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 Test

Laterally Loaded Piles

Single piles
- Driven
- Preinstalled
- Jacked

Pile groups
- Driven (4 piles)
## Model pile testing plan

<table>
<thead>
<tr>
<th>Pile</th>
<th>Installation</th>
<th>Soil Condition</th>
<th>Relative Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single pile</td>
<td>Driven</td>
<td>Dense sand</td>
<td>$D_R \approx 90%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium dense sand</td>
<td>$D_R \approx 60%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Loose sand</td>
<td>$D_R \approx 40%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multi-layer</td>
<td>$D_R \approx 60%, 90%$</td>
</tr>
<tr>
<td>Preinstalled</td>
<td></td>
<td>Dense sand</td>
<td>$D_R \approx 90%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium dense sand</td>
<td>$D_R \approx 60%$</td>
</tr>
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<tr>
<td></td>
<td></td>
<td>Loose sand</td>
<td>$D_R \approx 40%$</td>
</tr>
<tr>
<td>Group piles</td>
<td>Driven</td>
<td>Dense sand</td>
<td>$D_R \approx 90%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium dense sand</td>
<td>$D_R \approx 60%$</td>
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<tr>
<td></td>
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  - Pile groups
- Summary and Conclusions
Soil tank

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

- Hammer
- Guide rod
- Model pile

Guide arm for pile driving (rotatable and extensible)

Reaction beam support
Soil tank

Guide arm for pile driving

Reaction beam (detachable)

Holes for draining sand

Open

Close
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
Contents

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**Instrumented model pile**

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

![Collected wires at pile head](image1)

![Closed-ended pile base](image2)
**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
Preinstallation of model pile

Preinstalled pile
Pile jacking system
Pile jacking system

- Max. rate = 5 cm/min
Installation of Group piles

- Setup

Pile driving guide
(Wooden Box Frame)

Pile driving order

4 Piles & Steel Cap
Lateral loading system

Single pile

Pile groups
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Test results: Single pile

- Lateral load - deflection curves (driven pile)

Ultimate lateral loads

\[ Q_{\text{lat},5\%} \]
\[ Q_{\text{lat},10\%} \]
\[ Q_{\text{lat},20\%} \]

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

<table>
<thead>
<tr>
<th>Sand type</th>
<th>( Q_{\text{lat}, 5%} ) (kN)</th>
<th>( Q_{\text{lat}, 10%} ) (kN)</th>
<th>( Q_{\text{lat}, 20%} ) (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense</td>
<td>0.42</td>
<td>0.65</td>
<td>0.92</td>
</tr>
<tr>
<td>Medium dense</td>
<td>0.24</td>
<td>0.36</td>
<td>0.54</td>
</tr>
<tr>
<td>Loose</td>
<td>0.19</td>
<td>0.29</td>
<td>0.44</td>
</tr>
</tbody>
</table>

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%)

\[ M = \frac{EI \cdot (T_{\varepsilon} - C_{\varepsilon})}{h} \]

\varepsilon_T: tensile strain

\varepsilon_C: compressive strain

h: horizontal distance between gauges

EI: bending stiffness of pile

Rollins et al. (1998)
Test results: Single pile

- Lateral load - deflection curves (jacked pile)

![Graph showing lateral load vs deflection curves for different sand types](image)

<table>
<thead>
<tr>
<th>Sand type</th>
<th>( Q_{lat}, 5% ) (kN)</th>
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<th>( Q_{lat}, 20% ) (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense</td>
<td>0.51</td>
<td>0.71</td>
<td>0.97</td>
</tr>
<tr>
<td>Medium dense</td>
<td>0.32</td>
<td>0.42</td>
<td>0.59</td>
</tr>
<tr>
<td>Loose</td>
<td>0.21</td>
<td>0.31</td>
<td>0.47</td>
</tr>
</tbody>
</table>

1.0 kN = 225 lb
Test results: Single pile

- Bending moment profiles (jacked pile)

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

1.0 kN-m = 0.738 lb-kips
Test results: Single pile

- Lateral load - deflection curves (preinstalled pile)

![Graph showing lateral load-deflection curves for different sand types.]

