FB-MultiPier

Bridge Software Institute

API Soil Modeling Comparison

FB-MultiPier vs APile® / GROUP®

EXECUTIVE SUMMARY

This report summarizes American Petroleum Institute (API) soil load-transfer models that have been implemented into FB-MultiPier (v5.7.0). Contained herein are examples of modeling soil-structure interaction using the FB-MultiPier API soil models across various mechanisms, including p-y, t-z, and q-z relationships. While the models and results comparisons presented in this report focus upon methodologies provided in API RP 2A (2002), methodologies provided in API RP 2GEO 1 (2014) are also available in FB-MultiPier.

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Chapter 1

API Soil Models

1-1: Skin Friction (t-z) Curves

For provisions pertaining to API Clay and API Sand Models, refer to G.4.2, G.4.3, and G.7.2 API RP 2A LRFD.

1-2: Tip Resistance (q-z) Curves

For provisions pertaining to API Clay and API Sand Models, refer to G.4.2, G.4.3, and G.7.3 API RP 2A LRFD.

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 RP 2A LRFD.

Chapter 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 and GROUP 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 Chapter 3.

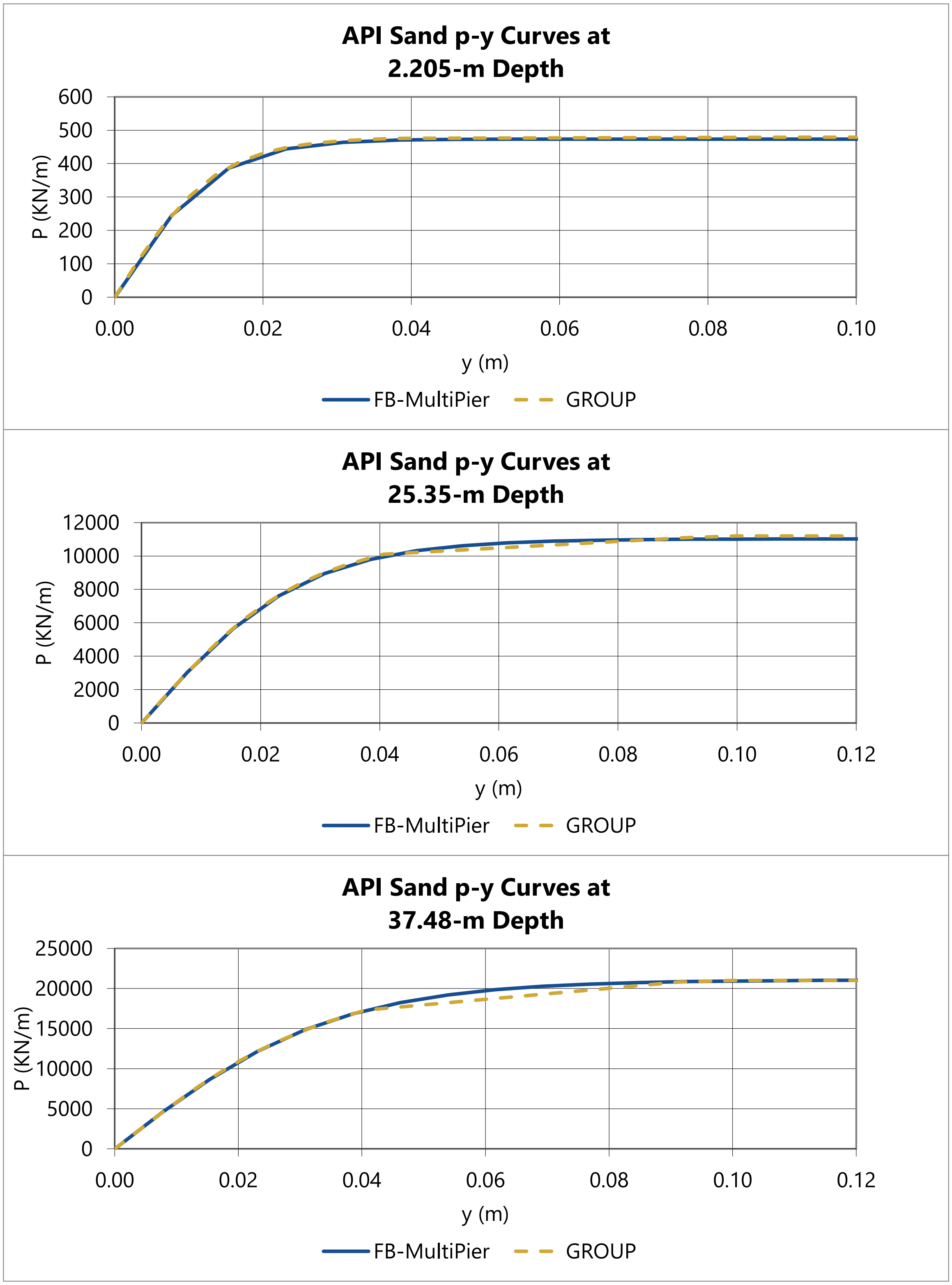


Figure 2.1 – Soil Reaction for a Laterally Loaded Pile

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 and APILE are plotted for API sand soils and presented at three depths shown in **Figure 2.2**. Pile dimensions and soil properties are given in Chapter 3.

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

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.

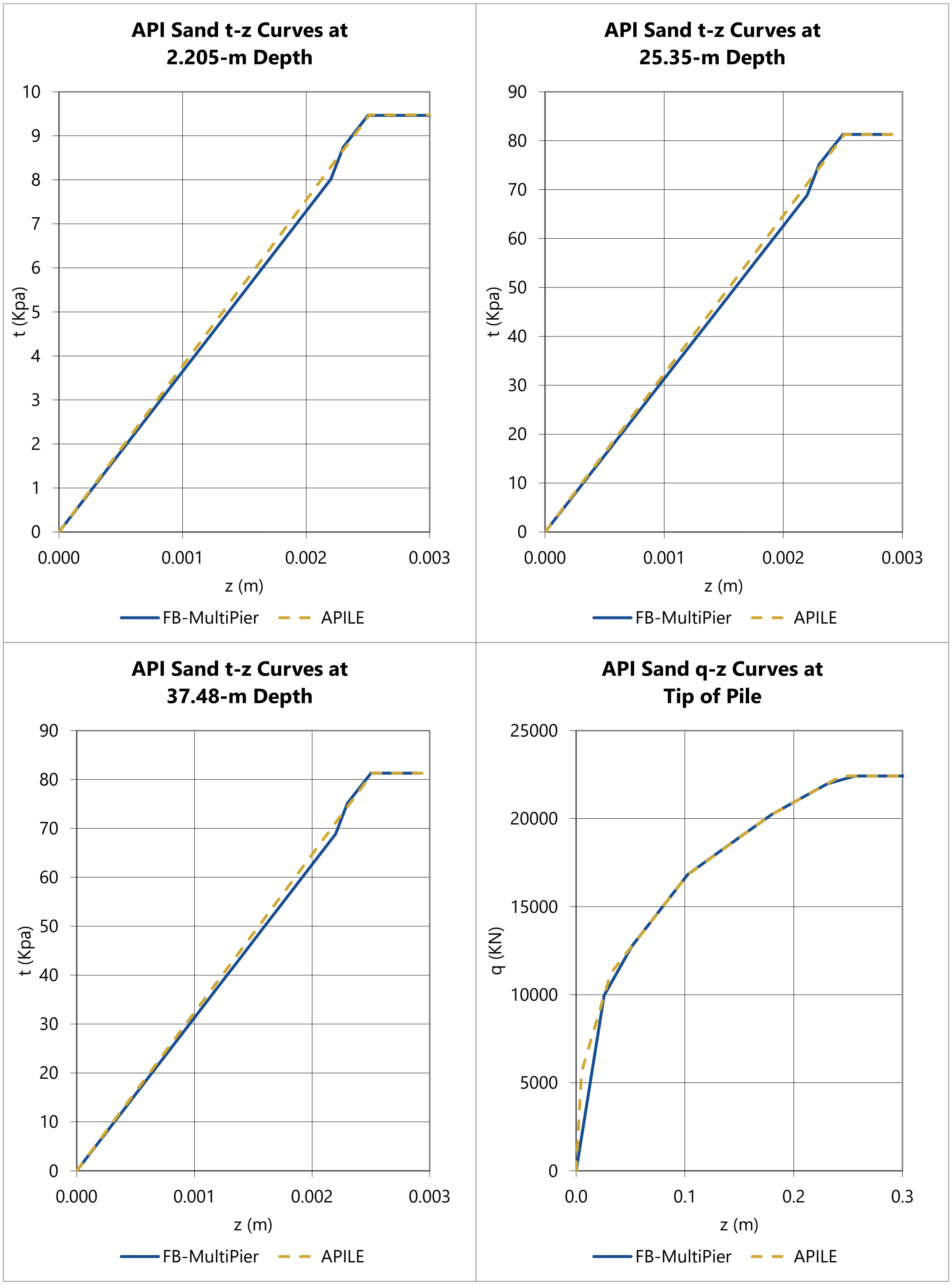


Figure 2.2 – Soil Reaction for an Axially Loaded Pile

2-3: Lateral Soil Response Curves (p-y) of API Clay Soil Model

Lateral soil response curves (p-y) obtained from FB-MultiPier and GROUP 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.

