Passive Force-Deflection Relationships for Bridge Abutments

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FHWA Pooled Fund Sponsors

- Utah DOT – Lead Agency
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- Wisconsin DOT
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Passive Force on Bridge Abutments

- Passive force contributes to resistance
- Using smaller passive force (lower $K_p$) may be conservative
LATERAL SPREAD

Before earthquake

Clay Crust
Liquefiable Sand

INITIAL SECTION

After earthquake

DEFORMED SECTION
Passive Force on Abument During Lateral Spreading

- Passive force contributes to load
- Using smaller passive force (lower $K_p$) is unconservative
Buckled Railroad Bridge Caused by Lateral Spread During the 1964 Alaska Earthquake
Lateral Spread Damage to Bridge

Bridge pushed into the river and off of supports by Lateral Spread in 1991 Limon Costa Rica Earthquake.
Modeling Lateral Spreading

Free-Field Displacement Profile

Non-liquefied Zone

Liquefied Zone

DH from Youd et al (2002)

Soil Behind Abutment

Soil Around Piles

DH from Youd et al (2002)
Large-Scale Passive Force Testing
Development of Passive Resistance

- **Clean Sand**: $\Delta/H_{max} = 0.034$
- **Fine Gravel**: $\Delta/H_{max} = 0.030$
- **Coarse Gravel**: $\Delta/H_{max} = 0.035$
- **Silty Sand**: $\Delta/H_{max} = 0.052$

“Backbone” Curve

- **Horizontal deflection at load point (mm)**
- **Passive force (kN)**
Passive Force for Non-Skewed Abutments


- Passive force best estimated using log-spiral method
- Peak passive force mobilized at displacement of 0.03H to 0.05H
- Hyperbolic curve best represents passive force-displacement curve
AASHTO Design Method

- Bi-linear relationship
- Failure occurs at 0.01-0.05H
- Peak passive force obtained using log spiral method
Earthquake Damage to Skewed Bridges
(Paine, Chile)

Top Bridge

Bridge decks have rotated and bridge was demolished.

Bottom Bridge

Bridge deck was offset and was eventually demolished.

Top Bridge

Bridge remained in service after the earthquake.
Damage rate for skewed bridges was twice that of non-skewed bridges (Toro et al 2013)
Skewed Bridge Abutment Overview

- ≈ 40% of 600,000 bridges in US are skewed
- Current AASHTO design code does not consider any effect of skew on passive force
- Observations of poor performance of skewed bridges

Shamsabadi et al. 2006
Interaction of Forces on Bridge Abutment

- Deck Length, $L$
- Skew Angle, $\theta$
- $P_L$
- $P_P$
- $P_R = cA + P_P \tan \delta$

Forces and interactions depicted in a diagram, showing the components of forces related to bridge abutment.
Lab Scale Test Layout

Plan view:

No Skew

1.22 m (4 ft)

Elevation view:

0.6 m (2 ft)
Lab Test Procedure

Plan view:

Elevation view:
Test “Abutment”
Test “Abutment”

30°
Test “Abutment”

Displacement: 60 mm 2.5” (0.10H)

Load measurements:
- Longitudinal
- Vertical
- Transverse
Passive Force-Displacement Curves
Reduction Factor for Skew Effects

\[ R_{\text{skew}} = \frac{P_{(\text{skew})}}{P_{\text{p (No-skew)}}} \]

where \( R_{\text{skew}} \) is a function of skew angle, and wall width is equal to non-skewed (projected) width.

\[ R_{\text{skew}} = 8 \times 10^{-5} \theta^2 - 0.018 \theta + 1.0 \]

(ASCE, J. of Bridge Engrg., Rollins and Jessee 2013)
Passive Force Reduction Factor vs. Skew

Reduction Factor, $R_{\text{skew}}$ vs. Skew Angle, $\theta$ [degrees]

$R_{\text{skew}} = 8 \times 10^{-05} \theta^2 - 0.018 \theta + 1$

$R^2 = 0.98$

Lab Tests
Numerical Analysis
Proposed Reduction Line

(ASCE, J. of Bridge Engrg., Rollins and Jessee 2013)
Large-Scale Field Test Setup - Plan View

- 12.75 inch Dia. Steel Pipe Piles
- 11 ft wide x 5.5 ft high Pile Cap
- 24 ft Transverse Wingwalls
- 2 x 4 ft Reinforced Concrete blocks
- 4 ft Dia. Bored Pile
- Sheet Pile Wall Section AZ-18
- 2 – 600 kip Actuators
Field Test Methodology

![Graph showing Pile Cap Deflection vs. Longitudinal Force and Baseline Resistance.]

