian Ocean Tsunami resulted in runup exceeding 40 m in some locations (CAEE, 2005). In addition to large-scale destruction of residential structures, the tsunami inundation caused complete failure of a number of coastal bridges on the island of Sumatra in Indonesia. Numerous lessons can be learned from these events to aid in the design and construction of future bridges, and retrofit of existing bridges, in regions threatened by storm surge or tsunami inundation.

The primary factors causing damage to coastal bridges were hydrodynamic uplift and lateral loading due to wave action, hydrostatic uplift due to buoyancy, deck-to-pier connection failure, and excessive sediment transport and scour around bridge abutments. These issues are addressed in detail by Robertson, et al. (2006a and 2006b). A comparison between theoretical hydrodynamic loading and bridge performance during Hurricane Katrina is presented by Douglass et al. (2006).

This paper presents a discussion of the performance of selected bridges along the U.S. Gulf coast, with particular attention to deck-to-pier connection details and abutment scour. Recommendations are made for

Figure 1. Deck damage on US90 bridge over Biloxi Bay.

improved performance of future bridges and retrofit of existing bridges.

2 US90 BRIDGE OVER BILOXI BAY

The US90 highway bridge over Biloxi Bay, between Biloxi and Ocean Springs, Mississippi, is composed of simply-supported bridge segments varying in length from 13.7 to 15.9 m. Each segment consists of six prestressed concrete girders supporting half of the roadway deck and one sidewalk. Hurricane Katrina storm surge at this bridge location was sufficient to submerge all low-level spans of this bridge (Fig. 1). When submerged, the air trapped between the girders, along with the reduction in self-weight due to submersion in sea-water, meant that these segments were very nearly buoyant once submerged (Fig. 2) (Robertson et al. 2006b). In the buoyancy calculations, air is assumed to fill the void under the bridge deck when the water level reaches the bottom of the end bulkheads. This volume of air is assumed trapped as the water level rises to submerge the entire deck section. Considering hydrostatic effects only, the water head

Figure 2. Inverted deck showing potential trapped air volume.

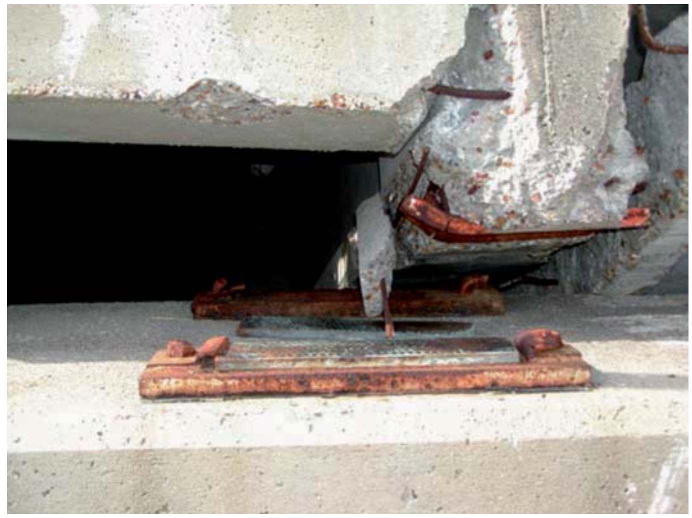

Figure 3. Friction bearing supporting US90 bridge girders.

acting on the trapped air will result in a slight decrease in the air volume. In addition, vertical and horizontal hy-drodynamic loads induced by wave action were sufficient to dislocate these deck elements (Douglass et al. 2006) (Figure 1).

The bearings supporting each end of the girders at the pier bents provided no restraint against uplift, and only nominal resistance against lateral movement (Fig. 3). Being a low seismic zone, there were no requirements for shear keys to provide lateral restraint or ties to prevent uplift, as is common in seismic regions. Friction induced by gravity load, and small 12mm thick steel angles, were the only physical restraint against lateral movement for these bridge segments. When subjected to the wave-induced hydrodynamic uplift and/or buoyancy effects, the segments were free to move off their supports under the lateral load from surge and wave action. Apart from the bridge segments elevated over the ship channel, every segment of this bridge was dislocated from its supports and collapsed into the bay (Figure 1).