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 is used for comparison purpose. The submerged soft clay model describes soil reaction for a laterally loaded pile in a hyperbolic relationship.

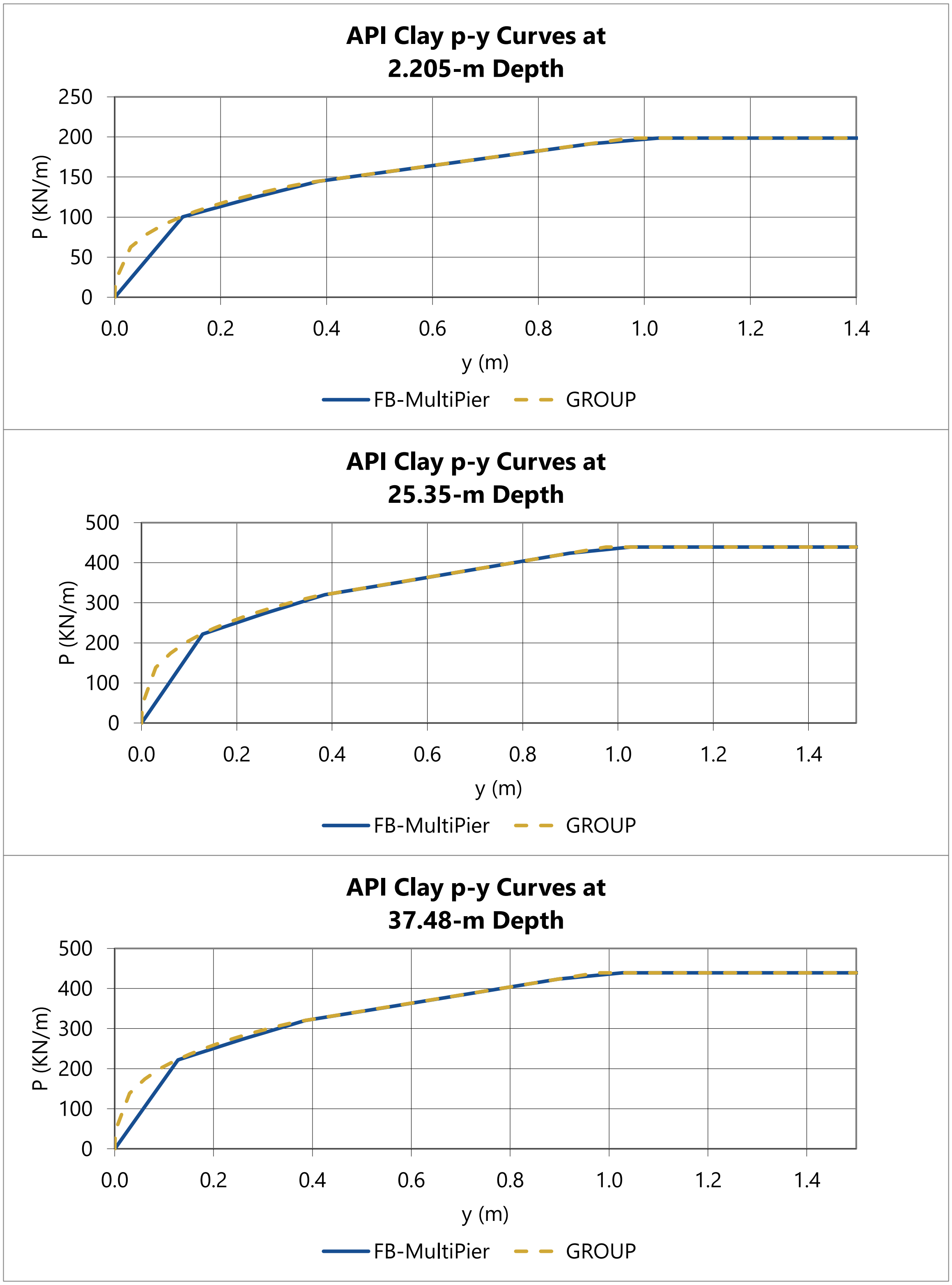


Figure 2.3 – Soil Reaction for a Laterally Loaded Pile

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 and APILE 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 Chapter 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 purposes. 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.

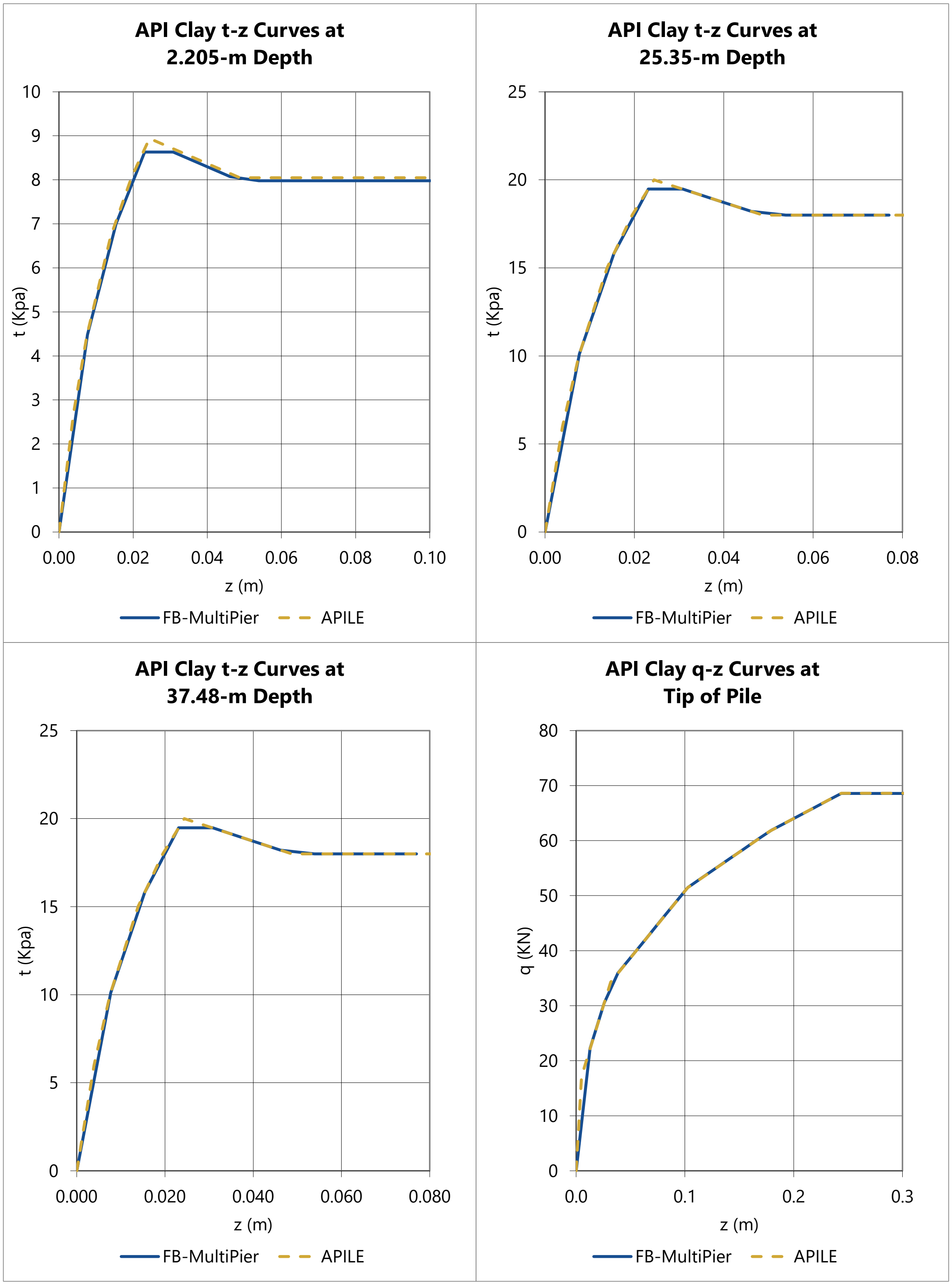


Figure 2.4 – Soil Reaction for an Axially Loaded Pile

Chapter 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 dimensions and properties:

