Lessons from Katrina

Despite differences in flow velocity and inundation duration, the effects on the coastal infrastructure in the inundation zones of Hurricane Katrina and the Indian Ocean tsunami of December 2004 were remarkably similar. Surveying the effects of Hurricane Katrina will no doubt assist in the ongoing study of tsunami loading on coastal construction. **By Ian N. Robertson, Ph.D., S.E., M.ASCE, H. Ronald Riggs, Ph.D., P.E., M.ASCE, Solomon Yim, Ph.D., M.ASCE, and Yin Lu Young, Ph.D., M.ASCE**

The authors are in the first year of a four-year project funded by the National Science Foundation's George E. Brown, Jr. Network for Earthquake Engineering Simulation Research to develop performance-based tsunami engineering principles for the design and construction of buildings and coastal structures in tsunami-prone regions. The development of design guidelines that could help coastal structures resist storm surge and tsunami wave loading has been hampered by a lack of experimental research and field data. Although excellent records are often collected of coastal run-up—via field surveys or satellite imagery—the effects of storm surge and tsunami loading on infrastructure have not been adequately documented. Hurricane Katrina afforded a rare opportunity to document the damage resulting from a tsunami-like event in an industrialized nation. Responding to a National Science Foundation request for proposals to survey the results of Katrina, the authors obtained a small grant for exploratory research. They made two reconnaissance trips to the Mississippi coastline, one at the end of September, the other in early November. This article—their firsthand assessment of the damage caused by storm surge and debris impact—will help engineers focus more clearly on the damage mechanisms at work in hurricanes and tsunamis.

Hurricane Katrina was the most costly natural disaster in our nation's history. Excluding the New Orleans flooding, most of the damage resulted from storm surge inundation in Louisiana, Mississippi, and Alabama rather than from high wind. The peak storm surge exceeded 25 ft (7.6 m) above sea level and occurred between Pass Christian and Biloxi, confirming computer model predictions made by Louisiana State University's Hurricane Center shortly before landfall. 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 around the Mississippi River Delta.

Traditionally, wind damage and rainfall-induced flooding account for the majority of damage during a hurricane. However, the significant storm surge associated with Katrina resulted in tremendous damage to the built environment along the affected coastline. The effect was particularly devastating for light-framed or masonry residential structures, many of which had withstood Hurricane Camille, which struck in 1969, and other events affecting this region of the Gulf Coast. In many coastal communities the only remaining evidence of residential construction was the ground-floor slab on grade and considerable piles of debris at the high-water mark. There were some notable exceptions: some residential buildings were able to survive substantial surge inundation. These exceptions were often constructed with concrete or steel frames and were elevated above the base flood elevation designated for this region. Many of the

The highway bridge on U.S. 90 in Mississippi from Biloxi to Ocean Springs was nearly demolished by the storm surge, *above.* An inverted segment of the bridge displays the volume of air probably trapped below the bridge deck, contributing to the buoyancy of the bridge segments. The complete collapse of the second level of a precast-concrete parking structure in Biloxi, *left,* was the result of buoyancy induced by trapped air. The negative bending moments induced by this uplift—combined with the prestress tendon forces—caused compression failure of the thin web sections at midspan of the precast double Ts, *inset.*

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The storm surge exceeded the elevation of the containment berm surrounding a series of fuel storage tanks at Rhodes Point, in Biloxi, Mississippi. Buoyancy of the empty or partially empty tanks resulted in failure of the corroded anchor bolts, *inset*.

lessons relating to residential construction will be included in a Federal Emergency Management Agency report on mitigation currently being prepared.

Of particular interest to us—and the primary focus of our reconnaissance trips—was the effect of the storm surge on engineered structures. Although devastating, the extent of damage to nonengineered residential construction could have been anticipated given the magnitude of the storm surge. Similar damage to residential construction occurred during the December 2004 Indian Ocean tsunami, and for this reason numerous parallels have been drawn between the two events. However, the extent of storm surge damage to engineered infrastructure along the Gulf Coast was greater than might have been anticipated. Numerous lessons can be learned from this event to aid in the design and construction of future coastal structures in regions subject to storm surge or tsunami inundation.

