Incorporation of Foundation Deformations in AASHTO LRFD Bridge Design Process

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R19B Product Page  
http://shrp2.transportation.org/Pages/R19B_ServiceLimitStateDesignforBridges.aspx
Incorporation of Foundation Deformations in AASHTO LRFD Bridge Design Process

Initial SHRP2-TRB Research Team for R19B

- Modjeski and Masters (M&M)
  - John M. Kulicki (Principal Investigator)
  - Wagdy G. Wassef (formerly M&M)
- University of Delaware (UD)
  - Dennis R. Mertz
- University of Nebraska – Lincoln (UNL)
  - Andrzej S. Nowak (now at Auburn)
- NCS Consultants, LLC (NCS)
  - Naresh C. Samtani

History of Work Related to Foundation Deformations

- Project R19B work started in 2009
  - Final Report published in 2015
- Presentations at AASHTO SCOBS Annual T-15 Committee Meetings
  - 2012, New Orleans, LA
  - 2014, Columbus, OH
  - 2015, Saratoga Springs, NY
  - 2016, Minneapolis, MN
- Presentation at AASHTO SCOBS Mid Year Joint Meeting of T-15 and T-5 committees on October 28, 2015, in Chicago, IL; included a flow chart
- Development of examples, draft agenda items for T-15 and T-5 committees, a white paper, and a training course

Authors: Naresh C. Samtani and John M. Kulicki
Bridge Configuration and Foundation Types

**Foundation Deformations**
- Vertical (Settlement)
- Lateral (Horizontal)
- Rotation

**AASHTO Table 3.4.1-1**

| Load Combination Limit State | DC | DD | DW | EH | EV | ES | IM | PL | PS | SH | WA | WS | WL | FR | TU | TG | SE | Use One of These at a Time |
|------------------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|-----------------------------|
| STRENGTH LIMIT               |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |                            |
| I                            | $y_a$ | 0.50 | 1.00 | 0.00 | 0.50 | 1.00 | 1.00 | 0.00 | 0.50 | 1.00 | 0.00 | 0.50 | 1.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 |
| III                          |     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |                            |
| IV                           |     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |                            |
| EXTREME EVENT                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |                            |
| I                            | $y_a$ | 0.50 | 1.00 | 0.00 | 0.50 | 1.00 | 1.00 | 0.00 | 0.50 | 1.00 | 1.00 | 0.00 | 0.50 | 1.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 |
| II                           |     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |                            |
| SERVICE LIMIT                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |                            |
| I                            | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| III                          |     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |                            |
| IV                           |     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |                            |
| FATIGUE - LL, IM & CE only  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |                            |
| I                            |     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |                            |
| II                           |     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |                            |

**Superimposed Deformations**

Reference: Nielson (2005)
Superimposed Deformations

**Article 3.12.6 – Settlement**
- “Force effects due to **extreme values** of differential settlement among substructures and within individual substructure units shall be considered.”

**Commentary**
- “Force effects due to settlement may be reduced by considering creep. Analysis for the load combinations in Tables 3.4.1-1 and 3.1.4-2 which include settlement should be repeated for settlement of each possible substructure unit settling individually, as well as combinations of substructure units settling, that could create critical force effects in the structure.”

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- **Article 3.3 – DEAD LOAD**
  - 3.3.2.1 “If differential settlement is anticipated in a structure, consideration should be given to stresses resulting from this settlement.”

- Since the above stipulation is under the parent article (**3.3, Dead Load**), it implies that settlement effects should be considered wherever dead load appears in the allowable stress design (ASD) or load factor design (LFD) load combinations.
**Key Points**

- Evaluation of differential deformation is mandated by AASHTO bridge design specifications regardless of design platform (ASD, LFD, or LRFD)
  - It is *not a new requirement*

- In LRFD platform,
  - Category of superimposed deformations
  - The $\gamma_{SE}$ load factor appears in both strength and service limit state load combinations

- The uncertainty of predicted deformations needs to be calibrated for the $\gamma_{SE}$ load factor within the overall framework of limit state design

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**Differential Settlement, $\Delta_d$**

- Differential settlement, $\Delta_d$, induces force effects within superstructure
- Differential settlement, $\Delta_d$, when normalized by span length, $L_S$, is an expression of angular distortion
Concept of Differential Settlement and Angular Distortion

<table>
<thead>
<tr>
<th>Span</th>
<th>Differential Settlement, $\Delta_d$</th>
<th>Angular Distortion, $A_d = \Delta_d/L_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\Delta_{d1} =</td>
<td>S_{A1} - S_{P1}</td>
</tr>
<tr>
<td>2</td>
<td>$\Delta_{d2} =</td>
<td>S_{P1} - S_{P2}</td>
</tr>
<tr>
<td>3</td>
<td>$\Delta_{d3} =</td>
<td>S_{P2} - S_{P3}</td>
</tr>
<tr>
<td>4</td>
<td>$\Delta_{d4} =</td>
<td>S_{P3} - S_{A2}</td>
</tr>
</tbody>
</table>

