The National Academies of
SCIENCES · ENGINEERING · MEDICINE

TRANSPORTATION RESEARCH BOARD

Seismic Design of Bridge Abutments

Thursday, September 28, 2017
2:00-4:00PM ET

The Transportation Research Board has met the standards and requirements of the Registered Continuing Education Providers Program. Credit earned on completion of this program will be reported to RCEP. A certificate of completion will be issued to participants that have registered and attended the entire session. As such, it does not include content that may be deemed or construed to be an approval or endorsement by RCEP.

RCEP

REGISTERED CONTINUING EDUCATION PROGRAM

Purpose

Discuss the latest research about theories on computing the ultimate passive force for abutment deflection.

Learning Objectives

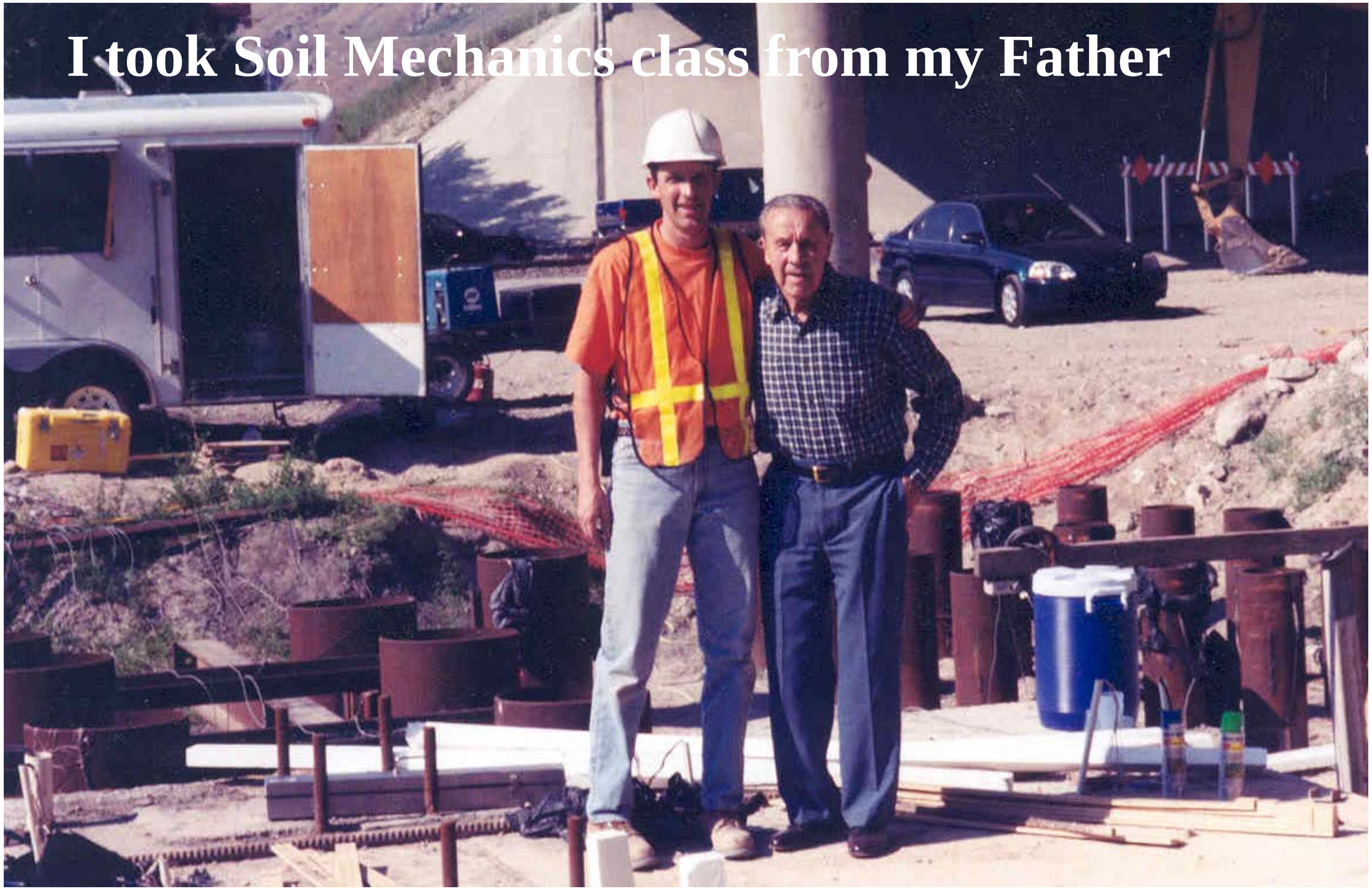
At the end of this webinar, you will be able to:

- Understand the differences between available methods for computing ultimate passive force and correctly compute ultimate passive force for four different materials, including: dense backfills, loose backfills, flowable fills/cellular concrete, and geofoam inclusions
- Compute and adjust passive force for several characteristics, including: skew angle of the abutment, and cyclic loading
- Understand how to select soil parameters for lateral pile analysis of abutment piles
- Use p-multipliers to reduce lateral pile resistance due to group interaction and piles near MSE walls

Seismic Design of Bridge Abutments

Kyle Rollins
Civil & Environmental Engineering
Brigham Young University

Ralph Rollins, performed geotechnical investigations for over 5000 structures



Rachel Rollins was Civil Engineering student

Granddaughter, Ella, shows early interest in soil behavior…

Seismic Design of Bridge Abutments

Kyle Rollins
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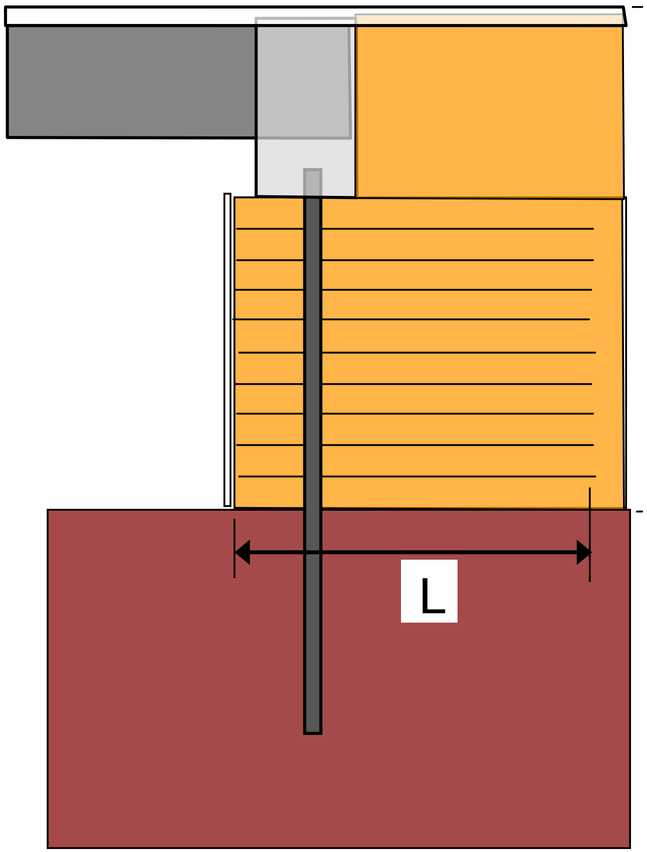
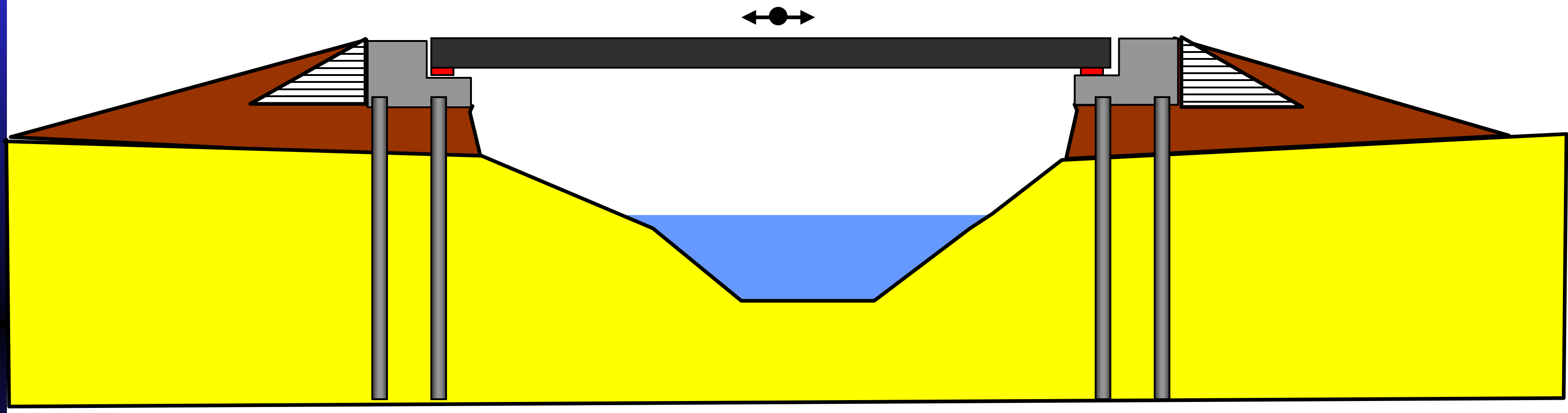
Brigham Young University

Lateral Resistance of Bridge Abutments



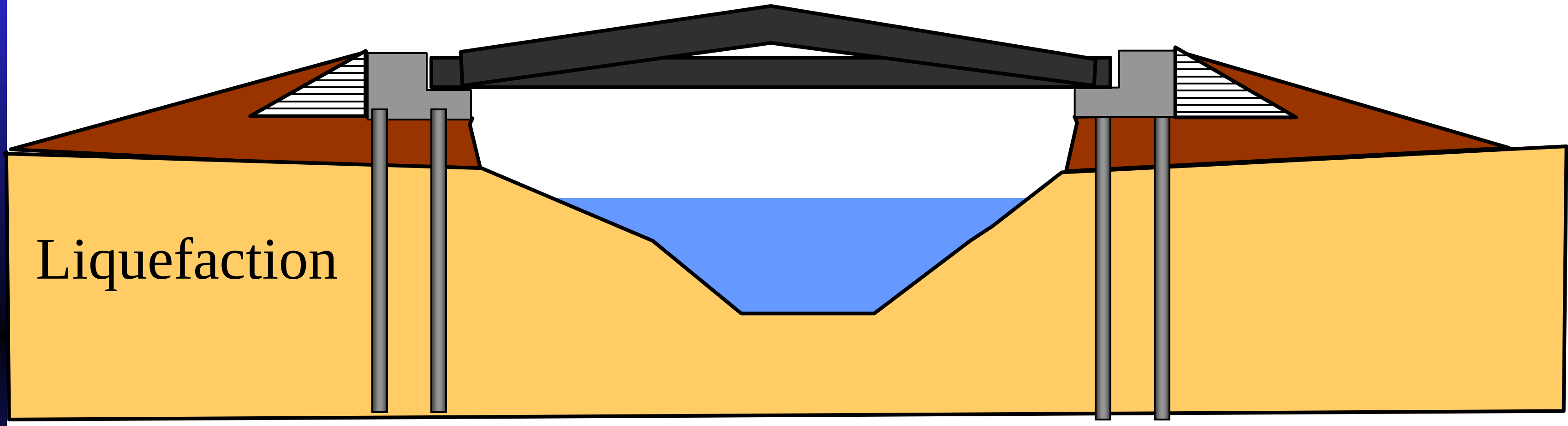
- Passive force-displacement against abutment
- Lateral resistance of piles near MSE wall faces

Passive Force on Bridge Abutments



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

Passive Force on Bridge Abutments



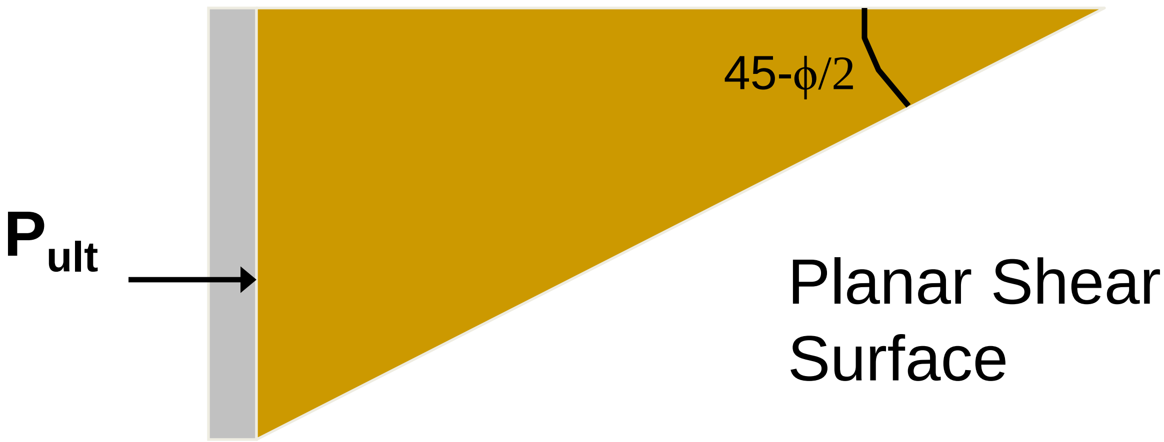
- Passive force contributes to load
- Using smaller passive force (lower K_p) is unconservative

Buckled Railroad Bridge Caused by Lateral Spread During the 1964 Alaska Earthquake

Summary of Passive Force Methods

- Rankine
- Coloumb
- Log Spiral
- Caltrans

Rankine Method



$P_{ult} = 0.5\ \gamma H^2 K_p$

$K_p = \tan^2(45+\phi/2)$

Advantages

- Simplicity
- Conservative

Limitations

- Planar Shear Surface
- Neglects wall friction (δ)

Only 30% to 50% of correct value

Coulomb Method

$$P_{ult} = 0.5\,\gamma H^2 K_p$$

$$K_p = \frac{\cos^2\phi}{\cos\delta \left\{1 - \sqrt{\frac{\sin(\phi+\delta)\sin\phi}{\cos\delta}}\right\}^2}$$

<u>Advantages</u>

- Accounts for wall friction (δ)
- Complex Geometries

<u>Limitations</u>

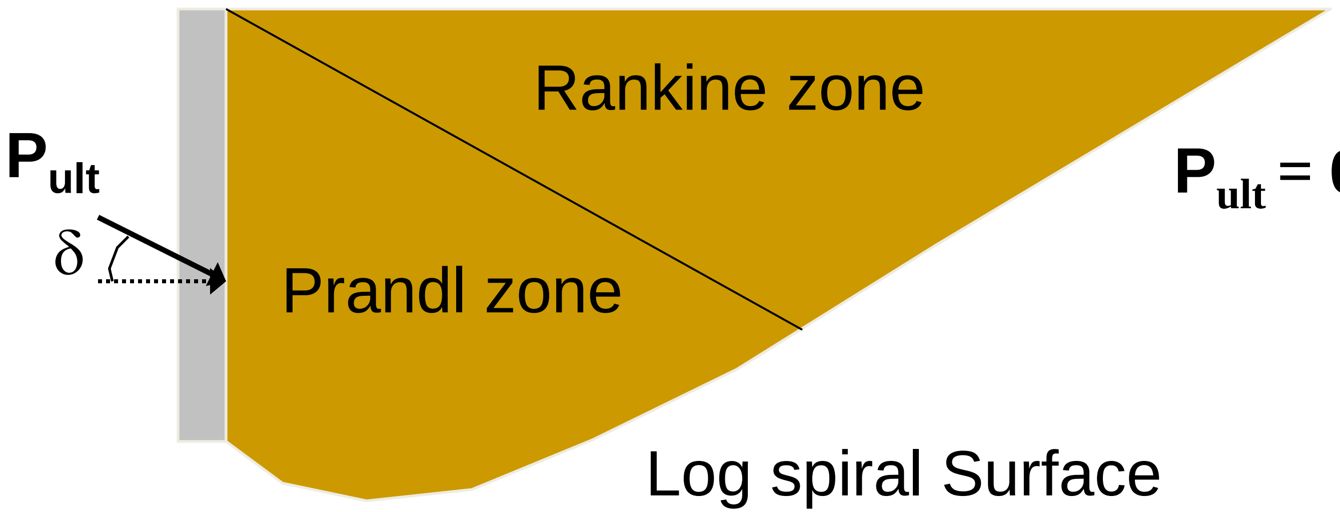
- Planar Shear Surface
- Yields Very High P_{ult} for $\delta > 0.4\phi$

Over 100% higher than correct value

Nature is often non-linear!

Nature likes log spirals!

Log Spiral Method



$$P_{ult} = 0.5\ \gamma H^2\ K_p$$

- Accounts for wall friction and shear shape
- More Complicated
- Graphical or numerical solution

Log Spiral Passive Force

$$P_p = 0.5\gamma H^2 K_p$$

ϕ = Soil friction angle

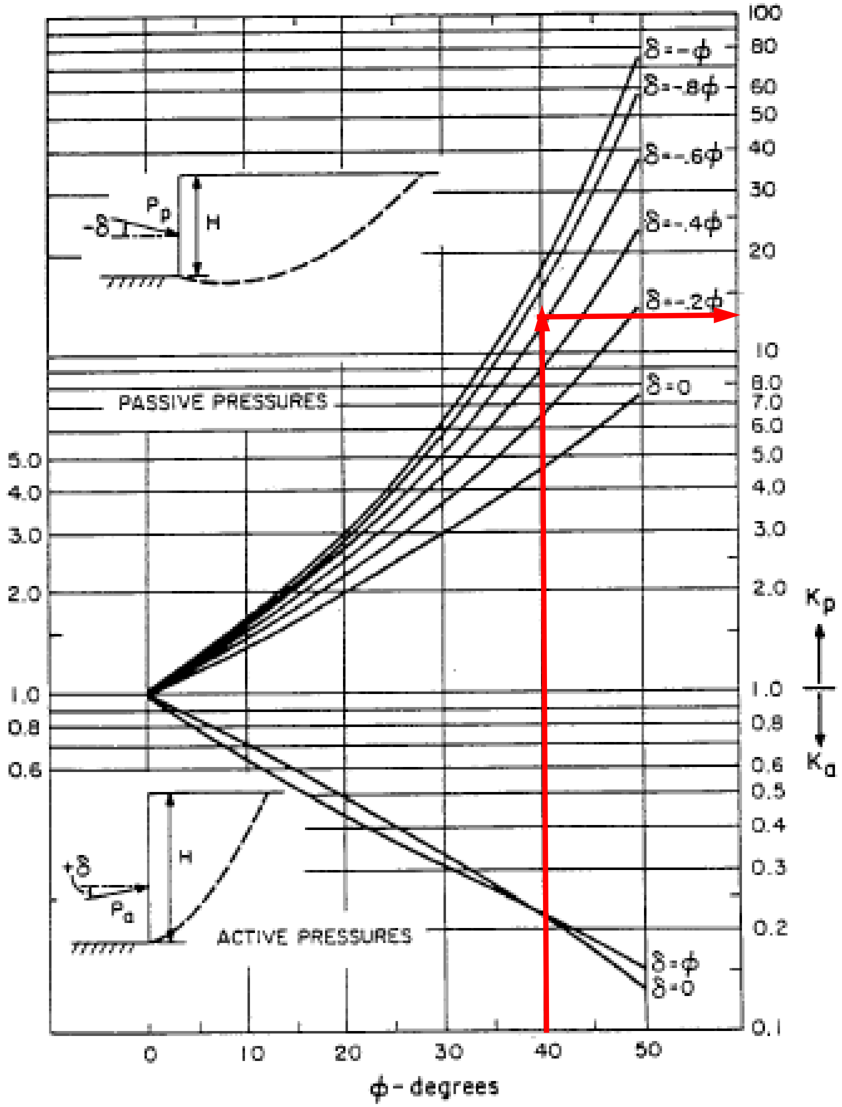
δ = wall friction angle

β=backfill slope angle

H= height of back wall

K_p=passive pressure coefficient

K_p can come from chart, Excel spreadsheet PYCAP



Wall Friction Angle, δ

Table 3.11.5.3-1—Friction Angle for Dissimilar Materials (U.S. Department of the Navy, 1982a)

Interface Materials	Friction Angle, δ (degrees)	Coefficient of Friction, tan δ (dim.)
Mass concrete on the following foundation materials:		
• Clean sound rock	35	0.70
• Clean gravel, gravel-sand mixtures, coarse sand	29 to 31	0.55 to 0.60
• Clean fine to medium sand, silty medium to coarse sand, silty or clayey gravel	24 to 29	0.45 to 0.55
• Clean fine sand, silty or clayey fine to medium sand	19 to 24	0.34 to 0.45
• Fine sandy silt, nonplastic silt	17 to 19	0.31 to 0.34
• Very stiff and hard residual or preconsolidated clay	22 to 26	0.40 to 0.49
• Medium stiff and stiff clay and silty clay	17 to 19	0.31 to 0.34
Masonry on foundation materials has same friction factors.		
Steel sheet piles against the following soils:		
• Clean gravel, gravel-sand mixtures, well-graded rock fill with spalls	22	0.40
• Clean sand, silty sand-gravel mixture, single-size hard rock fill	17	0.31
• Silty sand, gravel or sand mixed with silt or clay	14	0.25
• Fine sandy silt, nonplastic silt	11	0.19
Formed or precast concrete or concrete sheet piling against the following soils:		
• Clean gravel, gravel-sand mixture, well-graded rock fill with spalls	22 to 26	0.40 to 0.49
• Clean sand, silty sand-gravel mixture, single-size hard rock fill	17 to 22	0.31 to 0.40
• Silty sand, gravel or sand mixed with silt or clay	17	0.31
• Fine sandy silt, nonplastic silt	14	0.25

Noted in AASHTO LRFD (2010)

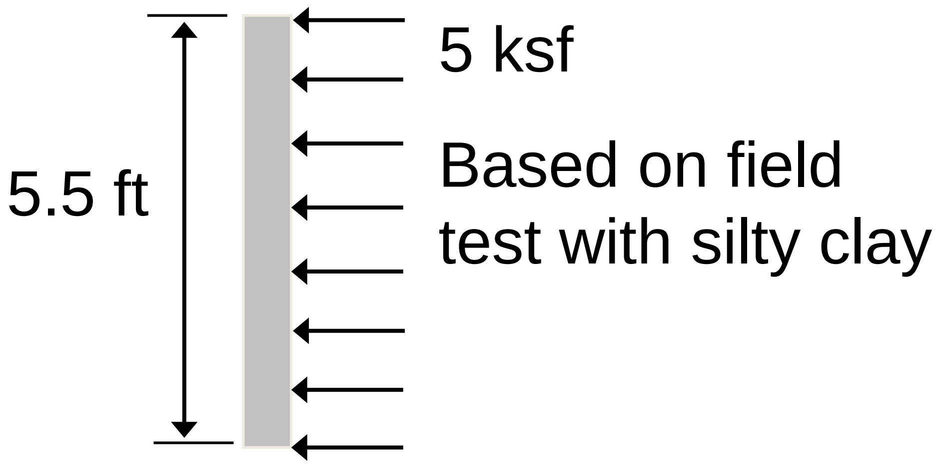
TABLE 1. Minimum Values of δ_{max}/ϕ Determined by Potyondy (1961)

Soil type (1)	Structural Material: Steel (δ_{max}/ϕ) (2)	Concrete (δ_{max}/ϕ) (3)	Wood (δ_{max}/ϕ) (4)
Sand	0.54	0.76	0.76
Silt and clay	0.54	0.50	0.55

Note: δ_{max} = interface friction angle, ϕ = angle of internal friction of soil.

Duncan and Mokwa (2001)

Caltrans Method



$$P_{ult} = A_e \times 5ksf \times \frac{h}{5.5}(kips)$$

Advantages

- Easy to apply

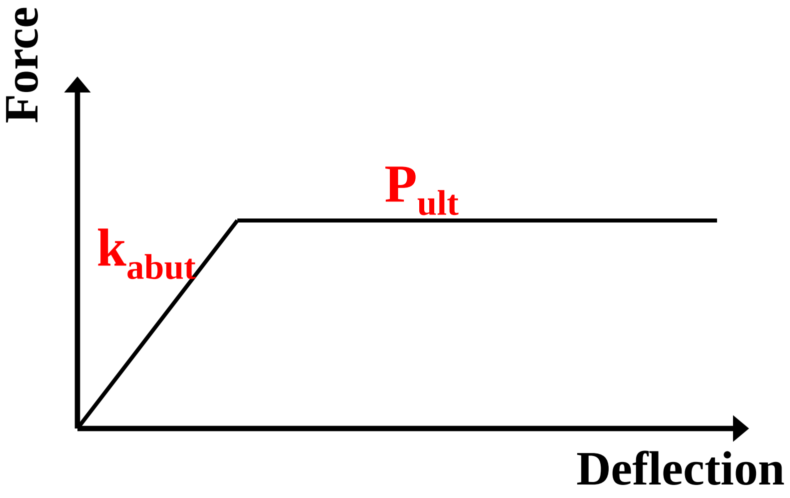
Limitations

- Assumes uniform pressure distribution
- Neglects variable soil strength parameters

Bi-Linear Passive Force-Deflection Curve (Caltrans, 2010)

Initial resistance, k_{abut} = (50 kip/in)*(H/5.5 ft)*w

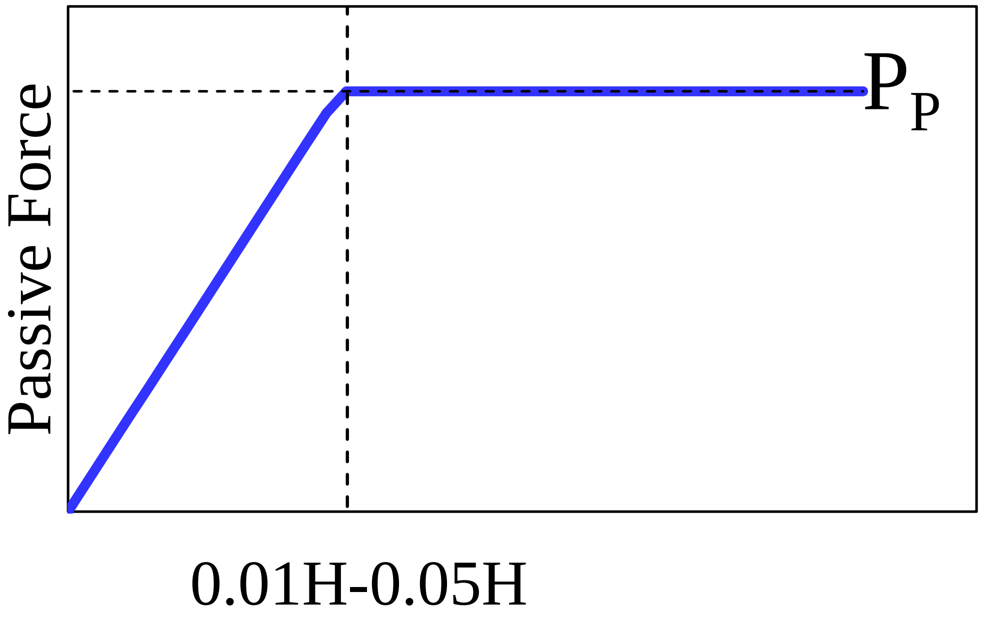
Ultimate resistance, P_{ult} = (5.0 ksf)(H/5.5 ft)A_{wall}



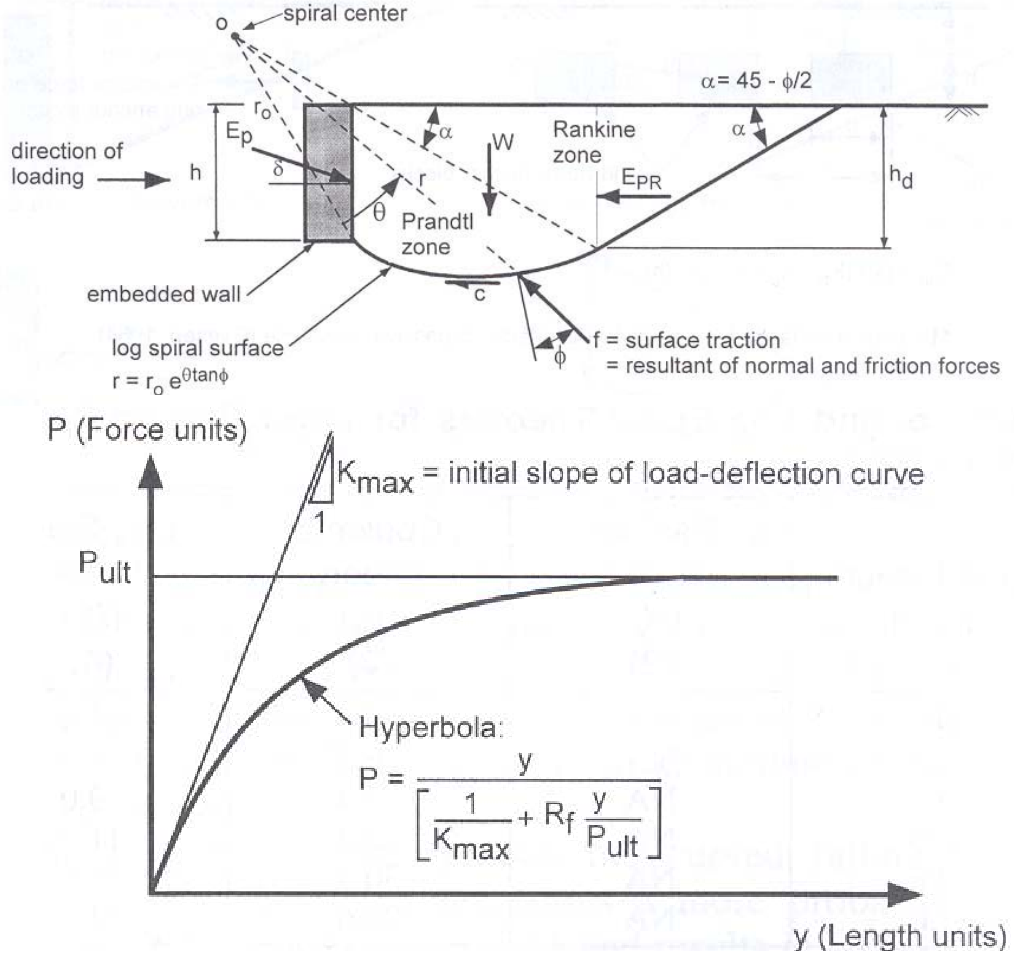
P_{ult} and k_{abut} based on load tests at BYU, UC-Davis and UCLA

AASHTO Design Method

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



Hyperbolic Load-Deflection Curve (Duncan and Mokwa, 2001 Shamsabadi et al 2006)



P_{ult} based on log-spiral method

P-y curve based on:

- Soil Type
- Soil density/stiffness
- Cap geometry

“One good test is worth a thousand expert opinions.”

