Phase III: Implementation of Shallow Foundations on Florida Limestone in FB-MultiPier

FDOT BED31-977-17

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GRIP August 15th, 2024

Bridge Software Institute

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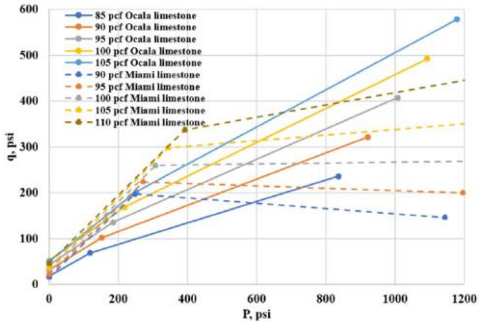
Project Background and Objectives

- FDOT has funded a multiphase research effort on the use of shallow foundations for bridge substructure on limestone.
- In Phase I (BDV31-977-51), a bi-linear strength envelopes were assessed for FL limestone formations (Miami, Ft Thompson, Ocala, etc.). Bearing capacity equations for any footing width, shape, embedment depth and rock-over-sand scenario were developed.
- In Phase II (BDV31-977-124), three full scale load tests performed to validate the bearing capacity equations and moduli by formation were developed for load-settlement predictions.
- **In Phase III (current phase)**, implement bearing capacity and load-settlement prediction methods into FB-MultiPier; investigate and implement lateral resistance of embedded footings and effects of inclined and eccentric loadings on bearing capacity and load-settlement; document the feature sets developed in FB-MulitPier in the user manual .

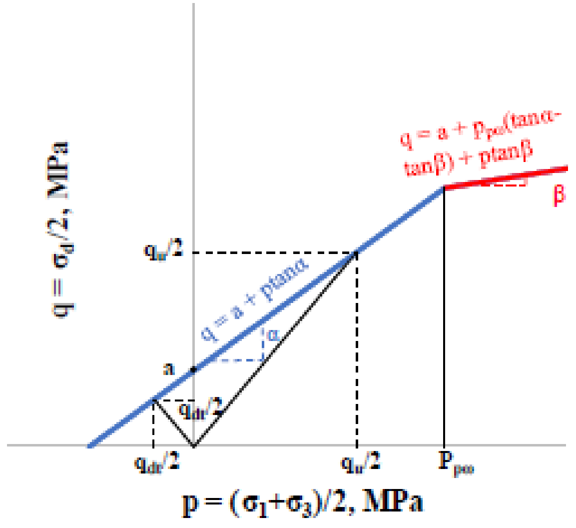


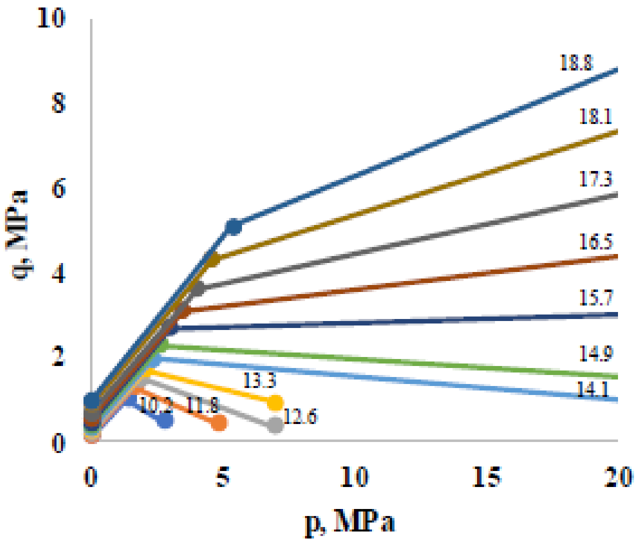
Project Tasks

- **Task 1 – Implement Strength Envelopes (completed)**
- **Task 2 – Implement Load-settlement Analysis (completed)**
- Task 3 – Implement Lateral Resistance (current)
- Task 4 – Investigate Effects of Inclined and Eccentric Loadings
- Task 5 – Develop Software Manual Documentation
- Task 6 – Draft Final and Closeout Teleconference
- Task 7 – Final Report

Task 1 – Implementation of strength envelopes and Florida bearing capacity analyses

- Bi-linear strength envelopes based on **Florida specific formations** and bulk dry unit weights.
- Bearing capacities (Q_u) based on the bi-linear strength parameters (c, φ, p_p, ω), footing geometry and site conditions (homogeneous rock, rock over sand).





$Q_u = min\ (Q_{u1}, Q_{u2}) * \xi / N_R$

$\xi =$ Shape factor;

$N_R =$ Rock over sand reduction factor;

$Q_{u1} = n * c * N_c + q * N_q$

$Q_{u2} = n * [c * N'_c + p_p * N_\gamma] + q * N_q$

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Task 1 – Implementation of strength envelopes and Florida bearing capacity analyses

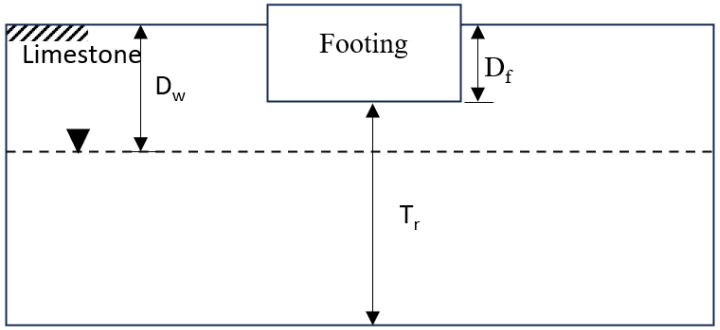
For the Florida bearing capacity analyses, six approaches to define the strength envelope were considered:

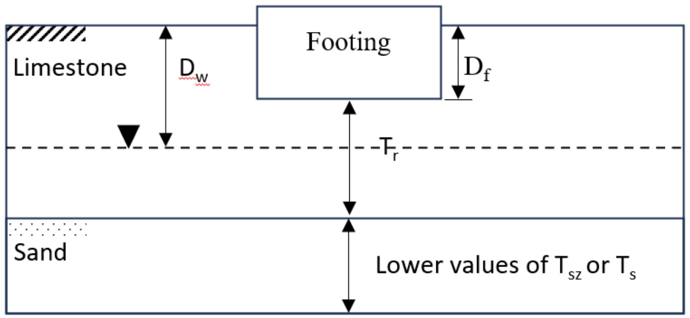
Homogeneous Subsurface

1. Using the bulk dry unit weight, formation, and recovery on a site along with strength data from Phase I & II.
2. User supplied strength parameters and recoveries from triaxial, qu and BST testing on a site
3. Using a combination of (1) and (2) data

Rock-over-sand Subsurface

4. Using the bulk dry unit weight, formation, recovery and (SPT) estimated sand modulus on a site along with strength data from Phase I & II.
5. User supplied strength parameters and recoveries from triaxial, qu and BST testing along with mass modulus of sand layer on the site
6. Using a combination of (1) and (2) data

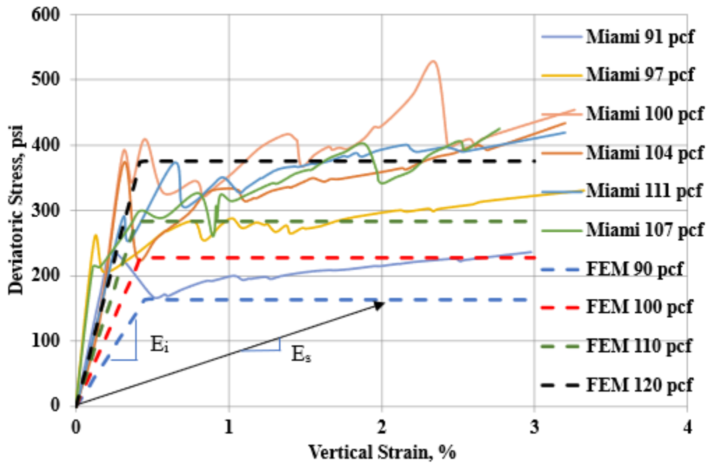




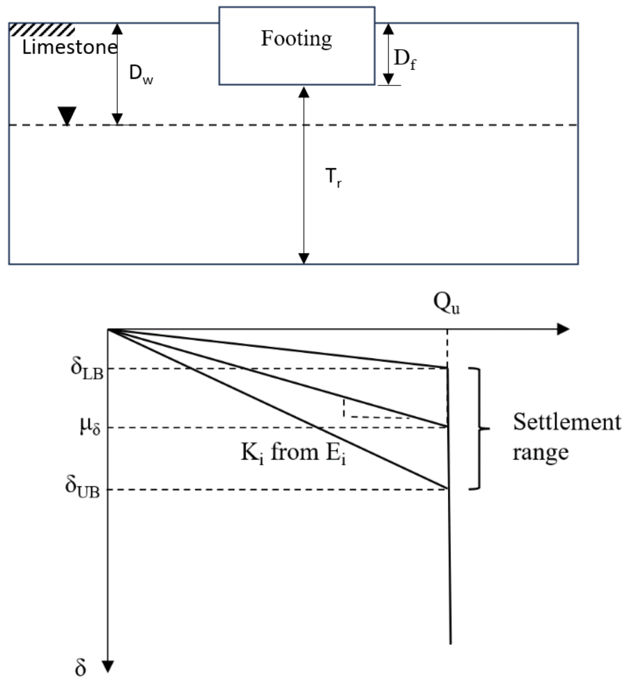
*Carter and Kulhawy (1988) bearing analysis for rocks, derived using the curved Hoek-Brown strength envelope (Hoek and Brown, 1980) was implemented as an additional option in FB-MultiPier for plane Strain condition (L/B >10).

Task 2 – Implement Load-settlement Analysis

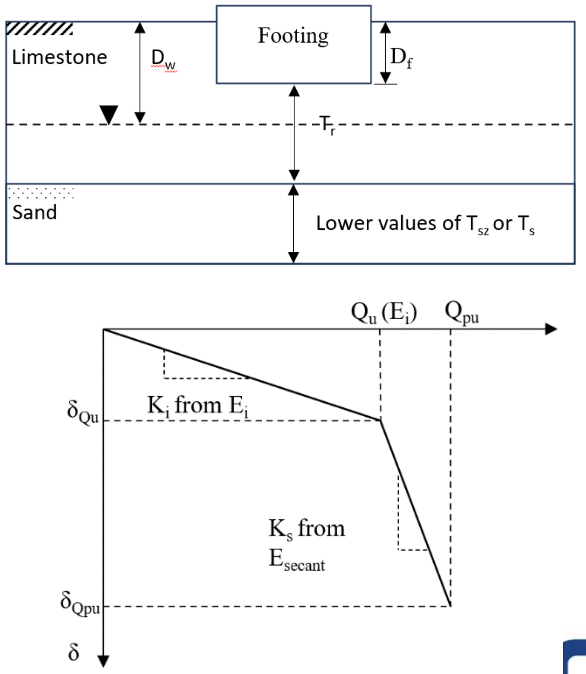
- In general, Florida Limestone exhibits elastic-perfectly plastic stress-strain behavior which may be characterized with E_i or E_s based on the strain level as shown below.
- In case of elastic-perfectly plastic rock behavior, the load-settlement response of homogeneous and rock over sand is shown below as function of E_i, E_s, and Q_u
- The Winkler spring model uses E_i up to Q_u (i.e., distributed nonlinear springs)and E_s subsequently (rock over sand) in Finite element method to compute deformations and stresses.



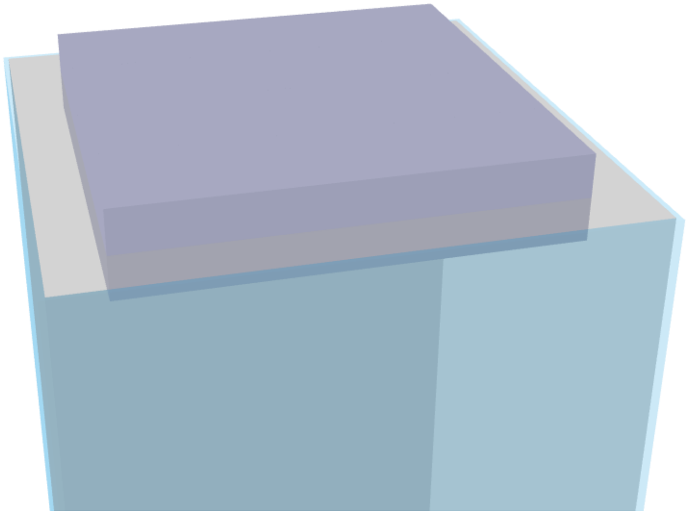
Homogeneous Case



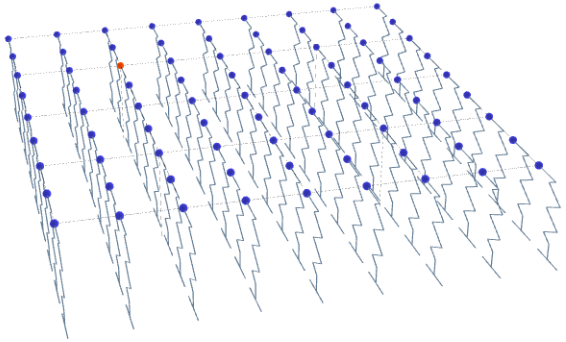
Rock-over-sand Case



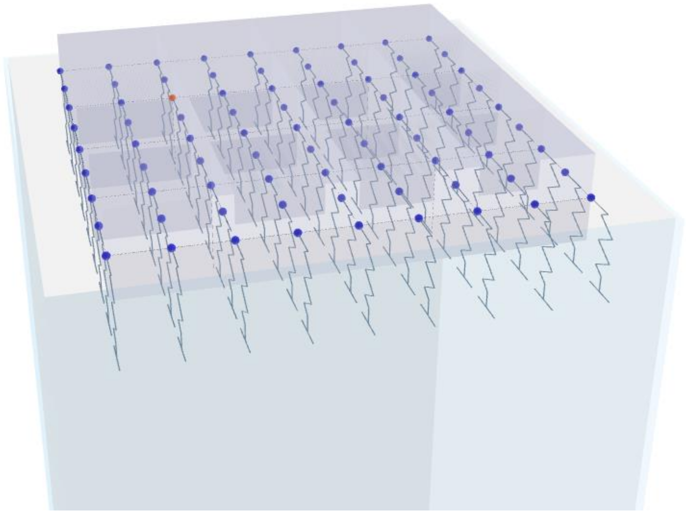
Bearing Spring Implementation



Shallow Foundation
FB-MultiPier (Thick View)



Shallow Foundation
FB-MultiPier (Element View
With Vertical Springs)



Shallow Foundation
FB-MultiPier (Overlay View)