Induced Moments in Continuous-Span Bridges

**EXAMPLE**

$$M_\Delta = \frac{6EI\Delta_d}{L_S^2} = 6 \left( \frac{EI}{L_S} \right) \left( \frac{\Delta_d}{L_S} \right)$$

$$M_\Delta = \text{func} \left( \frac{EI}{L_S} \right) \left( \frac{\Delta_d}{L_S} \right)$$

$EI/L_S$ is a representation of **Structure Stiffness**

$\Delta_d/L_S$ is **Angular Distortion** (dimensionless)
### Limiting (Tolerable) Angular Distortion

- Moulton et al. (1985) – For FHWA
- AASHTO – Standard (ASD) and LRFD Specifications

<table>
<thead>
<tr>
<th>Type of Bridge</th>
<th>Limiting Angular Distortion, $\Delta_d / L_S$</th>
<th>Moulton et al. (1985)</th>
<th>AASHTO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous Span</td>
<td>0.004 (4.8” in 100’)</td>
<td>0.004 (4.8” in 100’)</td>
<td></td>
</tr>
<tr>
<td>Simple Span</td>
<td>0.005 (6.0” in 100’)</td>
<td>0.008 (9.6” in 100’)</td>
<td></td>
</tr>
</tbody>
</table>

For rigid frames, perform case-specific analysis.

### Arbitrary Use of AASHTO Limiting Values

**Examples of arbitrary (inconsistent) application**

- 0.004 $\pm$ 0.0004 or 0.008 $\pm$ 0.0008
- I-25/I-40 T1 (BIG-I), NM: 0.004 $\pm$ 0.002, 0.008 $\pm$ 0.004
- WSDOT (From Chapter 8 of Geotech Design Manual)

<table>
<thead>
<tr>
<th>Total Settlement, $\delta$ at Pier or Abutment</th>
<th>Differential Settlement over 100 ft within Pier or Abutments and Differential Settlement Between Piers [Implied Limiting Angular Distortion, radians]</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta \leq 1”$</td>
<td>$\Delta_{d100} \leq 0.75” [0.000625]$</td>
<td>Design &amp; construct</td>
</tr>
<tr>
<td>$1” &lt; \delta \leq 4”$</td>
<td>$0.75” &lt; \Delta_{d100} \leq 3” [0.000625-0.0025]$</td>
<td>Ensure structure can tolerate settlement</td>
</tr>
<tr>
<td>$\delta &gt; 4”$</td>
<td>$\Delta_{d100} &gt; 3” [&gt; 0.0025]$</td>
<td>Need Dept approval</td>
</tr>
</tbody>
</table>

- Arizona DOT: “The bridge designer should limit the settlement of a foundation per 100 ft span to 0.75 in. Linear interpolation should be used for other span lengths.”
Settlement, $S$, and Angular Distortion, $A_d = \Delta_d / L_S$

- What is a **tolerable** value of $\Delta_d / L_S$?
- How **reliable** is the value of $S$?

Many Methods to Estimate Foundation Movements

- Vertical
  - Immediate settlement
    - Elastic method
    - Hough method
    - Schmertmann
    - Others
  - Long-term settlement
    - Based on 1-D consolidation theory
- Lateral
  - P-y analysis
  - Strain Wedge Method (SWM)
  - Others

- Are all methods equally reliable?
- What is the uncertainty in predicted values?
When is a Bridge Structure Affected?

**CONSTRUCTION POINT CONCEPT**

- Load during construction
- Long-term settlement (if applicable)
- Service Load (Service Limit)
- Factored Load (Strength Limit)
- Vertical Displacement

Foundation could be shallow (spread footings) or deep (piles, shafts, etc.)

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When is a Bridge Structure Affected?

**Construction-Point Concept**

- Riser Pipe
- Pier Wall
- Soil Fill
- Footing
- Tiltmeters
- Contact Pressure Cells
- Settlement Points

**Instrumentation**

Reference: Sargand, et al., (1999); Ohio DOT

**Example Data (Pier)**
Incorporation of Foundation Deformations in AASHTO LRFD Bridge Design Process

Calibration Process for Load Factor $\gamma_{SE}$

- What is the uncertainty in estimated values of foundation deformation?
- Need to express $\gamma_{SE}$ in terms of probability of exceedance (or reliability index)

Concept of Reversible-Irreversible Limit States

- Reversible-irreversible limit state is one where the effect of an irreversible limit state may be reversed by intervention.

- Example: Foundation deformation, which is an irreversible limit state with respect to foundation elements but may be reversible in terms of its effect on the bridge superstructure through intervention, e.g., through use of shims or jacking.