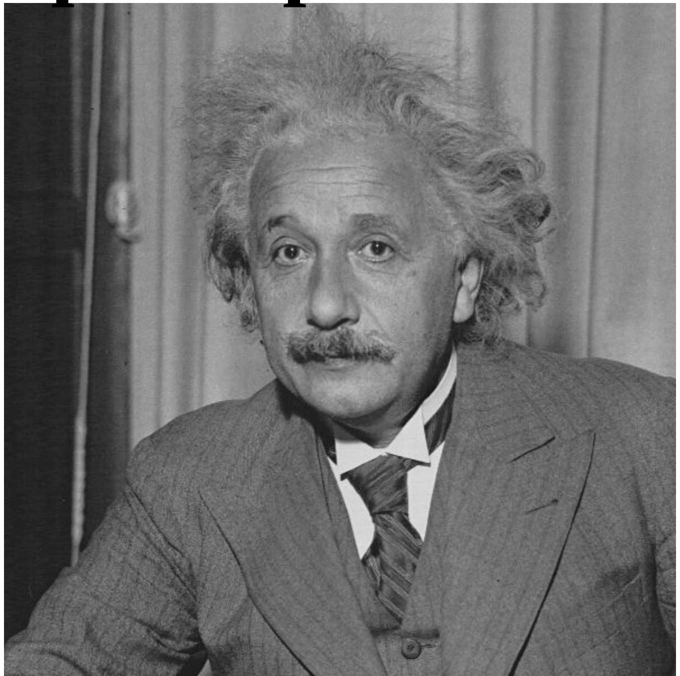
Werner Von Braun

Designer of Saturn V Moon Rocket

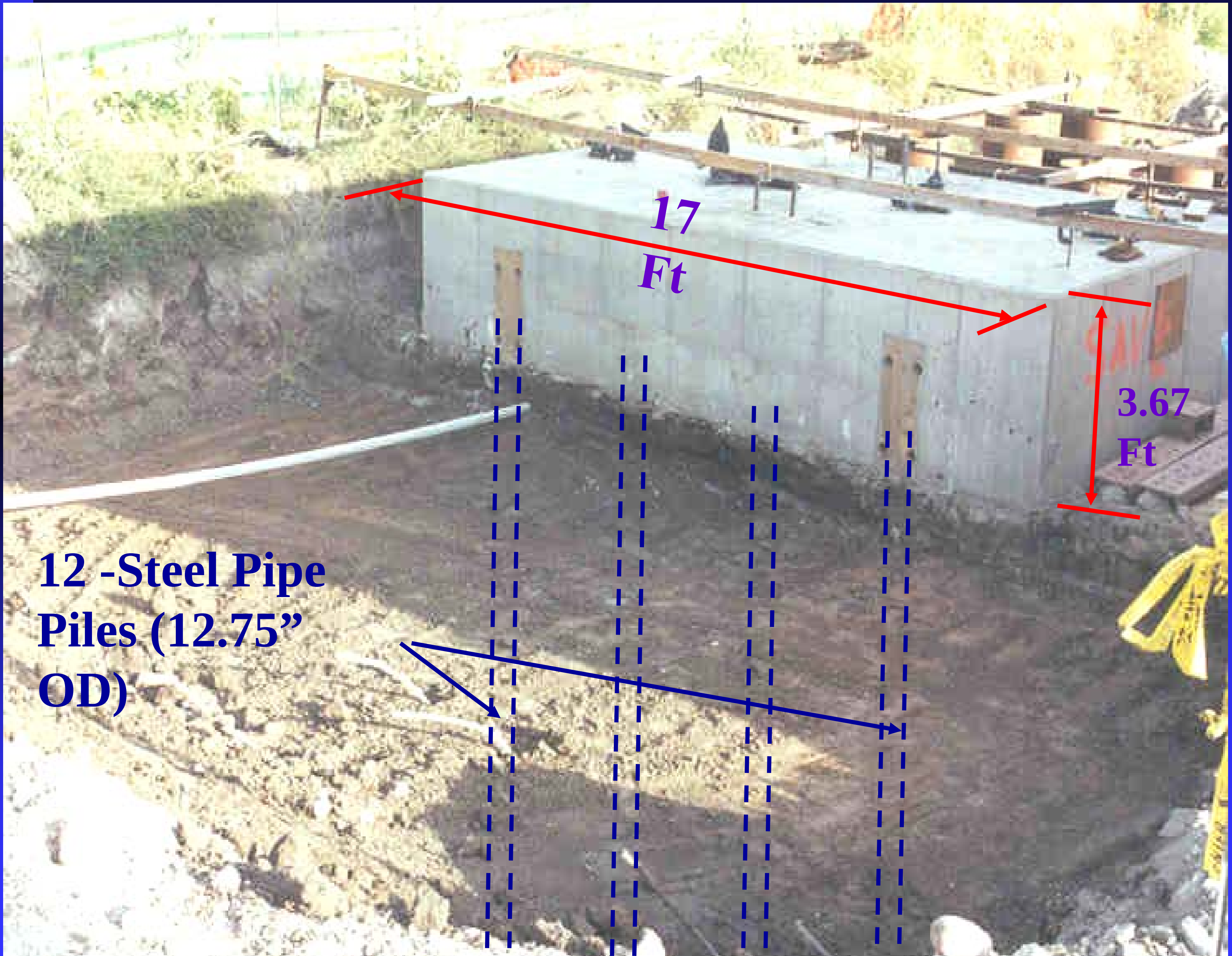
Healthy Skepticism about Tests

- **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**

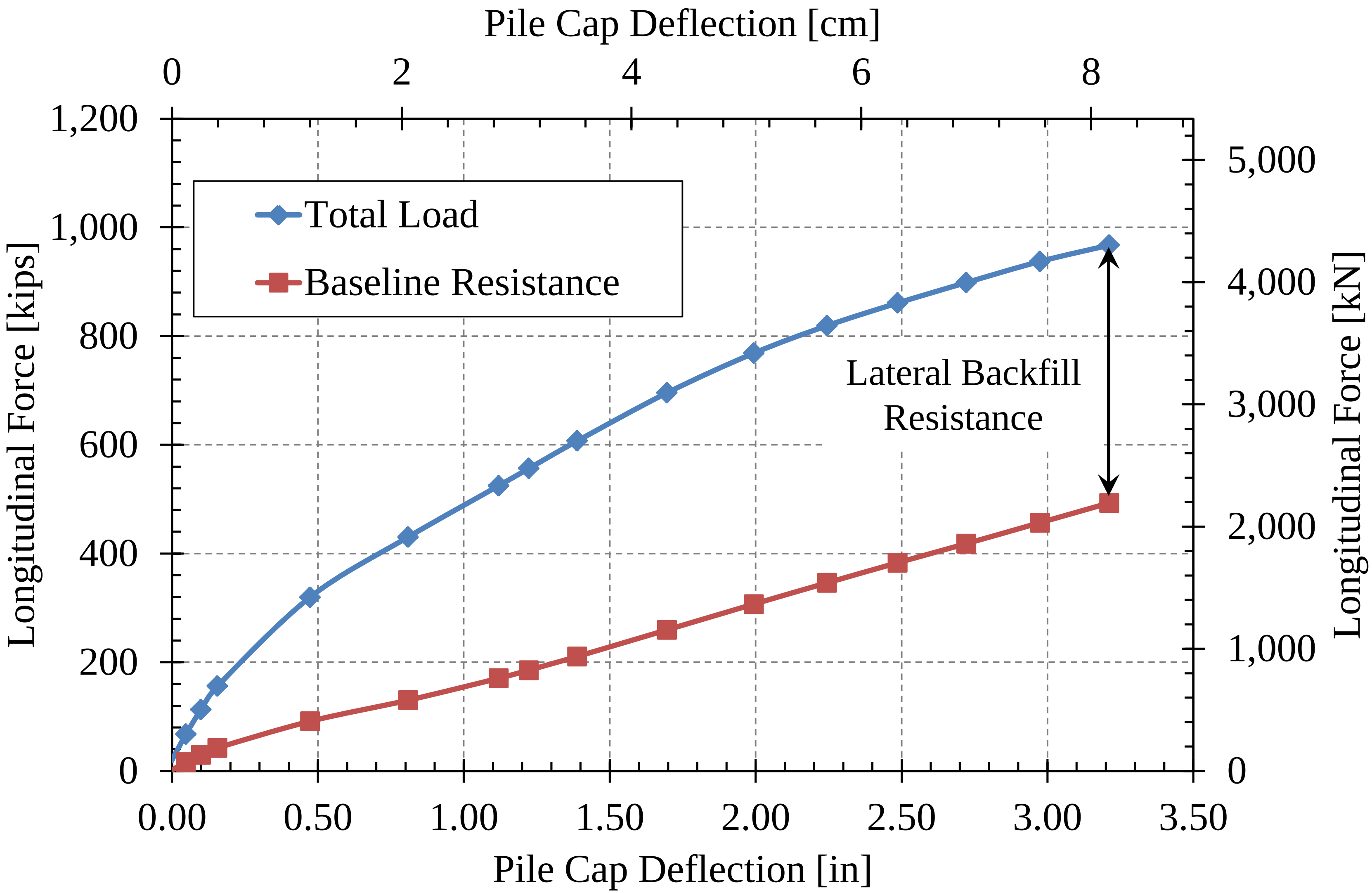
--Albert Einstein



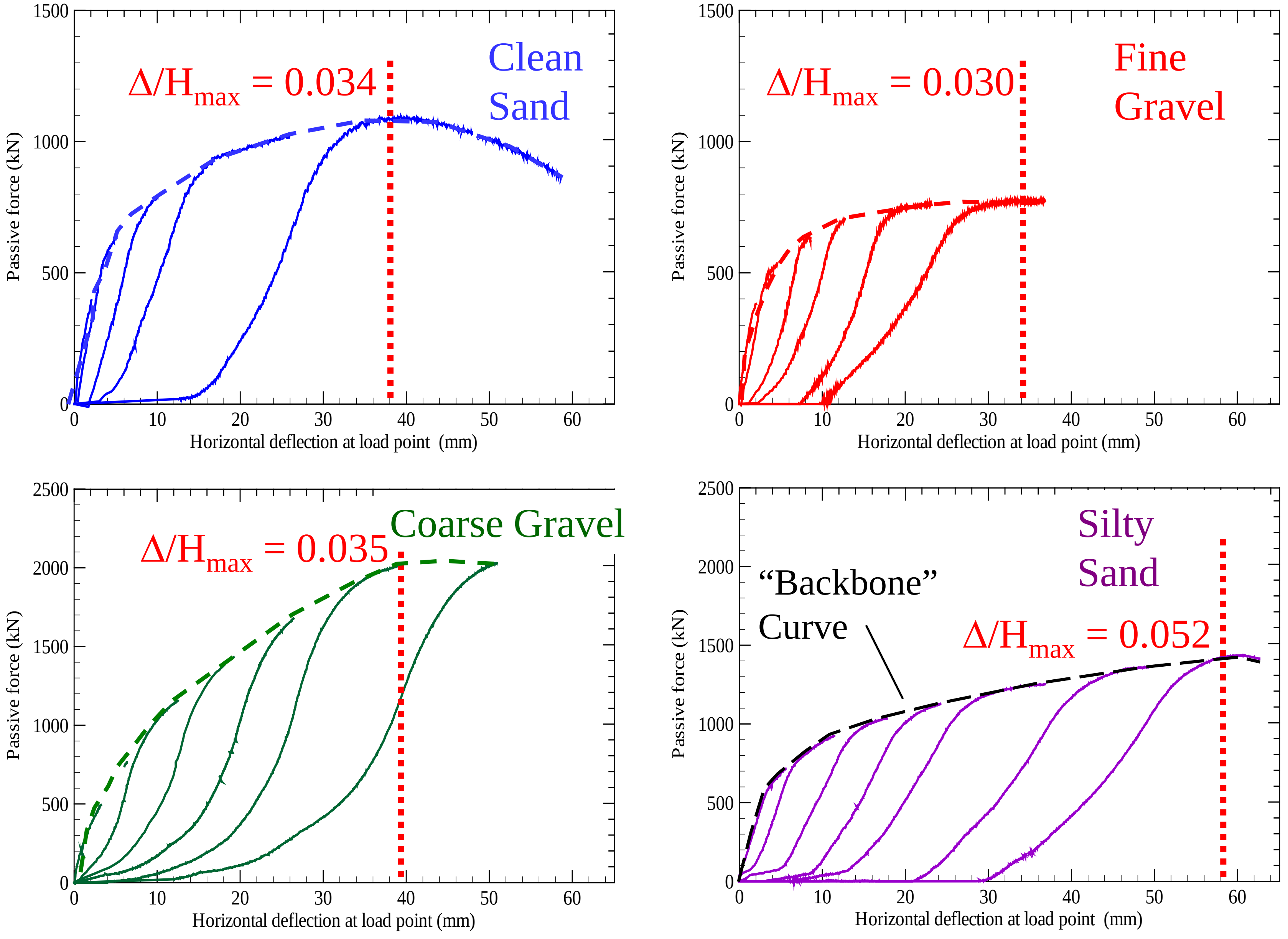
Pile Caps/Abutments



Field Test Methodology

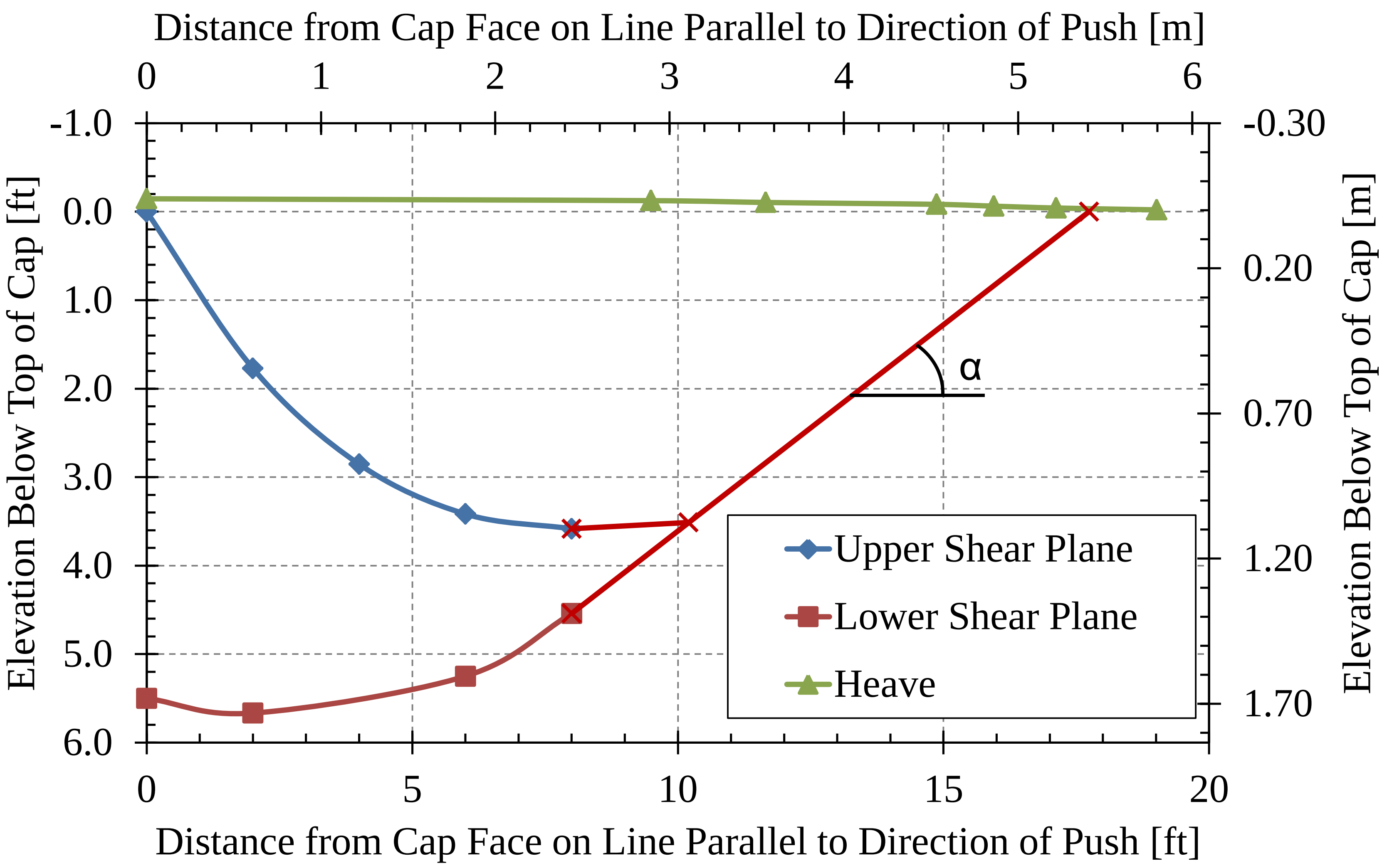


Development of Passive Resistance



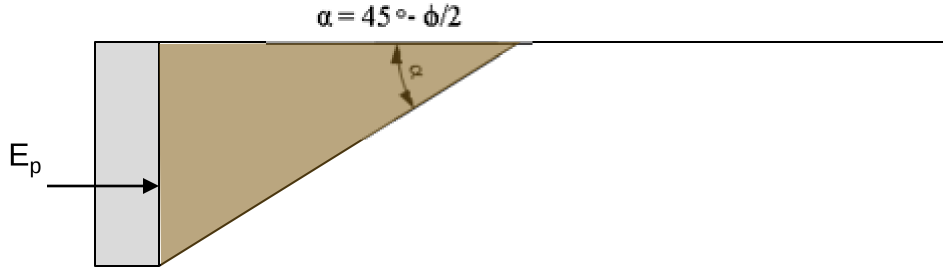
Failure Surface Geometry

Failure Surface Geometry

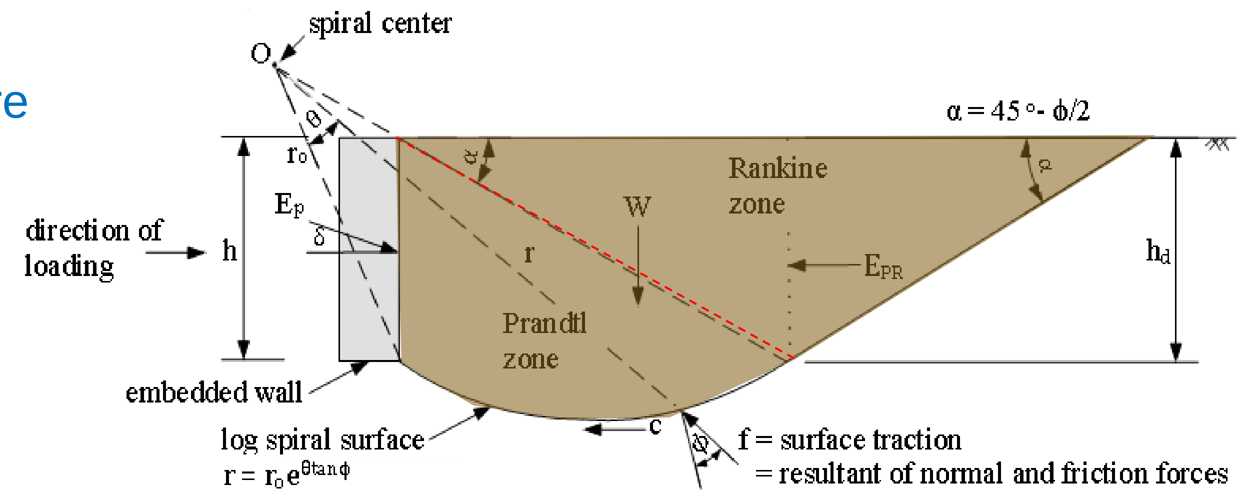


Comparison of Failure Geometries

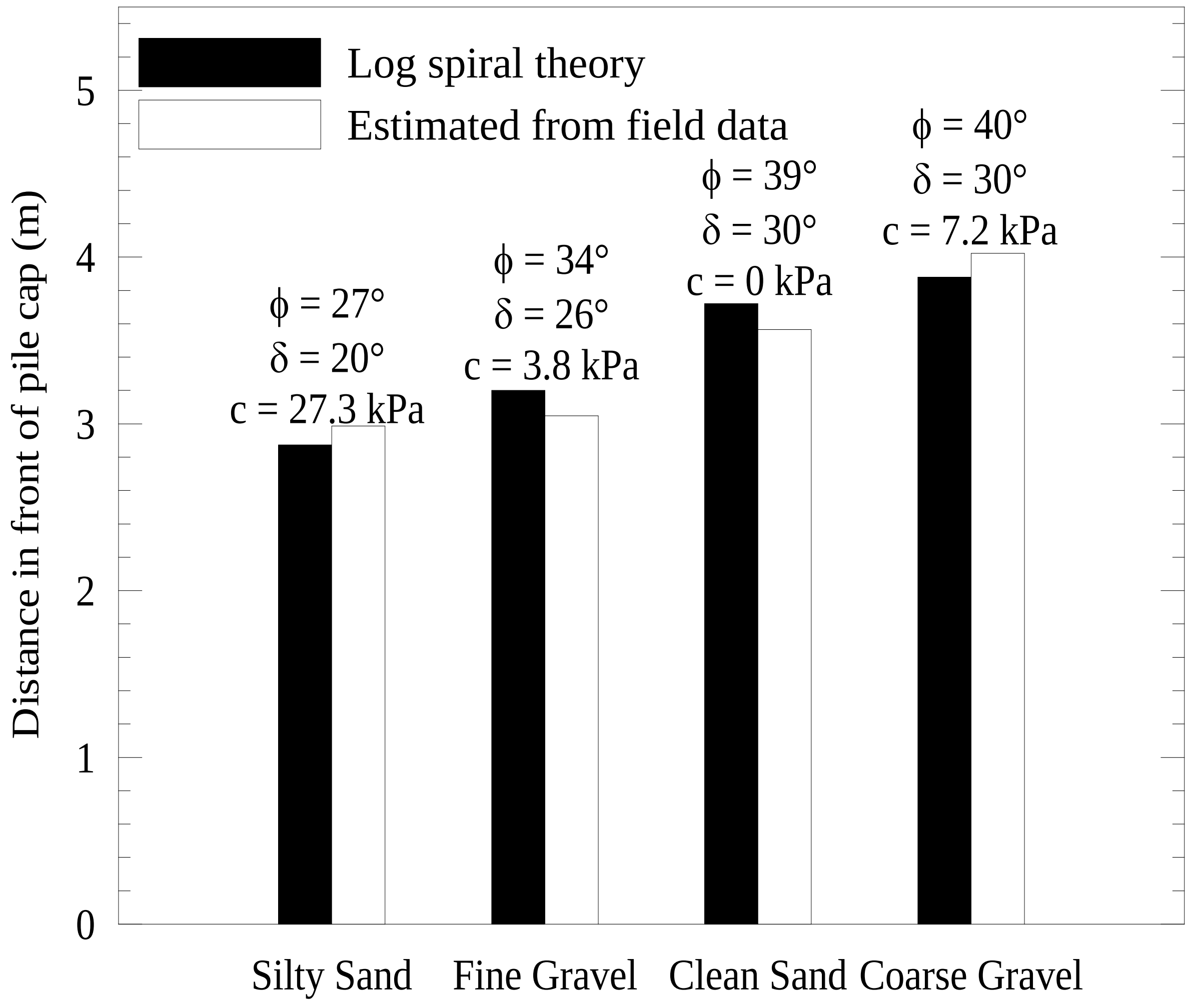
Rankine Failure Geometry



Log-Spiral Failure Geometry



Surface of Sliding Comparisons



Measured and Predicted Peak Passive Force

Method	Total passive force (kN)			
	Clean Sand	Fine Gravel	Coarse Gravel	Silty Sand
Measured	1090	774	1997	1428
Caltrans	914	914	914	914
Coulomb	1577	1149	3464	1575
	(1577)	*(824)*	*(2224)*	*(351)*
Log spiral numerical solution	922	817	1688	1210
Rankine	357	405	719	804
	(357)	*(300)*	*(474)*	*(194)*

Numbers in *(parenthesis)* neglect cohesion component

Log Spiral Passive Force-Example

$$P_p = 0.5\gamma H^2 K_p$$

Sandy Gravel

γ=135 pcf

ϕ = 40º

$\delta = 0.70\phi = 0.7(40^{\circ}) = 28^{\circ}$

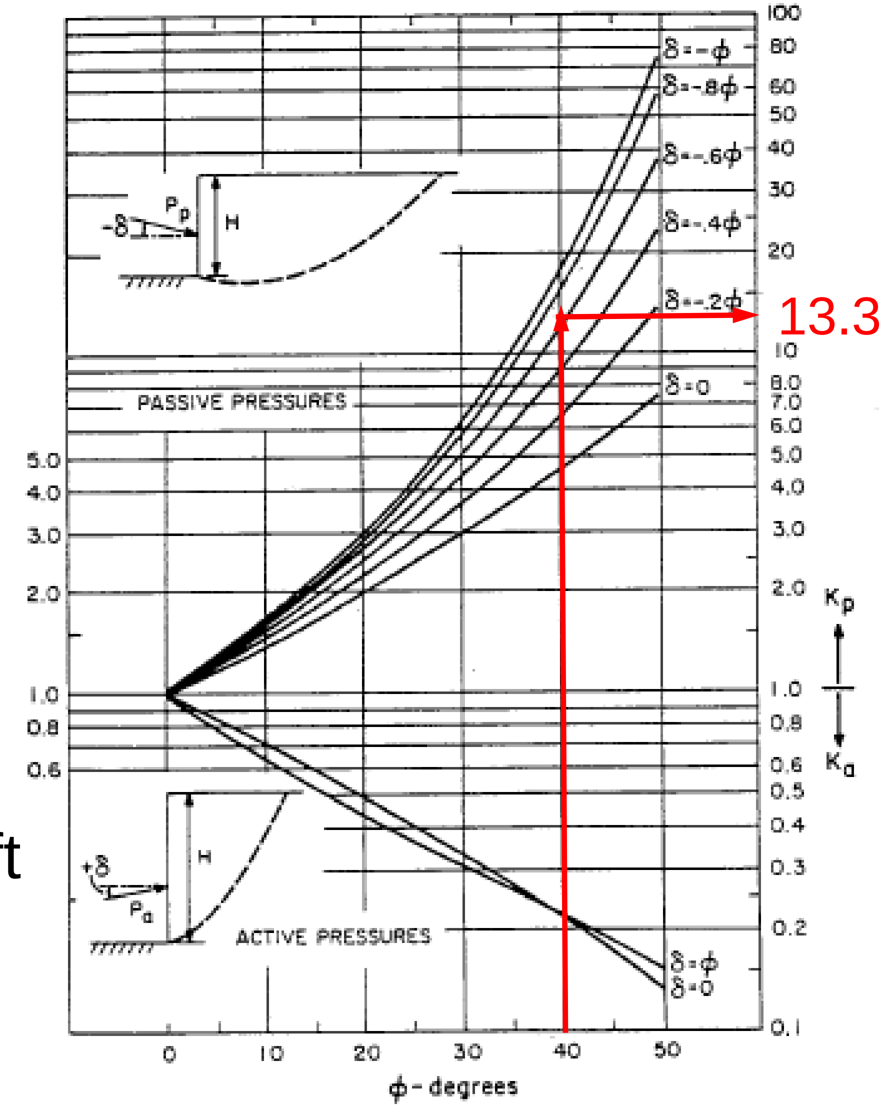
H= 6 ft

$K_p = 13.3$

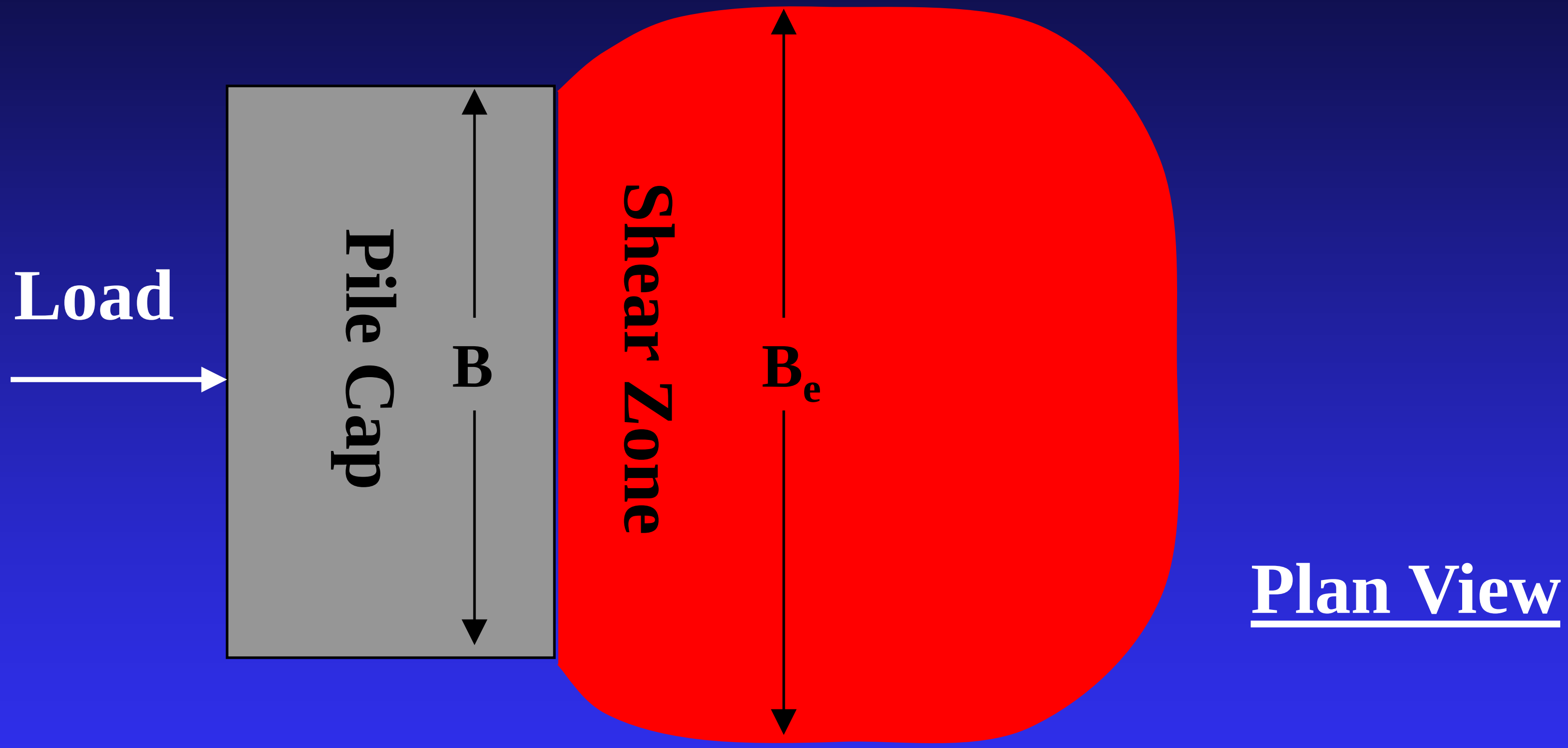
$P_p = 0.5(135)(6)^2\ (13.3) = 32.3$ k/ft

$P_{pH} = P_p \cos\delta = 32.3 \cos(28^{\circ})$

$P_{pH} = 28.5$ k/ft



3D Geometry Effects



- Shear zones extend beyond the edge of pile cap/abutment
- Increases the effective width of the abutment

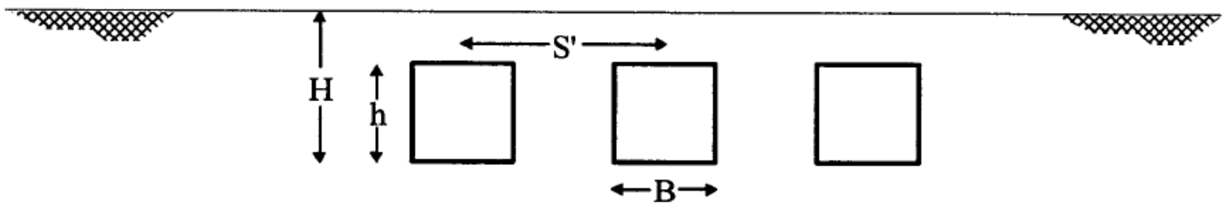
Equations for 3D Shear Effect

$P_p = E_p\, B\, R_{3D}$ (Duncan and Mokwa, 2001)

where E_p is passive force/width, B is width

$$R_{3D} = \left[1 + +(K_p - K_a)^{0.67}\left(1.1A^4 + \frac{1.6B_b}{1+5\left(\frac{B}{h}\right)} + \frac{0.4R_0 A^3 B_b^2}{1+0.05\left(\frac{B}{h}\right)}\right)\right] \quad \textbf{(2-8)}$$

$$A = 1 - \frac{h}{H} \qquad B_b = 1 - \left(\frac{B}{S'}\right)^2 \qquad R_o = K_p - K_a$$



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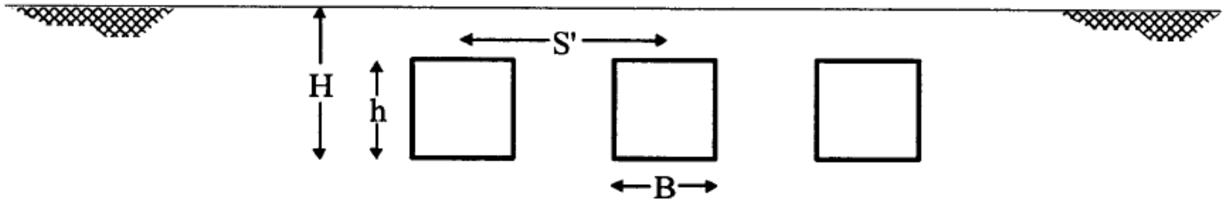
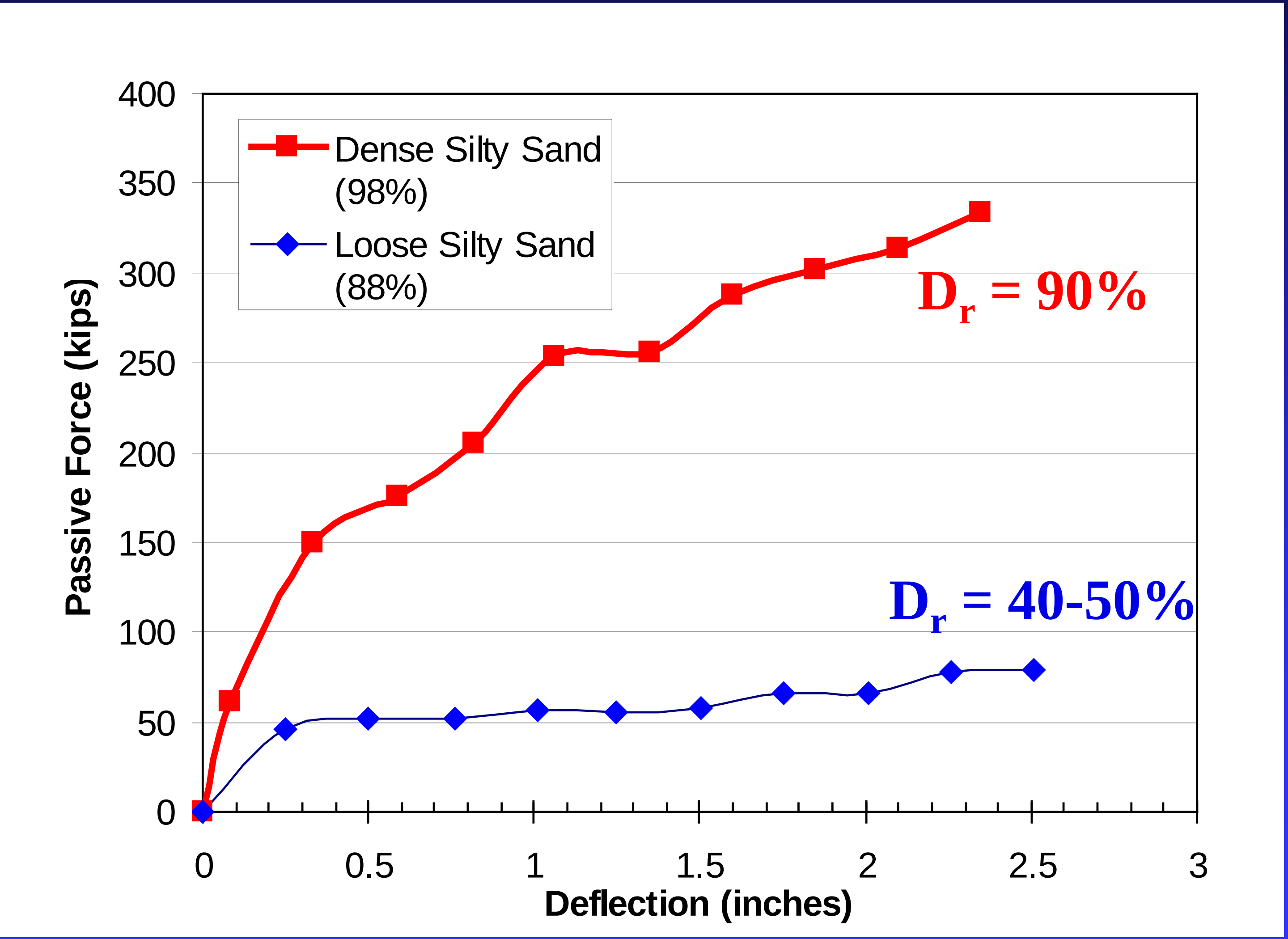


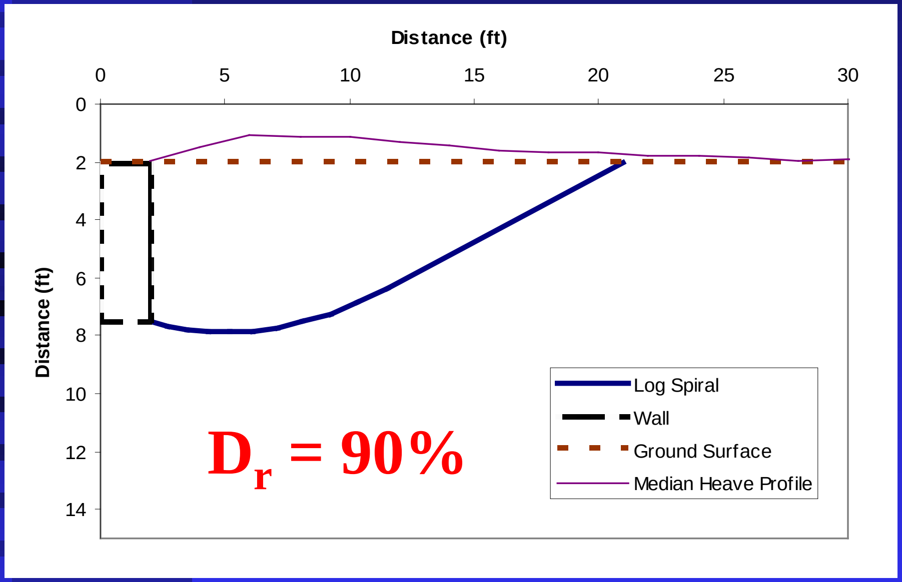
Influence of Relative Compaction



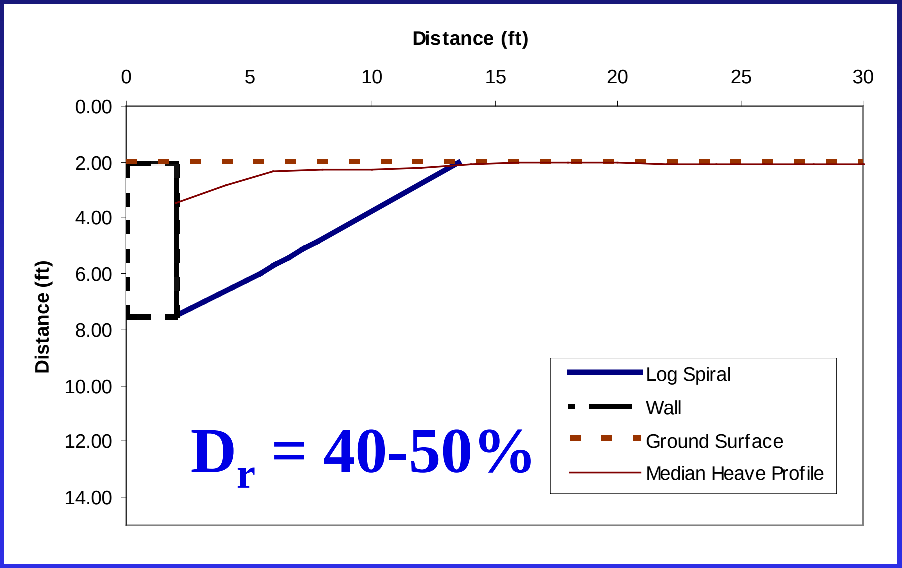
Failure Planes & Heave Profiles

CLEAN SAND

Densely Compacted



Loosely Compacted



- Shape of failure surfaces appear to reflect mobilization of wall friction
- Densely compacted backfill has log-spiral failure surface
- Loosely compacted backfill has planar (i.e., Rankine) failure surface

