A METHODOLOGY FOR DEVELOPING RISK-CONSISTENT DESIGN CRITERIA FOR COASTAL STRUCTURES EXPOSED TO MULTIPLE HAZARDS

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Abstract

A multi-hazard risk assessment approach is proposed for developing design criteria for structures subjected to hazards posed by hurricane wind speed and storm surge. The approach incorporates state-of-the-art hurricane simulation science, hydrology, probabilistic methods, and structural engineering, and involves the following steps: (1) simulation of a stochastic set of tracks and characteristics of hurricanes affecting the region of interest, and development of wind speed time histories at sites affected by those hurricanes, (2) hydrodynamic simulation of the region of interest, using the information of Step 1, and development of corresponding time histories of storm surge heights at those sites, and (3) use of wind speed and storm surge height time histories to develop (a) probabilistic information on joint wind speed/storm surge height hazards at a site, and (b) corresponding risk-consistent structural design criteria.

Introduction

Hurricane Katrina caused extensive damage to numerous coastal structures across Alabama, Mississippi, and Louisiana, including many major coastal highway and railroad bridges [NIST TN 1476, 2006]. Most structural damage to bridges involved the displacement and/or loss of superstructure spans and was caused primarily by the direct effects of storm surge. High storm surges induced dynamic lateral wave forces, uplift forces due to buoyancy, and horizontal impacts from floating barges and other debris acting on the superstructure and substructure of the bridges.

Instances of damage to major bridges caused by the direct effects of storm surge hazard include the I-10 twin span bridges, which carries traffic between New Orleans and areas north over Lake Pontchartrain in Louisiana, and the US-90 bridge in Biloxi, which carries traffic along the coast in the East-West direction between Biloxi and Ocean Springs over the Bay of Biloxi. These bridges were similarly constructed, with superstructures comprised of single concrete spans fabricated offsite and transported by barge for erection on the piers. Each span was a monolithically cast system consisting of a concrete deck, fascia section, and I-section concrete girders. Each span was simply supported on the piers

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through steel bearing plates that provided some restraint against displacement in the longitudinal direction but little, if any, restraint against transverse or vertical displacement (except for gravity). The superstructure spans of these bridges that were exposed to the direct effects of storm surge (surge-induced lateral wave and uplift forces) were either shifted severely out of alignment or dropped completely into the water due to the lack of restraint against these displacements. Figure 1 shows the I-10 twin span bridges, which lost a total of 64 spans and had 473 spans shifted out of alignment. Figure 2 shows the US-90 Biloxi-Ocean Springs bridge with many individual spans either partially or completely dropped into the water.

In contrast, bridges with additional engineering features that provide restraint against lateral and vertical displacements, despite being exposed to the same direct effects of storm surge caused by Hurricane Katrina, performed well and sustained only minor, nonstructural damage with none of their superstructure spans lost or misaligned. These include the US-11 highway bridge and the Norfolk Southern railroad bridge, which also carry traffic over Lake Pontchartrain and are in close proximity to the I-10 twin span bridges, and the CSX Biloxi-Ocean Springs railroad bridge, which carries railroad traffic over the Bay of Biloxi and is in close proximity to the US-90 highway bridge. The US-11 bridge's deck, girders, and piers were cast in place and the connections between the girders and piers were monolithic, thus providing positive connection between the superstructure and the piers (see Figure 3). The Norfolk Southern bridge's superstructure consists of a concrete deck supported by pre-stressed concrete box girders, and is simply supported on concrete piers with shear block detailing at each end to provide restraint against lateral displacement (see Figure 4). Similarly, the CSX bridge's superstructure is comprised of simply supported spans, each consisting of a concrete bridge deck cast on top of four pre-stressed concrete girders with I-sections. The four girders are further tied together by threaded bars. Each span is supported on the cap beam of the piers and confined and restrained from transverse displacement by two 15 in. (38 cm) high concrete shear blocks on both ends of the cap beam (see Figure 5).

It is not known why some of the bridges in the region were designed to have simple yet effective engineering features that allow them to resist, besides the conventional service and wind loads, additional hazards posed by direct effects of storm surge, while others in close proximity and thus exposed to the same multi-hazard conditions were not. What these instances of poor and successful performances clearly illustrate is the need for engineers to be informed of the risks posed by the combined effects of multiple hazards, such as extreme wind load and high storm surge in addition to the conventional service loads. Knowing the risks posed by multiple hazards allows the engineers to balance the importance of the structures with the risks and to design for them accordingly.

