Implementation of Laterally Loaded Piles in Multi-Layer Soils

JTRP SPR- 3261

Final SAC meeting

SAC members

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Purdue University

Introduction

- Analysis developed for the design of laterally loaded piles in multi-layer soil using energy principles (SPR 2630)

- Analysis validation for piles in sand
  - Model pile lateral load tests

    (single piles and pile groups)
    - Driven
    - Preinstalled
    - Jacked

Objectives

- Study the response of piles subjected to lateral load through a series of model pile load tests
- Evaluate the effect of pile installation (driven, jacked and preinstalled) on pile response
- Compare the model pile experimental results with results from the analysis for preinstalled model piles

General scope of work

Task 1 Purchase of sensors

Task 2 Fabrication of piles and pile caps

Task 3 Fabrication of jacking system

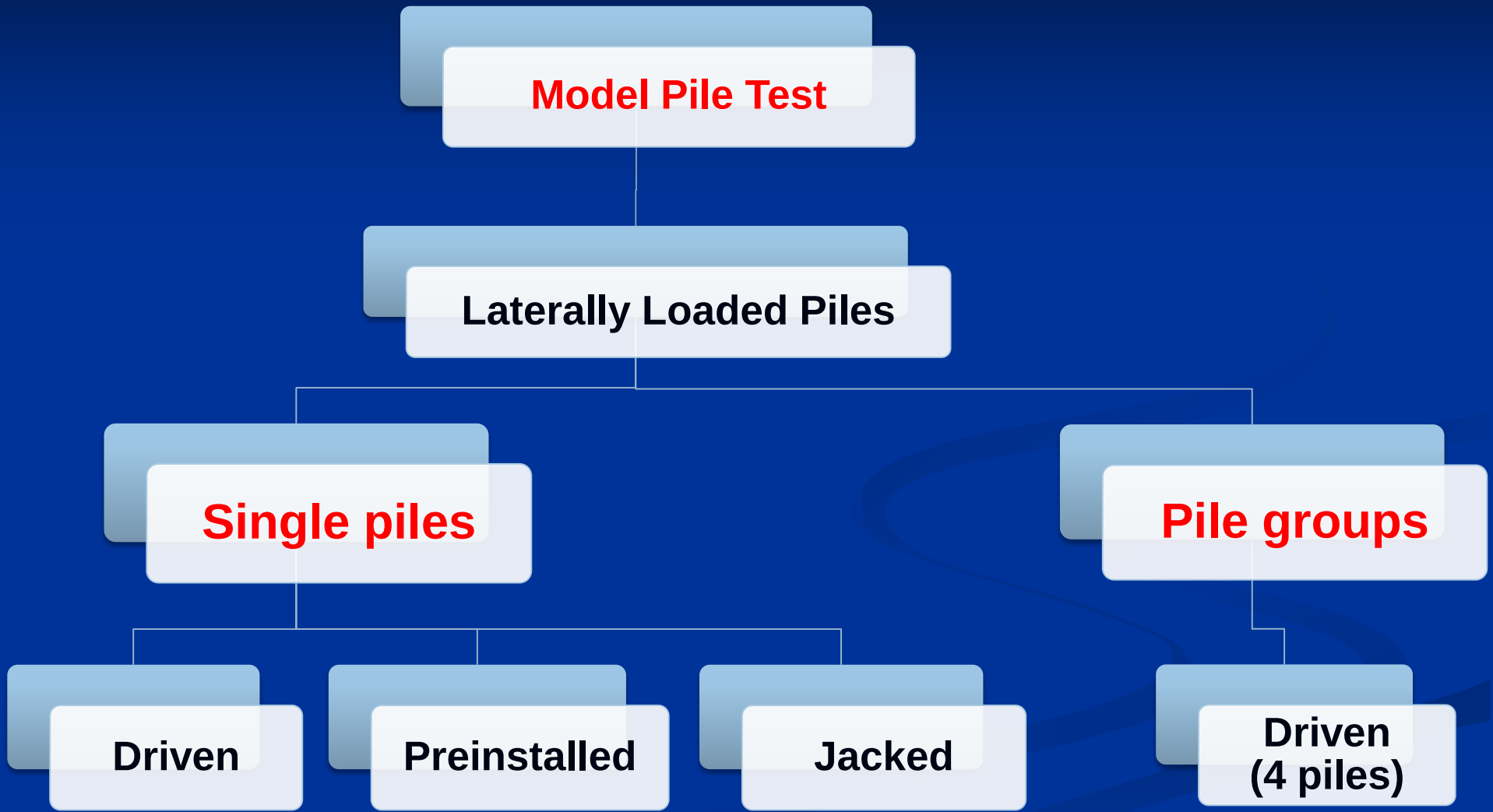
Task 4 Performance of model pile load tests

Task 5 Validation of the analysis

Contents

- Model pile testing plan
- Model pile testing
  - Sample preparation
    - Soil tank
    - Sand pluviator
  - Instrumented model pile
    - Driving system
    - Preinstallation method
    - Jacking system
  - Installation of piles for pile group testing
  - Lateral loading system
- Comparison of test and analysis results
  - Single piles
  - Pile groups
- Summary and Conclusions

Model pile testing plan



Model pile testing plan

Pile	Installation	Soil Condition	Relative Density
Single pile	Driven	Dense sand	$D_R \approx 90\%$
		Medium dense sand	$D_R \approx 60\%$
		Loose sand	$D_R \approx 40\%$
		Multi-layer	$D_R \approx 60\%$, 90 %
	Preinstalled	Dense sand	$D_R \approx 90\%$
		Medium dense sand	$D_R \approx 60\%$
	Jacked	Dense sand	$D_R \approx 90\%$
		Medium dense sand	$D_R \approx 60\%$
		Loose sand	$D_R \approx 40\%$
Group piles	Driven	Dense sand	$D_R \approx 90\%$
		Medium dense sand	$D_R \approx 60\%$
		Loose sand	$D_R \approx 40\%$
		Multi-layer	$D_R \approx 60\%$, 90 %

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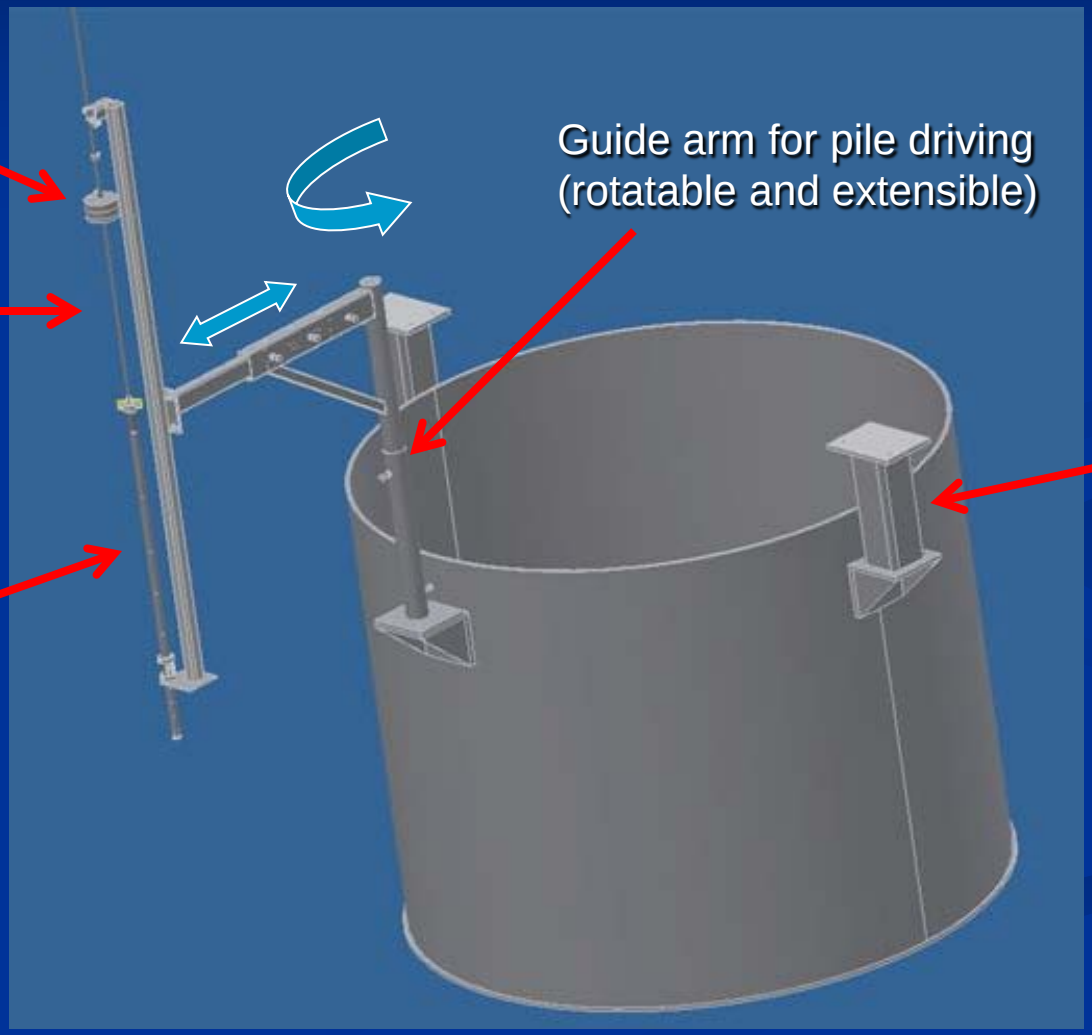
Soil tank

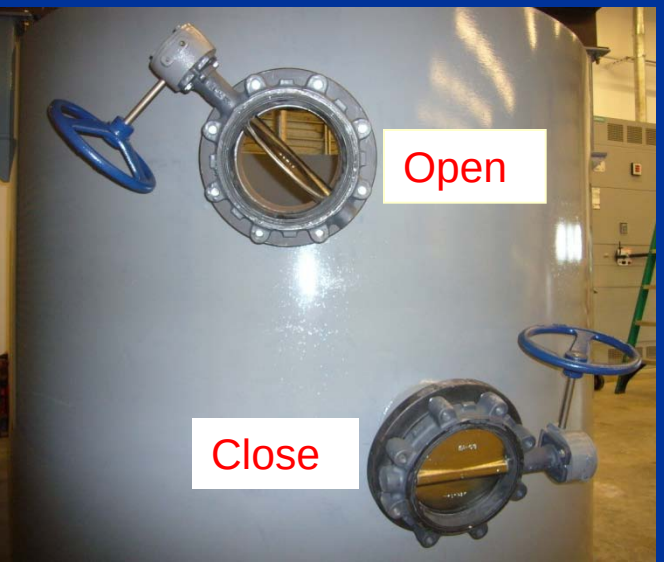
- Soil tank (D=2m, H=1.6m)



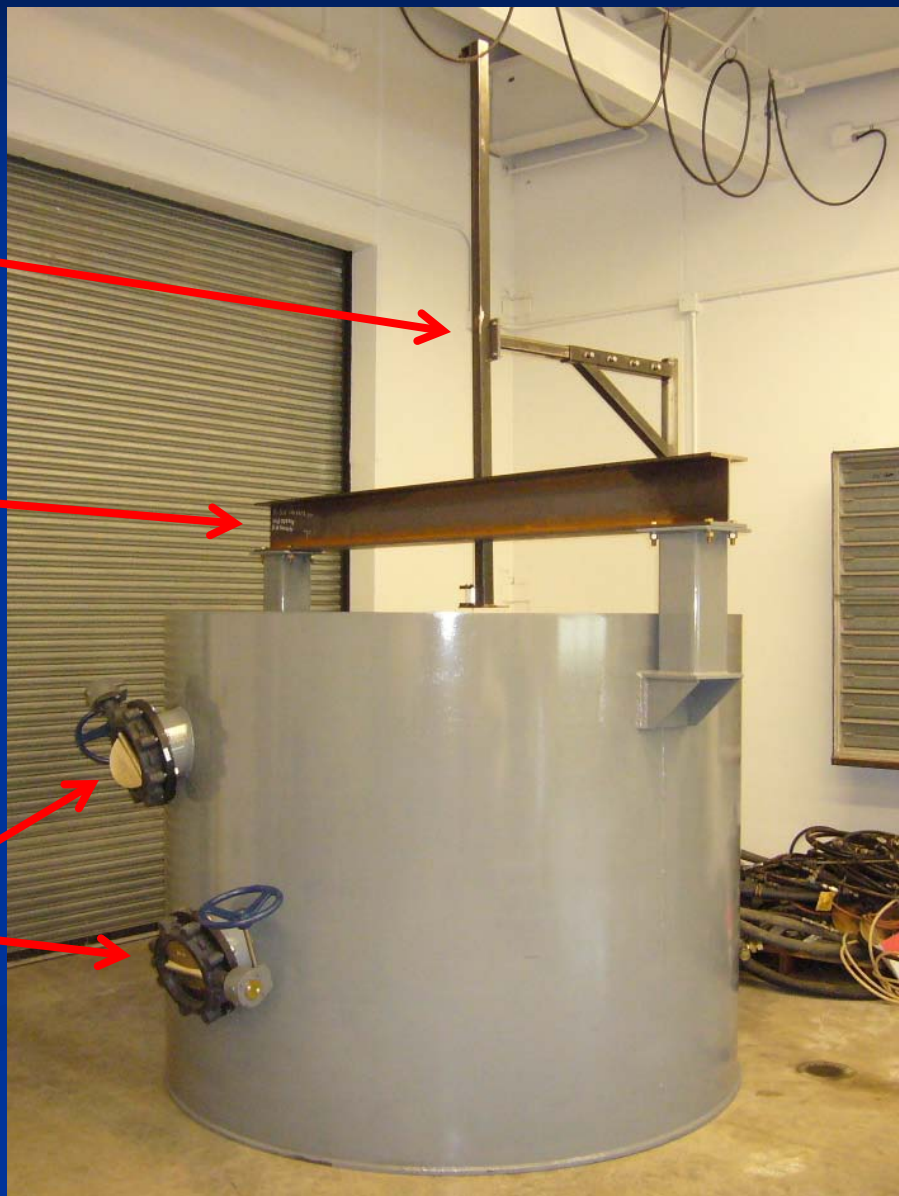
Soil tank

Guide arm for pile driving

Reaction beam (detachable)

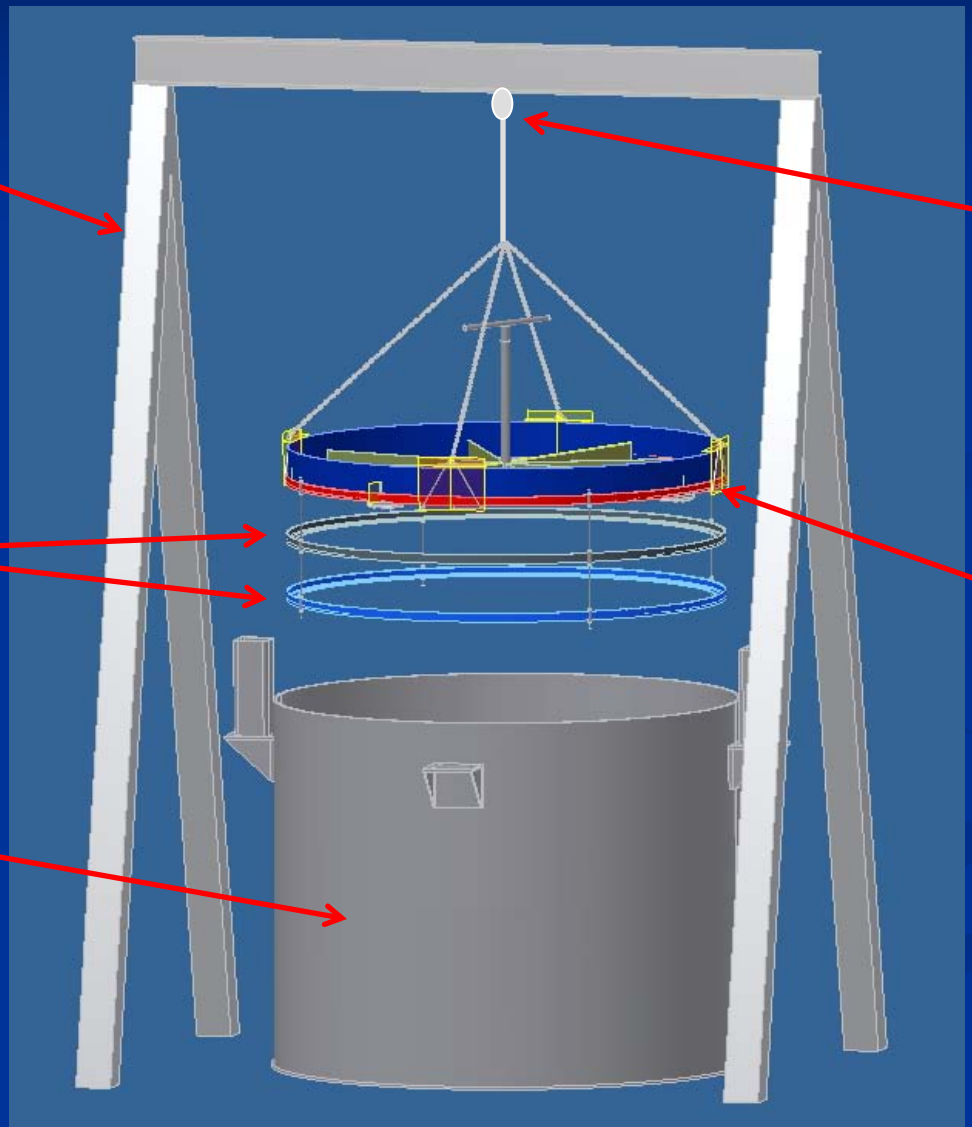


Holes for draining sand



Sand pluviator

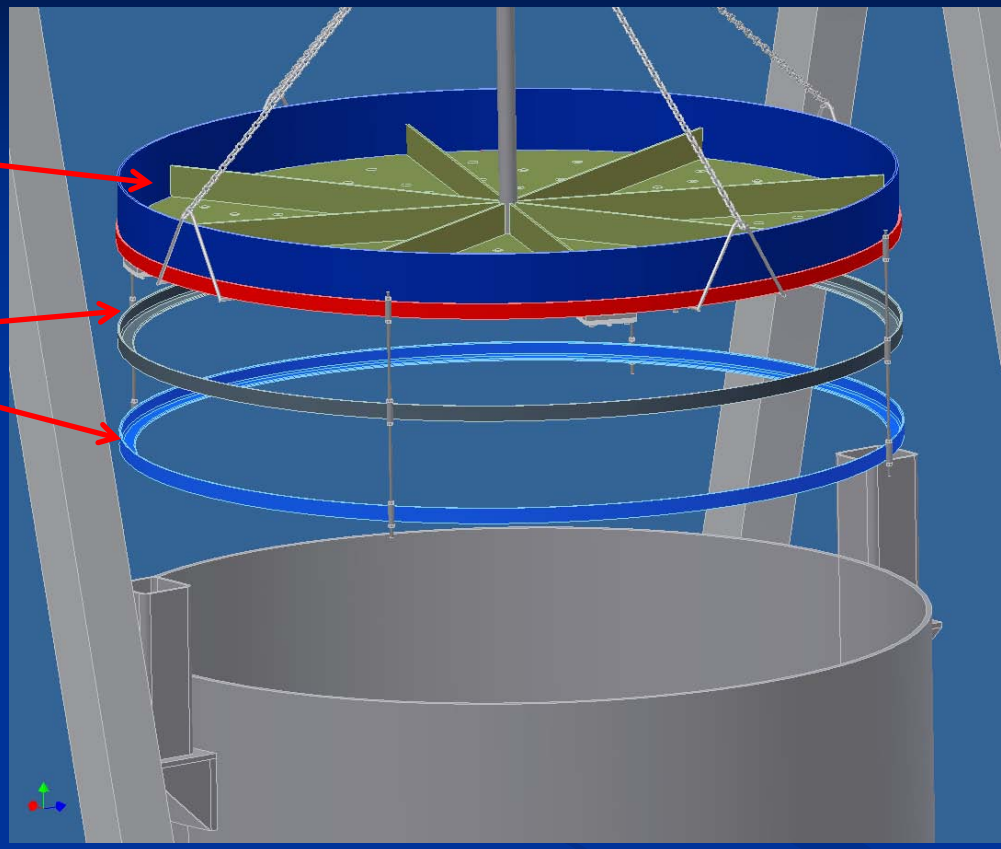
- Large-scale sand pluviation system (D=2m)

