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DEVELOPMENT OF GUIDE SPECIFICATIONS AND HANDBOOK OF RETROFIT OPTIONS FOR BRIDGES VULNERABLE TO COASTAL STORMS

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GUIDE SPECIFICATIONS FOR BRIDGES VULNERABLE TO COASTAL STORMS
Outline of Presentation

• Review of development of wave force predictor method – PBM and Parametric equations
• Levels of analysis
• Limit states and performance levels
• Calibration and reliability
• Conclusions
Introduction/Background

- Storm Surge and Wave Damage in Gulf of Mexico States
  - 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)
Basis for Choosing Wave Force Calculation Method

• Relationship to Experimental Results
• Prediction of Failures
• Theoretical Completeness
• Practicality
Review and Supplement

Ongoing Force Studies

• Wave Force Methods Initially Under Consideration:
  – Wallingford Exponential
  – Wallingford Linear
  – Douglas
  – Modified Kaplan

• After Some Review Wallingford Exponential Fell Out

• After Initial Comparisons Douglas Fell Out
Computer Model

• OEA, In-house Developed Computer Model, “Physics Based Model” (PBM)
  – Evaluates Bridge Superstructure Math Model
Quasi-static and slamming forces treated separately
Slamming force computed using parametric equation based on laboratory data
Total force = quasi-static + slamming
Moments as well as forces essential to computing structural response
Test with Girder Span
PBM Tracks Pressure Distribution as Wave Advances
Comparison Between Predicted and Measured Total Forces

Predicted (PBM) and Measured Total Vertical Force

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<th>Test</th>
<th>Predicted</th>
<th>Measured</th>
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Total Vertical Force

Graph showing Total Vertical Force with data points for 74% Air Entrapment, 0% Air Entrapment, Vertical Resistive Force, and Location of Damaged Spans. The graph includes a span number axis and a vertical force axis.
Development of Parametric Force/Moment Equations

- Need for algebraic predictive equations for AASHTO Specifications
- Not practical to conduct laboratory tests on wide range of structure widths, girder types, etc.
Development of Parametric Force/Moment Equations

• PBM was 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
Development of Parametric Force/Moment Equations

• Data generated with PBM used to determine the relationships between the dimensionless groups (i.e. the PARAMETRIC EQUATIONS)
Parametric Force/Moment Equations

• Data extracted from PBM results
  – Maximum vertical force and associated horizontal force and moment about lower trailing edge
  – Maximum horizontal force and associated vertical force and moment about lower trailing edge
Parametric Total Vertical Force

- 74% Air Entrapment
- 0% Air Entrapment
- Vertical Resistive Force
- Location of Damaged Spans

Span Number
Information Needed to Predict Storm Surge and Wave Forces/Moments on Bridges

- Design water elev. (storm surge + wind set-up)
- Water depth
- Design wave parameters (wave height and period, water particle velocities and accelerations)
- Structure Parameters (span type, dimensions, etc.)
- Span elevation relative to design water elevation
Met/Ocean Conditions

• Design water elevation
  – Design storm surge elevation
  – Local wind setup

• Design wave height and period
Met/Ocean Conditions

- Uses max surge, wave height and current simultaneously
- Surge may include astronomical tide and wind setup---need to verify
- Use of simultaneous maxes thought to be generally quite conservative
  - Exception-bridge near middle of large, roundish bay
  - FDOT/OEA Tampa Bay study may tell how conservative.
Three levels of analysis:

• Level 1 – Use existing information, FEMA/other storm surge elevation, empirical equations for computing wave heights and periods

• Level 2 – Use improved methods to refine storm surge and wave conditions (may employ computer models for surge and/or waves)

• Level 3 – More detailed analysis that can include hurricane hindcasting
Limit States and Performance Levels

