The Impact of Hurricane Ivan
on the Coastal Roads of Florida and Alabama:
A Preliminary Report

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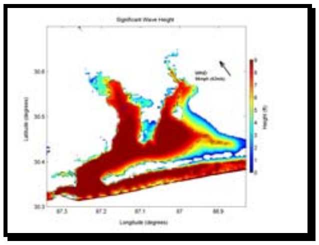

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September 30, 2004

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Executive Summary

Many miles of critical, coastal roads were severely damaged when Hurricane Ivan made landfall near the Alabama-Florida border on the night of September 15-16, 2004. The damage included the partial collapse of an Interstate-10 bridge deck, damage to the approach lanes to several other major bridges, the washing out of tens of miles of pavement, and the burial in sand of many more miles of roads by the storm surge and waves in the two-state area.

The University of South Alabama's Coastal Transportation Engineering Research & Education Center; funded by the Federal Highway Administration to develop, conduct, coordinate, and disseminate research on coastal highways; mobilized a team of civil engineers to make a preliminary assessment of the coastal roadway damage caused by Ivan. The goal was to rapidly capture some information on the types and causes of damage in order to aid in future analysis and design of more hurricane-resistant roads and bridges.

This report is primarily based on photographs of specific damage types. Some original, preliminary analyses of the storm surge and wave heights in the vicinity of the I-10 bridge deck collapse are also included.

All of the road and bridge damage in Ivan was due to combinations of storm surge (extreme rise in water level during the storm) and waves on top of the storm surge. The primary conclusion of this report is that better inclusion of coastal engineering concepts and tools in the planning and design of roads and bridges along the coast would be valuable in reducing this damage in the future. Some of the problems seen in Ivan (inadequate wave revetments and bridge approach failures) can be solved by the appropriate application of existing technologies. Some of the problems seen in Ivan, however, (bridge deck vulnerability and scour failure on the lee side shoulders) probably require some more focused research in order to develop and document more appropriate solutions.

This preliminary report will be followed by a more in-depth analysis and report by the Coastal Transportation Engineering Research and Education Center. Thus, any relevant information would be welcomed by the authors.

Hurricane Ivan

Hurricane Ivan made landfall as a major hurricane on the night of September 15-16, 2004 near the Alabama-Florida state line. It had been rated as a category 5 hurricane on the Saffir-Simpson scale when it was in the southern Gulf of Mexico. Prior to landfall, it weakened and the actual magnitude at landfall is still being discussed.

The track of Ivan took it between the cities of Mobile, Alabama and Pensacola, Florida (see Figure 1). The strongest winds of the right-front quadrant of the storm impacted the eastern Alabama coast and the western portion of the Florida panhandle coast. Thus, the highest offshore waves and the highest storm surges were experienced there. High water marks have been reported as high as 10 to 15 feet above sea level. Detailed high watermark surveys were in progress as this report was written. Further documentation of Ivan's recorded surge elevations, waves and windspeeds can be found elsewhere on the internet from other, original sources.

Photographs of Example Road and Bridge Damage

A field-inspection team of civil engineers organized by the Coastal Transportation Engineering Research and Education Center investigated roadway damage caused by Ivan beginning on Sunday, September 19th (fourth day after landfall). This Center was established by the University of South Alabama in April 2004 and is funded by the Federal Highway Administration to develop, conduct, coordinate, and disseminate research on coastal highways.

The bulk of this report is some of the photographs from those field-inspection trips. The general location of each photograph is identified on Figure 1. The following discussion is included as preliminary explanation of the damages with a focus on the causation mechanisms.

Photograph A. AL 193 revetment damage repairs. This damage was partly due to inadequate rock sizes for the storm waves.