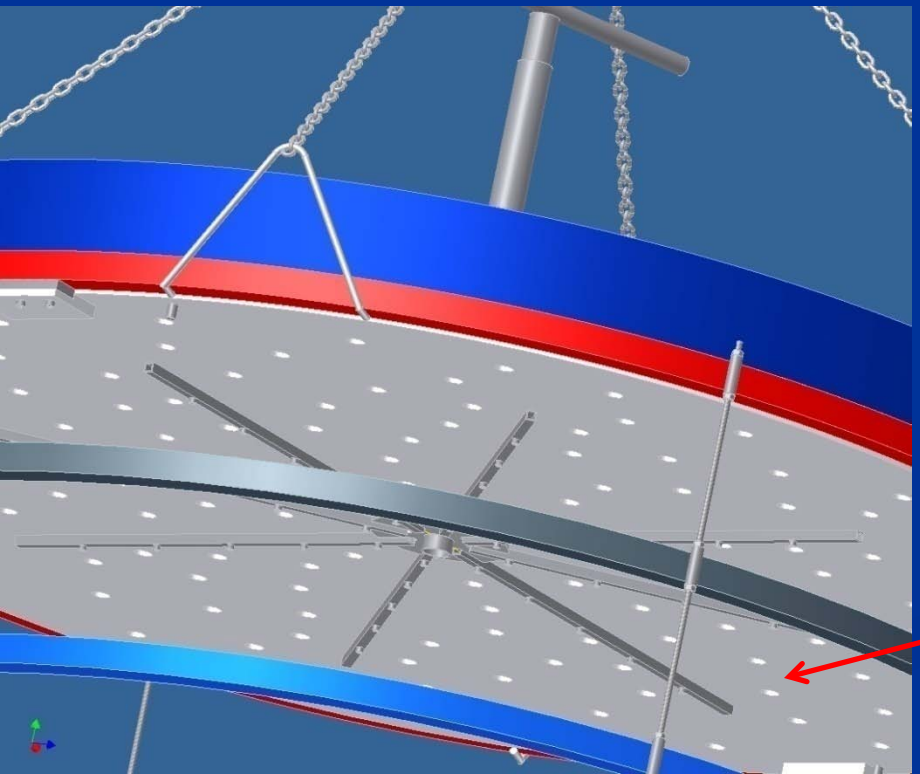


Sand pluviator

Top of pluviator

Two sieve layers

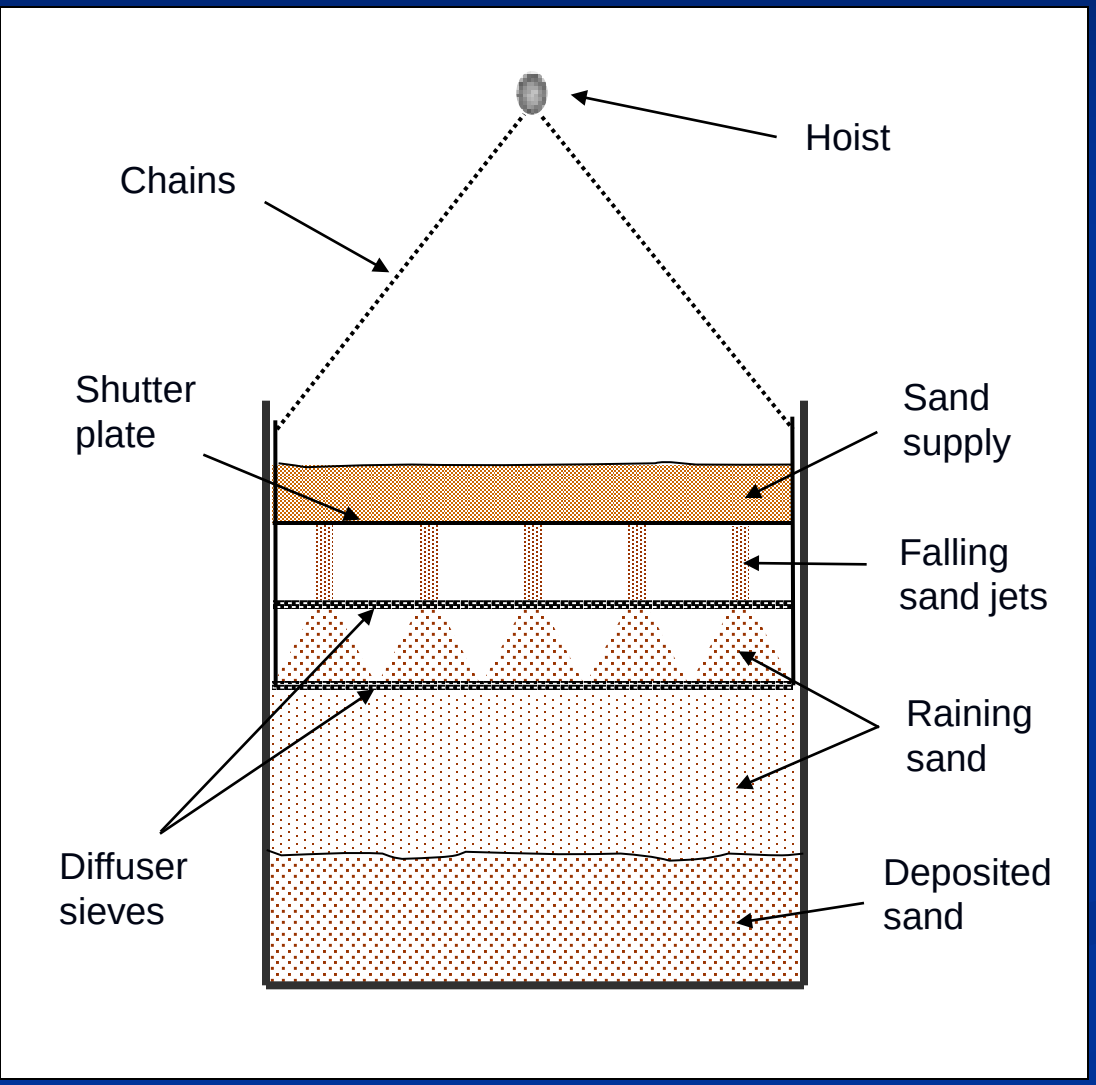




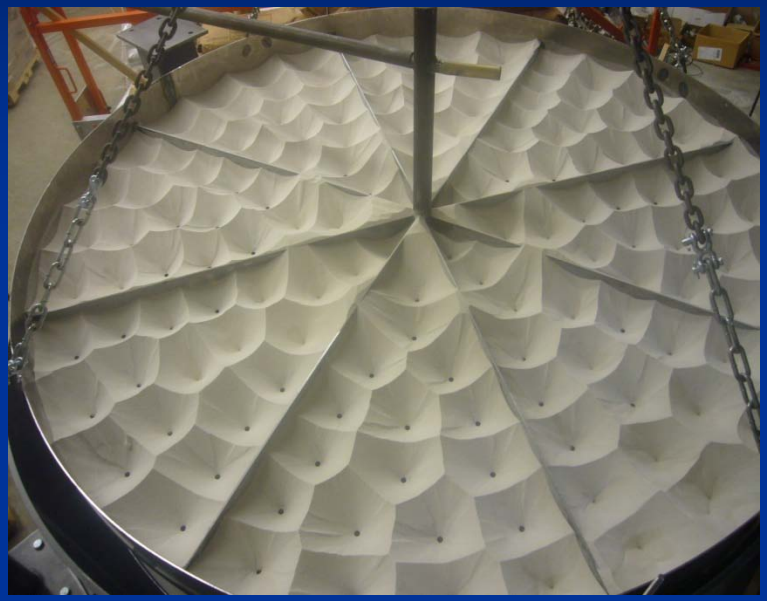
Holes for sand pluviation

Sand pluviator

- Schematic view and photo of sand pluviator



Sample preparation



Top view of pluviator

Sand pluviation

Draining sand

- Draining sand after the test

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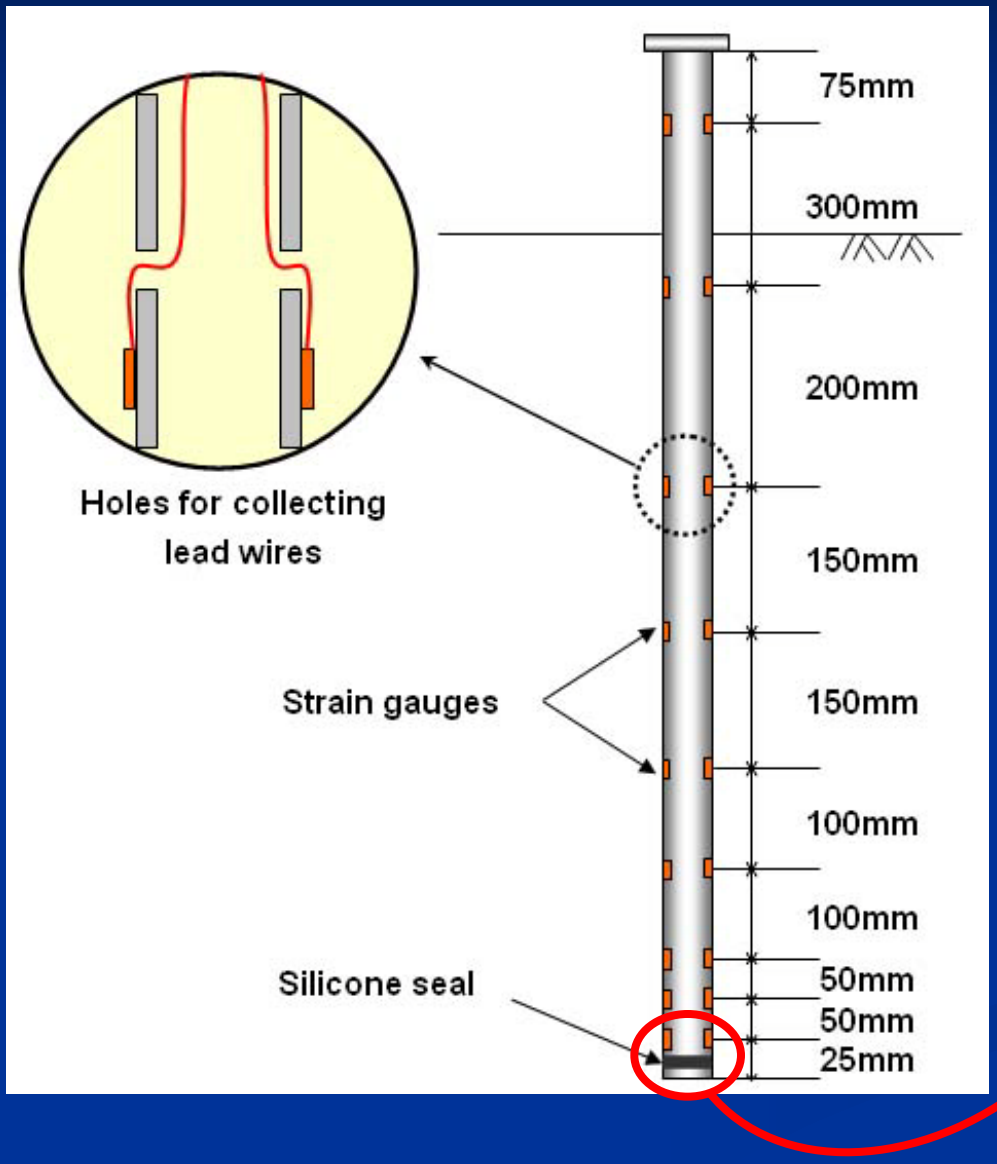
Instrumented model pile

- Smooth steel pipe (D=3cm, L=120cm, t=0.2cm)

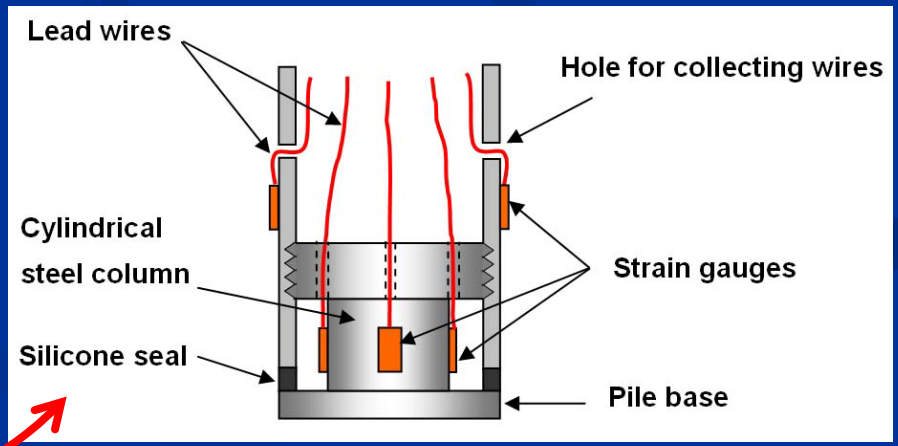
Collected wires at pile head

Closed-ended pile base

Instrumented model pile



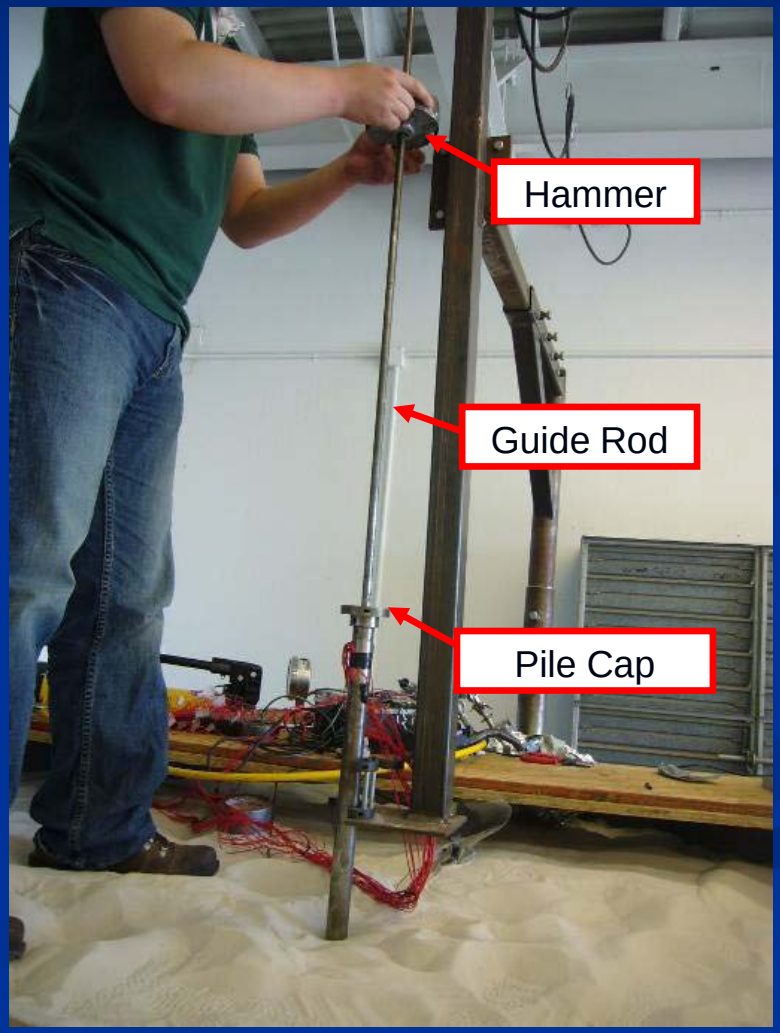
- 22 strain gauges
- Closer near the base (higher load transfer rate)
- Load cell-shaped pile base



