Insights on Seismic Soil-Structure Interaction for Bridges from Large-Scale Field Tests

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KU Geotechnical Conference
Nov. 7, 2024

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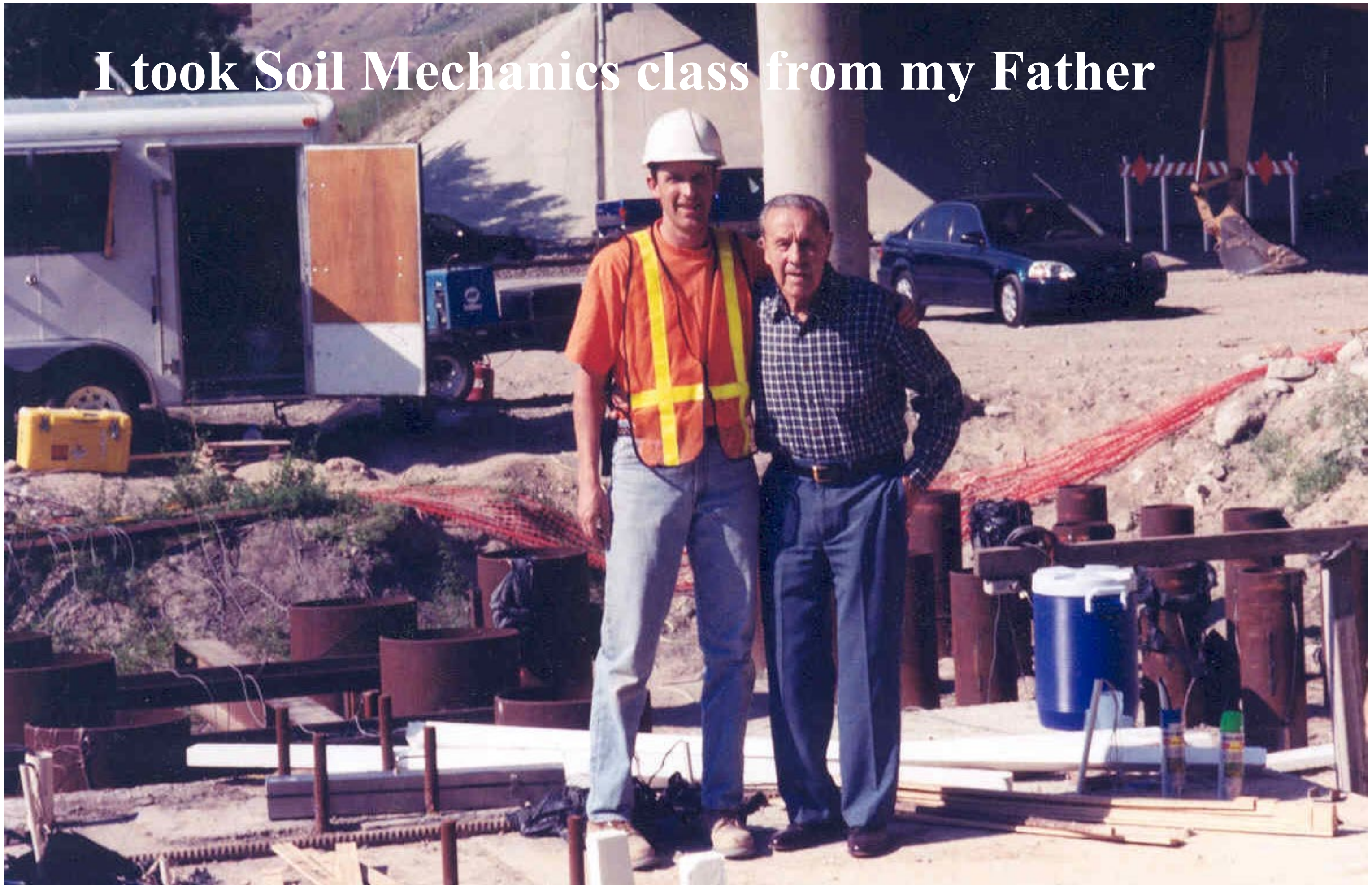
PROVO, UTAH

KU
THE UNIVERSITY OF
KANSAS

Ralph Rollins, performed geotechnical investigations for over 5000 structures



Rachel Rollins was a Civil Engineering student

Granddaughter, Ella, shows early interest in soil behavior…

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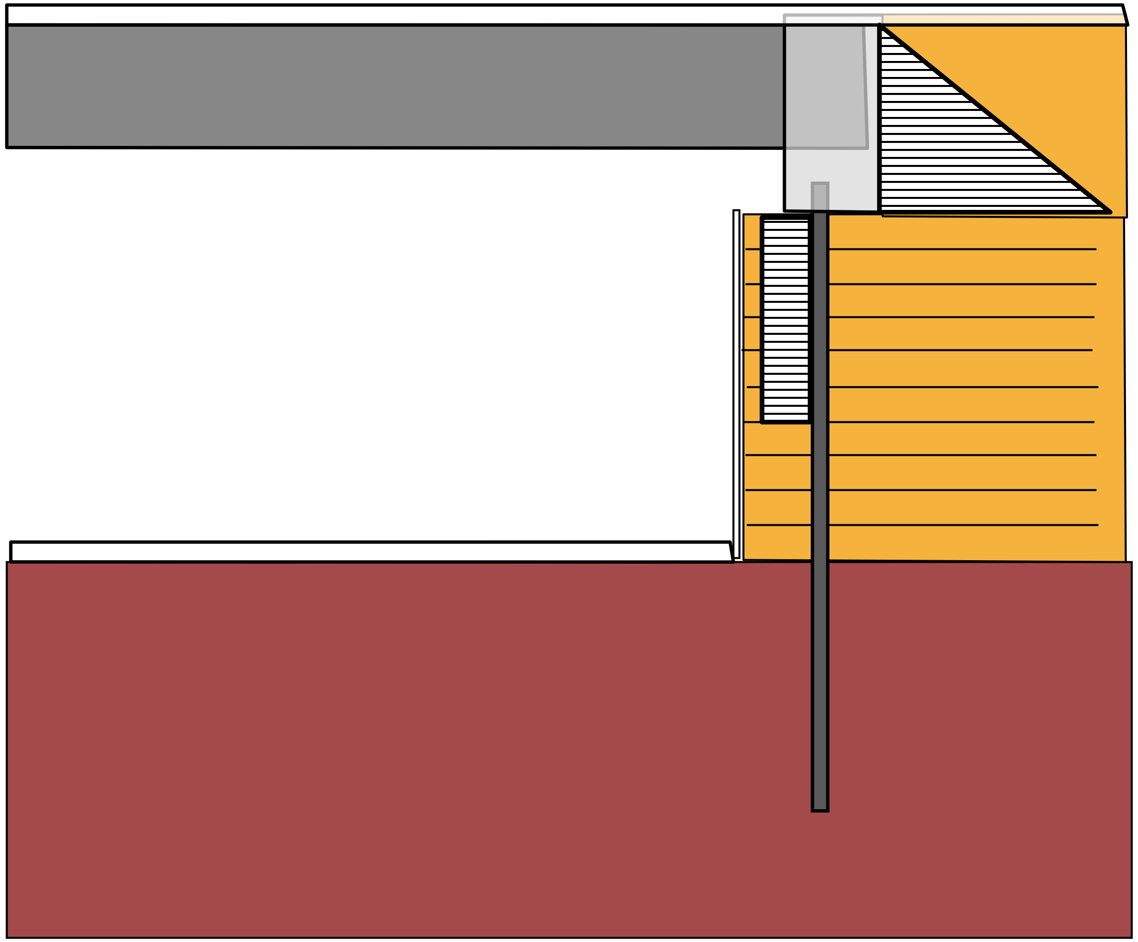
H. Bolton Seed

First, get the facts, to understand the basic mechanisms involved

Second, perform a series of tests or analyses to flesh out the details involved and how the parameters are related.

Third, package the results so that they can be easily understood and used by engineers

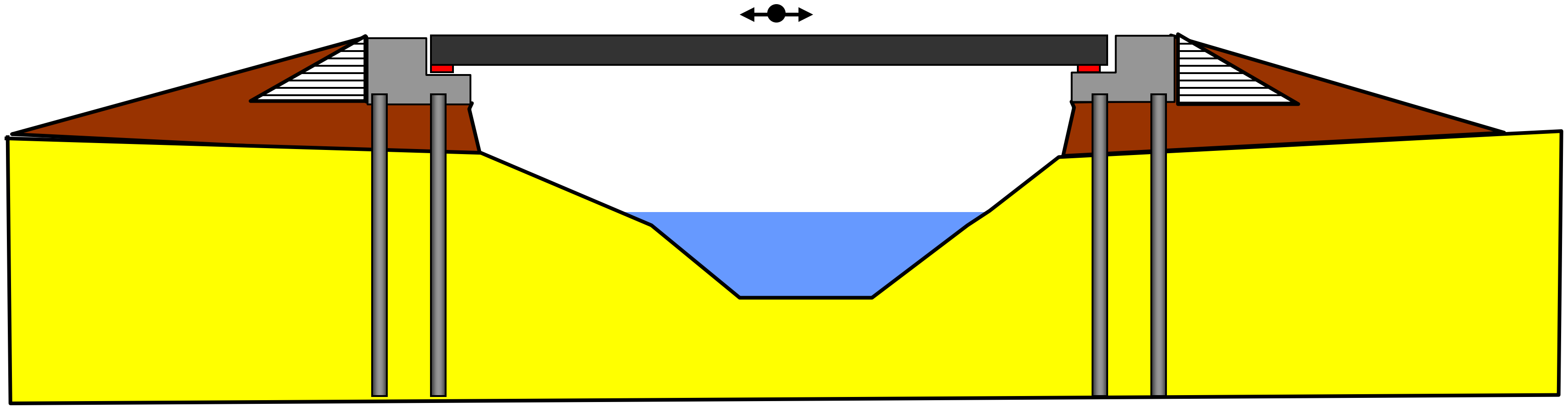
Lateral Resistance of Bridge Abutments and Piles



Passive Force-Deflection Curves for the Abutment

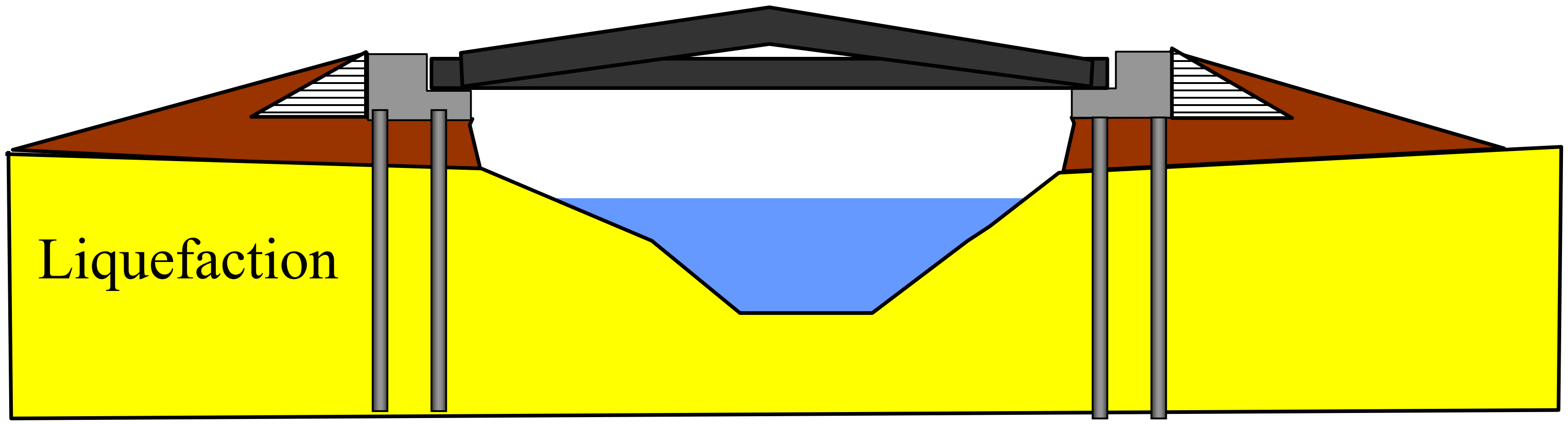
Force-Deflection Curves for Piles near MSE Walls

Passive Force on Bridge Abutments



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

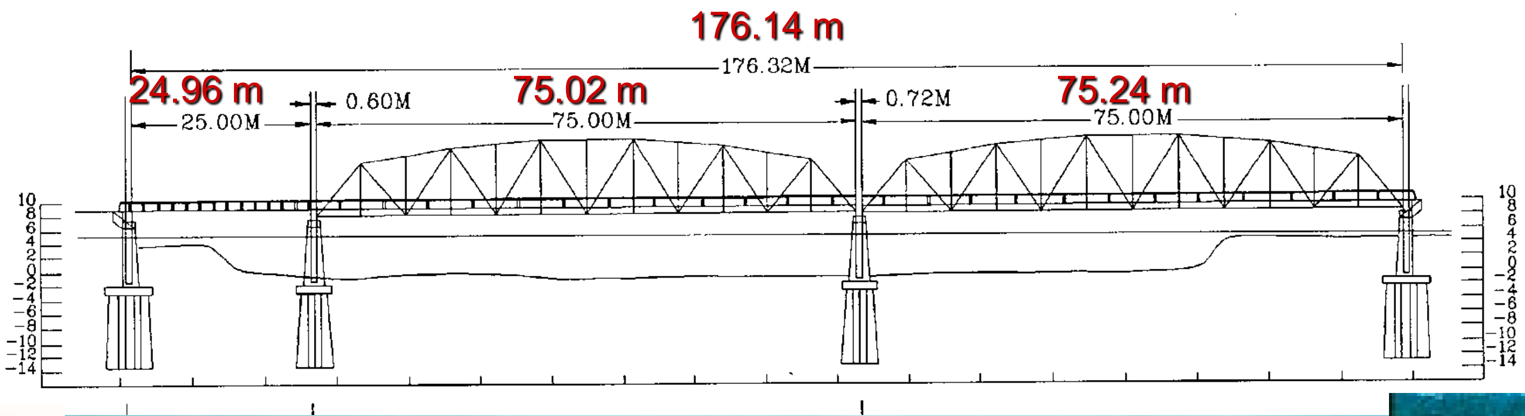
Passive Force During Lateral Spreading

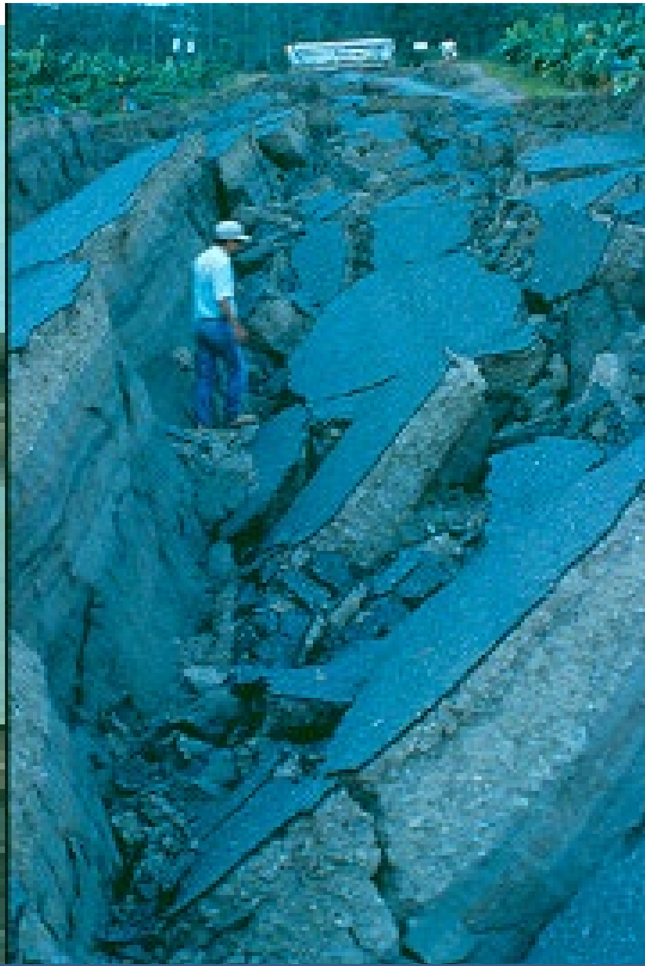


- Lateral Spread Displacement often Driven by Passive Force
- Lower K_p is not conservative; need realistic forces

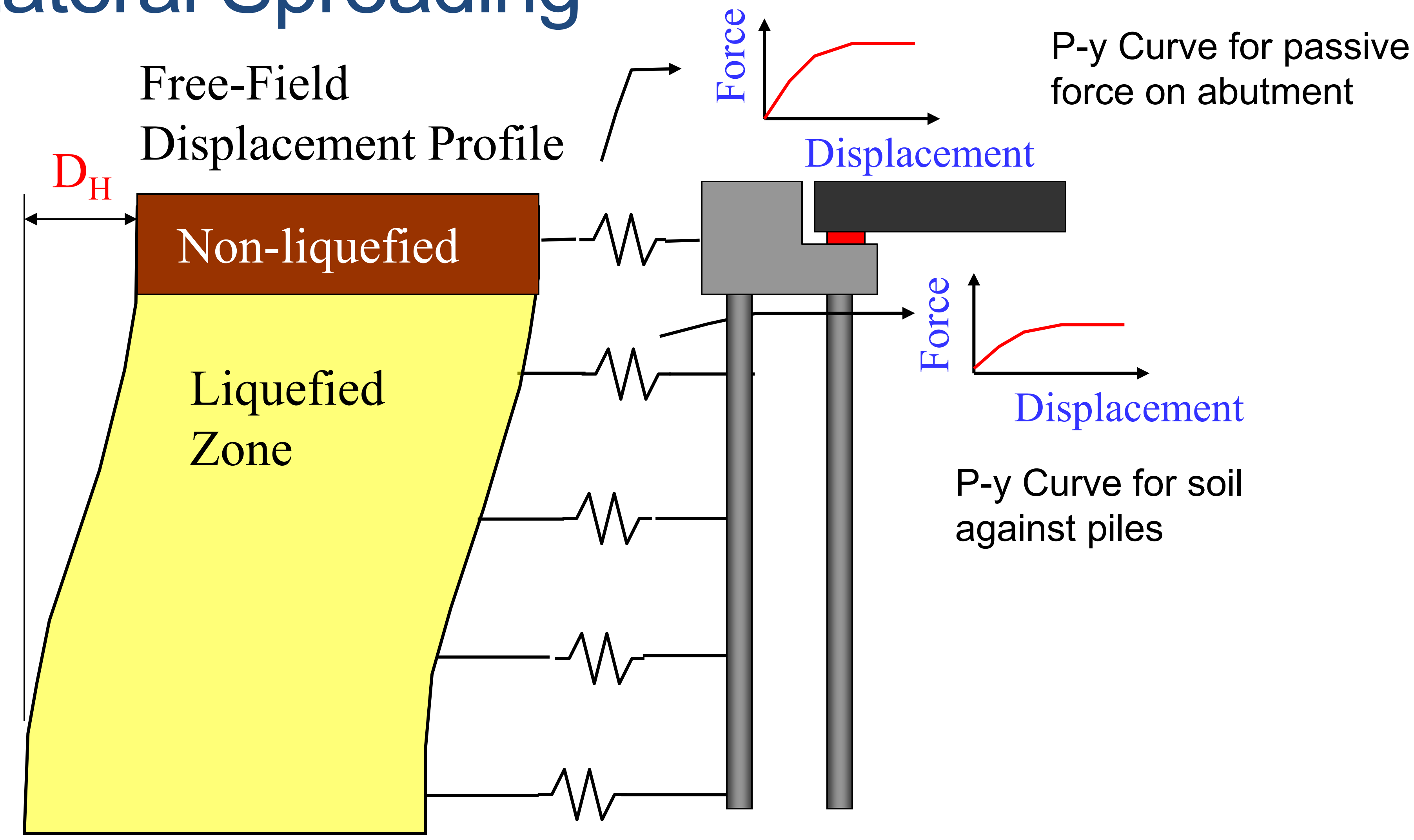
Buckled Railroad Bridge Caused by Lateral Spread During the 1964 Alaska Earthquake

Skewed bridge pushed off of supports due to lateral spread displacements in 1991 Costa Rica Earthquake


176.14 m
176.32M
24.96 m
0.60M
75.02 m
0.72M
75.24 m
25.00M
75.00M
75.00M



Modeling Lateral Spreading



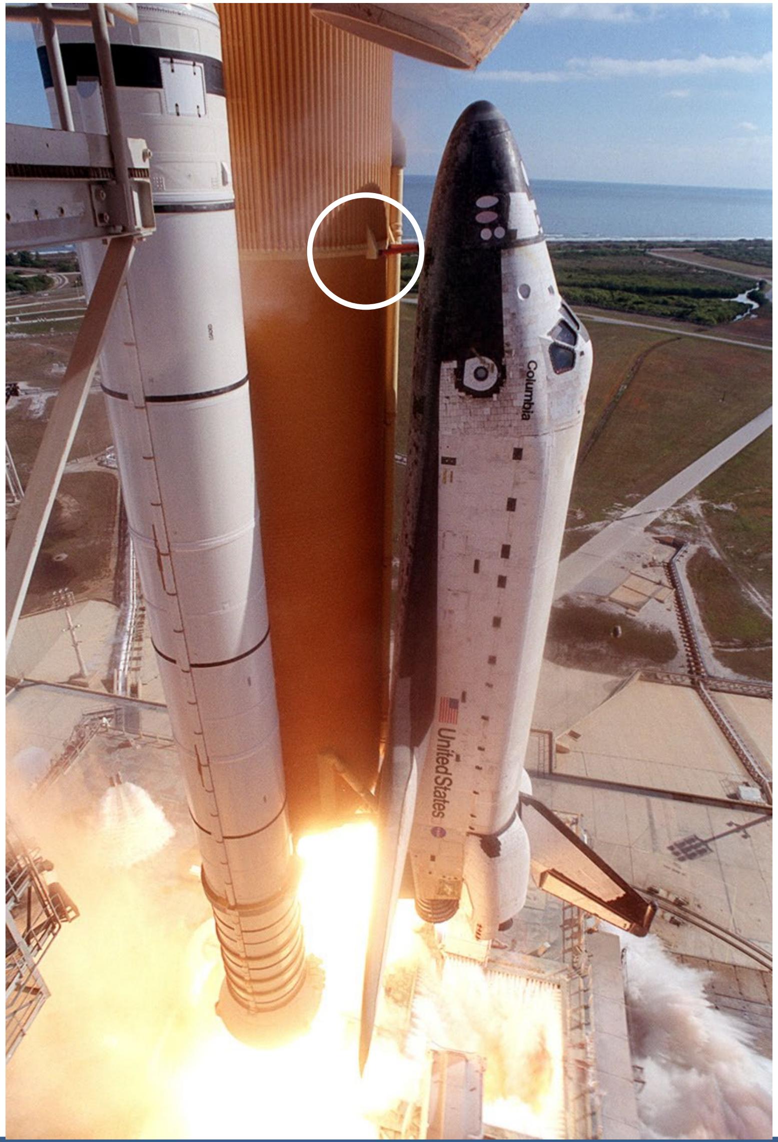
D_H from Youd et al (2002)

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

Werner Von Braun

Designer of Saturn V Moon Rocket

Space Shuttle Columbia Disaster



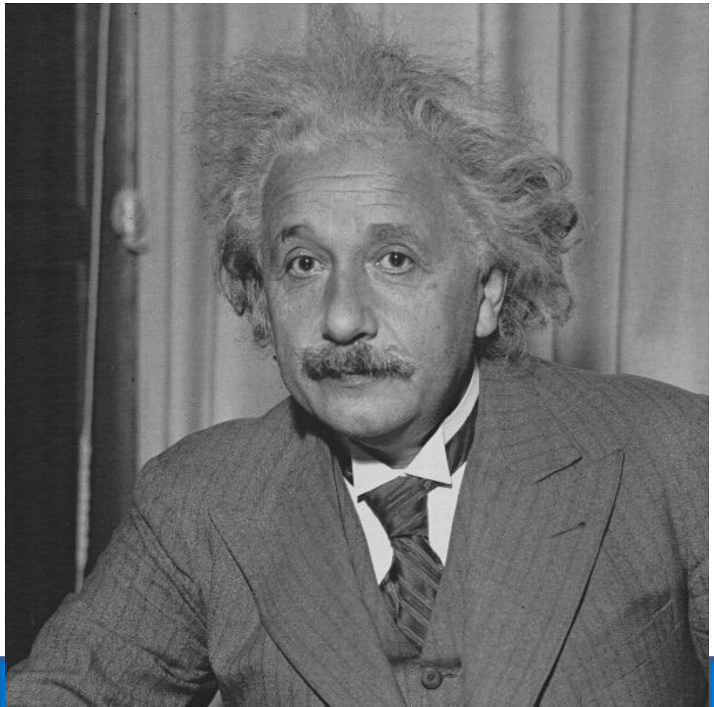
Numerical analyses based on impact of small ice particles imply styrofoam impact would not be a problem.

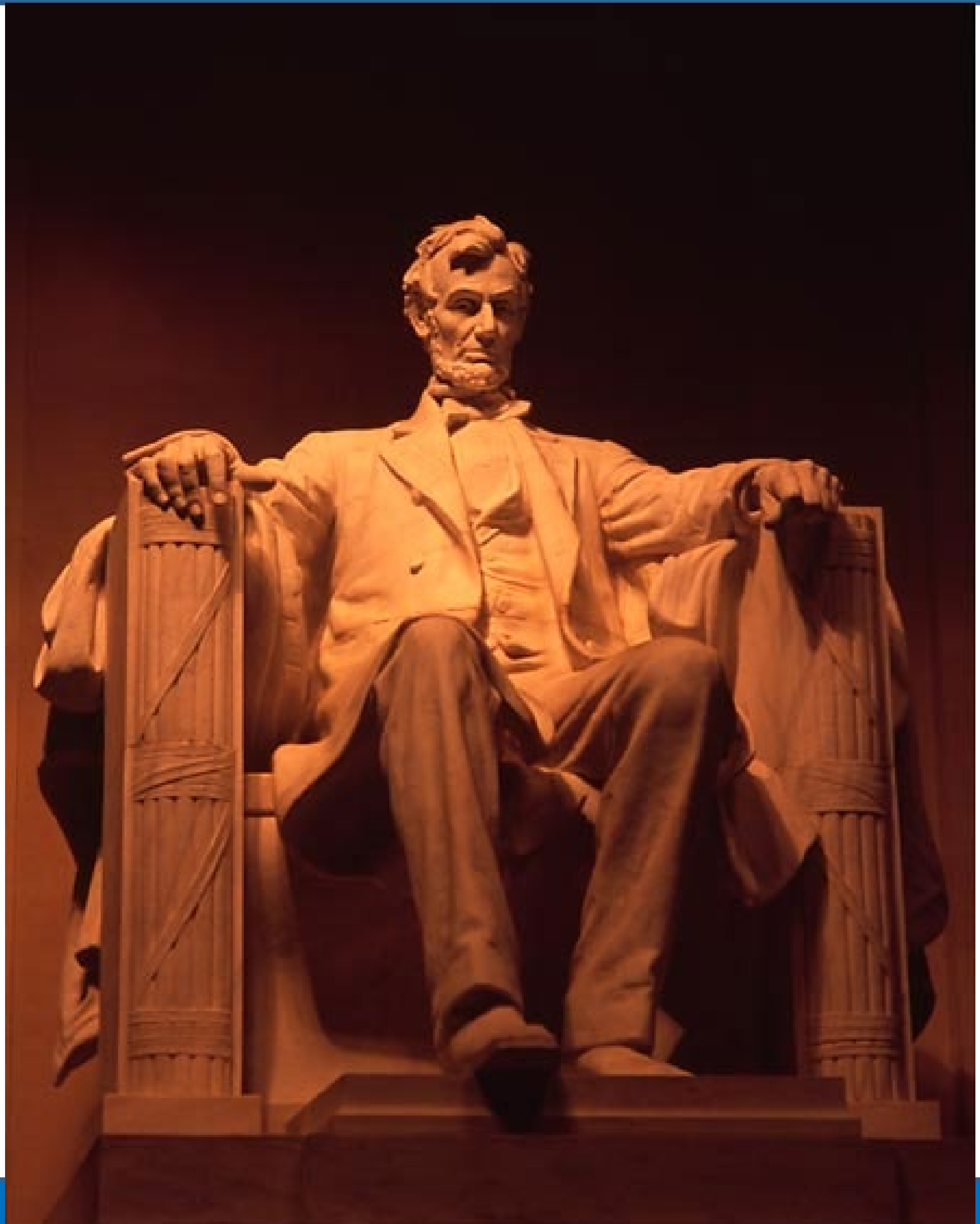
Full-scale test shows a problem

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





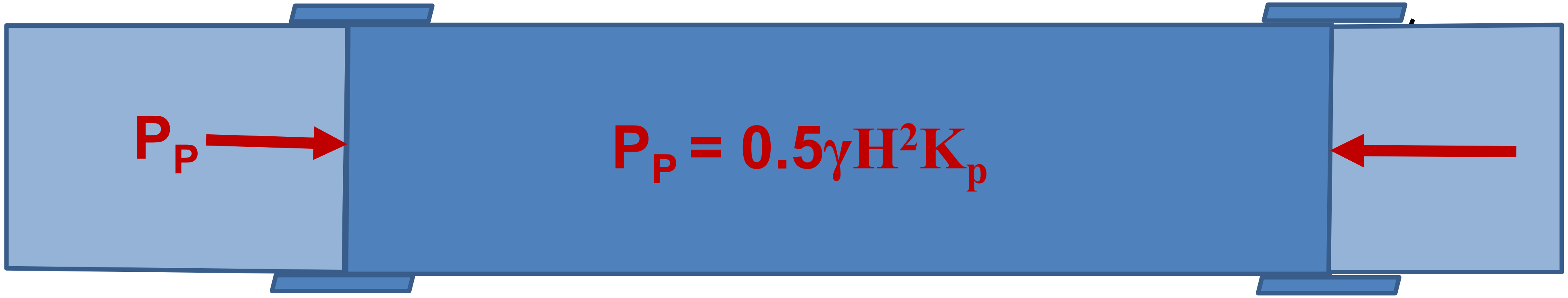
“The trouble with quotes on the internet is that it’s difficult to discern whether or not they are genuine.”