The design of structures in coastal high hazard areas is currently governed by ASCE 7-05 Minimum Design Loads for Buildings and Other Structures [ASCE, 2005] for wind loads, and ASCE 24 Flood Resistant Design and Construction [ASCE, 2006] for

resistance to flood, including high-velocity wave action. ASCE 7 provides contours of basic wind speeds (3-s peak gusts at 33 ft (10 m) over open terrain) for both non-hurricane and hurricane winds. Non-hurricane winds are based on a nominal 50-year mean recurrence interval (MRI) and hurricane winds are based on longer MRIs dependent on location. ASCE 24 specifies the elevation and foundation requirements for buildings and other structures. Neither ASCE 7 nor ASCE 24 addresses the combined effects of hurricane wind speed and storm surge as a design condition in a risk consistent manner.

Special design criteria that consider the combined effects of wind speed and storm surge have been developed and used in the past for special structures. The New Orleans flood protection system was designed on the basis of design criteria requiring that it resist the loads inherent in the Standard Project Hurricane (SPH). The SPH, developed in 1957 on the basis of analyses of hurricanes of record (from 1900 to 1956), is defined as the most severe hurricane that is considered reasonably characteristic of a region. For the New Orleans, Mississippi region, the SPH has a specified central barometric pressure of 27.6 in (935 mb) of mercury, a peripheral pressure of 29.92 in (1013 mb) of mercury, a maximum sustained wind speed of 110 mph (49 m/s) at 30 ft (9.1 m) elevation, a radius of maximum winds of 30 miles (48 km), a forward speed of 15 mph (6.7 m/s), and a storm surge of up to 12 ft (3.65 m). The level of risk inherent in the SPH is not known. The fact that Hurricane Katrina, with estimated maximum sustained wind speeds of approximately 125 mph (55.9 m/s, consistent with a category 3 hurricane on the Saffir Simpson Hurricane Scale) and maximum storm surge heights of approximately 28 ft (8.5 m) (9 ft to 10 ft (2.7 m to 3.0 m) estimated for New Orleans) [NIST TN 1476, 2006], clearly shows that (1) storm surge heights can substantially exceed those listed in the S/S HS for a given hurricane category, and (2) the SPH is inadequate as a design criterion for protection against possible combinations of hazards posed by high wind speed and storm surge.

Thus, at present there is a lack of risk-consistent design criteria for structures in coastal regions subjected to hurricane wind and storm surge. Such risk-consistent design criteria should be developed by accounting for annual probabilities of exceedance of joint wind speed/storm surge events. This requires consideration of the effects of local topography and bathymetry, on which storm surge at any specific location is highly dependent. The methodology for accounting for annual probabilities of exceedance of joint wind speed/storm surge hazards in coastal regions, which is the focus of this paper, constitutes a multi-hazard risk assessment approach based on which the risk-consistent design criteria for coastal structures can be developed.

Proposed Methodology for Multi-Hazard Risk Assessment for Coastal Structures Affected by Hurricanes

The proposed methodology for assessing combined risks posed by hazards due to hurricane wind and storm surge and for subsequent development of risk-consistent design criteria entails three steps:

1. *Simulation and selection of hurricane storm tracks and characteristics.* A stochastic set of hurricane storm tracks is generated, each hurricane being characterized by a set of climatological parameters, including pressure defect, radius of maximum wind speeds, and its track.

2. *Hydrodynamic simulation to generate time histories of wind speeds and storm surge heights.* Time histories of wind speeds and storm surge heights at a site are generated using an appropriate storm surge model and software. For the case studies presented herein, the software SLOSH (Sea, Lake, and Overland Surges from Hurricanes) [Jelesnianski et al., 1992] will be used. The selected hurricanes in step 1 are used to prescribe the environmental conditions in the simulation. In addition to the time histories of wind speeds and storm surge heights, SLOSH also generates time histories of wind direction to allow for consideration of wind directionality. In this work the time histories were saved at 5-min intervals, so that no significant wind speed peaks are likely to be missed, without resulting in an unduly large amount of data.

3. *Use of simulated hurricane wind speed and storm surge data (Steps 1 and 2) to develop probabilistic descriptions of joint wind speed/storm surge height events and their effects.* Joint histograms of wind speeds and storm surge heights are developed using the simulated time histories of the wind speeds and storm surge heights. The joint histograms, and the historically-based mean annual hurricane arrival rate at the site, are used to estimate probabilities of exceedance and corresponding MRIs of the joint wind speed/storm surge height events at that site. In addition, a design criterion is proposed based on probabilistic descriptions of wind effects induced by simultaneous wind speed/storm surge events.

The above steps are discussed in further detail in the following sections. In this paper, the proposed methodology is applied to five sites in Tampa Bay, Florida because hurricane simulations needed to characterize the storm environments in Step 1 were available through the Florida Public Hurricane Loss Model simulations (FPHLM, Version 1.0) [Powell et al., 2005]. These sites include: (1) Port of Tampa (N27.949/W82.445); (2) Clearwater Beach (N27.977/W82.829); (3) St. Petersburg Beach (N27.726/W82.744); (4) St. Petersburg on Tampa Bay (N27.754/W82.631); and (5) MacDill Air Force Base (N27.851/W82.510) (see Figure 6).

