U.S. Department of Transportation

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MDOT
MISSISSIPPI DEPARTMENT OF TRANSPORTATION

Henderson Point Connector (US HWY 90)

GREEN INFRASTRUCTURE TECHNIQUES FOR COASTAL HIGHWAY RESILIENCE

April 2018

This report documents a pilot project sponsored by the Federal Highway Administration (FHWA) and the Mississippi Department of Transportation (MDOT) to assess the potential for green infrastructure techniques to protect the Henderson Point connector bridge on US Highway 90 from coastal storm surge. It is one of five pilot projects FHWA sponsored to assess the potential for natural infrastructure to protect specific locations along coastal roads and bridges. More information can be found at: https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/green_infrastructure/index.cfm

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16. Abstract

The storm surge and waves generated by Hurricane Katrina caused widespread damage to built infrastructure in coastal Mississippi and neighboring states. A number of coastal bridges and roadways failed during this event. One such bridge in coastal Mississippi was the Henderson Point connector that carries US HWY 90 over railroad tracks and a small tidal creek. One two-lane span was completely displaced from its bent beams while the adjacent span shifted laterally by a few inches. The causes of the failure were not known before this study began. This particular site was chosen for the pilot project in order to address a key knowledge gap regarding the vulnerability of coastal bridges: the approach embankment and approach spans that pass through critical elevations where damage during extreme storms is likely. This green infrastructure pilot project seeks to develop a solution that addresses this vulnerability while increasing the resilience of the built and natural systems.

Multiple hydrodynamic models were used to determine the likely causes of failure at the Henderson Point bridge. A number of conventional gray adaptation solutions and green infrastructure adaptation options were considered in this study. A pair of vegetated berms were selected for evaluation as a green infrastructure solution (Figure ES 1). The berms would eliminate or substantially reduce flow velocities near the bridge abutment and low-elevation approach spans by redirecting flood flows away from those vulnerable elements. Even with a relatively low material cost (~$20,000 not including vegetation), the vegetated berms would reduce the likelihood of bridge span failure during its 50-yr design life from 64% to 39%, by protecting the bridge against the 1% annual chance coastal flood event (current protection level is to the 2% event).

There were three significant lessons learned in this pilot project. First, this may be the first known coastal bridge that failed as a result of hydrodynamic drag forces due to flowing water during a hurricane. Second, the application of multiple hydrodynamic models at varying spatial scales delivers superior information about damaging coastal hazards near a transportation asset. Third, there may be similar opportunities to improve the resilience of low-elevation bridge spans to similar types of damage in future storm events. For low-elevation bridge spans over land, extending the embankment to higher elevations, or using something similar to the vegetated berms considered here, could potentially reduce their vulnerability to extreme events now and in the future.

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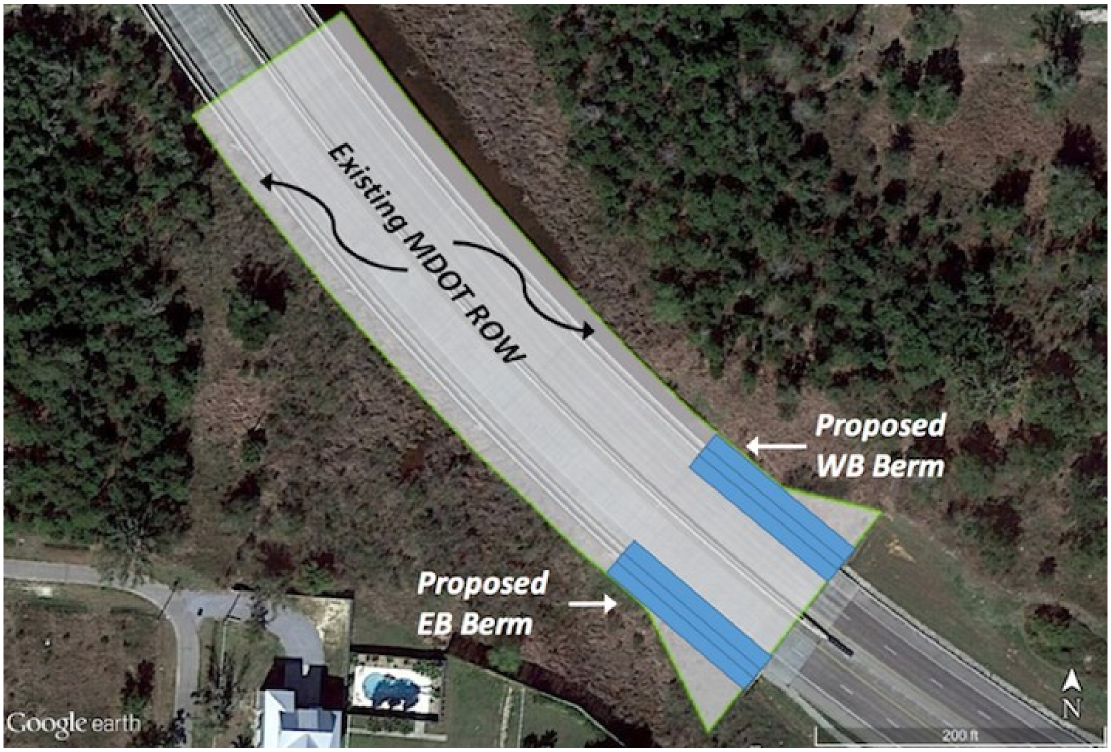
Executive Summary

The storm surge and waves generated by Hurricane Katrina caused widespread damage to built infrastructure in coastal Mississippi and neighboring states. A number of coastal bridges and roadways failed during this event. One such bridge in coastal Mississippi was the Henderson Point connector that carries US HWY 90 over railroad tracks and a small tidal creek. One two-lane span was completely displaced from its bent beams while the adjacent span shifted laterally by a few inches. The causes of the failure were not known before this study began. This particular site was chosen for the pilot project in order to address a key knowledge gap regarding the vulnerability of coastal bridges: the approach embankment and approach spans that pass through critical elevations where damage during extreme storms is likely. This green infrastructure pilot project seeks to develop a solution that addresses this vulnerability while increasing the resilience of the built and natural systems.

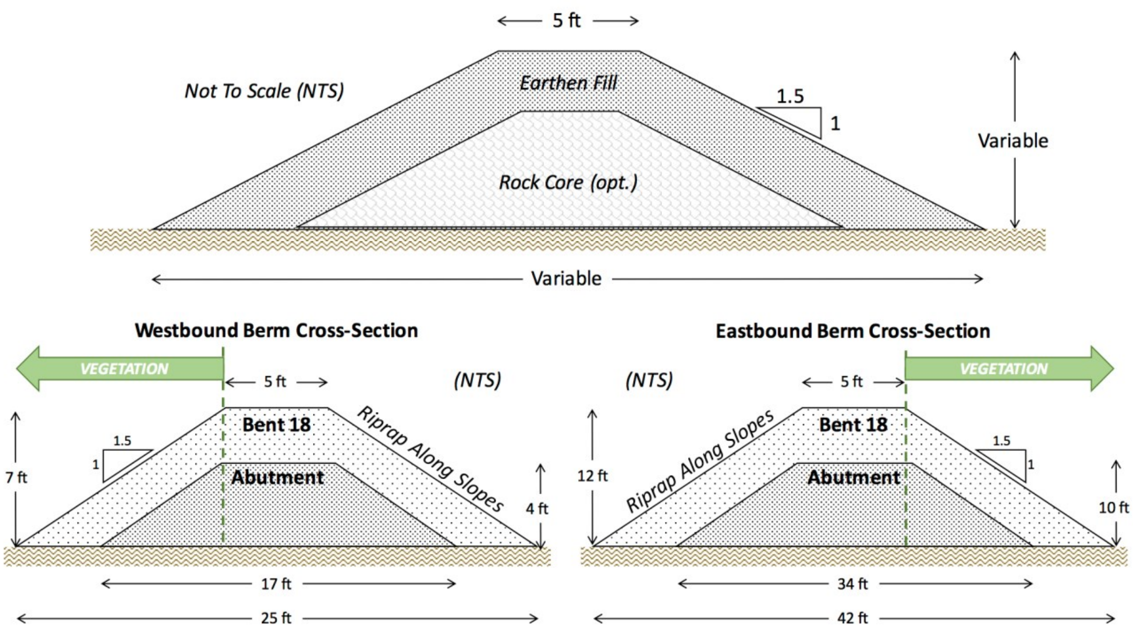
Multiple hydrodynamic models were used to determine the likely causes of failure at the Henderson Point bridge. Hurricane Katrina was simulated with a coupled storm surge and wave model (ADCIRC+SWAN) to provide the general hydrodynamic conditions near the bridge during the storm event. Results from the model were extracted and used as input to a more highly resolved hydrodynamic model (XBeach) that better described the terrain, water levels, waves, and currents near the bridge abutment. The XBeach model results were used to evaluate the potential for wave and drag-induced loads on the bridge spans. The potential effects of buoyancy and trapped air were also considered. Based on the analysis performed in this study, it was determined that the drag-induced forces generated by strong currents near the abutment provided the most likely explanation for the damage that occurred. Understanding this failure mechanism was a key component in selecting an appropriate green infrastructure solution to improve the resilience of this bridge.

A number of conventional gray adaptation solutions and green infrastructure adaptation options were considered in this study. Given that some gray adaptation options may cause unintended impacts to some other bridge component, these solutions were not considered for this pilot project. Additional research and study are needed before their use can be recommended. Instead, a pair of vegetated berms were selected for evaluation as a green infrastructure solution (Figure ES 1). The berms would eliminate or substantially reduce flow velocities near the bridge abutment and low-elevation approach spans by redirecting flood flows away from those vulnerable elements. Even with a relatively low material cost (~$20,000 not including vegetation), the vegetated berms (Figure ES 2) would reduce the likelihood of bridge span failure during its 50-yr design life from 64% to 39%, by protecting the bridge against the 1% annual

chance coastal flood event (current protection level is to the 2% event). The reduced likelihood of failure is a direct result of reducing the damaging event



ES 1. General location overview showing the existing MDOT right-of-way and proposed westbound (WB) and eastbound (EB) berm locations relative to the bridge approach and bridge spans. (Map Credit: Google Earth; Map©2018Google)



ES 2. Proposed berm cross-sections.

probability from a 2% annual chance event to the 1% annual chance event. The level of protection provided by the berms is twice as much as the threshold typically considered for this bridge, which provides adaptive capacity in light of uncertainty related to future sea levels and storm intensity and frequency.

