Soil-Foundation-Structure Interaction Webinar

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Outline

• Overview of Seismic Design Principles
• Design Example 1 – Pile-founded Bridge
• Design Example 2 – Drilled Shaft-founded Bridge

Scope: Ordinary bridges, not large, signature bridges, nor seismically isolated bridges
Workshop Learning Objectives

• List the steps necessary to develop foundation spring values

• Describe the effects of foundation flexibility on the push-over displacement check

• List several methods of approximating deep-foundation spring stiffnesses
Reference Materials

- AASHTO Guide Specifications for LRFD Seismic Bridge Design (GS)
- AASHTO LRFD Bridge Design Specifications (LS)
- NHI Course 130093A (3-Day) Displacement-Based LFRD Seismic Analysis and Design of Bridges
- NHI Course 130093 (5-Day) LFRD Seismic Analysis and Design of Bridges
- Associated Design Examples FHWA-NHI-14-039
- NHI Course 132094 and 132094A LRFD Seismic Analysis and Design of Transportation Geotechnical Features
Seismic Design Overview

Topics Covered:
• Basic objectives in seismic design
• Emphasis on displacement-based design
• Effects of foundation flexibility
• Design steps involved
Two Themes or “Subplots” of the Webinar

1. Designs are based on “Capacity Design” principles

2. Analysis uses equivalent linearization techniques to predict response
We Permit Earthquakes to Damage Bridges

The forces induced if the structure is to remain undamaged can be too large to deal with, thus uneconomical.
Plastic Hinge

Ground Acceleration

Bridges can be built to perform in a ductile manner

Evaluate Maximum Response

Yielding Structure Response

5-8
Chain Analogy - Capacity Protection

- Ductile Link
- Brittle Links

Force, $F$

- Brittle Links
- Ductile Link
- Brittle Links

Ductile Behavior, Provided $F_d < \text{All } F_{ib}$

Brittle Behavior, If Any One $F_{ib} < F_d$

Displacement, $\Delta$
Chain Analogy - Capacity Protection

- Ductile Link
- Brittle Links

Weakest $F_{ib}$

Ductile Behavior, Provided $F_d < \text{All } F_{ib}$

Brittle Behavior, If Any One $F_{ib} < F_d$

Displacement, $\Delta$
We Analyze Bridges Elastically

Can use linear elastic analysis to predict nonlinear displacements!
Inelastic to Elastic Response

Two common methods:

“Coefficient” Method  
(AASHTO – LS and GS)

Substitute Structure Method  
(Capacity Spectrum - Isolation)

\[ R_d \]

\[ S_a \]

\[ S_d \]

\[ T = \text{Fundamental Period of System} \]

\[ T_s = \text{“Corner” of Response Spectrum} \]

Area gives effective damping – based on hysteretic behavior.
# Basic Steps of Seismic Design

<table>
<thead>
<tr>
<th>Step</th>
<th>Basic Steps for Seismic Design</th>
</tr>
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<tr>
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</tr>
<tr>
<td>6</td>
<td>Capacity Protect the Remaining Elements</td>
</tr>
</tbody>
</table>
Foundation “K”s vs Structural “K”s

- δ
- V
- Force
- Foundation Displacement
- K_{struct} w/o Foundation
- K_{struct} w/ Foundation
- K_{struct} w/ Foundation at Structure Effective Yield

Column Effective Stiffness (at First Yield)

Lateral Force, V

Bridge System Displacement
Foundation “K”s vs Structural “K”s

- $K_{struct}$ with Foundation
- $K_{struct}$ with Foundation at Structure Effective Yield
- $\Delta e$ of structure using multi-mode spectral analysis
- Expected Inelastic Displacement Demand: $\Delta_D = R_d \Delta_e$
- 5% Damping
- Period $T_{eff}$
- Acceleration, $S_a$ vs Period
Displacement-Based Method (DBM)

**Displacement-Based Method (DBM)**

**F\text{Elastic}**

**F\text{non-Seismic}**

**F\text{Yield}**

**Elastic Response**

**Displacement Capacity Is Directly Checked, Based on Actual Provided Detailing. (Confinement)**

**Capacity**

**Yielding System**

**Inelastic after Rd adjustment**

**Only Minimum Required Force, But No Unique Force Required**
Ductile Design Activity - DBM

- **P-\(\Delta\) Requirements (Minimum Strength)**
- **No Unique Resistance (Force) Required!**
- **Minimum Strength RC Members**
- **No**
- **Adjust Bridge Characteristics**
- **Strain Limits and Ductility Demand Limit (SDC D)**
- **Transverse Steel (Confinement & Shear)**
- **Demand Analysis**
- **Displacement Capacity**
  - \(\Delta_C \geq \Delta_D\)
Soil-Foundation-Structure Interaction