Simulations of Storm Tracks, Wind Speed, and Storm Surge Height

Hurricane Storm Tracks Simulation. The FPHLM uses the concept of threat area to best capture the statistical characteristics of historical tropical cyclones that have affected the state. The threat area is divided into regions which contain the historical and seasonal characteristics of storm motion and intensity change. Genesis location, intensity, and motion for each storm are based on the geographic probability distributions of each

quantity for a given time within the season. A stochastic approach was used to model the storm genesis location, track, and intensity evolution. A probability distribution function (PDF) for the initial storm position is derived from the historical "genesis" data. Here genesis is defined as the time when the storm (tropical depression, tropical storm, or hurricane) forms in or first appears in the threat area. Discrete PDFs based on historical data provide the initial and subsequent motion and intensity of the storm. A storm is simulated by repeatedly sampling from these PDFs via a Monte Carlo approach. Once the storm has been given an initial condition, its evolution is governed by sampling the PDFs for change in intensity, change in translation speed, and change in heading angle in 6 hour increments. The time step is reduced to 1 hour when the storm is close to the coastline.

The change in intensity (difference between the central minimum sea level pressure and an outer peripheral pressure, assumed to be 1013 mb in our model) is modeled by using the observed geographic probability distribution of six-hour changes of central pressure as related to the relative intensity, and is limited so as to not exceed the maximum observed change for a particular geographic region. When a storm center crosses the coastline (landfall) the intensity change follows a pressure decay model. The PDFs for change in speed and direction depend on the current speed and direction, as well as geographic location and time of season. The radius of maximum wind at landfall is modeled as a function of latitude and minimum central barometric pressure P_{min} using a database constructed from a variety of landfall data, including [Ho et al., 1987; DeMaria et al., 2002], and NOAA Hurricane Research Division archives.

To capture hurricane tracks from the FPHLM that affect the selected sites, a 25 mi (40 km) buffer was established around the basin. The total number of tracks identified to cross inside this buffer was 23,166 of the 103,000 tracks in the 55,000 year simulated track dataset. From these, 19,806 tracks corresponding to hurricanes significant from a structural engineering viewpoint were selected. Figure 7 shows a portion of one of the storm tracks selected from the FPHLM model (track number 17526) with its wind field entering the area of interest in the Tampa Bay basin. Additional details on hurricane storm tracks simulation may be found in [Phan et al., 2007].

Wind Speeds and Storm Surge Heights Simulation. Time histories of wind speeds and storm surge heights, at 5 min intervals, at the five selected locations in Tampa Bay caused by the 19,806 hurricanes are simulated using the SLOSH model. SLOSH is a dynamic, two-dimensional numerical model developed by the NWS to estimate tropical storm surge flooding. SLOSH works from high resolution curvilinear polar, elliptical, or hyperbolic grids separated into 41 unique basins across the Gulf of Mexico, eastern seaboard, the Bahamas, Puerto Rico, and Hawaii. Each type of grid is mapped conformally onto a Cartesian type of grid using the relevant map factors and Jacobian. This grid-based coordinate system provides finer mesh near the pole point and becomes coarse at outer boundaries. As a result, high resolution data for areas of interest along the coast and inlet bays are available. Additionally, sub-grid elements such as channels, barriers, and rivers

are modeled to improve calculated surge values during processing. Storm surge is calculated by solving shallow water equations derived from the transport equations of motion and the continuity equation based on input such as topography, bathymetry, and storm track which includes change in pressure, radius of maximum winds (R_{max}), location, wind direction and wind speed [Jelesnianski et al., 1992]. Parameters not modeled in SLOSH at present include astronomical tides, rainfall, river flow, and wind-driven waves. Figure 8 shows a typical result of SLOSH simulation which indicates the effect, at one point in time, of hurricane track number 17544 on the Tampa Bay basin.