- Based on importance – “critical/essential” or “typical”
- Critical/essential defined like 2008 Seismic Guide Specifications
  - Open to all traffic after inspection, rescue and defense immediately
  - Like above but open to all traffic within days
  - Bridges formally designated on emergency plans
- “Typical” – everything else
Limit States and Performance Levels for Coastal Bridges

• **Critical/essential-strength limit state** should be used. Performance levels:
  – “Service Immediate”
    • Sufficiently undamaged, stable and aligned for rescue and recovery after cursory inspection
    • Backfill behind abutments can be sacrificial
  – “Repairable Damage”
    • Some repairs needed to go in service
    • Owner species outage duration
    • Load posting can be considered
    • Pre-positioned replacement spans may be used to meet outage limit
Limit States and Performance Levels for Coastal Bridges

• For “Typical Bridges”- Extreme Event Limit State may be used - Owner’s choice
  – Considered secondary to rescue and recovery
  – Major repair or replacement
  – Whatever time frame satisfies owner
Load Combination

\[ \gamma_p DC + \gamma_p DD + \gamma_p DW + \gamma_p EL + \gamma_{wave} WA \]

**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  
**WA** = wave forces \( F_T \), \( F_S \), \( F_H \) and \( M_T \)  
\( \gamma_p \) = minimum load factors for dead loads per AASHTO LRFD  
\( \gamma_{wave} \) = load factors on wave forces  
= 1.75 for strength, 1.0 for extreme event  
Wind too!
Calibration – the process of using data describing the randomness of load and resistance to determine how often a limit state function is exceeded.

Express as a reliability index, Beta
Calibration

• Limit State Function: $R - Q < 0$
  – $R =$ random resistance based in part on code specified equation with load factors included, and using Bias and COV.
  – $Q =$ a loading combination comprised of randomly varying individual loads based on variability in nature
Calibration

• For coastal spec:
  - $R =$ Dead Load with min load factor plus anchor capacity based on exceeding capacity of exterior tie down when the wave forced associated with the NDWCE overcomes the factored dead load
  - $Q =$ an extreme value of wave forces resulting from a random WCE based on the NDWCE and statistics of wind and surge.
  - Surge usually includes wind set-up and relatively high tide
Calibration

• Reliability index is related to number of times the limit state function is exceeded.

<table>
<thead>
<tr>
<th>BETA</th>
<th>% Exceedence</th>
<th>% Nonexceedence</th>
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<tr>
<td>0</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>1</td>
<td>14</td>
<td>86</td>
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<tr>
<td>2</td>
<td>3</td>
<td>97</td>
</tr>
<tr>
<td>3.5</td>
<td>0.02</td>
<td>99.98</td>
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Calibration

• Sources of data for calibration
  – ASCE study by Kriebel et al
    • II locations from NH to FL
    • Weibull distribution coefficients
    • Wind speeds and their distribution
    • Surge heights and their distribution
Calibration – Wind Data

The graph shows the non-exceedence probability of wind speed for various locations. The x-axis represents wind speed in miles per hour (mph), ranging from 50 to 150. The y-axis represents the non-exceedence probability, ranging from 0 to 1. Each curve corresponds to a different location:

- **Portsmouth**
- **Long Island**
- **Atlantic City**
- **Virginia Beach**
- **Myrtle Beach**
- **Jacksonville**
- **Palm Beach**
- **Ft. Myers**
- **Pensacola**
- **Galveston**
- **Port Isabel**
Calibration – Wind Data

Normalized Wind Speed

Non-exceedence Probability

Portsmouth
Long Island
Atlantic City
Virginia Beach
Myrtle Beach
Myrtle Beach
Palm Beach
Ft. Myers
Pensacola
Ft. Myers
Galveston
Port Isabel
Calibration – Surge Data

[Graph showing non-exceedence probability vs. surge height for various locations, with lines for different cities like Portsmouth, Long Island, Atlantic City, Virginia Beach, Myrtle Beach, Jacksonville, Palm Beach, Ft. Myers, Pensacola, Galveston, and Port Isabel.]
Calibration – Surge Data

