Multi-hazard Bridge Design Criteria

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Outline

• Challenges: From LRFD to Multi-hazard LRFD

• Multi-hazard Design Guide Development

• Roadmap for Future Study
Bridge Design Specifications

Past, Present, and Moving Forward

- WSD
- LFD
- LRFD (non-extreme loads)
- MH-LRFD (all loads)
- MH-LRFD (performance-based)
- Sustainability Design
The Goals for the Multi-hazard Bridge Design Development

• What?
  – Risk-based design
  – Straightforward implementation
  – Consistent with current LRFD

• Why?
  – Need more consistent safety
  – Need less waste in over-design
  – Need ease of future development/implementation
FHWA Studies on Consistent Multi-hazard Design

- Study Carried out by MCEER
  - Pilot Study, 2007-2008
    - Monograph stating the present problems and potential approaches
  - Framework Development and Survey, 2008-2014
    - Principles for considering all hazards on a consistent basis
    - Procedures for Multi-hazard calibration

- Current Study Led by Genex
  - Applies the Framework for calibration of select Limit States
Current Project: Multi-hazard Bridge Design Criteria

- Period: 9/2014 - 6/2017
- Research Team
  - Genex Systems (Contact: Jerry Shen)
  - MCEER
  - Modjeski and Masters
  - Arora and Associates
  - FHWA: Starting: W. Philip Yen
    Current: Sheila Duwadi (COR)
Relevant Projects

- FHWA Multi-hazard Design Research 2011
- NCHRP 12-48 (Extreme Hazard)
- NCHRP 12-49 (Seismic)
- NCHRP 12-33 (LRFD Calibration)
- NCHRP 24-31, 24-35 (Foundation Calibration)
- NCHRP 12-36, 12-47, 12-86 (Redundancy)
- NCHRP 24-34 (Scour)
- FHWA Identification of Redundancy Factor Modifiers (ongoing)
Extreme Events

• Working Definition: Those limit states where we allow the structure to exhibit behavior beyond that expected at the strength and service limit states.

• Have not generally been calibrated to achieve any specific reliability.

• Limited current guidance on which loads/conditions to combine.
Limit State—defined deterministically
AASHTO LRFD Design Limit State Equations
\[ \phi R_n = \gamma Q_n \]

To increase bridge reliability, i.e., reduce probability of failure:
1. Increase Load Factor
2. Reduce Resistance Factor

\( Q = \text{Load} \quad R = \text{Resistance} \)

\( \gamma \): Load factor
\( \phi \): Resistance factor

Probability Density Function

\( \mu_R - \mu_Q \)

Probability of failure

\( x_{\gamma} \times x_{\phi} \)

\( Q_n \)

\( R_n \)
AASHTO LRFD Design Limit State Equations

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\[ \gamma \text{: Load factor} \]
\[ \phi \text{: Resistance factor} \]
LRFD with Extreme Events (Multi-hazard)

- Reliability of LRFD is calibrated for dead load and live load applied on superstructure.
- Reliability for other loads and components are NOT fully calibrated.
- Extreme Events: higher risk, but less frequent.

<table>
<thead>
<tr>
<th>Load Combination Limit States</th>
<th>Dead Load*</th>
<th>Live Load</th>
<th>Water Load</th>
<th>Wind Load on Bridge</th>
<th>Wind Load on Truck</th>
<th>Use One of These at a Time</th>
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</thead>
<tbody>
<tr>
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<td>Earthquake</td>
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<td>Blast</td>
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<td>Ice Load</td>
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<td>Vehicular Collision</td>
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<td>Vessel Collision</td>
</tr>
</tbody>
</table>

- **Strength I**: 1.25, 1.75, 1.00, –, –, –, –
- **Strength II**: 1.25, 1.35, 1.00, –, –, –, –
- **Strength III**: 1.25, –, 1.00, 1.40, –, –, –
- **Strength IV**: 1.50, –, 1.00, –, –, –, –
- **Strength V**: 1.25, 1.35, 1.00, 0.40, 1.00, –, –
- **Service I**: 1.00, 1.00, 1.00, 0.30, 1.00, –, –
- **Service II**: 1.00, 1.30, 1.00, –, –, –, –
- **Service III**: 1.00, 0.80, 1.00, –, –, –, –
- **Service IV**: 1.00, –, 1.00, 0.70, –, –, –
- **Extreme Event I**: 1.25, 0.00, 1.00, –, –, 1.00, –
- **Extreme Event II**: 1.25, 0.5, 1.00, –, –, 1.00, 1.00, 1.00

Calibrated for superstructure
Not calibrated & Unknown risk
Challenges in the Probabilistic Analysis