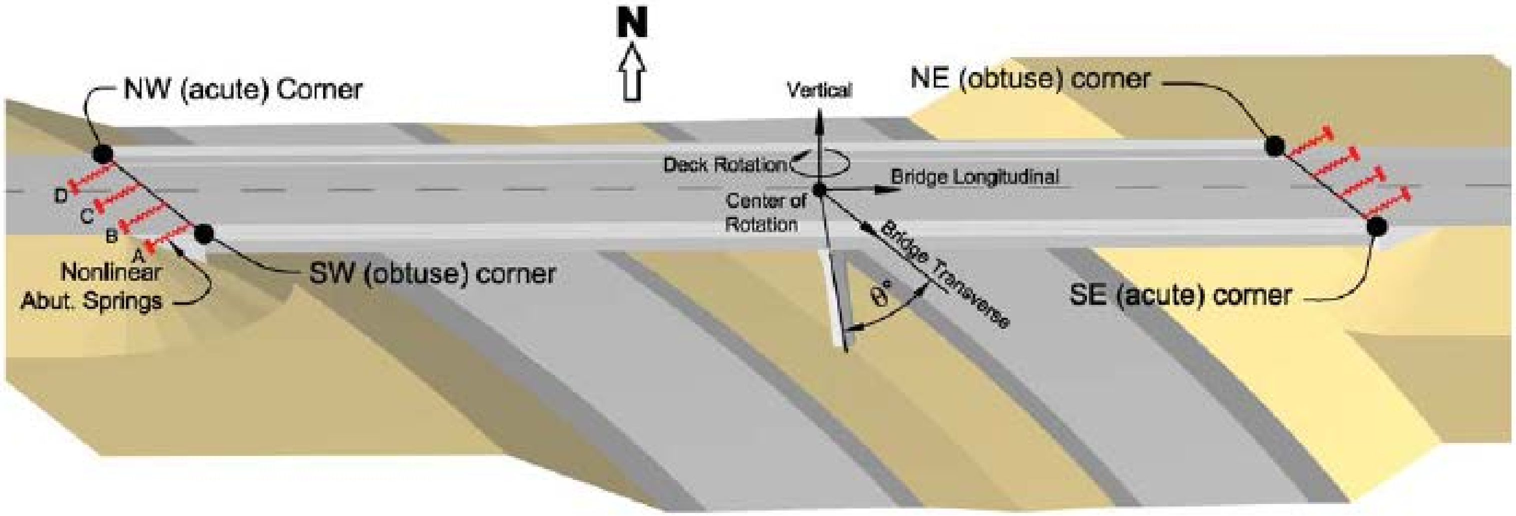
Summary

- Passive Pressure for non-skewed abutments (Maroney (1995), Duncan and Mokwa (2001), Rollins and Sparks (2002), Rollins and Cole (2006), Lemnitzer et al (2009)

- 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

Skewed Bridge Abutment Overview

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



Shamsabadi et al. 2006

Earthquake Damage to Skewed Bridges

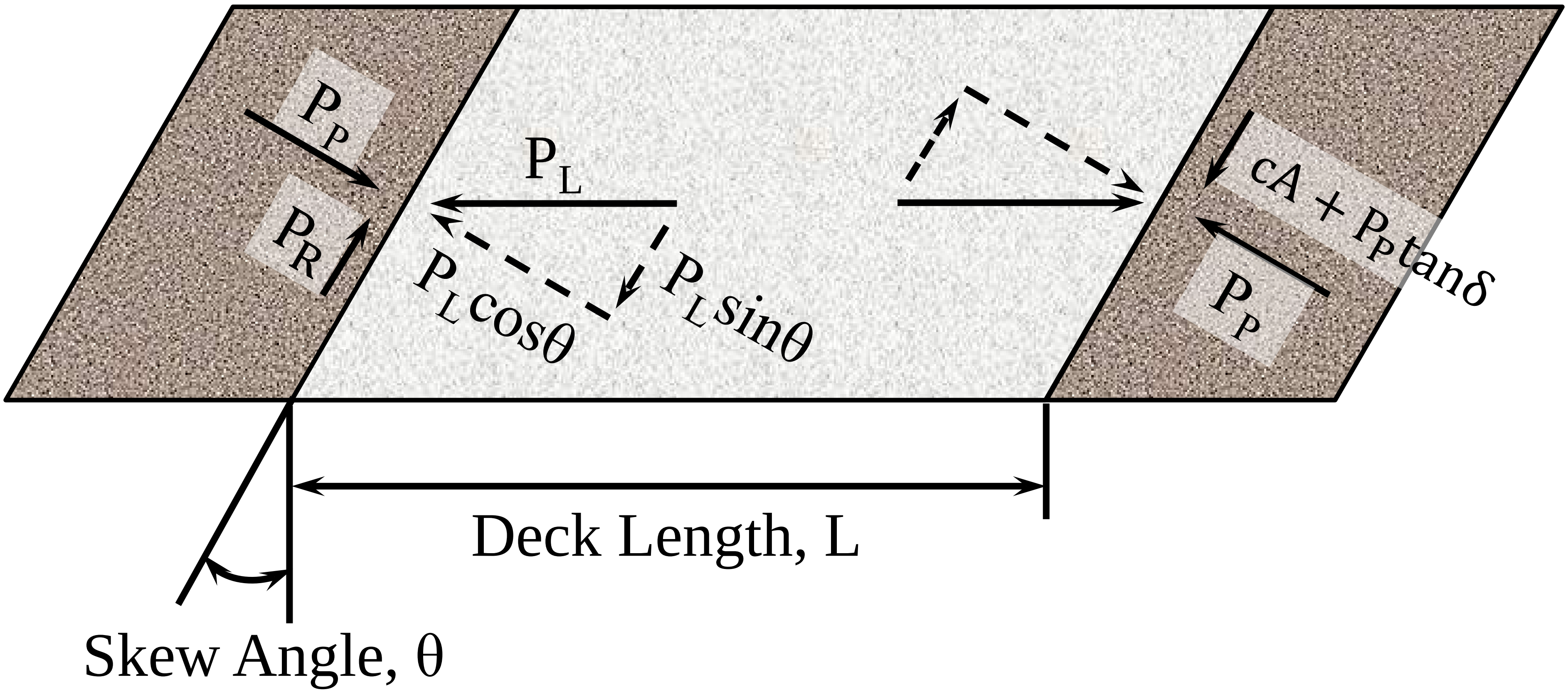
(Paine, Chile)

Bridge deck was offset and was eventually demolished

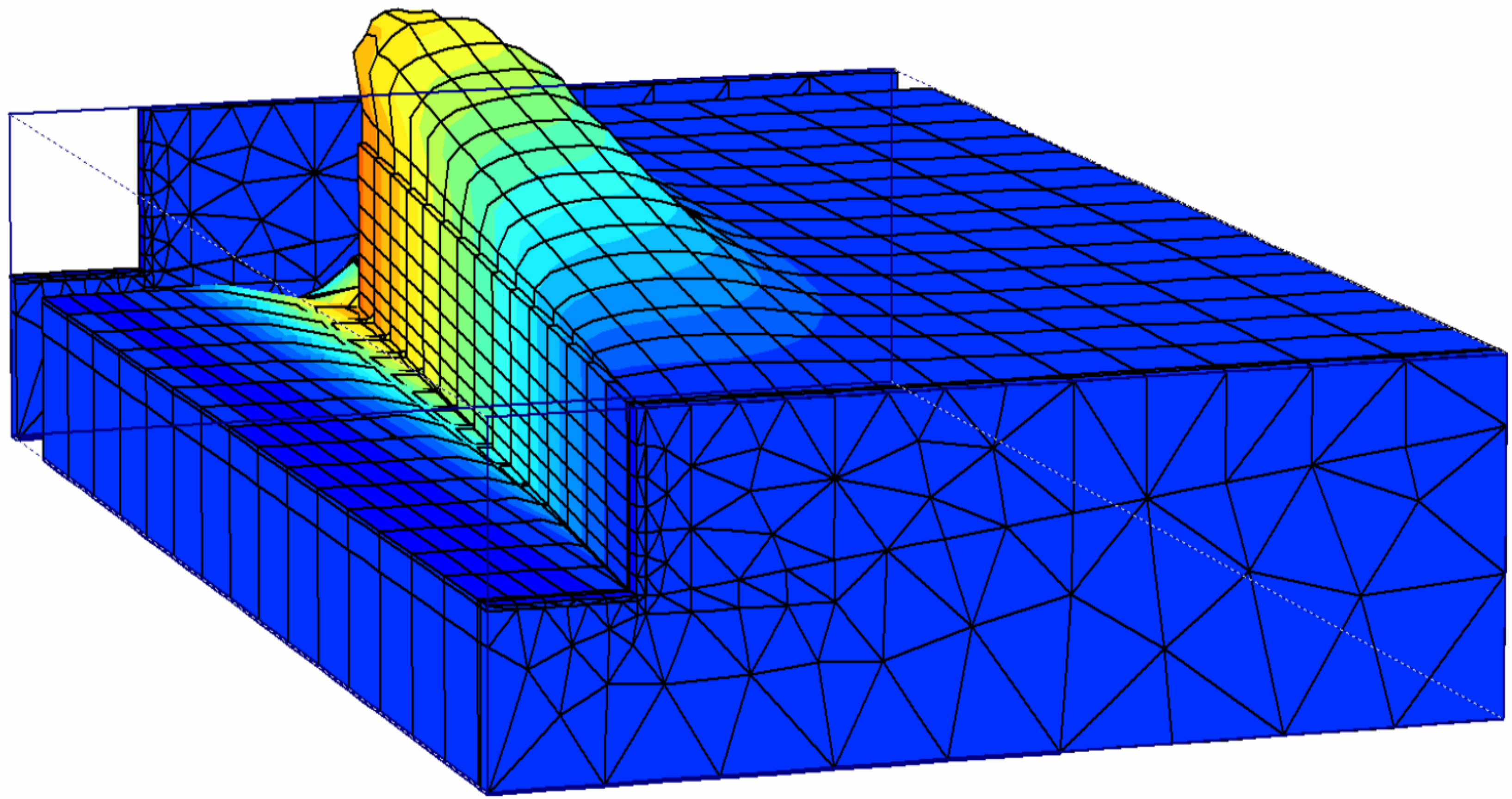
Bridge remained in service after the earthquake

Damage rate for skewed bridges was twice that of non-skewed bridges (Toro et al 2013)

Interaction of Forces on Bridge Abutment



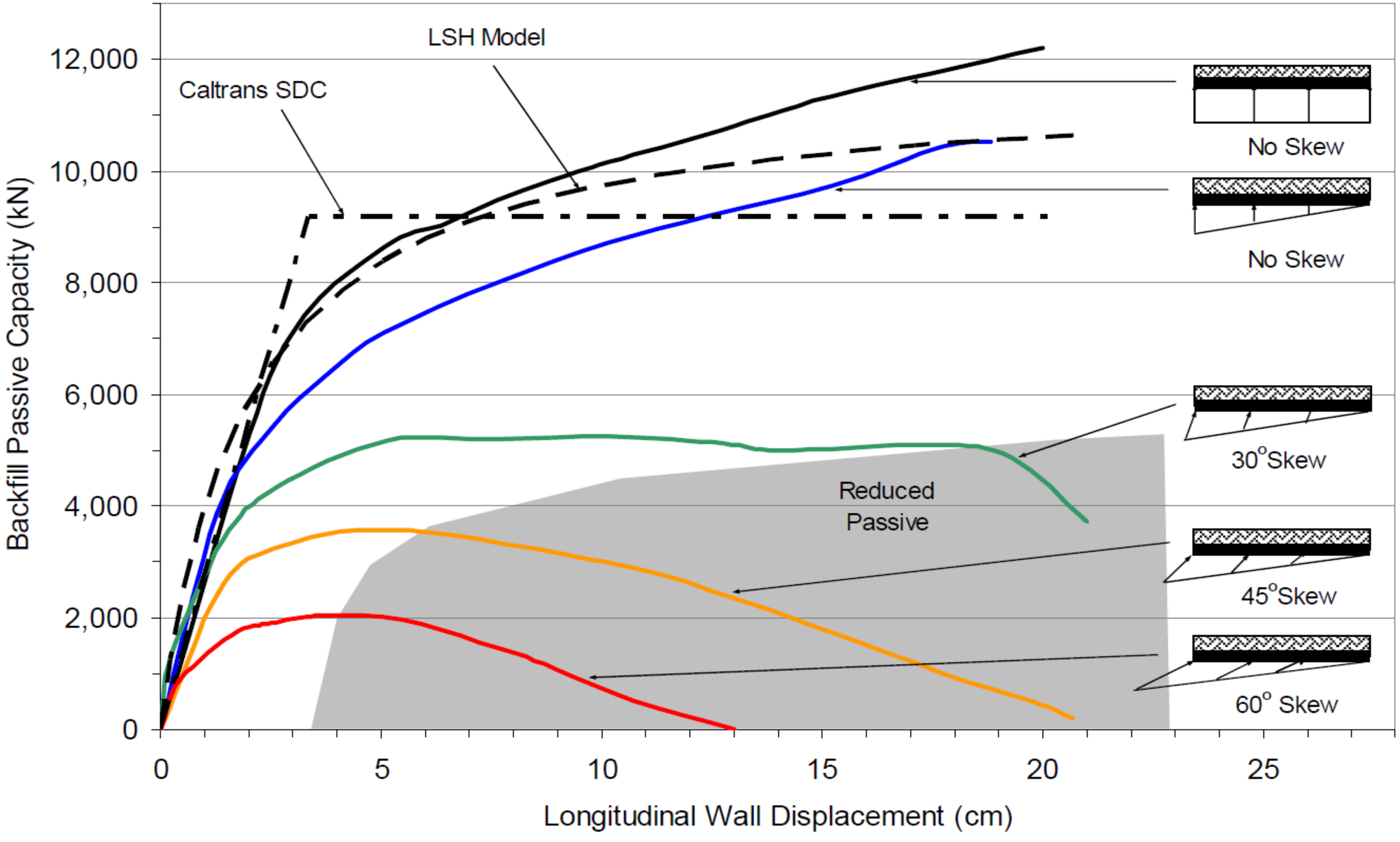
Numerical Analysis of Skewed Abutments



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

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

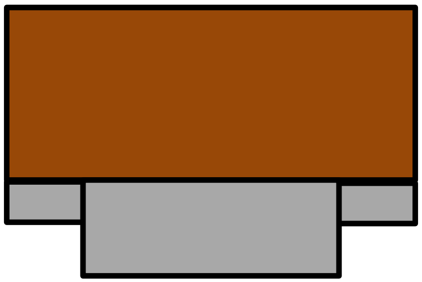
Results of Numerical Analysis



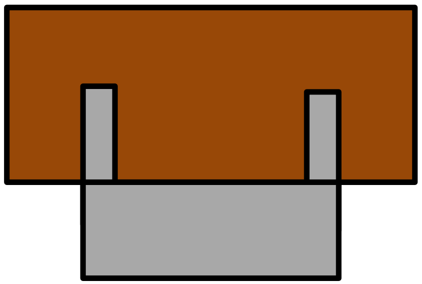
(5th NSC, Shamsabadi et al., 2006)

Testing Program

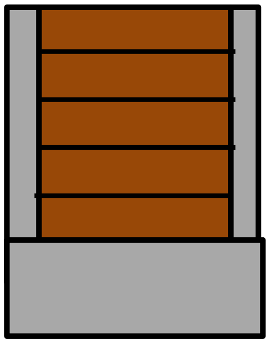
- Variations in Wingwall Geometry



Transverse Wingwalls



Parallel Wingwalls

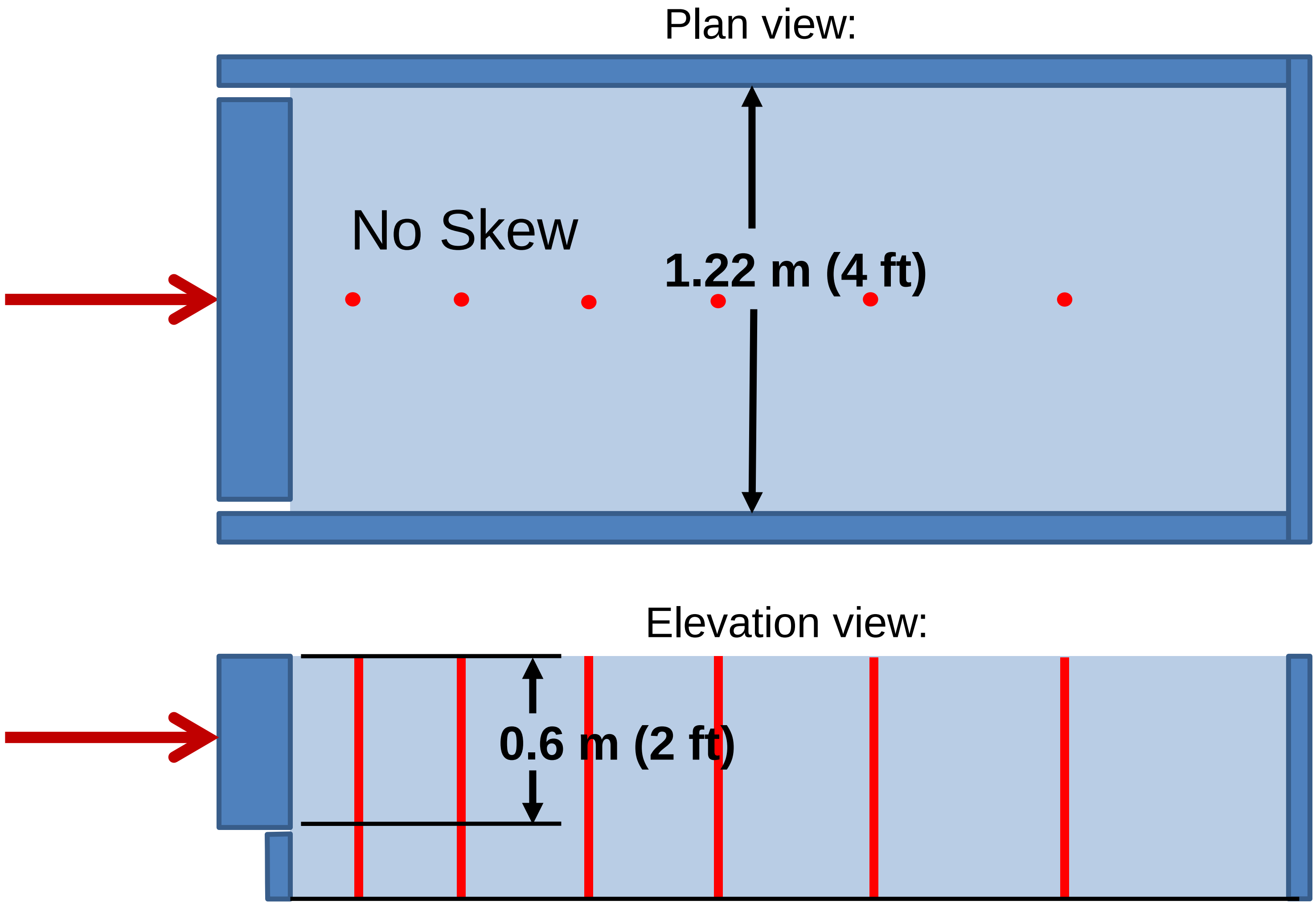


MSE Wingwalls

- Variations in Backfill Materials
  - Sand
  - Gravel
  - Geosynthetically Reinforced Soil (GRS)

Initial Laboratory Testing

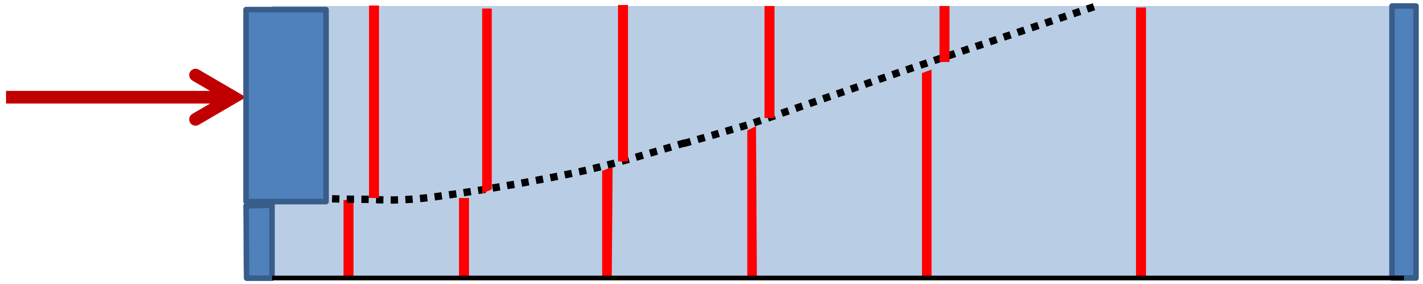
Test Layout



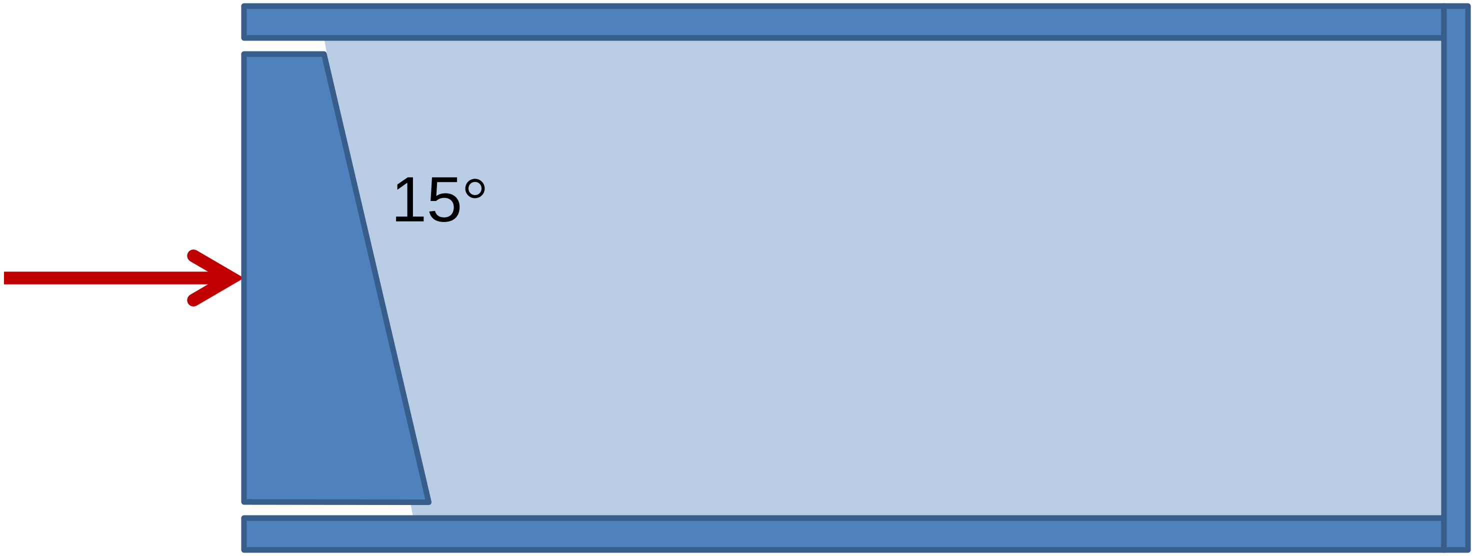
Test Procedure

Plan view:

Elevation view:



Test "Abutment"



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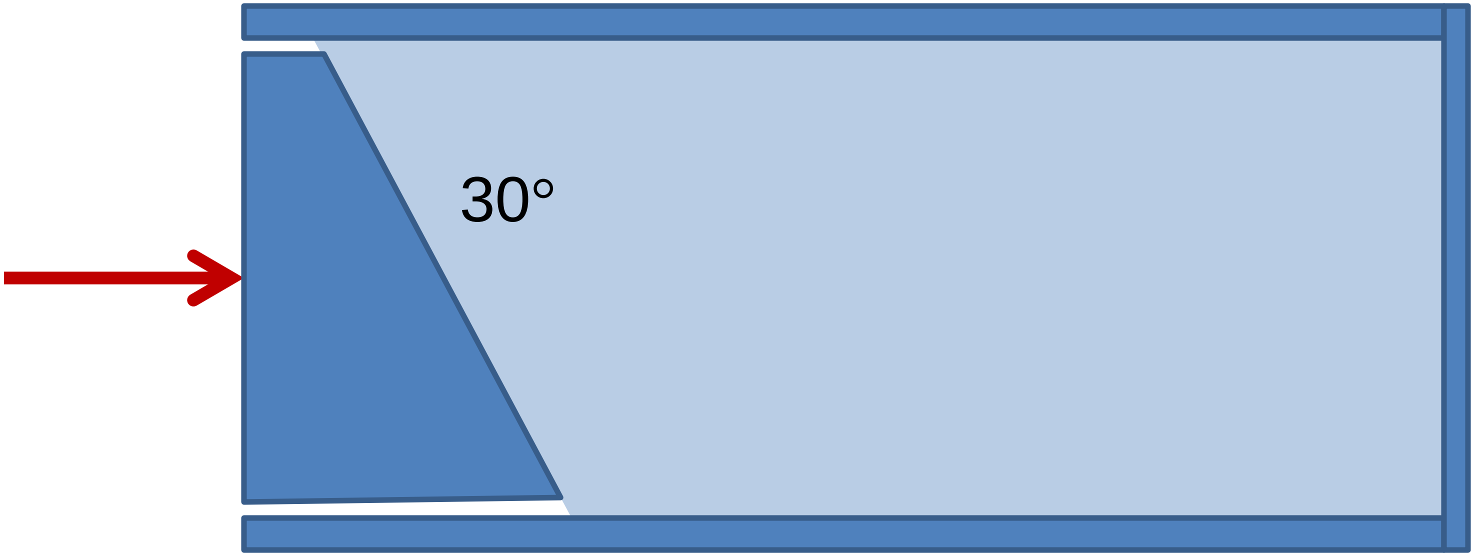

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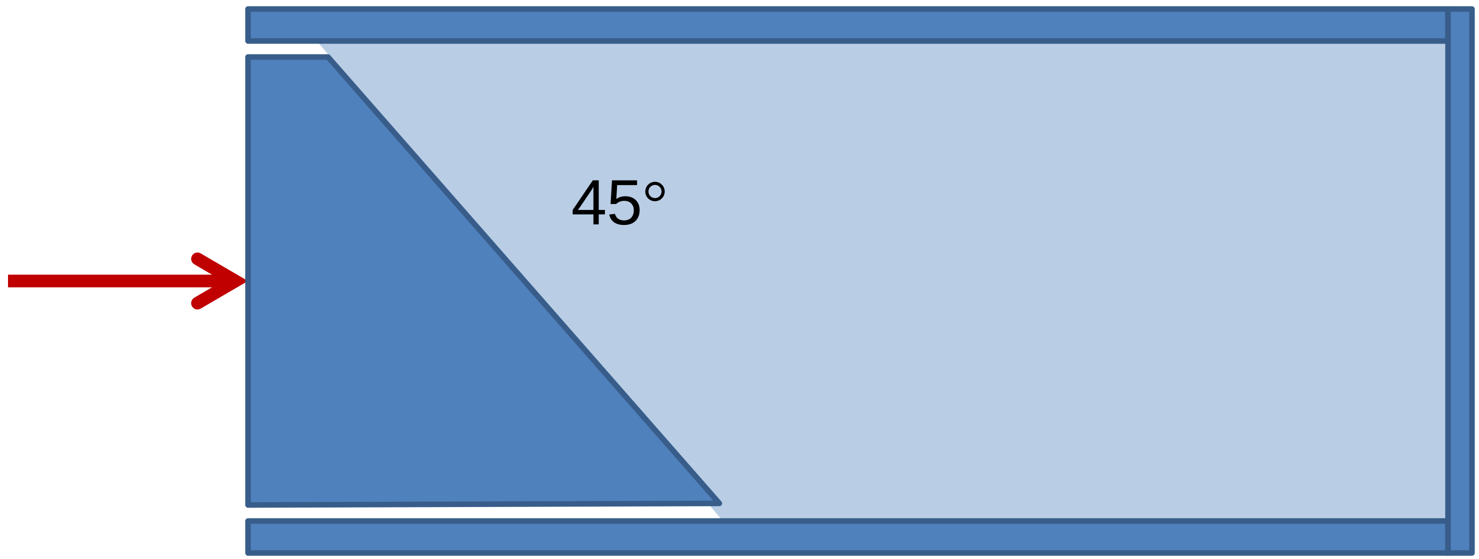
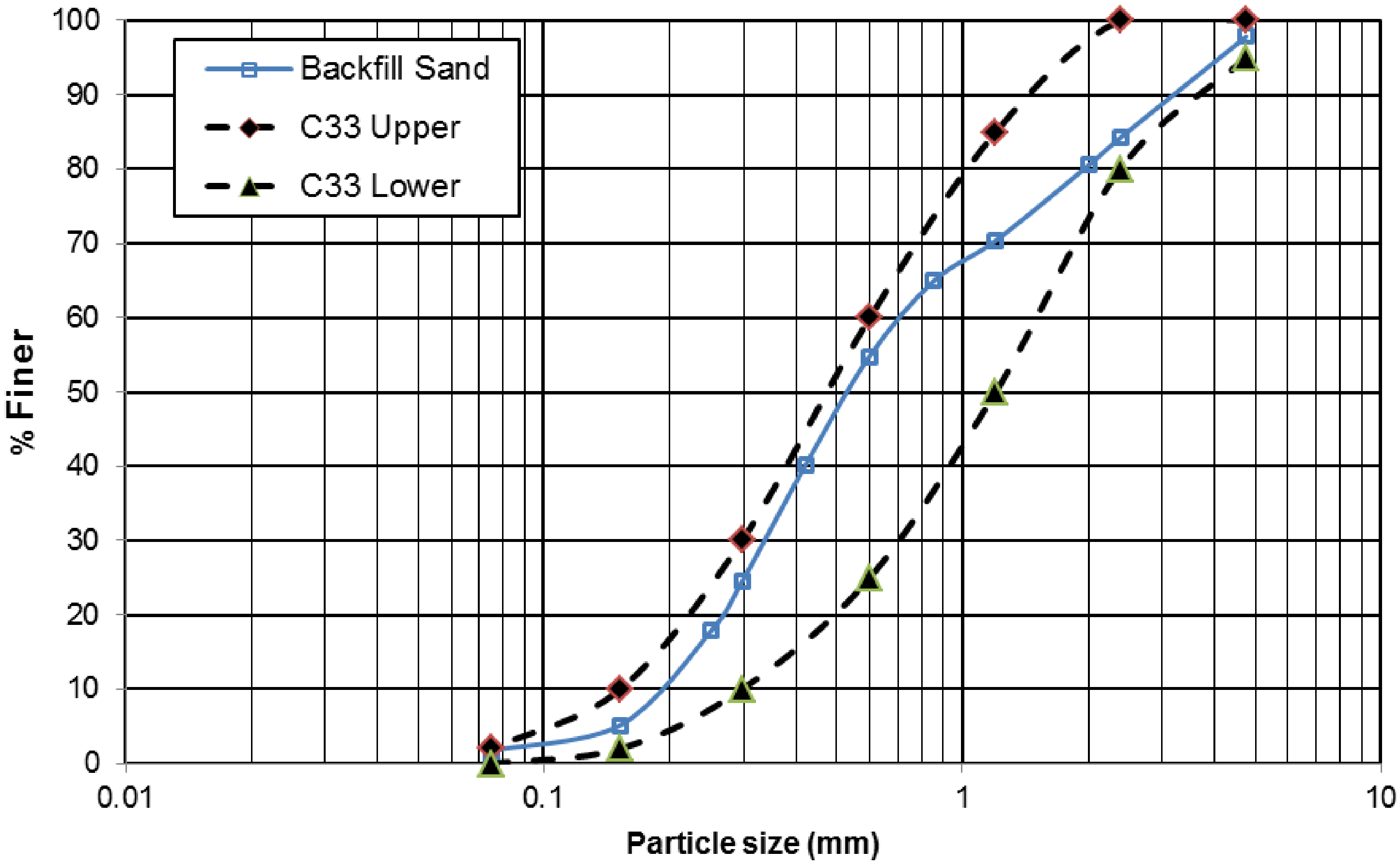


Displacement: 60 mm 2.5” (0.10H)

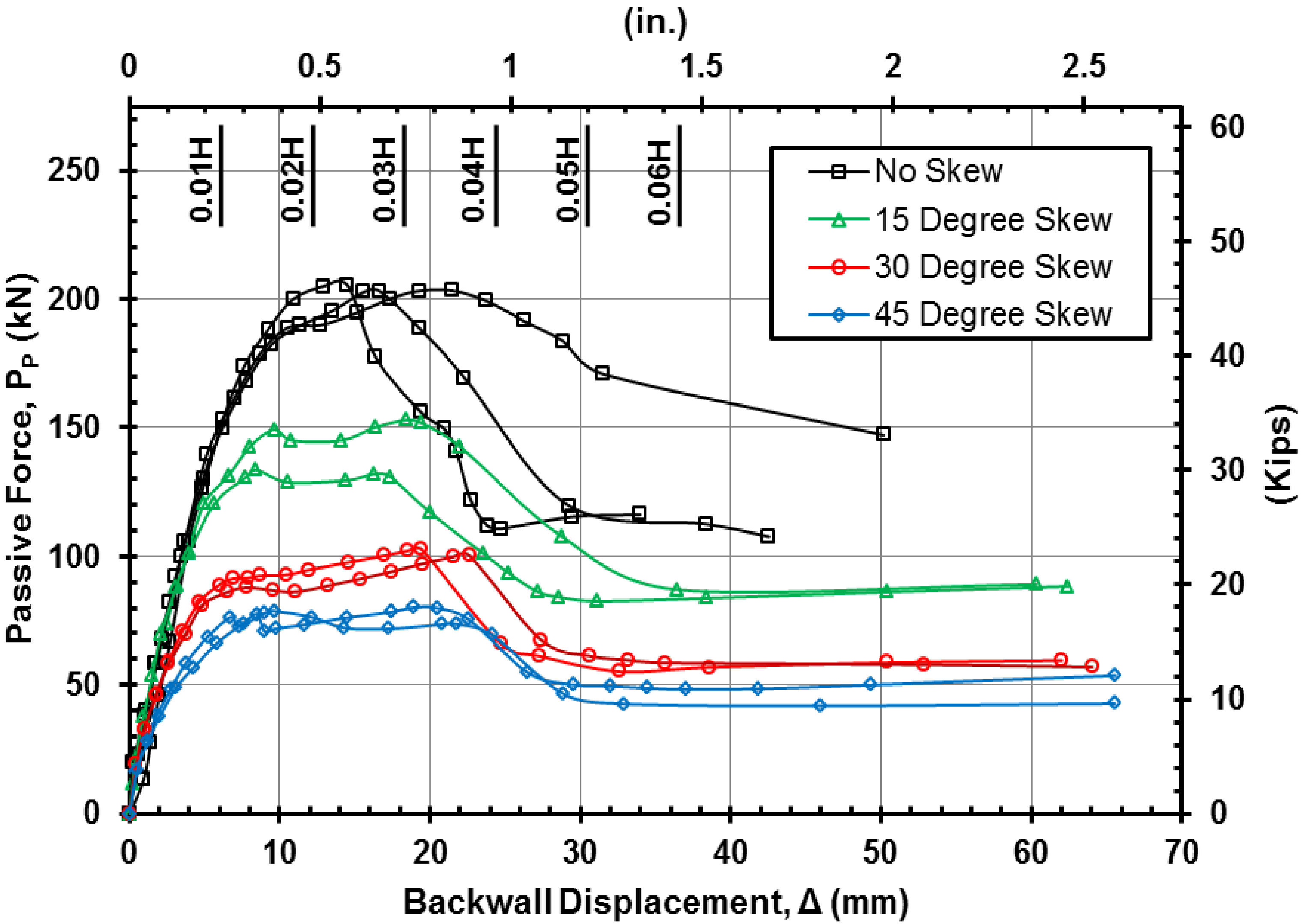
Load measurements:
- Longitudinal
- Vertical
- Transverse

