FB-MultiPier
API Soil Model Validation

FB-MultiPier V4.16 vs. APILE V4.0/GROUP V7.0

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EXECUTIVE SUMMARY

This report summarizes six API soil models that have been implemented into the FB-MultiPier computer program according to the American Petroleum Institute Recommended Practice 2A LRFD (API RP 2A LRFD). This report provides review of the theory, validation of the numerical models, and examples of modeling soil-structure interaction using the FB-MultiPier API soil models. As a further aid for the usage of FB-MultiPier, this report serves as a detailed user’s guide to current users of the program.
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1. API Soil Models

1-1. Axial Load Transfer (T-z) Curves

API Clay and API Sand Models (Refer to G.4.2, G.4.3, and G.7.2 API RP2A LRFD)

The unit skin friction and the T-z curves for clay and sand soils can be determined as per Section G.4.2 and Section G.4.3 API RP2A LRFD respectively. Figure 1.1 shows the T-z curves for non-carbonate soils, recommended by API RP2A LRFD.

For pipe piles in cohesive soils, the skin friction can be calculated by the equation.

\[ f = \alpha c \]

where \( c \) = undrained shear strength of the soil in stress units
\( \alpha \) = a dimensionless factor, which is defined as

\[ \alpha = 0.5 \Psi^{-0.5} \quad \text{for} \quad \Psi \leq 1.0 \]
\[ \alpha = 0.5 \Psi^{-0.25} \quad \text{for} \quad \Psi > 1.0 \]

\[ \Psi = \frac{c}{p'_o} \]

where \( p'_o \) = effective overburden pressure in stress units

For clay soils the ratio of residual stress to ultimate stress \( (t_{res}/t_{max}) \) ranges from 0.70 to 0.90 as shown in the Figure 1.1. In FB-MultiPier analysis, the \( t_{res}/t_{max} \) ratio is set equal to 0.90.

In FB-MultiPier analysis, the T-z curves for API clay are generated using piecewise linear function based on the data given in the table and is shown in Figure 1.2

<table>
<thead>
<tr>
<th>( z/D )</th>
<th>( t/t_{max} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0016</td>
<td>0.30</td>
</tr>
<tr>
<td>0.0031</td>
<td>0.50</td>
</tr>
<tr>
<td>0.0057</td>
<td>0.75</td>
</tr>
<tr>
<td>0.0080</td>
<td>0.90</td>
</tr>
<tr>
<td>0.0100</td>
<td>1.00</td>
</tr>
<tr>
<td>0.0200</td>
<td>0.90</td>
</tr>
<tr>
<td>( \infty )</td>
<td>0.90</td>
</tr>
</tbody>
</table>
Figure 1.1 Axial Pile Load Transfer- Displacement (T-z) Curves
(source: API RP2A LRFD 1993)

where $Z$ = local pile deflection
$D$ = pile diameter
$t$ = mobilized soil pile adhesion in stress units
$t_{\text{max}}$ = maximum soil pile adhesion or unit skin friction capacity computed

For pipe piles in cohesionless soils, the unit skin friction is calculated as

$$f = K \ p' \ \tan(\delta)$$

where $K$ = dimensionless coefficient of lateral earth pressure (ratio of horizontal to vertical normal effective stress, for unplugged $K=0.8$ and for plugged $K=1.0$)
$p'_o$ = effective overburden pressure in stress units
$\delta$ = friction angle between the soil and pile wall, which is defined as
\[ \delta = \varphi - 5^\circ \]

where \( \varphi \) = internal friction angle

It is recommended that the ultimate (limiting) values of unit skin friction, \( f_{ult} \), be considered, which are given in Table G.4.3-1 API RP2A LRFD. In FB-MultiPier analysis, the T-z curves for API sand are generated using piecewise linear function based on the data given in the table and shown in Figure 1.3

<table>
<thead>
<tr>
<th>( z ) (in)</th>
<th>( t/t_{max} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>0.10</td>
<td>1.00</td>
</tr>
<tr>
<td>( \infty )</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Figure 1.2 Normalized T-z curve for API Clay
Figure 1.3 Normalized T-z curve for API Sand