Aside from the benefit of protecting the low-elevation bridge spans, the vegetated berms could be constructed completely within the existing right-of-way and require little long-term maintenance. These were the only two constraints that the Mississippi Department of Transportation applied to the pilot project. The use of vegetated berms meets both constraints. Additionally, the berms will not impact existing tidal wetlands and will actually enhance the natural surroundings and complement an adjacent upland conservation area and pine forest. While there are tidal wetlands nearby, there are none within the footprint of the proposed berms.

There were three significant lessons learned in this pilot project. First, this may be the first known coastal bridge that failed as a result of hydrodynamic drag forces due to flowing water during a hurricane. While the bridge was subjected to wave and buoyancy forces as well, the span displacement is best described by the hydrodynamic forces. It is possible that a combination of all three forces contributed to damage in some way. The hydrodynamic forces represent a potential coastal bridge vulnerability that should be considered in future bridge assessments and designs. Further research on this topic is needed.

Second, the application of multiple hydrodynamic models at varying spatial scales delivers superior information about damaging coastal hazards near a transportation asset. This may be the first example of the benefits that can be realized by combining the large-scale storm surge and wave models, like ADCIRC and SWAN, with more detailed hydrodynamic modeling of coastal processes using XBeach. The level of detail provided by the XBeach model results made it possible to describe water levels, waves, and flow velocities at numerous points along each bridge span and around the bridge abutment.

Third, there may be similar opportunities to improve the resilience of low-elevation bridge spans to similar types of damage in future storm events. For low-elevation bridge spans over land, extending the embankment to higher elevations, or using something similar to the vegetated berms considered here, could potentially reduce their vulnerability to extreme events now and in the future. Also, combining green infrastructure adaptations with more traditional engineering adaptations or structural modifications may help to improve resilience. For example, venting the diaphragms of these bridge spans could possibly reduce or eliminate trapped air effects that are believed to augment the buoyancy forces acting on a span. Addressing the vulnerability of bridge approaches and approach spans, particularly for existing bridges, will lead to more resilient coastal transportation infrastructure.

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Abbreviations

ADCIRC	Advanced Circulation Model
BFE	Base Flood Elevation
EWL	Extreme Water Level
FEMA	Federal Emergency Management Agency
F_{hmax}	Maximum Horizontal Wave Load
F_{vmax}	Maximum Vertical Wave Load
H_s	Significant Wave Height
HWM	High Water Mark
LiDAR	Light Detecting and Ranging
NAVD/NAVD88	North American Vertical Datum
NOAA	National Oceanic and Atmospheric Administration
RSLC	Relative Sea Level Change
RSLR	Relative Sea Level Rise
SWL	Still Water Level
SWAN	Simulating Waves Nearshore
SLR	Sea Level Rise
USACE	United States Army Corps of Engineers
WSE	Water Surface Elevation
WCE	Wave Crest Elevation
WTE	Wave Trough Elevation

1 Problem & Context

This section of the report describes the asset to be enhanced with green infrastructure, provides some context about the site and its prior damage history, and identifies the major hazard and climate stressors of interest.

1.1 Asset Description

This green infrastructure pilot project is focused on the Henderson Point bridges along US HWY 90 (West Beach Blvd.), a major East-West corridor along the Gulf Coast in Harrison County, Mississippi. Constructed in 2000 and maintained by the Mississippi DOT, this crossing consists of two simply-supported bridges, each carrying two lanes of traffic in each direction, and spans a small tributary and CSX Railroad track line. A photo of the approach spans shown shortly after construction is provided in Figure 1.

The bridges are approximately 2250 feet in length, with eighteen 125-foot (38m) pre-stressed concrete beam spans and a 48-foot deck width. The end bent elevations are approximately +10 feet (NAVD88). The bridge attains its highest elevation at approximately +30 feet (NAVD88).

Figure 1. Image showing the Henderson Point bridges shortly after their construction (Photo Credit: MDOT).

1.2 Site Context

The Henderson Point bridges are located in southwest Harrison County and sit approximately 1000 feet north of Mississippi Sound and 2700 feet east of St. Louis Bay. The study area for this pilot project is approximately the yellow shaded region in Figure 2, which includes the approach embankment, the two lowest pairs of bridge decks, and the existing easements along either side of the bridge. The study area is approximately 2.5 acres in size. The bridges and roadway are surrounded by light residential development, a conservation area to the northeast, and tidal marsh and wetlands to the north. Immediately south of US HWY 90 are an engineered beach and dune system that covers an old reinforced concrete stepped revetment. The water body visible south of the beach is Mississippi Sound.

The Henderson Point bridges, as well as surrounding areas, were directly damaged by hurricane storm surge and waves during Hurricane Katrina in August 2005. In addition to erosion of the approach embankment, the lowest elevation westbound span was completely displaced (to the east) from the bent beams as shown in Figure 3 and Figure 4. The lowest elevation eastbound span was displaced laterally (to the east) a few inches. More specific information about the coastal flood hazard vulnerability of this location is provided in the subsequent section, including flood elevations sustained during Hurricane Katrina as well as the estimated 1% annual chance (100-yr return period) flood elevation.

Figure 2. Location overview image and study area (shaded region) for the Henderson Point green infrastructure pilot project (Map Credit: Google Earth; Map©2018Google).

Figure 3. Image showing damage to Henderson Point bridges during Hurricane Katrina (Photo credit: NOAA).

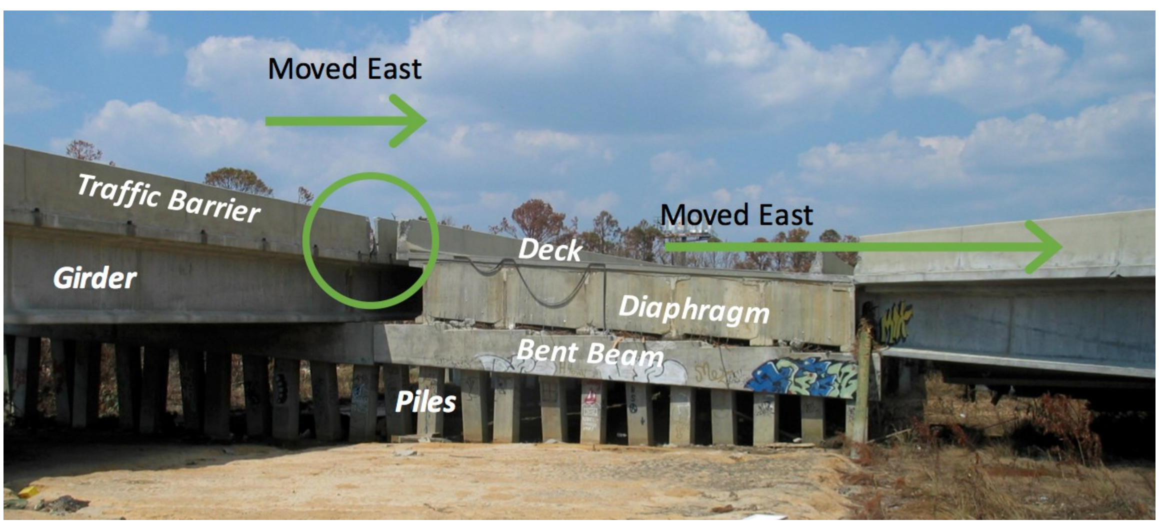

Figure 4. Image showing displacement of westbound span during Katrina (Photo credit: MDOT).

1.3 Climate & Other Stressors

The study area is susceptible to frequent flooding from extreme events like tropical storms and hurricanes. The National Hurricane Center's historical hurricane tracks database[1] reveals that 59 storms have passed within a 50 nautical mile radius of the project area between the years 1852 and 2017. Of those 59 storms, 43 were of tropical storm intensity or higher, and seven were major hurricanes (Category 3 and above). Those storm tracks are shown in Figure 5 for reference.

High water mark (HWM) elevations surveyed after Hurricane Katrina in 2005 revealed that still water elevations near the Henderson Point bridges may have reached +24 feet (NAVD88). A map showing selected Katrina HWMs and related storm information is provided in Figure 6. Typical ground surface elevations in the study area range from +5 to +10 feet (NAVD88), so there was a considerable amount of overland flooding at this location during Katrina (~15 to 20 feet). That flooding allowed large waves to propagate well inland.

The existing vulnerability of the bridge is to storm surge at levels similar to those of Hurricane Katrina under present climate conditions. Determining the exact frequency or return period of Katrina was not a goal of this study. However, based on established FEMA flood hazard maps of the area it is likely that Katrina was beyond a 100-yr return period (1% annual chance) storm event for water levels at this location. The effective FEMA flood hazard maps for the study area suggest that the 1% annual chance flood elevation is approximately +20 feet (NAVD88) as shown in Figure 7. The location of the Henderson Point bridges falls almost on the dividing line between the AE and VE flood hazard zones. This represents a transition from the coastal high hazard (VE) zone, characterized by high velocity and wave action, to the special flood hazard (AE) zone characterized by inundation (lack of wave action).

One relevant climate stressor for this bridge is future sea level rise (SLR), or more specifically, future relative sea level rise (RSLR). A long term sea level recording gage is located on Dauphin Island, Alabama approximately 70 miles from the Henderson Point Bridge. The linear trend reported by NOAA at the Dauphin Island tide gage[2] is approximately 0.01 feet per year (ft/yr). However, this linear trend does not account for possible future accelerations in the rate of RSLR.