Backfill Soil Properties

- Gradation and Strength



Passive Force-Displacement Curves



Reduction Factor for Skew Effects

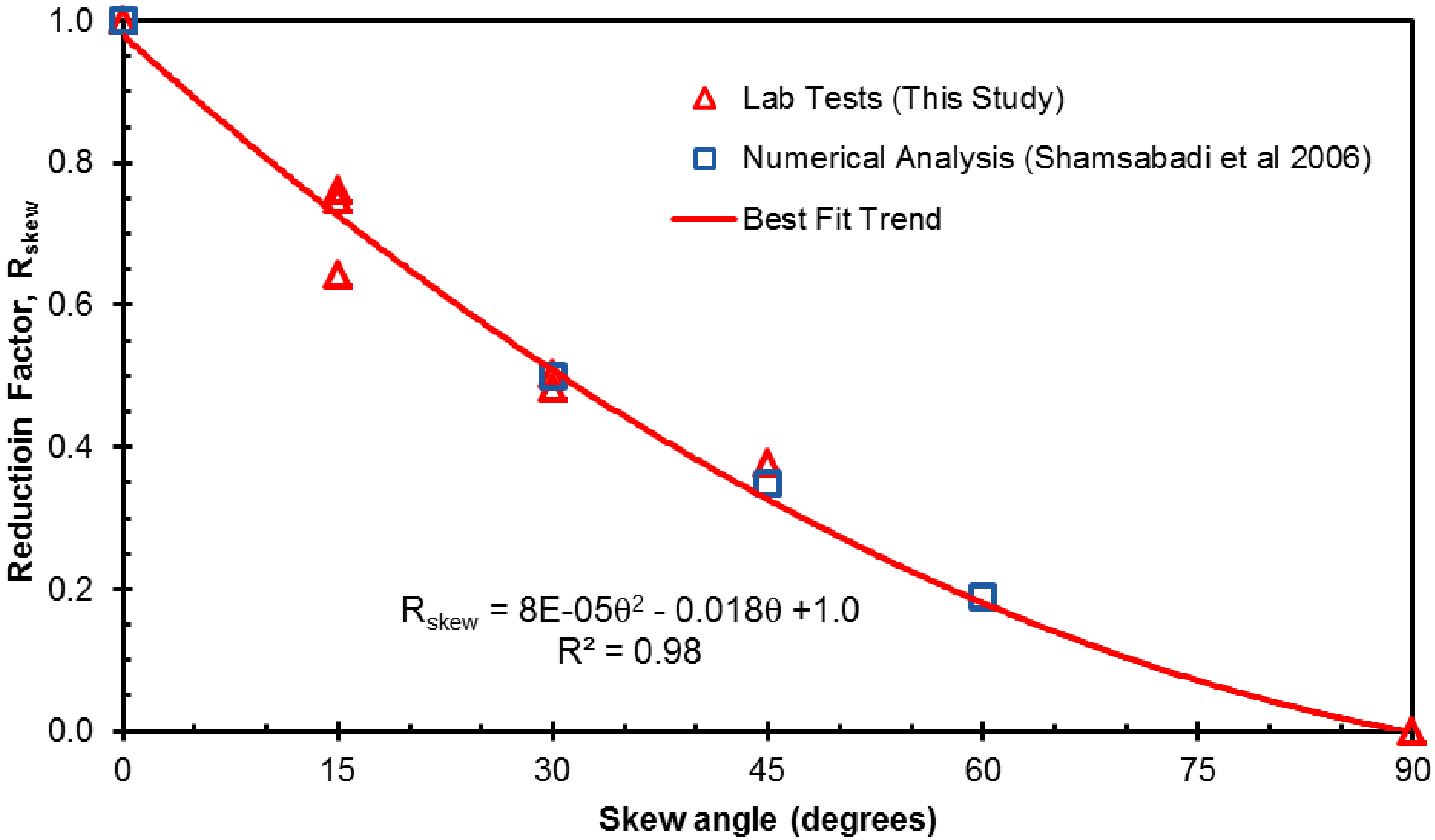
$$R_{skew} = P_{P(skew)}/P_{p\ (No\text{-}skew)}$$

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

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

(ASCE, J. of Bridge Engrg., Rollins and Jessee 2013)

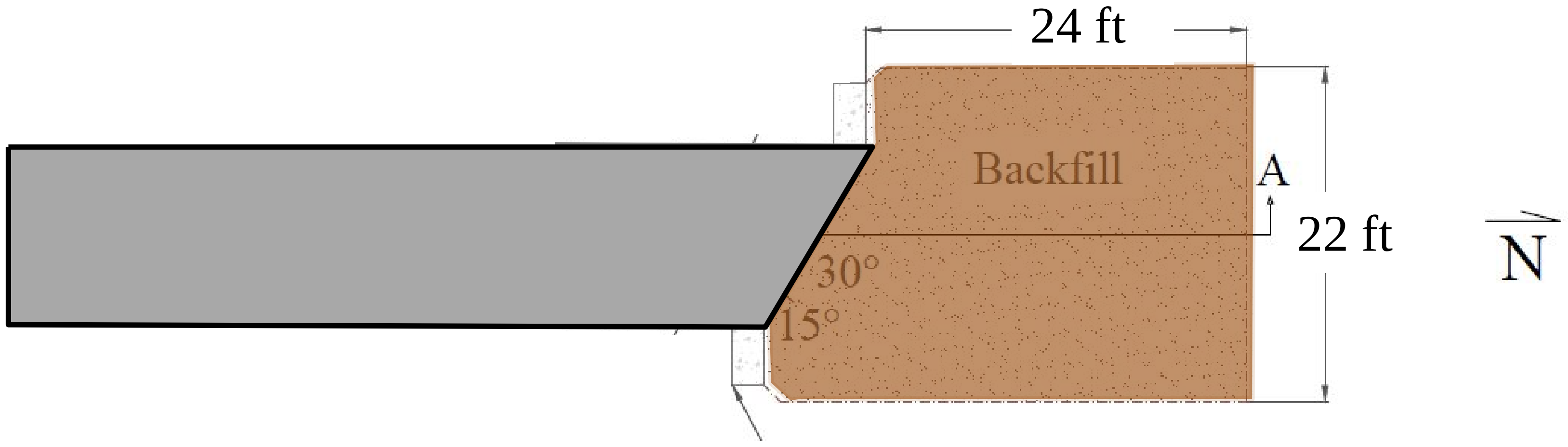
Normalized Passive Force vs Skew, θ



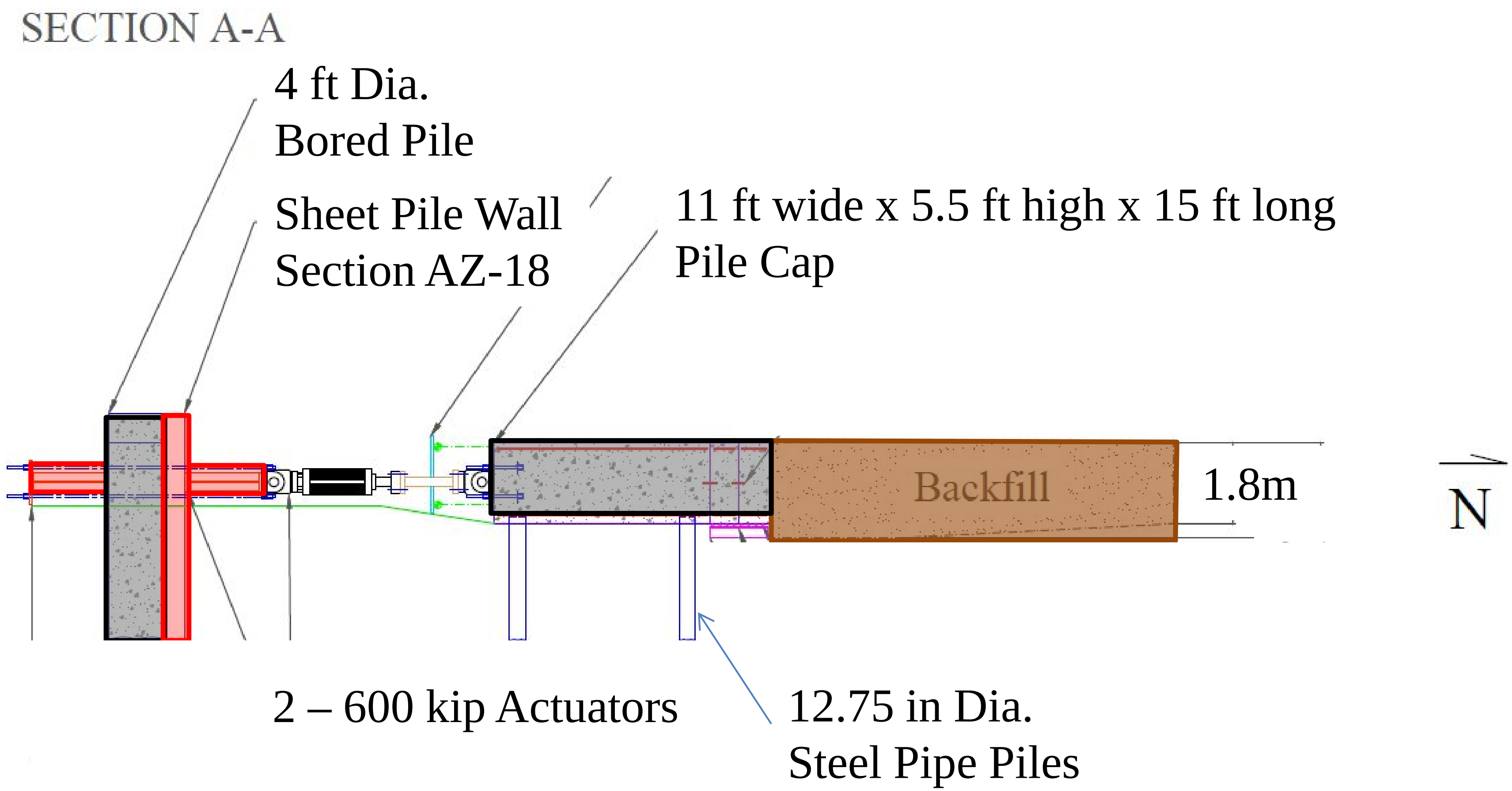
(ASCE, J. of Bridge Engrg., Rollins and Jessee 2013)

Large Scale Field Testing

Field Test Setup - Plan View



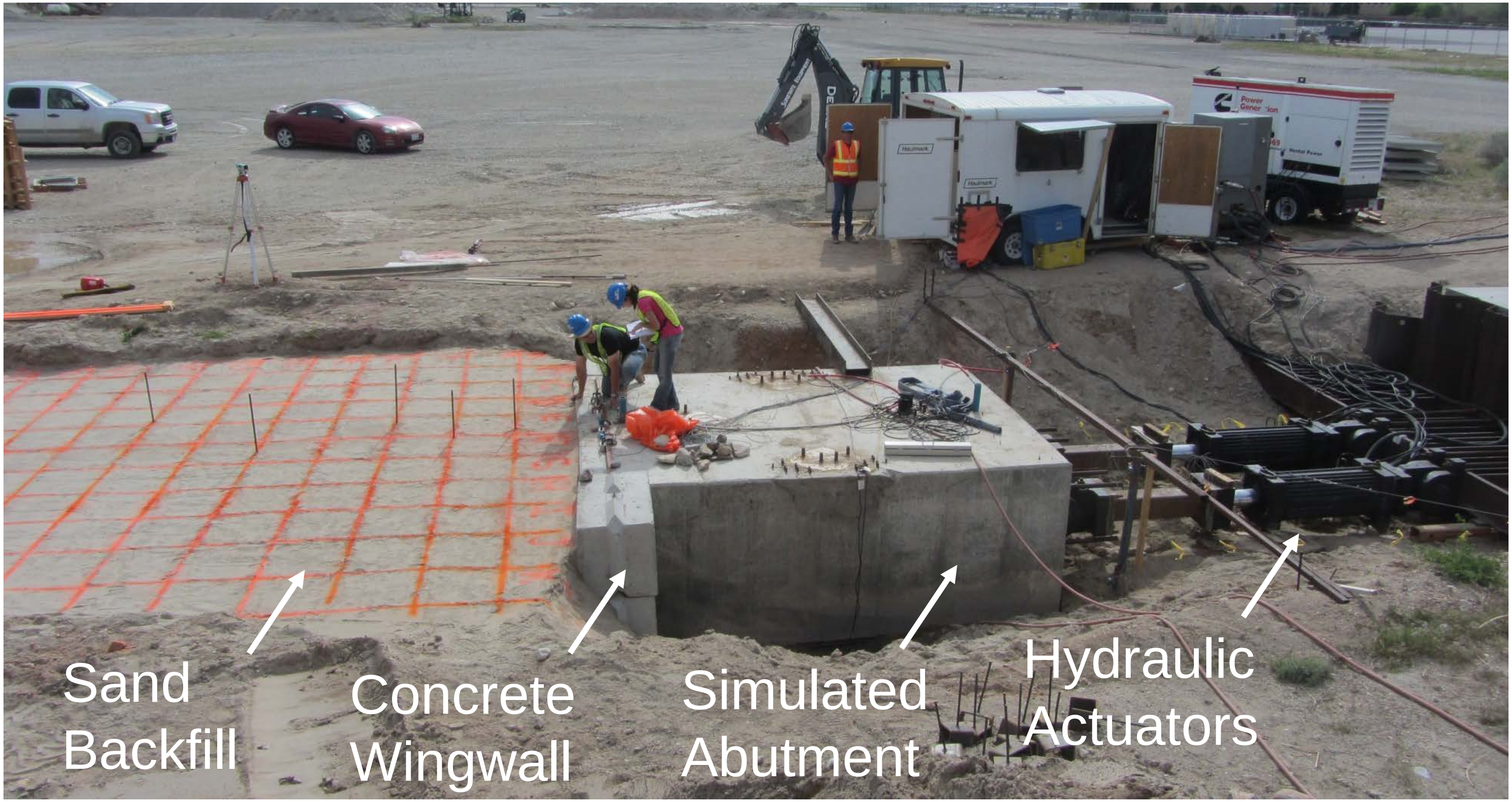
Field Test Setup Elevation View



Sand backfill properties

- Poorly graded sand (SP/A-1-b)
- 96% relative compaction
- $\phi = 41°$
- $c = 5$ kPa (100 lbs/ft^2)
- $\gamma_{max} = 17.5$ kN/m^3 (111.5 lbs/ft^3)

No Skew - 0° Test Setup



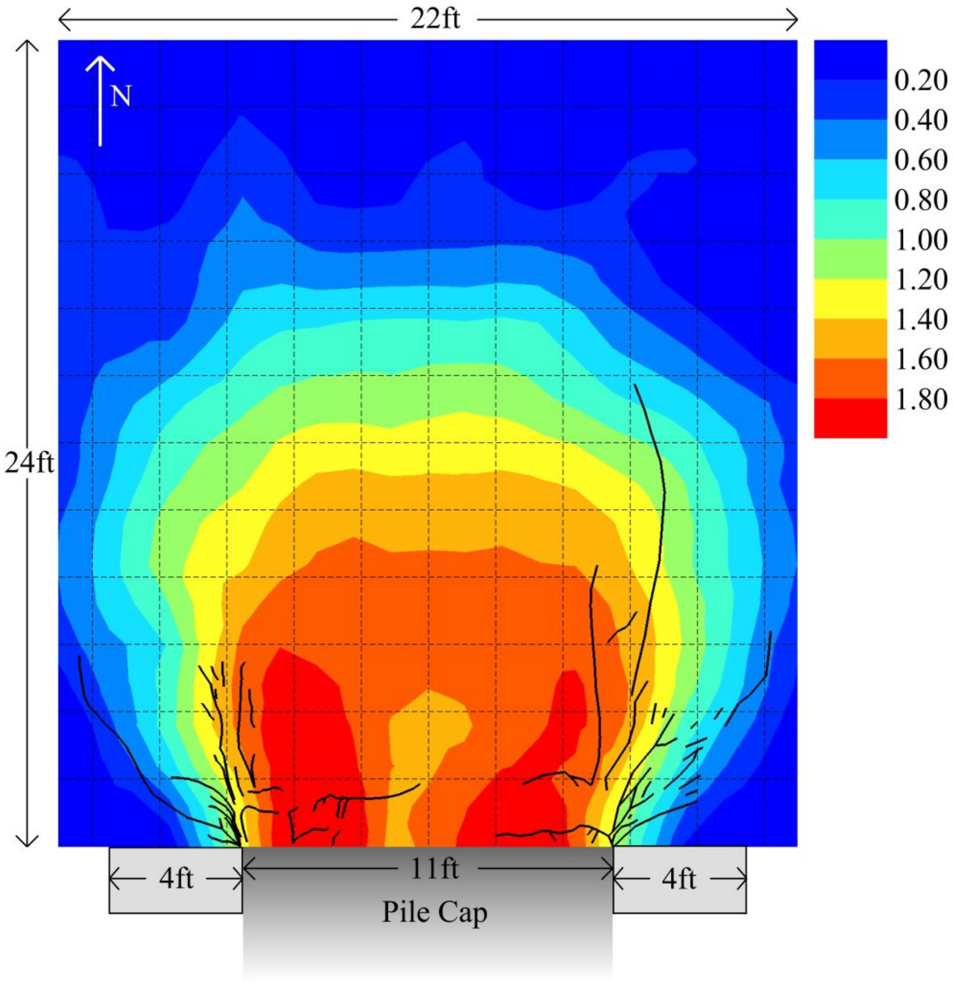
15° Skew Test Setup

30° Skew Test Setup

45° Skew Test Setup

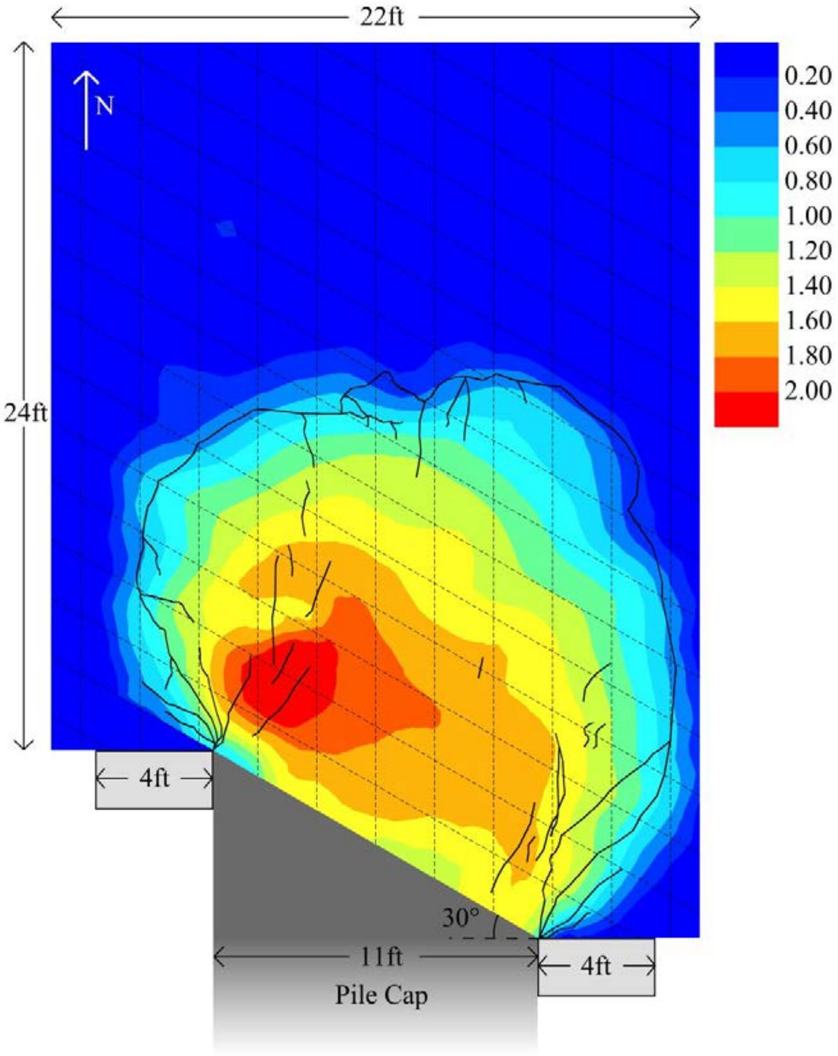
Heave Geometry at Test Completion

0º Skew



Test completed at 3.21 in (81.6 mm) of displacement

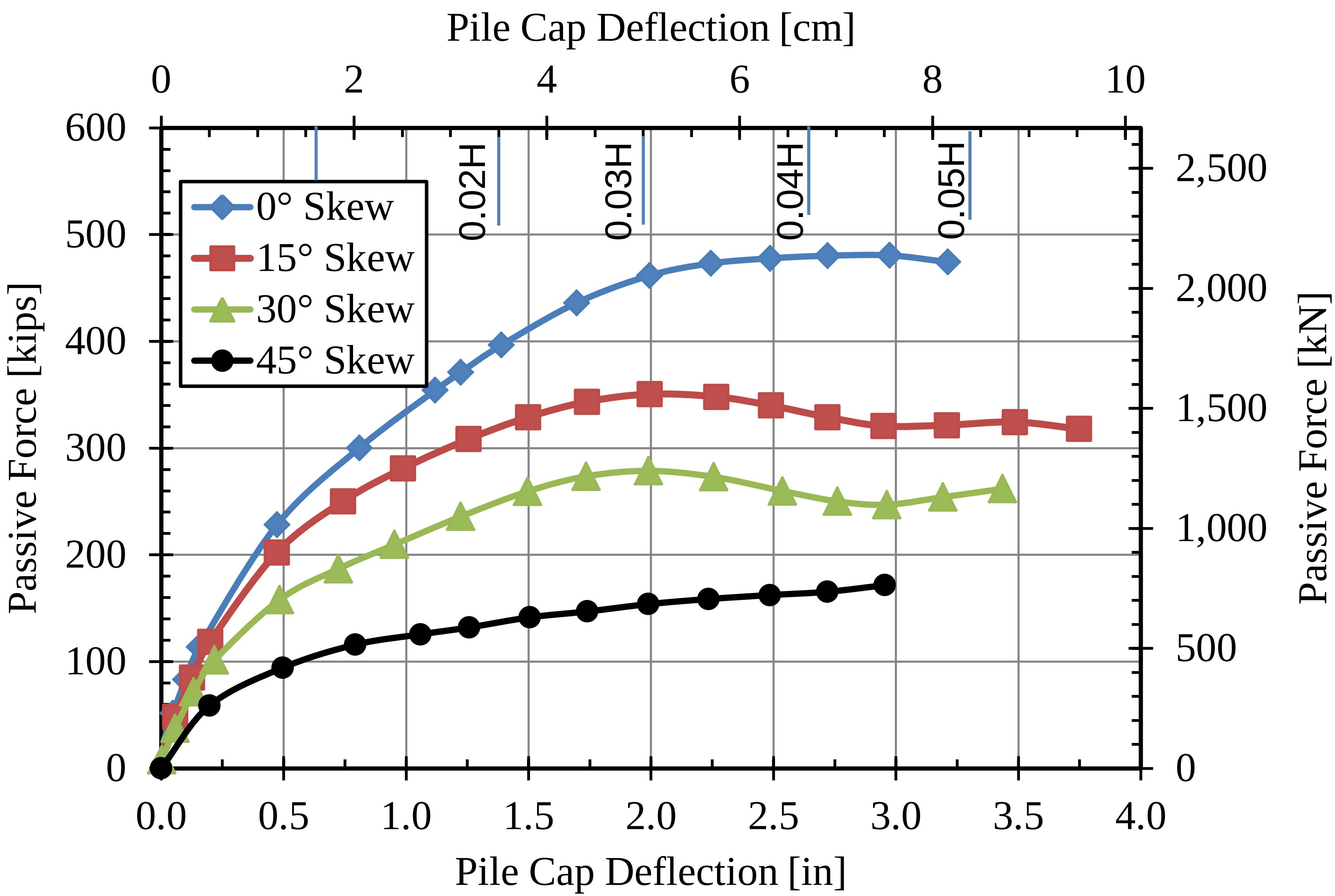
45º Skew



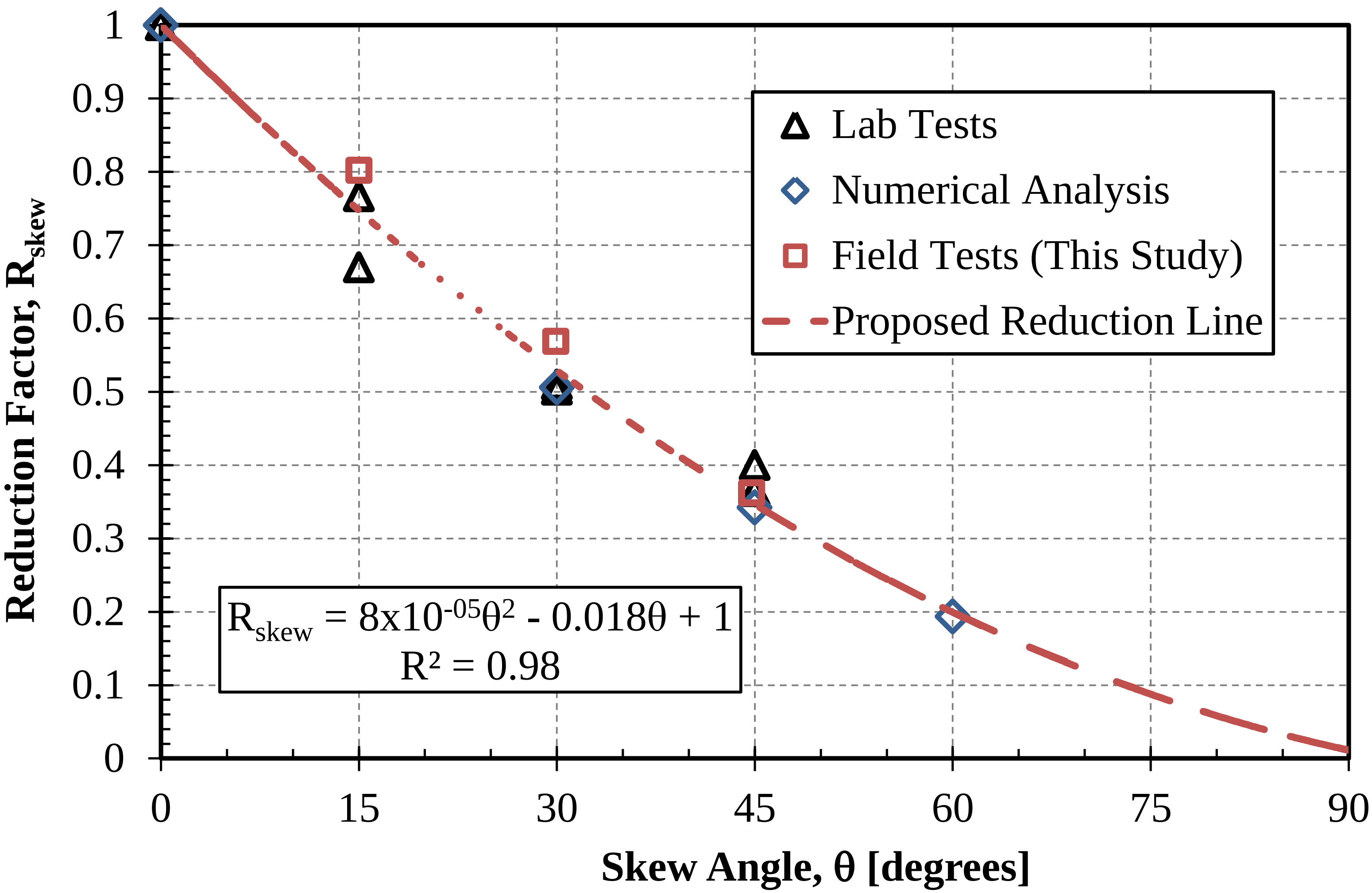
Test completed at 3.43 in (87.2 mm) of displacement

Surface Failure Geometry (30° Skew)

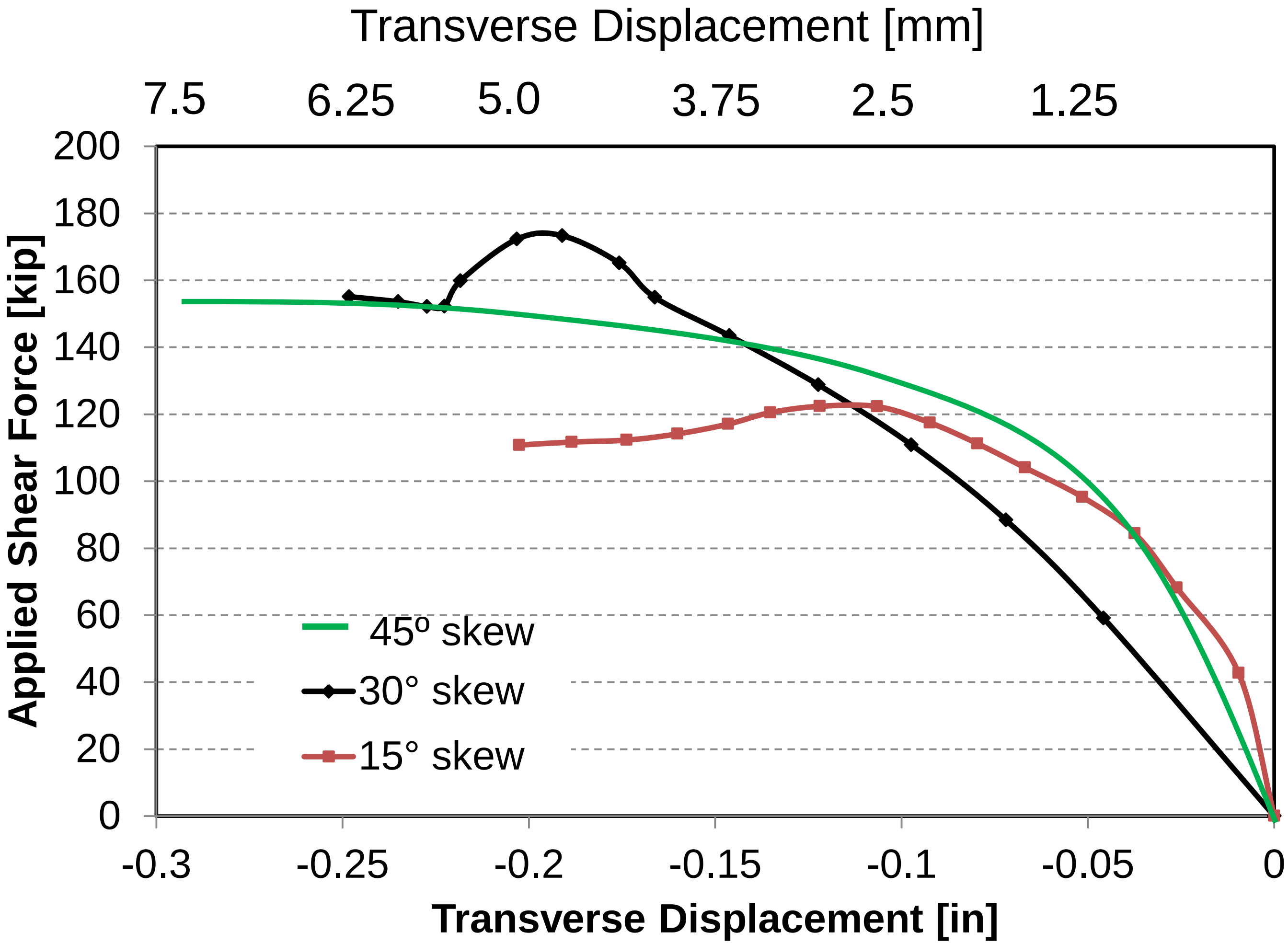
Passive Force vs. Displacement



Passive Force Reduction Factor vs. Skew

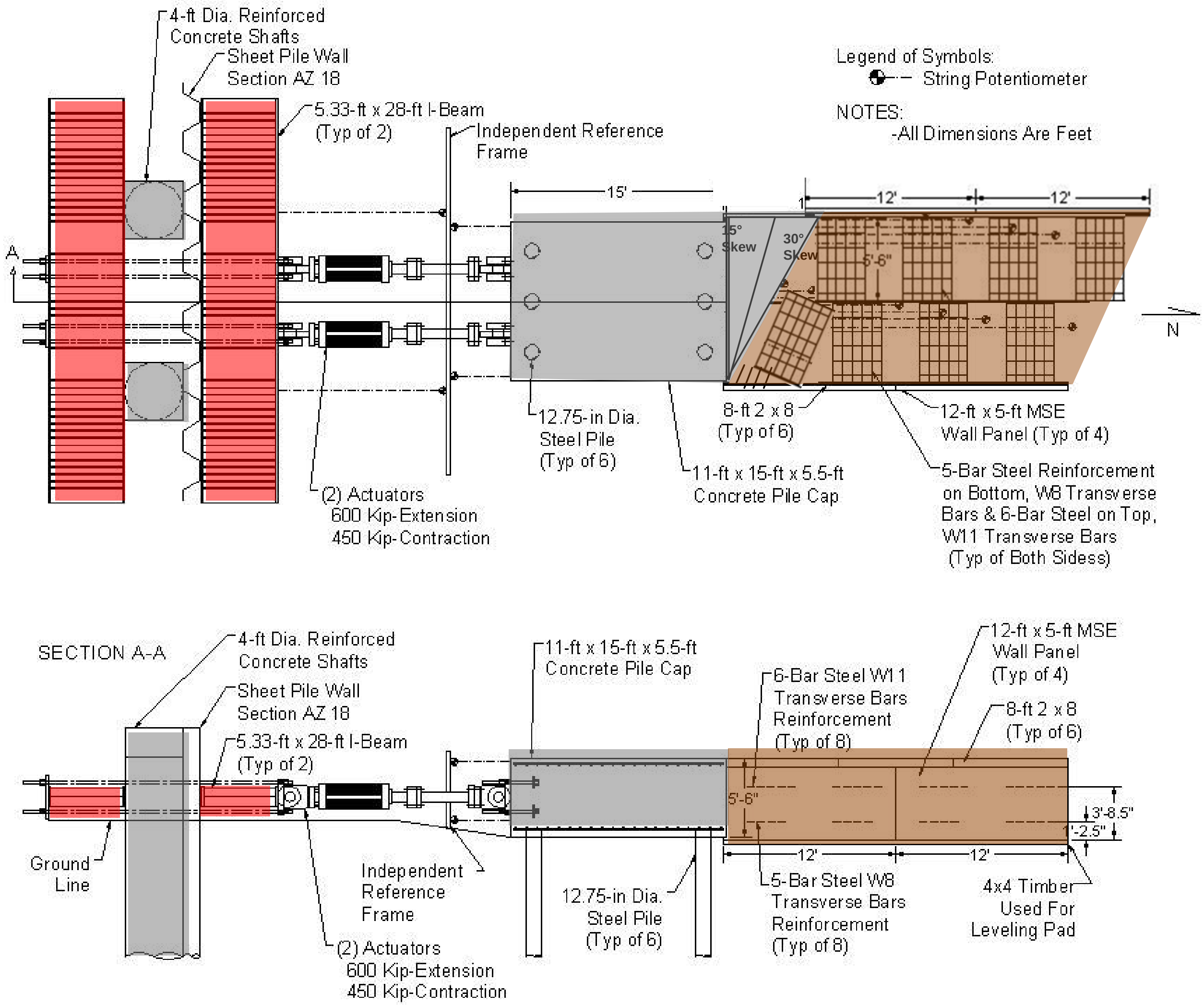


Shear force vs. transverse displacement



Abutment with MSE Wingwalls

Test Setup for MSE Wingwall Tests



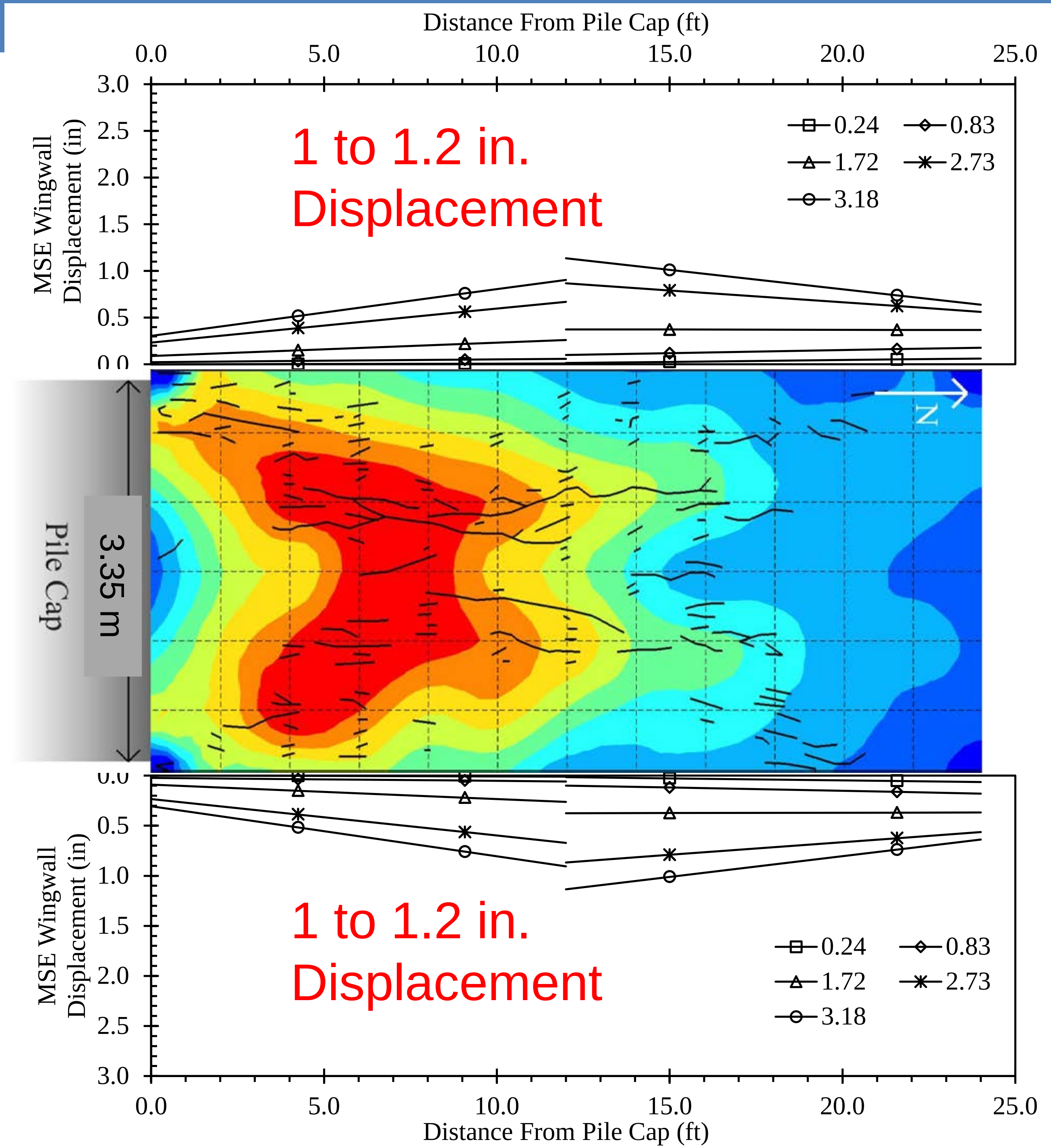
Welded Wire Grid Reinforcement (SSL)