• Inertial Response (structure ‘loads’ soil)
  Soil and structure respond dynamically due to their mass and the flexibility of the soil around foundation

  (Most often included form of SFSI and focus of this webinar)

• Kinematic Response (soil ‘loads’ structure)
  Presence and rigidity of foundation alters the free-field motion of soil
Foundation Modeling Aspects

• Masses
  Structural inertial forces usually dominant
  Inertia of soil and foundation is usually small and neglected

• Damping
  Difficult to properly account for radiation and material damping of foundation systems
  Material damping is strain dependent
  Additional (>5%) damping is typically and conservatively neglected

• Therefore usually only include stiffness effects!
### Foundation Modeling

- Little in LS about modeling (Appendix A10)
- GS more specific (Could be used with LS)
  - Method I – modeling: simple-to-none
  - Method II – detailed guidance

#### Table 5.3.1-1—Definition of Foundation Modeling Methods (FMMs)

<table>
<thead>
<tr>
<th>Foundation Type</th>
<th>Modeling Method I</th>
<th>Modeling Method II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spread Footing</td>
<td>Rigid</td>
<td>Rigid for Site Classes A and B. For other soil types, foundation springs required if footing flexibility contributes more than 20% to pier displacement.</td>
</tr>
<tr>
<td>Pile Footing with Pile Cap</td>
<td>Rigid</td>
<td>Foundation springs required if footing flexibility contributes more than 20% to pier displacement.</td>
</tr>
<tr>
<td>Pile Bent/Drilled Shaft</td>
<td>Estimated depth to fixity</td>
<td>Estimated depth to fixity or soil springs based on P-y curves.</td>
</tr>
</tbody>
</table>
Considering Foundation Effects

• Generally, demand model and assessment (pushover) models should be consistent (i.e. either both include flexibility or both ignore flexibility)

• If demand model includes foundation flexibility:
  
  OK to check without foundation considered, if all foundation effects are included with the plastic deformations (quick and dirty method)

  Do not include foundation effects as an increase in yield – unconservative!
Foundation Effects

Flexibility of adjacent members increases apparent yield point, but does not change the plastic component.

Effect of Foundation Flexibility on Structure Displacement Capacity
Structural / Geotech Collaboration

The more the structural and geotech work together, the less likely re-work is.
Capacity-Protected Elements

Example: Spread Footing

Plastic overstrength forces

Use the maximum forces that can be transmitted to element

\[ P_{po}, V_{po}, M_{po} \]

Design and detail to remain “elastic”.

Resistance factors (\( \phi \)) along with nominal or expected properties are used depending on desired conservatism.
Design Example No. 1

Topics Covered:

• *Guide Specifications for LRFD Seismic Bridge Design*
• Pile group and pile cap stiffness
• Structural modeling
• Displacement checks
• Capacity protection of pile group foundations
Design Example No. 1 - Elevation

Diagram showing elevation details with various levels and footings.

- EL 30.0
- EL 23.5
- EL 0.0
- EL -10.0
- EL -7.0
- EL -60.0
- EL -80.0
- 1"-0" DIA. CIP CONC. PILE W/ 3/8" STEEL CASING, TYP.
Design Example No. 1 - Sections
Design Example No. 1 - Abutments

[Diagram showing abutment design with dimensions and annotations, including:
- EL 30.0
- EL 23.5
- 9 - 1'-0" DIA. CIP CONC. PILE W/ 3/8" STEEL CASING, TYP.
- 8'-0" and 2'-6"]
Design Example No. 1 - Data

• Location – New Madrid, MO
• Zip Code 63873, Lat: 36.555 Long: - 89.618
• Guide Specifications for LRFD Seismic Bridge Design (GS)
• Operational Classification – “Other” (although not in SGS)
• SD1 = 0.83 g
• Site Class D
• Seismic Design Category D
• Multi-column Piers
• No skew or curve
## Basic Steps of Seismic Design

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Structural Model

Spine Model with Foundation Springs
Nonlinear Lateral Behavior of Piles
Development of Pier Springs

LPILE results. Stiffnesses for various shear values.

Axial Load to piles = 27.9 kips/pile
Number of Piles = 14
Pile Type: 12" Diameter CIP with steel casing
Spaced at 3'-0" center to center Long.
Spaced at 3'-6" center to center Trans.

