

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

**FDOT BED31-977-17**

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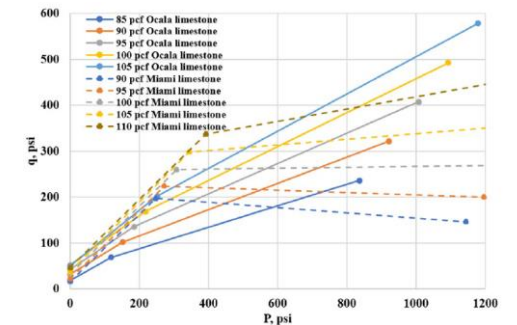
Michael McVay (UF)

Michael Faraone (BSI)

Anand Patil (BSI)

# 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-MultiPier in the user manual .

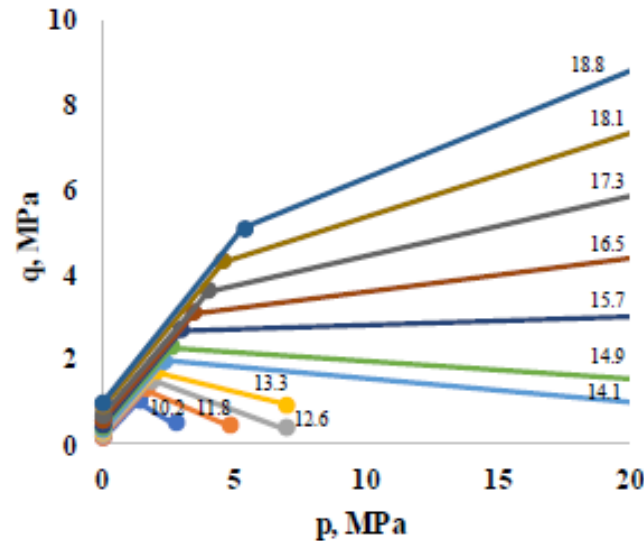
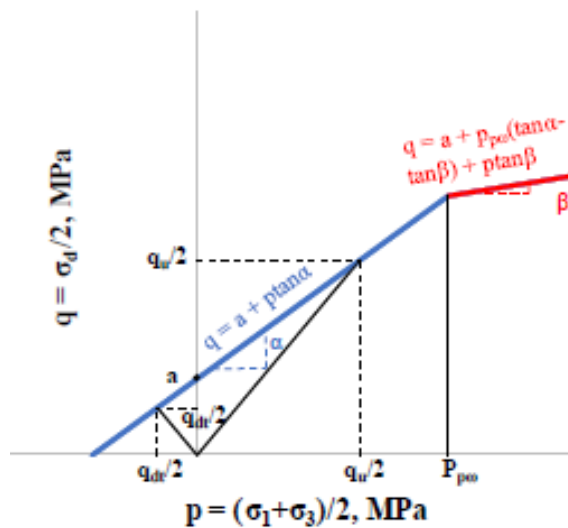


Bell , FL

- **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 ( $c$ ,  $\phi$ ,  $p_p$ ,  $\omega$ ), 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;

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

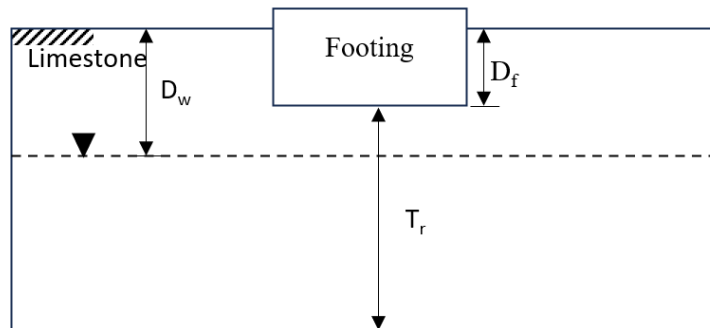
$$Q_{u2} = n * [c * N'_c + p_p * N_\gamma] + q * N_q$$

# 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:

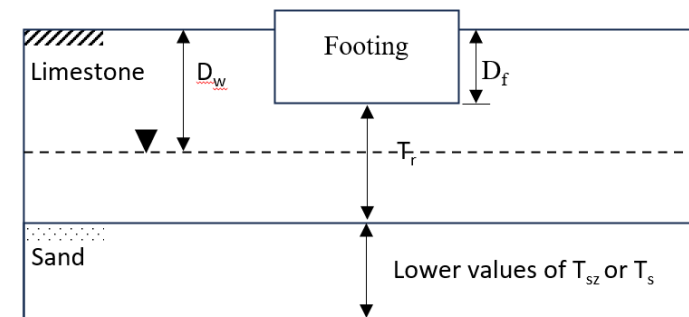
## Homogeneous Subsurface

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,  $q_u$  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,  $q_u$  and BST testing along with mass modulus of sand layer on the site
6. Using a combination of (1) and (2) data

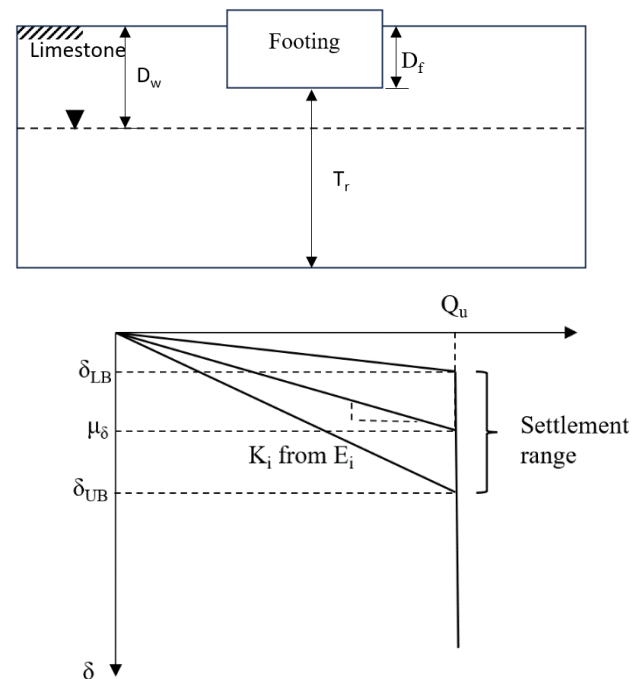
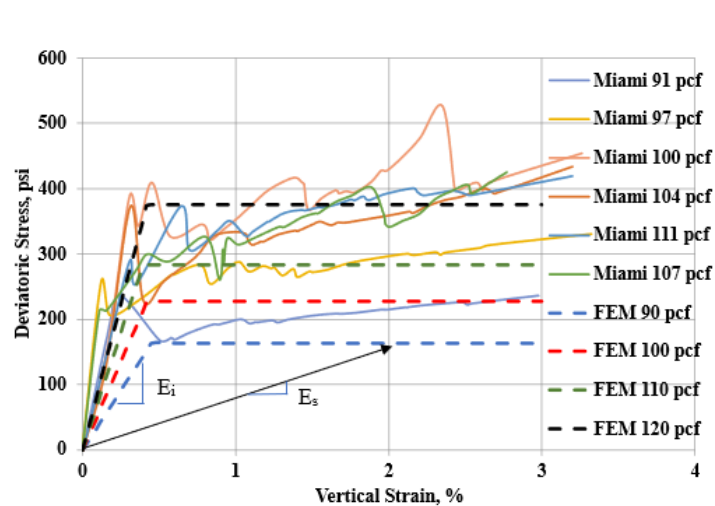


\*Carter and Kulhawy (1988) bearing analysis for rocks, derived using the curved Hoek-Brown strength envelope (Hoek and Brown, 1980) was implemented as an additional option in FB-MultiPier for plane Strain condition ( $L/B > 10$ ).

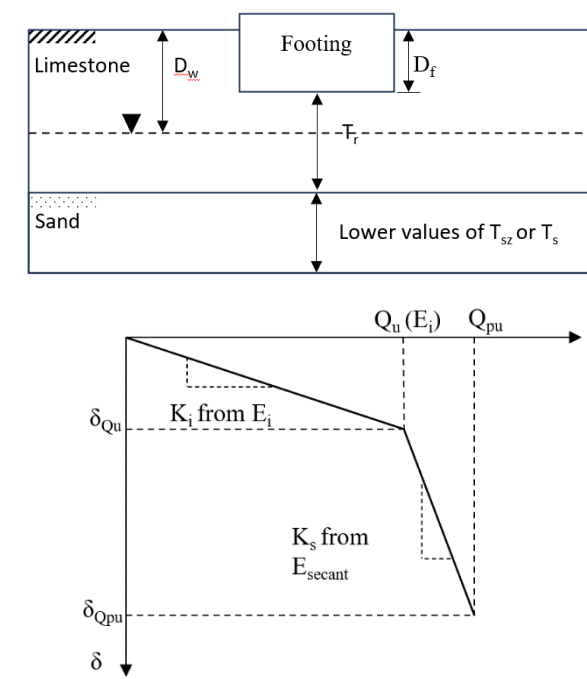
# Task 2 – Implement Load-settlement Analysis

- 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.

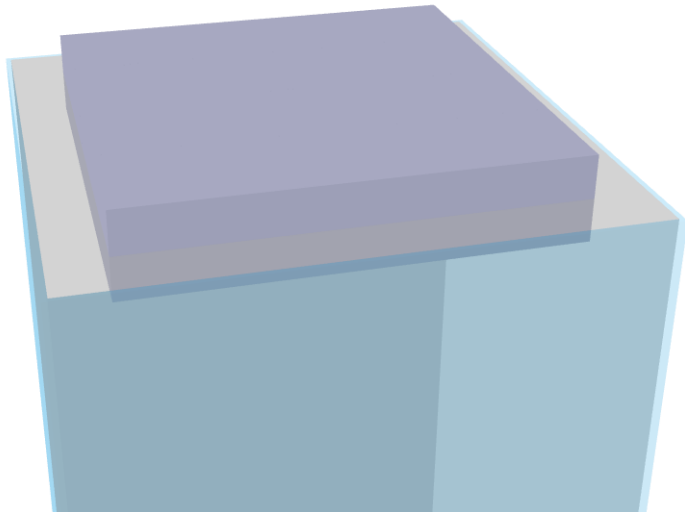
Homogeneous Case



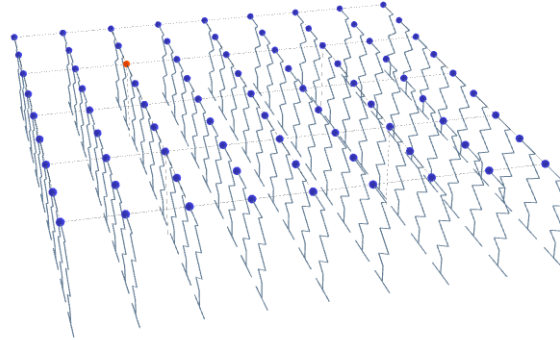
Rock-over-sand Case



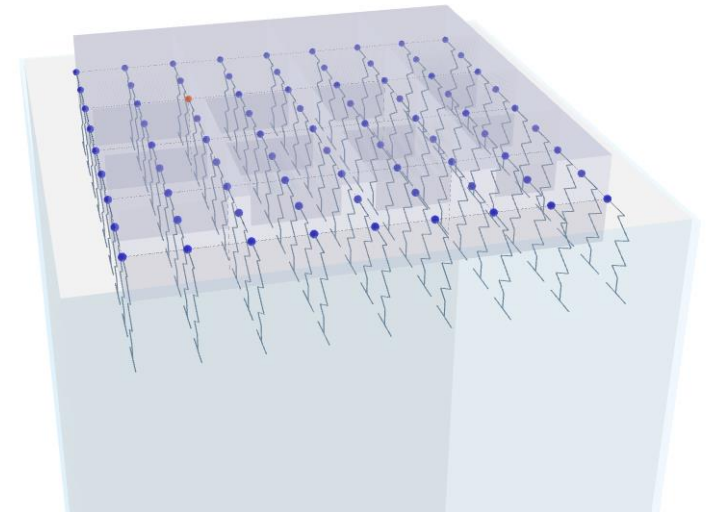
# Bearing Spring Implementation



Shallow Foundation  
FB-MultiPier (Thick View)