3 US90 BRIDGE OVER ST. LOUIS BAY

The US90 highway bridge across St. Louis Bay, between Pass Christian and Bay St. Louis, Mississippi, consists of simply-supported rectangular concrete girders supporting a concrete deck slab (Fig. 4). The bulkhead and bridging elements provided between the girders of this deck are only partial depth allowing much of the air below the deck to escape. Nevertheless, virtually every segment of this bridge was dislodged from the supporting piers. This failure is attributed to the combination of reduced self-weight due to buoyancy and the hydrodynamic uplift and lateral loads from surge and wave action, combined with the lack of restraint against uplift or lateral movement at the support bearings. Fig. 5 shows the rocker bearings at the ends of each span. The only restraint against lateral movement of the girders was the three small shear

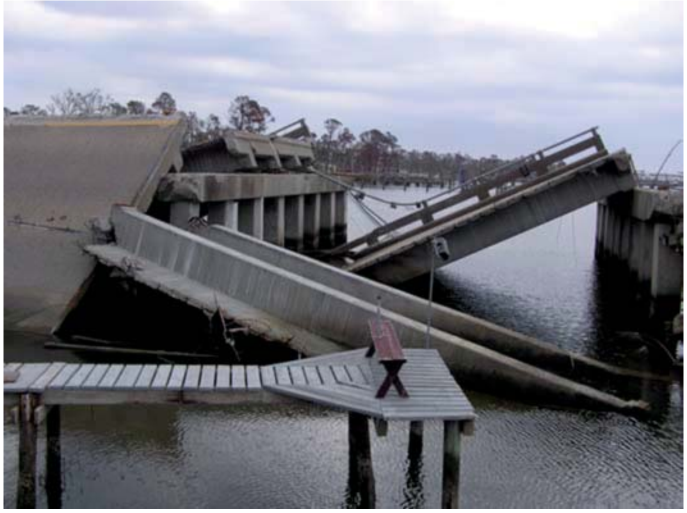

Figure 4. Deck segments of US90 bridge at St. Louis Bay.

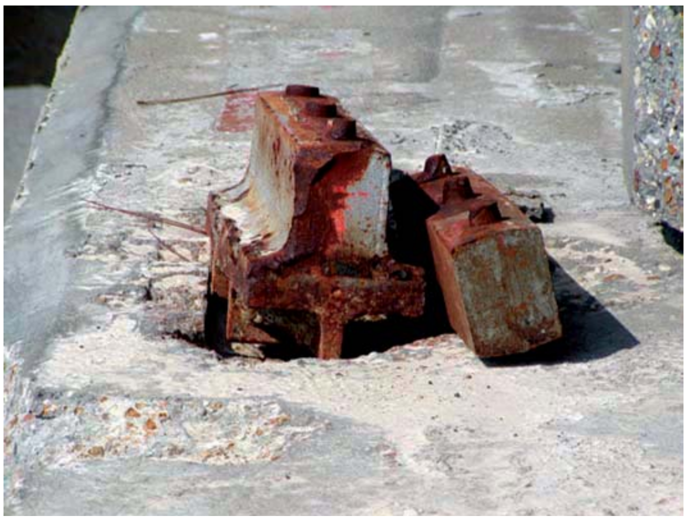

Figure 5. Bearing with limited lateral and no uplift restraint.

studs provided between the rocker and the bearing plate in the girder soffit.

Significant scour was evident under the approach slabs and abutments at both ends of this bridge (Fig. 6). The embankments surrounding the abutment piles were originally covered with concrete slabs which had been completely removed by the storm surge. Extensive scour during the Indian Ocean Tsunami resulted in complete transformation of coastlines and undermining of numerous building and bridge foundations (CAEE, 2006).

Two types of scour mechanism were identified: shear-induced scour due to pick up and transport of sediments by the flowing water and debris; and liquefaction-induced scour due to soil instability as a result of pore pressure gradients within the sediment bed (Robertson et al. 2006b).

4 US90 APPROACH SPAN, PASS CHRISTIAN

Long-span prestressed concrete bridge girders support the roadway forming the approach span to an elevated section of the US90 highway in Pass Christian, Mississippi. The first inland segment of this bridge was dislocated from its supports on the abutment and first pier bent (Fig. 7). This was the lowest segment on the bridge and although the extent of submersion by the storm surge is not known precisely, it is suspected that the large volume of air potentially trapped between the deep bridge girders resulted in significant uplift (Fig. 8). The limited reinforcing steel dowels between the bridge bent and the bulkheads at one end of the span were clearly not adequate to restrain the uplift forces and prevent dislocation of the segment (Fig. 9).

