Coastal Bridge Vulnerability due to Hurricane Wave Action

- Jeff Pouliotte, PE, FDOT, State Structures Maintenance Engineer
- Phil Dompe, PE, INTERA Inc., Senior Coastal and Hydraulic Engineer
- Atiq Alvi, PE, T.Y. Lin International, Vice President
Bridge Wave Vulnerability Introduction and History

- Hurricane Ivan – 2004
- Hurricane Katrina – 2005
- FDOT Hurricane Wave Vulnerability Study with Ocean Engineering
- FDOT District 6 – Keys Bridge Emergency Response Plans (ERP)
- FDOT District 7 – Tampa Bay Bridge ERP
- FDOT Statewide ERP Effort
Bridge Wave Vulnerability Presentation

- The Presentation is divided into three Parts:
  - Hurricane Wave Action Study - Phil Dompe
  - Structural Evaluation of Wave Actions on Bridges and Emergency Response Plan - Atiq Alvi
  - Owner’s Perspective - Jeff Pouliotte
Motivation - Failures

  - I-10 over Escambia Bay, FL
- Hurricane Katrina (2005)
  - I-10 over Lake Pontchartrain, LA
  - US 90 over Bay St. Louis, MS
  - US 90 over Biloxi Bay, MS
- Hurricane Camille (1969)
- Hurricane Frederic (1979)
Motivation - Cost

• Replacement Bridges
  • Lost investment in the asset
  • Loss of commerce
  • Cost of repair/temporary and replacement bridge

• Example: I-10 over Lake Pontchartrain
  • Repair exceeded $30 million
  • Replacement exceeded $800 million
  • Largest public works contract in LA history
Motivation

- Recent failures due to combination of storm surge and wave loading
- Wave and surge forces not included in bridge design
  - Need to assess risk of existing bridges
Wave and Surge Forces/Moments on Superstructure

- AASHTO Guide Specification for Bridges Vulnerable to Coastal Storms
  - Wave force equations (parametric equations Based on INTERA’s Physics Based Model or PBM)
  - Guidance for developing design conditions
  - Load combinations
Information Needed to Predict Storm Surge and Wave Forces/Moments on Bridges

• Design water elevation
• Design wave parameters (wave height and period)
• Structure parameters (span type, dimensions, etc.)
• Span elevation relative to the design water elevation
Design Water Elevation

- In coastal waters – Design water elevation = storm surge + local wind setup + wave setup

- Sources
  - FEMA Flood Insurance Studies
  - Computer models
Design Wave Parameters

- Wave heights and periods depend on:
  - Wind speed and duration
  - Fetch length
  - Water depth

- Sources
  - Empirical equations
  - Computer models
AASHTO Guidance for Design Conditions

- Three levels of analysis:
  - Level I – Use existing information, FEMA/other storm surge elevation, ASCE 7-05 wind maps, and empirical equations for computing wave heights and periods
  - Level II – Use improved methods to refine storm surge and wave conditions (may employ computer models for surge and/or waves)
  - Level III – More detailed analysis that includes hurricane hindcasting
FDOT Pilot Study
Level III Approach

- Develop and calibrate WAM, SWAN, and ADCIRC models
- Identify a list of storms from the historical record
- Hindcast storms with WAM, SWAN, and ADCIRC Models
- Apply extreme value analysis to the model results
- Calculate wave forces and assign vulnerability indices
Model Development

WAM Grid
Model Development

SWAN Grids
Model Development

ADCIRC (Surge/Hydraulic) Model Mesh
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

- WAM and SWAN calibration compares wave heights and periods

- ADCIRC calibration compares measured tide and storm surge
Model Calibration

WAM Calibration Summary
Model Calibration (cont.)

SWAN Calibration Summary
Model Calibration (cont.)
ADCIRC Calibration Summary

Tidal Calibration
Model Calibration (cont.)

ADCIRC Calibration Summary

Hurricane Gordon Calibration

Graph showing water surface elevation (m-MSL) over time from 9/15/00 12:00 to 9/21/00 12:00, with measured and ADCIRC data compared.
Hurricane Hindcasts

- Historical Hurricane Data
  - Wind and Pressure Fields for Historical Events
  - Provides Inputs to Hindcast Simulations
  - 1850-2004
  - 11 Hurricanes, 15 Tropical Storms, 1 Winter Storm
Hurricane Hindcasts (cont.)