<table>
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<tr>
<th>Sand type</th>
<th>$Q_{lat, 5%}$ (kN)</th>
<th>$Q_{lat, 10%}$ (kN)</th>
<th>$Q_{lat, 20%}$ (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense</td>
<td>0.35</td>
<td>0.52</td>
<td>0.73</td>
</tr>
<tr>
<td>Medium dense</td>
<td>0.22</td>
<td>0.35</td>
<td>0.52</td>
</tr>
</tbody>
</table>

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)

<table>
<thead>
<tr>
<th>Sand type</th>
<th>$Q_{lat}, 5%$ (kN)</th>
<th>$Q_{lat}, 10%$ (kN)</th>
<th>$Q_{lat}, 20%$ (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi layer</td>
<td>0.28</td>
<td>0.41</td>
<td>0.61</td>
</tr>
</tbody>
</table>
Effect of pile installation method

**Dense sand**

\[ Q_{lat,10\%} \text{ (preinstalled piles)} = 73\% \text{ of } Q_{lat,10\%} \text{ (jacked piles)} \]

<table>
<thead>
<tr>
<th>Installation Method</th>
<th>( Q_{lat, 10%} ) (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jacked</td>
<td>0.71</td>
</tr>
<tr>
<td>Driven</td>
<td>0.65</td>
</tr>
<tr>
<td>Preinstalled</td>
<td>0.52</td>
</tr>
</tbody>
</table>

**Medium dense sand**

\[ Q_{lat,10\%} \text{ (preinstalled piles)} = 84\% \text{ of } Q_{lat,10\%} \text{ (jacked piles)} \]

<table>
<thead>
<tr>
<th>Installation Method</th>
<th>( Q_{lat, 10%} ) (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jacked</td>
<td>0.42</td>
</tr>
<tr>
<td>Driven</td>
<td>0.36</td>
</tr>
<tr>
<td>Preinstalled</td>
<td>0.35</td>
</tr>
</tbody>
</table>

1.0 kN = 225 lb
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

![Graph showing comparison of predicted and measured bending moment profiles](image)

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 sand.

Dense sand ($D_R=91\%$)

Medium dense sand ($D_R=59\%$)
Input parameters (present analysis)

### Input parameters for the model pile

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>1.2</td>
</tr>
<tr>
<td>Diameter / width (m)</td>
<td>0.03</td>
</tr>
<tr>
<td>Pile modulus (GPa)</td>
<td>210</td>
</tr>
</tbody>
</table>

### Input parameters for the soil

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical-state friction angle (deg.)</td>
<td>32.8</td>
</tr>
<tr>
<td>Max. void ratio ($e_{\text{max}}$)</td>
<td>0.78</td>
</tr>
<tr>
<td>Min. void ratio ($e_{\text{min}}$)</td>
<td>0.47</td>
</tr>
<tr>
<td>Coefficient of earth pressure</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Model: $f$-$g$ model

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

<table>
<thead>
<tr>
<th>$D_R$ (%)</th>
<th>$f$</th>
<th>$g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.98</td>
<td>0.17</td>
</tr>
<tr>
<td>50</td>
<td>0.97</td>
<td>0.2</td>
</tr>
<tr>
<td>70</td>
<td>0.96</td>
<td>0.23</td>
</tr>
<tr>
<td>90</td>
<td>0.95</td>
<td>0.26</td>
</tr>
</tbody>
</table>
## Input parameters (PYGMY)