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



Shallow Foundation  
FB-MultiPier (Overlay View)

# FB-MultiPier Shallow Foundation

The screenshot displays the FB-MultiPier software interface, showing the following components:

- Model Data Panel:**
  - Global Data:** Model, Analysis Settings, Lateral Stability, Substructure, Pile Cap, Pile, Soil, Pier, Extra Members, Load, Springs, Retained Soil, Superstructure, Bridge, Span Load.
  - Soil Layer Data:**
    - Soil Set: Set 1
    - Soil Layer: Layer 1
    - Soil Type: Rock
    - Unit Weight: 115 pcf
    - Soil Layer Models: Lateral (Limestone (McVay)), Axial (Driven Pile (McVay)), Torsional (Hyperbolic), Tip (Driven Pile (McVay)).
    - Soil Strength Criteria:  Cyclic Loading, Edit SPT, Axial Design.
  - Shallow Foundation Data:**
    - Axial: FL Limestone (Homogeneous)
    - Lateral (Passive): FL Limestone
    - Lateral (Friction): FL Limestone
    - Elevations: Water Table (-1.5 ft), Top of Layer (0 ft), Bottom of Layer (-20 ft).
    - Soil Data Importing and Exporting: Retrieve from File, Import, Save to File, Export.
- File Plan View:** A 2D grid representing the foundation layout with a central orange square indicating the pier location. A coordinate system shows  $X_p$  (red) and  $Y_p$  (green) axes.
- Soil Edit Panel:**
  - Soil Set 1 | Pile 1 | Pile Type 1
  - Elevation (ft) scale from 0.0 to -20.0.
  - Water table level at -1.5 ft.
  - Layer 1 properties: Top:  $q_u=0.1$  Gamma=115 | Bot.:  $q_u=0.1$  Gamma=115.
  - Soil thickness shown as 4 ft.
- 3D View:** A 3D perspective view of the foundation and pier. A coordinate system shows  $X_p$  (red),  $Y_p$  (green), and  $Z_p$  (blue) axes.
- Global Axes:** A 3D coordinate system showing X, Y, and Z axes.



# FB-MultiPier Shallow Foundation

**Model Data**

**Global Data**

- Model
- Analysis Settings
- Design Specs.
- Lateral Stability

**Substructure**

- Pile Cap
- Pile
- Soil**
- Pier
- Extra Members
- Load
- Springs
- Retained Soil

**Superstructure**

- Bridge
- Span Load

**Soil**

**Soil Layer Data**

? Soil Set Set 1 Add Del Replace

Soil Layer Layer 1 Add Del Replace

Soil Type Rock

Unit Weight 115 pcf Advanced

**Shallow Foundation Data**

Axial FL Limestone (Homogeneous)

Lateral (Passive) FL Limestone

Lateral (Friction) FL Limestone

Edit Plot

**Soil Layer Models**

Lateral Limestone (McVay) Edit

Axial Driven Pile (McVay) Plot

Torsional Hyperbolic Group

Tip Driven Pile (McVay) Table

Specify Top and Bottom Layer Props.

**Soil Strength Criteria**

Cyclic Loading Edit SPT Axial Design

**Elevations**

Water Table -1.5 ft

Top of Layer 0 ft

Bottom of Layer -20 ft

**Soil Data Importing and Exporting**

Retrieve from File Import

Save to File Export

# FB-MultiPier Shallow Foundation

**Model Data**

**Global Data**

- Model
- Analysis Settings
- Design Specs.
- Lateral Stability

**Substructure**

- Pile Cap
- Pile
- Soil**
- Pier
- Extra Members
- Load
- Springs
- Retained Soil

**Superstructure**

- Bridge
- Span Load

**Soil**

**Soil Layer Data**

? Soil Set Set 1 Add Del Replace

Soil Layer Layer 1 Add Del Replace

Soil Type Rock

Unit Weight 115 pcf Advanced

**Shallow Foundation Data**

Axial FL Limestone (Homogeneous)

Lateral (Passive) FL Limestone (Homogeneous)

Lateral (Friction) Hoek & Brown (Carter & Kulhawy)

FL Limestone (Rock over Sand)

Edit Plot

**Soil Layer Models**

Lateral Limestone (McVay) Edit

Axial Driven Pile (McVay) Plot

Torsional Hyperbolic Group

Tip Driven Pile (McVay) Table

Specify Top and Bottom Layer Props.

**Soil Strength Criteria**

Cyclic Loading Edit SPT Axial Design

**Elevations**

Water Table -1.5 ft

Top of Layer 0 ft

Bottom of Layer -20 ft

**Soil Data Importing and Exporting**

Retrieve from File Import

Save to File Export

# FB-MultiPier Florida Limestone

Pile Cap Vertical Bearing Resistance - FL Limestone (Homogeneous) - Soil Set 1

Footing Dimensions		
Footing Width	10	ft
Footing Length	15	ft
Load Eccentricity along Footing Width (eB)	0	ft
Load Eccentricity along Footing Length (eL)	0	ft
Embedment Depth	4.5	ft

Rock Properties		
Total Unit Weight of Embedment Layer	115	pcf
Limestone Formation	Miami	
Bulk Dry Unit Weight	100	pcf
Rock Recovery	0.8	
Intact Cohesion (c <sub>i</sub> )	58.9	psi
Intact Friction Angle (Phi <sub>i</sub> )	44.2	deg
Intact Reduced Angle (Omega <sub>i</sub> )	0.8	deg
Intact Modulus, Rock Layer (E <sub>i,rock</sub> )	36.59	ksi
Peak Stress (Pp)	306	psi
Mass Cohesion (c <sub>m</sub> )	40.68	psi
Mass Friction Angle (Phi <sub>m</sub> )	33.92	deg
Mass Reduced Angle (Omega <sub>m</sub> )	0.64	deg
Mass Modulus, Rock Layer (E <sub>m,rock</sub> )	20.71	ksi
Rock Thickness	15.5	ft

Strength Envelope (Tau-Sigma Space)

Tau-Sigma Space     p-q Space  
 Mass Curve     Intact Curve

Update Plot    Settlement Plot

Notes

1. This method assumes a rigid boundary at bottom of the rock layer.

OK    Cancel    Show Table

# FB-MultiPier Florida Limestone

Pile Cap Vertical Bearing Resistance - FL Limestone (Homogeneous) - Soil Set 1

Footing Dimensions		
Footing Width	10	ft
Footing Length	15	ft
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Rock Properties		
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Limestone Formation	Miami	
Bulk Dry Unit Weight		pcf
Rock Recovery		
Intact Cohesion (c <sub>i</sub> )		psi
Intact Friction Angle (Phi <sub>i</sub> )		deg
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**Strength Envelope (Tau-Sigma Space)**

Tau-Sigma Space      p-q Space  
 Mass Curve      Intact Curve

Update Plot     Settlement Plot

**Notes**

- This method assumes a rigid boundary at bottom of the rock layer.

# Formation Data

Pile Cap Vertical Bearing Resistance - FL Limestone (Homogeneous) - Soil Set 1

**Footings Dimensions**

- Footing Width: 10 ft
- Footing Length: 15 ft
- Load Eccentricity along Footing Width (eB): 0 ft
- Load Eccentricity along Footing Length (eL): 0 ft
- Embedment Depth: 4.5 ft

**Rock Properties**

- Total Unit Weight of Embedment Layer: 115 pcf
- Limestone Formation: **Miami**
- Bulk Dry Unit Weight: pcf
- Rock Recovery: psi
- Intact Cohesion (c<sub>i</sub>): leg
- Intact Friction Angle (Phi<sub>i</sub>): deg
- Intact Reduced Angle (Omega<sub>i</sub>): deg
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**Strength Envelope (Tau-Sigma Space)**

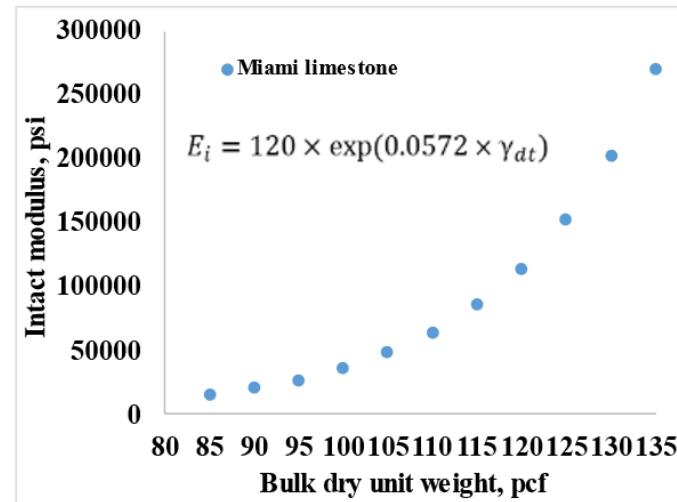
Tau-Sigma Space     p-q Space  
 Mass Curve     Intact Curve

Update Plot    Settlement Plot

Notes  
 1. This method assumes a rigid boundary at bottom of the rock layer.

OK    Cancel    Show Table

Formation	$\gamma_{dt}$ , pcf	$c_i$ , psi	$\phi_i$ , °	$\sigma_{peak}$ , psi	$\omega_i$ , °	$a_i$ , psi	$\alpha_i$ , °	$P_p$ , psi	$\beta_i$ , °
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



# Formation Data - Continued

Pile Cap Vertical Bearing Resistance - FL Limestone (Homogeneous) - Soil Set 1

**Footings Dimensions**

Footing Width: 10 ft  
 Footing Length: 15 ft  
 Load Eccentricity along Footing Width (eB): 0 ft  
 Load Eccentricity along Footing Length (eL): 0 ft  
 Embedment Depth: 4.5 ft

**Rock Properties**

Total Unit Weight of Embedment Layer: 115 pcf

Limestone Formation: Miami

Bulk Dry Unit Weight: 100 pcf  
 Rock Recovery: 0.8

Intact Cohesion (c<sub>i</sub>): 58.9 psi  
 Intact Friction Angle (Phi<sub>i</sub>): 44.2 deg  
 Intact Reduced Angle (Omega<sub>i</sub>): 0.8 deg  
 Intact Modulus, Rock Layer (E<sub>i,rock</sub>): 36.59 ksi  
 Peak Stress (P<sub>p</sub>): 306 psi  
 Mass Cohesion (c<sub>m</sub>): 40.68 psi  
 Mass Friction Angle (Phi<sub>m</sub>): 33.92 deg  
 Mass Reduced Angle (Omega<sub>m</sub>): 0.64 deg  
 Mass Modulus, Rock Layer (E<sub>m,rock</sub>): 20.71 ksi  
 Rock Thickness: 15.5 ft

**Strength Envelope (Tau-Sigma Space)**

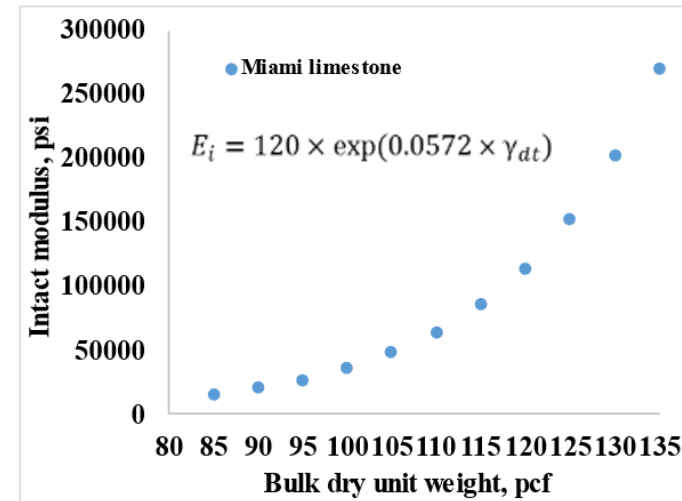
Tau-Sigma Space     p-q Space  
 Mass Curve     Intact Curve

Update Plot    Settlement Plot

Notes  
 1. This method assumes a rigid boundary at bottom of the rock layer.

