FB-MultiPier: P-Y Model Validation

FB-MultiPier V4.19 vs. LPILE V6.0.15®

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EXECUTIVE SUMMARY

This report summarizes the comparison between FB-MultiPier V4.19 and LPILE V6.0.15® in which the soil lateral resistance is numerically predicted using various P-Y models.
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In this chapter, analysis results of load-deformation behaviors of a pile foundation are compared between FB-MultiPier V4.19 and LPILE V6.0.15® (referred to as LPILE in the remainder of the report) and presented for resultant shear, moment, head displacement of a circular-section pile, and soil lateral resistance. For direct comparison, gross-sectional properties are used in linear elastic analysis for the circular pile section; treatment of nonlinear behavior of the pile in FB-MultiPier analysis is different from that of LPILE. FB-MultiPier computes resultant forces using the numerical integration of stress both flexural and axial over 256 integration points, i.e., “fibers” of the cross section, while taking into consideration both material nonlinearity (e.g., elastic-perfectly plastic constitutive stress-strain relationship of steel) and large-deformation nonlinear behavior (i.e., p-Δ effects). Upon request, the input model of FB-MultiPier will be available to current users of the program.
Example 1-1: Single 24” Pipe Pile in Sand (Reese)

**Problem Description:** Analyze a single 24” pipe pile subjected to lateral loading condition. The pile is embedded in a single layer of sand which is modeled using the Reese sand model. The pile is assumed to remain linear elastic.

<table>
<thead>
<tr>
<th>P = 10 kips</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 ft</td>
</tr>
<tr>
<td>56.7 ft</td>
</tr>
</tbody>
</table>

\[ \phi = 32^\circ \]
\[ k = 60 \text{ pci} \]
\[ \gamma = 110 \text{ pcf} \]

File: Example_1-1_v419.in

24” Pipe Pile Section
Figure 1.1

- **a)** Shear force
- **b)** Bending moment
- **c)** Soil lateral force per unit length
- **d)** Deflection
**Example 1-2: Single 24” Pipe Pile in Sand (API)**

**Problem Description:** Analyze a single 24” pipe pile subjected to lateral loading condition. The pile is embedded in a single layer of sand which is modeled using the API sand model. The pile is assumed to remain linear elastic. (API – American Petroleum Institute)

<table>
<thead>
<tr>
<th>P = 30 kips</th>
<th>10 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi = 32^\circ$</td>
<td>56.7 ft</td>
</tr>
<tr>
<td>$k = 60$ pci</td>
<td></td>
</tr>
<tr>
<td>$\gamma = 110$ pcf</td>
<td></td>
</tr>
</tbody>
</table>

![24” Pipe Pile Section](image)
Figure 1.2

a) Shear force

b) Bending moment

c) Soil lateral force per unit length

d) Deflection
### Example 1-3: Single 36” Drilled Shaft in Sand (Reese)

**Problem Description:** Analyze a single 36” drilled shaft subjected to lateral loading condition. The pile is embedded in a single layer of sand which is modeled using the Reese sand model. The pile is assumed to remain linear elastic.

<table>
<thead>
<tr>
<th>P = 10 kips</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi = 32^\circ$</td>
</tr>
<tr>
<td>$k = 60$ pci</td>
</tr>
<tr>
<td>$\gamma = 110$ pcf</td>
</tr>
</tbody>
</table>

File: Example_1-3_v419.in
Figure 1.3

a) Shear force

b) Bending moment

c) Soil lateral force per unit length

d) Deflection
Example 1-4: Single 36” Drilled Shaft in Sand (API)

**Problem Description:** Analyze a single 36” drilled shaft subjected to lateral loading condition. The pile is embedded in a single layer of sand which is modeled using the API sand model. The pile is assumed to remain linear elastic.

