LTRC

LTRC Project No. 10-4ST

Development of Wave and Surge Atlas for the Design and Protection of Coastal Bridges in South Louisiana

D. Max Sheppard
Phil Dompe
INTERA

Workshop Outline

- Introduction 8:30-8:35
- Objectives - project, workshop 8:35-8:45
- Background 8:45-9:05
  - AASHTO Guide Specification
  - Levels I, II, III analyses
  - Surge/wave force and moment equations
- Level III met/ocean analysis 9:05-9:25
- Bridge vulnerability analysis 9:25-9:45
- Break 9:45-10:00
- Use of Storm Surge/Wave Atlas 10:00-11:30
- Additional work 11:30-11:50
- Questions/Comments 11:50-12:00

Introduction

- Presenters
  - D. Max Sheppard – OEA/INTERA
  - Phil Dompe – OEA/INTERA
- Other Contributors
  - ZhengZheng Fu – LADOTD
  - Stephanie Cavalier – LADOTD
  - Huseyin Demir – OEA/INTERA
  - Jacob McBee – OEA/INTERA
  - Brian Lampp – OEA/INTERA
  - Mark Gosselin - OEA/INTERA

Objectives

- Project
  - Analyze vulnerability of LADOTD coastal bridges to storm surge and wave loading (surge/wave loading)
  - Develop a Surge/Wave Atlas for Louisiana coastal waters
- Workshop
  - Present overview of project
  - Tutorial on use of Atlas and its contents

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Background

- Major coastal bridge losses in recent history due to storm surge/wave loading

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Bridge Failures

I10 Bridges over Lake Pontchartrain
New Orleans, LA

Bridge Failures

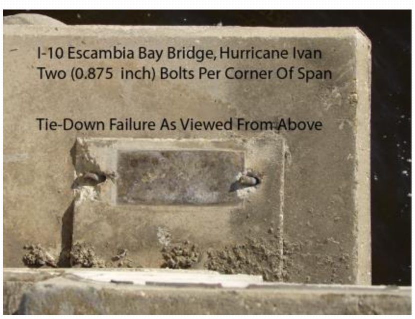
Pensacola, FL

Bay Saint Louis, MS

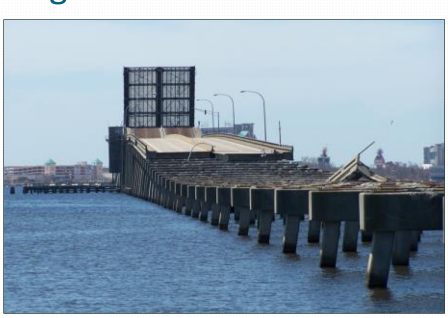
Biloxi, MS

Biloxi, MS

I10-Escambia Bay Span Tie-Down



Bridge Failures



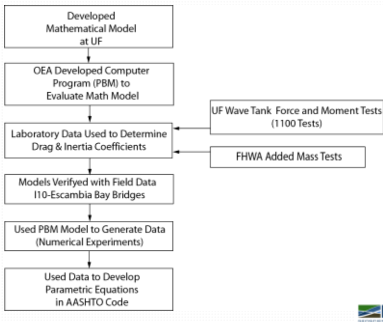
Bridge Failures

Bridge Failures

Background (cont.)

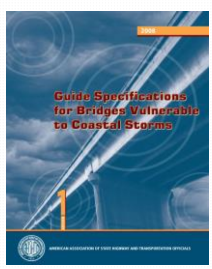
- FHWA – AASHTO, FDOT Studies
  - Objective
    - Develop tools for computing surge/wave loads on bridges
  - Methodology
    - Develop mathematical model for forces (predictive equations)
    - Conduct wave tank tests to calibrate and test math model
    - Validate model with field data
    - Use model to generate data for wide range of structure and surge/wave conditions
    - Use data to develop parametric equations for AASHTO Guide Specification

Development of AASHTO Equations



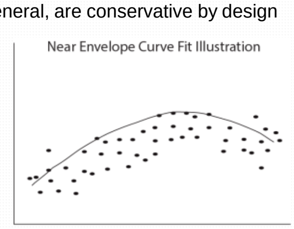
Surge/Wave Loading

- AASHTO Code: "*Guide Specification for Bridges Vulnerable to Coastal Storms*"
  - Developed by: Modjeski and Masters with <u>OEA, Inc. providing the surge/wave procedures and development of force & moment equations</u>



Background (cont.)

- Parametric equations in AASHTO Guide Spec
  - Envelope surface fits to data
  - In general, are conservative by design



Information Needed to Compute Loads

- Design (100-year) storm water levels
- Design (100-year) wave heights and periods
- Superstructure design, dimensions, elevation, orientation
- Force and Moment predictive equations

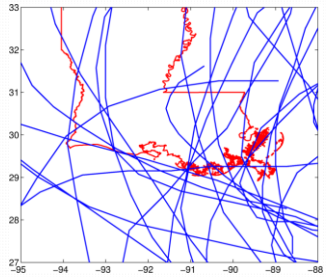
Background (cont.)

- For surge/wave loads need 100-year met/ocean conditions
  - Maximum storm water level and wave height
- AASHTO Guide Spec outlines 3 levels of analysis
  - Level I – uses existing data (very conservative)
  - Level II – more effort than Level I (conservative)
  - Level III – most effort and most accurate

Background (cont.)

- Level III analysis performed for this project
  - Hindcasted all major tropical storms and hurricanes that have impacted Louisiana Coastal Waters in last 156 years
  - Performed extreme value analyses on hindcasted data to obtain 100-year met/ocean parameters

Hurricane Paths that Occurred Before 1920



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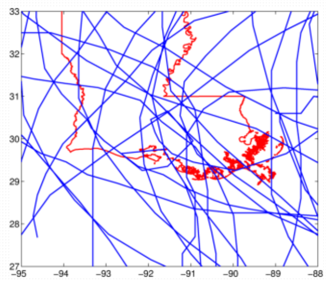
Hurricane Paths that Occurred After 1920



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Extreme Value Analysis

- Data extracted from surge/wave solution files
  - Maximum water elevations
  - Wave heights at time of maximum water elevation
  - Maximum wave heights
  - Water elevation at time of maximum wave heights
- Extreme value analysis
  - Obtain 100-Year maximum water elevation throughout study area
  - Obtain 100-Year associated wave heights throughout study area

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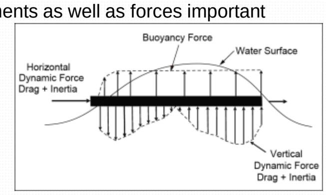
Extreme Value Analysis

- Extreme value analysis (cont.)
  - Obtain 100-Year maximum wave heights throughout study area
  - Obtain 100-Year associated water elevations throughout study area

Background (cont.)

- Forces and Moments
  - Forces and moments on bridge superstructures more complex than those on substructure
  - Vary in both time and space as wave progresses past structure
  - Moments as well as forces important



Background (cont.)

- Mathematical model

Horizontal Forces

$$F_H = F_{Drag} + F_{Inertia} + F_{CAM} + F_{Slamming}$$

Vertical Forces

$$F_V = F_{Buoyancy} + F_{Drag} + F_{Inertia} + F_{CAM} + F_{Slamming}$$

Surge/Wave Forces

$$F_{Drag} = C_d \frac{1}{2} \rho L w V |V|$$

$$F_{Inertia} = C_{Inertia} \frac{d(m_e V)}{dt} = \left(C_{cam} \frac{dm_e}{dt} V + C_m m_e \frac{dV}{dt} \right)$$

$$F_{Buoyancy} = \rho g \forall$$

where $\forall$ = wetted volume

m_e = effective mass =
mass displaced + added mass

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Surge/Wave Forces (cont.)

$$m_{av} = \frac{\rho \pi L W^2}{4\left[1+\left(\frac{W}{b_d}\right)^2\right]^{\frac{1}{2}}} \left[1+\frac{1}{2}\left(\frac{b_d}{W}\right)^{0.4}\right]$$

$$m_{ah} = \frac{\rho \pi L b_d^{\,2}}{4\left[1+\left(\frac{b_d}{W}\right)^2\right]^{\frac{1}{2}}} \left[1+\frac{1}{2}\left(\frac{W}{b_d}\right)^{0.4}\right]$$

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Change in Added mass

$$\frac{dm_{av}}{dt} = \frac{\rho \pi L W^2}{4\left[1+\left(\frac{W}{b_d}\right)^2\right]^{\frac{1}{2}}} \left\{ \begin{array}{l} \left[1+\frac{1}{2}\left(\frac{b_d}{W}\right)^{0.4}\right]\left[2\frac{\frac{\partial W}{\partial t}}{W} - \frac{W\frac{\partial W}{\partial t}}{W^2+L^2}\right] + \\ \left[\frac{1}{5}\left(\frac{b_d}{W}\right)^{0.4}\left(\frac{\frac{\partial b_d}{\partial t}}{b_d} - \frac{\frac{\partial W}{\partial t}}{W}\right)\right] \end{array} \right\}$$

$\rho \equiv$ Density of Water
$W \equiv$ Wetted Span Width
$L \equiv$ Span Length
$b_d \equiv$ Wetted Span Height
$t \equiv$ Time

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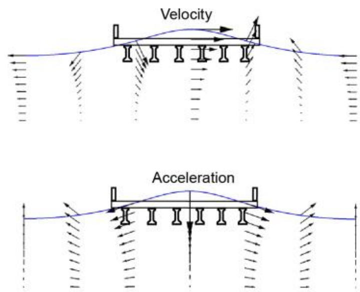
Water Motion in Waves



Example
Wave
Kinematics

Water Depth = 30 ft,
Wave Height = 10 ft,
Wave Period = 5 sec

Background (cont.)