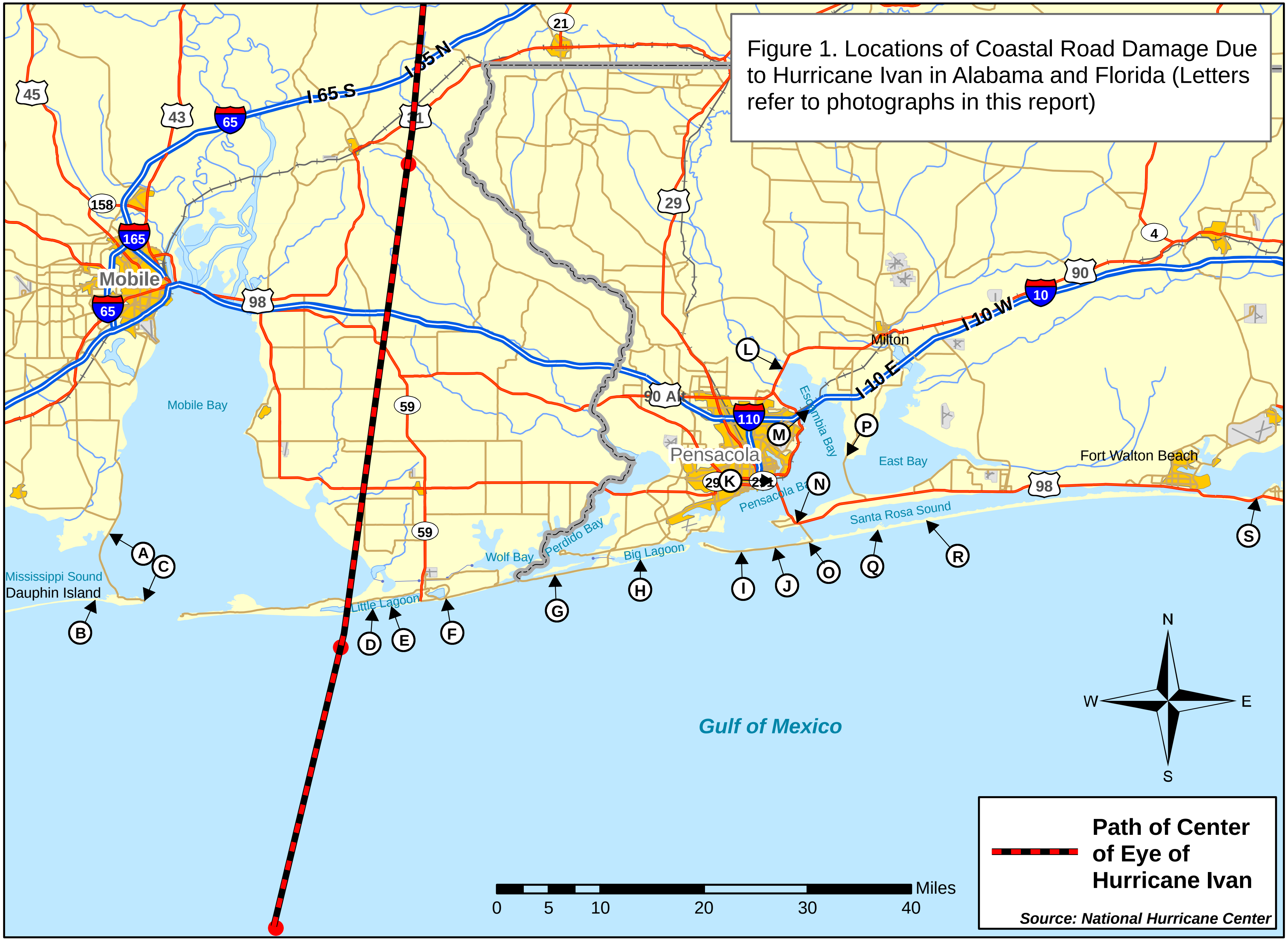

Figure 1. Locations of Coastal Road Damage Due to Hurricane Ivan in Alabama and Florida (Letters refer to photographs in this report)

Source: National Hurricane Center

Photograph A shows the on-going repair of a portion of AL 193, the causeway to Dauphin Island. It is the only access road. The photograph was taken five days after the storm and shows repairs to the northbound lanes that are behind a rock revetment. This revetment was built in 1999 after Hurricane Georges caused similar damage in this area. Ground inspection showed that some of the stones from the revetment washed across the road during Ivan. They were not large enough to withstand the waves from the strong winds from the east blowing across a fetch of up to 20 miles across Mobile Bay. A revetment a few miles north of this location at a county park designed using Hudson's Stability Equation (US Army Shore Protection Manual, 1984) fared much better in both Hurricane Ivan and Hurricane Georges (1998).

