Considerations for Incorporation of Foundation Deformations in LRFD Specifications

Foundation Deformations

• Vertical Deformations
  – Settlement

• Lateral deformations
  – Horizontal movements

• Combination of vertical and horizontal deformations
  – Rotation
Settlement Patterns for Bridges

<table>
<thead>
<tr>
<th>Uniform Settlement</th>
<th>Uniform Tilt (Rotation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonuniform settlement</td>
<td>Regular pattern of settlement</td>
</tr>
<tr>
<td>Nonuniform settlement</td>
<td>Irregular pattern of settlement</td>
</tr>
</tbody>
</table>

Reference: Duncan and Tan (1991)

Differential Settlement

- Difference in settlement between two points, \( \delta \)
- Differential settlement alone cannot quantify rotation
Induced Moments in Continuous Span Bridges

**Example**

\[ FEM = \frac{6EI\delta}{L^2} = \left( \frac{6E}{L} \right) \frac{\delta}{L} \]

- What is the value of \( \delta \)? How reliable is it?
- What does \( \delta/L \) mean? It is angular distortion.

Angular Distortion, A

- \( A = \delta/L \)
- Correlates differential settlement, \( \delta \), with span length, \( L \)
Tolerable Settlements
(FHWA, 1985; AASHTO – Standard and LRFD Specifications)

<table>
<thead>
<tr>
<th>Type of Bridge</th>
<th>Limiting Angular Distortion, $\delta/L$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FHWA</td>
</tr>
<tr>
<td>Continuous Span</td>
<td>0.004 (4.8&quot; in 100')</td>
</tr>
<tr>
<td>Simple Span</td>
<td>0.005 (6.0&quot; in 100')</td>
</tr>
</tbody>
</table>

For rigid frames perform case-specific analysis

What do Agencies do?

- Arbitrary (no consistency in application)
  - 0.004 $\rightarrow$ 0.0004 or 0.008 $\rightarrow$ 0.0008
  - Bigger (I-25/I-40), NM: 0.004 $\rightarrow$ 0.002, 0.008 $\rightarrow$ 0.004
  - WSDOT (From Chapter 8 of Geotech Design Manual)

<table>
<thead>
<tr>
<th>Total Settlement at Pier or Abutment</th>
<th>Differential Sett over 100 ft within pier or abut &amp; diff sett between piers</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta H \leq 1&quot;$</td>
<td>$\Delta H_{100} \leq 0.75&quot;$ [0.000625]</td>
<td>Design &amp; Construct</td>
</tr>
<tr>
<td>$1&quot; &lt; \Delta H \leq 4&quot;$</td>
<td>$0.75&quot; &lt; \Delta H_{100} \leq 3&quot;$ [0.000625-0.0025]</td>
<td>Ensure structure can tolerate settlement</td>
</tr>
<tr>
<td>$\Delta H &gt; 4&quot;$</td>
<td>$\Delta H_{100} &gt; 3&quot;$ [&gt; 0.0025]</td>
<td>Need Dept approval</td>
</tr>
</tbody>
</table>

- No guidance on lateral movements
A Rational Approach – FHWA 2010

**Step 1 – Estimate Total/Diff Settlements and Angular Distortions**

<table>
<thead>
<tr>
<th>Span</th>
<th>Differential Settlement</th>
<th>Angular Distortion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$</td>
<td>\delta_{A1} - \delta_{P1}</td>
</tr>
<tr>
<td>2</td>
<td>$</td>
<td>\delta_{P1} - \delta_{P2}</td>
</tr>
<tr>
<td>3</td>
<td>$</td>
<td>\delta_{P2} - \delta_{P3}</td>
</tr>
<tr>
<td>4</td>
<td>$</td>
<td>\delta_{P3} - \delta_{A2}</td>
</tr>
</tbody>
</table>