Probabilistic Descriptions of Joint Wind Speed/Storm Surge Hazards

Joint Histograms of Wind Speeds and Storm Surge Heights. The same hurricanes were considered for all five sites, since the distances between those sites are sufficiently small (less than 20 mi (32 km), see Figure 6). Let n denote the number of simulated hurricane storm tracks being considered (in this study $n=19,806$). For each hurricane h_i ($i=1,2,…,n$) hydrodynamic simulation using SLOSH yields time histories of the wind speed v_{ij} and storm surge height s_{ij} for all five locations (j is the index that denotes the number of time intervals; the corresponding time is $t_j = j\Delta t$, where Δt is a 5-min time interval). Under the effect of the same hurricane h_i, the wind speeds v_{ij} and the storm surge height s_{ij} differ from site to site owing to the respective topographies and bathymetries. Thus, for hurricane track h_i, a data pair consisting of the maximum wind speed $v_{i,max} \equiv \max_j(v_{ij})$ and the maximum storm surge height $s_{i,max} \equiv \max_j(s_{ij})$ at a site can be extracted from the simulated time histories of wind speed and storm surge height. Note that the speed $v_{i,max}$ and the storm surge height $s_{i,max}$ generally do not occur at the same time during the life of hurricane h_i. Therefore, designing under the assumption that they occur simultaneously would result in conservative designs. For the n selected hurricanes, data pairs $v_{i,max}$, $s_{i,max}$ ($i=1,2,…,n$) can be similarly extracted for each site of interest from the results of n SLOSH simulations. Next, the data pairs $v_{i,max}$, $s_{i,max}$ ($i=1,2,…,n$) for each site are rank-ordered based first on decreasing values of $v_{i,max}$ and then on decreasing values of $s_{i,max}$. An example of the data pairs of wind speed and storm surge height occurring at a site after rank ordering based on $v_{i,max}$ is shown below.

$v_{i,max}$ (1-minute m/s)	$s_{i,max}$ (m)
70	6
70	5.5
68	6
68	5.3
65	5.5
65	4.7
60	5.0
55	4.5
…	…

For each site, a joint histogram that includes the above *n* pairs of peak wind speed/storm surge height data can be constructed. These data pairs occur during the time interval T=55,000 years associated with the *n* hurricanes. Figure 9 shows typical joint histogram of peak wind speeds/storm surge heights that can be expected to occur at the Port of Tampa site. Note that the histogram for each site is unique for the site owing to local topography.

Joint Annual Probabilities of Exceedance.   From the above histograms, estimates of the annual probability of exceedance, denoted by $P(V>v, S>s)$, of the joint event with wind speed $V > v$ and storm surge height $S > s$, can be obtained by (1) counting the number of data pairs with wind speeds greater than *v* and storm surge heights greater than *s* in each of the joint histograms, (2) dividing that number by the total number of data pairs, *n*=19,806, and (3) multiplying the outcome by the mean annual hurricane rate of occurrence λ, where $\lambda = n/T = 19,806/55,000 = 0.3601$ hurricane/year. A plot of the estimated joint annual probability of exceedance of events *v,s* is shown in Figure 10 (for additional plots see Phan et al. (2007)). Each contour plotted on the wind speed/storm surge height plane indicates wind speeds and storm surge heights for which the estimated joint annual probabilities of exceedance has the same value.

MRIs of Joint Wind Speed/Storm Surge Events.   The MRI in years, of event *v,s*, (i.e., the average time between the occurrence of a wind speed of at least *v* and a storm surge of at least *s*) for each site is the inverse of the bivariate joint annual probability of exceedance for the respective site.   Port of Tampa MRIs corresponding to various joint wind speed/storm surge height events (*v, s*) are shown in Table 1. It should be noted again that, because the wind speeds and storm surge heights considered in these estimates do not occur simultaneously, their combination for structural design purposes would result in conservative designs. However, the MRI of a wind speed/storm surge pair is a useful measure of the probability of occurrence of that pair at the same site and during the same hurricane. Note also that estimates of storm surge height at a site are influenced not only by the maximum wind speed, but also by the hurricane's central barometric pressure, radius of maximum wind speed, and speed and direction of its forward motion. This explains why hurricanes with Category 3 wind speeds can produce storm surge heights as high as 29 ft (8.8 m), as was the case for hurricane Katrina. As noted earlier, storm surge height at a site also depends strongly on the site's geographical position, bathymetry, and topography. This explains why the ordinates of the joint distributions estimated as shown herein do not necessarily increase monotonically as either the wind speed or the storm surge height increases.

Proposed Design Citerion for Coastal Structure Subjected to Combined Effect of Hazards due to Wind and Storm Surge

From the MRI tables such as Table 1 for any given site, the design criterion for structures at that site (which, as indicated previously, is conservative) can be established as

follows:

"Ordinary structures shall be designed for the effects of load combinations calculated on the basis of wind speed/storm surge height events with 50-year MRI if the Allowable Stress Design method is used, or with 500-year MRI if the Load and Resistance Factor Design method is used. Special structures shall be designed for load combinations consistent with wind speed/storm surge height events with MRIs determined by the authority having jurisdiction."

Summary and Conclusions

A methodology for developing risk-consistent design criteria for use in designing coastal structures subjected to the combined effects of hazards posed by wind speed and storm surge is proposed. The methodology requires, as a first step, the selection of a set of stochastic hurricanes that affect the area of interest. For this step, the existing FPHLM was utilized. The next step involves hydrodynamic simulations for the basin of interest. For this step the program SLOSH, with the simulated hurricanes in the previous step as input, was used to develop time histories of wind speeds and storm surge heights for the sites within the basin. The final step involves the application of probabilistic methods to time histories of wind speed and storm surge height to produce estimates of joint probabilities of exceedance and MRIs of wind speed/storm surge height events, and a corresponding risk-consistent and site-specific framework for the development of design criteria for the combined effect of wind speed and storm surge.