The primary effects of storm surge on a coastal structure are through hydrostatic and hydrodynamic loads—both lateral and vertical—debris impact and damming loads, and scour of supporting soils. Each of these topics is discussed here in the context of our firsthand observations.

Inundation of coastal structures resulted in buoyancy effects not accommodated in the design. Numerous low-level coastal bridges were severely damaged or destroyed by the storm surge. Although lateral hydrodynamic loads from the surge and wave action would have contributed to this damage, a primary factor was the reduction in self-weight—that is, the weight in the absence of loads—of the bridge spans when submerged. Not only was the effective self-weight of concrete bridge girders and deck reduced from around 150 pounds per cubic foot, or pcf (2,403 kg/m³), to 86 pcf (1,378 kg/m³) owing to submersion in seawater, but air trapped below the roadway deck—between the girders, transverse bridging, and end bulkheads—provided sufficient flotation to make some of the bridge spans fully buoyant. This effect was also suggested by researchers from the Multidisciplinary Center for Earthquake Engineering Research, which was established by the National Science Foundation and is based at the State University of New York at Buffalo, in a special report that appeared in the February 2006 issue of the *Structural Engineer.*

The bridge on U.S. 90 in Mississippi between Biloxi and Ocean Springs is composed of simply supported 45 ft (13.7 m) bridge segments, each consisting of six prestressed-concrete girders supporting half of the roadway deck and one sidewalk. The air trapped between the girders, along with the reduction in self-weight caused by submersion in seawater, meant that these segments were buoyant when fully submerged. The bearings supporting each end of the girders at the pier bents provided no restraint against uplift and only nominal resistance against lateral movement. Because it is in a zone of low seismic activity, there were no requirements for shear keys to provide lateral restraint or for ties to prevent uplift, requirements that are common in seismic regions. Friction induced by gravity load—and small, ½ in. (12.7 mm) thick steel angles—were the only lateral restraints for these bridge segments. Once buoyant, 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.

Similar damage occurred at numerous other coastal bridges from the Lake Pontchartrain causeway and Interstate 10 east of New Orleans to a low-level I-10 on-ramp in Mobile, Alabama. Many of these bridge decks were at or close to buoyant because of entrapped air and reduced self-weight. However, even bridges with significant residual gravity load when submerged suffered failures because the shear keys to prevent lateral movement of the bridge deck segments were inadequate.

A notable exception to the poor performance of low-level bridge structures was the railroad bridge from Biloxi to Ocean Springs. Although the railway tracks, sleepers, and ballast were all swept into the bay, the prestressed-concrete bridge girders and the deck remained intact. The superior performance of this structure is attributed to the increased density of the closely spaced girders, which resulted in a net dead weight of approximately 36 percent when fully submerged, combined with superior lateral restraint provided by 15 in. (38.1 cm) high concrete shear keys on either side of the exterior girders at each support pier. Not a single segment of this bridge collapsed, although it was subjected to

The casino of the Hard Rock Hotel & Casino Biloxi was built on floating pontoons enclosed in a fixed exterior structure. Collapse of the entire structure, *top*, is thought to have resulted from pounding between the pontoons and the inland columns supporting the exterior structure. Hydrodynamic uplift of the posttensioned flat slab in the bay closest to the shoreline appears to have initiated the frame collapse of a concrete building frame under construction on U.S. 90 in Pass Christian, Mississippi, *above*.

The partial collapse of the four-story reinforced-concrete Oakmont apartment building in Biloxi, Mississippi, *right,* resulted from the impact of a barge-mounted casino that broke free from the Biloxi President Casino some 3,609 ft (1,100 m) east of this site. Scour to a depth of 15 ft (4.6 m) occurred around the abutment in Bay St. Louis, Mississippi, of the U.S. 90 bridge to Pass Christian, Mississippi. Liquefaction-induced scour may have contributed to the failure of the concrete apron intended to protect the backfill, allowing shear-induced scour around the abutment and piles and below the approach roadway, *below right.*

the same inundation as the adjacent highway bridge on U.S. 90 described above.