- ADCIRC+SWAN
  - ADCIRC
    - Input – wind, pressure, tidal constituents, and radiation stresses
    - Passes – WSE and currents
  - SWAN
    - Input – wind, WSE, and currents
    - Passes – radiation stresses
Model Results

- Water surface elevations
- Wave heights and periods
- Wave crest elevations
Example Model Results

Maximum Water Surface Elevations during the 1852 Unnamed Hurricane

Maximum Water Surface Elevations during the 1921 Unnamed Hurricane
Example Model Results

Maximum of the Maximum Wave Heights for all the Hurricane Hindcasts

Maximum of the Maximum Wave Crest Elevations for all the Hurricane Hindcasts
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

- **Case 1**
  - 100-Year maximum wave height and the associated water surface elevation at each bridge

- **Case 2**
  - 100-Year maximum water surface elevation and the associated wave heights at each bridge
Extreme Value Analysis
West bound Howard Franklin Bridge

Elevation (ft - MSL)

Bed Elevation
100-yr Water Surface Elevation
Low Cord Elevation
100-yr Wave Crest Elevation

Bent / Pier Number (west to east)
Wave and Surge Loading

Equations

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

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

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

where \( V \) = wetted volume

\[ m_e = \text{effective mass} = \text{mass displaced} + \text{added mass} \]
Wave and Surge Loading

Equations (cont.)

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

\[\rho \equiv \text{Density of Water}\]
\[W \equiv \text{Wetted Span Width}\]
\[L \equiv \text{Span Length}\]
\[b_d \equiv \text{Wetted Span Height}\]
\[t \equiv \text{Time}\]
INTERA developed Computer Model, “Physics Based Model” (PBM)

- Evaluates storm surge/wave force and moment equations at each element and at each time step
- Has built-in nonlinear wave model to compute wave velocities and accelerations
- Used to develop the parametric equations in the AASHTO Specifications
Wave and Surge Loading

- Maximum Vertical Force
  - Associated Horizontal Force
  - Associated Moment
- Maximum Horizontal Force
  - Associated Vertical Force
  - Associated Moment
- Maximum Moment
  - Associated Vertical Force
  - Associated Horizontal Force
Wave and Surge Loading
West bound Howard Franklin Bridge
Wave and Surge Loading

Limit states and performance objectives

- Bridges designated by the owner as “critical/essential”
  - Design at the strength limit state
    - Wave force load factor = 1.75
- Bridges designated by the owner as “typical bridges”
  - Design at the extreme event limit state
    - Wave force load factor = 1.00
### Wave and Surge Loading

#### Vulnerability Index

- **VI** = \((LF \times \text{Wave Load})/\text{resistance}\)

<table>
<thead>
<tr>
<th>Bridge Number</th>
<th>Owner Designation</th>
<th>Load Factor</th>
<th>Vulnerability Index</th>
<th>Conclusion</th>
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Wave and Surge Loading

- Initial 52 Bridges
Wave and Surge Loading

- 11 Critical Bridges (8 locations)
## Critical Bridges

<table>
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<tr>
<th>Point Label</th>
<th>Location</th>
<th>Year Built</th>
<th>Spans</th>
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<td>SR 600 EB over Old Tampa Bay (Gandy)</td>
<td>1974</td>
<td>250</td>
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<tr>
<td>D</td>
<td>SR 60 over Old Tampa Bay</td>
<td>1974</td>
<td>10</td>
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<tr>
<td>E</td>
<td>SR 60 over Old Tampa Bay (Courtney Campbell Causeway)</td>
<td>1974</td>
<td>5</td>
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<tr>
<td>F</td>
<td>SR 60 over Rocky Point Creek</td>
<td>1952</td>
<td>5</td>
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<tr>
<td>G</td>
<td>SR 687 NB over Big Island Gap</td>
<td>1959</td>
<td>5</td>
</tr>
<tr>
<td>H</td>
<td>SR 687 SB over Big Island Gap</td>
<td>1954</td>
<td>5</td>
</tr>
<tr>
<td>I</td>
<td>I-275 over Big Island Gap</td>
<td>2004</td>
<td>5</td>
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<tr>
<td>J</td>
<td>SR 580 WB over Safety Harbor Bay</td>
<td>1988</td>
<td>5</td>
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<tr>
<td>K</td>
<td>SR 580 EB over Safety Harbor Bay</td>
<td>1988</td>
<td>5</td>
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</table>
Inundation Map of Critical Bridges
Map of Critical Bridges
Howard Frankland Bridges
Map of Critical Bridges
Courtney Campbell Causeway Bridge (West)
Map of Critical Bridges
Courtney Campbell Causeway Bridge (East)
Map of Critical Bridges
SR 60 over Rocky Point Point
Map of Critical Bridges
SR 687/Big Island Gap Bridges
Map of Critical Bridges
I-275/Big Island Gap Bridges
# Vulnerable Bridges