OK    Cancel    Show Table

Formation	$\gamma_{dt}$ , pcf	$c_i$ , psi	$\phi_i$ , °	$\sigma_{peak}$ , psi	$\omega_i$ , °	$a_i$ , psi	$\alpha_i$ , °	$P_p$ , psi	$\beta_i$ , °
Miami Limestone	90	42.0	42.2	444	-3.0	31.1	33.9	247	-3
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	135	202.5	51.1	1541	35.4	127.1	37.9	795	30.1



- 3000 Unconfined Compression test
- 225 Triaxial Test

# Custom Rock Properties

Pile Cap Vertical Bearing Resistance - FL Limestone (Homogeneous) - Soil Set 1

Footing Dimensions

- Footing Width: 10 ft
- Footing Length: 15 ft
- Load Eccentricity along Footing Width (eB): 0 ft
- Load Eccentricity along Footing Length (eL): 0 ft
- Embedment Depth: 4.5 ft

Rock Properties

- Total Unit Weight of Embedment Layer: 115 pcf
- Limestone Formation: Custom Intact
- Bulk Dry Unit Weight: N/A pcf
- Rock Recovery: 0.8
- Intact Cohesion (c<sub>i</sub>): 58.9 psi
- Intact Friction Angle (Phi<sub>i</sub>): 44.2 deg
- Intact Reduced Angle (Omega<sub>i</sub>): 0.8 deg
- Intact Modulus, Rock Layer (E<sub>i,rock</sub>): 36.59 ksi
- Peak Stress (Pp): 306 psi
- Mass Cohesion (c<sub>m</sub>): 40.7 psi
- Mass Friction Angle (Phi<sub>m</sub>): 33.9 deg
- Mass Reduced Angle (Omega<sub>m</sub>): 0.64 deg
- Mass Modulus, Rock Layer (E<sub>m,rock</sub>): 20.71 ksi
- Rock Thickness: 15.5 ft

Strength Envelope (Tau-Sigma Space)

Tau-Sigma Space     p-q Space  
 Mass Curve     Intact Curve

Notes

- This method assumes a rigid boundary at bottom of the rock layer.

Pile Cap Vertical Bearing Resistance - FL Limestone (Homogeneous) - Soil Set 1

Footing Dimensions

- Footing Width: 10 ft
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- Load Eccentricity along Footing Width (eB): 0 ft
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- Embedment Depth: 4.5 ft

Rock Properties

- Total Unit Weight of Embedment Layer: 115 pcf
- Limestone Formation: Custom Mass
- Bulk Dry Unit Weight: N/A pcf
- Rock Recovery: N/A
- Intact Cohesion (c<sub>i</sub>): N/A psi
- Intact Friction Angle (Phi<sub>i</sub>): N/A deg
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Strength Envelope (Tau-Sigma Space)

Tau-Sigma Space     p-q Space  
 Mass Curve     Intact Curve

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# FB-MultiPier Shallow Foundation

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Tau-Sigma Space     p-q Space  
 Mass Curve     Intact Curve

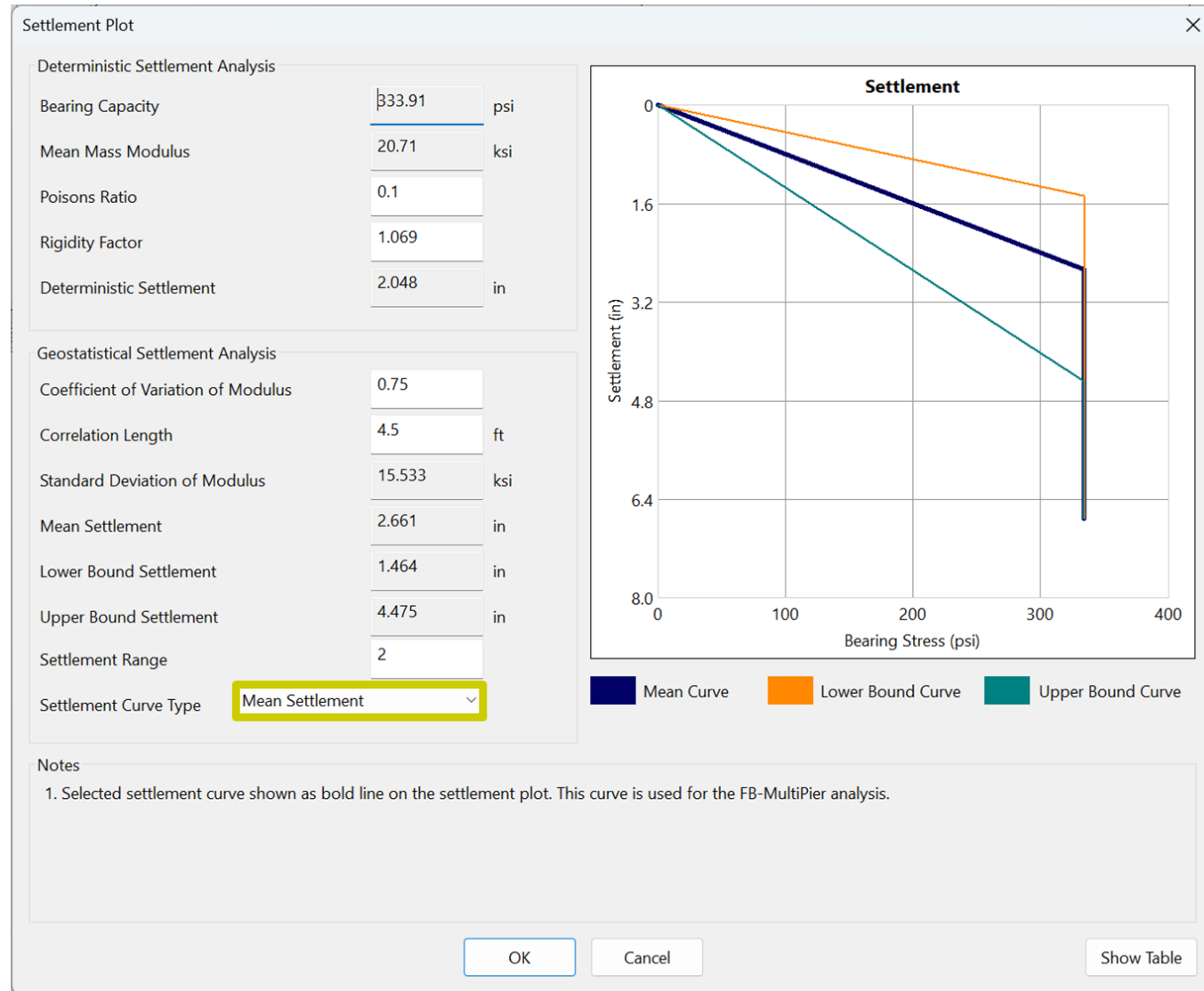
  

Notes

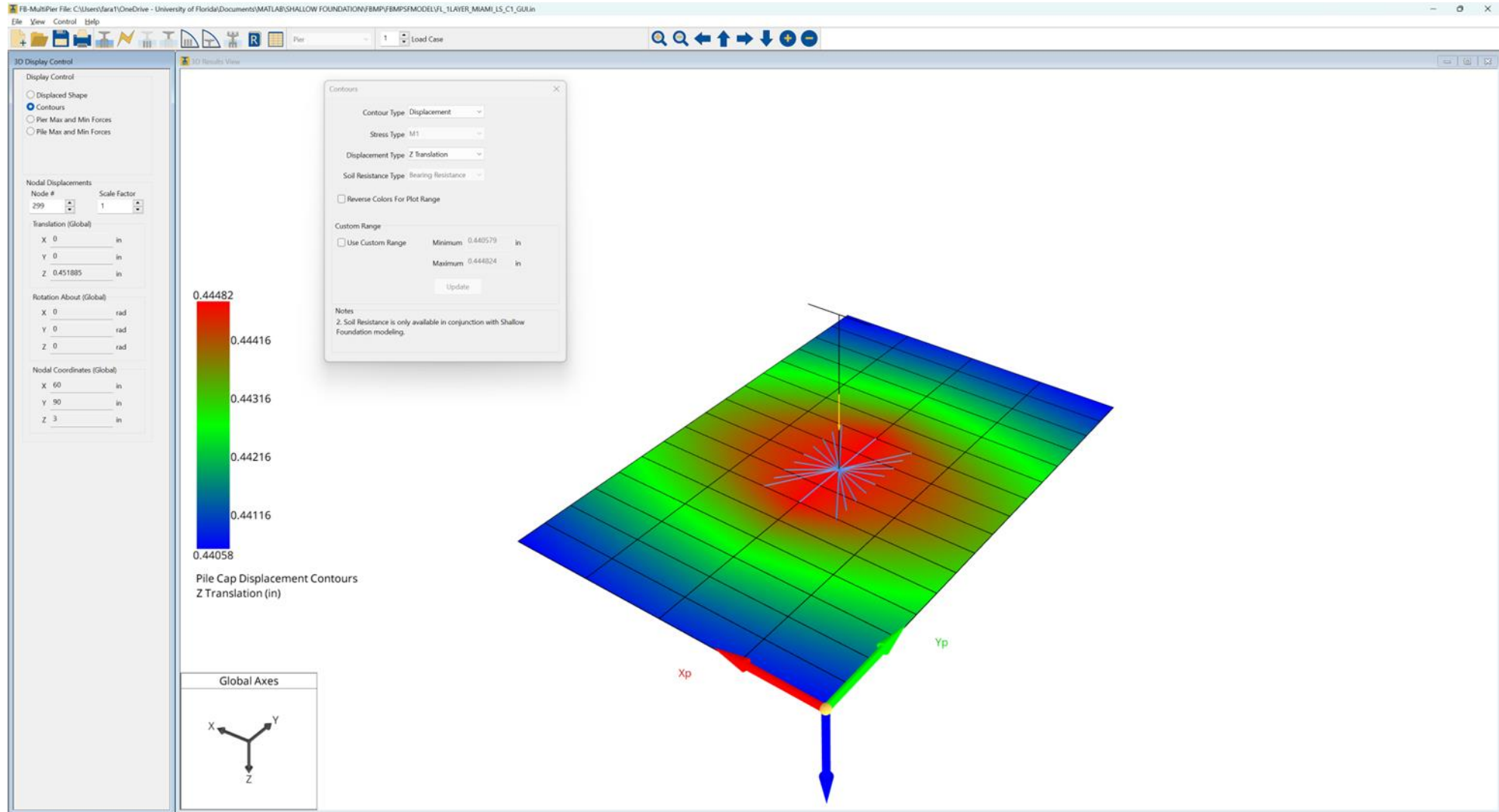
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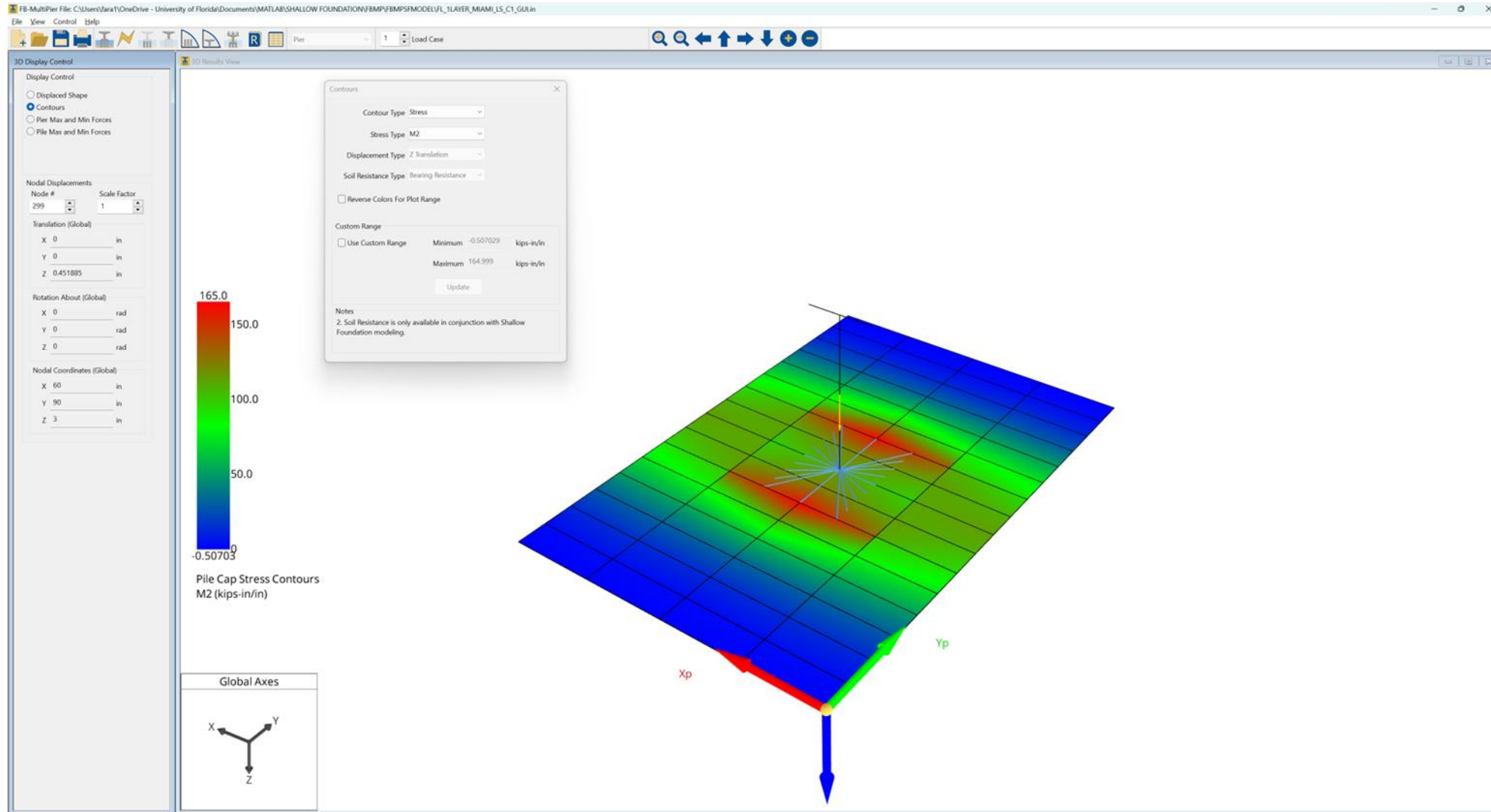
# FB-MultiPier Shallow Foundation