- Target reliability index is a function of reversible, irreversible, and reversible-irreversible limit states
Development of $\gamma_{SE}$ for Different Methods Based on $\beta$ Value

- $\gamma_{SE}=1.25$
- $\gamma_{SE}=1.70$

Section 3, Table 3.4.1-3

<table>
<thead>
<tr>
<th>Bridge Component</th>
<th>PS</th>
<th>CR, SH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superstructures—Segmental Concrete Substructures supporting Segmental Superstructures (see 3.12.4, 3.12.5)</td>
<td>1.0</td>
<td>See $\gamma_P$ for DC, Table 3.4.1-2</td>
</tr>
<tr>
<td>Concrete Superstructures—Non-Segmental Substructures supporting Non-Segmental Superstructures</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>• using $I_g$</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>• using $I_{effective}$</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Steel Substructures</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

- Include the $\gamma_{SE}$ in above table or develop a similar table
Section 3, Proposed New Table 3.4.1-4 for $\gamma_{SE}$

<table>
<thead>
<tr>
<th>Deformation</th>
<th>$\gamma_{SE}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immediate settlement</td>
<td>1.00</td>
</tr>
<tr>
<td>- Hough method</td>
<td></td>
</tr>
<tr>
<td>- Schmertmann method</td>
<td>1.25</td>
</tr>
<tr>
<td>- Local method</td>
<td>*</td>
</tr>
<tr>
<td>Consolidation settlement</td>
<td>1.00</td>
</tr>
<tr>
<td>Lateral deformation</td>
<td></td>
</tr>
<tr>
<td>- P-y or SWM soil-structure interaction method</td>
<td>1.00</td>
</tr>
<tr>
<td>- Local method</td>
<td>*</td>
</tr>
</tbody>
</table>

*To be determined by the owner based on local geologic conditions and target reliability index.

Implementation Tools

- White paper
  - Flow Chart
  - Several examples
- Proposed LRFD specification revisions and commentaries
- SHRP2 Round 7 Implementation Assistance Program (IAP)
Some Observations

- Deformations generate additional force effects.
  - Load factor of SE is similar to PS, CR, SH, TU, and TG

- The value of $\gamma_{SE}$ must not be taken literally
  - $\gamma_{SE} = 1.25$ does not mean that the total force effects will increase by 25%.
  - $\gamma_{SE}$ is only one component in a load combination.

- Use of **construction point concept** in conjunction with $\gamma_{SE}$ incorporates force effects related to expected sequence of construction along with quantification of uncertainty in predicted deformations.

Benefits of Using Calibrated Foundation Deformations

- Consideration of calibrated foundation deformations in the bridge design process can lead to use of cost-effective structures with more efficient foundation systems
  - Permit enhanced use of cost-effective spread footings and true bridge abutments (spread footing on top of MSE wall)

- The proposed revisions provide a more rational basis to compare alternatives
Benefits of Using Calibrated Foundation Deformations

- Approach and modifications will help avoid overly conservative criteria that can lead to:
  a) foundations that are larger than needed, or
  b) a choice of less economical foundation type (such as, using a deep foundation at a location where a shallow foundation would be adequate)

Example of Foundation Efficiency

SPT N60 = 25: USCS Soil Designation = SC. No Groundwater, Embedment = 5 ft, Footing Length = 30 ft, Schmertmann’s Method

\[ S_t = 1.80 \text{ in} \]

\[ S_t = 3.50 \text{ in} \]
Settlement of Deep Foundations

- Article 10.7.2.3
  - Use equivalent footing

- Can reduce:
  - length of deep foundations
  - plan size of deep foundation system
  - number of deep foundation elements in a group
Closing Comments

- Consideration of foundation deformations in bridge design is not new – it is in fact required by specifications.
- The uncertainty in predicted deformations can now be quantified through the mechanism of SE load factor, $\gamma_{SE}$.
- The calibration process is general and can be applied to any foundation or wall type and any type of deformation.
- Proposed LRFD specification revisions and commentaries have been developed.
- Significant cost efficiencies can be realized.
- SHRP2 Round 7 Implementation Assistance Program (IAP) and other training opportunities.

Next Steps

- SHRP2 Round 7 Implementation Assistance Program (IAP) User Incentive Awards
  - Federal Lands Highway
    - Central Division: Denver, CO: May 23 and 24, 2017
    - Eastern Division: Sterling, VA: June 27 and 28, 2017
    - Western Division: Vancouver, WA: July 19 and 20, 2017
  - Caltrans: TBD
- Agenda items under consideration for balloting by AASHTO SCOBS T-15 and T-5 subcommittees
- R19B Product Page
  - [http://shrp2.transportation.org/Pages/R19B_ServiceLimitStateDesignforBridges.aspx](http://shrp2.transportation.org/Pages/R19B_ServiceLimitStateDesignforBridges.aspx)
  - Presentations, webinars, tools, and technologies
Questions and Contacts

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http://SHRP2.transportation.org or https://www.fhwa.dot.gov/goshrp2