<table>
<thead>
<tr>
<th>Shear</th>
<th>Deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 kips</td>
<td>0 in</td>
</tr>
<tr>
<td>10 kips</td>
<td>0.05 in</td>
</tr>
<tr>
<td>25 kips</td>
<td>0.271 in</td>
</tr>
<tr>
<td>35 kips</td>
<td>0.502 in</td>
</tr>
<tr>
<td>50 kips</td>
<td>0.985 in</td>
</tr>
</tbody>
</table>

Pile Stiffness (Fixed)
### Development of Pier Springs

**Axial Stiffness of Pile**
- **12" CIP pile Steel Encased**
  - Area = 190 in^2
  - E = 4372 ksi
  - Length = 63 ft
  - Alpha = Skin
  - Modifier = 2 Friction
  - \( K = 550 \text{ kips/in} \)
  - \( K_{tot} = 7.70\times10^3 \text{ kips/in} \)

**Pile Group effects AASHTO LRFD Table 10.7.2.4-1**

<table>
<thead>
<tr>
<th>Spacing</th>
<th>Row 1</th>
<th>Row 2</th>
<th>Row 3+</th>
</tr>
</thead>
<tbody>
<tr>
<td>3B</td>
<td>0.7</td>
<td>0.5</td>
<td>0.35</td>
</tr>
<tr>
<td>3.5</td>
<td>0.78</td>
<td>0.59</td>
<td>0.44</td>
</tr>
<tr>
<td>5B</td>
<td>1</td>
<td>0.85</td>
<td>0.7</td>
</tr>
</tbody>
</table>

**Requires Iteration with Structural Model**

<table>
<thead>
<tr>
<th><strong>Longitudinal Stiffness of Pile</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Elastic Deflection</td>
</tr>
<tr>
<td>Pile Longitudinal Axis Stiffness</td>
</tr>
<tr>
<td>Group Longitudinal Axis Stiffness</td>
</tr>
<tr>
<td>Including Pile Cap</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Longitudinal Pile Cap Passive Stiffness</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>4 ft = Cap Height</td>
</tr>
<tr>
<td>4.35 = Kp (Passive Pressure)</td>
</tr>
<tr>
<td>115pcf = Soil Unit Weight</td>
</tr>
<tr>
<td>10 ft = Cap Width</td>
</tr>
<tr>
<td>40 kips = Plastic Soil Resistance</td>
</tr>
<tr>
<td>0.02 = Fw for Medium Dense Sand</td>
</tr>
<tr>
<td>0.96 in = Yield Deflection</td>
</tr>
<tr>
<td>41.7 kips/in = Stiffness at Elastic Deflection</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Transverse Stiffness of Pile</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse Elastic Deflection</td>
</tr>
<tr>
<td>Pile Transverse Axis Stiffness</td>
</tr>
<tr>
<td>Group Transverse Axis Stiffness</td>
</tr>
<tr>
<td>Including Pile Cap</td>
</tr>
</tbody>
</table>

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<tr>
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</tr>
<tr>
<td>4.35 = Kp (Passive Pressure)</td>
</tr>
<tr>
<td>115pcf = Soil Unit Weight</td>
</tr>
<tr>
<td>15 ft = Cap Width</td>
</tr>
<tr>
<td>60 kips = Plastic Soil Resistance</td>
</tr>
<tr>
<td>0.02 = Fw for Medium Dense Sand</td>
</tr>
<tr>
<td>0.96 in = Yield Deflection</td>
</tr>
<tr>
<td>62.5 kips/in = Stiffness at Elastic Deflection</td>
</tr>
</tbody>
</table>
### Development of Pier Springs

#### Rotational Stiffness about Vertical Axis

<table>
<thead>
<tr>
<th>Longitudinal stiffness of a single pile (kips/in)</th>
<th>Transverse stiffness of a single pile (kips/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse Dimension to locate pile (ft)</td>
<td>Longitudinal Dimension to locate pile (ft)</td>
</tr>
<tr>
<td>56.10, 56.10, 56.10, 3.5, 0, 3.5</td>
<td>55.52, 42.09, 31.34, 6, 6, 6</td>
</tr>
<tr>
<td>40.07, 40.07, 40.07, 3.5, 0, 3.5</td>
<td>55.52, 42.09, 31.34, 3, 3, 3</td>
</tr>
<tr>
<td>28.05, 28.05, 28.05, 3.5, 0, 3.5</td>
<td>55.52, 42.09, 31.34, 0, 0, 0</td>
</tr>
<tr>
<td>28.05, 28.05, 28.05, 3.5, 0, 3.5</td>
<td>55.52, 42.09, 31.34, 3, 3, 3</td>
</tr>
<tr>
<td>28.05, 28.05, 28.05, 3.5, 0, 3.5</td>
<td>55.52, 42.09, 31.34, 6, 6, 6</td>
</tr>
</tbody>
</table>