No Skew - 0° Test Setup

15º Skew Test with MSE Wingwalls

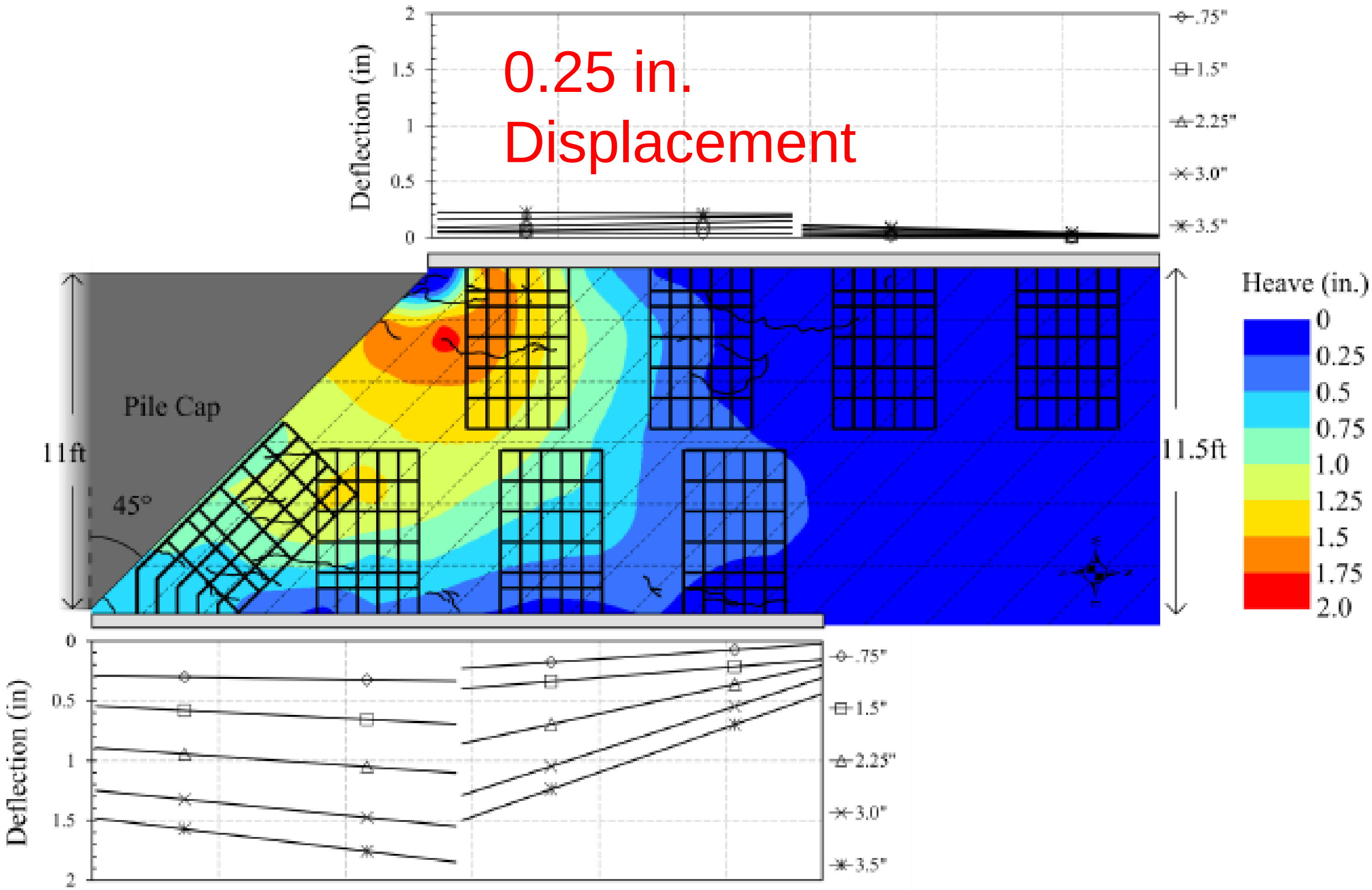
Field Test with 30º Skew & MSE Walls

0º Skew



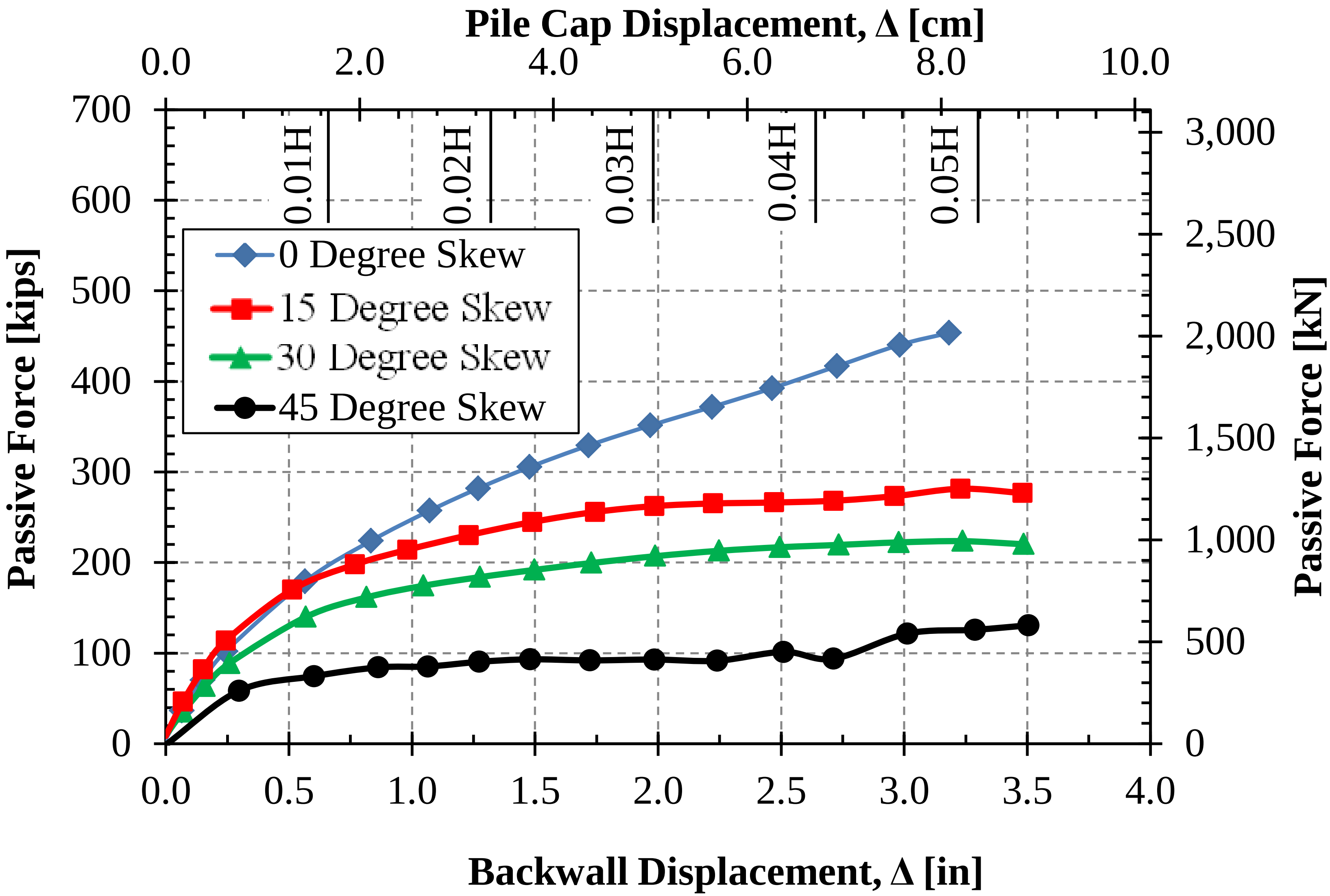
Distance From Pile Cap (ft)
MSE Wingwall Displacement (in)
1 to 1.2 in. Displacement
0.24
0.83
1.72
2.73
3.18
Pile Cap
3.35 m
N
MSE Wingwall Displacement (in)
1 to 1.2 in. Displacement
0.24
0.83
1.72
2.73
3.18
Distance From Pile Cap (ft)

45° Skew

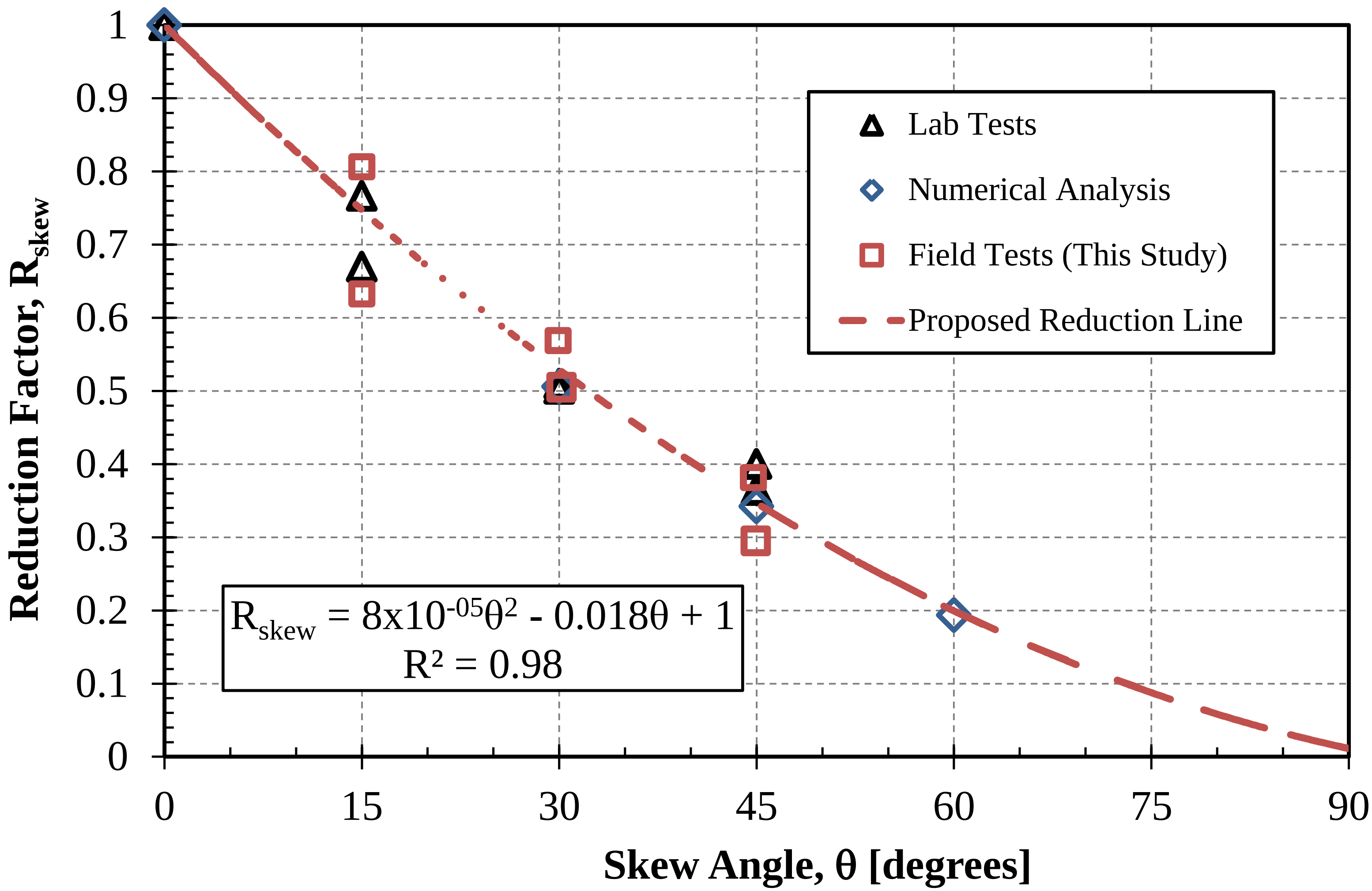


1.5-1.8 in.
Displacement

Passive Force-Displacement curves

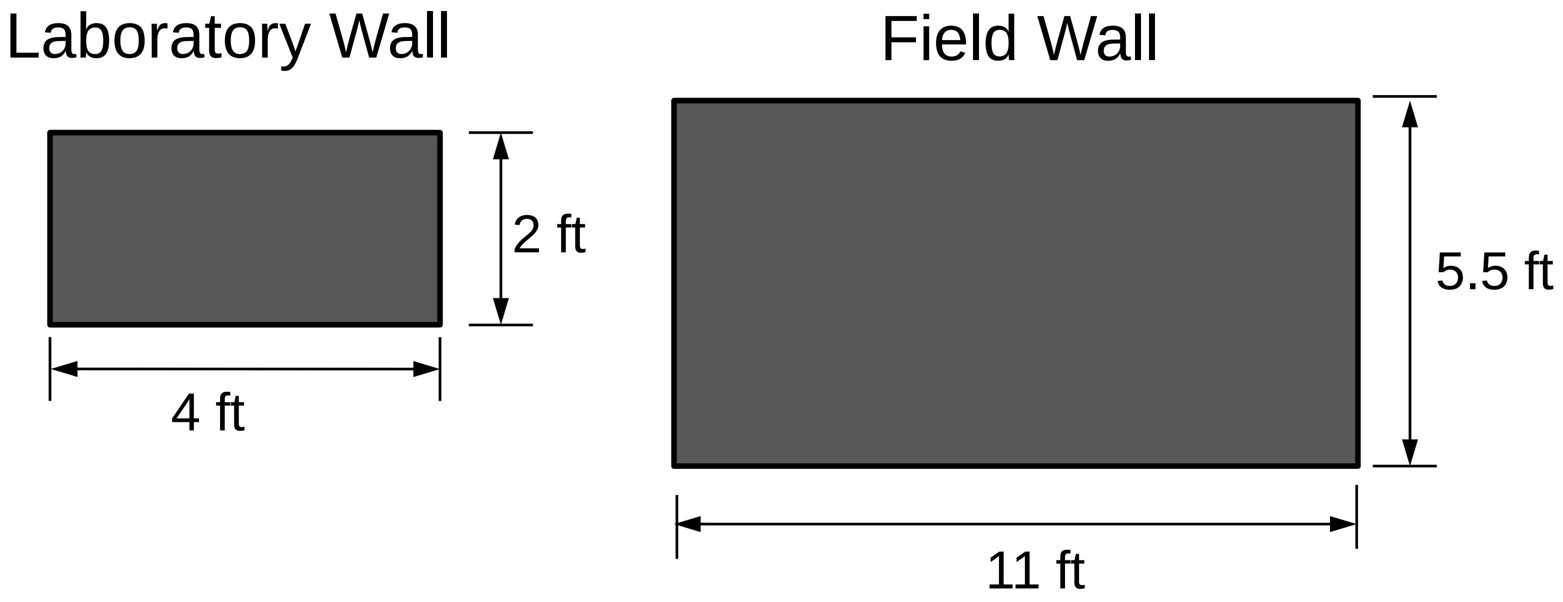


Passive Force Reduction Factor vs. Skew



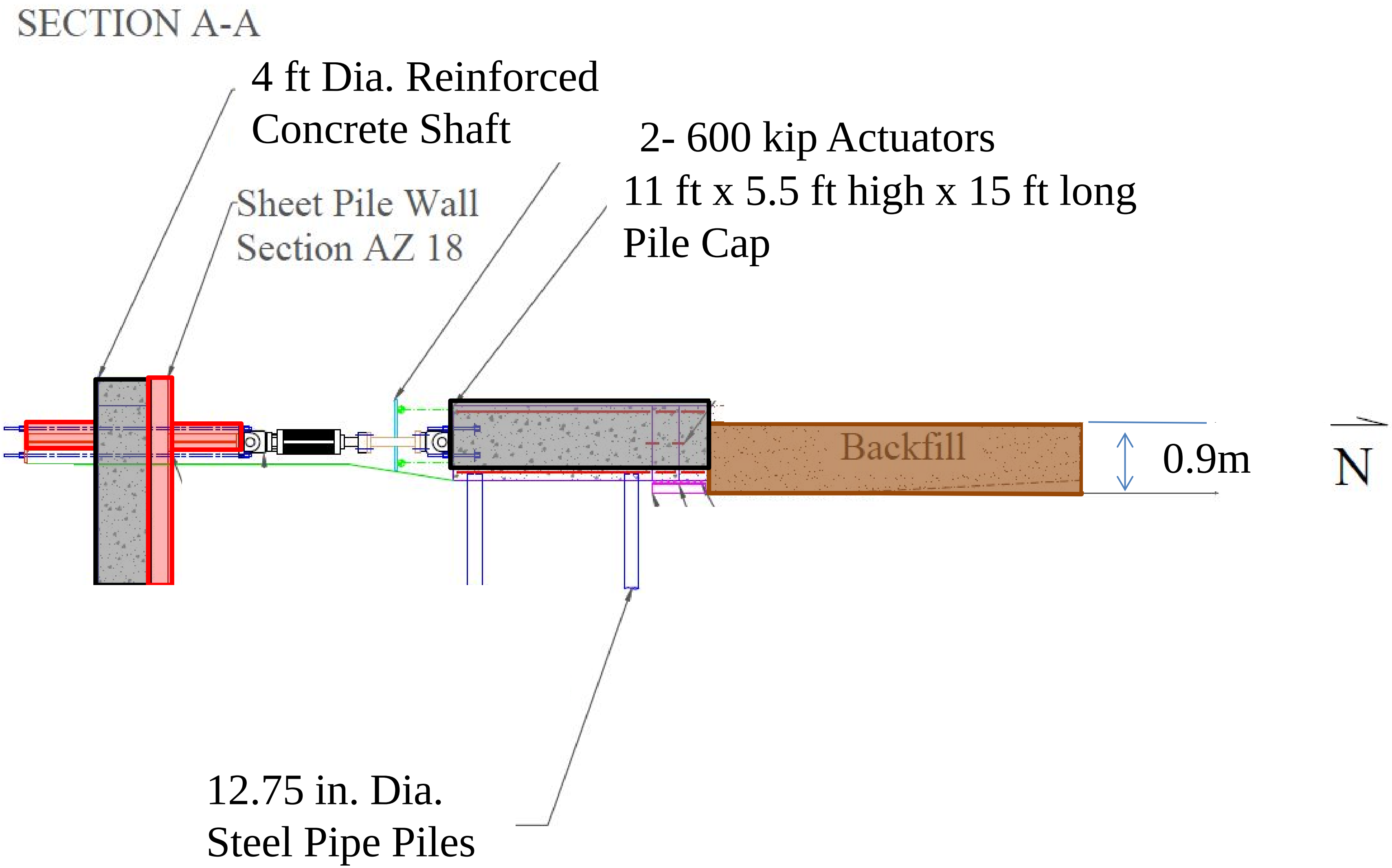
Geometry Effects?

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

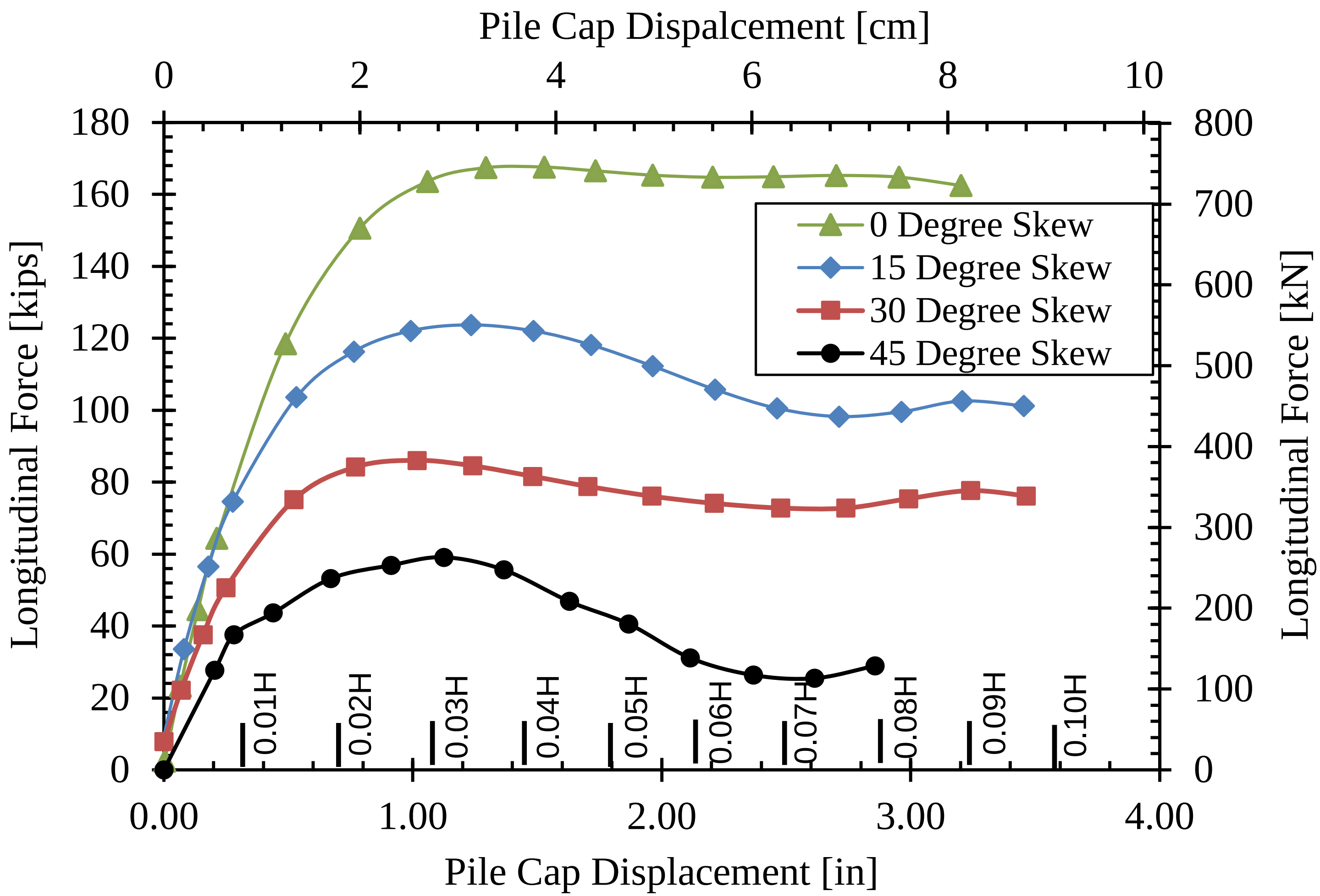


- Does this ratio impact the results?

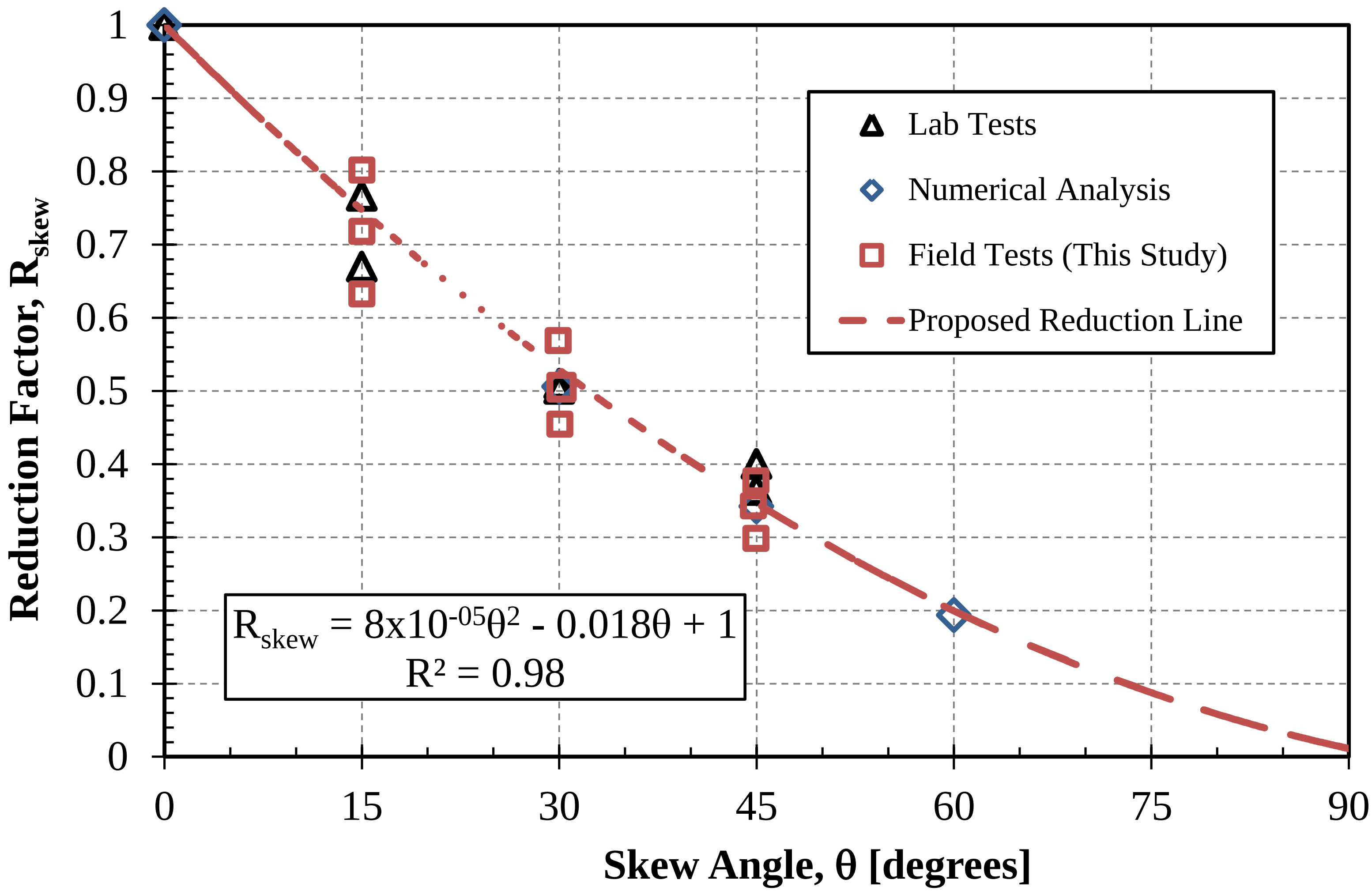
Field Test with 0.9m Backfill - W/H=3.7



Passive Force-Displacement Curves

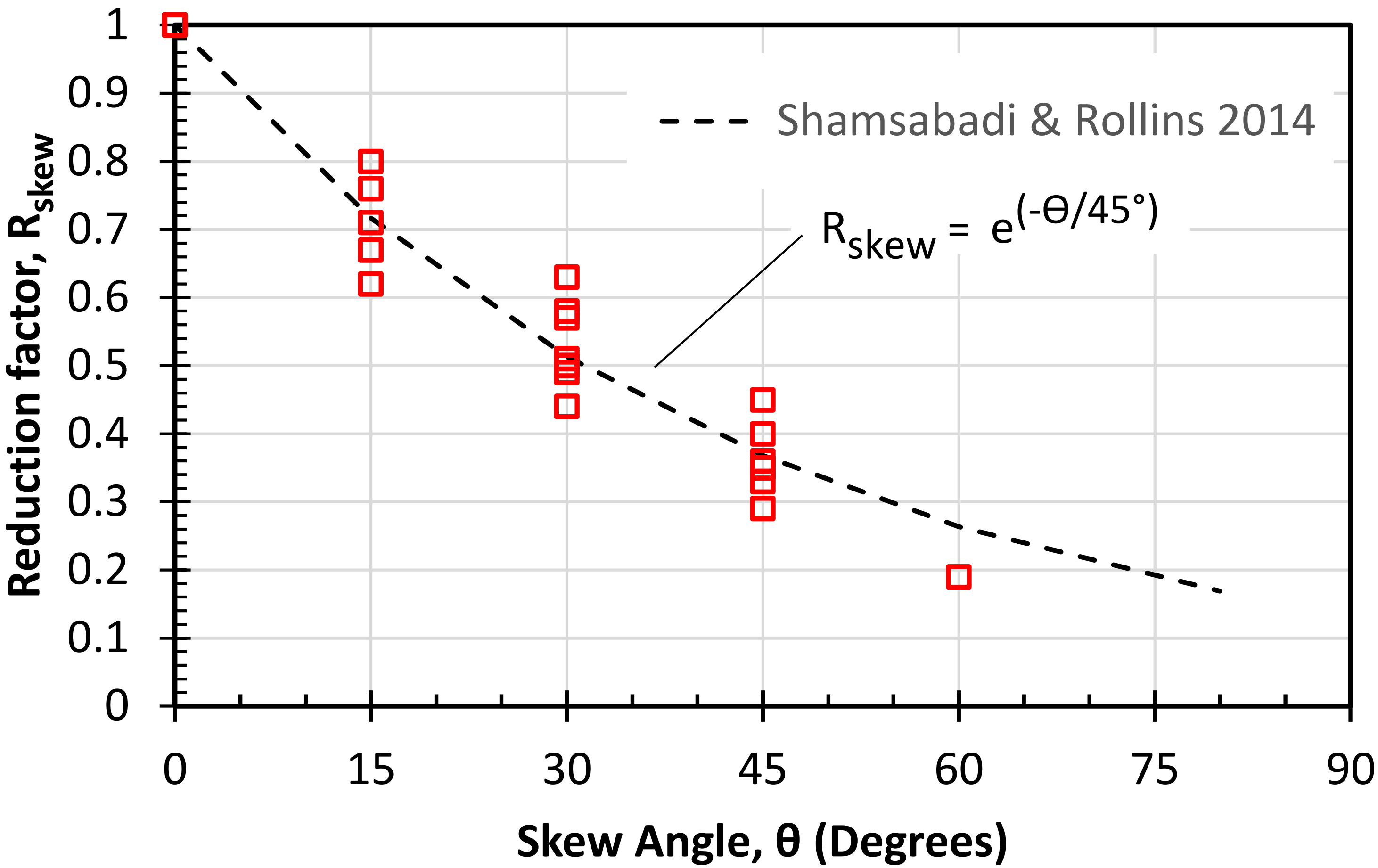


Passive Force Reduction Factor vs. Skew



45º Skew with RC Wingwalls

Overall Best Fit – Simplified Equation



Summary Relative to Skew Effects

- Significant decrease in passive force with increase in skew angle.
  - Numerical Analysis
  - 8 Small Scale Lab Tests
  - 11 Large Scale Field tests
- Simple reduction factor can account effect of skew angle on passive force
- Reduction factor not much affected by wall W/H ratio
- Reduction factor not much affected by sand, gravel, or GRS backfill type
- Passive force typically mobilized at $\Delta/H \approx$ 3 to 5%
- Shear resistance largely mobilized with 0.25 inch of movement at interface

Example Problem

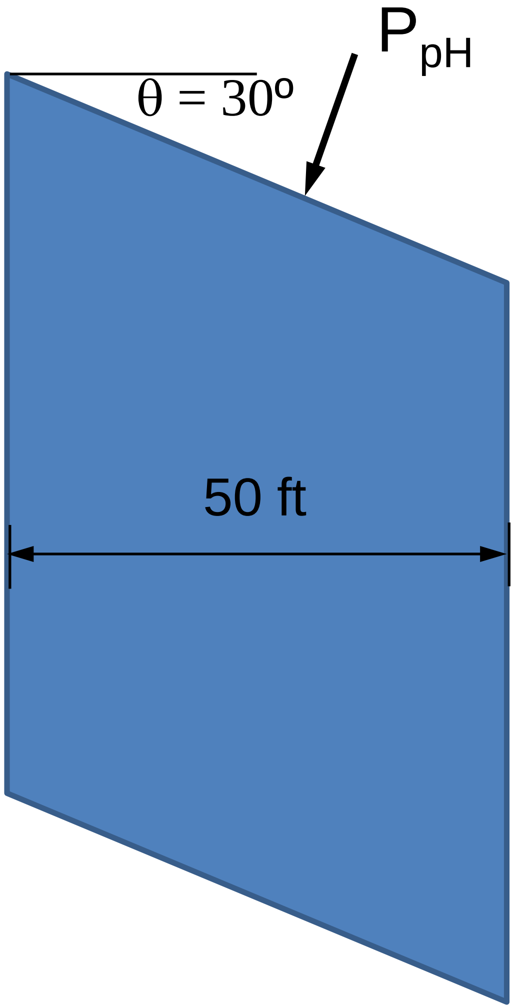
Given:

- Abutment wall 6 ft high and 50 ft wide.
- Backfill soil is sandy gravel (A-1-a) compacted to 95% of Modified Proctor density. (γ_{moist} = 135 pcf)
- Soil friction angle, ϕ, of 40º with no cohesion
- Assume soil/wall friction angle, δ, is 0.7ϕ = 28º
- **Skew angle, θ, of 30º**

