2-D Soil-Structure Interaction Analysis and Its Application for 3-D Structural Designs

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E-mail Address: Jianhua.Li@amec.com
• 2-D LPILE Soil-Pile Interaction Analysis
  - Evaluation of group effects;
  - Evaluation of boundary conditions due to close proximity of the drilled shafts to adjacent existing subsurface structures (boundary effects)

• Application of 2-D LPILE Results for 3-D Structural Modeling
Example of Site Configurations

PLAN VIEW

1"-THICK EXPANSION JOINT BETWEEN PILE CAP & BASE WALL

4'-THICK R.C. Basement Wall

PILE CAP

28' x 28' x 4'-THICK

12'-4" (TYP.)
Example of Site Configurations

- **Basement Wall**: 2' 4'
- **Granular Soil**:
  - \(Y = 126 \text{ pcf}\)
  - \(C = 0\)
  - \(\phi = 32^\circ\)
  - \(k = 78 \text{ pci}\)
  - Subgrade modulus for lateral load analysis
- **Bedrock**:
  - \(Y = 170 \text{ pcf}\)
  - \(E = 900000 \text{ psi}\)
Pile Group Effects
Subject to Lateral Loading

FIGURE 5.50 Typical stress zones for pile foundations under lateral load.
p-y modification factors:
- p-multiplier ($p_m$)
- y-multiplier ($y_m$)
### Table 1: Summary of $p$-multipliers based on previous full-scale lateral pile group tests. (Modified from Rollins et al., 2002)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Group Size</th>
<th>Pile Sp.</th>
<th>$p$-multipliers (by row)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meimon (1986)</td>
<td>3x2</td>
<td>3d</td>
<td></td>
<td>0.9</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Brown (1987)</td>
<td>3x3</td>
<td>3d</td>
<td></td>
<td>0.7</td>
<td>0.6</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>Brown (1988)</td>
<td>3x3</td>
<td>3d</td>
<td></td>
<td>0.8</td>
<td>0.4</td>
<td>0.3</td>
<td>-</td>
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<tr>
<td>Townsend (1997)</td>
<td>4x4</td>
<td>3d</td>
<td></td>
<td>0.8</td>
<td>0.7</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Rollins (1998)</td>
<td>3x3</td>
<td>3d</td>
<td></td>
<td>0.6</td>
<td>0.4</td>
<td>0.4</td>
<td>-</td>
</tr>
</tbody>
</table>

### Table 2: Summary of $p$-multipliers based on previous centrifuge tests. (Modified from Rollins, et al., 2002)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Grp Size</th>
<th>Pile Sp.</th>
<th>$p$-multipliers (by row)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
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<tr>
<td>McVay (1995)</td>
<td>3x3</td>
<td>3d</td>
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<td>.45</td>
<td>.35</td>
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</tr>
<tr>
<td></td>
<td>3x3</td>
<td>3d</td>
<td></td>
<td>.80</td>
<td>.45</td>
<td>.30</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td>3x3</td>
<td>5d</td>
<td></td>
<td>1.0</td>
<td>.85</td>
<td>.70</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>McVay (1995)</td>
<td>3x3</td>
<td>3d</td>
<td></td>
<td>.80</td>
<td>.40</td>
<td>.30</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3x4</td>
<td>3d</td>
<td></td>
<td>.80</td>
<td>.40</td>
<td>.30</td>
<td>.30</td>
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<td></td>
<td>3x5</td>
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<td>.20</td>
<td>.30</td>
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<tr>
<td></td>
<td>3x6</td>
<td>3d</td>
<td></td>
<td>.80</td>
<td>.40</td>
<td>.30</td>
<td>.20</td>
<td>.20</td>
<td>.30</td>
</tr>
<tr>
<td></td>
<td>3x7</td>
<td>3d</td>
<td></td>
<td>.80</td>
<td>.40</td>
<td>.30</td>
<td>.20</td>
<td>.20</td>
<td>.20</td>
</tr>
<tr>
<td>Garnier (1998)</td>
<td>1x2</td>
<td>2d</td>
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<td>-</td>
<td>.52</td>
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<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1x2</td>
<td>4d</td>
<td></td>
<td>-</td>
<td>.82</td>
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<td>1x2</td>
<td>6d</td>
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<td>-</td>
<td>.93</td>
<td>-</td>
<td>-</td>
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</tbody>
</table>
For the first (leading) row piles

\[ f_m = 0.26 \ln(S/D) + 0.5 \leq 1.0 \]

For the second row

\[ f_m = 0.52 \ln(S/D) \leq 1.0 \]

For the third and higher row piles

\[ f_m = 0.60 \ln(S/D) - 0.25 \leq 1.0 \]

In case of caissons spacing **non-uniformly**, the following rules are adopted in utilizing the above equations:

- For caissons at the first and second rows, the S-value is taken as the distance between these two rows;
- For caissons at the third row, the S-value is taken as the distance to the second row caisson located in front of it.