The proposed methodology provides a state of the art approach to establishing engineering design criteria for the design of coastal structures or other engineering systems, including systems located in the coastal high hazard zones defined by the FEMA's FIRM map and subjected to the combined effect of hurricane wind speed and storm surge. However, the methodology has the following limitations:

The methodology is applicable only if a stochastic set of hurricane storm tracks and a current hydrodynamic model of the area of interest (SLOSH basins) are available. For the State of Florida, both of these exist, thus design criteria can be developed for the State of Florida using the methodology developed here. Even for Florida the possible evolution in time of the bathymetry of the sites needs to be taken into consideration. Furthermore, changes to the terrain, including both dunes building during beach restoration projects and destruction due to hurricane will impact the surge results. For other regions along the eastern seaboard and the Gulf coast, while hydrodynamic models of various basins exist, a public stochastic hurricane simulation model similar to the State of Florida FPHLM may not be available.

The hydrodynamic simulations performed in this study using SLOSH did not consider the effect of waves and tides, both of which would increase the total water levels.

Subsequent studies will need to investigate the feasibility of incorporating wave modeling and consider the effect of tides in the hydrodynamic simulation, and to compare results with other simulation tools such as the Advanced Circulation Model for Oceanic, Coastal and Estuarine Water (ADCIRC).

For simplicity, wind directionality was not considered in this work, even though time histories of wind direction can be obtained from the hydrodynamic simulation by SLOSH. This factor needs to be addressed in a subsequent phase of this study.

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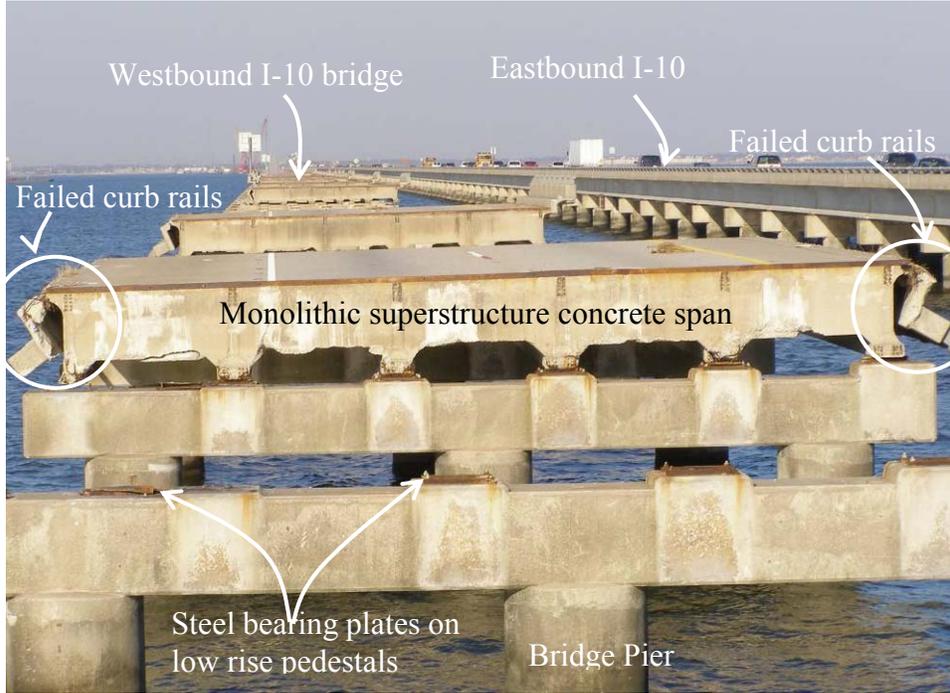
Figure 1. View Looking North from West Abutment of I-10 Twin Span Bridges over Lake Pontchartrain (photo credit: NIST)

Figure 2. US-90 Biloxi-Ocean Springs Highway Bridge with Superstructure Spans Displaced North Off Their Piers (photo credit: J. O'Connor, MCEER).

Figure 3.   Cast-in-Place Concrete US-11 Bridge over Lake Pontchartrain (photo credit: J. O'Connor, MCEER).