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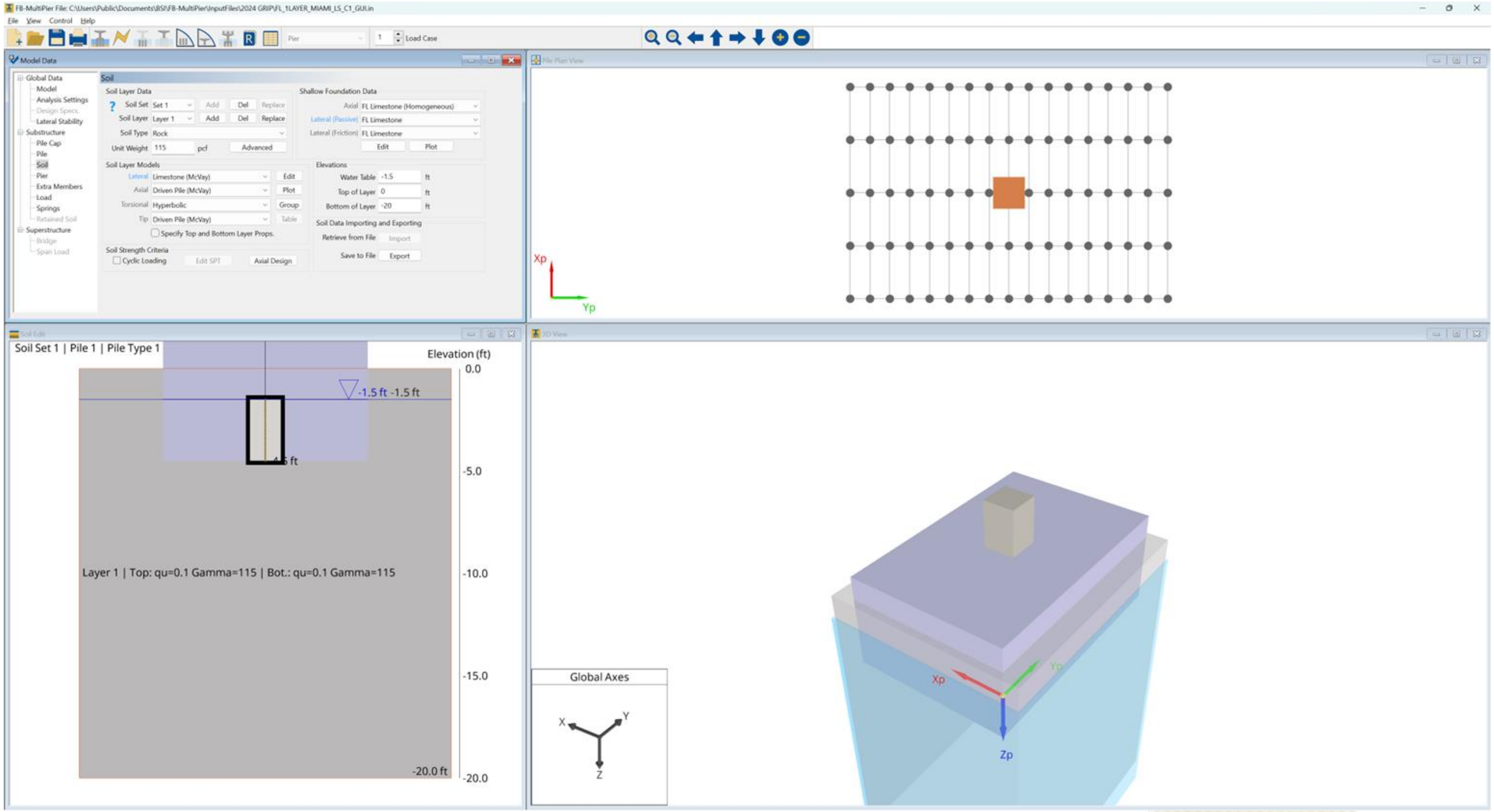
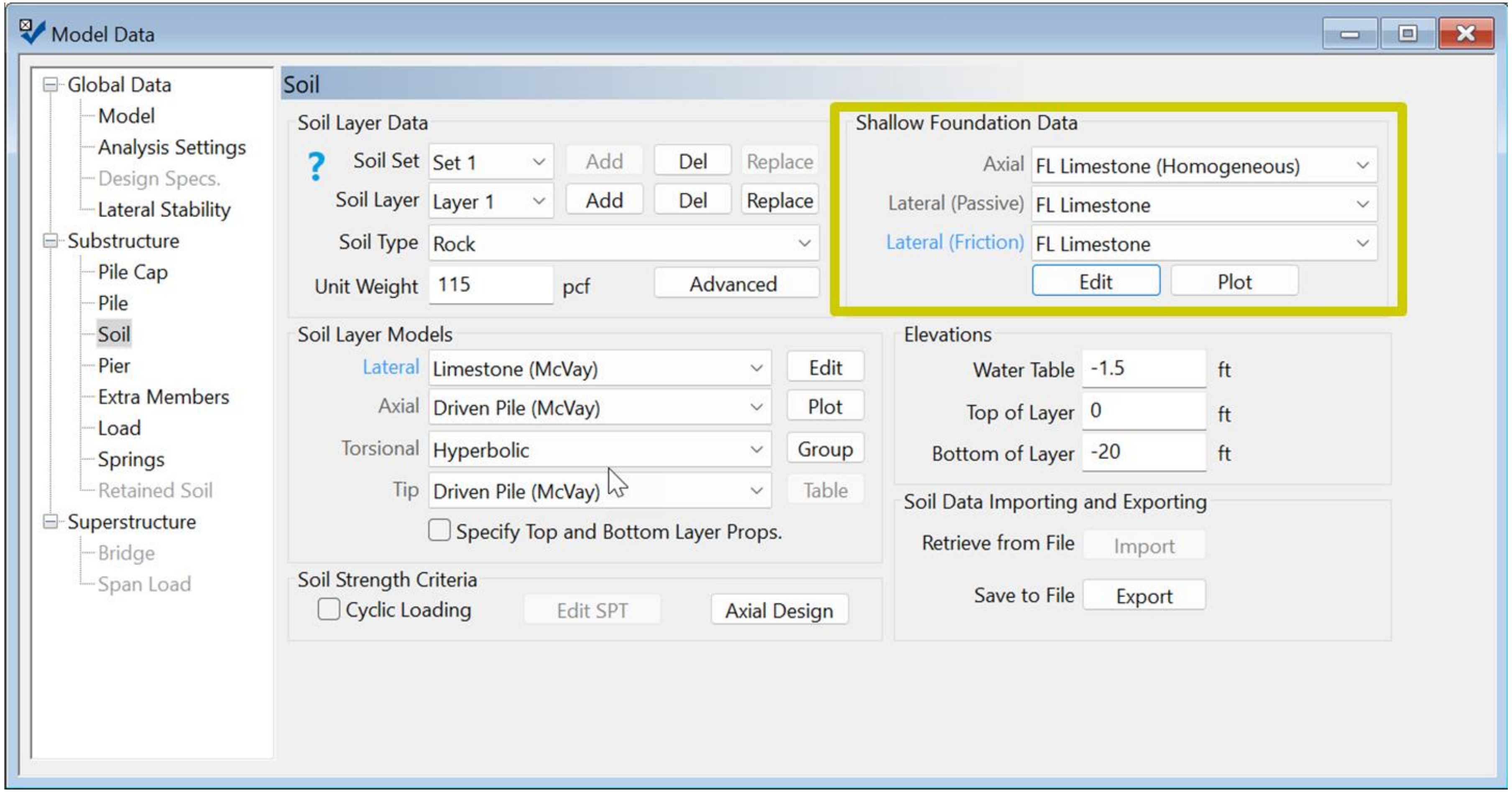
FB-MultiPier Shallow Foundation



FB-MultiPier Shallow Foundation



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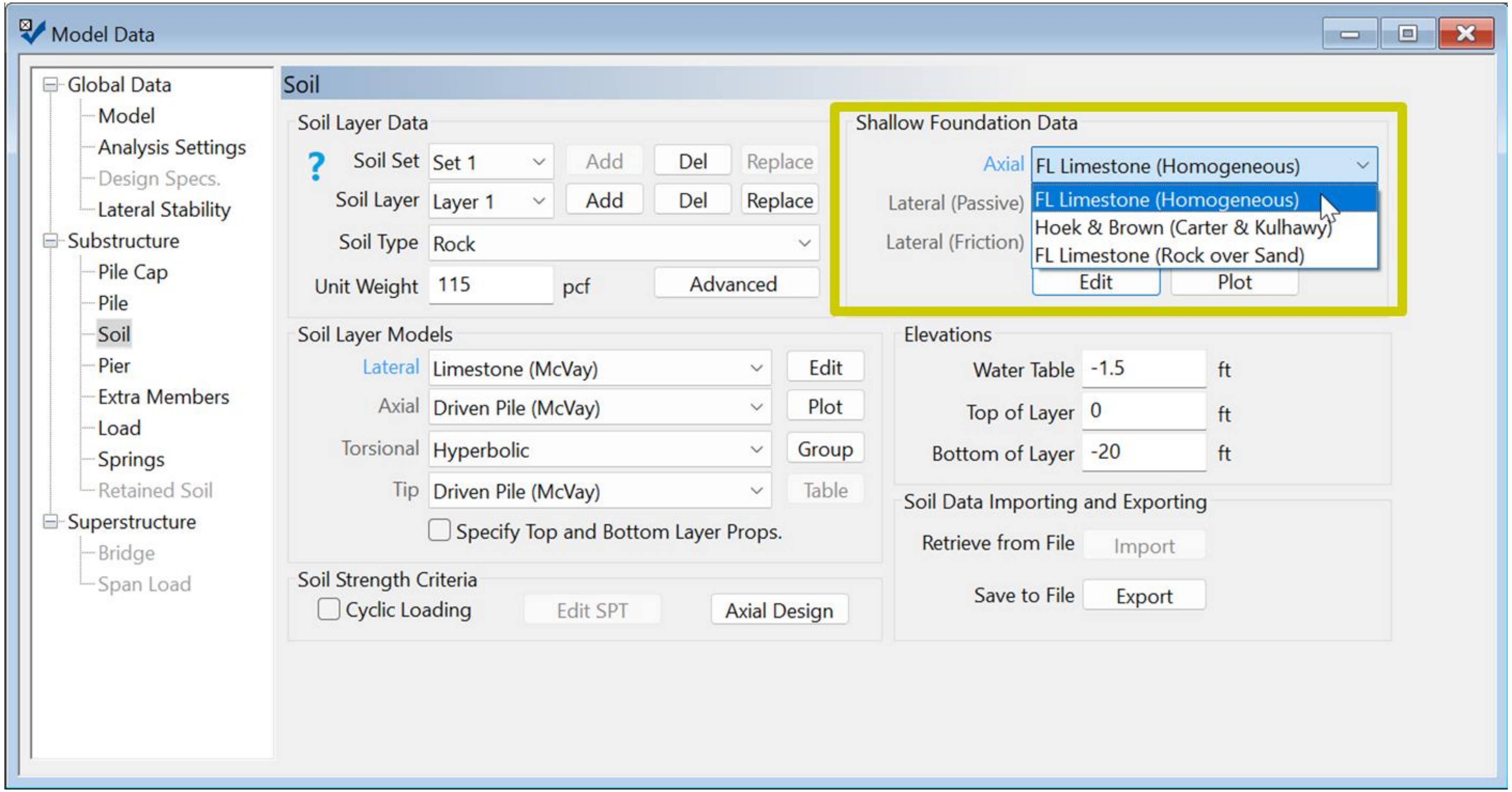
FB-MultiPier Shallow Foundation



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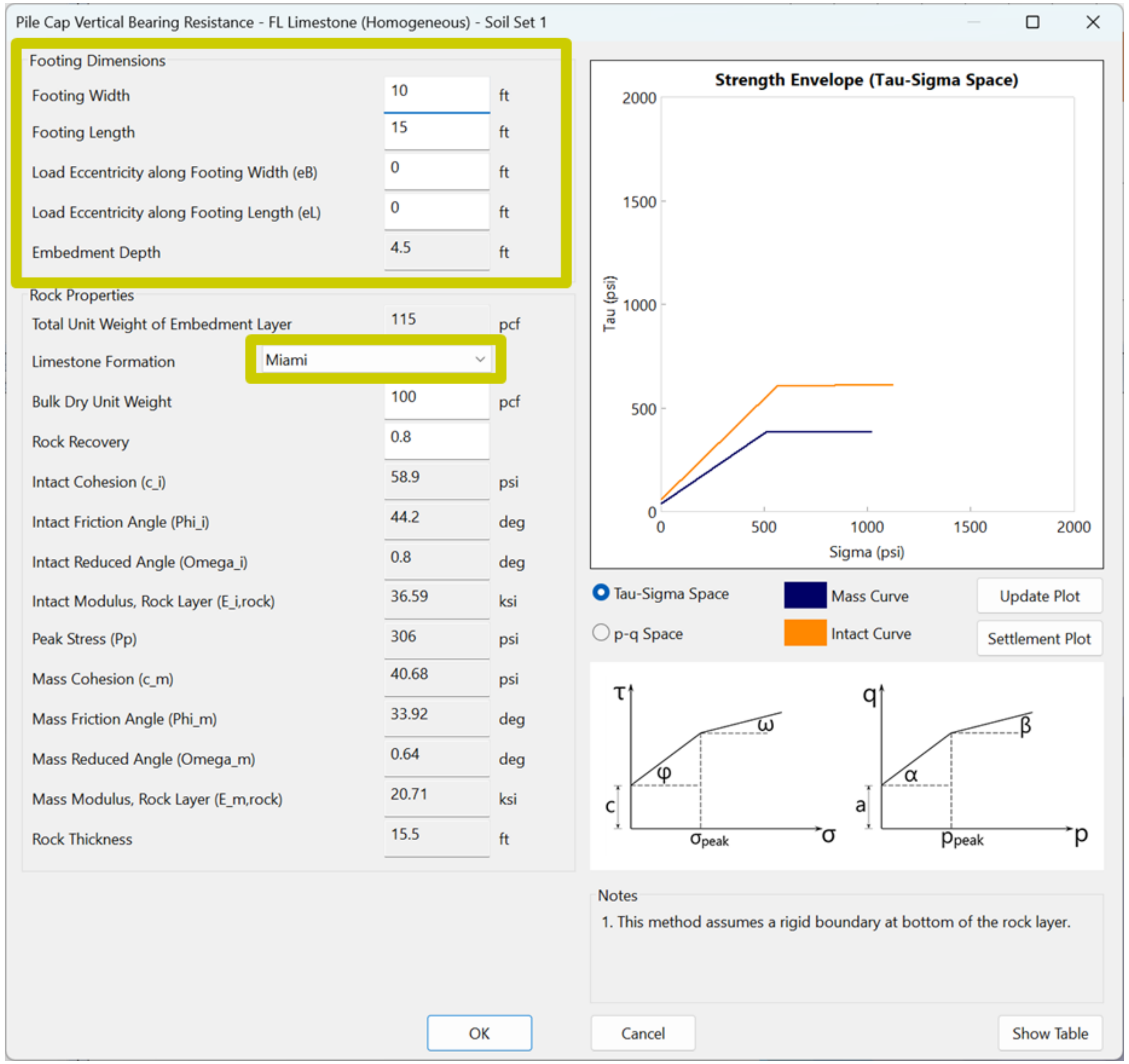
FB-MultiPier Florida Limestone



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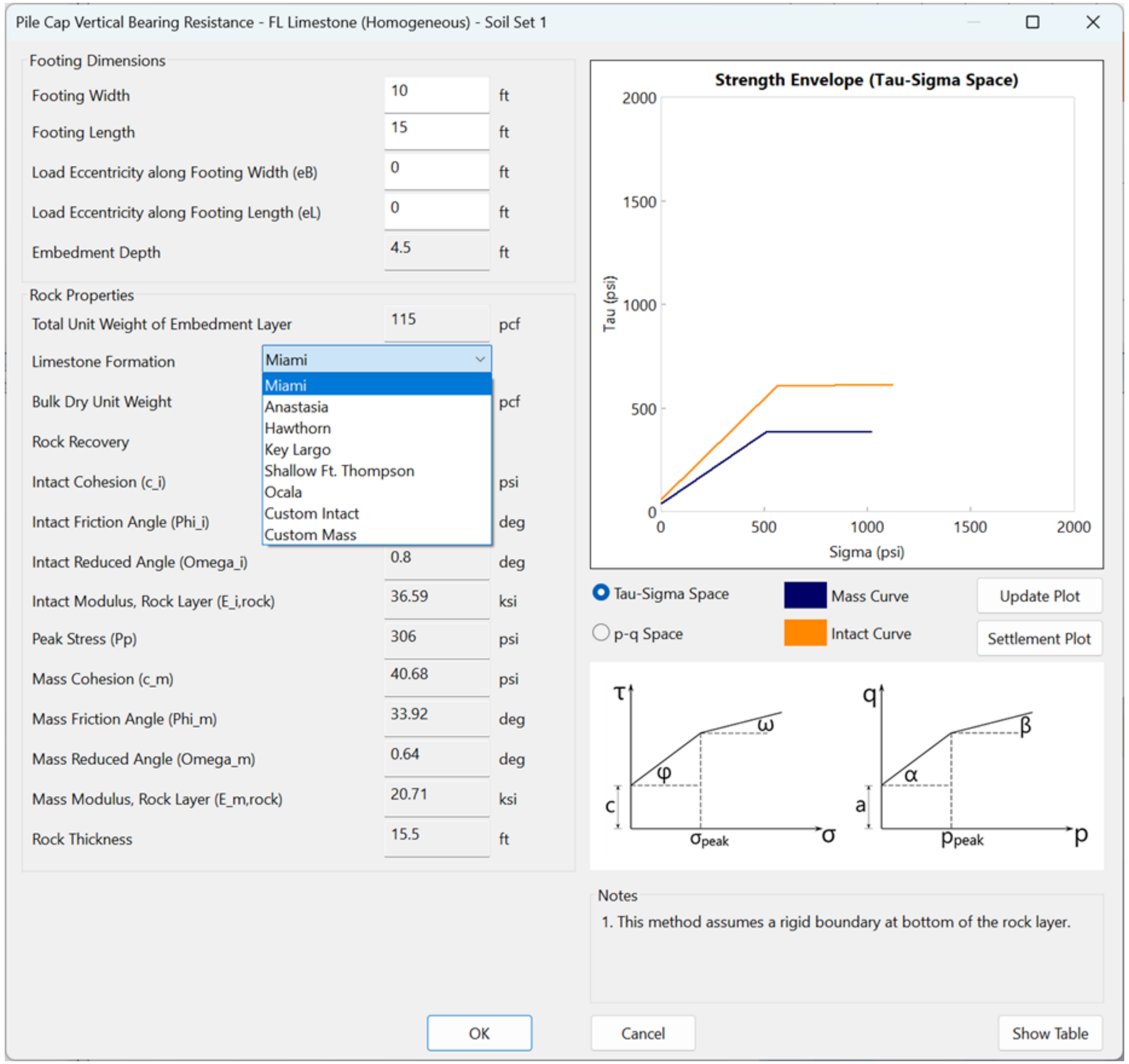
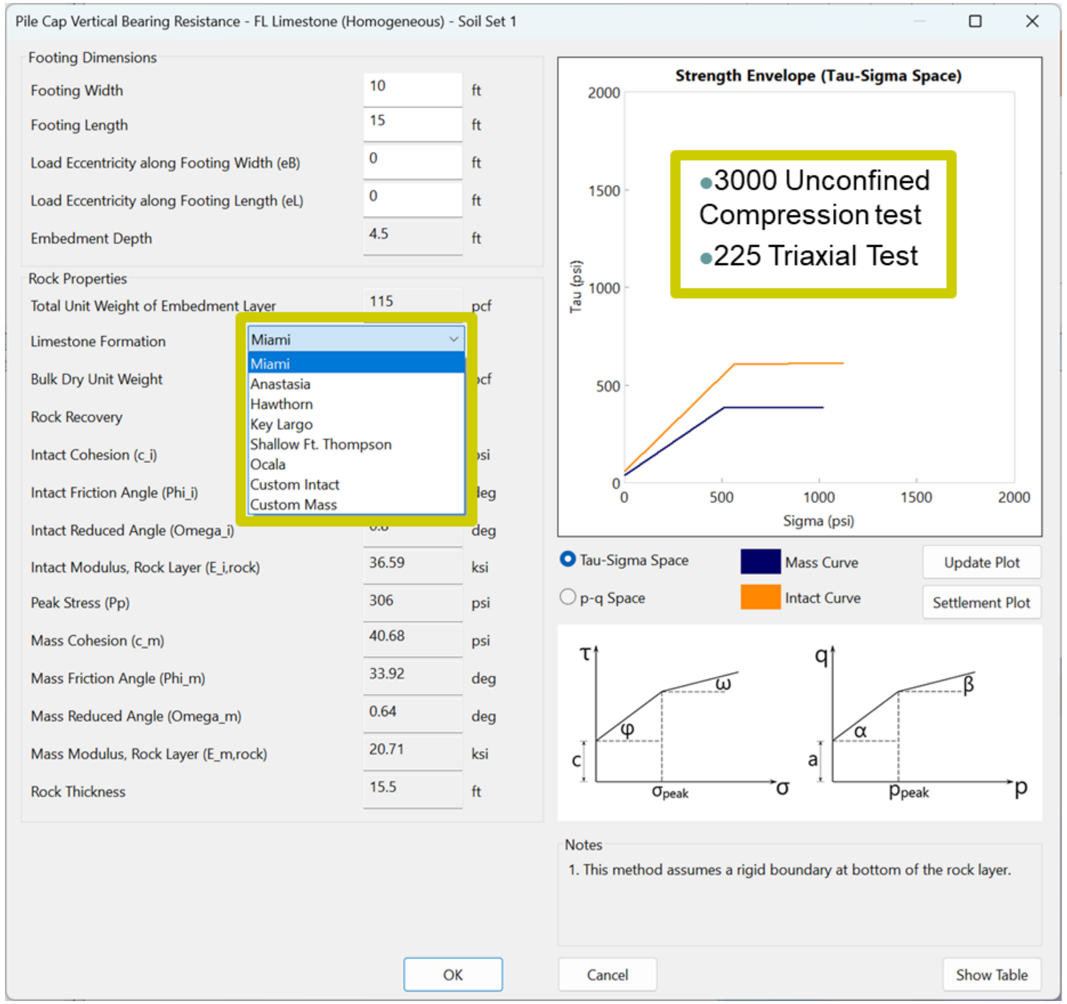
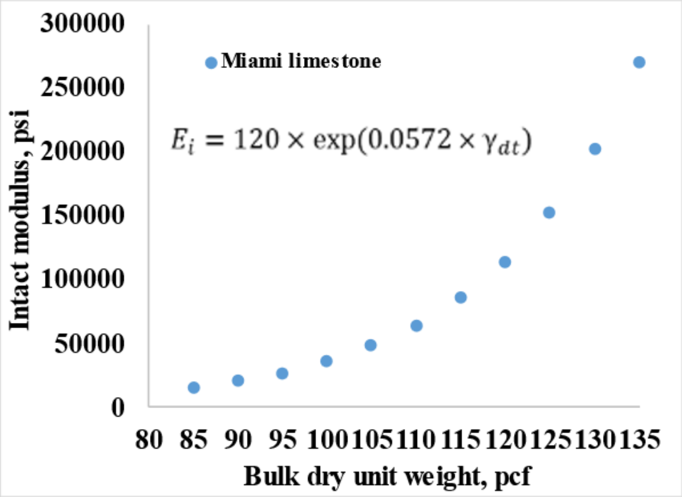
FB-MultiPier Florida Limestone