– Abraham Lincoln

Passive Force-Deflection from Large-Scale Testing

Background

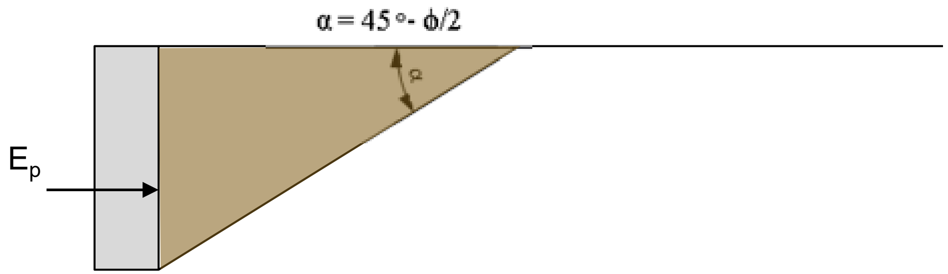
- Passive Pressure for non-skewed abutments (Maroney (1995), Duncan and Mokwa (2001), Rollins and Sparks (2002), Rollins and Cole (2006), Lemnitzer et al (2009)



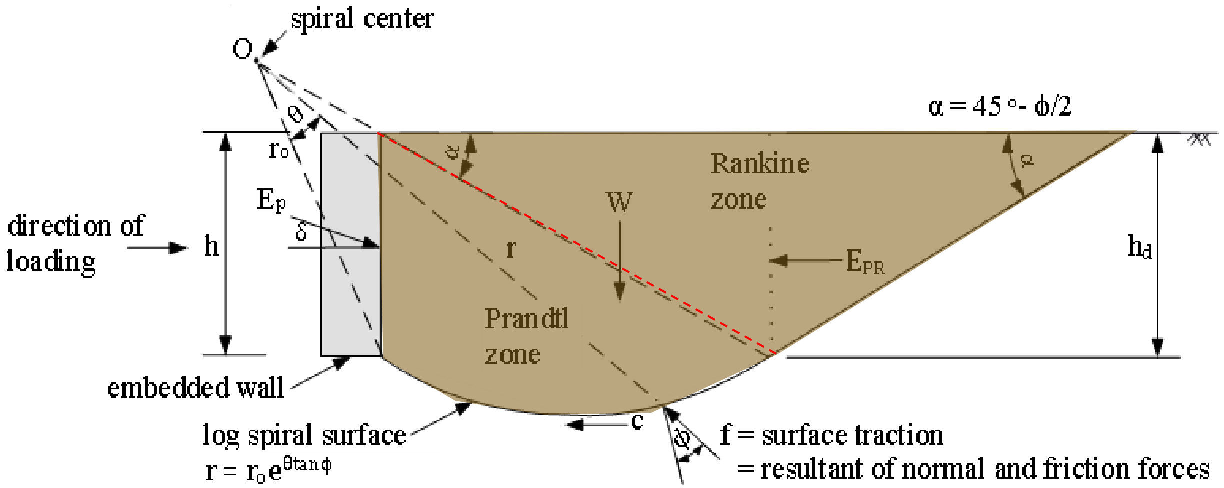
- Passive force best estimated using log-spiral method
- Peak passive force mobilized at displacement of 0.03H to 0.05H
- Hyperbolic curve best represents passive force-displacement curve

Comparison of Failure Geometries

Rankine Failure Geometry

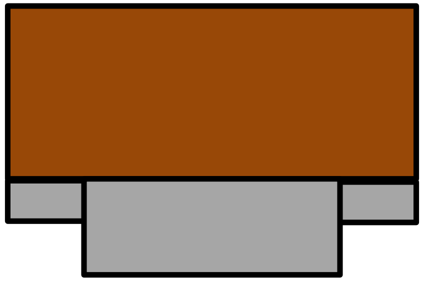


Log-Spiral Failure Geometry

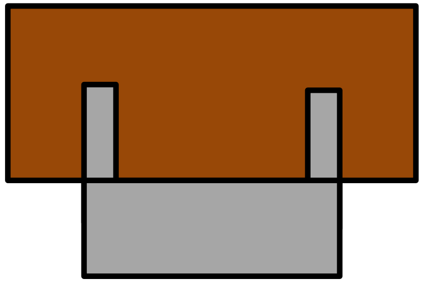


Testing Program

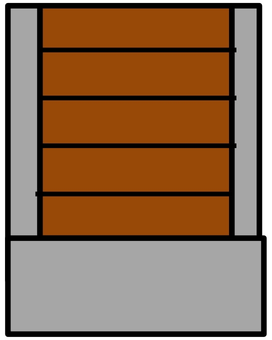
- Variations in Wingwall Geometry



Transverse Wingwalls



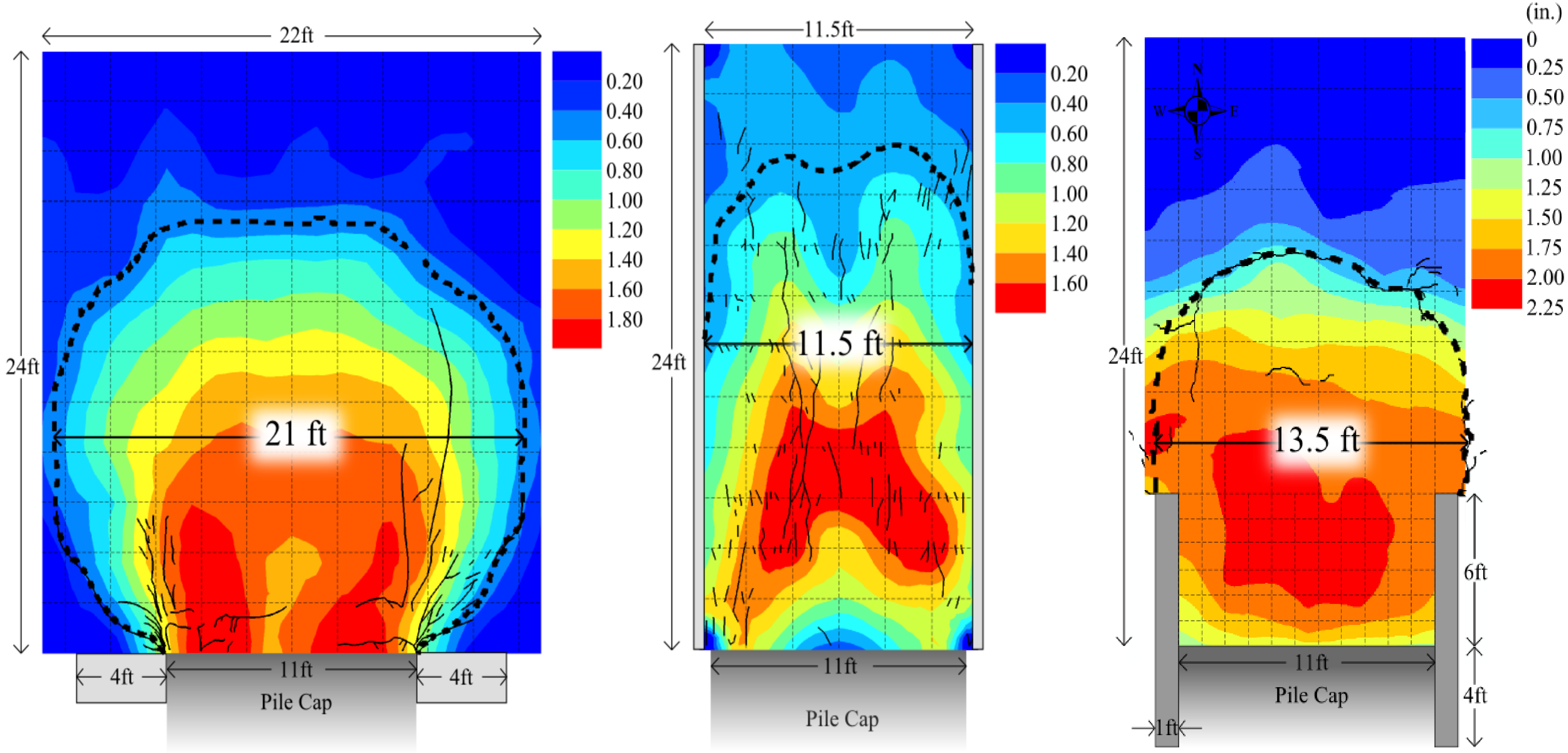
Parallel Wingwalls



MSE Wingwalls

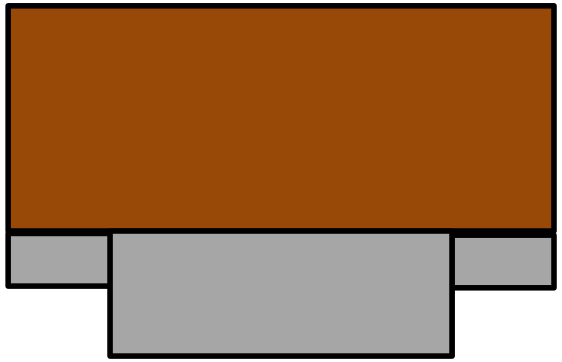
- Variations in Backfill Materials
  - Sand
  - Gravel
  - Geosynthetically Reinforced Soil (GRS)
  - Lightweight Cellular Concrete (LCC)

Backfill Heave and Failure Surfaces

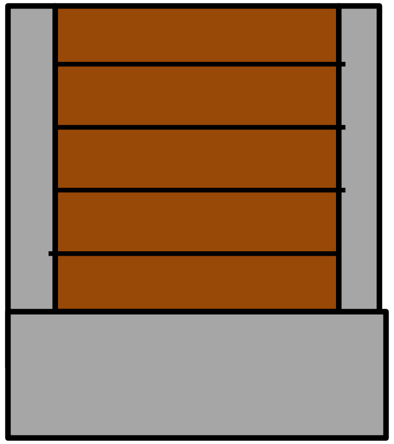


	Transverse Wingwalls	MSE Wingwalls	Parallel Wingwalls
P_p/width	23 kips/ft	38 kips/ft (65% Higher)	23 kips/ft
P_p	485 kips	448 kips	310 kips

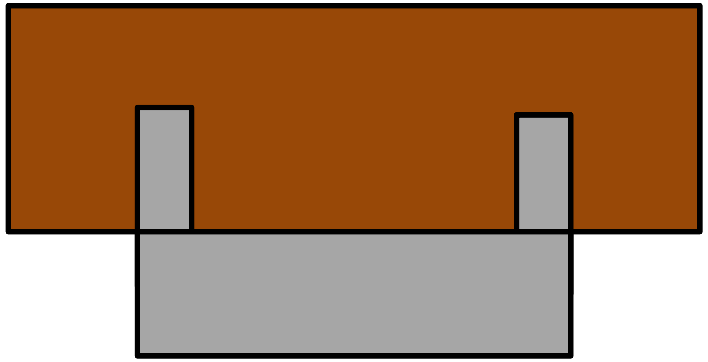
Variation in ϕ and K_p for Different Walls



Transverse Wingwalls



MSE Wingwalls



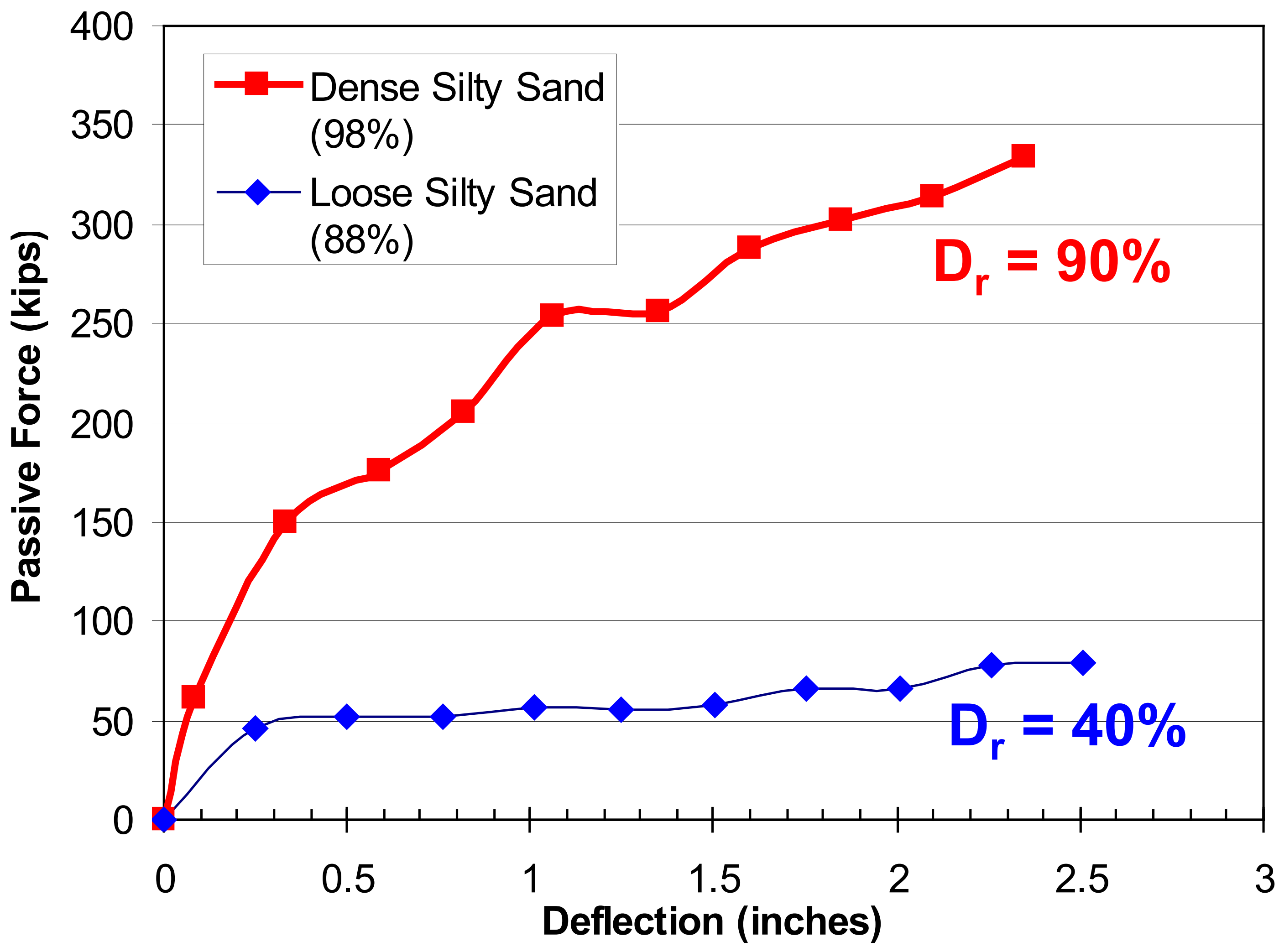
Parallel Wingwalls

	Transverse Wingwalls	MSE Wingwalls	Parallel Wingwalls
Friction Angle, ϕ	40°	45°	40°

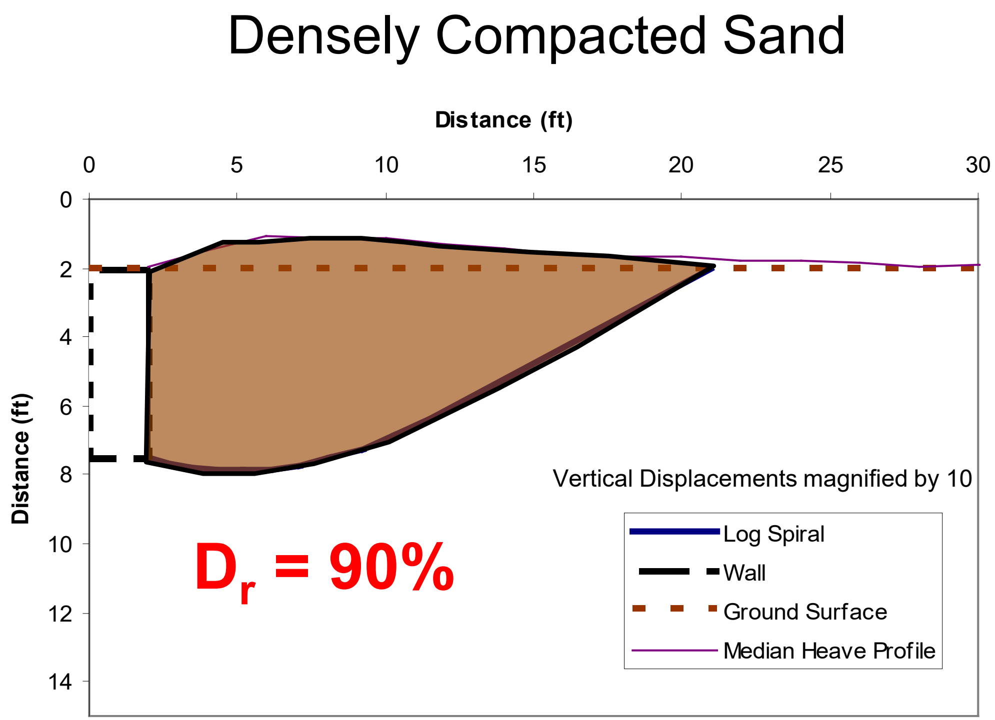
Plane Strain Friction Angle, $\phi_{PS} = 1.12\ \phi_{TRIAXIAL} = 1.12\ (40°) = 44.8°$

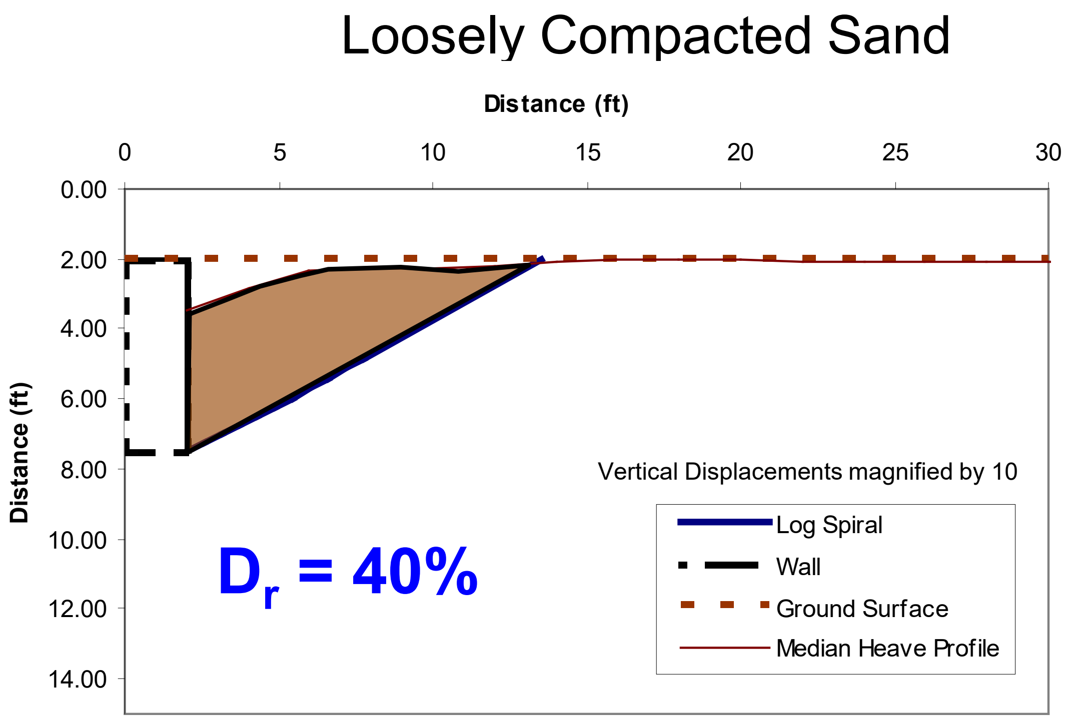
	Transverse Wingwalls	MSE Wingwalls	Parallel Wingwalls
K_p	12.9	21.8 (65%)	12.9

Influence of Relative Compaction



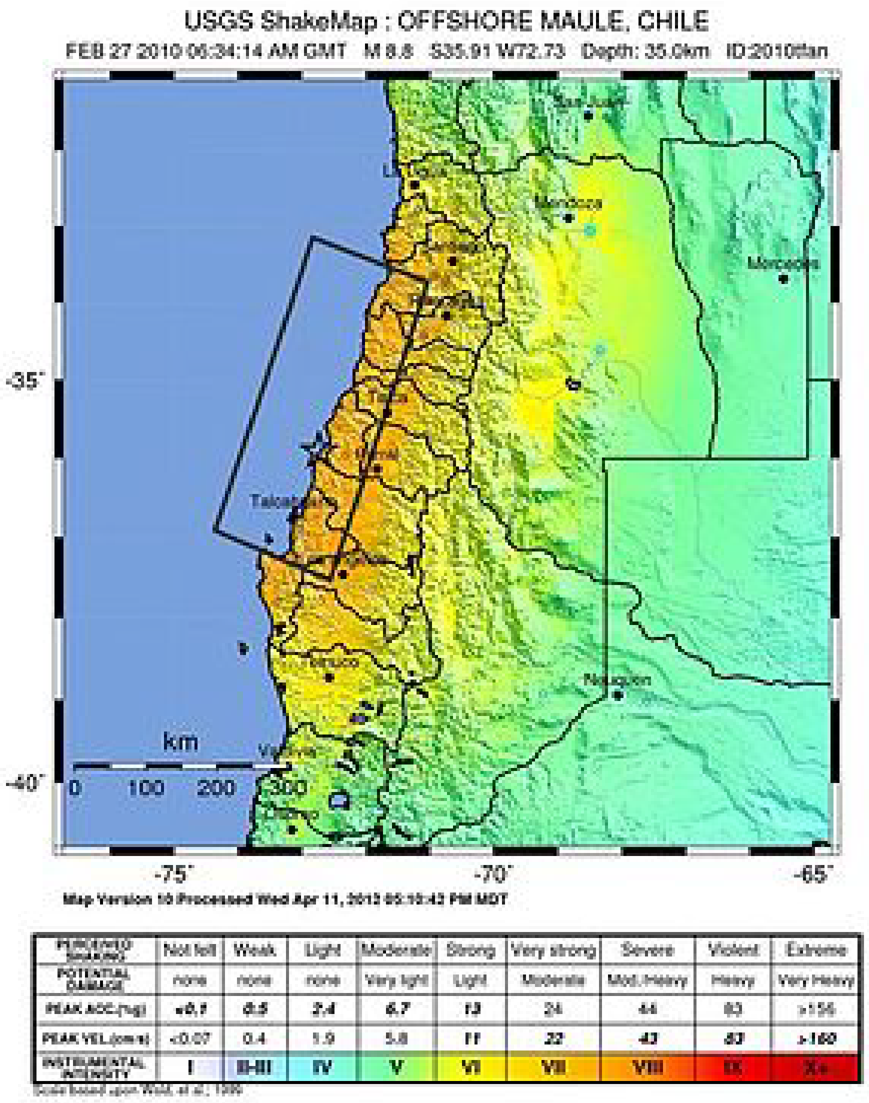
Failure Planes & Heave Profiles

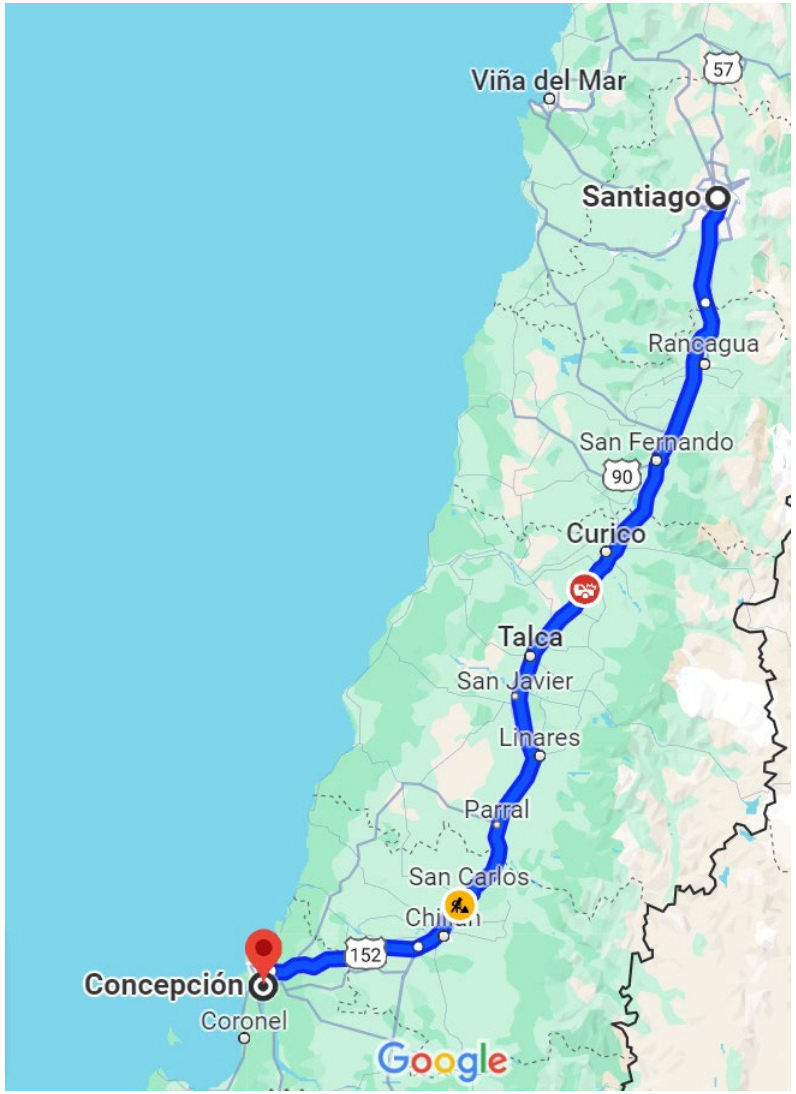




- Densely compacted backfill has log-spiral failure surface with heaving in the shear zone
- Loosely compacted backfill has planar (i.e., Rankine) failure surface with settlement in the shear zone

Damage to Bridges with Skewed Abutments-Chile





George Mylonakis

Domniki Asimaki

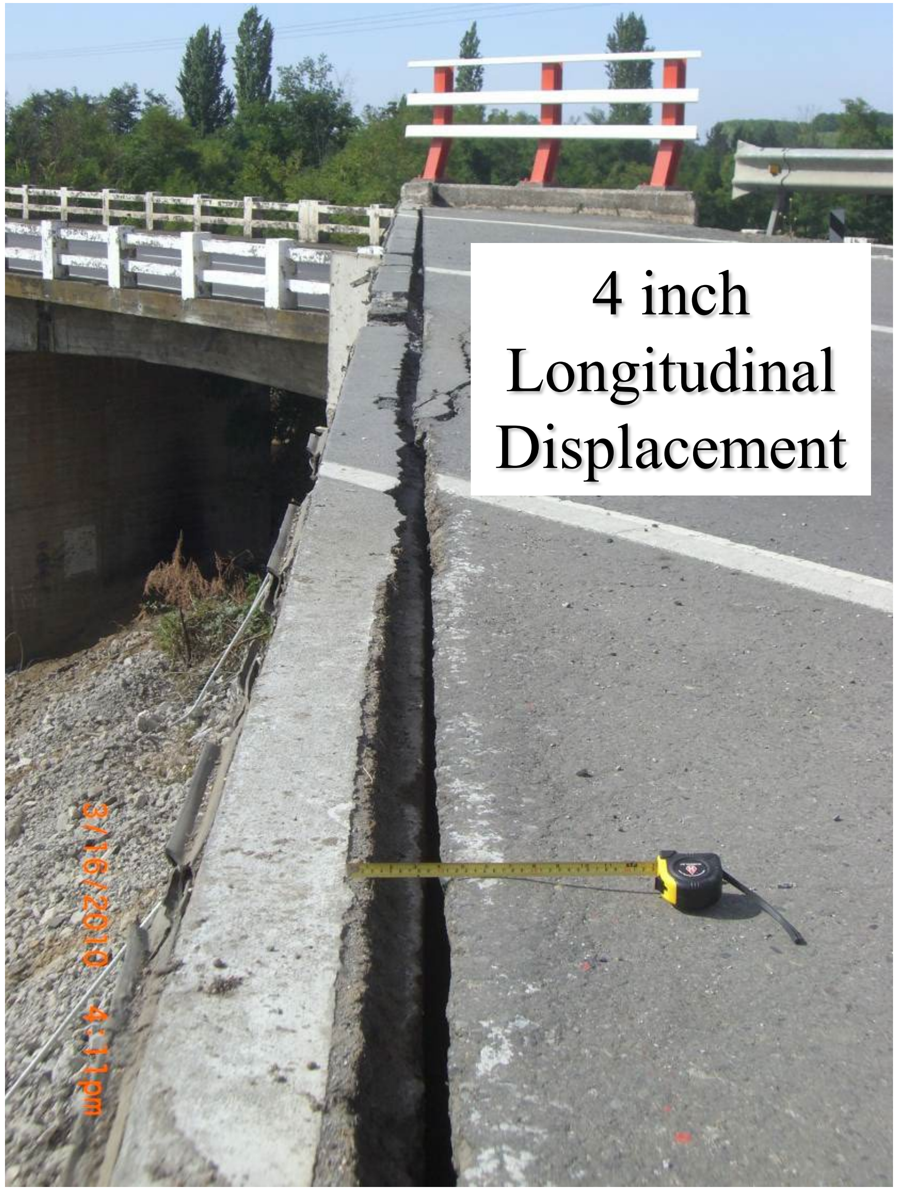
Kyle Rollinopoulos

Earthquake Damage to Skewed Bridges
(Paine, Chile)

Bridge deck was offset and was eventually demolished

Bridge remained in service after the earthquake

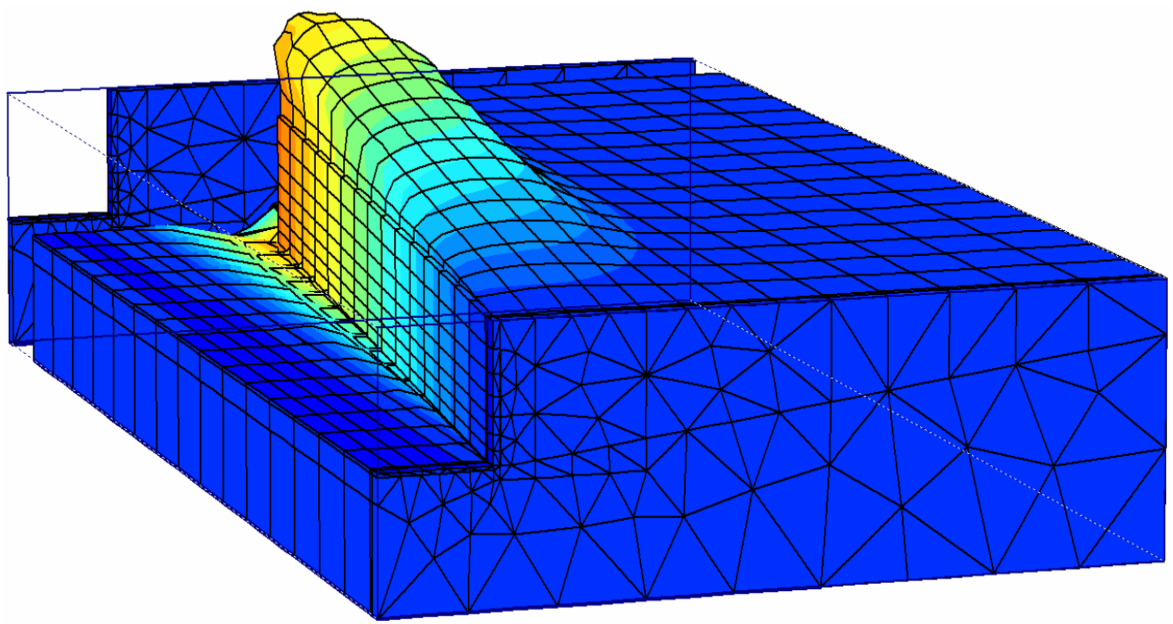
Permanent Abutment Offset at Skewed Bridge