Outer Diameter	2.4384	m
Thickness	0.0508	m
Unit Weight	77	kN/m^3
Length	51.55	m
Yield Stress	415000	kPa
Modulus	200000000	kPa

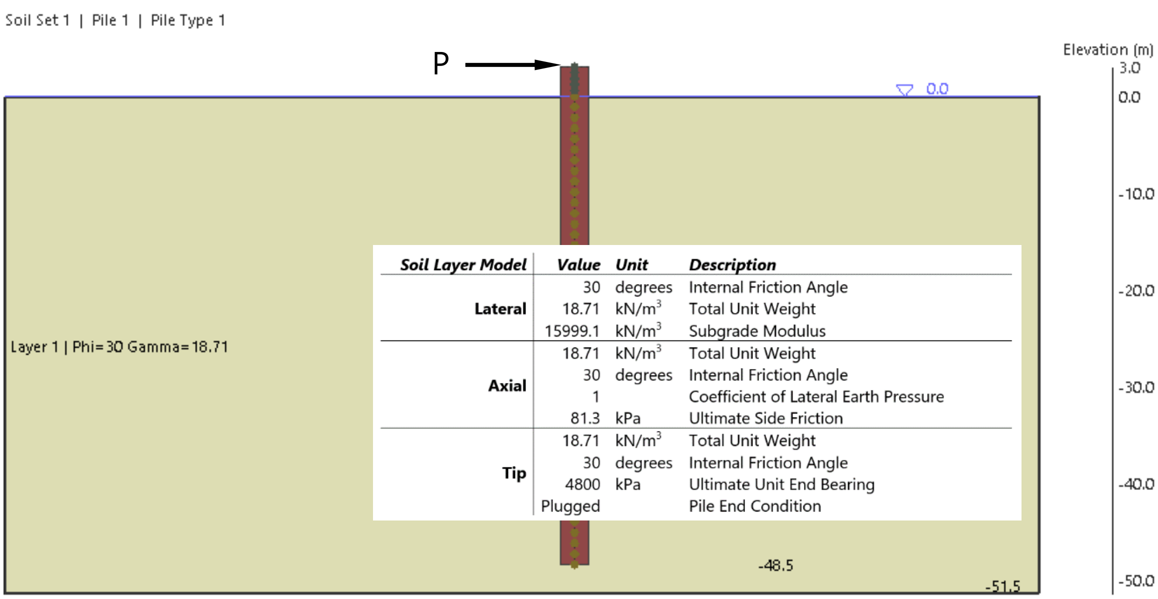


Figure 3.1 – FB-MultiPier Lateral Soil-Structure Interaction Analysis Model

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 and GROUP are plotted in **Figure 3.2**.

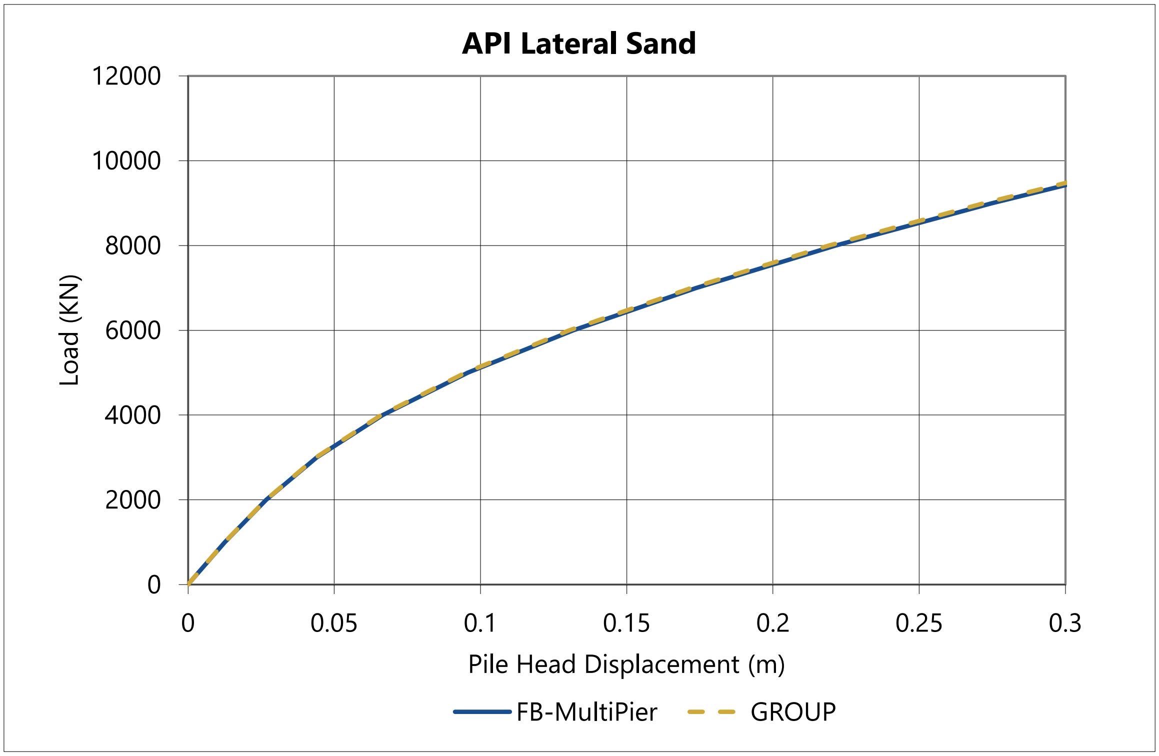


Figure 3.2 – Lateral Load-Displacement Results

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.

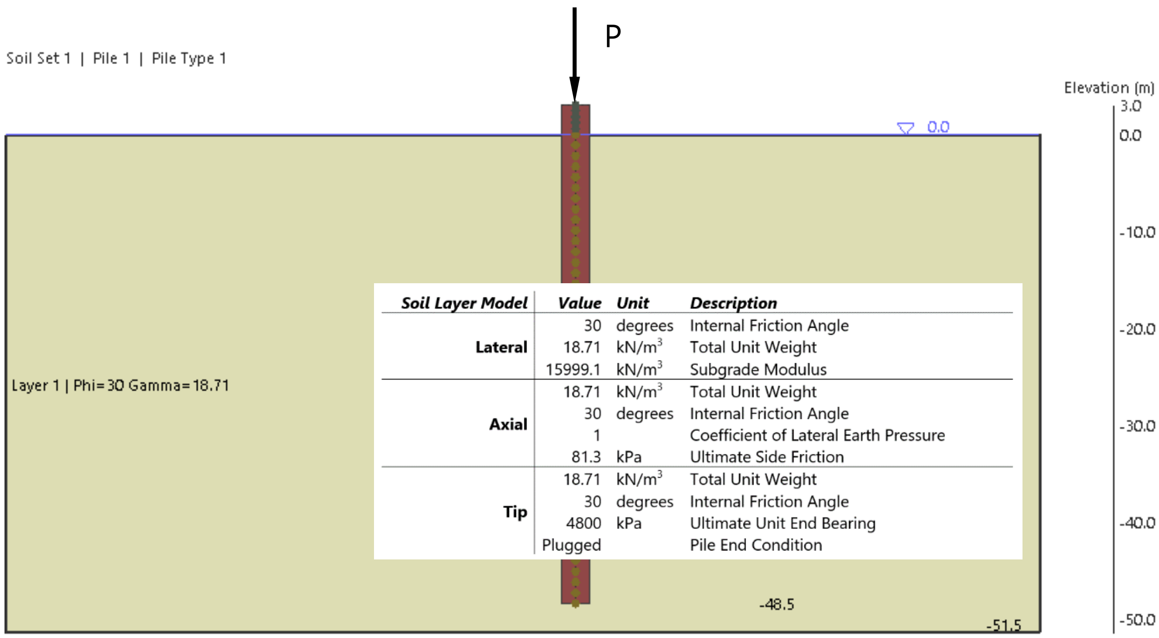


Figure 3.3 – FB-MultiPier Axial Soil-Structure Interaction Analysis Model

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 and APILE are plotted below. The agreement in results is reasonable, but differences are observed and shown in **Figure 3.4**. 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 (**Figure 3.5**).