Notation used for axis labels is defined as

\[ \frac{t}{t_{\text{max}}} \] = mobilized skin friction

\[ t_{\text{max}} \] = maximum unit skin friction capacity \((f)\)

\( z \) = local pile deflection

\( D \) = diameter of pile
1-2. Tip Load-Displacement ($Q$-$z$) Curves

**API Clay and API Sand Models** (Refer to G.4.2, G.4.3, and G.7.3 API RP2A LRFD)

The unit end bearing capacity and $Q$-$z$ curves for clay and sand soils can be determined as per Section G.4.2 and Section G.4.3 API RP2A LRFD respectively. A relatively large pile tip movement which is required to fully mobilize the end bearing resistance may be achieved by a pile tip displacement up to 10% of the pile diameter. Figure 1.4 shows the $Q$-$z$ curves of both sand and clay soils as recommended in API RP2A LRFD.

The unit end bearing of pipe pile founded in cohesive soil is given by

$$ q = 9c $$

where $c$ = undrained shear strength of the soil, in stress units, at the pile tip

The unit end bearing of pipe pile founded in cohesionless soil is given by

$$ q = p'_o N_q $$

where $p'_o$ = effective overburden pressure, in stress units, at the pile tip

$N_q = \text{dimensionless bearing capacity factor, which is defined as}$

$$ N_q = e^{\frac{\tan(\phi')}{2}} \tan^{2} \left( 45^0 + \frac{\phi'}{2} \right) $$

where $\phi'$ = effective internal friction angle at the pile tip

The ultimate end bearing capacity is then calculated

$$ Q_p = q A $$

where $A = \text{sectional area at the tip of pile, which is based on the pile end condition; plugged – a gross sectional area is used to compute ultimate end bearing capacity}$

unplugged – a cross sectional area is used to compute ultimate end bearing capacity
Figure 1.4 Pile Tip – Load Displacement (Q-z) Curve
(source: API RP2A LRFD 1993)

where \( z \) = axial pile deflection  
\( D \) = pile diameter  
\( Q \) = mobilized end bearing capacity in force units  
\( Q_p \) = total end bearing computed

It is recommended that the ultimate (limiting) values of unit end bearing for cohesionless soils, \( q_{ult} \), be considered, which are given in Table G.4.3-1 API RP2A LRFD.

In FB-MultiPier analysis, Q-z curves of API clay and API sand are defined as a piecewise linear function based on the data given in the table and is shown in Figure 1.5.

<table>
<thead>
<tr>
<th>( \frac{z}{D} )</th>
<th>( \frac{Q}{Q_p} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.002</td>
<td>0.25</td>
</tr>
<tr>
<td>0.013</td>
<td>0.50</td>
</tr>
<tr>
<td>0.042</td>
<td>0.75</td>
</tr>
<tr>
<td>0.073</td>
<td>0.90</td>
</tr>
<tr>
<td>0.100</td>
<td>1.00</td>
</tr>
<tr>
<td>( \infty )</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Notation used for axis labels is defined as

\[
\begin{align*}
Q & = \text{mobilized end bearing capacity} \\
Q_p & = \text{total end bearing capacity} \\
z & = \text{axial deflection of pile tip} \\
D & = \text{diameter of pile}
\end{align*}
\]

Figure 1.5 Normalized Q-z curve for API Clay and API Sand
1-3. Lateral Soil Resistance - Deflection (P-y) Curves

**API Clay and API Sand Models** (Refer to G.8.2 to G.8.7 API RP2A LRFD)

The ultimate lateral soil resistance and P-y curves may be calculated using section G.8.2 to G.8.7 API RP2A LRFD. The soil resistance equations are not applicable if the strength variation along the depth of the soil is inconsistent.