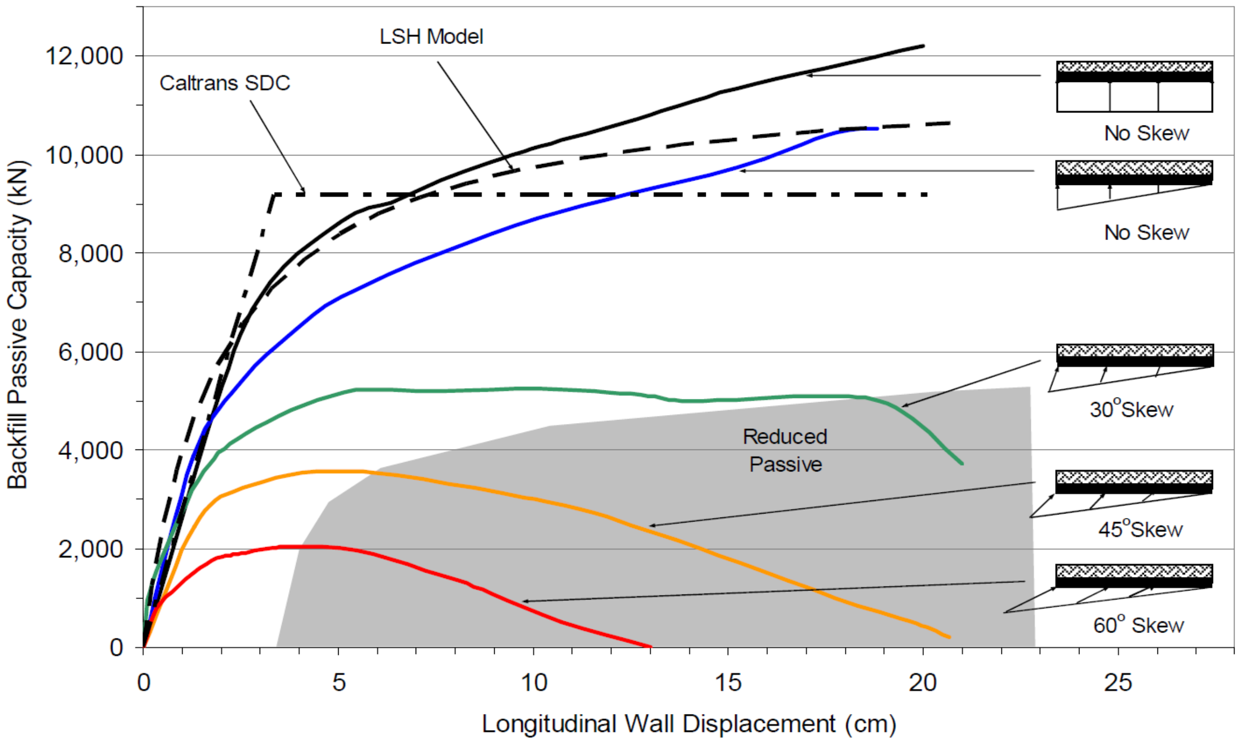


Settlement and Sliding of Approach Fills

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

Numerical Analysis of Skewed Abutments



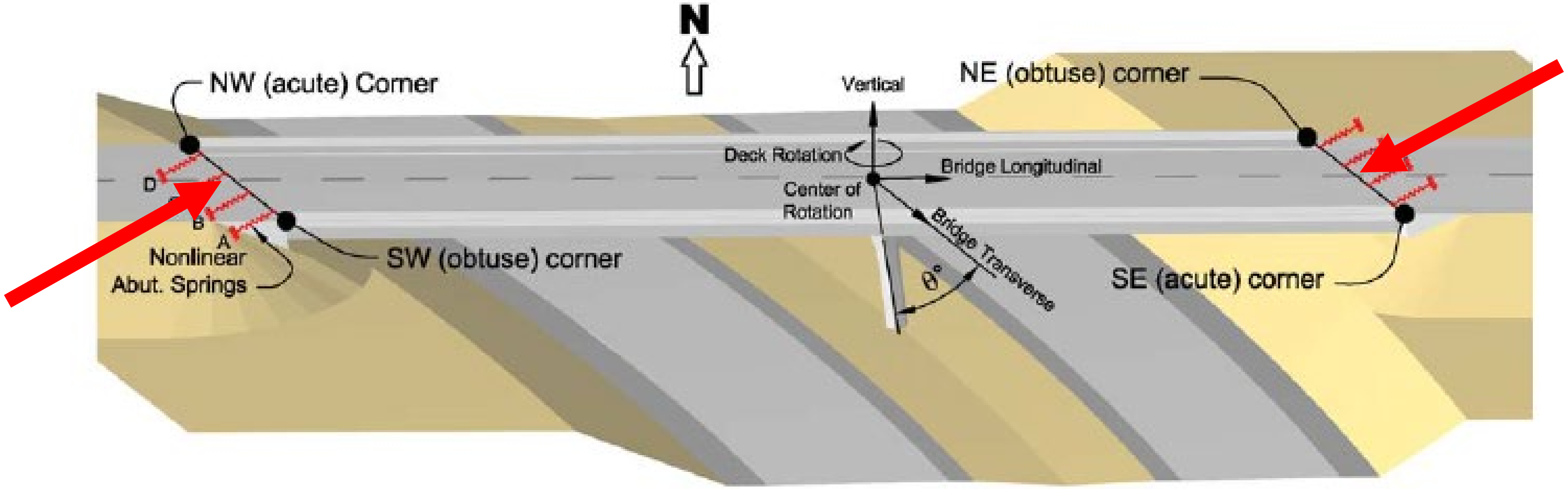


23 m (75 ft) wide abutment with 2.4 m (8 ft) high backwall

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

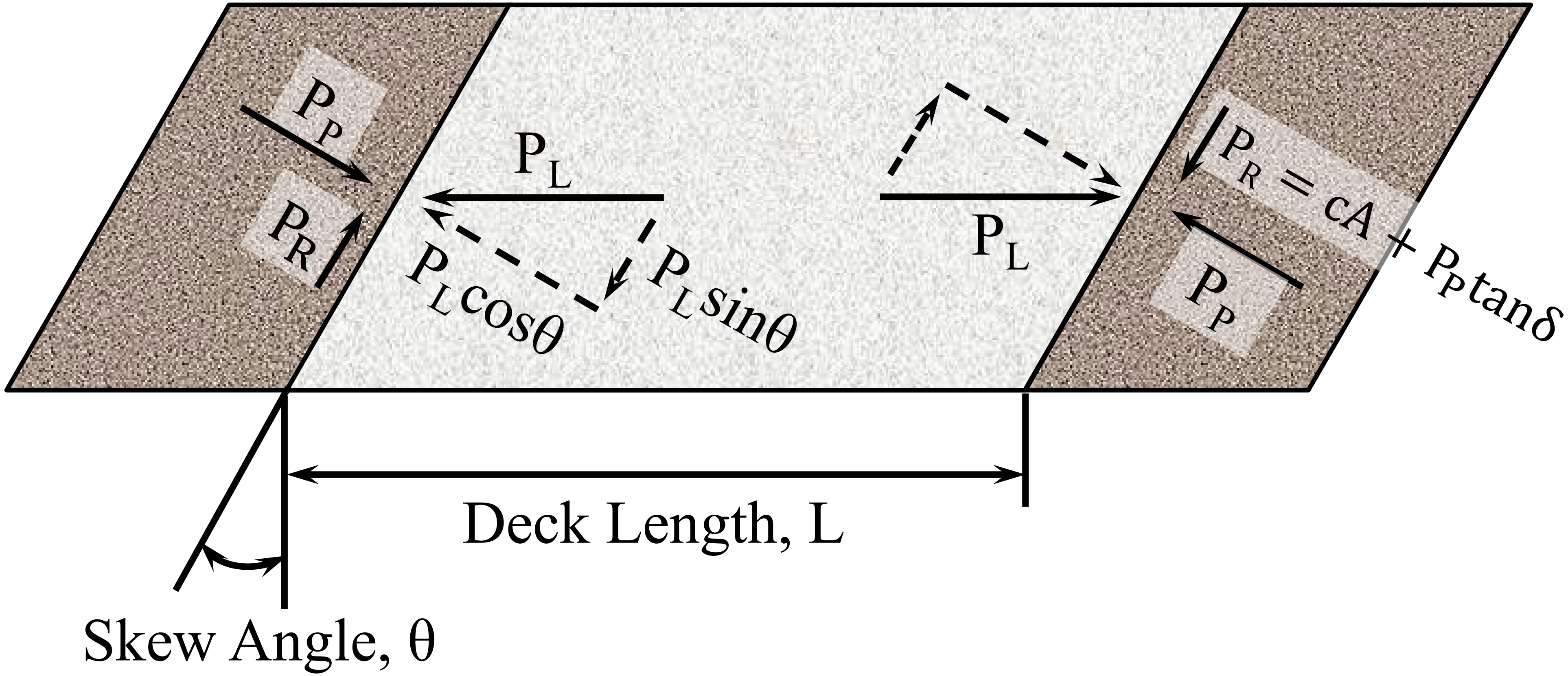
Skewed Bridge Abutment Overview

- ≈ 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



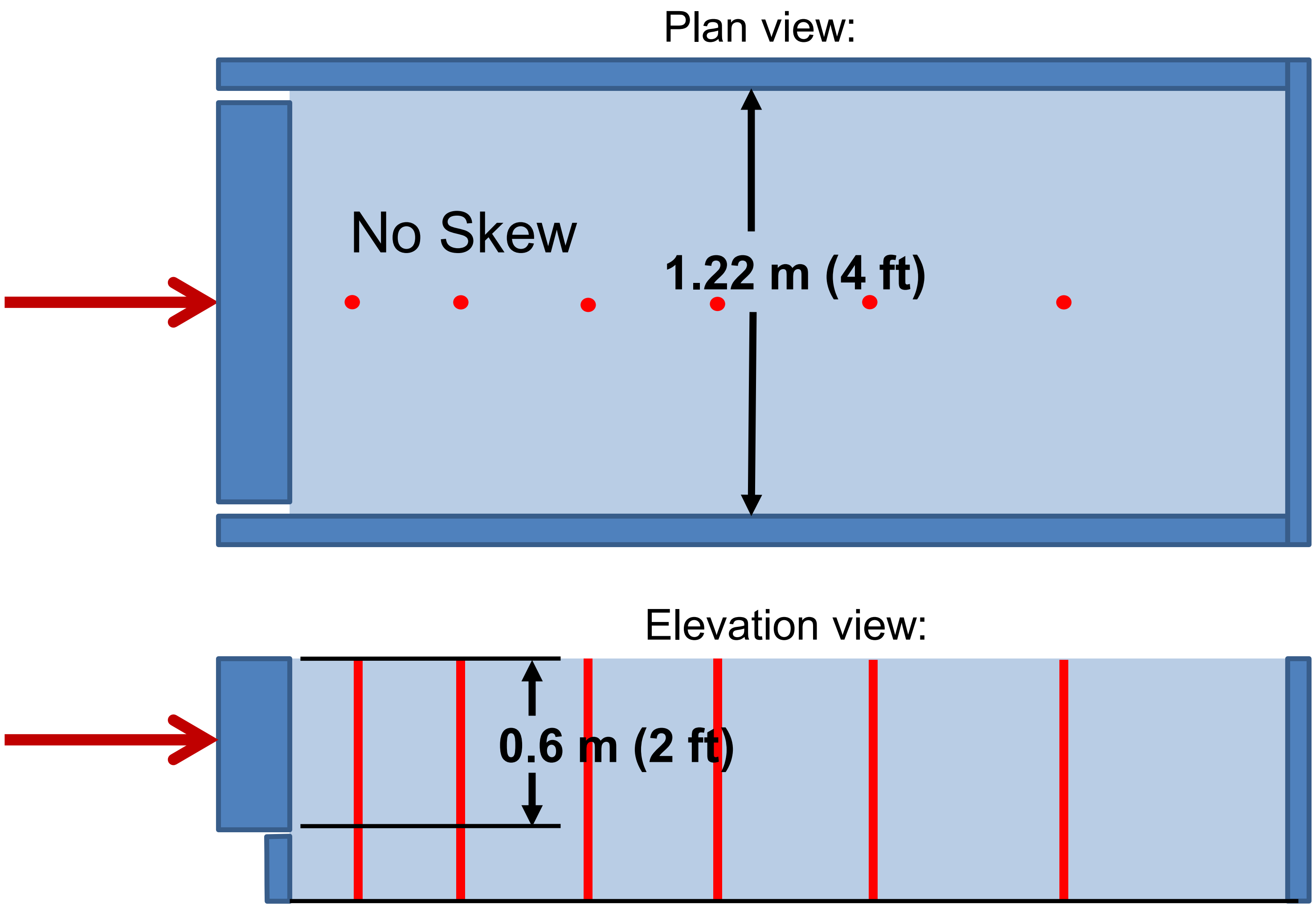
Shamsabadi et al. 2006

Interaction of Forces on Bridge Abutment



Initial Laboratory Testing

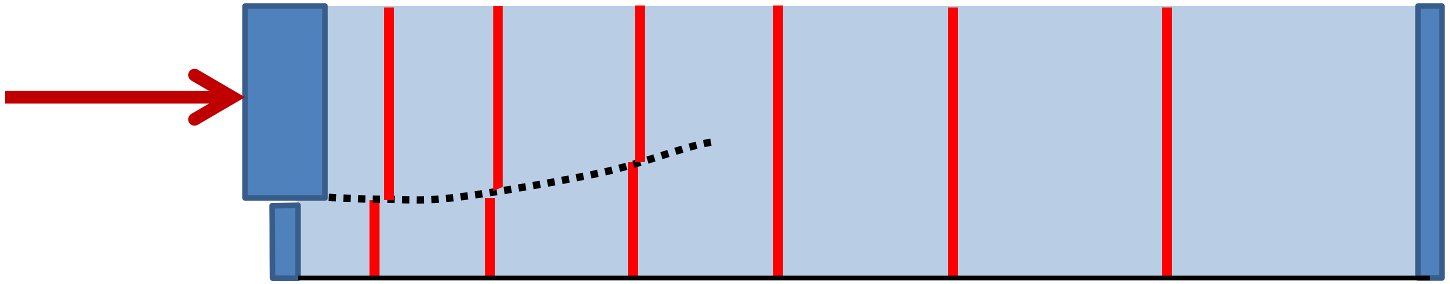
Test Layout



Test Procedure

Plan view:

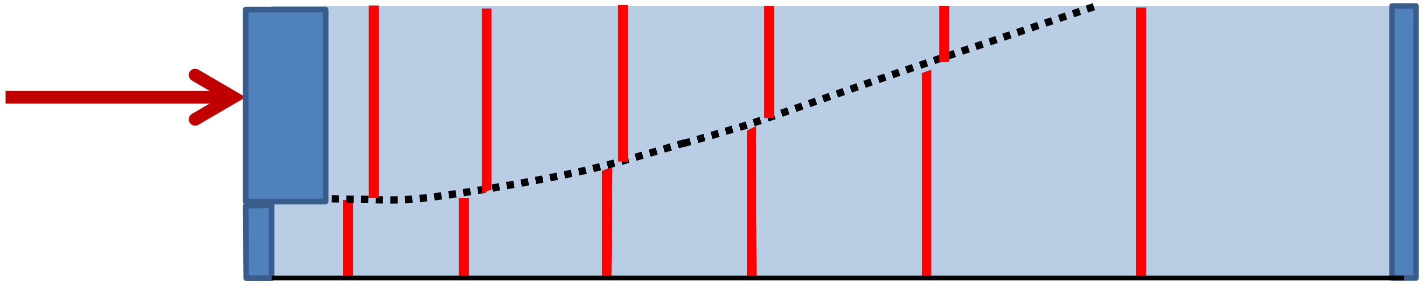
Elevation view:



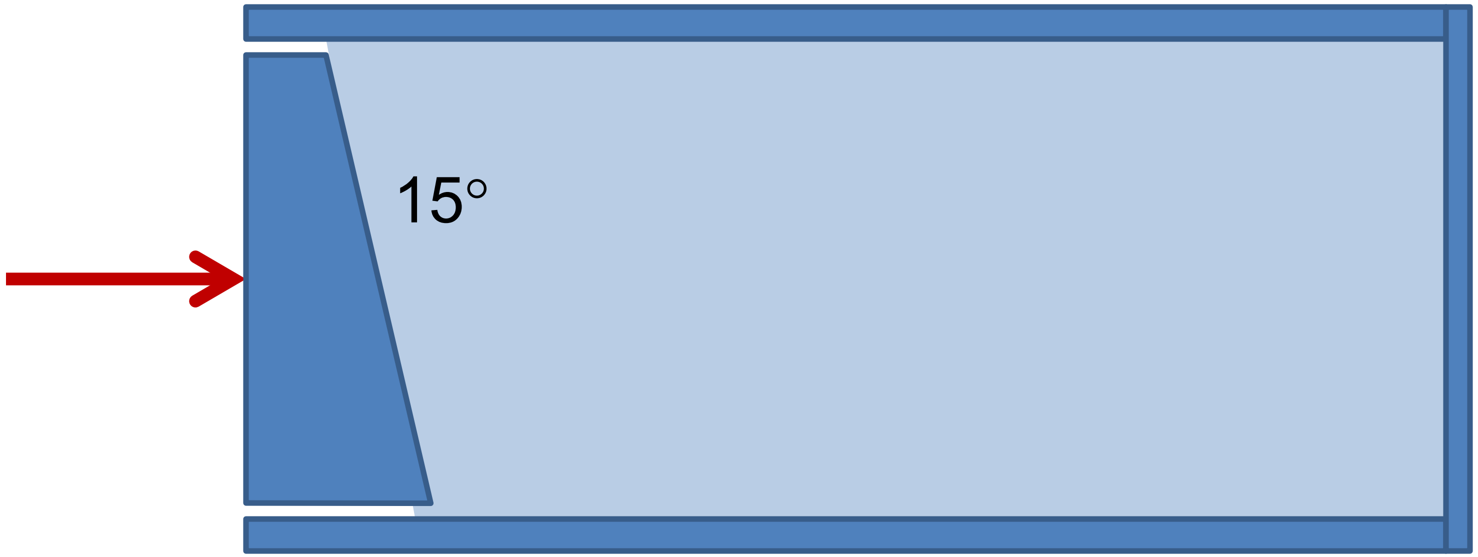
Test Procedure

Plan view:

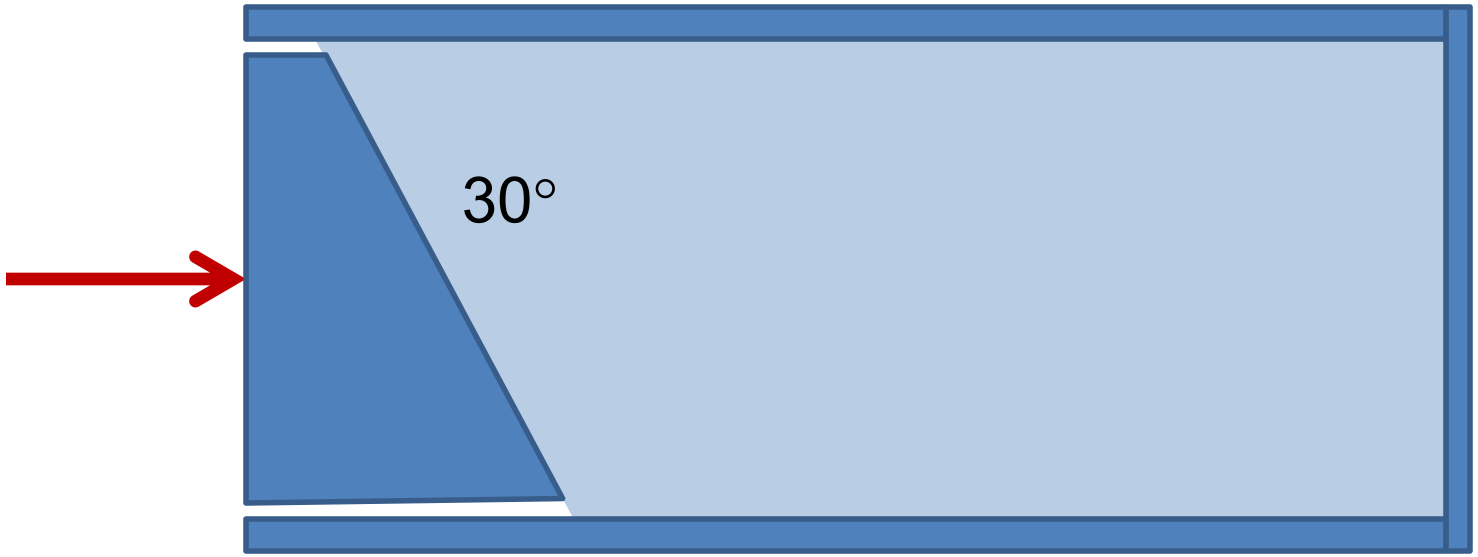
Elevation view:



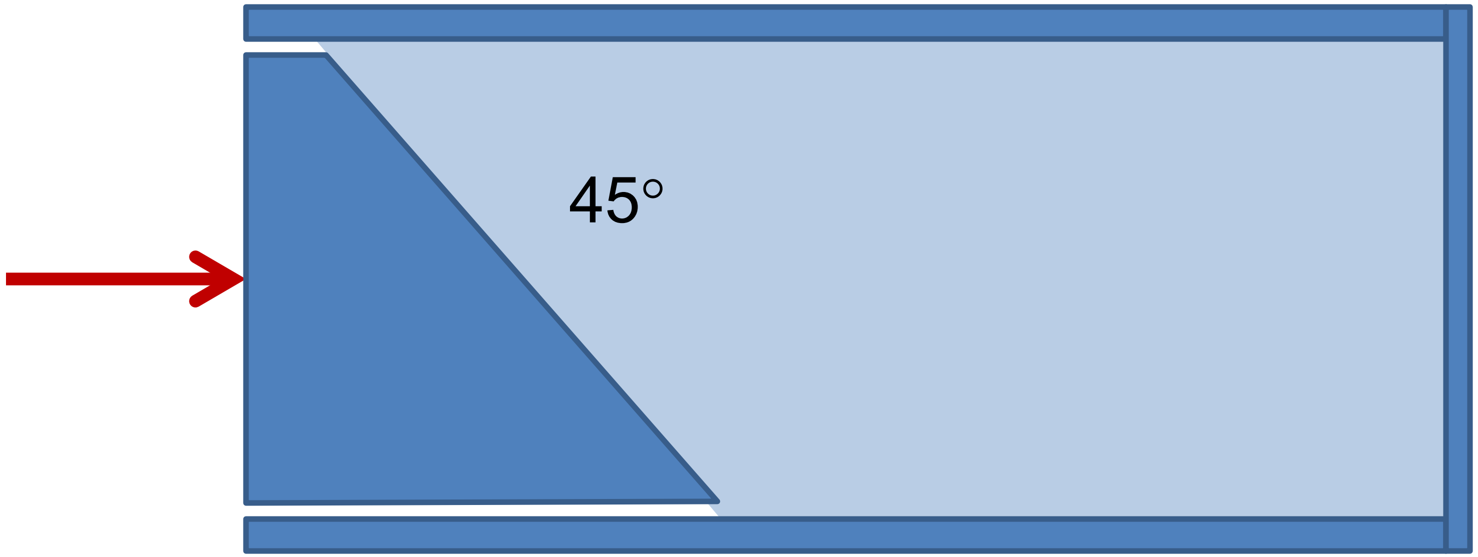
Test “Abutment”



Test “Abutment”



Test “Abutment”



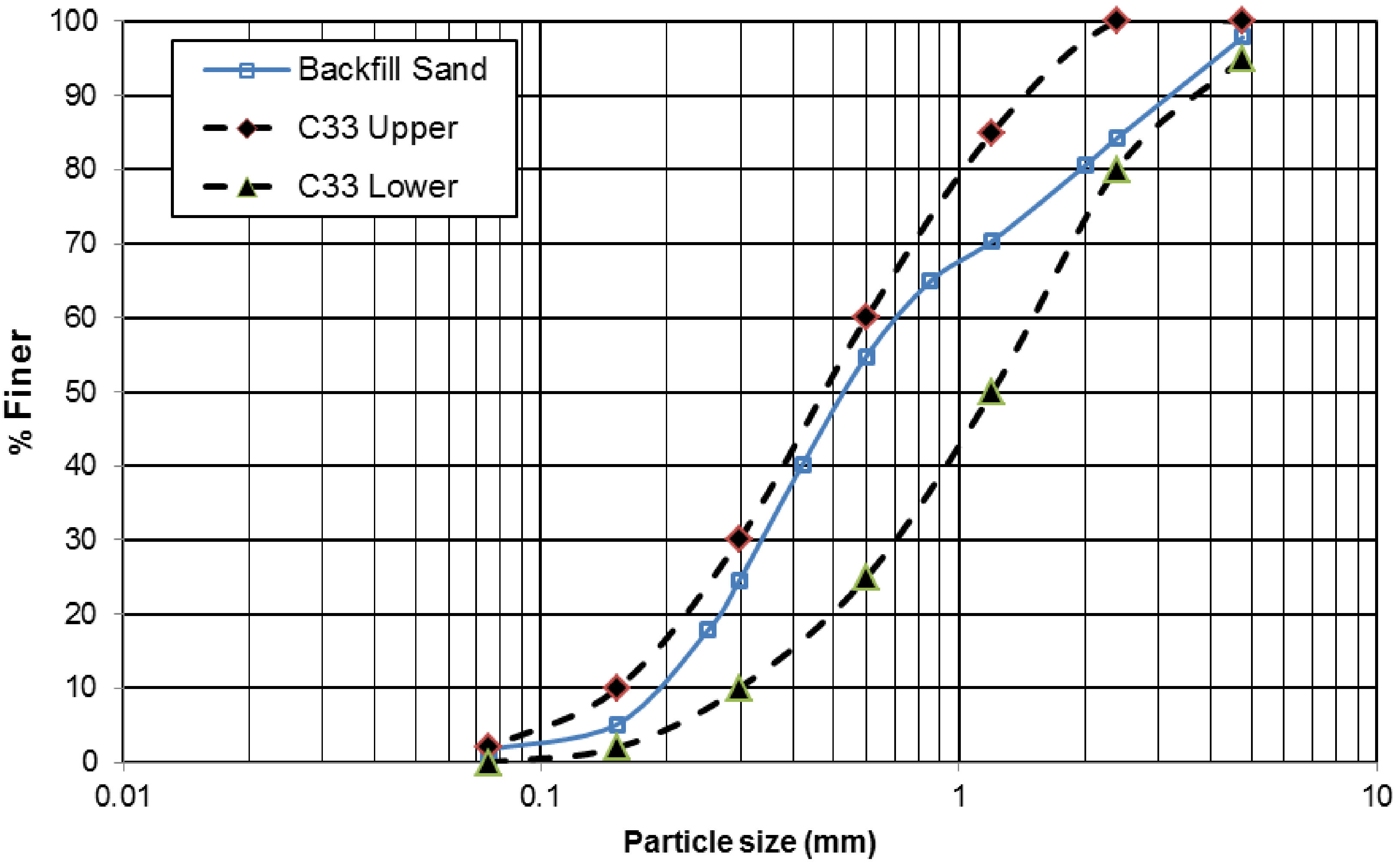
Displacement: 60 mm 2.5” (0.10H)

Load measurements:

- Longitudinal
- Vertical
- Transverse

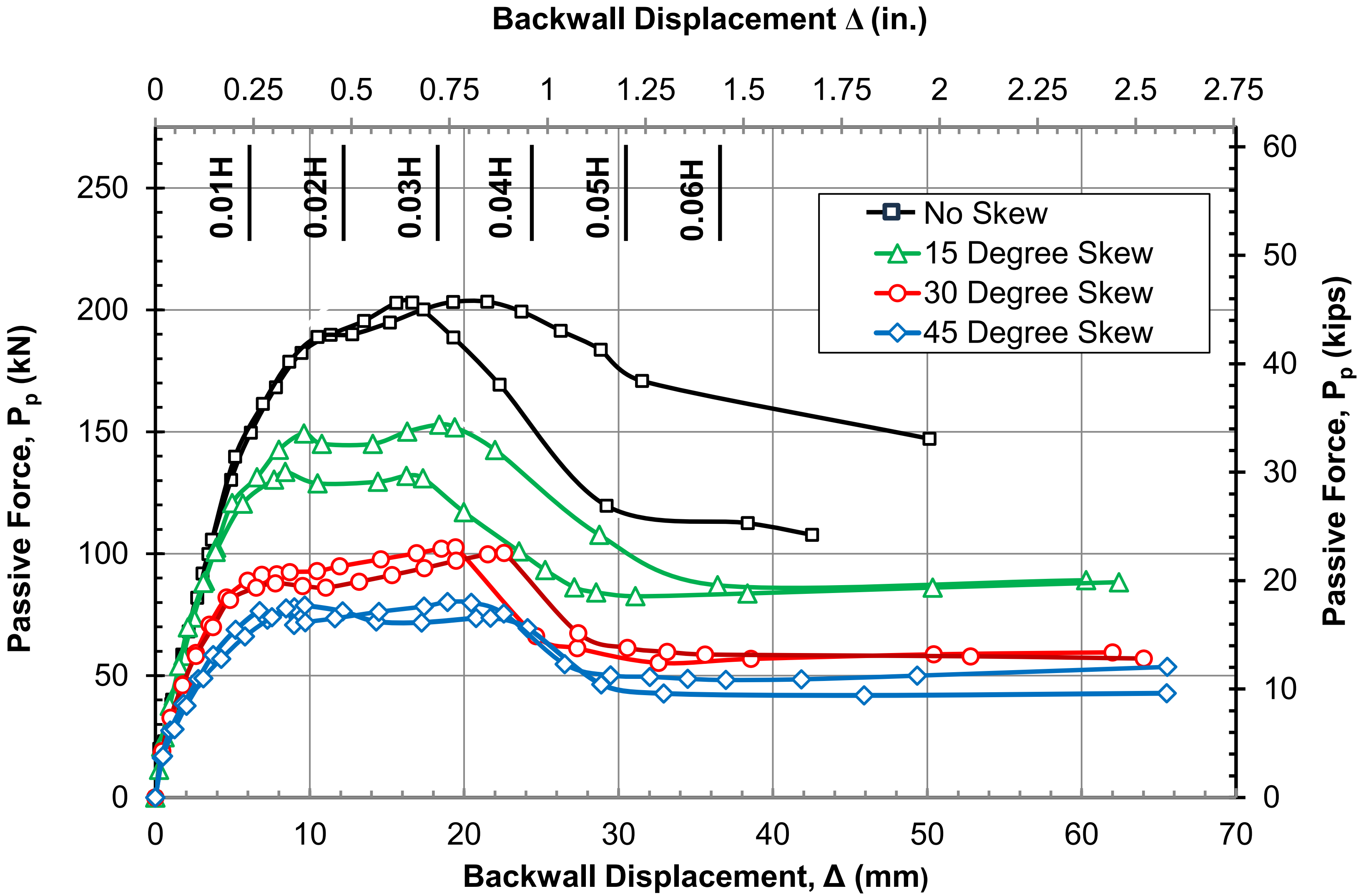
Surface Failure Rupture - 30º Skew

Backfill Soil Properties

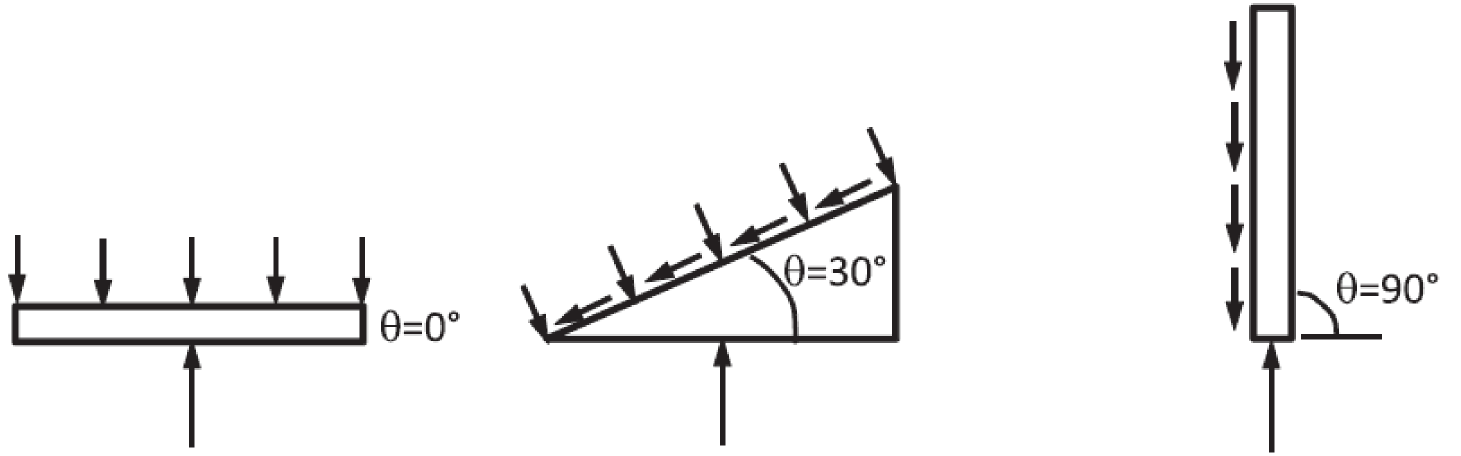


Passive Force-Displacement Curves

Shon Jessee



Passive & Shear Stress vs. Skew



(a) θ = 0°
Pure Passive Resistance,
No Shear Resistance

(b) 0° < θ < 90°
Combined Passive Resistance
and Shear Resistance

(c) θ = 90°
Pure Shear Resistance,
No Passive Resistance

Recommended Design Procedure for Skew Effects

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

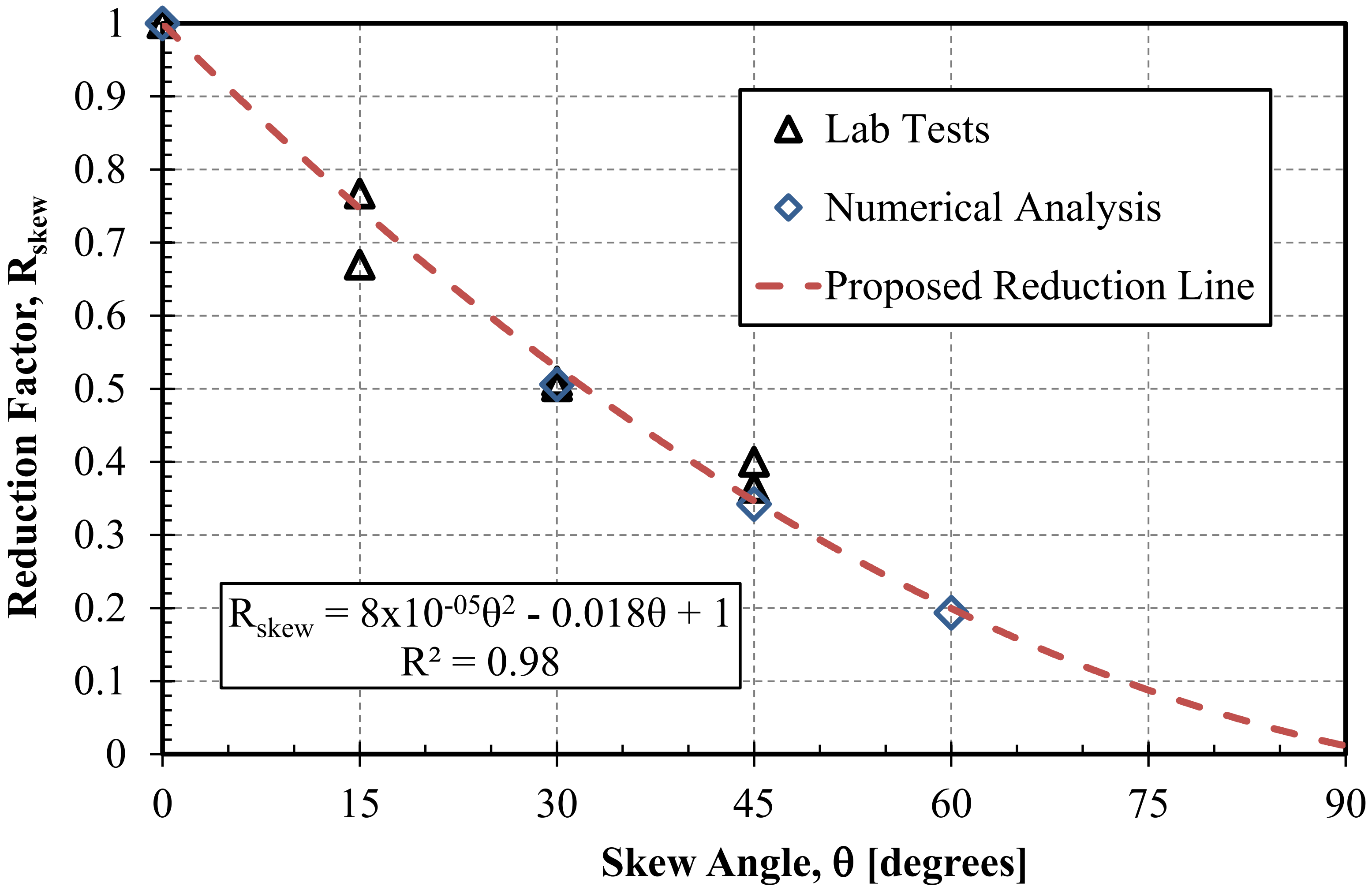
where R_{skew} is a given by the equation

