FB-MultiPier

Bridge Software Institute

p-y Modeling Comparison

FB-MultiPier vs LPile®

EXECUTIVE SUMMARY

This report summarizes comparisons between FB-MultiPier (v6.0.0) and LPILE®, in which soil lateral resistance and pile/shaft response are numerically computed using p-y models.

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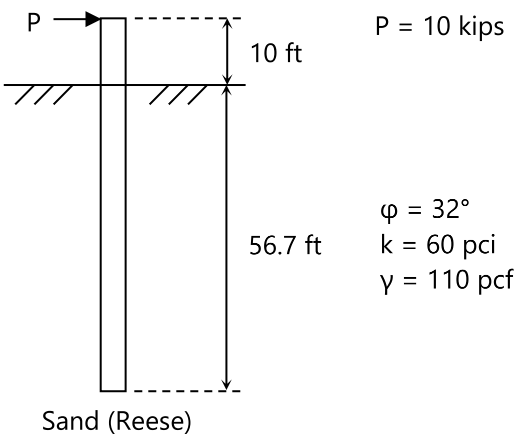
Chapter 1

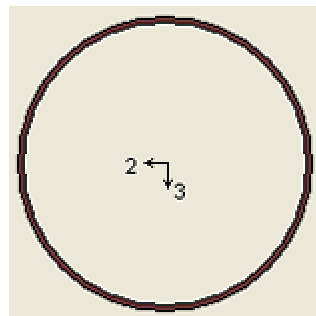
Circular Sections

In this chapter, deep foundation analysis results are compared between FB-MultiPier and LPILE® (referred to as LPILE in the remainder of the report) for laterally loaded circular piles/shafts. Lateral-load response comparisons include profiles of internal forces such as shear and moment. Additionally, profiles of lateral displacement and soil lateral resistance are presented. To facilitate soil resistance comparisons, linear-elastic section properties are used in analyzing the laterally loaded circular pile sections. Nonlinear behavior of piles/shafts in FB-MultiPier (finite element method) differs from LPILE (finite difference method), where FB-MultiPier computes resultant forces using numerical integration of cross-section stresses over numerous integration points (called fibers). Further, FB-MultiPier takes into consideration both constitutive (stress-strain) and kinematic nonlinearity (e.g., p-Δ effects). Please note that the FB-MultiPier models can be made available to licensed 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. The pile is embedded in a single layer of sand (Reese). The pile is assumed to remain linear elastic.





24" Pipe Pile Section

File: *Example_1-1.in*

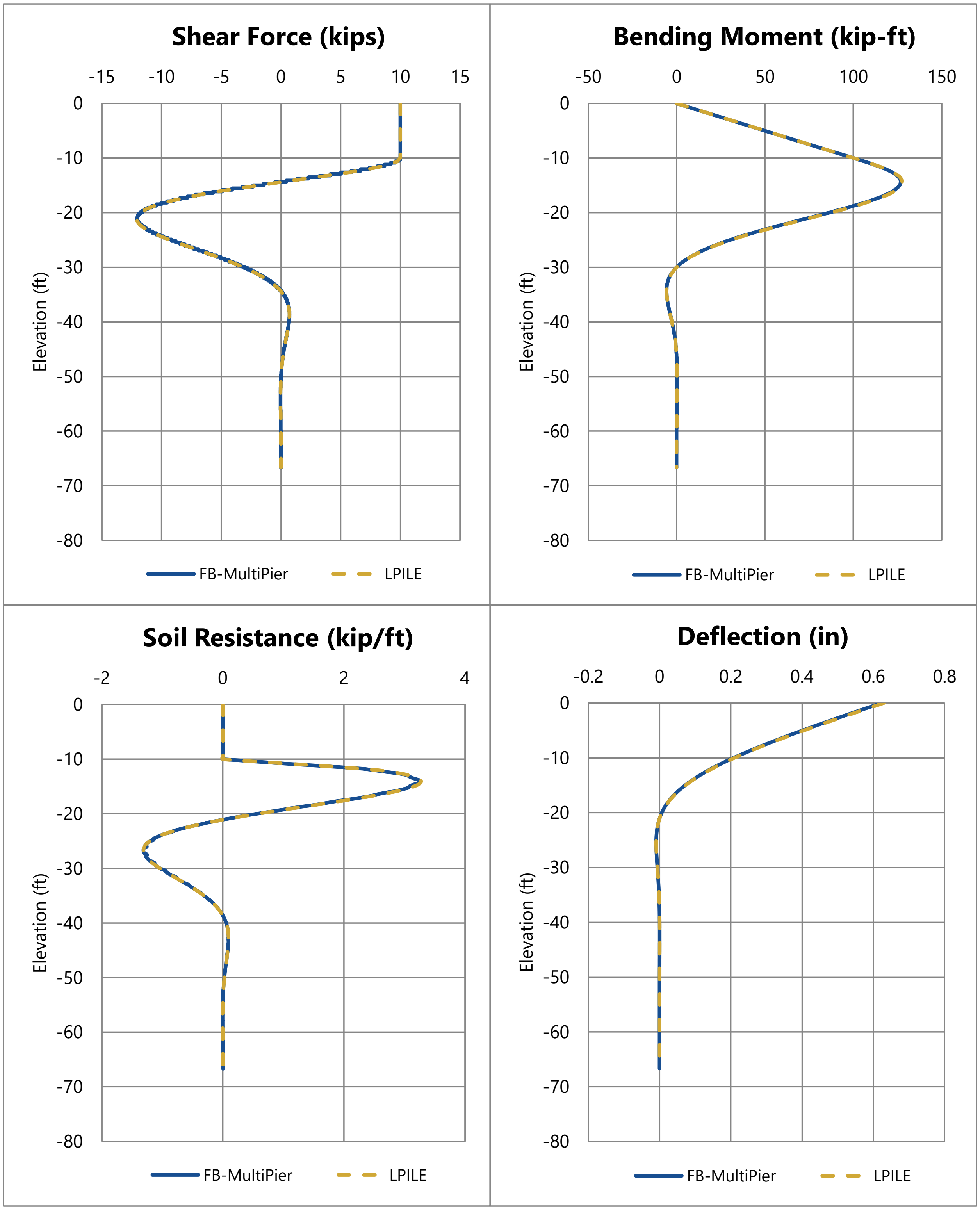
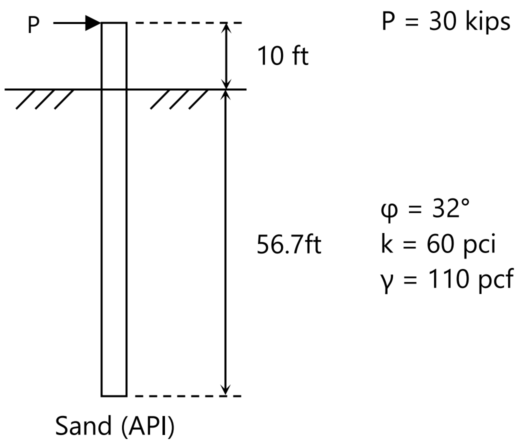
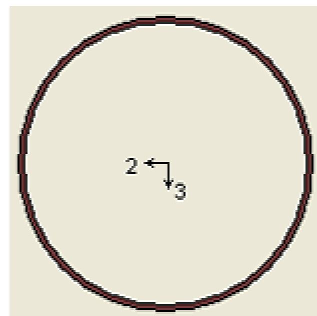


Figure 1.1 – Comparison of Results Between FB-MultiPier and LPILE for Example 1-1

Example 1-2: Single 24" Pipe Pile in Sand (API)

Problem Description: Analyze a single 24" pipe pile subjected to lateral loading. The pile is embedded in a single layer of sand (API, American Petroleum Institute). The pile is assumed to remain linear elastic.





24" Pipe Pile Section

File: *Example_1-2.in*

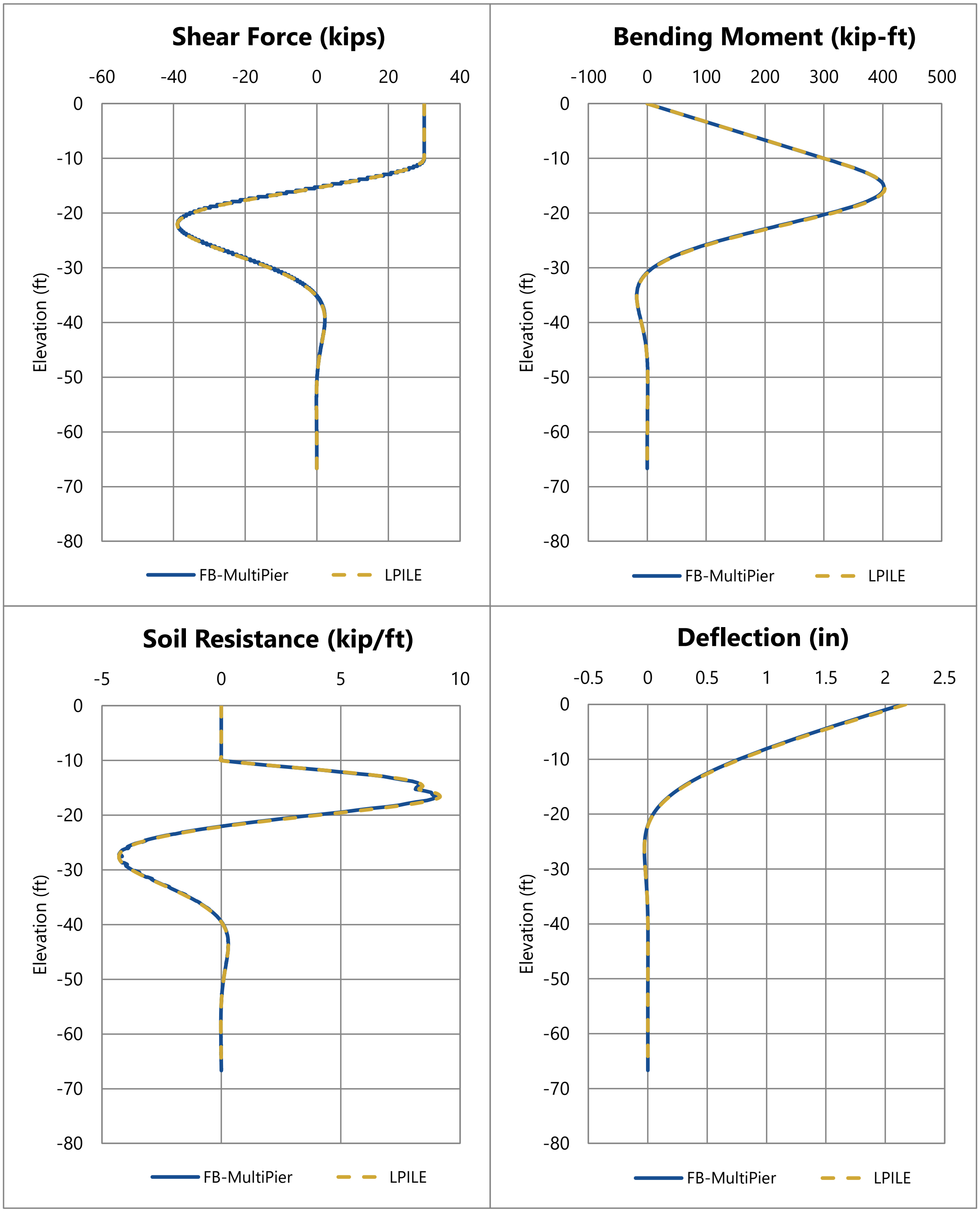
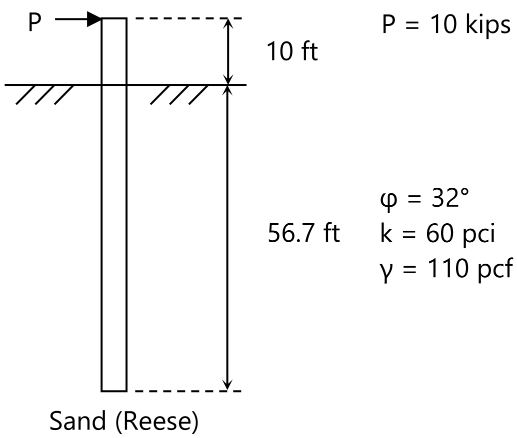
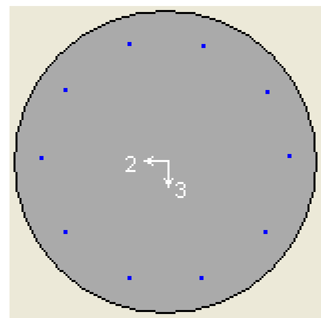


Figure 1.2 – Comparison of Results Between FB-MultiPier and LPILE for Example 1-2

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

Problem Description: Analyze a single 36” drilled shaft subjected to lateral loading. The shaft is embedded in a single layer of sand (Reese). The shaft is assumed to remain linear elastic.