Formation Data



Formation	γ_{dt}, pcf	c_i, psi	φ_i, °	$\sigma_{peak\ i}$, psi	ω_i, °	a_i, psi	α_i, °	Pp, psi	β_i, °
Miami Limestone	90	42.0	42.2	444	-3.0	31.1	33.9	247	-3
	95	49.9	43.2	498	-1.4	36.4	34.4	274	-1.4
	100	58.9	44.2	562	0.8	42.2	34.9	306	0.8
	105	70.9	45.3	640	3.7	49.9	35.4	345	3.7
	110	84.1	46.4	730	7.3	58	35.9	390	7.2
	115	99.9	47.3	840	11.6	67.8	36.3	445	11.4
	120	118.8	48.2	969	16.6	79.2	36.7	510	15.9
	125	141.8	49.1	1126	22.2	92.8	37.1	588	20.7
	130	169.0	50.1	1314	28.5	108.4	37.5	682	25.5
	135	202.5	51.1	1541	35.4	127.1	37.9	795	30.1



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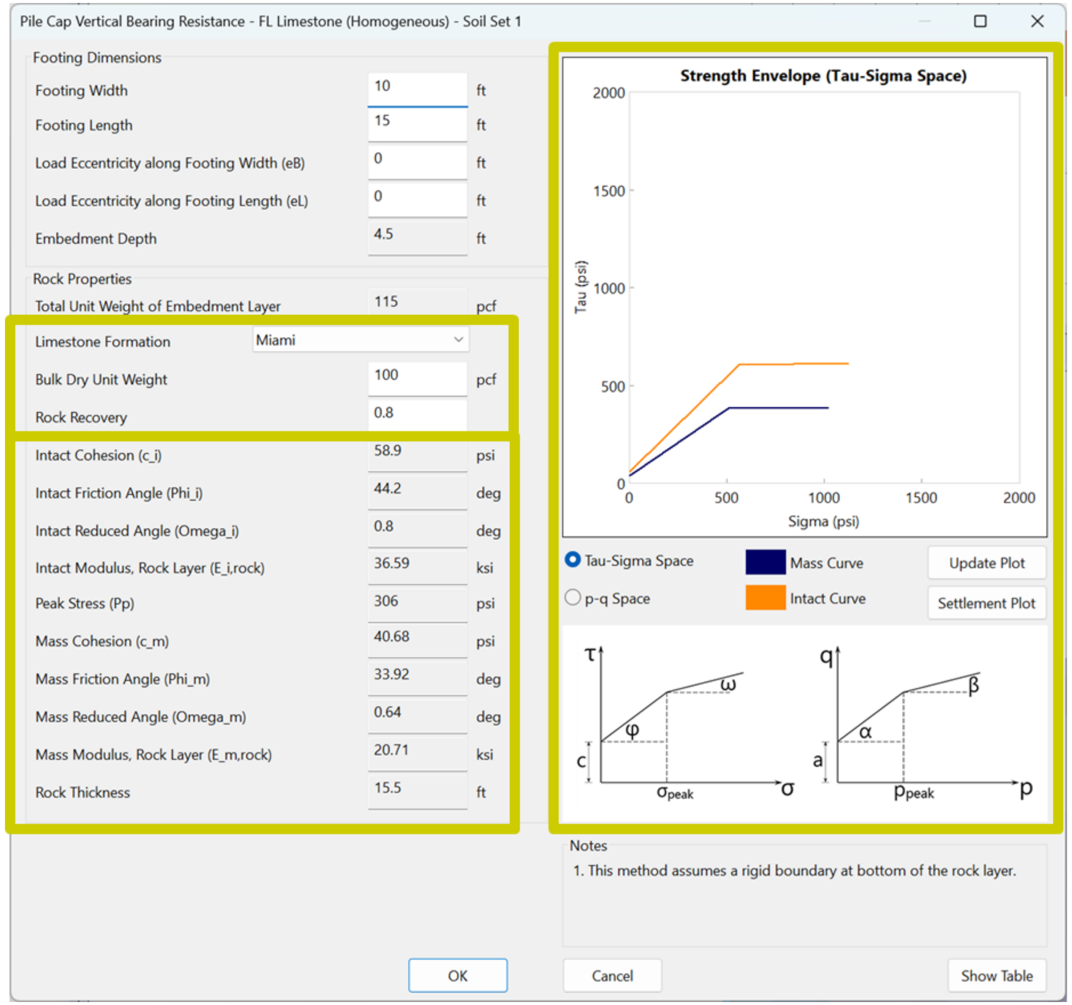
Formation Data - Continued



Formation	γ_{dt}, pcf	c_i, psi	φ_i, °	$\sigma_{peak\ i}$, psi	ω_i, °	a_i, psi	α_i, °	Pp, psi	β_i, °
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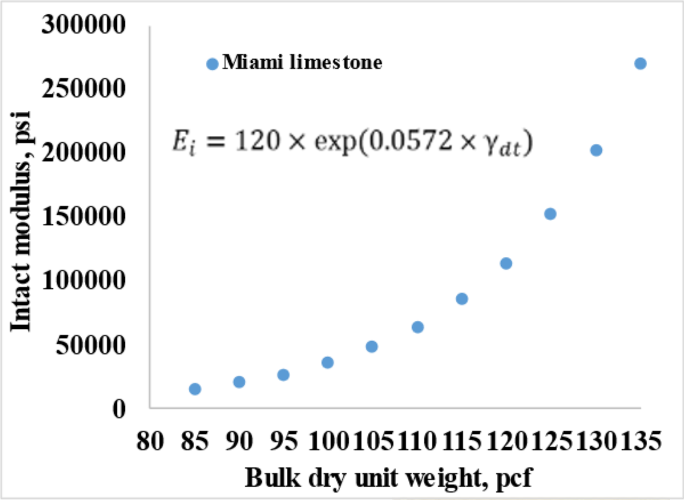
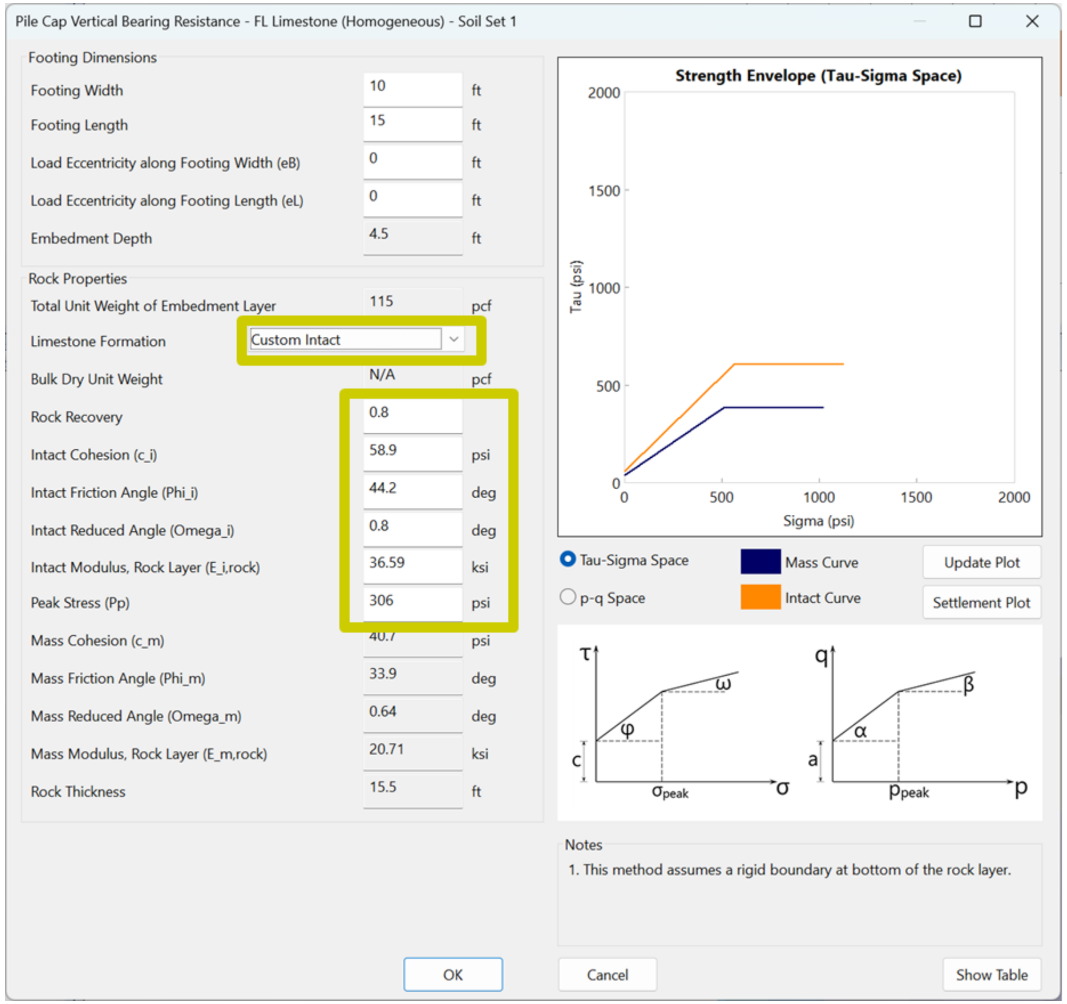
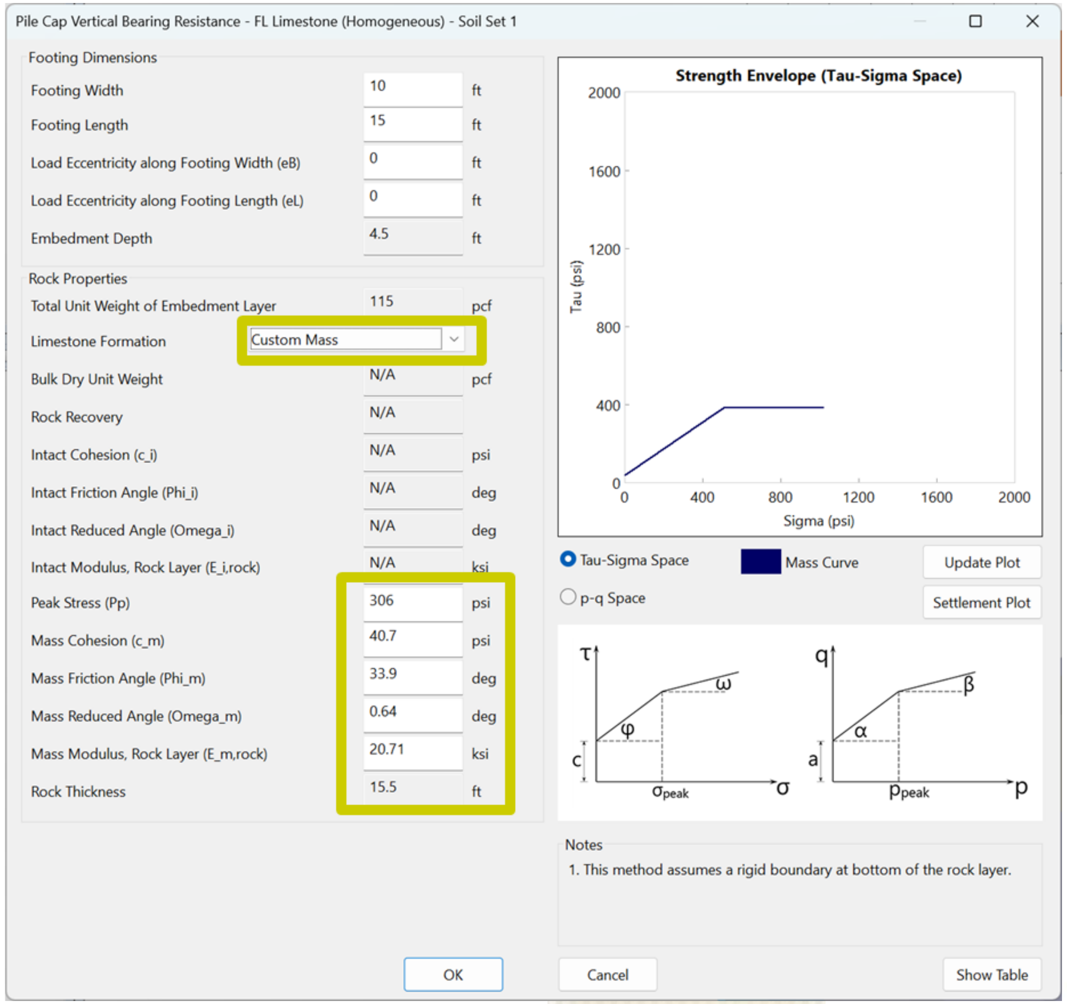


- 3000 Unconfined Compression test
- 225 Triaxial Test

Custom Rock Properties





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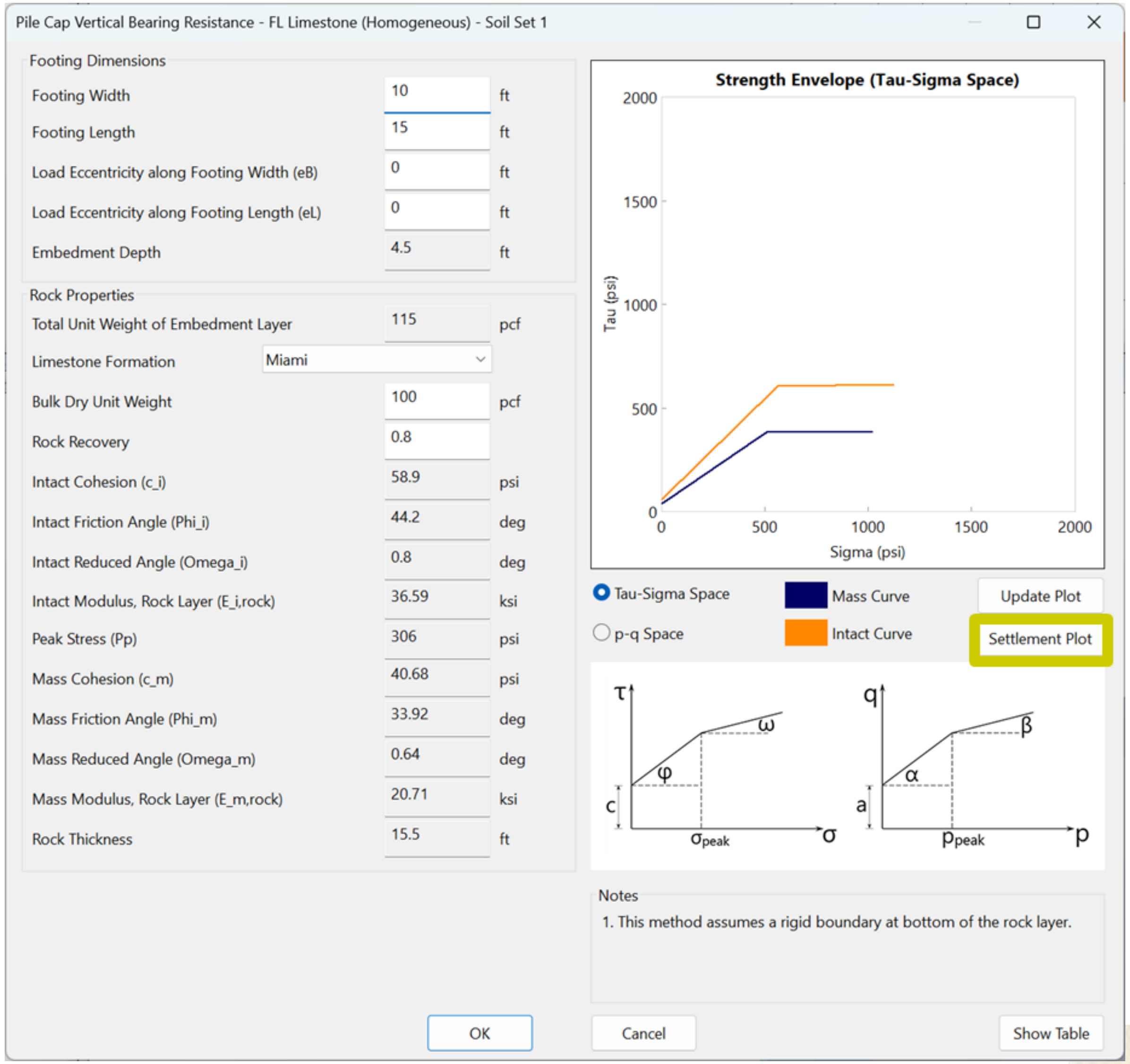
FB-MultiPier Shallow Foundation