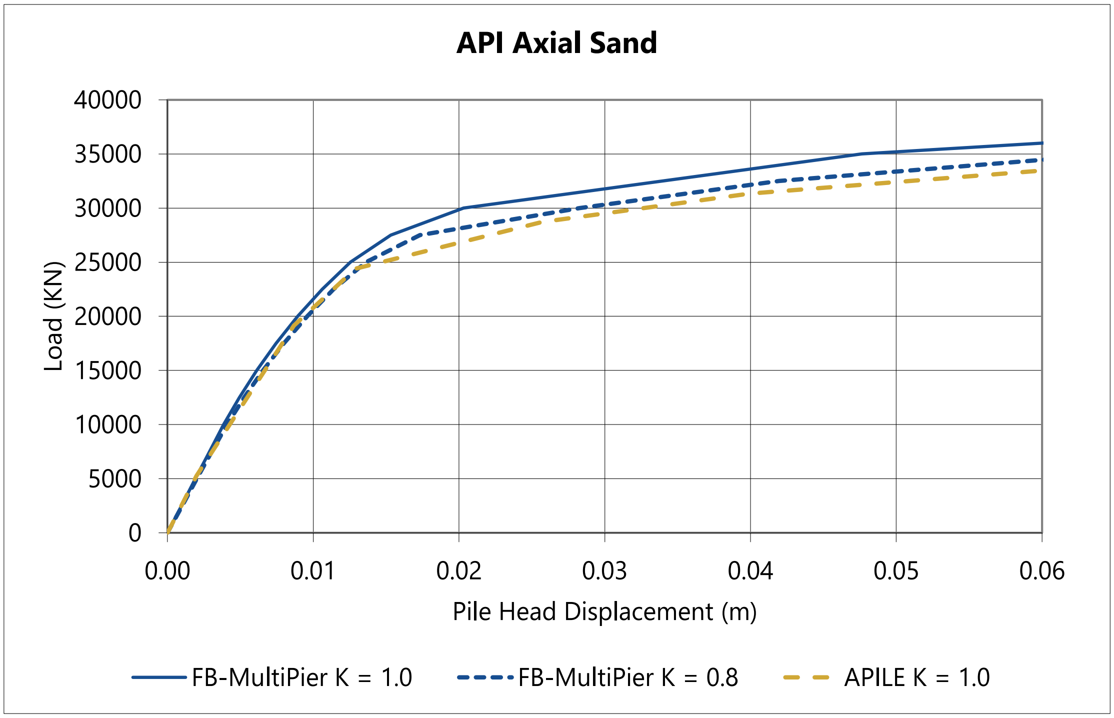


Figure 3.4 – Load-Displacement Curve Comparison

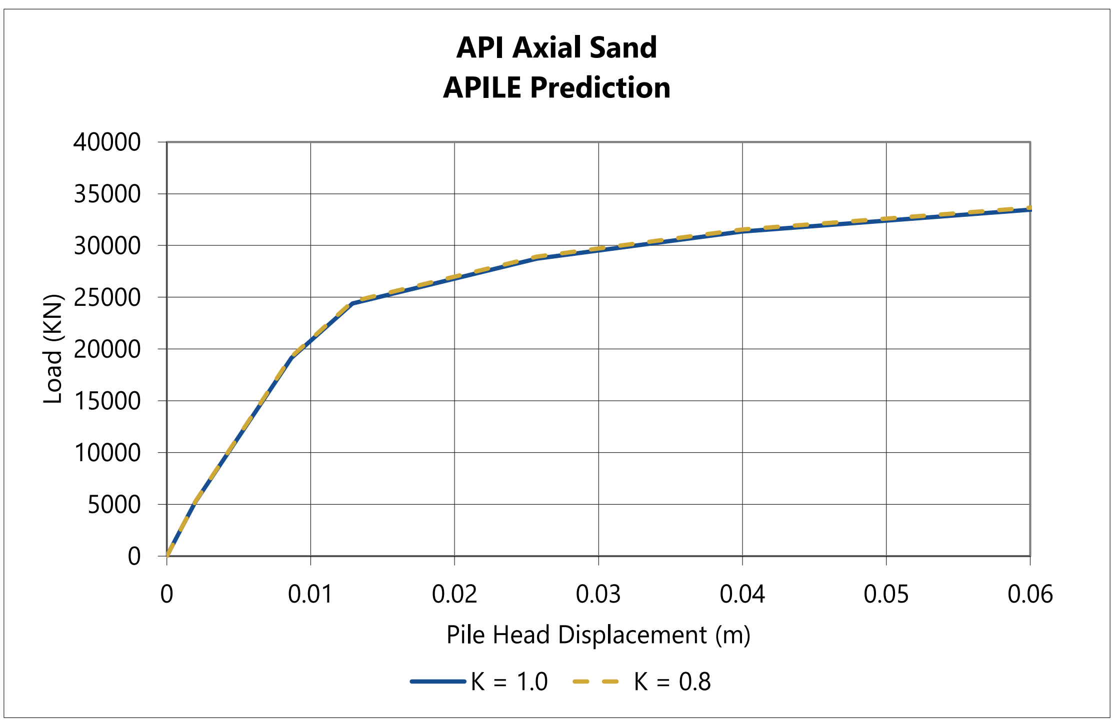


Figure 3.5 – Results from APILE Simulations

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

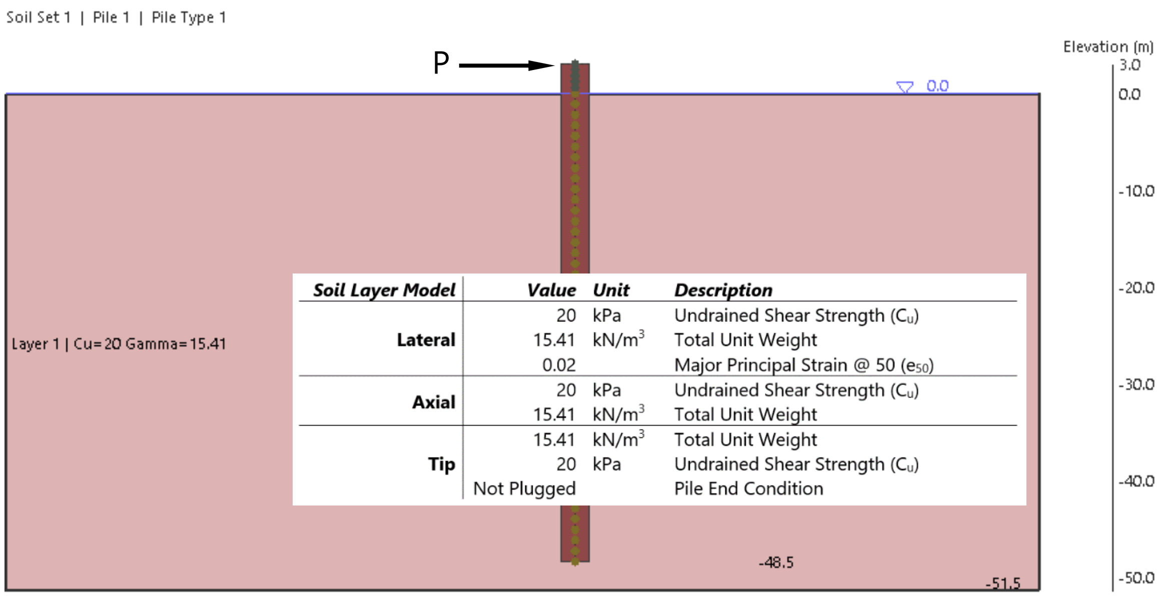


Figure 3.6 – FB-MultiPier Lateral Soil-Structure Interaction Analysis Model

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 and GROUP are plotted in **Figure 3.7**.