36” Drilled Shaft

File: *Example_1-3.in*

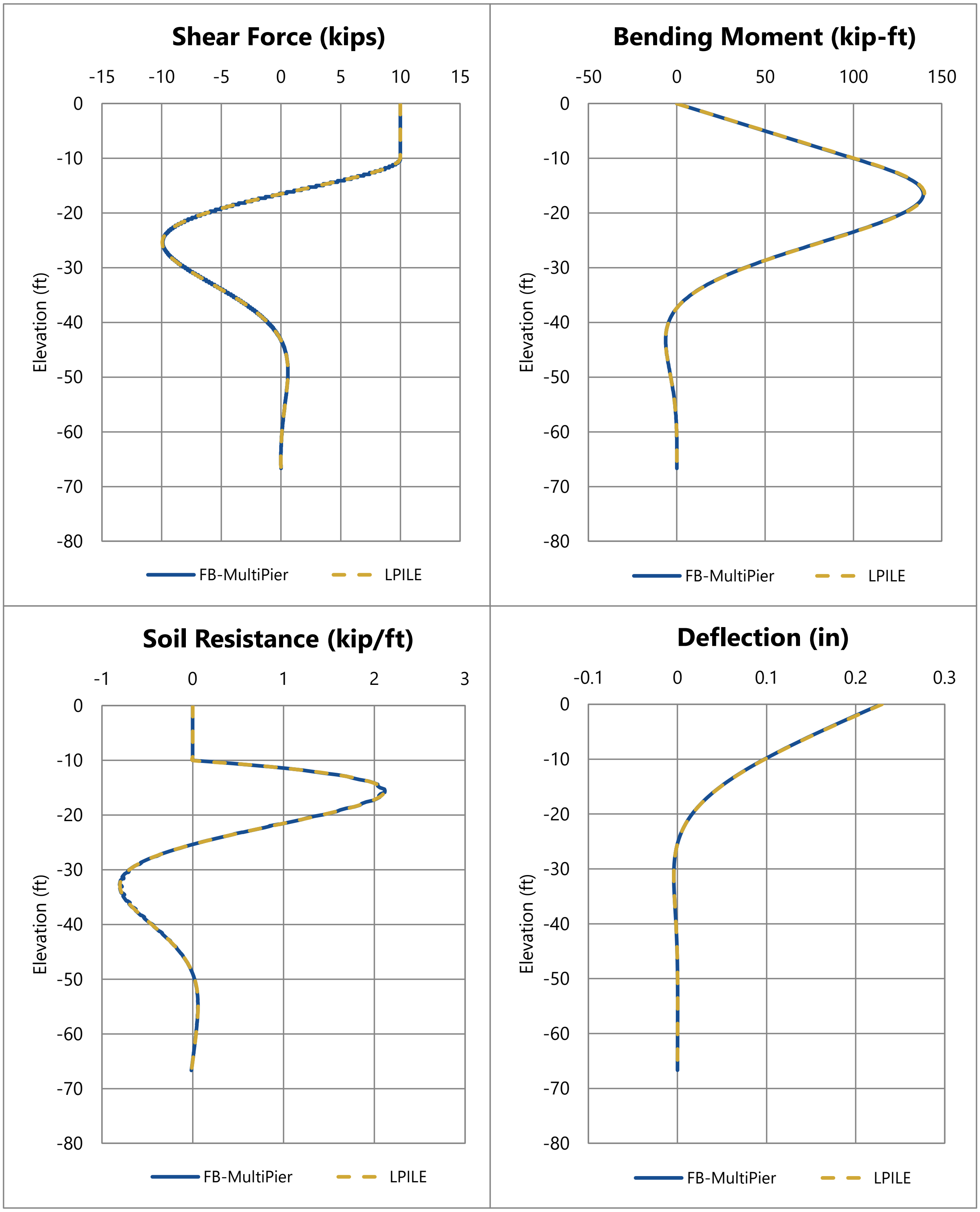
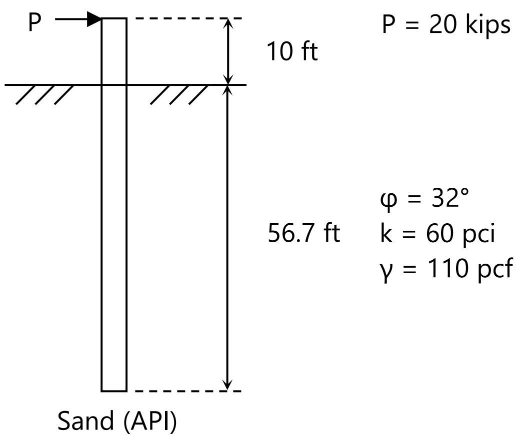
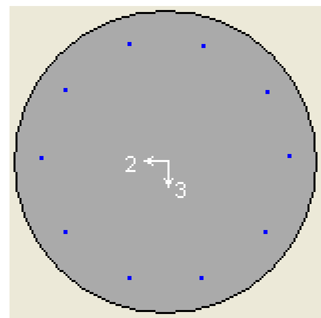


Figure 1.3 – Comparison of Results Between FB-MultiPier and LPILE for Example 1-3

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

Problem Description: Analyze a single 36” drilled shaft subjected to lateral loading. The shaft is embedded in a single layer of API sand. The shaft is assumed to remain linear elastic.





36” Drilled Shaft

File: *Example_1-4.in*

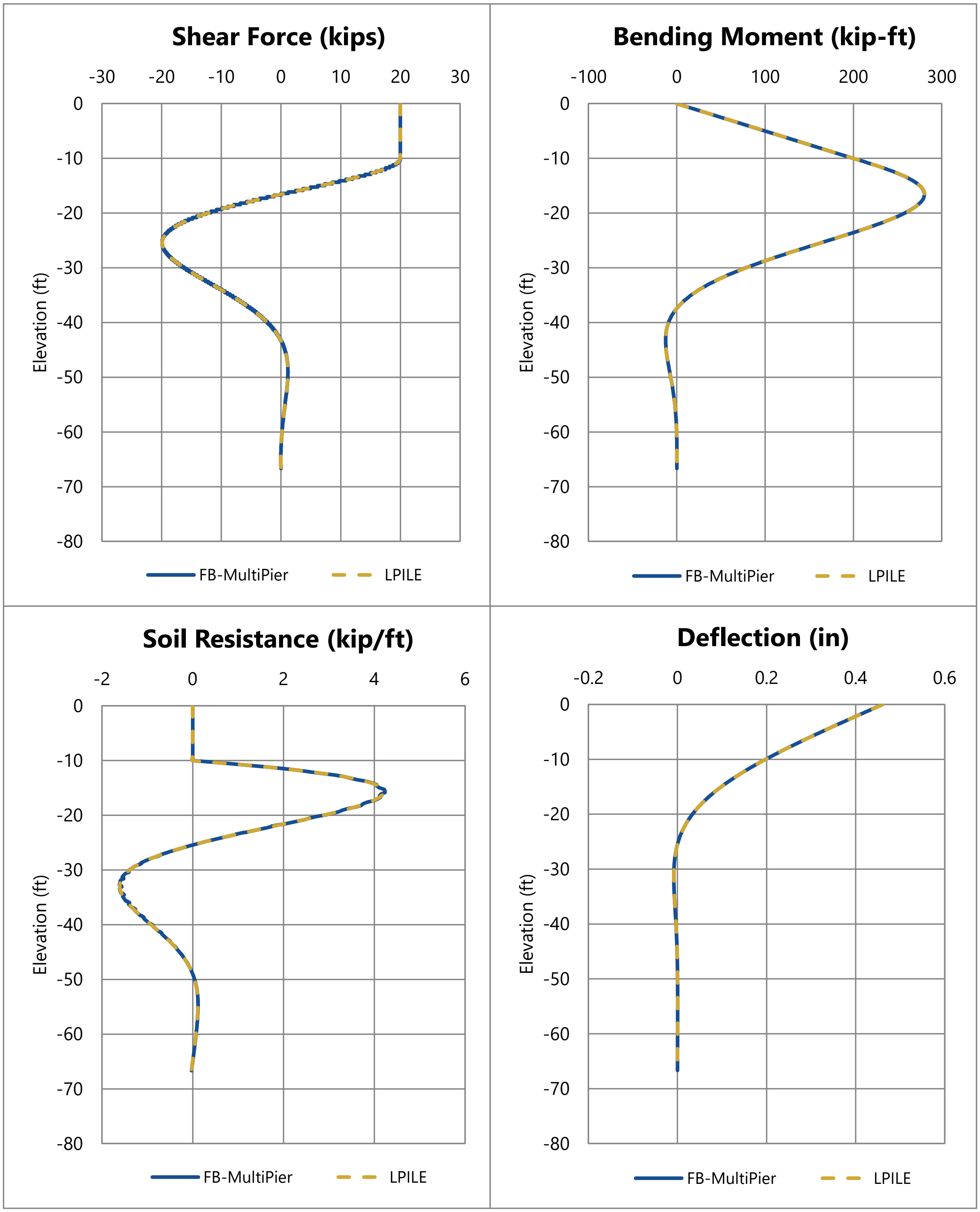
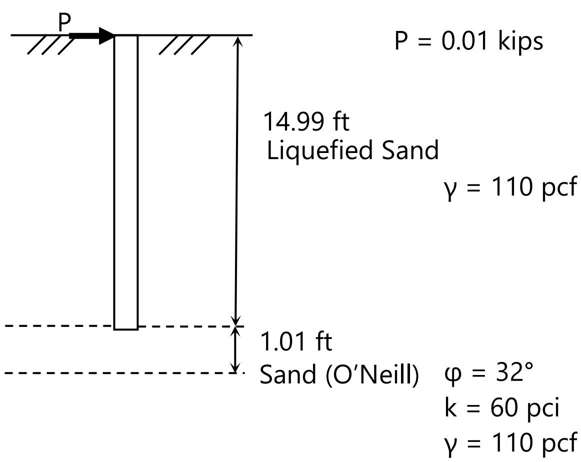
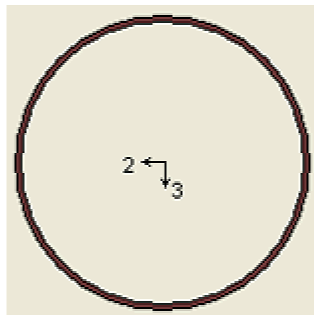


Figure 1.4 – Comparison of Results Between FB-MultiPier and LPILE for Example 1-4

Example 1-5: Single 24” Pipe Pile in Liquefied Sand (Rollins)

Problem Description: Analyze a single 24” pipe pile subjected to lateral loading. The 15’ pile is embedded in a layer of Liquefied Sand, above a layer of sand (O’Neill). The pile is assumed to remain linear elastic.





24” Pile Pipe Section

File: *Example_1-5.in*

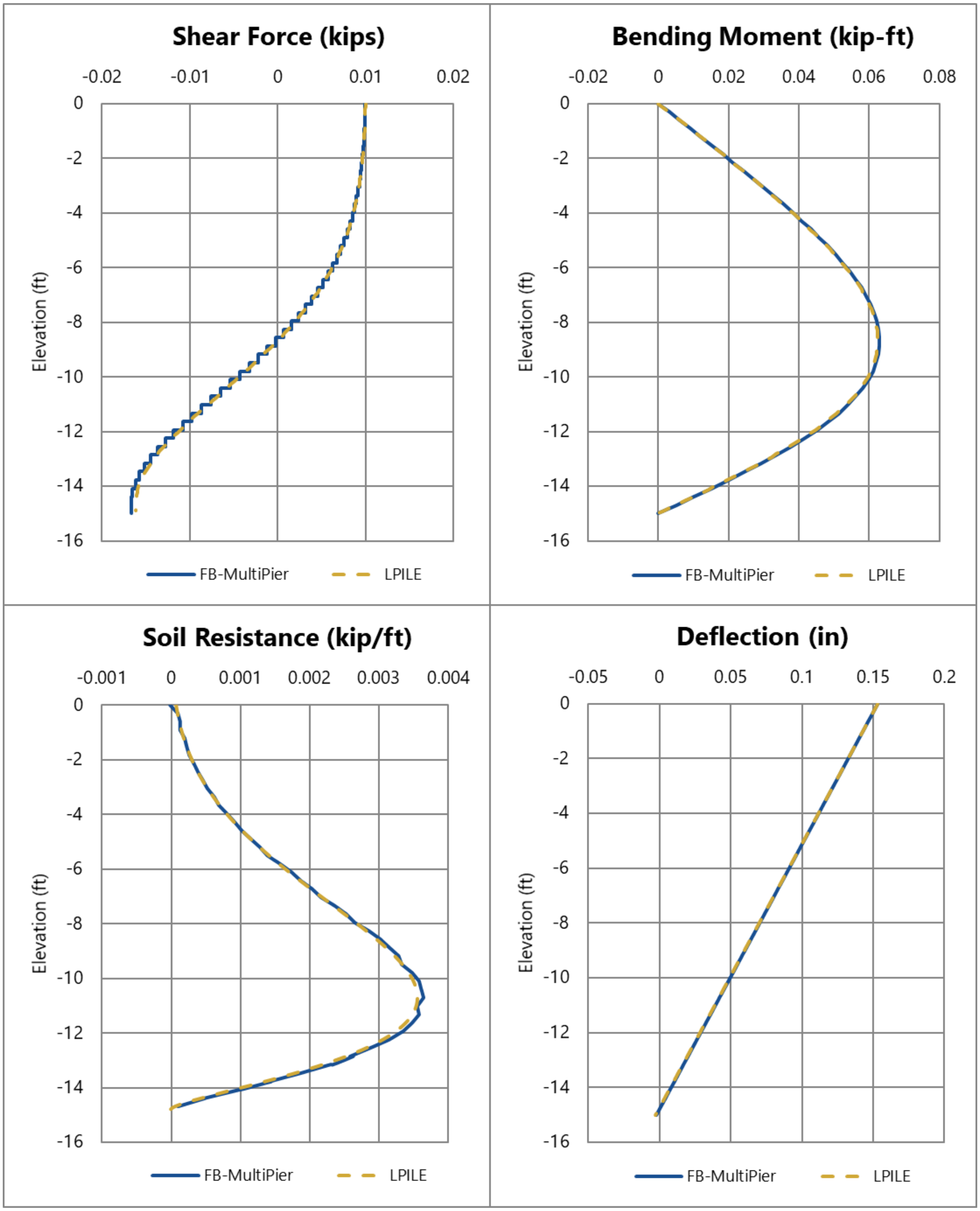
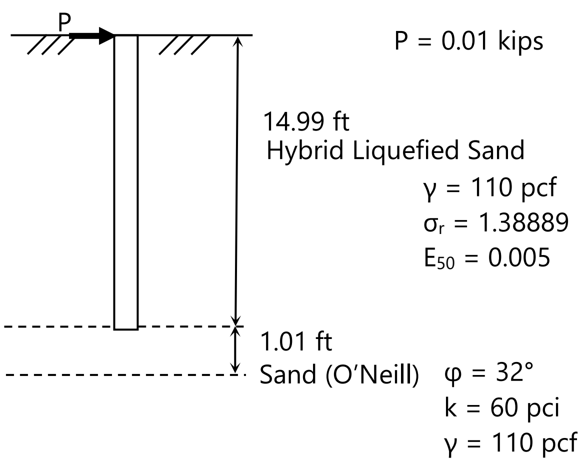
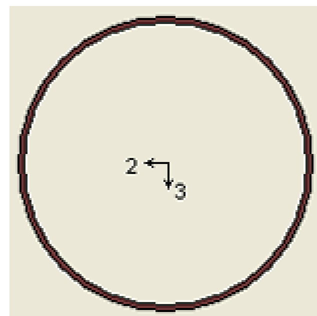


Figure 1.5 – Comparison of Results Between FB-MultiPier and LPILE for Example 1-5

Example 1-6: Single 24″ Pipe Pile in Hybrid Liquefied Sand

Problem Description: Analyze a single 24″ pipe pile subjected to lateral loading. The 15′ pile is embedded in a layer of Hybrid Liquefied Sand, above a layer of sand (O'Neill). The pile is assumed to remain linear elastic.