#### Rotational Stiffness

- **5 rows @ 3' of 3 piles @ 3.5' centers**
  - (no pile under column, 14 total)
- **About Long Axis**: 9.70E+06 k-in/rad
- **About Trans Axis**: 2.14E+07 k-in/rad

### Rotational Stiffness

<table>
<thead>
<tr>
<th>K (Y²) (Kip-ft/rad)</th>
<th>K (Y²) (Kip-ft/rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>57.27, 0.00, 57.27</td>
<td>166.57, 126.27, 94.03</td>
</tr>
<tr>
<td>40.91, 0.00, 40.91</td>
<td>41.64, 31.57, 23.51</td>
</tr>
<tr>
<td>28.64, 28.64</td>
<td>0.00, 0.00</td>
</tr>
<tr>
<td>28.64, 28.64</td>
<td>41.64, 31.57, 23.51</td>
</tr>
<tr>
<td>28.64, 28.64</td>
<td>166.57, 126.27, 94.03</td>
</tr>
</tbody>
</table>

**SUM**: 368.17 Kip-ft/rad

**SUM**: 967.16 Kip-ft/rad

**Combined SUM**: 1335.33 Kip-ft/rad

**16023.98 Kip-in/rad**
232 kip/in Initial Stiffness

4.8 inches Displacement (Requires Iteration)

64 kip/in Effective Stiffness

306 kips Backwall Resistance
Model Results

Model Results – Longitudinal Direction

<table>
<thead>
<tr>
<th>Mode</th>
<th>T</th>
<th>$C_a$</th>
<th>$(\text{mass} \times C_a)^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[---]</td>
<td>[second s]</td>
<td>[g]</td>
<td>[---]</td>
</tr>
<tr>
<td>1</td>
<td>0.6287</td>
<td>1.328</td>
<td>0.000</td>
</tr>
<tr>
<td>2</td>
<td>0.5606</td>
<td>1.509</td>
<td>1.342</td>
</tr>
<tr>
<td>3 to 20</td>
<td>&lt; 0.44</td>
<td>1.888</td>
<td>0.189</td>
</tr>
<tr>
<td>Total:</td>
<td></td>
<td></td>
<td>1.53</td>
</tr>
</tbody>
</table>

Model Results – Response Spectrum Displacements

<table>
<thead>
<tr>
<th>Pier</th>
<th>Joint</th>
<th>Longitudinal EQ X</th>
<th>Transverse EQ Y</th>
<th>Transverse EQ X</th>
</tr>
</thead>
<tbody>
<tr>
<td>[---]</td>
<td>[---]</td>
<td>[inches]</td>
<td>[inches]</td>
<td>[inches]</td>
</tr>
<tr>
<td>2</td>
<td>521</td>
<td>4.04</td>
<td>0.00</td>
<td>5.69</td>
</tr>
<tr>
<td>3</td>
<td>531</td>
<td>4.04</td>
<td>0.00</td>
<td>5.69</td>
</tr>
</tbody>
</table>

Load Case 1: 100% EQ LONGITUDINAL + 30% EQ TRANSVERSE
Load Case 2: 30% EQ LONGITUDINAL + 100% EQ TRANSVERSE
NOTE: All displacements are in the longitudinal direction.

\[ \Delta = 4.77 \text{ in.} \]
\[ \Delta = 4.40 \text{ in.} \]
\[ \Delta = 4.04 \text{ in.} \]
\[ \Delta = 4.75 \text{ in.} \]
\[ \Delta = 0.36 \text{ in.} \]
NOTE: All displacements are in the transverse direction

Δ = 5.73 in.
Δ = 5.70 in.
Δ = 5.69 in.
Δ = 0.29 in.
Δ = 0.47 in.
Displacement Magnification

Longitudinal Direction

\[ T = 0.561 \text{s} \]

\[ \frac{T^*}{T} = \frac{0.55 \text{s}}{0.561 \text{s}} = 0.98 < 1.0 \]

Displacement magnification is not required

Transverse Direction

\[ T = 0.629 \text{s} \]

\[ \frac{T^*}{T} = \frac{0.55 \text{s}}{0.629 \text{s}} = 0.87 < 1.0 \]

Displacement magnification is not required

\[ R_d = \left(1 - \frac{1}{\mu_D}\right) \times \frac{T}{T^*} + \frac{1}{\mu_D} \]

\[ T_s = \frac{SD_1}{SD_S} = \frac{0.831g}{1.888g} = 0.44\text{s} \]

\[ T^* = 1.25 \times 0.44\text{s} = 0.55\text{s} \]
Pushover Analysis Models

Longitudinal

- Elastic Beam-Column Element
- Concentrated P-M Interaction Plastic Hinge
- Rigid Offset
- Foundation Springs