- **Load:** $P = 20$ kips
- **Angle:** $\phi = 32^\circ$
- **Modulus:** $k = 60$ pci
- **Density:** $\gamma = 110$ pcf

**File:** Example_1-4_v419.in
a) Shear force

b) Bending moment

c) Soil lateral force per unit length

d) Deflection

Figure 1.4
Chapter 2

Noncircular Section

In this chapter, analysis results of load-deformation behaviors of noncircular pile foundations are compared between FB-MultiPier and LPILE and presented for resultant shear, moment, pile head displacement, and soil lateral resistance. For direct comparison, gross-sectional properties are used in linear elastic analysis for the noncircular section.

In FB-MultiPier analysis for Example 2-1 through 2-9, “effective” diameters of the noncircular piles are computed using \( D_{\text{eff}} = \frac{2(t_d + t_w)}{\pi} \) where effective diameter is denoted by \( D_{\text{eff}} \), and \( t_w \) and \( t_d \) are width and depth of the section. Since the p-y curve was originally developed for circular sections and thus a function of the diameter, an empirical equation for calculating the circumference is used to approximate an equivalent diameter to the dimensions of noncircular section, which results in increased soil lateral resistance due to the noncircular shape of the pile; Ashour and Norris (2000) studied analytically the influence of pile cross-sectional shapes on the p-y curves. They found that if two piles have the same “width” perpendicular to the lateral load yet different shapes such that one has a circular section and the other has a square section, then the resulting p-y curves can be different. Their findings are based on numerical studies of soil wedge formation. Reese and Van Impe (2001) also pointed out the influence of the shape of the pile cross section on the soil resistance such that the square pile would induce a soil resistance higher than the circular pile. No full-scale load test result has been found in the literature.

Reference:
1. FHWA-HRT-04-043: 8.3.1 P-y Curves; 8.3.1.1 Introduction where a schematic sketch illustrates the lateral resistance of soil with respect to pile shapes [http://www.fhwa.dot.gov/publications/research/infrastructure/structures/04043/08.cfm](http://www.fhwa.dot.gov/publications/research/infrastructure/structures/04043/08.cfm)
# Example 2-1: Single 18” Precast Pile in Sand (Reese)

**Problem Description:** Analyze a single 18” precast, prestressed pile subjected to lateral loading condition. The pile is embedded in a single layer of sand which is modeled using Reese sand model. The pile is assumed to remain linear elastic.

<table>
<thead>
<tr>
<th><strong>P</strong></th>
<th>10 ft</th>
<th><strong>P = 10 kips</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (Reese)</td>
<td>56.7 ft</td>
<td>( \phi = 32^\circ )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( k = 60 \text{ pci} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \gamma = 110 \text{ pcf} )</td>
</tr>
</tbody>
</table>

18” Square FDOT Standard Prestressed Pile

File: Example_2-1_v419.in
Figure 2.1

(a) Shear force

(b) Bending moment

(c) Soil lateral force per unit length

(d) Deflection
**Example 2-2: Single 18” Precast Pile in Sand (API)**

**Problem Description:** Analyze a single 18” precast, prestressed pile subjected to lateral loading condition. The pile is embedded in a single layer of sand which is modeled using API sand model. The pile is assumed to remain linear elastic.

P = 10 kips

φ = 32°

k = 60 pci

γ = 110 pcf

18” Square FDOT Standard Prestressed Pile

File: Example_2-2_v419.in
Figure 2.2

a) Shear force

b) Bending moment

c) Soil lateral force per unit length

d) Deflection
## Example 2-3: Single 18” Precast Pile in Clay (Soft < Water)

**Problem Description:** Analyze a single 18” precast, prestressed pile subjected to lateral loading condition. The pile is embedded in a single layer of clay which is modeled using the soft clay below the water table model. The pile is assumed to remain linear elastic.