24″ Pile Pipe Section

File: *Example_1-6.in*

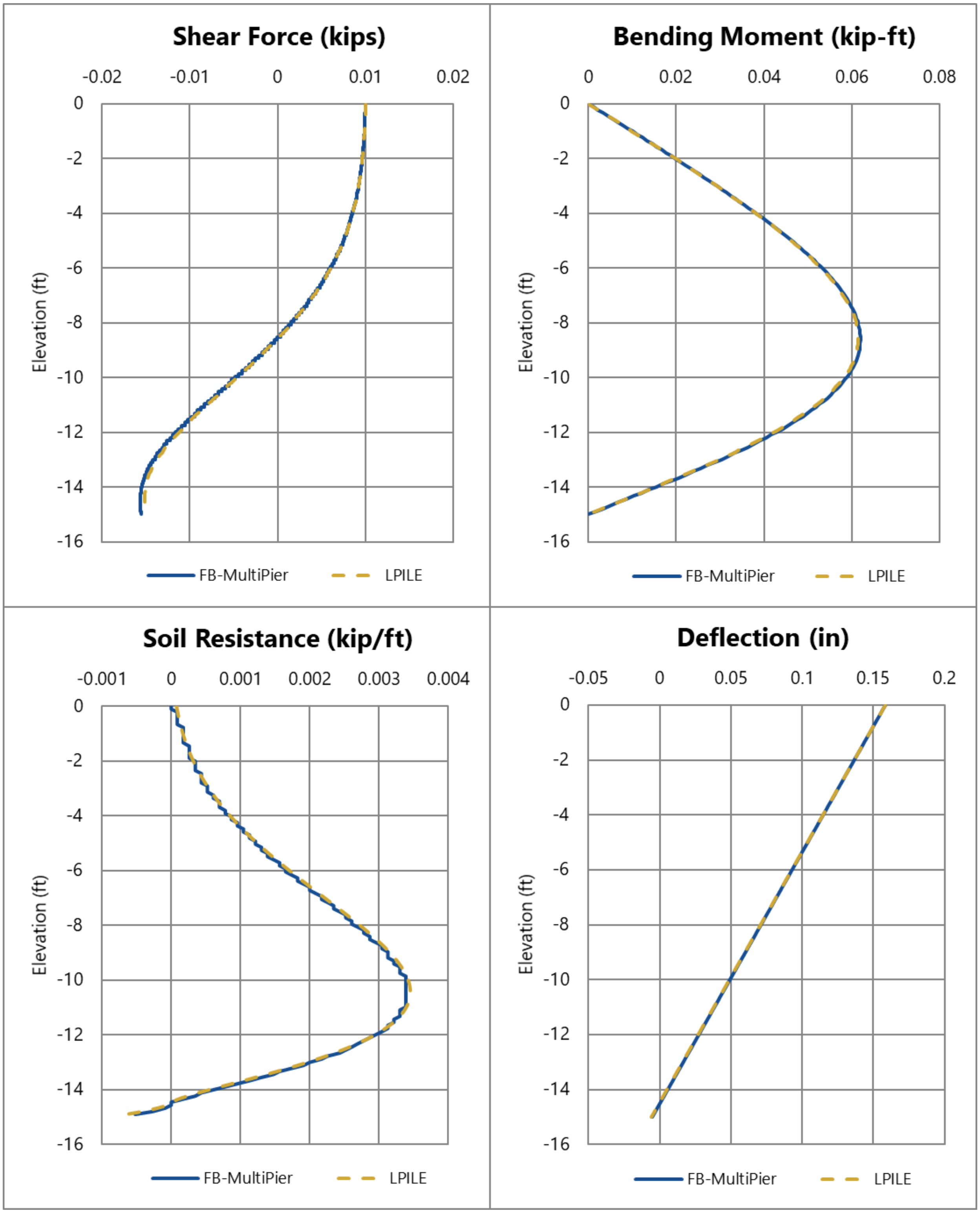
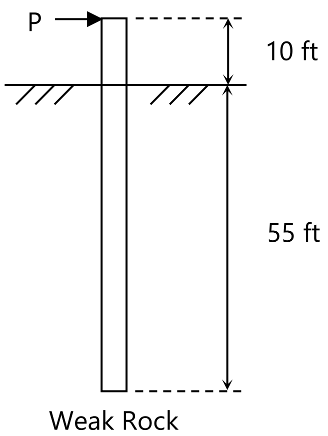


Figure 1.6 – Comparison of Results Between FB-MultiPier and LPILE for Example 1-6

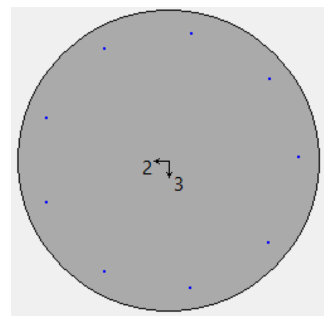
Example 1-7: Single 24” Drilled Shaft in Weak Rock

Problem Description: Analyze a single 24” drilled shaft subjected to lateral loading. The shaft is embedded in a single layer of Weak Rock. The shaft is assumed to remain linear elastic.



P = 12.5 kips

γ = 130 pcf
q_u = 57419.9 psf
E_m = 64.91 ksi
RQD = 53.44%
Stiffness Constant
= 0.0005



24” Drilled Shaft

File: *Example_1-7.in*

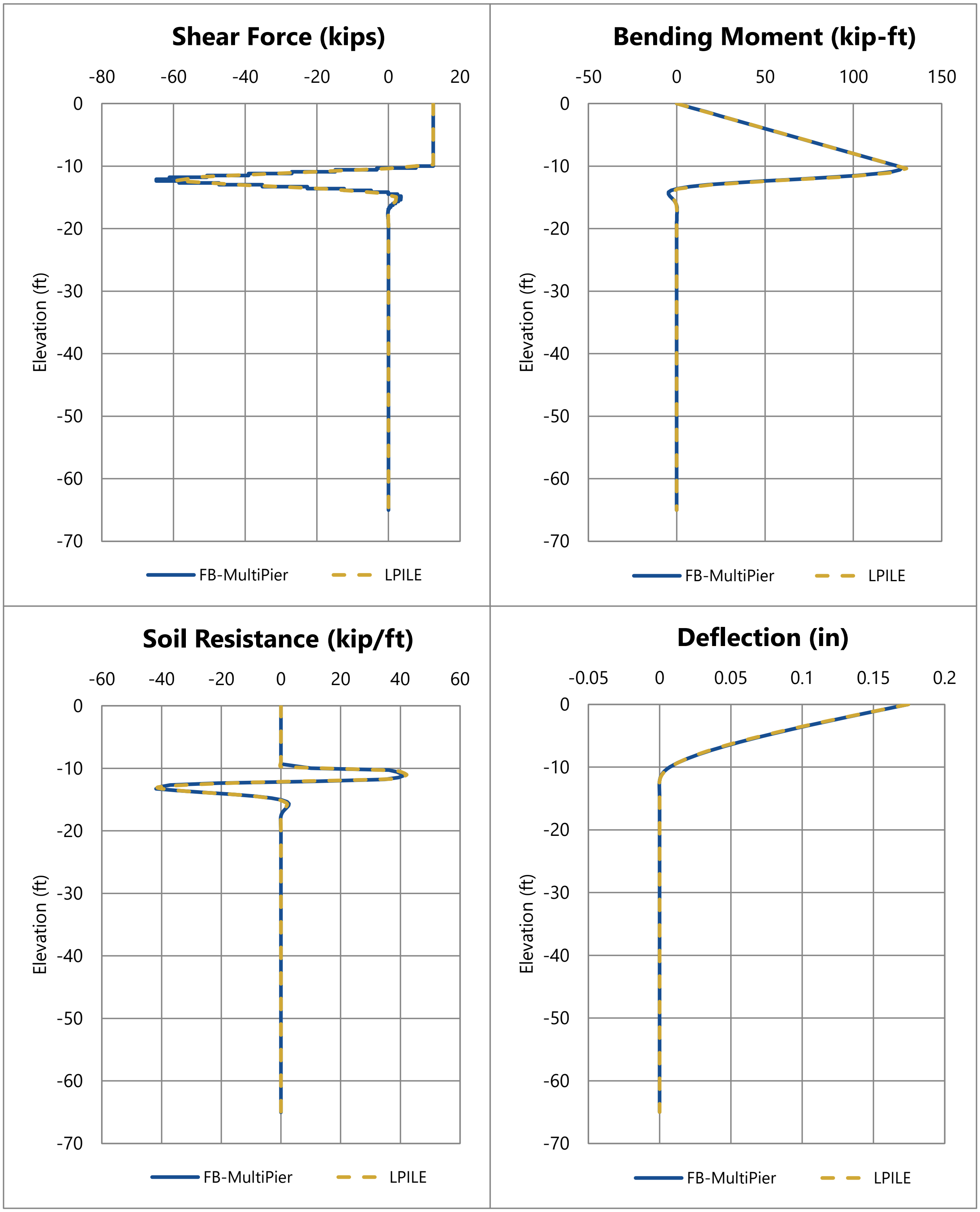
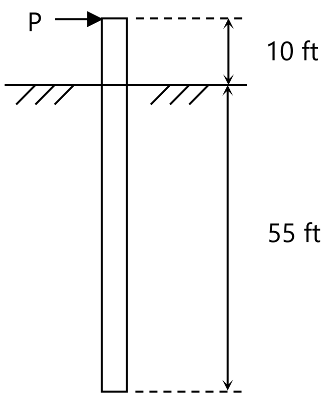


Figure 1.7 – Comparison of Results Between FB-MultiPier and LPILE for Example 1-7

Example 1-8: Single 24” Drilled Shaft in Strong Rock

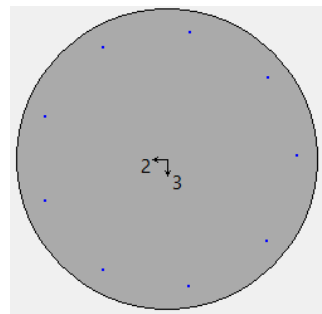
Problem Description: Analyze a single 24” drilled shaft subjected to lateral loading. The shaft is embedded in a single layer of Strong Rock. The shaft is assumed to remain linear elastic.



P = 2.5 kips

γ = 160 pcf
q_u = 145000 psf

Strong Rock



24” Drilled Shaft

File: *Example_1-8.in*

FB-MultiPier results for soil force per unit length (Fig. 1.8) are reported at a more refined spacing than those of the LPILE results.

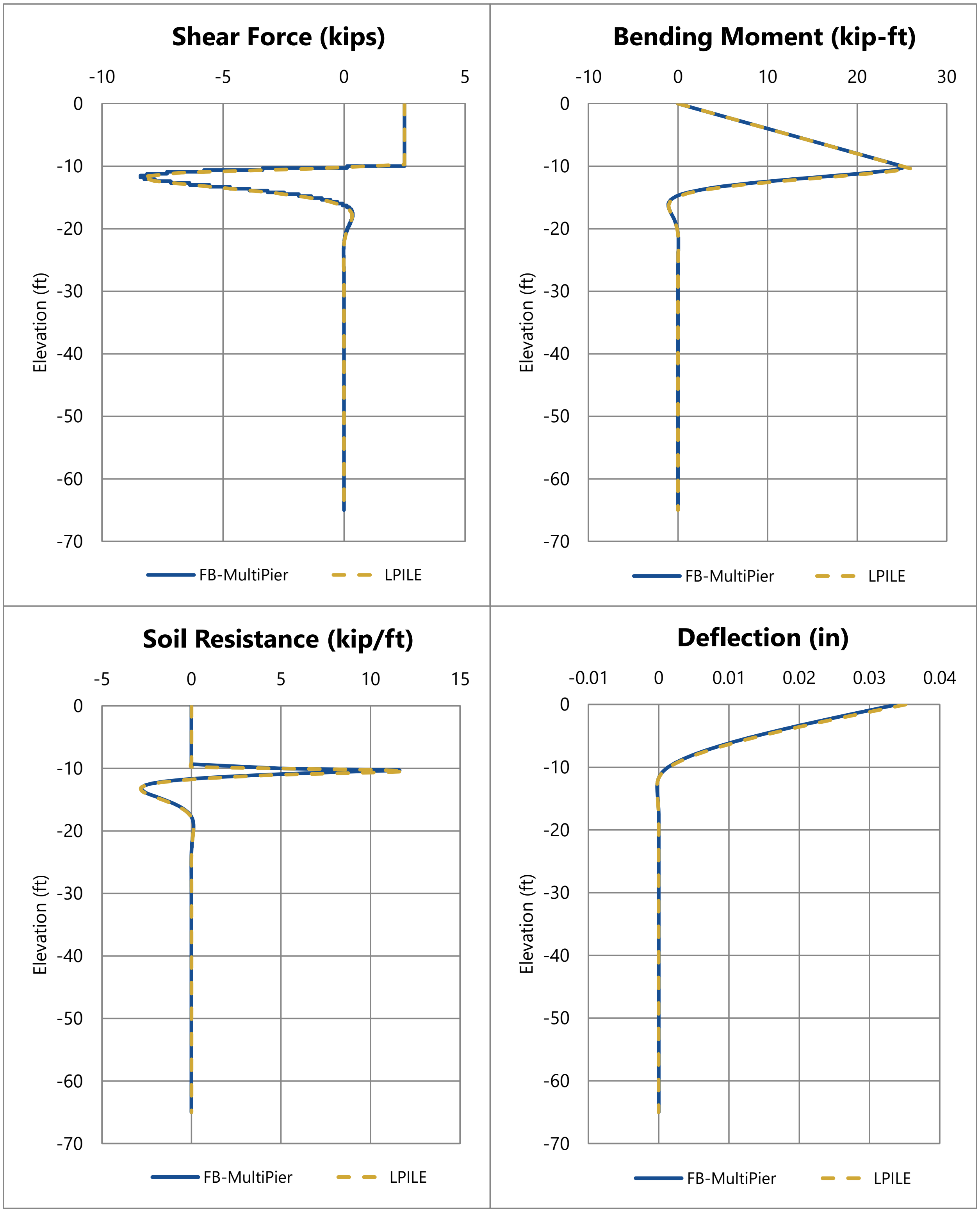
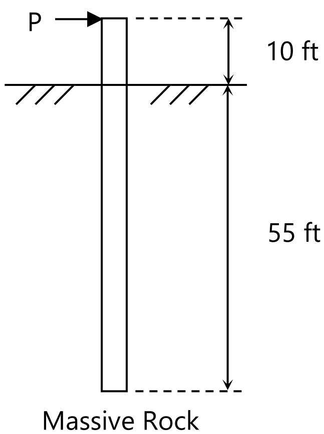


Figure 1.8 – Comparison of Results Between FB-MultiPier and LPILE for Example 1-8

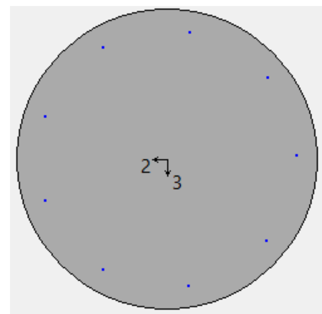
Example 1-9: Single 24″ Drilled Shaft in Massive Rock

Problem Description: Analyze a single 24″ drilled shaft subjected to lateral loading. The shaft is embedded in a single layer of Massive Rock. The shaft is assumed to remain linear elastic.