2D LPILE Analysis – p-Multiplier

![Graphs showing lateral deflection and soil reaction with depth for Rock and Saprolite layers with different p-multipliers.](image-url)
• Calculate the **far-field** caisson movement; with $H = (6.8) D$

• Calculate the **near-field** caisson movement; based on actual edge-to-edge clearance between caisson and basement.

• How to calculate the Caisson movement?
• The caisson movement is calculated as settlement of the loaded rectangular footing:

\[ \Delta H = q_0 \frac{1 - \mu^2}{E_s} \left( I_1 + \frac{1 - 2\mu}{1 - \mu} I_2 \right) I_F \]

The influence factors \( I_1 \) and \( I_2 \) can be computed using the Steinbrenner equations.

• The ratio of the near-field to the far-field movement is applied as a “\( y \)-multiplier”.

\[ \frac{H_{\text{near}}}{H_{\text{far}}} = \frac{\Delta H_{\text{near}}}{\Delta H_{\text{far}}} \]
2D LPILE Analysis – y-Multiplier

Lateral Deflection (in)

Soil Reaction, p (kips/in. length of pile)

Depths (ft)

Depths (ft)

Saprolite

Rock

ym=1.0

ym=0.41

ym=1.0

ym=0.41
3-D Soil-Pile Interaction

Fig. 1.2 Three dimensional soil-pile interaction (after Bryant, 1977)
Springs Coordinates & Stiffness Matrix

- GTSTRUDL uses a 3-dimensional global coordinate system

- Spring outputs from LPILE are based on 2-dimensional local coordinate system

\[
\begin{bmatrix}
P_x & V_y & V_z & M_x & M_y & M_z \\
V_y & K_{22} & 0 & 0 & 0 & 0 \\
V_z & 0 & K_{11} & 0 & 0 & K_{16} \\
M_x & 0 & 0 & K_{33} & 0 & K_{34} \\
M_y & 0 & 0 & 0 & K_{55} & 0 \\
M_z & 0 & 0 & K_{43} & K_{44} & 0 \\
\end{bmatrix}
\begin{bmatrix}
\Delta x \\
\Delta y \\
\Delta z \\
\end{bmatrix}
= 
\begin{bmatrix}
F_x \\
F_y \\
F_z \\
\end{bmatrix}
\]

(a) For GTStrudl Structural Modeling

\[
\begin{bmatrix}
K_{22} & K_{23} \\
K_{32} & K_{33} \\
\end{bmatrix}
\begin{bmatrix}
\theta_x \\
\theta_y \\
\theta_z \\
\end{bmatrix}
\]

(b) For LPILE Analyses with Horizontal Loading in N-S & E-W Directions
Springs Coordinates & Stiffness Matrix

- Conversion for using LPILE stiffness values for GTSTRUDL analyses.

<table>
<thead>
<tr>
<th>Stiffness Parameters</th>
<th>L-Pile Outputs</th>
<th>GTStrudl Inputs</th>
<th>Description</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K22 (south-north)</td>
<td>K11</td>
<td>Longitudinal lateral loading stiffness, (lb/in)</td>
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<tr>
<td></td>
<td>K33 (south-north)</td>
<td>K66</td>
<td>Longitudinal moment stiffness, (lb-in/rad)</td>
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<td></td>
<td>K32 (south-north)</td>
<td>K61</td>
<td>Longitudinal moment cross-couple term, (lb-in/in)</td>
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<td>K23 (south-north)</td>
<td>K16</td>
<td>Longitudinal lateral loading cross-couple term, (lb/rad)</td>
<td></td>
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<tr>
<td></td>
<td>K22 (east-west)</td>
<td>K33</td>
<td>Transverse lateral loading stiffness, (lb/in)</td>
<td></td>
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<tr>
<td></td>
<td>K33 (east-west)</td>
<td>K44</td>
<td>Transverse moment stiffness, (lb-in/rad)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>K32 (east-west)</td>
<td>K43</td>
<td>Transverse moment cross-couple term, (lb-in/in)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>K23 (east-west)</td>
<td>K34</td>
<td>Transverse lateral loading cross-couple term, (lb/rad)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>K22</td>
<td>Axial loading stiffness, (lb/in)</td>
<td>Not given by L-Pile.</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>K55</td>
<td>Torsional stiffness, (lb-in/rad)</td>
<td>Not given by L-Pile.</td>
</tr>
</tbody>
</table>
Conclusion

• In 2-D LPILE soil-pile interaction analysis, group effects and boundary effects can be considered by using p-y modification factors (p-multiplier or y-multiplier);

• Spring values from 2-D LPILE analysis can be used for the 3-D structural model, which greatly saves the computational time and cost for the project.
Questions & Discussion