The effects of buoyancy induced by entrapped air were even more pronounced when considering the performance of precast parking garages inundated by the storm surge. As many as 10 different precast parking garages in the region encompassing Biloxi and Gulfport, Mississippi, suffered major damage or even total collapse of the second-floor level because of the storm surge. The elevated floors of these precast parking structures consist of prestressed-concrete double-T girders supporting a 2 to 3 in. (50.8 to 76.2 mm) thick cast-in-place concrete topping slab. Air trapped between the girder webs below the floor deck cannot escape because of the supporting inverted T beams or spandrel beams at either end of the span. Additionally, the cast-in-place topping slab covers the joint between adjacent double Ts and any gap between the double T and the supporting elements at either end of the span. Unable to escape, the air below the floor slab induces uplift well in excess of the submerged dead weight of the double T plus topping, resulting in significant negative bending of the precast sections. Designed for gravity load, these double Ts are extremely weak in negative bending, particularly since placement of the prestressing tendons is intended to balance much of the original unsubmerged dead weight.

Collapse of double-T floor systems was observed regardless of the end support details. Some double Ts were supported on continuous ledges or individual corbels; others were supported in sockets in the spandrel beams. When supported on ledges or individual corbels, the double-T sections are free to rise under the effects of uplift, the only restraint coming from nominal dowel reinforcement in the topping slab. When supported in sockets in the spandrel beams, the double-T sections are prevented from rising at these supports but are still subject to negative bending at midspan owing to the buoyancy effects of entrapped air.

The complete failure of North Beach Boulevard—the coastal highway through Bay St. Louis, Mississippi—was due to a combination of liquefaction and shear-induced scour.

After the floor system collapsed, many of the exterior spandrel beams and interior inverted T beams broke free of their supports because of the loss of restraint provided by the double Ts and the topping slab. It is possible that some of the spandrel beam failures were caused by lateral hydrodynamic loads. However, had the floor system remained intact, it would have provided lateral support for the spandrel beams, and many of the spandrel beam failures would have been prevented.

Buoyancy also resulted in the relocation of a number of storage containers that were inadequately restrained against uplift. Lack of adequate restraint and deterioration of hold-down bolts as a result of corrosion were common factors in the uplift failure of empty or partially empty storage tanks, cement silos, and similar steel structures.

In addition to floor failures induced by buoyancy of entrapped air, there were also a number of failures of flat slab and prestressed-concrete floor slab systems as a result of hydrodynamic uplift induced by surge and wave action below the level of the second floor. The Windjammer condominium building in Biloxi is a multistory reinforced-concrete flat slab structure. Each floor consists of a cast-in-place flat plate supported on columns. More than half of the second-floor slab collapsed as a result of punching shear failure at the slab–column connections. This shear failure appeared to result from uplift caused by surge or wave action below the slab or by a combination of the two. The shear failures were initiated by upward punching of the slab, followed by collapse under gravity load caused by the absence of integrity reinforcement in the bottom of the slab passing through the supporting columns.

An adjacent flat slab structure suffered no apparent structural damage. Designed to support mechanical equipment for the Hard Rock Hotel & Casino Biloxi, this thick flat slab had drop panels at each support column. Because of the larger design dead and live loads, it was probably more heavily reinforced than the slab in the condominium building that failed. It illustrates that flat slab floor systems can be designed to resist the loads applied by storm surge inundation and wave action.

Hydrodynamic uplift is also suspected of causing failure in a number of posttensioned one-way flat slab floor systems. A cast-in-place posttensioned parking garage at the Hard Rock Hotel & Casino Biloxi suffered significant damage and partial collapse of the second-floor bays adjacent to the coastline. Moment reversal and upward shear load resulted in combined flexural and shear failure of the slab at the supporting beams. Repeated loading cycles resulted in the deterioration of the slab elements, often leading to complete collapse of the slab bay.