P = 12.5 kips

γ = 128.22 pcf
q_u = 816620 psf
ν = 0.3
GSI = 51
Material Index = 6
E_{Intact} = 590.01 ksi



24″ Drilled Shaft

File: *Example_1-9.in*

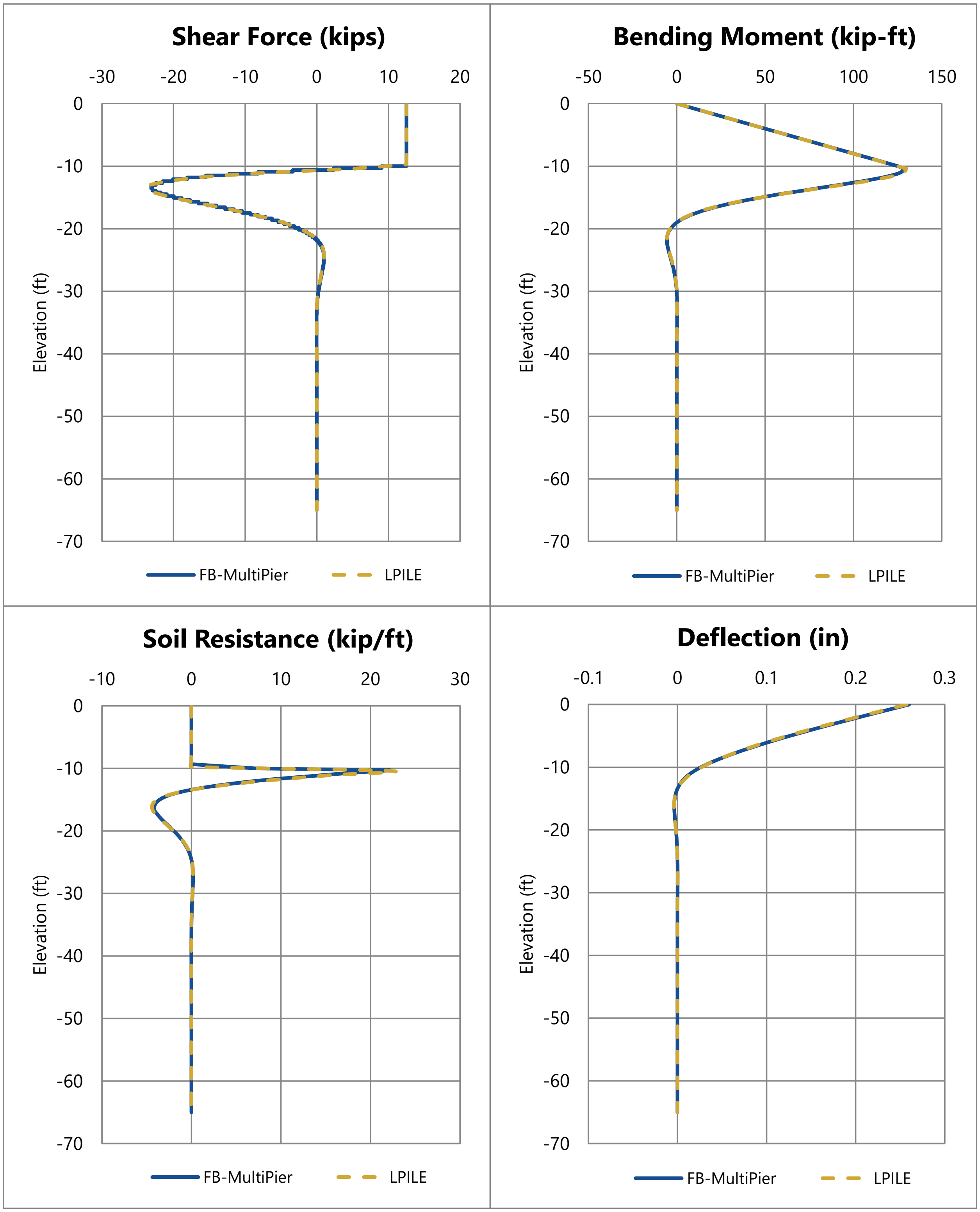
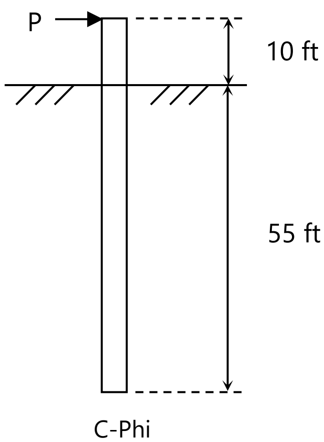


Figure 1.9 – Comparison of Results Between FB-MultiPier and LPILE for Example 1-9

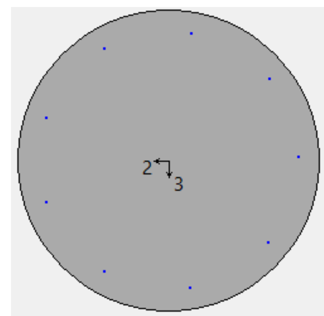
Example 1-10: Single 24″ Drilled Shaft in C-Phi Soil

Problem Description: Analyze a single 24″ drilled shaft subjected to lateral loading. The shaft is embedded in a single layer of C-Phi soil. The shaft is assumed to remain linear elastic.



$P = 12.5$ kips

$\gamma = 130$ pcf
$k = 900$ pci
$\phi = 30°$
$C_u = 3000$ psf



24″ Drilled Shaft

File: *Example_1-10.in*

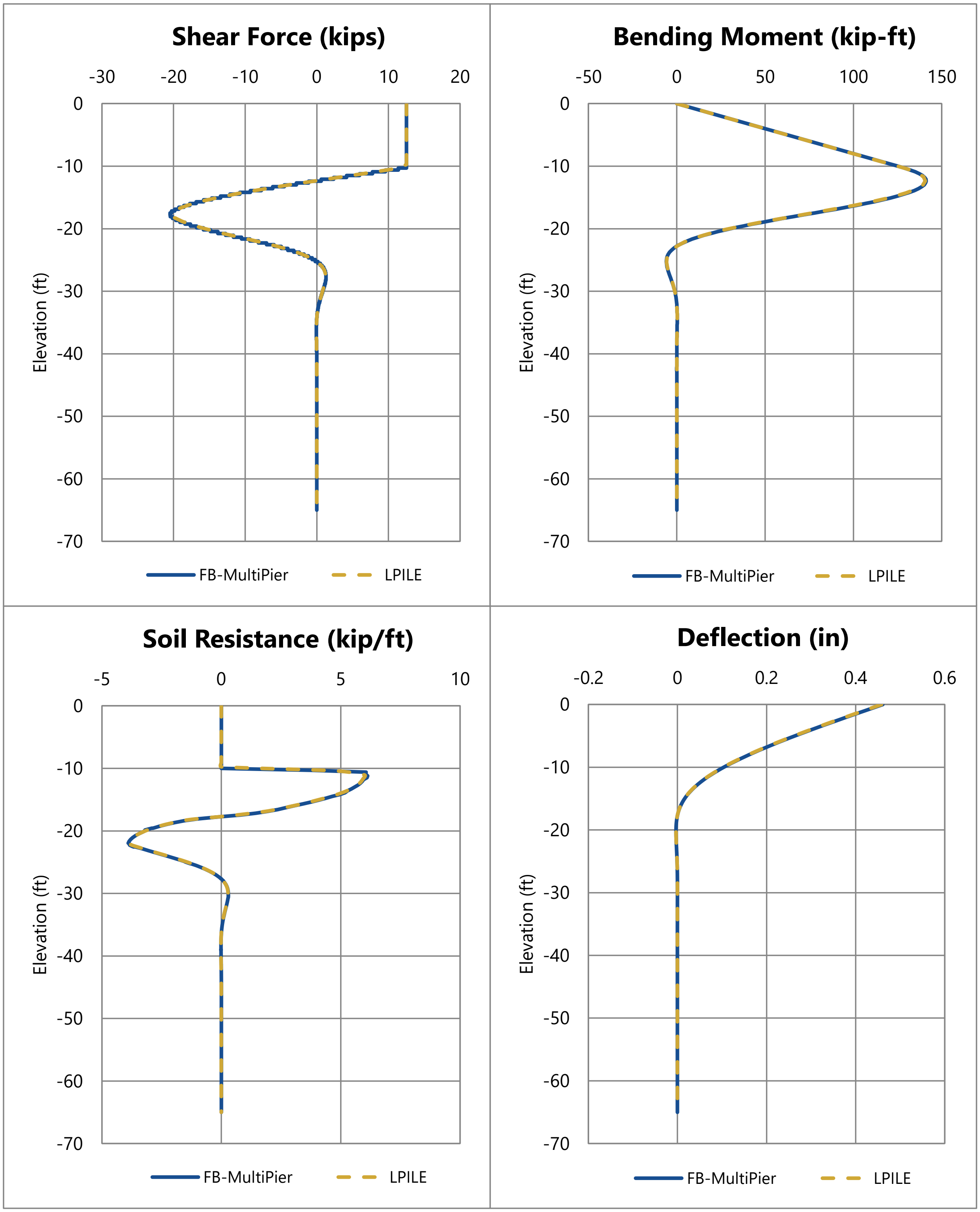
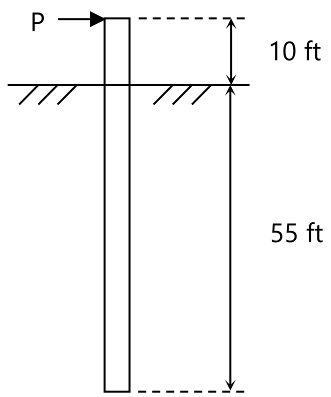


Figure 1.10 – Comparison of Results Between FB-MultiPier and LPILE for Example 1-10

Example 1-11: Single 24” Drilled Shaft in Piedmont Residual Soil

Problem Description: Analyze a single 24” drilled shaft subjected to lateral loading. The shaft is embedded in a single layer of Piedmont Residual soil. The shaft is assumed to remain linear elastic.

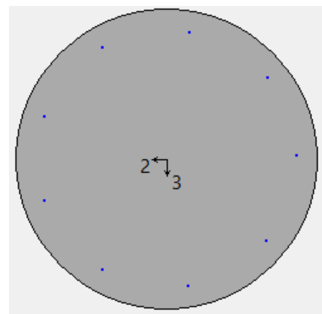


Piedmont Residual

P = 12.5 kips

γ = 130 pcf

$E_{press\text{-}meter}$ = 900 psi



24” Drilled Shaft

File: *Example_1-11.in*

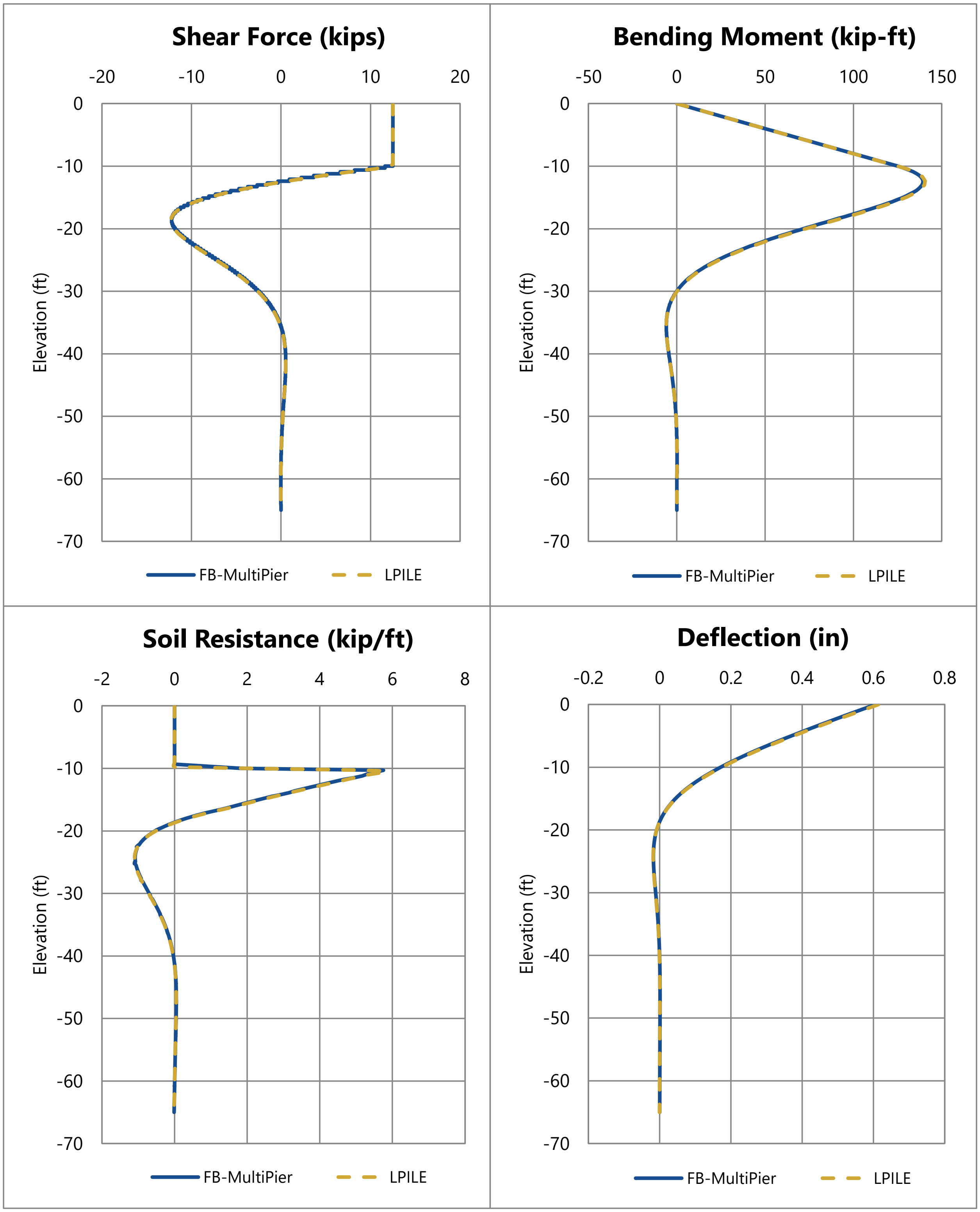
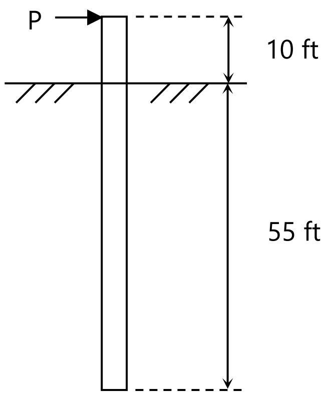


Figure 1.11 – Comparison of Results Between FB-MultiPier and LPILE for Example 1-11

Example 1-12: Single 24″ Drilled Shaft in Linear (Subgrade) Soil

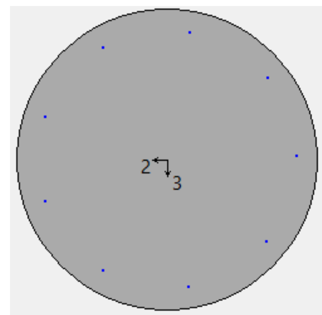
Problem Description: Analyze a single 24″ drilled shaft subjected to lateral loading. The shaft is embedded in a single layer of Linear (Subgrade) soil. The shaft is assumed to remain linear elastic.