Driving System

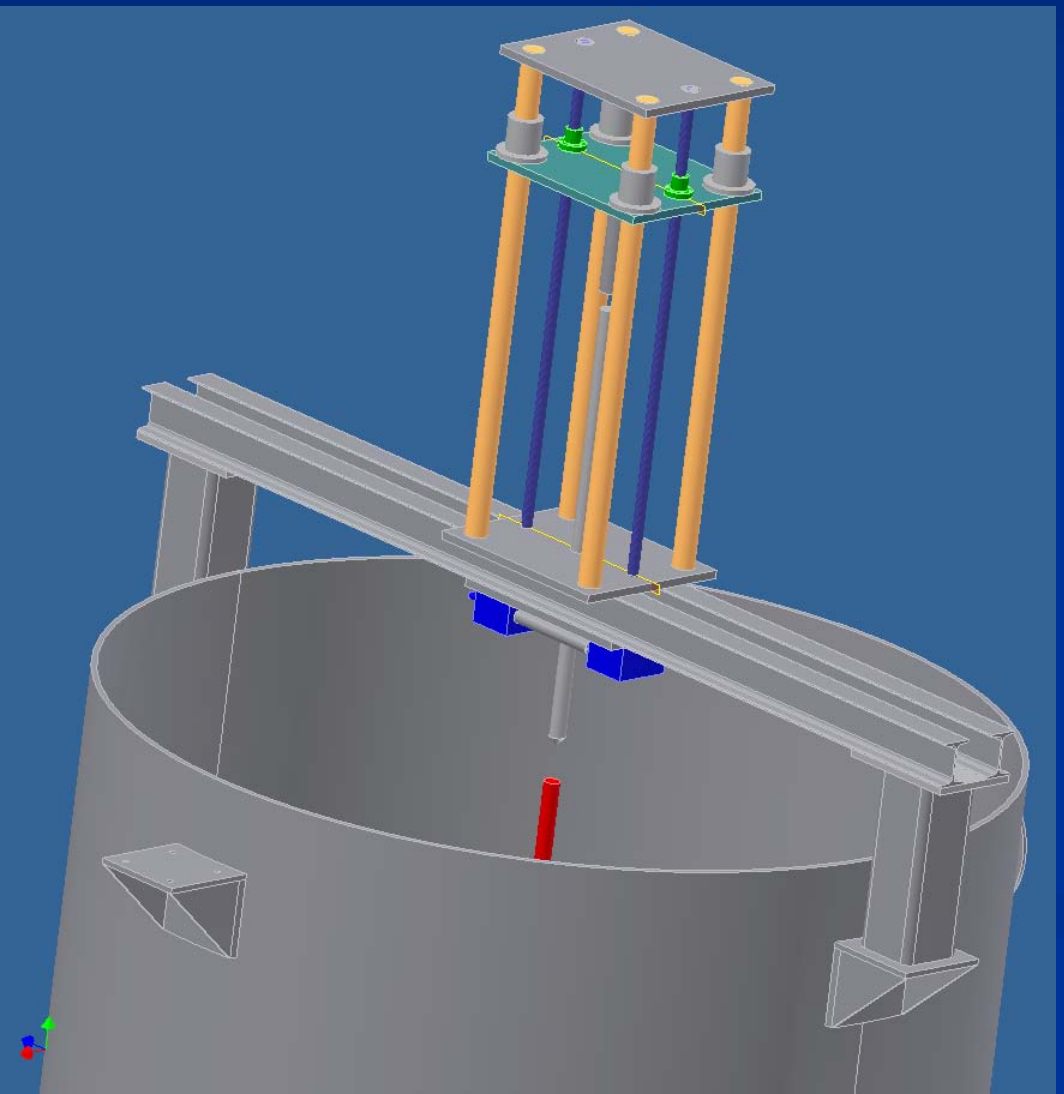
- Installation of driven pile

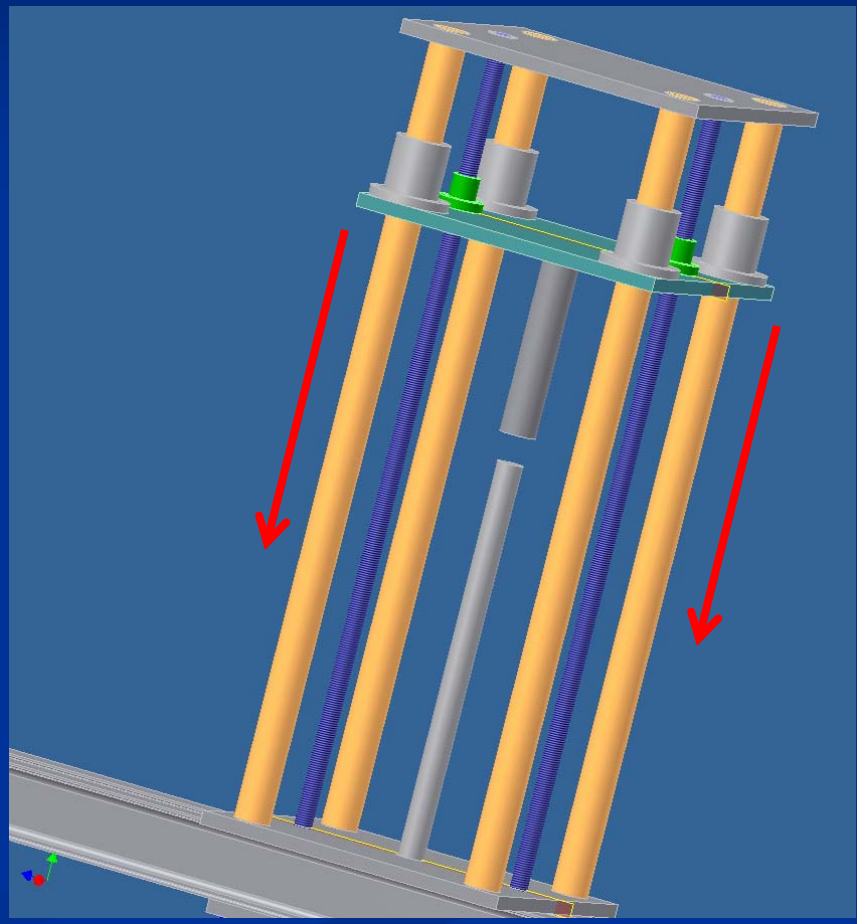
Filled soil tank



Preinstallation of model pile

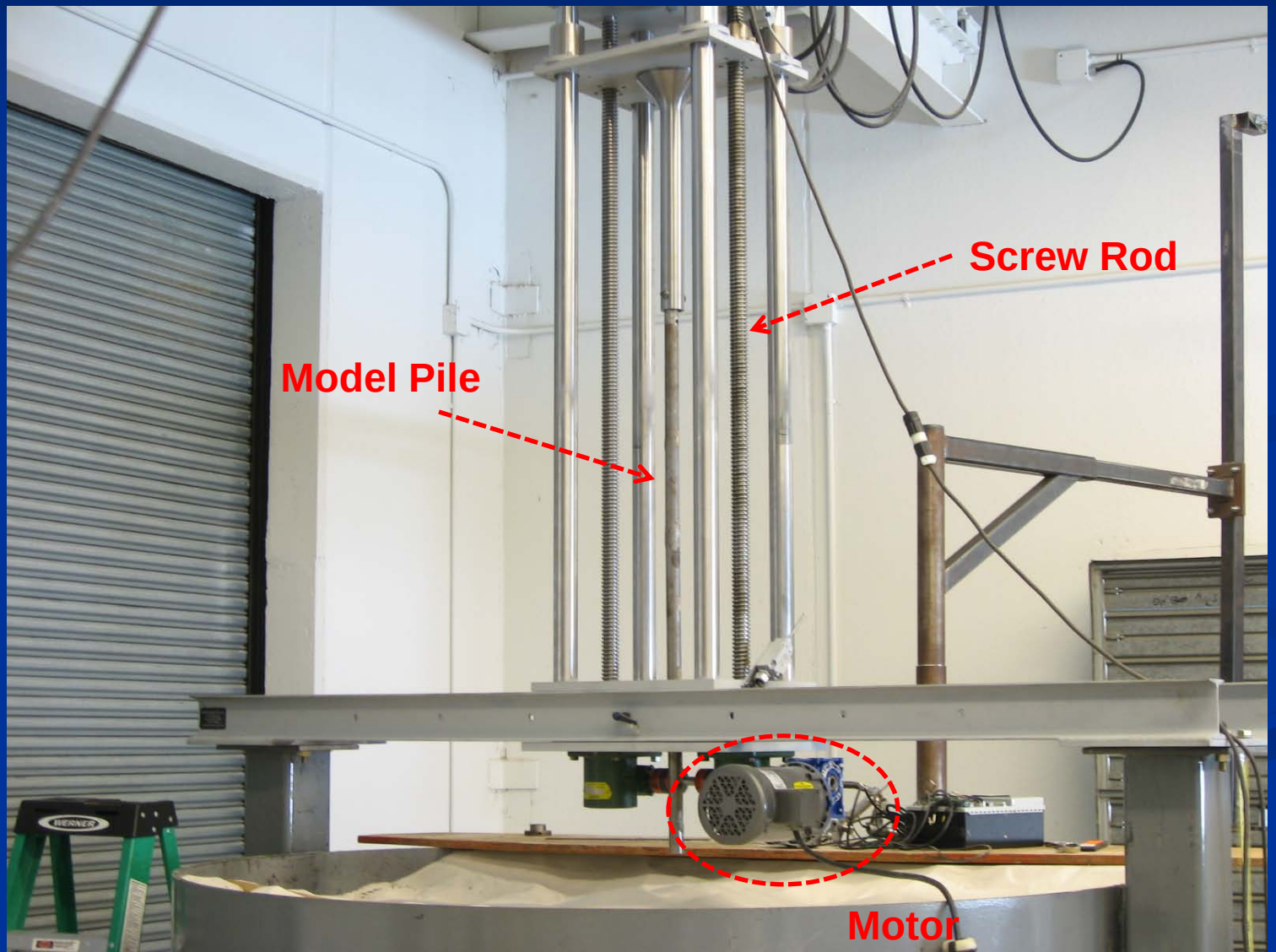
Pile jacking system





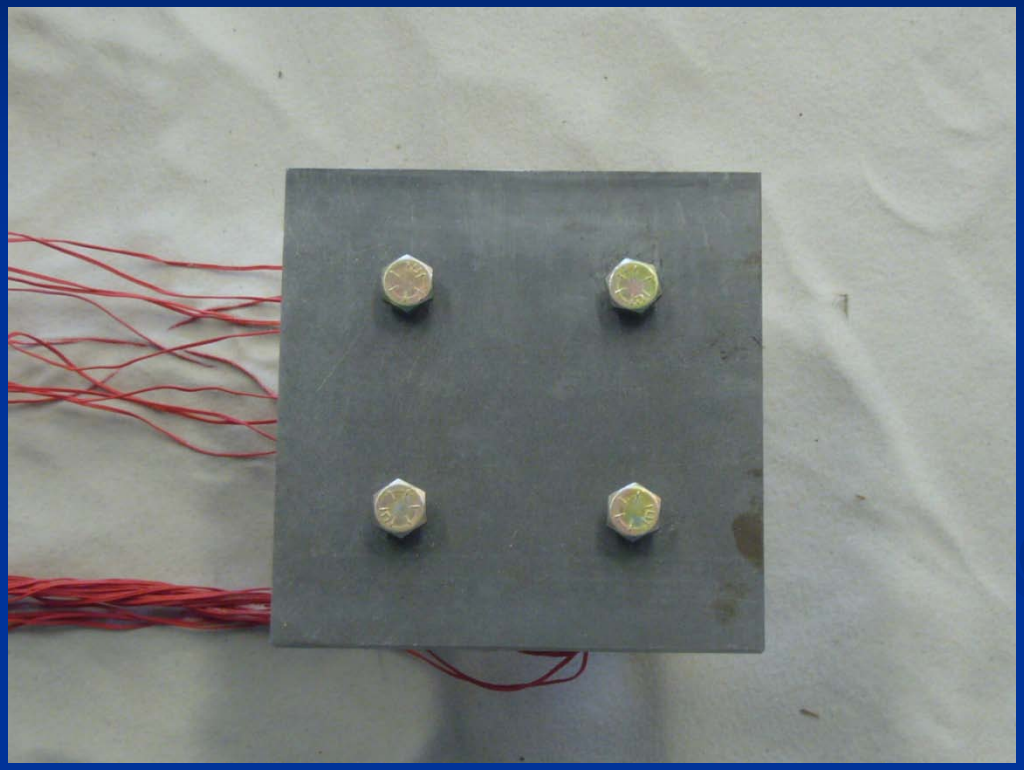
Pile jacking system

- Max. rate = 5 cm/min



Installation of Group piles

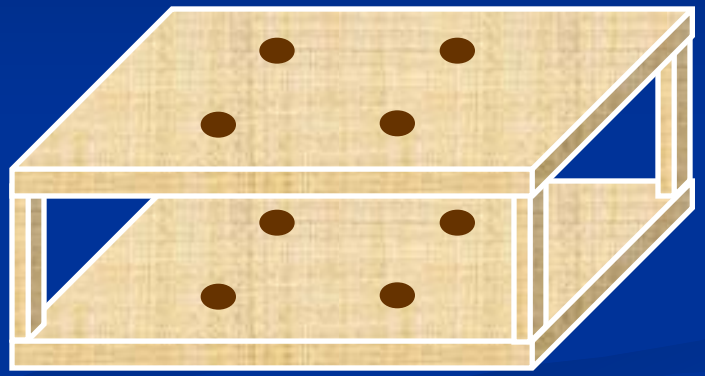
- Setup



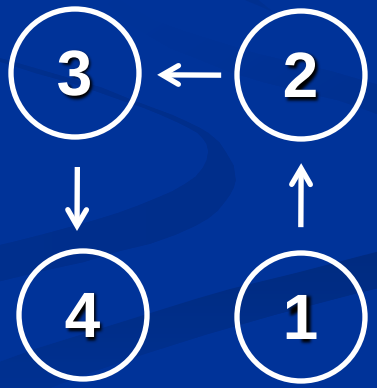
4 Piles & Steel Cap

Pile driving guide

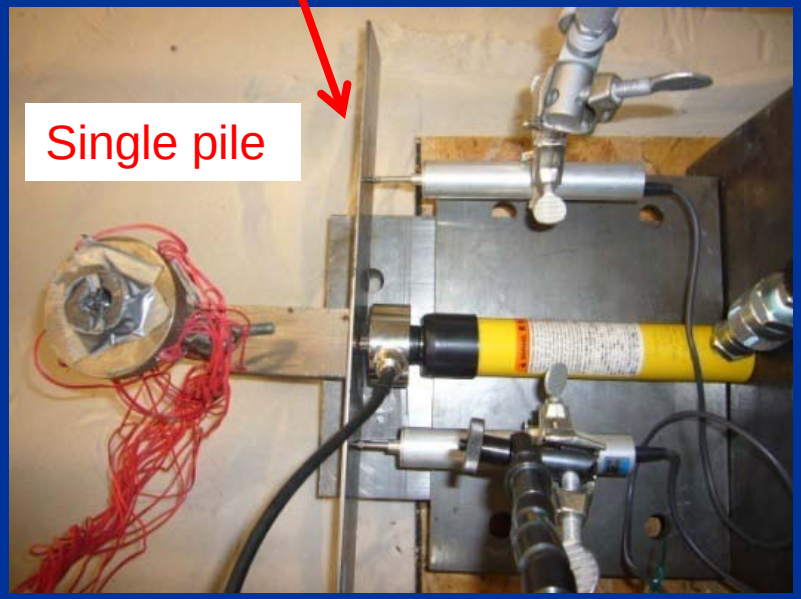
(Wooden Box Frame)



Pile driving order



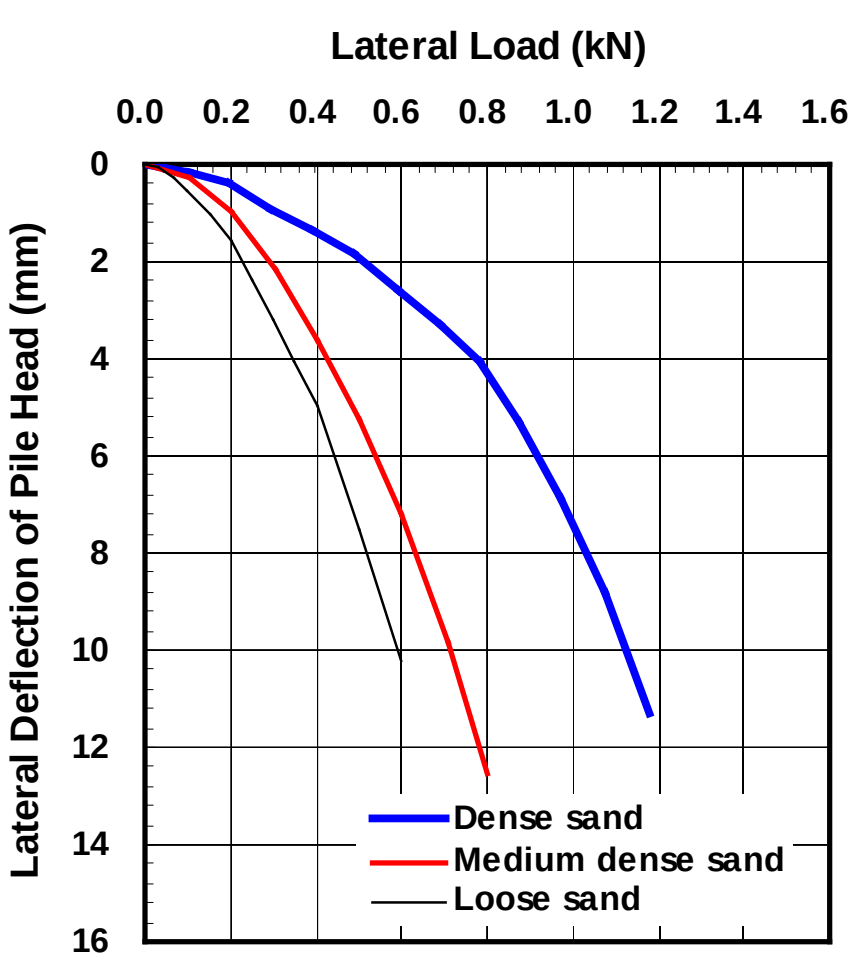
Lateral loading system



Contents

Test results: Single pile

- Lateral load - deflection curves (driven pile)



Ultimate lateral loads

$Q_{lat,5\%}$,

$Q_{lat,10\%}$

$Q_{lat,20\%}$

corresponding to lateral pile head deflections of 5, 10 and 20 % of the pile diameter

Sand type	$Q_{lat,\ 5\%}$ (kN)	$Q_{lat,\ 10\%}$ (kN)	$Q_{lat,\ 20\%}$ (kN)
Dense	0.42	0.65	0.92
Medium dense	0.24	0.36	0.54
Loose	0.19	0.29	0.44

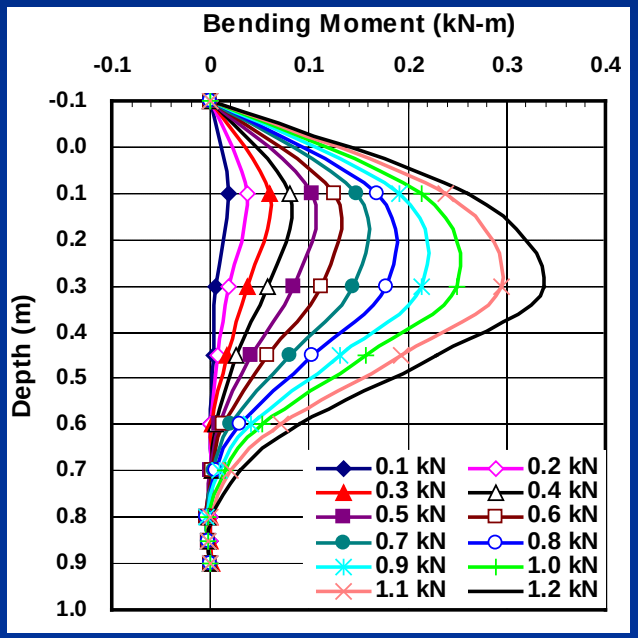
1.0 kN = 225 lb

Test results: Single pile

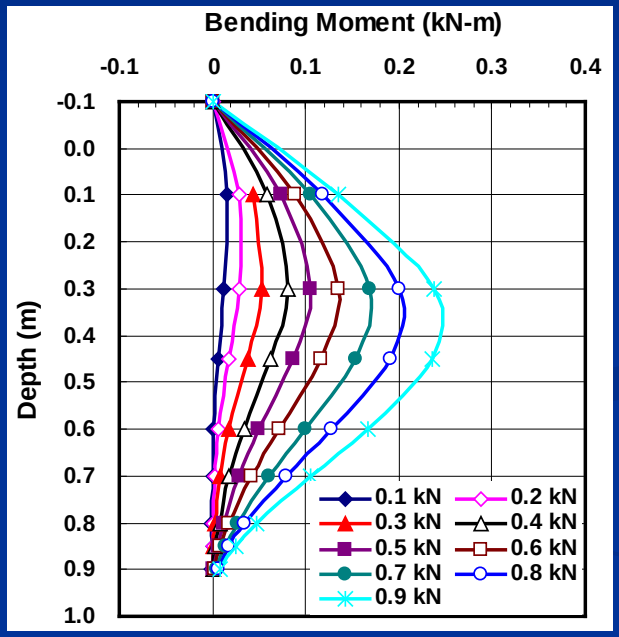
- Bending moment profiles (driven pile)

1.0 kN-m = 0.738 lb-kips

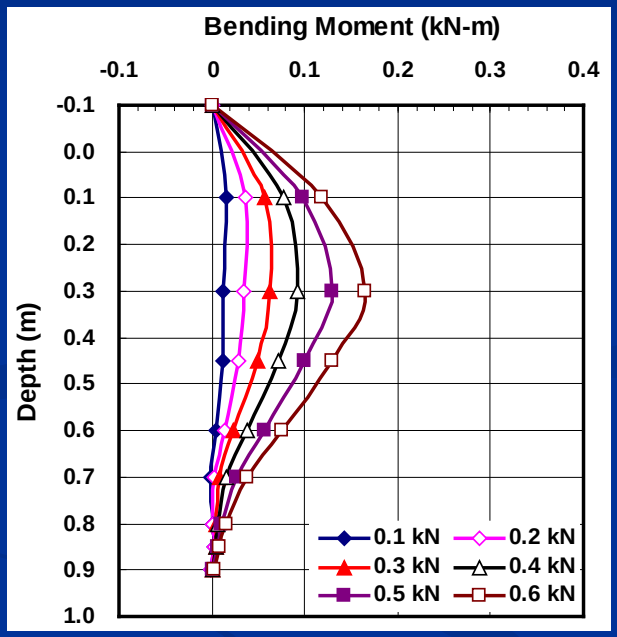
Dense sand (D_R=91%)



Medium dense sand (D_R=59%)



Loose sand (D_R=38%)



Bending moment

$$M = \frac{EI \cdot (\varepsilon_T - \varepsilon_c)}{h}$$

Rollins et al. (1998)

ε_T : tensile strain

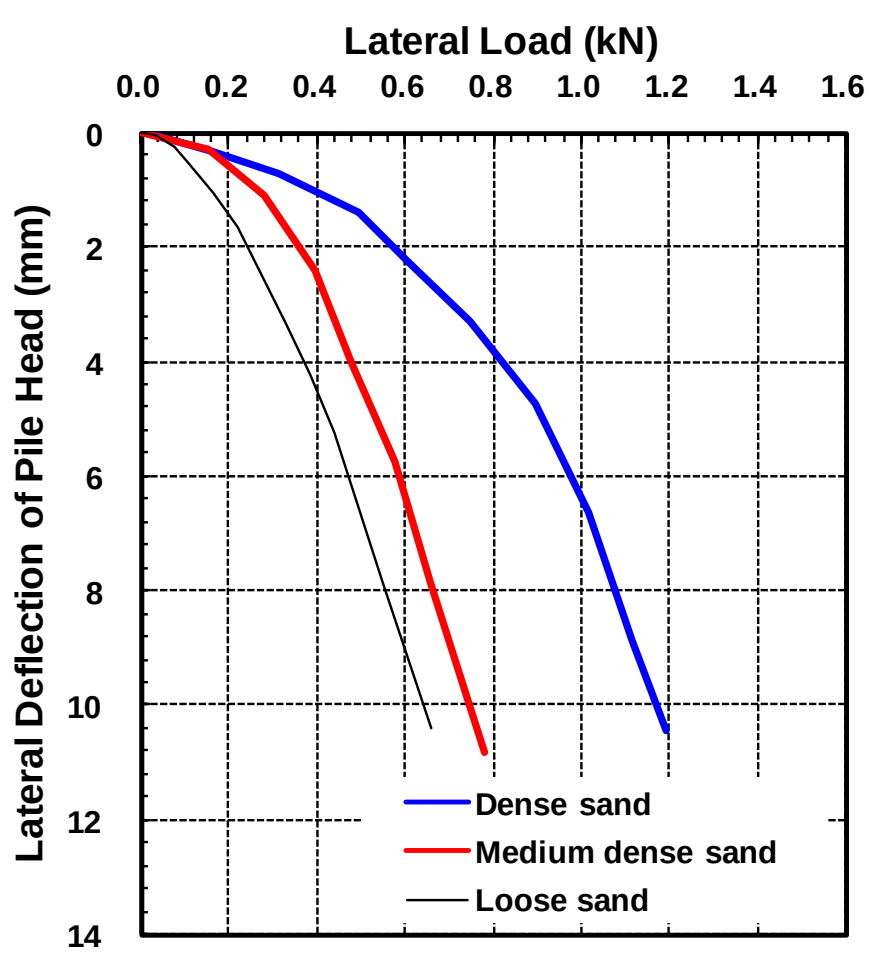
ε_c : compressive strain

h: horizontal distance between gauges

EI: bending stiffness of pile

Test results: Single pile

- Lateral load - deflection curves (jacked pile)



