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

FDOT BED31-977-17

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GRIP August 14th, 2025

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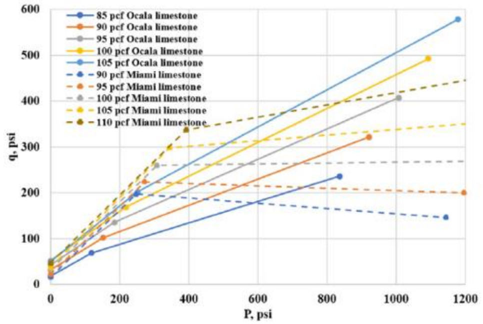
Project Background and Objectives

- FDOT has funded a multiphase research effort on the use of shallow foundations for bridge substructure on limestone.
  - In Phase I (BDV31-977-51) – Developed bearing capacity equations for any footing width, shape, embedment depth and rock-over-sand scenario
  - In Phase II (BDV31-977-124) – Performed three full scale load tests to validate the bearing capacity equations
    - Developed moduli by formation 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
  - Effects of inclined and eccentric loadings on bearing capacity and load-settlement
- Document the feature sets developed in FB-MulitPier in the user manual

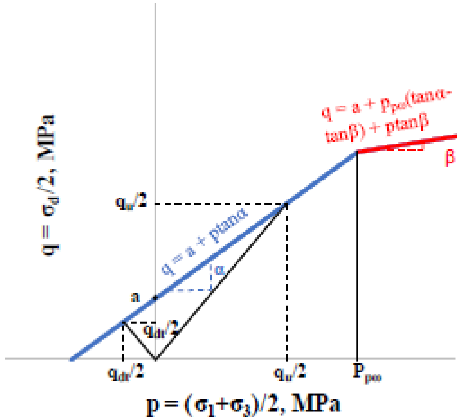


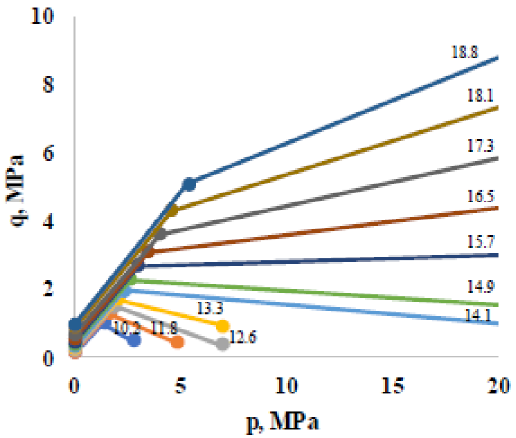
Project Tasks

- **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 (current)
- Task 5 – Develop Software Manual Documentation
- Task 6 – Draft Final and Closeout Teleconference
- Task 7 – Final Report

Task 1 – Implement Strength Envelopes – Summary

- **FB-MultiPier Integration**
  - Implemented Florida bearing capacity equations and Carter & Kulhawy analyses for pier design
  - Bi-linear strength parameters based on bulk dry unit weight/porosity and formation
  - Rock-over-sand case requires modulus ratio and intact modulus functions
- **UI and Engine Updates**
  - FB-MultiPier UI updated for shallow foundation design in Florida limestone
  - Analytical engines enhanced for accuracy
- **Bearing Stress Comparisons**
  - Extensive comparisons between FB-MultiPier and Florida bearing equations
  - Errors <2.5% in both English and SI units, considered acceptable





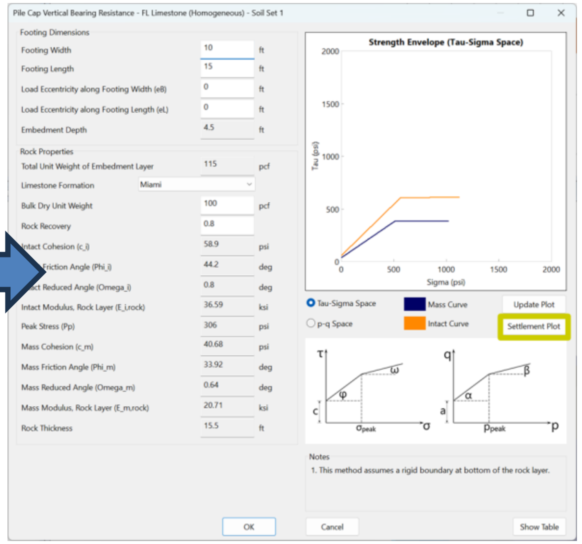
$$Q_u = min\,(Q_{u1}, Q_{u2}) * \xi / N_R$$