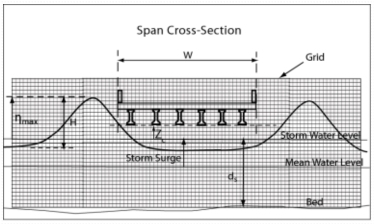
- Wave tank tests at the University of Florida

PBM

- Evaluates storm surge/save force and moment equations at each element and at each time step
- Has built-in nonlinear wave model to compute wave velocities and accelerations

Evaluation of Equations

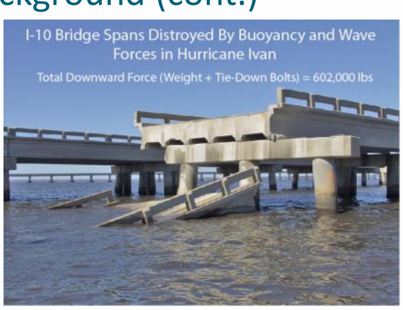
- OEA/INTERA developed an in-house computer program “Physics Based Model” or “PBM” to evaluate the equations



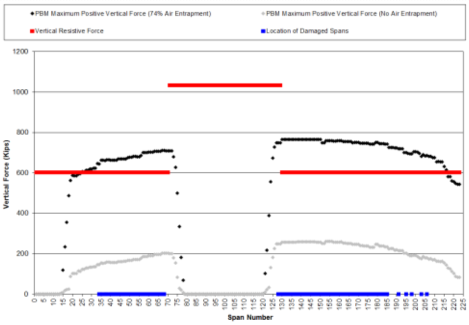
Background (cont.)

- Model vetting
  - I-10 Escambia Bay Bridges – Hurricane Ivan 2004
    - Refined Hurricane Ivan hindcast
    - Good span by span damage assessment
  - Estimate resistive force for each span
    - Vertical Force
      - Dead weight
      - Tie-down strength

Background (cont.)



Background (cont.)

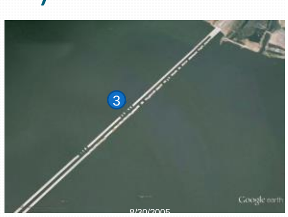


Background (cont.)

- Model vetting
  - I-10 Lake Pontchartrain and US-11 Bridges – Hurricane Katrina 2005
    - Refined Hurricane Katrina hindcast
    - I-10 experienced failures and US-11 did not

Background (cont.)

- I-10 Lake Pontchartrain – Hurricane Katrina 2005
  - Based on vertical Forces PBM predicts failure

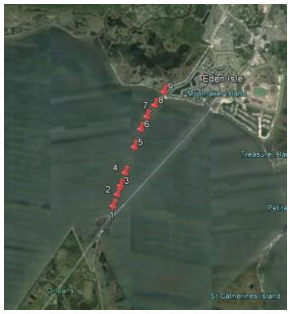


Location	Deadweight (kips)	Maximum Vertical Force (kips)
1	500	633
2	500	508
3	500	562

Background (cont.)

- US-11 Lake Pontchartrain – Hurricane Katrina 2005
  - Based on vertical Forces PBM DOES NOT predict failure

Location	Dead Weight (kips)	Maximum Vertical Force (kips)
1	218	0
2	218	11
3	218	36
4	218	46
5	218	45
6	218	38
7	218	26
8	218	13
9	218	0



Level III Analysis

- Hindcasted 50 actual and 74 path shifted storms
  - Mesh development
  - Surge and Wave models calibrated
  - Storm selection process
- Extreme value analyses
  - At each node in mesh 100-year
    - Maximum water level and associated wave height
    - Maximum wave height and associated water level

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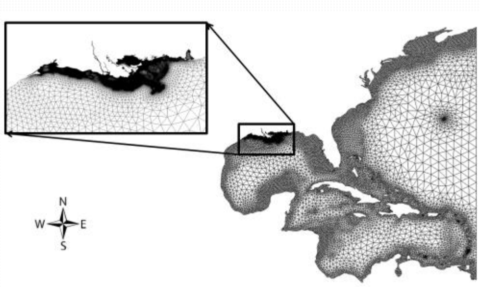
ADCIRC Mesh



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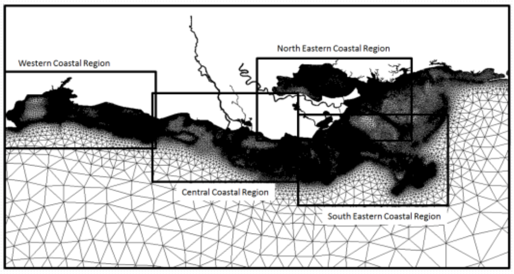
ADCIRC Mesh



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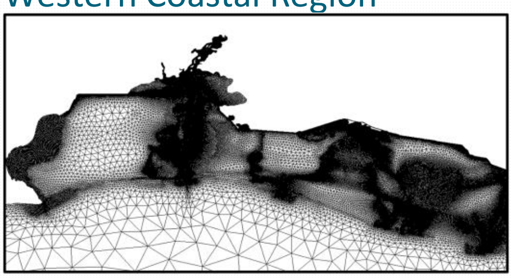
Western Coastal Region



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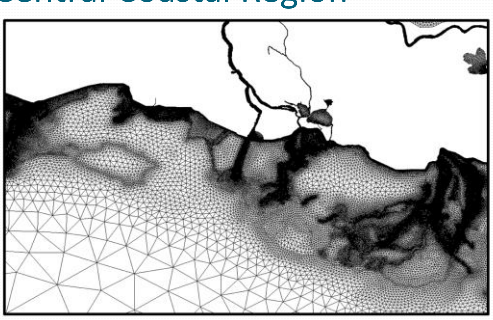
Central Coastal Region



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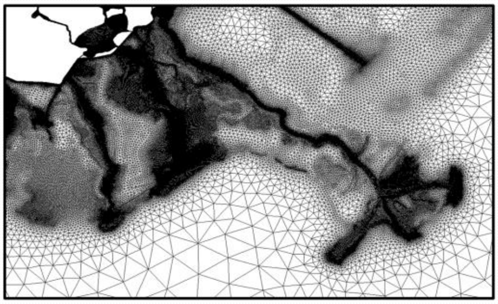
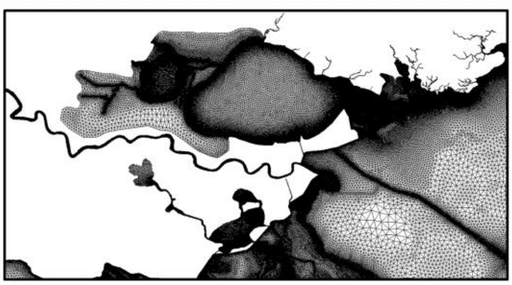
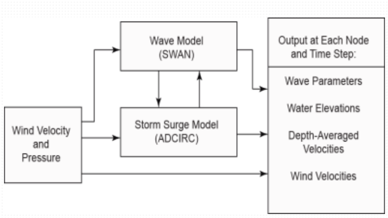
Southeastern Coastal Region



Northeastern Coastal Region



Coupled Model Diagram



Model Calibration

- Iterative processes of adjusting model parameters until model results match measured results within acceptable limits
- FEMA defines the acceptable limit as;
  - 10% or less for tidal calibrations
  - greater under storm conditions due to complexity
- For ADCIRC calibration model parameters are bottom friction and lateral eddy viscosity
- For SWAN calibration model parameters are bottom friction, white capping and breaking criteria

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Model Calibration Data
NOAA Tide Gage Locations

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Model Calibration Data
USGS Tide Gage Locations