## Retrofit Costs

<table>
<thead>
<tr>
<th>Point Label</th>
<th>Location</th>
<th>Retrofit Cost Estimate (1.0 Load Factor)</th>
<th>Retrofit Cost Estimate (1.75 Load Factor)</th>
<th>Estimated Remaining Service Life (Years)</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>I-275 SB over Old Tampa Bay (Howard Frankland)</td>
<td>$52,308</td>
<td>$5,174,672</td>
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<td>$113,114,174</td>
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<td>$49,464,417</td>
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<td>25</td>
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<td>E</td>
<td>SR 60 over Old Tampa Bay (Courtney Campbell Causeway)</td>
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<td>$608,855</td>
<td>20</td>
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<td>F</td>
<td>SR 60 over Rocky Point Creek</td>
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<td>$53,760</td>
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<td>G</td>
<td>SR 687 NB over Big Island Gap</td>
<td>$227,000</td>
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<td>SR 687 SB over Big Island Gap</td>
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<td>15</td>
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<td>I</td>
<td>I-275 over Big Island Gap</td>
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<td>$89,222</td>
<td>50</td>
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<td>J</td>
<td>SR 580 WB over Safety Harbor Bay</td>
<td>$891,337</td>
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<td>50</td>
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<td>K</td>
<td>SR 580 EB over Safety Harbor Bay</td>
<td>$625,600</td>
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<td>Total Costs</td>
<td></td>
<td>$26,138,245</td>
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# Vulnerable Bridges

## Structural Analysis Results

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<tr>
<th>Point Label</th>
<th>Location</th>
<th>Substructure Analysis (1.0 Load Factor)</th>
<th>Substructure Analysis (1.75 Load Factor)</th>
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<tbody>
<tr>
<td>A</td>
<td>I-275 SB over Old Tampa Bay (Howard Frankland)</td>
<td>Stable</td>
<td>Unstable</td>
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<tr>
<td>B</td>
<td>I-275 NB over Old Tampa Bay (Howard Frankland)</td>
<td>Unstable</td>
<td>Unstable</td>
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<tr>
<td>C</td>
<td>SR 600 EB over Old Tampa Bay (Gandy)</td>
<td>Unstable</td>
<td>Unstable</td>
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<tr>
<td>D</td>
<td>SR 60 over Old Tampa Bay</td>
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<td>Unstable</td>
</tr>
<tr>
<td>E</td>
<td>SR 60 over Old Tampa Bay (Courtney Campbell Causeway)</td>
<td>Unstable</td>
<td>Unstable</td>
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<tr>
<td>F</td>
<td>SR 60 over Rocky Point Creek</td>
<td>Unstable</td>
<td>Unstable</td>
</tr>
<tr>
<td>G</td>
<td>SR 687 NB over Big Island Gap</td>
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<td>H</td>
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<tr>
<td>I</td>
<td>I-275 over Big Island Gap</td>
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<tr>
<td>J</td>
<td>SR 580 WB over Safety Harbor Bay</td>
<td>Stable</td>
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<tr>
<td>K</td>
<td>SR 580 EB over Safety Harbor Bay</td>
<td>Stable</td>
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</table>
# Vulnerable Bridges

## Retrofit Cost Estimates

<table>
<thead>
<tr>
<th>Point Label</th>
<th>Location</th>
<th>Year Built</th>
<th>Retrofit Cost Estimate (1.00 Load Factor) Based on Economy</th>
<th>Retrofit Cost Estimate (1.35 Load Factor) Based on Economy</th>
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<tbody>
<tr>
<td>F</td>
<td>SR 60 over Rocky Point Creek</td>
<td>1952</td>
<td>$7,680</td>
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<td>H</td>
<td>SR 687 SB over Big Island Gap</td>
<td>1954</td>
<td>$227,000</td>
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<tr>
<td>B</td>
<td>I-275 NB over Old Tampa Bay (Howard Frankland)</td>
<td>1959</td>
<td>$18,515,000</td>
<td>$29,379,356</td>
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<tr>
<td>G</td>
<td>SR 687 NB over Big Island Gap</td>
<td>1959</td>
<td>$227,000</td>
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<td>D</td>
<td>SR 60 over Old Tampa Bay</td>
<td>1974</td>
<td></td>
<td></td>
</tr>
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<td>J</td>
<td>SR 580 WB over Safety Harbor Bay</td>
<td>1988</td>
<td>$891,337</td>
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<td>K</td>
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<td>1988</td>
<td>$625,600</td>
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<td>A</td>
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<td>I</td>
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<td>2004</td>
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<td>$61,340</td>
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<td><strong>Total Costs</strong></td>
<td></td>
<td><strong>$26,138,245</strong></td>
<td><strong>$65,850,552</strong></td>
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</table>
Vulnerable Bridges

Retrofit Conceptual Designs
Vulnerable Bridges

Retrofit Conceptual Designs
Vulnerable Bridges

Retrofit Conceptual Designs

NOTE:
1. All structural steel shall conform for AASHTO M270 Grade 30
2. All anchor bolts shall be hot-dipped galvanized.
3. Applicable to Project Number 110664

