Revision of AASHTO LRFD Bridge Design Specification Section 10.4 – Status Update

J. Erik Loehr, Ph.D., P.E.

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Committee on Bridges and Structures Annual Meeting
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Motivation

Low Site Variability

High Site Variability

AASHTO LRFD Specifications, 2012
Opportunity…

- If we do this right…
  - Can improve consistency of achieving target reliability
  - Can enable and empower designers to get appropriate investigations
  - Can design more efficiently
  - Can reduce risk for design and construction

…without adding excessive complexity to design!
Requirements

- We have to change the code…while still maintaining practicality and usefulness

- We will have to calculate/estimate variability and uncertainty for design parameters in some way…
  
  …some added complexity is necessary!

- We will need conscientious effort to develop and effectively implement
Codes Reviewed

- AASHTO LRFD Specification – 8th Edition
- FHWA GEC 5 – 2017 Revision
- MoDOT Engineering Policy Guidelines
- Canadian Highway Bridge Design Code – S6-14: Update No. 1 – April 2016
  - BC Ministry of Transportation & Infrastructure Supplement to CHBDC
- Eurocode 7: EN1997
- Select state guidelines/specifications
<table>
<thead>
<tr>
<th>Characteristic Value</th>
<th>AASHTO</th>
<th>AASHTO-GEC5</th>
<th>MoDOT EPG</th>
<th>Euro7</th>
<th>CHBDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean?</td>
<td>Mean?</td>
<td>Mean?</td>
<td>Mean?</td>
<td>Mean?</td>
<td>Mean?</td>
</tr>
<tr>
<td>Factors</td>
<td>Resistance</td>
<td>Resistance</td>
<td>Partial</td>
<td>Both</td>
<td>Resistance</td>
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<tr>
<td>Parameter Uncertainty</td>
<td>Prescriptive</td>
<td>Prescriptive</td>
<td>Quantitative</td>
<td>Quantitative</td>
<td>Subjective</td>
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<tr>
<td>Distinguish Indirect/Derived Parameters</td>
<td>No</td>
<td>Sort of?</td>
<td>Yes</td>
<td>Yes and No</td>
<td>No?</td>
</tr>
</tbody>
</table>
2017 Update to GEC-5

- Content on parameter uncertainty dramatically expanded, including consideration of indirect measurements
- Challenging to rigorously address uncertainty within constraints of current AASHTO code
- As a stop-gap measure, recommended:
  - “important” design parameters be established to have $COV_{model} \leq 0.30$
  - If $COV_{model} > 0.30$, conservative estimates for design parameters should be used
AASHTO w/ GEC-5

**Low Site Variability**

- Over Reliable
- Satisfactory
- Under Reliable

**High Site Variability**

- Over Reliable
- Satisfactory
- Under Reliable

AASHTO LRFD Specifications, 2012
Resistance Factor for Unit Tip Resistance, $\phi_{qp}$

COV of Mean Uniaxial Compressive Strength, $COV_{qu}$

- Bridges on Minor Roads
- Bridges on Major Roads
- Major Bridges (<$100 million)
- Major Bridges (>=$100 million)

AASHTO Value
MoDOT EPG Performance

Low Variability Site

High Variability Site

Number of Measurements, \( n \)

Percentage of cases

Satisfactory

Under Reliable

Over Reliable

Over Reliable

Satisfactory

Under Reliable
Example…

- Bridge on major road
- Drilled shaft foundations
- Factored load of 3000 kips
- Site characterization from Frankford Load Test site used as example
Example: minimal characterization

Uniaxial Compressive Strength, $UCS$ (ksf)

- Maquoketa Formation A
  - $\mu_{UCS} = 3.5$ ksf
  - $COV_{model} = 0.14$

- Maquoketa Formation B
  - $\mu_{UCS} = 6.1$ ksf
  - $COV_{model} = 0.48$

- Maquoketa Formation C
  - $\mu_{UCS} = 68.1$ ksf
  - $COV_{model} = 0.12$
Example: extensive characterization

Uniaxial Compressive Strength, $UCS$ (ksf)

- Maquoketa Formation A
  - $\mu_{UCS} = 3.3$ ksf
  - $COV_{model} = 0.06$

- Maquoketa Formation B
  - $\mu_{UCS} = 10.4$ ksf
  - $COV_{model} = 0.15$

- Maquoketa Formation C
  - $\mu_{UCS} = 66.2$ ksf
  - $COV_{model} = 0.03$
**Implications - example**