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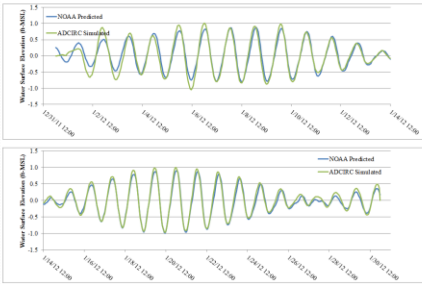
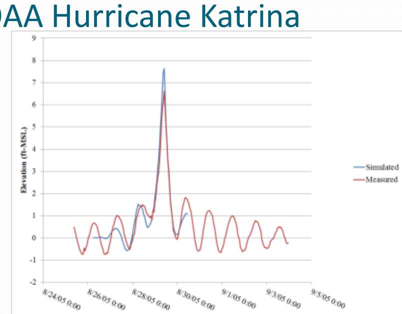
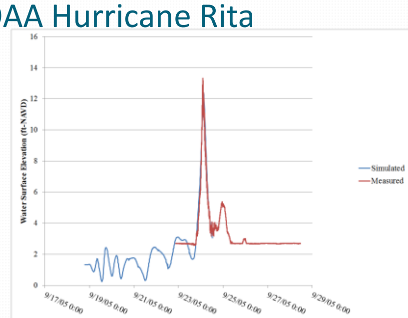
Model Calibration NOAA Tides



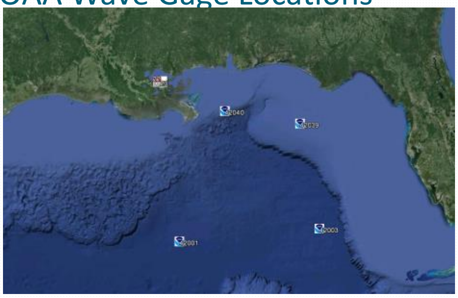
Model Validation
NOAA Hurricane Katrina



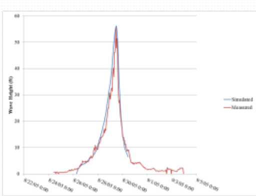
Model Validation
NOAA Hurricane Rita



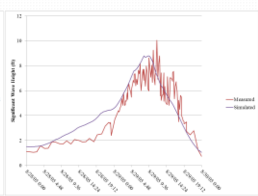
Model Calibration Data
NOAA Wave Gage Locations



SWAN Model Calibration – Significant Wave Height

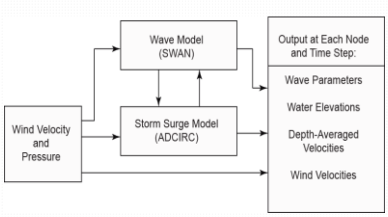


Hurricane Katrina Comparison at NOAA Gage 42040

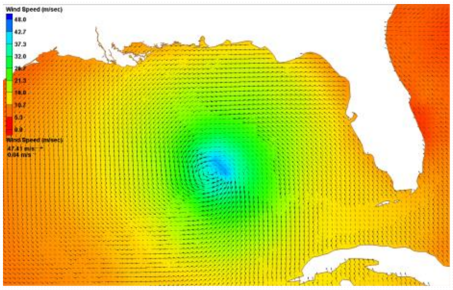


Hurricane Katrina Comparison at USACE Gage 23

Tropical Storm/Hurricane Hindcasts

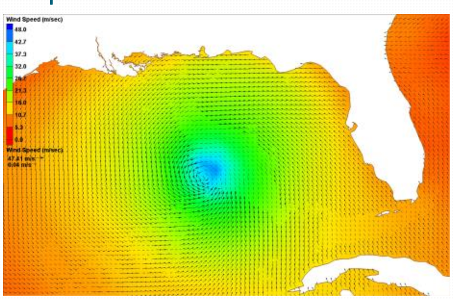


Example Hurricane Hindcast



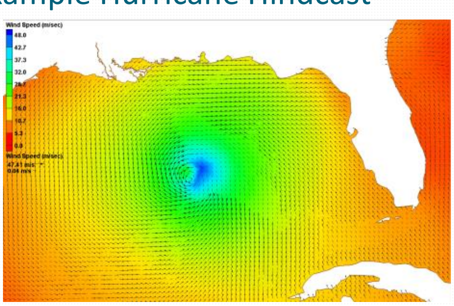
Hurricane Katrina Wind Fields

Example Hurricane Hindcast



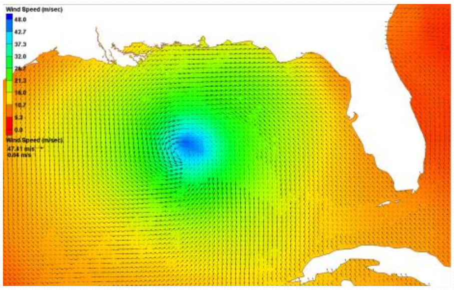
Hurricane Katrina Wind Fields

Example Hurricane Hindcast



Hurricane Katrina Wind Fields

Example Hurricane Hindcast



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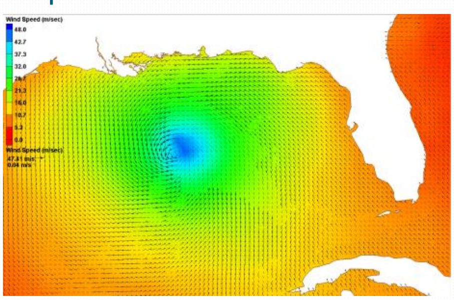

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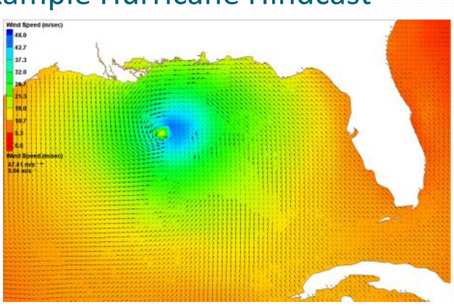

Hurricane Katrina Wind Fields

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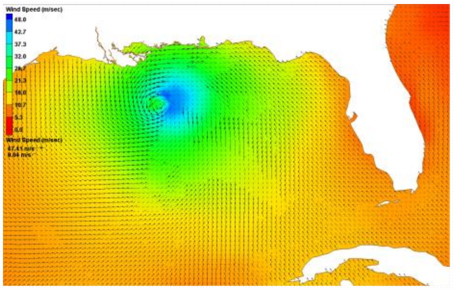
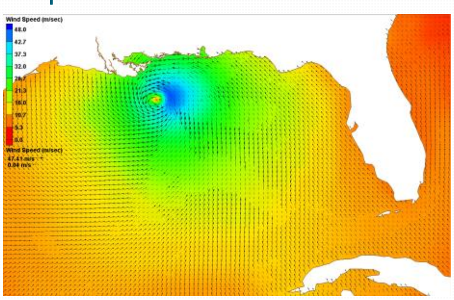


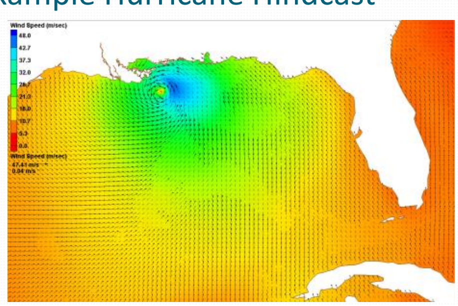
Hurricane Katrina Wind Fields

Example Hurricane Hindcast



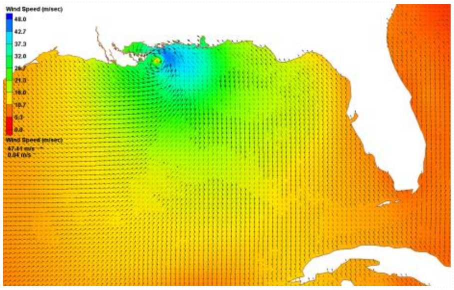
Hurricane Katrina Wind Fields

Example Hurricane Hindcast



Hurricane Katrina Wind Fields

Example Hurricane Hindcast



Hurricane Katrina Wind Fields

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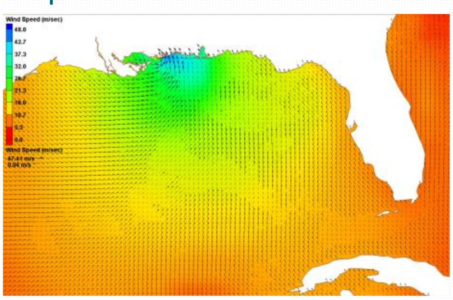

Hurricane Katrina Wind Fields

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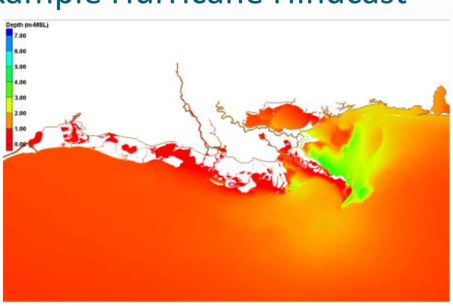
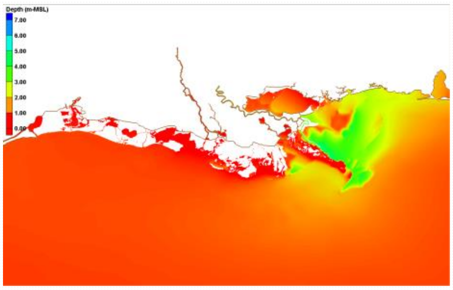