**A Rational Approach – FHWA 2010**

**Step 2 – Estimate Design Values Based on δ-0 Concept**

<table>
<thead>
<tr>
<th>Span</th>
<th>Design Differential Settlement</th>
<th>Design Angular Distortion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$D\delta_{p1} = \delta_{p1}$ (assume $\delta_{p1} = 0$)</td>
<td>$DA_1 = D\delta_{p1} / L_1$</td>
</tr>
<tr>
<td>2</td>
<td>$D\delta_{p1} = \delta_{p1}$ (assume $\delta_{p2} = 0$)</td>
<td>$DA_2 = D\delta_{p1} / L_2$</td>
</tr>
<tr>
<td>3</td>
<td>$D\delta_{p3} = \delta_{p3}$ (assume $\delta_{p2} = 0$)</td>
<td>$DA_3 = D\delta_{p3} / L_3$</td>
</tr>
<tr>
<td>4</td>
<td>$D\delta_{A2} = \delta_{A2}$ (assume $\delta_{p3} = 0$)</td>
<td>$DA_4 = D\delta_{A2} / L_4$</td>
</tr>
</tbody>
</table>
When is a Bridge Structure Affected?

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

Long-term settlement

During construction

Factored Load (Strength Limit)

Service Load (Service Limit)

Vertical Displacement

δ_w δ_x δ_y δ_z

Construction Point Concept

A Rational Approach – FHWA 2010
Step 3 – Estimate Relevant Values

• Based on construction point concept, estimate relevant values (which can be up to half of the design values)

Impact of Lateral (Horizontal) Movements

• Impact could more severe on superstructure and bearings particularly when combined with settlements
• Flexibility of substructures

Reference: FHWA (2010)
Considerations for Incorporation of Foundation Deformations in LRFD Specifications

Tolerable Horizontal Movements (FHWA, 1985)

- Varies between 1 to 2 inches
  - Suggested limit of 1.5 inches
- Lateral (horizontal) movements actually cause more damage than vertical movements
- Damage is more severe when vertical and horizontal movements occur simultaneously

Calibration Approach

In Brief
Considerations for Incorporation of Foundation Deformations in LRFD Specifications

\[ \gamma = \text{Load Factor} \quad \phi = \text{Resistance Factor} \]

**The Q-δ dimension**

\[ f(R,Q) \]

\[ Q_{mean} \quad R_{mean} \]

\[ Q_n \quad R_n \]

\[ \gamma Q_n \phi R_n \]

\[ \lambda_Q \quad \lambda_R \]

\[ \delta_S \quad \delta_F \quad \delta_N \quad \delta \]

\[ \text{Mean curve} \]

\[ \text{PDF of curve} \]

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Considerations for Incorporation of Foundation Deformations in LRFD Specifications

Range and Distribution of $Q-\delta$

Correlation of Measured Mean with Theoretical Prediction

Bias Factor, $\lambda = \frac{\text{Measured Mean}}{\text{Predicted}}$
Considerations for Incorporation of Foundation Deformations in LRFD Specifications

Serviceability Limit State(s)

• For strength limit state, common expression is 
  \[ g = R - Q \]

• For service limit state, the expression can be
  \[ g = \delta_T - \delta_P \]
  \[ \begin{align*}
  \delta_T & = \text{target (design or tolerable)} \\
  \delta_P & = \text{predicted (estimated)} \\
  \delta_T & \text{is Resistance and } \delta_P \text{ is Load Effect}
  \end{align*} \]

• Need statistics for \( \delta_T \) and \( \delta_P \)
Considerations for Incorporation of Foundation Deformations in LRFD Specifications

\[ \lambda_\delta = \text{Deformation Bias Factor} \quad \gamma_D = \text{Deformation Load Factor} \]

Data for Immediate Settlement of Spread Footings (FHWA 1987)
Considerations for Incorporation of Foundation Deformations in LRFD Specifications