The US Army Corps of Engineers' (USACE) Sea Level Change calculator[3] was used to evaluate the impacts of possible future rates of RSLR on the Henderson Point bridge. The change in the FEMA Base Flood Elevation (BFE) of +20 feet NAVD88 was modeled under the USACE low, intermediate, and high

[1] https://coast.noaa.gov/hurricanes/

[2] https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8735180

[3] http://www.corpsclimate.us/ccaceslcurves.cfm

sea level rise rate scenarios. The time at which the existing BFE reaches the observed Katrina HWM of +24 feet NAVD88 was identified for each RSLR scenario. In other words, when the relative sea level has increased by 4 feet, the current 1% annual chance storm event may cause damage similar to that of Katrina, but for a storm weaker than Katrina. This simplified approach ignores possible storm intensification that may occur over time as future sea levels increase beyond their present-day levels.

An example of the BFE modeled on the USACE high SLR rate scenario is shown in Figure 8. The years corresponding to this intersection of critical elevations for the high, intermediate, and low SLR rate scenarios are 2083, 2156, and 2409, respectively. Assuming that future damage to the bridge in its current condition requires an event producing a still water elevation equal to or greater than Katrina's +24 feet, these represent the years at which future sea levels increase the current 1% annual chance flood hazard elevation to that tipping point or threshold for damage. In other words, the 1% annual chance flood hazard elevation may result in damage to the bridge as early as the year 2083 or as late as 2409. Between now and 2083, the bridge may be damaged by an event having an impact greater than the 1% annual chance flood but a storm less intense than Katrina. Sea level projections beyond the year 2100 are uncertain, making it difficult to determine with confidence the actual years when the intermediate and low SLR rate scenarios may impact the bridge.

Another relevant climate stressor is the potential intensification of tropical cyclones (i.e., hurricanes). While there is no definitive projection of tropical cyclone characteristics for the Gulf of Mexico, studies (e.g., Knutson et al., 2010; Emanuel, 2015; Knutson et al., 2015) broadly point to an increase in storm intensity (~20%) and a corresponding decrease in frequency of occurrence (~10%). Storm intensification is typically described in terms of decreased central pressure and increased wind speeds in the hurricane. The combined effects of more intense, but less frequent, storms on future flood hazard probabilities is unknown at this time.

To summarize, the current vulnerability of the Henderson Point bridges is to coastal flooding more extreme than the 1% annual chance storm event (i.e., beyond the 100-yr flood event). Hurricane Katrina was such an event and it caused damage to this bridge. However, the existing 1% annual chance flood may reach Katrina-like levels as soon as 2083 or as late as 2409 accounting for future sea level rise. Future vulnerability that accounts for both sea level rise and storm intensification may cause those elevated flood levels to occur sooner than the years stated above.

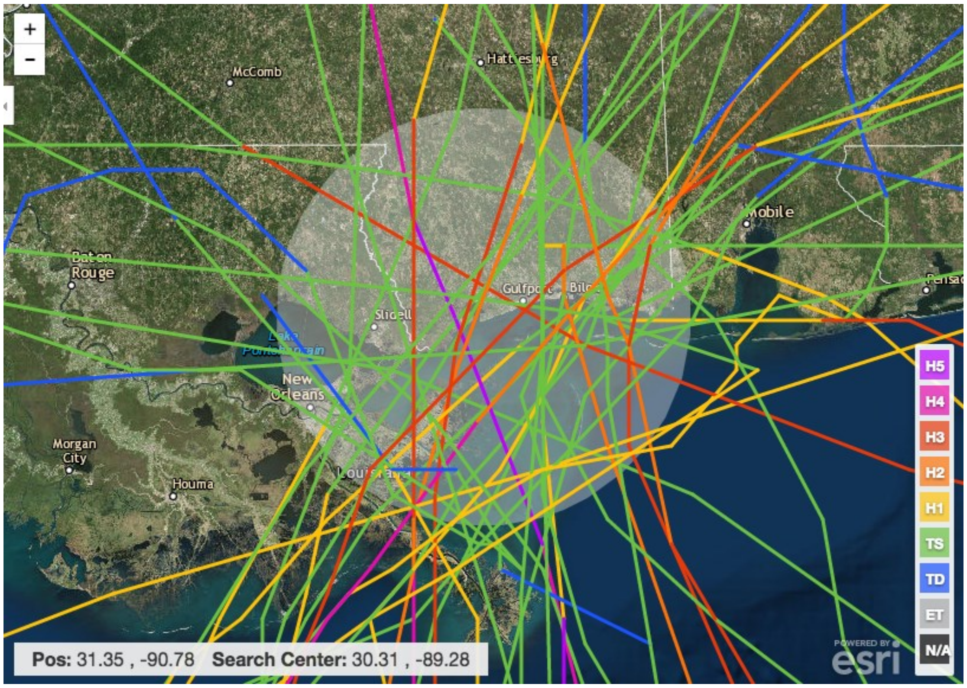

Figure 5. Historical storm and hurricane tracks within a 50 n.mi. radius of the study area for the period 1852-2017. The legend labels correspond to Saffir-Simpson Scale Category 5 (H5), Category 4 (H4), Category 3 (H3), Category 2 (H2), Category 1 (H1), Tropical Storm (TS), and Tropical Depression (TD) events. The designation ET stands for extra-tropical cyclone (Photo credit: NOAA).

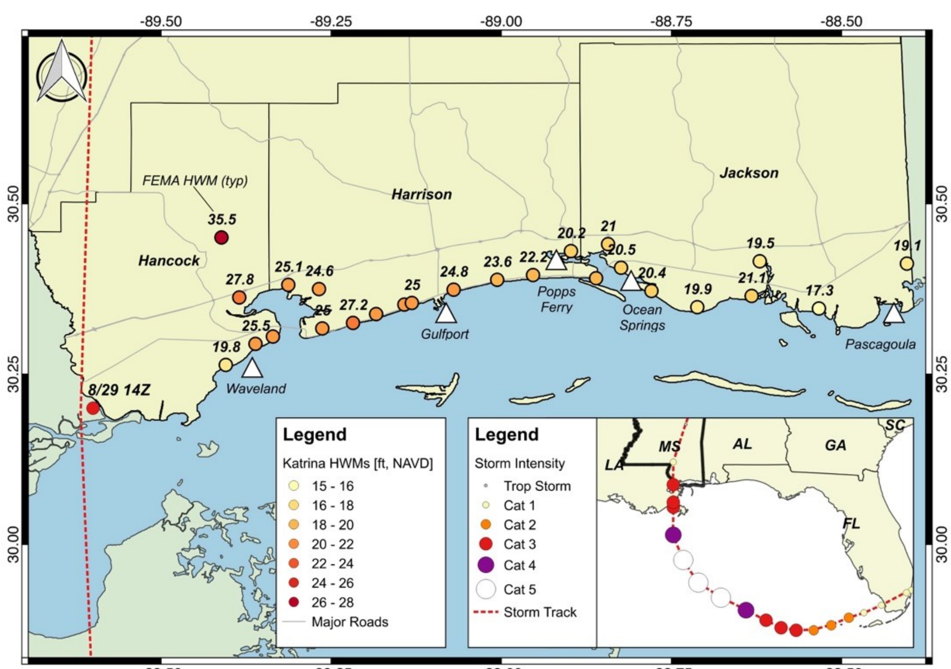

Figure 6. Selected high water mark elevations recorded after Hurricane Katrina.

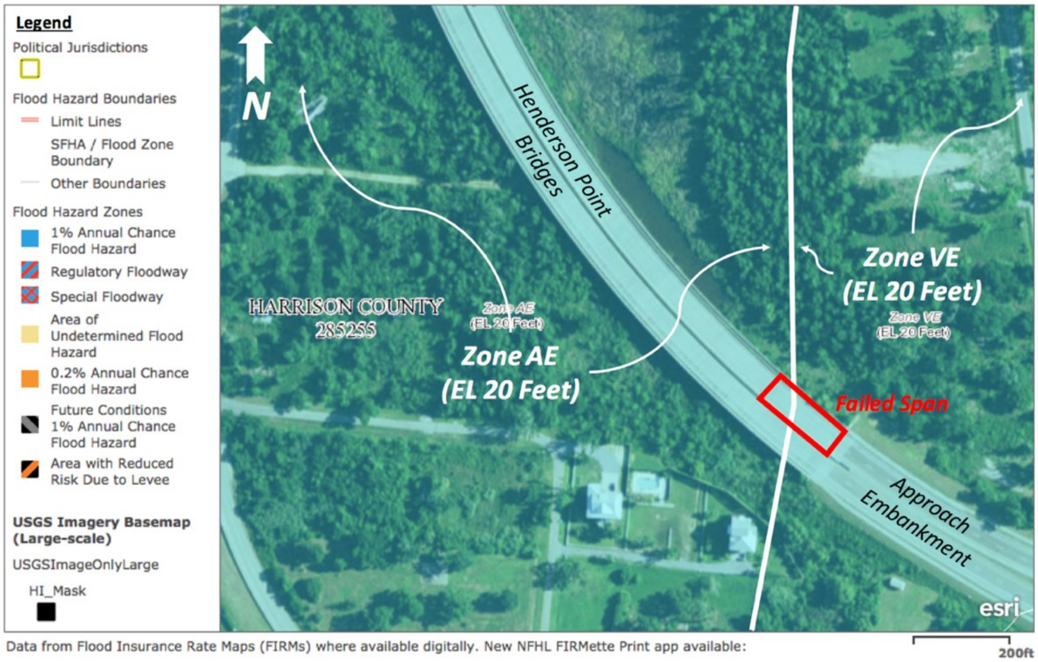

Figure 7. FEMA NFIP flood hazard layer showing the 1% annual chance flood zones (AE, VE) and elevations (20 feet). Note the dividing line between the AE and VE flood zones passes through the location of the failed bridge span. The line separating the two zones represents a transition from high velocity and wave action to inundation only.