Hurricane Katrina Water Surface Elevations

Example Hurricane Hindcast



Hurricane Katrina Water Surface Elevations

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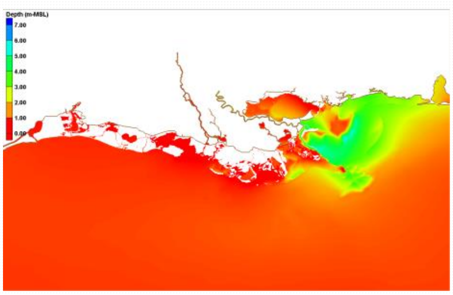
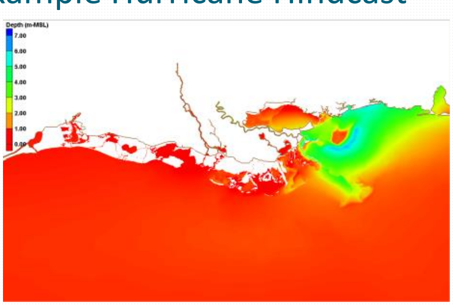


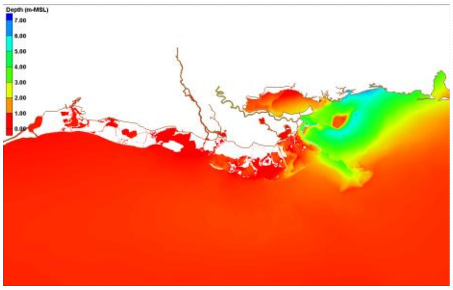
Hurricane Katrina Water Surface Elevations

Example Hurricane Hindcast



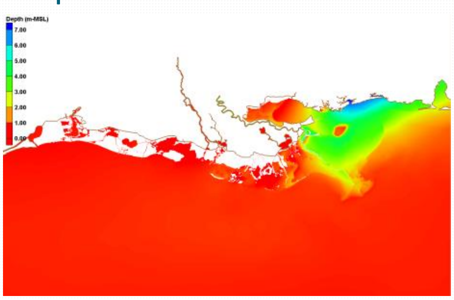
Hurricane Katrina Water Surface Elevations

Example Hurricane Hindcast



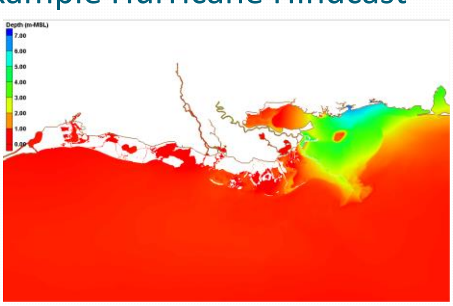
Hurricane Katrina Water Surface Elevations

Example Hurricane Hindcast



Hurricane Katrina Water Surface Elevations

Example Hurricane Hindcast



Hurricane Katrina Water Surface Elevations

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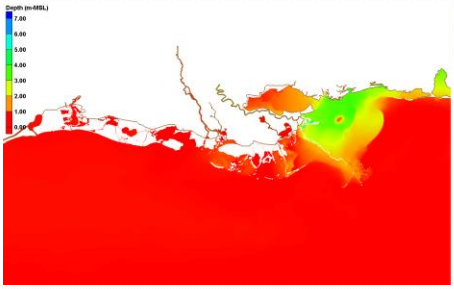
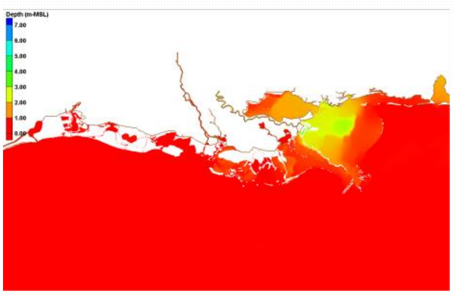


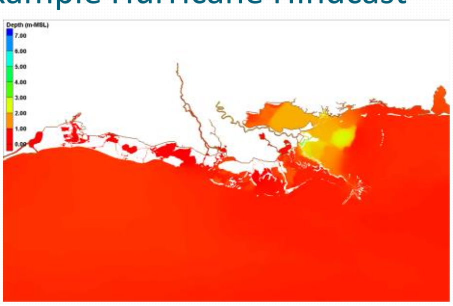
Hurricane Katrina Water Surface Elevations

Example Hurricane Hindcast



Hurricane Katrina Water Surface Elevations

Example Hurricane Hindcast



Hurricane Katrina Water Surface Elevations

Extreme Value Analysis

- Data extracted from surge/wave solution files
  - Maximum water elevations
  - Wave heights at time of maximum water elevation
  - Maximum wave heights
  - Water elevation at time of maximum wave heights
- Extreme value analysis
  - Obtain 100-Year maximum water elevation and associated wave heights throughout study area
  - Obtain 100-Year maximum wave heights and associated water elevations throughout study area

INTERA

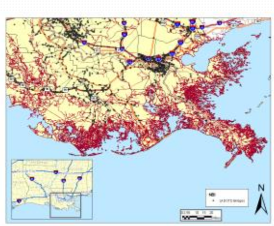
Study Results – Surge/Wave Atlas

- Many uses for study results beyond surge/wave loads on existing bridges, e.g.,
  - Design of new bridges (elevations, hydrodynamic loads, sediment scour, etc.)
  - Design of erosion protection for existing and new coastal roadways
  - Channel bank erosion protection design

INTERA

Surge/Wave Loading on Bridges

- Significant number of bridges in South Louisiana



INTERA

Bridge Selection

- 3177 Initial bridges
- Initial screening reduced list to 471
- Second screening further reduced list to 101
- Final number of bridges to be analyzed 65

INTERA

Vulnerable Bridge Criteria

- When surge/wave forces and/or moments exceed resistive forces and/or moments DUE TO DEAD WEIGHT ONLY
- Load factors applied to computed forces and moments

Criticality Index	Description
1	Minor impact to economy or emergency needs if closed (alternative routes exist)
2	Medium impact if closed - may lead to a barrier island but an alternative route exists
3	Major impact if closed – only road to a barrier island, evacuation route with no reasonable alternatives
4	Extreme impact if closed – Interstate or major economic connector (detour very long)

INTERA

Bridges Analyzed

No.	Bridge Recall Number	Load Factor	Maximum Vertical Force (kips)	Dead Weight (kips)	Vertical Force Vulnerability Index	Maximum Moment (ft-kips)	Dead Weight Resistive Moment (ft-kips)	Moment Vulnerability Index	Conclusion
1	000810	1.75	0	386	0	0	4,245	0	Not Vulnerable
2	001552	1.75	44	218	0.4	419	3,274	0.2	Not Vulnerable
3	002631	1.75	64	132	0.8	1,883	2,640	1.2	Vulnerable
4	002632	1.75	67	132	0.9	1,979	2,640	1.3	Vulnerable
5	002650	1.75	258	131	3.5	4,788	1,634	5.1	Vulnerable
6	002892	1.75	426	493	1.5	6,731	10,715	1.1	Vulnerable
7	002894	1.75	426	493	1.5	6,731	10,715	1.1	Vulnerable
8	003390	1.75	0	443	0	0	6,753	0	Not Vulnerable
9	003432	1.75	2254	443	8.9	26,423	6,753	6.8	Vulnerable
10	003440	1.75	246	246	1.7	2,846	4,124	1.2	Vulnerable
11	003450	1.75	1839	383	8.4	20,612	5,260	6.9	Vulnerable
12	003480	1.75	204	138	2.6	3073	1170	4.6	Vulnerable
13	003510	1.75	62	81	1.3	1,261	1,094	2	Vulnerable
14	003520	1.75	65	81	1.4	1,288	1,094	2.1	Vulnerable
15	003641	1.75	51	122	0.7	589	2,259	0.5	Not Vulnerable
16	003690	1.75	68	29	4.1	1,082	363	5.2	Vulnerable
17	009020	1	0	138	0	0	2,769	0	Not Vulnerable
18	009030	1.75	64	85	1.3	919	978	1.6	Vulnerable
19	009060	1	0	65	0	4	875	0	Not Vulnerable
20	009198	1.75	0	863	0	0	17,817	0	Not Vulnerable
21	009570	1.75	0	110	0	0	1,209	0	Not Vulnerable
22	009580	1.75	0	62	0	0	850	0	Not Vulnerable
23	009590	1.75	0	62	0	0	850	0	Not Vulnerable
24	009600	1.75	0	62	0	0	850	0	Not Vulnerable
25	009610	1.75	0	62	0	0	850	0	Not Vulnerable
26	009620	1.75	0	62	0	0	850	0	Not Vulnerable
27	009630	1.75	0	62	0	0	850	0	Not Vulnerable
28	009700	1.75	0	96	0	0	1,388	0	Not Vulnerable
29	009710	1.75	0	96	0	0	1,388	0	Not Vulnerable
30	020185	1	0	334	0	0	8,349	0	Not Vulnerable
31	020186	1	0	251	0	0	6,283	0	Not Vulnerable
32	020266	1.75	30	73	0.7	631	1,167	0.9	Not Vulnerable
33	020319	1.75	0	473	0	0	7,808	0	Not Vulnerable