The ultimate unit lateral resistance, \( p_u \), of soft clay under static loading conditions can vary between 8c to 12c except at the shallow depths. In the absence of more definitive criteria, use the empirical equation given by API RP2A LFRD:

\[
p_u = \begin{cases} 
3c + p'_{o} + J \frac{c z}{D} & \text{for } z < X_R \\
9c & \text{for } z \geq X_R
\end{cases}
\]

where
- \( c \) = undrained shear strength of undisturbed clay soil samples in stress units
- \( p'_{o} \) = effective overburden pressure in stress units
- \( z \) = depth below ground surface
- \( D \) = diameter of the pile
- \( J \) = dimensionless empirical constant
- \( X_R \) = depth from the ground surface to the bottom of reduced resistance zone, which is defined as;

\[
X_R = \frac{6D}{\gamma' \frac{D}{c} + J} \geq 2.5D
\]

where \( \gamma' \) = effective unit weight of soil in weight density units

In FB-MultiPier analysis, the value of \( J \) is set equal to 0.5, which is recommended for Gulf of Mexico clays. The P-y curves of API clay under cyclic and static loading conditions are defined as a piecewise linear function based on the data given in the table and is shown in Figure 1.6 and Figure 1.7.
<table>
<thead>
<tr>
<th>$p/p_u$</th>
<th>$y/y_c$</th>
<th>$p/p_u$</th>
<th>$y/y_c$</th>
<th>$p/p_u$</th>
<th>$y/y_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.0</td>
<td>0.00</td>
<td>0.0</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>0.50</td>
<td>1.0</td>
<td>0.50</td>
<td>1.0</td>
<td>0.50</td>
<td>1.0</td>
</tr>
<tr>
<td>0.72</td>
<td>3.0</td>
<td>0.72</td>
<td>3.0</td>
<td>0.72</td>
<td>3.0</td>
</tr>
<tr>
<td>1.00</td>
<td>8.0</td>
<td>0.72</td>
<td>$\infty$</td>
<td>0.72 $z/X_R$</td>
<td>15.0</td>
</tr>
<tr>
<td>1.00</td>
<td>$\infty$</td>
<td>0.72 $z/X_R$</td>
<td>15.0</td>
<td>0.72 $z/X_R$</td>
<td>$\infty$</td>
</tr>
</tbody>
</table>

Figure 1.6 Normalized P-y curve for API Clay (for $z < X_R$)
Figure 1.7 Normalized P-y curve for API Clay (for $z \geq X_R$)

Notation used for axis labels is defined as

- $P =$ actual lateral resistance in stress units
- $Pu =$ ultimate lateral bearing capacity in stress units
- $y =$ actual lateral deflection
- $y_c =$ defined as: $y_c = 2.5 \varepsilon_c D$

where $\varepsilon_c =$ strain occurring at one-half the maximum stress on laboratory undrained compression tests of undisturbed soil samples
The ultimate lateral bearing capacity for sand at a given depth is used as the smaller value between $p_{us}$ (ultimate lateral resistance at shallow depths) to $p_{ud}$ (ultimate lateral resistance at greater depths), which are determined by the following equations

$$p_{us} = \left(C_1 z + C_2 D\right) p'_o$$

$$p_{ud} = C_3 D \ p'_o$$

where $z$ = depth below ground surface

$p'_o$ = effective overburden pressure in stress units

$D$ = diameter of the pile

$C_1, C_2, \& C_3$ = coefficients determined from Figure 1.8, which is a function of $\phi'$

$\phi'$ = effective internal friction angle

The variation of coefficients of $C_1$, $C_2$, and $C_3$ with $\phi'$ is given in the graph below.