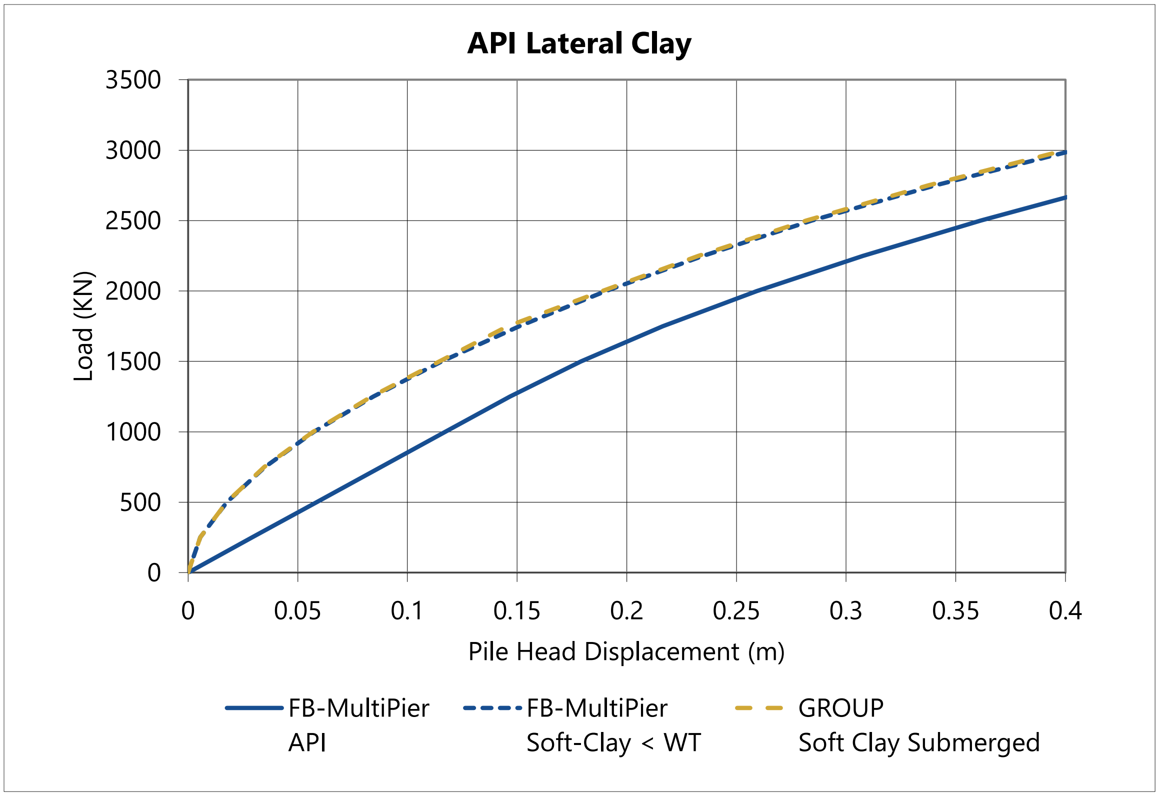


Figure 3.7 – Lateral Load-Displacement Results

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 is used (Also see Section 2-3 for the difference in soil reaction predicted by FB-MultiPier and GROUP). 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 3.8**. Pile dimension and properties are same as used in Case 1.

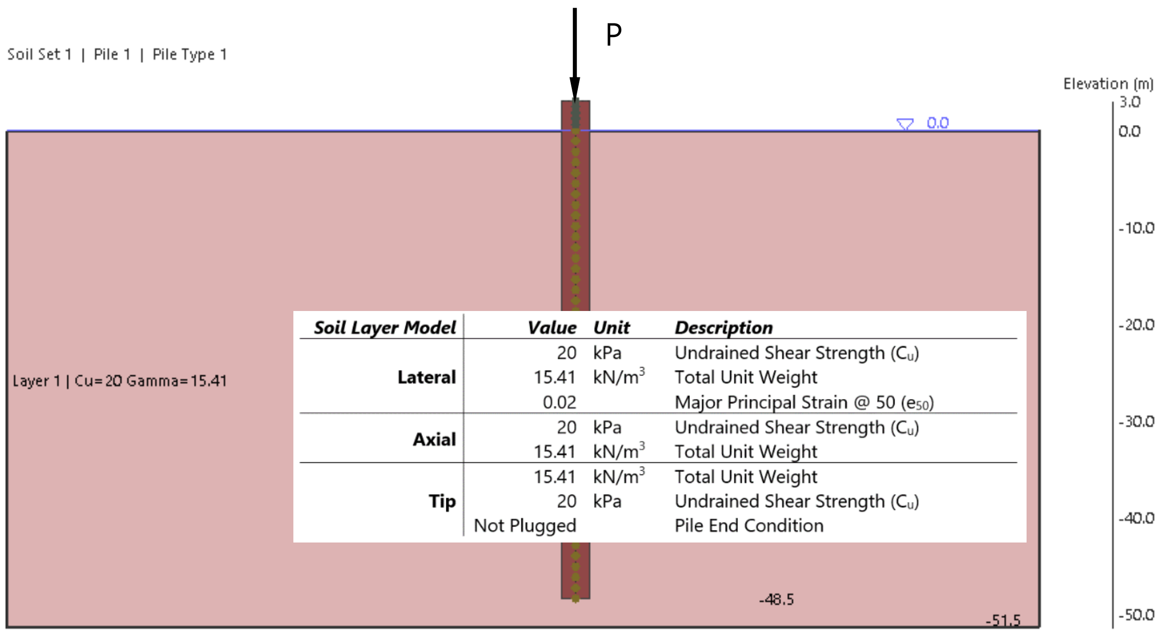


Figure 3.8 – FB-MultiPier Axial Soil-Structure Interaction Analysis Model

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 and APILE are plotted in **Figure 3.9**.

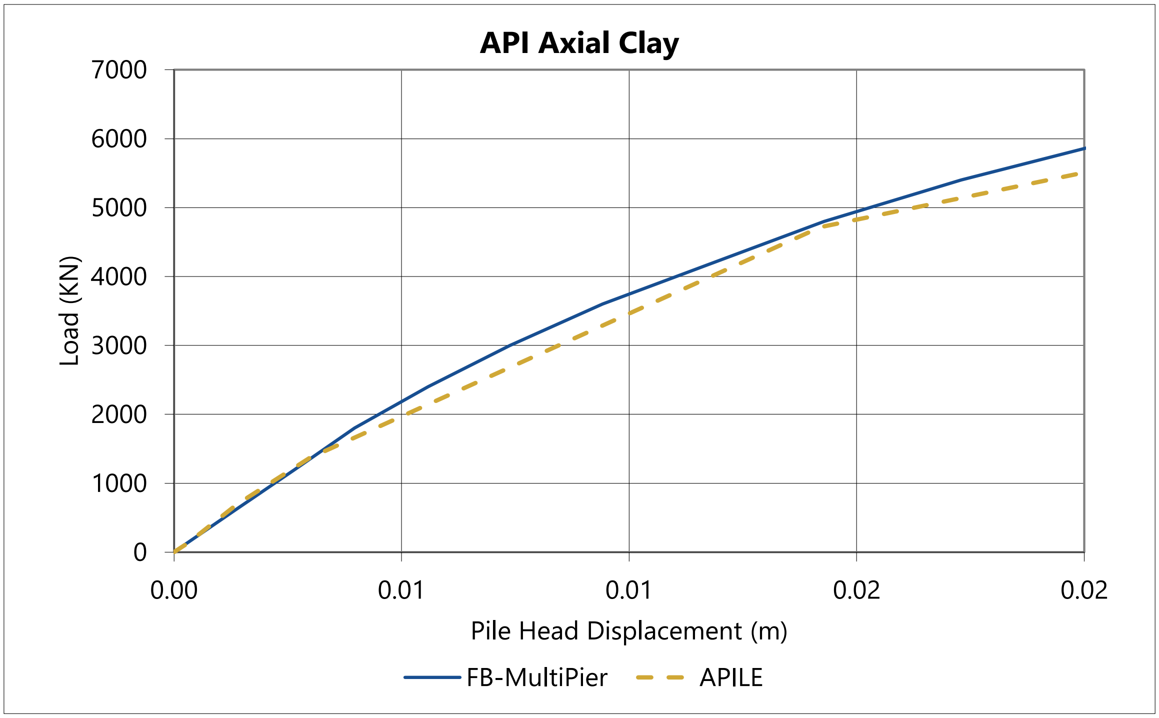


Figure 3.9 – Axial Load-Displacement Results

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 3.9**).