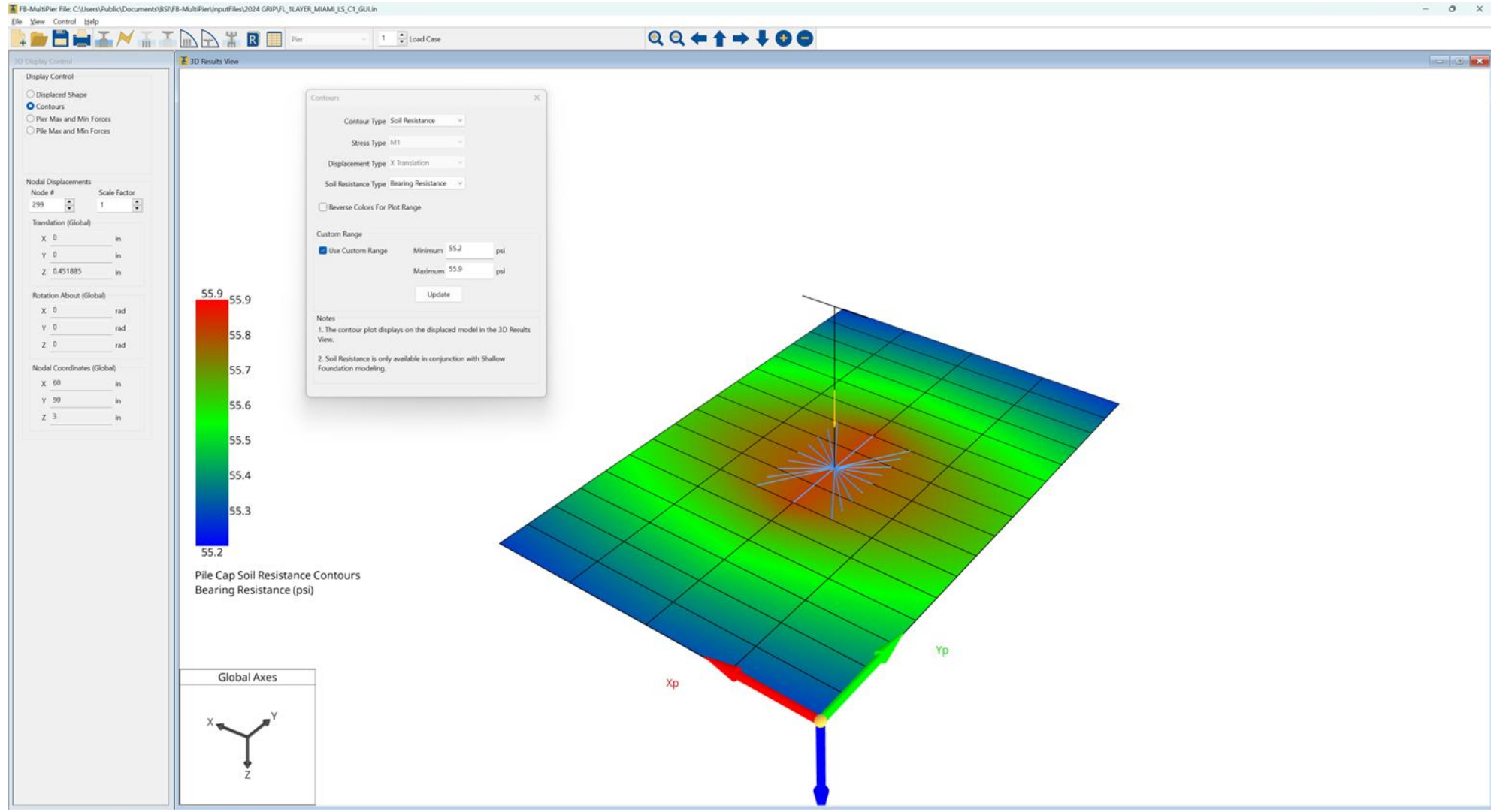
# FB-MultiPier Shallow Foundation Results



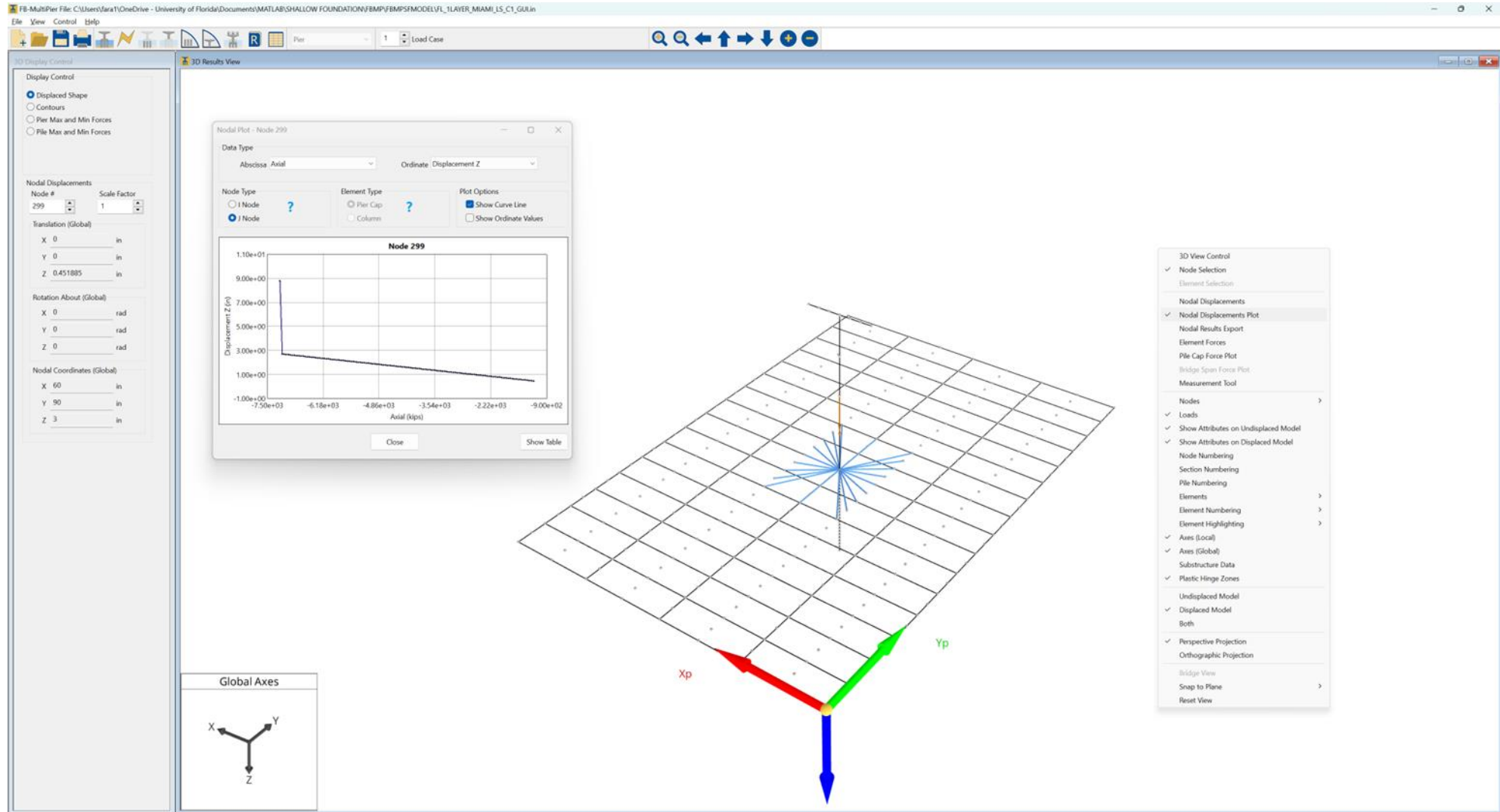
# FB-MultiPier Shallow Foundation Results



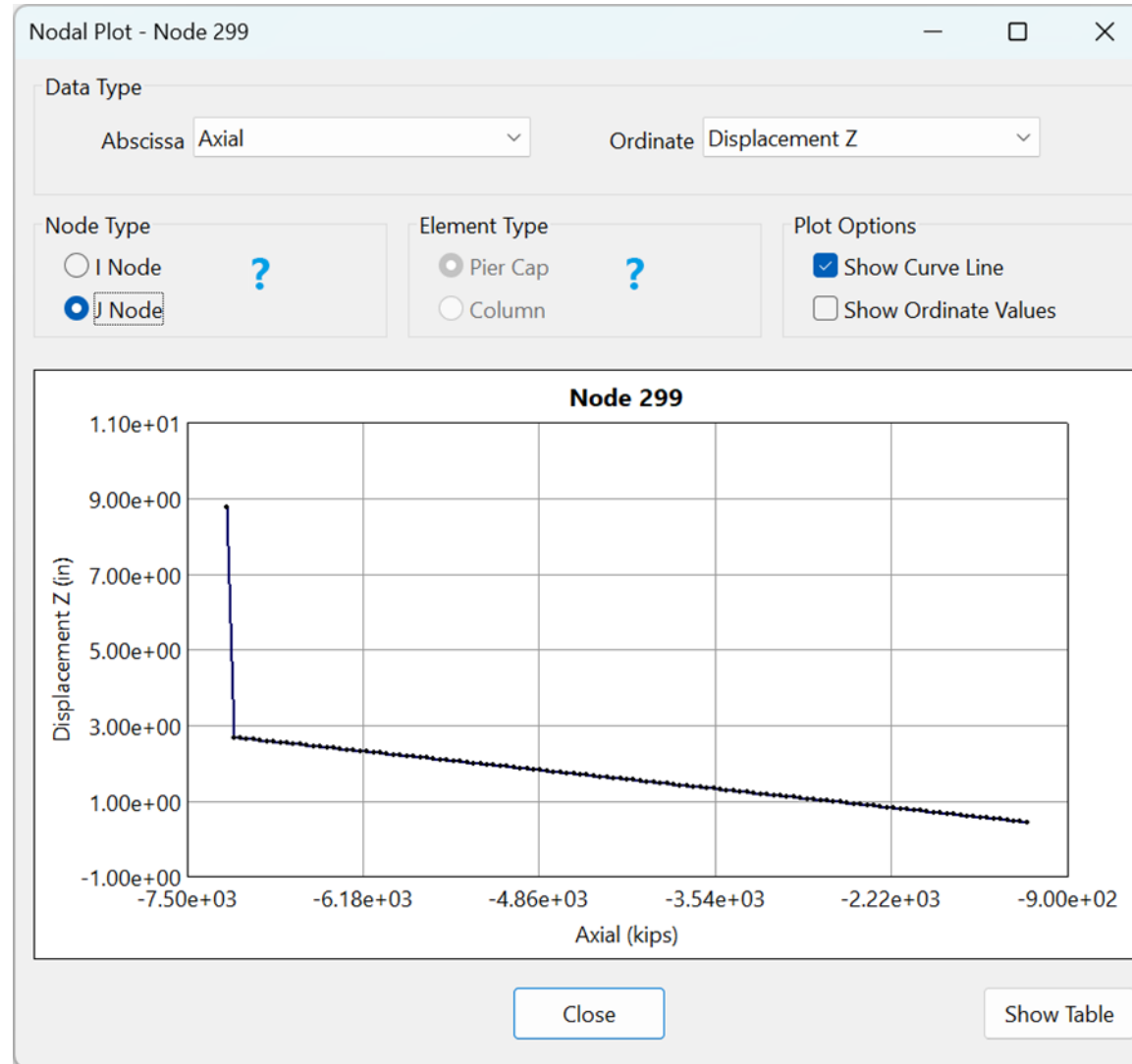
# FB-MultiPier Shallow Foundation Results