P = 2.5 kips

γ = 130 pcf
k = 920.98 pci

Linear (Subgrade)



24″ Drilled Shaft

File: *Example_1-12.in*

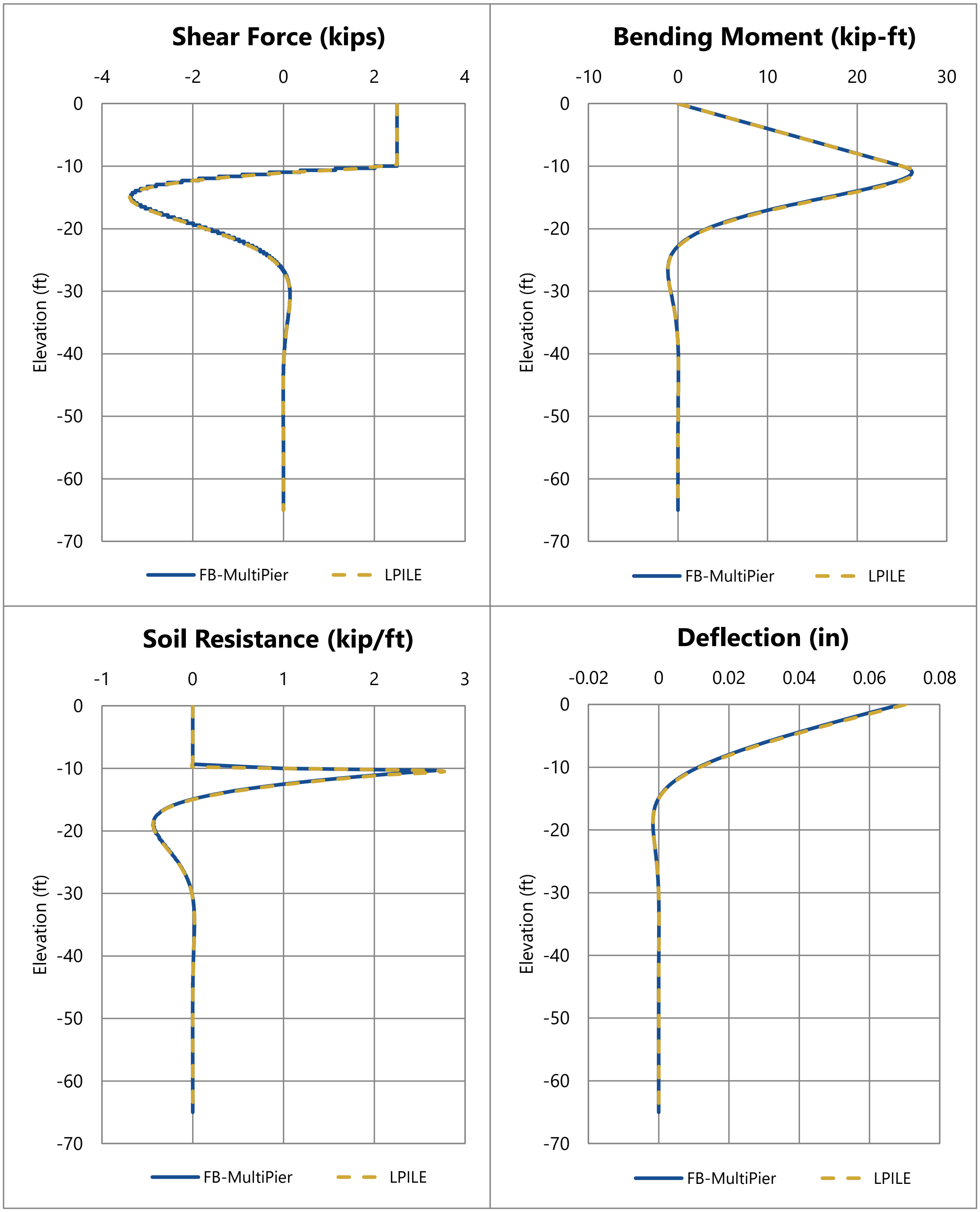


Figure 1.12 – Comparison of Results Between FB-MultiPier and LPILE for Example 1-12

Chapter 2

Noncircular Sections

In this chapter, noncircular pile foundations are analyzed and compared between FB-MultiPier and LPILE. Results are presented for shear, moment, lateral displacement, and soil lateral resistance. To facilitate comparisons, linear-elastic properties are used to models the noncircular sections.

In FB-MultiPier analysis for Example 2-1 through 2-9, "effective" diameters of the noncircular piles are computed using the following equation:

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

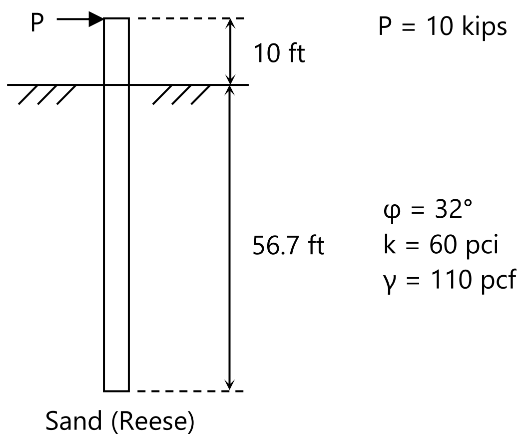
where effective diameter is denoted by D_{eff}, width by t_w, and depth by t_d. Because p-y curves were originally developed for circular sections, and thus a function of the diameter, an empirical equation for calculating the circumference is used to approximate an equivalent diameter for analyzing noncircular sections. For example, Ashour and Norris (2000) studied soil wedge formation and the influence of pile cross-sectional shapes on p-y curves. Findings from this study indicated 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 likewise differ. Reese and Van Impe (2001) also noted the influence of the shape of the pile cross section on soil resistance.

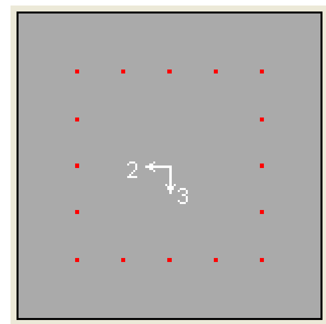
References:

1. FHWA-HRT-04-043: 8.3.1 P-y Curves; 8.3.1.1 Introduction.
   http://www.fhwa.dot.gov/publications/research/infrastructure/structures/04043/08.cfm
2. Mohamed Ashour, G. Norris (2000), "Modeling Lateral Soil-Pile Response Based on Soil-Pile Interaction", *J. Geotech. Geoenviron. Eng.*, 2000, 126(5), pp. 420–428.
3. Reese, L. C., and Van Impe, W. F. (2001), "*Single Piles and Pile Group under Lateral Loading*", A. A. Balkema, Rotterdam, Netherlands.

Example 2-1: Single 18" Precast Pile in Sand (Reese)

Problem Description: Analyze a single 18" precast, prestressed pile subjected to lateral loading. The pile is embedded in a single layer of sand (Reese). The pile is assumed to remain linear elastic.





18" Square FDOT Standard Prestressed Pile

File: *Example_2-1.in*

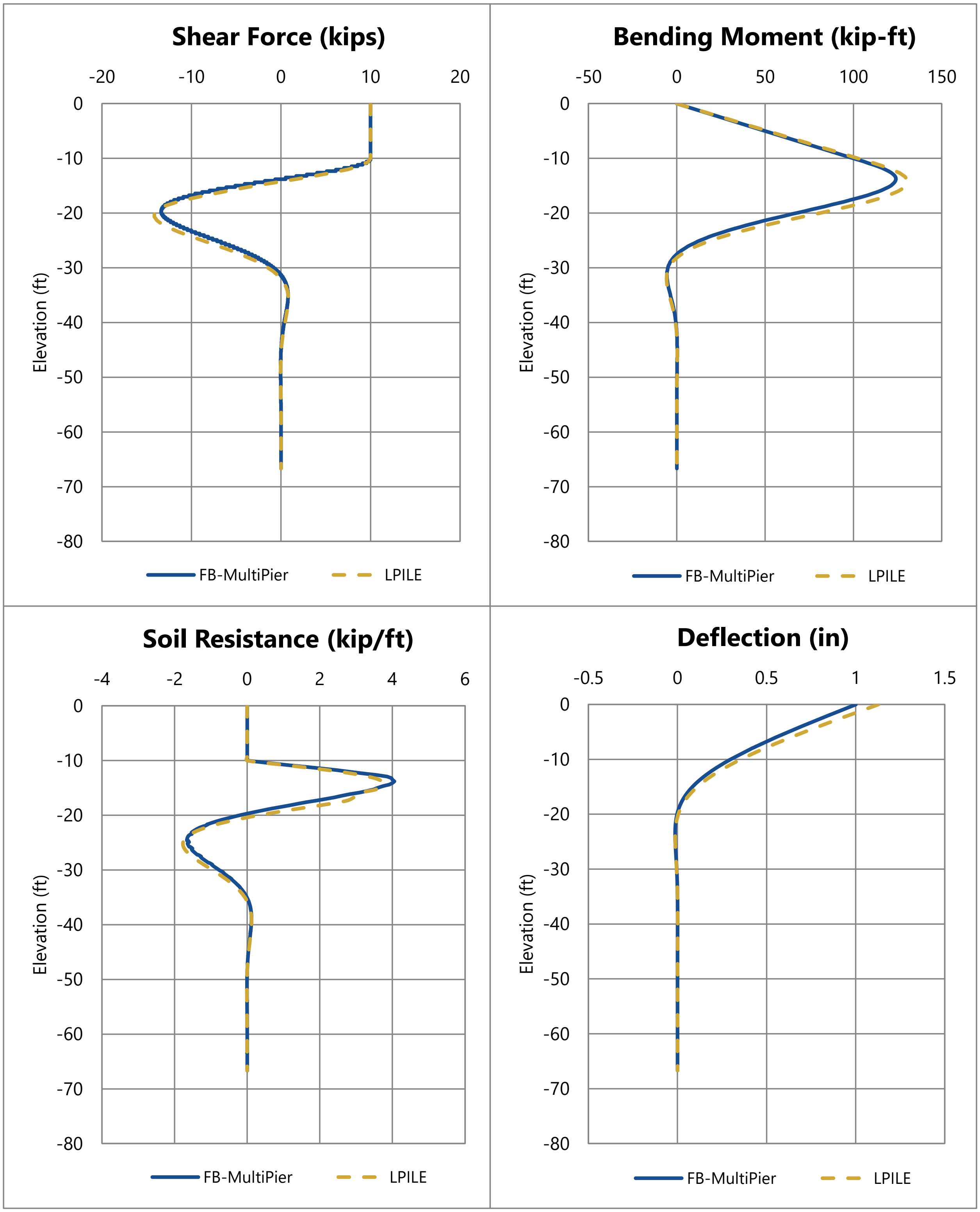
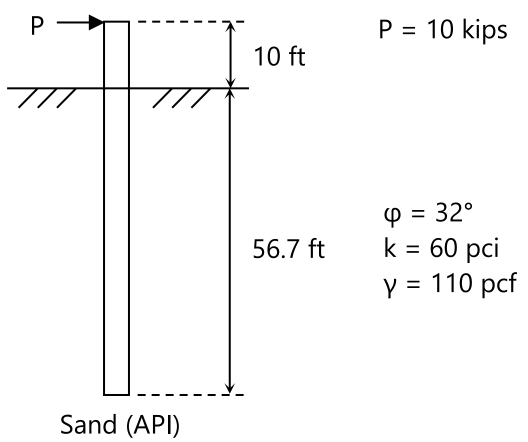
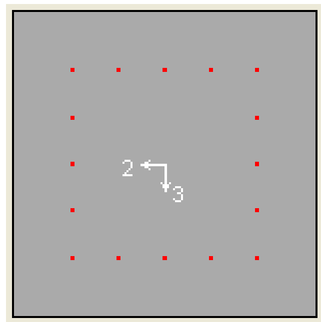


Figure 2.1 – Comparison of Results Between FB-MultiPier and LPILE for Example 2-1