FB-MultiPier Shallow Foundation

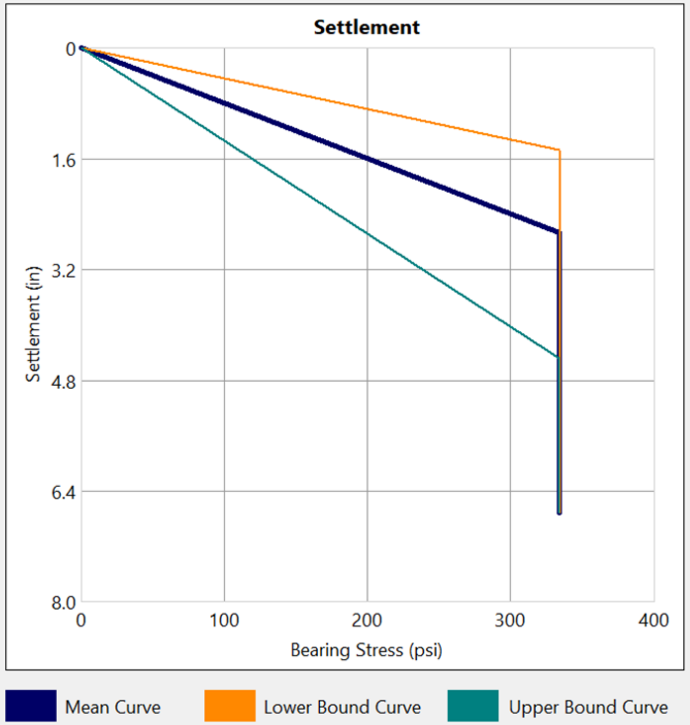
Settlement Plot

Deterministic Settlement Analysis

Bearing Capacity	333.91	psi
Mean Mass Modulus	20.71	ksi
Poisons Ratio	0.1	
Rigidity Factor	1.069	
Deterministic Settlement	2.048	in

Geostatistical Settlement Analysis

Coefficient of Variation of Modulus	0.75	
Correlation Length	4.5	ft
Standard Deviation of Modulus	15.533	ksi
Mean Settlement	2.661	in
Lower Bound Settlement	1.464	in
Upper Bound Settlement	4.475	in
Settlement Range	2	
Settlement Curve Type	Mean Settlement	

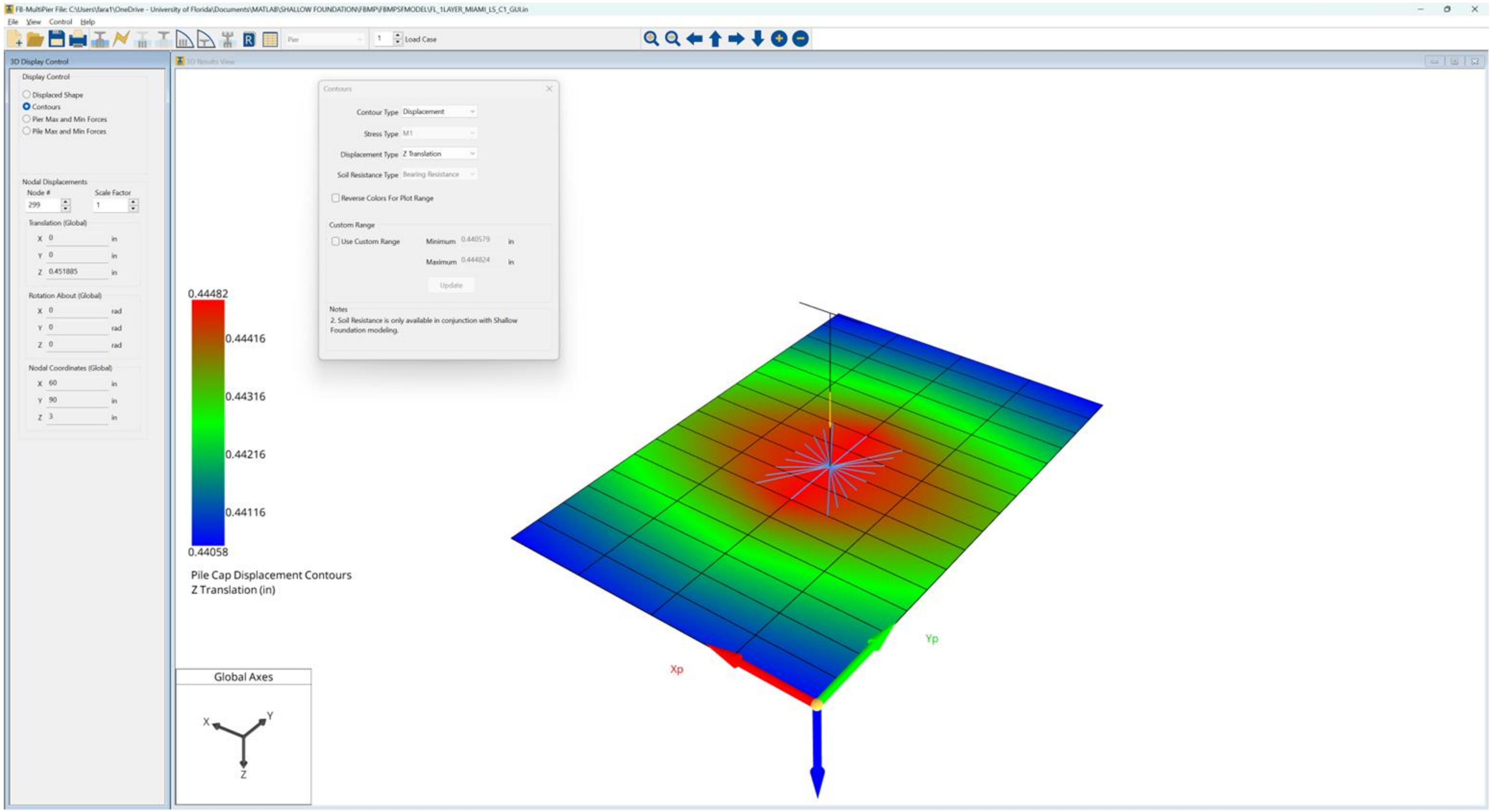


Notes

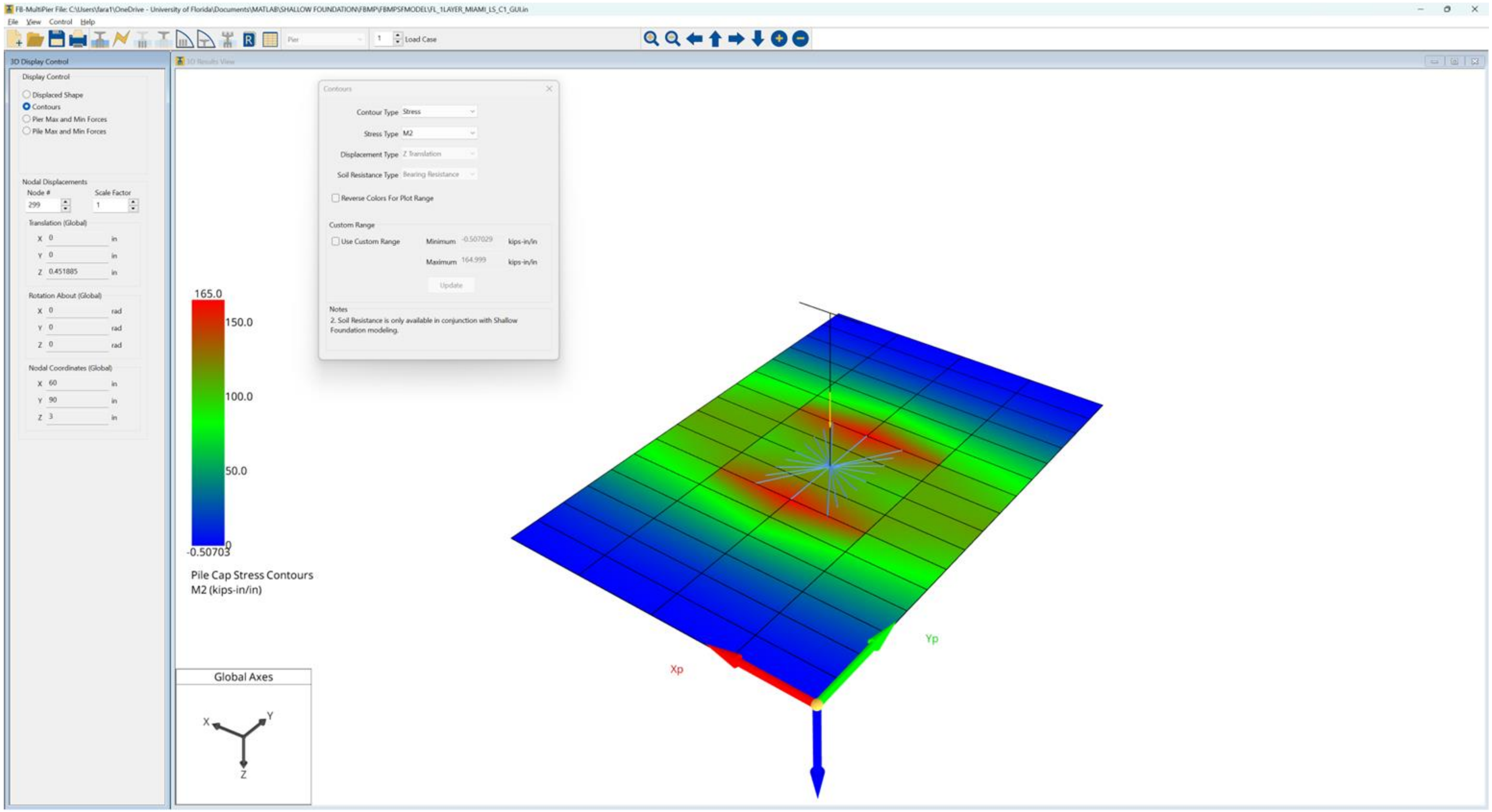
1. Selected settlement curve shown as bold line on the settlement plot. This curve is used for the FB-MultiPier analysis.