![Graph showing variation of coefficients $C_1$, $C_2$, and $C_3$ with $\phi'$](source: API RP2A LRFD 1993)
Using the ultimate lateral resistance, the lateral soil resistance – deflection (P-y) relationship for sand is approximated as

\[ P = A \ p_u \ tanh \left( \frac{k z}{A \ p_u} y \right) \]

where  
- \( p_u \) = ultimate bearing capacity, which is defined as smaller value of \( p_{us} \) and \( p_{ud} \)
- \( k \) = subgrade modulus, force per volume units, is determined from Figure G.8-2, which is a function of \( \phi' \)
- \( \phi' \) = effective internal friction angle
- \( z \) = depth below ground surface
- \( Y \) = lateral deflection
- \( A \) = factor to account for cyclic or static loading conditions, which is defined as
  - For cyclic loading, \( A = 0.9 \)
  - For static loading, \( A = 3.0 - 0.8 \left( \frac{z}{D} \right) \geq 0.9 \)
2. Validation of FB-MultiPier API Soil Models

2.1. Lateral soil response curves (P-y) of API sand soil model

Lateral soil response curves (P-y) obtained from FB-MultiPier V4.16 and GROUP V7.0.24 are plotted for the API sand soil type and presented at three depths shown in Figure 2.1. Pile dimensions and soil properties are given in Section 3.

![API Sand P-y Curves](image)

(a) P-y plots at a depth of 2.2 m

(b) P-y plots at a depth of 25.4 m

(c) P-y plots at a depth of 37.5 m

Figure 2.1 Soil reaction for a laterally loaded pile
2-2. Axial soil response curves (T-z, Q-z) of API sand soil model

Axial soil response curves (T-z, Q-z) obtained from FB-MultiPier V4.16 and APILE Plus V4.0 are plotted for API sand soils and presented at three depths shown in Figure 2.2. Pile dimensions and soil properties are given in Section 3.

It is assumed that the friction angle between the pipe wall and soil, \( \delta \), is determined in FB-MultiPier by subtracting 5° from the angle of internal friction in sand, \( \delta = \phi - 5^\circ \), which is based on feedback from engineers at Exxon. For comparison purposes of axial soil response, \( \phi \) of 30.75° is used for FB-MultiPier T-z model whereas \( \phi \) of 30° is used for the APILE Plus V4.0 T-z model. It is evident that the APILE Plus V4.0 T-z model does not use the relationship: \( \delta = \phi - 5^\circ \).

Although the two sets of Q-z curves are not identical, their general form is in good agreement. Because the Q-z curve of FB-MultiPier has been developed using a piecewise linear curve obtained from Section G.7.3 of API RP 2A LRFD with fourteen significant figures in a double precision, the interpretation of the piecewise linear relationship between the normalized displacement (abscissa) by pile diameter and the corresponding end bearing load may cause this minor discrepancy at the early stages of loading. However, the agreement shown in Figure 2.2 suggests a degree of validity in the relationships presented by both FB-MultiPier and APILE.

![API Sand T-z Curves](image)

(a) T-z plots at a depth of 2.2 m

Figure 2.2 Soil reaction for an axially loaded pile

*Figure 2.2 continued on the next page.*
Figure 2.2 cont.

Figure 2.2 Soil reaction for an axially loaded pile
2-3. *Lateral soil response curves (P-y) of API clay soil model*

Lateral soil response curves (P-y) obtained from FB-MultiPier V4.16 and GROUP V7.0.24 are plotted for the API clay soil type and presented at three depths shown in Figure 2.3. Pile dimensions and soil properties are given in Section 3.

![API Clay P-y Curves Depth = 2.205 m](image)

(a) P-y plots at a depth of 2.2 m

![API Clay P-y Curves Depth = 25.35 m](image)

(b) P-y plots at a depth of 25.4 m

![API Clay P-y Curves Depth = 37.48 m](image)

(c) P-y plots at a depth of 37.5 m

Figure 2.3 Soil reaction for a laterally loaded pile
Since the API clay soil model described as a piecewise linear curve in API RP 2A LRFD is not available in GROUP V7.0.24, a submerged soft clay model of GROUP V7.0.24 is used for comparison purpose. The submerged soft clay model describes soil reaction for a laterally loaded pile in a hyperbolic relationship.