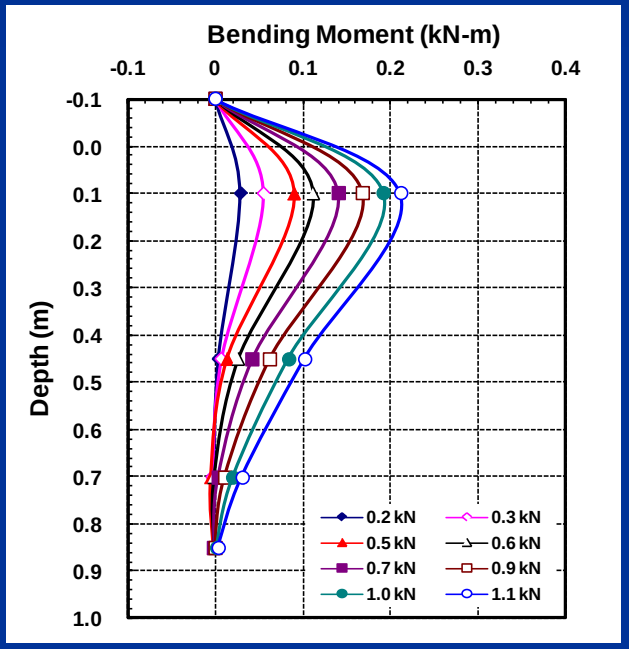
Sand type	$Q_{lat, 5\%}$ (kN)	$Q_{lat, 10\%}$ (kN)	$Q_{lat, 20\%}$ (kN)
Dense	0.51	0.71	0.97
Medium dense	0.32	0.42	0.59
Loose	0.21	0.31	0.47

1.0 kN = 225 lb

Test results: Single pile

- Bending moment profiles (jacked pile)

Dense sand (D_R=91%)



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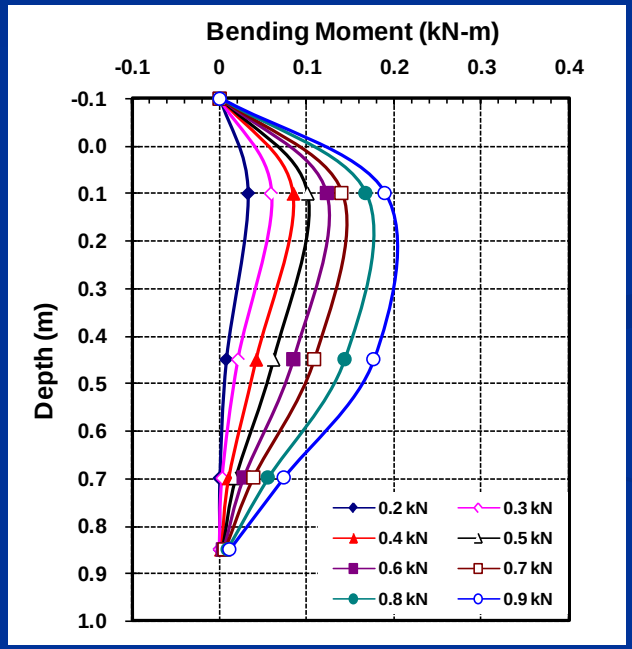
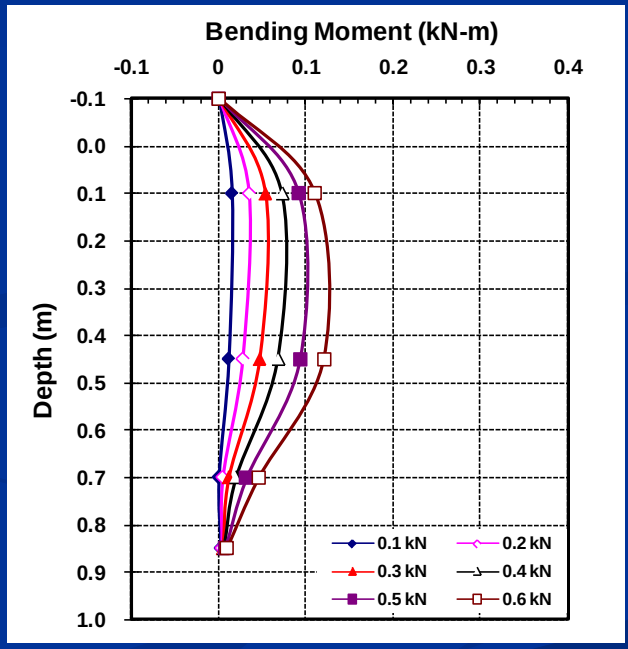


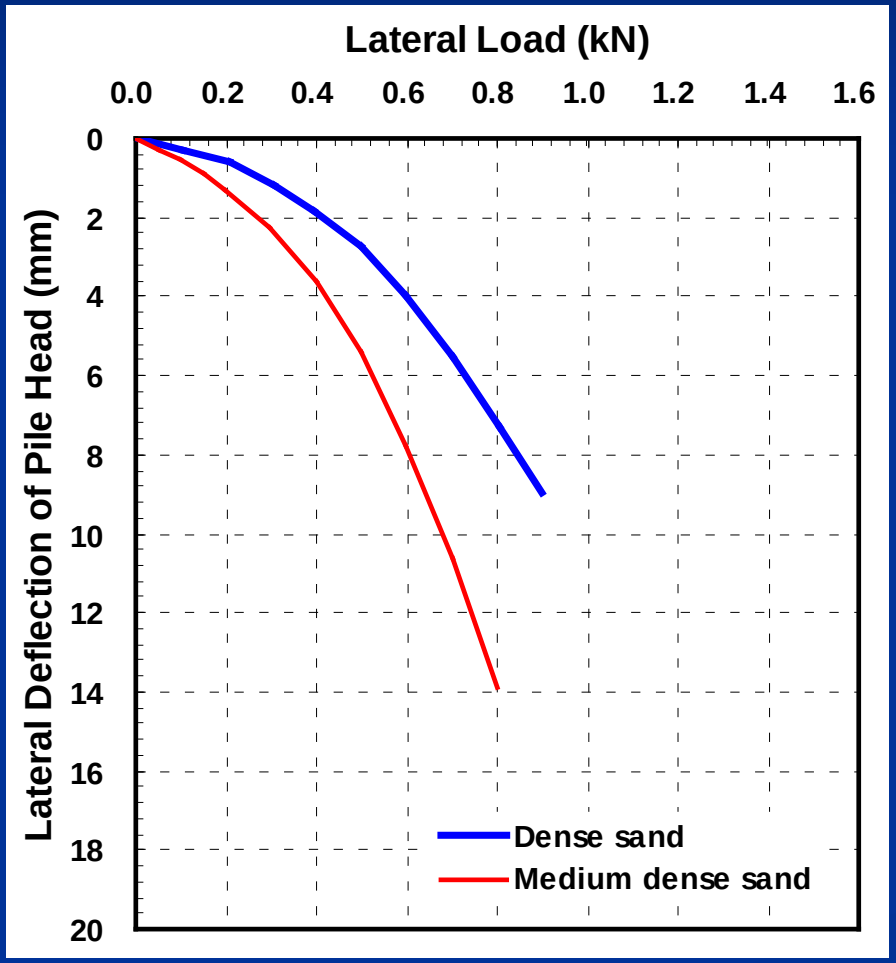
Loose sand (D_R=38%)



1.0 kN-m = 0.738 lb-kips

Test results: Single pile

- Lateral load - deflection curves (preinstalled pile)



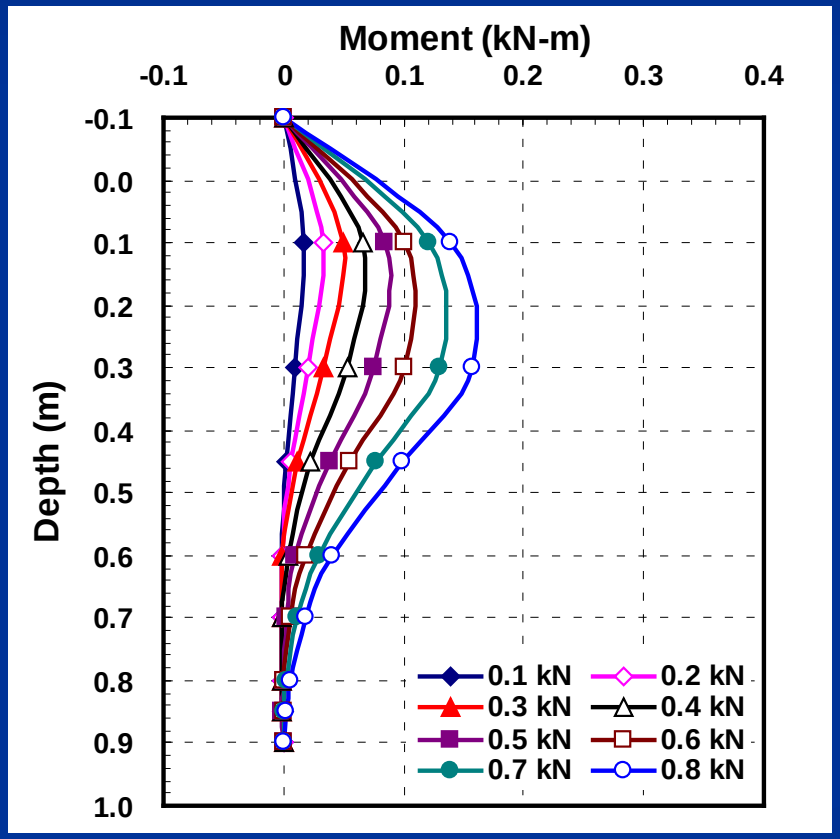
Sand type	$Q_{lat, 5\%}$ (kN)	$Q_{lat, 10\%}$ (kN)	$Q_{lat, 20\%}$ (kN)
Dense	0.35	0.52	0.73
Medium dense	0.22	0.35	0.52

1.0 kN = 225 lb

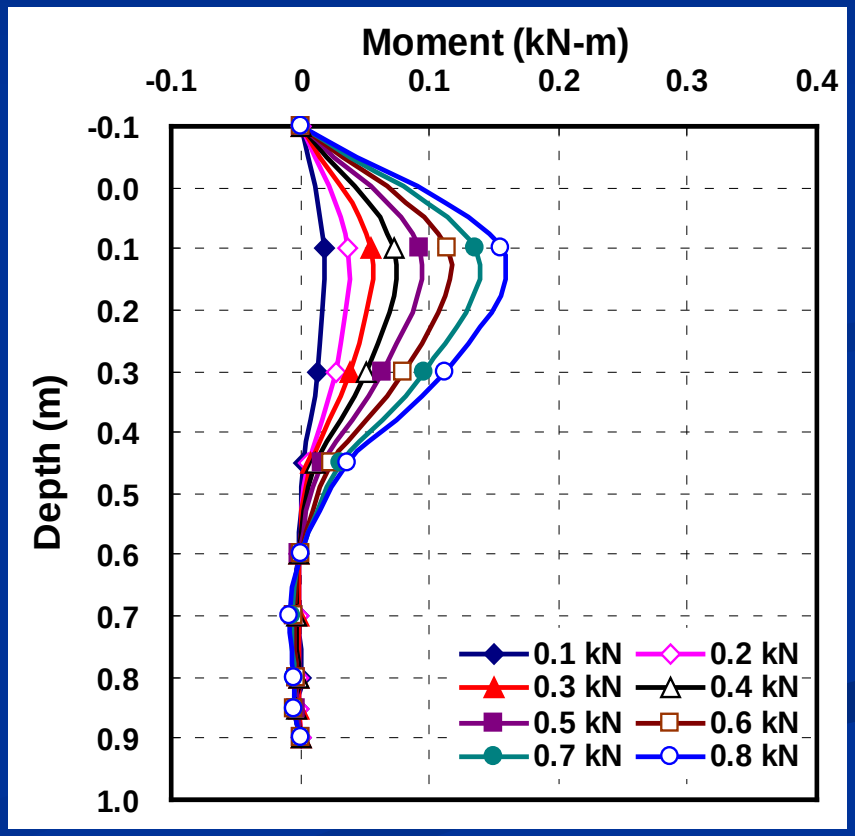
Test results: Single pile

- Bending moment profiles (preinstalled pile)

Dense sand (D_R=91%)



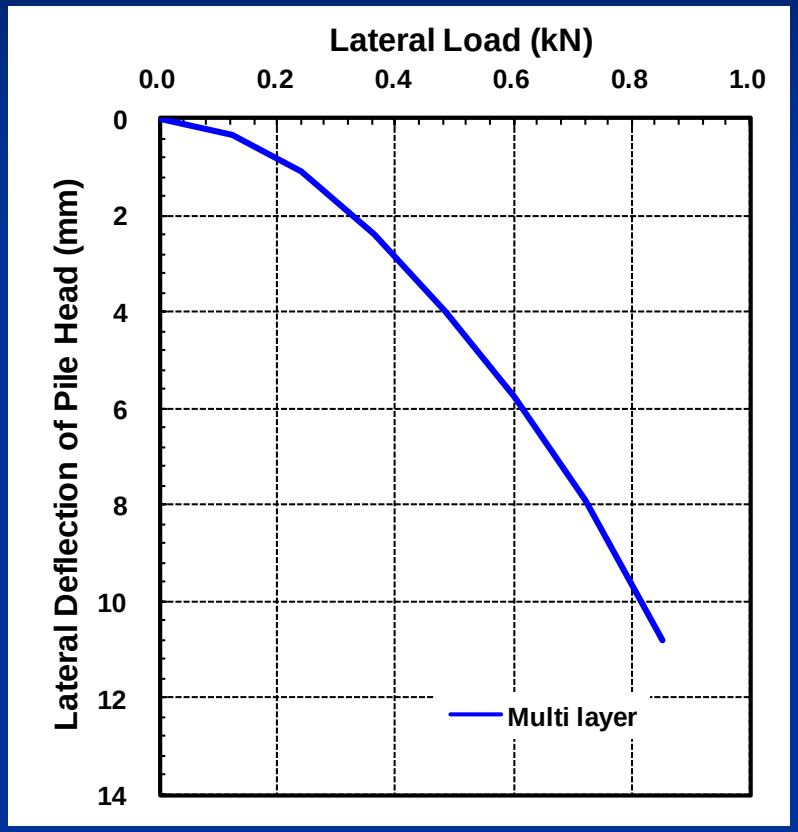
Medium dense sand (D_R=59%)

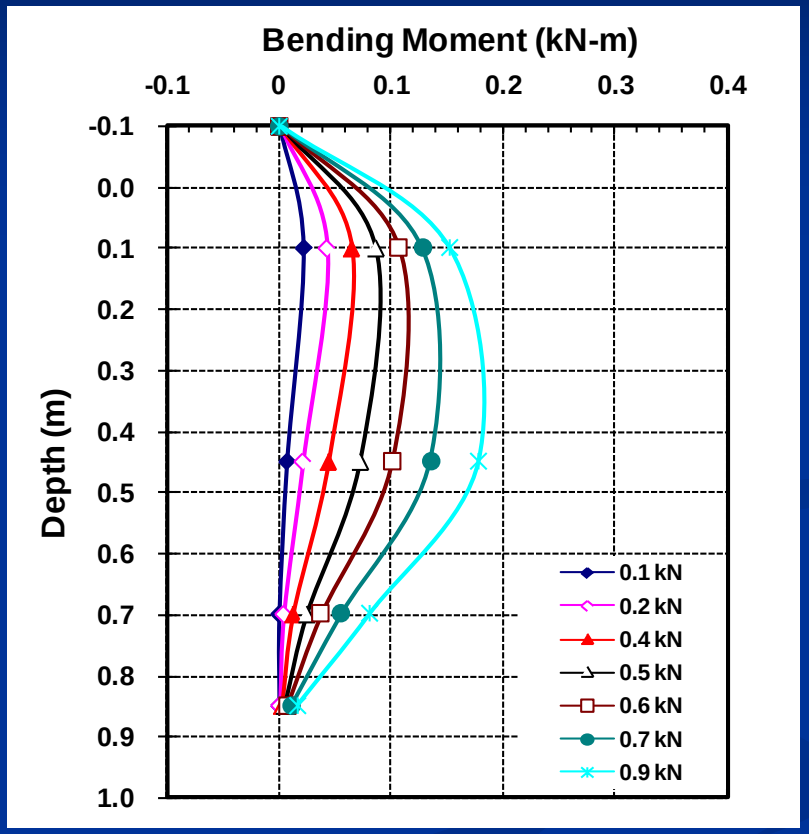


1.0 kN-m = 0.738 lb-kips

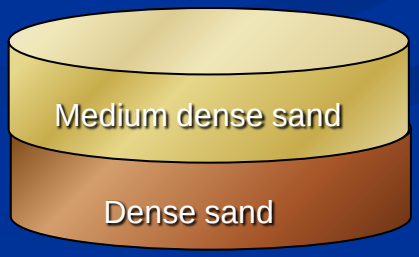
Test results: Single pile

- Load-deflection curves and bending moment profiles (Multi-layer soils)



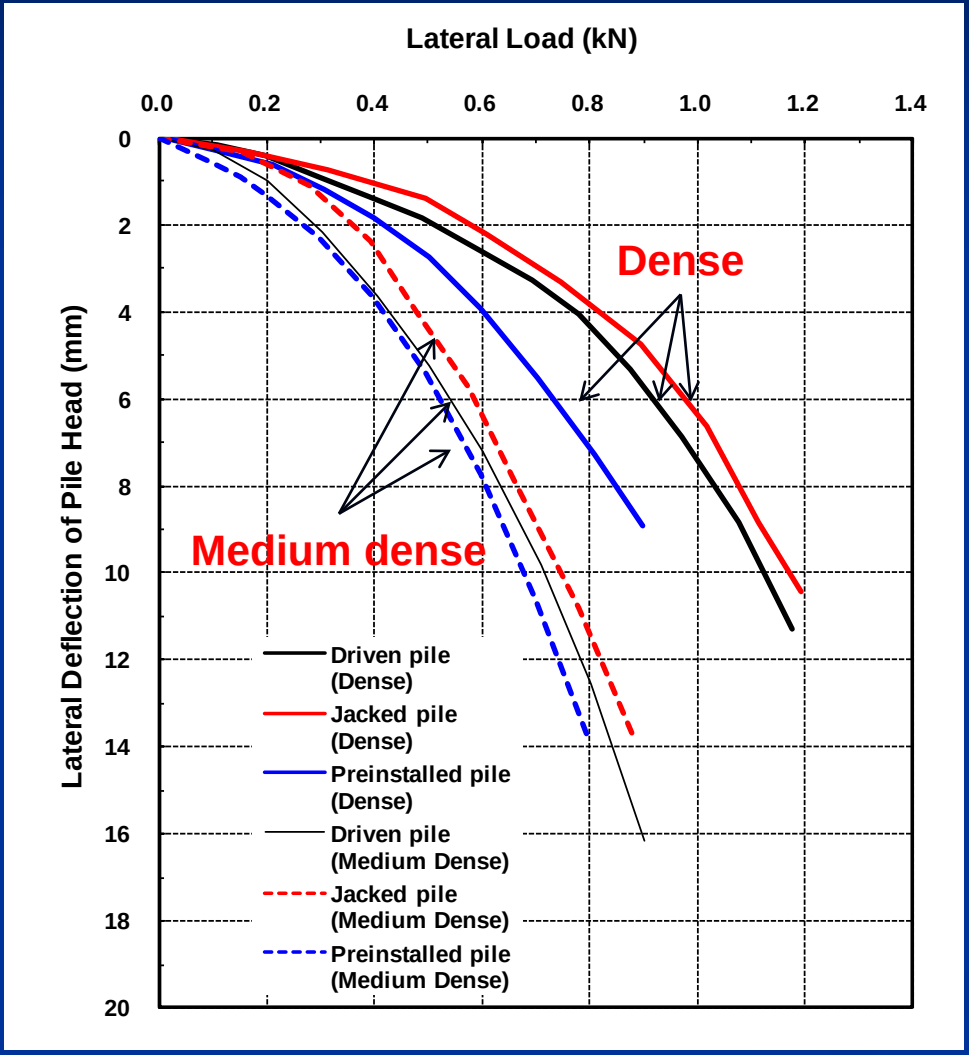


Sand type	$Q_{lat, 5\%}$ (kN)	$Q_{lat, 10\%}$ (kN)	$Q_{lat, 20\%}$ (kN)
Multi layer	0.28	0.41	0.61



Soil Tank

Effect of pile installation method



1.0 kN = 225 lb

Dense sand

$Q_{lat,10\%}$ (preinstalled piles)

= 73% of $Q_{lat,10\%}$ (jacked piles)

Installation Method	$Q_{lat,\ 10\%}$ (kN)
Jacked	0.71
Driven	0.65
Preinstalled	0.52

Medium dense sand

$Q_{lat,10\%}$ (preinstalled piles)