OK | Cancel | Show Table

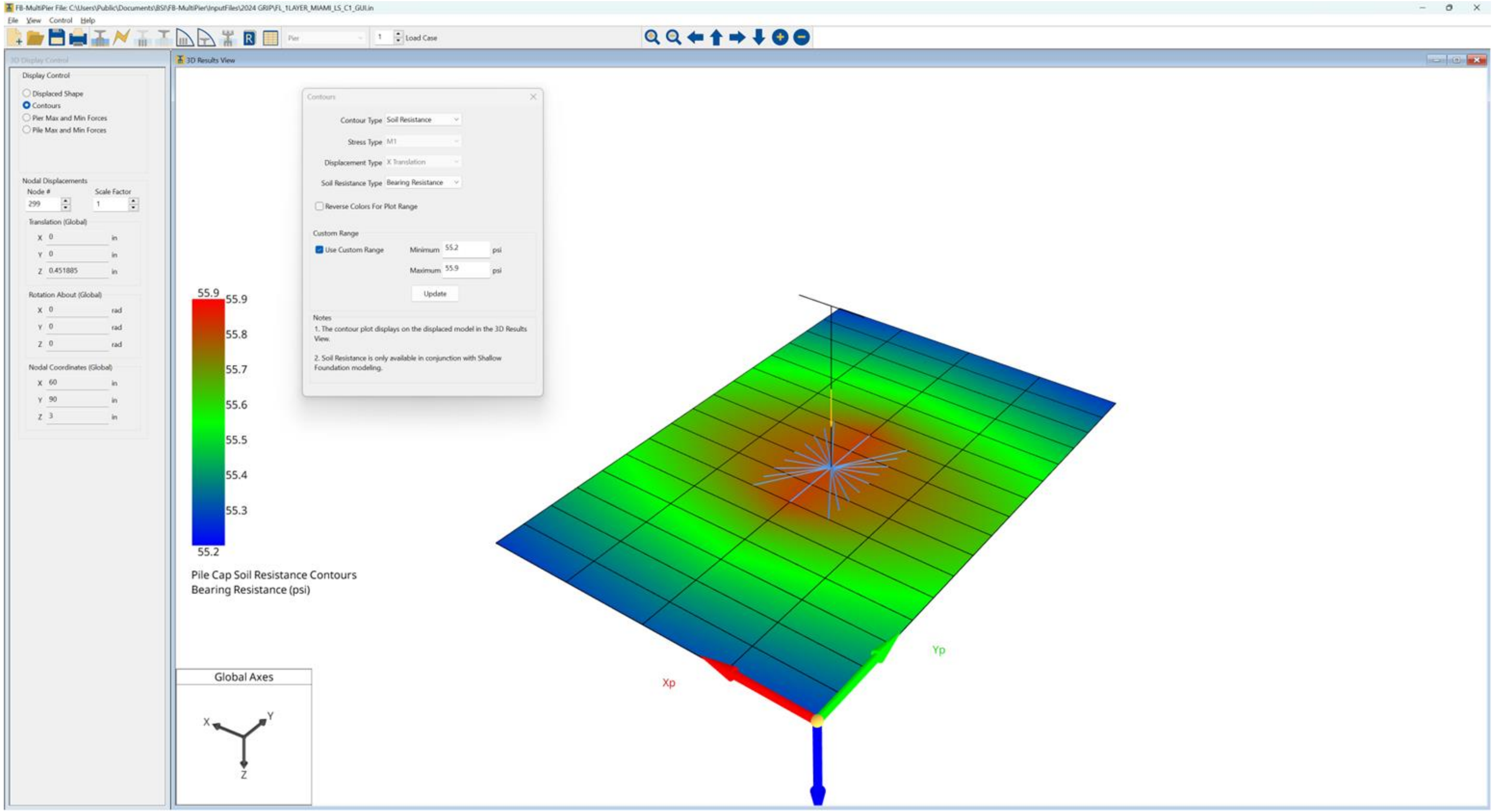
FB-MultiPier Shallow Foundation Results



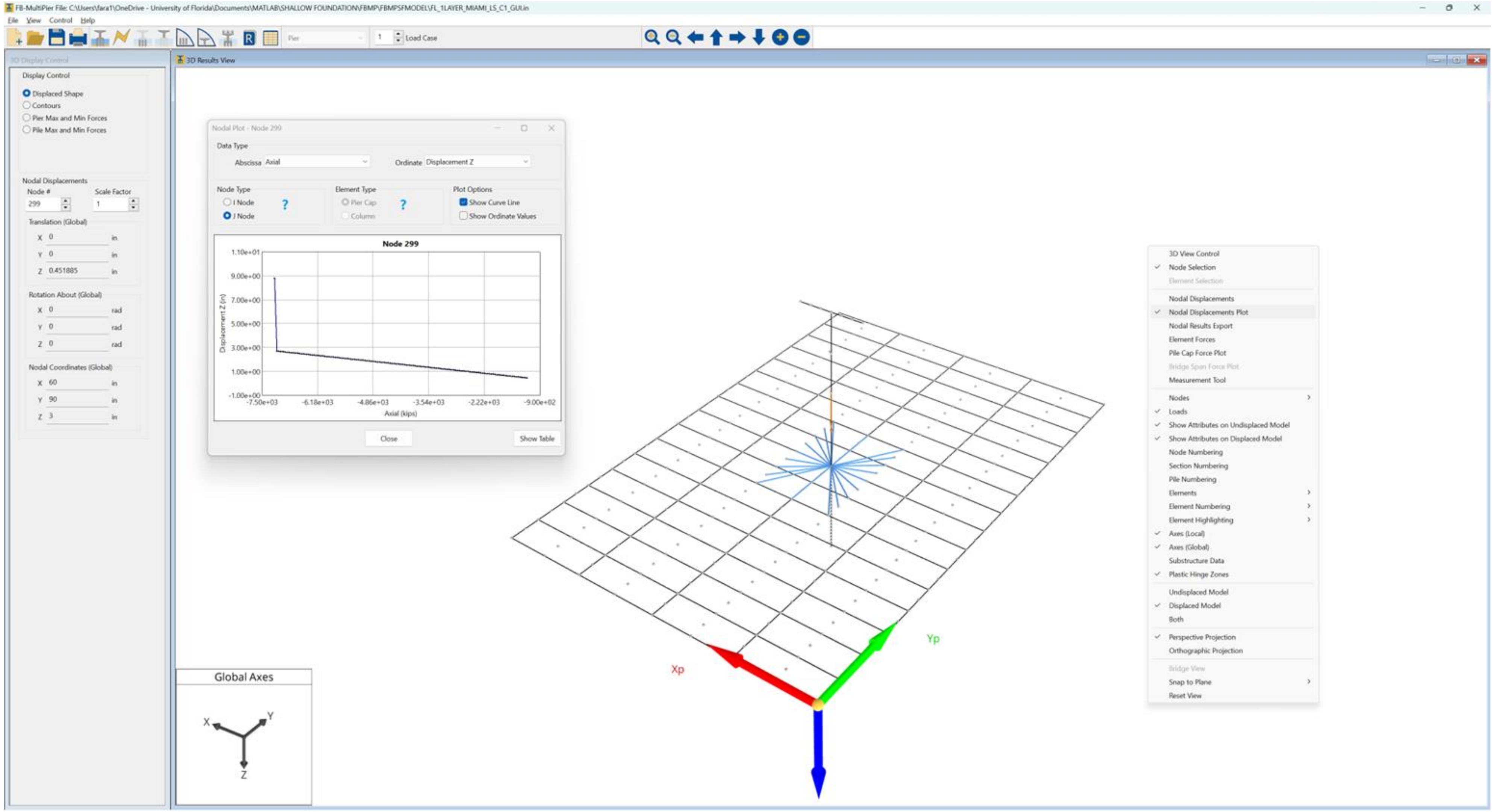
FB-MultiPier Shallow Foundation Results



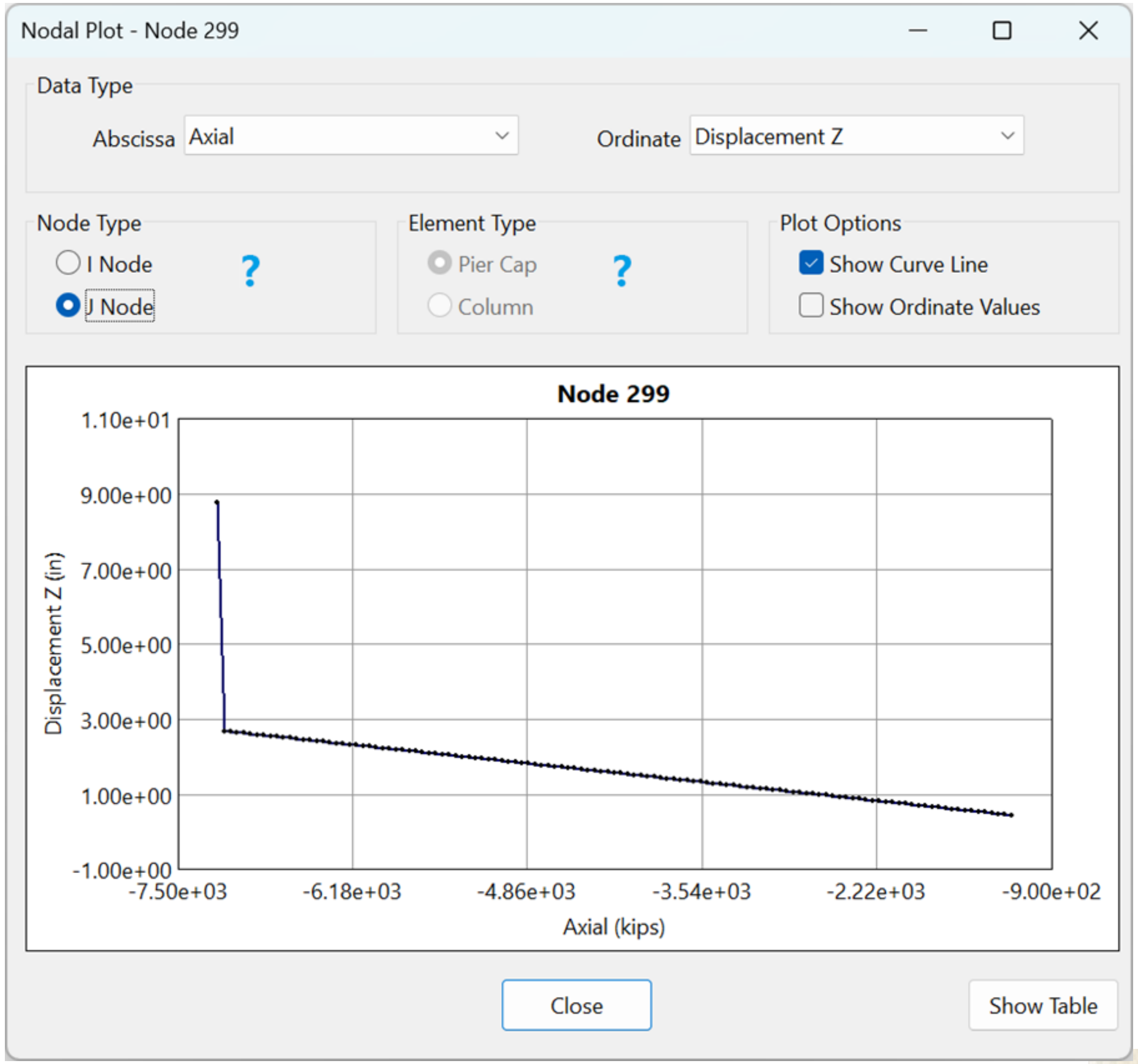
FB-MultiPier Shallow Foundation Results



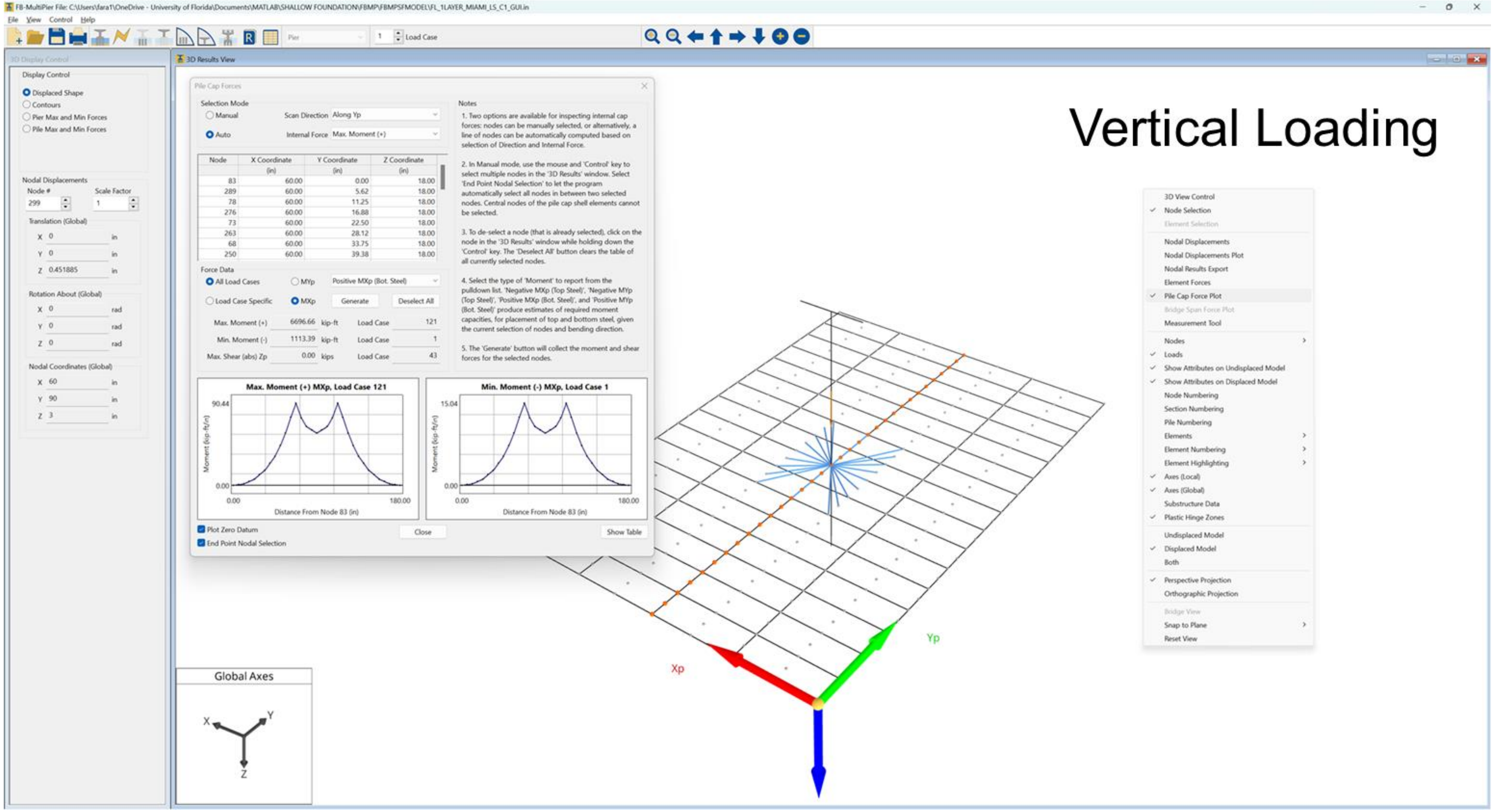
Nodal Displacement Plot



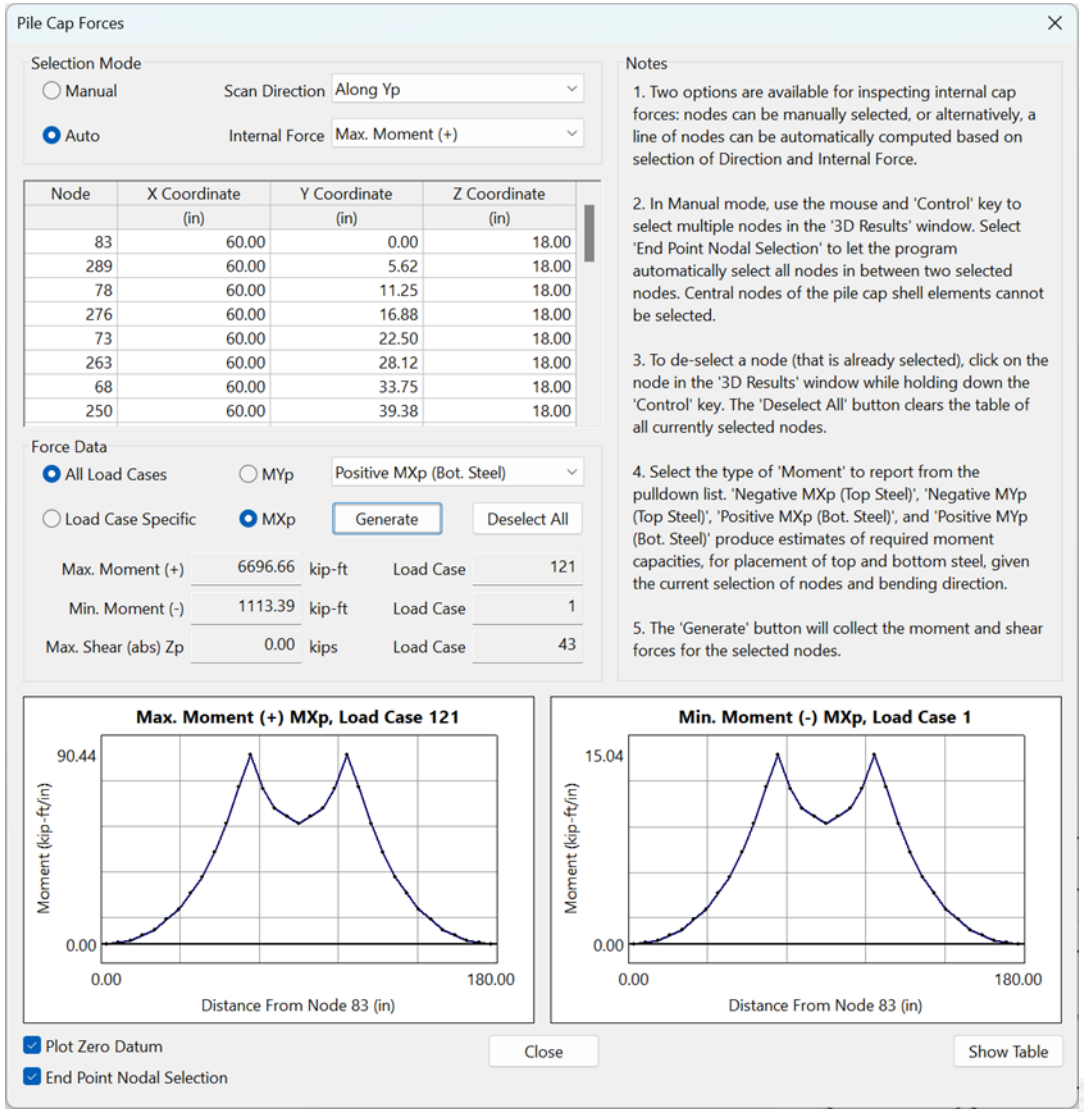
Nodal Displacement Plot



FB-MultiPier Shallow Foundation

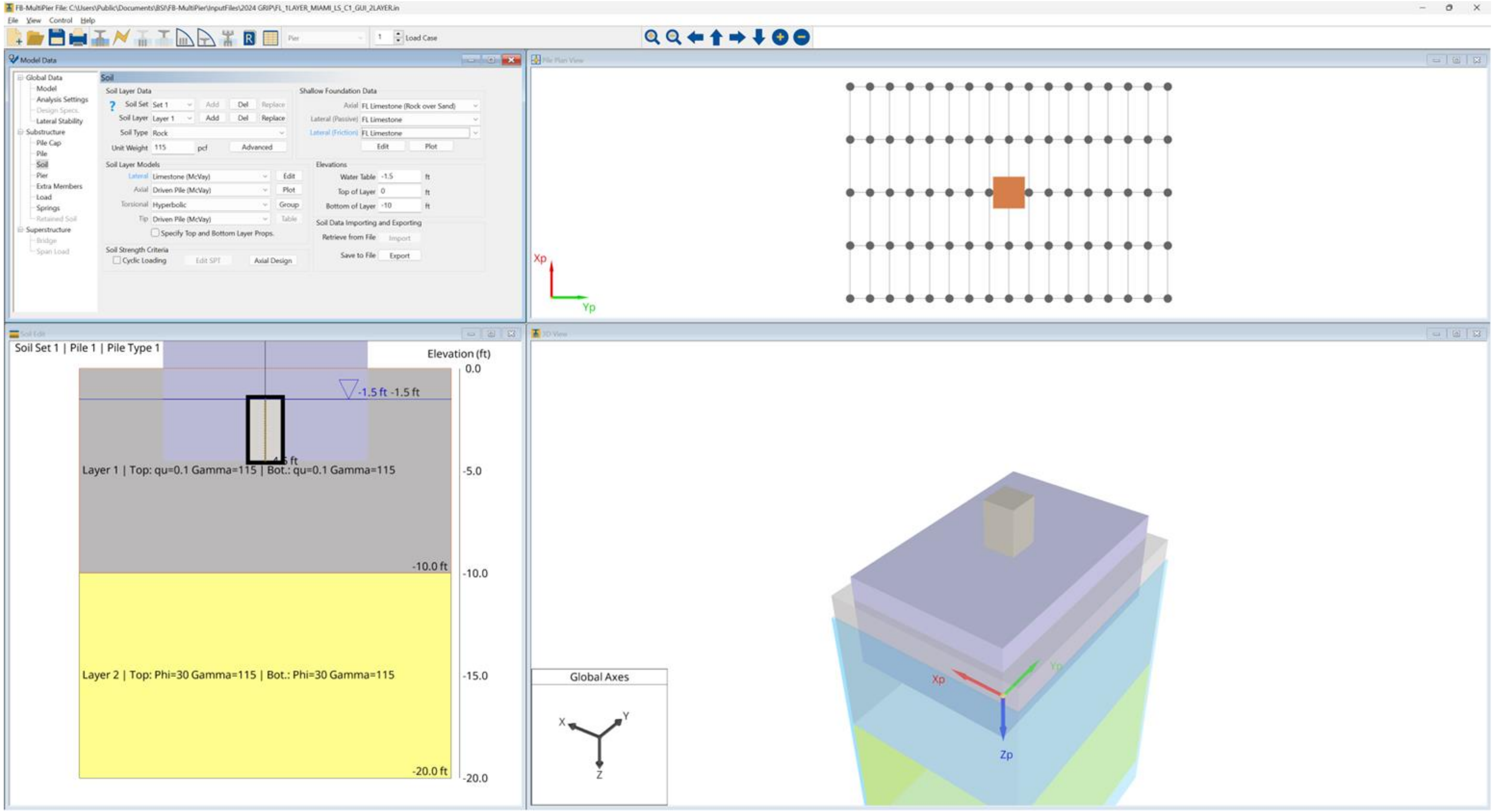


FB-MultiPier Shallow Foundation

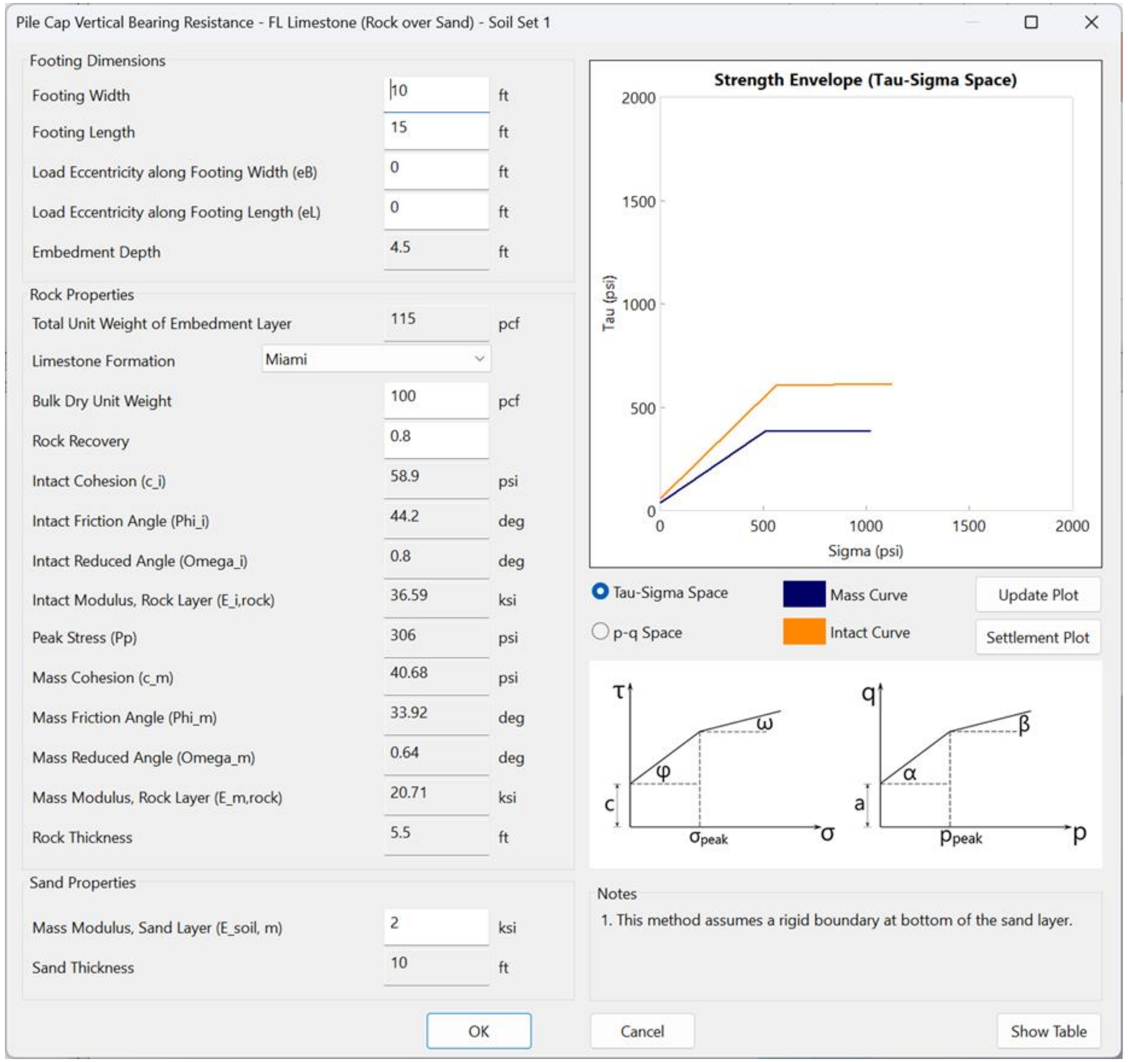


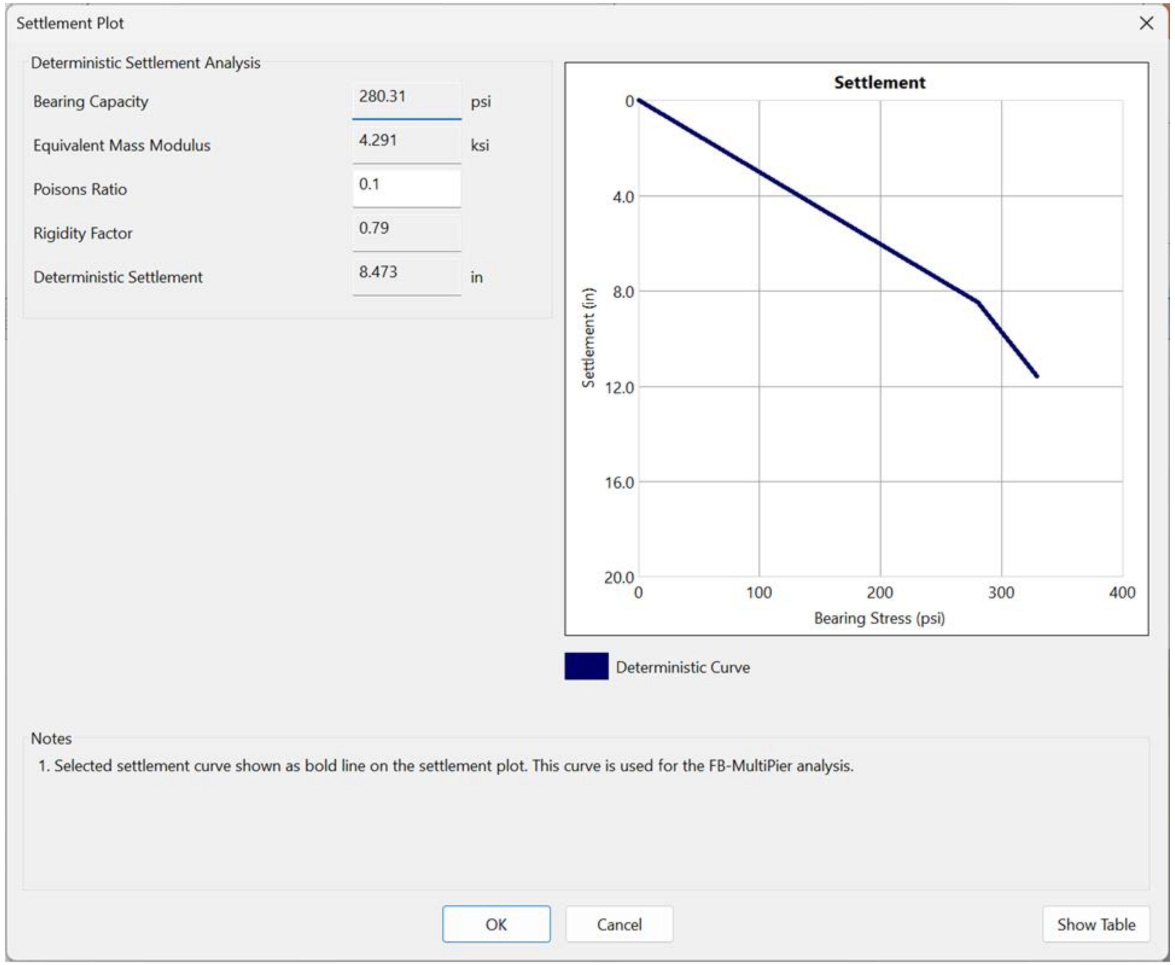
Vertical Loading

Florida Limestone Over Sand



Florida Limestone Over Sand





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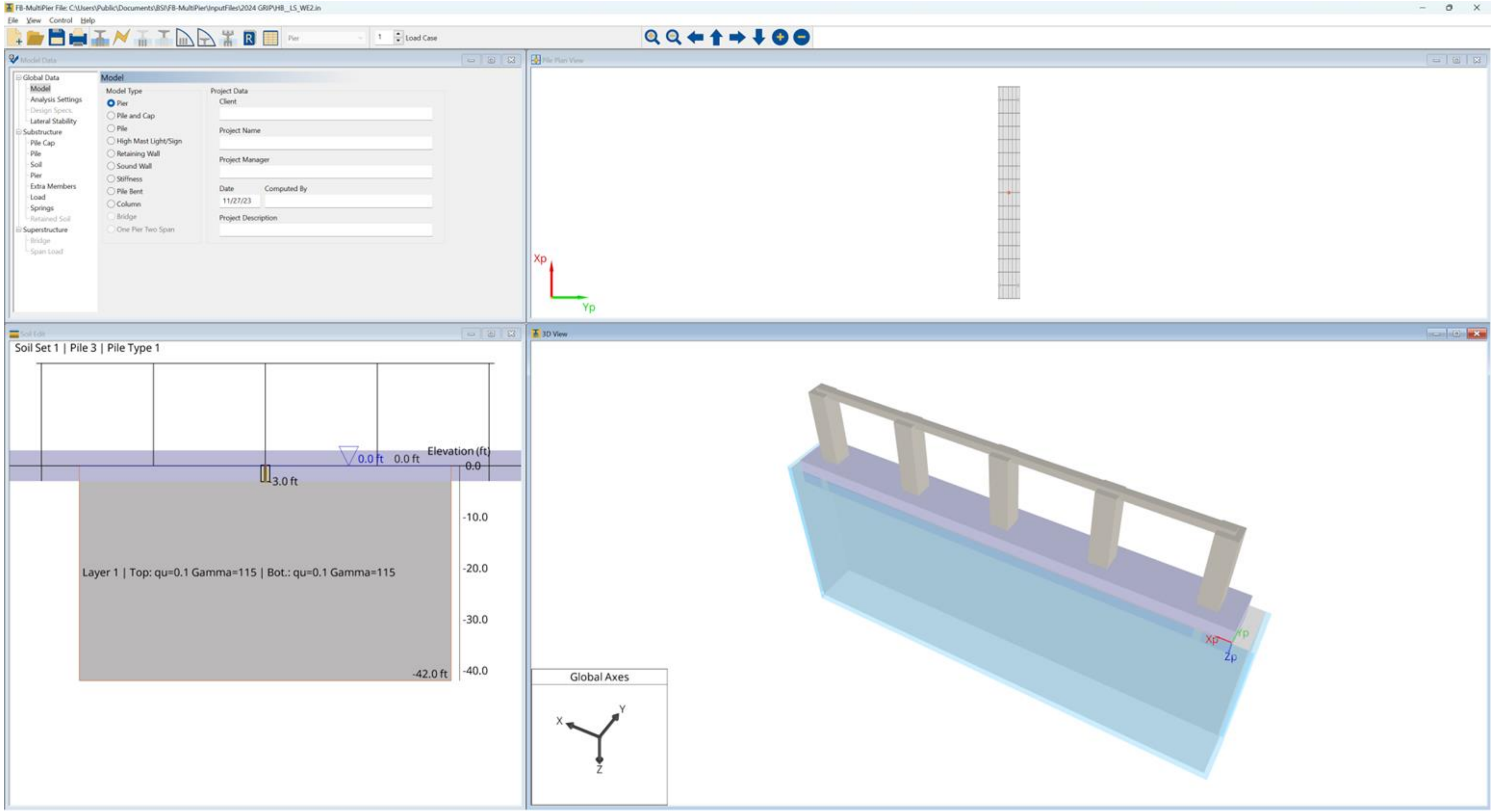