$$R_{skew} = 8x10^{-5}\theta^2 - 0.018\,\theta + 1.0$$

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

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

Passive Force Reduction Factor vs. Skew



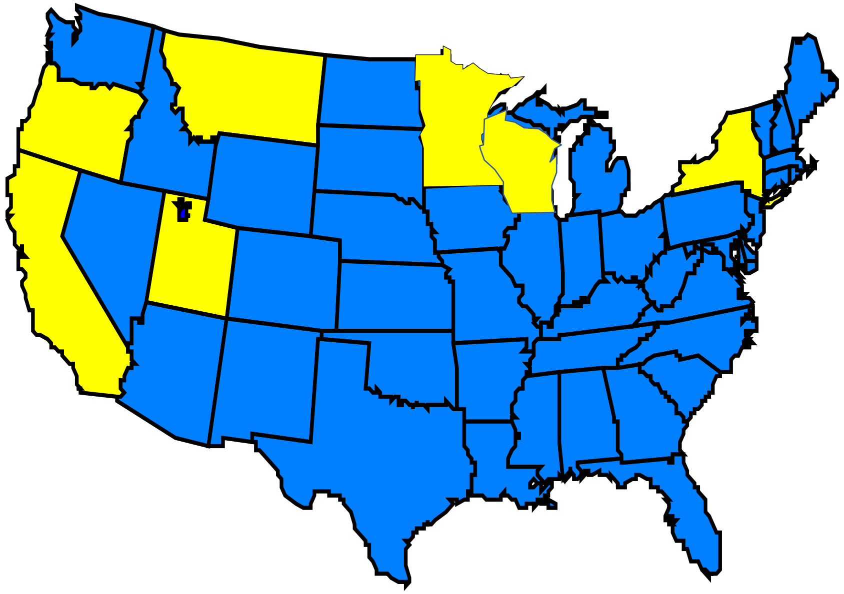
(ASCE, J. of Bridge Engrg., Rollins and Jessee 2013)

Large-Scale Field Testing

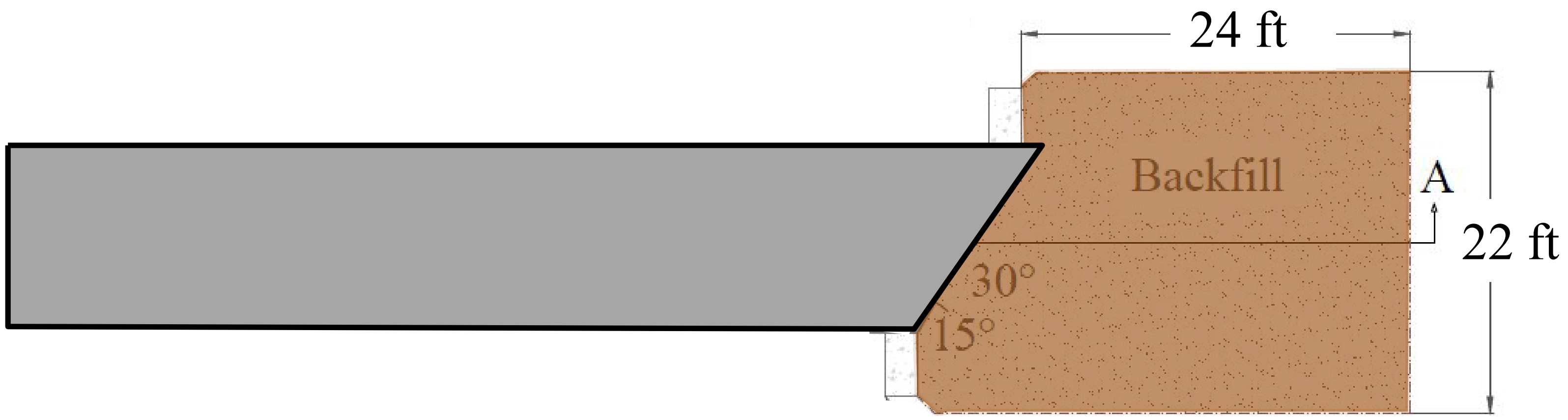
TPF-5(264) Passive Force-Deflection Behavior for Skewed Abutments

Sponsors

- Utah DOT – Lead Agency
- Oregon DOT
- Montana DOT
- California DOT
- New York DOT
- Minnesota DOT
- Wisconsin DOT
- FHWA



Field Test Setup - Plan View



Students on Skewed Abutment Study


Shon Jessee


Aaron Marsh

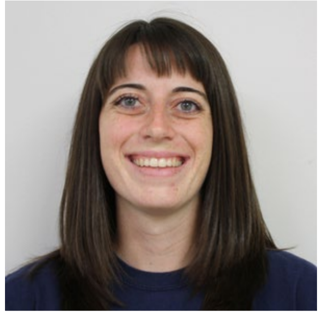

Bryan Franke


Katie Palmer


Jaycee Smith


Dalin Russell


Kyle Smith


Amy Fredrickson


Daniel Schwicht


Josh Curtis


Tyler Remund

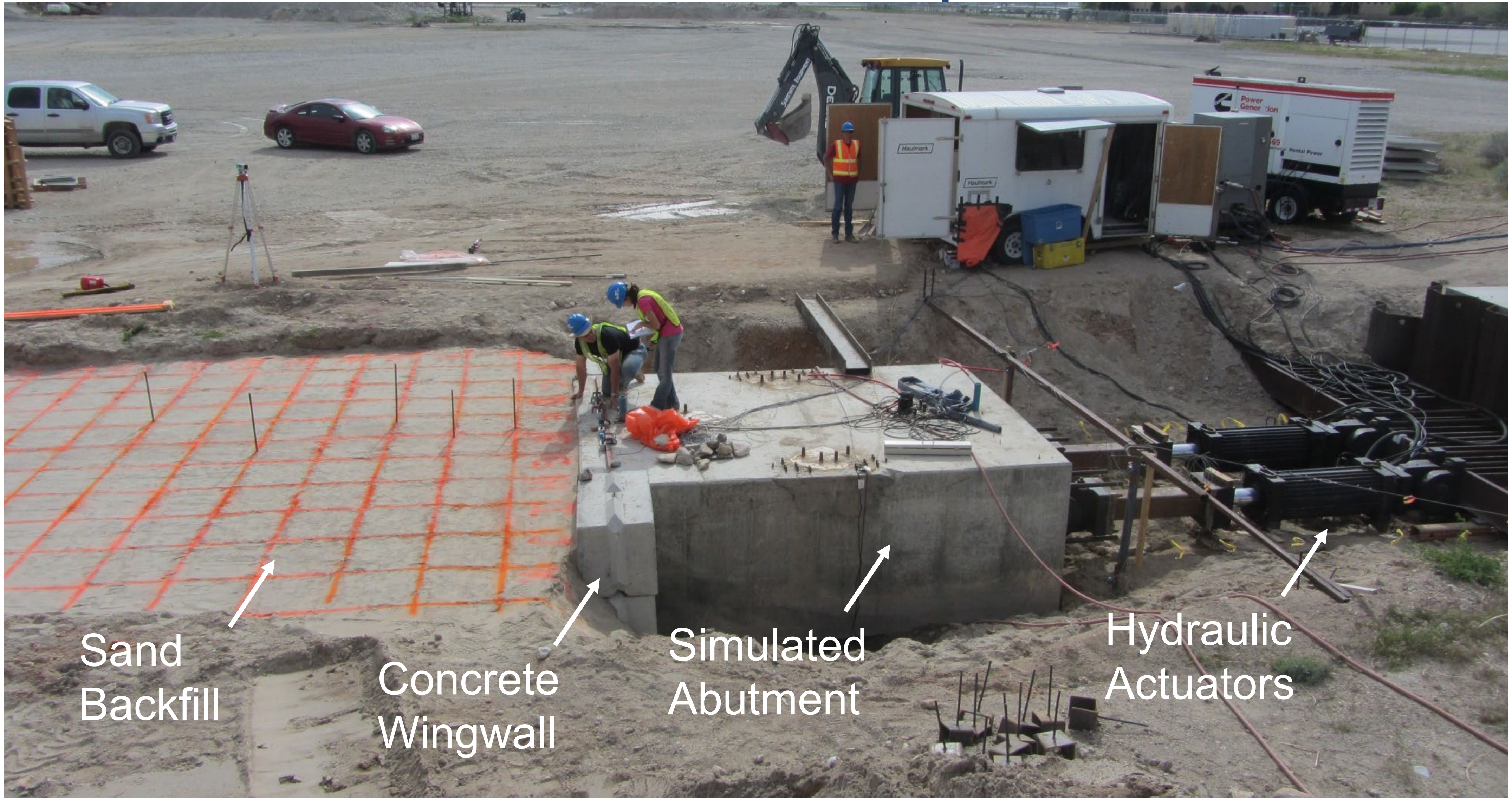

Rebecca Black


Scott Snow

Sand backfill properties

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

No Skew - 0° Test Setup



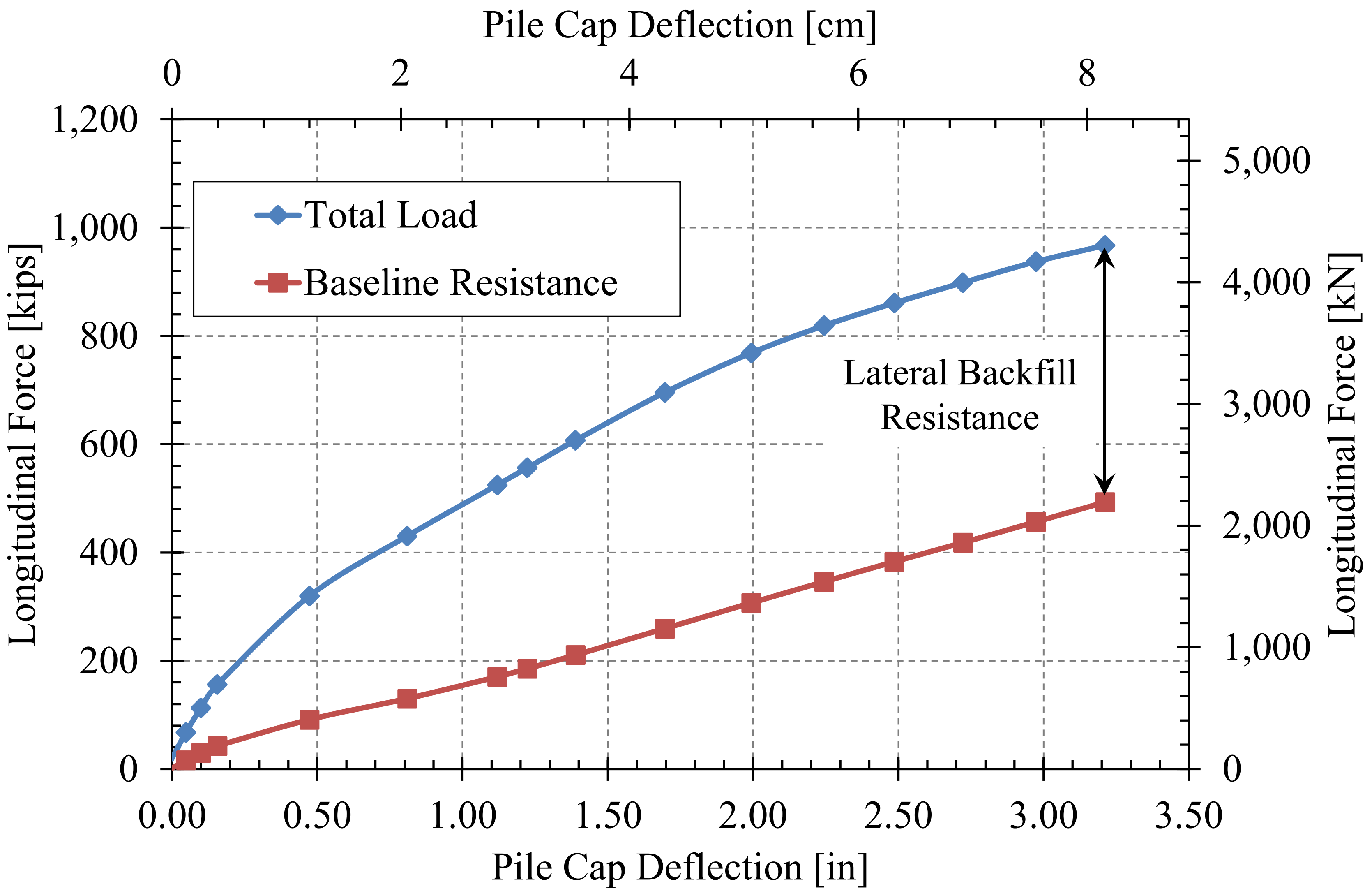
15° Skew Test Setup

30° Skew Test Setup

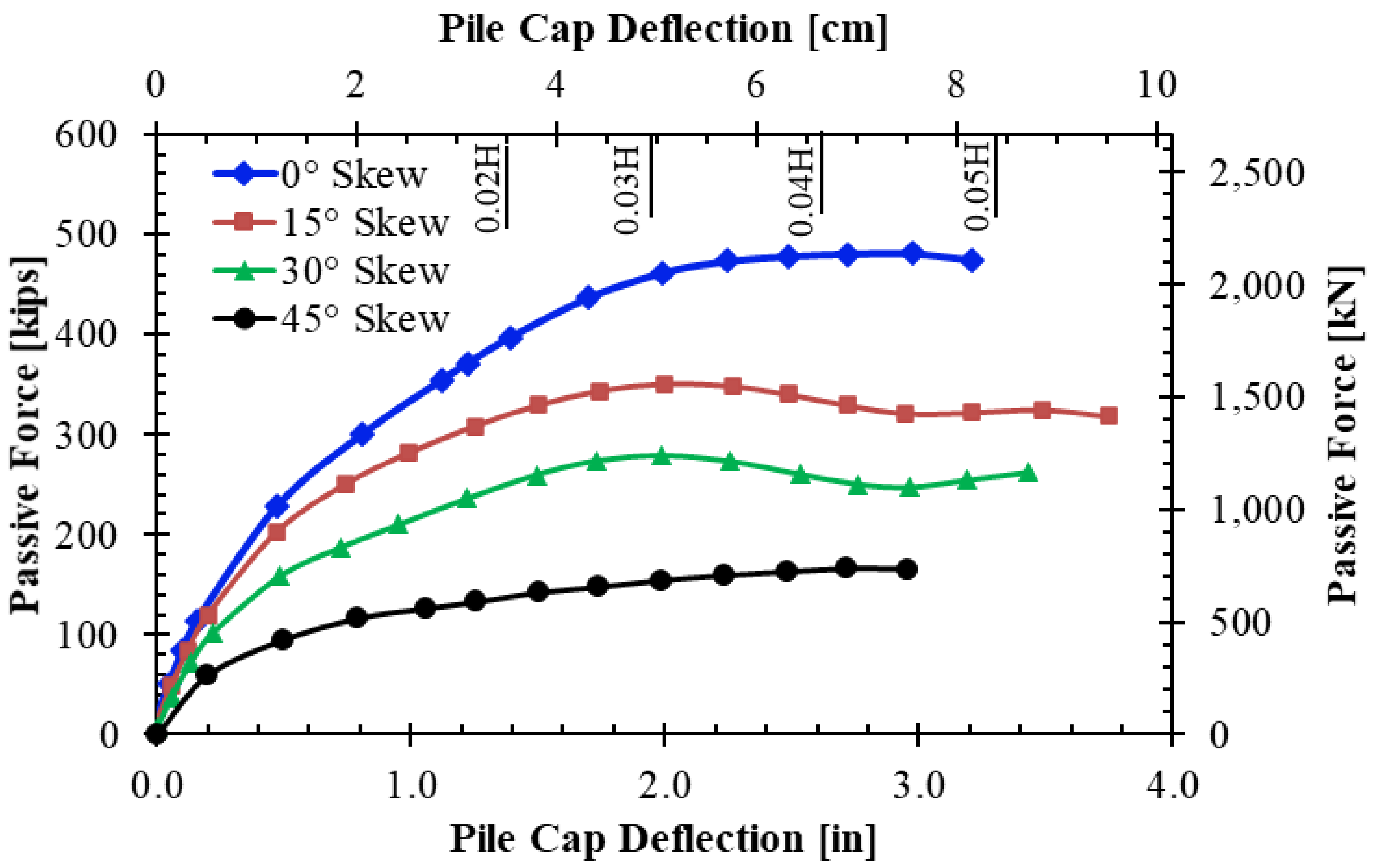
45° Skew Test Setup

Surface Failure Geometry (30° Skew)

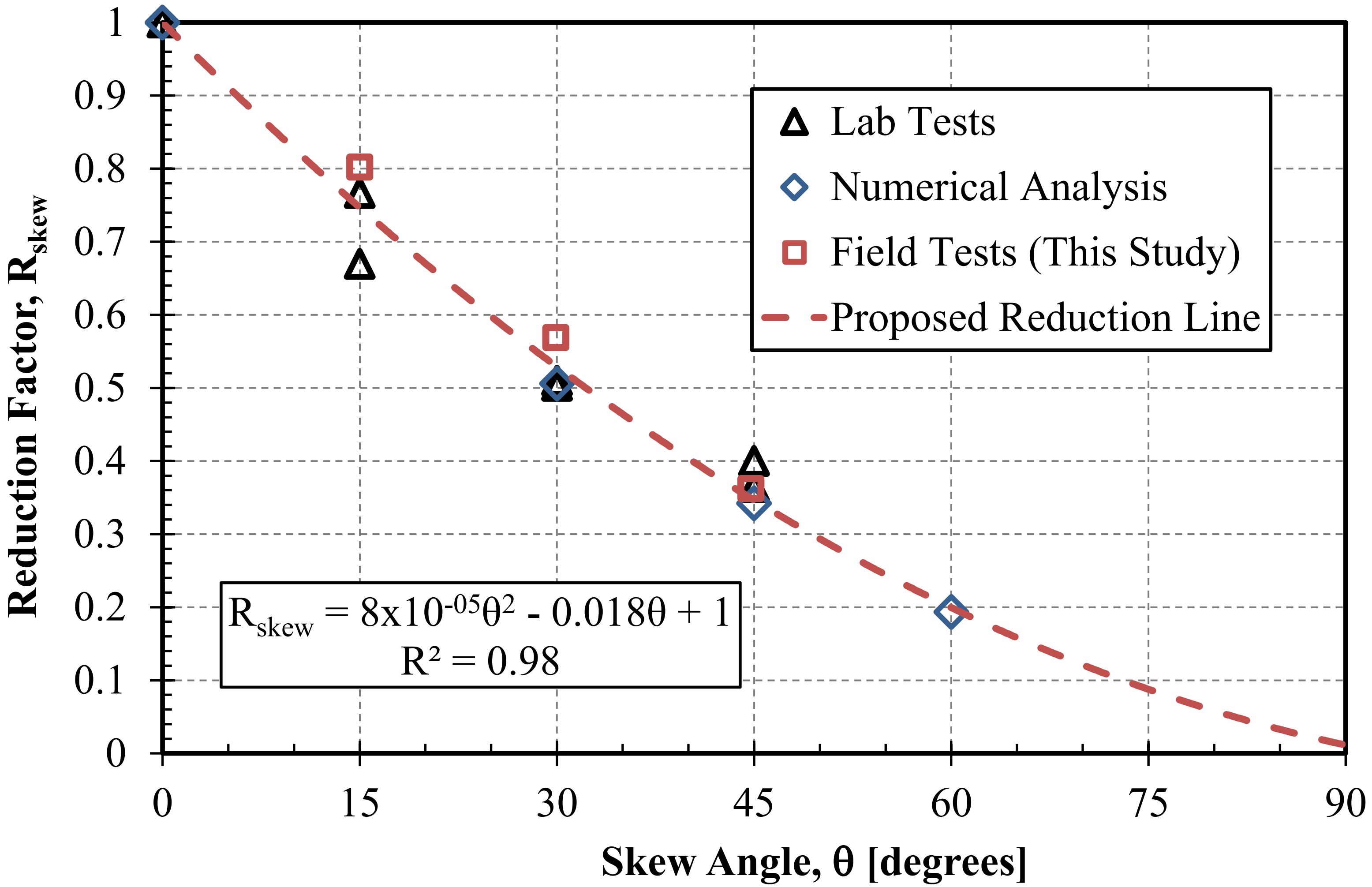
Field Test Methodology



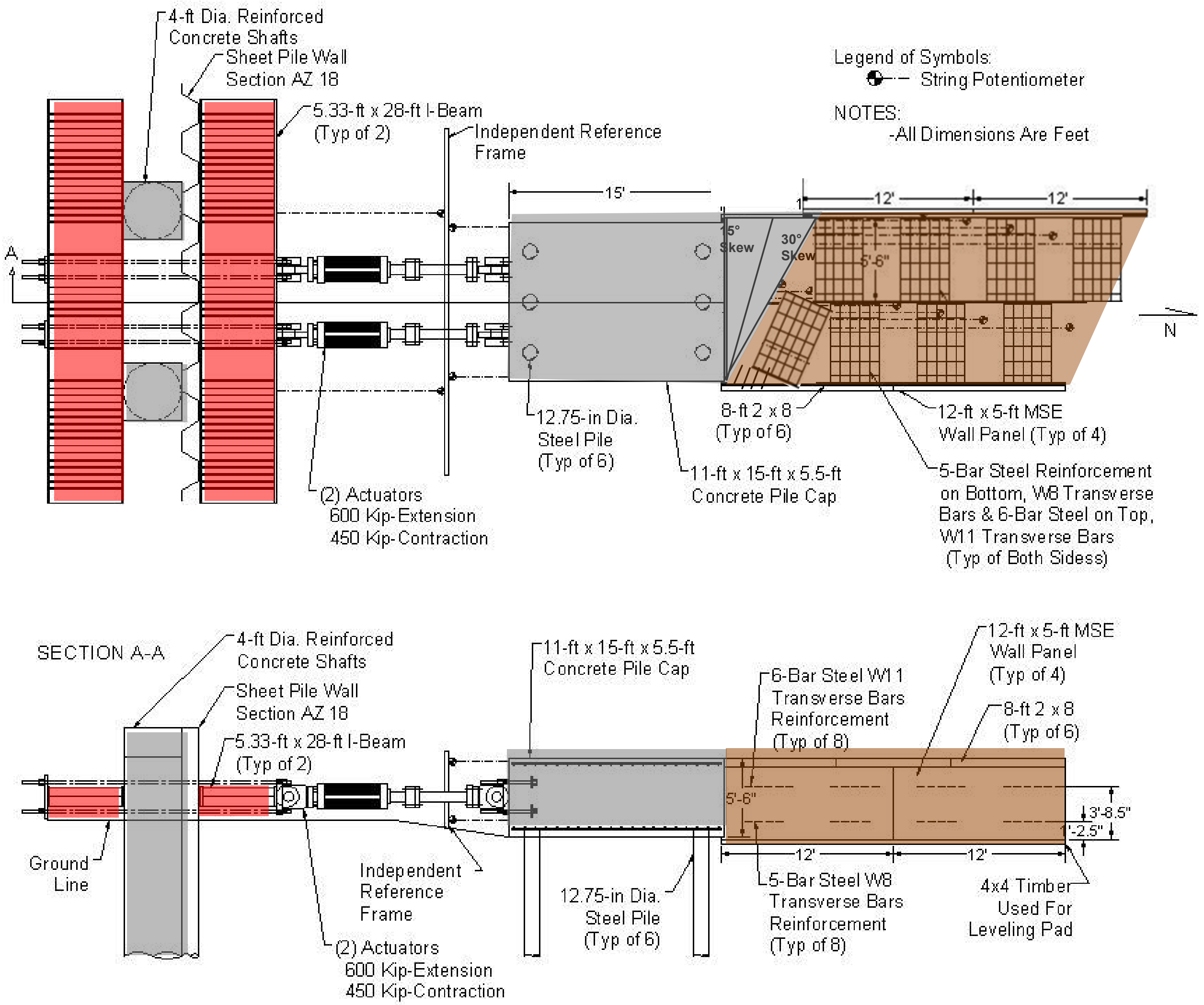
Passive Force vs. Displacement



Passive Force Reduction Factor vs. Skew



Test Setup for MSE Wingwall Tests

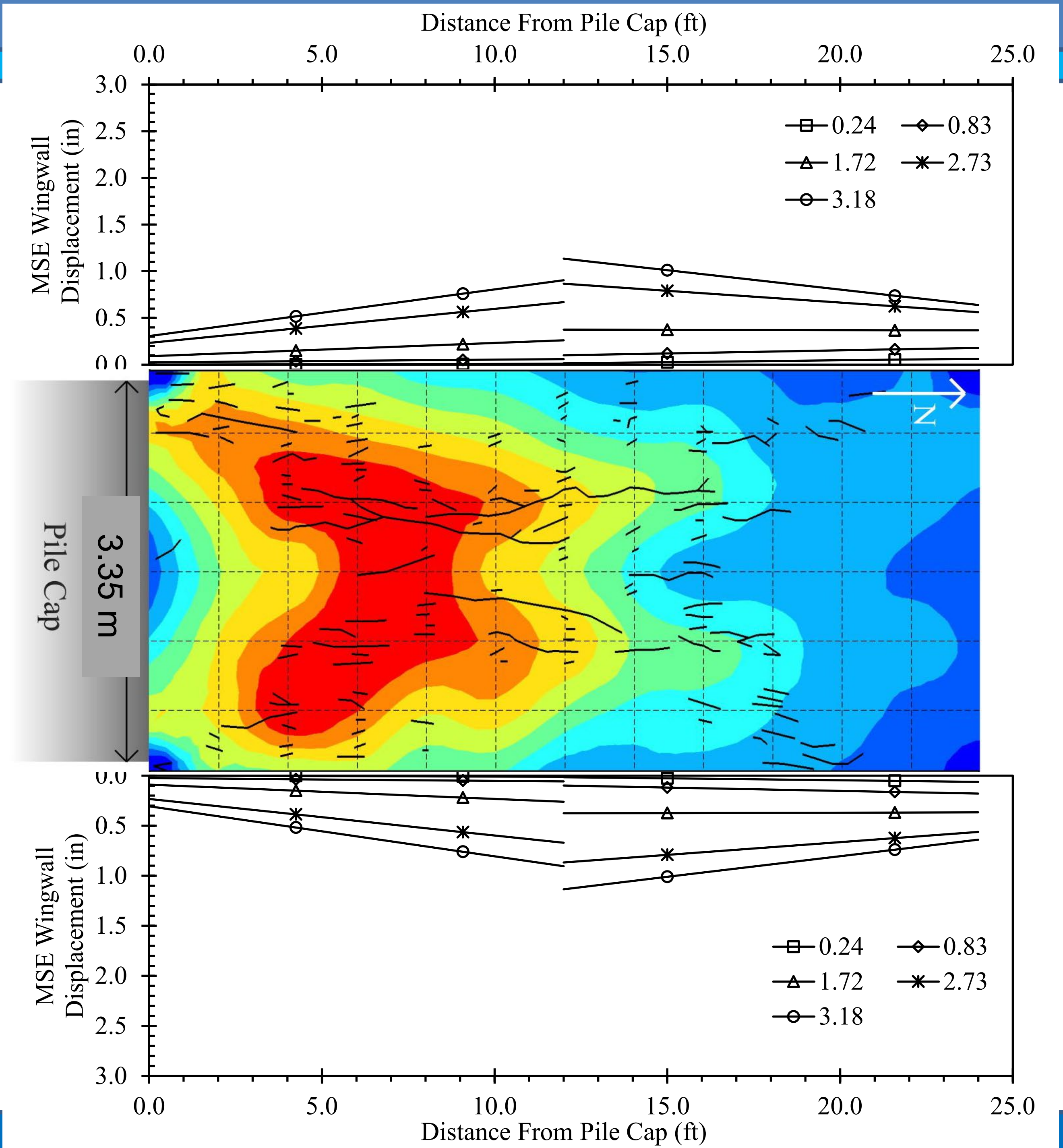


Welded Wire Grid Reinforcement (SSL)