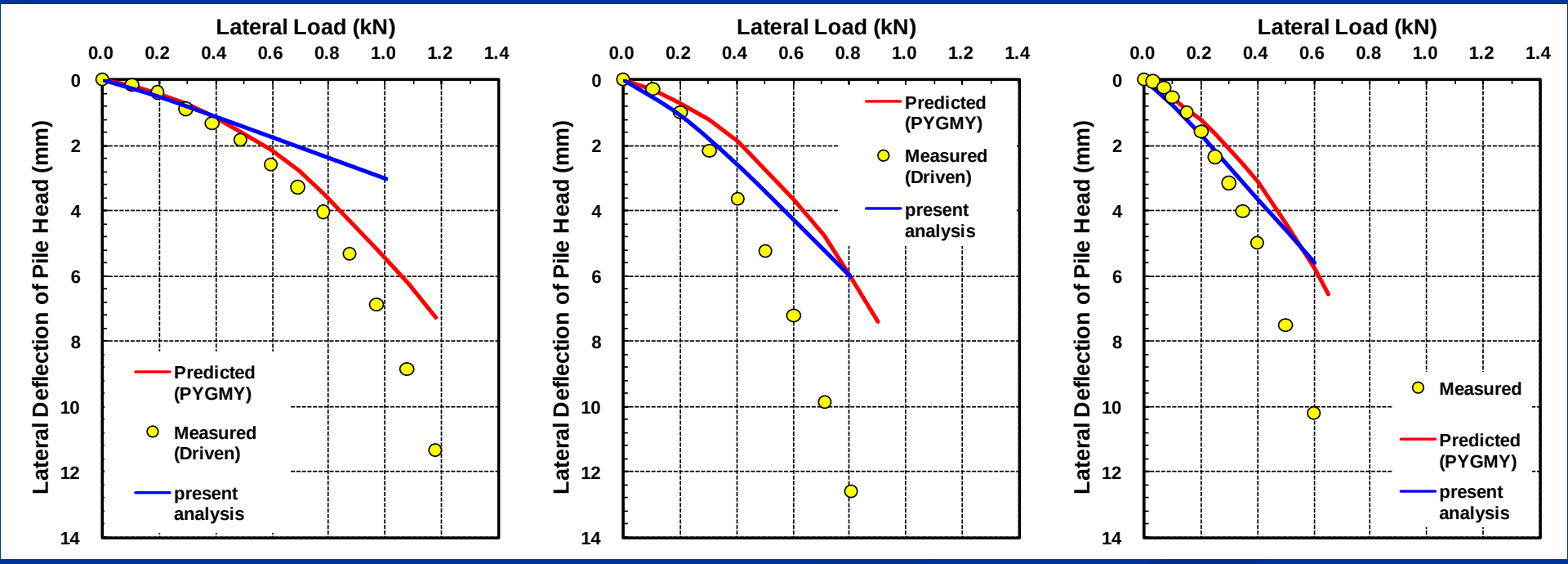
= 84% of $Q_{lat,10\%}$ (jacked piles)

Installation Method	$Q_{lat,\ 10\%}$ (kN)
Jacked	0.42
Driven	0.36
Preinstalled	0.35

Comparison of Result with Predictions

- Comparison of predictions (PYGMY, present analysis) with measurements from model piles driven in dense, medium dense, and loose sand

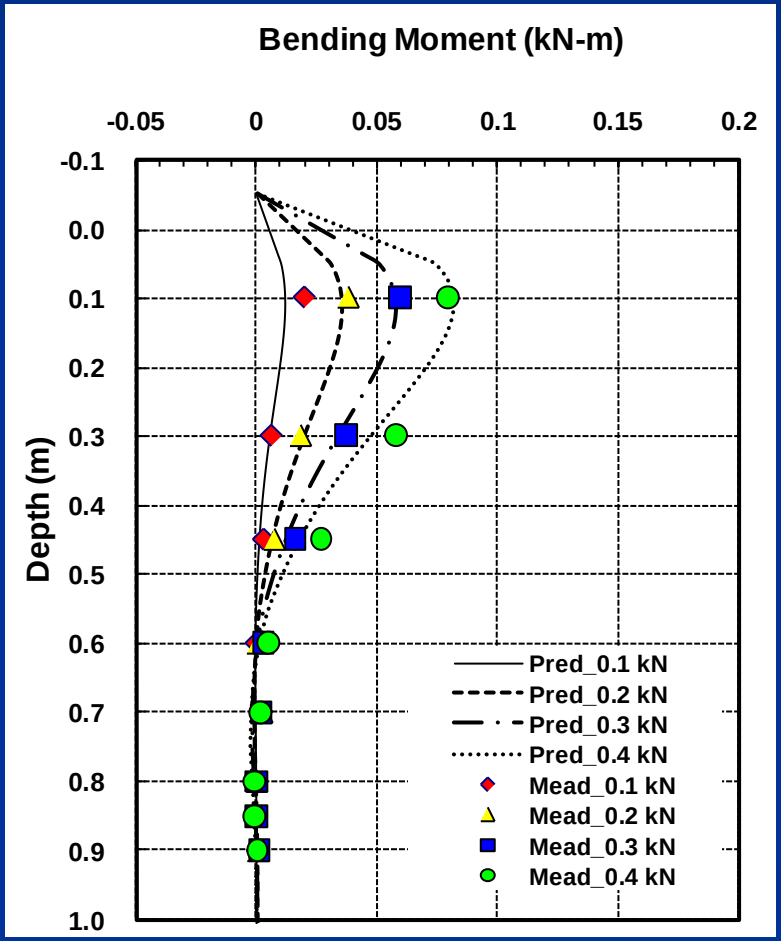
Dense sand (D_R=91%) Medium dense sand (D_R=59%) Loose sand (D_R=38%)

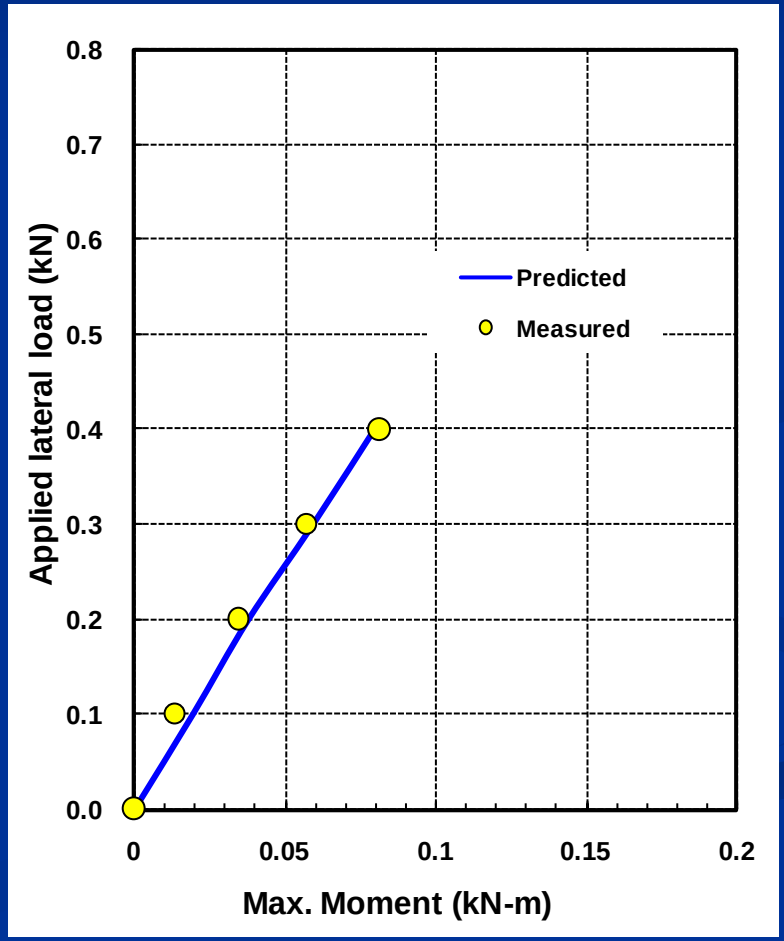


1.0 kN = 225 lb

Comparison of Result with Predictions

- Comparison of predicted and measured bending moment profiles for model piles driven in dense sand

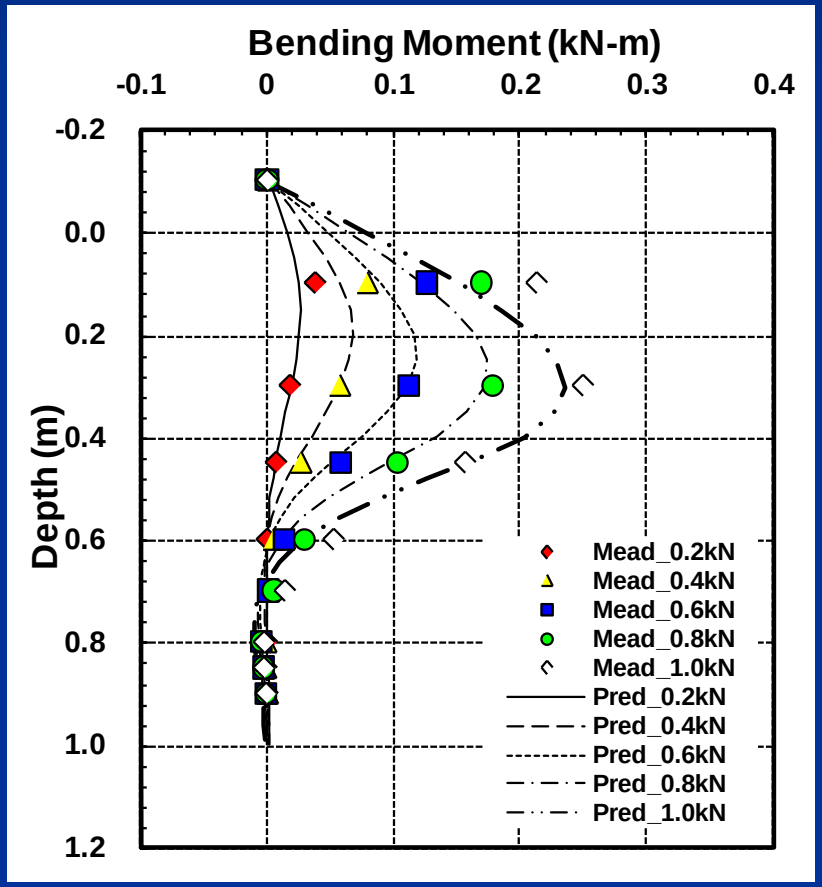


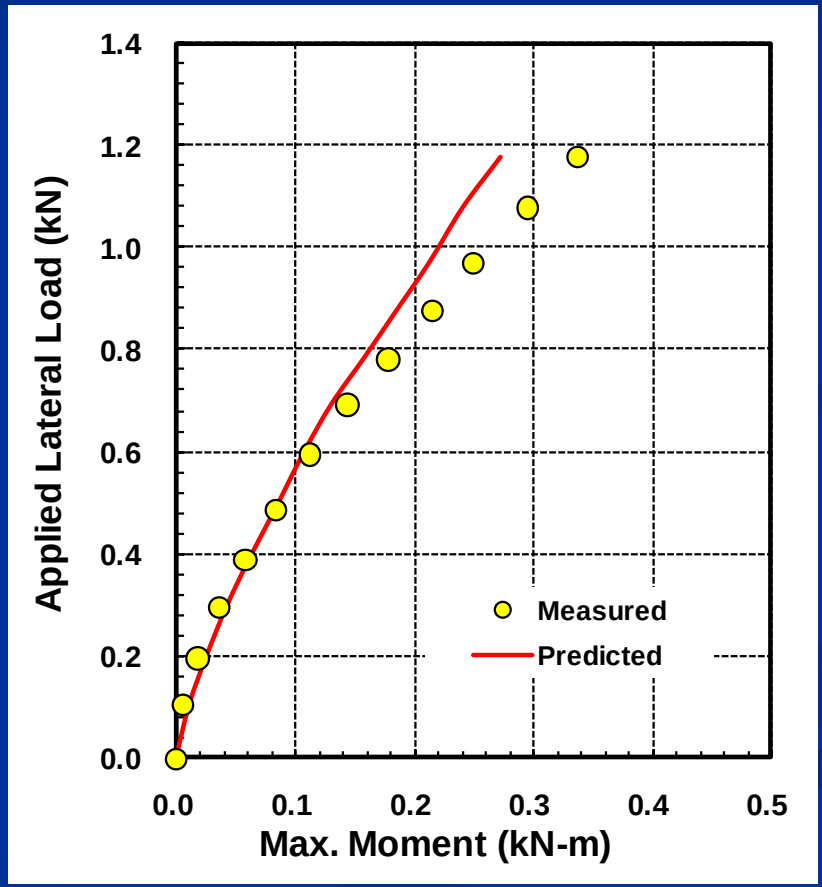


1.0 kN-m = 0.738 lb-kips

Comparison of Results with PYGMY

- Comparison of predicted and measured bending moment profiles for model piles driven in dense sand



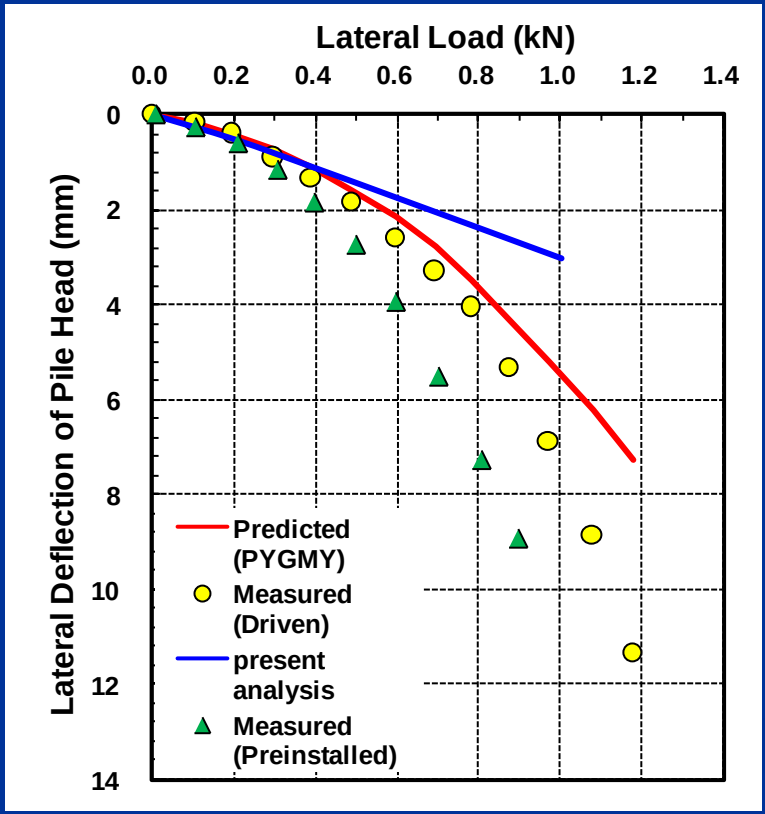


1.0 kN-m = 0.738 lb-kips

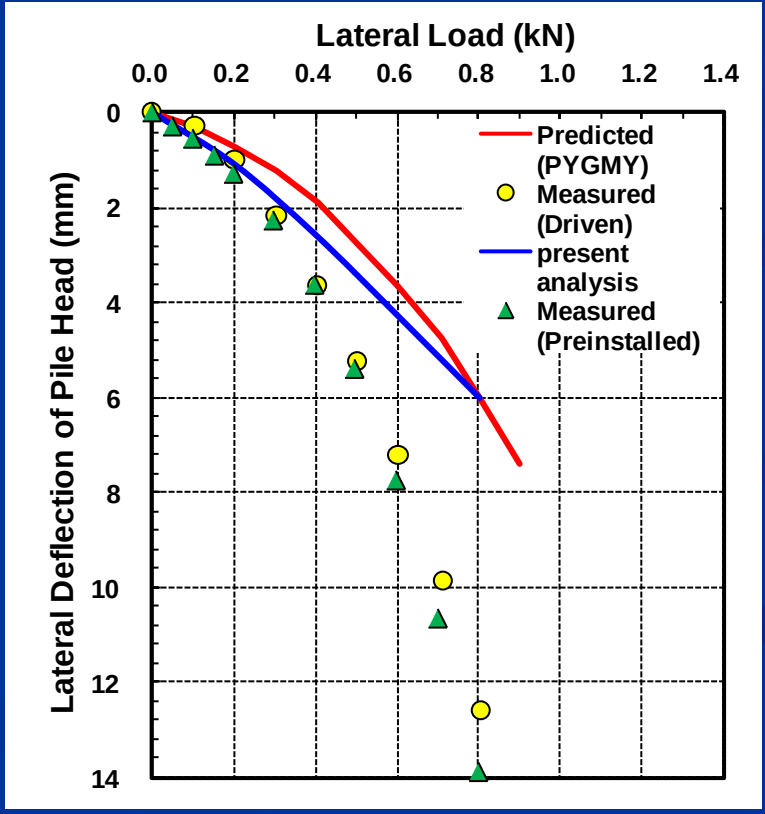
Comparison of Results

- Comparison of predictions with measurements from model piles driven and preinstalled in dense, medium dense

Dense sand (D_R=91%)



Medium dense sand (D_R=59%)



Input parameters (present analysis)

Input parameters for the model pile	
Length (m)	1.2
Diameter / width (m)	0.03
Pile modulus (GPa)	210

Input parameters for the soil	
Critical-state friction angle (deg.)	32.8
Max. void ratio (e_{max})	0.78
Min. void ratio (e_{min})	0.47
Coefficient of earth pressure	0.4
Model	*f-g* model

- Suggested *f* and *g* (Lee and Salgado, 2000)

D_R(%)	*f*	*g*
30	0.98	0.17
50	0.97	0.2
70	0.96	0.23
90	0.95	0.26

Input parameters (PYGMY)

PYGMY input parameters for the model pile	
Pile property	Input value
Length (m)	1.2
Diameter / width (m)	0.03
Bending stiffness of pile, E_pI_p (kN·m^2)	3.862
Plastic moment (kN·m)	0.5
No. of elements	30

PYGMY input parameters for the soil			
Soil property	Dense sand	Medium dense sand	Loose sand
Peak friction angle (deg.)	44	39	36
Initial stiffness gradient (kPa/m)	82,000	34,000	12,000
Effective unit weight (kN/m^3)	17.34	16.27	15.64
No. of soil layers	1	1	1

p-y curve (PYGMY)

- Sand: API criterion (1993)

$$p = A \cdot p_u \cdot \tanh\left(\frac{k \cdot x \cdot y}{A \cdot p_u \cdot B}\right)$$

p: lateral pressure

A: factor to account for static or cyclic loading

$A = 0.9$ where equilibrium has been reached under cyclic loading

$A = (0.3 - 0.8x / B) \geq 0.9$ for static loading

p_u = fultimate bearing pressure at the current depth, x

k = gradient of initial modulus of subgrade reaction with depth (kPa/m)

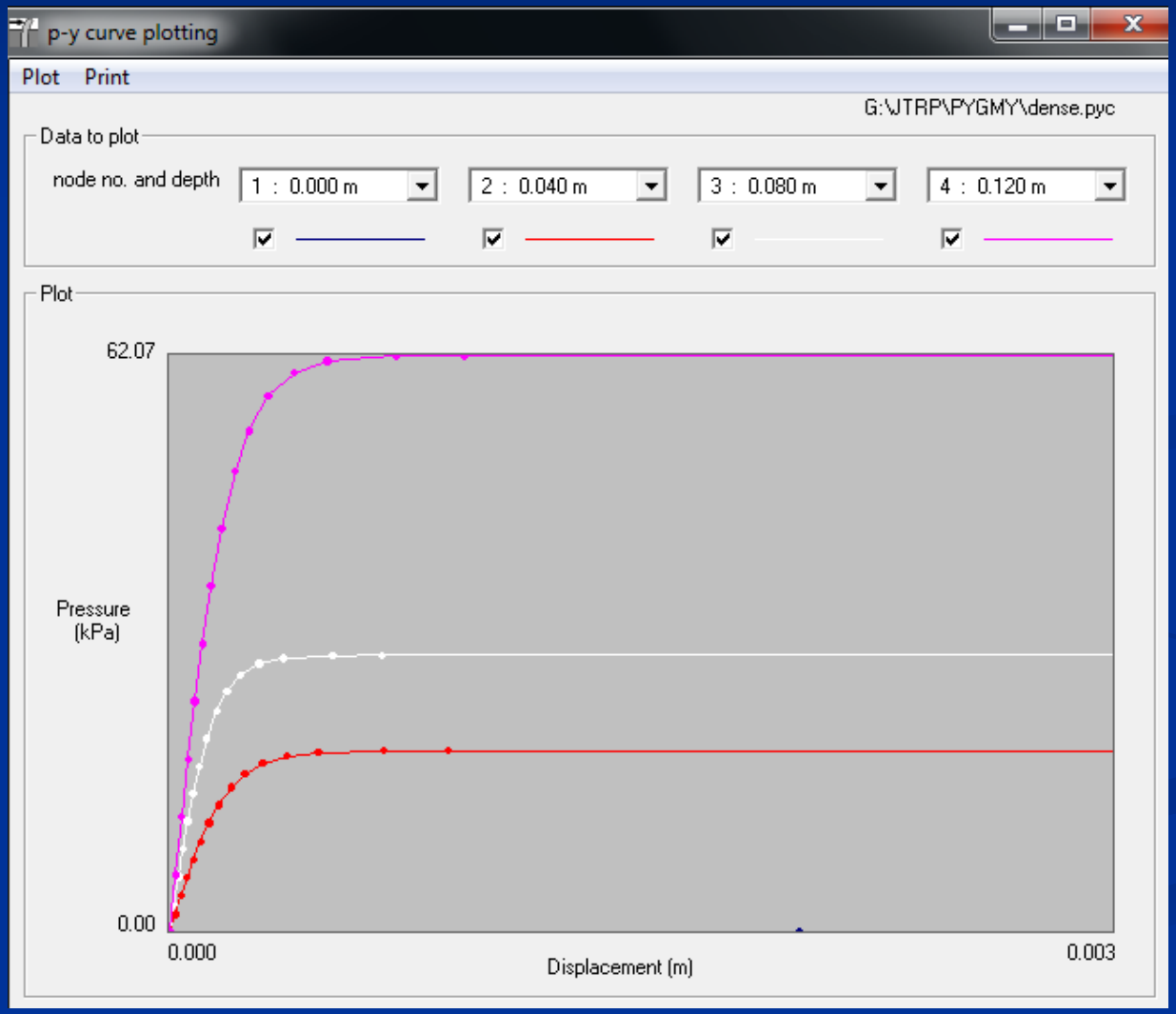
y = lateral displacement

x = depth below surface

B = pile diameter

p-y curves (PYGMY)