Photograph B shows sand piles that have been scraped off Bienville Boulevard on Dauphin Island, Alabama. This portion of this local road runs parallel to the coast about 500 feet back from the water. Portions of this pavement were washed out in Hurricane Georges in 1998 but not in Hurricane Ivan. The primary design difference is that after Georges, the road was rebuilt at the same elevation as the surrounding sand. Thus, there was no additional roadbed elevation for rainfall drainage (except a very slight crown). This intentional design decision appears to have worked very well during Ivan. The road was likely buried by overwash sand early in the storm and the pavement was essentially insulated from the highest velocities of waves and surge. This photograph is in stark contrast to many miles of roads that were damaged in Ivan elsewhere (e.g. see photographs D, G, H, J, Q, R of this report).

Photograph B. Bienville Blvd. was buried in sand during Ivan but the pavement was intact. Thus, the road was open immediately after sand removal. This intentional strategy, low elevation road construction, appears to have been successful at reducing pavement damages.

Photograph C shows damage to pavement on Bienville Boulevard at the eastern tip of Dauphin Island, Alabama. The pavement was fronted by a large seawall/revetment designed to protect the road and historic Ft. Gaines. This seawall was originally built in 1904 and was rebuilt in 1996. A few of the revetment stones moved across the road. This damage was due to waves from Ivan on top of the storm surge.

Photograph C. Pavement damage at eastern end of Dauphin Island, Alabama

Photograph D shows damage to pavement on the south shoulder of AL 182 in Gulf Shores, Alabama. This portion of the road is locally known as West Beach Boulevard. It is on a barrier spit of sand between the Gulf of Mexico and a small bay called Little Lagoon. While this damage may have been caused by waves, it appears more likely that it was due to water flowing back out to the Gulf from Little Lagoon across the barrier spit later in the storm when the storm surge began to recede. It is possible that the roadway pavement was acting like a broad-crested weir and the sand on the south side was exposed to fast-flowing (super-critical flow into a hydraulic jump) water that scoured the sand as shown.

Photograph D. Pavement damage to AL 182 that was likely due to storm surge return flow.

Photograph E shows some emergency repairs to damage to the approach to a small bridge on AL 182 over a very small tidal inlet, called Little Lagoon Pass, between Little Lagoon and the Gulf of Mexico. This photograph is of damage on the northwest side of the bridge looking west. There was damage on each side of both approaches. Similar damage was found on approaches to bridge abutments at other locations (e.g. see photographs N, O, and P of this report). These approaches are exposed to severe wave and current forces when storm surge raises the water level during hurricanes. These forces are probably much different and more severe than experienced by approaches to inland bridges during riverine flooding events.

Photograph E. AL 182 emergency repairs to damage to approach to Little Lagoon bridge.

Photograph F shows emergency repair crews closing off a new inlet from a series on inland lakes (called Shelby Lakes) to the Gulf of Mexico. This photograph was taken five days after the storm. Similar breaches of the barrier island have occurred in this general area after other major hurricanes. The damage is due to a combination of surge, waves, and overwash raising the lake levels during the storm and then the water wanting to flow back out to the sea after the storm passes.

Photograph F. Ongoing repairs to breach in AL 182 at Shelby Lakes area.

Photograph G. Pavement damage on north side of FL 292 due to “weir-like” flow down back side.

Photograph G shows pavement damage on the north side of a highway. This is FL 292 on Perdido Key very near the Alabama state line. It appears that the scour of the shoulder followed by scour of the underlying road base eventually undermines the pavement. The pavement then breaks off in blocks as its weight exceeds its internal adhesion. This type of damage was fairly common (e.g. see Photograph Q of this report). It had also been seen in several different locations around the country after other hurricanes.[5] It is worth noting that the damage is on the side of the roadway away from the primary water body. The likely mechanism is water flowing across the road as the storm surge rises. The roadway pavement acts like a broad-crested weir and flow down the back shoulder of the

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[5] Douglass, S.L. presentation at FHWA’s National Hydraulics Conference, Asheville, NC, Sept. 2, 2004.

road is likely high-velocity, super-critical flow down to a hydraulic jump. The roadway is usually elevated above the adjacent ground and so it acts like a dam with the back side acting like a spillway. This scour mechanism may be exacerbated by broken waves periodically pumping water across the roadway. The velocity of the flow is clearly high enough under such a scenario for scour to occur on the unconsolidated and unvegetated shoulder. The University of South Alabama's Coastal Transportation Engineering Research and Education Center is planning to conduct laboratory investigations of this road damage mechanism in the coming year. These investigations are planned for both a large-scale river flume and a small-scale wave basin.