There were a number of barges in the Biloxi and Gulfport areas that could not be relocated in advance of the hurricane. Some of these were industrial barges and some were floating casinos. The mooring systems for such structures must consider both absolute and relative motions. Several structures in Biloxi illustrate what can happen when the restraint system is inadequate.

The Hard Rock casino was located on floating barges and was enclosed in a fixed "shell," which presumably was designed to resist wind loads. The exterior shell collapsed onto the casino, virtually demolishing it. This casino was the most severely damaged of all the casinos surveyed. Three possible failure mechanisms can be discerned. First, excessive vertical motion of the barges could have exceeded the clearance between the casino and the fixed roof, inducing collapse. The surge was probably at least 20 ft (6.1 m), and this may not have been accommodated in the design. A second scenario is that the roll induced by the incoming surge and waves caused the top part of the casino to impact the columns of the shell, resulting in progressive collapse. However, the most likely explanation is that the surge and waves elevated and pushed the barges inland, causing the inland columns of the exterior shell to collapse, which in turn caused progressive collapse of the entire system.

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The storm surge associated with Katrina demonstrated that any floating or mobile object near the shore can become floating debris. This includes shipping containers, boats, unrestrained storage containers, 18-wheel truck beds, and barges. As the debris accumulates, floating debris fields can develop that can cause substantial loads as they block the fluid flow. Debris effects on structures assume two forms: impact and water damming.

An example of impact is clearly demonstrated by the collision between the barge of the Biloxi President Casino and the Oakmont apartment building in Biloxi. The considerable mass of this barge—at only a modest speed—will impose a large force on any structure it impacts. Little evidence was found of significant debris impact damage to major engineered structures other than from such large floating structures as barges.

In addition to impact damage, there was substantial evidence of damage from the water-damming effect. This happens when large pieces of debris become lodged against structures—especially broadside—and there are significant drag and inertia forces that result from the disruption of the flow field. Shipping containers are relatively ubiquitous and therefore represent a common type of debris that can cause substantial fluid forces on structures, even those that under normal circumstances would be considered relatively transparent to waves. In one instance, a shipping container formed a bridge between two slender steel pipe columns supporting the roof of a car dealership. As evidenced by the crumpling of the upstream side of the container, significant hydrodynamic forces resulted from this damming effect. The steel columns held, but not without significant damage. In a similar situation at a multistory reinforced-concrete hotel building, the reinforced-concrete column was able to resist the applied load. Clearly, even structures with slender columns, which normally do not attract significant fluid forces, must be designed to resist impact and damming forces from such debris.

In another incident involving a shipping container, a steel-framed apartment building in Gulfport was significantly damaged, leading to partial progressive collapse. This damage probably resulted from a combination of debris impact and damming. In any event, the failure of the steel pipe columns at the first level resulted in progressive collapse of the balconies on the upper levels.

Extensive scour was observed around bridge abutments and piers, building foundations, and highway pavement structures along the affected areas of the Gulf Coast. This scour contributed to the partial or complete collapse of a number of coastal structures. Two types of scour mechanisms were established: shear-induced scour resulting from the pickup and transport of sediment by the flowing water and debris; and liquefaction-induced scour arising from soil instability as a result of pore pressure buildup within the sediment bed. Although both mechanisms contributed to the scour of beaches and coastal structures, liquefaction-induced scour is believed to be responsible for the extensive scour damage observed under building foundations and highway pavements.

During a storm surge event, liquefaction-induced scour occurs when the vertical effective stress between soil particles is reduced to nearly zero as a result of phase difference, that is, time lag, between pore pressure variation in the soil and water pressure variation on the surface of the sediment bed. This mechanism is enhanced by the rapid drawdown as the surge or tsunami inundation water recedes. Scour can occur very rapidly under such conditions because the soil loses almost all of its shear strength and thus behaves like a heavy liquid that can be transported easily by the flowing fluid. During Katrina, the storm surge lasted for several hours and exceeded 20 ft (6.1 m) along much of the Mississippi coastline. The nearly saturated sandy deposits were then subjected to pressure fluctuations as a result of wave action, which can induce liquefaction. This wave-induced liquefaction can be even more severe during wave drawdown or ebb surge caused by a decrease of the water level that is so rapid that there is not enough time for the internal pore pressure to dissipate.