2-4. Axial soil response curves (T-z, Q-z) of API clay soil model

Axial soil response curves (T-z, Q-z) obtained from FB-MultiPier V4.16 and APILE Plus V4.0 are plotted for the API clay soil type and presented at three depths shown in Figure 2.4. Pile dimensions and soil properties are given in Section 3. It is noted that a value of 0.9 is used for the normalized residual shear stress (\(t/t_{res}\)) in the FB-MultiPier for validation purpose. The end condition of a pile is assumed as unplugged for Q-z validation. This takes into account the annulus of the pile tip for the determination of the ultimate end bearing capacity.

![API Clay T-z Curves](a) T-z plots at a depth of 2.2 m

![API Clay T-z Curves](b) T-z plots at a depth of 25.4 m

Figure 2.4 Soil reaction for an axially loaded pile

*Figure 2.4 continued on the next page.*
Figure 2.4 cont.

(c) T-z plots at a depth of 37.5 m

(d) Q-z plots at the tip of pile

Figure 2.4 Soil reaction for an axially loaded pile
3. Case Study and Comparison

3-1. Case 1: Lateral soil-pile interaction analysis using API sand soil

Problem description: A single pipe pile embedded in a single layer of API sand soil is subjected to incremental lateral loads at the pile head shown in Figure 3.1.

Pile dimension and properties:
- Outer Diameter: 2.4384 m
- Thickness: 0.0508 m
- Unit Weight: 77 KN/m³
- Length: 51.55 m
- Yield Stress: 415000 KPa
- Modulus: 200000000 KPa

Figure 3.1 FB-MultiPier lateral soil-structure interaction analysis model

Lateral loads are incrementally applied to the head, ranging from 1,000 KN to 10,000 KN. Lateral displacements at the pile head obtained from FB-MultiPier V4.16 and GROUP V7.0.24 are plotted in Figure 3.2.
3.2. Case 2: Axial soil-pile interaction analysis using API sand soil

Problem description: A single pipe pile embedded in a single layer of API sand soil is subjected to incremental axial loads at the pile head shown in Figure 3.3.

Pile dimensions and properties are the same as used in Case 1.

Axial loads are incrementally applied to the pile head, ranging from 2,500 KN to 42,500 KN. Vertical displacements at the pile head obtained from FB-MultiPier V4.16 and APILE Plus V4.0 are plotted in Figure 3.4. The agreement in results is reasonable, but differences are observed and shown in Figure 3.4a. Particularly, predicted axial behavior of API sand soil can vary noticeably with respect to the values of the dimensionless coefficient of lateral earth pressure (i.e., ratio of horizontal to vertical normal effective stress). In order to demonstrate, two different values of the coefficient, i.e., 0.8 and 1.0, are used in both FB-MultiPier and APILE simulations. Results obtained from FB-MultiPier simulations show that full displacement piles (plugged) or open-ended piles (unplugged) can be modeled using a value of either 1.0 or 0.8, which is according to Equation G.4-5 of API RP 2A-LRFD 93, whereas no significant differences are observed in simulations using APILE Plus V4.0 (Figure 3.4b).
(a) Load - displacement curve comparison

(b) Results from APILE simulations

Figure 3.4 Axial load-displacement results
3-3. Case 3: Lateral soil-pile interaction analysis using API clay soil

Problem description: A single pipe pile embedded in a single layer of API clay soil is subjected to incremental lateral loads at the pile head shown in Figure 3.5.

Pile dimension and properties are same as used in Case 1.

Figure 3.5 FB-MultiPier lateral soil-structure interaction analysis model

Lateral loads are incrementally applied to the head, ranging from 250 KN to 2,500 KN. Lateral displacements at the pile head obtained from FB-MultiPier V4.16 and GROUP V7.0.24 are plotted in Figure 3.6.

