WAVE FORCE GUIDANCE FOR COASTAL STRUCTURES VULNERABLE TO COASTAL STORMS
Outline

- Background
- Guidance Development
- Method Validation
- Applications
- Summary and Conclusions
Background

- Loss of four (and several minor) bridges in the southeast due to surge/wave loading
  - I-10, Escambia Bay (Pensacola, FL)
  - US-90, Biloxi Bay (Biloxi, MS)
  - US-90, Saint Louis Bay (Bay Saint Louis, MS)
  - I-10, Lake Pontchartrain (New Orleans, LA)
Background – Bridge Failures

1 – Pensacola, FL
2 – Bay St. Louis, MS
3 – Biloxi, MS
Background – Bridge Failures

1, 2 – I-10 Escambia Bay, FL
3 – Biloxi, MS
4 – I-10 near Mobile, AL
Guidance

- American Association of State Highway Transportation Officials Guide Specifications for Bridges Vulnerable to Coastal Storms
  - Modjeski & Masters Inc. – Prime
  - OEA, Inc.
  - Moffat and Nichol, Inc.
  - D’Appolonia, Inc.
  - Dr. Dennis R. Mertz
Guidance

- Avoid wave forces on superstructure
  - Design low member elevation above 100-yr wave crest elevation plus 1 ft freeboard

- Mitigate wave forces
  - Reduce amount of trapped air between beams
  - Use slab spans instead of girders to lessen superstructure depth and reduce trapped air

- Accommodate wave forces
Wave Forces

- Significant work on wave loads on *vertical* structures
- Very little work on wave loads on *horizontal* structures
  - Open coast piers – H.R. Wallingford (McConnell et al., 2004)
  - Limited laboratory tests
- Objective
  - Develop method for predicting horizontal and vertical wave forces and moments on bridge spans located in coastal and inland waters
Offshore Structures

- Long, large amplitude waves
- Small variations in velocities and accelerations over structure
- Structure has minor effect on wave
Coastal/Inland Structures

- Short, small amplitude waves
- Large variations in velocities and accelerations over span
- Structure has major effect on wave
Wave Forces

**Definition Sketch**
- Flat Bottom – No Air Entrapment
- Slow Varying Force

**Girder Span (9 Girders)**
- Air Entrapment
- Quasi-Static Force
- Multiple Slamming Forces

**Submerged Span**
- Total Force (Only Quasi-Static)
Development Overview

1. Mathematical model development
2. Computer program to evaluate model
3. Calibrate model with laboratory data – drag and inertia coefficients
4. Verify model with field data
5. Use model to generate data (numerical experiments)
6. Apply data to develop AASHTO parametric equations
7. UF wave tank tests
Mathematical Model

- Developed for Bridge Superstructure Shapes
  - Slab spans
  - Girder spans (possible air entrapment)
- Based on concepts in
  - Morison’s equation for wave forces on vertical piles
  - Kaplan’s method for wave forces on offshore platform decks
Mathematical Model

Quasi-static + slamming forces

\[ F_H = F_{\text{Drag}} + F_{\text{Inertia}} + F_{\text{CAM}} + F_{\text{Slam}} \]

\[ F_V = F_{\text{Buoyancy}} + F_{\text{Drag}} + F_{\text{Inertia}} + F_{\text{CAM}} + F_{\text{Slam}} \]

\[ F_{\text{Drag}} = C_d \frac{1}{2} \rho L w V |V| \]

\[ F_{\text{Inertia}} = C_{\text{Inertia}} \frac{d(m_e V)}{dt} = \left( C_{\text{cam}} \frac{dm_e}{dt} V + C_{m m_e} \frac{dV}{dt} \right) \]

\[ F_{\text{Buoyancy}} = \rho g \mathcal{V} \]

where \( \mathcal{V} = \) wetted volume
Mathematical Model

\[ m_e = m_s + m_a \]

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

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

\[
\frac{\partial m_{av}}{\partial t} = \frac{\rho \pi L W^2}{4 \left[ 1 + \left( \frac{W}{b_d} \right)^2 \right]^{1/2} \left[ 1 + \frac{1}{2} \left( \frac{b_d}{W} \right)^{0.4} \right]} \left[ 2 \frac{\partial W}{\partial t} - \frac{W}{W^2 + L^2} \right] + \left[ \frac{1}{5} \left( \frac{b_d}{W} \right)^{0.4} \left( \frac{\partial b_d}{\partial t} - \frac{\partial W}{\partial t} \right) \right]
\]