INTERA

Bridges Analyzed

No.	Bridge Recall Number	Load Factor	Maximum Vertical Force (kips)	Dead Weight (kips)	Vertical Force Vulnerability Index	Maximum Moment (ft-kips)	Dead Weight Resistive Moment (ft-kips)	Moment Vulnerability Index	Conclusion
34	030242	1.75	0	858	0	0	17,512	0	Not Vulnerable
35	031755	1.75	297	340	1.5	6,075	7,021	1.5	Vulnerable
36	032266	1.75	0	1442	0	0	33,171	0	Not Vulnerable
37	032780	1.75	0	296	0	0	8,981	0	Not Vulnerable
38	033210	1.75	0	536	0	0	17,083	0	Not Vulnerable
39	033590	1.75	0	177	0	0	3,778	0	Not Vulnerable
40	033602	1.75	0	645	0	0	13,312	0	Not Vulnerable
41	033650	1.75	44	215	0.4	1,326	4,719	0.5	Not Vulnerable
42	033660	1.75	52	215	0.4	1,308	4,719	0.5	Not Vulnerable
43	033672	1.75	0	91	0	0	1,824	0	Not Vulnerable
44	033681	1.75	0	136	0	0	2,572	0	Not Vulnerable
45	033698	1.75	48	64	1.3	1,071	894	2.1	Vulnerable
46	033700	1.75	124	81	2.7	1,811	1,094	2.9	Vulnerable
47	033730	1.75	0	371	0	0	3,892	0	Not Vulnerable
48	033750	1	0	96	0	0	1,388	0	Not Vulnerable
49	058910	1.75	0	87	0	0	1,090	0	Not Vulnerable
50	058920	1.75	0	87	0	0	1,090	0	Not Vulnerable
51	058930	1.75	0	328	0	0	4,585	0	Not Vulnerable
52	058940	1.75	0	87	0	0	1,090	0	Not Vulnerable
53	059482	1.75	949	863	1.9	24,442	14,669	2.9	Vulnerable
54	060360	1	81	53	1.5	1,088	504	2.2	Vulnerable
55	060412	1.75	0	815	0	0	12,964	0	Not Vulnerable
56	062100	1	22	239	0.1	528	5,434	0.1	Not Vulnerable
57	070096	1.75	83	177	0.8	1,047	3,778	0.5	Not Vulnerable
58	070097	1	41	100	0.4	797	1,605	0.5	Not Vulnerable
59	070119	1	0	73	0	0	1,167	0	Not Vulnerable
60	070137	1.75	60	177	0.6	729	3,778	0.3	Not Vulnerable
61	070141	1.75	0	177	0	0	3,778	0	Not Vulnerable
62	070142	1.75	4	177	0	6	3,778	0	Not Vulnerable
63	070143	1.75	0	177	0	0	3,778	0	Not Vulnerable
64	070144	1.75	0	177	0	0	3,778	0	Not Vulnerable
65	070166	1	35	73	0.5	908	1,167	0.8	Not Vulnerable

15 Minute Break

Questions/Comments on Previous Material

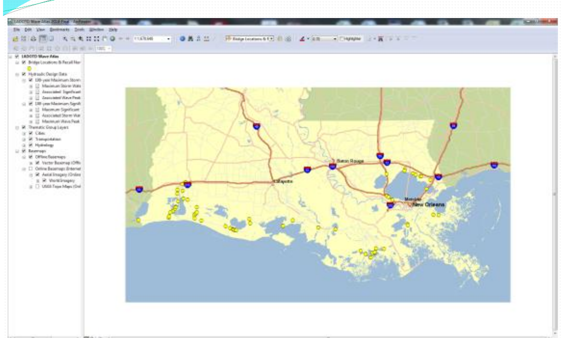
Storm Surge and Wave Atlas

- GIS database with 100-year met/ocean information
  - Map of study area containing 100-year:
    - Maximum water level and associated wave height and peak period
    - Maximum wave height and peak period and associated water level

INTERA

Open GIS Surge/Wave Atlas with GIS Reader

INTERA



INTERA

Example Surge/Wave Load Analysis

- The problem is to determine the vulnerability of a span on a particular LADOTD bridge using the methodology in the AASHTO Guide Spec and the Surge/Wave Atlas

INTERA

Example Surge/Wave Load Analysis

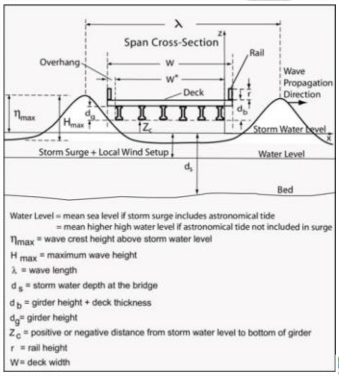
- Extract 100-year met/ocean data from Surge/Wave Atlas for bridge location
- Obtain bridge superstructure information
- Follow AASHTO Guide Specification to compute:
  - Surge/wave forces and moments and assign proper load factors
  - Resistive forces and moments due to superstructure dead weight
  - Bridge vulnerability

INTERA

LADOTD Bridge Recall Number 003440

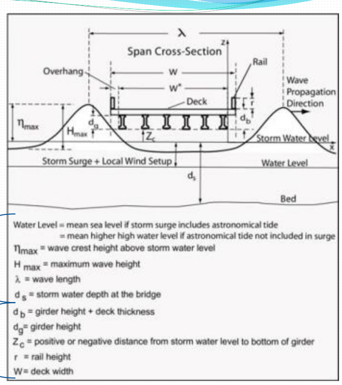
INTERA

Figure 6.1.2.2.1-1 Nomenclature in Equations 1-8

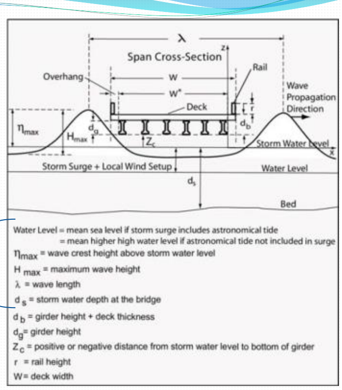


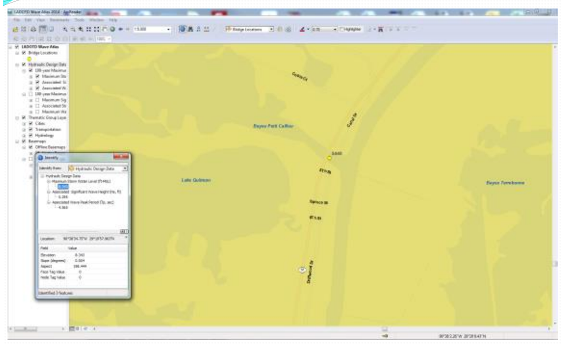
Met/Ocean Data

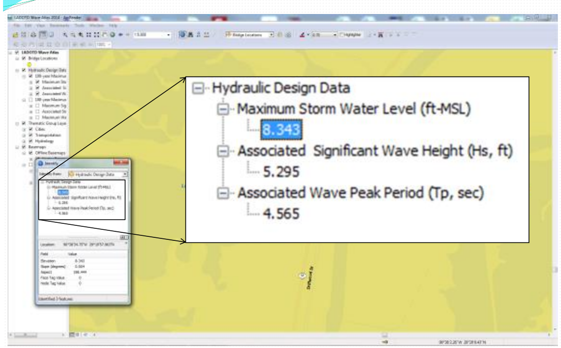
Structure Data



Met/Ocean Data



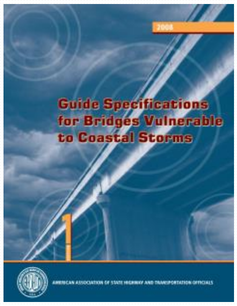




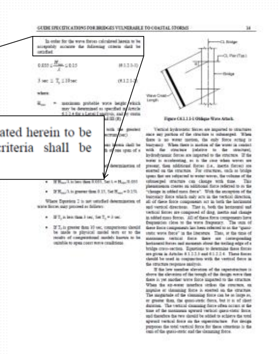
100-Year Met/Ocean Parameters

Storm Water Level (ft)	Associated Significant Wave Height (ft)	Peak Wave Period (sec)	Water Depth d_s (ft)	λ (ft)	H_{max} (ft)	Depth Limited Wave Height (ft)	Steepness Limited Wave Height (ft)	η_{max} (ft)
8.3	5.3	4.6						