Photograph H. Pavement damage in Johnson Beach unit of Gulf Island National Seashore

Photograph H shows pavement moved north by Ivan. This damage occurred on a narrow, low barrier island spit that is part of the Johnson Beach unit of the Gulf Island National Seashore. The barrier island was probably several feet below sea level during the peak of the storm surge as large waves rolled across it. The photograph shows that sand was moved from the beach and dunes across the island and deposited in overwash fans on the north side of the island that extended into the back bay (Big Lagoon).

Photograph I. Ft. Pickens Road in Gulf Islands National Seashore damaged by overwash.

Photograph I shows a portion of an overwashed barrier island spit. The pavement was destroyed in a number of places similar to this one. The road is barely visible (look at the edges of the photo). This road is Ft. Pickens Road in the Gulf Islands National Seashore. The back bay here is the main body of Pensacola Bay and the barrier island has a very low elevation. This was a major overwash area.

Photograph J shows pavement damage along Ft. Pickens Road in the Gulf Islands National Seashore. Similar damage was seen along miles of roadway throughout the Gulf Island National Seashore. In some locations, the pavement was moved across the barrier island. Broken pavement was found north of the former roadway in many places. Some pieces had been lifted and some had been flipped over. At other locations, broken pavement was found south of the former roadway. This damage was likely caused by a combination of the incoming and outgoing storm surge and the waves moving across the barrier island during the storm surge. In some locations, the pavement was not visible. Similar damage was experienced along most of these roads in Hurricane Opal (1995) and this roadway was rebuilt in 1996.

Photograph J. Pavement damage to Ft. Pickens Road in Gulf Islands National Seashore

Photograph K shows damage to the pavement on the southeast-bound lanes of US 98 along the waterfront in Pensacola, Florida. Some emergency repairs were underway before the photograph was taken. This damage appears to be due to wave attack on the road embankment. Pensacola Bay is immediately to the left in the photograph. There was some bluff stabilization attempt here before the storm but it did not adequately protect the roadway from the waves on top of the storm surge.

Photograph K. US 98 pavement damage in Pensacola

Photograph L shows repairs to the northeast bound lanes of US 90 along the waterfront at the north end of the Escambia Bay arm of Pensacola Bay. The photograph was taken 10 days after the storm. The emergency repairs appear to have included the reconstruction of the embankment and the pavement of both lanes. This road is now the main detour around the bridge collapse for passenger vehicles on Interstate-10. This damage was caused by wave-induced erosion at the storm surge levels. There appears to have been some limited form of shore protection prior to the storm but it did not adequately protect the roadway. Some preliminary analysis of the storm surge included in the next section of this report (Figure 2) indicates that this upper portion of the bay experienced extremely high surge as winds pushed the water up into this area. The waves in this area were also very large (Figure 3).

Photograph L. Repairs to damages to US 90 at north end of Escambia Bay arm of Pensacola Bay. Numerical simulations indicate that this end of the bay should have had the highest surge elevations and very large wave heights (up to 9 feet). The existing shore protection was not adequate to protect the road.

Photograph M. Interstate 10 bridge collapse into the Escambia Bay arm of Pensacola Bay (AP photo from web). This damage was from waves hitting the bridge decks due to the storm surge.

Photograph M shows damaged portions of the bridge deck of Interstate-10 crossing the Escambia Bay arm of Pensacola Bay. Sheppard and Renna[6] have already investigated this damage and concluded that it is due to the waves and storm surge. The storm surge raised the mean water level to an elevation at or near the horizontal bridge spans. This allowed them to be exposed to large wave loadings. The waves would have brought much greater forces to bear on the spans than could be caused by the mean current due to the storm surge (This is confirmed by the hydrodynamic model results in the next section

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[6] Sheppard, D.M. and R. Renna, "A Preliminary Forensic Investigation of Damage at the I-10 Bridge over Escambia Bay during Hurricane Ivan," 7 pp., Sept. 20, 2004.

of this report). The fact that the lower spans near the middle of the bay failed could be explained due to the higher waves that would be expected in the deeper depths farther from shore in this bay under extreme south-southeast winds (This is also preliminarily confirmed by wave modeling results in the next section of this report). There was also erosion behind the abutments at the east end of the I-10 bridge.