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

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





18” Square FDOT Standard Prestressed Pile

File: *Example_2-2.in*

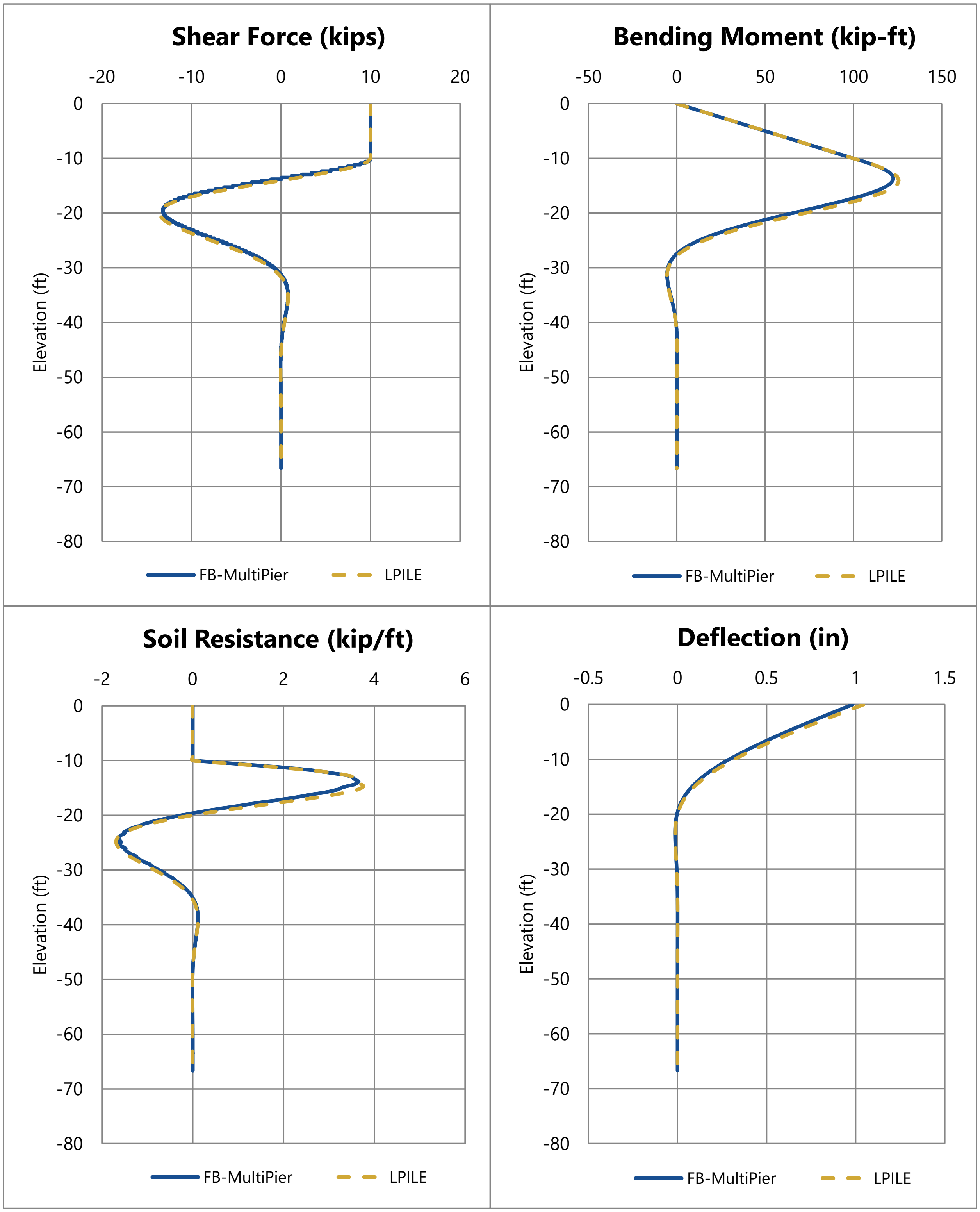
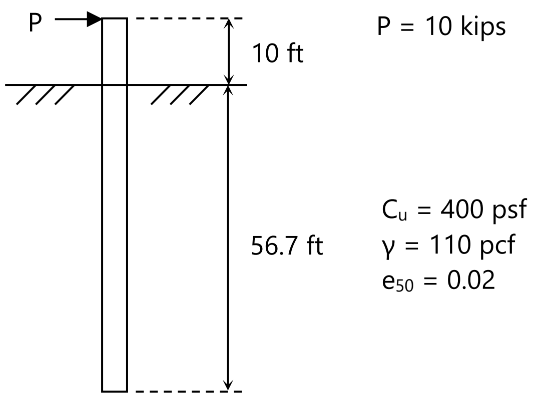
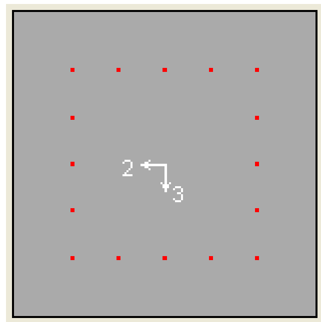


Figure 2.2 – Comparison of Results Between FB-MultiPier and LPILE for Example 2-2

Example 2-3: Single 18" Precast Pile in Clay (Soft, Matlock)	
Problem Description: Analyze a single 18" precast, prestressed pile subjected to lateral loading. The pile is embedded in a single layer of clay (Soft, Matlock). The pile is assumed to remain linear elastic.	
 Clay (Soft, Matlock)	 18" Square FDOT Standard Prestressed Pile
File: *Example_2-3.in*	

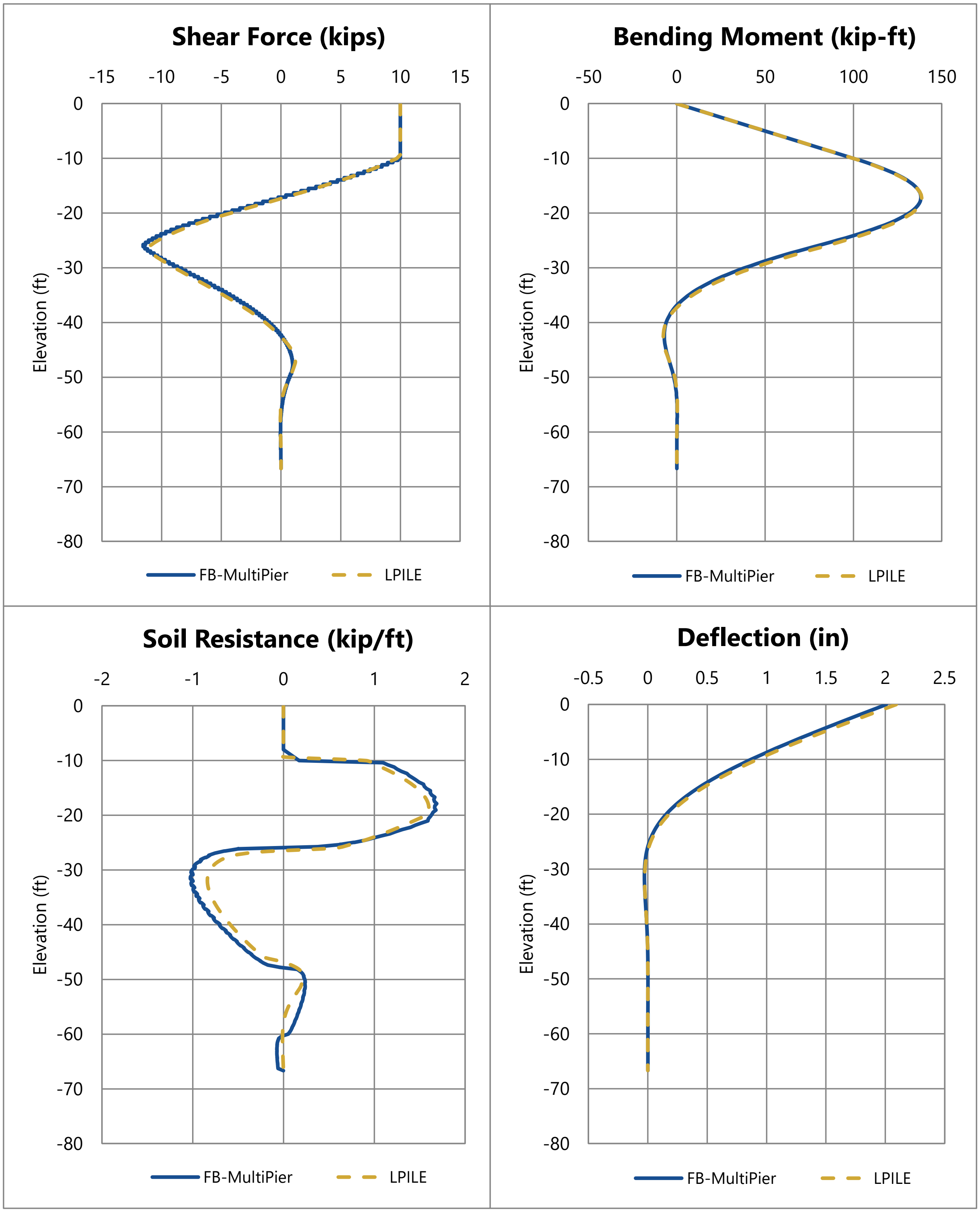
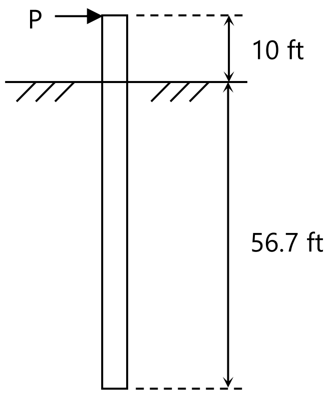


Figure 2.3 – Comparison of Results Between FB-MultiPier and LPILE for Example 2-3

Example 2-4: Single 18” Precast Pile in Clay (Stiff, with free water)

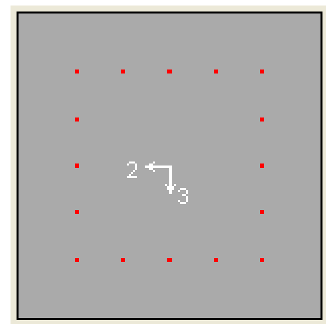
Problem Description: Analyze a single 18” precast, prestressed pile subjected to lateral loading. The pile is embedded in a single layer of clay (Stiff, with free water). The pile is assumed to remain linear elastic.



P = 10 kips

C_u = 2000 psf
γ = 110 pcf
k = 100 pci
e_{50} = 0.005
C_{avg} = 2000 psf

Clay (Stiff, with free water)



18” Square FDOT Standard Prestressed Pile

File: *Example_2-4.in*

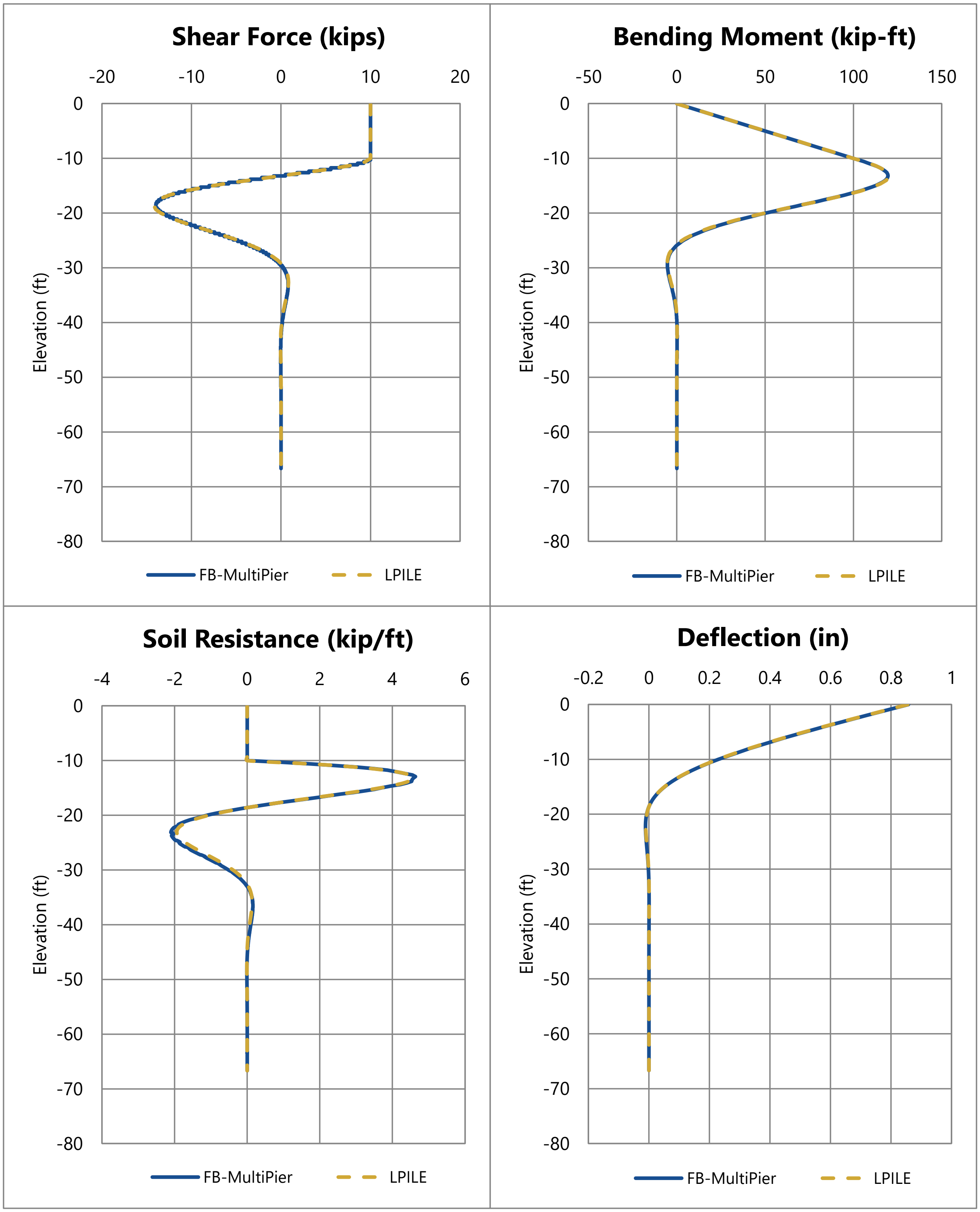
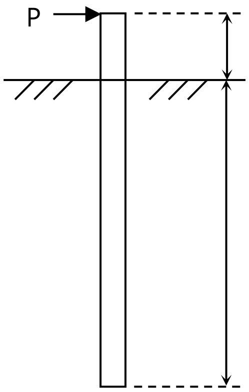


Figure 2.4 – Comparison of Results Between FB-MultiPier and LPILE for Example 2-4

Example 2-5: Single 18” Precast Pile in Clay (Stiff, without free water)

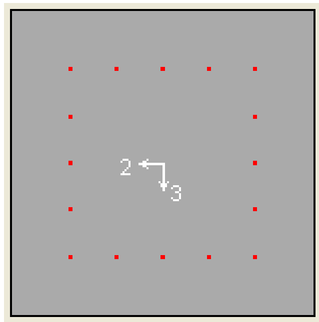
Problem Description: Analyze a single 18” precast, prestressed pile subjected to lateral loading. The pile is embedded in a single layer of clay (Stiff, without free water). The pile is assumed to remain linear elastic.