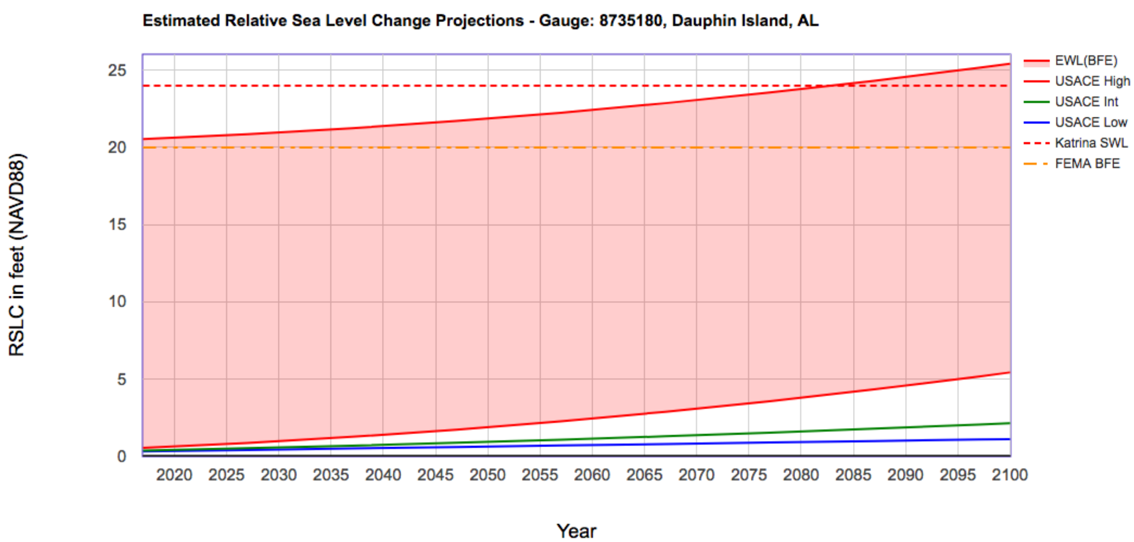

Figure 8. Relative sea level rise projection of the Henderson Point BFE under the USACE high SLR rate scenario. The dashed orange line shows the elevation of the current BFE. The red dashed line shows the still water elevation experienced during Katrina. The blue and green lines show USACE low and intermediate projections of relative sea level rise, respectively. The red shaded region shows the change in the extreme water level (EWL), in this case the existing BFE, over time with the lower limit (lower red line) indicating the future relative sea level rise under the USACE high scenario.

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2 Methods

In order to better understand the events leading to the failure of the Henderson Point bridge, comprehensive hydrodynamic modeling of Hurricane Katrina was performed. The modeling is briefly described below. It is important to note that Katrina's water levels were somewhat beyond the 1% annual chance (100-yr return period) flood elevation at this bridge, and that the design storm event for this particular asset is a 50-yr return period (2% annual chance) event. Therefore, choosing Katrina as a benchmark for performance is somewhat extreme, but perhaps provides some degree of enhanced resilience to address any potential changes in future coastal hazards.

2.1 Technical Approach

To improve the resilience of this bridge, the reasons for its damage during Katrina must first be determined. The damage sustained by this bridge was somewhat unique relative to other nearby bridge failures in Mississippi. First, three out of the four lowest approach spans were completely submerged (above deck elevation) by storm surge, yet only one of them was displaced. Second, the deck that failed was displaced in a somewhat counterintuitive direction relative to a presumed direction of wave propagation. Finally, these bridge decks had considerable steel reinforcing connections from the diaphragms down through the tops of the bent beams. It is clear that more detailed information about Katrina's characteristics at this bridge location are needed to reach some reasonable conclusion as to its actual impacts.

A hindcast simulation of Hurricane Katrina was performed using the dynamically coupled (Dietrich et al., 2011 and 2012), two-dimensional version of the ADCIRC (Luettich et al., 1992; Westerink et al., 1994) and SWAN (Booij et al., 1996) models. The coupled models were forced with predicted tides and Automated Tropical Cyclone Forecast Best Track storm data (e.g., storm locations, winds, pressures, etc.) to simulate the storm's effects on water levels and waves near the study area. The model results were validated using available tide gage data and surveyed high water mark (HWM) elevations. Model predictions of maximum still water levels near the bridge were in the range of +22 to +24 feet NAVD while maximum predicted significant wave heights ranged from 6 to 8 feet (Figure 9).

Even though a relatively high-resolution mesh was used in the hindcast simulation, the mesh size was not able to adequately refine the embankment approach and surrounding terrain for the purpose of this study. To overcome this issue, model data were extracted from the ADCIRC+SWAN simulation and used as input to XBeach (Roelvink et al., 2009), a two-dimensional hydrodynamic model capable of simulating water levels, currents, and waves at high resolution. The XBeach grid was developed using Mississippi Light Detection and

Ranging (LiDAR) digital elevation data, with a final horizontal spacing of approximately 13 feet (4 meters) between model grid points. This resolution was suitable for representing the approach embankment and surrounding terrain features of interest, including the HWY 90 roadway alignment and other nearby features. The ADCIRC+SWAN mesh and XBeach grid are shown in Figure 10 and Figure 11. The XBeach simulation results are described in the following section of the report.

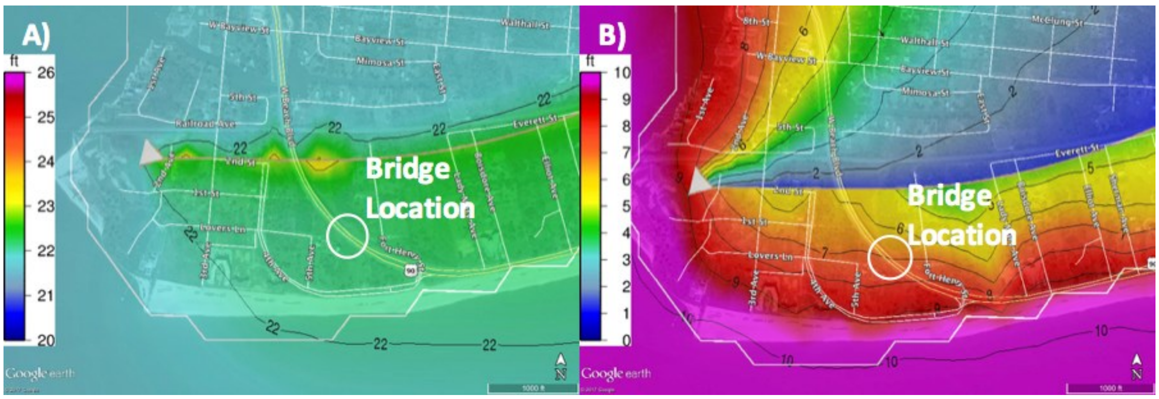

Figure 9. Katrina model simulation results from ADCIRC+SWAN showing the A) maximum still water levels (feet, NAVD), and B) maximum significant wave heights (feet).

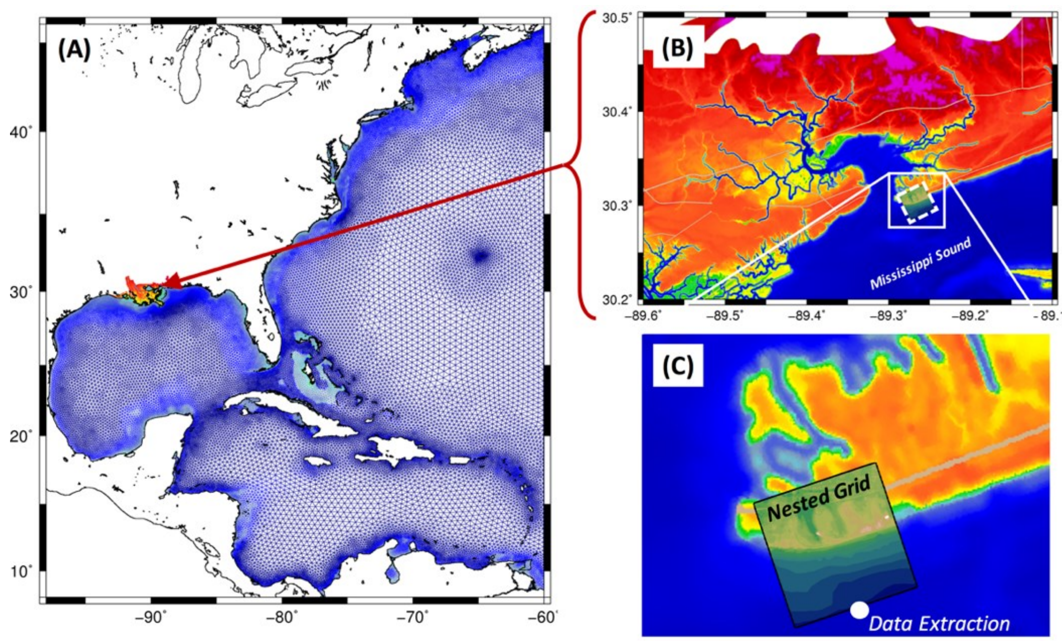

Figure 10. The A) full ADCIRC+SWAN unstructured mesh with local refinement in Mississippi and Louisiana, B) a detailed view of elevation contours near Henderson Point, and C) the location of the nested XBeach grid relative to the unstructured mesh.