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

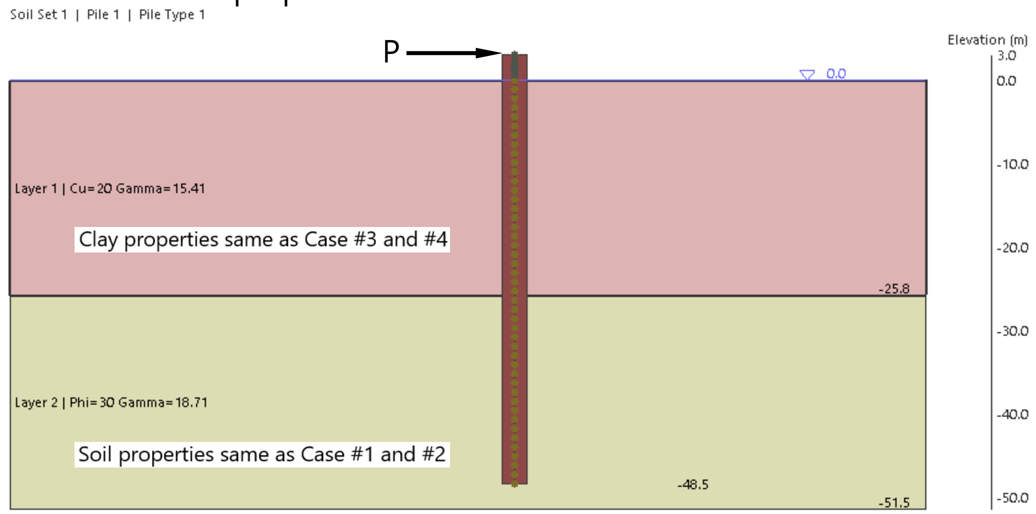


Figure 3.10 – FB-MultiPier Multi-Layered Soil-Structure Interaction Analysis Model

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, 1.33 m for FB-MultiPier and 1.29 m for GROUP, 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 4.1 – Comparison of Results Between FB-MultiPier and GROUP for Case 5

Load (KN)	Displacement (m)	Model	Tolerance
5500	0.92	GROUP	0.1 m
	0.87	FB-MultiPier	0.01 KN
	0.80	GROUP	0.0001 m
7500	1.50	GROUP	0.1 m
	1.33	FB-MultiPier	0.01 KN
	1.28	GROUP	0.0001 m

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

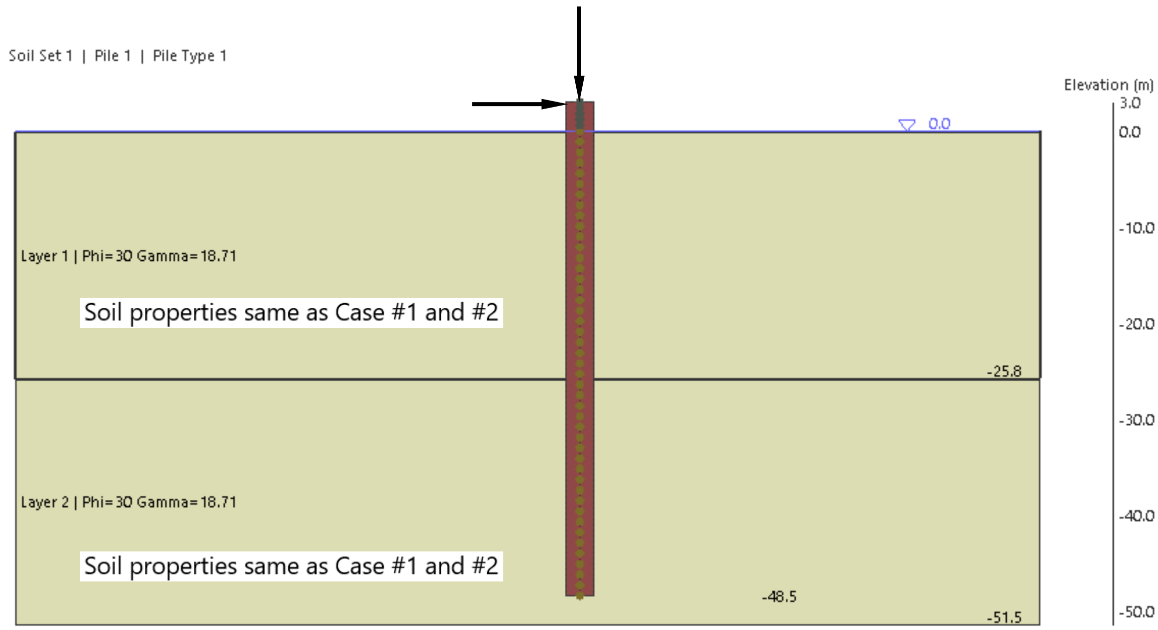


Figure 3.11 – FB-MultiPier Soil-Structure Interaction Analysis Model for a Combined Loading Condition

Case 6 represents a two-layer sand model and a combination of axial load (25,000KN) and lateral load (9000 KN) is applied to validate the soil-pile stiffness represented in FB-MultiPier against GROUP. 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 (7500KN) 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 and by GROUP demonstrate that both the soil-pile lateral/axial stiffness modeled by the two computer programs is in good agreement.

Table 3.2 – Comparison of Results Between FB-MultiPier and GROUP for Case 6

Load		**Displacement (FB-MultiPier)**		**Displacement (GROUP)**	
Lateral (KN)	**Vertical (KN)**	**Lateral (m)**	**Vertical (m)**	**Lateral (m)**	**Vertical (m)**
4500	25000	0.08	0.013	0.08	0.011
7500	25000	0.20	0.013	0.21	0.011
9000	25000	0.28	0.013	0.30	0.011

Chapter 4

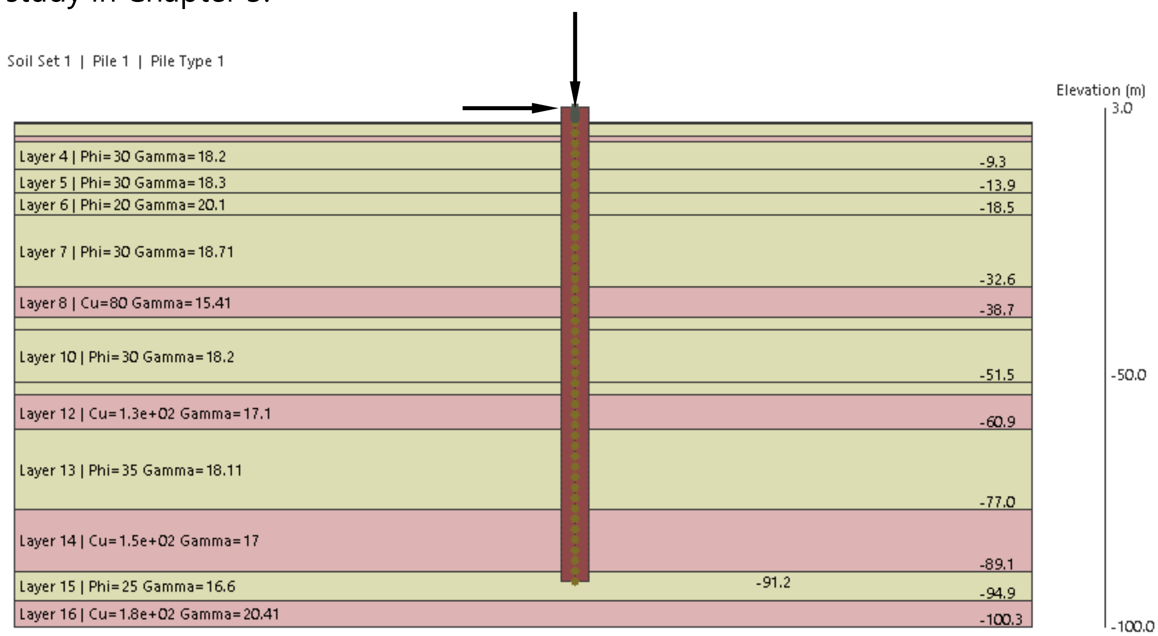
Summary and Conclusion

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 soil models presented here offer an improved tool for studying 3D soil-pile interactions under various loading conditions.

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 loads at the pile head shown in the Figure below. Pile dimensions and properties are the same as used in the case study in Chapter 3.