Find: (a) Passive Force vs. Deflection Curve

(b) Shear Resistance vs. Deflection Curve

Adjustment for Width & Skew



Previously P_{pH} = 28.5 k/ft

For 0º skew condition

P_{pH} = (28.5 k/ft) (50ft) = 1425 k

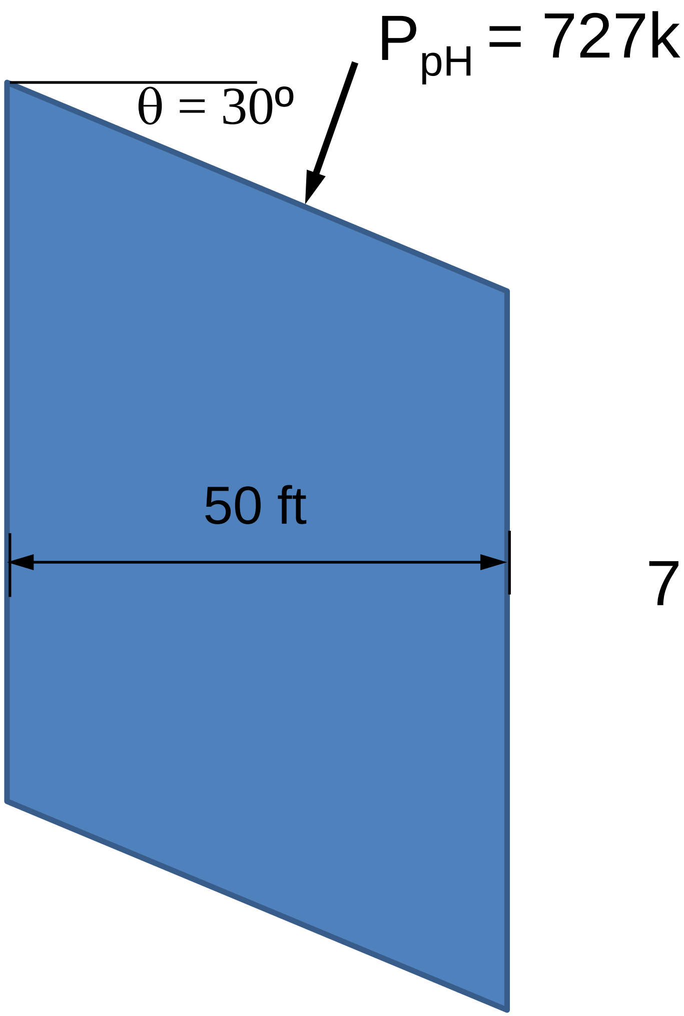
Compute skew reduction factor

$R_{skew} = e^{(-\Theta/45^o)} = e^{(-30^o/45^o)} = 0.51$

For 30º skew condition

P_{pH} = (1425 k)(0.51) = 727 k

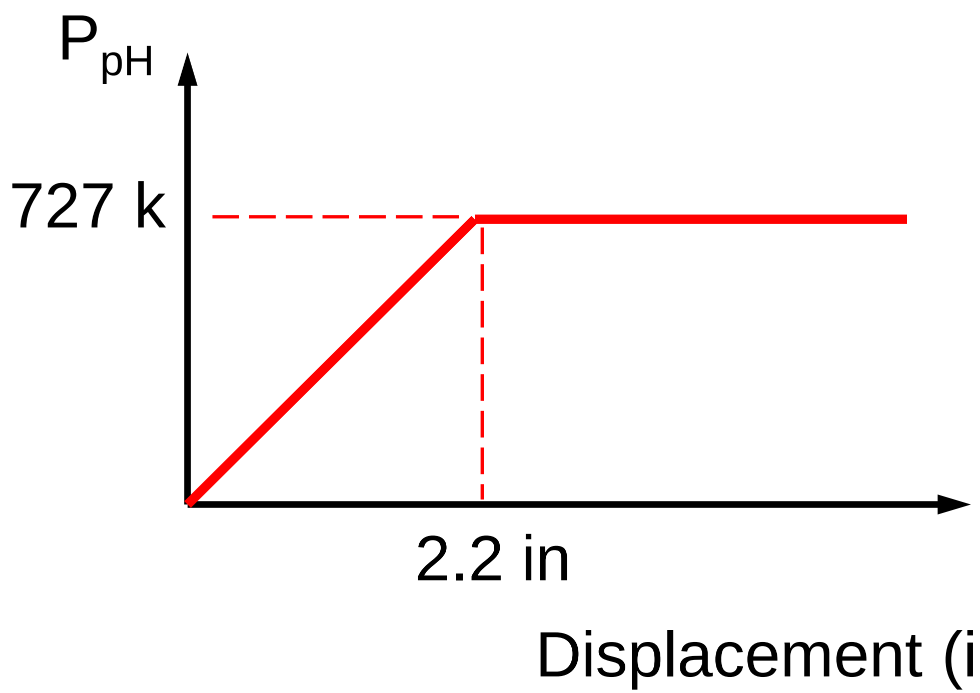
Passive Force-Displacement



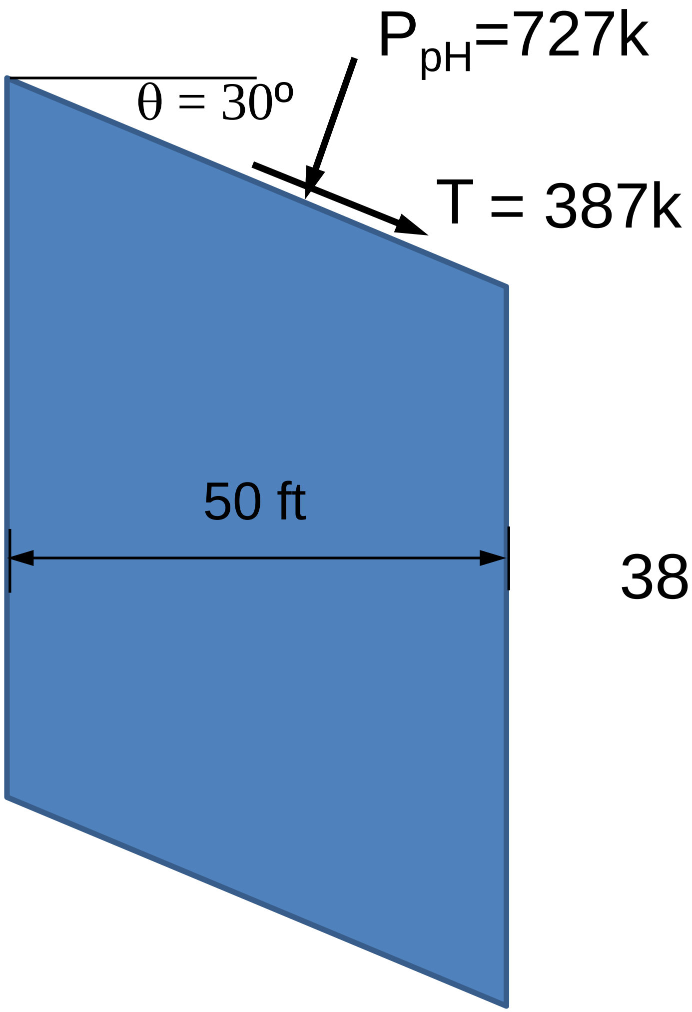
For a 6 ft high backwall:

Peak at 0.03H = 0.03(6 ft)(12in/ft)

= 2.2 in



Shear Force-Displacement

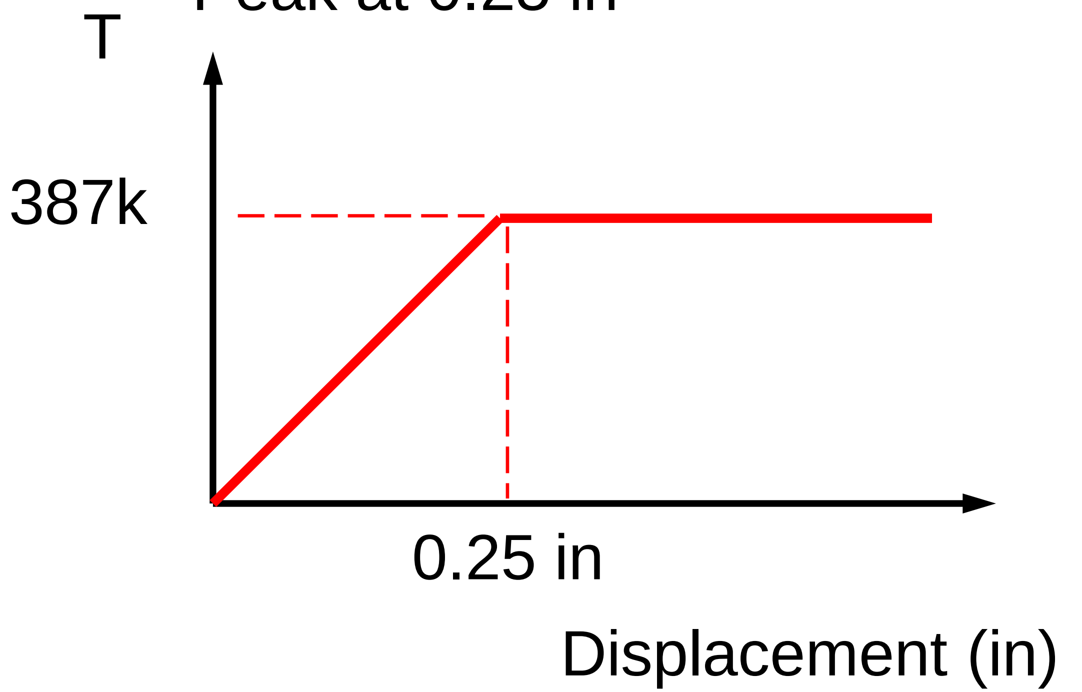


For a δ=28º = 0.70ϕ

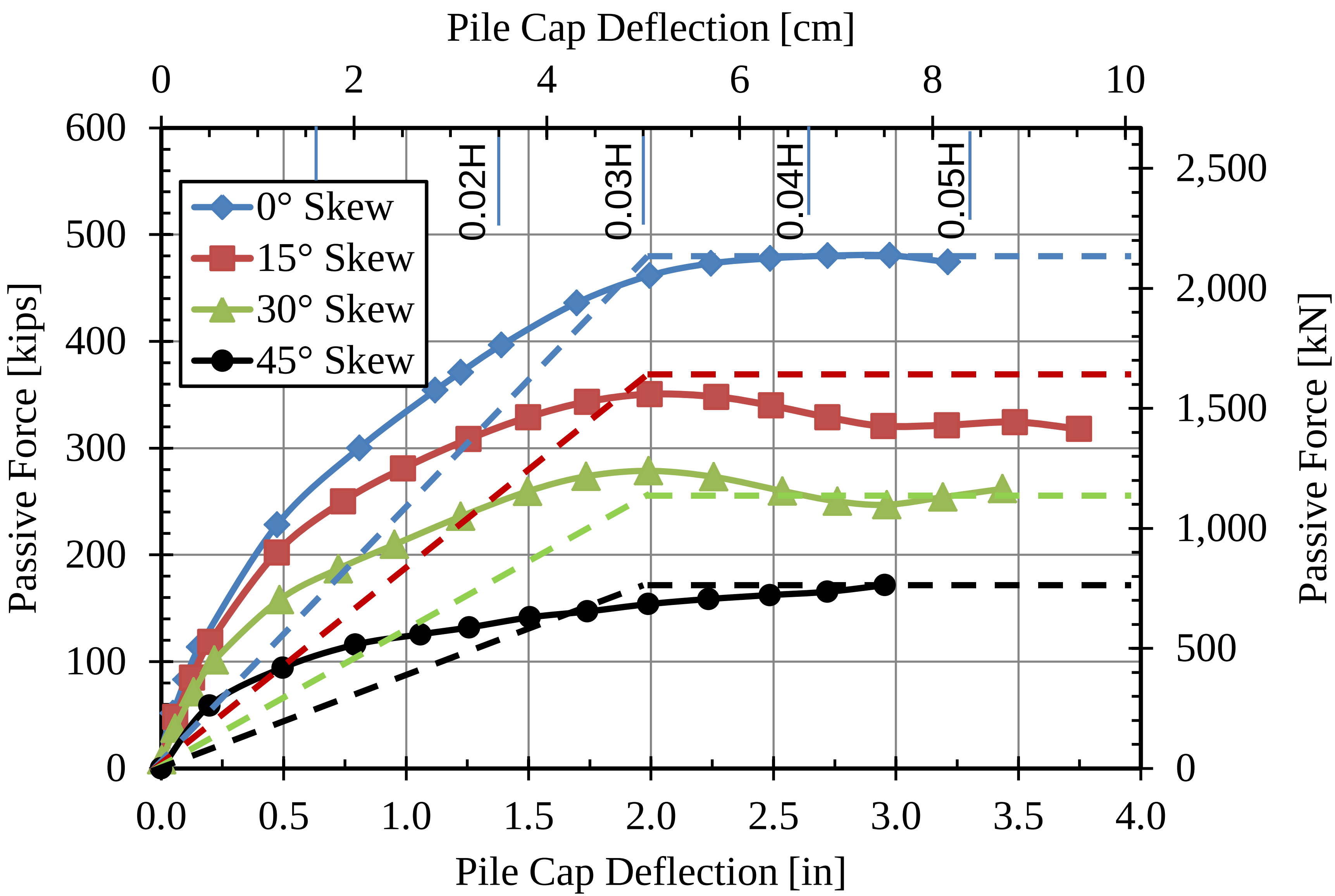
$T = cA + P_{pH}\tan\delta$

$= 0 + (727\text{ k})\tan(28^{o}) = 387\text{k}$

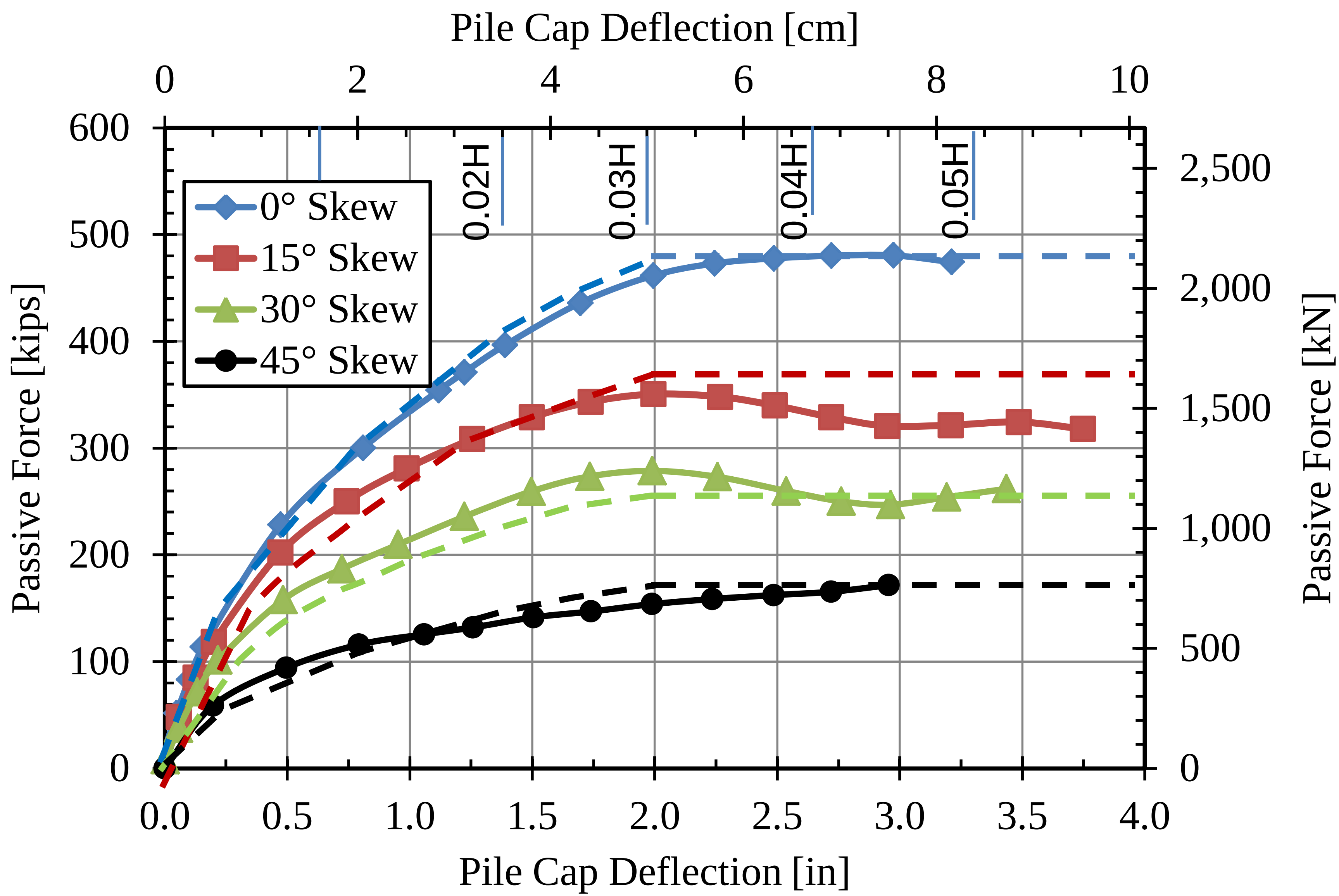
Peak at 0.25 in



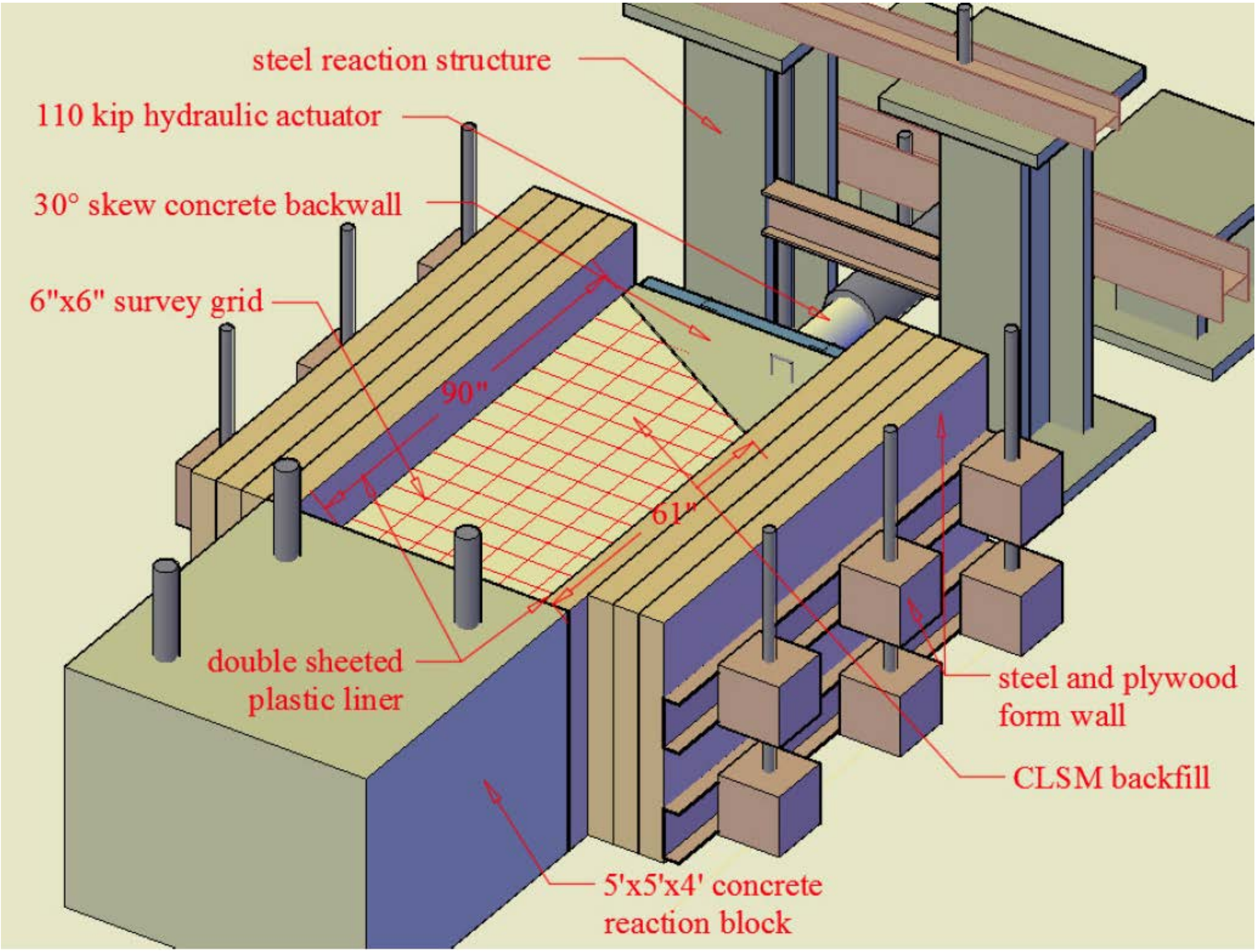
Bi-linear Passive Force vs. Displacement



Hyperbolic Passive Force vs. Displacement



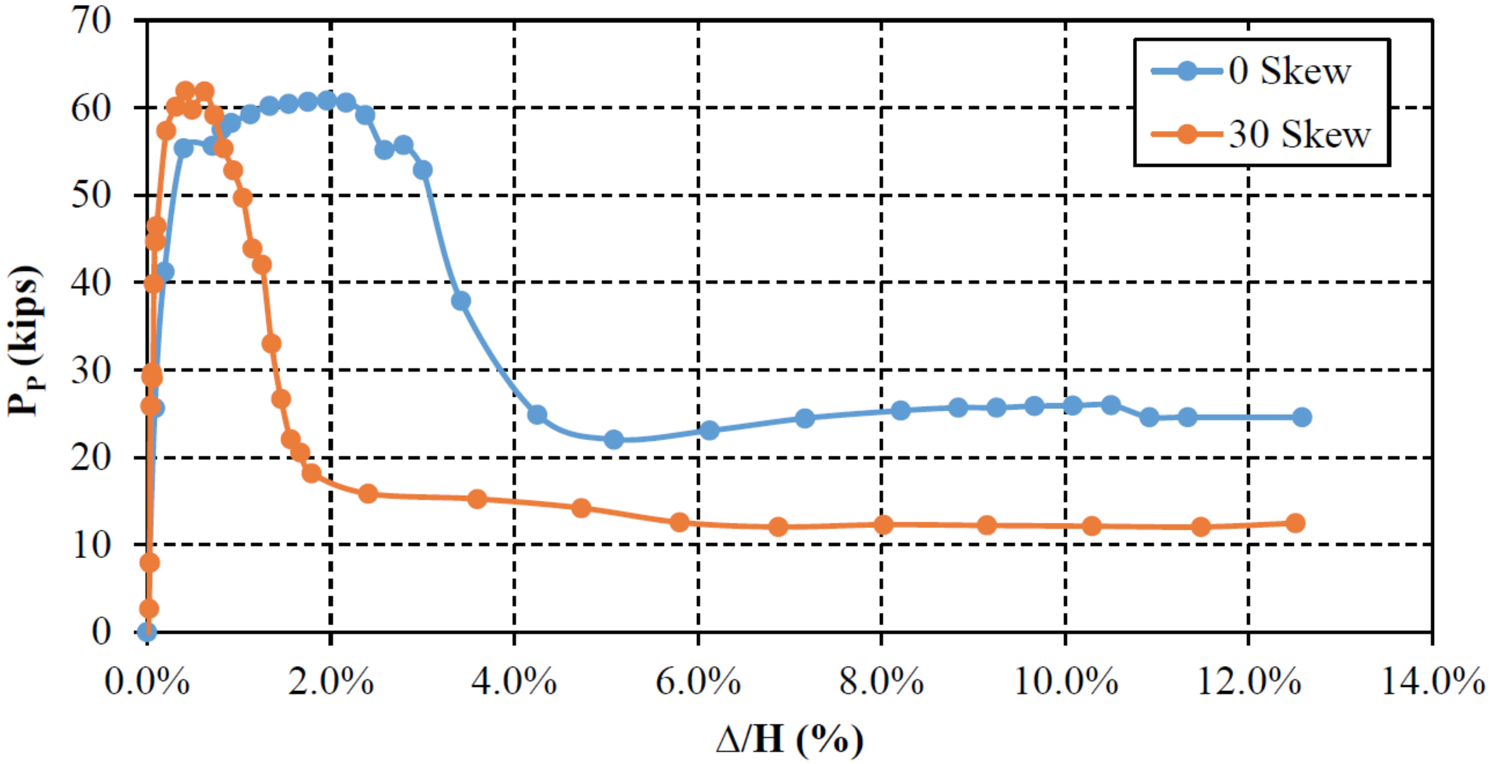
Flowable Fill Abutment Tests



γ = 127 lbs/ft^3

UCS = 50 to 60 psi

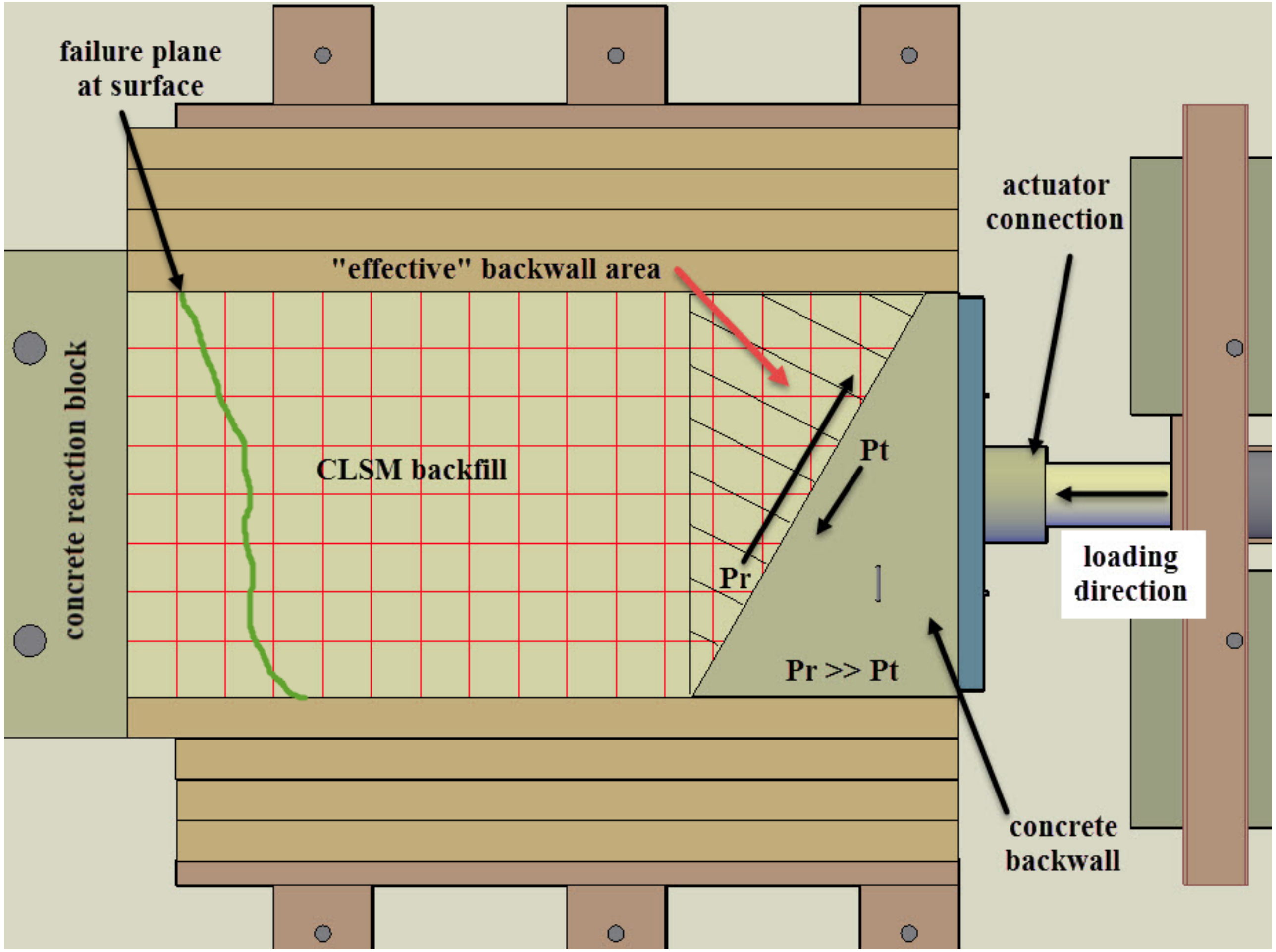
Flowable Fill Abutment Tests



$P_p = 0.5\gamma H^2 B + 2cHB$, Passive force for cohesive soil

$c = UCS/2$

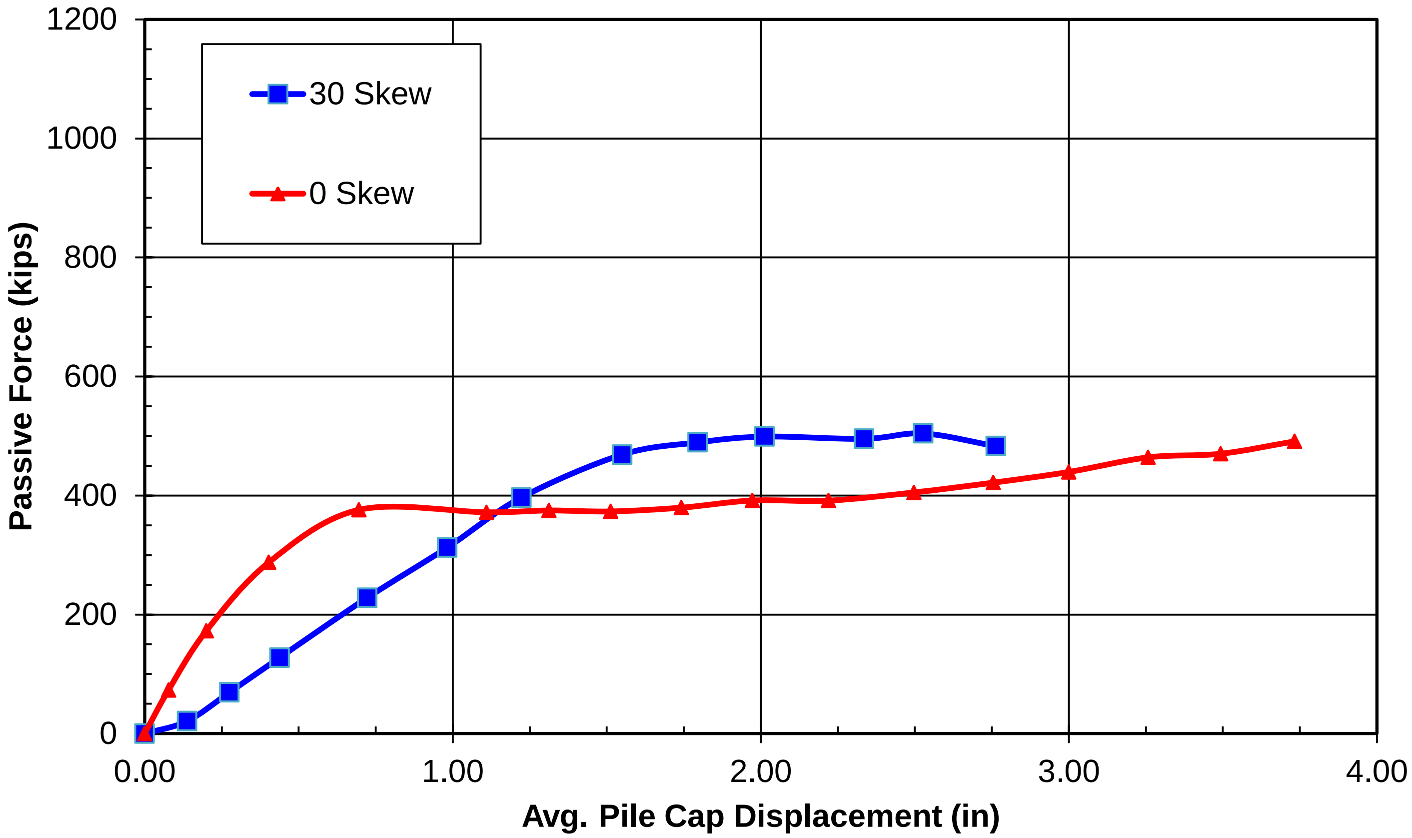
Flowable Fill Abutment Tests



Lightweight Cellular Concrete Backfill

γ = 30 lbs/ft^3
UCS = 50 to 60 psi

Passive Force-Deflection Curves

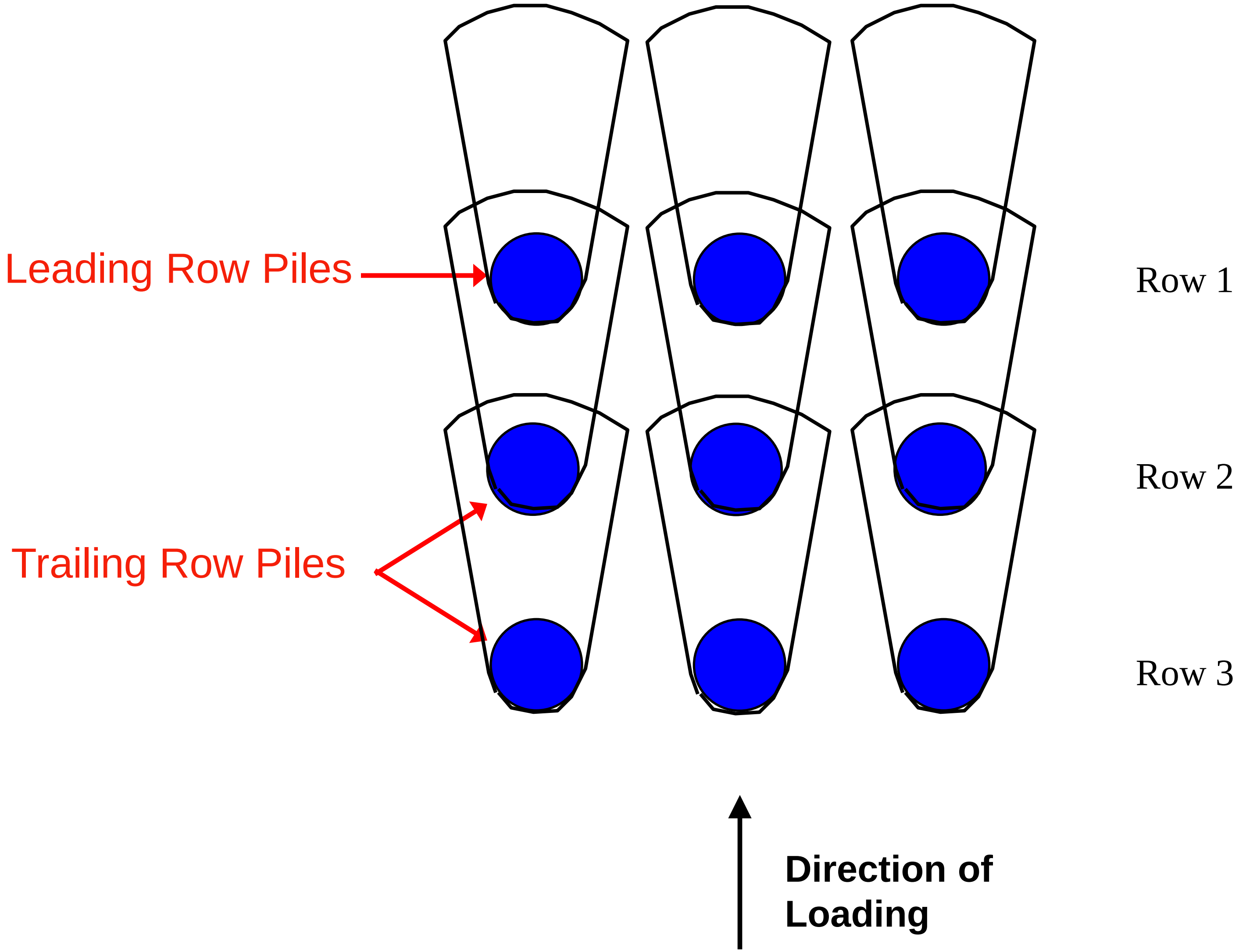


$P_p = 0.5\gamma H^2 B + 2cHB$, Passive force for cohesive soil

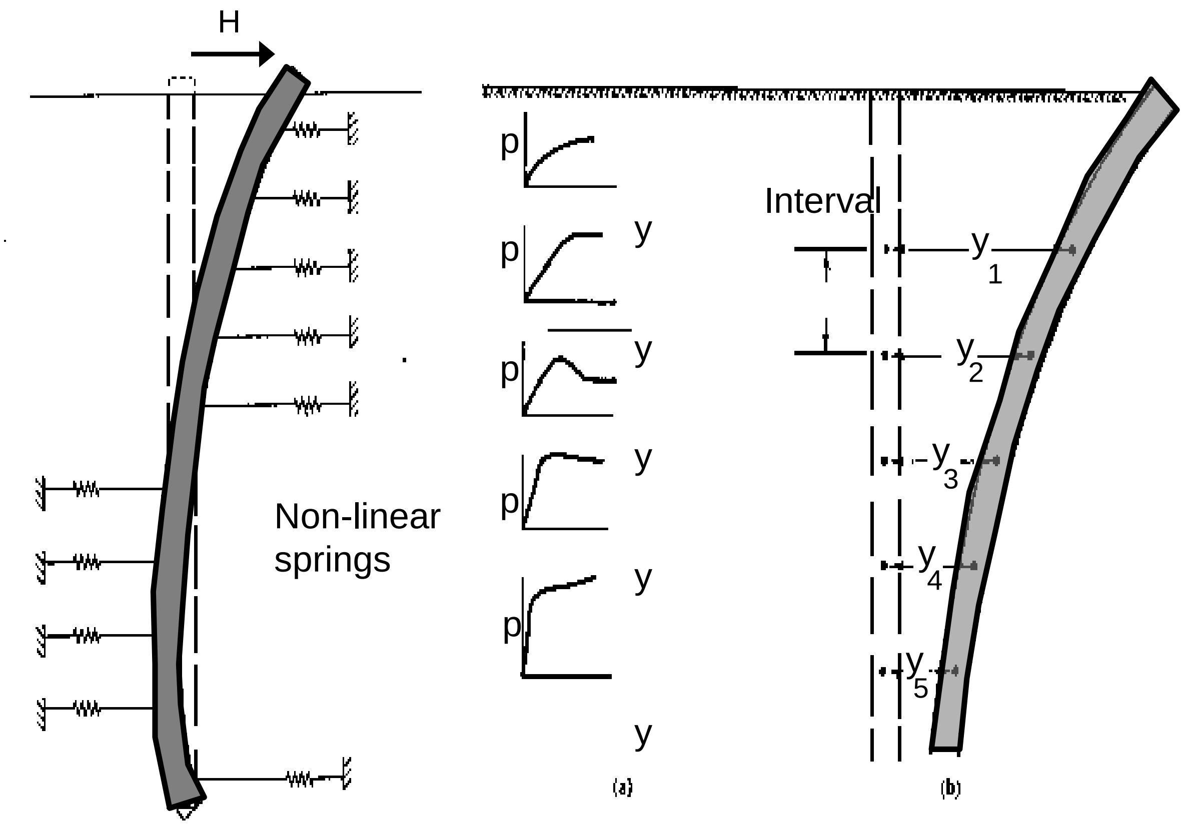
Lateral Pile Resistance at Abutments

- Group interaction factors (P-multipliers)
- Reduction factors for presence of MSE wall face