$\xi =$ Shape factor;

$N_R =$ Rock over sand reduction factor;

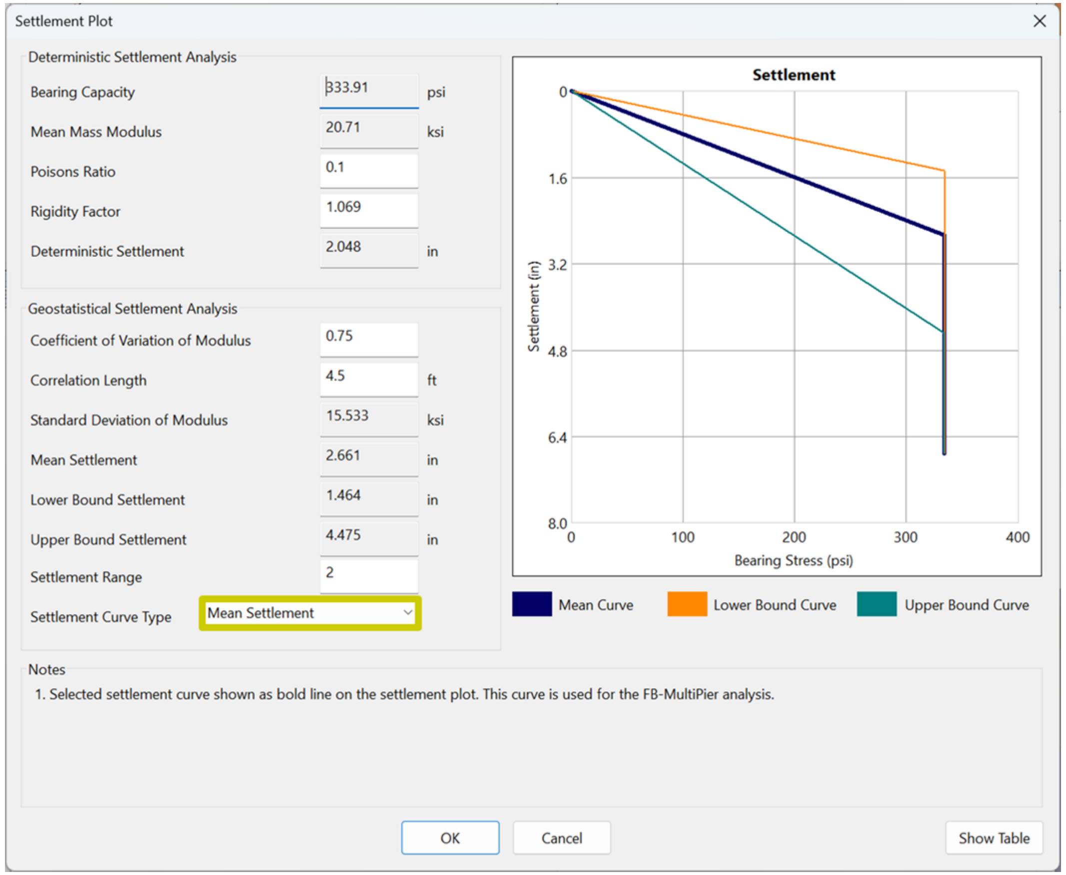
$$Q_{u1} = n * c * N_c + q * N_q$$

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



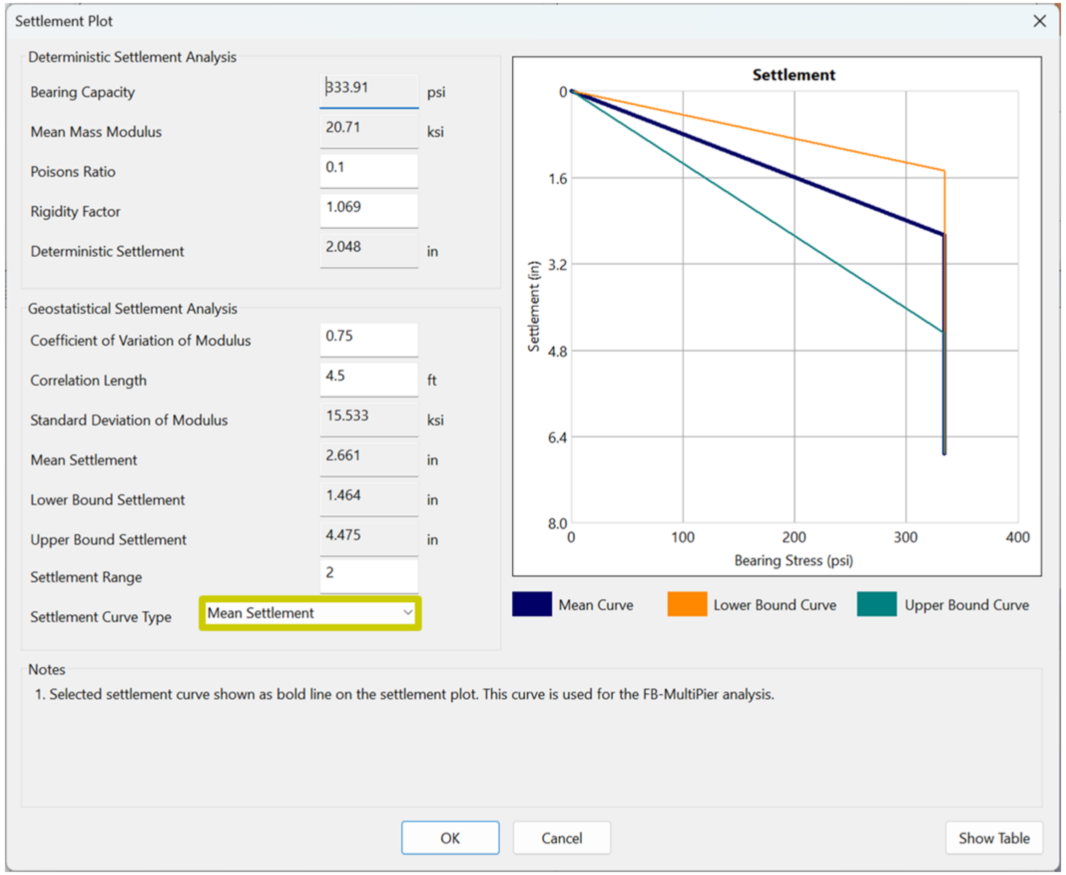
Task 2 – Implement Load-settlement Analysis – Summary

- **Florida Limestone Characteristics**
  - High bulk porosity
    - Bi-linear strength envelopes, ductile stress-strain response, and low Young's Modulus compared to sand
  - Service limit state (settlement) may control shallow foundation design
- **Probabilistic Settlement Approach**
  - High CV of Young's Modulus
    - Use probabilistic settlement approach (Fenton & Griffith)
  - Large zone of influence (2B) affects differential and mean settlement
- **Stress-Strain Response & Bearing Failure**
  - Bilinear stress-strain response: linear until failure/crushing
  - Excessive rock crushing due to limestone's high porosity
- **Rock-over-Sand Layer Analysis**
  - FEM used to analyze footing on rock-over-sand
  - Harmonic Mean Modulus replicates FEM results for modulus and zone of influence
- **Field Load Test Validation**
  - Validated with field load tests in Phase II
  - Numerical simulations in Phase III
- **FB-MultiPier Implementation (Task 2)**
  - Settlement predictions for homogeneous and rock-over-sand cases implemented into FB-MultiPier
  - Settlement influenced by rock mass modulus CV, modulus ratio, and stress-dependent harmonic mean modulus for rock-over-sand cases