# Nodal Displacement Plot



# Nodal Displacement Plot



# FB-MultiPier Shallow Foundation

**3D Results View**

**Pile Cap Forces**

Selection Mode:  Manual  Auto

Scan Direction: Along Yp

Internal Force: Max. Moment (+)

Node	X Coordinate (in)	Y Coordinate (in)	Z Coordinate (in)
83	60.00	0.00	18.00
289	60.00	5.62	18.00
78	60.00	11.25	18.00
276	60.00	16.88	18.00
73	60.00	22.50	18.00
263	60.00	28.12	18.00
68	60.00	33.75	18.00
250	60.00	39.38	18.00

**Force Data**

All Load Cases  Myp  Positive MXp (Bot. Steel)

Load Case Specific  MXp

Max. Moment (+) 6696.66 kip-ft Load Case 121

Min. Moment (-) 1113.39 kip-ft Load Case 1

Max. Shear (abs) Zp 0.00 kips Load Case 43

**Max. Moment (+) MXp, Load Case 121**

**Min. Moment (-) MXp, Load Case 1**

**Vertical Loading**

# FB-MultiPier Shallow Foundation

**Pile Cap Forces** ✕

Selection Mode  
 Manual      Scan Direction: Along Yp ▾  
 Auto            Internal Force: Max. Moment (+) ▾

Node	X Coordinate (in)	Y Coordinate (in)	Z Coordinate (in)
83	60.00	0.00	18.00
289	60.00	5.62	18.00
78	60.00	11.25	18.00
276	60.00	16.88	18.00
73	60.00	22.50	18.00
263	60.00	28.12	18.00
68	60.00	33.75	18.00
250	60.00	39.38	18.00

Force Data  
 All Load Cases       MYp      Positive MXp (Bot. Steel) ▾  
 Load Case Specific       MXp      Generate      Deselect All

Max. Moment (+)	6696.66	kip-ft	Load Case	121
Min. Moment (-)	1113.39	kip-ft	Load Case	1
Max. Shear (abs) Zp	0.00	kips	Load Case	43

**Max. Moment (+) MXp, Load Case 121**

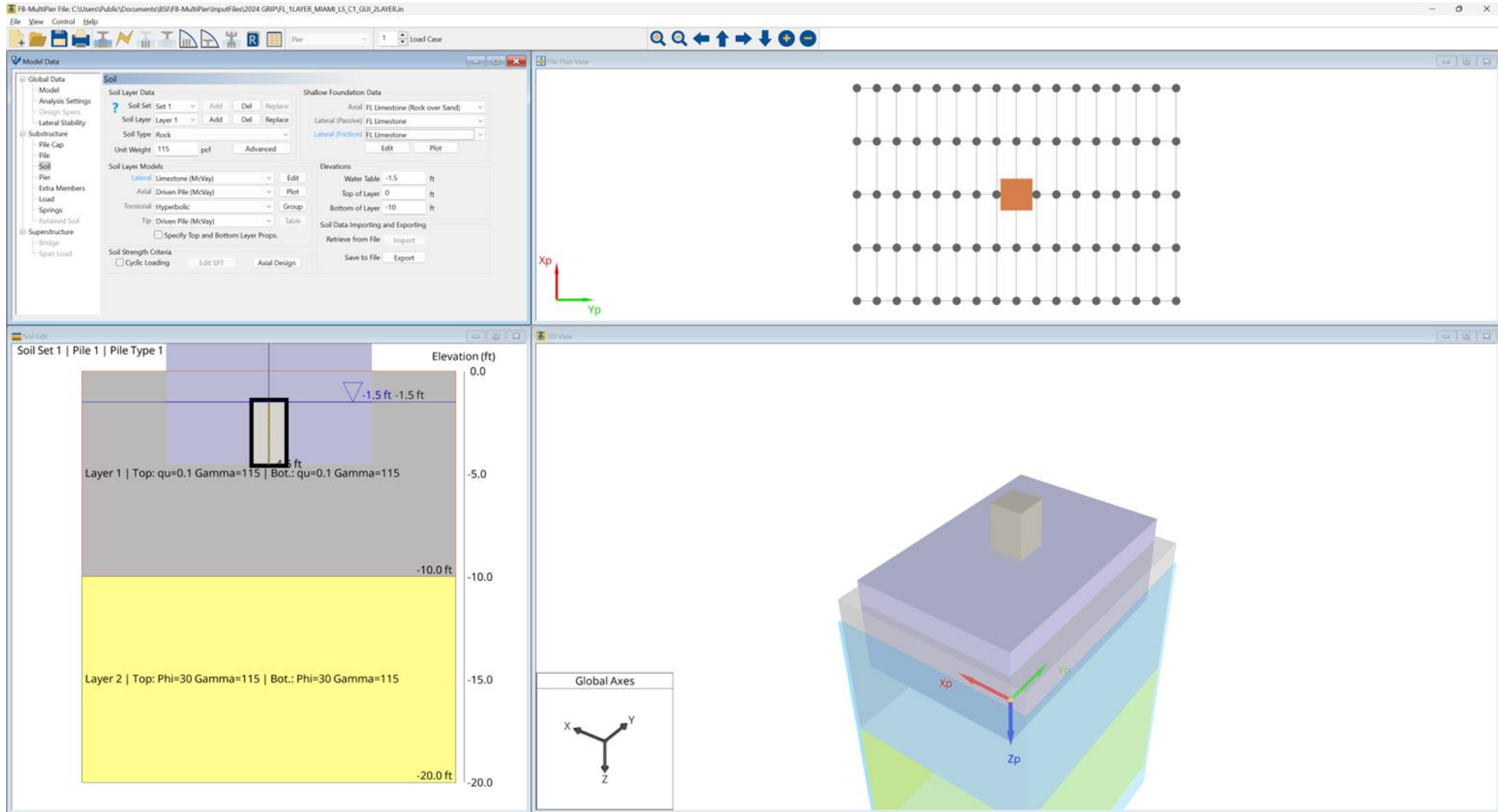
**Min. Moment (-) MXp, Load Case 1**

Plot Zero Datum      Close      Show Table  
 End Point Nodal Selection

## Vertical Loading



# Florida Limestone Over Sand



# Florida Limestone Over Sand

Pile Cap Vertical Bearing Resistance - FL Limestone (Rock over Sand) - Soil Set 1

Footing Dimensions	
Footing Width	10 ft
Footing Length	15 ft
Load Eccentricity along Footing Width (eB)	0 ft
Load Eccentricity along Footing Length (eL)	0 ft
Embedment Depth	4.5 ft

Rock Properties	
Total Unit Weight of Embedment Layer	115 pcf
Limestone Formation	Miami
Bulk Dry Unit Weight	100 pcf
Rock Recovery	0.8
Intact Cohesion (c <sub>i</sub> )	58.9 psi
Intact Friction Angle (Phi <sub>i</sub> )	44.2 deg
Intact Reduced Angle (Omega <sub>i</sub> )	0.8 deg
Intact Modulus, Rock Layer (E <sub>i,rock</sub> )	36.59 ksi
Peak Stress (P <sub>p</sub> )	306 psi
Mass Cohesion (c <sub>m</sub> )	40.68 psi
Mass Friction Angle (Phi <sub>m</sub> )	33.92 deg
Mass Reduced Angle (Omega <sub>m</sub> )	0.64 deg
Mass Modulus, Rock Layer (E <sub>m,rock</sub> )	20.71 ksi
Rock Thickness	5.5 ft

Sand Properties	
Mass Modulus, Sand Layer (E <sub>soil, m</sub> )	2 ksi
Sand Thickness	10 ft

Strength Envelope (Tau-Sigma Space)

Tau-Sigma Space     Mass Curve    Update Plot  
 p-q Space     Intact Curve    Settlement Plot

Notes

1. This method assumes a rigid boundary at bottom of the sand layer.

OK    Cancel    Show Table

Settlement Plot

Deterministic Settlement Analysis	
Bearing Capacity	280.31 psi
Equivalent Mass Modulus	4.291 ksi
Poisons Ratio	0.1
Rigidity Factor	0.79
Deterministic Settlement	8.473 in

Settlement

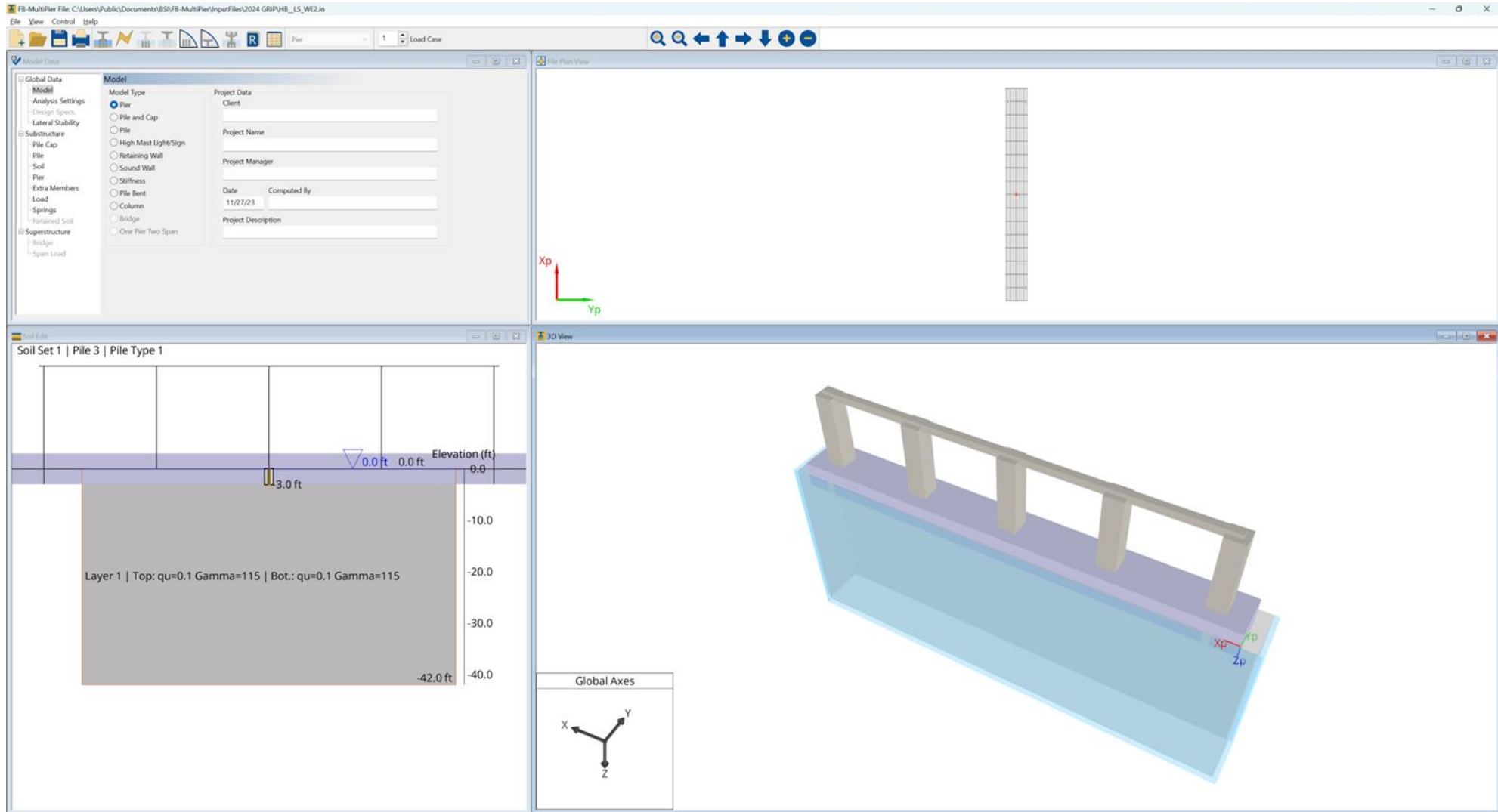
Deterministic Curve

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

# 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 <sub>m,rock</sub> )	11.3425	ksi
Rock Thickness	39	ft

Strength Envelope (Tau-Sigma Space)