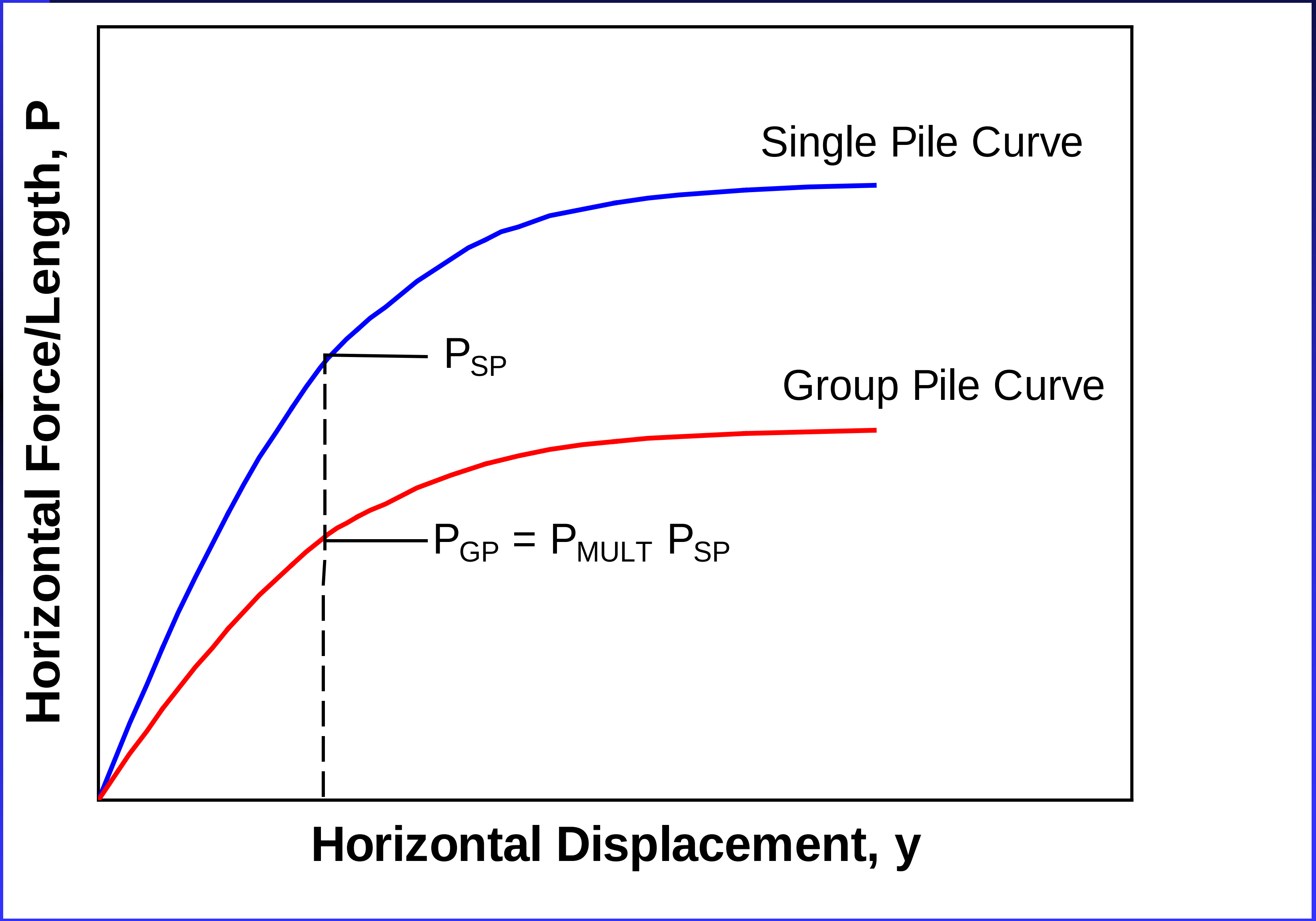
Pile Group Interaction



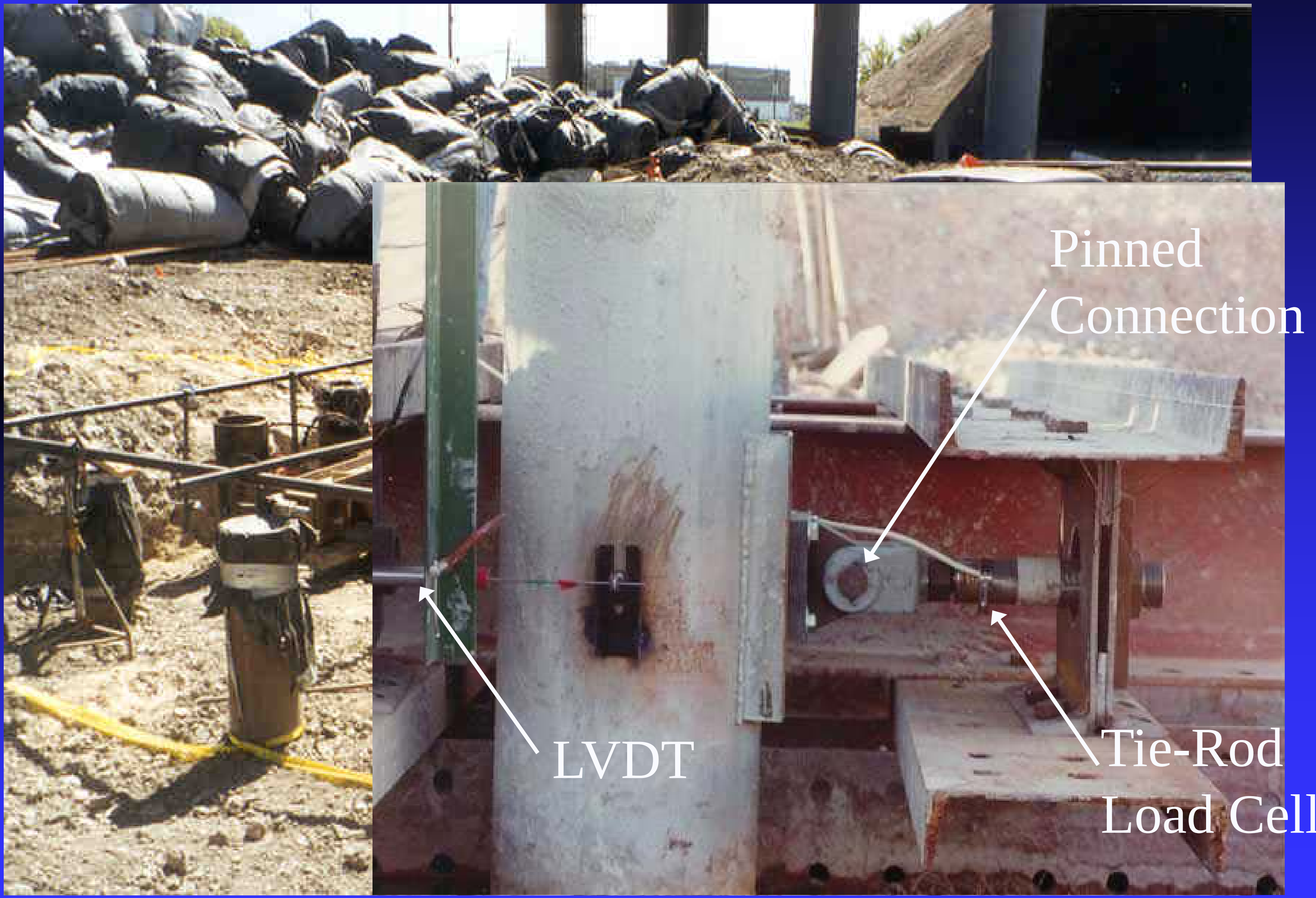
Lateral Load Analysis for Piles with *p-y* Curves



P-Multiplier Concept (Brown et al, 1988)

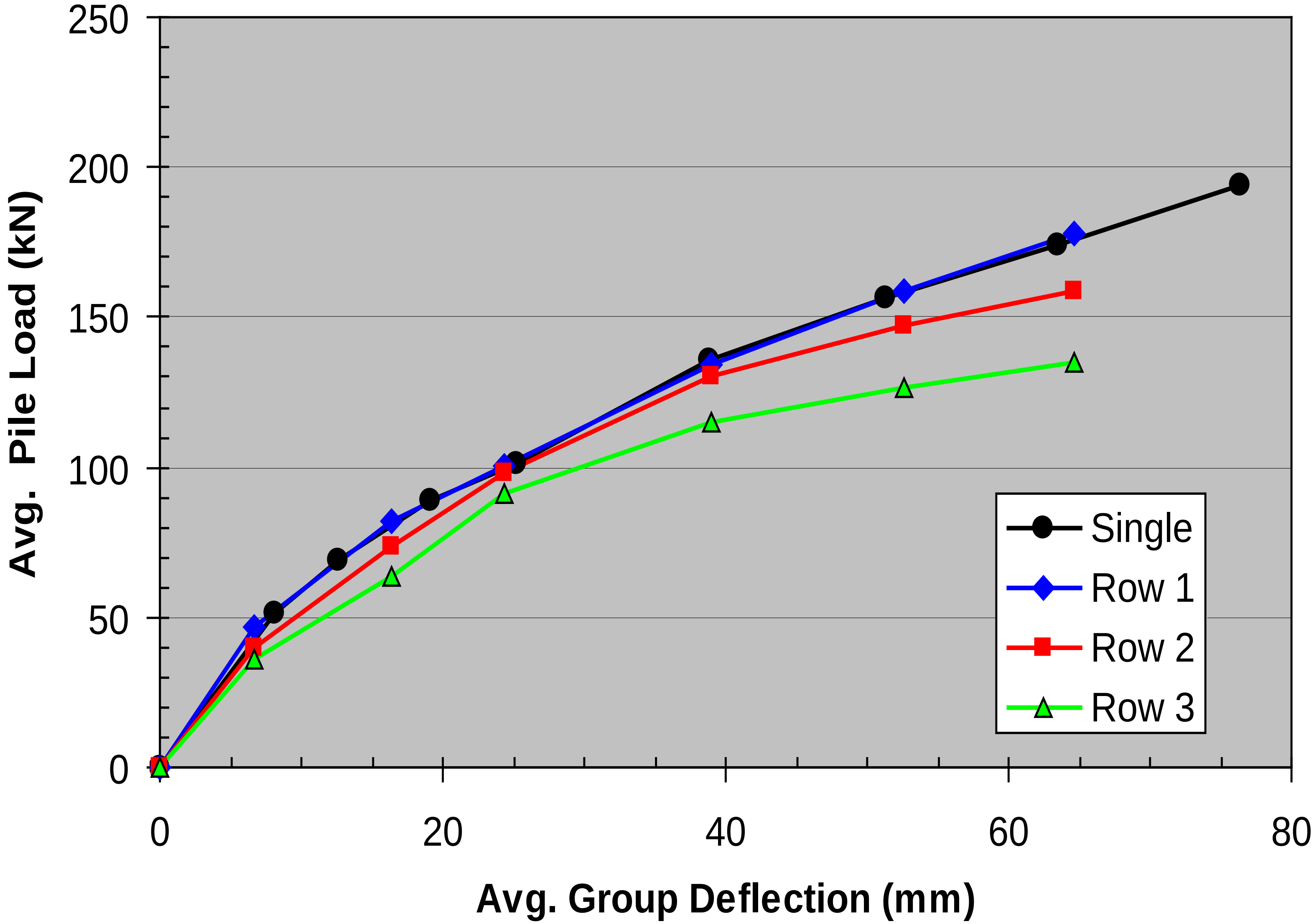


9 Pile Group at 5.6 D Spacing

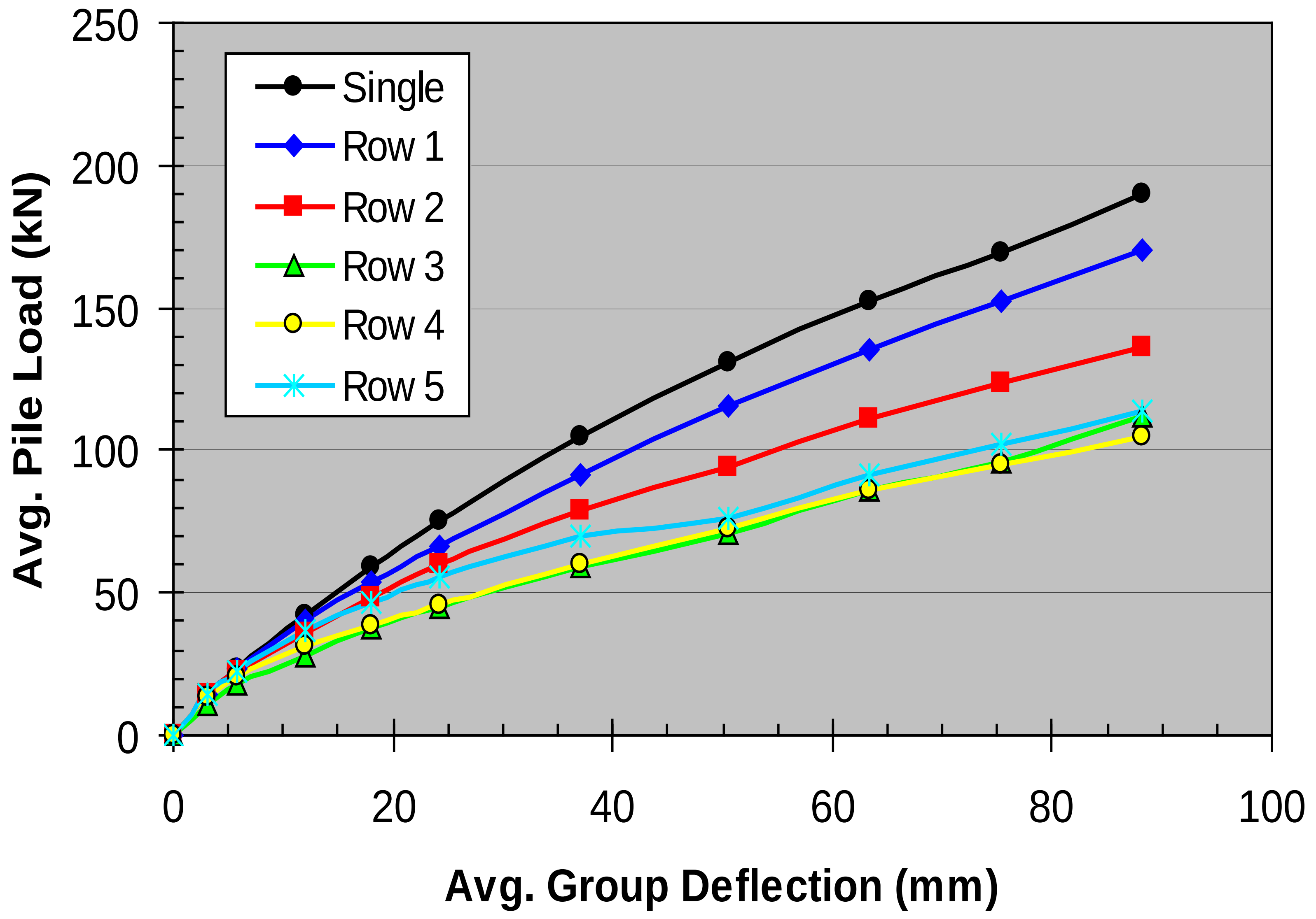


3x5 Pile Group at 3.3 D Spacing

3x3 Pile Group at 5.6 Dia. Spacing



3x5 Pile Group at 3.3D Spacing

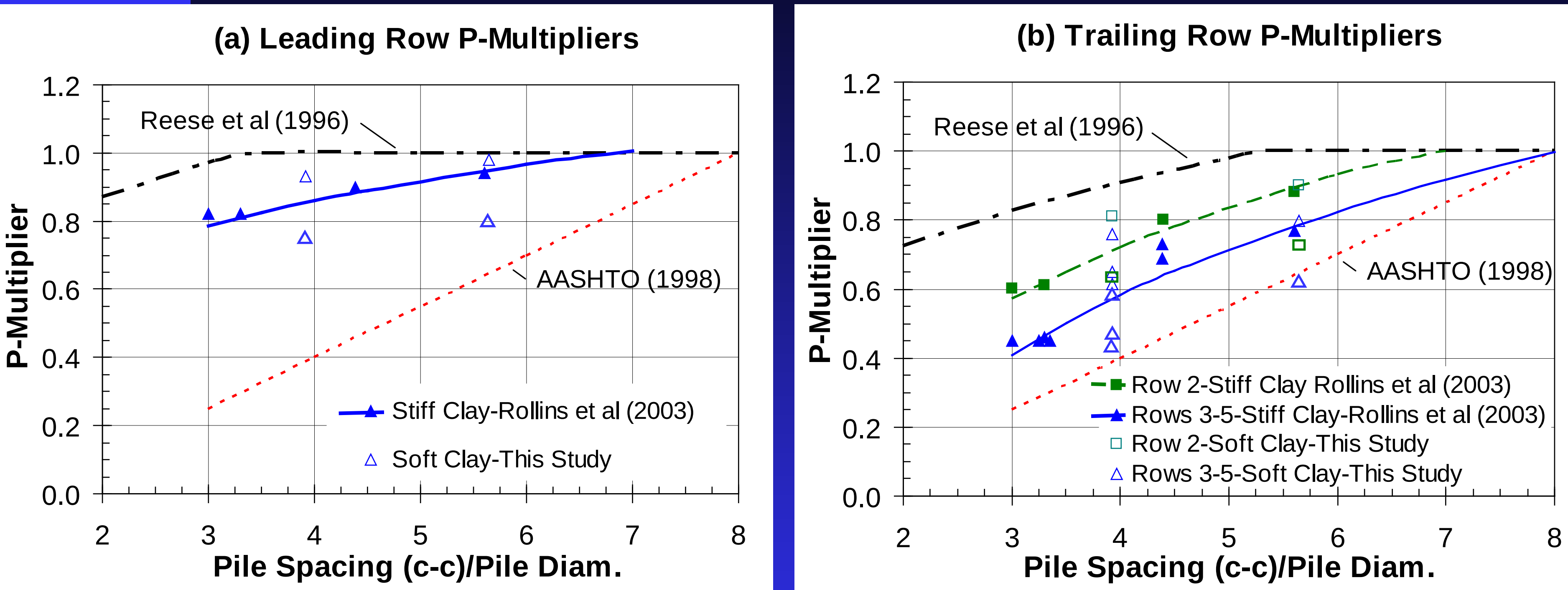


P-Multipliers from AASHTO

Table 10.7.2.4-1—Pile P-Multipliers, P_m, for Multiple Row Shading (averaged from Hannigan et al., 2006)

Pile *CTC* spacing (in the direction of loading)	*P*-Multipliers, P_m		
	Row 1	Row 2	Row 3 and higher
3*B*	0.8	0.4	0.3
5*B*	1.0	0.85	0.7

P-Multipliers from Tests



first (lead) row piles

$$f_m = 0.26 \ln(S/D) + 0.5 \leqslant 1.0 \qquad (1)$$

second row piles

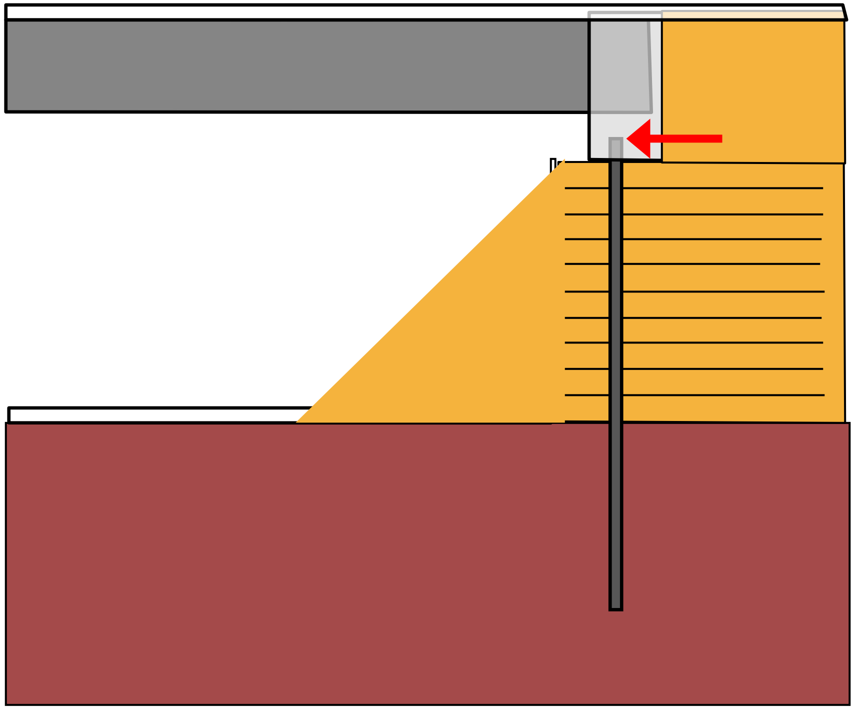
$$f_m = 0.52 \ln(S/D) \leqslant 1.0 \qquad (2)$$

third or higher row piles

$$f_m = 0.60 \ln(S/D) - 0.25 \leqslant 1.0 \qquad (3)$$

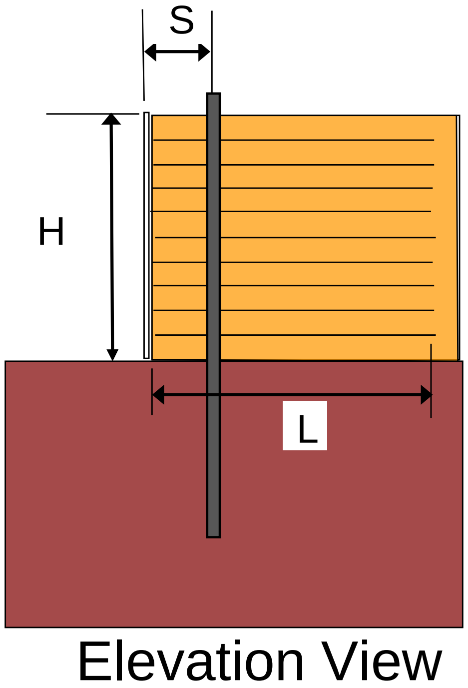
Rollins et al., 2005

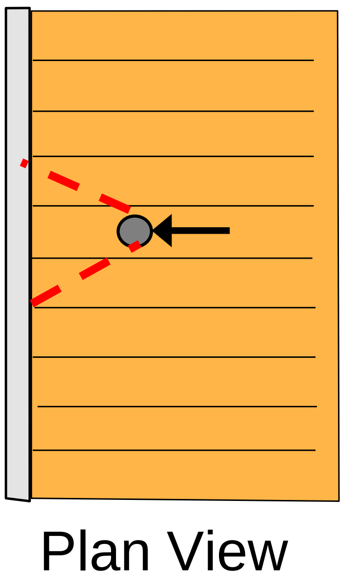
Abutment Piles near MSE Walls



Abutment Piles Near MSE Walls

MSE Wall Geometry

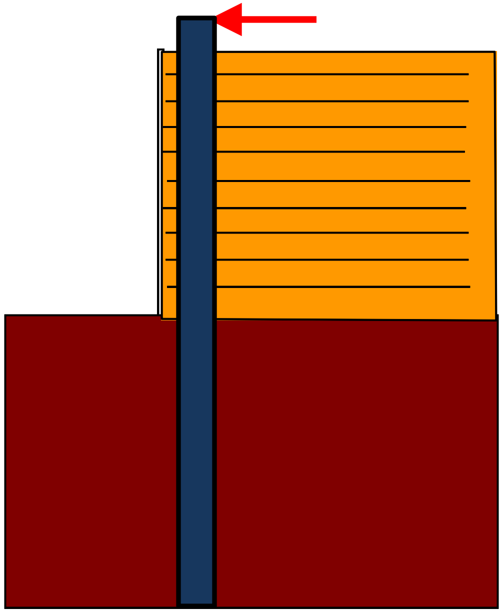




- Wall decreases lateral pile resistance
- Pile load increases force on reinforcement

Approaches to the Problem

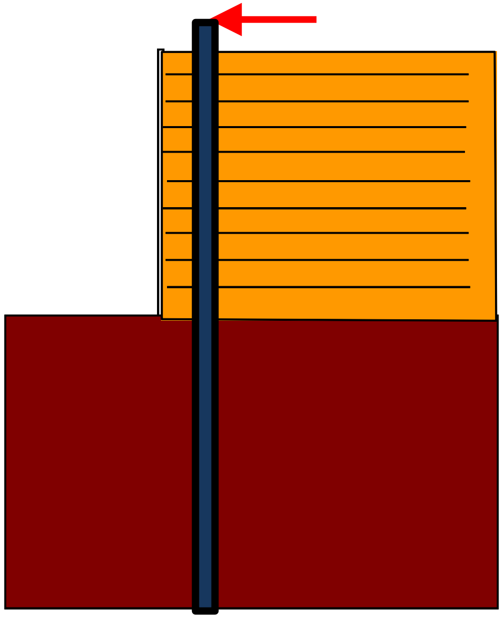
Ignore Soil Resistance



Increased Cost from Larger Pile Diameter or More Piles

Approaches to the Problem

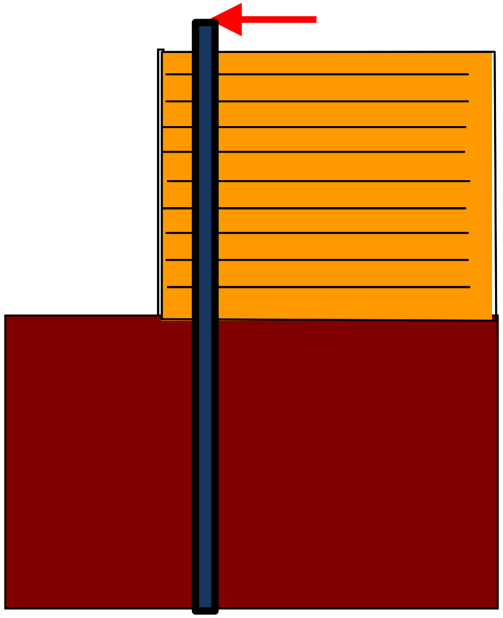
Increase Spacing to Eliminate Interaction



Increased Cost from Larger Bridge Span

Approaches to the Problem

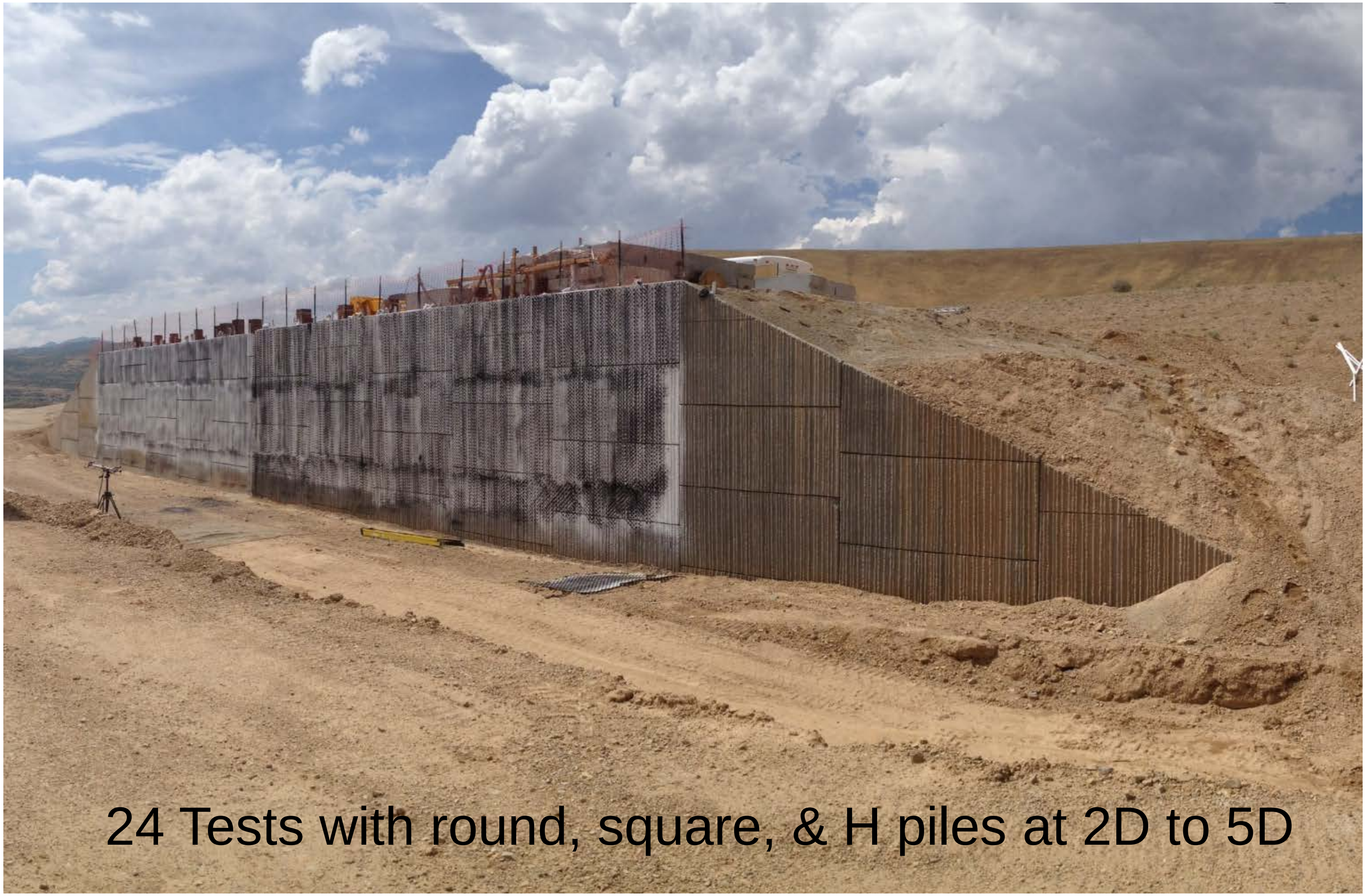
Estimate a Reduction Factor



What should the reduction be?