$P = 10$ kips

$C_u = 2000$ psf
$\gamma = 110$ pcf
$e_{50} = 0.005$
$C_{avg} = 2000$ psf

Clay (Stiff, without free water)



18” Square FDOT Standard Prestressed Pile

File: *Example_2-5.in*

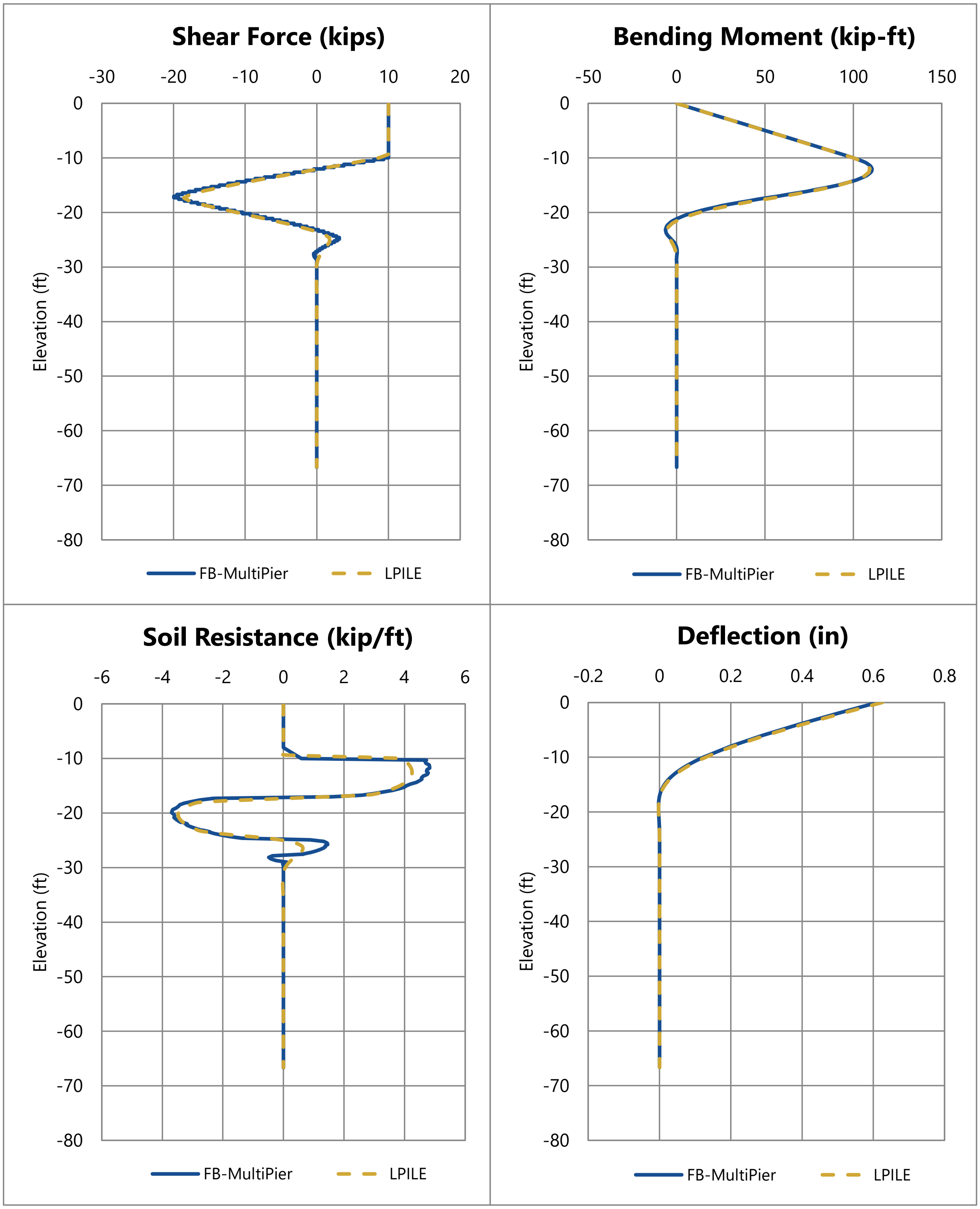
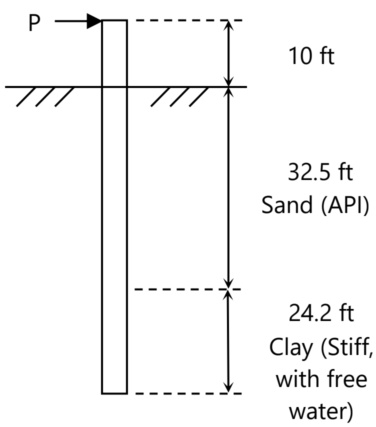


Figure 2.5 – Comparison of Results Between FB-MultiPier and LPILE for Example 2-5

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

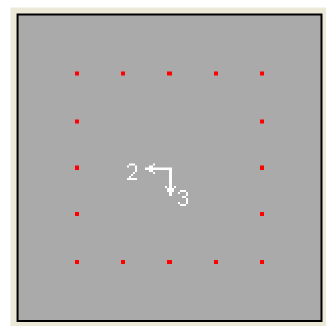
Problem Description: Analyze a single 18" precast, prestressed pile subjected to lateral loading. The pile is embedded in a double layer of API sand and clay (Stiff, with free water). The pile is assumed to remain linear elastic.



P = 10 kips

ϕ = 32°
γ_{sand} = 110 pcf
k_{sand} = 60 pci

C_u = 2000 psf
γ_{clay} = 110 pcf
k_{clay} = 100 pci
e_{50} = 0.005
C_{avg} = 2000 psf



18" Square FDOT Standard Prestressed Pile

File: *Example_2-6.in*

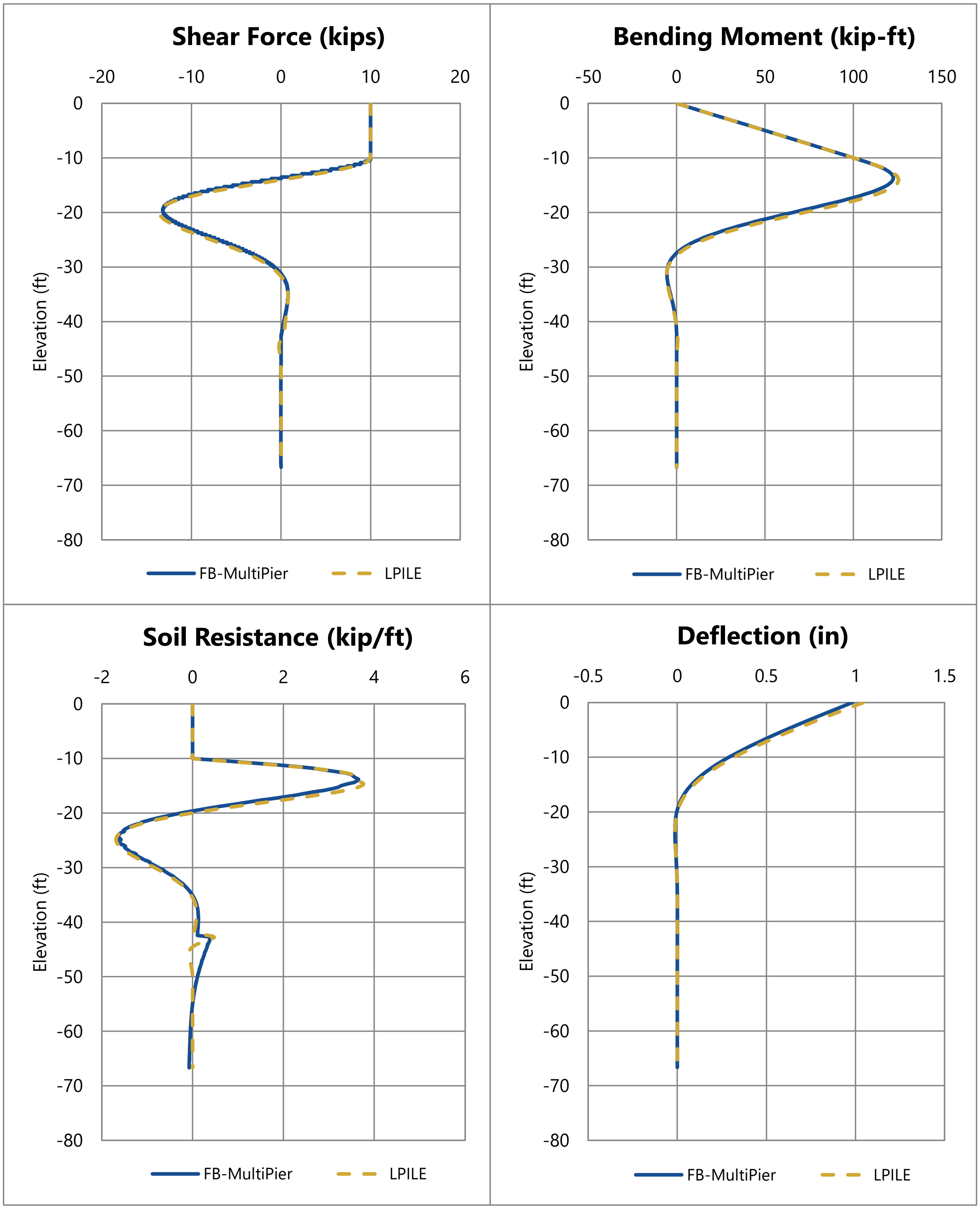
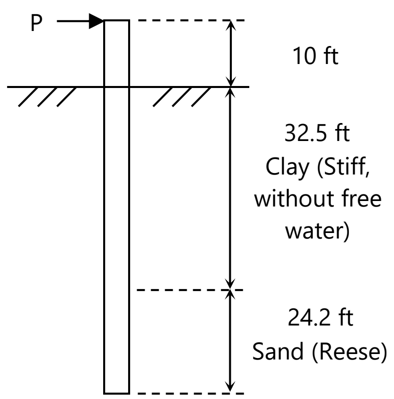


Figure 2.6 – Comparison of Results Between FB-MultiPier and LPILE for Example 2-6

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

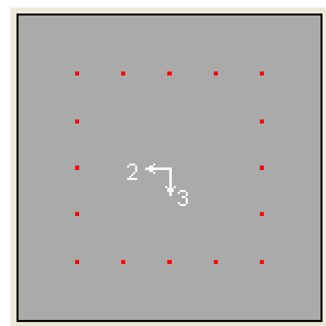
Problem Description: Analyze a single precast, prestressed pile subjected to lateral loading. The pile is embedded in a double layer of Reese sand and clay (Stiff, without free water). The pile is assumed to remain linear elastic.



P = 10 kips

C_u = 2000 psf
γ_{clay} = 110 pcf
e_{50} = 0.005
C_{avg} = 2000 psf
G_{clay} = 3.5 ksi
ν_{clay} = 0.5

ϕ = 32°
γ_{sand} = 110 pcf
k_{sand} = 60 pci



18” Square FDOT Standard Prestressed Pile

File: *Example_2-7.in*

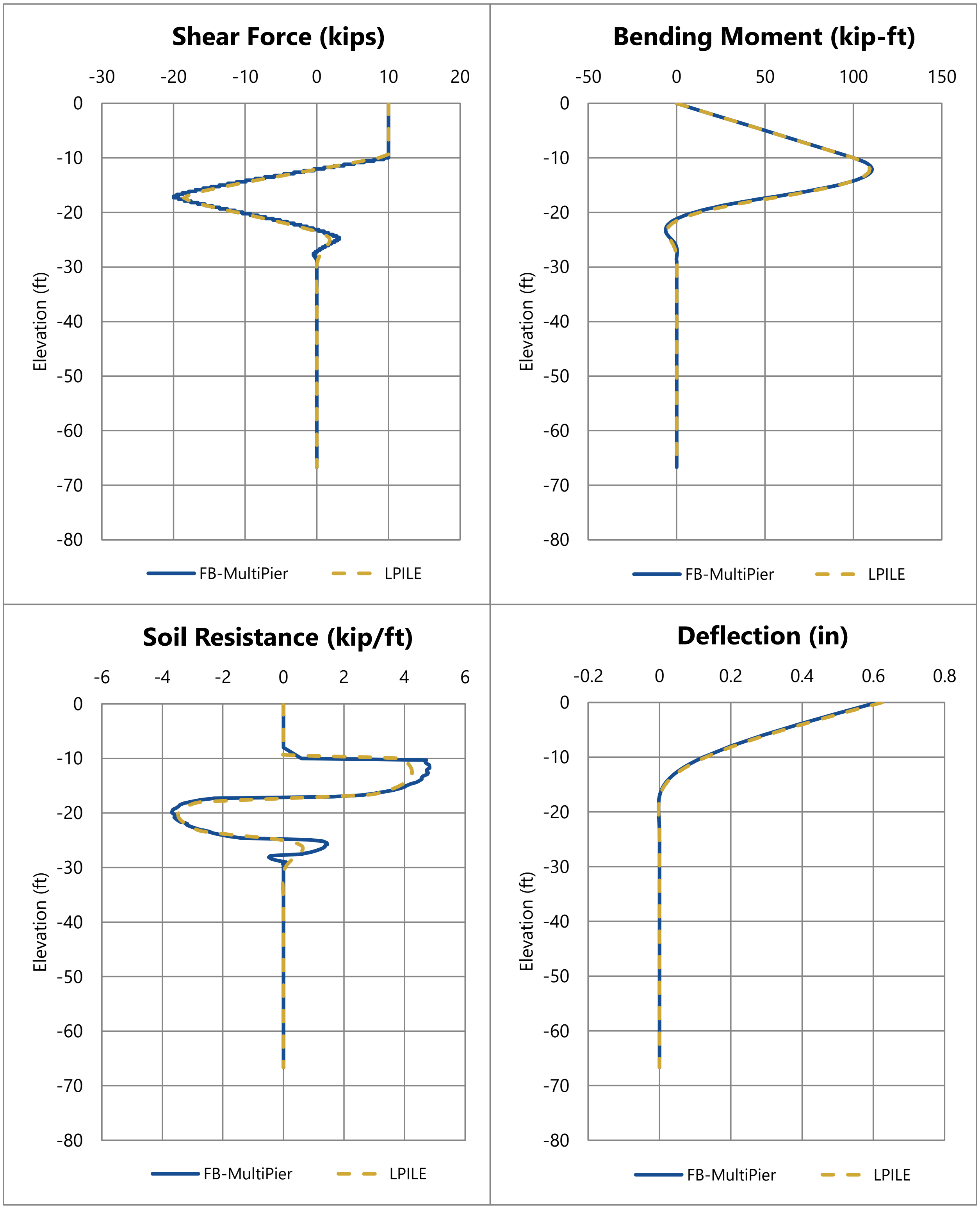
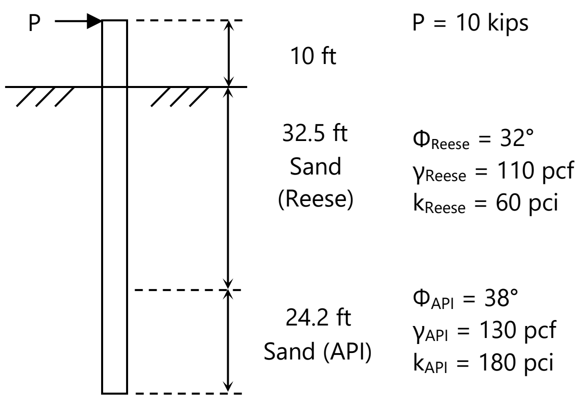
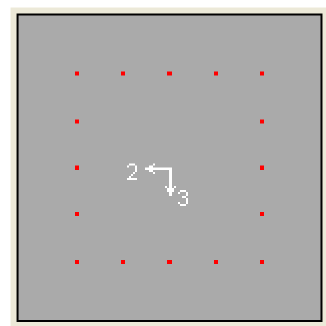


Figure 2.7 – Comparison of Results Between FB-MultiPier and LPILE for Example 2-7

Example 2-8: Single 18” Precast Pile in Dual Sand Layers

Problem Description: Analyze a single precast, prestressed pile subjected to lateral loading. 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.