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

Mean Curve     Lower Bound Curve     Upper Bound Curve

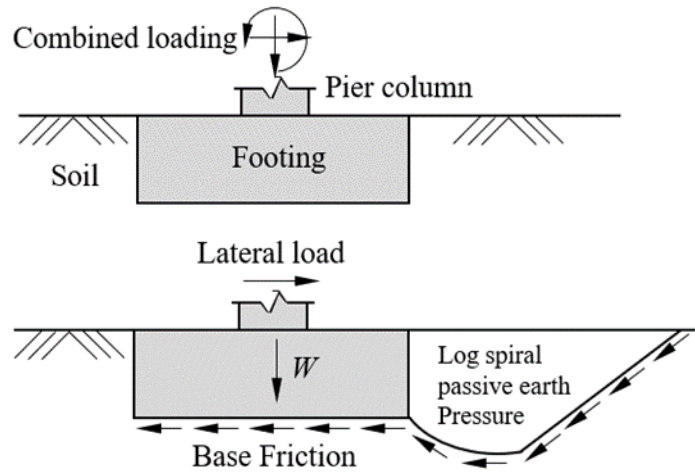
Notes

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

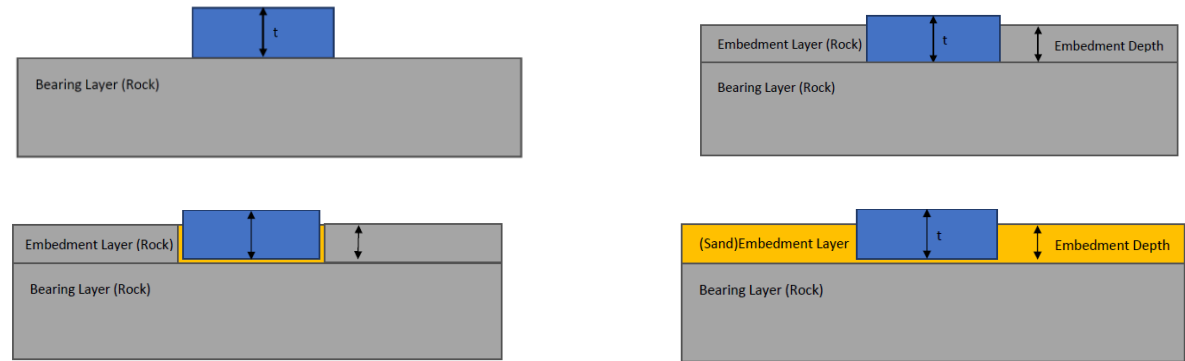
OK    Cancel    Show Table

# Task 3 – Implement Lateral Resistance

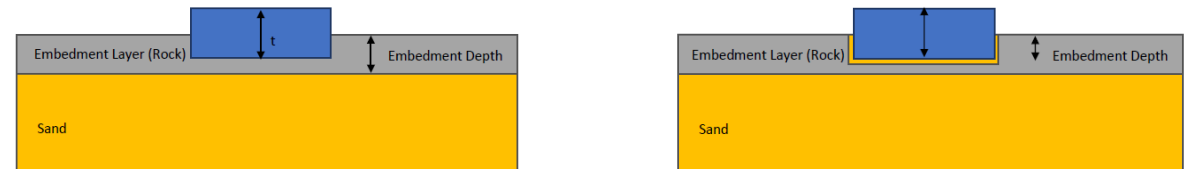
- Vertical and lateral resistance for numerical stability of bridge foundation models.
- Lateral resistance of embedded footings in FL limerock and sand.
- FL limerock passive resistance (based on model in  $q$ - $p$  space and base friction).
- Sand passive resistance (Log-spiral).
- Validate formulations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



## Homogeneous Limerock

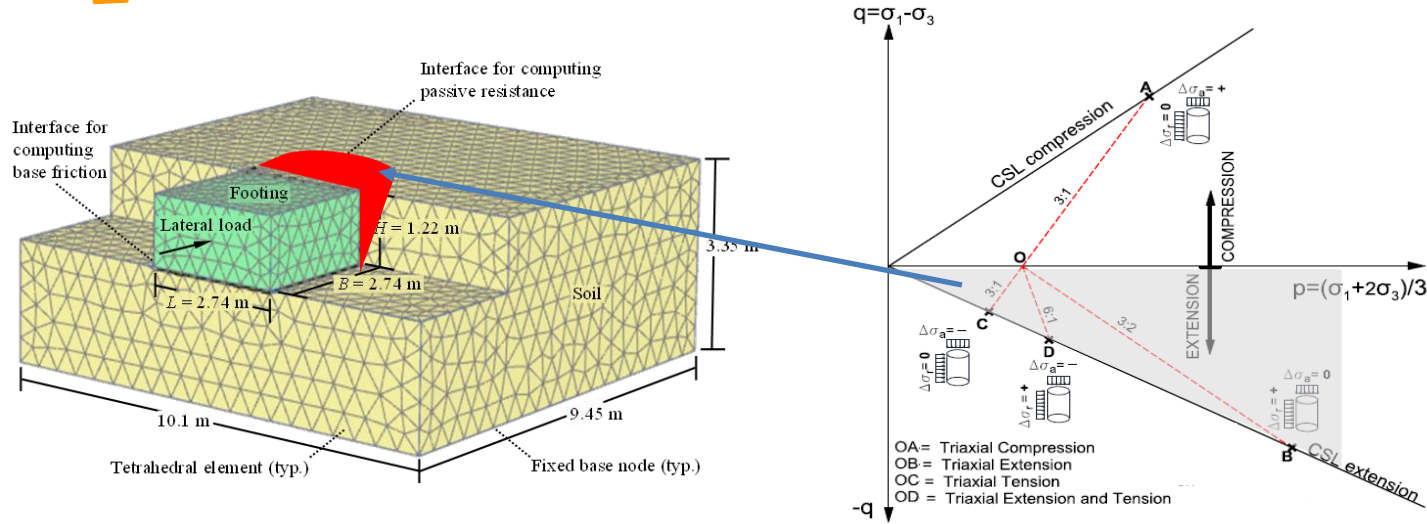


## Limerock over Sand

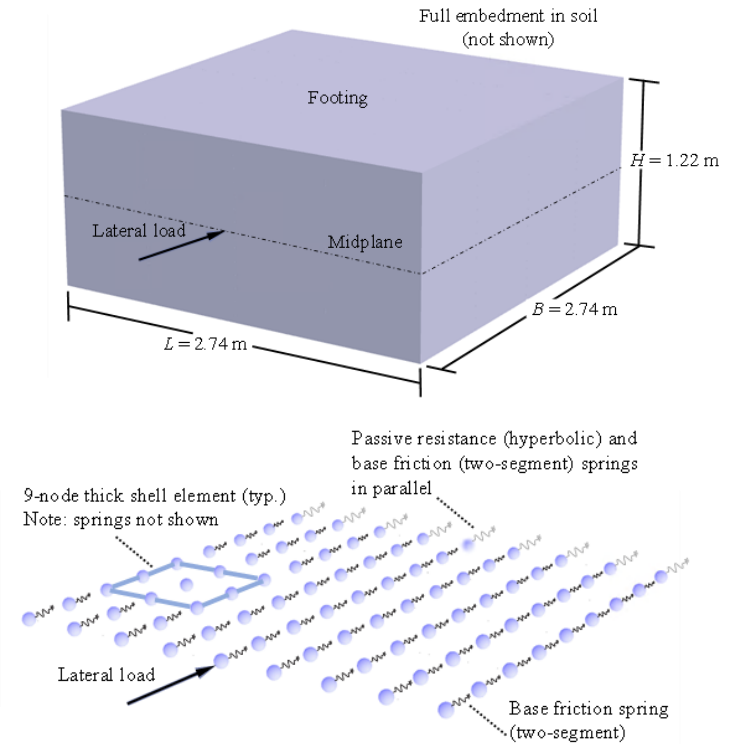


# Task 3 – Implement Lateral Resistance

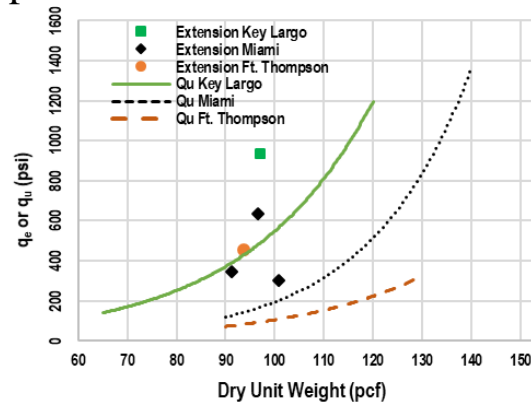
FEM



FB-Multiplier



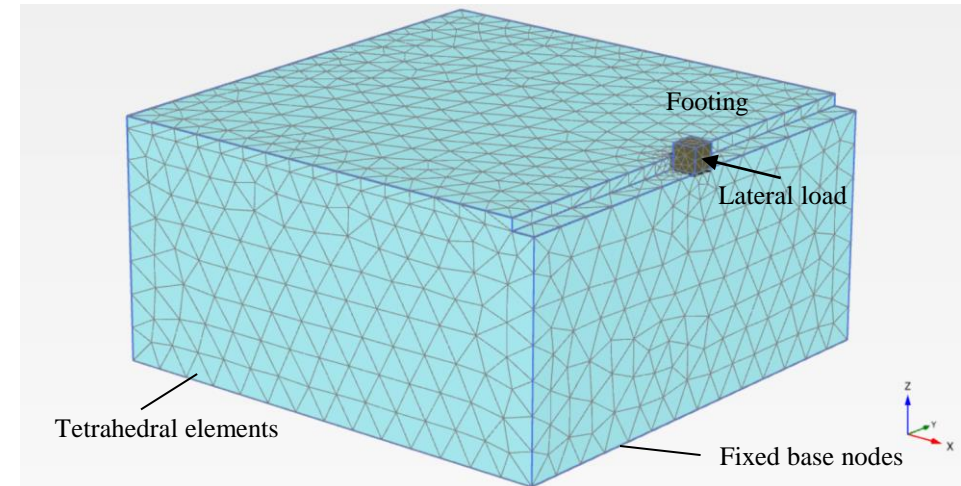
- Stress path in extension space may be critical-SMO performing triaxial tests
- Extension strength influenced by porosity and sedimentary formation process
- Phase I research tested a few rock cores in extension space
- Extension strength,  $q_e$ , at vertical stress  $= 0 \geq q_u$
- Extension strength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