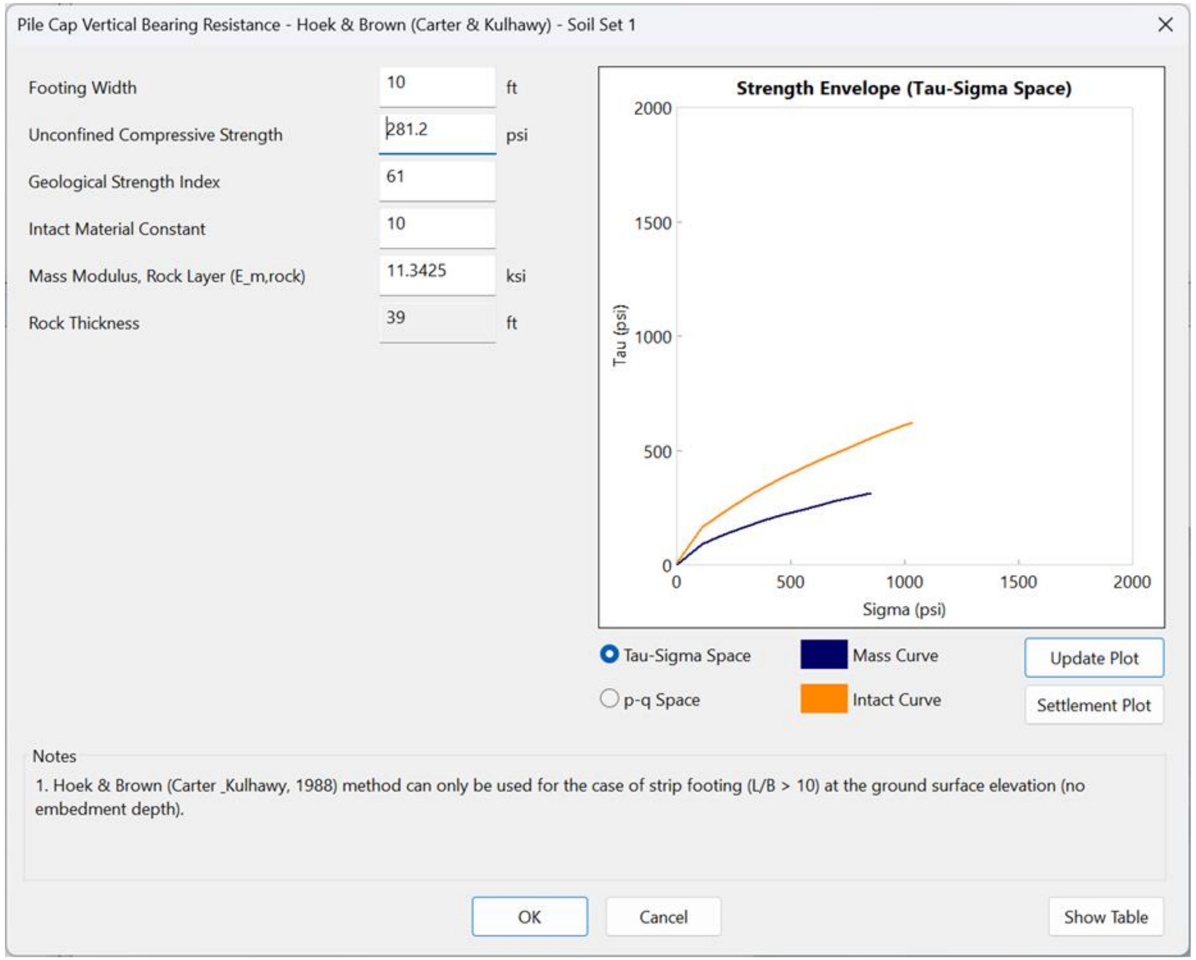
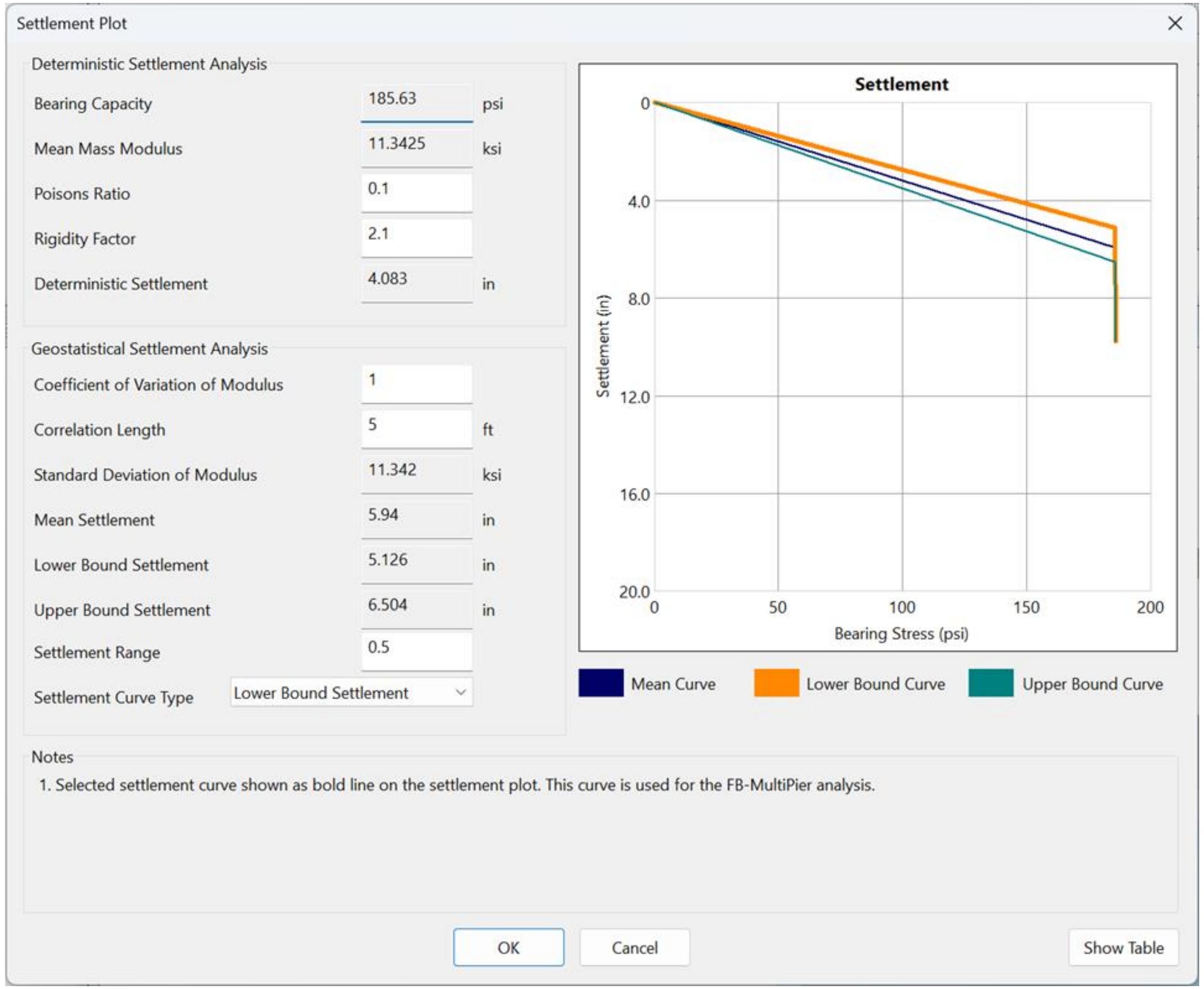
Strip Footing



Hoek Brown



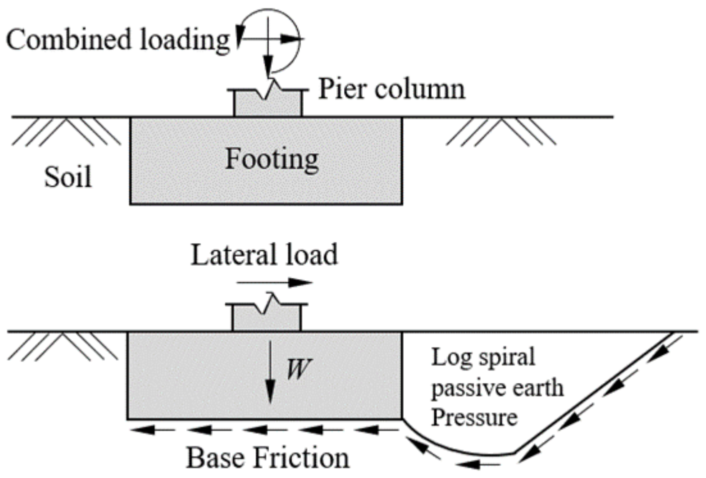
Pile Cap Vertical Bearing Resistance - Hoek & Brown (Carter & Kulhawy) - Soil Set 1
Footing Width 10 ft
Unconfined Compressive Strength 281.2 psi
Geological Strength Index 61
Intact Material Constant 10
Mass Modulus, Rock Layer (E_m,rock) 11.3425 ksi
Rock Thickness 39 ft
Strength Envelope (Tau-Sigma Space)
Tau (psi)
Sigma (psi)
0
500
1000
1500
2000
Tau-Sigma Space
p-q Space
Mass Curve
Intact Curve
Update Plot
Settlement Plot
Notes
1. Hoek & Brown (Carter _Kulhawy, 1988) method can only be used for the case of strip footing (L/B > 10) at the ground surface elevation (no embedment depth).
OK
Cancel
Show Table