- **Pile Cap Deflection [cm]**
- **Longitudinal Force [kN]**
- **Longitudinal Force [kips]**
- **Total Load**
- **Baseline Resistance**
- **Lateral Backfill Resistance**
No Skew - 0° Test Setup, Transverse Wingwalls
15° Skew Test Setup
30° Skew Test Setup
Passive Force vs. Displacement

Pile Cap Deflection [cm]

Passive Force [kips]

Passive Force [kN]

Pile Cap Deflection [in]

0° Skew
15° Skew
30° Skew
45° Skew

0.02H
0.03H
0.04H
0.05H
Passive Force Reduction Factor vs. Skew

\[ R_{\text{skew}} = 8 \times 10^{-05} \theta^2 - 0.018 \theta + 1 \]

\[ R^2 = 0.98 \]
No Skew - 0° Test Setup, Parallel (MSE) Wingwalls
30° Test Setup, Parallel (MSE) Wingwalls
0 & 45º Skew with RC Wingwalls
Reduction Factor vs. Skew for All Data

Shamsabadi & Rollins (2014)

\[ R_{\text{skew}} = e^{-\theta/45^\circ} \]
Hyperbolic Curve from Caltrans SDC

\[ F(y) = \frac{C_y}{1 + D_y R(\theta)} \]

\[ C = 2K_{50} - \frac{F_{ult}}{y_{max}} \]

\[ D = 2\left(\frac{K_{50}}{F_{ult}} - \frac{1}{y_{max}}\right) \]

\[ K_{50} = (11H + 40) \]

\[ R(\theta) = \exp\left(-\frac{\theta}{45}\right) \]
Conclusions Regarding Skew Effects:

- Significant decrease in passive force with increase in skew angle.
  - Numerical Analysis
  - 8 Large Scale Lab Tests
  - 11 Large Scale Field tests
- Simple reduction factor can account for the effect of skew angle on passive force
- Reduction factor not much affected by backfill or wingwall geometry
- Reduction factor not much affected by sand, gravel, or GRS backfill type
- Passive force typically mobilized at $\Delta/H \approx 3$ to $5\%$
Passive Force-Deflection for CLSM
(Controlled Low Strength Material, Flowable Fill)

No Skew Reduction Effects, Brittle Behavior
Lightweight Cellular Concrete (LCC)
## California LCC Classes

<table>
<thead>
<tr>
<th>Cellular Concrete Class</th>
<th>Cast Density (lb/ft^3)</th>
<th>Minimum 28-day Compressive Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>24-29</td>
<td>10</td>
</tr>
<tr>
<td>II</td>
<td>30-35</td>
<td>40</td>
</tr>
<tr>
<td>III</td>
<td>36-41</td>
<td>80</td>
</tr>
<tr>
<td>IV</td>
<td>42-49</td>
<td>120</td>
</tr>
<tr>
<td>V</td>
<td>50-79</td>
<td>160</td>
</tr>
<tr>
<td>VI</td>
<td>80-90</td>
<td>300</td>
</tr>
</tbody>
</table>
Benefits

- Low unit weight / Reduced Settlement
- Easily excavated
- Reduced number of cement trucks
- Easy to place
- Good flowability / Self-Leveling
Large-Scale Testing

4 ft x 2 ft  
0° Skew

11 ft x 5.5 ft  
0° Skew
Passive Force-Deflection for Sand, LCC, and CLSM

<table>
<thead>
<tr>
<th>Material</th>
<th>Stiffness (kips/in/ft)</th>
<th>Peak Load (kips)</th>
<th>Deflection at Peak (%H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>32.5</td>
<td>45</td>
<td>3.3</td>
</tr>
<tr>
<td>LCC</td>
<td>76</td>
<td>52</td>
<td>2.1</td>
</tr>
<tr>
<td>CLSM</td>
<td>325</td>
<td>61</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Graph showing backwall displacement (Δ in.) and passive force (Pp (kN)) for different materials.
Reduction factor, \( R_{\text{skew}} \), vs. Skew Angle, \( \theta \) (Degrees)

Shamsabadi & Rollins (2014)

\[ R_{\text{skew}} = e^{-\theta/45^\circ} \]
Conclusions Related To CLSM, LCC Backfill

- CLSM minimizes skew reduction but exhibits brittle post-peak behavior
- LCC less sensitive to skew and has ductile post-peak behavior
- CLSM and LCC both somewhat stiffer than sand backfill
Questions?
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