Statistics of Various Methods

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Schmertmann</th>
<th>Hough</th>
<th>D’Appolonia</th>
<th>Peck &amp; Bazzara</th>
<th>Burland &amp; Burbridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Count</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Min</td>
<td>0.295</td>
<td>0.656</td>
<td>0.311</td>
<td>0.202</td>
<td>0.138</td>
</tr>
<tr>
<td>Max</td>
<td>4.618</td>
<td>4.294</td>
<td>2.176</td>
<td>4.000</td>
<td>4.735</td>
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<tr>
<td>M</td>
<td>1.381</td>
<td>1.971</td>
<td>1.031</td>
<td>0.779</td>
<td>0.829</td>
</tr>
<tr>
<td>SD</td>
<td>1.006</td>
<td>0.769</td>
<td>0.476</td>
<td>0.796</td>
<td>0.968</td>
</tr>
<tr>
<td>COV</td>
<td>0.729</td>
<td>0.390</td>
<td>0.462</td>
<td>1.022</td>
<td>1.168</td>
</tr>
</tbody>
</table>

Legend:
M = Mean
SD = Standard Deviation
COV = Coefficient of Variation (=SD/M)

Typical PDF

For Schmertmann et al. method
Considerations for Incorporation of Foundation Deformations in LRFD Specifications

Probability Exceedance Chart (PEC)

Schematic. Probability Exceedance Chart (PEC) for evaluation of deformation at service limit state.

Example

Probability Exceedance of Tolerable Settlement, %

Predicted (Calculated) Settlement, in

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

Example

1.0 in
2.0 in
3.0 in

Probability of Exceedance of Tolerable Settlement, %

Predicted (Calculated) Deformation, \( \delta_p \)

\( \delta_{T1} \)
\( \delta_{T2} \)
\( \delta_{T3} \)

Probability of Exceedance, \( P_e \)

\( P_{e1} \)
\( P_{e2} \)
\( P_{e3} \)
Express Probability of Exceedance, $P_e$, in Terms of Reliability Index, $\beta$

- Conventional definition of $\beta$
  \[ \beta = \frac{R_{\text{mean}} - Q_{\text{mean}}}{\sqrt{s_R^2 + s_Q^2}} \]

- Using Microsoft Excel, the relationship can be expressed as follows:
  \[ \beta = \text{NORMSINV}(1 - P_e) \]

### Table

<table>
<thead>
<tr>
<th>$P_{e_0}$ (%)</th>
<th>$\beta$</th>
<th>$P_{e_0}$ (%)</th>
<th>$\beta$</th>
<th>$P_{e_0}$ (%)</th>
<th>$\beta$</th>
<th>$P_{e_0}$ (%)</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>3.719</td>
<td>11</td>
<td>1.227</td>
<td>25</td>
<td>0.674</td>
<td>39</td>
<td>0.279</td>
</tr>
<tr>
<td>0.02</td>
<td>3.540</td>
<td>12</td>
<td>1.175</td>
<td>26</td>
<td>0.643</td>
<td>40</td>
<td>0.253</td>
</tr>
<tr>
<td>0.05</td>
<td>3.291</td>
<td>13</td>
<td>1.126</td>
<td>27</td>
<td>0.613</td>
<td>41</td>
<td>0.228</td>
</tr>
<tr>
<td>0.1</td>
<td>3.090</td>
<td>14</td>
<td>1.080</td>
<td>28</td>
<td>0.583</td>
<td>42</td>
<td>0.202</td>
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<tr>
<td>1</td>
<td>2.326</td>
<td>15</td>
<td>1.036</td>
<td>29</td>
<td>0.553</td>
<td>43</td>
<td>0.176</td>
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<tr>
<td>2</td>
<td>2.050</td>
<td>16</td>
<td>0.994</td>
<td>30</td>
<td>0.524</td>
<td>44</td>
<td>0.151</td>
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<tr>
<td>3</td>
<td>1.875</td>
<td>17</td>
<td>0.954</td>
<td>31</td>
<td>0.496</td>
<td>45</td>
<td>0.126</td>
</tr>
<tr>
<td>4</td>
<td>1.750</td>
<td>18</td>
<td>0.915</td>
<td>32</td>
<td>0.468</td>
<td>46</td>
<td>0.100</td>
</tr>
<tr>
<td>5</td>
<td>1.645</td>
<td>19</td>
<td>0.878</td>
<td>33</td>
<td>0.440</td>
<td>47</td>
<td>0.075</td>
</tr>
<tr>
<td>6</td>
<td>1.555</td>
<td>20</td>
<td>0.842</td>
<td>34</td>
<td>0.412</td>
<td>48</td>
<td>0.050</td>
</tr>
<tr>
<td>7</td>
<td>1.476</td>
<td>21</td>
<td>0.806</td>
<td>35</td>
<td>0.385</td>
<td>49</td>
<td>0.025</td>
</tr>
<tr>
<td>8</td>
<td>1.405</td>
<td>22</td>
<td>0.772</td>
<td>36</td>
<td>0.358</td>
<td>50</td>
<td>0.000</td>
</tr>
<tr>
<td>9</td>
<td>1.341</td>
<td>23</td>
<td>0.739</td>
<td>37</td>
<td>0.332</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.282</td>
<td>24</td>
<td>0.706</td>
<td>38</td>
<td>0.305</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Question:** What value of $\beta$ to use?
Considerations for Incorporation of Foundation Deformations in LRFD Specifications