- Characteristics of loads
  - Time-variable vs. time-invariable
  - Correlation among loads/conditions and resistance
- Redundancy (System Reliability)
- Variation in practice
- Multidisciplinary design considerations (structure, geotech, hydraulics, seismic, etc.)
- Simplicity of design formulas
Correlation of Time-Variable Loads

Correlated Loads

\[ Q_1 \cup Q_2 = Q_1 + Q_2 \]

Independent Loads

\[ Q_1 \cup Q_2 < Q_1 + Q_2 \]
Variations in Practice

- Example: foundation design with scour consideration

(a) Long term degradation + Contraction scour
(b) Design option 1
(c) Design option 2

- Soils
- Bed after scour
- Required pile length
- Local scour (complex pier)
- Local scour (single pier)
- Bed after scour
Calibration Approach

Procedure for Code Writer

- Deterministic Analysis

Equation for Bridge Designer

- Nominal Loads, Resistance and Scour ($Q_n, R_n & y_s$)

Track 1

Nominal Loads, Resistance and Scour ($Q_n, R_n & y_s$)

Statistical Models

- Probability of failure $\phi R_n = \sum \eta_i y_i Q_{ni}$

Calibrated Reliability

Target $\beta$

Statistical Models

- Probability of failure $\phi R_n$

Calibrated Load and Resistance Factors

Track 2A

Track 2B
Calibration Cases

• Calibration 1—Strength I
  – DL + LL ∪ SC
  – Current Design: Full factored dead load and live load with 1.0 total scour from design flood
  – 90 Bridges of three bridge spans, three hydrology uncertainties, two types of piles and five design methods

• Calibration 2—Extreme Event I
  – DL + LL ∪ SC ∪ EQ
  – Current Design: Full factored dead load ~0.5 live load with 1.0 or less total scour from design flood (scour varies among states) and 1.0 earthquake
  – Vertical Forces on Piles
  – Lateral Forces on Piles
Demo Calibration Case –
DL + LL U SC U EQ

Pile Loads and Resistance
Seismic Loading

• Seismic load from plastic hinge—capacity protection design

Gravity and moment from EQ

Pile moment
Pile shear

Soil reaction force

Horizontal force
Variation of Design Cases

- Pile capacity method
  - Meyerhof (Sand)
  - Nordlund (Sand)
  - $\alpha$-Tomlinson (Clay)
  - $\beta$ method (Clay)
  - $\lambda$ method (Clay)

- Displacement pile and non-displacement pile

- Bridge span (varies DL/LL and scour components)

- Hydrological uncertainty (varies scour)
Identify possible failure mechanisms

- Different failure mechanisms can lead to different limit state equations.

- Force demand

\[
\phi(1 - \gamma_{SR} q_{SR}) R_n \geq \gamma_D Q_D + \gamma_L Q_L + \gamma_{EARS} (1 - \gamma_{SQ} q_{SQ}) Q_E
\]

\[
\phi R_n \geq S_n \left( \gamma_D Q_D + \gamma_L Q_L + \gamma_{EARS} (1 - \gamma_{SQ} q_{SQ}) Q_E \right)
\]

- Capacity protection

\[
\phi (1 - \gamma_S S_n) R_n = \gamma_D Q_D + \gamma_L Q_L + \gamma_E Q_E
\]

\[
\phi R_n = S_n \left( \gamma_D Q_D + \gamma_L Q_L + \gamma_E Q_E \right)
\]

- Displacement demand

\[
\phi_{\Delta_c} \left[ \left( 1 + \gamma_{SAc} q_{SAc} \right) \Delta_f + \Delta_{col} + \Delta_p \right] \geq \gamma_{E\Delta_D} \left( 1 + \gamma_{SA_D} q_{SA_D} \right) \Delta_D
\]
Option 1: Constant Reliability for all Methods (Target $\beta = 2.00$)
No Constraint on Factors

Option 2: Constant Reliability for all Methods (Target $\beta = 2.00$)
Fix $\phi = 1.00, \gamma_D = 1.25, \gamma_L = 0.50$

Option 3: Constant Reliability for all Methods (Target $\beta = 2.00$)
Fix $\phi = 1.00, \gamma_D = 1.25, \gamma_L = 0.50, \gamma_s = 0.00$

Option 4: Constant Reliability for all Methods (Target $\beta = 2.00$)
Fix $\phi = 1.00, \gamma_D = 1.25, \gamma_L = 0.50, \gamma_s = -1.00$

Option 5: Constant Reliability for all Methods (Target $\beta = 2.00$)
Fix $\gamma_E = 1.00, \gamma_D = 1.25, \gamma_L = 0.50, \gamma_s = -1.00$