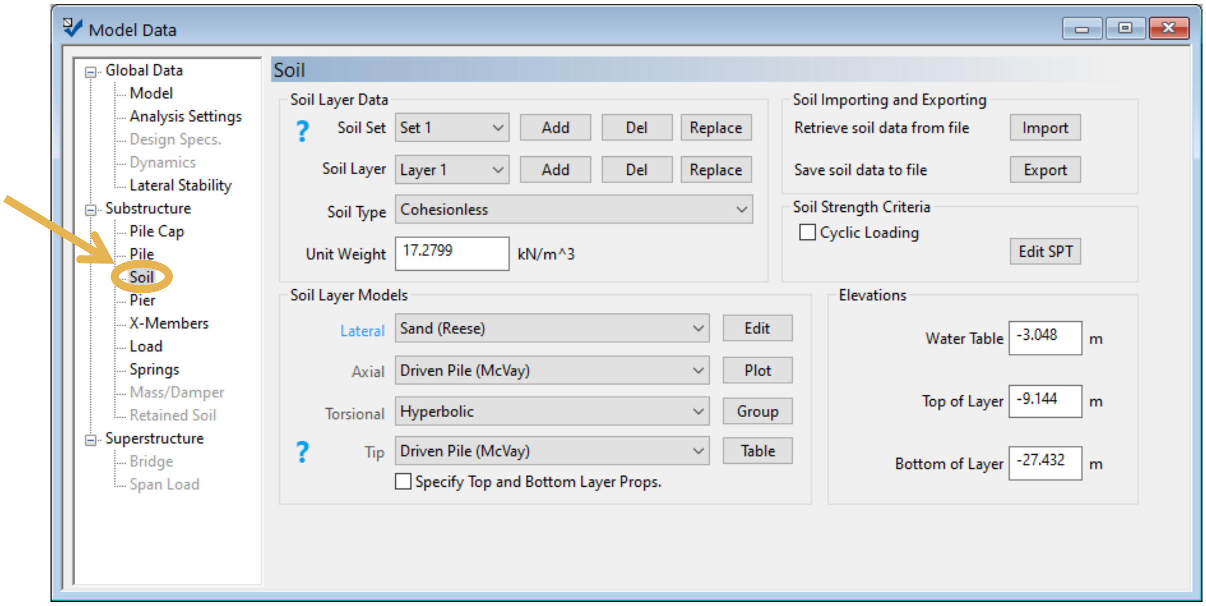
The soil properties provided by a consultant are used to develop the model. Comparison is made between results obtained from the new API soil models and existing soil models “Sand (Reese)” and “Clay (Soft, Matlock)” of FB-MultiPier. In general, the lateral soil resistance of the API sand soil model seems 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.

Analysis Results	Lateral Displacement (m)	Y-rotation (radian)	Vertical Displacement (m)
API Soil Models	0.283	-0.0231	0.012
Other	0.329	-0.0250	0.012

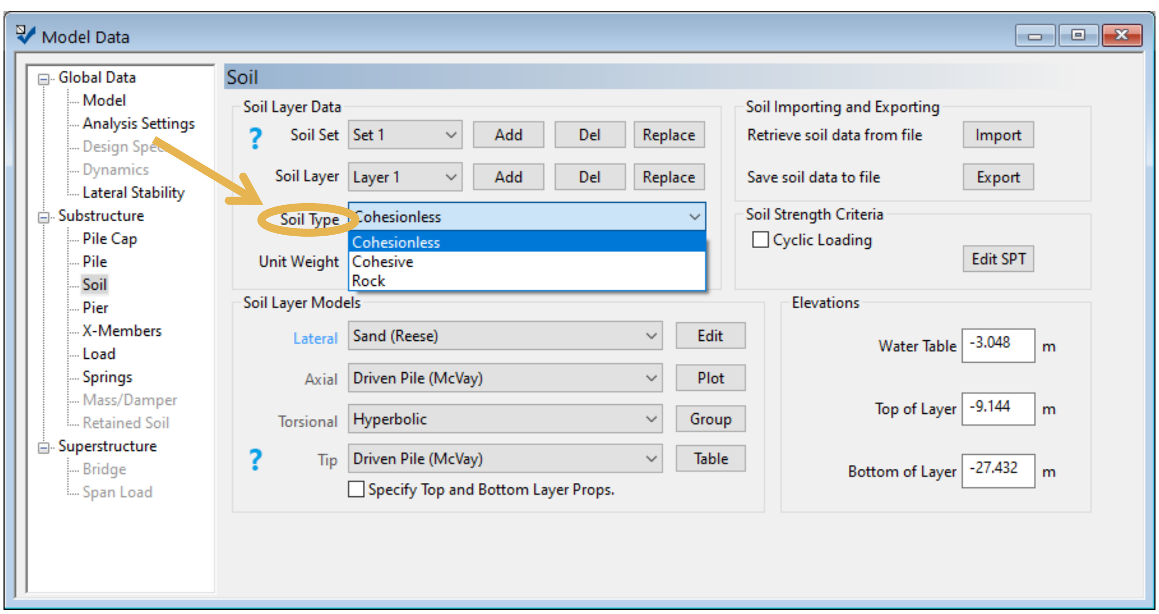
APPENDIX B

Application of API Soil Models in FB-MultiPier

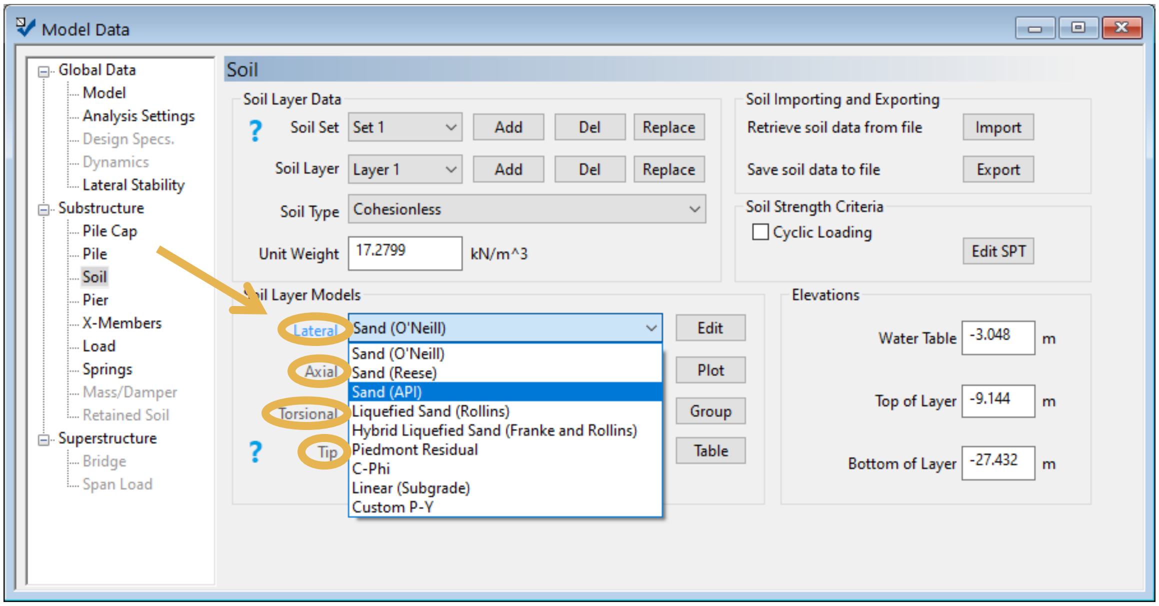
Select the Soil Page.



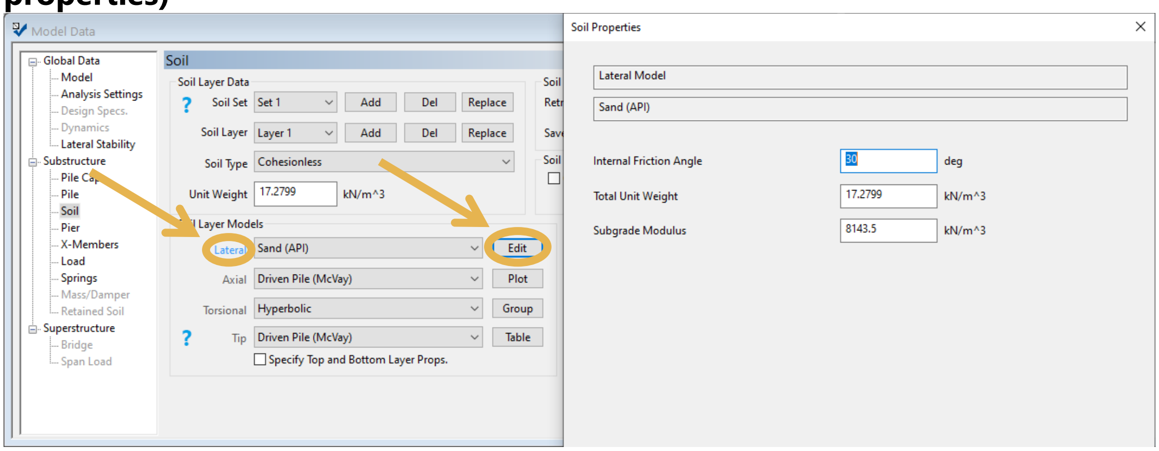
Choose a soil Type.