Wave-induced liquefaction is also believed to be responsible for the scour under ground-floor slabs and highway subgrades. The thin floor slab or highway pavement helps to prevent current-induced scour and postpone the point at which liquefaction occurs. Nevertheless, the supporting sandy soil or backfill is still susceptible to liquefaction-induced scour, particularly during wave drawdown or ebb surge. Once the supporting soil liquefies, the thin floor slab or highway pavement will collapse, which can lead to total collapse of the structure.

Numerous examples of liquefaction-induced scour under floor slabs and footings were observed throughout the Mississippi coastline. Craters similar to sinkholes were observed in many locations along the coastal highways as a result of drawdown and wave-induced liquefaction of the subgrade below the pavement. The most extensive scour observed along the Mississippi coastline was at the western abutment of the bridge on U.S. 90 in the town of Bay St. Louis. The abutment was originally surrounded by a soil embankment protected by a retaining wall and a concrete apron. Massive scour of all backfill and sandy subsoil was observed below the collapsed embankment apron. The maximum scour depth was approximately 15 ft (4.6 m), and the scour extended behind the abutment wall and undermined the approach slabs by as much as 8 ft (2.4 m). Similarly, a combination of wave-induced liquefaction and shear-induced scour is believed to be responsible for the complete scour of North Beach Boulevard in Bay St. Louis, where the maximum scour depth was 5 to 6 ft (1.5 to 1.8 m). A number of residential and low-rise commercial buildings suffered foundation failure and partial collapse as a result of undermining by scour.

In summary, Katrina resulted in very large storm surge along the Gulf Coast, especially in Mississippi. The areas hardest hit—from Biloxi to Pass Christian—suffered a storm surge of between 20 and 25 ft (6.1 and 7.6 m). This surge resulted in substantial damage to some engineered structures. In the case of low-lying bridges, segments were lifted up by a combination of hydrostatic forces (from submersion and entrapped air) and hydrodynamic forces (from waves) and then displaced laterally by the hydrodynamic forces from surge and waves. In similar fashion, parking garages constructed of precast double-T sections, which are weak in negative bending, suffered substantially from similar uplift forces. Floors in condominiums and similar structures also suffered substantial damage—even collapse—when the slab systems were not able to handle the unanticipated uplift forces.

Katrina demonstrated that any floating or mobile object can become floating debris. The debris in this case included floating casino barges, industrial barges, shipping containers, and 18-wheel trucks. Several damage modes can be discerned. Fixed structures adjacent to floating structures were damaged by the relative motion between them. With respect to casino barges that broke free, while the velocities were probably relatively small, their large mass meant that the momentum was still substantial when impact occurred, causing large impulsive forces. Smaller debris also poses risks to structures, including those resulting from flow damming. Even structures that are transparent to waves, such as those on columns, can be subjected to large forces when, for example, shipping containers become lodged against those columns, damming the water and vastly increasing the surface area exposed to the flow.

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 caused by liquefaction occurred in backfill below foundation slabs and highway pavements, even though these soils were protected from shear-induced scour by the overlying structure.

In summary, this survey demonstrates that engineered structures in regions subject to hurricane-induced storm surge or tsunami inundation have significant risk factors associated with loads that are sometimes unanticipated, for example, uplift, debris impact, water damming, and liquefaction-induced scour. We are currently preparing more detailed analyses of the observed damage for future publication. These observations will also be incorporated into our ongoing development of performance-based tsunami engineering guidelines for coastal construction. Engineers, developers, insurers, and building officials should be aware of these unusual loading conditions so that they can better assess risks and more effectively manage coastal facilities. ■

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