Photograph N. Damage to the approach to the bridge abutment at the north end of Bob Sykes Bridge on FL 399. Note that the entire two southbound lanes are destroyed for about twenty feet.

Photograph N shows damage to the approach to a bridge abutment for FL 399 as it approaches the north side of the Bob Sykes bridge between Gulf Breeze and Pensacola Beach. This picture was taken five days after the storm. The photograph shows the entire southbound lanes (two lanes plus bike path) removed. The repaired portion is actually the northbound lanes behind the missing southbound lanes. In Photograph N, the bridge was closed for emergency repairs which is why the vehicle is parked going the wrong direction. Close inspection of the photograph shows the pre-storm soil line on the bridge abutment (right side of photograph). The up-right concrete structure on the left side of the photograph is a drop inlet box for storm water runoff that was entirely below grade prior to the storm. This approach was protected by some form of revetment prior to the storm that failed to adequately protect the roadway.

Photograph O. Wave damage to pavement on the approach at the south end of Bob Sykes Bridge, FL 399 in Pensacola Beach

Photograph O shows damage to the approach at the south end of the same bridge as shown in Photograph N. This type of damage was likely due to waves attacking the embankment on top of the elevated storm surge. This sort of damage to bridge approaches during hurricanes is common. It has been seen after other hurricanes as well as in Photographs E, N, and P of this report.

Photograph P. Repairs to damage at north end of Garcon Point Bridge

Photograph P also shows repairs to damage to an approach to the bridge abutment for Escambia County Road 191 at the north end of the southbound lanes of the Garcon Point Bridge across Pensacola Bay. This picture was taken eleven days after the storm. The repair shown indicates that a portion of one lane was damaged in the storm. A shore protection revetment failed to protect the roadway. This damage, like much of the damage to bridge approaches, was due to wave attack on top of the storm surge.

Photograph Q. Pavement damage to FL 399 east of Pensacola Beach.

Photograph Q shows roadway damage to FL 399 on Santa Rosa Island east of Pensacola Beach. This portion of the roadway was elevated over 10 feet above sea level. It was also built at a higher elevation than the sand immediately to the north. The indications are that this pavement damage was due to the weir flow mechanism (see discussion for Photograph G). The broken up pavement on the road in Photograph Q is from a parking lot that was south of the road behind where the picture was taken. The broken up pavement off to the right was from the road and from a bike path that paralleled the road. Immediately east of this location (50 yards behind the photographer), the elevation of the barrier island and the roadway dropped down about 5 feet. That lower portion of the roadway was completely destroyed (not shown).

Photograph R. Damage to a portion of FL 399 in Gulf Islands National Seashore that had been relocated north to prevent such damage in 1996.

Photograph R shows a portion of FL 399 in the GINS that had been relocated farther north when it was rebuilt after Hurricane Opal (1995). This same portion had suffered limited pavement damage during Hurricane Georges (1998) and Tropical Storm Isadore (2002). The roadway was built on an overwash fan from Opal but was built elevated a few feet above the adjacent sand. Thus, unlike the road on Dauphin Island, Alabama shown in Photograph B, this road probably acted like a weir when the storm surge got to it instead of being buried by overwashing sand. From this photograph, it is not clear how much of the pavement is damaged and how much is buried in sand. Field investigations on the ground will be needed to determine the extent of the damage. Possible overwash channels with evidence for both northward and southward flowing currents are seen.

Photograph S shows repair underway on US 98 west of the bridge to Destin, Florida. This picture was taken the fifth day after the storm. It appears that this portion of the road may have suffered under direct wave attack.

Photograph S. Repairs underway on US 98 west of the East Pass Bridge.

Preliminary Storm Surge and Wave Analysis for Escambia Bay (US 90 and I-10)

In order to investigate the potential role of storm surge and waves in the collapse of the I-10 bridge spans and the US 90 erosion, preliminary applications of two complex numerical models were developed. These preliminary results are presented here but will be further refined and validated in the future.