Proposed Modifications to AASHTO

- Criteria
  - Provide practical guidance for bridge designers
  - Allow modifications at a regional level
  - Encourage use of more efficient foundation deformation prediction methods
  - Reflect effect of foundation deformation at superstructure level
Proposed Modifications to AASHTO

• Article 10.5.2 – “Service Limit States”

• Article 10.5.2 is cross-referenced in articles for various foundations types such as spread footings, driven piles, drilled shafts, micropiles, retaining walls, joints, etc.

• Making change in Article 10.5.2 will permeate through all the relevant sections of AASHTO

Article 10.5.2

• Include the $\delta$-0 Concept

• Compute angular distortion, $A_{\text{dist}} = \delta/L$ based on consideration of construction points

• Compute modified deformation $\delta_m$, and angular distortion, $A_{\text{distm}}$, as follows:

  $\delta_m = \gamma_{SE} (\delta)$  \hspace{1cm} $A_{\text{distm}} = \gamma_{SE} (A_{\text{dist}})$

  where $\gamma_{SE}$ is the load factor due to settlement

• Perform bridge analysis using $\delta_m$ and $A_{\text{dist}}$
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</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Concrete Substructures supporting Segmental Superstructures (see 3.12.4, 3.12.5)</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Concrete Superstructures—non-segmental</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Substructures supporting non-segmental Superstructures</td>
<td></td>
<td></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 or develop a similar table

Section 3, 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>1.0</td>
</tr>
<tr>
<td>• Hough method</td>
<td></td>
</tr>
<tr>
<td>• Schmertmann method</td>
<td>1.2</td>
</tr>
<tr>
<td>• XYZ method (e.g., a regional method)</td>
<td>1.X</td>
</tr>
<tr>
<td>Consolidation settlement</td>
<td>1.0</td>
</tr>
<tr>
<td>Lateral deformation</td>
<td></td>
</tr>
<tr>
<td>• P-y or SWM soil-structure interaction method</td>
<td>1.2</td>
</tr>
<tr>
<td>• XYZ method (e.g., a regional method)</td>
<td>1.X</td>
</tr>
</tbody>
</table>
General Comments and Summary

• Recognize that foundation deformations need to be evaluated on a consistent basis as deformations of other elements of a bridge

• Reflect the effect of foundation deformations and their reliability in a single load factor for deformations that will be incorporated in bridge designs through $\gamma_{SE}$

• Provide a tool kit to permit modifications at a regional level

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General Comments and Summary

• Permit updating in the sense that the proposed $\gamma_{SE}$ values can be modified based on expanding databases

• Be practical and do not over-complicate issues
  – Deal with the modification at the most basic level rather than introduction of various additional limit states
  – $\delta$-0 concept with $\gamma_{SE}$ tackles the issues at basic level that works within the current processes used by bridge and geotechnical specialists

• Stay tuned for final findings of the SHRP2 Project R19B

SHRP 2 Project R19B
Project R19B

- Develop new design codes that incorporate a rational approach based on service limit state (SLS)

- Develop performance measures

- Develop design procedures, proposed specification changes, and implementation tools
Project R19B

• Transition