### PYGMY input parameters for the model pile

<table>
<thead>
<tr>
<th>Pile property</th>
<th>Input value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>1.2</td>
</tr>
<tr>
<td>Diameter / width (m)</td>
<td>0.03</td>
</tr>
<tr>
<td>Bending stiffness of pile, $E_p I_p$ (kN·m²)</td>
<td>3.862</td>
</tr>
<tr>
<td>Plastic moment (kN·m)</td>
<td>0.5</td>
</tr>
<tr>
<td>No. of elements</td>
<td>30</td>
</tr>
</tbody>
</table>

### PYGMY input parameters for the soil

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Dense sand</th>
<th>Medium dense sand</th>
<th>Loose sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak friction angle (deg.)</td>
<td>44</td>
<td>39</td>
<td>36</td>
</tr>
<tr>
<td>Initial stiffness gradient (kPa/m)</td>
<td>82,000</td>
<td>34,000</td>
<td>12,000</td>
</tr>
<tr>
<td>Effective unit weight (kN/m³)</td>
<td>17.34</td>
<td>16.27</td>
<td>15.64</td>
</tr>
<tr>
<td>No. of soil layers</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
**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)
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- Summary and Conclusions
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

\[
Q_{\text{lat, 5\%}} = 0.91 \text{ kN} \\
Q_{\text{lat, 10\%}} = 1.59 \text{ kN} \\
Q_{\text{lat, 20\%}} = 2.25 \text{ kN}
\]

Lateral Load (kN) vs Lateral Deflection of Pile Head (mm)

1.0 kN = 225 lb
Group piles: Dense sand ($D_R=90\%$)

- Distribution of lateral load

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

For lateral load

$Q_h$

Pile top

2cm

4 strain gauges

Lateral Deflection of Pile Head (mm)

Lateral Load (kN)

1.0 kN = 225 lb
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

$1.0 \text{ kN-m} = 0.738 \text{ lb-kips}$
Group piles: Dense sand (DR=90%)

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

![Graph showing measured $p$-multipliers and distribution of lateral load]

**Measured $p$-multipliers**

<table>
<thead>
<tr>
<th>Lateral deflection</th>
<th>Leading Pile</th>
<th>Trailing Pile</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 % of B</td>
<td>0.76</td>
<td>0.59</td>
</tr>
<tr>
<td>10 % of B</td>
<td>0.74</td>
<td>0.58</td>
</tr>
<tr>
<td>20 % of B</td>
<td>0.82</td>
<td>0.63</td>
</tr>
</tbody>
</table>

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

Lateral deflection load:
- $Q_{lat, 5\%} = 0.60 \text{ kN}$
- $Q_{lat, 10\%} = 1.20 \text{ kN}$
- $Q_{lat, 20\%} = 1.56 \text{ kN}$

Graph showing:
- Lateral Load (kN) vs. Lateral Deflection of Pile Head (mm)
- Single pile and Pile group

1.0 kN = 225 lb
Group piles: Medium dense sand (DR=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**

<table>
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<tbody>
<tr>
<td>5 % of B</td>
<td>0.70</td>
<td>0.60</td>
</tr>
<tr>
<td>10 % of B</td>
<td>0.68</td>
<td>0.59</td>
</tr>
<tr>
<td>20 % of B</td>
<td>0.82</td>
<td>0.71</td>
</tr>
</tbody>
</table>

$1.0\text{ kN} = 225 \text{ lb}$
Group piles: Loose sand ($D_R=40\%$)

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

**Lateral Deflection of Pile Head (mm)**

<table>
<thead>
<tr>
<th>Lateral Load (kN)</th>
<th>Single pile</th>
<th>Pile group</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1.0</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>1.5</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>2.0</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>2.5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>3.0</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>3.5</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>4.0</td>
<td>8</td>
<td>16</td>
</tr>
</tbody>
</table>

- $Q_{\text{lat}, 5\%} = 0.47 \text{ kN}$
- $Q_{\text{lat}, 10\%} = 0.80 \text{ kN}$
- $Q_{\text{lat}, 20\%} = 1.23 \text{ kN}$