5 I-10 ONRAMP, MOBILE, ALABAMA

The I-10 onramp in Mobile, Alabama, was some distance from the main storm surge caused by Hurricane Katrina. Nevertheless, five segments of this bridge were dislocated from their supports (Fig. 10). It appears that the curvature of the bridge allowed for wedging of the segments, thereby preventing their complete collapse into the bay. Apparently efforts had been made to reduce the effect of entrapped air through reduction of the bridging depth and provision of holes

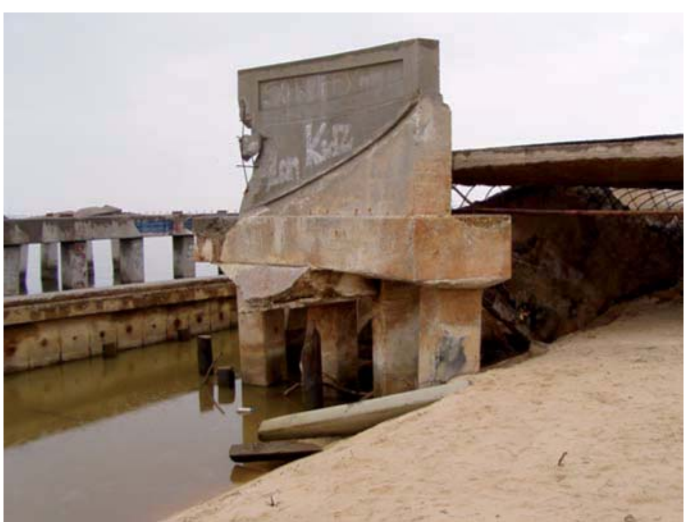

Figure 6. Scour around abutment and under approach slab.

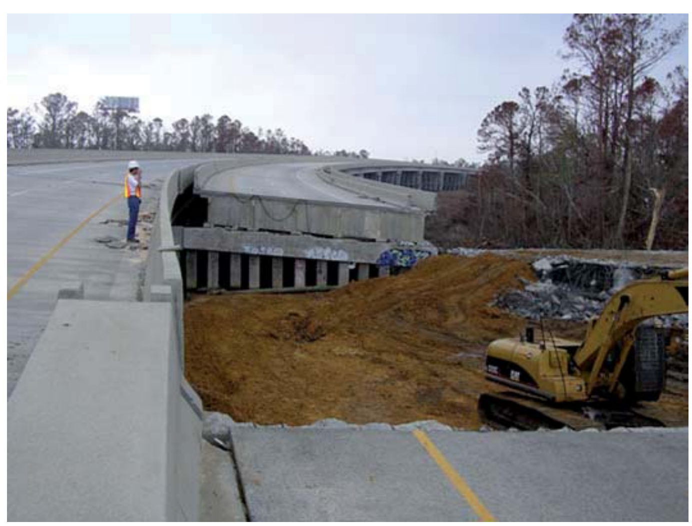

Figure 7. Single span of US90 washed from supports.

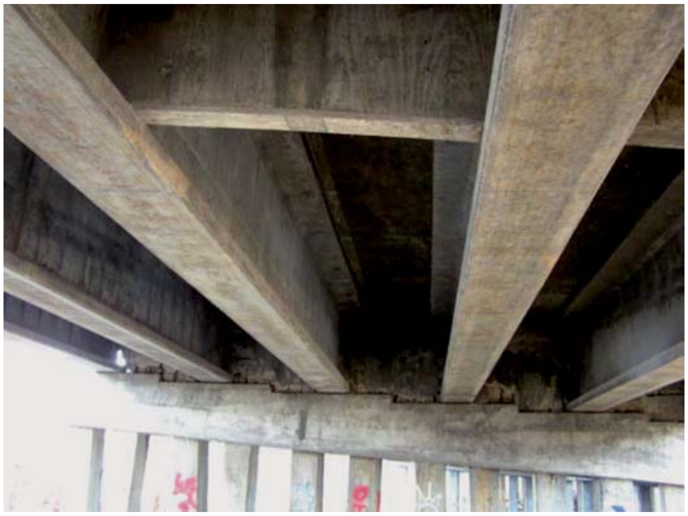

Figure 8. Soffit of US90 span showing potential trapped air volume.