<table>
<thead>
<tr>
<th>P</th>
<th>10 ft</th>
<th>Cu = 400psf</th>
</tr>
</thead>
<tbody>
<tr>
<td>56.7 ft</td>
<td>( E_{50} = 0.02 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \gamma = 110 \text{pcf} )</td>
<td></td>
</tr>
</tbody>
</table>

18” Square FDOT Standard Prestressed Pile

File: Example_2-3_v419.in
Figure 2.3

- a) Shear force
- b) Bending moment
- c) Soil lateral force per unit length
- d) Deflection
## Example 2-4: Single 18” Precast Pile in Clay (Stiff < Water)

**Problem Description:** Analyze a single 18” precast, prestressed pile subjected to lateral loading condition. The pile is embedded in a single layer of clay which is modeled using the stiff clay below the water table model. The pile is assumed to remain linear elastic.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Depth</td>
<td>10 ft</td>
</tr>
<tr>
<td>Horizontal Depth</td>
<td>56.7 ft</td>
</tr>
<tr>
<td>Load</td>
<td>P = 10 kips</td>
</tr>
<tr>
<td>Soil Modulus</td>
<td>k = 100 pci</td>
</tr>
<tr>
<td>Density</td>
<td>γ = 110 pcf</td>
</tr>
<tr>
<td>Ultimate Strength</td>
<td>Cu = 2000 psf</td>
</tr>
<tr>
<td>Stress Function</td>
<td>E50 = 0.005</td>
</tr>
<tr>
<td>Average Stress</td>
<td>Cavg = 2000 psf</td>
</tr>
</tbody>
</table>

File: Example_2-4_v419.in
a) Shear force

b) Bending moment

c) Soil lateral force per unit length

d) Deflection

Figure 2.4
Example 2-5: Single 18” Precast Pile in Clay (Stiff > Water)

**Problem Description:** Analyze a single 18” precast, prestressed pile subjected to lateral loading condition. The pile is embedded in a single layer of clay which is modeled using the stiff clay above the water table model. The pile is assumed to remain linear elastic.

\[
\begin{align*}
\gamma &= 110 \text{ pcf} \\
C_u &= 2000 \text{ psf} \\
E_{50} &= 0.005 \\
C_{avg} &= 2000 \text{ psf}
\end{align*}
\]

P = 10 kips

Clay (Stiff > Water)

File: Example_2-5_v419.in
Figure 2.5

a) Shear force

b) Bending moment

c) Soil lateral force per unit length

d) Deflection
Example 2-6: Single 18” Precast Pile in Dual Soil Layers (Sand over Clay)

**Problem Description:** Analyze a single 18” precast, prestressed pile subjected to lateral loading condition. The pile is embedded in a double layer of sand and clay which is modeled using the API sand and the stiff clay below water table models. The pile is assumed to remain linear elastic.

- **P =** 10 kips
- **γ**<sub>sand</sub> = 110pcf
- **φ** = 32°
- **k**<sub>sand</sub> = 60pci
- **γ**<sub>clay</sub> = 110pcf
- **C**<sub>u</sub> = 2000psf
- **k**<sub>clay</sub> = 100pci
- **E**<sub>50</sub> = 0.005

File: Example_2-6_v419.in
a) Shear force

b) Bending moment

c) Soil lateral force per unit length

d) Deflection

Figure 2.6
Example 2-7: Single 18” Precast Pile in Dual Soil Layers (Clay over Sand)

Problem Description: Analyze a single precast, prestressed pile subjected to lateral loading condition. The pile is embedded in a double layer of sand and clay which is modeled using the stiff clay above water table and Reese sand models. The pile is assumed to have to remain linear elastic.

\[
\begin{align*}
P &= 10 \text{ kips} \\
\gamma_{\text{clay}} &= 110 \text{ pcf} \\
\gamma_{\text{sand}} &= 110 \text{ pcf} \\
v &= 0.5 \\
C_u &= 2000 \text{ psf} \\
G &= 3.5 \text{ ksi} \\
E_0 &= 0.005 \\
\phi &= 32^\circ \\
k &= 60 \text{ pci}
\end{align*}
\]

File: Example_2-7_v419.in
Figure 2.7

(Images of graphs showing shear force, bending moment, soil lateral force per unit length, and deflection.)
**Example 2-8: Single 18” Precast Pile in Dual Sand Layers**

**Problem Description:** Analyze a single precast, prestressed pile subjected to lateral loading condition. The pile is embedded in a double layer of sand which is modeled using the Reese sand and API sand models. The pile is assumed to remain linear elastic.