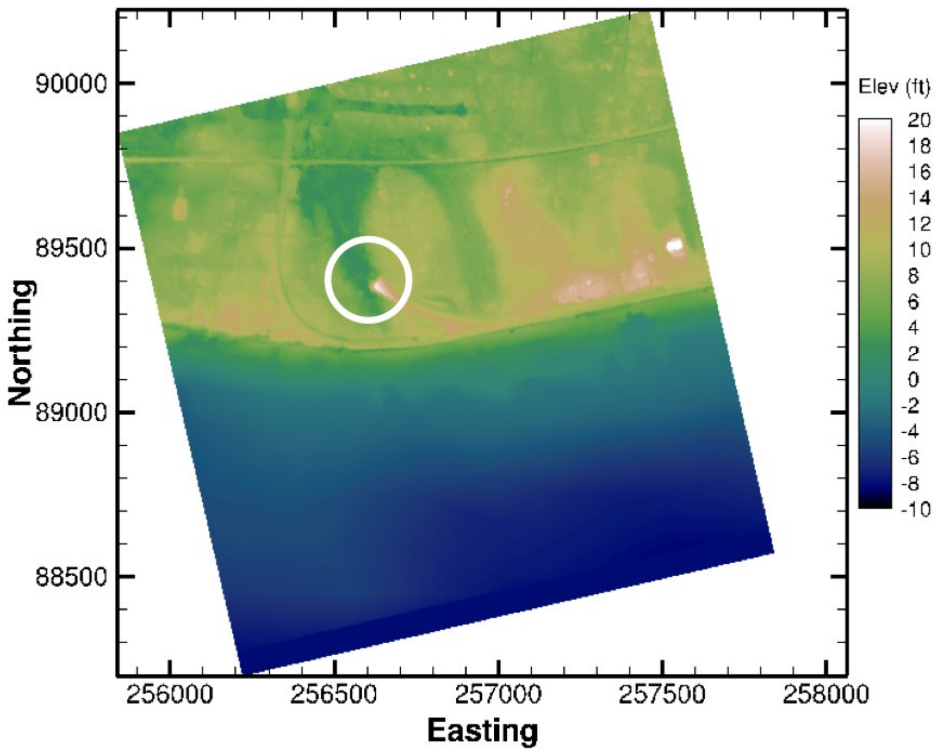

Figure 11. XBeach grid of Henderson Point showing elevation contours (feet, NAVD) and the location of the bridge failure (circle).

2.2 Analysis Methods

There are three possible mechanisms that could have contributed to failure of the Henderson Point bridge westbound span: wave loads, buoyancy combined with trapped air effects, and hydrodynamic loads due to currents. Wave loads and buoyancy effects have both been identified as contributing factors to other bridge span failures during hurricanes (e.g., Douglass et al., 2007; FHWA, 2008; Okeil and Cai, 2008), but hydrodynamic loads due to currents have not. The contributions of buoyancy and trapped air to bridge deck failures are still not well understood under storm conditions. Here, we used the results of the XBeach model to identify the most likely forces contributing to the failure of the study bridge.

The XBeach model was able to better predict the time-varying water levels, wave heights, and velocities near the bridge abutment and embankment during Katrina. Those results, shown in Figure 12, reveal that the maximum still water level, significant wave height, and velocity were +25 feet (NAVD), 6.3 feet, and 5.2 feet per second (ft/s), respectively. Note that the modeled maximum still water level of +25 feet is in very good agreement with the closest observed high water mark elevation of +24 feet. Also shown in Figure 12 are the elevations corresponding to the bottom of beam (girder), bottom of deck, and top of barrier near the midpoint of the span that failed. Note that the significant wave crest elevations exceeded that of the top of barrier for over two hours during the storm. The maximum wave crest elevations would have been substantially higher (+32.9 feet), occurring over a longer period of time. However, the wave direction and flow velocity are not shown in Figure 12, and they are central to the discussion that follows. At the peak of the storm, waves were traveling to the west and north, while flow velocity was oriented to the east and south, as depicted in Figure 13.

The Hydraulic Engineering Circular No. 25 "Highways in the Coastal Environment" provides guidance on the planning, design, and operation of highways and bridges along the coast (HEC-25: FHWA, 2008). The methodology presented in HEC-25 was used to estimate the maximum vertical and horizontal wave loads on the bridge spans. Using bridge span information and elevations provided by MDOT, the calculations suggest that all six of the lowest elevation spans should have failed or been displaced due to the vertical and/or horizontal wave loads. The vertical wave loads alone exceeded the span weights (1,525,000 pounds or 1525 kips) by factors ranging from 2.7 (highest of the six spans) to 5.6 (lowest of the six spans). A summary of those calculations is provided in Table 1. Given the fact that only one span failed, and also that the waves were traveling in a direction opposite to that of the span displacement, it seems unlikely that waves alone caused the damage to the westbound span (WBS1).

Buoyancy and trapped air effects have been cited in the literature as being possible contributors to bridge failures in Louisiana and Mississippi during Katrina (Okeil and Cai, 2008). These factors were evaluated for Henderson Point bridge and deemed not to be contributors to the displacement of the westbound span. The buoyancy of each bridge span was approximately 650 kips, or 43% of the span weight. If one were to assume that all of the air contained in the compartments defined by the beams (girders) and full diaphragms were trapped and contributed to total displacement of water, the enhanced buoyancy of the span would be 2380 kips, or about 1.6 times larger than the span weight. As unlikely as it would be to occur, this would certainly be enough to overcome the span weight, as well as the additional resistance provided by the steel bar connections (~143 kips), and lead to displacement. However, this would have occurred for five of the six lowest spans but only one was displaced. It is therefore unlikely that buoyancy or trapped air played a primary role in the damage to the westbound span.

The most likely, primary contribution to span displacement at this bridge was the hydrodynamic load, or drag force, due to strong currents near the abutment. The presence of the abutment and approach embankment caused a local increase in velocity, with values exceeding 6 ft/s, near the displaced span. The velocity at the next highest westbound span, further from the abutment, was less than 5 ft/s. The drag force on the girders, barriers, and deck of the displaced span would have exceeded the full weight of the span by more than 30%, not accounting for reduced weight due to buoyancy. The drag forces on the other spans were all substantially smaller as shown in Table 2. Furthermore, the displaced span moved in the same direction as the velocity orientation (to the east). The adjacent eastbound span was also displaced laterally, but only by a few inches. It was at a higher elevation and therefore was less susceptible to large increases in flow velocity due to convergence under the bridge spans. The hydrodynamic loads on the eastbound span were approximately 42% of the span weight, or 73% of the reduced span weight. The drag force is the only contributing factor that explains why and how one span failed and the other adjacent spans did not. It also explains why the span was displaced to the east. While not definitive proof of the exact cause of failure, the large drag-induced hydrodynamic forces constitute a potential vulnerability not typically considered for coastal bridges.

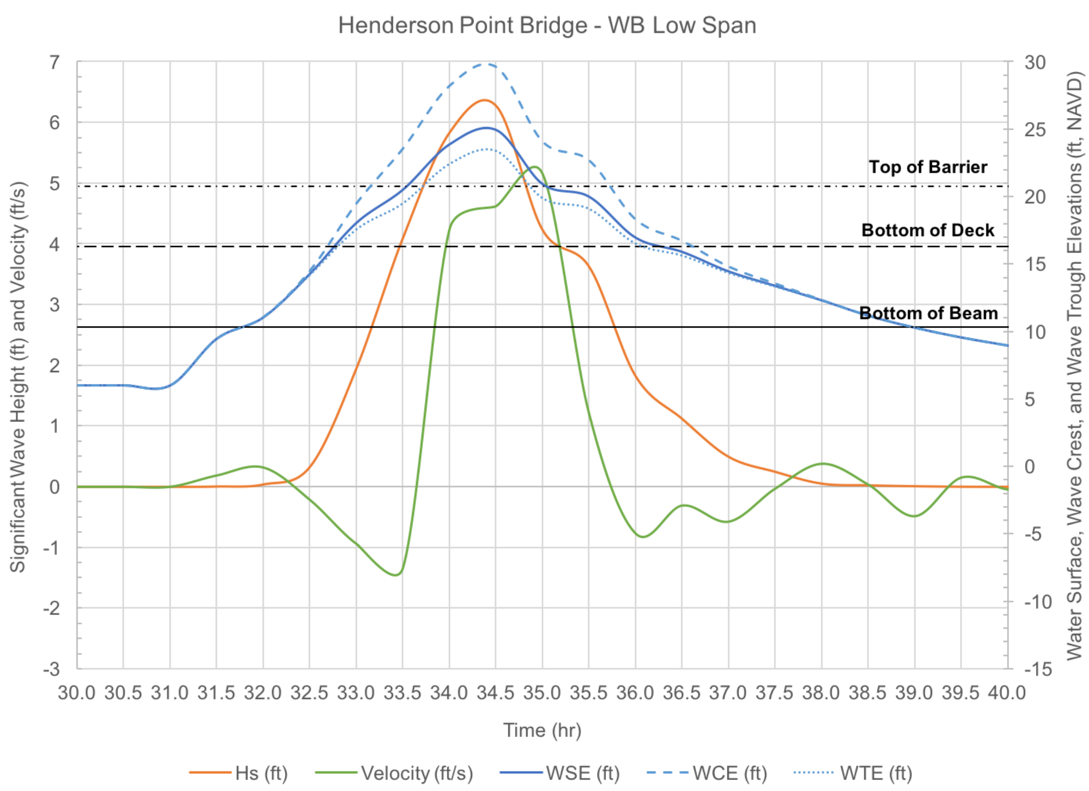

Figure 12. XBeach simulation results extracted near the bridge abutment during the hindcast of Hurricane Katrina. The Water Surface Elevation (WSE), Wave Crest Elevation (WCE), and Wave Trough Elevation (WTE) correspond to the vertical axis on the right.