Field Test with 0° Skew and MSE Wingwalls

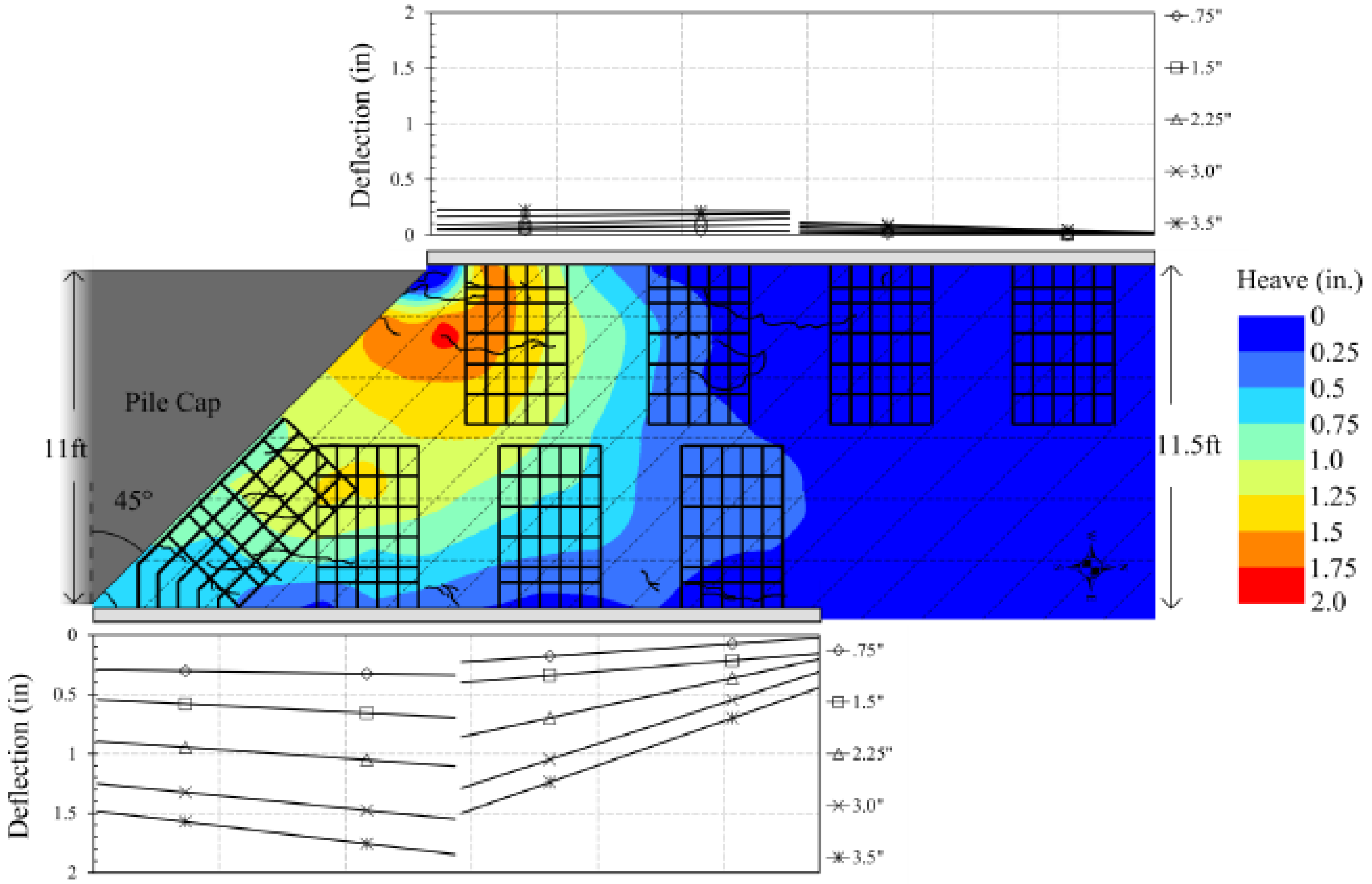
Field Test with 30º Skew & MSE Walls

0° Skew



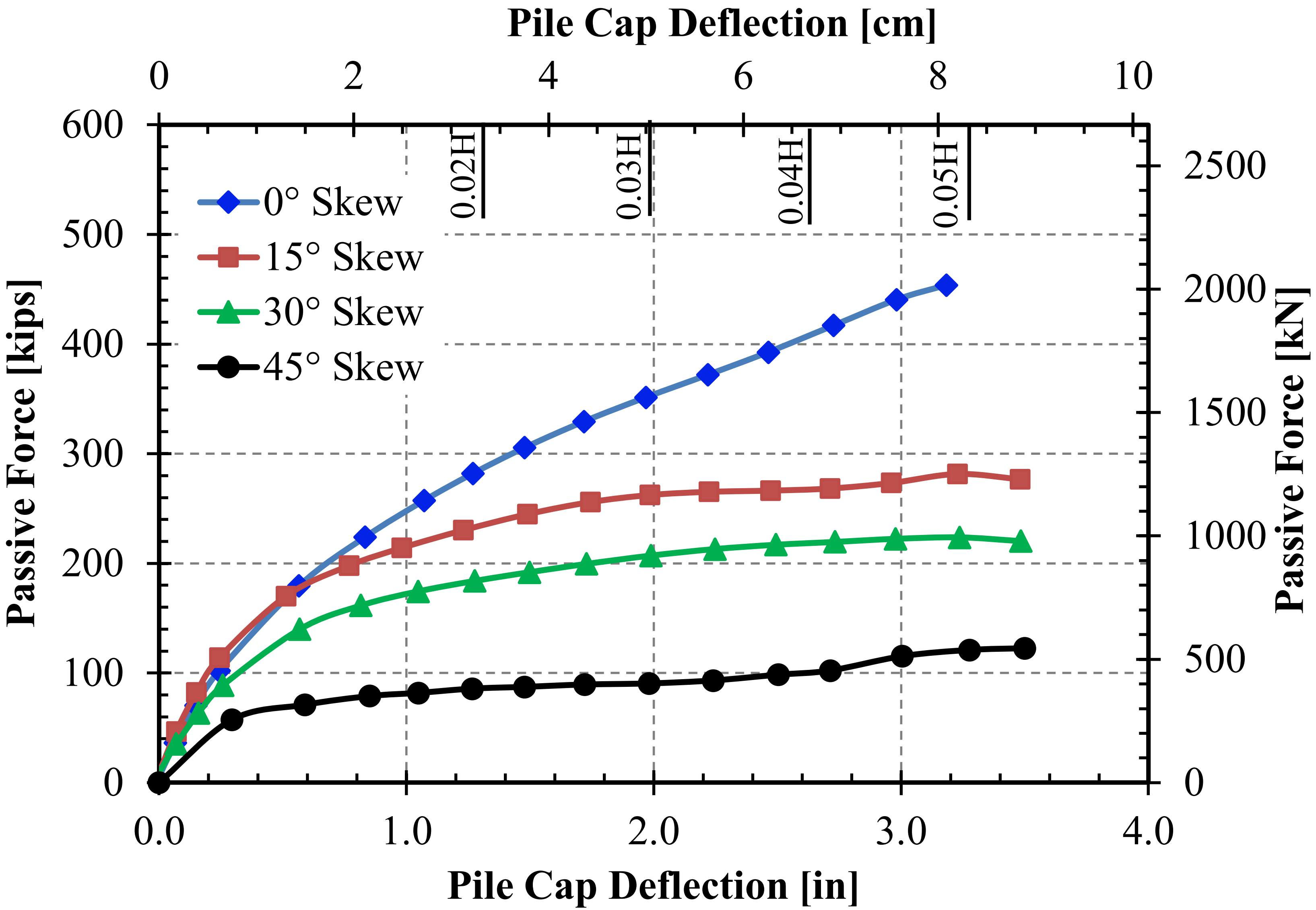
Distance From Pile Cap (ft)
0.0
5.0
10.0
15.0
20.0
25.0
MSE Wingwall Displacement (in)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.24
0.83
1.72
2.73
3.18
N
Pile Cap
3.35 m
MSE Wingwall Displacement (in)
0.24
0.83
1.72
2.73
3.18
Distance From Pile Cap (ft)

45° Skew

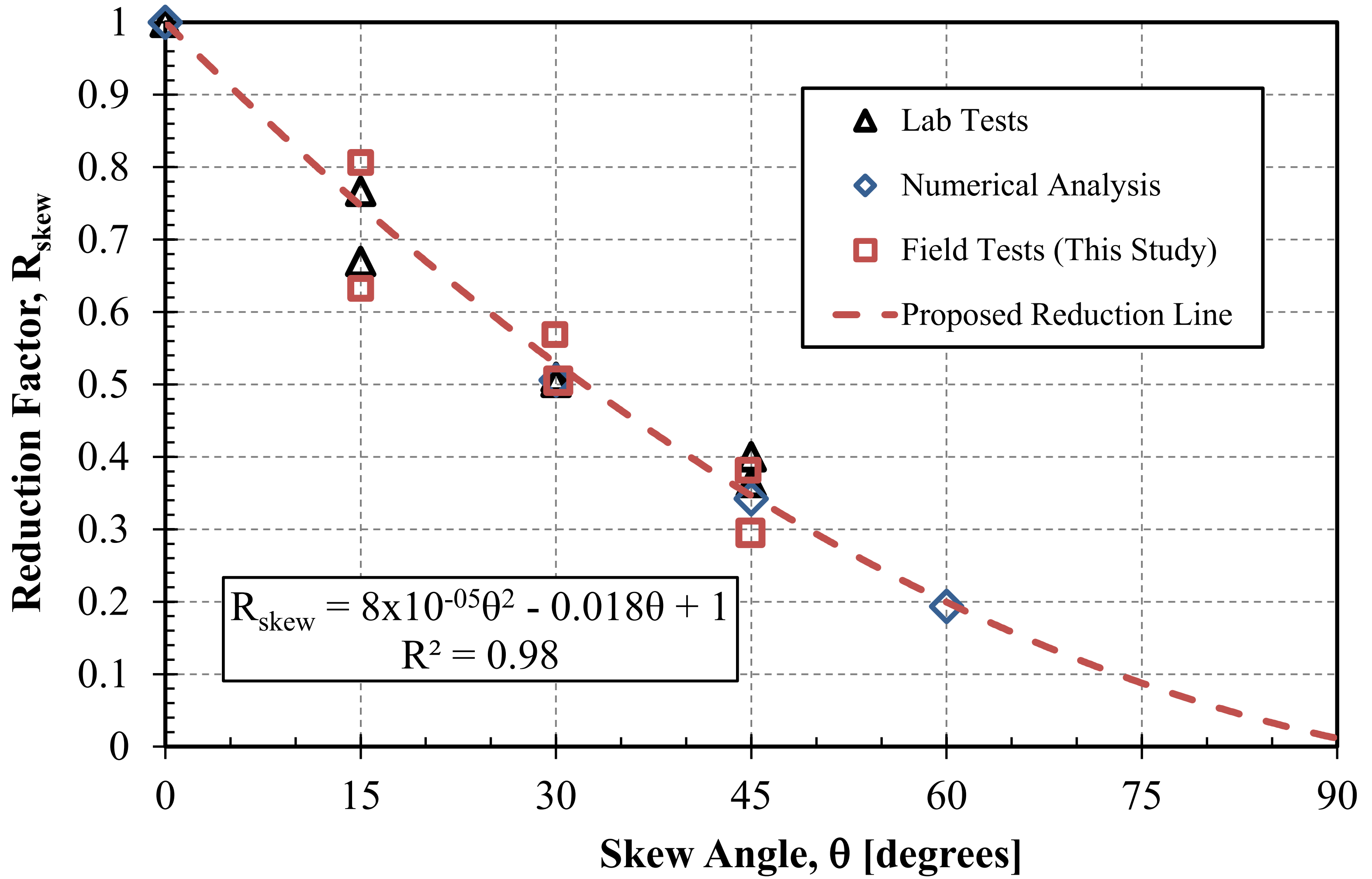


Deflection (in)
2
1.5
1
0.5
0
.75"
1.5"
2.25"
3.0"
3.5"
Pile Cap
11ft
45°
11.5ft
Heave (in.)
0
0.25
0.5
0.75
1.0
1.25
1.5
1.75
2.0
0
0.5
1
1.5
2
Deflection (in)
.75"
1.5"
2.25"
3.0"
3.5"

Passive Force-Displacement curves – MSE Wingwalls

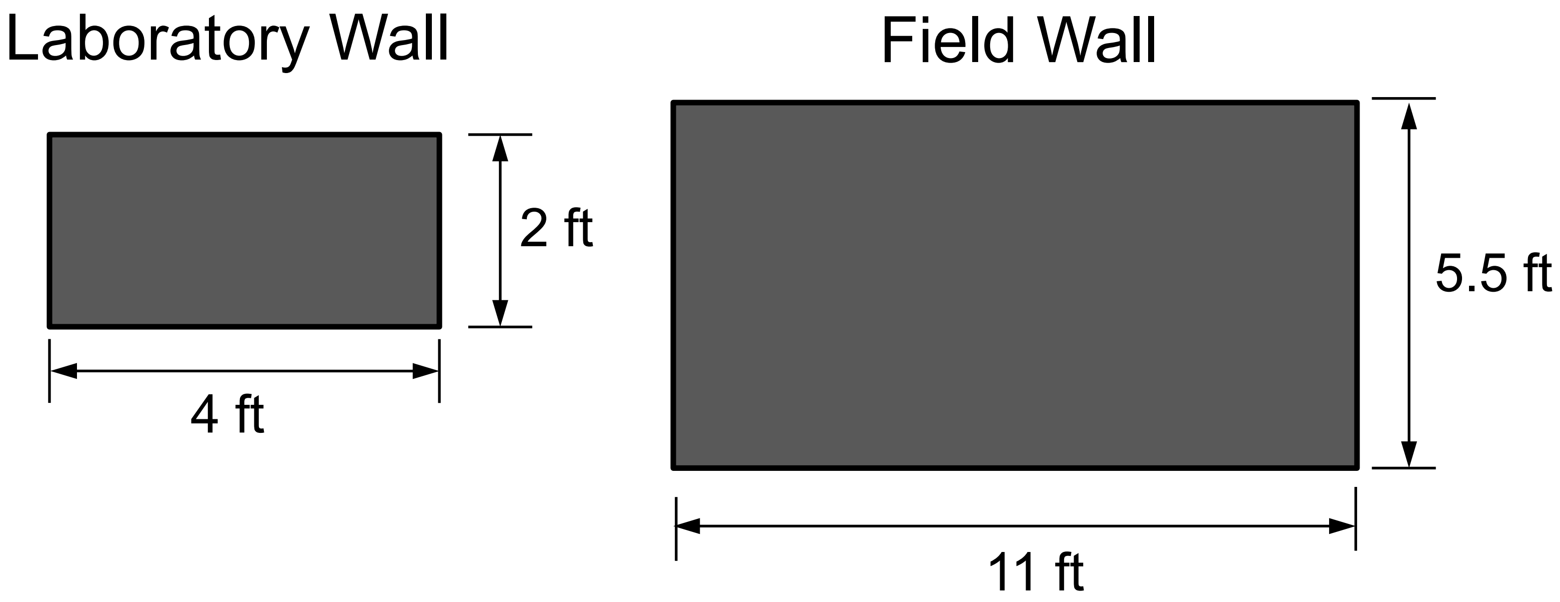


Passive Force Reduction Factor vs. Skew



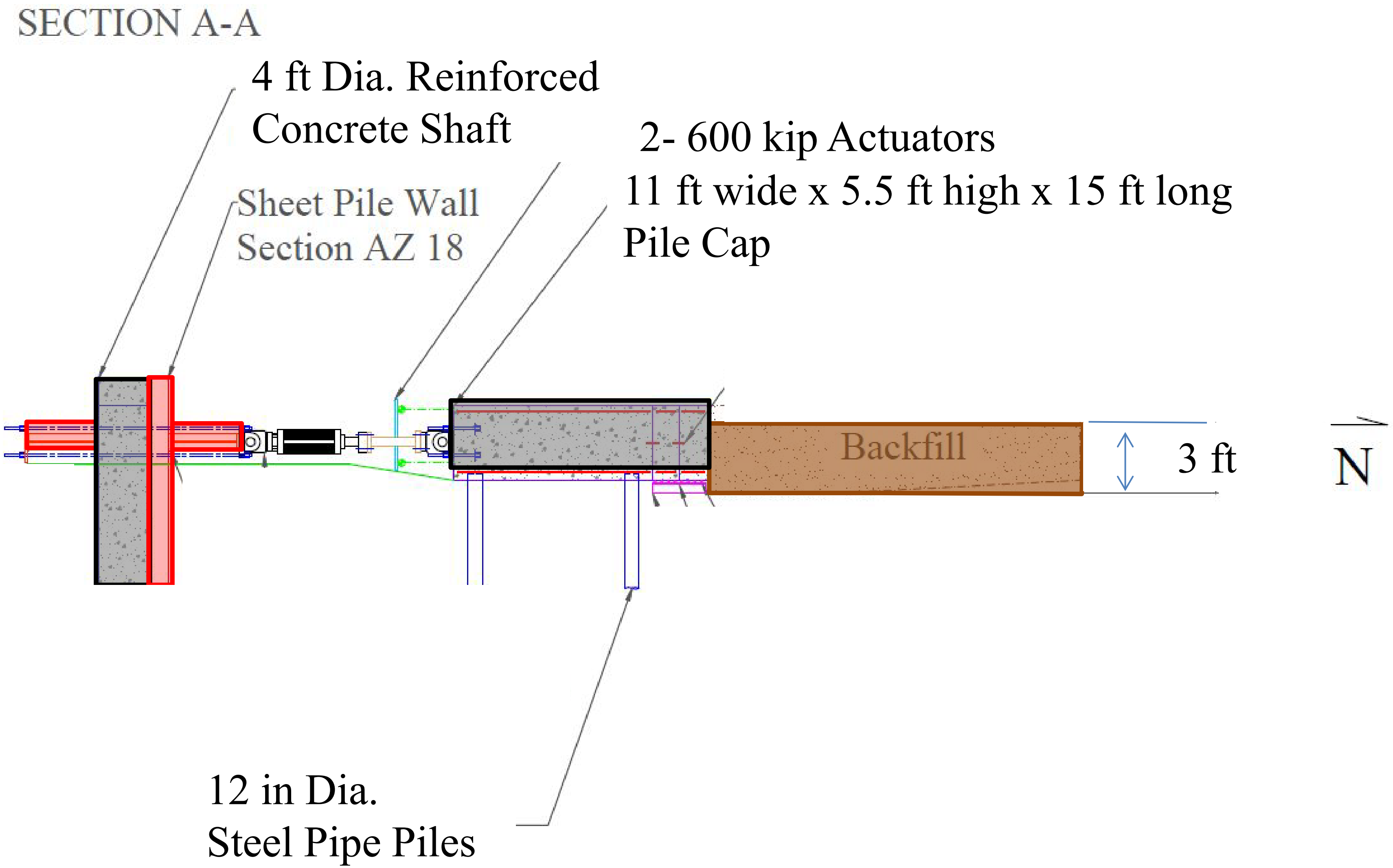
Geometry Effects?

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

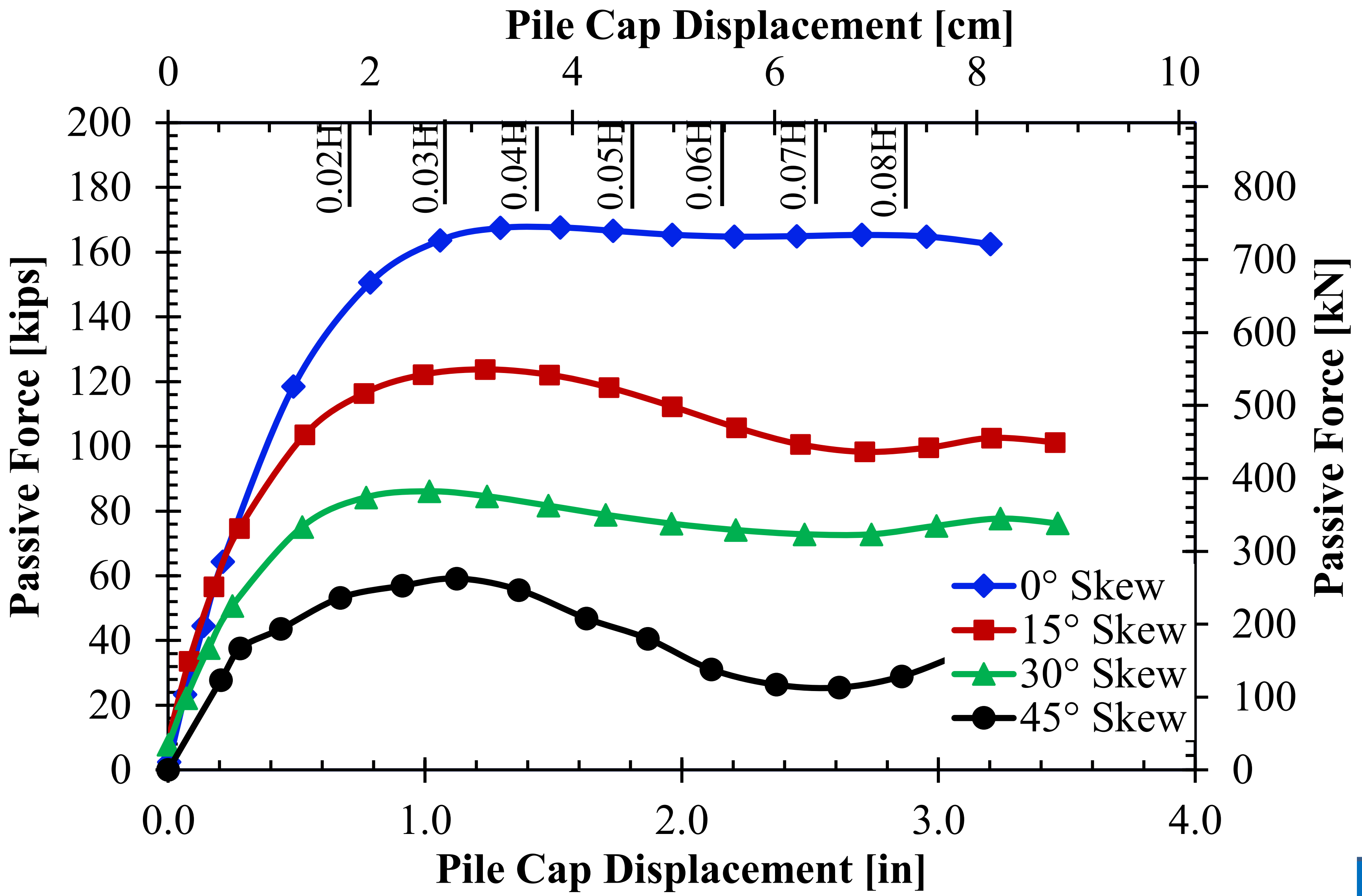


- Does this ratio impact the results?