Normalized Surge Height

Non-Exceedence Probability

Portsmouth
Long Island
Atlantic City
Virginia Beach
Myrtle Beach
Jacksonville
Palm Beach
Ft. Myers
Pensacola
Galveston
Port Isabel
Calibration

- Sources of data – cont
  - Experience of coastal team members
    - Normal random distribution
    - USCOE equations for $H_S$ and Wave Length
    - COV = 0.2, Bias = 1.0
  - LRFD Specs
    - Dead load – random normal - COV = 0.10, Bias = 1.05
    - Resistance – Lognormal – COV = 0.10, Bias = 1.12
Calibration – Data

- Port Isabel seemed to be most variable wind and surge – used with 3 other sites
- Max depth and max fetch or min depth and min fetch (2 cases) bounded results – no need to look at other combination.
- Average water depths of 6’ and 15’ along fetch were used
- Fetchs of 5,000’ to 40,000’ were used
- AASTO Type III, FLDOT 78” bulb tee, 21’ voided slab and 36” adjacent box
Calibration – Process

• For bridge type
• For bridge width
• For each location
  – Vary fetch & depth (max-max and min-min)
  – Vary position of bridge relative to NDWCE
    • Try 20,000 combinations of random wind speed, surge height, dead load and resistance
    • Count number of time in 20,000 when $R - Q < 0$, probability of failure
    • Convert to reliability index
Calibration – Assumptions

• No account of joint probability of wind and surge, and therefore tide and wind setup
  – Wind and surge both max simultaneously
  – Max-max thought to be conservative
    • possibly very conservative
    • Currently being studied at Tampa Bay
  – Bridge in worst position and orientation
  – $H_{MAX}$ used – Average of highest 1% of waves in a storm, assumed to be $1.8H_S$
Calibration – Type III girders

AASHTO Type III Girders
(for various locations, bridge widths, water depths, and fetch lengths)
Calibration – 78” Bulb Tees

78” Bulb Tee Girders
(for various locations, bridge widths, water depths, and fetch lengths)
Calibration - 21" Voided Slabs

21" Voided Slab
(for various locations, bridge widths, water depths, and fetch lengths)

Reliability Index Beta

Eta - Zc

-10 -8 -6 -4 -2 0 2 4 6 8 10
36" Adjacent Box Girders
(for various locations, bridge widths, water depths, and fetch lengths)
Are These Reliability Indices Acceptable?

- They are certainly less than dead + live
- We expect the nominal LL to be experienced regularly in 75 year life---often weekly or daily
- In coastal case we are dealing with 100 yr wind and surge at same time – neglects joint probability
- Very few bridges will experience design event in their lifetime
Are These Reliability Indices Acceptable?

- Worst combination of location, water depth and fetch length used.
- Using Min load factor for DL – another neglected joint probability
Can Reliability Indices Be Increased?

- Increase Load Factor >1.75

**Effect of Load Factors on Beta**

![Graph showing the effect of load factors on beta](image)

- **Load Factor = 1.75**
- **Load Factor = 2.0**
- **Load Factor = 2.5**
Can Reliability Indices Be Increased?

- Specify a min. tie down load – done for voided slabs
Recommendation

- Stay with recommended load factor = 1.75 for general use
- Owners can make any exceptions they deem necessary
Bridge Superstructure Model

Quasi-Static Force

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

\[ F_V = F_{\text{Buoyancy}} + F_{\text{Drag}} + F_{\text{Inertia}} + F_{\text{CAM}} \]
Bridge Superstructure Model

Quasi-Static Force (cont.)

\[ F_v = \frac{d(m_e V)}{dt} + F_{\text{drag}} + F_{\text{buoyancy}} \]

\[ = \frac{d(m_e V)}{dt} + \frac{1}{2} \rho L w C_d V |V| + F_{\text{buoyancy}} \]

\[ \frac{d(m_e V)}{dt} = \frac{dm_e}{dt} V + m_e \frac{dV}{dt} \]
Bridge Superstructure Model

\[ m_e = m_s + m_a \]