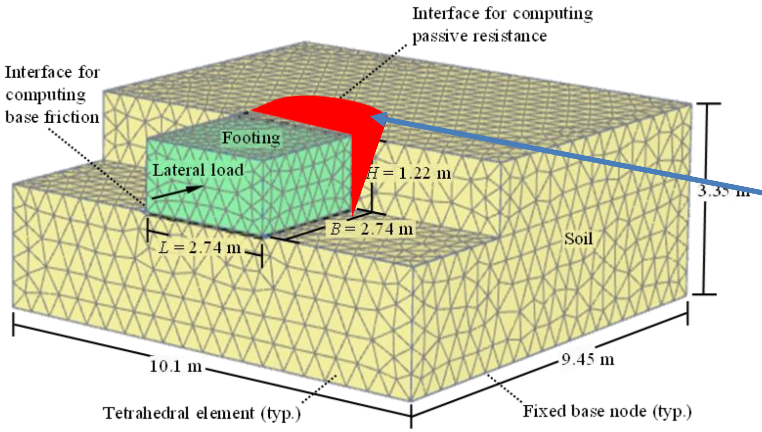
Task 2 – Implement Load-settlement Analysis – Summary

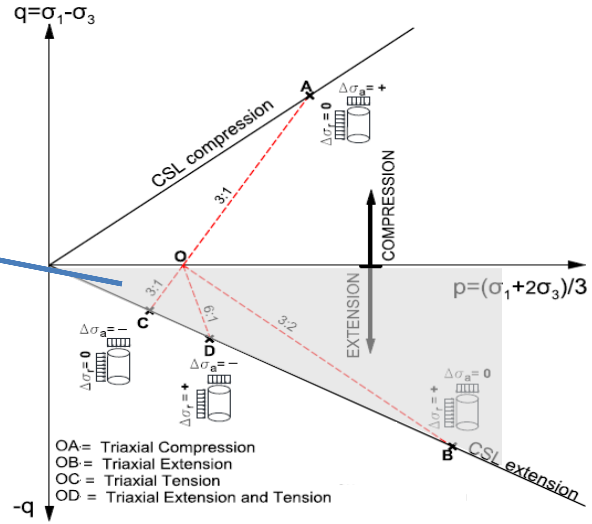
- **Florida Limestone Characteristics**
  - High bulk porosity → bi-linear, ductile stress-strain response
  - Young's Modulus only slightly higher than sand
  - Settlement often governs foundation design
- **Probabilistic Settlement Approach**
  - High variability (CV) in Young's Modulus
  - Use Fenton & Griffith probabilistic method
  - Large influence zone (2B) affects mean and differential settlement
- **Stress-Strain Response & Bearing Failure**
  - Bilinear: linear up to failure/crushing
  - Excessive rock crushing due to high porosity
- **Rock-over-Sand Foundations**
  - FEM analysis for layer effects
  - Harmonic Mean Modulus replicates FEM results
- **Validation & Implementation**
  - Field load tests (Phase II) and numerical simulations (Phase III)
  - Settlement predictions integrated into FB-MultiPier
  - Influencing factors: rock mass modulus CV, modulus ratio, stress-dependent harmonic mean