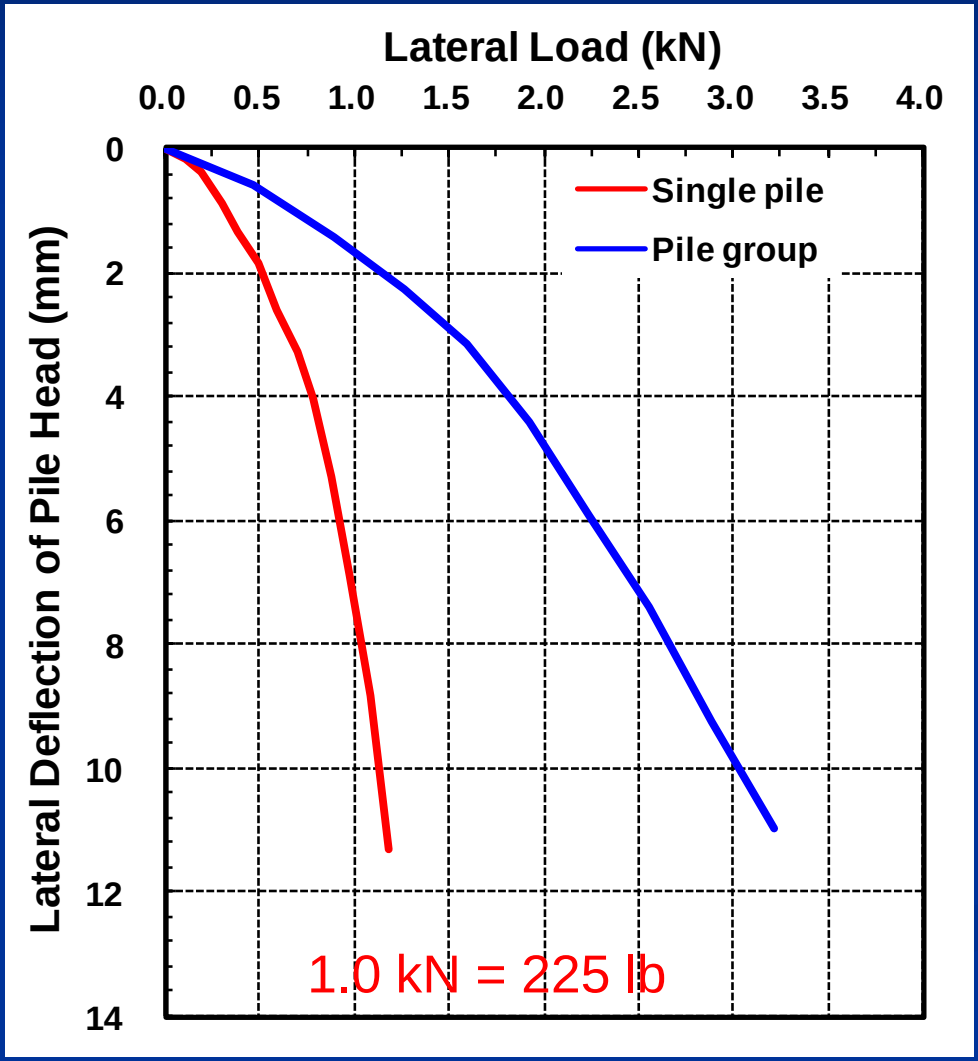
- predicted p-y curves (dense sand)



Contents

Group piles: Dense sand (D_R=90%)

- Lateral deflection of pile head (4 piles, 3B spacing)



Lateral deflection
= 5%, 10%, 20% of the pile diameter

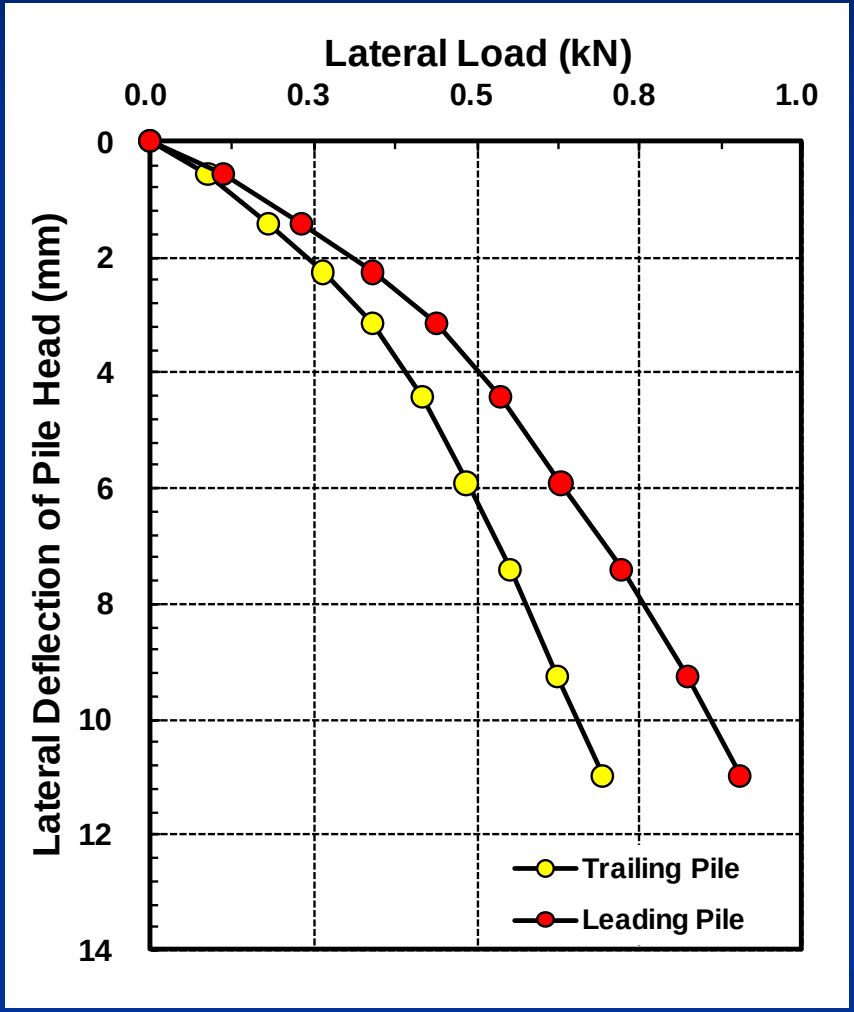
$Q_{lat,\ 5\%}$ = 0.91 kN

$Q_{lat,\ 10\%}$ = 1.59 kN

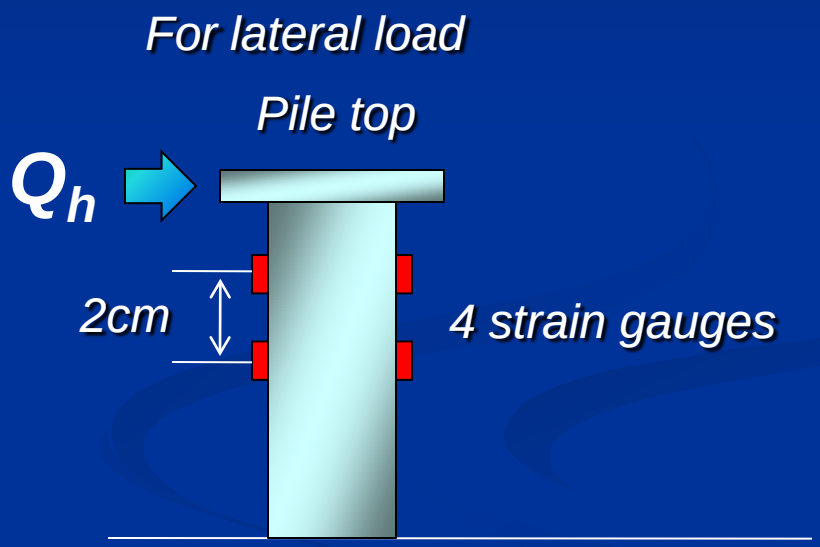
$Q_{lat,\ 20\%}$ = 2.25 kN

Group piles: Dense sand (D_R=90%)

- Distribution of lateral load



1.0 kN = 225 lb

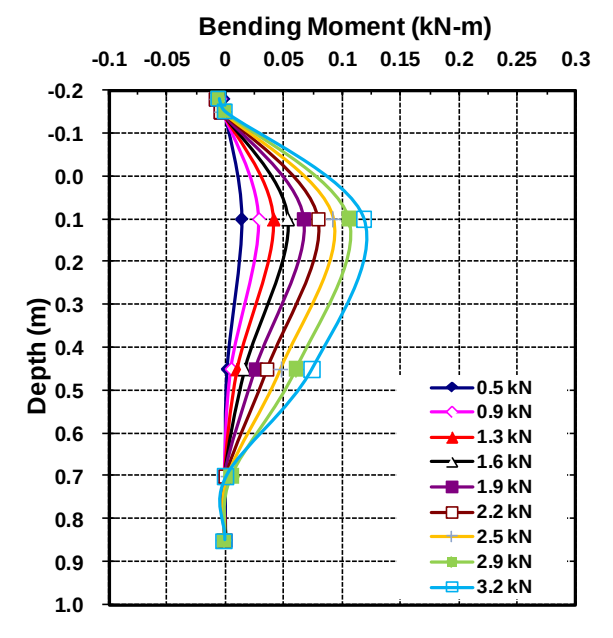


The difference in the bending moments divided by the distance between the strain gauges is equal to the lateral load in the pile

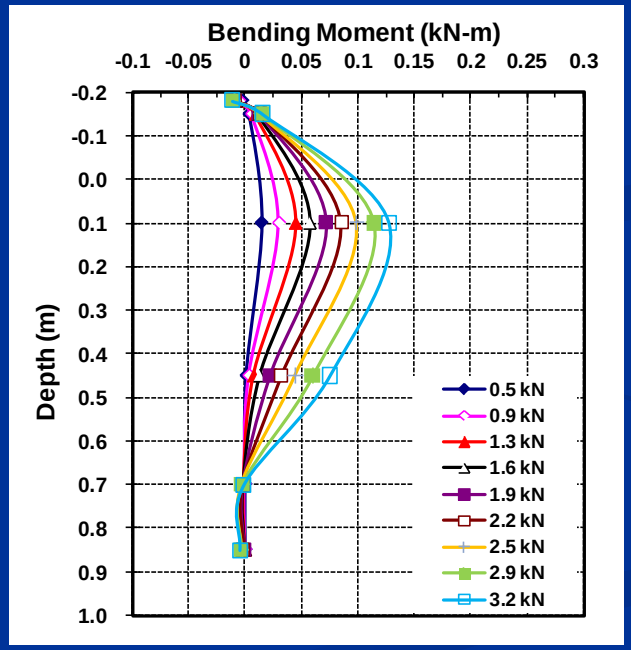
Group piles: Dense sand (D_R=90%)

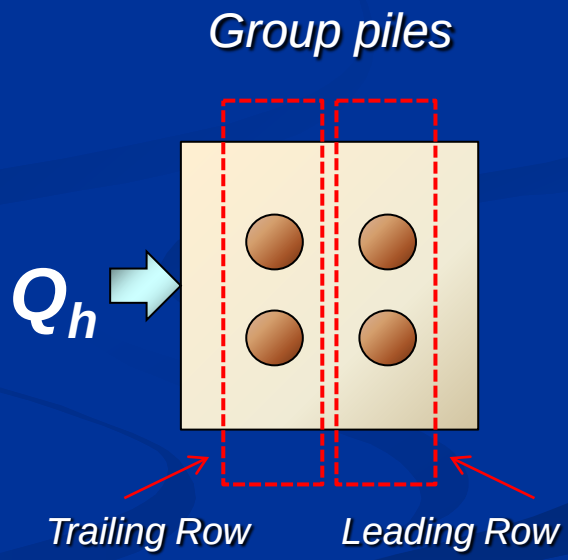
- Bending moment of leading and trailing piles

Distribution of bending moments of trailing piles



Distribution of bending moments of leading piles

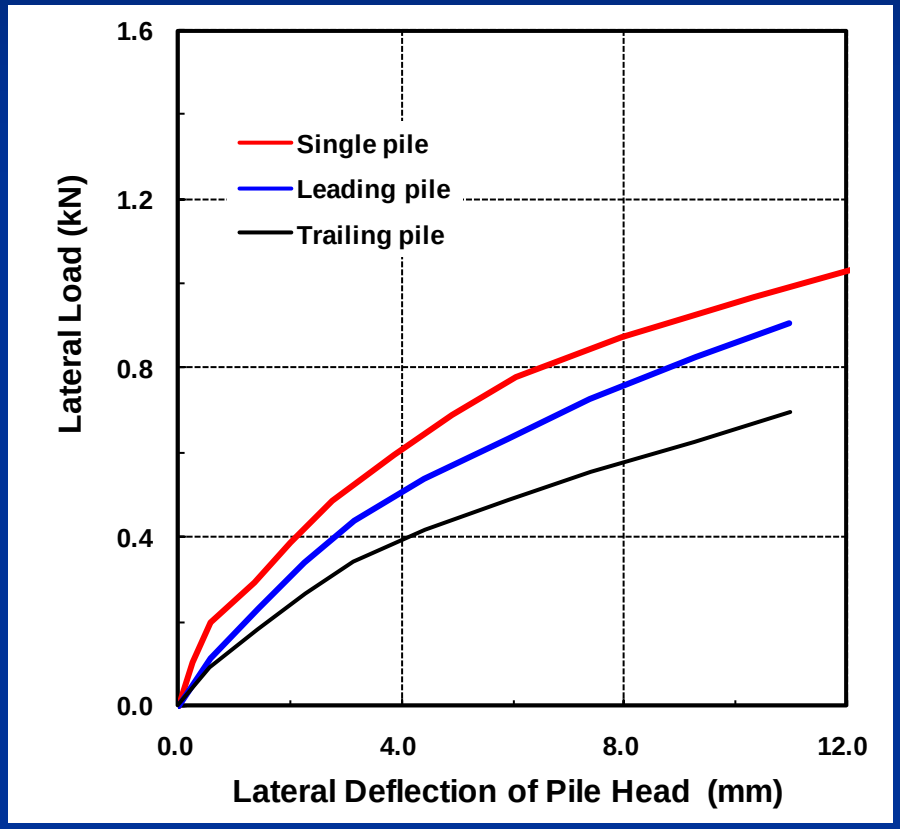




1.0 kN-m = 0.738 lb-kips

Group piles: Dense sand (D_R=90%)

- Measured *p*-multipliers and distribution of lateral load



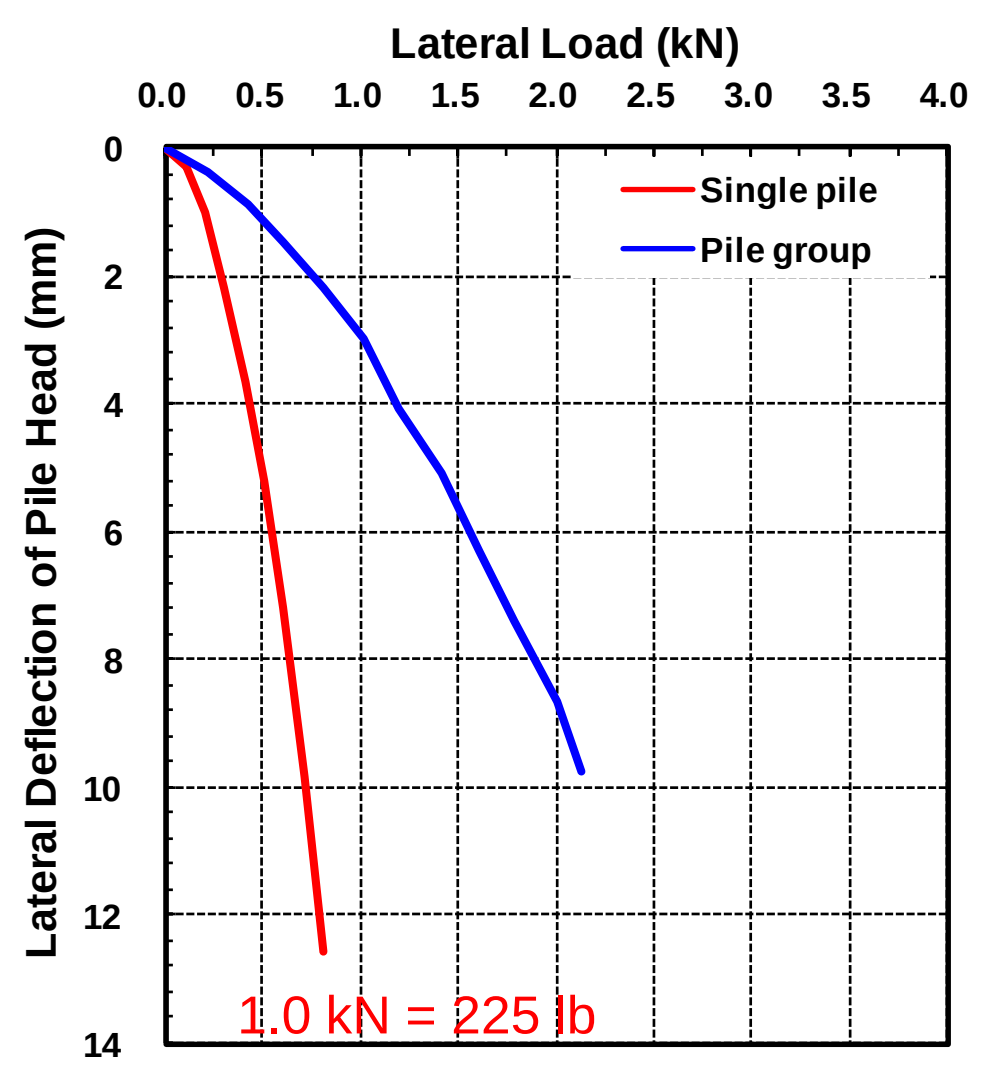
Measured *p*-multipliers

Lateral deflection	Leading Pile	Trailing Pile
5 % of B	0.76	0.59
10 % of B	0.74	0.58
20 % of B	0.82	0.63

1.0 kN = 225 lb

Group piles: Medium dense sand (D_R=60%)

- Lateral deflection of pile head (4 piles, 3B spacing)