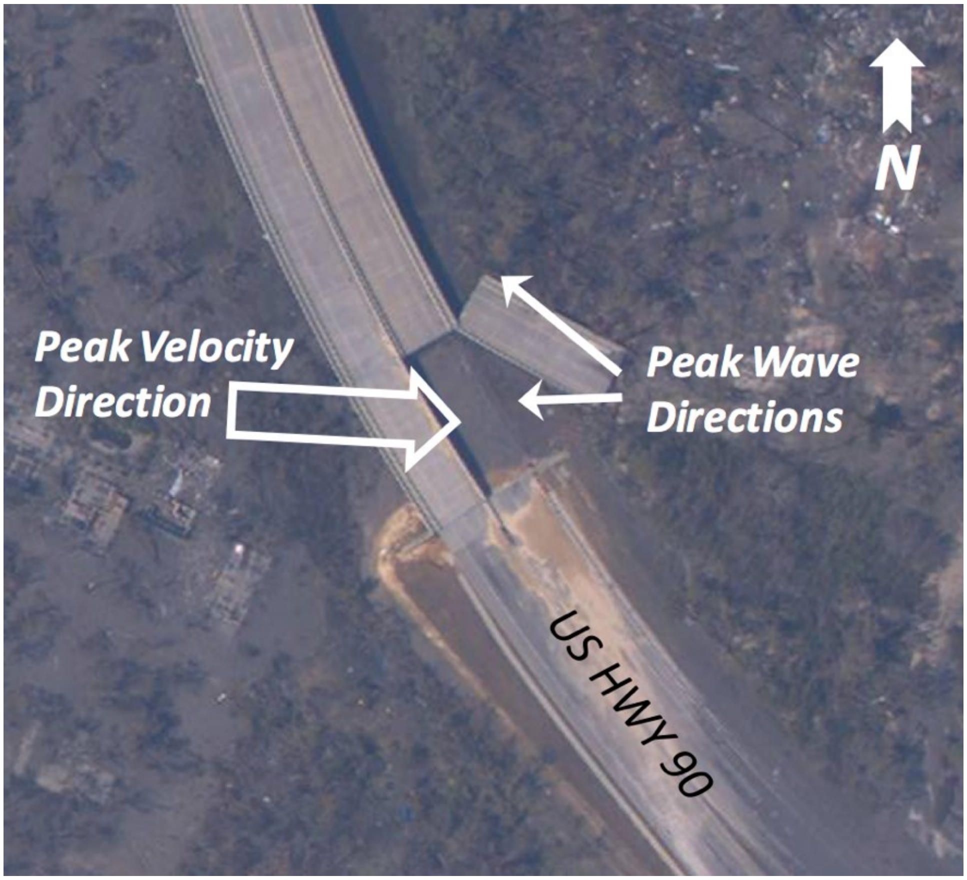

Figure 13. Maximum simulated wave and velocity directions during Hurricane Katrina. (Photo Credit: NOAA)

Table 1. Estimated maximum vertical and horizontal wave loads on the lowest six westbound spans (WBS) and eastbound spans (EBS) nearest to Pass Christian, MS.

Span ID	F_{vmax} (kips)	F_{hmax} (kips)
WBS1	***8534***	***6827***
EBS1	6354	6988
WBS2	7470	6822
EBS2	5281	6993
WBS3	6373	6782
EBS3	4139	6867

Table 2. Estimated maximum hydrodynamic drag forces (F_{max}) on the lowest six westbound spans (WBS) and eastbound spans (EBS) nearest to Pass Christian, MS. Also shown is the ratio of drag force to span weight (1525 pounds).

Span ID	F_{max} (kips)	F_{max} / Span Weight
WBS1	***2018***	***1.32***
EBS1	637	0.42
WBS2	978	0.64
EBS2	429	0.28
WBS3	679	0.44
EBS3	358	0.23

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3 Adaptation Options

This section of the report describes the adaptation options considered at an early phase of the project, before the exact damage mechanism had been identified. Some of the adaptations listed, therefore, would not necessarily address the flow-related failure mechanism explained in the previous section. However, all of the potential adaptations are briefly described including conventional gray solutions, green infrastructure solutions, combinations thereof, and the potential for non-structural (policy) solutions.

3.1 General Description

When the list of potential adaptation solutions for this bridge was first developed, it was unclear whether the failure mechanism was related to direct wave attack, buoyancy and/or trapped air effects, or hydrodynamic drag forces due to flowing water. A number of potential adaptations were identified in order to address the multiple, potential causes of failure. As a result of the failure analysis performed in this study, it appears likely that the primary cause of span displacement was the drag force. The preferred adaptation solution described in the next report section addresses this specific damage mechanism while accommodating the others (waves and trapped air) to a lesser degree.

3.2 Conventional Gray Solutions

A number of potential gray adaptation solutions have been proposed to address bridge failures during hurricanes, but to date only one has been used in practice: increasing the bridge elevation to avoid wave loads. The Henderson Point bridge was chosen specifically because increasing its elevation would not address the damage sustained during Katrina. The fact remains that all bridges (including their approach spans) must, at some point, pass through an elevation where it will be vulnerable to many different coastal hazards. Addressing this vulnerability, therefore, served as the motivation and focus of this pilot project.

An engineering adaptation study available on the FHWA website[4] describes a number of potential retrofits that could be used to increase the resilience of a coastal bridge in a setting similar to that of Henderson Point bridge, and exposed to many of the same hazards. The conventional gray adaptations described in that study include: increased connection strength; shear blocks; continuous span reinforcement; and modified bridge shapes. In that study, it was determined that strengthening one component of the bridge,

[4] https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/al_i-10/index.cfm

or its connections to the substructure, leads to a cascading failure whereby subsequent bridge elements fail. The ultimate conclusion was that some of these adaptation solutions could be combined with more moderate increases in bridge elevation, but only to address vulnerability during replacement or new construction. However, the findings of that study were specific to wave loads as the primary damaging mechanism. It is possible that some of these adaptation solutions may adequately address the specific vulnerability of the Henderson Point bridge to flow magnitude and direction.

Three conventional gray adaptation solutions were considered for the purpose of this study and they include:

- increased connection strength,
- shear blocks, and
- vented diaphragms.

Note that a full structural analysis was not performed for any of these adaptation options. The Henderson Point bridge already has more connection resistance between the bridge beams (girders) and pile bent beams than most simply supported bridge spans. It is unclear whether additional connections between the bridge and bent beams would substantially add to the existing resistance. Given that the westbound span appears to have simply been displaced laterally, shear blocks cast into the tops of the bent beams on either side of each bridge beam would prevent lateral movement of the span. This constraint could, however, lead to structural failures elsewhere in the span and a load path analysis would need to be performed. Finally, venting the span diaphragms would allow any trapped air to escape from below the deck and may help equalize any pressure differences that develop below and above the deck. Although the trapped air effect does not appear to be the primary reason for failure during Katrina, some studies suggest that it can play a role in span displacement (e.g., Bozorgnia et al., 2011; Bricker and Nakayama, 2014).

3.3 Green Infrastructure Solutions

Given the setting in which the Henderson Point bridge is found, a number of possible green infrastructure solutions may assist, in some way, in reducing the bridge's vulnerability to hurricane storm surge and waves. The adaptations considered here included:

- an expanded beach and dune system to the south,
- dense tree plantings to mimic a maritime forest,
- enhancements of the existing tidal marsh, and
- vegetated berm features.

A goal of this project was to identify an adaptation solution that could be implemented within the existing MDOT right-of-way, and one that required little to no routine maintenance. While all of the green adaptations listed above satisfy the latter constraint, only the vegetated berms could effectively satisfy the right-of-way limitation. Expanding the beach and dune system to the south would certainly improve the resilience of US HWY 90 before it reaches the bridge approach, but given the constraints listed above and the fact that it would not substantially address the failure mechanism identified, it was eliminated. Healthy tidal marshes and dense maritime forests have been shown to effectively reduce velocity and wave action, but to be effective those activities would need to take place well outside of the right-of-way and would likely require the purchase of additional land. Furthermore, the benefits of a maritime forest are not realized until many years after planting. A vegetated berm-like feature, however, could be constructed completely within the existing right-of-way, could be designed to address the flow-related failure mechanism, and would require little to no maintenance over time.

3.4 Hybrid Green-Gray Solutions

There are potentially some adaptation solutions that combine conventional methods with "greener" or "softer" solutions in a way that addresses the bridge's vulnerability to hurricane storm surge, currents, and waves. For example, the vegetated berm concept could be implemented in combination with shear blocks or diaphragm venting in order to address multiple potential failure mechanisms. The vegetated berms could likewise be reinforced internally, with a rock core or sheet pile wall, to provide additional resilience during wave attack.

Another potential hybrid adaptation solution would be to extend the approach embankment to the pile bent at the end of the lowest elevation spans. In this approach, the bridge spans and abutment would be left in their original configuration and earthen fill would be placed below and adjacent to the spans to continue the embankment to the next pile bent (Bent 18, STA 4+259). There are two potential limitations to this approach. First, the constructability would be difficult when trying to place fill below the bridge spans, particularly when trying to establish a continuous grade elevation below the spans and within the beams. Second, the footprint of the embankment would likely spread outside of the existing MDOT right-of-way prior to reaching the next pile bent (the right-of-way narrows to 125 feet total width about 53 feet before the next pile bent).

3.5 Non-Structural Solutions

Non-structural solutions were not considered as part of this adaptation assessment. The only potential policy solution would be to eliminate the bridge if it were to fail again in the future. However, eliminating the bridge would require a 24-mile detour by eliminating access to the US HWY 90 Bay St. Louis bridge.

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4 Adaptation Description

This section of the report provides a general description of the selected green infrastructure adaptation solution that best addresses the bridge's vulnerability while meeting the right-of-way and maintenance constraints. Other potential adaptations, like shear blocks, diaphragm venting, and the potential use of rip-rap around the abutment headwalls to protect the edge of pavement, are not described in this report.

4.1 Selected Adaptation Measure

The green infrastructure solution selected to improve the resilience of the Henderson Point bridge is a vegetated berm, or series of vegetated berms. The primary goal of the berms is to serve as a sort of training structure that redirects flow away from the bridge abutment and approach spans and toward the higher elevation spans. As demonstrated in the model results, the velocity decreases with distance from the abutment. Redirecting flow away from the abutment and to the higher elevation spans should also eliminate the flow convergence leading to higher velocities under the lower elevation approach spans. This flow convergence is shown in the model results of Figure 14. Given that the next set of spans are at higher elevations, they are not as susceptible to these drag-induced hydrodynamic forces, as shown in Table 2. The berms will also serve to induce wave breaking, leading to reduced wave loads on the bridge spans.