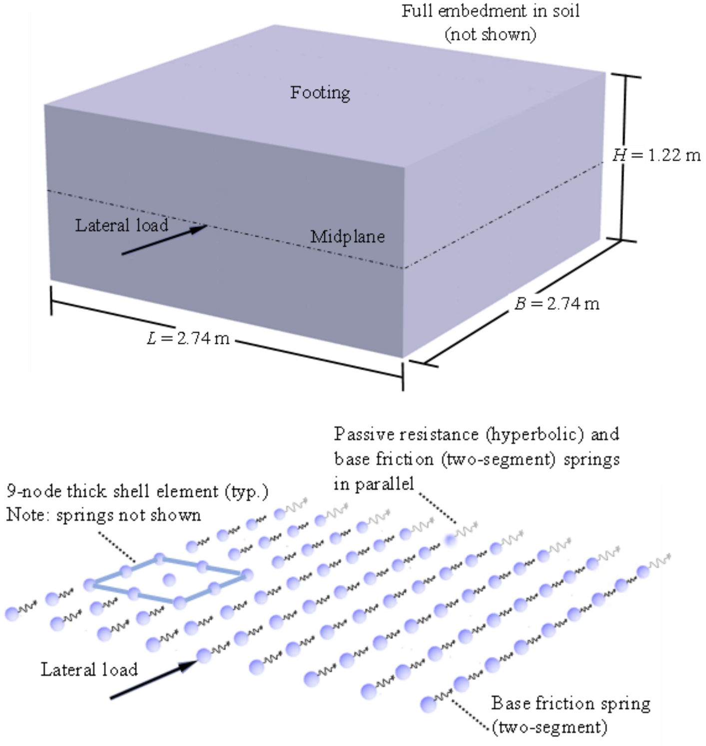
Task 3 – Implement Lateral Resistance

FEM

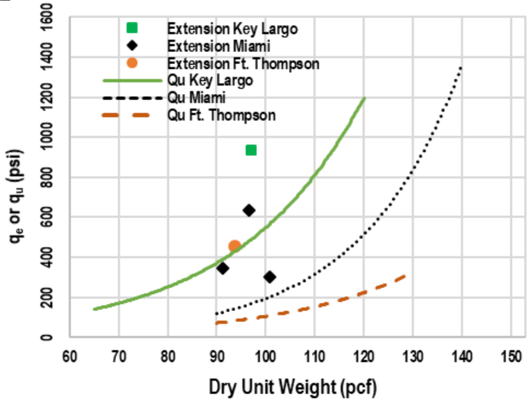




FB-Multipier



- 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

Log-Spiral Based Passive Earth Pressure Coefficients

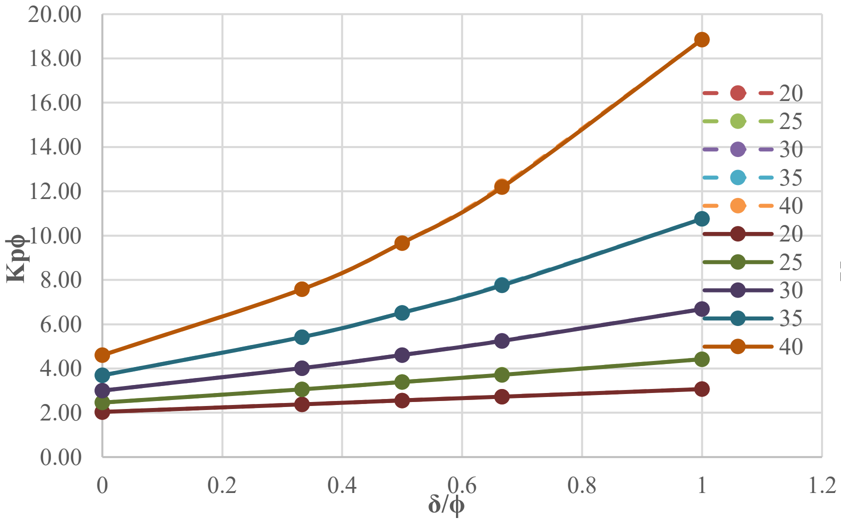
- Soil (c,ϕ) failure surface is observed to be generally log-spiral
- Coulomb's theory over-estimates Kp with increasing interface friction
- Lui et al (2018) used a modified log-spiral method and verified with FEM
- Kp functions for friction, cohesion, and surcharge contributions developed for implementation in FB-MultiPier.

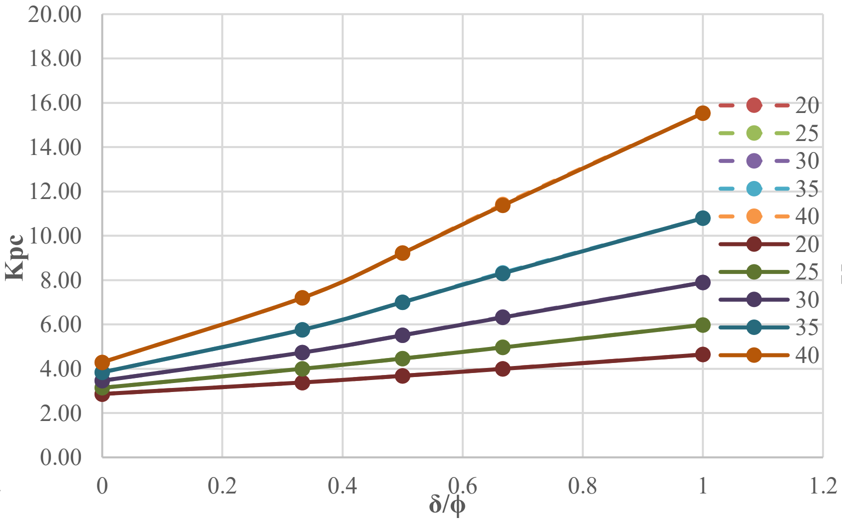
Table 1
Results comparison ($\varphi = 40°$).