Lateral deflection
= 5%, 10%, 20% of the pile diameter

$Q_{lat,\ 5\%}$ = 0.60 kN

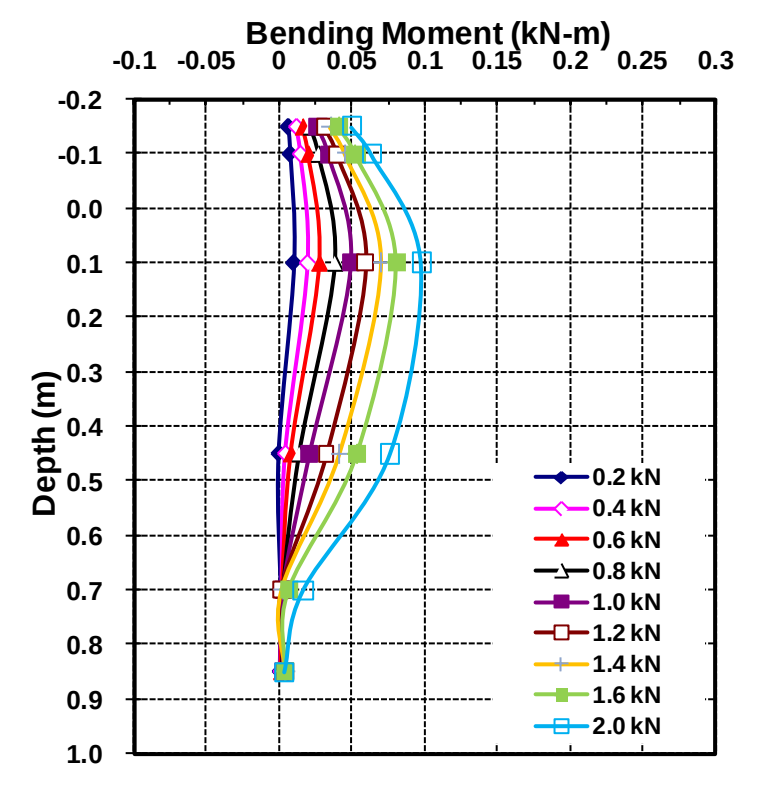
$Q_{lat,\ 10\%}$ = 1.20 kN

$Q_{lat,\ 20\%}$ = 1.56 kN

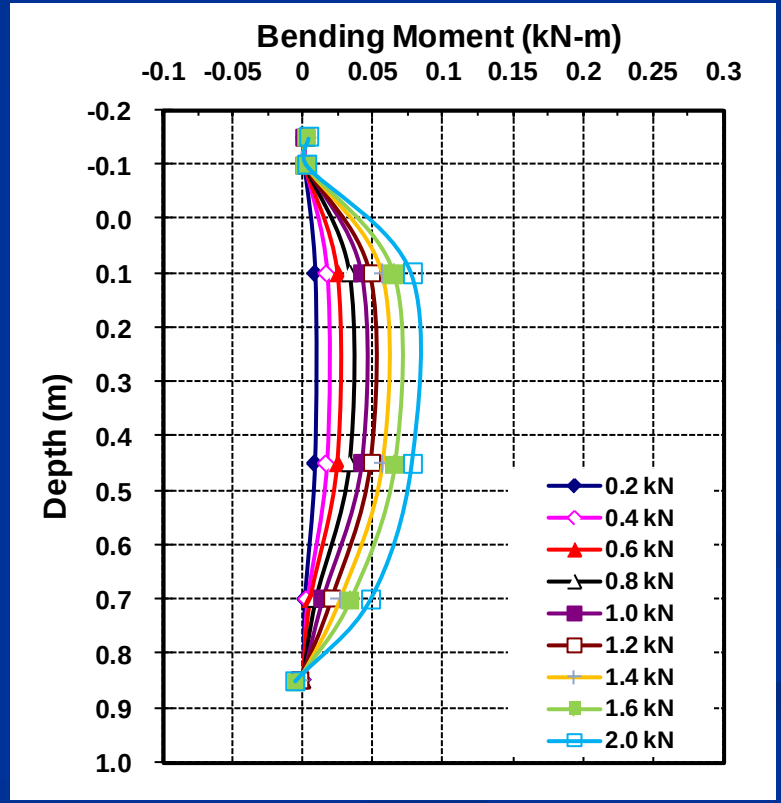
Group piles: Medium dense sand (D_R=60%)

- Bending moment of leading and trailing piles

Distribution of bending moments of trailing piles



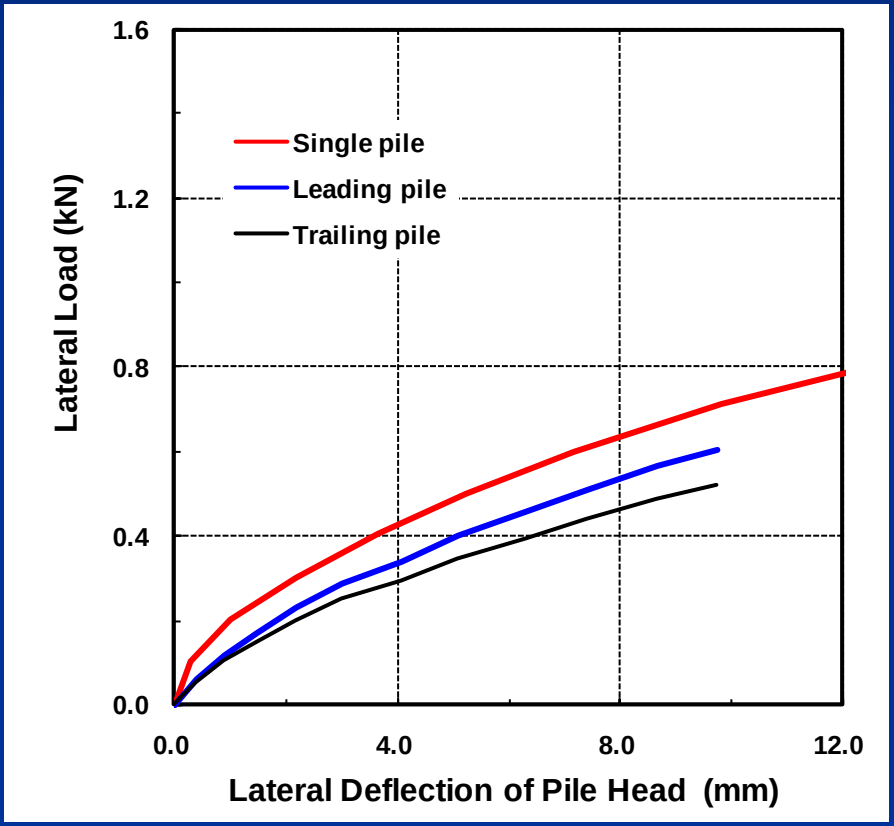
Distribution of bending moments of leading piles



1.0 kN-m = 0.738 lb-kips

Group piles: Medium dense sand (D_R=60%)

- Measured *p*-multipliers and distribution of lateral load



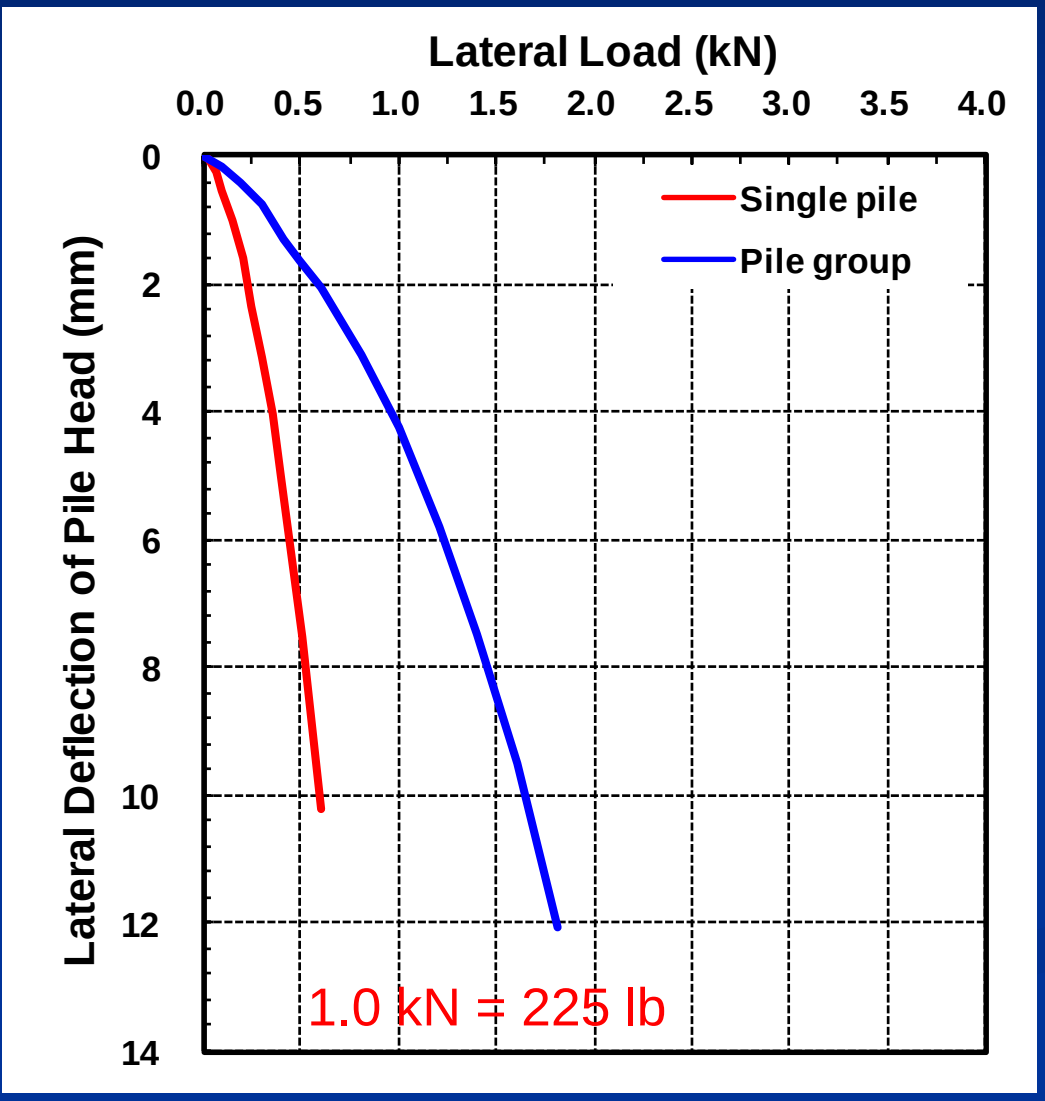
Measured *p*-multipliers

Lateral deflection	Leading Pile	Trailing Pile
5 % of B	0.70	0.60
10 % of B	0.68	0.59
20 % of B	0.82	0.71

1.0 kN = 225 lb

Group piles: Loose sand (D_R=40%)

- Lateral deflection of pile head (4 piles, 3B spacing)



Lateral deflection
= 5%, 10%, 20% of the pile diameter

$Q_{lat,\ 5\%}$ = 0.47 kN

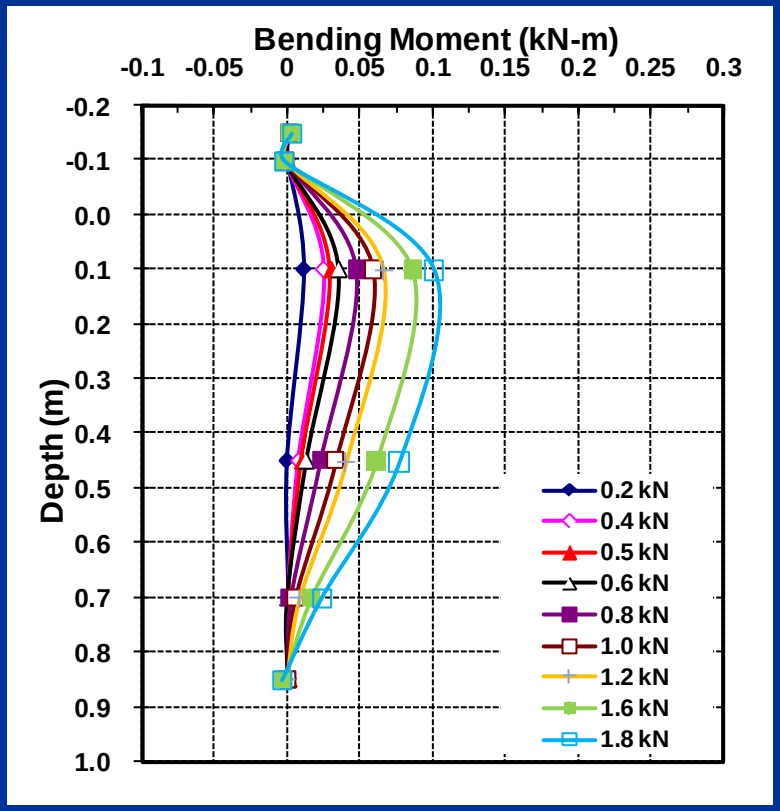
$Q_{lat,\ 10\%}$ = 0.80 kN

$Q_{lat,\ 20\%}$ = 1.23 kN

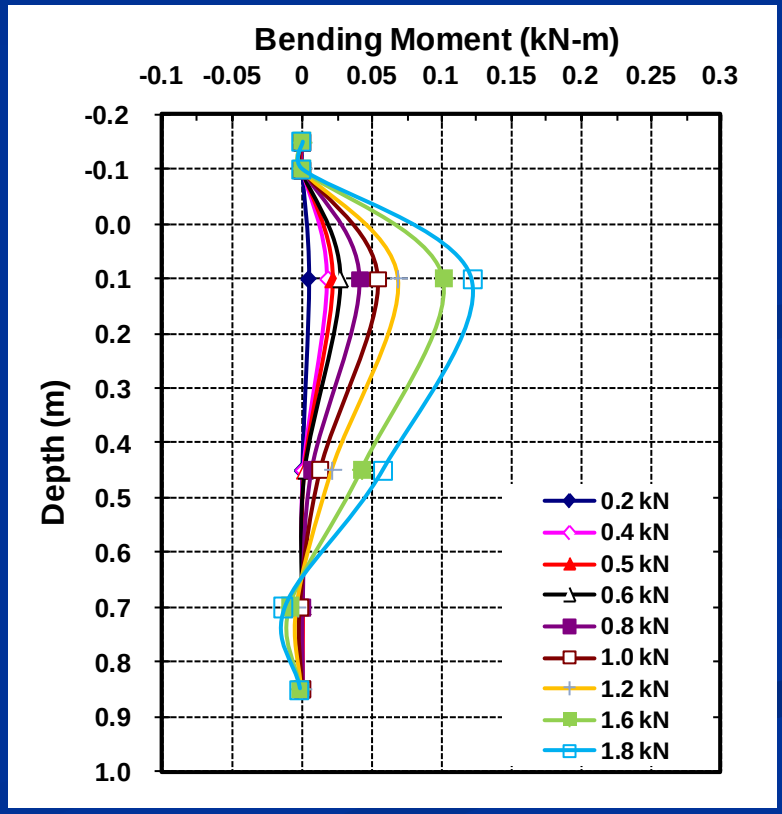
Group piles: Loose sand (D_R=40%)

- Bending Moment of leading and trailing piles

Distribution of bending moments of trailing piles



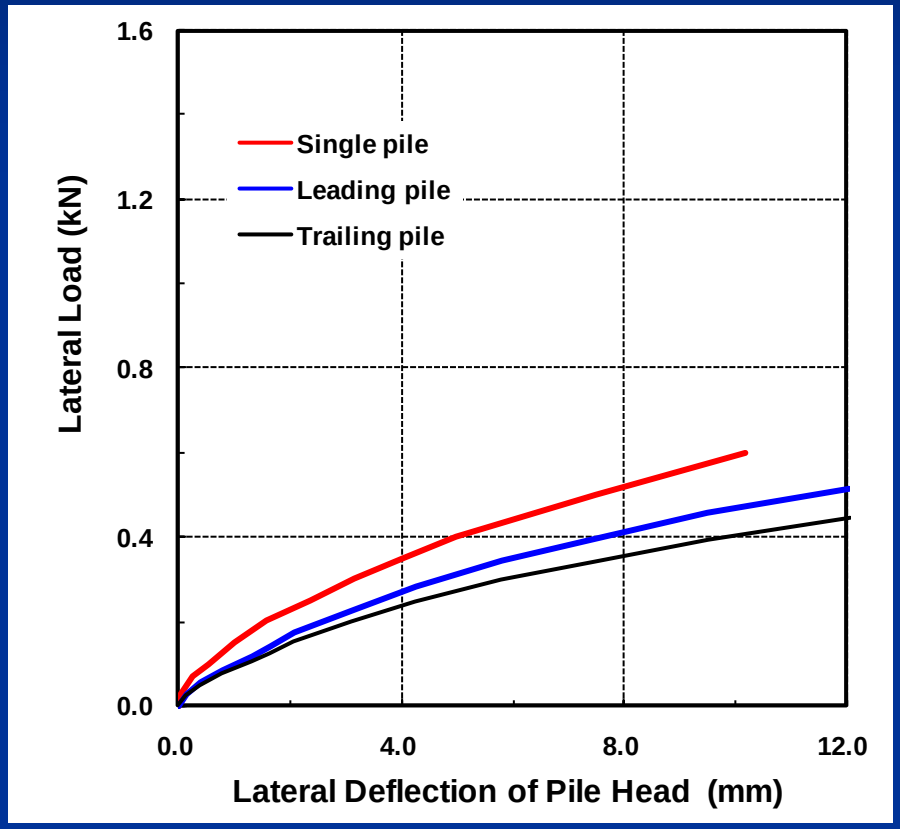
Distribution of bending moments of leading piles



1.0 kN-m = 0.738 lb-kips

Group piles: Loose sand (D_R=40%)

- Measured *p*-multipliers and distribution of lateral load

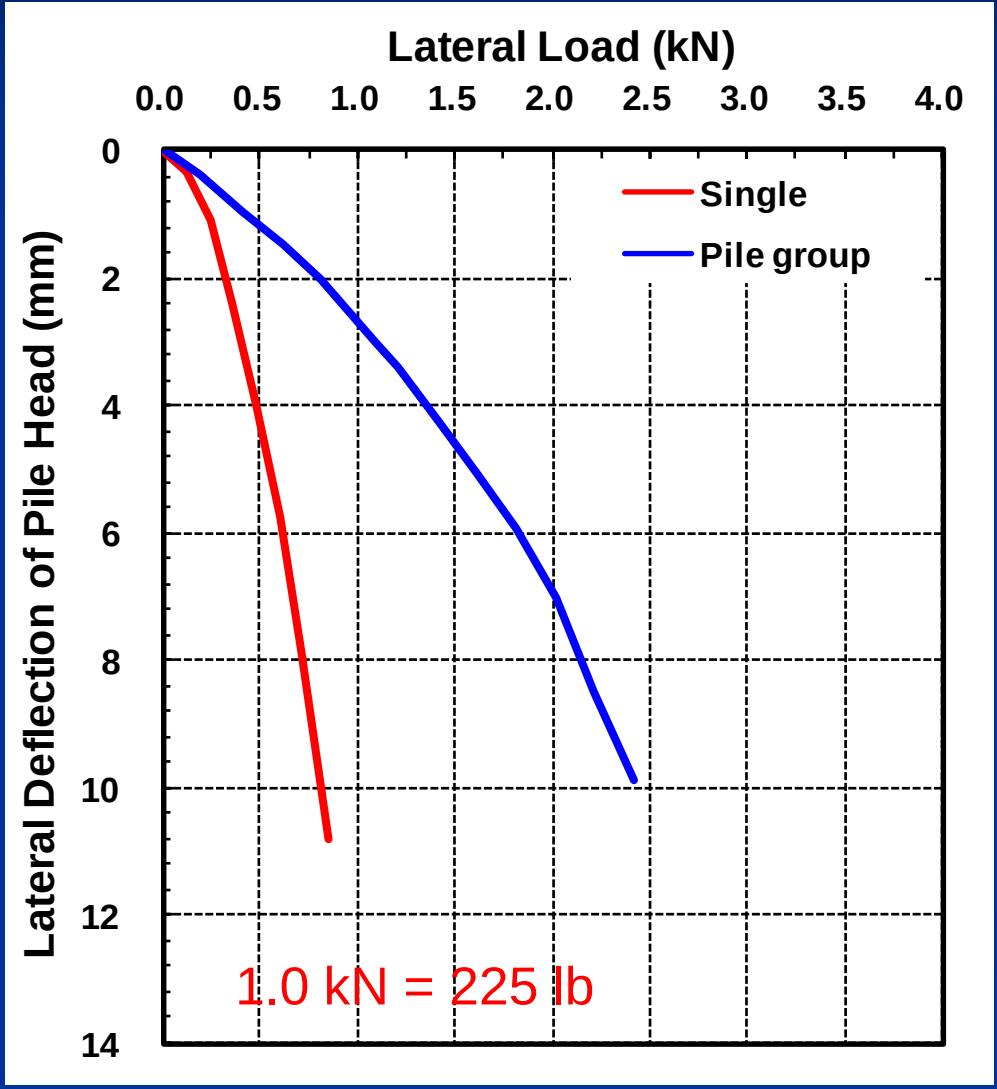


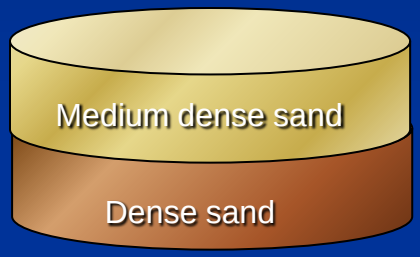
Measured *p*-multipliers

Lateral deflection	Leading Pile	Trailing Pile
5 % of B	0.68	0.59
10 % of B	0.76	0.65
20 % of B	0.80	0.69

Group piles: two-layer sand sample

- Lateral deflection of pile head (4 piles, 3B spacing)