Figure 2 presents some preliminary, numerical storm surge modeling results for Hurricane Ivan. Pensacola Bay including Escambia Bay (the northwest arm) is modeled. The mean water surface elevation at the peak of the surge is shown. The location of the damaged portion of US 90 in Photograph L is in the darkest blue portion of the figure (the modeled floodplain extends over land). Thus, this analysis indicates that this portion of the roadway experienced some of the highest storm surges in Ivan.

The Interstate-10 bridge is located in the blue area of Figure 2. This high surge in the north end of Escambia Bay was partially caused by wind setup within the bay due to the extreme sustained winds blowing up the length of the bay. The hydrodynamic model is ADCIRC. These results are preliminary and subject to refinement and possible change. The record of the Pensacola tide gauge was used as the boundary condition and the measured average winds from the Pensacola airport were applied. The concept that the upper end of this bay experienced extremely high surges was also mentioned by Sheppard and Renna (2004). These preliminary model results indicate that the mean water level due to the surge could have been roughly 3.2 m (10½ feet) higher than normal. This would have placed the water level roughly even with the bottom of the bridge spans and thus exposed the spans to the maximum possible wave-induced lateral and uplift loads.

Figure 3 presents some preliminary, numerical wave model results for the area. The wave model is SWAN. The significant wave height in the vicinity of the bridge exceeds 9 feet. Many individual waves will exceed this height in such a sea-state. These results are large enough to cause excessive lateral and uplift wave loads on a rigid bridge deck. Also, the variation of wave height across the bay at the location of the bridge (line across Escambia Bay arm) indicates that the waves were highest in the middle of the bay. This is consistent with the failures shown in Photograph M.

The bridge decks would have been subjected to loads that were near the critical loads to move them off the pile caps. Where the loads were slightly larger, the decks dropped. Where the loads were slightly smaller, the decks just moved. And where the loads were smaller, they did not move.

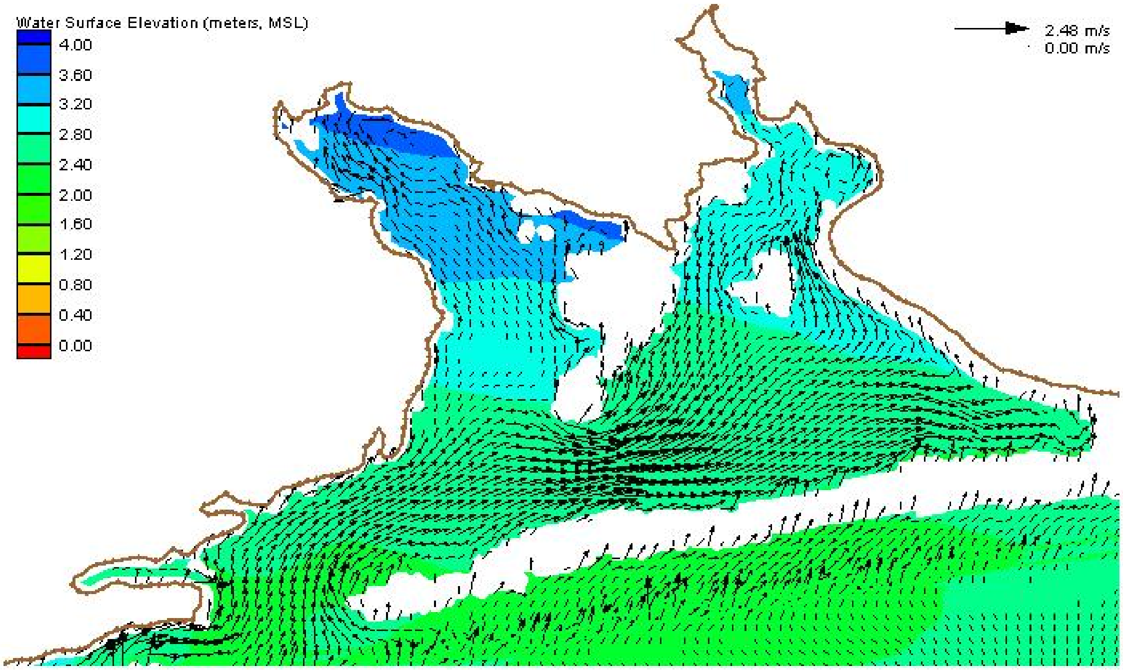

Figure 2. Estimated storm surge elevations in Pensacola Bay during Hurricane Ivan