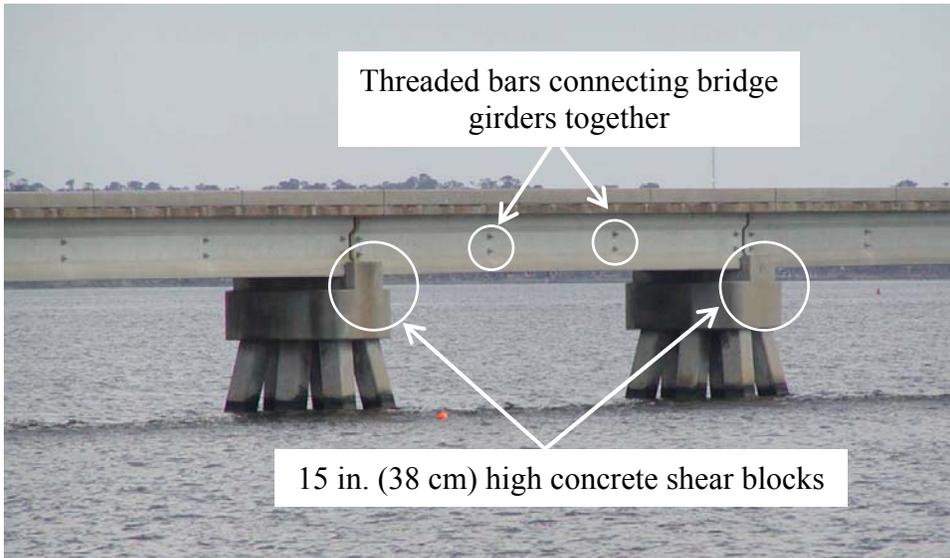Figure 4.   Norfolk Southern Railroad Bridge over Lake Pontchartrain (photo credit: J. O'Connor, MCEER).

Figure 5.   The CSX Railroad Bridge Survived with Minor Damage, Likely Due to the Presence of High Shear Blocks (photo credit: LA DOTD).
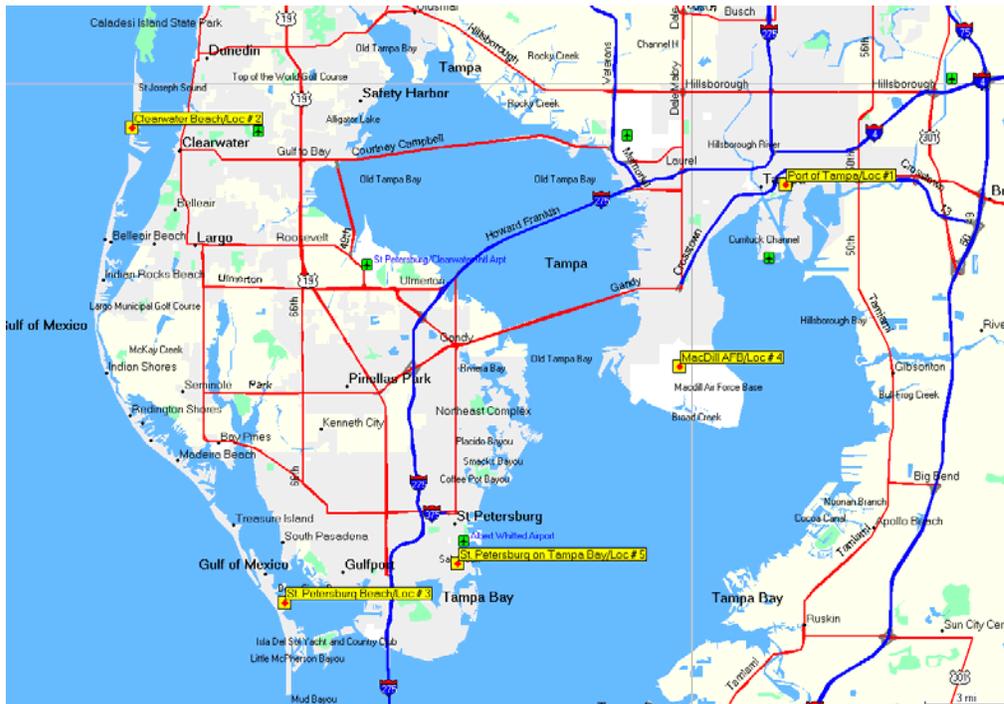