Settlement Plot
Deterministic Settlement Analysis
Bearing Capacity 185.63 psi
Mean Mass Modulus 11.3425 ksi
Poisons Ratio 0.1
Rigidity Factor 2.1
Deterministic Settlement 4.083 in
Geostatistical Settlement Analysis
Coefficient of Variation of Modulus 1
Correlation Length 5 ft
Standard Deviation of Modulus 11.342 ksi
Mean Settlement 5.94 in
Lower Bound Settlement 5.126 in
Upper Bound Settlement 6.504 in
Settlement Range 0.5
Settlement Curve Type Lower Bound Settlement
Settlement
Settlement (in)
Bearing Stress (psi)
0
4.0
8.0
12.0
16.0
20.0
0
50
100
150
200
Mean Curve
Lower Bound Curve
Upper Bound Curve
Notes
1. Selected settlement curve shown as bold line on the settlement plot. This curve is used for the FB-MultiPier analysis.
OK
Cancel
Show Table

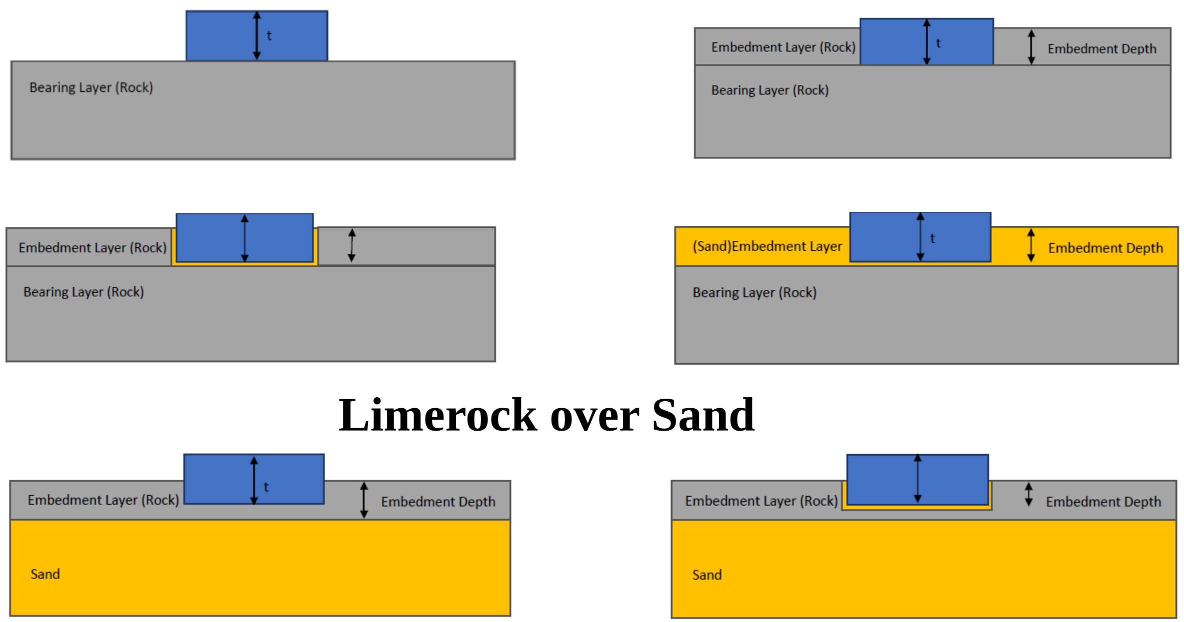
Task 3 – Implement Lateral Resistance

- Vertical and lateral resistance for numerical stability of bridge foundation models.
- Lateral resistance of embedded footings in FL limerock and sand.
- FL limerock passive resistance (based on model in q-p space and base friction).
- Sand passive resistance (Log-spiral).
- Validate formulations and conduct parametric study (footing geometry: B, L, D_f; Rock properties: q_u, q_t, γ_{dt}, REC, T; with and without backfilled annular).



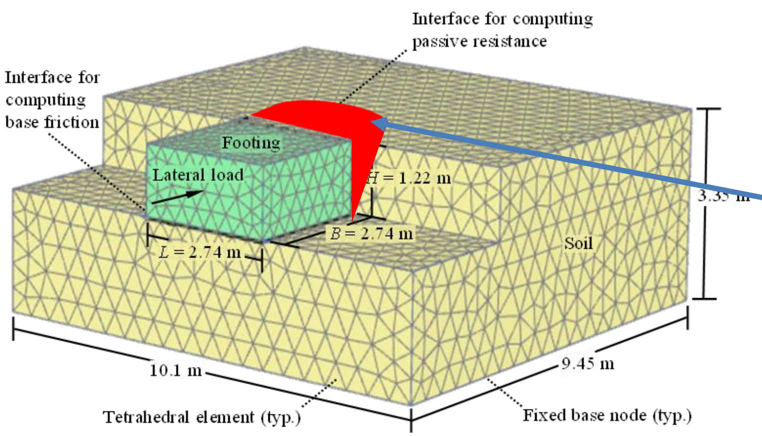
Homogeneous Limerock

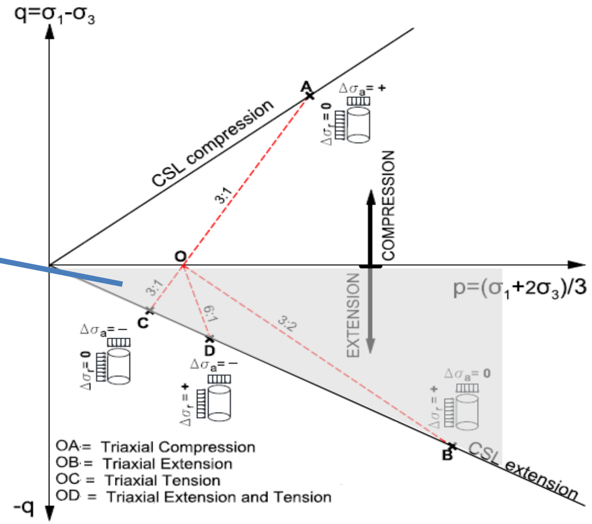
Limerock over Sand



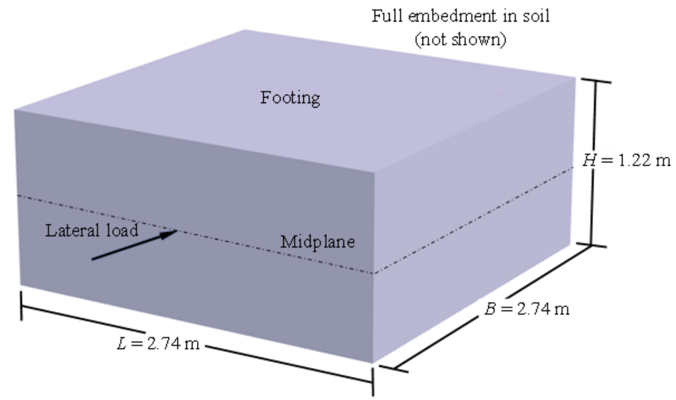
Task 3 – Implement Lateral Resistance

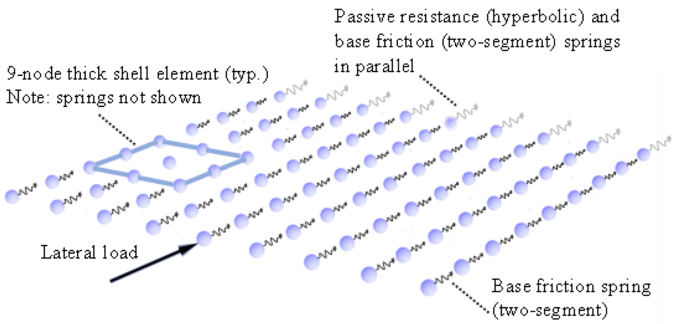
FEM



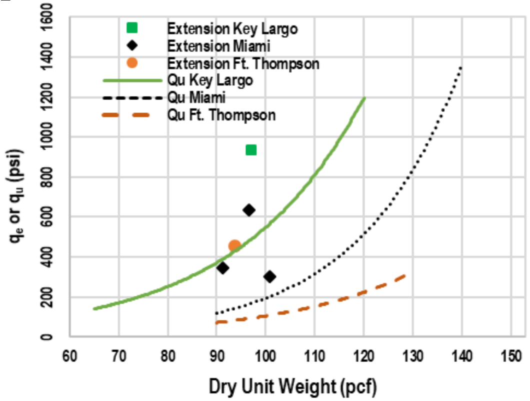


FB-Multipier





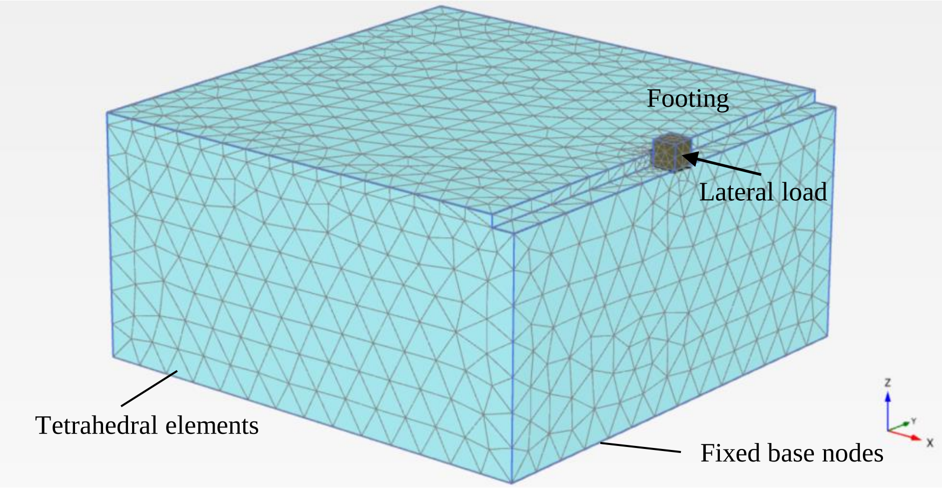
- Stress path in extension space may be critical-SMO performing triaxial tests
- Extension strength influenced by porosity and sedimentary formation process
- Phase I research tested a few rock cores in extension space
- Extension strength, q_e, at vertical stress = 0 ≥ q_u
- Extension strength at vertical stress representative of overburden stress need to be tested



Task 3 – Implement Lateral Resistance

Sand: Plaxis passive force model (L=B=H= 5 m, D_f = 2.5 m)

SOIL	Soil Model	γ_{sat} (kN/m³)	γ_{unsat} (kN/m³)	E'_{ref} (kN/m²)	v (nu)	c'_{ref} (kN/m²)	φ' (phi)	ψ'(psi)
Footing	Linear-elastic	21	-	200×10^6	0.2	-	-	-
Sand	Mohr-coulomb	19	19	95.76×10^3	0.27	10	39	14
Interface	Mohr-coulomb	19	19	95.76×10^3	0.27	6.6667	26.13	3



Task 3 – Implement Lateral Resistance

Predicted passive and base friction force (L=B=H= 5 m, D_f = 2.5 m)

Coulomb $$K_p = \frac{\cos^2(\emptyset+\theta)}{\cos^2\theta\ \cos(\delta-\theta)\left[1+\sqrt{\frac{\sin(\delta+\emptyset)\sin(\emptyset+a)}{\cos(\delta-\theta)\cos(\theta-\alpha)}}\right]^2}$$

Rankine $$k_p = \tan^2\left(45^o+\frac{\emptyset}{2}\right) = \frac{1+\sin\emptyset}{1-\sin\emptyset}$$

Passive earth force		Base friction	
γ_{sat} (kN/m^3)	19	α	0.6
D (m)	2.5	c'_{ref} (kN/m^2)	6.8
B (m)	5	L = B (m)	5
ϕ (degrees)	39	W (kN)	2625
K_p (Rankine)	4.395	δ (degrees)	26
K_p (Coulomb)	16.4	tanδ	0.49
Kp_{phi} (Mokwa)	11.2168		
Kp_c (Mokwa)	4.3627	Base Friction (kN) F = α.c.L.B+W. tanδ	1380.2
P_{ult} (Log-spiral method) (kN)	7060.12		
Passive earth force (kN) $P_p = 0.5\gamma D^2K_pB + cBDK_p^{0.5}$	5374.96142		

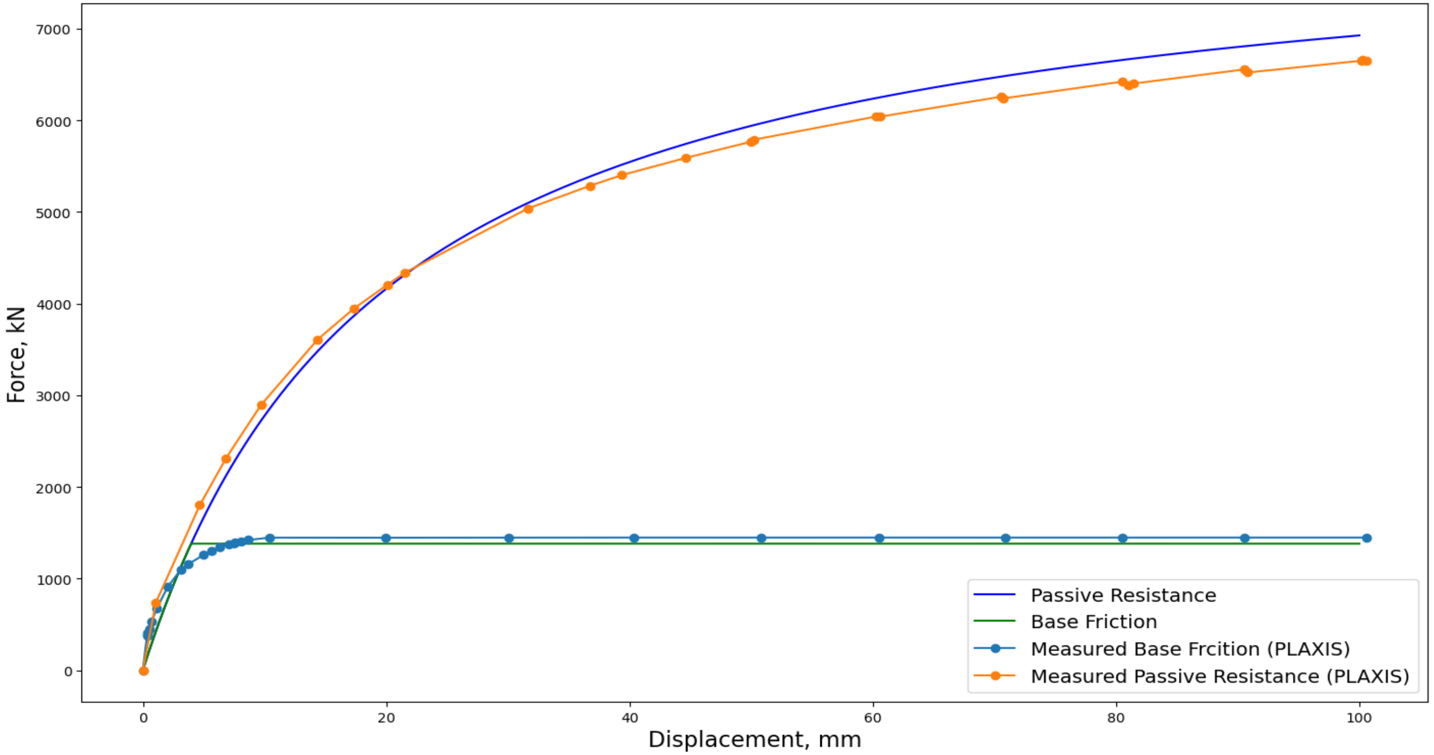
$$P_{ult} = R_{3D}\cdot E_p\cdot \mathrm{B}\cdot \mathrm{D_f}$$

$$E_p = \frac{1}{2}\gamma H^2K_{p\phi} + 2cHK_{pc} + qHK_{pq}$$

where R_{3D} is a correction factor to account for 3D effects given underlying use of log-spiral theory, E_p is the unit-length ultimate passive force from log-spiral theory (Duncan and Mokwa, 2001), B is the horizontal footing width.