Option 6: Constant Reliability for all Methods (Target $\beta = 2.00$)
Fix $\gamma_E = 1.00, \gamma_D = 1.25, \gamma_L = 0.50, \gamma_s = -1.50$

Option 7: **Different Reliability** for each Methods (Target $\beta$ Varies)
Fix $\gamma_E = 1.00, \gamma_D = 1.25, \gamma_L = 0.50, \gamma_s = -1.50$

<table>
<thead>
<tr>
<th>Method</th>
<th>Nordlund (Sand)</th>
<th>$\alpha$-Tomlinson (Clay)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-Pile</td>
<td>$\phi$</td>
<td>0.835</td>
</tr>
<tr>
<td>Concrete-Pile</td>
<td>$\phi$</td>
<td>0.802</td>
</tr>
</tbody>
</table>
Reduced Variation of Reliability—Vertical

- Reliability for proposed bridge design equation

\[ \gamma_E = 1.00, \ \gamma_D = 1.25, \ \gamma_L = 0.50, \ \gamma_S = -1.50 \]
Seismic Load on a Pile—Lateral (moment)

- Potential DLSE formulation for lateral force
Seismic Load on a Pile—Lateral (shear)

• Potential DLSE formulation for lateral force
Seismic Load on a Pile—Lateral

- Track 2A - Calibrate the reliability for current bridge design - Lateral

![Estimated Reliability Index (β) for 18 Bridge Cases](image-url)
Findings/Accomplishments in this Project

- Probabilistic analysis tools based on MCEER Framework were developed in this study to consider the complex cases in multi-hazard LRFD calibration.

- Strength I and Extreme Event I Limit States were calibrated for deep (pile) foundation with consideration of scour.

- Scour exhibited significant conservativeness in the vertical load and bending moment on piles, but not in shear load on piles.

- More calibration cases needs to be done considering all practical design details in multiple disciplines.
Roadmap

• A maximum set of calibration cases was composed.
• Unnecessary calibration cases were eliminated when possible.
• Keep formulas simple as possible.
• May need to repeat when new data/technology is available.
• Prioritization
## Roadmap for Future Study
### Dimensions of the Task Matrix

<table>
<thead>
<tr>
<th>Bridge Components</th>
<th>Loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Bridge Elements</td>
<td>• Load Components</td>
</tr>
<tr>
<td>- Beam-Slab</td>
<td>- Moment</td>
</tr>
<tr>
<td>- Truss</td>
<td>- Shear</td>
</tr>
<tr>
<td>- Piers, ...</td>
<td>- Axial Force</td>
</tr>
<tr>
<td>- Foundations</td>
<td>- Displacement</td>
</tr>
<tr>
<td>• System/Sub system</td>
<td></td>
</tr>
<tr>
<td>• Failure Mechanism / Performance Level</td>
<td>• Load Combinations</td>
</tr>
<tr>
<td>- Rupture of longitudinal rebars</td>
<td>- DL + LL ∪ EQ ∪ SC</td>
</tr>
<tr>
<td>- Concrete crushing</td>
<td>- DL + SC</td>
</tr>
<tr>
<td>- Buckling</td>
<td>- DL + LL ∪ EQ</td>
</tr>
<tr>
<td>- Soil failure (displacement limit)</td>
<td>- DL + LL ∪ CV ∪ SC</td>
</tr>
<tr>
<td>- Unseating</td>
<td>- …</td>
</tr>
<tr>
<td>- Shear bar failure</td>
<td></td>
</tr>
</tbody>
</table>
Data Guidelines

• Guidance for loads and resistance
• Important properties:
  – Model uncertainties and randomness from nature
  – Time-dependent /Time-independent intensity
  – Correlation
  – Annual rate of events
  – Duration of an event
• Sample Immediate Needs:
  – Resistance models
  – Scour distribution
Recommended Future Effort

- The complete calibration of LRFD will benefit the bridge owners by offering better basis for decision making.

- It is recommended to set up a plan to gradually complete the calibration of LRFD.

- Bridge design specification is a living document that continues taking advantage of new data and technology.
  - A small cross-disciplinary team working with the SCOBS and bridge community continuously
  - 5 year may be a good calibration/planning cycle
Acknowledgement

• Oversight committee
  – Bruce Johnson, Oregon DOT (Co-chair)
  – Susan Hida, California DOT
  – Richard Pratt, Alaska DOT
  – Wahid Albert, New York DOT
  – Bijan Khaleghi, Washington DOT
  – Wassem Dekelbab, NCHRP
  – Phil Yen, FHWA (Former Chair)
  – Sheila Duwadi, FHWA (Chair)

• Meeting/Documentation
  – Richard Land, GPI
  – Eric Thorkildsen, GPI
Thank you!

Questions? Please contact:

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