**Minimal Characterization**
- 3000 kip factored load
- Required shaft:
  - 4-ft diameter
  - 25-ft length
- Nominal cost: $15,000 per shaft

**Extensive Characterization**
- 3000 kip factored load
- Required shaft:
  - 4-ft diameter
  - 17-ft length
- Nominal cost: $10,000 per shaft

Benefit of added characterization is approximately $5000 per shaft
What might this look like in new AASHTO?
Eurocode 7

- Uses so-called “Partial Factors” applied to loads, material parameters, and/or resistances

- Design parameters used are so-called “characteristic values”:
  - Defined as “…[values] selected as a cautious estimate of the value affecting the occurrence of the limit state”
  - May be selected subjectively or objectively using statistical methods
  - Values are fundamentally less than the mean value
\[ X_{\text{characteristic}} = X_{\text{mean}} (1 - k_n CV_x) \]
What might this look like in new AASHTO?

- “base” resistance factors would look similar to now
- Would add a “parameter uncertainty factor” that would be multiplied by “base resistance factor
- Complexity of “parameter uncertainty factor” is yet to be determined
  - Fundamentally varies with different design methods and parameters
  - Might be able to approximate for broader application?
## CHBD Code

<table>
<thead>
<tr>
<th>Application</th>
<th>Limit state</th>
<th>Test Method/Model</th>
<th>Degree of understanding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow foundations</td>
<td>Bearing, $\phi_{gu}$</td>
<td>Analysis</td>
<td>0.45 0.50 0.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scale model test</td>
<td>0.50 0.55 0.65</td>
</tr>
<tr>
<td></td>
<td>Sliding, $\phi_{gu}$ Frictional</td>
<td>Analysis</td>
<td>0.70 0.80 0.90</td>
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<td></td>
<td></td>
<td>Scale model test</td>
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<tr>
<td></td>
<td>Sliding, $\phi_{gu}$ Cohesive</td>
<td>Analysis</td>
<td>0.55 0.60 0.65</td>
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<tr>
<td></td>
<td></td>
<td>Scale model test</td>
<td>0.60 0.65 0.70</td>
</tr>
<tr>
<td>Passive resistance, $\phi_{gu}$</td>
<td>Analysis</td>
<td>0.40 0.50 0.55</td>
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<tr>
<td>Settlement or lateral movement, $\phi_{gs}$</td>
<td>Analysis</td>
<td>0.7 0.8 0.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scale model test</td>
<td>0.8 0.9 1.0</td>
<td></td>
</tr>
</tbody>
</table>

(Continued)
Degree of Understanding

- High understanding - extensive project-specific investigation procedures and/or knowledge are combined with prediction models of demonstrated quality to achieve a high level of confidence with performance predictions.

- Typical understanding — typical project-specific investigation procedures and/or knowledge are combined with conventional prediction models to achieve a typical level of confidence with performance predictions.

- Low understanding — limited representative information (e.g., previous experience, extrapolation from nearby and/or similar sites) combined with conventional prediction models to achieve a lower level of confidence with performance predictions.
What might this look like in new AASHTO?

- Would look similar to what is provided in CHBDC
- Values based on calculated uncertainty rather than subjective variability
- Suggest adopt explicit ranges for uncertainty rather than subjective approach
# Pros and cons

<table>
<thead>
<tr>
<th>Approach</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>MoDOT</td>
<td>• Familiar application</td>
<td>• Significant revision to form</td>
</tr>
<tr>
<td></td>
<td>• Most accurate/precise</td>
<td>• Error potential?</td>
</tr>
<tr>
<td></td>
<td>• Most “transparent”</td>
<td></td>
</tr>
<tr>
<td>Eurocode (i.e. modification factor)</td>
<td>• Least revision to code</td>
<td>• Introduces additional term</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Likely least accurate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Least “transparent”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Judgment difficult</td>
</tr>
<tr>
<td>CHBDC</td>
<td>• Familiar application</td>
<td>• Intermediate accuracy &amp; transparency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• “perverse incentives”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Adds significant complexity to tables</td>
</tr>
</tbody>
</table>
Recommendations and Discussion Topics

- Questions/concerns?
- General thoughts/feedback?
Consequences of changes

- Perhaps shown comparison of OLS vs. Weighted Deming Regression from DD
Need buy in for:

- Using uncertainty in mean rather than variability
- Get feedback on using mean value as characteristic value.
Mean value of $s_u$

Mean undrained shear strength, $\mu_{s_u}$ (psf)

<table>
<thead>
<tr>
<th>Number of measurements, $n$</th>
<th>Mean undrained shear strength, $\mu_{s_u}$ (psf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5000</td>
</tr>
<tr>
<td>10</td>
<td>4500</td>
</tr>
<tr>
<td>20</td>
<td>4000</td>
</tr>
<tr>
<td>30</td>
<td>3500</td>
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<tr>
<td>40</td>
<td>3000</td>
</tr>
<tr>
<td>50</td>
<td>2500</td>
</tr>
</tbody>
</table>

Pemiscot Site

95th percentile = 6025 psf when $n=3$

Warrensburg Site

95th percentile = 6025 psf when $n=3$
COV of $s_u$ - “variability and uncertainty”

Total variability and uncertainty for $s_u$, $COV_{s_u}$

Number of measurements, $n$

95$^{th}$ percentile=3.7 when $n=3$
95$^{th}$ percentile=2.4 when $n=4
COV of mean $s_u$ - “uncertainty”

Pemiscot Site

Uncertainty in mean $s_u$, $COV_{\mu_{s_u}}$

Number of measurements, $n$

Warrensburg Site

Uncertainty in mean $s_u$, $COV_{\mu_{s_u}}$

95th percentile = 3.4 when $n=3$
95th percentile = 2.0 when $n=4$
Resistance Factors

- Strength I limit state, $\phi = 0$ conditions

![Graph showing resistance factors for different coefficient of variations.](image)

- Modified AASHTO
  - $p_f \approx 1/1,500$

- AASHTO (2012)
  - $p_f \approx 1/4,300$

- MoDOT (2011) & Modified MoDOT
  - $p_f \approx 1/1,500$
Simulation Results – $p_f$

$n = N$

$n = 25$

Pemiscot Site

Satisfactory

Under Reliable

Over Reliable

0.5 \cdot p_T

1.0 \cdot p_T

1.5 \cdot p_T

Frequency of $p_f$

Probability of Failure, $p_f$
Benefits of variable resistance factors

- Produce greater precision without undue effort
  ➔ Using funds where most needed

- Provide quantifiable value to site characterization
  ➔ Improves decision making

- Illustrate most significant source of variability
  ➔ Promotes continuous improvement

- Use of guidelines is saving MoDOT money
Tip resistance – shafts in clay

Resistance Factor for Unit Tip Resistance, $\phi_{tp}$

COV of Mean Undrained Shear Strength, $C_{OV_{su}}$
Side resistance – shafts in hard rock

![Graph showing the relationship between COV of Mean Uniaxial Compressive Strength and Resistance Factor for Unit Side Resistance. The graph compares different categories of bridges: Bridges on Minor Roads, Bridges on Major Roads, Major Bridges (<$100 million), and Major Bridges (>=$100 million).]
Tip resistance – shafts in shale using SPT

![Graph showing the relationship between COV of Mean Equivalent SPT N-value and Resistance Factor for Unit Tip Resistance.]

- Bridges on Minor Roads
- Bridges on Major Roads
- Major Bridges (<$100 million)
- Major Bridges (>$100 million)
Test quantity modifier

\[ \zeta = \frac{(n + 2.5)}{(n - 1)} \]
Conclusions for MoDOT Provisions

- Percentage of “under-reliable” designs is small and practically independent of $n$

- Increasing $n$ increases percentage of “satisfactory” designs while decreasing percentage of “over-reliable” designs

- Improvement most significant for “good sites”
Code Differences

- Definition of “characteristic values”
- “resistance factors” vs. “partial factors”
- Methods for addressing parameter uncertainty
  - Prescriptive
  - Subjective
  - Quantitative
- Consideration of “indirect” or “derived” values
Conclusions for AASHTO Provisions

- Percentage of “satisfactory” designs is small and practically independent of $n$
- Increasing $n$ reduces “under-reliable” designs while increasing “over-reliable” designs

For “good sites”:
- Few designs practically achieve target reliability
- Few under-reliable designs but many over-reliable designs

For “bad sites”:
- Few designs practically achieve target reliability
- Greater numbers of under-reliable designs but fewer over-reliable designs