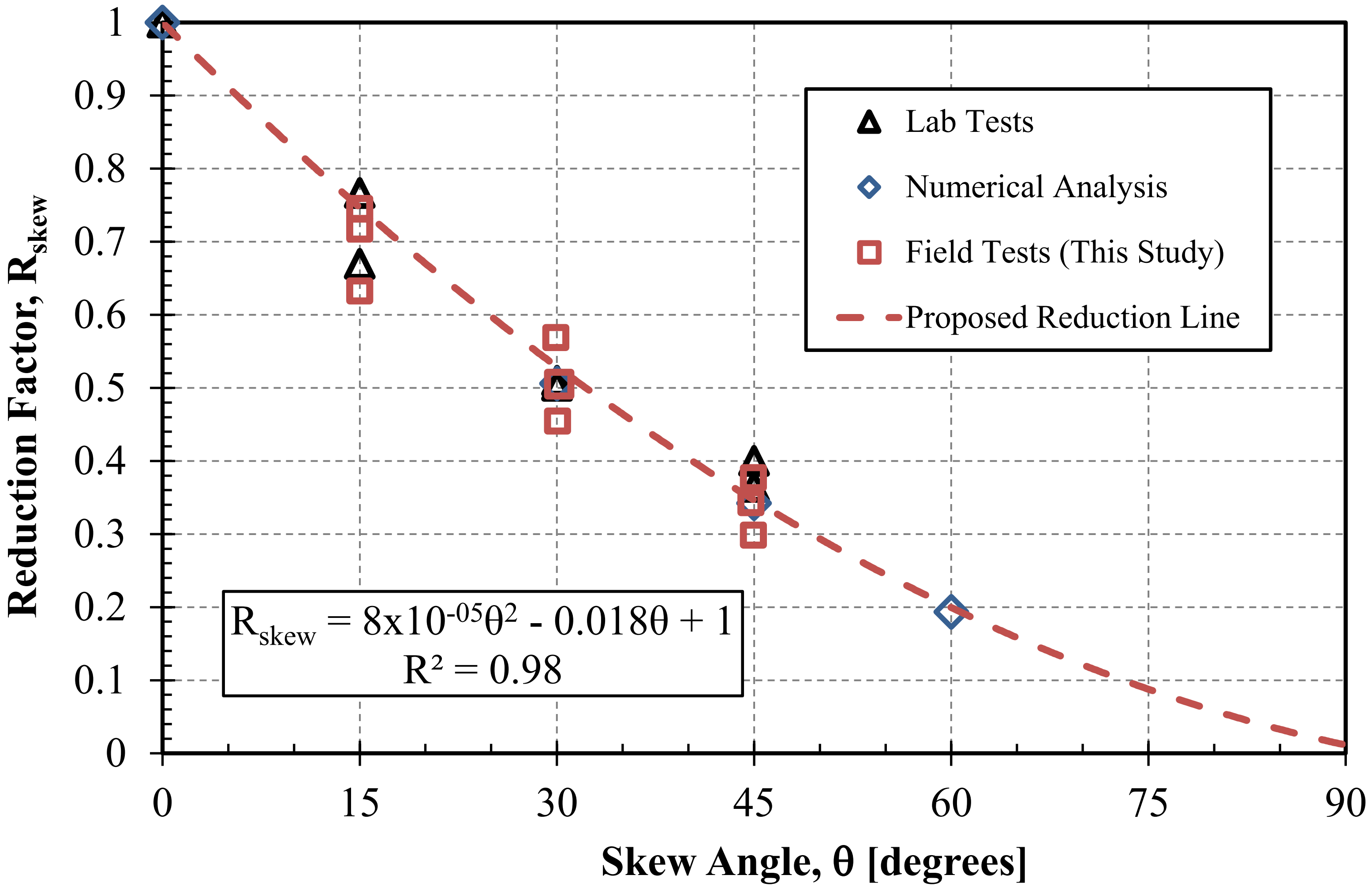
Field Test with 3 ft Backfill - W/H=3.7



Passive Force-Displacement Curves – L/H = 3.7



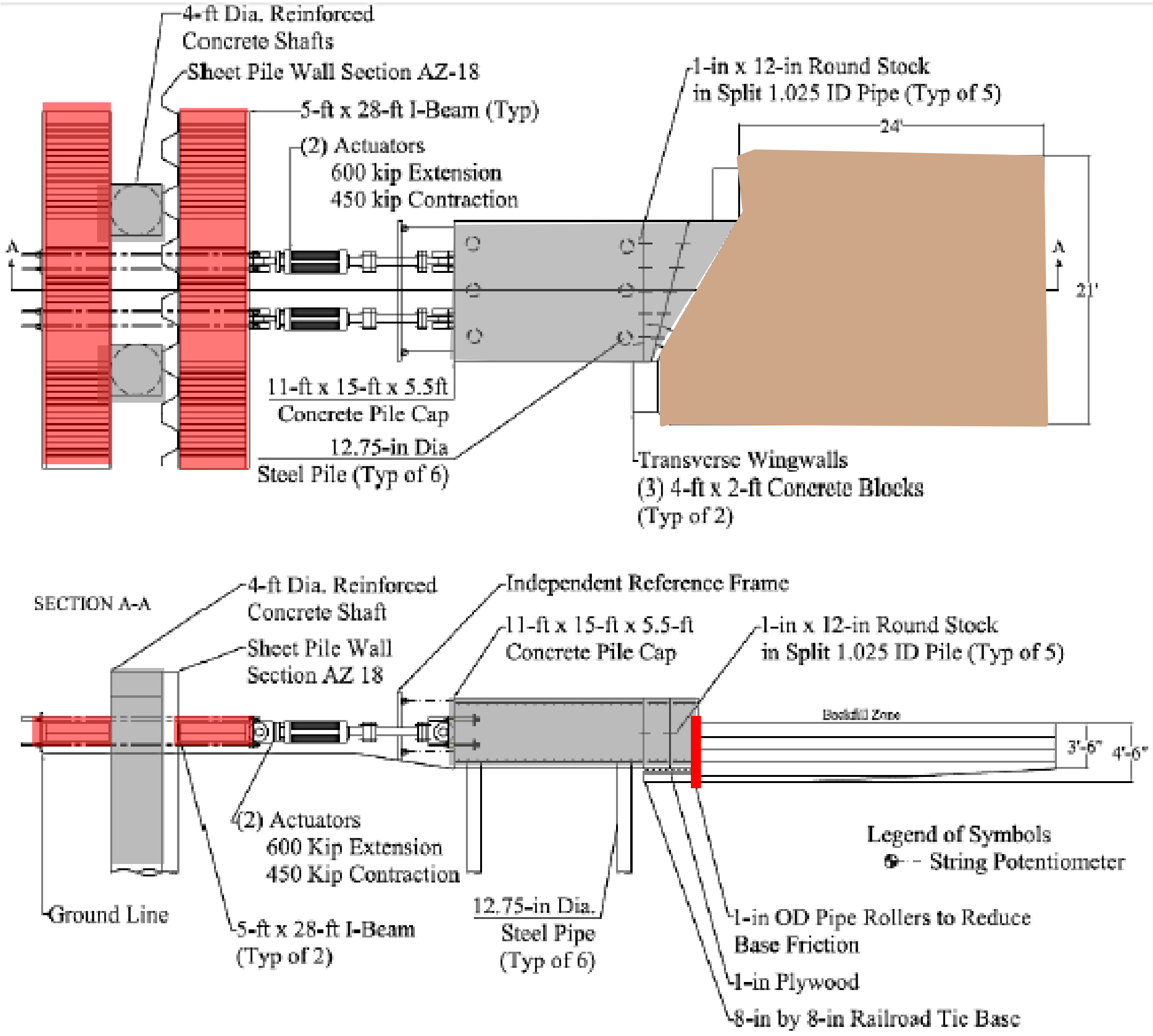
Passive Force Reduction Factor vs. Skew



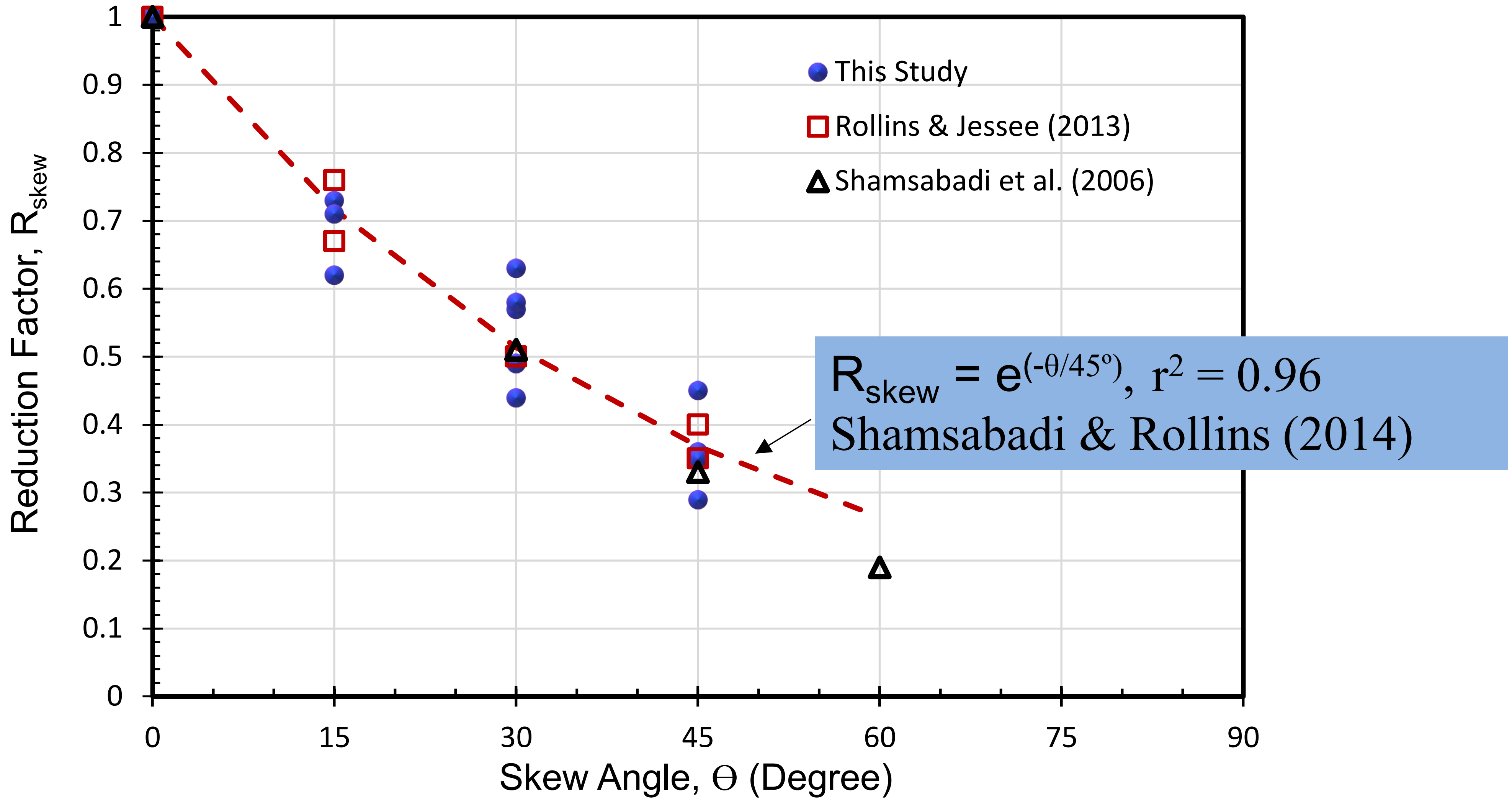
45º Skew with RC Wingwalls

GRS Test Setup - 0° and 30° Tests

Passive Force Tests with GRS Backfill

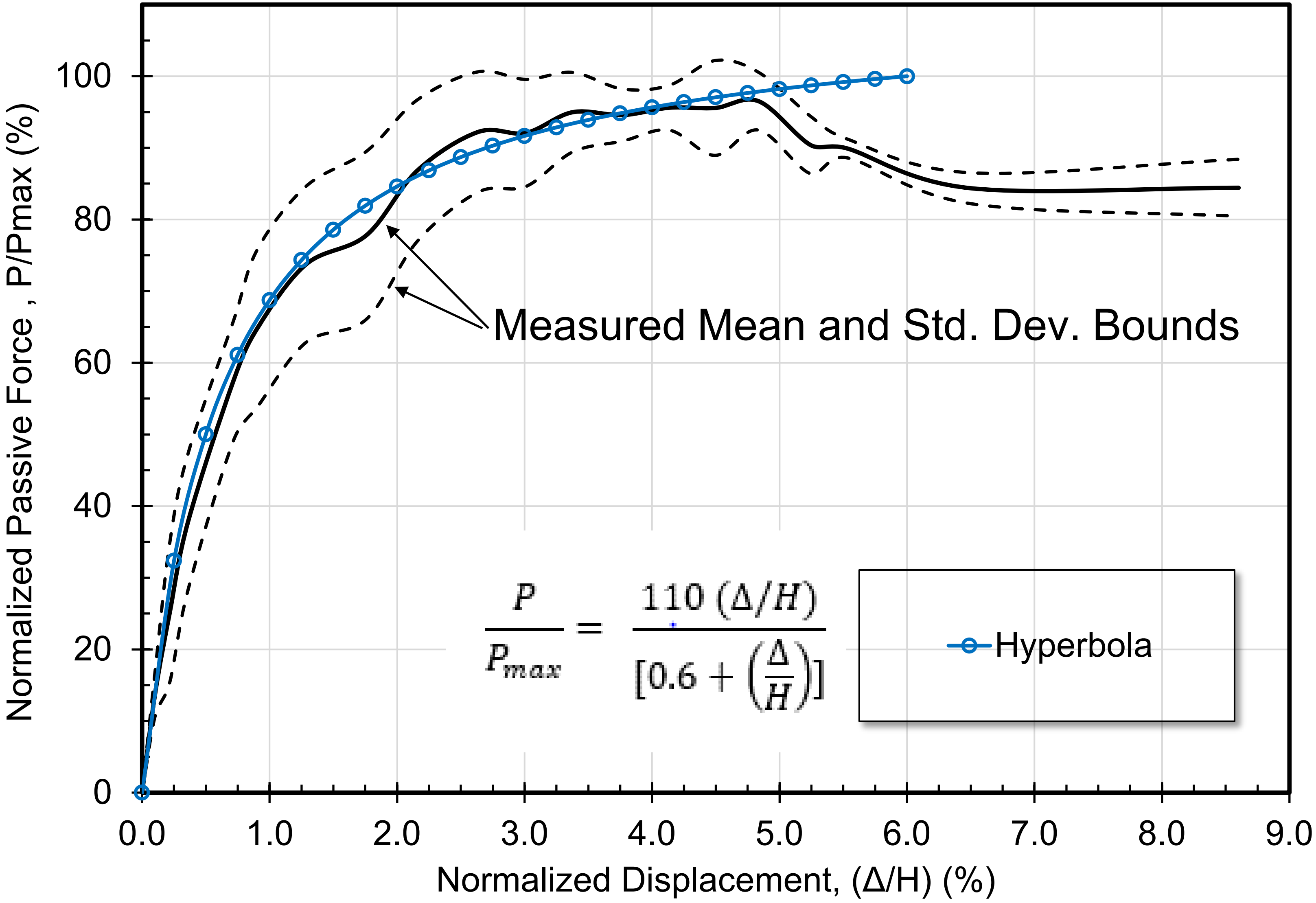


Skew Reduction Factor vs. Skew Angle – All Tests



Results incorporated in Caltrans SDC, Utah, & Oregon Geotech guidelines

Normalized Passive Force vs. Normalized Displacement

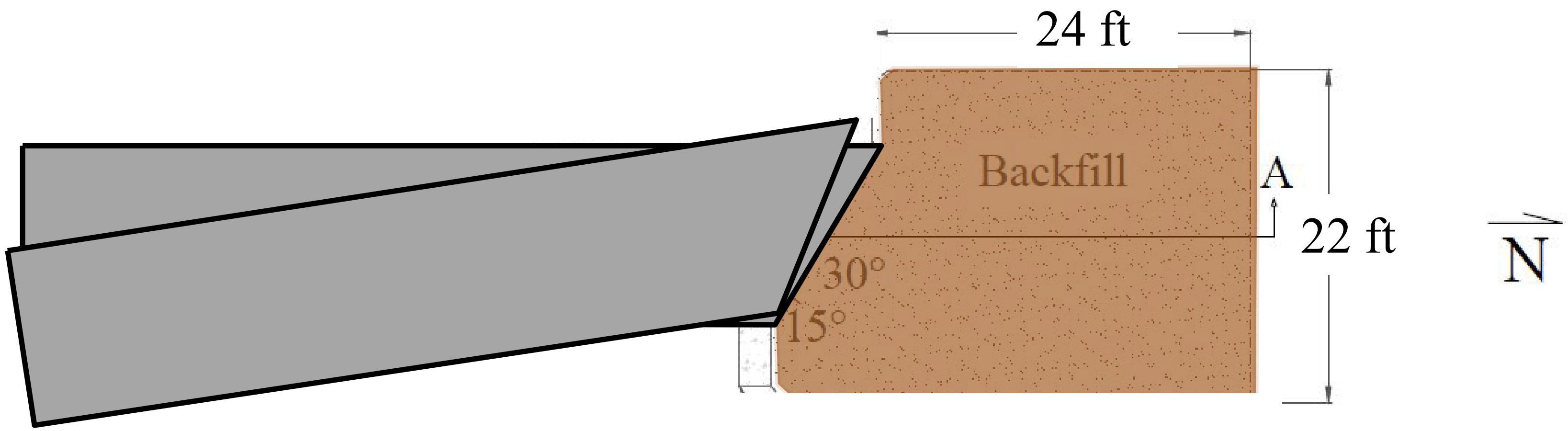


Summary of Results for Skewed Abutments

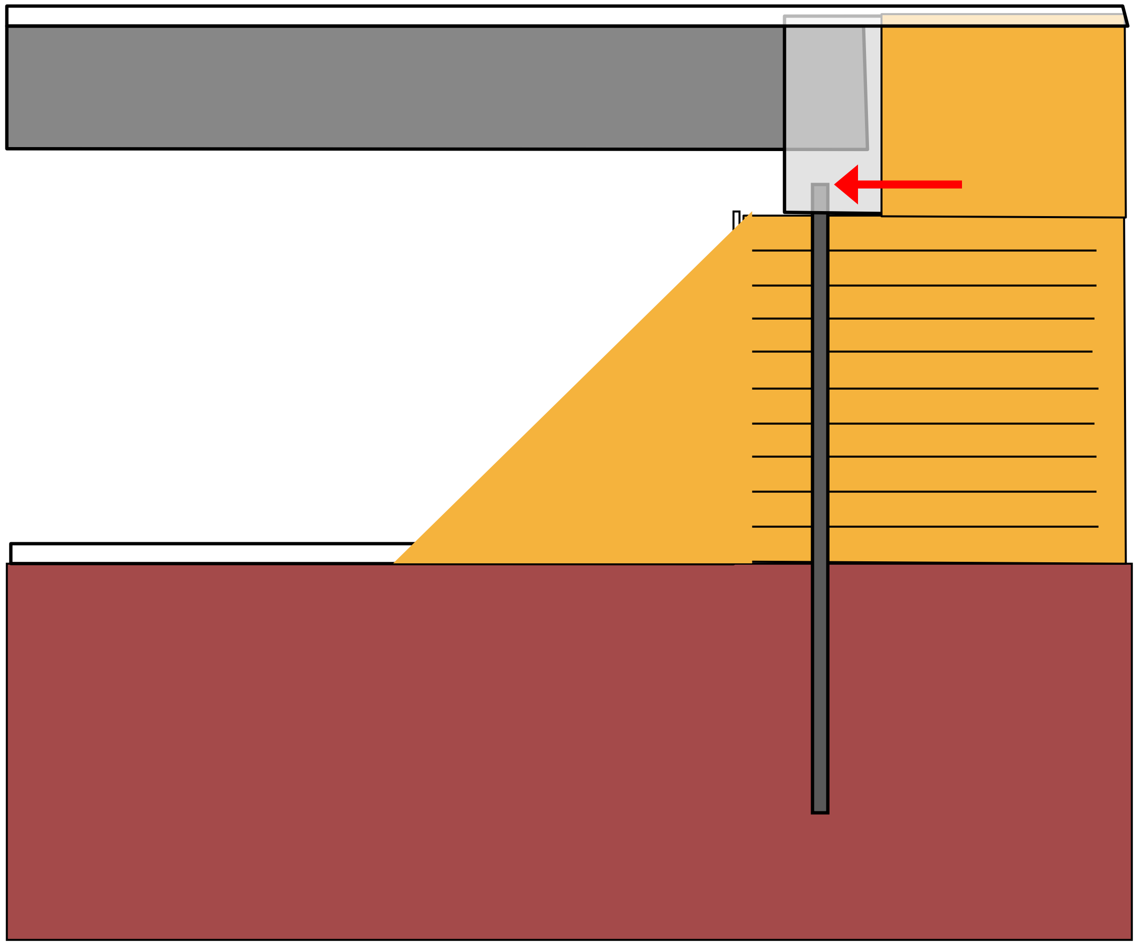
- Significant decrease in passive force with increase in skew angle.
  - Numerical Analysis
  - 8 Small Scale Lab Tests
  - 16 Large Scale Field tests
- Reduction factor proposed by Rollins and Jessee (2013) is applicable for various soil types and wingwall geometries
- Reduction factor not much affected by wall L/H ratio
- Normalized passive force-deflection curve provided by a hyperbola

Problem: All Field Tests have Involved Longitudinal Loading

Real Situation Involves Loading at an Angle due to Rotation

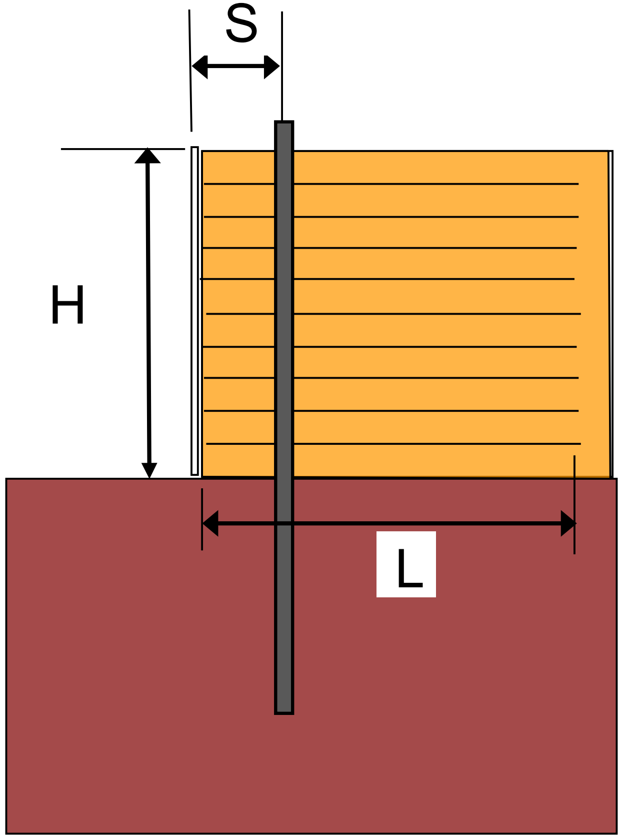


Abutment Piles near MSE Walls

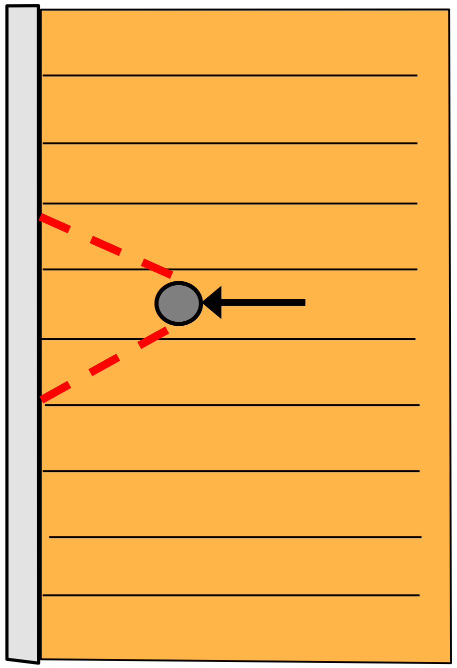


Abutment Piles Near MSE Walls

MSE Wall Geometry



Elevation View

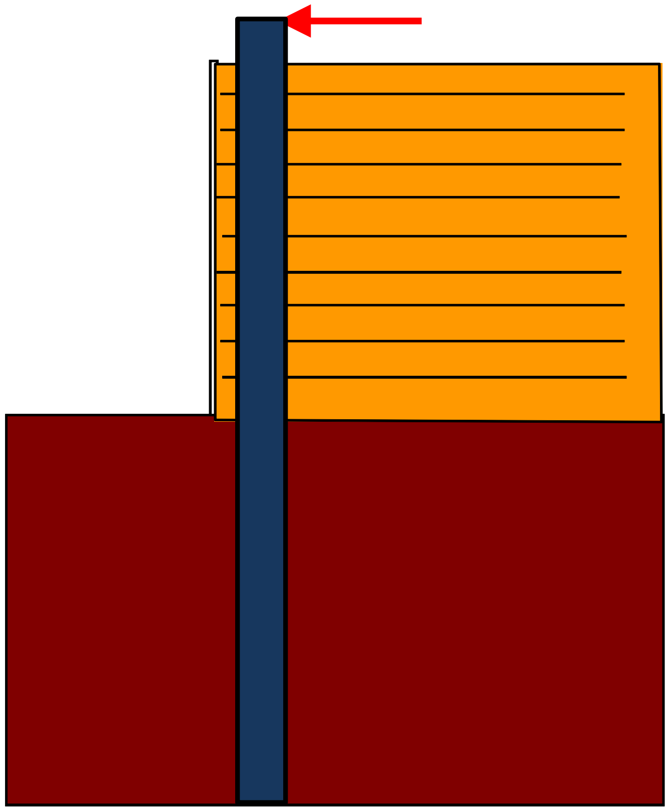


Plan View

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

Approaches to the Problem

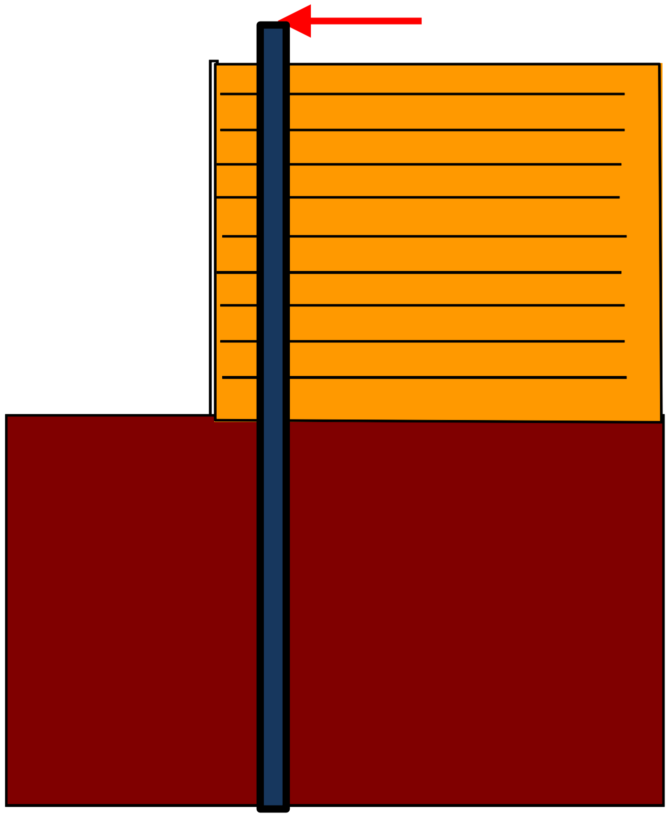
Ignore Soil Resistance



Increased Cost from Larger Pile Diameter or More Piles

Approaches to the Problem

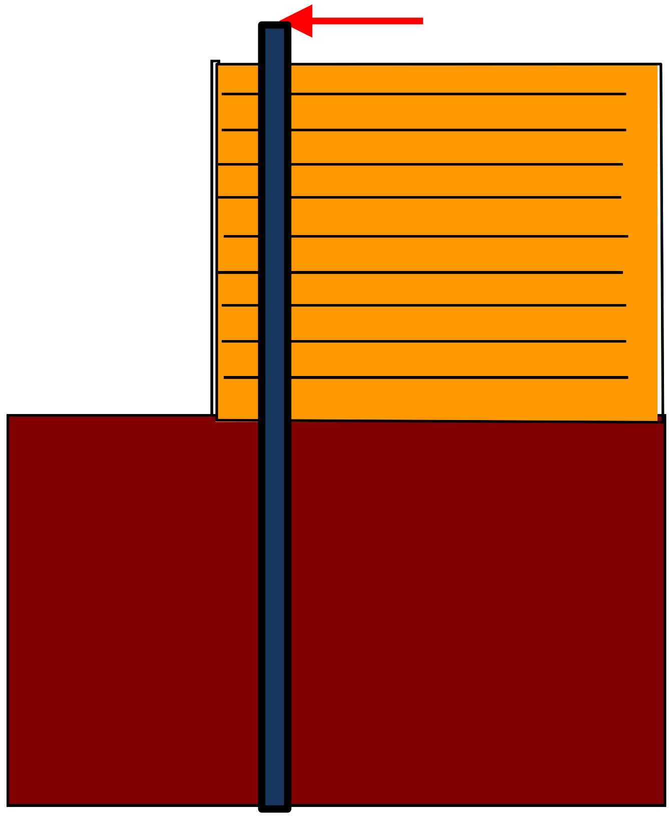
Increase Spacing to Eliminate Interaction



Increased Cost from Larger Bridge Span

Approaches to the Problem

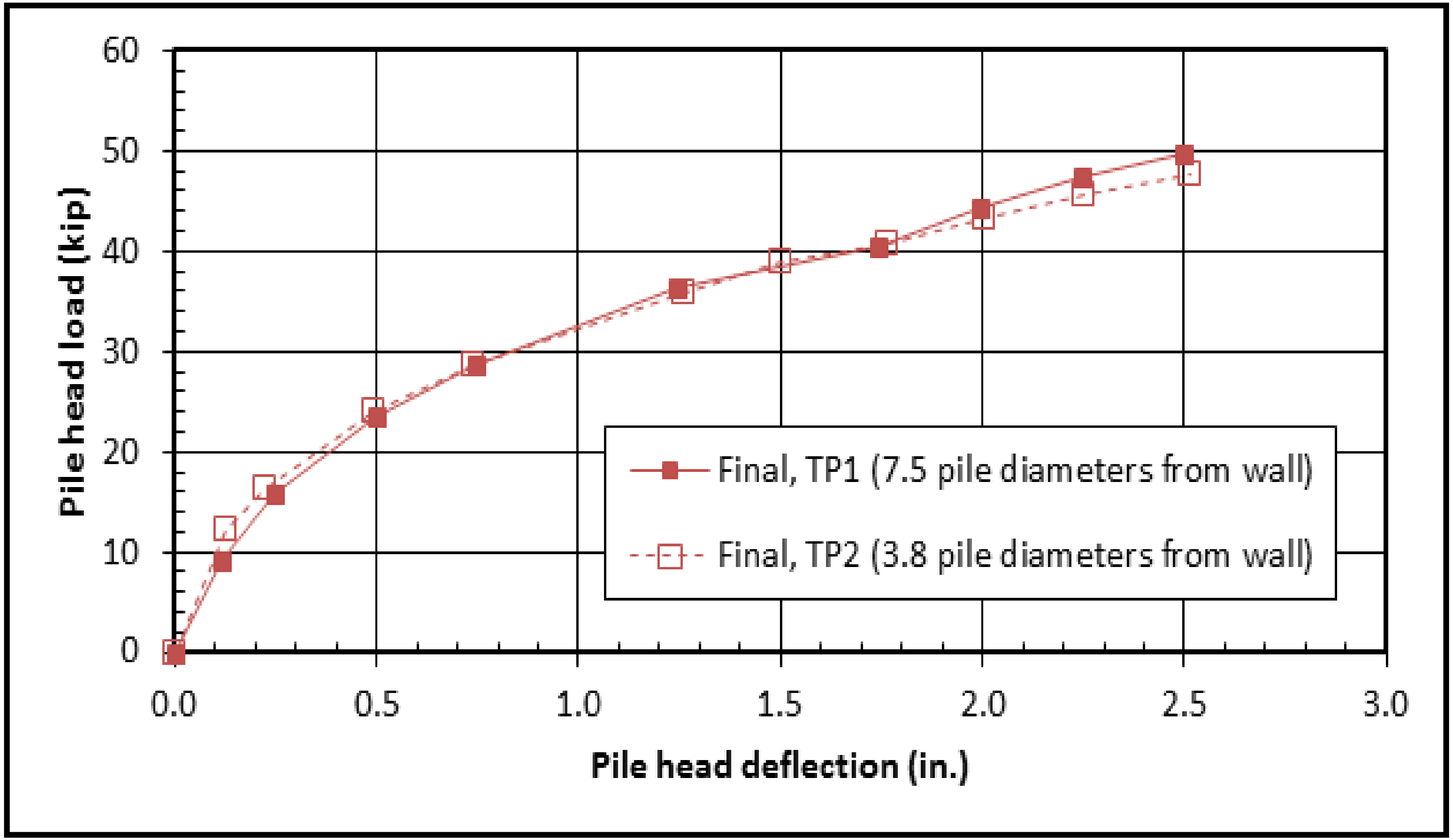
Estimate a Reduction Factor



What should the reduction be?

Initial Field Testing at Bridges Under Construction

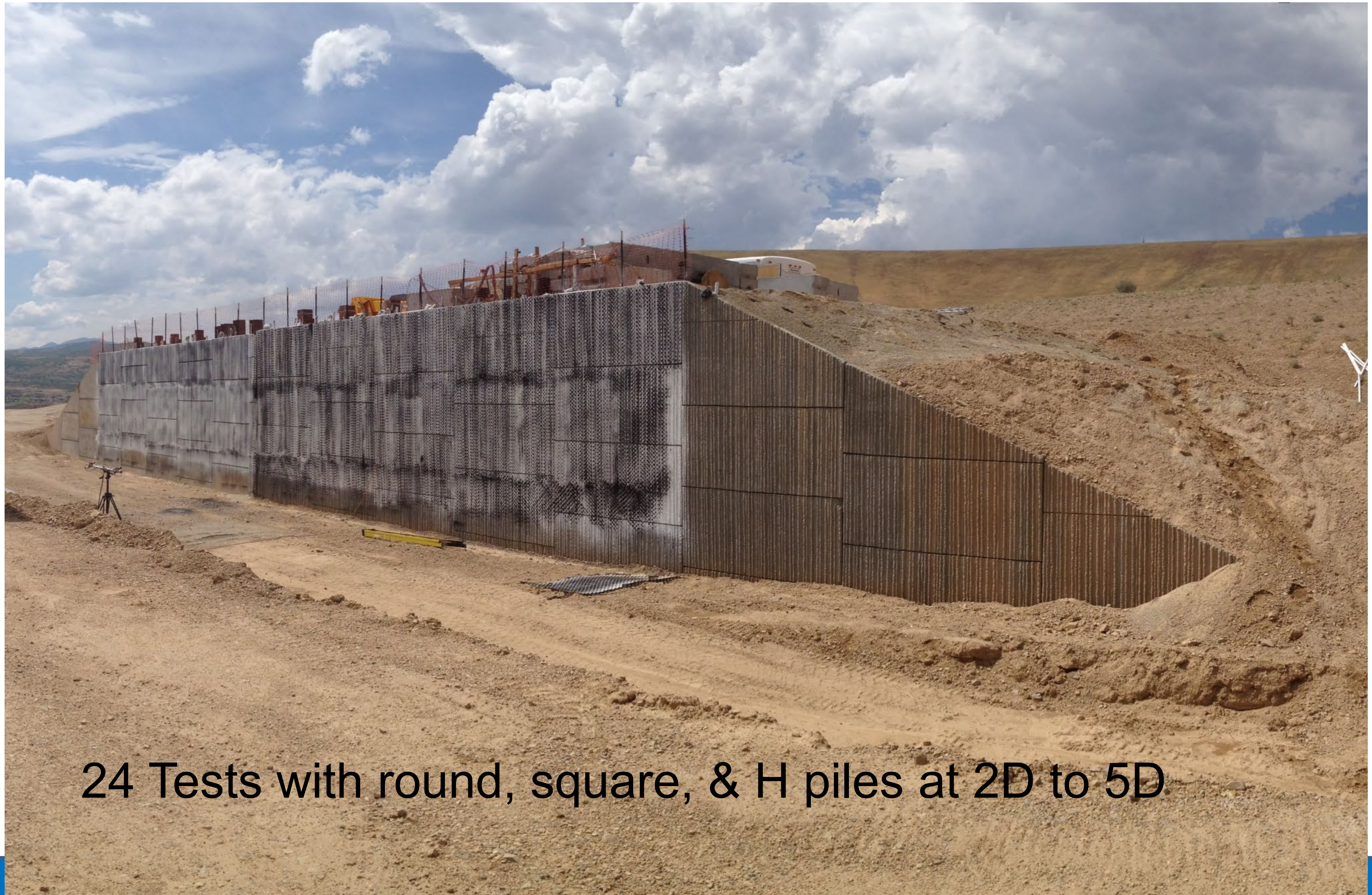
U.S. Hwy 89 Lateral Load vs. Deflection



Large-Scale Field Testing

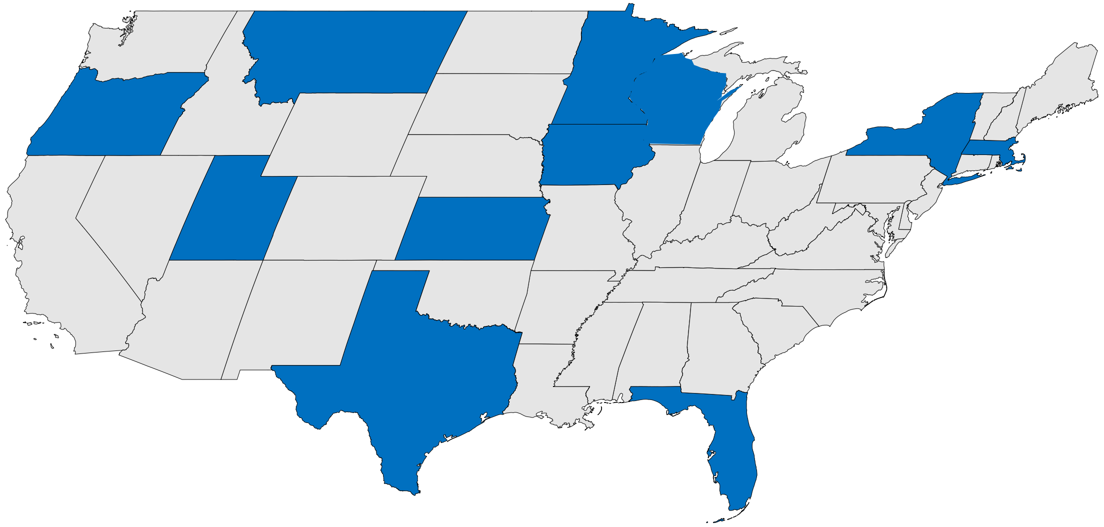
Mechanically Stabilized Earth Abutment Wall

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



FHWA Pooled Fund Sponsors

- Utah DOT – Lead Agency
- Florida DOT
- Iowa DOT
- Kansas DOT
- MassDOT
- Minnesota DOT
- Montana DOT
- New York DOT
- Oregon DOT
- Texas DOT
- Wisconsin DOT