Transverse

- Elastic Cap Beam Element
- Concentrated P-M Interaction Plastic Hinge
- Rigid Offset
- Foundation Springs

C.G. of Superstructure

Rigid Offsets
Pier Pushover Longitudinal Direction

Longitudinal Pushover Curve

- Base Shear (kips)
  - 160
  - 140
  - 120
  - 100
  - 80
  - 60
  - 40
  - 20
  - 0

- Displacement Capacity (controlled by crushing of conf. concrete)
- Yield Point
- Demand Displacement (w/ abut passive pressure)
- Demand Displacement (wo/ abut passive pressure)

Displacement at top of Column (in)

- 4.04” (See §4.4.3 of this example)
- 27.5 in, 137.8 kips
Transverse Pushover Curve

**Base Shear (kips)**

- Yield Points
- Demand Capacity (controlled by crushing of conf. concrete) on first failed hinge
- Demand Displacement
- 5.69” (See §4.4.3 of this example)

**Displacement at top of Column (in)**

- 16.4 in.
- 914.6 kips
Elastic and Plastic Overstrength Forces

**Elastic Forces**

- \( P_e = 469.3 \text{ kip} \)
- \( V_e = 272.4 \text{ kip} \)
- \( M_e = 3,355 \text{ kip-ft} \)
- \( \Delta_e = 0.47 \text{ in.} \)

**Plastic Overstrength Forces**

- \( P_{po} = 471 \text{ kip} \)
- \( V_{po} = 124.6 \text{ kip} \)
- \( M_{po} = 1,663 \text{ kip-ft} \)
- \( \Delta_{po} = 0.19 \text{ in.} \)

**NOTES:**

1. Forces are taken at the bottom of the exterior column under \(+\Delta P\) transverse loading.
2. Plastic forces are taken from the pier capacity protection design forces.
3. \( \Delta_{po} = \frac{V_{po}}{K_{trans}} \)
Take the horizontal translation of the pile cap under elastic and overstrength forces and apply to an individual pile pushover (without group effects).

\[ \frac{k_e}{k_{po}} = \frac{68.7 \text{ kip/in}}{105 \text{ kip/in}} = 0.65 \]

**Individual Pile Pushover**

- \( V_e \)
- \( V_{po} \)
- \( k_e = 32.3 \text{ kip} / 0.47 \text{ in.} = 68.7 \text{ kip/in.} \)
- \( k_{po} = 20 \text{ kip} / 0.19 \text{ in.} = 105 \text{ kip/in.} \)

**NOTE:**
Forces are taken at the bottom of the exterior column under +\( \Delta P \) transverse loading.
The pile flexural and shear capacities should be checked against the in-ground demands due to column plastic overstrength forces:

\[ M_{po} = 880 \text{ kip-in.} \]
\[ V_{po} = 20 \text{ kips} \]

**NOTE:** Forces are taken at the bottom of the exterior column under \( +\Delta P \) transverse loading.
Column Ductility Checks

\[ \mu_D = \frac{\Delta_D}{\Delta_y} \]

\[ \mu_{D,fdn} = \frac{\Delta_D}{\Delta_y + \Delta_{fdn}} \]

Therefore: \( \mu_{D,fdn} \leq \mu_D \)

**Ductility without Foundation Effects**

**Ductility with Foundation Effects**

\[ \Delta_C \text{ with foundation flexibility} \]

\[ \Delta_C \text{ without foundation flexibility} \]

**AASHTO GS Article C4.9**

“In calculating the yield displacement and plastic displacement demand, any contribution to the displacements from foundation, capbeam, or superstructure should be removed. **Inclusion of such flexibilities is unconservative**”
## Column Ductility Checks

### Ductility *without* Foundation Effects

\[ \mu_D = \frac{\Delta_D}{\Delta_y} \]

\[ \Delta_y = 2 \left( \frac{\phi_y L^2}{3} \right) \]

\[ \Delta_D = 5.69 \text{ in} \]