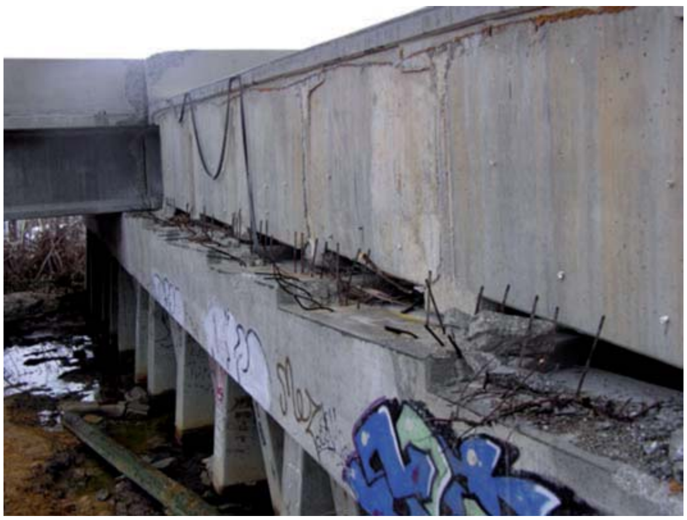

Figure 9. Inadequate dowels at bent support.

through the bridging and bulkheads to allow air to escape (Fig. 11). Although these measures may have helped during the slow water level rise induced by hurricane storm surge, they will likely be less effective during the rapid inundation caused by a tsunami.

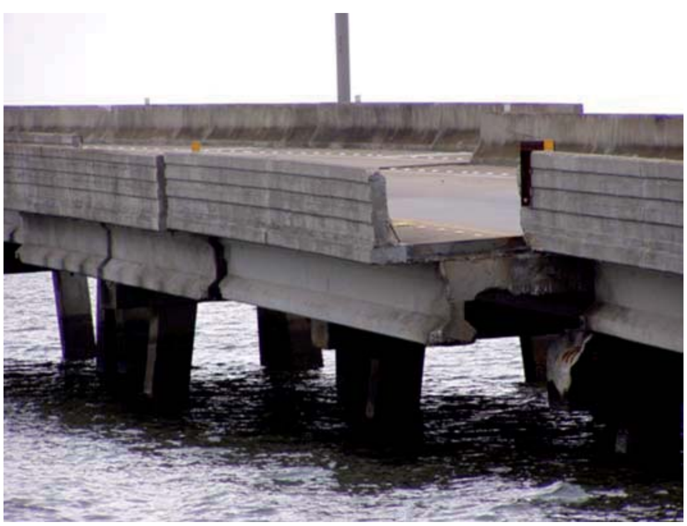

Figure 10. Dislocated segments of I-10 onramp, Mobile, AL.

Figure 11. Reduced bridging and holes to allow airflow.

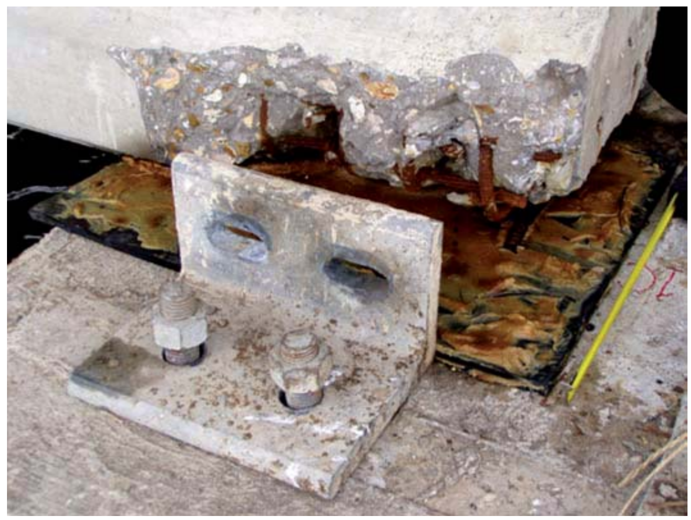

Figure 12. Failure of restraint due to anchor bolt pull-out.