4.2 General Specifications

The vegetated berms suggested here would be constructed parallel and adjacent to the outside edge of each of the two lowest bridge spans (between the abutment and Bent 18). In order to maximize the potential for vegetation, the berms are designed to follow the edge of the spans instead of wrapping underneath the bridge spans where there would be little sunlight. The berm could be constructed completely of earthen fill or be reinforced with a core of rock suitable to resist wave attack during a storm event (1200 pound median weight, 2.5 foot median diameter). The berm's outside slopes (facing away from the bridge spans) would be stabilized with natural ground cover, native vegetation, and trees (Corcoran et al., 2010). Typical erosion control ground cover treatment for MDOT includes the use of Bermuda grass, Bahia grass, and/or tall fescue. Additional bank stabilization methods could be incorporated as is done to protect levees exposed to overtopping and waves (Hughes, 2008), but the existing approach embankment performed well with only native coverings. In lieu of using vegetation along portions of the berm under the bridge, use of stabilizing material such as geotextiles and stone or riprap will reduce the potential for erosion. The crest elevation of the berm would be set equal to or slightly below the lowest bridge beam elevations to aid in constructability. The berm side slopes would be 1:1.5 (V:H) in order to fit within MDOTs existing right-of-way. The crest width of the berms would be no less than 5 feet. Sketches of the berm locations and cross-sections are provided in Figure 15 and Figure 16, respectively.

The approximate berm dimensions were used to estimate material quantities and costs. Assuming a variable crest height that follows the low chord elevation of the bridge, and the 1:1.5 side slopes, the volumes of the berms along the westbound and eastbound spans would be approximately 330 and 1100 cubic yards (cy). These volumes were estimated using the average end-area method and were assumed to run the full 125-foot length of the spans. Using an estimated unit cost for truck-hauled fill of $15/cy, the material cost for fill would be less than $22,000. Using a rock core would substantially reduce the volume and cost of fill material, but would cost substantially more due to the higher unit cost of rock. The estimated incremental cost difference for using a rock core is approximately $100,000.

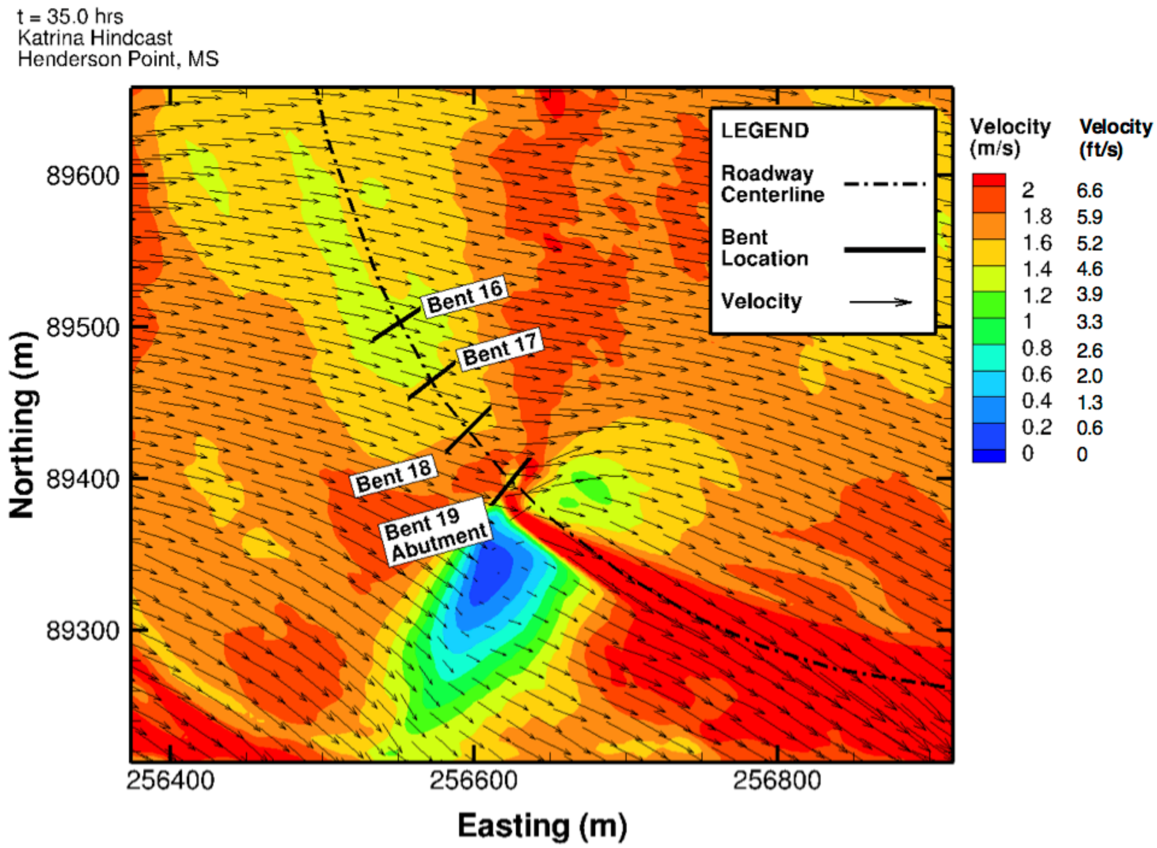

Figure 14. XBeach hydrodynamic model results showing maximum flow velocity magnitude (colors) and direction (vectors) in the bridge vicinity. The span that failed was in between Bent 18 and Bent 19 to the right of the roadway centerline.

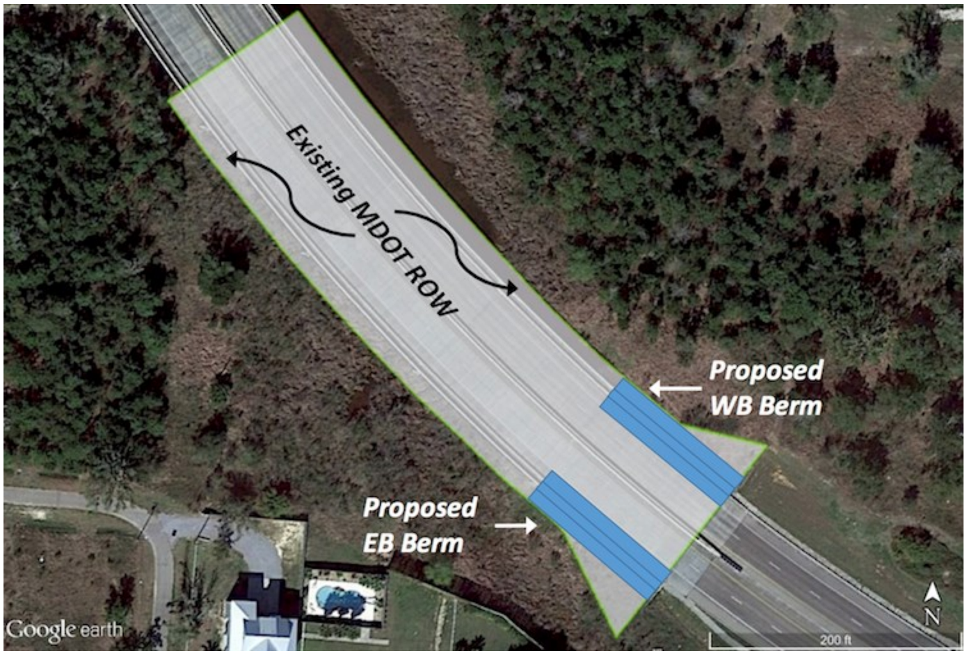

Figure 15. Overview image showing MDOTs existing right-of-way and the locations of the proposed berms adjacent to the lowest spans. (Photo credit: Google Earth; Map©2018Google)

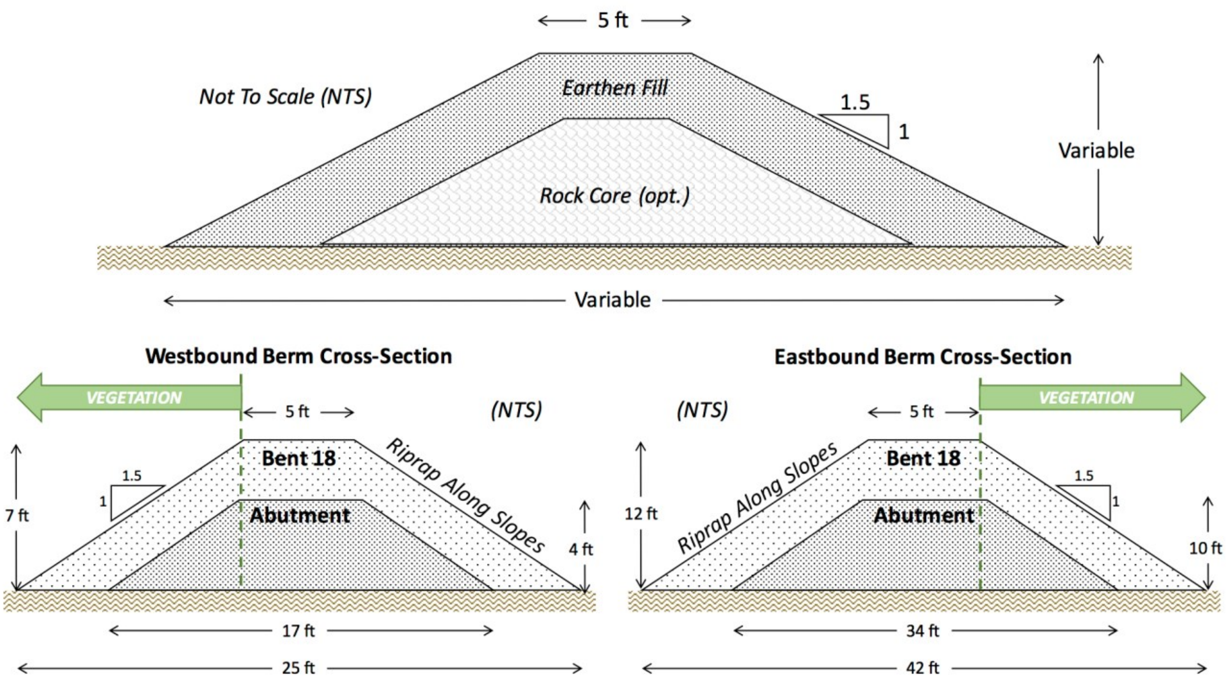

Figure 16. Approximate cross-section sketches and dimensions of the vegetated berms adjacent to the westbound and eastbound spans.