Students on Piles behind MSE Walls


Jake Price


Kent Nelson


Andrew Luna


Ryan Budd


Cody Hatch

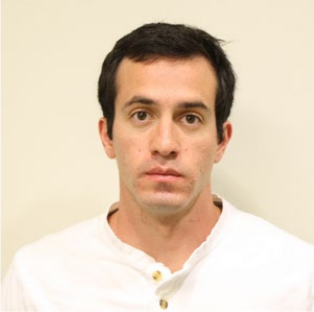

Jason Besendorfer


Jarell Han

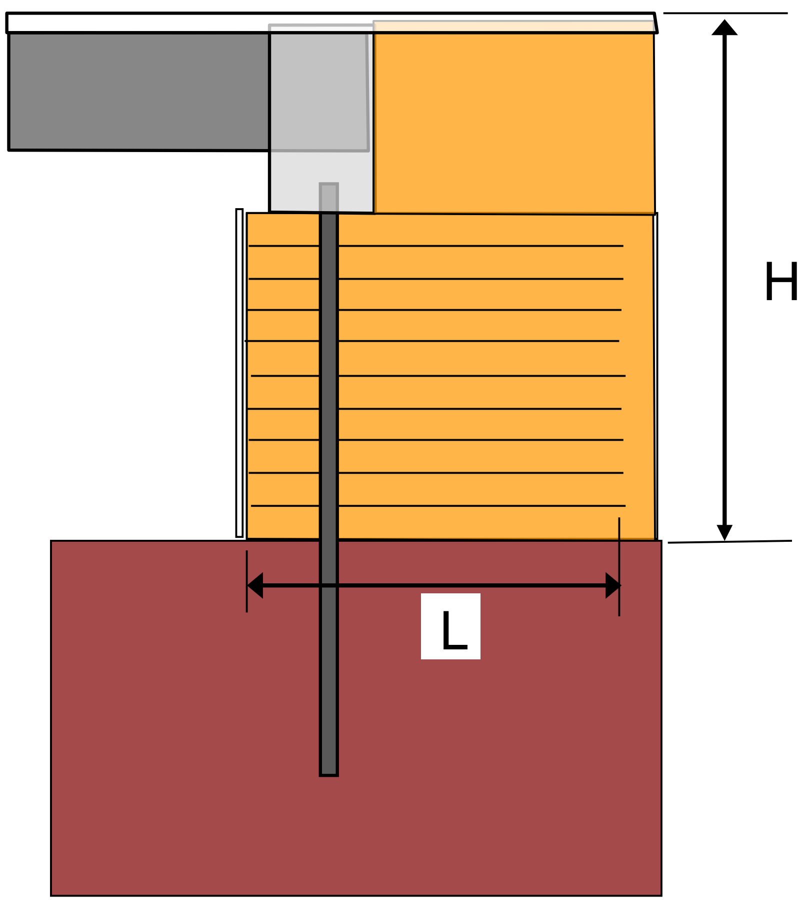

Addison Wilson


Pedro Garcia

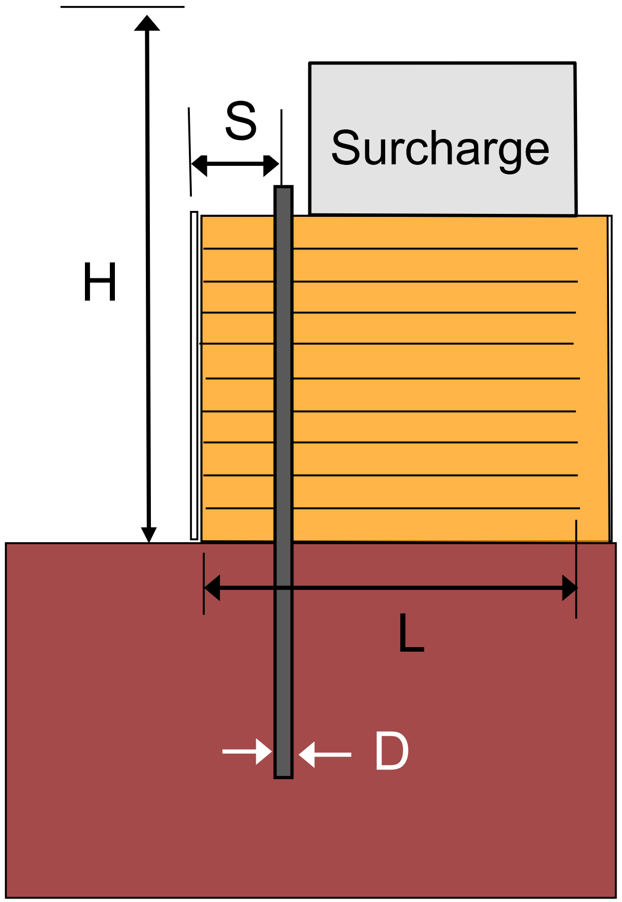

Zachary Farnsworth


Guillermo Bustamante

Profile View of Test Layout

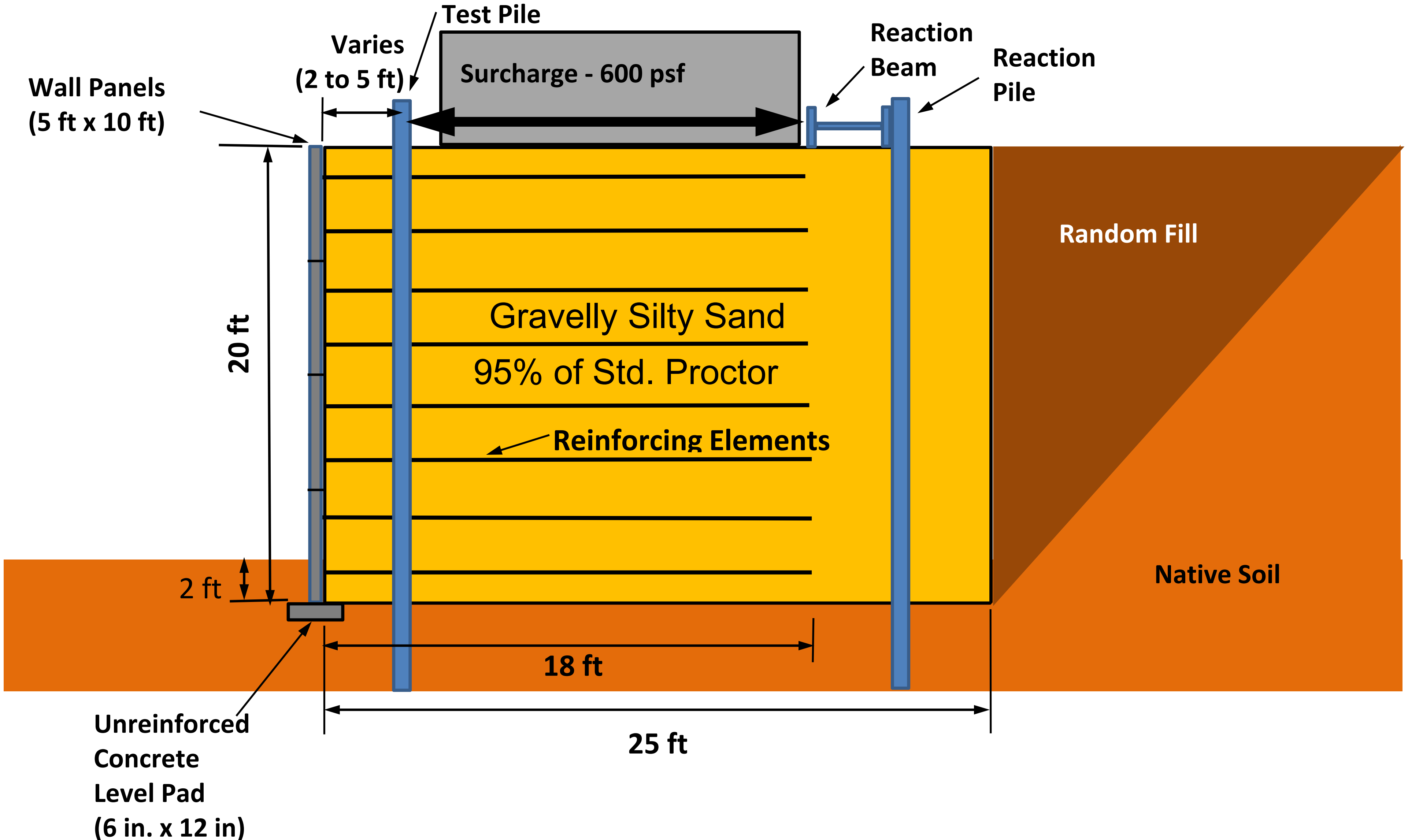


Ultimate Design

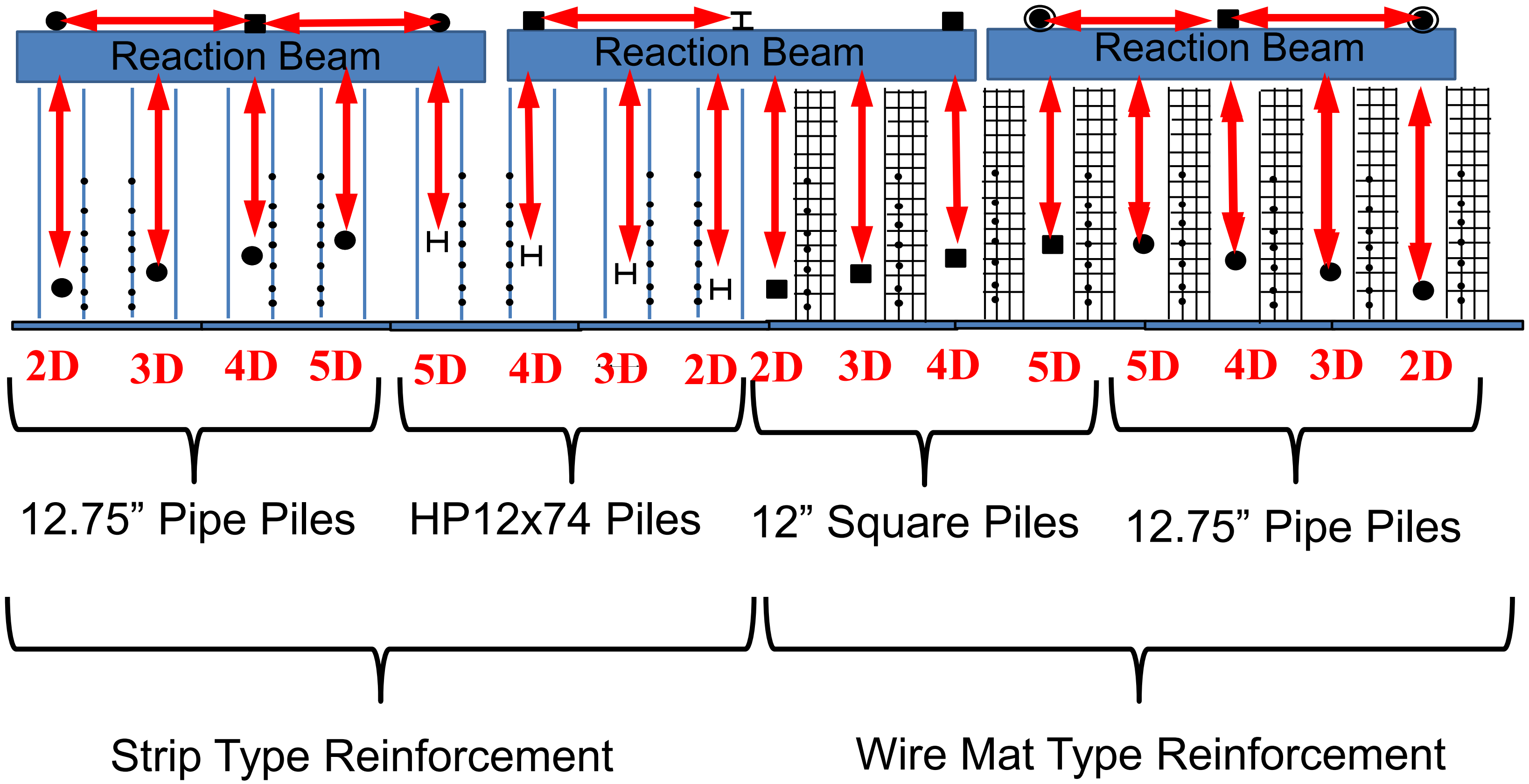


Layout During Tests

Cross-Section Through MSE Wall



Pile Testing Sequence



20 ft Wall L/H = 0.7

15 ft Wall L/H = 0.9

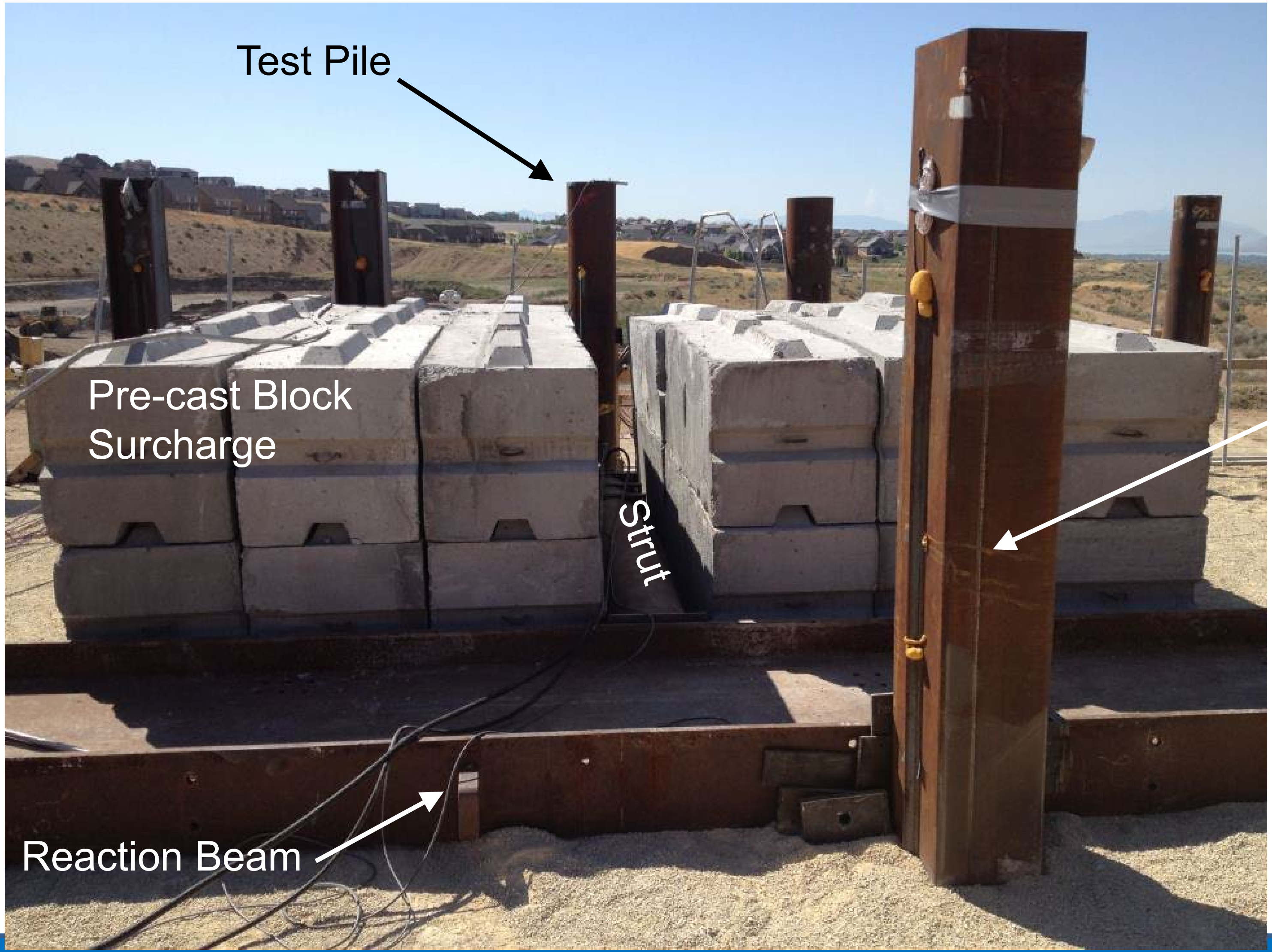
Total of 31 Tests

Installation of Reinforcements

Ribbed-Strip Reinforcements

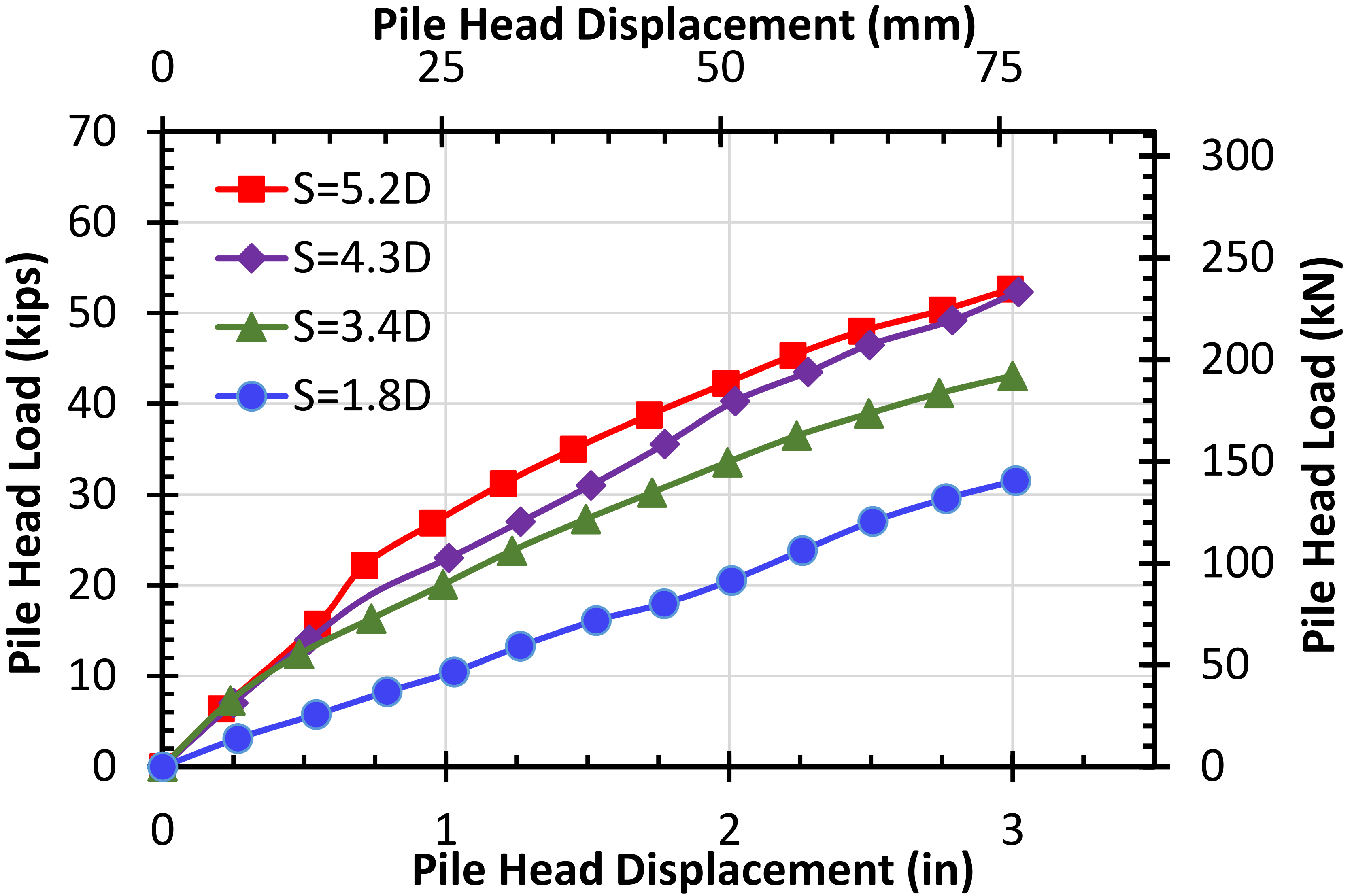
Welded Wire Reinforcements

Typical Load Test Set-up

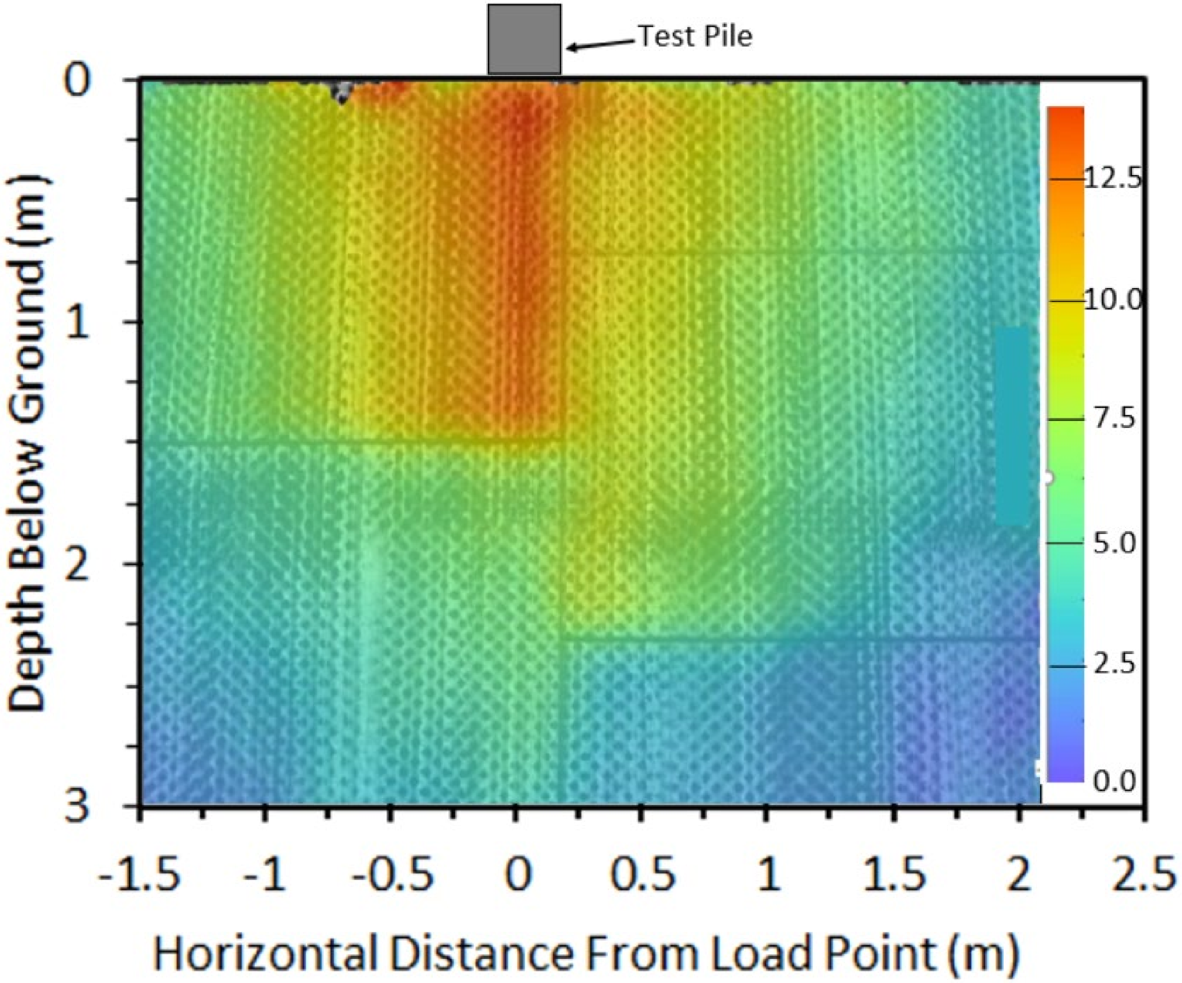


Reaction Pile

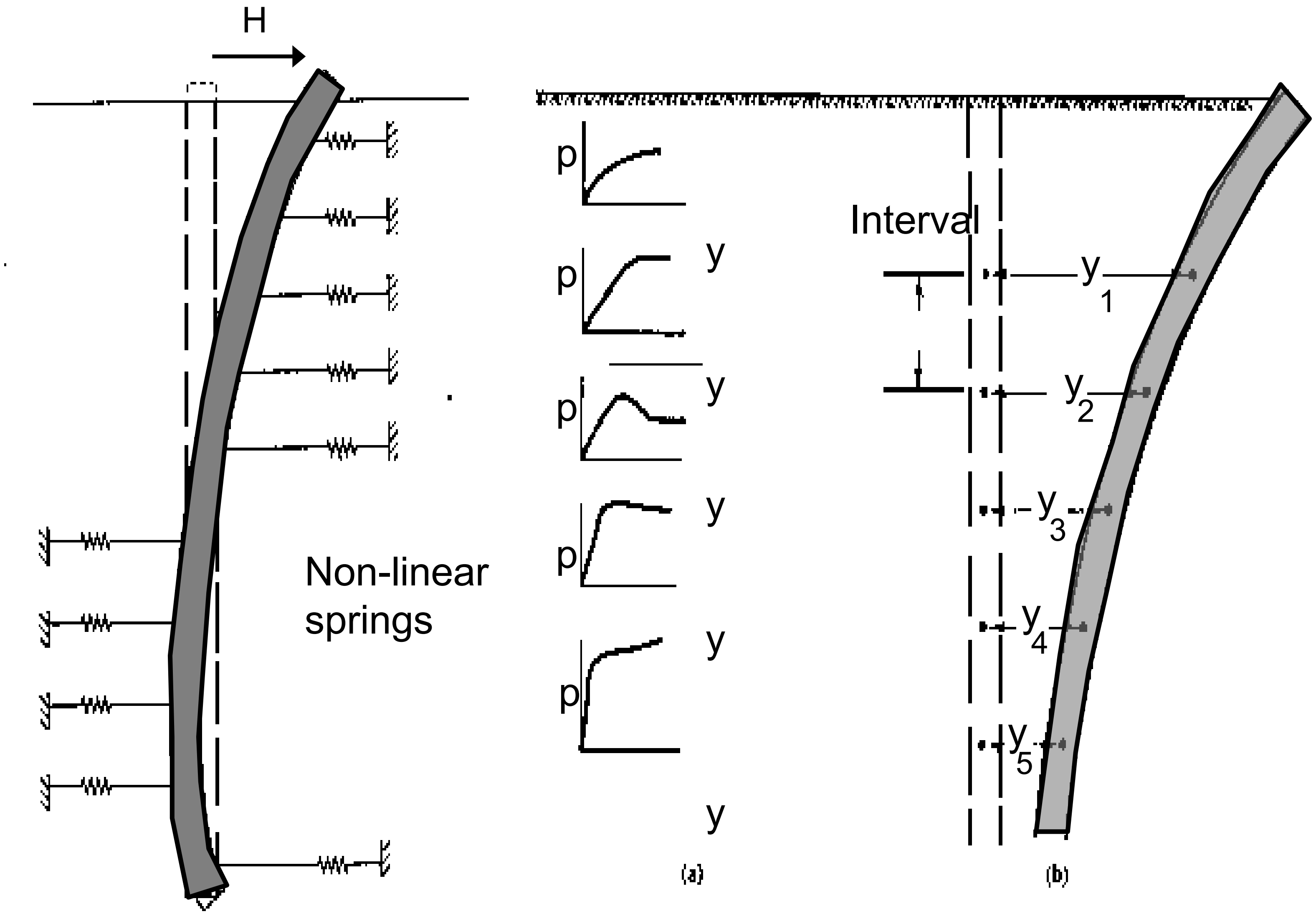
Measured Load-Deflection Curves



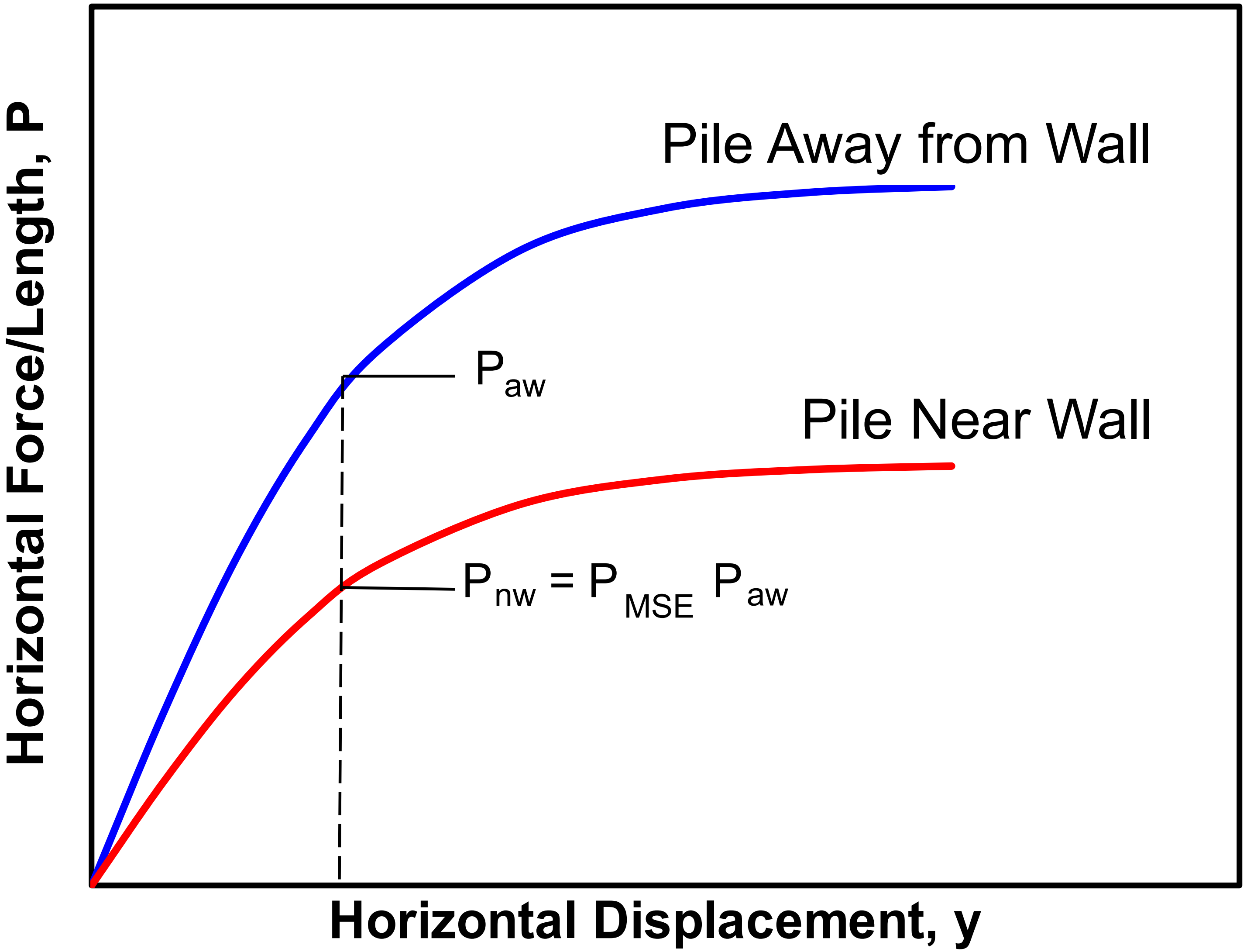
Digital Image Correlation System for Wall Displacement