- **P** = 10 kips
- \( \gamma_{\text{SandReese}} = 110 \text{pcf} \)
- \( \phi = 32^\circ \)
- \( k = 60 \text{pci} \)
- \( \gamma_{\text{SandAPI}} = 130 \text{pcf} \)
- \( \phi = 38^\circ \)
- \( k = 180 \text{pci} \)

File: Example_2-8_v419.in
Figure 2.8

a) Shear force

b) Bending moment

c) Soil lateral force per unit length

d) Deflection
Example 2-9: Single H-Pile in Sand (Reese)

**Problem Description:** Analyze a single H-pile subjected to lateral loading condition. The pile is embedded in a single layer of sand which is modeled using the Reese sand model. The pile is assumed to remain linear elastic. The lateral load is applied perpendicular to the strong axis of the section.

File: Example_2-9_v419.in

**NOTE:** The “effective” diameter of the FB-MultiPier model is NOT equal to the width of the square section, which LPILE uses as the “diameter” of the H-pile section in this example. Minor discrepancies in the prediction of the soil-pile interaction are observed as shown in Figure 2-9.
Figure 2.9

a) Shear force

b) Bending moment

c) Soil lateral force per unit length

d) Deflection
Example 2-10: Single H-Pile in Sand (Reese)

In this example, section properties (such as cross-sectional area and moment of inertia) are defined same as those of H-pile section of 14.21 inches by 14.21 inches although the dimensions are intentionally defined as 11.16 inches by 11.16 inches, which results in an effective diameter of 14.21 inches.

As mentioned in the preface of Chapter 2, the input dimensions of noncircular section determine an “effective” diameter in the FB-MultiPier analysis. An empirical equation is used to approximate an equivalent diameter to the dimensions of noncircular section:

$$D_{eff} = 2(t_d + t_w)/\pi$$

where effective diameter is denoted by $D_{eff}$, and $t_w$ and $t_d$ are width and depth of the section.

The purpose of using the effective diameter is to simulate increased soil lateral resistance due to the noncircular shape of the pile (Ashour and Norris 2000, Reese and Van Impe 2001). In Example 2-10, the input dimensions of H-pile of FB-MultiPier model are intentionally modified such that the effective diameter of FB-MultiPier analysis becomes identical to the “diameter” value of the LPILE program whereas the section properties remain same as those of the original dimensions of the section. Subsequently, direct comparison of the numerical results is made in consideration of both the effect of the “diameter” on the soil lateral resistance and the cross-sectional properties used in the linear analysis of the pile. The input parameters of linear analysis for the pile are given below.

File: Example_2-10_v419.in

**FB-MultiPier**
- Flange width ($t_w$) = 11.16 in
- Depth ($t_d$) = 11.16 in
- Moment of inertia ($I$) = 1163.19 in$^4$
- Area ($A$) = 33.021 in$^2$
- Effective diameter = 14.21 in (computed)

**LPILE**
- Flange width ($t_w$) = 14.21 in
- Depth ($t_d$) = 14.21 in
- Moment of inertia ($I$) = 1163.19 in$^4$
- Area ($A$) = 33.021 in$^2$
- Pile diameter = 14.21 in (defined)

Dimensions of H-Pile used in FB-MultiPier analysis:
- 11.16”x11.16”
- Flange thickness $t = 0.805”$
a) Shear force

b) Bending moment

c) Soil lateral force per unit length

d) Deflection

Figure 2.10