Passive Force-Deflection Behavior for Skewed Abutments

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FHWA Pooled Fund Sponsors

- Utah DOT – Lead Agency
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Background


- 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
Background

Unclear: Effect of skew on passive force
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
Damage to Skewed Integral Abutments

(Steinberg & Sargand, 2010)
Earthquake Damage to Skewed Bridges
(Paine, Chile)

Top Bridge

Bottom Bridge

Bridge decks were displaced off service after the earthquake.
Damage rate for skewed bridges was twice that of non-skewed bridges (Toro et al. 2013)
Passive force contributes to resistance

- Using smaller passive force (lower $K_p$) may be conservative
Passive Force from Lateral Spreading

- Passive force often drives displacement
- Selection of smaller passive force (lower $K_p$) may be unconservative
Driving Force on Skewed Abutments
Interaction of Forces on Bridge Abutment

- Deck Length, $L$
- Skew Angle, $\theta$
- $P_L$
- $P_R = cA + P \tan \theta$
- $P_P$
- $P_L \cos \theta$
- $P_L \sin \theta$
Numerical Analysis of Skewed Abutments

23 m (75 ft) wide abutment with 2.4 m (8 ft) high backwall

(5th NSC, Shamsabadi et al., 2006)
Results of Numerical Analysis

(5th NSC, Shamsabadi et al., 2006)
Objectives

1. Determine static passive force-displacement curves for skewed abutments from large-scale tests
2. Provide comparisons of behavior of skewed abutments with that of normal abutments.
3. Evaluate the effect of wingwalls on skewed abutment response.
4. Develop design procedures for calculating passive force-displacement curves and shear-displacement or skewed abutments.
“One good test is worth a thousand expert opinions.”

Werner Von Braun
Designer of Saturn V Moon Rocket
Healthy Skepticism for Tests

- A theory is something nobody believes, except the person who proposed it.
- An experiment (test) is something everybody believes, except the person who performed it.

--Albert Einstein
Initial Laboratory Testing
Test Layout

Plan view:

No Skew
1.22 m (4 ft)

Elevation view:
0.6 m (2 ft)
Test Procedure

Plan view:

Elevation view:
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
Rollers Below Base of “Abutment”
Surface Failure Rupture - 30° Skew
Backfill Soil Properties

- Gradation and Strength

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<th>Property</th>
<th>Value</th>
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<td>b</td>
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<td>Cu</td>
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<td>ϕ</td>
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Passive Force-Displacement Curves

[Graph showing passive force-displacement curves for different backwall displacements and skew angles.]
Reduction Factor for Skew Effects

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

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)
Normalized Passive Force vs Skew, $\theta$

$R_{skew} = 8E-05\theta^2 - 0.018\theta + 1.0$

$R^2 = 0.98$

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

4 ft Dia.
Bored Pile

Sheet Pile Wall Section
AZ-18

2 – 600 kip Actuators

4 ft Dia.
Bored Pile

24 ft
22 ft

30°
15°

11 ft wide x 5.5 ft high
Pile Cap

12.75 inch Dia.
Steel Pipe Piles

Transverse Wingwalls
2 x 4 ft Reinforced
Concrete blocks

Backfill

N
Field Test Setup Elevation View

SECTION A-A

4 ft Dia. Bored Pile
Sheet Pile Wall Section AZ-18
11 ft m wide x 5.5 ft high x 15 ft long Pile Cap
1-in x 12-in Round Stock in Split 1.025 ID Pile (Typ of 5)

2 – 600 kip Actuators
12.75 inch Dia. Steel Pipe Piles

Backfill

N
Sand backfill properties

- Poorly graded sand (SP/A-1-b) that generally falls within ASTM C33 washed concrete sand gradation requirements
- 96% relative compaction
- $\phi = 41^\circ$
- $c = 4.6$ kPa (100 lbs/ft$^2$)
- $\gamma_{\text{max}} = 17.5$ kN/m$^3$ (111.5 lbs/ft$^3$)
No Skew - 0° Test Setup
15° Skew Test Setup
30° Skew Test Setup
Rollers under the base of 45° wedge
45° Skew Test Setup
45° Skew Test Setup
Heave Geometry at Test Completion

0° Skew

Test completed at 3.21 in (81.6 mm) of displacement

45° Skew

Test completed at 3.43 in (87.2 mm) of displacement
Field Test Methodology

![Graph showing the relationship between Pile Cap Deflection [cm] and Longitudinal Force [kN]. The graph includes two lines:
- Blue line representing Total Load.
- Red line representing Baseline Resistance.

Key findings:
- Lateral Backfill Resistance is indicated by an arrow.
- The deflection increases as the load increases.