AASHTO Guide Spec

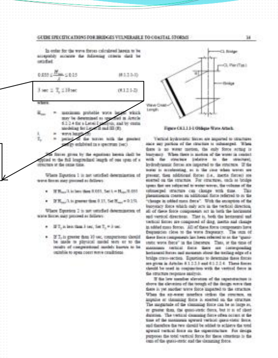


INTERA



In order for the wave forces calculated herein to be acceptably accurate the following criteria shall be satisfied:

INTERA



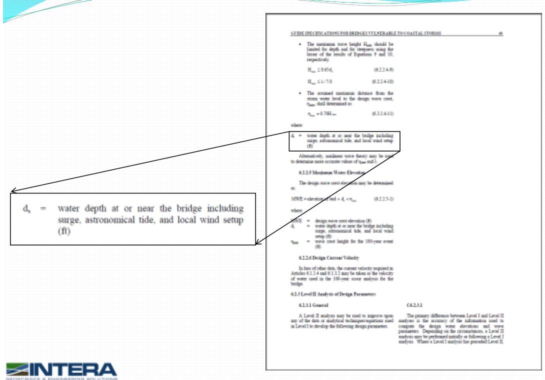
$3 \text{ sec} \leq T_p \leq 10 \text{ sec}$ (6.1.2.1-2)

INTERA

Met/ocean parameters used in the force and moment calculations

Storm Water Level (ft)	Associated Significant Wave Height (ft)	Peak Wave Period (sec)	Water Depth d_s (ft)	λ (ft)	H_{max} (ft)	Depth Limited Wave Height (ft)	Steepness Limited Wave Height (ft)	η_{max} (ft)
8.3	5.3	4.6						

INTERA



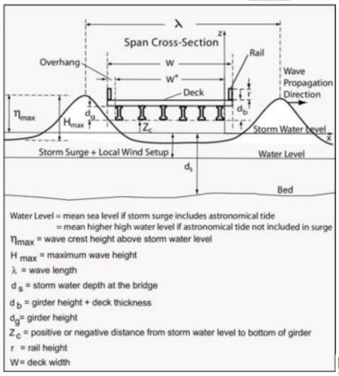
INTERA

Met/ocean parameters used in the force and moment calculations

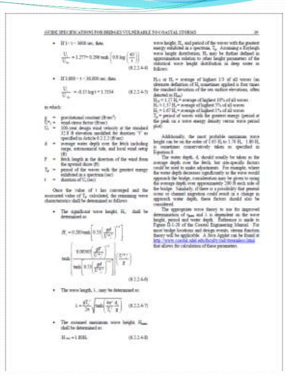
Storm Water Level (ft)	Associated Significant Wave Height (ft)	Peak Wave Period (sec)	Water Depth d_s (ft)	λ (ft)	H_{max} (ft)	Depth Limited Wave Height (ft)	Steepness Limited Wave Height (ft)	η_{max} (ft)
8.3	5.3	4.6	28.3					

INTERA

Figure 6.1.2.2.1-1 Nomenclature in Equations 1-8

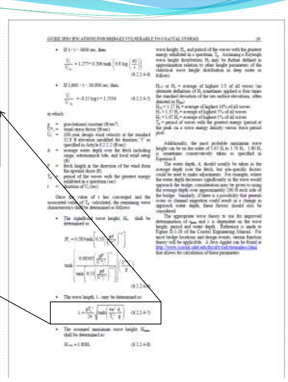


INTERA



INTERA

$$\lambda = \frac{gT_p^2}{2\pi}\sqrt{\tanh\left(\frac{4\pi^2}{T_p^2}\frac{d_s}{g}\right)} \quad (6.2.2.4\text{-}7)$$

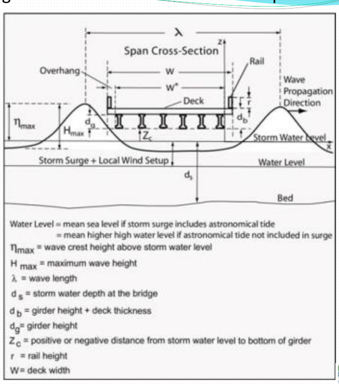


INTERA

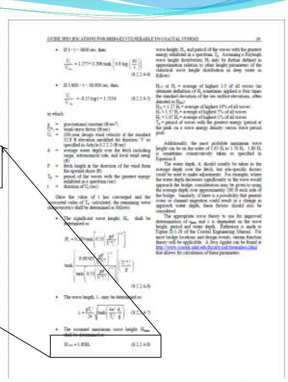
Met/ocean parameters used in the force and moment calculations

Storm Water Level (ft)	Associated Significant Wave Height (ft)	Peak Wave Period (sec)	Water Depth d_s (ft)	λ (ft)	H_{max} (ft)	Depth Limited Wave Height (ft)	Steepness Limited Wave Height (ft)	η_{max} (ft)
8.3	5.3	4.6	28.3	104.4				

Figure 6.1.2.2.1-1 Nomenclature in Equations 1-8



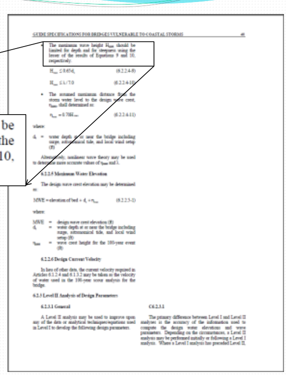
$$H_{max} = 1.80 H_s \qquad (6.2.2.4\text{-}8)$$



Met/ocean parameters used in the force and moment calculations

Storm Water Level (ft)	Associated Significant Wave Height (ft)	Peak Wave Period (sec)	Water Depth d_s (ft)	λ (ft)	H_{max} (ft)	Depth Limited Wave Height (ft)	Steepness Limited Wave Height (ft)	η_{max} (ft)
8.3	5.3	4.6	28.3	104.4	9.5			

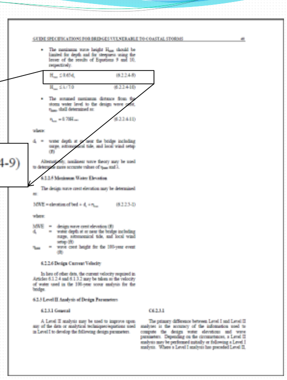
INTERA



GUIDE SPECIFICATIONS FOR BRIDGES VULNERABLE TO COASTAL STORMS

The maximum wave height H_{max} should be limited for depth and for steepness using the lesser of the results of Equations 9 and 10, respectively.

INTERA



GUIDE SPECIFICATIONS FOR BRIDGES VULNERABLE TO COASTAL STORMS

$$H_{max} \le 0.65 d_s \qquad (6.2.2.4\text{-}9)$$

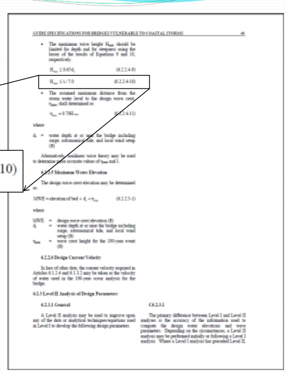
INTERA

Met/ocean parameters used in the force and moment calculations

Storm Water Level (ft)	Associated Significant Wave Height (ft)	Peak Wave Period (sec)	Water Depth d_s (ft)	λ (ft)	H_{max} (ft)	Depth Limited Wave Height (ft)	Steepness Limited Wave Height (ft)	η_{max} (ft)
8.3	5.3	4.6	28.3	104.4	9.5	18.4		

INTERA

$$H_{max} \le \lambda / 7.0 \qquad (6.2.2.4\text{-}10)$$


GUIDE SPECIFICATIONS FOR BRIDGES VULNERABLE TO COASTAL STORMS 40

- The maximum wave height H_{max} should be limited for depth and for steepness using the lesser of the results of Equations 9 and 10, respectively.

$H_{max} \le 0.65 d_s$ (6.2.2.4-9)

$H_{max} \le \lambda / 7.0$ (6.2.2.4-10)

- The assumed maximum distance from the storm water level to the design wave crest, η_{max}, shall determined as:

$\eta_{max} = 0.70 H_{max}$ (6.2.2.4-11)

where:

d_s = water depth at or near the bridge including surge, astronomical tide, and local wind setup (ft)

Alternatively, nonlinear wave theory may be used to determine more accurate values of η_{max} and λ.

6.2.2.5 Maximum Water Elevation

The design wave crest elevation may be determined as:

MWE = elevation of bed + d_s + η_{max} (6.2.2.5-1)

where:

MWE = design wave crest elevation (ft)
d_s = water depth at or near the bridge including surge, astronomical tide, and local wind setup (ft)
η_{max} = wave crest height for the 100-year event (ft)

6.2.2.6 Design Current Velocity

In lieu of other data, the current velocity required in Articles 6.1.2.4 and 6.1.3.2 may be taken as the velocity of water used in the 100-year scour analysis for the bridge.

6.2.3 Level II Analysis of Design Parameters

6.2.3.1 General

A Level II analysis may be used to improve upon any of the data or analytical techniques/equations used in Level I to develop the following design parameters.