<table>
<thead>
<tr>
<th></th>
<th>Left Column</th>
<th>Center Column</th>
<th>Right Column</th>
</tr>
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<tbody>
<tr>
<td><strong>Axial Load (kip)</strong></td>
<td>37</td>
<td>254</td>
<td>471</td>
</tr>
<tr>
<td><strong>( \phi_y ) (1/in.)</strong></td>
<td>0.000154</td>
<td>0.000150</td>
<td>0.000144</td>
</tr>
<tr>
<td><strong>L (in.)</strong></td>
<td>159</td>
<td>159</td>
<td>159</td>
</tr>
<tr>
<td><strong>( \Delta_y ) (in.)</strong></td>
<td>2.60</td>
<td>2.52</td>
<td>2.43</td>
</tr>
<tr>
<td><strong>( \mu_D )</strong></td>
<td><strong>2.19</strong></td>
<td><strong>2.26</strong></td>
<td><strong>2.34</strong></td>
</tr>
</tbody>
</table>

### Ductility *with* Foundation Effects

\[ \mu_D = \frac{\Delta_D}{\Delta_y + \Delta_{fdn}} \]

\[ \Delta_y = 2 \left( \frac{\phi_y L^2}{3} \right) \]

<table>
<thead>
<tr>
<th></th>
<th>Left Column</th>
<th>Center Column</th>
<th>Right Column</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Axial Load (kip)</strong></td>
<td>37</td>
<td>254</td>
<td>471</td>
</tr>
<tr>
<td><strong>( \phi_y ) (1/in.)</strong></td>
<td>0.000154</td>
<td>0.000150</td>
<td>0.000144</td>
</tr>
<tr>
<td><strong>L (in.)</strong></td>
<td>159</td>
<td>159</td>
<td>159</td>
</tr>
<tr>
<td><strong>( \Delta_y ) (in.)</strong></td>
<td>2.60</td>
<td>2.52</td>
<td>2.43</td>
</tr>
<tr>
<td><strong>( \Delta_{fdn} ) (in.)</strong></td>
<td>0.13</td>
<td>0.16</td>
<td>0.19</td>
</tr>
<tr>
<td><strong>( \mu_D )</strong></td>
<td><strong>2.08</strong></td>
<td><strong>2.12</strong></td>
<td><strong>2.17</strong></td>
</tr>
</tbody>
</table>

OK < 6  GS 4.9 Multicolumn Piers SDC D
Design Example No. 2

Topics Covered:

- *LRFD Bridge Design Specifications* – seismic design
- Drilled shaft stiffness
- Structural modeling
- Column design
- Capacity protection of drilled shafts
Design Example No. 2 – Elev and Plan

ABUTMENT 1

PIER 2

ABUTMENT 2

BEARING

EXP

FIX

EXP

BEARING

BRIDGE

ELEVATION

PLAN

25’-4’
Design Example No. 2 – Section at Pier
Design Example No. 2 - Data

- Location – Big Arm, MT (Flathead Lake)
  Zip Code 59910, Lat: 47.798 Long: -114.309
- LRFD Bridge Design Specifications
- Operational Classification – “Other”
- SD1 = 0.39 g
- Site Class D
- Seismic Zone 3
- Multi-column Bent, R=5
Spine Model

Model of all substructure elements (column and foundation) for the intermediate pier

Stick, frame element or spine model for bridge
Modeling Deep Foundation Stiffnesses

Direct foundation spring model, P-y springs

Equivalent Cantilever Model, Depth-to-fixity

Coupled or Decoupled Spring Model
Characteristic Length

$$T = \left( \frac{EI}{n_h} \right)^{1/5}$$

$EI$ - Pile Flexural Stiffness

$n_h$ – Coefficient of Lateral Subgrade Reaction (sometimes “$f$”)

$L / T$ = Measure of Pile Embedment
Equivalent Depth to Fixity – Extended Column

The lengths listed are derived to match the quantities listed – stiffness and moment – **not points on the p-y deflected shape plot.**
Single-Pile Lateral Stiffness Iteration

1. Model entire pile using P-y based program

2. Generate P-y curves for springs along pile [FHWA (1986) or other]

3. Load model and determine $\Delta$ and $\theta$

4. For a given $\Delta$ and $\theta$ calculate foundation springs (uncoupled or coupled)

5. Analyze mathematical model of bridge

6. Using foundation forces from bridge model (must judge elastic vs plastic), determine new $\Delta$ and $\theta$ from P-y model

Iterate until convergence is obtained
Limitation of Superposition

Line Load, $P$, Along Pile

$y_{V+M} > y_V + y_M$

$M$ only

$V$ only

$y_M$

$y_V$

$y_{V+M}$

P-y spring
Development of Spring Stiffnesses

\[ \Delta V = \Delta V_0 \]

\[ V = V_e \]
Development of Spring Stiffnesses

\[ M = M_0 \]

\[ V = 0 \]

\[ \Delta_{M0} \]

\[ \Delta_e \]

\[ \Delta \]
Development of Spring Stiffnesses

\[ V_e & M_e \]

\[ V = V_e \]

\[ M = M_e \]

\[ \Delta V_0 \]

\[ \Delta e \]

\[ \Delta M_0 \]

\[ \Delta e \]
Development of Spring Stiffnesses

Uncoupled Springs

$k_{t\,\text{eff}}$

$k_{r\,\text{eff}}$

Only Valid at $\Delta_e$ & $\theta_e$ ($V_e$ & $M_e$)