# Task 3 – Implement Lateral Resistance

**Sand: Plaxis passive force model (  $L=B=H=5\text{ m}$ ,  $D_f=2.5\text{ m}$  )**

SOIL	Soil Model	$\gamma_{\text{sat}}$ ( $\text{kN/m}^3$ )	$\gamma_{\text{unsat}}$ ( $\text{kN/m}^3$ )	$E'_{\text{ref}}$ ( $\text{kN/m}^2$ )	$\nu$ (nu)	$c'_{\text{ref}}$ ( $\text{kN/m}^2$ )	$\phi'$ (phi)	$\psi'$ (psi )
<b>Footing</b>	Linear-elastic	21	-	$200 \times 10^6$	0.2	-	-	-
<b>Sand</b>	Mohr-coulomb	19	19	$95.76 \times 10^3$	0.27	10	39	14
<b>Interface</b>	Mohr-coulomb	19	19	$95.76 \times 10^3$	0.27	6.6667	26.13	3



# Task 3 – Implement Lateral Resistance

**Predicted passive and base friction force ( $L=B=H= 5 \text{ m}$ ,  $D_f = 2.5 \text{ m}$ )**

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

**Rankine**

$$k_p = \tan^2 \left( 45^\circ + \frac{\phi}{2} \right) = \frac{1 + \sin \phi}{1 - \sin \phi}$$

Passive earth force		Base friction	
$\gamma_{\text{sat}}$ (kN/m <sup>3</sup> )	19	$\alpha$	0.6
D (m)	2.5	$c'_{\text{ref}}$ (kN/m <sup>2</sup> )	6.8
B (m)	5	L = B (m)	5
$\phi$ (degrees)	39	W (kN)	2625
$K_p$ (Rankine)	4.395	$\delta$ (degrees)	26
$K_p$ (Coulomb)	16.4	$\tan\delta$	0.49
$K_{p\phi}$ (Mokwa)	11.2168		
$K_{pc}$ (Mokwa)	4.3627	Base Friction (kN) $F = \alpha \cdot c \cdot L \cdot B + W \cdot \tan\delta$	1380.2
$P_{\text{ult}}$ (Log-spiral method) (kN)	7060.12		
Passive earth force (kN) $P_p = 0.5\gamma D^2 K_p B + cBDK_p^{0.5}$	5374.96142		

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

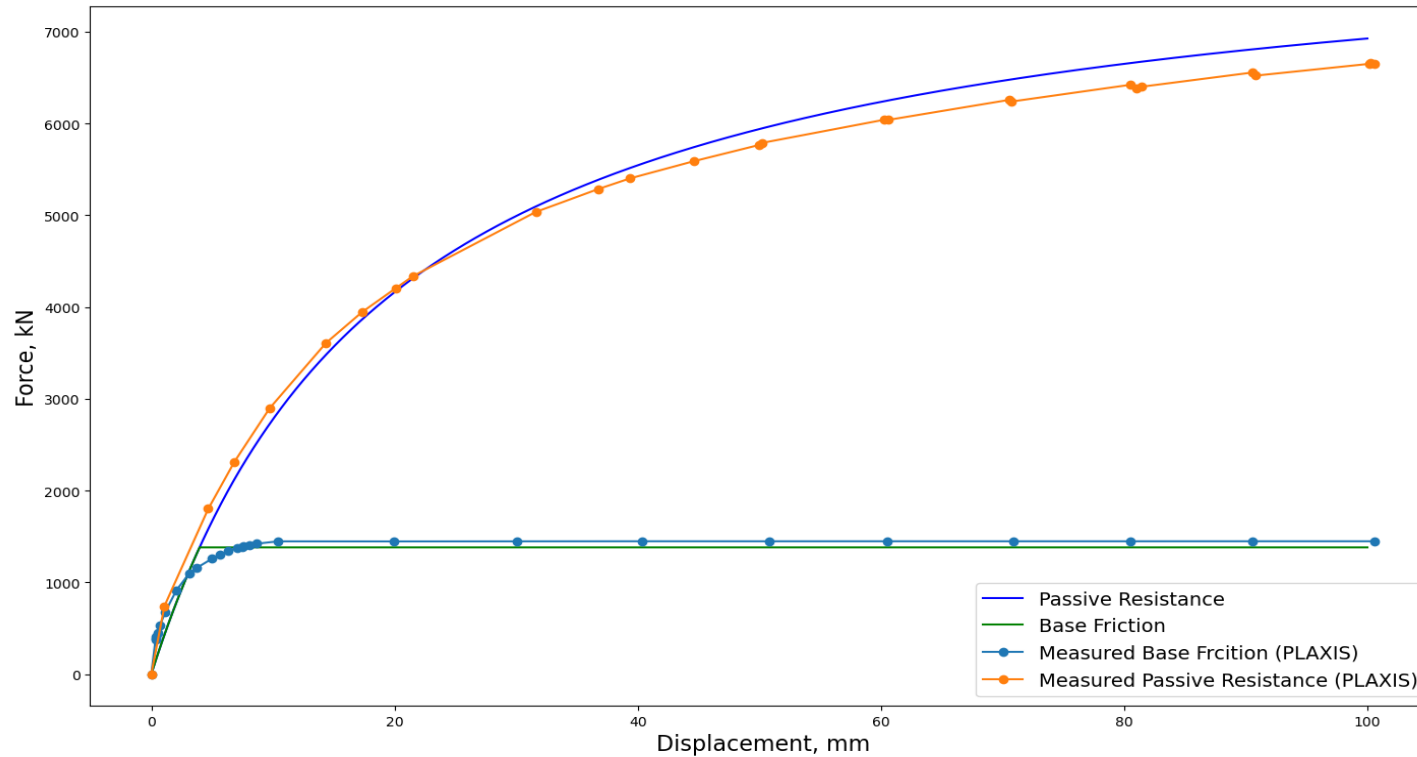
$$E_p = \frac{1}{2} \gamma H^2 K_{p\phi} + 2cHK_{pc} + qHK_{pq}$$

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**  
 (  $L=B=H=5\text{ m}$ ,  $D_f=2.5\text{ m}$  )



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

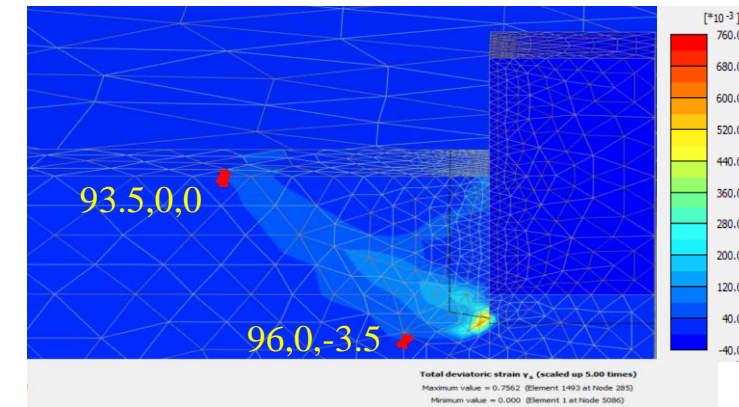
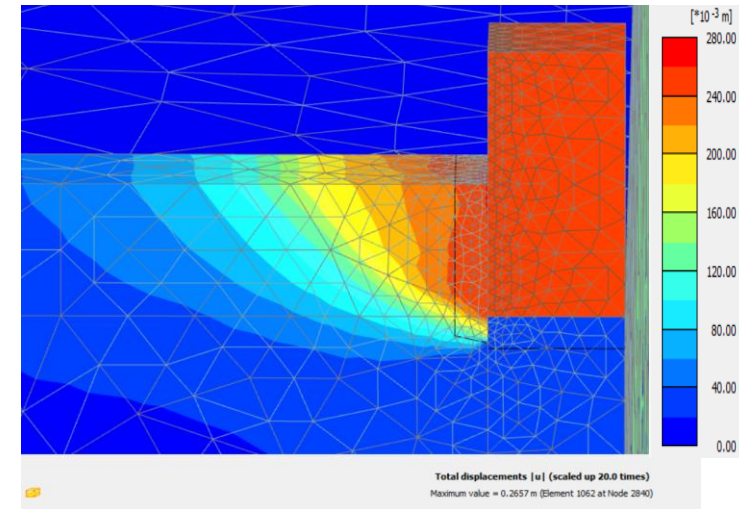
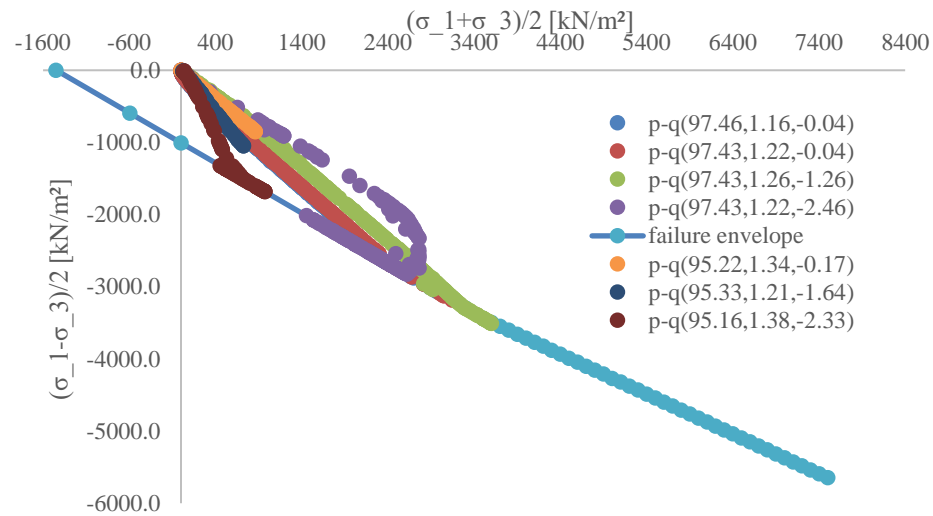
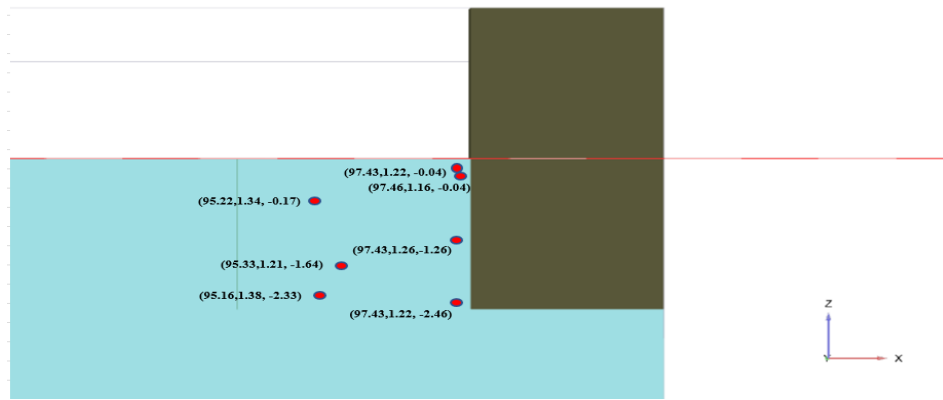
Base Friction Model