Soil Tank

Lateral deflection
= 5%, 10%, 20% of the pile diameter

$Q_{lat,\ 5\%}$ = 0.62 kN

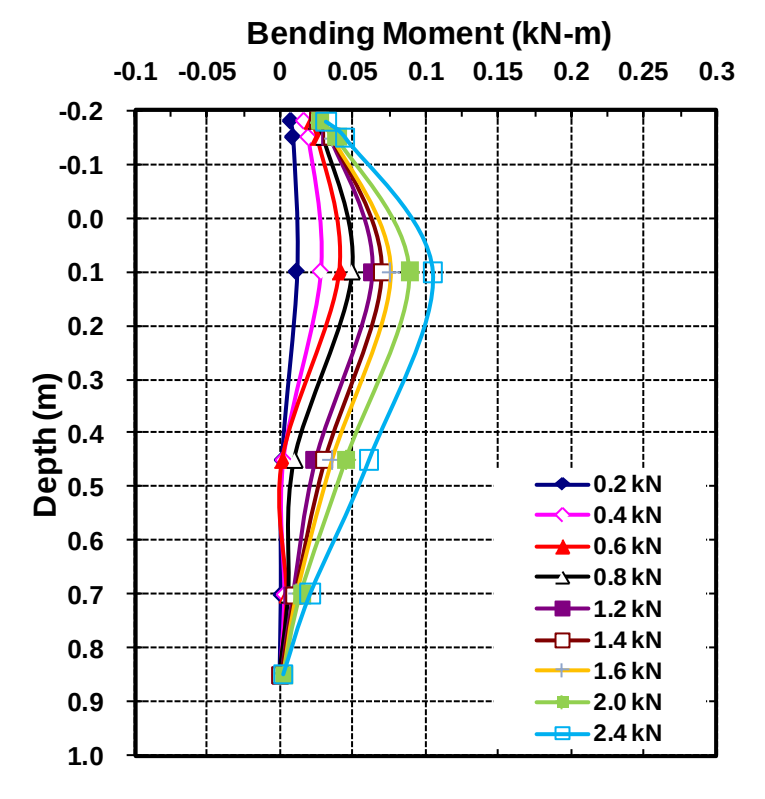
$Q_{lat,\ 10\%}$ = 1.21 kN

$Q_{lat,\ 20\%}$ = 1.82 kN

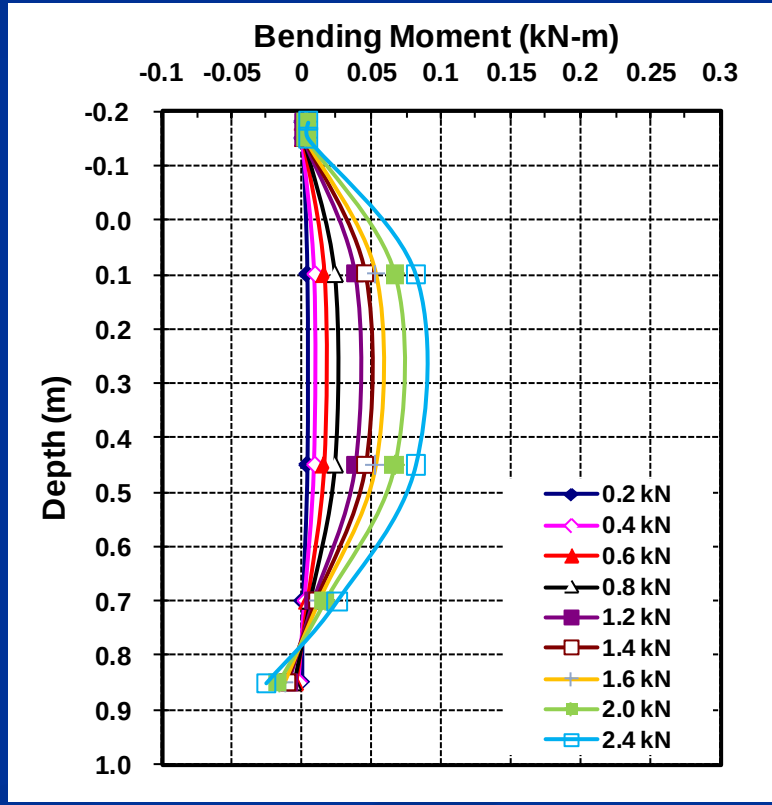
Group piles: two-layer sand sample

- Bending Moment of leading and trailing piles

Distribution of bending moments of trailing piles



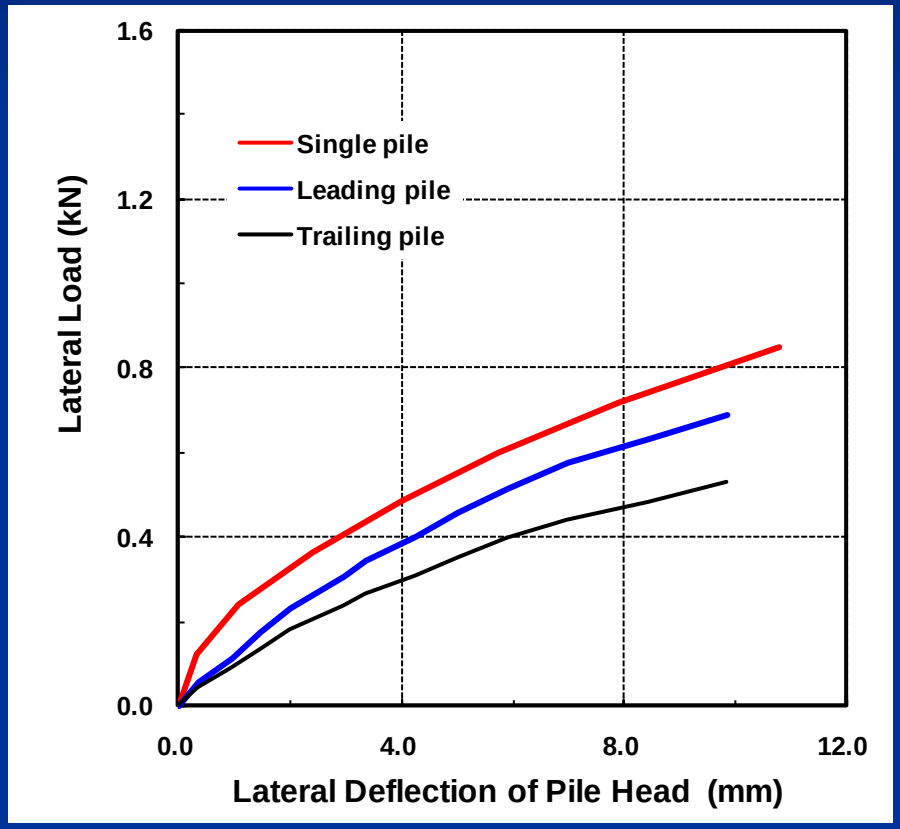
Distribution of bending moments of leading piles



1.0 kN-m = 0.738 lb-kips

Group piles: two-layer sand sample

- Measured *p*-multipliers and distribution of lateral load



Measured *p*-multipliers

Lateral deflection	Leading Pile	Trailing Pile
5 % of B	0.63	0.49
10 % of B	0.71	0.55
20 % of B	0.84	0.65

1.0 kN = 225 lb

Group piles: *p*-multipliers

- p-multipliers f

- *p-y* relationship for single pile

- Reduction in *p* values for each pile in the group by using f

Reese et al (2006)

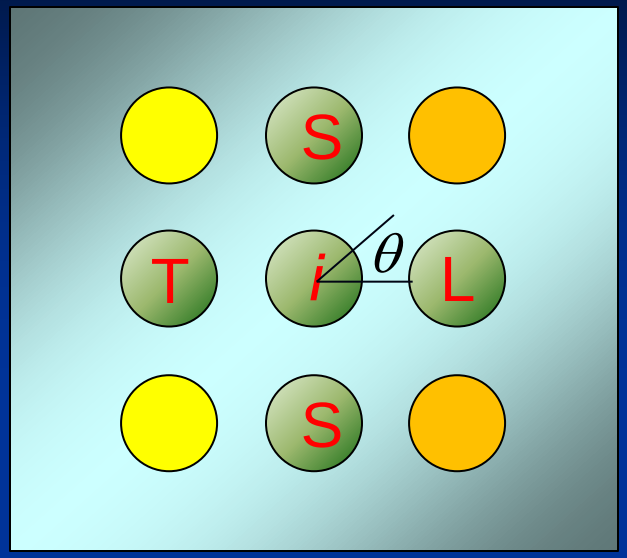
$$f_i = \prod_{j=1}^{n_p} \beta_{ij}$$

β_{ij} : interaction coefficients (pile i and pile j)

$\beta_{ij} = 1$ if $i = j$

Group piles: *p*-multipliers

Q_h



leading offset pile

trailing offset pile

s_{piL}, s_{piT}, s_{piS} : center-to-center spacing

B : pile diameter

$$\beta_{iL} = 0.48\left(\frac{s_{piL}}{B}\right)^{0.38} \le 1$$ for a leading pile

$$\beta_{iT} = 0.7\left(\frac{s_{piT}}{B}\right)^{0.26} \le 1$$ for a trailing pile

$$\beta_{iT} = 0.64\left(\frac{s_{piS}}{B}\right)^{0.34} \le 1$$ for a side-by-side pile

$$\beta_{i\theta} = \sqrt{\beta_{iL}^2 \cos^2\theta + \beta_{iS}^2 \sin^2\theta}$$

for leading offset pile

$$\beta_{i\theta} = \sqrt{\beta_{iT}^2 \cos^2\theta + \beta_{iS}^2 \sin^2\theta}$$

for trailing offset pile

Group piles: *p*-multipliers

for a leading pile

$$\beta_{12} = 0.48\left(\frac{s_{piL}}{B}\right)^{0.38} = 0.48\left(\frac{0.09}{0.03}\right)^{0.38} = 0.72$$

for a side-by-side pile

$$\beta_{13} = 0.64\left(\frac{s_{piT}}{B}\right)^{0.34} = 0.64\left(\frac{0.09}{0.03}\right)^{0.34} = 0.92$$

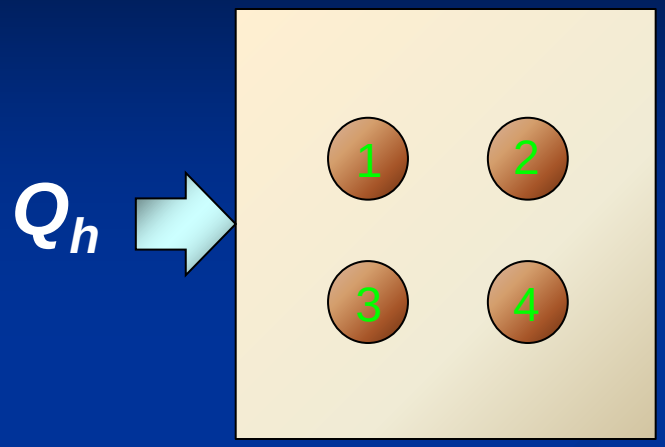
for leading offset pile

$$\beta_{14} = \sqrt{\beta_{1L}^2 \cos^2\theta + \beta_{1S}^2 \sin^2\theta}$$

$$\beta_{1L} = 0.48\left(\frac{s_{piL}}{B}\right)^{0.38} = 0.48\left(\frac{0.09\cdot\sqrt{2}}{0.03}\right)^{0.38} = 0.83$$

$$\beta_{1S} = 0.64\left(\frac{s_{piL}}{B}\right)^{0.34} = 0.64\left(\frac{0.09\cdot\sqrt{2}}{0.03}\right)^{0.34} = 1.04 \rightarrow 1$$

$$\beta_{14} = \sqrt{\beta_{1L}^2 \cos^2\theta + \beta_{1S}^2 \sin^2\theta} = 0.919$$



4 piles, 3B spacing (=0.09m)

$$f_1 = \prod_{j=1}^{n_p} \beta_{ij} = \beta_{12}\beta_{12}\beta_{13}\beta_{14} = 0.623$$

Group piles: *p*-multipliers

Mokwa (1999)

$$f_L = 0.64 + 0.06\left(\frac{s_p}{B}\right) \le 1$$ for the leading row

$$f_{T1} = 0.34 + 0.11\left(\frac{s_p}{B}\right) \le 1$$ for the 1st trailing row

$$f_{T2} = 0.16 + 0.14\left(\frac{s_p}{B}\right) \le 1$$ for the 2nd trailing row

$$f_{T3} = 0.04 + 0.16\left(\frac{s_p}{B}\right) \le 1$$ for the 3rd and subsequent trailing row

Group piles: *p*-multipliers

Mokwa (1999)

$$f_L = 0.64 + 0.06\left(\frac{s_p}{B}\right) = 0.64 + 0.06(3) = 0.82$$ for the leading row

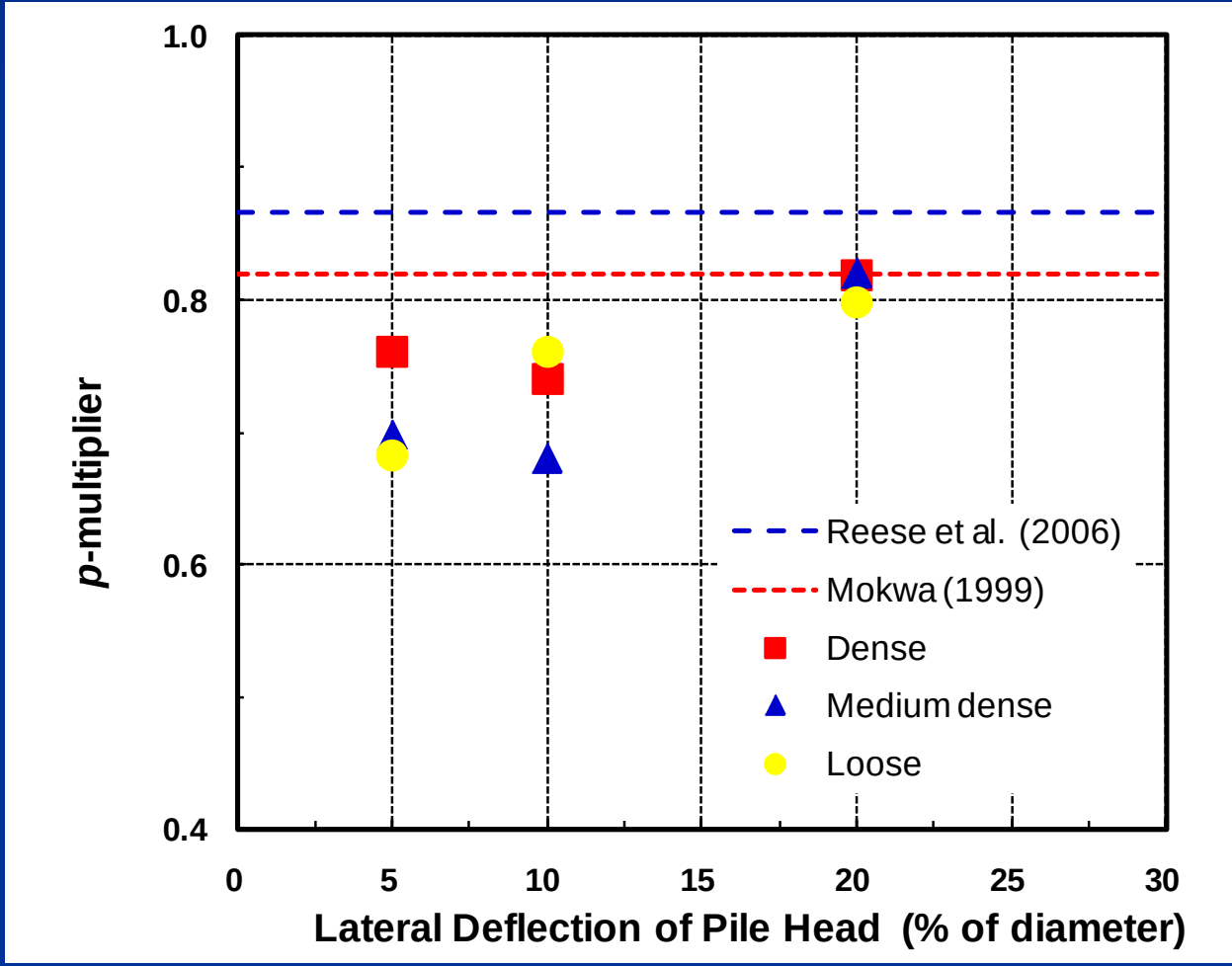
$$f_{T1} = 0.34 + 0.11\left(\frac{s_p}{B}\right) = 0.34 + 0.11(3) = 0.67$$ for the 1st trailing row

Predicted *p*-multipliers

	Leading Pile	Trailing Pile
Reese et al (2006)	0.866	0.623
Mokwa (1999)	0.820	0.670

Group piles: comparison of p-multipliers

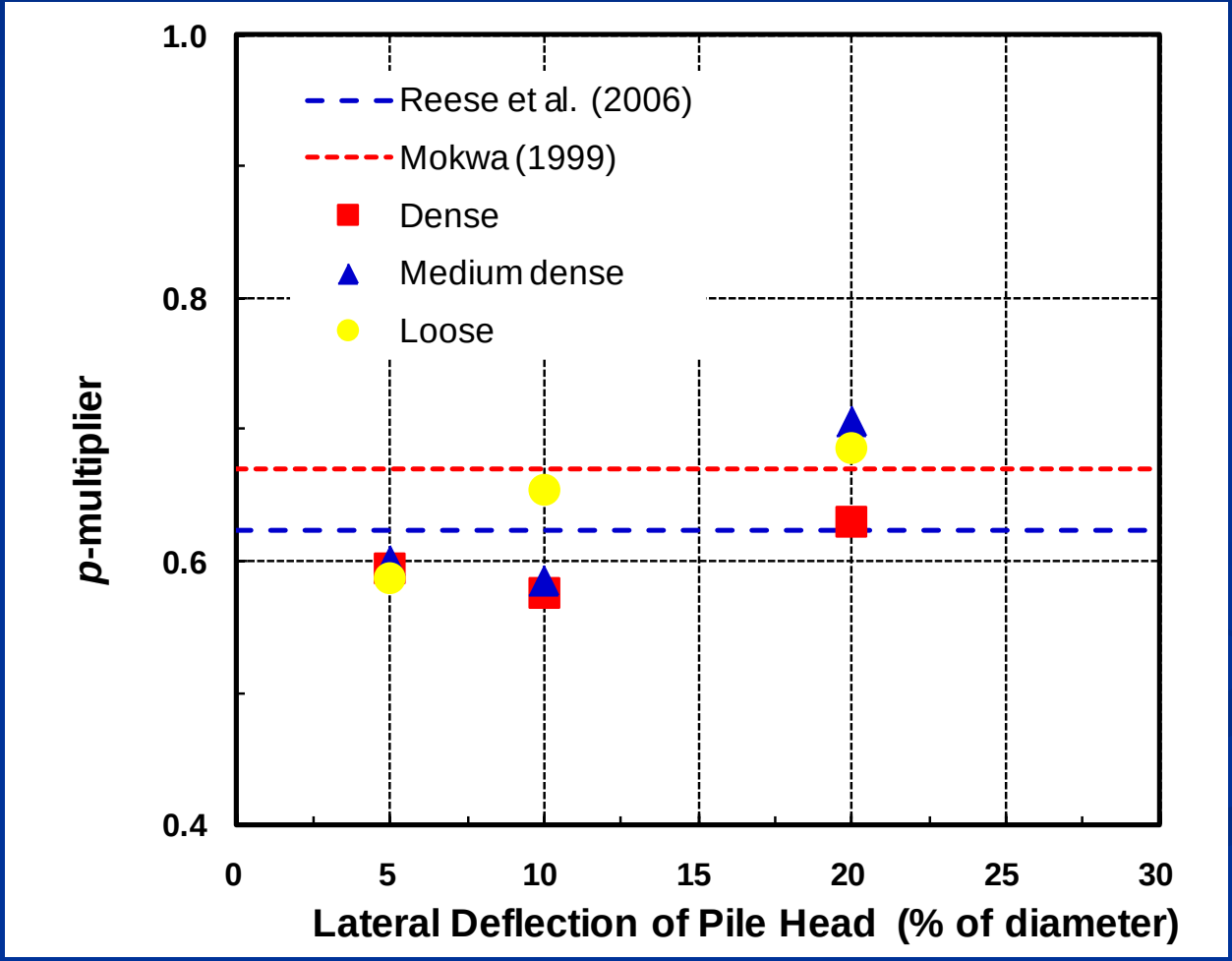
- Comparison of predicted *p*-multipliers with measurements from pile group tests in dense, medium dense and loose sand



Leading piles

Group piles: comparison of p-multipliers

- Comparison of predicted *p*-multipliers with measurements from pile group tests in dense, medium dense and loose sand



Trailing piles

Summary and Conclusions

- An instrumented model pile, a soil tank, a large-scale pluviator, a driving system, and a jacking system were fabricated

- Lateral load tests were performed on preinstalled, driven and jacked model piles installed in sand prepared at different densities

- The effects of soil conditions and pile installation method on the model pile capacities were evaluated

Summary and Conclusions

- For single piles, the predictions from the developed analysis were in good agreement with the model pile test results for small pile head deflections (up to 10% of the pile diameter)

- For pile groups, the measured *p*-multipliers are in reasonable agreement with those obtained from Mokwa (1999) and Reese et al. (2006)

  - the measured *p*-multipliers for the leading piles were 85%~90% less than the predicted values

  - for the trailing piles, the measured *p*-multipliers were in good agreement with the predictions

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