This bridge was provided with steel angle restraints on either side of each exterior girder at each support bent (Fig. 12). Unfortunately, the capacity of these restraints was limited by the failure of the anchor bolts embedded in the bridge girders (Figure 12) and spalling of the concrete around the anchor bolts embedded in the supporting bridge bents (Fig. 13).

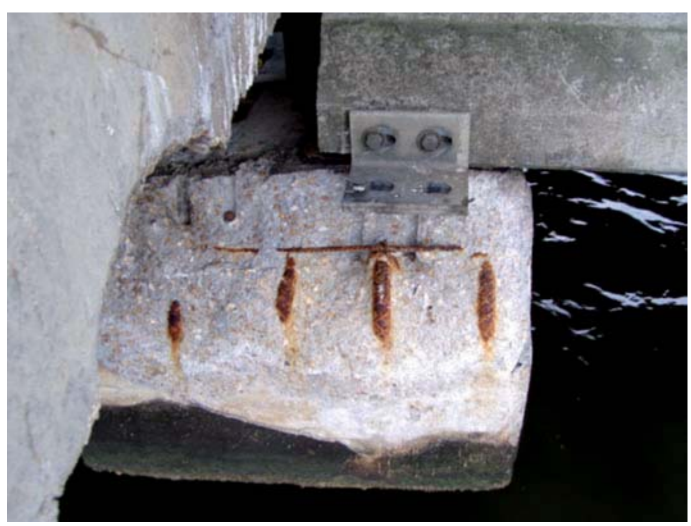

Figure 13. Failure of restraint due to anchor bolt edge spall.

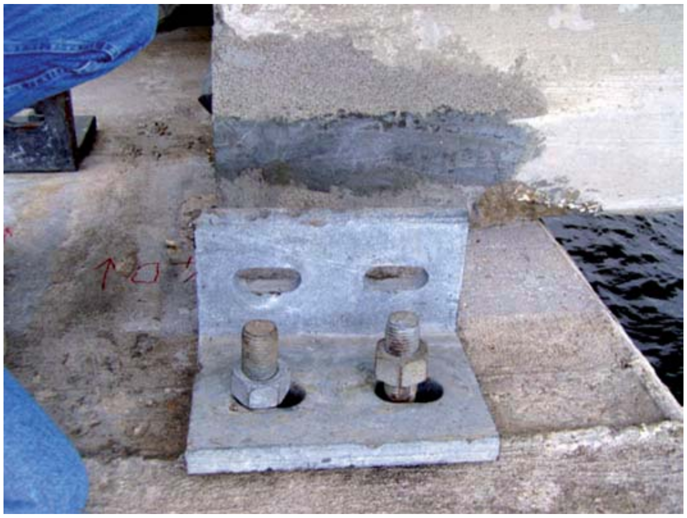

Figure 14. Anchor bolts missing from restraint angle.

In addition, a number of the restraint angles appeared to have been installed incorrectly. Fig. 14 shows a location where the horizontal anchor bolts had not been installed into the bottom of the bridge girder, possibly because of misalignment of the inserts. Fig. 15 shows the poor performance of a restraint angle where the bolt holes had been enlarged by flame cutting, presumably to accommodate anchor bolt misalignment.

A properly designed restraint system such as that shown in Figures 12 through 14 could be used to retrofit existing bridges for future tsunami or storm surge inundation. However, better detailing and attention to quality of construction are required to prevent the failures noted in these figures.

When considering a retrofit which results in strengthening the connection between bridge decks and supporting pier bents, it is also important to consider the supporting foundation capacity. During future inundation, the increased loads on the pier bent may overload the existing foundation system. However, the conservatism in foundation design will often accommodate these increased loads. For example, the piles supporting a cast-in-place section of the I-10 onramp adjacent to the damaged spans suffered no visible damage during Hurricane Katrina (Fig. 16).

Figure 16. Undamaged bridge deck cast integral with support piles.

6 RAILROAD BRIDGE OVER BILOXI BAY

A notable exception to the poor performance of low-level bridge structures was the railroad bridge over Biloxi Bay (Fig. 17). Although the entire railway tracks, sleepers and ballast were swept into the bay, the prestressed concrete bridge girders and deck remained intact. The superior performance of this structure is attributed to the reduced hydrodynamic uplift due to the small width of the bridge deck and the relatively small volume of entrapped air because of the closely spaced girders (Fig. 18) (Robertson et al. 2006b).