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

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

# Task 3 – Implement Lateral Resistance

**Rock: Plaxis stress paths in passive state (  $L=B=H= 2.5\text{ m}$ ,  $D_f = 2.5\text{ m}$  )**



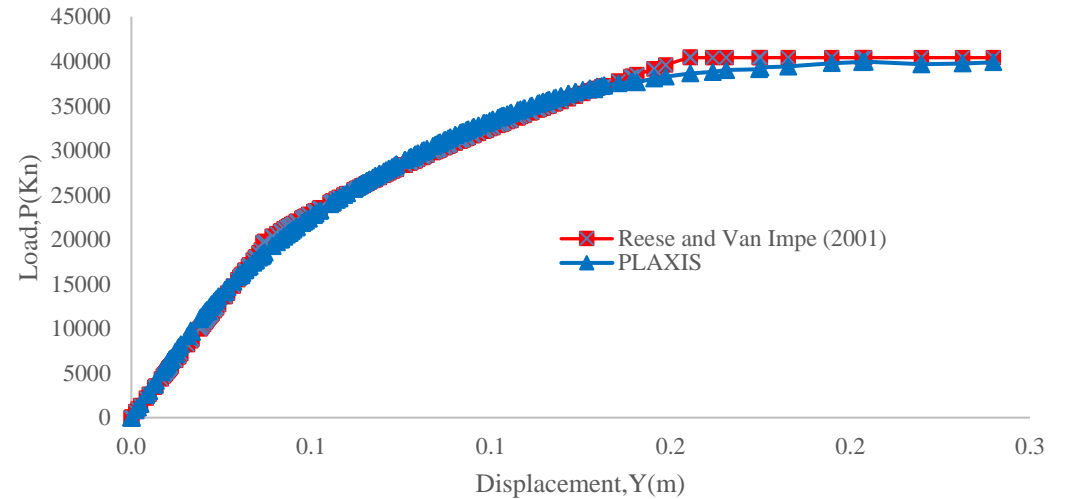
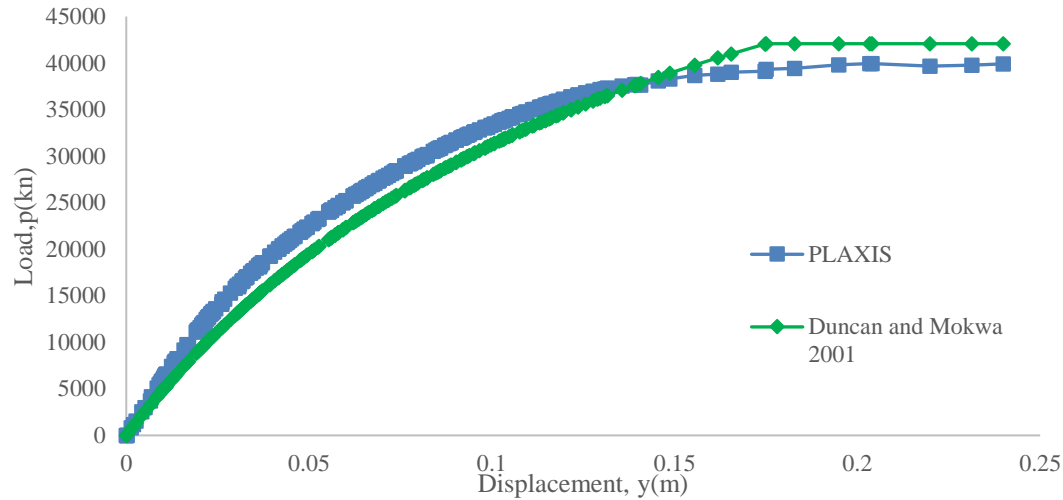
# Task 3 – Implement Lateral Resistance

**Rock: Passive and base friction properties and predicted maximum force  
(  $L=B=H= 2.5 \text{ m}$ ,  $D_f = 2.5 \text{ m}$  )**

Passive earth force		Base friction	
$\gamma_{\text{sat}}$ (kN/m <sup>3</sup> )	24	$\alpha$	0.5
$D_f$ (m)	2.5	$c'_{\text{ref}}$ (kN/m <sup>2</sup> )	1400
$B$ (m)	2.5	$L = B$ (m)	2.5
$E_{\text{mass}}/E_{\text{intact}}$	0.7	$W$ (kN)	656.3
$q_u$ (kN/m <sup>2</sup> )	7700		
Depth below rock surface, $Z_r$ (m)	2.5	$\delta$ (degrees)	29.5
Depth of embedment (m)	2.5		
$K_p$	5.5	$\tan\delta$	0.57
Passive earth force (kN) $P_p = 0.5\gamma D^2 K_p B + 2cDB(K_p)^{1/2}$	42072.4		
Passive earth force $P_p$ (kN) (Reese and Van Impe 2001)	40425	Base Friction (kN) $F = \alpha \cdot c \cdot L \cdot B + W \cdot \tan\delta$	4746.3
$P_p = (E_{\text{mass}}/E_{\text{intact}}) \cdot q_u \cdot B \cdot (1 + 1.4 \cdot (Z_r/B)) \cdot (D_f/2)$			

# Task 3 – Implement Lateral Resistance

**Rock: Plaxis and predicted passive force-displacement ( $L=B=H= 2.5\text{ m}, D_f = 2.5\text{ m}$ )**



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

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

$K_{max}$  is the initial stiffness

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

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

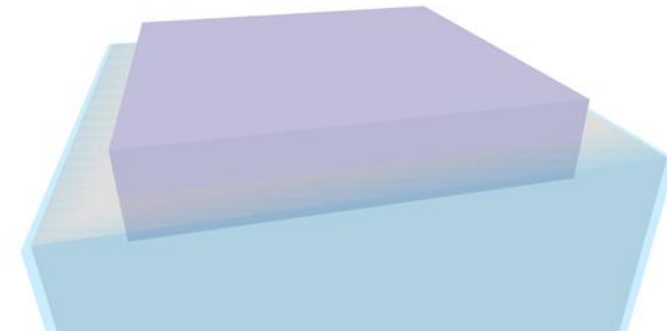
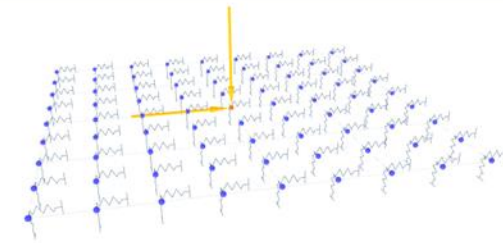
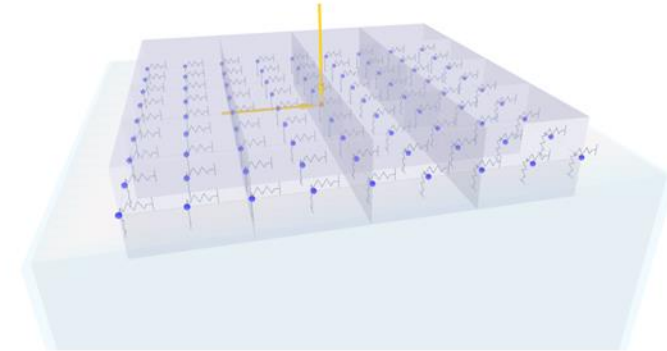
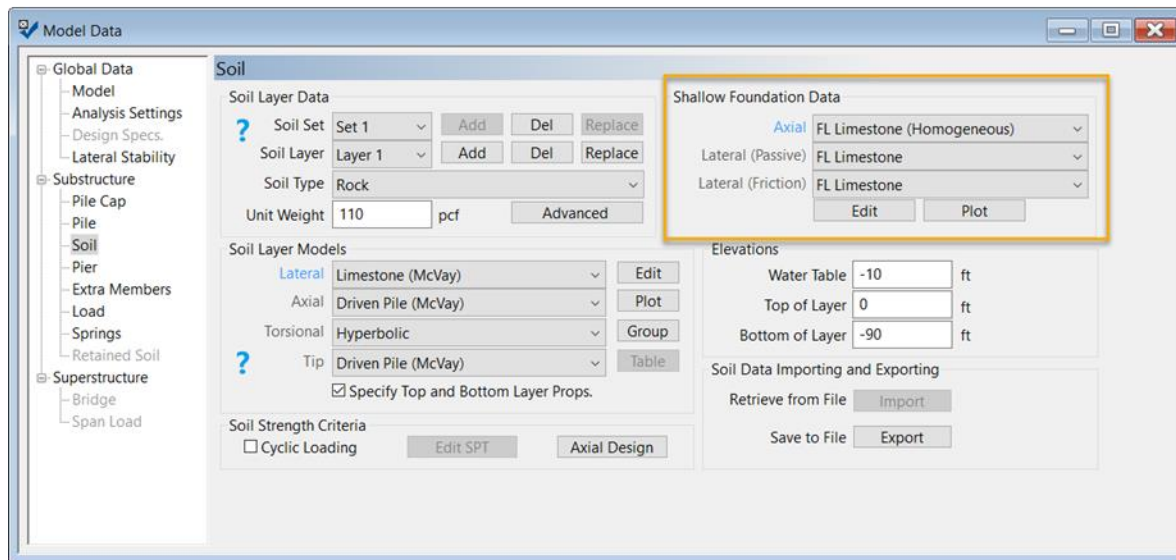
$$p = P_{ult} \quad y \geq 15y_{rm}$$

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

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

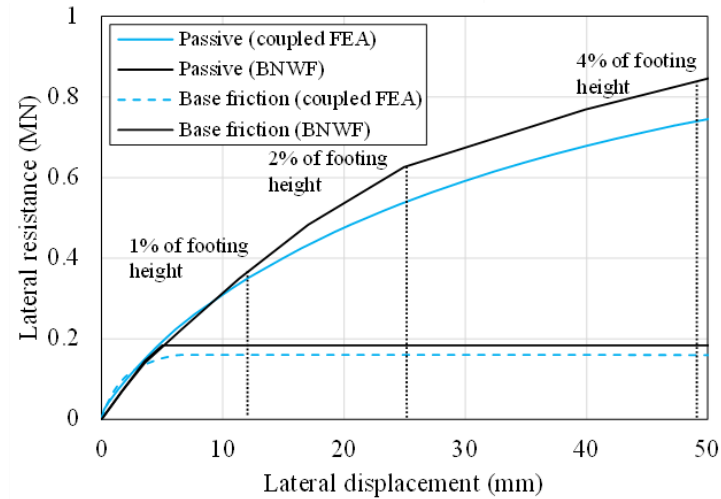
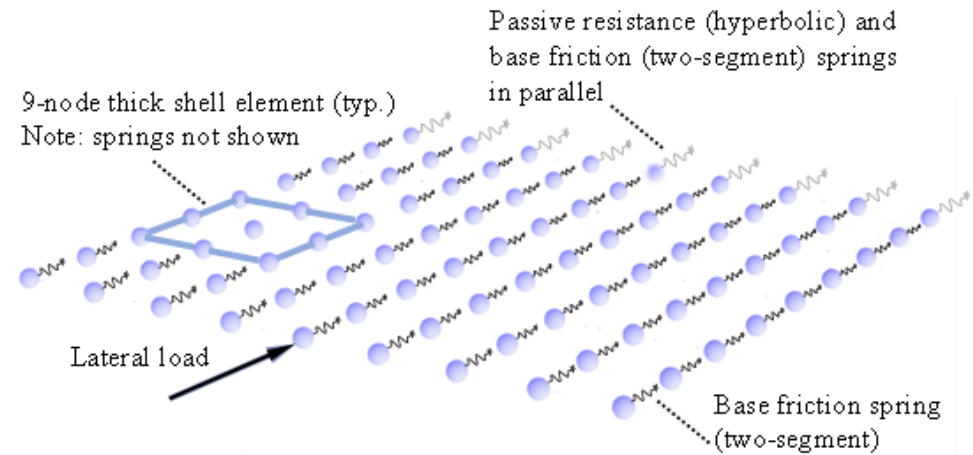
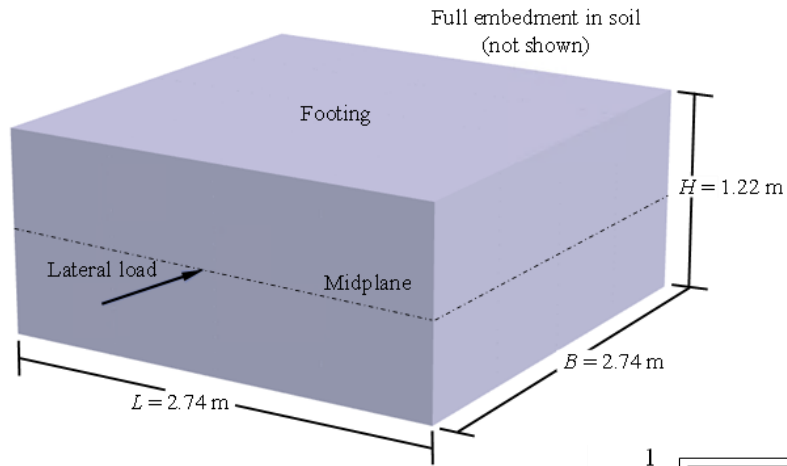
# Task 3 – Implement Lateral Resistance

- Horizontal Passive Resistance Springs
- Horizontal Friction Resistance Springs



# Task 3 – Implement Lateral Resistance

## Spring Model Validation



FEA and the BNWF force-displacement comparison

**Thank You!**

**Questions & Answers**