1-1/2 x 1/2" Plate
On Reeded
Deck Slab

-deck slab

TYPE I ELEVATION

SECTION A-A
Vulnerable Bridges

Retrofit Conceptual Designs

NOTE:
1. All structural steel shall conform for ASTM A 500 Grade 50.
2. All anchor bolts shall be hot-dipped galvanized.
3. Applicable to project number 100064.
Vulnerable Bridges
Retrofit Conceptual Designs

NOTE:
1. ALL STRUCTURAL STEEL SHALL CONFORM FOR AASHTO M30 GRADE 50
2. ALL ANCHOR BOLTS SHALL BE HOT DIPPED GALVANIZED
3. APPLICABLE TO PROJECT NUMBER 150108, 150014 AND 150107
Vulnerable Bridges

Retrofit Conceptual Designs

NOTE:
1. ALL STRUCTURAL STEEL SHALL CONFORM FOR A36/ASTM A653 GRADE 33.
2. ALL ANCHOR BOLTS SHALL BE HOT DIPPED GALVANIZED.
3. APPLICABLE TO PROJECT NUMBER 10830.
Emergency Response Plan

Vulnerable Bridges

- Superstructure retrofit costs too high
- Substructures failing

Result ➔ Emergency Response Plan (ERP)
Emergency Response Plan

Objective

- Coordinated response to damage to vulnerable bridge(s)
- Identify potential traffic control measures
- Help accelerate the bridge repair process
Emergency Response Plan

Main Contents

- Situation
- Concept of Operations
- Roles and Responsibilities
- Detour Routes for Bridge Damage Scenarios
Emergency Response Plan

Options Considered for Vulnerable Bridges

- Detours
- Ferry Boats
- Temporary Bridges
Emergency Response Plan

FDOT Stock: Acrow 300,700 Series and Mabey Bridging

- FDOT owns approximately 9,300 feet
- An average of 5,000 feet is available at one time
- 60 feet long spans
- Primarily used for construction projects
- Substructure
  - Existing Bridge’s if in tact
  - Steel girders for temporary substructure
  - Steel pipe or H-piles for temporary foundation
Emergency Response Plan

Acrow Bridges
# Emergency Response Plan

**Acrow Bridges**

<table>
<thead>
<tr>
<th>Point Label</th>
<th>Location</th>
<th>Vulnerable Span Length(s)</th>
<th>Total Vulnerable Span Lengths (ft)</th>
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<td>43'-0&quot;</td>
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<td>61'-6&quot;</td>
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<td>G</td>
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<td>K</td>
<td>SR 580 EB over Safety Harbor Bay</td>
<td>70'-0&quot;</td>
<td>490.00</td>
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</table>
Emergency Response Plan

FDOT Temporary Bridging (Acrow and Mabey)

- If needs exceed the 9,300 feet, contractor will need to buy/rent temporary bridging.
  - Buy at $140K/Unit and $1.2K/Unit Shipping
  - Additional orders can be manufactured in days
- FDOT normally has 5,000 feet of temporary bridging in stock
- Borrow from Louisiana DOT- Owns 3,000 feet
Owner’s Perspective

- **New Bridges:**
  - Bathometric Study needed to Optimize Design
  - Design Bridge Superstructures above Storm Surge
  - Design Bridge Superstructures to withstand Wave Action Forces

- **Existing Bridge Superstructures below Storm Surge Elevations:**
  - Most Bridges are not designed to withstand Wave Action Forces
  - Most Bridges cannot be economically retrofitted to withstand Wave Action Forces
  - Cost of Bridge Replacement is prohibitive and storm return interval is unknown
  - Damage to Bridge Embankments and Approach Roadways likely

- **FDOT Statewide ERP Effort**
Summary of ERP Considerations

- Bridges need to be evaluated and ERPs need to be prepared prior to Event
- Quick response is an economic and a life/safety concern
- Communication network and personnel roles need to be established prior to Event
- Contact Lists to concerned parties need to be established and maintained (first responders, utility companies, local governments, police, Coast Guard, etc.)
- Utility damage may occur and site access may be limited
- Identify potential construction staging areas, prior to an event
Summary of ERP Considerations (cont.)

• Identify alternate detour routes, ferry locations, airports, etc., prior to an event

• Extent of Bridge Damage will vary as will damage to Approach Roadways

• ERP needs to outline potential courses of action depending upon severity of Event

• Potential Resources need to be identified ahead of time

• Environmental Issues and Permits need to be addressed

• Coordinate with FHWA and FEMA for assistance and funding

• ERP is preliminary and needs to change when circumstances change
Thank you

Questions?

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