Lateral deflection

- $= 5\%, 10\%, 20\%$ of the pile diameter

1.0 kN = 225 lb
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**

$1.0 \text{ kN-m} = 0.738 \text{ lb-kips}$
Group piles: Loose sand ($D_R=40\%$)

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

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</tr>
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<td>10 % of B</td>
<td>0.76</td>
<td>0.65</td>
</tr>
<tr>
<td>20 % of B</td>
<td>0.80</td>
<td>0.69</td>
</tr>
</tbody>
</table>
Group piles: two-layer sand sample

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

\[ Q_{\text{lat}}, 5\% = 0.62 \text{ kN} \]
\[ Q_{\text{lat}}, 10\% = 1.21 \text{ kN} \]
\[ Q_{\text{lat}}, 20\% = 1.82 \text{ kN} \]

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

1.0 kN = 225 lb
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

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<td>0.71</td>
<td>0.55</td>
</tr>
<tr>
<td>20 % of B</td>
<td>0.84</td>
<td>0.65</td>
</tr>
</tbody>
</table>

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 $f$


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

$\beta_{ij}$ : interaction coefficients (pile $i$ and pile $j$)

$\beta_{ij} = 1$ if $i = j$
Group piles: \( p \)-multipliers

\[
\begin{align*}
\beta_{iL} &= 0.48 \left( \frac{s_{piL}}{B} \right)^{0.38} \leq 1 \quad \text{for a leading pile} \\
\beta_{iT} &= 0.7 \left( \frac{s_{piT}}{B} \right)^{0.26} \leq 1 \quad \text{for a trailing pile} \\
\beta_{iS} &= 0.64 \left( \frac{s_{piS}}{B} \right)^{0.34} \leq 1 \quad \text{for a side-by-side pile}
\end{align*}
\]

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

for leading offset pile

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

for trailing offset pile

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

\( B \): pile diameter
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

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

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

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

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

\[Q_h\]

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

\[ f_L = 0.64 + 0.06 \left( \frac{S_p}{B} \right) \leq 1 \] for the leading row

\[ f_{T_1} = 0.34 + 0.11 \left( \frac{S_p}{B} \right) \leq 1 \] for the 1st trailing row

\[ f_{T_2} = 0.16 + 0.14 \left( \frac{S_p}{B} \right) \leq 1 \] for the 2nd trailing row

\[ f_{T_3} = 0.04 + 0.16 \left( \frac{S_p}{B} \right) \leq 1 \] for the 3rd and subsequent trailing row

Mokwa (1999)
Group piles: \( p \)-multipliers

**Mokwa (1999)**

\[
\begin{align*}
  f_L &= 0.64 + 0.06 \left( \frac{S_p}{B} \right) = 0.64 + 0.06(3) = 0.82 \quad \text{for the leading row} \\
  f_{T1} &= 0.34 + 0.11 \left( \frac{S_p}{B} \right) = 0.34 + 0.11(3) = 0.67 \quad \text{for the 1st trailing row}
\end{align*}
\]

**Predicted \( p \)-multipliers**

<table>
<thead>
<tr>
<th></th>
<th>Leading Pile</th>
<th>Trailing Pile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reese et al (2006)</td>
<td>0.866</td>
<td>0.623</td>
</tr>
<tr>
<td>Mokwa (1999)</td>
<td>0.820</td>
<td>0.670</td>
</tr>
</tbody>
</table>
Group piles: comparison of p-multipliers

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

![Graph showing Lateral Deflection of Pile Head (% of diameter) vs. p-multiplier for different sand densities. The graph includes data from Reese et al. (2006) and Mokwa (1999).](image)
Group piles: comparison of $p$-multipliers

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

\[
\begin{align*}
\text{Reese et al. (2006)} & \quad \text{Mokwa (1999)} \\
\text{Dense} & \quad \text{Medium dense} \\
\text{Loose} & \\
\end{align*}
\]
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.
References