$V = V_e$

$M = M_e$

$\theta_{M0}$

$\theta_e$

$\Delta_{M0}$

$\Delta_e$

$\Delta$
Example: 7-ft Drilled Shaft DE2

\[ M = 5.79E4 \text{ kip in} \]
\[ V = 386 \text{ kip} \]
\[ \Delta = 1.36 \text{ in} \]

\[ \theta = 0.00508 \text{ rad} \]

Uncoupled Springs

Only Valid at \( \Delta_e \) & \( \theta_e \) (\( V_e \) & \( M_e \))

\[ k_{t_{\text{eff}}} = 284 \text{ kip/in} \]

\[ k_{r_{\text{eff}}} = 11.4 \times 10^6 \text{ kip-in/rad} \]
Development of Coupled Matrix Coefficients

\[
K_{2x2} = \begin{bmatrix}
    k_{\Delta\Delta} & k_{\Delta\theta} \\
    k_{\theta\Delta} & k_{\theta\theta}
\end{bmatrix}
\]

\[
K_{6x6} = \begin{bmatrix}
    K_{x_{2x2}} & 0 & 0 & 0 & 0 \\
    0 & 0 & K_{y_{2x2}} & 0 & 0 \\
    0 & 0 & 0 & K_{axial} & 0 \\
    0 & 0 & 0 & 0 & K_{torque}
\end{bmatrix}
\]

\[
\Delta = 1 \quad \Delta = 0 \\
\theta = 0 \quad \theta = 1 \\
\Delta = 0 \quad \theta = 1 \\
\Delta = 1 \quad \theta = 0
\]

Note: Soil Nonlinearity is Different; Non-Symmetric!
Example: 7-ft Drilled Shaft DE 2

\[ K_{2x2} = \begin{bmatrix} 1407 & -2.89E5 \\ -2.37E5 & 7.37E7 \end{bmatrix} \]

\[ K_{6x6} = \begin{bmatrix} K_{x_{-2x2}} & 0 & 0 & 0 & 0 \\ 0 & K_{y_{-2x2}} & 0 & 0 \\ 0 & 0 & K_{axial} & 0 \\ 0 & 0 & 0 & K_{torque} \end{bmatrix} \]

\[ \Delta = 1 \quad \Delta = 0 \\
\theta = 0 \quad \theta = 1 \\
\Delta = 0 \quad \Delta = 0.275 \text{ in} \\
\theta = 0.000786 \text{ rad} \quad \theta = 0 \]

Note: Soil Nonlinearity is Different; Non-Symmetric!

57,907 k-in
65,200
386 kip

227 kip

000786.0 \theta 1
000786.0 \theta 1

000786.0 \theta 1
000786.0 \theta 1
Comparison – Uncoupled vs Coupled

Uncoupled Springs:
\[ V = 386 \text{ kip} \quad \Delta = 1.34 \text{ in}, \]
\[ M = 57,907 \text{ k-in} \quad \theta = 0.00508 \text{ rad} \]

Coupled Springs:
\[ V = 386 \text{ kip} \quad \Delta = 1.29 \text{ in} \quad (94\% \text{ of uncoupled}), \]
\[ M = 57,907 \text{ k-in} \quad \theta = 0.00494 \text{ rad} \quad (97\% \text{ uncoupled}) \]

Difference is due to soil nonlinearity for combined V and M
**Design Example 2: Dynamic Model Results**

<table>
<thead>
<tr>
<th>Top of Column Displacements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pier</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>[---]</td>
</tr>
<tr>
<td>2</td>
</tr>
</tbody>
</table>

**Longitudinal (X-axis) | Transverse (Y-axis)**
- Fundamental Period:     1.33 sec | 0.52 sec
- Total Mass Participation: 98.9 % | 99.1 %
- Calculated Base Shear: 1,394 kips | 3,620 kips
- Model Base Shear Reaction: 1,445 kips | 3,732 kips
- % Difference: -3.6 % | -3.1 %
Displacement Magnification

Transverse Direction

\[ T_S = 0.85 \cdot \text{sec} \]
\[ 1.25 \cdot T_S = 1.25 \cdot (0.85 \cdot \text{sec}) = 1.06 \cdot \text{sec} \]
\[ T = 0.52 \cdot \text{sec} < 1.25 \cdot T_S = 1.06 \cdot \text{sec} \]