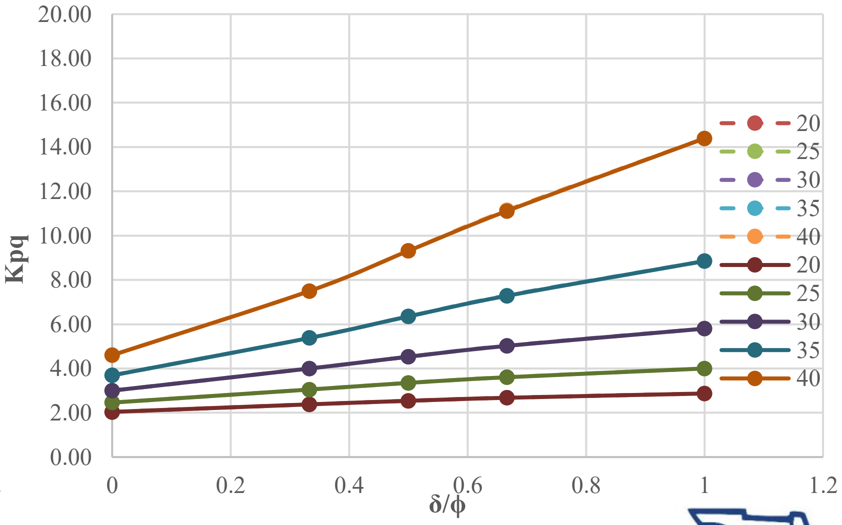
δ/φ	$K_p = 2P_p/(\gamma H^2) = 2P_{p,h}/(\gamma H^2 \cos\delta)$					
	Coulomb theory	Soubra and Macuh (2002)	Patki et al. (2015b)	Shiau et al. (2008), LB (UB)	Logarithmic spiral method	
					Duncan and Mokwa (2001)	This study
0	4.6	4.6	4.6	4.6 (4.61)	4.6	4.6
1/3	8.15	7.62	7.62	6.87 (7.79)	8.17	7.58
1/2	11.77	9.81	9.82	8.79 (10.03)	10.5	9.67
2/3	18.72	12.6	12.6	11.3 (12.87)	13.08	12.24
1	92.72	20.01	20.01	18.64 (20.1)	17.5	18.86

Note: LB and UB are the lower and upper bounds, respectively.

from Lui et al. (2018)

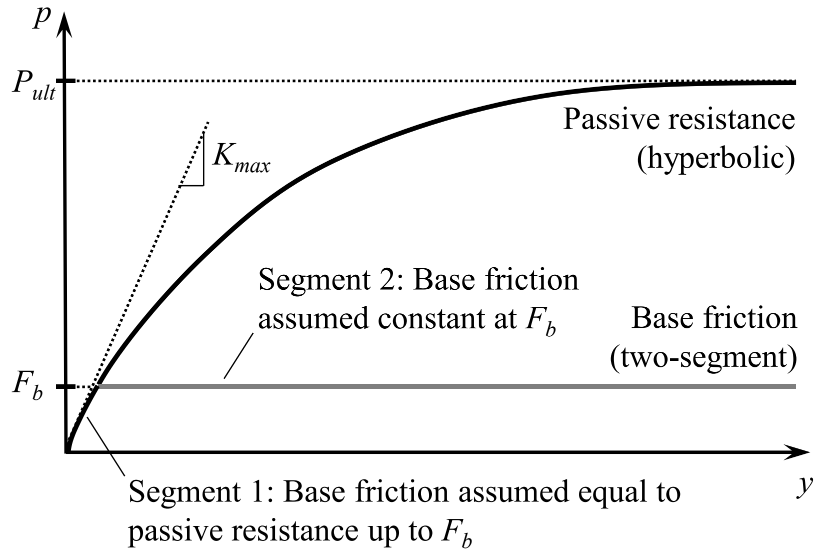






Task 3 – Implement Lateral Resistance

Passive Force, P, and Base Friction, F_b, Displacement, y, Model



Passive Resistance

$$P = \frac{y}{\left[\frac{1}{K_{max}} + R_f \frac{y}{P_{ult}}\right]} \qquad R_f = 1 - \frac{P_{ult}}{K_{max} \cdot \Delta_{max}}$$