18” Square FDOT Standard Prestressed Pile

File: *Example_2-8.in*

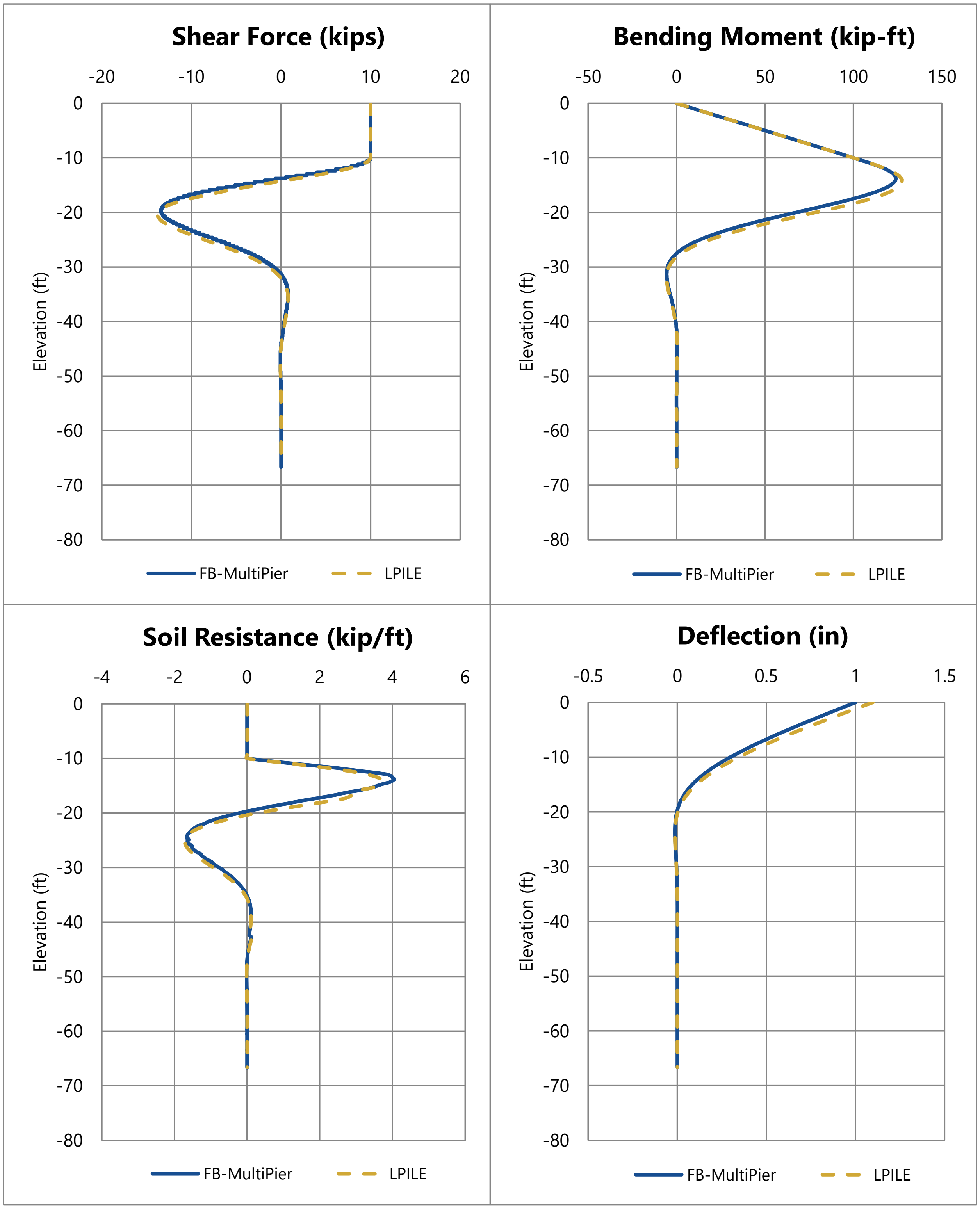
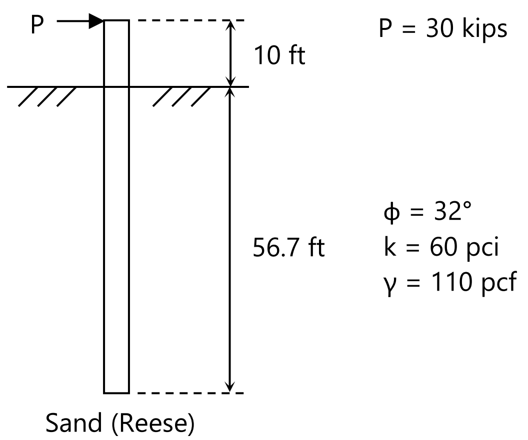
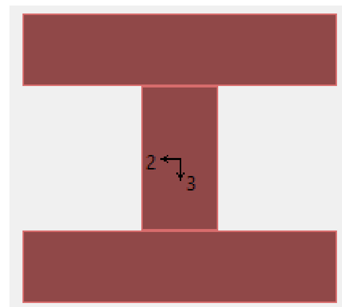


Figure 2.8 – Comparison of Results Between FB-MultiPier and LPILE for Example 2-8

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

Problem Description: Analyze a single H-pile subjected to lateral loading. 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.





H-Pile 14.21”x14.21”
Thickness t = 0.805”

File: *Example_2-9.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 calculation of the soil-pile interaction are observed as shown in Figure 2.9.

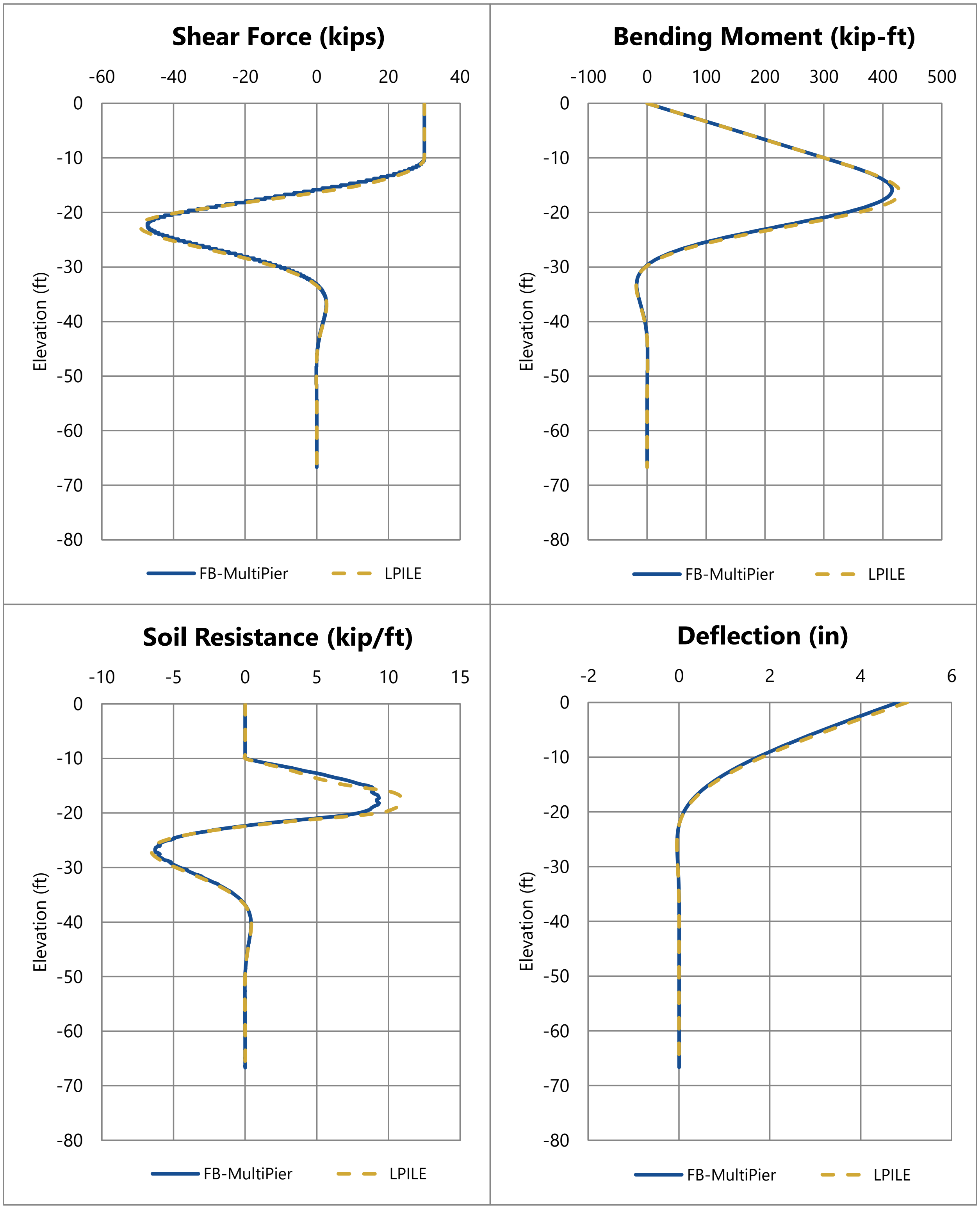


Figure 2.9 – Comparison of Results Between FB-MultiPier and LPILE for Example 2-9

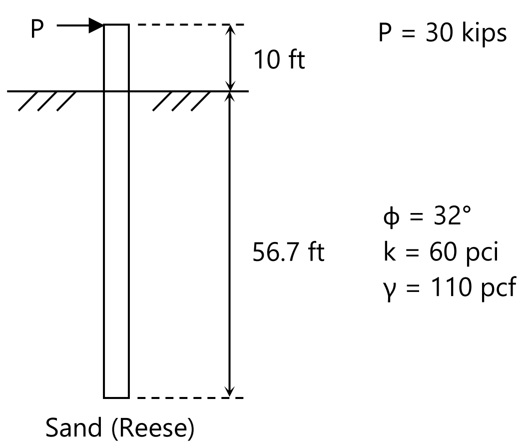
Example 2-10: Single H-Pile in Sand (Reese)

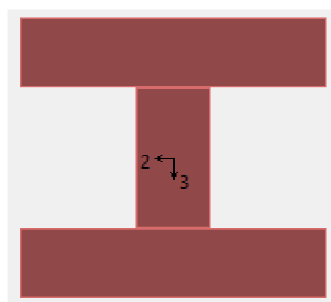
As mentioned in the preface of Chapter 2, the input dimensions of noncircular sections determine an "effective" diameter in FB-MultiPier. An empirical equation is used to approximate an equivalent diameter to the dimensions of noncircular sections:

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

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

Problem Description: In this example, input dimensions of the H-pile model are intentionally modified such that the effective diameter in the 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 permitted, accounting for 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 for the pile are given below.





Dimensions of H-Pile used in FB-MultiPier:
11.16"x11.16"
Flange thickness t = 0.805"

Software:	FB-MultiPier	LPILE
Flange Width (t_w) (in):	11.16	14.21
Depth (t_d) (in):	11.16	14.21
Moment of inertia (I_2) (in^4):	1163.19	1163.19
Area (A) (in^2):	33.0211	33.0211
Effective Diameter (D_{eff}) (in):	14.21 (computed)	14.21 (defined)

File: *Example_2-10.in*

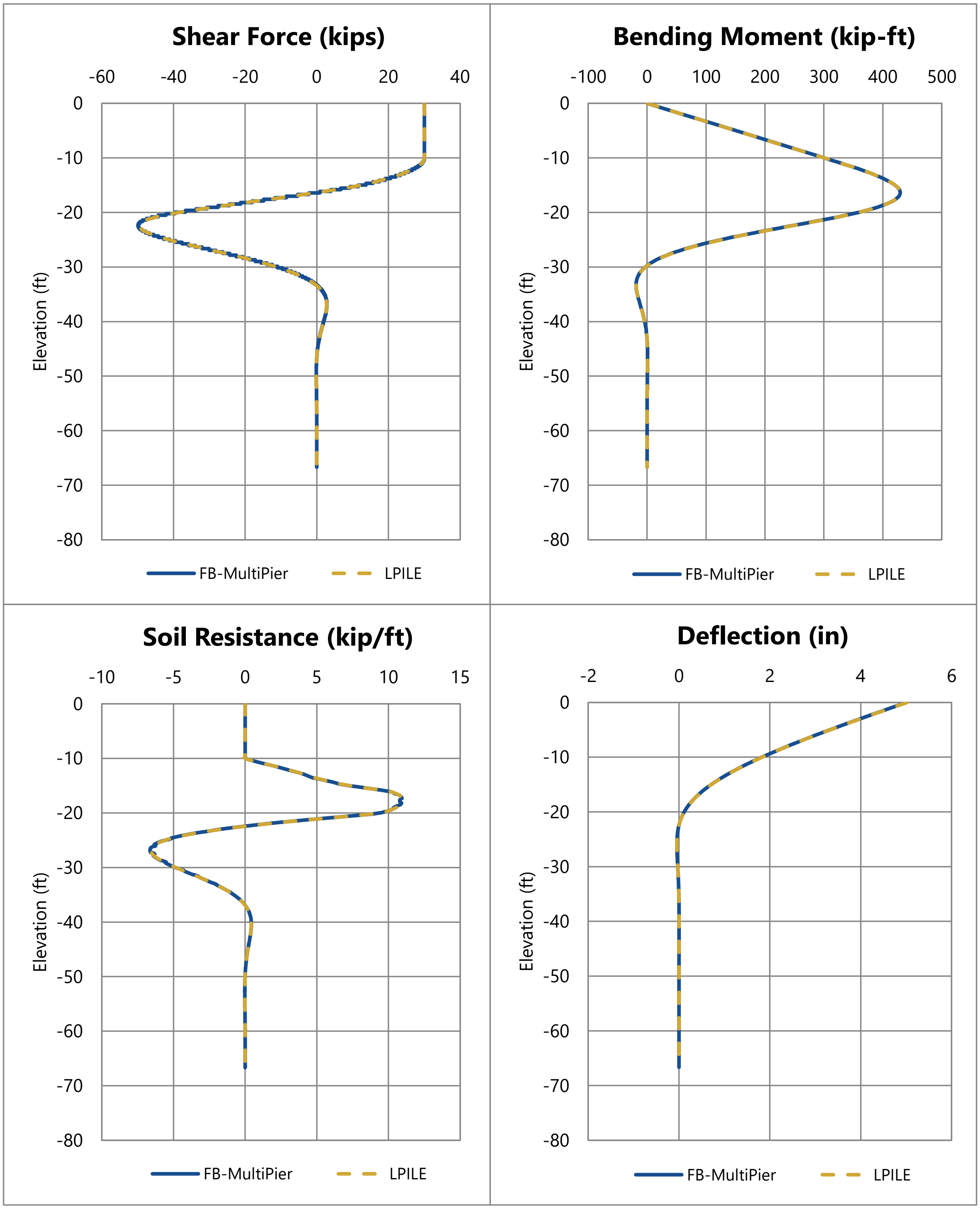


Figure 2.10 – Comparison of Results Between FB-MultiPier and LPILE for Example 2-10

ACKNOWLEDGEMENT

This report was developed by BSI engineers and researchers, including, but not limited to: Henry Bollmann, Anand Patil, Michael Davidson, Amirata Taghavi, Brandon Lypher, Wilmer Carrion, Maleigh Carpenter, and Brandon Crow.