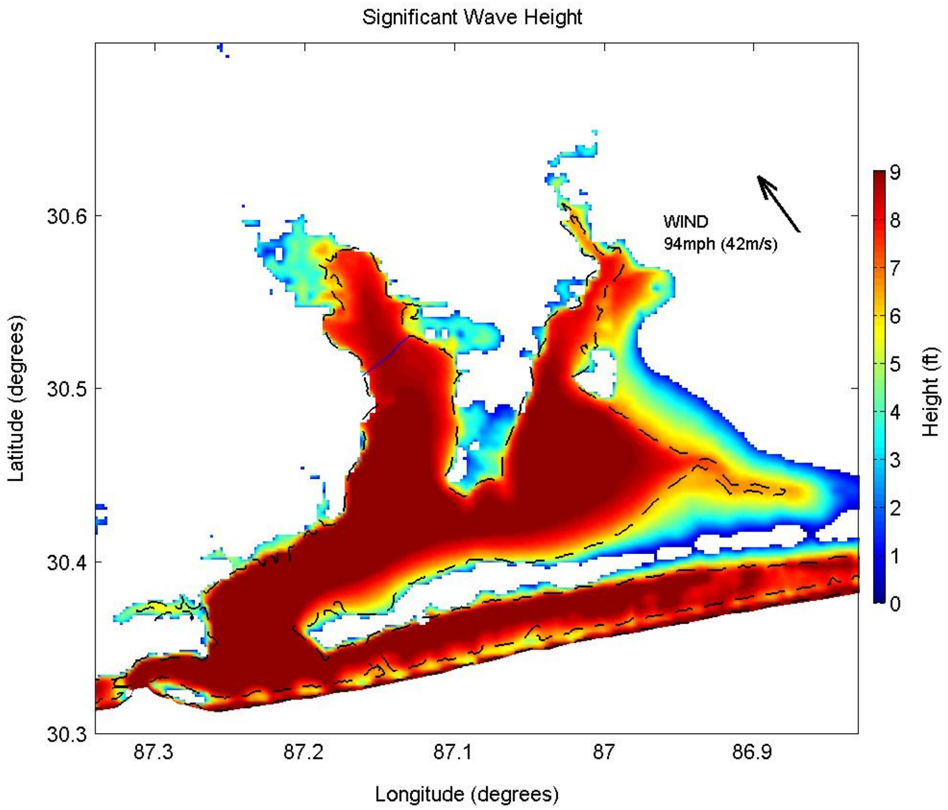

Figure 3. Estimated wave heights in Pensacola Bay during Hurricane Ivan (the I-10 bridge is shown as the line across the northwest arm of the bay).

Summary of Road and Bridge Damage Mechanisms

Hurricane Ivan caused damage to coastal roads and bridges through several different mechanisms. Waves on storm surge is the common denominator to each.

One damage mechanism was scour due to waves and currents on the approaches to bridge abutments (e.g. Photographs E, N, O, P). These areas are not exposed to waves under normal conditions but are during major hurricanes. The unprotected, or underprotected, embankment slopes were not able to withstand the waves and currents produced by Ivan.

A second damage mechanism was water flow across roads during the storm. There was evidence of this damage on either side of the road. Much of this damage was on the north side (side away from the Gulf) of the pavement of shore parallel roads along the Gulf that were elevated compared to the adjacent ground elevations (e.g. Photographs G and Q). There was likely some high velocity flows down the north side shoulder as the storm surge and waves began to overtop the pavement crest. This “weir-like” flow damage has been observed in previous storms. Some of this damage was on the south side of the roadway apparently due to receding storm surge. This damage mechanism may have been more widespread than was obvious after the storm. It could have been the damage initiation mechanism in areas where pavement was completely destroyed later in the storm (e.g. Photograph J).

Another mechanism for damages was direct wave attack on revetment slopes (Photographs A, C, K, L). In this case damage appears to be partly due to inadequate armor layer design. Part of the problem is that the stones may be too small for the storm wave conditions. Attempts to make these slopes rigid with poured concrete also did not seem to work well (e.g. see foreground of Photograph N). Rigid revetments in coastal situations have a long history of undermining problems.