K_{max} is the initial stiffness

$$P_{ult} = R_{3D} \cdot E_p \cdot B \qquad E_P = \frac{1}{2}\gamma H^2 K_{p\varphi} + cHK_{pc} + qHK_{pq}$$

$$R_{3D} = 1 + \left(K_{p\phi} - K_a\right)^{\frac{2}{3}}\left[1.1S^4 + \frac{1.6x}{1 + 5\frac{B}{H}} + \frac{0.4\left(K_{p\phi} - K_a\right)S^3x^2}{1 + 0.05\frac{B}{H}}\right] \qquad S = 1 - \frac{H}{D_t + H}$$

where R_{3D} is a 3-D modifying factor, B is the footing width, $K_a = tan(45 - \frac{\varphi}{2})^2$, $K_{p\varphi}$, K_{pc}, and K_{pq} represent the passive earth pressure coefficients associated with friction angle, cohesion, and surcharge, respectively, γ is the unit weight of soil, H denotes the footing thickness, c is the cohesion, q is the surcharge loading, x=1 for a single footing, D_t is the distance from the ground surface to the top of the footing.

Base Friction

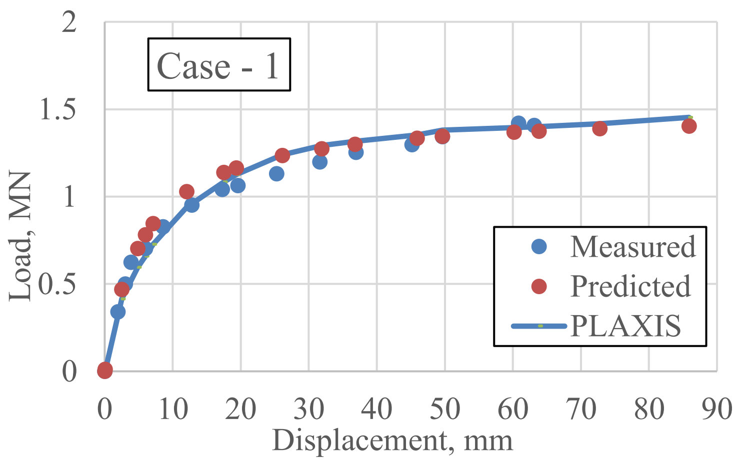
$$F_b = \alpha \cdot c \cdot L \cdot B + W \cdot tan\delta$$

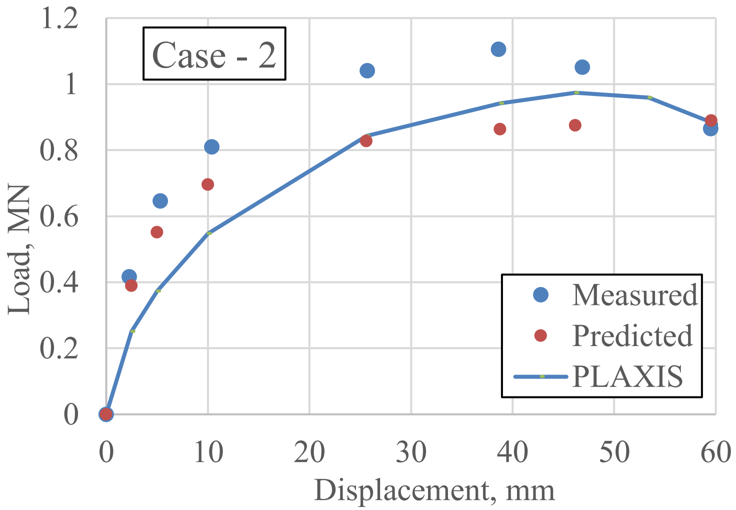
where α is the adhesion factor, c is cohesion, L is the footing length, W is the dead load on footing, δ is the interface friction.