→ Magnification is required.

\[ R_d = \left(1 - \frac{1}{R}\right) \cdot \frac{1.25 \cdot T_S}{T} + \frac{1}{R} = \left(1 - \frac{1}{5}\right) \cdot \frac{1.06 \cdot \text{sec}}{0.52 \cdot \text{sec}} + \frac{1}{5} = 1.83 \]

\[ \Delta_{\text{trans}} = R_d \cdot \Delta_e = 1.83 \cdot (2.08 \text{ in.}) = 3.82 \text{ in.} \]

Longitudinal Direction

\[ T_S = 0.85 \cdot \text{sec} \]
\[ 1.25 \cdot T_S = 1.25 \cdot (0.85 \cdot \text{sec}) = 1.06 \cdot \text{sec} \]
\[ T = 1.33 \cdot \text{sec} > 1.25 \cdot T_S = 1.06 \cdot \text{sec} \]

→ Magnification is not required.

Transverse

\[ \frac{T}{T_S} = \frac{0.52}{0.85} = 0.62 \]

Longitudinal

\[ \frac{T}{T_S} = \frac{1.33}{0.85} = 1.56 \]
Displacement Magnification

However, the structure is nearly elastic under transverse loading, determine distribution of forces:

\[ V_{\text{trans}} \approx 3,732 \cdot \text{kips} \]
\[ V_{\text{pier}} = 3 \cdot V_{\text{col}} = 3 \cdot (220 \cdot \text{kips}) = 660 \cdot \text{kips} \]
\[ V_{\text{abut}} = V_{\text{trans}} - V_{\text{pier}} = 3,732 \cdot \text{kips} - 660 \cdot \text{kips} = 3,072 \cdot \text{kips} \]

Prorate the base shear to determine the effective R value:

\[ \frac{V_{\text{trans}}}{R_{\text{eff}}} = V_{\text{abut}} + \frac{V_{\text{pier}}}{R} \]
\[ R_{\text{eff}} = \frac{V_{\text{trans}}}{V_{\text{abut}} + \frac{V_{\text{pier}}}{R}} = \frac{3,732 \cdot \text{kips}}{3,072 \cdot \text{kips} + \frac{660 \cdot \text{kips}}{5}} = 1.16 \]

\[ R_d = \left(1 - \frac{1}{R_{\text{eff}}} \right) \cdot 1.25 \cdot \frac{T_s}{T} + \frac{1}{R_{\text{eff}}} = \left(1 - \frac{1}{1.16} \right) \cdot 1.06 + \frac{1}{1.16} = 1.14 \]
\[ \Delta_{\text{trans}} = R_d \cdot \Delta_e = 1.14 \cdot (2.08 \cdot \text{in.}) = 2.37 \cdot \text{in.} \]
Lateral Deflection vs Depth for Shafts

Shaft Deflection

Transverse 0.63 in
Longitudinal

Depth, feet

Deflection, in.

Column Deflection

Soffit of Box Girder
25’-4” Clear
Top of Drilled Shaft 2.08 inches
Bending Moment vs Depth/Height

Soffit of Box Girder
25’-4” Clear
Top of Drilled Shaft

Longitudinal

Transverse

Depth, feet

Bending Moment, kips-in.

79,780 kip-in
38,000
66,350
29,000
20,000
40,000
60,000
80,000
100,000
120,000
Moment vs Depth at Plastic Hinging

Soffit of Box Girder

Top of Drilled Shaft

\[ M_{po} = 47,000 \]

\[ 48,000 = M_{po} \]

Elastic Longitudinal

Elastic Transverse

Inelastic Hinging

Depth, feet

Bending Moment, kips-in.
Moment vs Depth at Plastic Hinging

- Soffit of Box Girder
- Top of Drilled Shaft

Elastic Longitudinal
Elastic Transverse
Inelastic Hinging

\[ M_{po} = 47,000 \]

\[ 48,000 = M_{po} \]

Flexural Capacity (Strength)
Capacity Protection for this Bridge

• Column designed for overstrength shear based on plastic mechanism

• Drilled shaft designed for overstrength forces for full length (use bounding or 1.25 increase for soil variability)

• Abutments should be designed to mobilize backfill force whether or not it is counted on

• Abutment shear keys must consider post-failure response (i.e. torsion about vertical)
Webinar Summary

• Equivalent linear analysis is the workhorse of most bridge demand calculations

• Consider whether elastic or plastic overstress conditions should be used for soil/foundation springs

• Several different foundation spring models may be used

• Assessment models should be consistent with demand models
Thank You!