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

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

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

\[
\rho \equiv \text{Density of Water}
\]

\[
W \equiv \text{Wetted Span Width}
\]

\[
L \equiv \text{Span Length}
\]

\[
b_d \equiv \text{Wetted Span Height}
\]

\[
t \equiv \text{Time}
\]
Comparison Between Predicted and Measured Quasi-Static Forces

Predicted (PBM) and Measured Quasi-Static Vertical Force

- Predicted
- Measured

Tests: S043, S047, S053, S057, S063, S067, S073, G043, G047, G053, G057, G063, G067, G073, G077
Quasi-Static Vertical Force

- 74% Air Entrapment
- 0% Air Entrapment
- Vertical Resistive Force
- Location of Damaged Spans

Span Number

Quasi-Static Vertical Force
Parametric Force/Moment Equations

- Time of maximum vertical force

\[ F_{V,MAX} = \text{Maximum Vertical Quasi-Static Force} \]

\[ = f \left( \text{structure type, structure dimensions, water and wave parameters, entrapped air} \right) \]

\[ F_s = \text{Vertical Slamming Force} \]

\[ = f \left( \text{span clearence, and wave parameters} \right) \]
Parametric Force/Moment Equations

- Time of maximum vertical force
  \[ F_{H_{-AV}} = \text{Associated Horizontal Quasi-Static Force} \]
  \[ = f \left( \text{structure type, structure dimensions,} \right) \]
  \[ \text{water and wave parameters} \]

- Associated Quasi-Static Moment about Trailing Edge
  \[ M_{T_{-AV}} = \text{Associated Quasi-Static Moment} \]
  \[ = f \left( \text{maximum vertical force, asso. horizontal force,} \right) \]
  \[ \text{span dimensions and wave parameters} \]
Parametric Force/Moment Equations

• Time of maximum horizontal force

\[ F_{H\text{-MAX}} = \text{Maximum Horizontal Quasi-Static Force} \]

\[ = f \left( \text{structure type, structure dimensions, water and wave parameters} \right) \]
Parametric Force/Moment Equations

• Time of maximum horizontal force

\[ F_{V-AH} = \text{Associated Vertical Quasi-Static Force} \]
\[ = f \left( \text{structure type, structure dimensions, water and wave parameters, and entrapped air} \right) \]

\[ F_s = \text{Vertical Slamming Force} \]
\[ = f \left( \text{span clearence, and wave parameters} \right) \]

\[ M_{T-AH} = \text{Associated Quasi-Static Moment about Trailing Edge} \]
\[ = f \left( \text{maximum horizontal force, asso. vertical force, span dimensions and wave parameters} \right) \]
Parametric Force/Moment Equations

\[ F_{V-MAX} = \gamma_w \bar{W} \beta \left(-1.3 \frac{H_{max}}{d_s} + 1.8\right) \]

\[
\left[1.35 - 0.35 \tanh(1.2 (T_P) - 8.5)\right]
\]

\[
b_0 + b_1 x + \frac{b_2}{y} + b_3 x^2
\]

\[
+ \frac{b_4}{y^2} + \frac{b_5 x}{y} + b_6 x^3\right)\text{(TAF)}
\]
Parametric Force/Moment Equations

\[ \overline{W} = \left[ \lambda - \left( \frac{\lambda}{H} \right) \left( Z_c + \frac{H}{2} \right) \right] \]

If \( \frac{\overline{W}}{W} < 0.15 \) Then \( \overline{W} = 0.15W \)

If \( (\eta_{\text{max}} - Z_c) \leq 0 \), then \( \beta = 0 \)