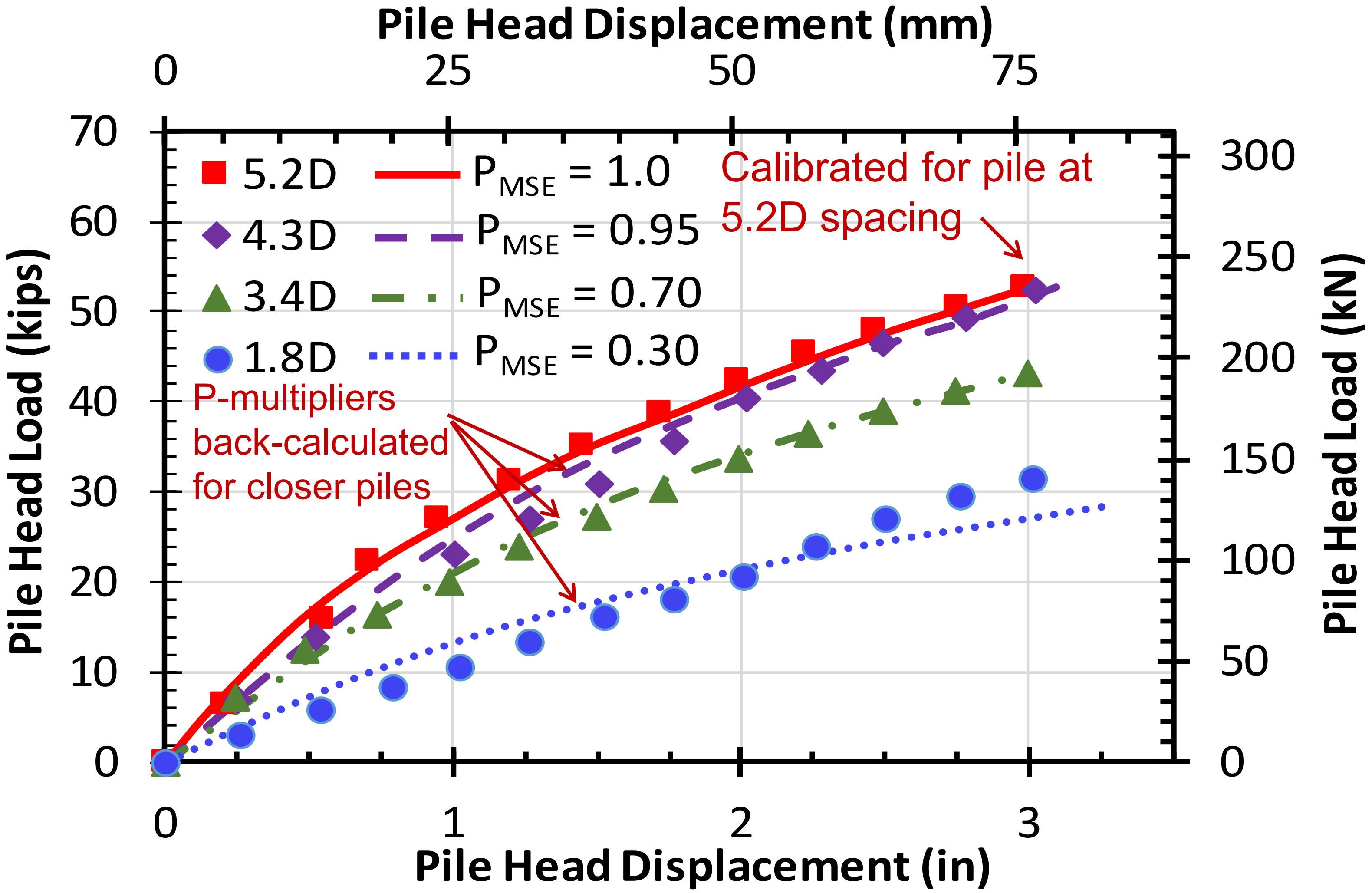
Lateral Load Analysis for Piles with *p-y* Curves



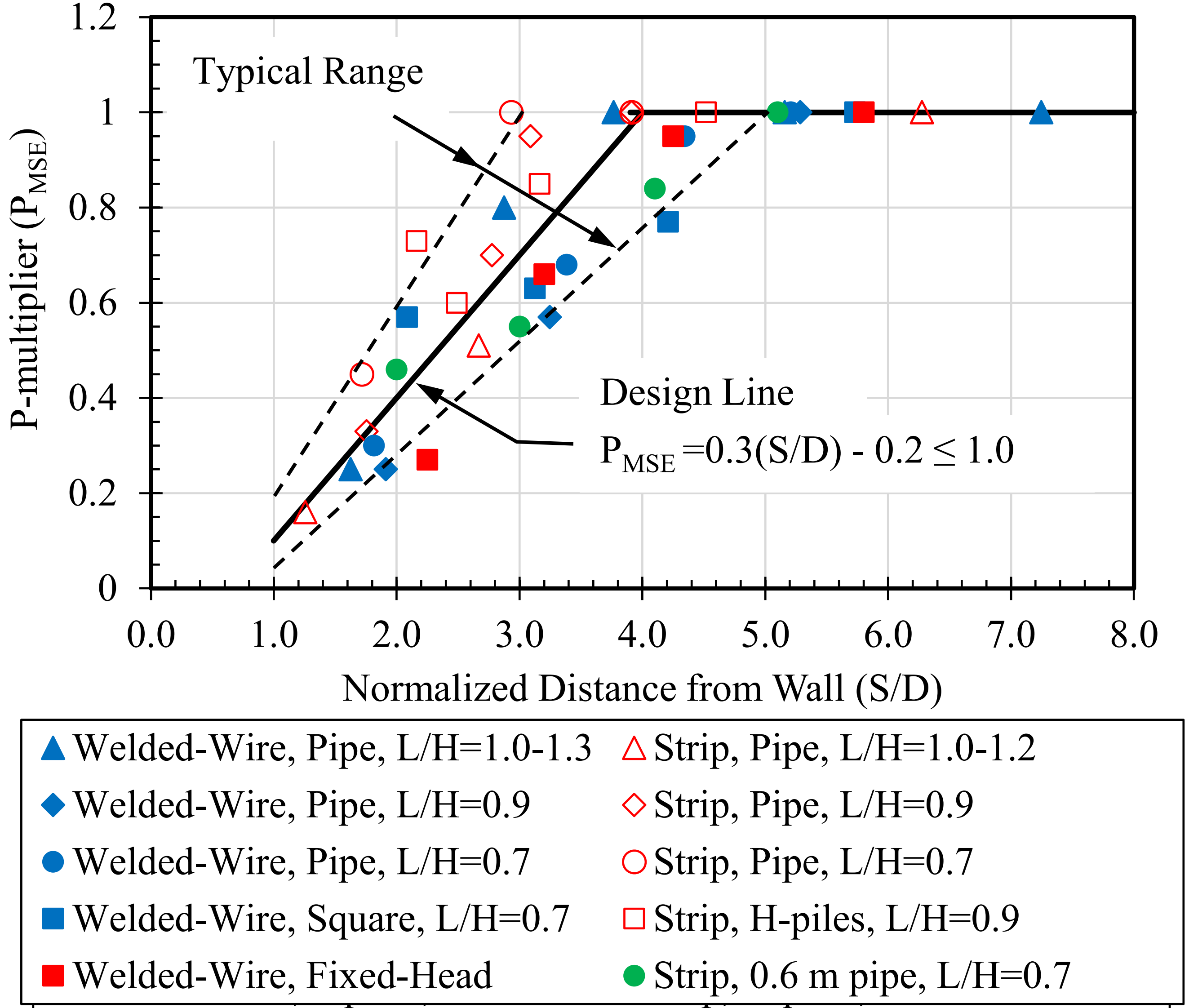
P-multiplier Concept For Proximity of the Wall



Measured and Computed Load-Deflection Curves

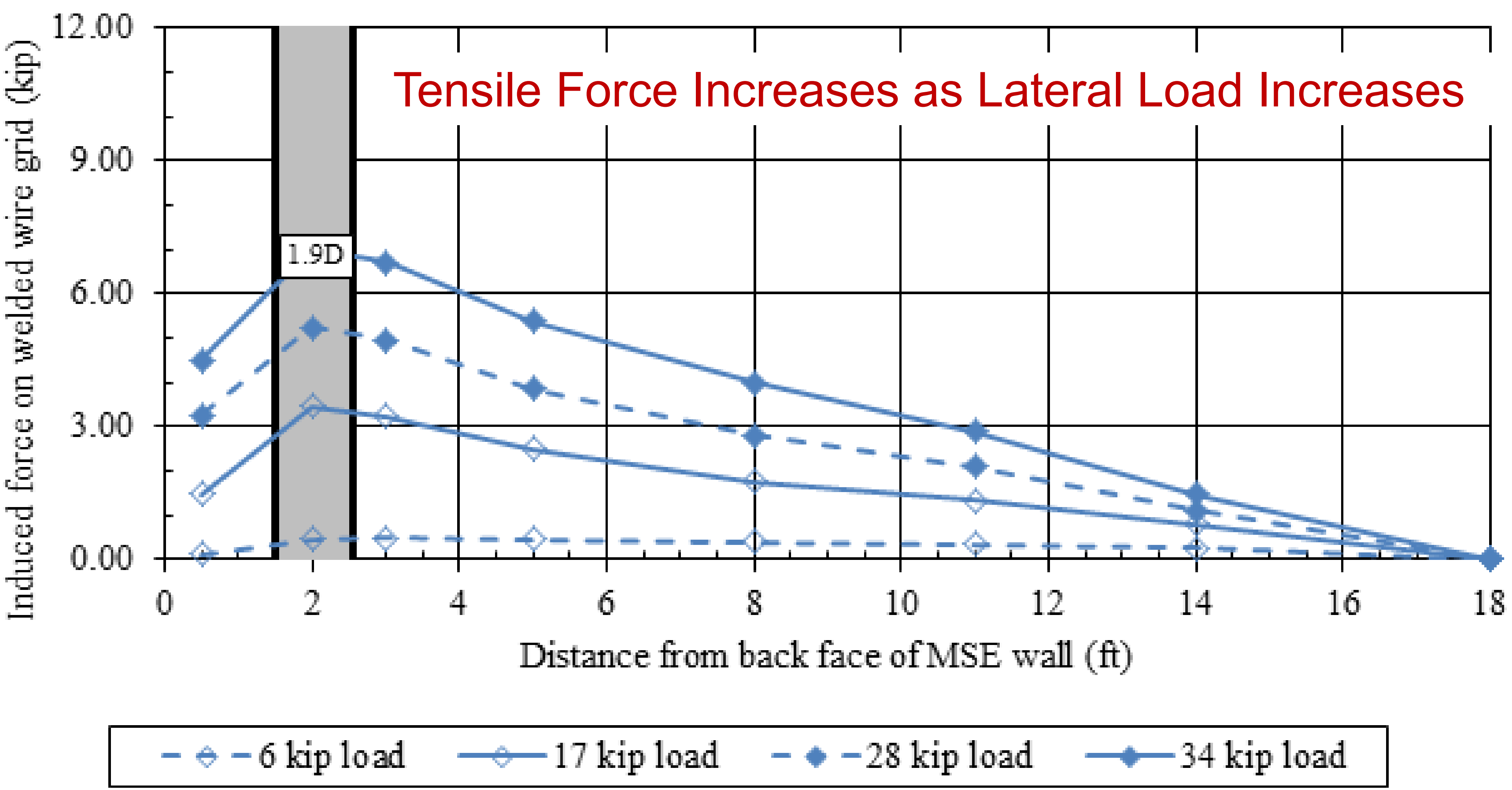


P-multipliers from All Tests - 12 inch Piles

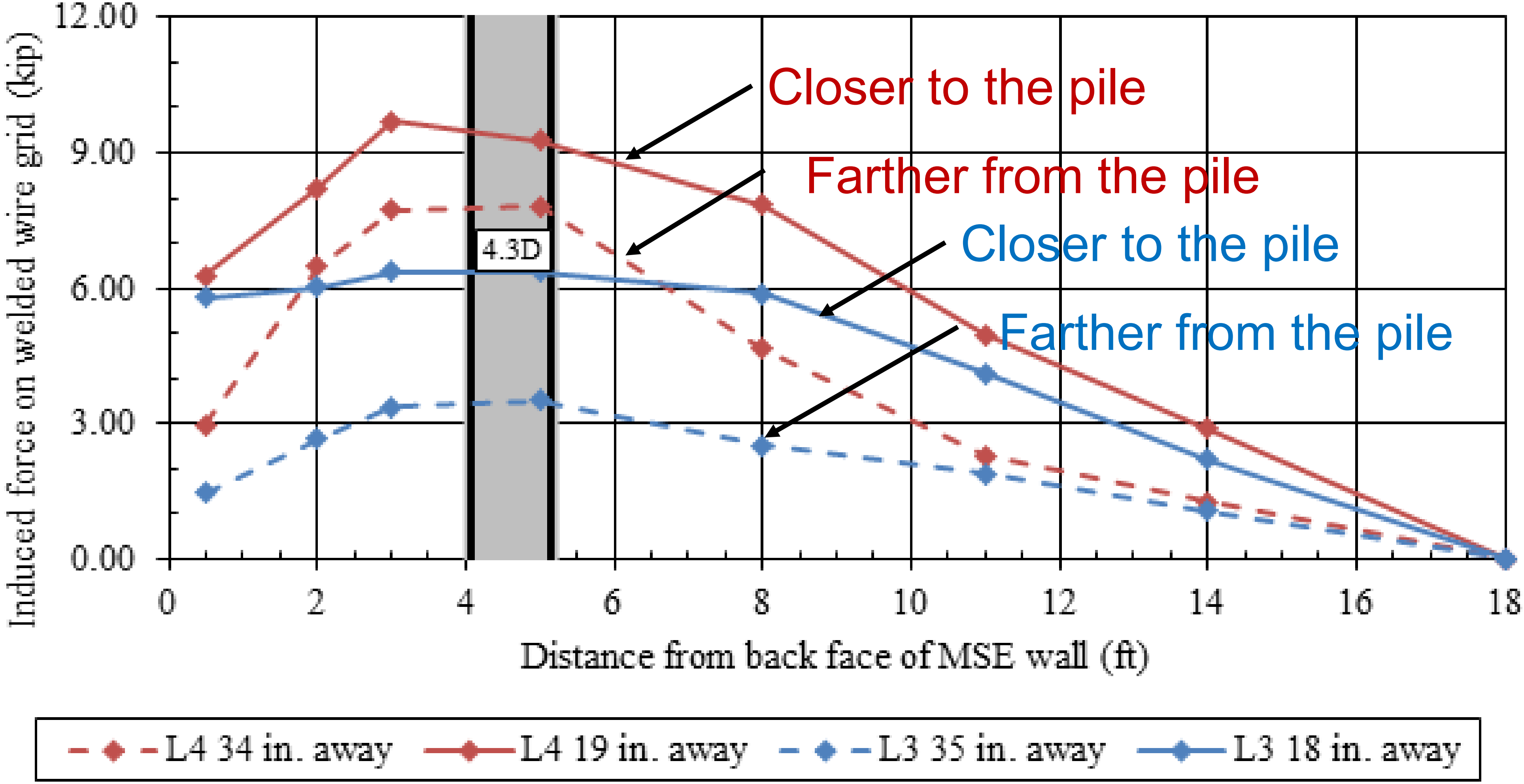


Induced Force on Reinforcements

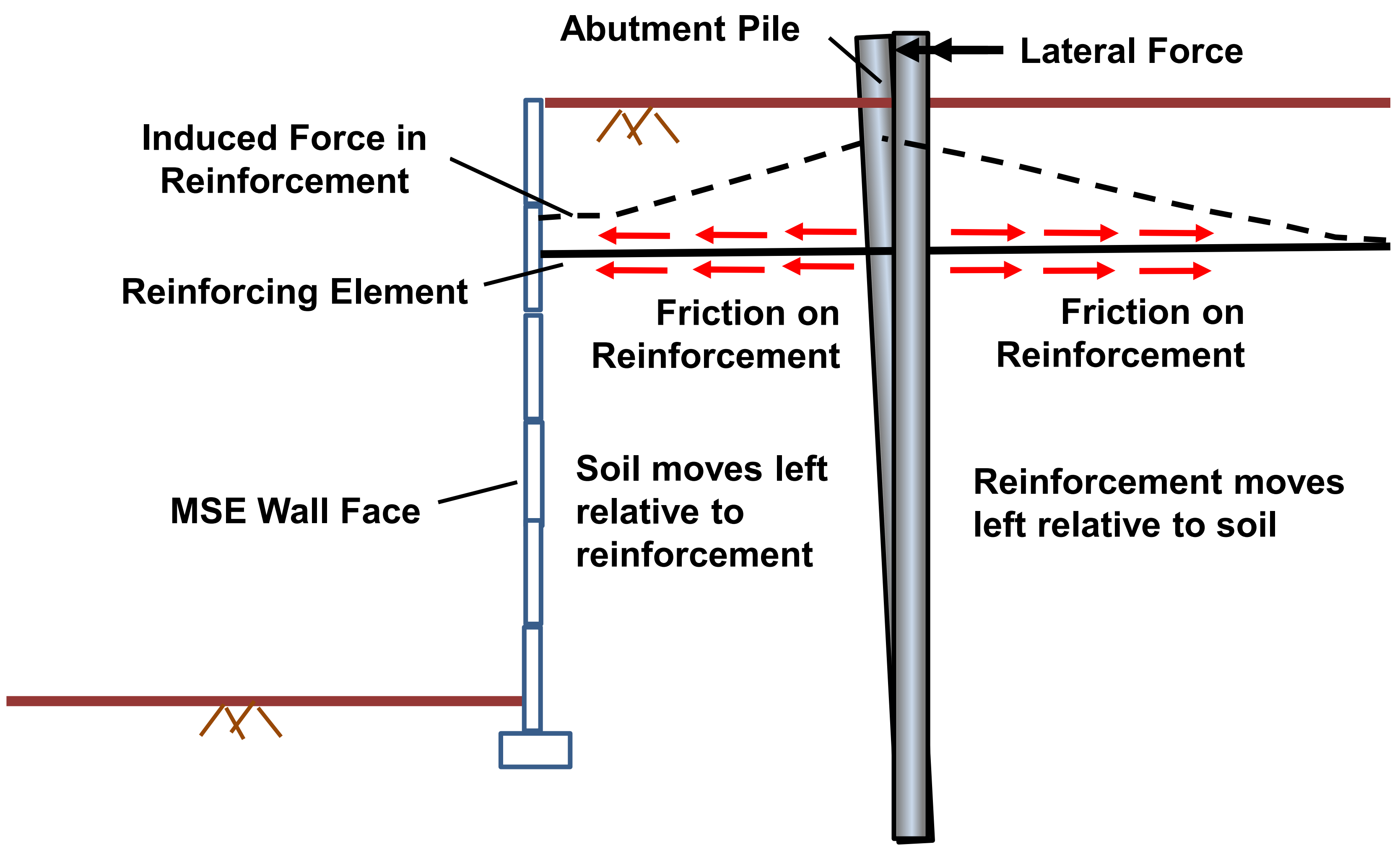
Effect of Lateral Load on Tensile Force



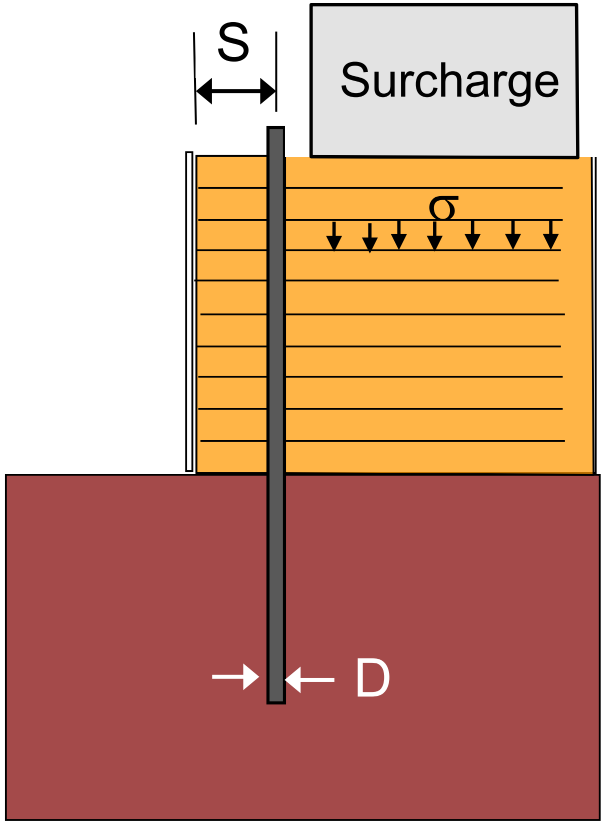
Effect of Transverse Distance on Tensile Force

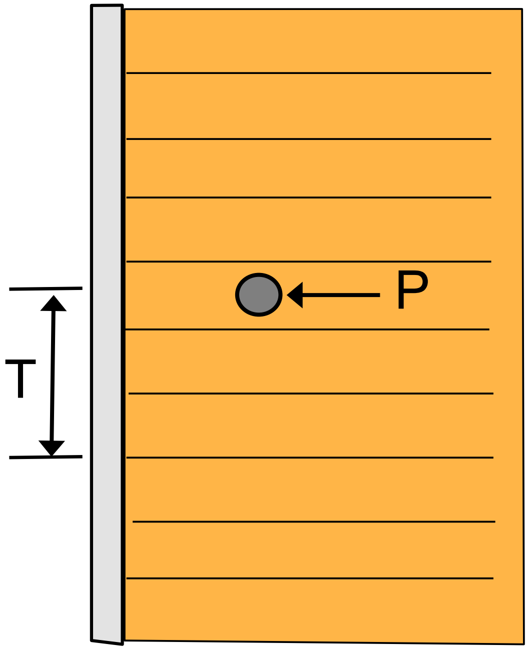


Schematic of Pile-Reinforcement Interaction



Parameters Affecting Max. Reinforcement Force





P = Applied lateral load (kips)

σ = Vertical Stress (psf)

T = Transverse distance from load point (Normalized by D)

S = Distance Behind the wall (Normalized by D)

Statistical Regression Equations

Ribbed Strip Reinforcement

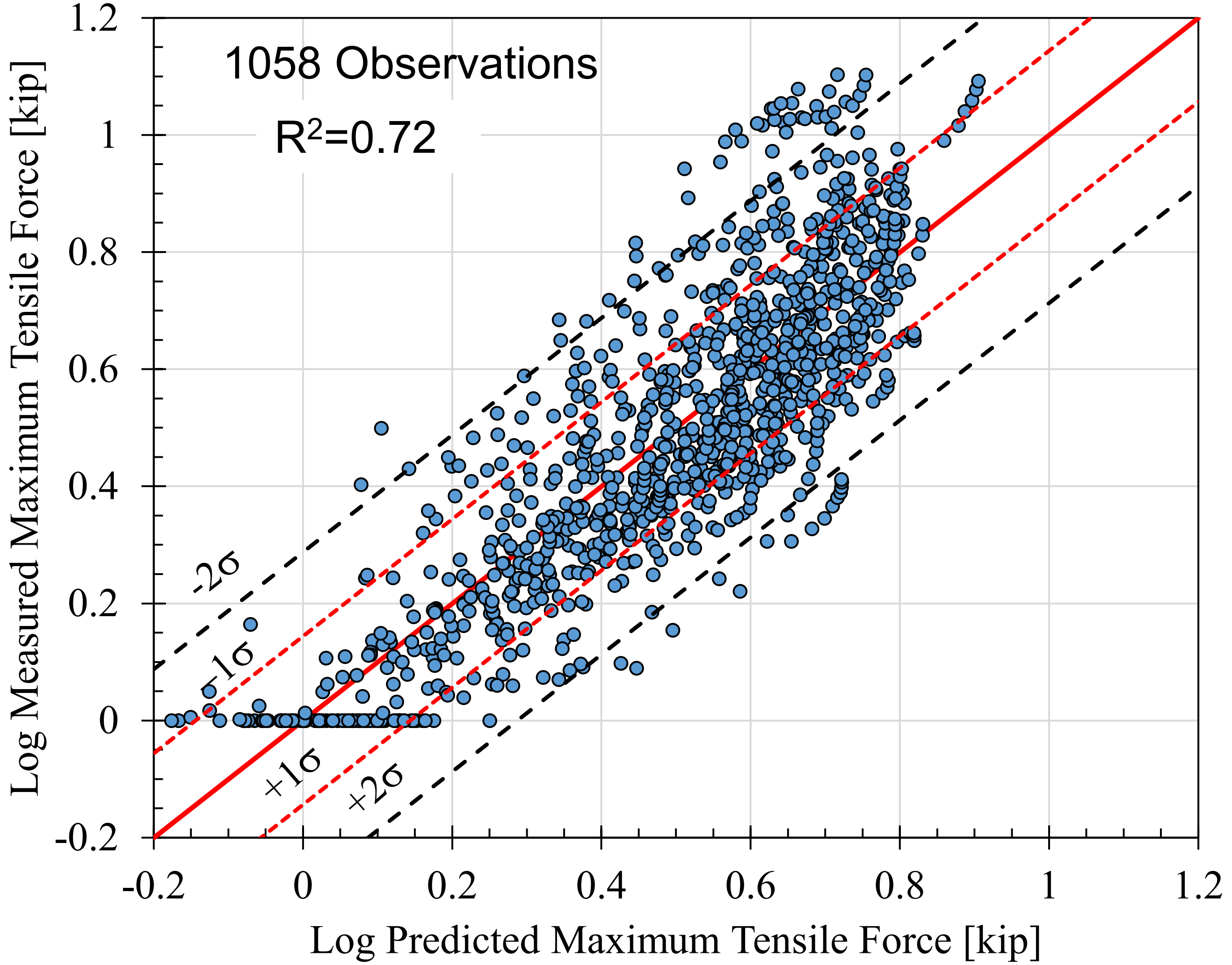
$$\Delta F = 10^\wedge\left(0.13 + 0.028P - 2.2x10^{-4}P^2 - 0.01\frac{T}{D} - 0.0021P\frac{T}{D} - 0.031\frac{S}{D}\right) - 1$$

Where:

ΔF is the maximum tensile force induced in the reinforcement (kips),
P is the pile head load (kips),
T is the transverse distance from the pile (in),
S is the distance from the back of wall to center of pile (in),
D is the pile diameter (in),

Log Measured vs Log Computed Induced Tensile Force

All Welded Wire Reinforcement – 5 wire grid



Statistical Regression Equations

All Welded Wire Reinforcement

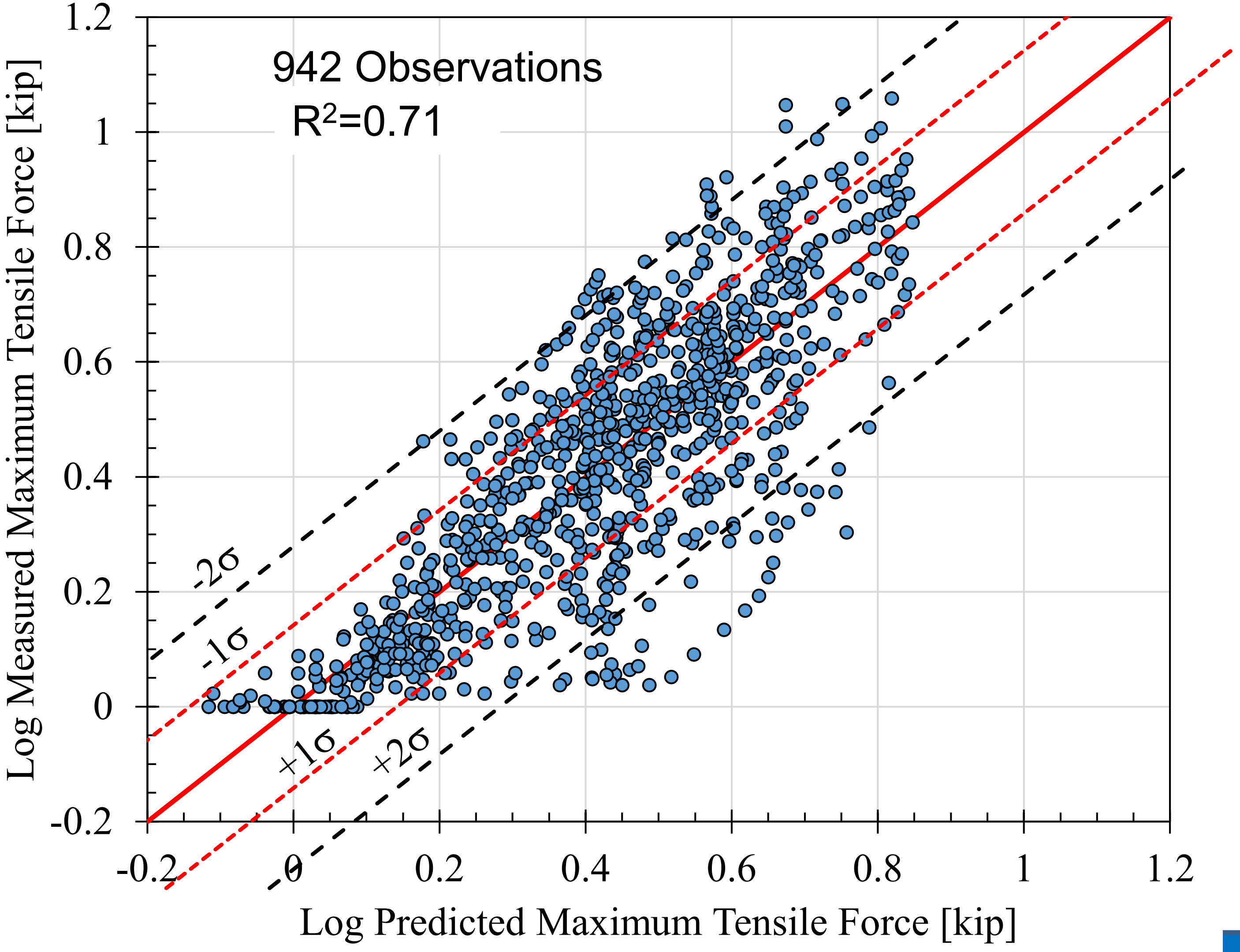
$$\Delta F = 10\wedge\left(-0.04 + 0.027P - 2.7x10^{-4}P^2 + 5.7x10^{-4}\sigma_V - 2.6x10^{-7}\sigma_V^2 - 0.08\frac{T}{D}\right) - 1$$

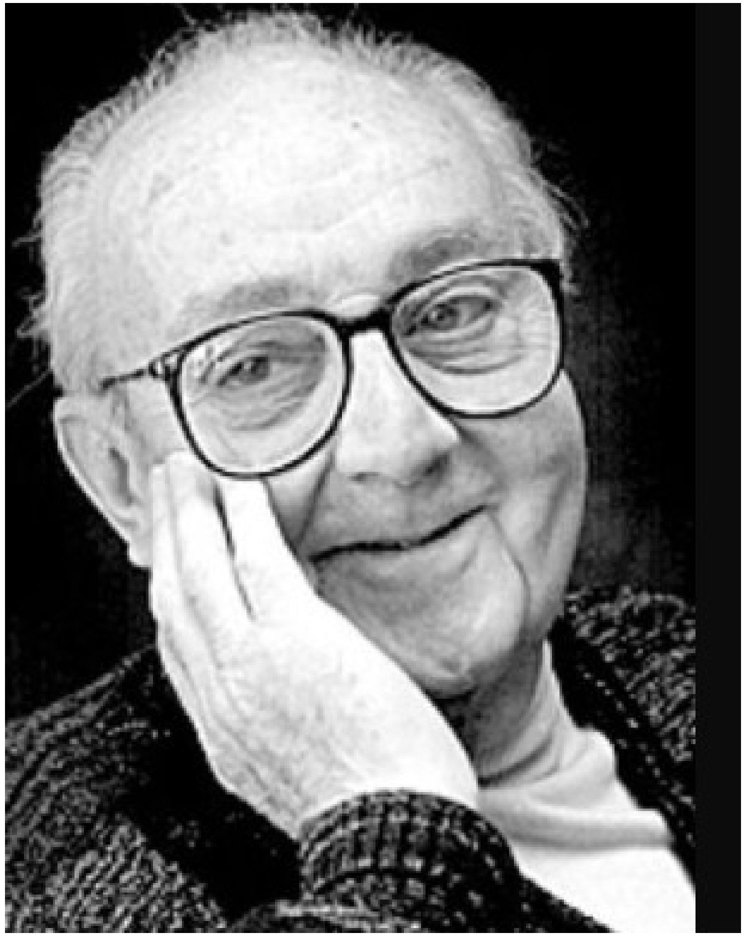
Where:

ΔF is the maximum tensile force induced in the reinforcement (kips),
P is the pile head load (kips),
σ_v is the vertical stress on the reinforcement (psf),
T is the transverse distance from the pile (in),
D is the pile diameter (in),

Measured vs Computed Induced Tensile Force

All Strip Reinforcement – Single strip





"…all models are approximations. Essentially, all models are wrong, but some are useful. The approximate nature of the model must always be borne in mind"

-- George E. P. Box

Eminent Statistician

Conclusions Regarding Piles Near MSE Walls

- Significant reductions in lateral resistance as piles are placed closer than about 4D from the wall
- Simple p-multiplier approach can account for reduction in lateral resistance
  - P_{MSE} = 1.0 for S > 4D
  - P_{MSE} decreases linearly for smaller spacings
- Maximum reinforcement force:
  - Occurs near the pile location
  - Increases with applied load
  - Increases as pile is placed closer to wall
  - Decreases with transverse distance from the pile
  - Statistical regression equations can account for ≈ 72% of variation

Questions?

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