The I-10 bridge damage appears to be due to wave loads on the deck due to the storm surge. This is consistent with the damage found by Sheppard and Renna (2004) as well as the storm surge and wave modeling in Figures 2 and 3.

A fifth damage mechanism may have been the actual "floating" of pavement (Photograph H). This problem, due to the uplift pressures of high velocity flow and positive pore pressures, has been found on non-coastal roads subjected to flood flows. It may also have been a problem here in Ivan.

Implications for Future Research and Education Needs

The damages from Hurricane Ivan point to several areas for improved design education and several areas where some focused research could be fruitful. The "lowest-hanging fruit" is probably the direct damage by waves to revetments. The coastal engineering community currently has the tools to design revetments that can survive hurricane attack. In general, the techniques typically used for stormwater runoff scour control are not the same as the tools that should be used in the coastal wave environment. Specifically, the design of rip-rap revetment for bank stabilization for rainfall events is different than the design of a coastal revetment exposed to the magnitude of wave heights generated by Ivan. The transportation design and planning community needs to be aware of the available coastal engineering tools and use them where appropriate. More technology transfer between the two engineering communities, coastal and transportation, can help address this problem. The recently added requirement by the Florida DOT of a qualified coastal engineer on bridge scour design teams is a step in the right direction. The FHWA-funded Coastal Transportation Engineering Research and Education Center at the University of South Alabama is taking a lead role in this transfer of coastal engineering technology into the transportation engineering community.

The design of the approach slopes to bridge abutments is a more challenging design problem. However, the coastal revetment design concepts could be adopted to bridge approaches. This is an area where some new guidance could be developed for the transportation engineering community. Also, an inventory of existing approaches that could be damaged during future storms would be valuable. It may even make sense to consider a retrofit program for countermeasures to prevent future approach damages.

The weir-like flow scour problem is an area where some research is warranted. Armoring the shoulders of coastal roads is one possible countermeasure for this sort of scour but this can be expensive. Significant cost savings might be realized for this option by optimizing the shoulder protection and avoiding overdesign. Another design option is the lowering of the elevation of the road to more closely match the surrounding grade. The goal would be to allow the road to be buried by sand early in the storm before damage begins (e.g. see Photograph B). This would be most successful on roads located a sufficient distance from the water. This distance may be able to be predicted by existing dune erosion models such as SBEACH. The Coastal Transportation Engineering Research and Education Center at the University of South Alabama was already planning some laboratory experiments into the weir-like damage mechanism prior to Ivan.

The probable cause of the Interstate-10 bridge collapse raises a number of important questions including: are there other bridges that are vulnerable to similar damages? Should we evaluate the vulnerability of other existing coastal bridges to similar damages through numerical simulations such as shown in Figures 2 and 3? How could be best retrofit vulnerable bridges? Given the problems caused by this collapse, each of these questions should be asked and answered by the transportation engineering community in the coming years.

Conclusions

All of the road and bridge damage in Ivan was due to combinations of storm surge (extreme rise in water level during the storm) and waves on top of the storm surge. The primary conclusion of this report is that better inclusion of coastal engineering concepts and tools in the planning and design of roads and bridges along the coast would be valuable in reducing this damage in the future. Some of the problems seen in Ivan (inadequate wave revetments and bridge approach failures) can be solved by the appropriate application of existing technologies. Some of the problems seen in Ivan, however, (bridge deck vulnerability and scour failure on the lee side shoulders) probably require some more focused research in order to develop and document more appropriate solutions.

Acknowledgements

This effort was helped by cooperation from dozens of officials and staff in the aftermath of Ivan by providing access to the sites. The cooperation and help from the City of Orange Beach Alabama, City of Gulf Shores Alabama, Town of Dauphin Island Alabama, Alabama Emergency Management Agency, Alabama Department of Transportation, FEMA, FHWA, FHWA-Alabama Division, FHWA-Florida Division, Florida Department of Transportation, Civil Air Patrol, Santa Rosa Island Authority, Dewberry & Davis, PBS&J, Chris Jones, and all the law enforcement personnel manning the disaster checkpoints is sincerely appreciated. Joel Richards and Lixia Wang prepared the figures in this report.

This report is a product of the Coastal Transportation Engineering Research and Education Center at the University of South Alabama which is supported by the Federal Highway Administration.