If \( (\eta_{\text{max}} - Z_c) \leq d_b \), then \( \beta = \frac{\eta_{\text{max}} - Z_c}{d_b} \)

If \( (\eta_{\text{max}} - Z_c) > d_b \), then \( \beta = 1 \)
Parametric Force/Moment Equations

\[ x = \frac{H_{\text{max}}}{\lambda} \]

\[ y = \frac{W}{\lambda} \]

Variables \( b_0 \) through \( b_6 \) and the trapped air factor, TAF, are given in the following slides for girder and slab spans.
Parametric Force/Moment Equations

For Girder Spans

\[ b_1 = -0.18 d_g + 56.7 \text{ ft} \]
\[ b_2 = 0.0028 d_g + 0.0454 \text{ ft} \]
\[ b_3 = 0.2352 d_g - 193.6 \text{ ft} \]
\[ b_4 = -0.00006 d_g - 0.0003 \text{ ft} \]
\[ b_5 = 0.184 d_g - 0.608 \text{ ft} \]
\[ b_6 = 2.1 d_g + 1.56 \text{ ft} \]
Parametric Force/Moment Equations

Trapped Air Factor (TAF)

\[ TAF = A_{AIR}(\%AIR) + B_{AIR} \leq 1.0 \]

\[ A_{AIR} = 0.0123 - 0.0045 e^{(-Z_c/\eta_{\text{max}})} + 0.0014 \ln(W/\nu) \]

\[ B_{AIR} = e^{-2.477 + 1.002 e^{(-Z_c/\eta_{\text{max}})} - 0.403 \ln(W/\nu)} \]

If \( 0 < \frac{\eta_{\text{max}} - Z_c}{d_g} \leq 1 \), then \( \%\text{Air} \) may be selected from \( 100 \left[ 1 - \left( \frac{\eta_{\text{max}} - Z_c}{d_g} \right) \right] \) to the maximum amount possible.
Trapped Air Factor (TAF)

If \( 0 < \frac{n_{\text{max}} - Z_c}{d_g} \leq 1 \), then %Air may be selected from

\[
100 \left[ 1 - \left( \frac{n_{\text{max}} - Z_c}{d_g} \right) \right]
\]

to the maximum amount possible.

If \( \frac{n_{\text{max}} - Z_c}{d_g} > 1 \), then %Air may be selected from the range 0 to the maximum amount possible.
Parametric Equations Verification

- Compute forces on I-10 Escambia Bridge Spans
- Compare with resistive forces
Parametric Quasi-Static Vertical Force

- 74% Air Entrapment
- 0% Air Entrapment
- Vertical Resistive Force
- Location of Damaged Spans

Span Number

| Span Number | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | 100 | 105 | 110 | 115 | 120 |
|-------------|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 74% Air Entrapment | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ | ▪ |
| 0% Air Entrapment | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| Vertical Resistive Force | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ | ▢ |
| Location of Damaged Spans | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
Met/Ocean Conditions

• Level 1 Analysis
  – FEMA storm surge elevations
  – If not in FEMA storm surge, wind setup equation
  – USA Corps of Engineers empirical wave equations
  – Wave-induced water particle velocities and accelerations from online wave model/other
  – Current velocities from BHRs or other studies
Met/Ocean Conditions

• Level 2 Analysis
  – Obtain better bathymetric data
  – Obtain better wind data
  – Refine FEMA/other storm surge predictions
  – Use computer wave model to improve wave parameter predictions
Met/Ocean Conditions

• Level 3 Analysis
  – Improved storm surge analysis
    • Hindcast of record storm at site
    • Hindcast of all storms impacting site
  – Improved wave parameters
    • Hindcast wave field for record storm
    • Hindcast wave fields for all storms impacting site
Definition Sketch

Span Cross-Section

\[ \eta_{\text{max}} \]
\[ H \]

Wind

Storm Water Level

Mean Water Level

Bed

Grid

Storm Surge

\[ d_s \]