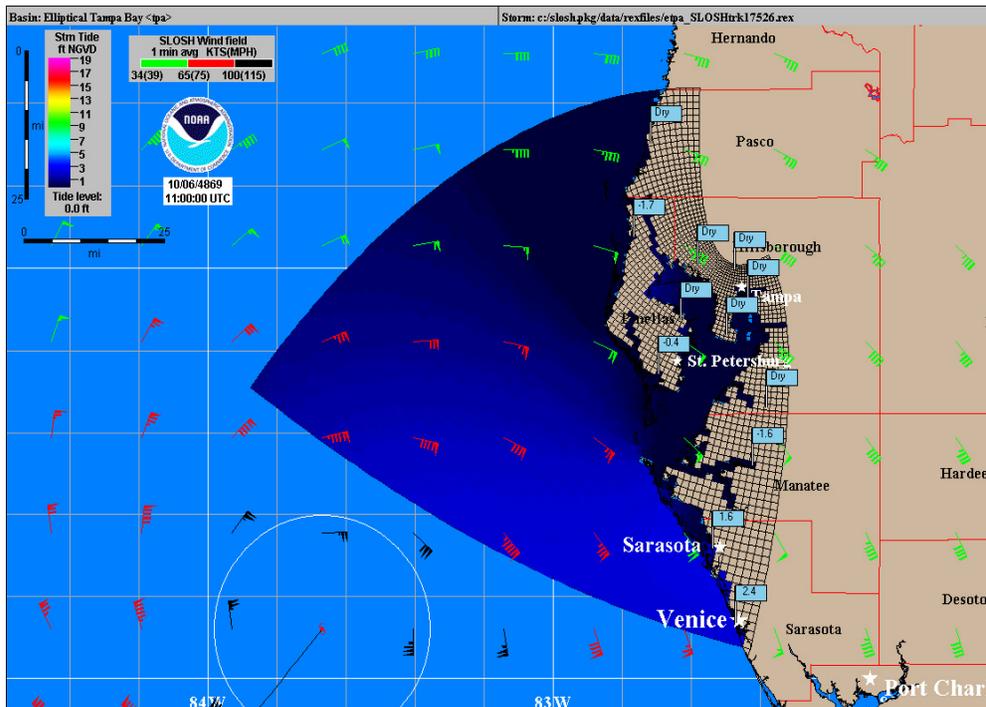Figure 6. Locations of Five Sites of Interest in the Tampa Bay Basin

Figure 7.   Selected Hurricane Storm Track (# 17526) From the 55,000-Year FPHLM over the Area of Interest.
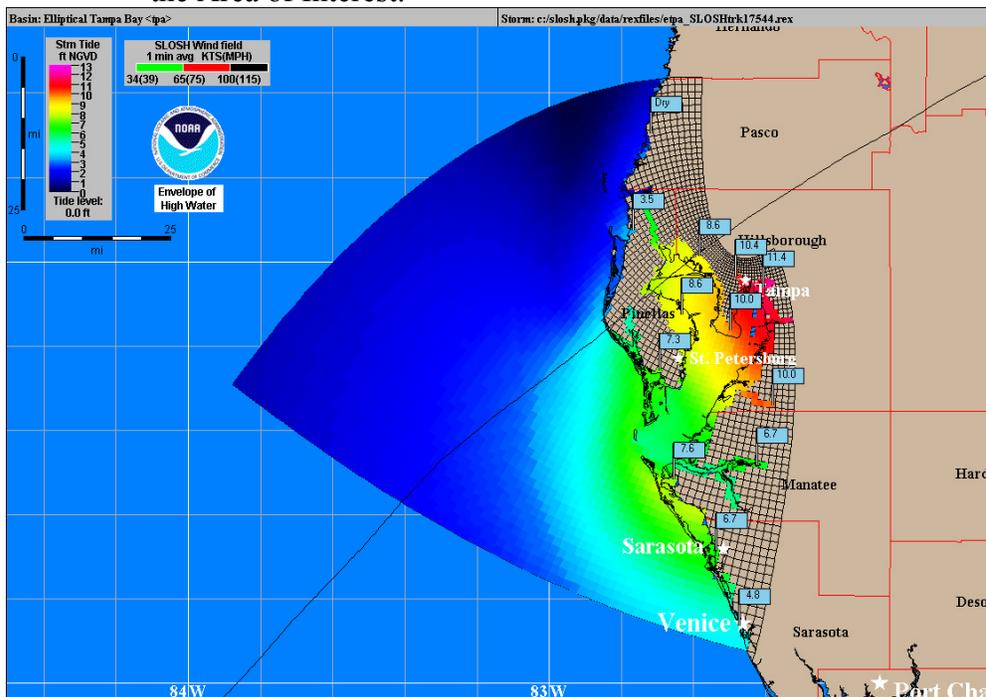