The graph demonstrates the effect of load on pile cap deflection, with specific focus on the baseline resistance and lateral backfill resistance.
Passive Force vs. Displacement

![Graph showing Passive Force vs. Pile Cap Deflection for 0°, 15°, 30°, and 45° Skews. The y-axis represents Passive Force in kips, and the x-axis represents Pile Cap Deflection in inches. The graph includes four lines: blue for 0° Skew, red for 15° Skew, green for 30° Skew, and black for 45° Skew. Each line represents different deflection values at 0.02H, 0.03H, 0.04H, and 0.05H.]
Passive Force Reduction Factor vs. Skew

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

\[ R^2 = 0.98 \]
Failure Geometry for Zero-Skew Test

\[ \phi_{meas} = 41^\circ \]
\[ \alpha = 45 - \frac{\phi'}{2} \]
\[ \phi \approx 40^\circ \]
Comparison of Failure Geometries

Rankine Failure Geometry

Log-Spiral Failure Geometry

\[ \alpha = 45^\circ - \phi/2 \]

\[ r = r_0 e^{\delta \tan \phi} \]

\[ f = \text{surface traction} \]

\[ \text{resultant of normal and friction forces} \]
Interface Forces with Respect to Skew

![Graph showing forces with respect to skew angle]

- **Longitudinal Force, $P_L$**
- **Passive Force, $P_p$**
- **Shear Resistance, $P_R$**
- **Applied Shear Force, $P_T$**

**Axes:**
- Y-axis: Force (Kips)
- X-axis: Skew Angle $\theta$, (°)

**Force Values:**
- 0 Kips at 0°
- 500 Kips at 30°
- 1,000 Kips at 20°
- 1,500 Kips at 15°
- 2,000 Kips at 10°
Shear force vs. transverse displacement

Applied Shear Force [kip] vs. Transverse Displacement [in]

- 45° skew
- 30° skew
- 15° skew
Test Setup for MSE Wingwall Tests

- 4-ft Dia. Reinforced Concrete Shafts
- Sheet Pile Wall
- Section AZ 18
- 5.33-ft x 20-ft I-Beam (Typ of 2)
- Independent Reference Frame
- 12.75-in Dia. Steel Pile (Typ of 6)
- 11-ft x 15-ft x 5.5-ft Concrete Pile Cap
- 8-ft 2 x 3 (Typ of 6)
- 12-ft x 5-ft MSE Wall Panel (Typ of 4)
- 5-Bar Steel Reinforcement on Bottom, W6 Transverse Bars & 6-Bar Steel on Top, W11 Transverse Bars (Typ of Both Sides)

NOTES:
- All Dimensions Are Feet

Legend of Symbols:
- String Potentiometer

SECTION A-A
- 4-ft Dia. Reinforced Concrete Shafts
- Sheet Pile Wall
- Section AZ 18
- 5.33-ft x 20-ft I-Beam (Typ of 2)
- Independent Reference Frame
- (2) Actuators 600 Kip-Extension, 450 Kip-Contraction
- 12.75-in Dia. Steel Pile (Typ of 6)
- 11-ft x 15-ft x 5.5-ft Concrete Pile Cap
- L5-Bar Steel W11 Transverse Bars Reinforcement (Typ of 8)
- 12-ft x 5-ft MSE Wall Panel (Typ of 4)
- 6-ft 2 x 8 (Typ of 6)
- 4 x 4 Timber Used For Leveling Pad
Welded Wire Grid Reinforcement (SSL)
No Skew - 0° Test Setup
15° Skew Test with MSE Wingwalls
Field Test with $30^\circ$ Skew & MSE Walls
0° Skew

3.35 m

Distance From Pile Cap (ft)

MSE Wingwall Displacement (in)

- 0.24
- 0.83
- 1.72
- 2.73
- 3.18
45° Skew

Deflection (in)

0
.75" 1.5" 2.25" 3.0" 3.5"

Deflection (in)

0
.75" 1.5" 2.25" 3.0" 3.5"

Deflection (in)

0
.75" 1.5" 2.25" 3.0" 3.5"

Deflection (in)

0
.75" 1.5" 2.25" 3.0" 3.5"
Passive Force-Displacement curves

Pile Cap Displacement, $\Delta$ [cm]

Backwall Displacement, $\Delta$ [in]

0 Degree Skew
30 Degree Skew
15 Degree Skew
45 Degree Skew

Passive Force [kips]
Passive Force [kN]
Passive Force Reduction Factor vs. Skew

\[ R_{\text{skew}} = 8 \times 10^{-0.05} \theta^2 - 0.018 \theta + 1 \]

\[ R^2 = 0.98 \]
Geometry Effects?