5 Benefits

This section of the report describes the overall benefits of the proposed green infrastructure adaptation. The benefits described here include the anticipated level of protection that the adaptation provides, the corresponding reduction in vulnerability, and potential life-cycle costs.

5.1 Level of Protection

The typical design event for this bridge is a 50-yr return period (2% annual chance) storm. The storm event evaluated as part of this adaptation assessment is somewhat beyond a 100-yr return period (1% annual chance) event based on the storm surge elevation alone. Conservatively, the berms should provide a level of protection that would prevent similar damage during a future 100-yr return period storm event. The fact that this adaptation addresses a higher return period storm event (100-yr > 50-yr) than would typically be used provides some adaptive capacity to address the uncertainty in future sea levels or changes in storm intensity and/or frequency.

5.2 Vulnerability Reduction

The selected adaptation solution will reduce the vulnerability of the bridge to hurricane storm damage and the effects of relative sea level rise. Assuming that the current bridge was designed to survive a 50-yr return period event, and that the expected life of the bridge is 50 years, the likelihood of failure during the bridge's 50-yr design life is reduced from 64% to 39%. In other words, the reliability of the system increases from 36% to 61%. The enhanced resilience of the bridge is likely justifiable given the cost of the berms relative to the repair costs following Katrina, or complete replacement costs for total failure. Per the Mississippi DOT Construction Division, post-Katrina repair costs for the Henderson Point bridge were approximately $1,945,700.

5.3 Potential Life-Cycle Costs

Initially, new vegetation and trees will need regular watering to ensure root growth and development. This can be accomplished via a pumper truck from the outer lanes of either bridge span. Seasonal mowing and occasional weed abatement will be needed, but otherwise the vegetated berms should be self-maintaining after establishment. No additional or special maintenance measures are anticipated with this project.

It is possible that repair or replacement of the berms may be necessary at some point over the life span of the bridge, although magnitude and frequency of such needs are not predictable. The berms could be damaged by extreme weather events or other unforeseen circumstances. The optional rock core incorporated into the design would mitigate the need for substantial repair or replacement.

6 Implementation Considerations

The potential implementation challenges, anticipated maintenance requirements, and regulatory considerations related to the proposed green infrastructure adaptation are described in the following sections. In general, the green infrastructure would provide positive benefits without the need for impacting existing tidal wetlands near the bridge and right-of-way.

6.1 Potential Challenges

Since the proposed adaptation solution is situated completely within MDOTs existing right-of-way, there are few external challenges to its implementation. There are tidal wetlands near the bridge site, but there are none within the footprint of the proposed berms. There is also an adjacent conservation area to the east of the bridge, but it is well beyond the existing MDOT right-of-way. There may be some constructability challenges related to working completely within the right-of-way, and the placement of fill beneath the existing spans will require special equipment. Also, in order to remain completely within the right-of-way, only one-half of the berm will be outside of the edge of the span and receive direct sunlight—the other half will be under the span and cannot be vegetated. If additional right-of-way easement were available, the berms could be shifted laterally away from the edges of the span in order to provide more area for vegetation. Alternatively, the portion of the berm under the spans could be replaced with a mechanically stabilized earth (MSE) wall. This would solve the soil stabilization and constructability issues, but may lead to higher implementation costs.

6.2 Anticipated Maintenance

As previously described, the anticipated maintenance of the vegetated berm is very low after grass, plant, and tree establishment. Aside from staying within the right-of-way, MDOT also requested a solution with no to low long-term maintenance costs. Seasonal mowing and occasional weed abatement will be needed, but there are already crews performing similar work along the approach embankment slopes. Some occasional trimming of tree limbs may also be required to prevent interference with the spans and/or sight distances. Also, maintaining adequate clear space for drainage of the bridge deck will be an important consideration, and deck scuppers and drains may need to be modified so that drainage does not negatively impact the vegetated berms.

6.3 Regulatory Compliance & Permitting

A Section 404 (Federal Clean Water Act) permit from the United States Army Corps of Engineers (USACE) and General Permit from the Mississippi Department of Marine Resources (DMR) are anticipated with this project. Application for these permits will be coordinated by MDOT Environmental Division and submitted by way of the Joint Application and Notification through DMR. The application should be submitted at least 120 days prior to advertising for this project. A Wetland and Other Waters Assessment will need to be completed using the MDOT reporting template and included in the application.

Section 401 certification may be required in conjunction with any Section 404 permits. In such a case, MDOT Environmental Division will coordinate securing Section 401 certification through the Mississippi Department of Environmental Quality (MDEQ).

It is unknown whether wetland mitigation will be necessary, but this will be addressed as needed. Wetland permitting will be coordinated between MDOT Environmental Division and the Department of Marine Resources (DMR), again as needed. There are currently no wetlands within the proposed berm footprint, but an assessment on potential impacts to nearby tidal wetlands would need to be performed in a future engineering design and permitting phase of the project.

As dictated by the size and nature of the construction project and associated disturbed area, a National Pollutant Discharge Elimination System (NPDES) construction permit will be needed. The MDEQ administers the NPDES program for the State of Mississippi, while the MDOT Environmental Division oversees compliance with the NPDES Program as it applies to MDOT projects. A Storm Water Pollution Prevention Plan (SWPPP) is required under construction storm water general permits. The purpose of a SWPPP is to identify possible pollutant sources to storm water and to identify Best Management Practices (BMPs) that, when implemented, will reduce water quality impacts. The SWPPP is a living document and must reflect actual on-the-ground conditions at all times. For MDOT projects, the SWPPP is typically supplied and updated by the contractor, along with any erosion control plans as supporting documentation of that SWPPP.

Section 9 and 10 Navigable Waters Permits (Rivers and Harbors Appropriation Act) are not expected to be applicable to this project.

MDOT Environmental will coordinate with United States Fish & Wildlife Service (USFWS) for this project. The findings of the USFWS review will be provided along with the DMR submittal and incorporated in project design and construction.

6.4 Estimated Impacts

The vegetated berms are not expected to have negative impacts. They will not interfere with tidal wetlands near the bridge, nor will they negatively impact existing ground cover or established vegetation communities along the bridge alignment. Most of the existing ground cover is dominated by weeds and low shrubs.

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7 Next Steps

The following sections describe additional actions that MDOT intends to take or is considering taking regarding the green infrastructure adaptation solution proposed here. Also provided are brief comments regarding other climate adaptation practices and issues that MDOT is currently using or considering.

7.1 Selected Adaptation Option

MDOT has been involved in this green infrastructure proposal for Henderson Point and is considering its implementation. Should implementation be further pursued, these preliminary investigations would be expanded through a more comprehensive engineering analysis and design phase. The additional engineering analysis would include, at a minimum, a hydrodynamic simulation to evaluate the potential impacts of the berms and redirected flows on adjacent areas and bridge components, as well as their effectiveness in reducing the flow related hazard. Potential changes in water levels, waves, and scour would also be evaluated in this analysis. The analysis results would further be used to evaluate the stability of the berm itself, including the ability of coverings and/or reinforcements to resists shear stresses and wave action.

7.2 Climate Adaptation

MDOT considers climate adaptation in some design procedures. Sea level rise is currently considered in hydraulic design performed in coastal areas. Updated rainfall data are utilized in determination of design flows for hydraulic analysis and design.

With respect to sea level rise, MDOT uses the information and guidance provided in HEC-25 (FHWA, 2008) and HEC-25 Volume 2 (FHWA, 2014). These documents are used by MDOT in the planning, design, evaluation, and vulnerability assessment of highways and bridges in coastal environments. As described in HEC-25 Volume 2, MDOT evaluates future projections of relative sea level rise as part of their transportation design process.

7.3 Use of Green Infrastructure

MDOT utilizes green infrastructure elements in some aspects of construction and design. Examples of such infrastructure include:

- Vegetated ditches and grassing for erosion control,
- Vegetated buffers for sediment control,

- Vegetated riparian zones for stream stability, and
- Longitudinal fill stone toe protection.

MDOTs main coast parallel highway, US HWY 90 or Beach Boulevard, is the beneficiary of green infrastructure protection. Since 1951, Beach Boulevard has been protected by a 26.5-mile-long beach nourishment project consisting of nearly 6 million cubic yards of sand dredged from Mississippi Sound. The resulting 265-foot-wide beach now covers the reinforced concrete stepped revetment previously constructed during the years 1924 to 1930.

8 Lessons Learned

There were some significant lessons learned during this adaptation study. First, we believe that the span displacement at Henderson Point bridge may be the first known example of a bridge that failed not due to waves or buoyancy, but rather due to drag-induced hydrodynamic forces resulting from very strong currents near the abutment. This could explain the cause of damage for some other bridge spans that failed during hurricanes, particularly those protected from considerable wave action, but additional research would need to be performed in order to confirm this suspicion. Second, identification of the drag-induced failure mechanism was only possible due to the application of multiple hydrodynamic models at varying scales of resolution. To our knowledge, this is the first time that the models ADCIRC, SWAN, and XBeach have been used in combination to evaluate the vulnerability of a coastal bridge. Finally, we believe that similar approaches could be used, perhaps in combination with conventional adaptations like shear blocks, to increase the resilience of low-elevation spans. The use of vegetated berms, and opportunities to reinforce them to serve as breakwaters, is something that should be explored further as a potential adaptation option. The ability to apply levee slope protection techniques, like turf reinforcement mats, to vegetated berms should also be considered.

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