\( \rho \equiv \text{Density of water} \)

\( W \equiv \text{Wetted span width} \)

\( L \equiv \text{Span length} \)

\( b_d \equiv \text{Wetted span height} \)

\( t \equiv \text{Time} \)
Physical Modeling

- Need laboratory data to determine drag and inertia coefficients
- Wave tank tests at Coastal Engineering Laboratory at University of Florida
Physical Modeling

- **Testing Conditions**
  - Non-breaking, monochromatic waves
  - Varied wave period
  - Varied wave height
  - Varied water depth
  - Varied deck elevation relative to water level

- **Test Sequence**
  - Flat plate
  - Slab span
  - Girder span
Physics Based Model

- Stream Function Theory computes WSE along the wave and the velocities and accelerations.
- Compute wave forces at each time step as the wave(s) propagate past the span.
Physics Based Model

- **Input**
  - Span dimensions and elevation
  - Water depth at span
  - Water level
  - Wave height and period

- **Output**
  - Horizontal forces
  - Vertical forces
  - Moment about centroid
Validation – Part 1

- I10 – Escambia Bay Bridges – Hurricane Ivan (2005)
  - Refined Hurricane Ivan hindcast
  - Good span by span damage assessment
- Use PBM with hindcast met/ocean parameters to predict forces on each span
  - Percent air entrapment unknown
    - Compute for 0% and max. % (74%)
Validation – Part 1

I-10 Bridge over Escambia Bay

Gulf of Mexico

East Bay

Escambia Bay

Pensacola Bay

Santa Rosa Sound
Validation – Part 1
**Maximum Resistance**

**74% Air**

**0% Air**

**Failed Spans**
Validation – Part 2

- Howard Frankland Approach Bridge – St. Petersburg, FL
  - Constructed 1959
  - Most severe storm since 1959
    - 1968 Hurricane Gladys
  - Met/Ocean Conditions at Site
    - Storm surge + wind setup = 6.8 ft
    - Maximum wave height = 2.7 ft
    - Wave period = 2 sec
  - Clearance = -0.7 ft
Validation – Part 2
Total Vertical Force

- AASHTO
- Wallingford
- Vertical Resistance

Time (Hrs):
132.5, 133, 133.5, 134, 134.5, 135, 135.5, 136, 136.5, 137, 137.5, 138, 138.5, 139, 139.5, 140

Total Vertical Force (kips):
0, 50, 100, 150, 200, 250, 300, 350, 400
Physics Based Model

- PBM run for a wide range of structure and met/ocean conditions:
  - Structure
  - Span type (slab, girder)
  - Girder type
  - Span width
  - Position relative to water level
  - Water depth
  - Wave height
  - Wave period
Physics Based Model

- Data extracted from PBM results
  - Maximum vertical force
    - Associated horizontal force
    - Associated moment
  - Maximum horizontal force
    - Associated vertical force
    - Associated moment

- *Data generated with PBM used to develop parametric AASHTO equations*
Bridge Applications

- OEA evaluated 100’s of coastal bridges in FL and NC as part of wave vulnerability studies
- Some constructed examples:
  - A. Max Brewer Bridge (SR 406 over Indian River Lagoon), Brevard County
  - Flagler Memorial Bridge (SR A1A over ICWW), Palm Beach County
  - US 90 Bridge over Bass Hole Cove (upper Escambia Bay), Santa Rosa County
Pier/Dock Applications

- Titusville Veterans' Memorial Fishing Pier
  - Completed: 2010
  - Engineer: DRMP (OEA)
Pier/Dock Applications

- Bahia Urbana Waterfront Redevelopment Project Pier
  - Completed: 2012
  - Engineer: Taylor Engineering

Photo Credit: Taylor Engineering
Summary and Conclusions

- AASHTO Guide Specification provides parametric equations for use with **coastal** design
- Bridge, pier, and fixed dock applications
- Conservative load predictions = $$$ retrofit/construct coastal infrastructure
- Non-conservative load predictions = potential loss of structures and lives
Wave Force Guidance for Coastal Structures Vulnerable to Coastal Storms

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Thank You

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