Figure 3.6 Lateral load-displacement results

It is noted that the lateral behavior of the API clay soil is modeled as piecewise linear P-y curves in FB-MultiPier whereas the same type of clay model is not available in GROUP V7.0.24. Instead, a hyperbolic P-y curve model (submerged soft clay) of GROUP V7.0.24 is used (Also see Section 2-3 for the difference in soil reaction
predicted by FB-MultiPier V4.16 and GROUP V7.0.24). For comparison purpose, additional simulations using an existing hyperbolic P-y curve (submerged soft clay model of FB-MultiPier) are performed. It is evident that the lateral behavior of the API clay soil is softer than that of submerged soft clay models of both FB-MultiPier and GROUP.
3-4. Case 4: Axial soil-pile interaction analysis using API clay soil

Problem description: A single pipe pile embedded in a single layer of API clay soil is subjected to incremental axial loads at the pile head shown in Figure 3.7.

Pile dimension and properties are same as used in Case 1.

Axial loads are incrementally applied to the head, ranging from 600 KN to 6,000 KN. Axial displacements at the pile head obtained from FB-MultiPier V4.16 and APile Plus V4.0 are plotted in Figure 3.8.

To ensure the accuracy of the numerical solution, a parametric sensitivity study is performed using several different tolerances by trial and error. Since APile Plus V4.0 does not provide an option for user’s specified tolerance in a control parameter, the length of element in APile models is used as a means to mimic a tolerance used for a
force equilibrium check in FB-MultiPier, i.e., tolerance = 0.01 KN. However, minor differences are observed where the applied load approaches a failure load. As a result, even minor differences in the length of element will yield significantly different predicted displacements at a near-failure load (Figure 3.8).
3-5. Case 5: Lateral soil-pile interaction analysis using a multi-layered API clay/sand soil model

Problem description: A single pipe pile embedded in a double-layer of API clay and sand soils is subjected to a lateral load at the pile head shown in Figure 3.9.

Pile dimensions and properties are the same as used in Case 1.

![Figure 3.9 FB-MultiPier multi-layered soil-structure interaction analysis model](image)

Case 5 represents an extreme lateral load for the soft upper clay layer. The 7500 KN load is possible because of the strong sand layer located beneath the clay. This loading develops the plastic bending moment in the pipe pile equal to 130,591 KN-m at 26.5 meters below the soil surface. The near equal lateral displacements of the cantilever pile, 1.33m for FB-MultiPier V4.16 and 1.29m for GROUP V7.0.24, demonstrates that the soil-pile lateral stiffness modeled by the two computer programs compare very well. The difference in displacement prediction is believed to be due to a different numerical solution procedure and a tolerance used in convergence checks in the programs. Additional simulations are conducted using different tolerances and results are presented in the table given below.

<table>
<thead>
<tr>
<th>Load (KN)</th>
<th>Displacement (m)</th>
<th>Model</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>5500</td>
<td>0.92</td>
<td>GROUP</td>
<td>0.1 m</td>
</tr>
<tr>
<td></td>
<td>0.87</td>
<td>FB-MultiPier</td>
<td>0.01 KN</td>
</tr>
<tr>
<td></td>
<td>0.80</td>
<td>GROUP</td>
<td>0.0001 m</td>
</tr>
<tr>
<td>7500</td>
<td>1.50</td>
<td>GROUP</td>
<td>0.1 m</td>
</tr>
<tr>
<td></td>
<td>1.33</td>
<td>FB-MultiPier</td>
<td>0.01 KN</td>
</tr>
<tr>
<td></td>
<td>1.28</td>
<td>GROUP</td>
<td>0.0001 m</td>
</tr>
</tbody>
</table>
3.6. Case 6: Combined lateral/axial soil-structure interaction analysis using a multi-layered API sand soil model

Problem description: A single pipe pile embedded in a double-layer of API sand soil is subjected to both lateral and axial loads at the pile head shown in Figure 3.10.

Pile dimensions and properties are the same as used in Case 1.

Figure 3.10 FB-MultiPier soil-structure interaction analysis model for a combined loading condition

Case 6 represents a two-layer sand model and a combination of axial load (25,000 KN) and lateral load (9000 KN) is applied to validate the soil – pile stiffness represented in FB-MultiPier V4.16 against GROUP V7.0.24. The lateral load is selected so as to develop the first yield moment in the pipe-pile. Note that the lateral load is considerably larger than the lateral load (7500 KN) which would develop the plastic moment in case 5, where the weak clay layer is present in the surface layer.