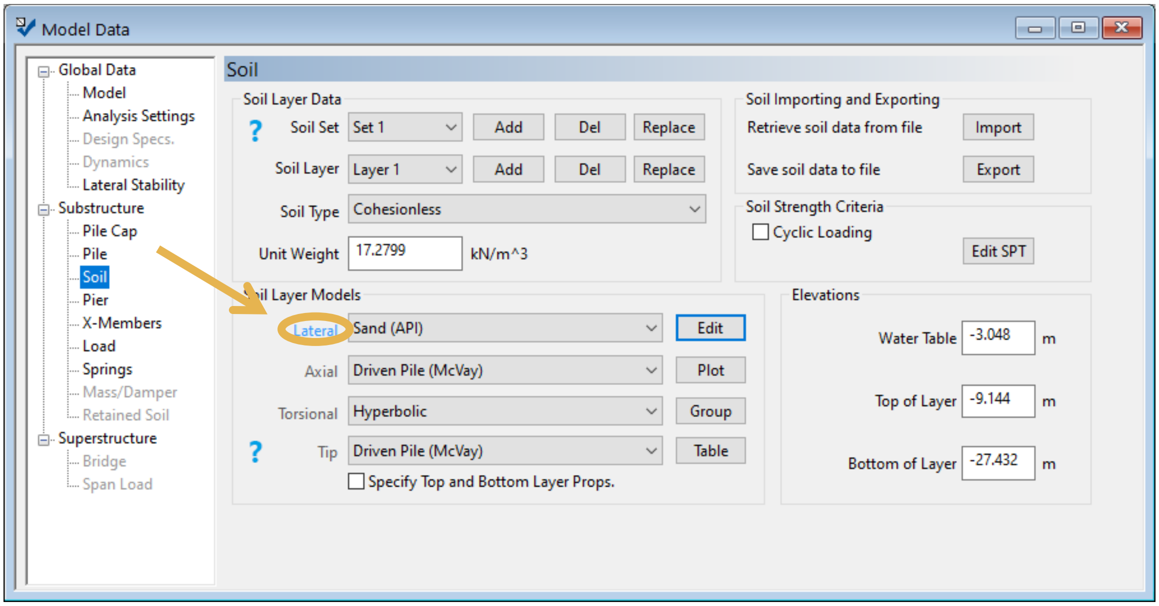
Select each of the four soil models: Lateral, Axial, Torsional, and Tip.



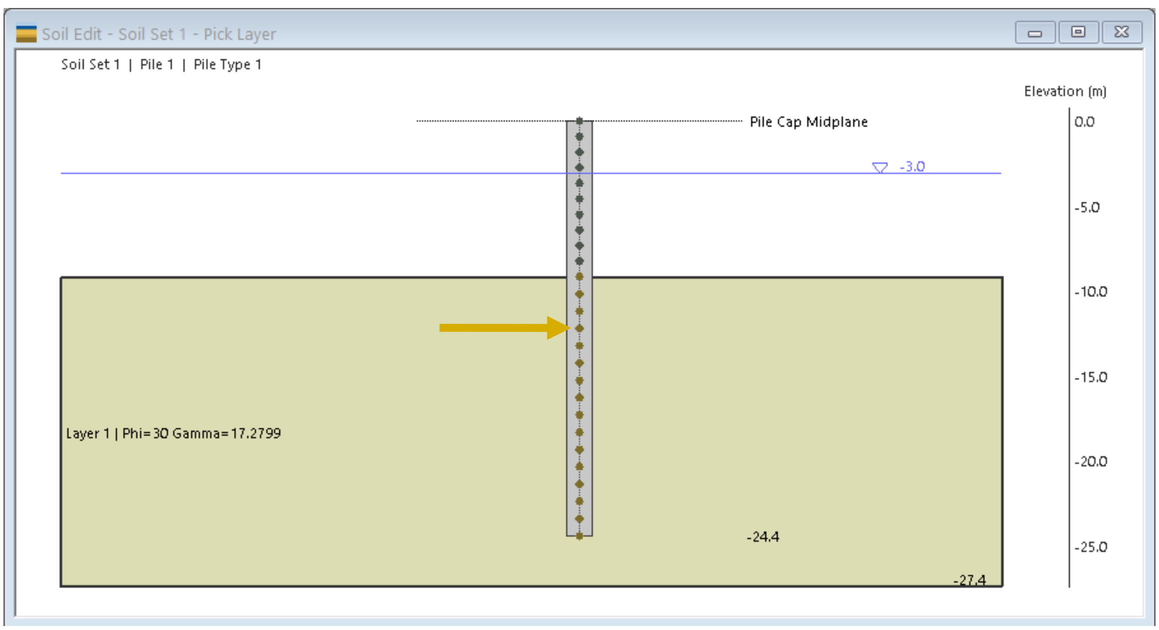
Enter properties for each soil Model. To do this, click on the soil model, then click the edit button. (The Soil Table can also be used to enter all soil properties)



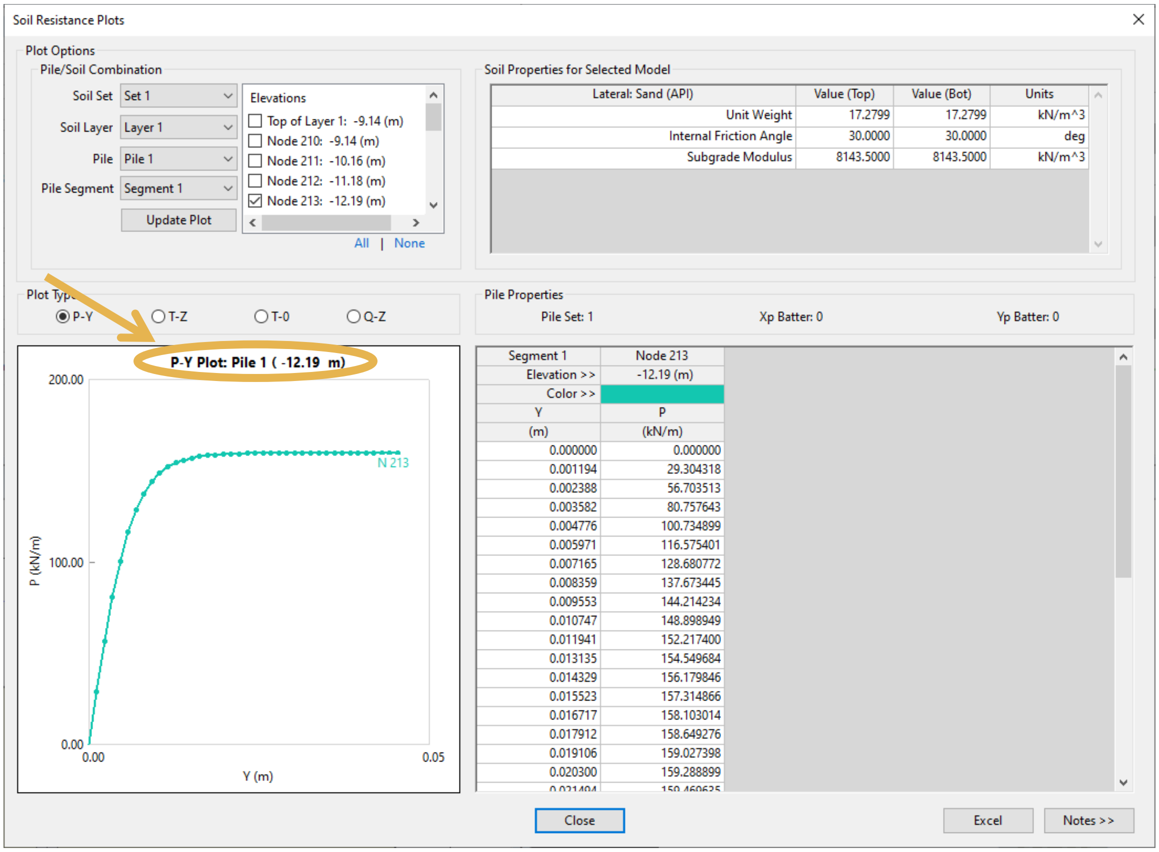
To display a soil curve, select the desired soil model.



Then click a node on the pile in the Soil Edit Window.



This will display a curve at the elevation of the selected node.



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