Task 3 – Implement Lateral Resistance

Plaxis and predicted force-displacements: Passive and base friction (L=B=H= 5 m, D_f = 2.5 m)



Passive Model

$$p = \frac{y}{\left[\frac{1}{K_{max}} + R_f \frac{y}{P_{ult}}\right]}$$

$$R_f = 1 - \frac{P_{ult}}{K_{max} \cdot \Delta_{max}}$$

K_{max} is the initial stiffness

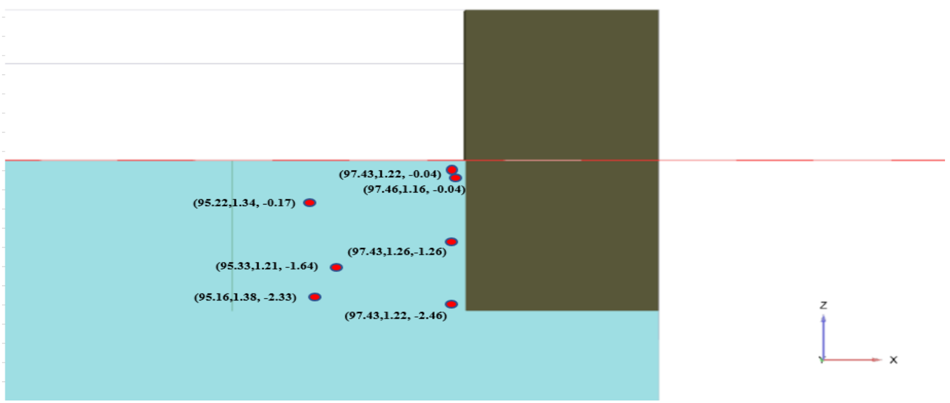
Base Friction Model

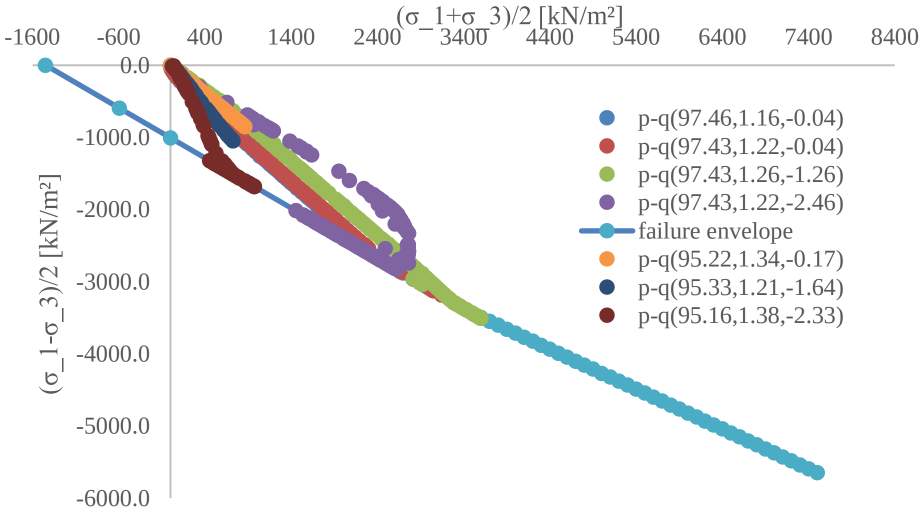
$F = K_{max}\, y \quad y \le y_{\text{intersection with Pult}}$

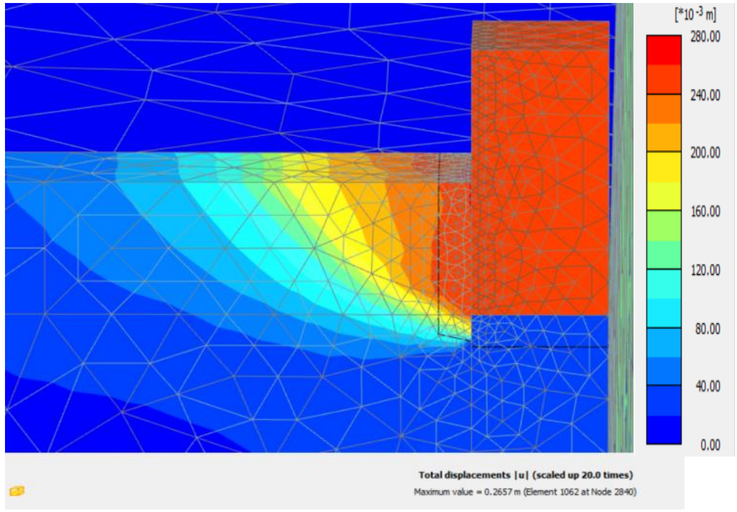
$F = F_{ult} \quad y > y_{\text{intersection with Pult}}$

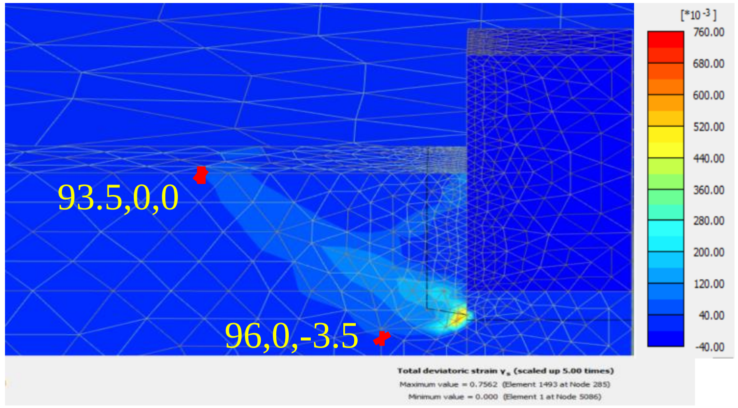
Task 3 – Implement Lateral Resistance

Rock: Plaxis stress paths in passive state (L=B=H= 2.5 m, D_f = 2.5 m)









Task 3 – Implement Lateral Resistance

Rock: Passive and base friction properties and predicted maximum force (L=B=H= 2.5 m, D_f = 2.5 m)

Passive earth force	
γ_{sat} (kN/m^3)	24
D_f (m)	2.5
B (m)	2.5
E_{mass}/E_{intact}	0.7
q_u (kN/m^2)	7700
Depth below rock surface, Z_r (m)	2.5
Depth of embedment (m)	2.5
K_p	5.5
Passive earth force (kN) **$P_p = 0.5\gamma D^2 K_p B + 2cDB(Kp)^{1/2}$**	42072.4
Passive earth force Pp (kN) **(Reese and Van Impe 2001)** **$Pp = (E_{mass}/E_{intact}).q_u. B.(1+1.4.(Zr/B))).(D_f/2)$**	40425

Base friction	
α	0.5
c'_{ref} (kN/m^2)	1400
L = B (m)	2.5
W (kN)	656.3
δ (degrees)	29.5
tanδ	0.57
Base Friction (kN) **F = α.c.L.B+W. tanδ**	4746.3

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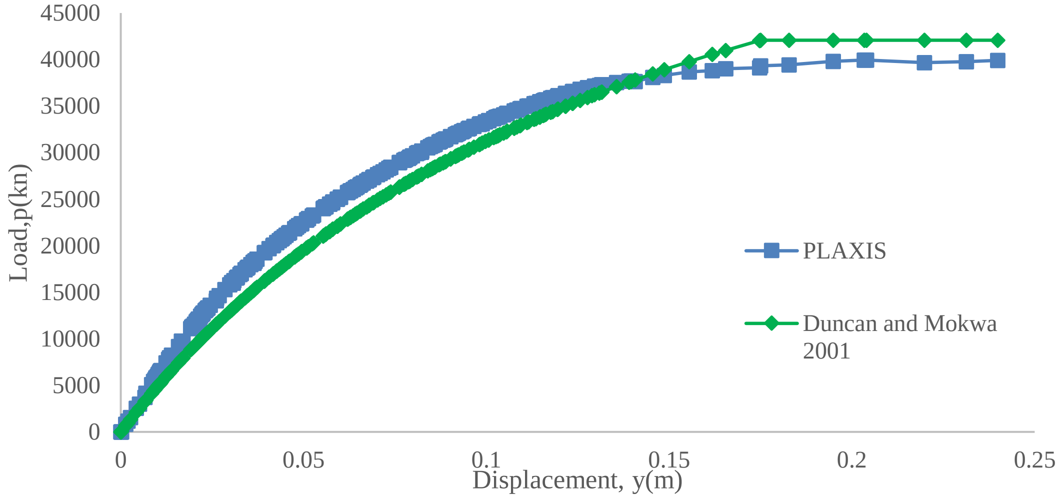
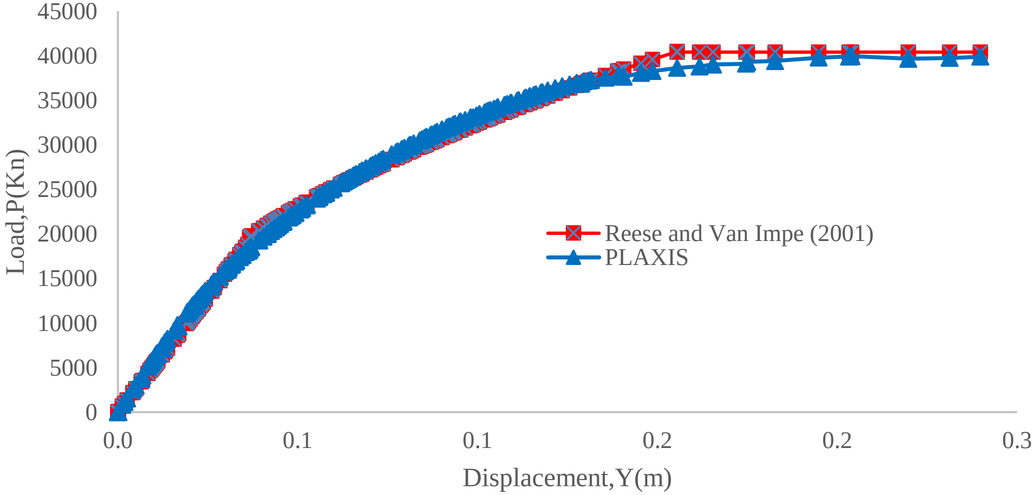
Task 3 – Implement Lateral Resistance

Rock: Plaxis and predicted passive force-displacement (L=B=H= 2.5 m, D_f = 2.5 m)





$$p = \frac{y}{\left[\frac{1}{K_{max}} + R_f \frac{y}{P_{ult}}\right]}$$

$$R_f = 1 - \frac{P_{ult}}{K_{max} \cdot \Delta_{max}}$$

K_{max} is the initial stiffness

$$p = K_{max} y \quad y \leq y_A$$

$$p = P_{ult}\left(\frac{y}{y_{rm}}\right)^n$$

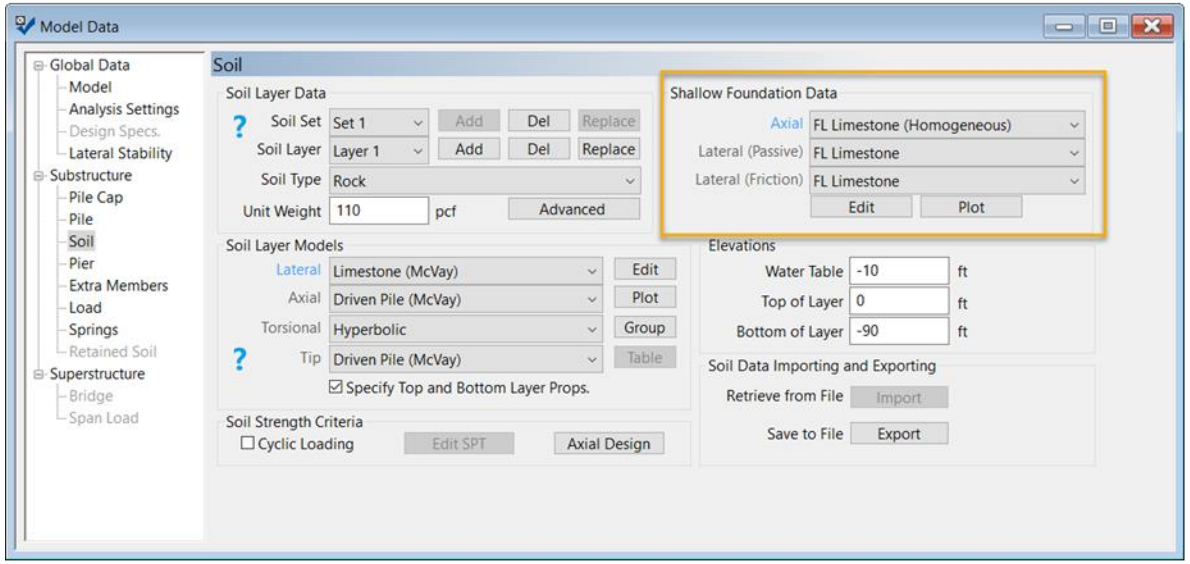
$$p = P_{ult} \quad y \geq 15 y_{rm}$$

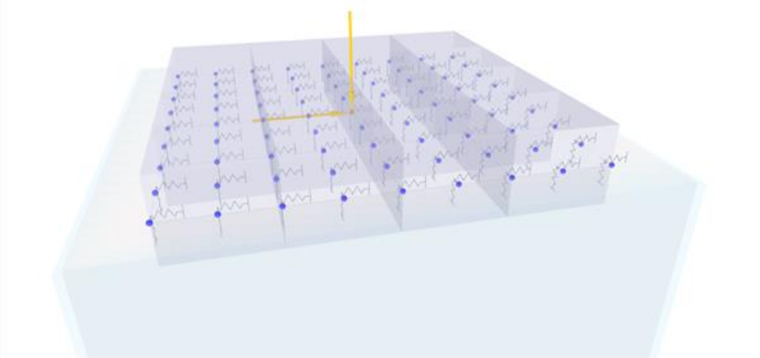
$$y_{rm} = k_{rm} B$$

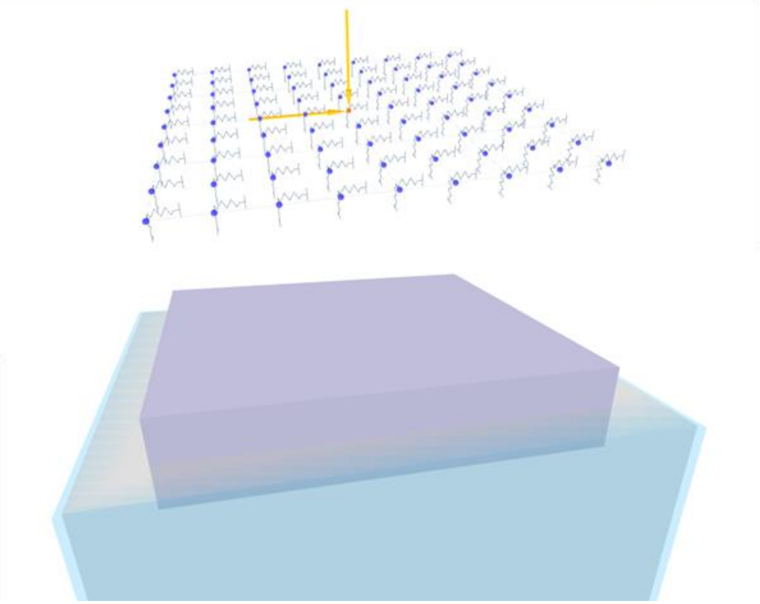
Where k_{rm} is a constant set to 0.05 for the footing model.

Task 3 – Implement Lateral Resistance

- Horizontal Passive Resistance Springs
- Horizontal Friction Resistance Springs

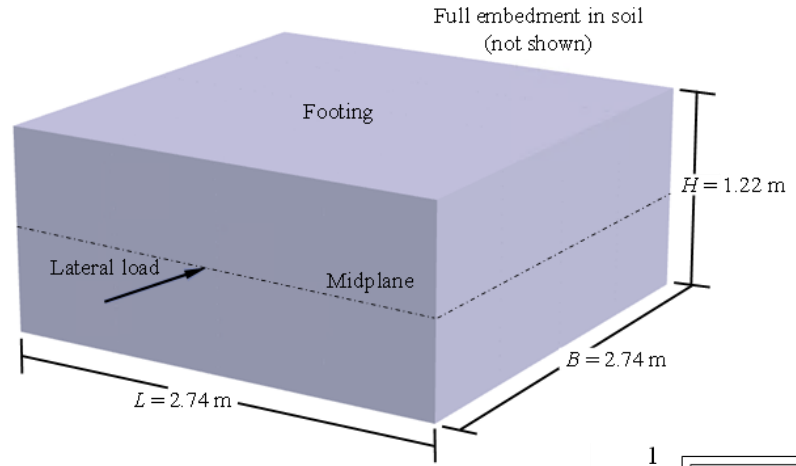


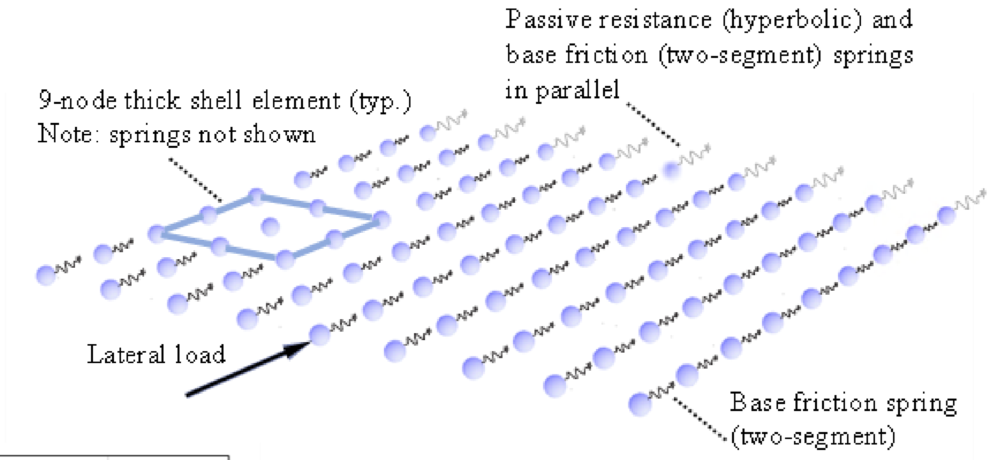


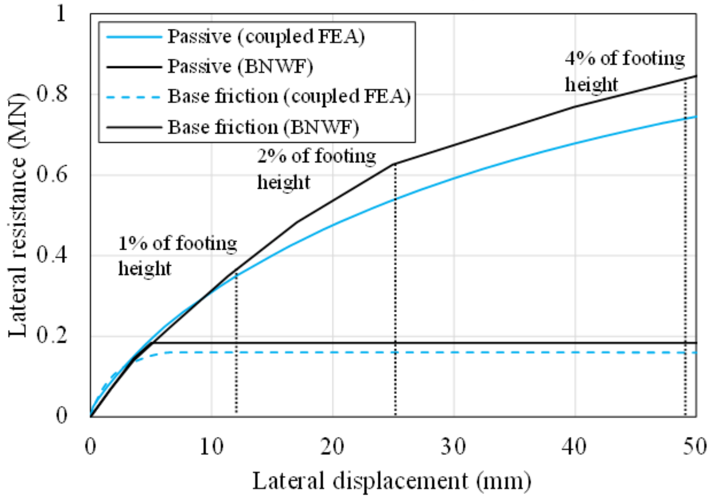


Task 3 – Implement Lateral Resistance

Spring Model Validation







FEA and the BNWF force-displacement comparison

Closing Page

Thank You!

Questions & Answers