C6.2.3.1

The primary difference between Level I and Level II analyses is the accuracy of the information used to compute the design water elevations and wave parameters. Depending on the circumstances, a Level II analysis may be performed initially or following a Level I analysis. Where a Level I analysis has preceded Level II,

INTERA

Met/ocean parameters used in the force and moment calculations

Storm Water Level (ft)	Associated Significant Wave Height (ft)	Peak Wave Period (sec)	Water Depth d_s (ft)	λ (ft)	H_{max} (ft)	Depth Limited Wave Height (ft)	Steepness Limited Wave Height (ft)	η_{max} (ft)
8.3	5.3	4.6	28.3	104.4	9.5	18.4	14.9	

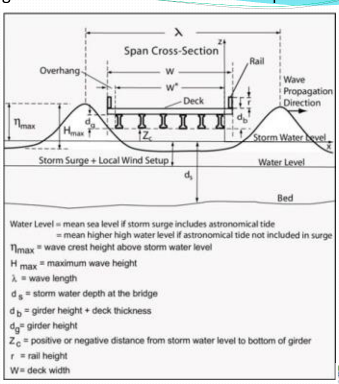
INTERA

Met/ocean parameters used in the force and moment calculations

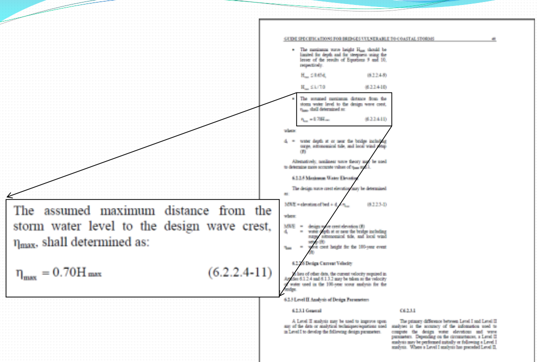
Storm Water Level (ft)	Associated Significant Wave Height (ft)	Peak Wave Period (sec)	Water Depth d_s (ft)	λ (ft)	H_{max} (ft)	η_{max} (ft)
8.3	5.3	4.6	28.3	104.4	9.5	

INTERA

Figure 6.1.2.2.1-1 Nomenclature in Equations 1-8



INTERA

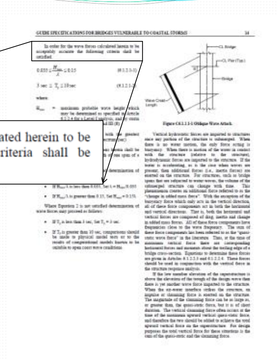


INTERA

Met/ocean parameters used in the force and moment calculations

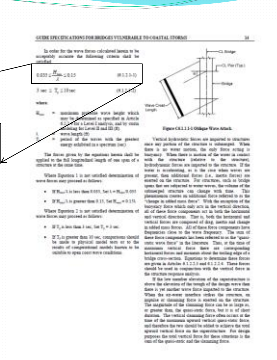
Storm Water Level (ft)	Associated Significant Wave Height (ft)	Peak Wave Period (sec)	Water Depth d_s (ft)	λ (ft)	H_{max} (ft)	η_{max} (ft)
8.3	5.3	4.6	28.3	104.4	9.5	6.7

INTERA



In order for the wave forces calculated herein to be acceptably accurate the following criteria shall be satisfied:

INTERA



$$0.035 \le \frac{H_{max}}{\lambda} \le 0.15 \qquad (6.1.2.1\text{-}1)$$

INTERA

Met/ocean parameters used in the force and moment calculations

Storm Water Level (ft)	Associated Significant Wave Height (ft)	Peak Wave Period (sec)	Water Depth d_s (ft)	λ (ft)	H_{max} (ft)	η_{max} (ft)
8.3	5.3	4.6	28.3	104.4	9.5	6.7

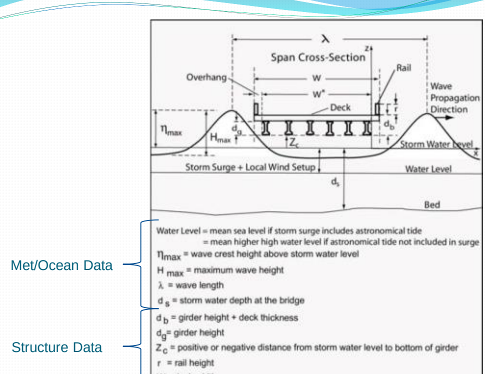
Steepness = H_{max}/λ = 9.5/104.4 = 0.091

INTERA

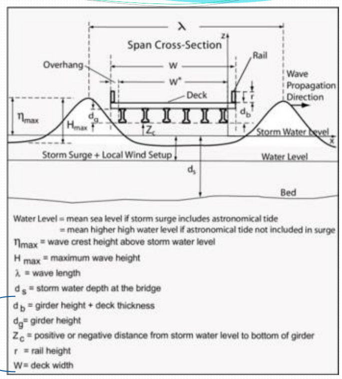
Met/ocean parameters used in the force and moment calculations

Storm Water Level (ft)	Associated Significant Wave Height (ft)	Peak Wave Period (sec)	Water Depth d_s (ft)	λ (ft)	H_{max} (ft)	η_{max} (ft)
8.3	5.3	4.6	28.3	104.4	9.5	6.7

INTERA



INTERA



Structure Data

Bridge Recall No. 003440 superstructure data

Low Chord (ft)	Z_c (ft)	Span Length (ft)	Span Width (ft)	Deck Height (ft)	Over Hang (ft)	Beam Height (ft)	Number of Beams	Rail Height (ft)
10.5		35	33.5	1.43	1	1.43	0	2.667

Met/ocean parameters used in the force and moment calculations

Storm Water Level (ft)	Associated Significant Wave Height (ft)	Peak Wave Period (sec)	Water Depth d_s (ft)	λ (ft)	H_{max} (ft)	η_{max} (ft)
8.3	5.3	4.6	28.3	104.4	9.5	6.7

Bridge Recall No. 003440 superstructure data

Low Chord (ft)	Z_c (ft)	Span Length (ft)	Span Width (ft)	Deck Height (ft)	Over Hang (ft)	Beam Height (ft)	Number of Beams	Rail Height (ft)
10.5	2.2	35	33.5	1.43	1	1.43	0	2.667

INTERA

Surge/wave loading at time of maximum horizontal force

PBM			Parametric Equations		
Maximum Horizontal Force (kips)	Associated Vertical Force (kips)	Associated Moment about the Trailing Edge (ft-kips)	Maximum Horizontal Force (kips)	Associated Vertical Force (kips)	Associated Moment about the Trailing Edge (ft-kips)
48	96	649	83	131	3869

INTERA

Surge/wave loading at time of maximum vertical force

PBM			Parametric Equations		
Maximum Vertical Force (kips)	Associated Horizontal Force (kips)	Associated Moment about the Trailing Edge (ft-kips)	Maximum Vertical Force (kips)	Associated Horizontal Force (kips)	Associated Moment about the Trailing Edge (ft-kips)
177	41	1859	314	41	6755

INTERA

Criticality and Load Factors

For this bridge LADOTD assigned a Criticality of 3

Criticality Index	Description
1	Minor impact to economy or emergency needs if closed (alternative routes exist)
2	Medium impact if closed - may lead to a barrier island but an alternative route exists
3	Major impact if closed – only road to a barrier island, evacuation route with no reasonable alternatives
4	Extreme impact if closed – Interstate or major economic connector (detour very long)

Criticality and Load Factors

5.1 LIMIT STATES AND PERFORMANCE OBJECTIVES FOR BRIDGES, OR SPANS OF BRIDGES WHICH CANNOT BE RAISED ABOVE THE WAVE ZONE

Bridges which are designated as "critical/essential" by the owner should be designed at the strength limit state using Equation 5.2-1 to achieve a performance level of "Service Immediate," or "Repairable Damage," depending on how quickly they must be passable after the hurricane.

Criticality and Load Factors

"Typical bridges", considered secondary to rescue and recovery may be designed at the Extreme Event Limit State for the performance level of major repair or replacement needed, primarily due to superstructure dislodgement.

Criticality and Load Factors

Where bridges are designed for the Strength Limit State, the following load combination shall be considered, in addition to the minimum load specified in Article 5.3, for bridges vulnerable to wave or surge forces associated with coastal storms:

$$\gamma_p DC + \gamma_p DD + \gamma_p DW + \gamma_p EL + \gamma_{wave} WA \quad (5.2\text{-}1)$$

where:

DC	=	dead load of structural components and nonstructural attachments
DD		downdrag
DW	=	dead load of wearing surfaces and utilities
EL	=	accumulated locked-in force effects resulting from the construction process, including the secondary forces from post-tensioning
WA	=	wave forces F_V, F_S, F_H and M_T specified in Articles 6.1.2 and 6.1.3
γ_p	=	minimum load factors for dead loads as specified in Article 3.4.1 of the *AASHTO LRFD Bridge Design Specifications*
γ_{wave}	=	load factors on wave forces

The load factor for wave loads, γ_{wave}, shall be taken as 1.75.