Loads and corresponding displacements of the pile head are investigated and presented in the table below. Although minor discrepancies are observed, it is considered mainly due to numerical issues related to convergence (tolerance). Additional simulations using different tolerances and results are compared in three different load cases. Displacements predicted by FB-MultiPier V4.16 and by GROUP V7.0.24 demonstrate that both the soil-pile lateral/axial stiffness modeled by the two computer programs is in good agreement.

<table>
<thead>
<tr>
<th>Lateral Load (KN)</th>
<th>Vertical Load (KN)</th>
<th>FB-MultiPier Lateral Displ. (m)</th>
<th>FB-MultiPier Vertical Displ. (m)</th>
<th>GROUP Lateral Displ. (m)</th>
<th>GROUP Vertical Displ. (m)</th>
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</thead>
<tbody>
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<td>4500</td>
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<td>0.08</td>
<td>0.011</td>
</tr>
<tr>
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<td>25000</td>
<td>0.20</td>
<td>0.013</td>
<td>0.21</td>
<td>0.011</td>
</tr>
<tr>
<td>9000</td>
<td>25000</td>
<td>0.28</td>
<td>0.013</td>
<td>0.30</td>
<td>0.011</td>
</tr>
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</table>
4. Summary and Conclusion

Six soil curves that represent the behaviors of the API sand and clay soils have been implemented and validated. Using FB-MultiPier, soil-pile interaction has been investigated in connection with the development of the API sand and clay soil models. The numerical model presented here also accounts for three important factors involved in load transfer of piles: (1) pile end condition, (2) the concept of equivalent depth, and (3) effects of effective vertical stress on soil behavior of sub-layer soils in determination of ultimate resistance of sub-layer soil in vicinity of the interface.

The new soil models presented here offer an improved tool for studying multidimensional soil-pile interaction subjected to various loading conditions. In addition, it serves as a basis for developing improved FB-MultiPier soil models. For example, one factor influencing soil behavior under dynamic loading, i.e., soil gap forming, is currently being investigated for the application of the FB-MultiPier soil models to seismic analysis. In the future, an enhanced soil model incorporating such effects may be implemented once additional experimental data become available.
5. References


Appendix A

Showcase model: soil-pile interaction analysis using FB-MultiPier

Problem description: A single pile embedded in soil that consists of 16 layers of both sand and clay soil is subjected to multiple load at the pile head shown in the Figure below.

Pile dimensions and properties are the same as used in the case study in Section 3.

The soil properties provided by a consultant are used to develop the model. Comparison is made between results obtained from the new API soil models and existing soil models “Sand (Reese)” and “Soft Clay (below water table)” of FB-MultiPier. In general, the lateral soil resistance of the API sand soil model seems greater than that of an existing sand model “Sand (Reese)” of FB-MultiPier. The pile head displacements in lateral and vertical directions are given in the table.

<table>
<thead>
<tr>
<th></th>
<th>Lateral Displacement (m)</th>
<th>Y-rotation (radian)</th>
<th>Vertical Displacement (m)</th>
</tr>
</thead>
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<tr>
<td>Analysis results from using the new API soil models</td>
<td>0.283</td>
<td>-0.0231</td>
<td>0.012</td>
</tr>
<tr>
<td>Analysis results from using the existing soil models</td>
<td>0.329</td>
<td>-0.0250</td>
<td>0.012</td>
</tr>
</tbody>
</table>
Appendix B

Application of API Soil Models in FB-MultiPier

Select the Soil Page.

Choose a soil Type.
Select each of the four soil models: Lateral, Axial, Torsional, and Tip.

Enter properties for each soil model. To do this, click on the soil model, then click the edit button. (The Soil Table can also be used to enter all soil properties)
To display a soil curve, select the desired soil model.

Then click a node on pile in the Soil Edit Window.
This will display a curve at the elevation of the selected node.