- Field and Lab tests involved W/H ratios of 2.0

- Does this ratio impact the results?
Field Test with 3 ft Backfill - W/H=3.7

SECTION A-A

4 ft Dia. Reinforced Concrete Shaft

2- 600 kip Actuators
11 ft wide x 5.5 ft high x 15 ft long Pile Cap

Sheet Pile Wall Section AZ 18

12 in Dia. Steel Pipe Piles
Passive Force-Displacement Curves

![Graph showing passive force-displacement curves for different pile cap displacements and skew angles. The y-axis represents Passive Force in kips and the x-axis represents Pile Cap Displacement in inches. The graph includes lines for 0 Degree Skew, 15 Degree Skew, 30 Degree Skew, and 45 Degree Skew. Each line represents a curve starting from the origin, increasing, and then reaching a peak before decreasing slightly.]
Passive Force Reduction Factor vs. Skew

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

\[ R^2 = 0.98 \]

- Lab Tests
- Numerical Analysis
- Field Tests (This Study)
- Proposed Reduction Line

Skew Angle, \( \theta \) [degrees]
Tests with Gravel Backfill

Horizontal Deflection [cm]

Passive Force [kN]

0 degree Skew

30 Degree Skew
45º Skew with RC Wingwalls
45° Skew with RC Wingwalls
0º Skew with RC Wingwalls
Passive Force Reduction Factor vs. Skew

\[ R_{\text{skew}} = 8 \times 10^{-0.05} \theta^2 - 0.018 \theta + 1 \]

\[ R^2 = 0.98 \]

- Lab Tests
- Numerical Analysis
- Field Tests (This Study)
- Proposed Reduction Line
Horizontal Displacement

- **> 2 in**
- **> 1 in & < 2 in**
- **< 1 in**

Vector scale 3:1

0 degree skew 5.5ft sand with reinforced concrete wingwalls

45 degree skew 5.5ft sand with reinforced concrete wingwalls

Length (ft)

Width (ft)

Pile Cap
Summary of Results

- Significant decrease in passive force with increase in skew angle.
  - Numerical Analysis
  - 8 Small Scale Lab Tests
  - 16 Large Scale Field tests

- Reduction factor proposed by Rollins and Jessee (2013) is generally applicable for both perpendicular and parallel (MSE) wingwall cases

- Reduction factor not much affected by wall L/H ratio

- Passive force typically mobilized at $\Delta/H \approx 0.03$ or 3%

- Shear resistance mobilized in 0.2 to 0.3 inches of transverse movement
AASHTO Design Method

- Bi-linear relationship
- Failure occurs at 0.01-0.05H
- Peak passive force obtained using log spiral method
Log Spiral Passive Force

\[ P_p = 0.5\gamma H^2 K_p \]

\( \gamma \) = moist unit weight
\( \phi \) = Soil friction angle
\( \delta \) = wall friction angle
\( \beta \) = backfill slope angle
\( H \) = height of back wall
\( K_p \) = passive pressure coefficient

Figure 3.11.5.4-2—Computational Procedures for Passive Earth Pressures for Vertical Wall with Sloping Backfill (U.S. Department of the Navy, 1982a)
Recommended Design Procedure for Skew Effects

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

where \( R_{\text{skew}} \) is given by the equation

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

and wall width is equal to non-skewed (projected) width.

(ASCE, J. of Bridge Engrg., Rollins and Jessee 2013)
Adjustment for width & Skew

\[ P_{pH} = 28.5 \text{ k/ft} \]

For 0° skew condition
\[ P_{pH} = (28.5 \text{ k/ft}) \times (50 \text{ ft}) = 1425 \text{ k} \]

Compute skew reduction factor
\[ R_{\text{skew}} = 8 \times 10^{-5} (30)^2 - 0.018 (30) + 1.0 \]
\[ = 0.53 \]

For 30° skew condition
\[ P_{pH} = (1425 \text{ k})(0.53) = 755 \text{ k} \]
Passive Force-Displacement

For a 6 ft high backwall:
Peak at \(0.03H = 0.03(6 \text{ ft})(12 \text{ in/ft})\)
\[= 2.2 \text{ in}\]

\[P_{pH} = 755k\]
Shear Force-Displacement

\[ \theta = 30^\circ \]
\[ P_{PH} = 755k \]
\[ T = 401k \]

For a \( \delta = 28^\circ = 0.70\phi \)
\[ T = cA + P_{PH} \tan \delta \]
\[ = 0 + (755 \text{ k}) \tan(28^\circ) = 401k \]

Peak at 0.25 in
Hyperbolic Passive Force vs. Displacement

Pile Cap Deflection [cm]

Passive Force [kN]

0° Skew
15° Skew
30° Skew
45° Skew

0.02H
0.03H
0.04H
0.05H

Passive Force [kips]

Pile Cap Deflection [in]
Questions?
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