Where bridges are designed for the Extreme Event Limit State, the design force requirement shall be taken as that given by Equation 1 with the load factors for wave forces taken as unity.

INTERA

Criticality and Load Factors

$$\gamma_p DC + \gamma_p DD + \gamma_p DW + \gamma_p EL + \gamma_{wave} WA \quad (5.2\text{-}1)$$

where:

DC	=	dead load of structural components and nonstructural attachments
DD		downdrag
DW	=	dead load of wearing surfaces and utilities
EL	=	accumulated locked-in force effects resulting from the construction process, including the secondary forces from post-tensioning
WA	=	wave forces F_V, F_S, F_H and M_T specified in Articles 6.1.2 and 6.1.3
γ_p	=	minimum load factors for dead loads as specified in Article 3.4.1 of the *AASHTO LRFD Bridge Design Specifications*
γ_{wave}	=	load factors on wave forces

INTERA

Example Problem Conclusions

- Vulnerability Index = Load Factor x Wave Force / Deadweight
  - Vulnerability Index = (1.75 x 314)/246 = 2.2
  - Since the Vulnerability Index is greater than 1, the bridge is vulnerable

INTERA

Possible Additional Work

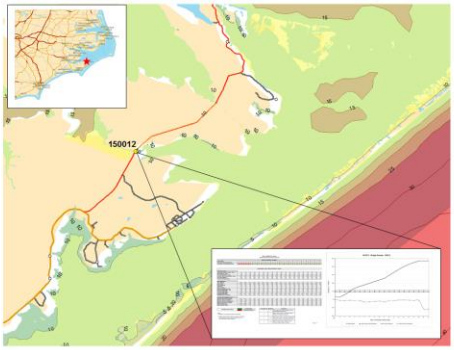
Possible Additional Work

- Additional met/ocean information and a computer program that may be of interest and use
  - Vulnerability analysis for all spans on bridges determined to be vulnerable in this analysis
  - Additional GIS databases with
    - 10-year return interval met/ocean parameters
    - 25-year return interval met/ocean parameters
    - 50-year return interval met/ocean parameters
    - Maximum met/ocean parameters for actual storms
    - Maximum met/ocean parameters for actual + shifted path storms

Possible Additional Work Cont.)

- Addition of pdf pop-up with structural information (used in surge and wave loading analysis) in Surge and Wave Atlas
- Development of a Visual Basic Program to evaluate the vulnerability of a bridge span following the methodology and equations in the AASHTO Specification
  - Input to the program:
    - Met/ocean values from the Surge and Wave Atlas
    - Structural parameter values
  - Output:
    - Surge wave and resistive forces and moments
    - Span vulnerability

Pop-up with Structure Information



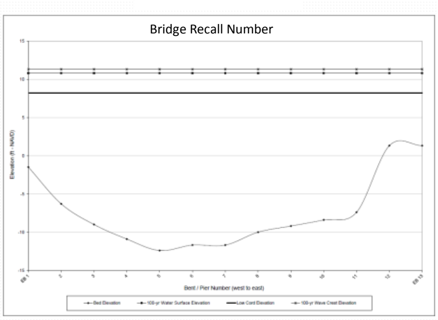
Pop-up with Structure Information

BRIDGE VULNERABILITY SUMMARY												
SPAN NUMBER	1	2	3	4	5	6	7	8	9	10	11	12
CRITICALITY INDEX (defined below)	4	4	4	4	4	4	4	4	4	4	4	4
VULNERABILITY INDEX (defined below)	2.0	2.0	2.0	2.0	2.0	2.7	2.0	2.0	2.0	2.0	2.0	2.0

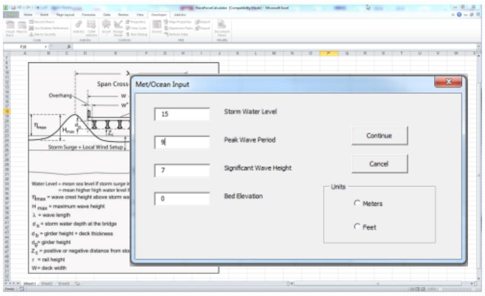
SURGE/WAVE LOAD COMPUTATION INPUT VALUES												
HYDRAULIC VALUES												
100-yr Water Surface Elevation (ft - NAVD)	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8
Bed Elevation (ft - NAVD)	-1	-6	-9	-11	-12	-12	-10	-9	-8	-7	1	1
Low Chord Elevation (ft - NAVD)	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2
100-yr Max Wave Crest Elevation (ft - NAVD)	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3
100-yr Wave Height (ft)	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
100-yr Wave Period (seconds)	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8
SPAN PROPERITES												
Span Length (ft)	24.3	23.5	25.5	24.6	24.5	39.2	24.5	24.5	24.5	24.5	24.5	24.5
Span Width (ft)	25.3	25.3	25.3	25.3	25.3	25.3	25.3	25.3	25.3	25.3	25.3	25.3
Deck Thickness (ft)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Overhang (ft)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Number of Beams	6	6	6	6	6	4	6	6	6	6	6	6
Beam Dead Weight (lb/lf) - Each	52	52	52	52	52	52	52	52	52	52	52	52
Beam Dead Weight (kip/ft) - Total	0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Slab Dead Weight (kip/ft)	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
Total Dead Weight (kip/ft)	2.2	2.2	2.2	2.2	2.2	2.1	2.2	2.2	2.2	2.2	2.2	2.2
Resisting Moment (kft/ft)	25.8	25.8	25.8	25.8	25.8	24.6	25.8	25.8	25.8	25.8	25.8	25.8
Resisting Vertical Force (kip/ft)	2.2	2.2	2.2	2.2	2.2	2.1	2.2	2.2	2.2	2.2	2.2	2.2
100-YEAR FORCE-MOMENT VALUES												
Maximum Vertical Force (kips/span)	50.3	48.0	52.5	50.4	50.1	101.3	50.2	50.4	50.3	50.3	50.2	50.2
Maximum Vertical Force (kips/ft)	2.1	2.0	2.1	2.0	2.0	2.6	2.0	2.1	2.1	2.1	2.0	2.0
Maximum Horizontal Force (kips/span)	0.9	0.9	1.0	0.9	0.9	2.3	0.9	0.9	0.9	0.9	0.9	0.9
Maximum Horizontal Force (kips/ft)	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Maximum Moment (k-ft)	726.9	696.8	761.5	729.5	724.3	1487.5	727.7	731.9	731.1	729.1	723.8	723.8
Maximum Moment (k-ft/ft)	30.0	29.6	29.9	29.7	29.6	38.0	29.7	29.9	29.8	29.8	29.5	29.5

Vulnerability Index Legend		
	(green)	Not Vulnerable
	(red)	Potentially Vulnerable

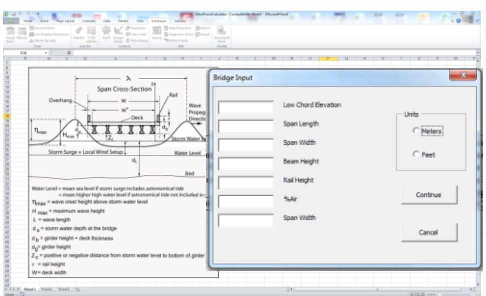
Pop-up with Structure Information



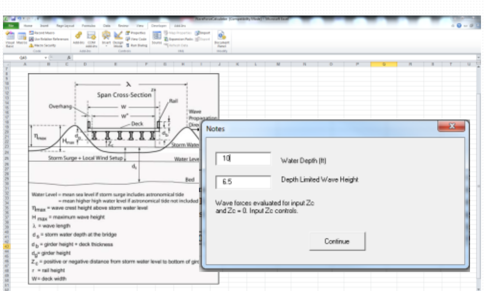
Possible Program Format



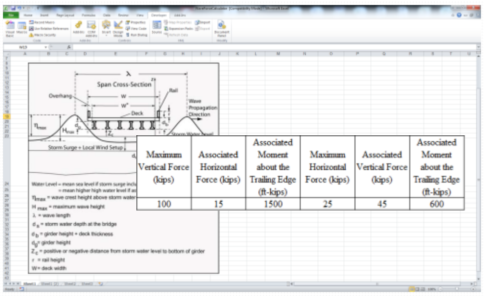
Possible Program Format (cont.)



Possible Program Format (cont.)



Possible Program Format (cont.)



Maximum Vertical Force (kips)	Associated Horizontal Force (kips)	Associated Moment about the Trailing Edge (ft-kips)	Maximum Horizontal Force (kips)	Associated Vertical Force (kips)	Associated Moment about the Trailing Edge (ft-kips)
100	15	1500	25	45	600

Questions/Comments