Figure 8.   SLOSH Simulation Showing Effect of Hurricane Track Number 17544 on the Tampa Bay Basin.
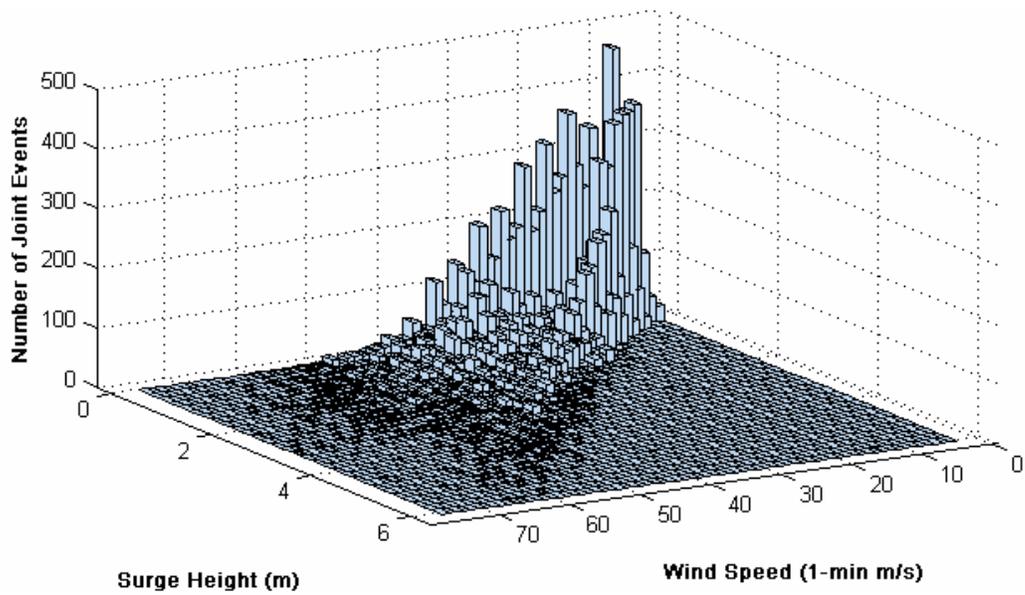
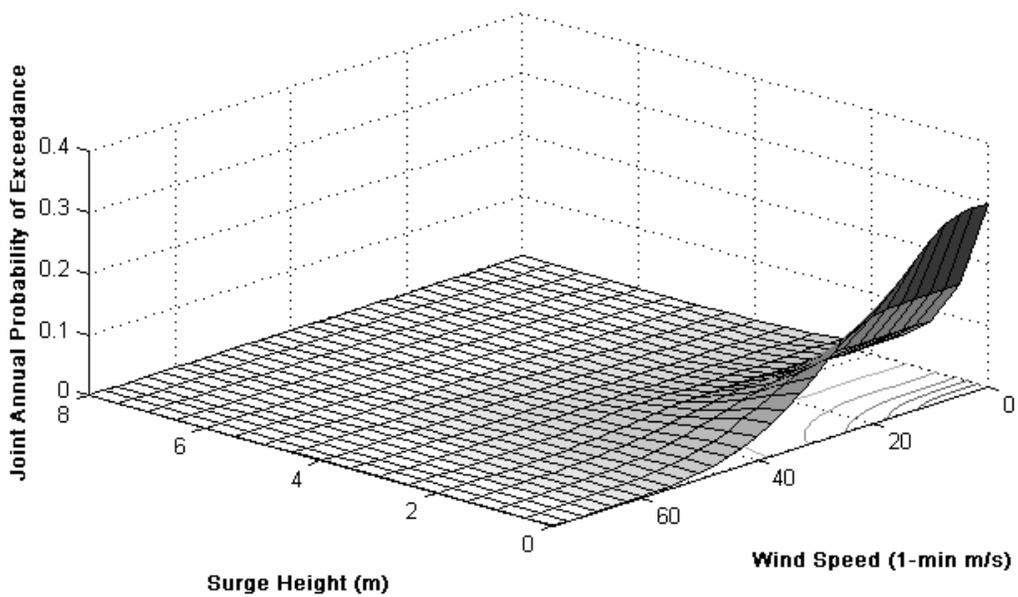Figure 9. Joint Histogram of Peak Wind Speed/Surge Height for Port of Tampa

Figure 10. Joint Probability of Exceedance for Port of Tampa Site

Table 1. MRI (in Years) for Port of Tampa Site

Wind Speed (1-min) (m/s)	Storm Surge Height (m)									
	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
32.5	30	49	86	158	299	611	1447	2895	13750	55000
35.0	35	53	88	158	299	611	1447	2895	13750	55000
37.5	41	61	92	160	299	611	1447	2895	13750	55000
40.0	51	76	106	172	302	611	1447	2895	13750	55000
42.5	66	99	134	190	313	611	1447	2895	13750	55000
45.0	83	126	165	230	355	625	1447	2895	13750	55000
47.5	115	174	234	324	451	663	1447	2895	13750	55000
50.0	149	224	309	414	556	764	1486	2895	13750	55000
52.5	212	318	455	640	833	1038	1618	3056	13750	55000
55.0	320	433	647	982	1279	1486	2115	3438	13750	55000
57.5	447	598	902	1486	1964	2200	2750	4583	13750	55000
60.0	724	932	1310	2292	3235	3438	3929	5500	13750	55000
62.5	1038	1375	1774	3438	5500	6111	6875	9167	18333	55000
65.0	1774	2115	3056	6875	13750	18333	18333	27500	55000	
67.5	3235	3235	3929	9167	27500	27500	27500	55000		
70.0	5500	5500	6111	13750	55000	55000	55000			