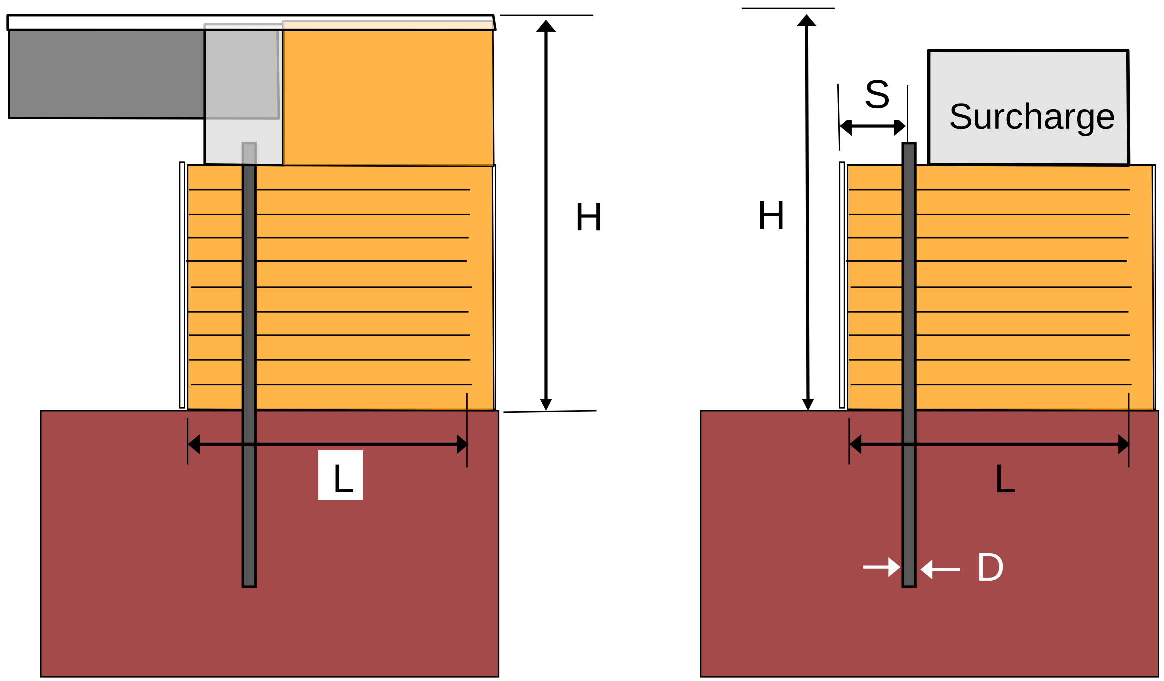
Mechanically Stabilized Earth Abutment Wall

MSE Test Wall (20 ft high & 100 ft long)



24 Tests with round, square, & H piles at 2D to 5D

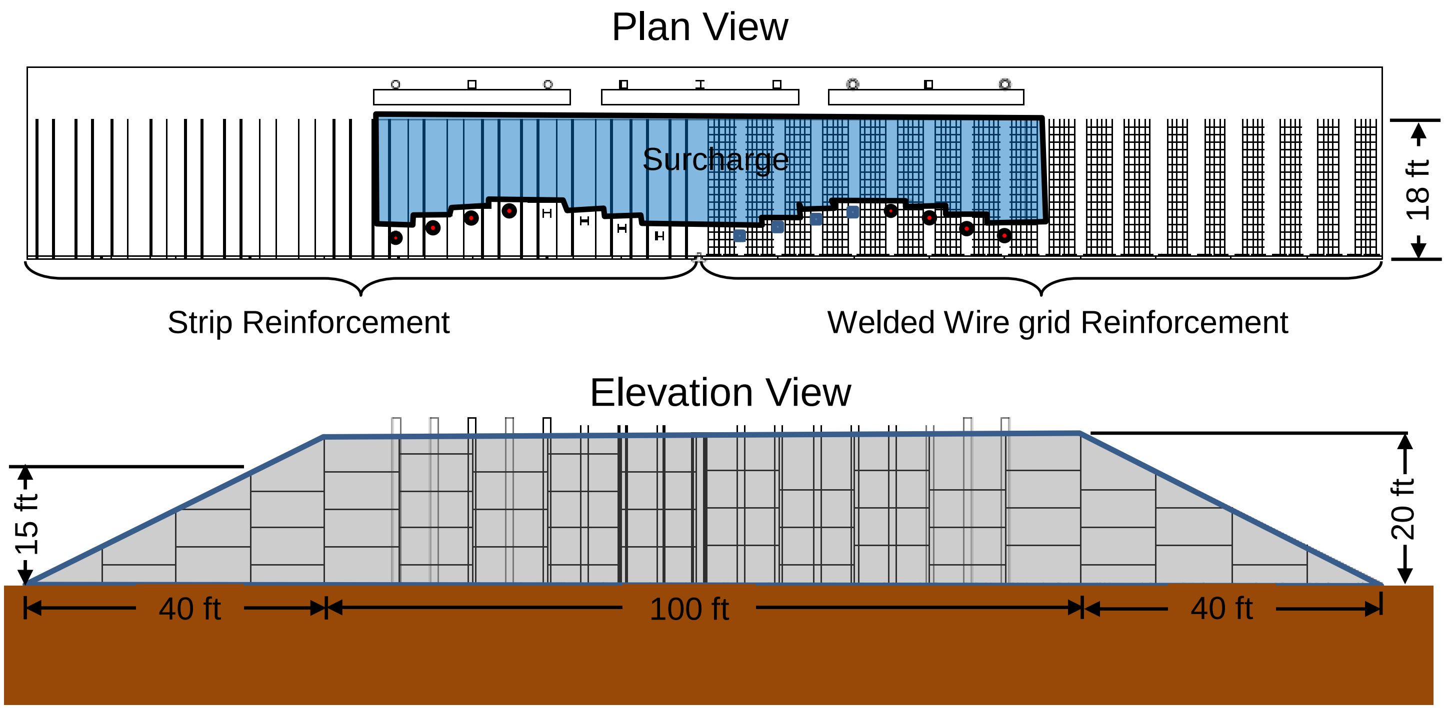
Profile View of Test Layout



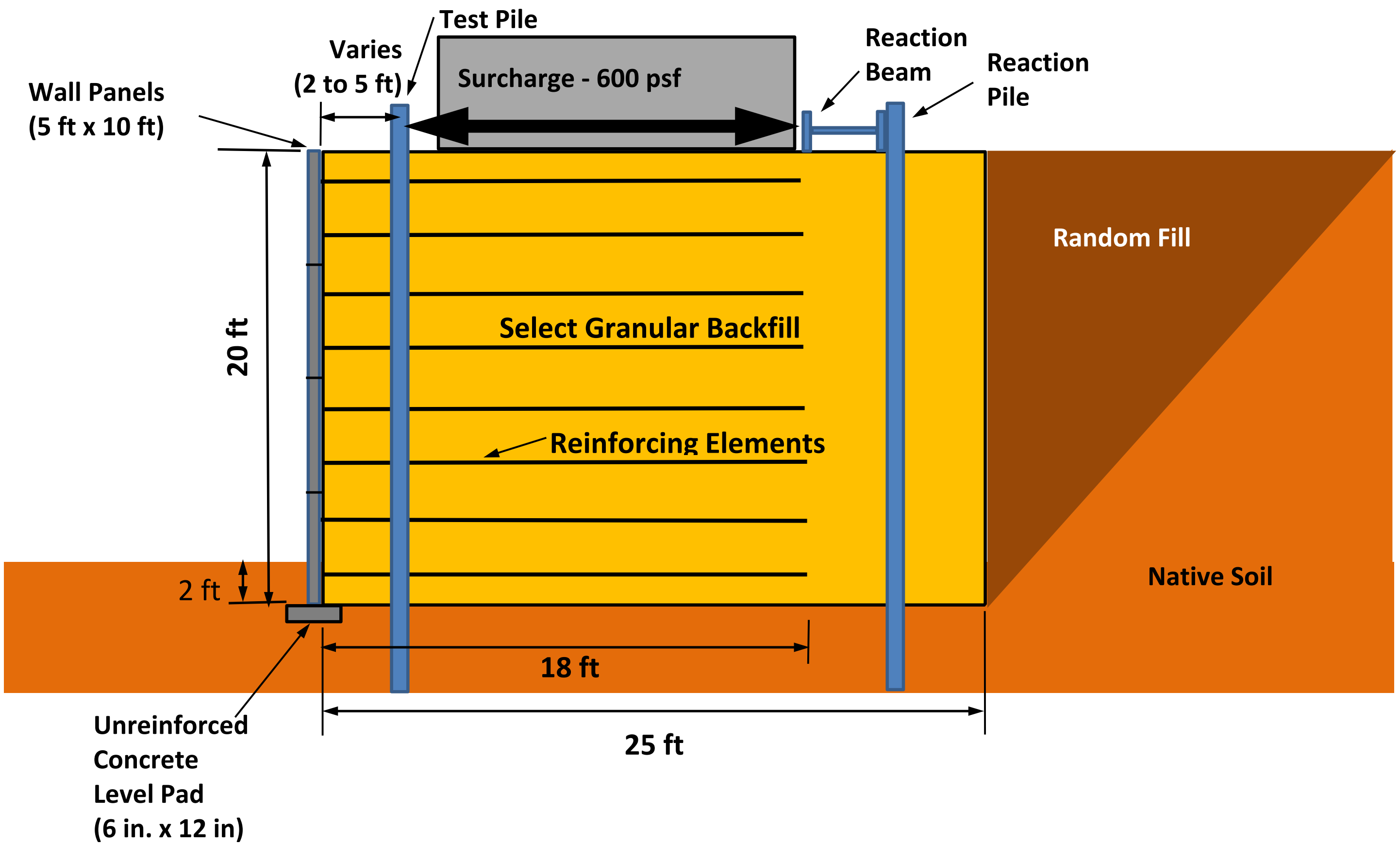
Ultimate Design

Layout During Tests

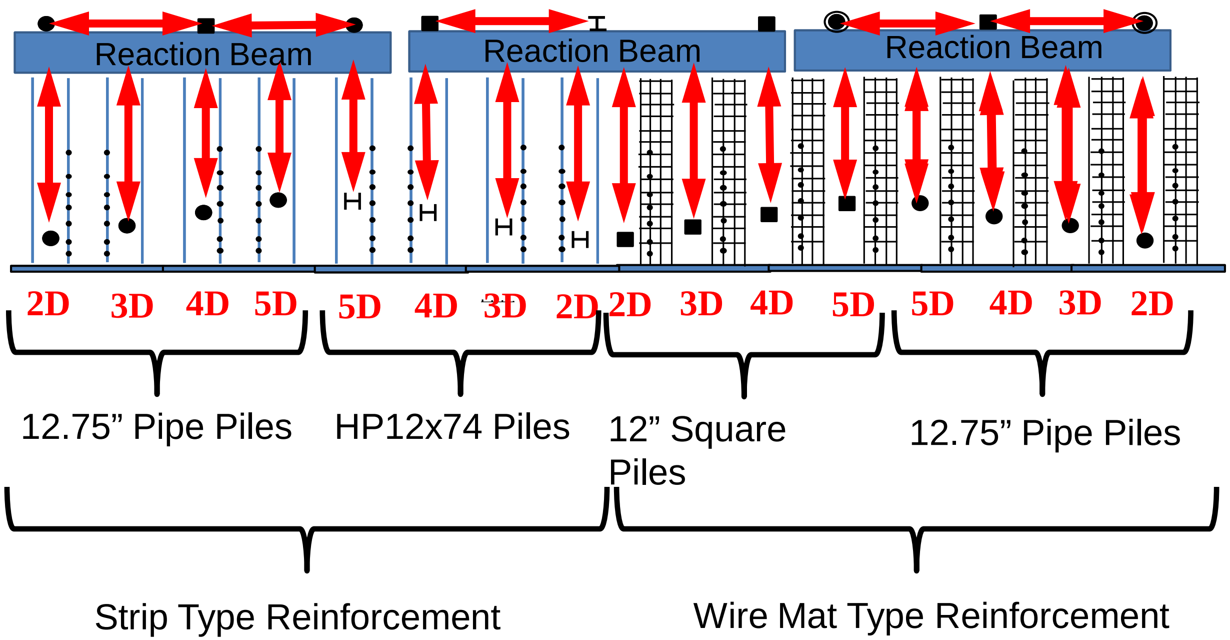
Plan and Elevation View of Test Abutment



Cross-Section Through MSE Wall



Pile Testing Sequence

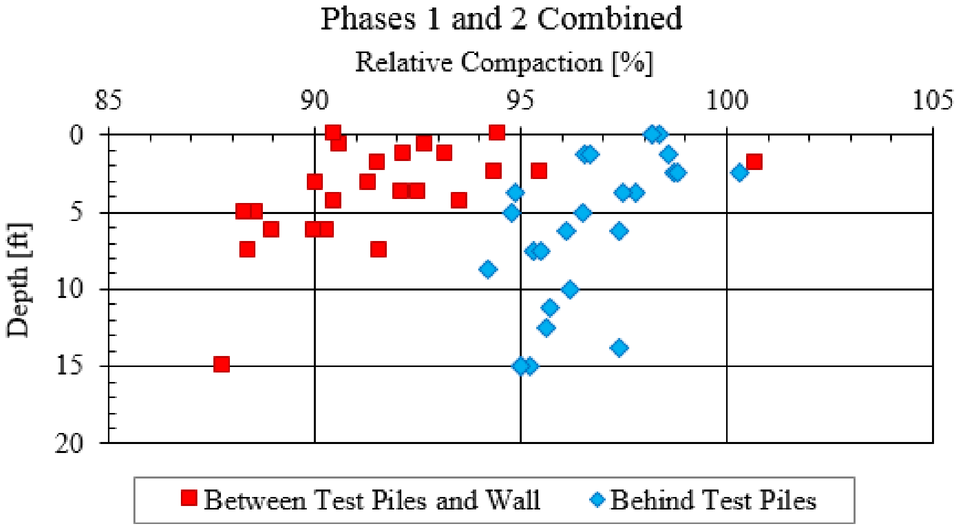


20 ft Wall – L/H = 0.7

15 ft Wall – L/H = 0.9

Total of 31 Tests

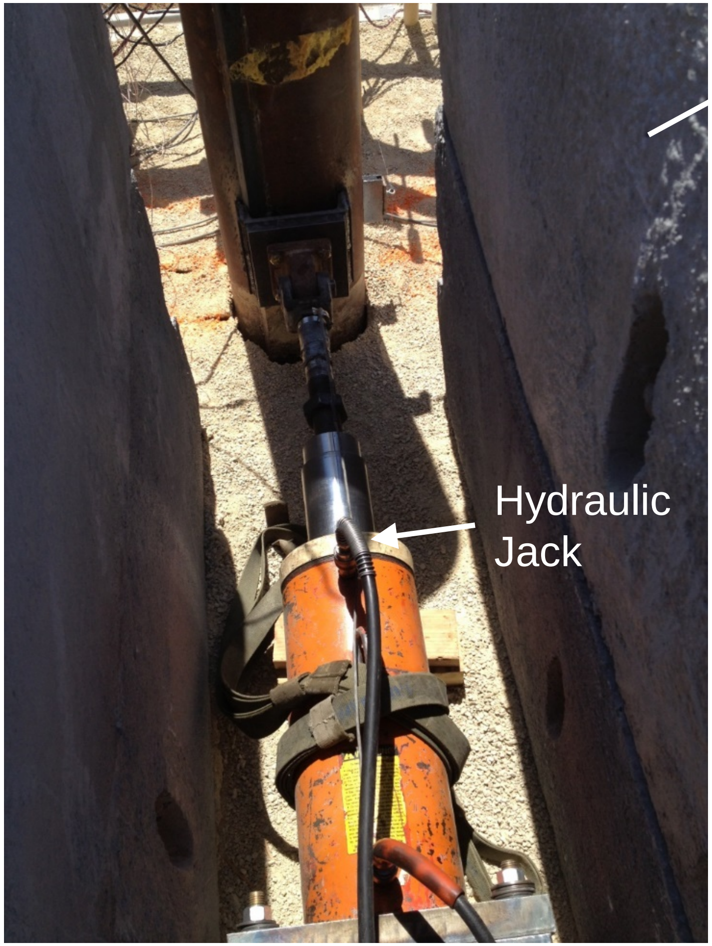
Nuclear Density Gauge Tests



Typical Test Set-up

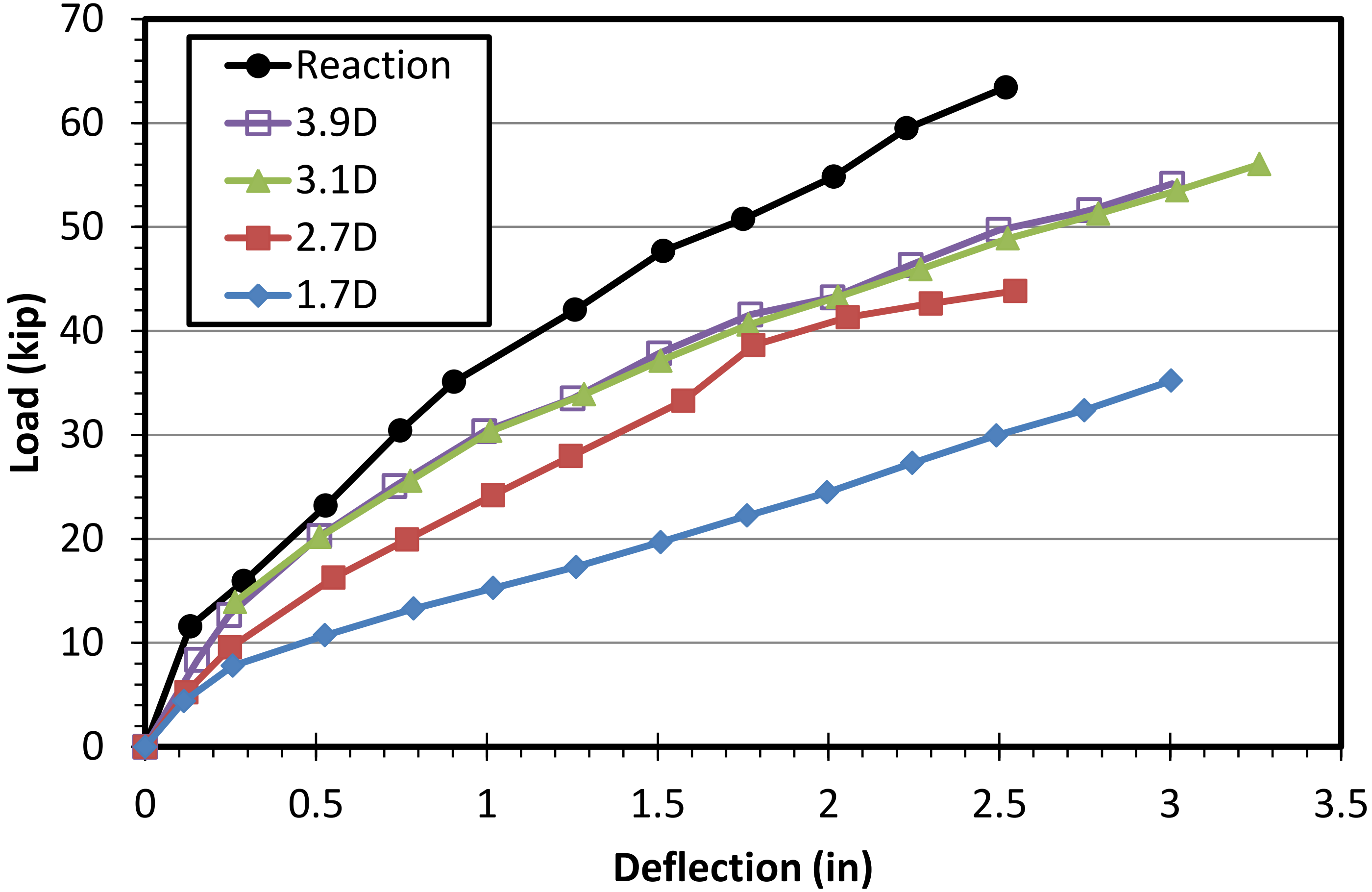
Typical Test Set-up

Load Test Photos

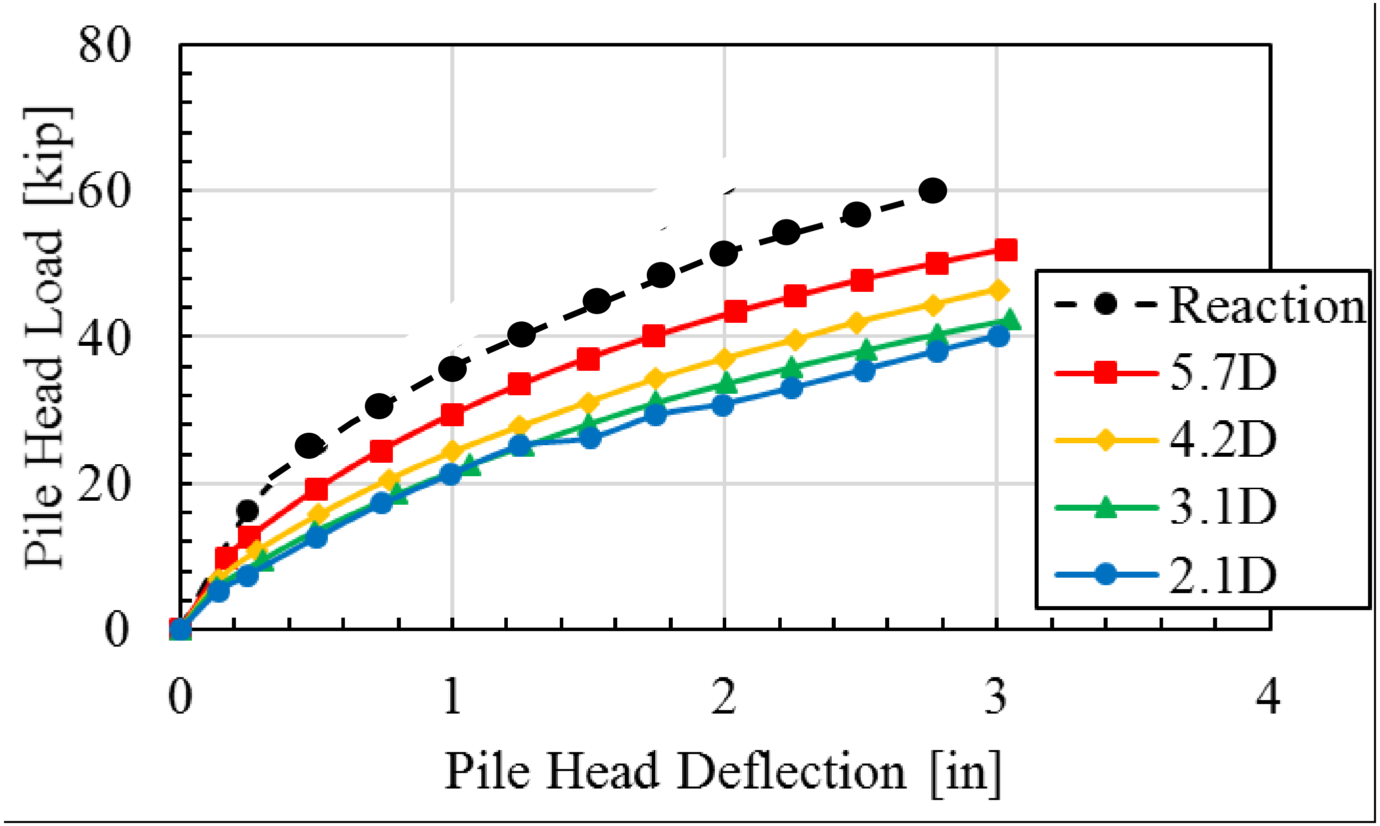


Effect of MSE Wall on Lateral Pile Resistance

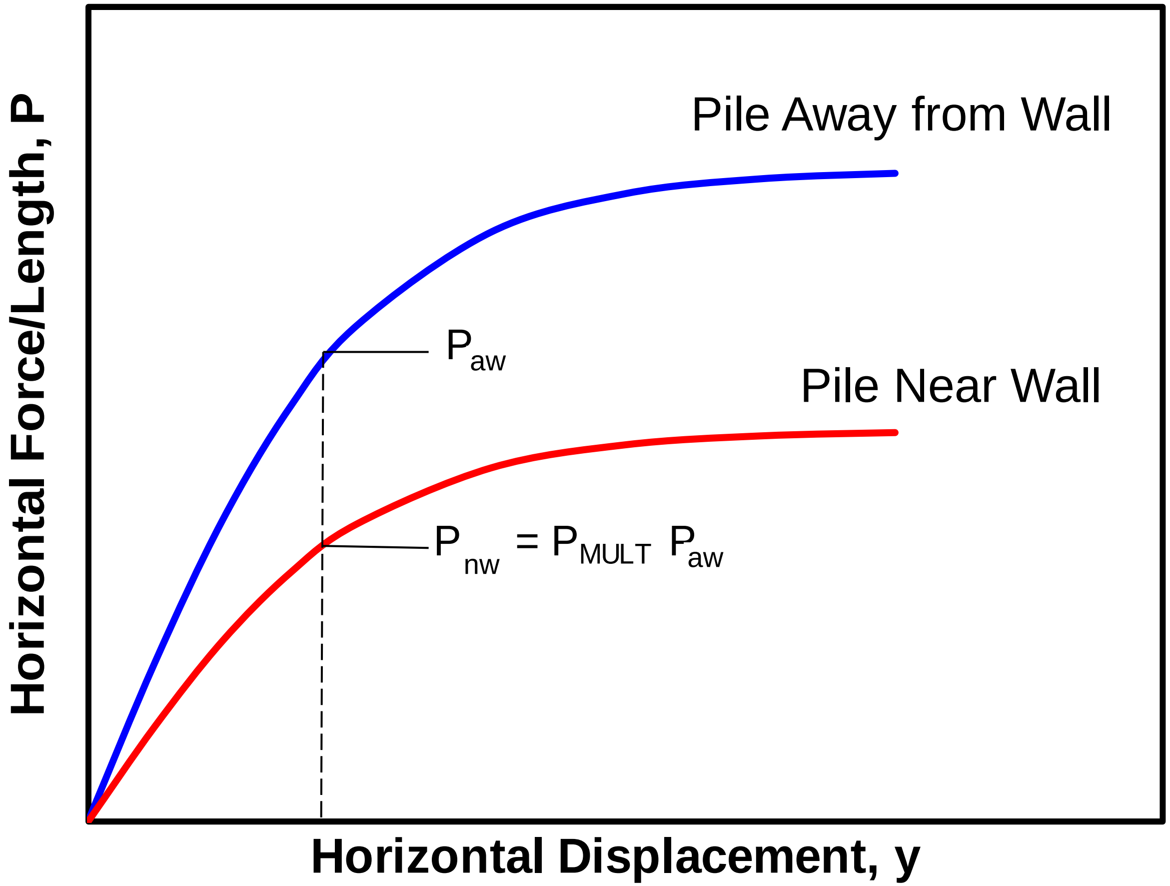
Pipe Piles with Strip Reinforcement



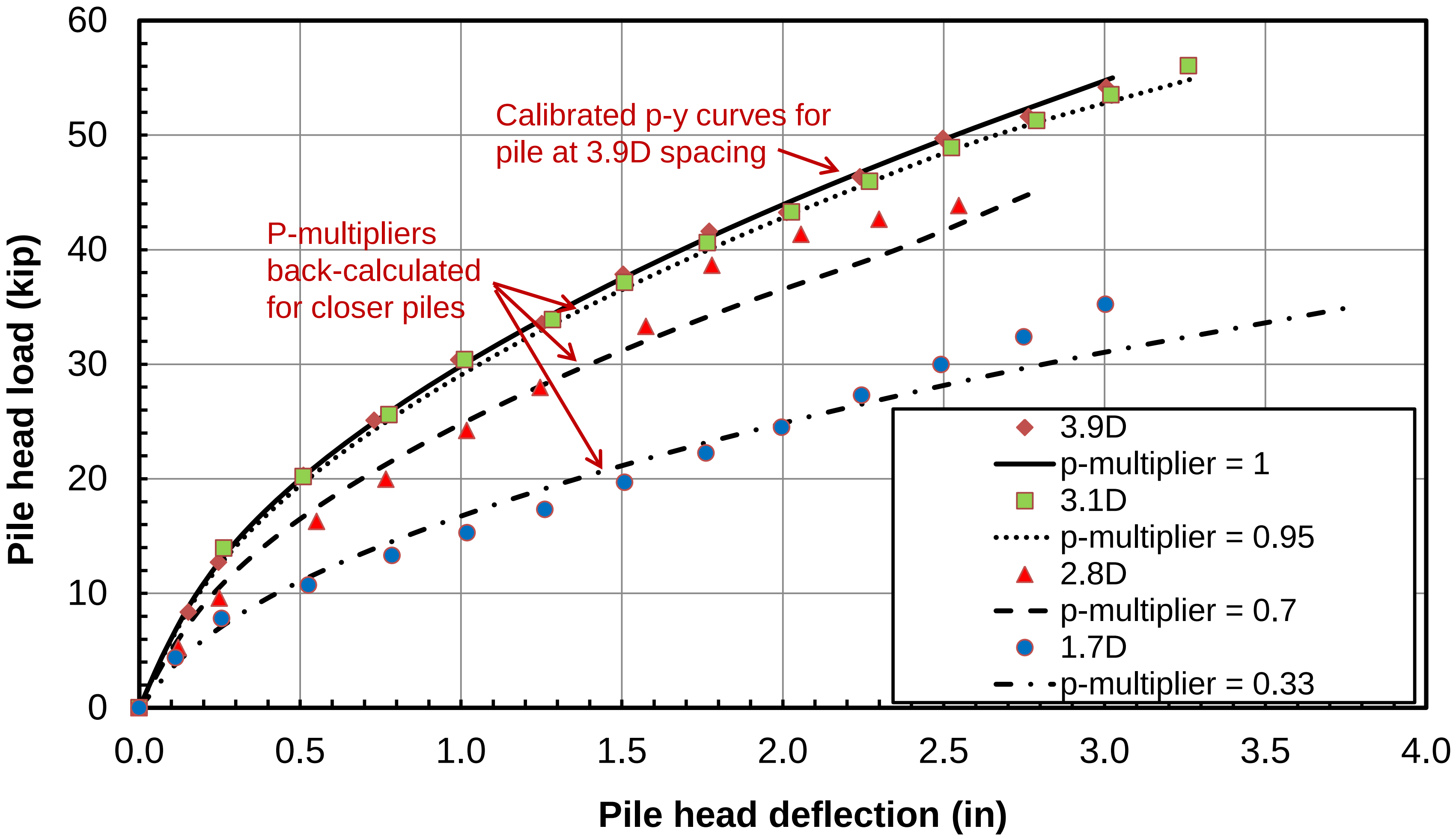
Square Piles with Welded-Wire Reinforcement



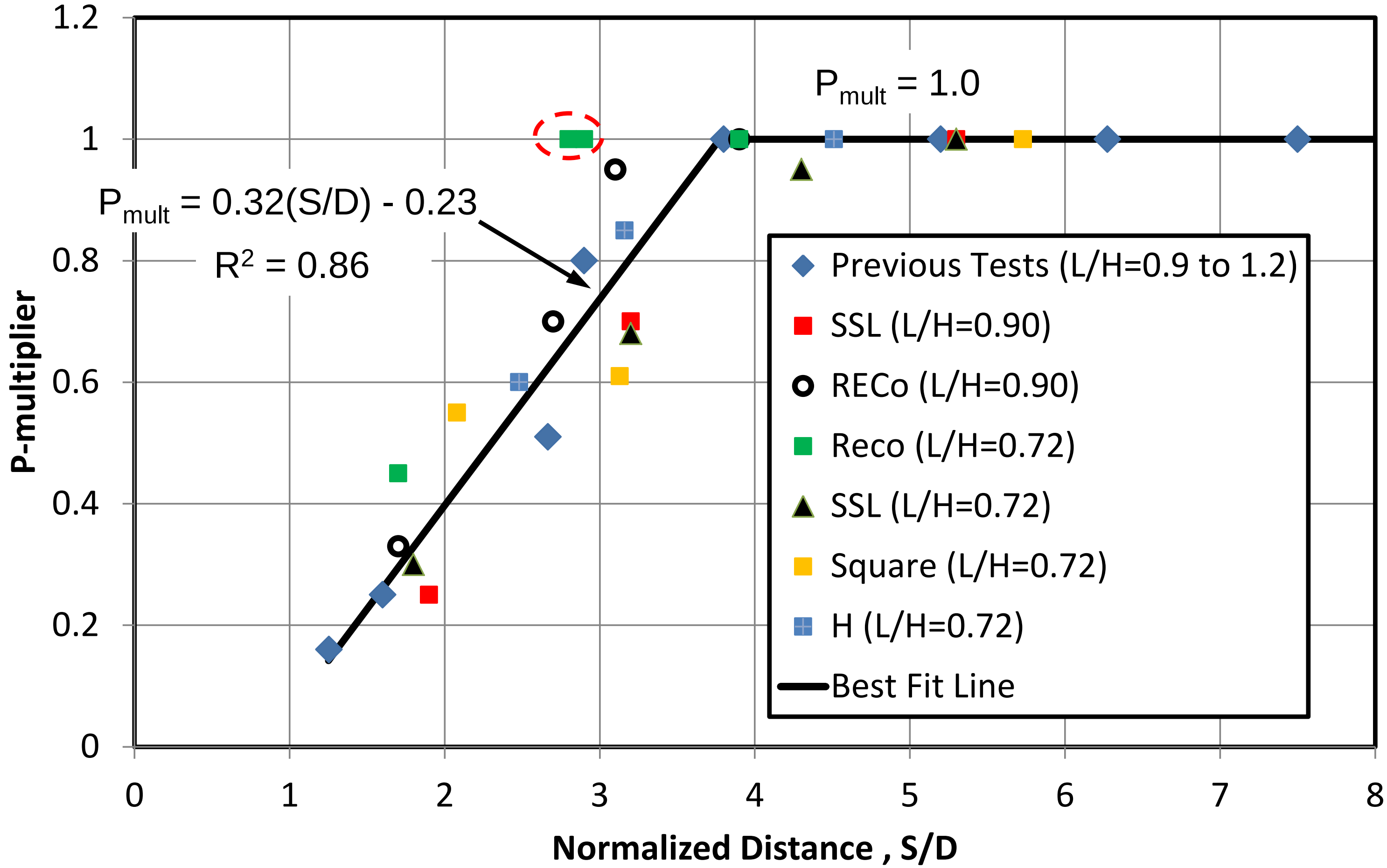
P-multiplier Concept For Proximity of the Wall



Measured and Computed Load-Deflection

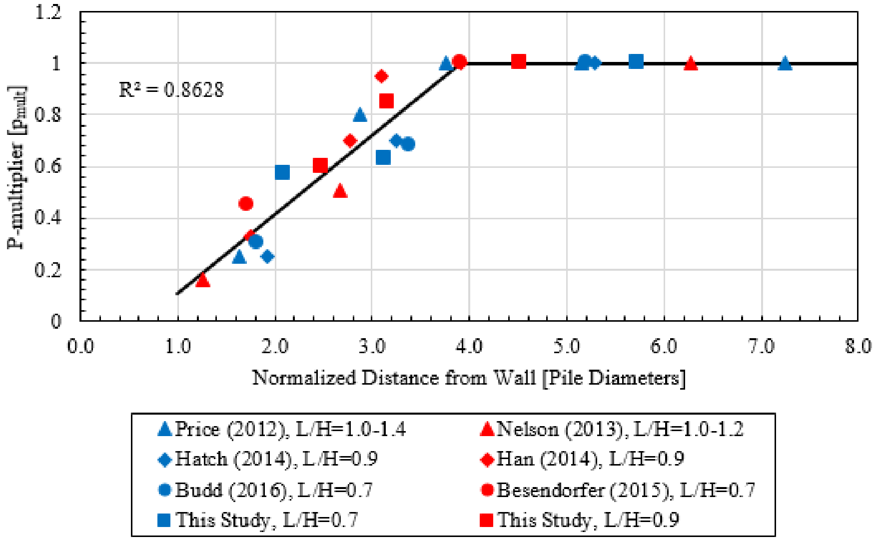


P-multipliers from All Tests



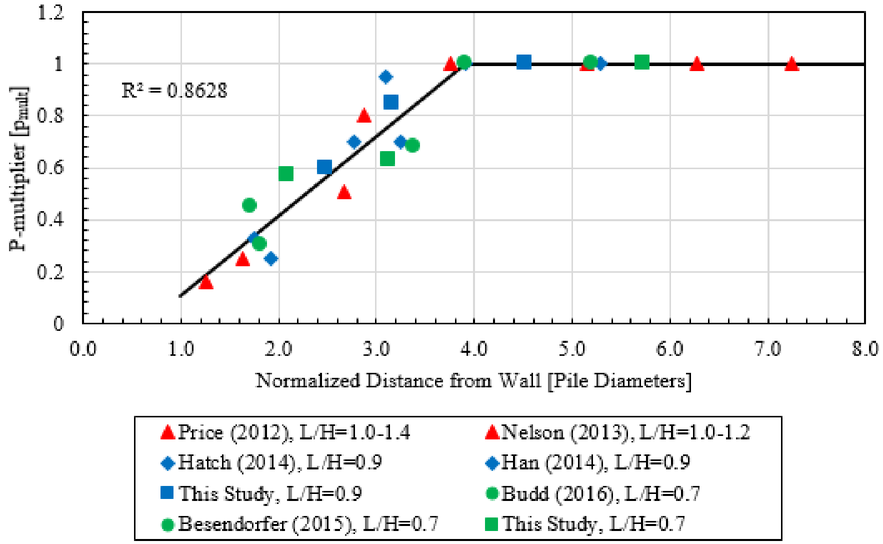
Effect of Variables on P-multiplier Equation

Not significantly affected by reinforcement type



RED = ribbed strips
BLUE = welded wire

Not significantly affected by L/H ratio



RED = L/H of 1.0+
BLUE = L/H of 0.9
GREEN = L/H of 0.7

Passive Force References

- Duncan, M.J. and Mokwa, R.L. (2001). "Passive earth pressure: theories and tests," J. Geotech. & Geoenv. Engrg. ASCE, 127(3), 248-257.
- Cole, R.T and Rollins, K.M. (2006). "Passive Earth Pressure Mobilization During Cyclic Loading." J. Geotechnical and Geoenvironmental Engrg., Vol. 132, No. 9, 1154-1164.
- Rollins, K.M. and Cole, R.T. (2006). "Cyclic Lateral Load Behavior of a Pile Cap and Backfill." J. Geotechnical and Geoenvironmental Engrg., ASCE, Vol. 132, No. 9, 1143-1153.
- Rollins, K.M. and Sparks, A.E. (2002) "Lateral Load Capacity of a Full-Scale Fixed-Head Pile Group." J. Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 128, No. 9, p. 711-723.
- Rollins, K.M., Sparks, A.E., Peterson, K.T. (2000) "Lateral Load Capacity and Passive Resistance of a Full-Scale Pile Group and Cap." Transportation Research Record 1736, Transportation Research Board, p. 24-32
- Rollins, K. M. and Jessee, S. (2013). "Passive Force-Deflection Curves for Skewed Abutments". Journal of Bridge Engineering, ASCE, Vol. 18, No. 10, p. 1086-1094
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Questions?

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