In addition, the superior lateral restraint provided by 380mm high concrete shear keys on either side of the girders at each support pier (Figure 18) was sufficient to resist the lateral hydrodynamic loads. Not

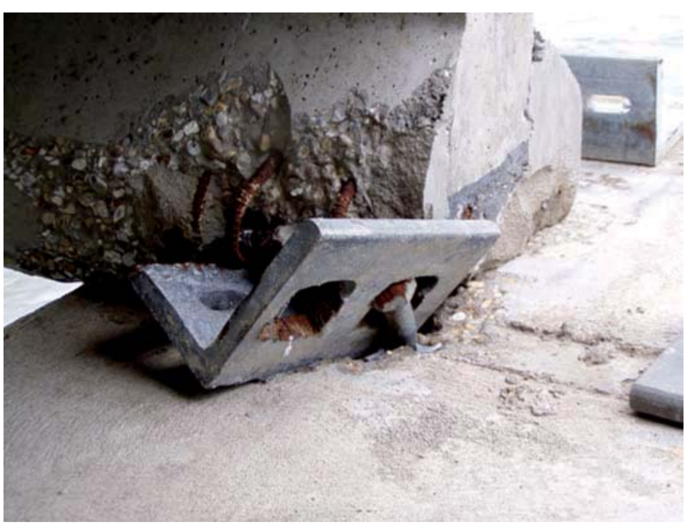

Figure 15. Failure of restraint due to flame cut oversized hole.

Figure 17. Railroad bridge over Biloxi Bay, Mississippi.

Figure 18. Large concrete shear keys on either side of closely spaced railroad bridge girders.

a single segment of this bridge collapsed although it was subjected to the same storm surge and wave action that destroyed the adjacent US90 highway bridge described above.

7 SUMMARY AND DISCUSSION

Hurricane Katrina caused very large storm surge along the U.S. Gulf Coast, especially in Mississippi. The hardest hit areas, from Biloxi to Pass Christian, suffered a storm surge exceeding 7.5 m. This storm surge caused substantial damage to numerous low-level coastal bridges. Bridge segments were lifted by a combination of hydrodynamic uplift and buoyancy enhanced by trapped air, and then displaced laterally by the lateral forces from surge and wave action.

Substantial scour resulted from both shear-induced sediment transport and liquefaction induced flow resulting from rapid pore pressure changes in sandy backfill and subsurface deposits. Scour due to liquefaction occurred in backfill below concrete apron slabs and highway pavements, even though these soils were protected from shear-induced scour by the overlying structure.

Similar bridge failures and scour occurred during the Indian Ocean Tsunami in December 2004. Numerous coastal bridges in Indonesia were partially or totally destroyed by the hydrodynamic effects of the tsunami bore (CAEE, 2005). Uplift and lateral transport of the bridge decks appeared to be very similar to what occurred during Hurricane Katrina.

Bridge engineers and highway officials must accommodate these loading and scour conditions in order to achieve better bridge performance and reduce the damage to coastal highway structures during future natural disasters.

8 CONCLUSIONS

Based on the observations made during two reconnaissance surveys of the U.S. Gulf coast affected by the storm surge from Hurricane Katrina, and similar observations made after the Indian Ocean Tsunami, the following conclusions were drawn.

- Bridge decks submerged during coastal inundation are subjected to significant hydraulic loads, including hydrostatic uplift due to buoyancy, which is amplified by the effect of entrapped air, and hydrodynamic uplift due to vertical wave action.
- Deck segments of low-level bridges in regions subject to coastal inundation should be restrained against uplift and provided with shear keys designed to resist all anticipated lateral loads. No reliance should be placed on the effect of gravity induced friction to restrain movement of the deck segments.
- Bridge foundations must be designed to resist the anticipated uplift loads. In retrofit of existing bridges, review of the foundation pile design will be necessary to ensure adequate performance.
- Bridge foundations and approach roadways must be designed to accommodate scour induced by the surge and wave action. Scour results both from shear-induced particulate transport, and liquefaction- induced soil flow.
- Backfill around foundations and under earth- supported slabs should be selected to avoid liquefac tion during rapid drawdown. Soil stabilization could be considered to reduce or prevent both liquefaction and shear-induced scour.

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