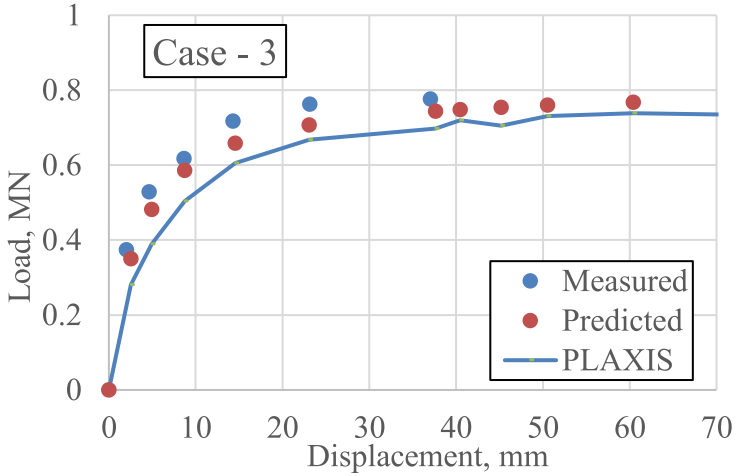
Task 3 – Implement Lateral Resistance

Passive Force-Displacement in Sand: Full-Scale Tests

Case	Source	Soil Type	Foundation Member Geometry			Soil Properties				Test Results	
			L (m)	B (m)	H (m)	c (kPa)	ϕ (°)	γ (kN/m^3)	δ (°)	P_{ult}, kN	Δ_{max}/H
1	(Rollins and Cole, 2006)	Silty Sand	5.18	3.05	1.12	27.3	27	19	21	1428	0.05
2	(Rollins and Cole, 2006)	Clean Sand	5.18	3.05	1.12	0	39	18.4	30	1090	0.05
3	(Rollins and Cole, 2006)	Fine Gravel	5.18	3.05	1.12	3.8	34	20.8	26	774	0.04







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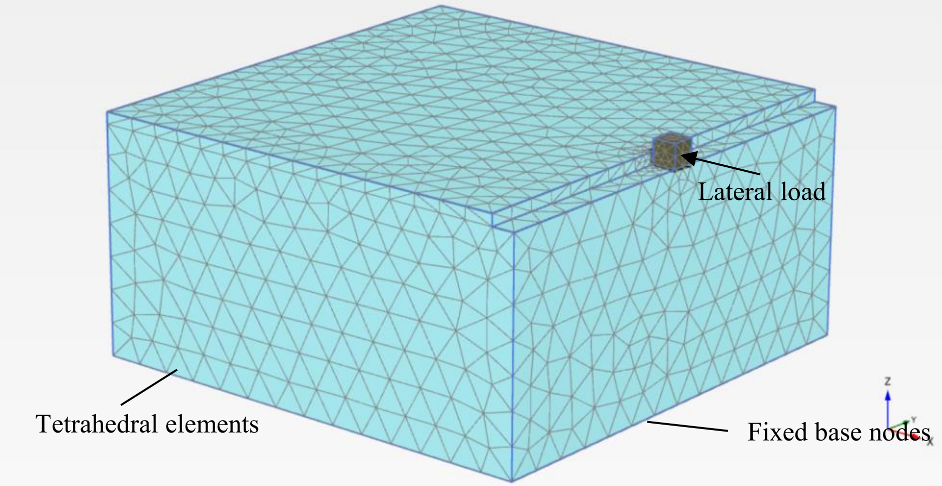
Task 3 – Implement Lateral Resistance

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

SOIL	Soil Model	γ_{sat} (kN/m^3)	γ_{unsat} (kN/m^3)	E'_{ref} (kN/m^2)	v (nu)	c'_{ref} (kN/m^2)	φ' (phi)	ψ'(psi)
Footing	Linear-elastic	21	-	200x10^6	0.2	-	-	-
Sand	Mohr-coulomb	19	19 Footing	95.76x10^3	0.27	10	39	14
Interface	Mohr-coulomb	19	19	95.76x10^3	0.27	6.6667	26.13	3



Passive Model

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

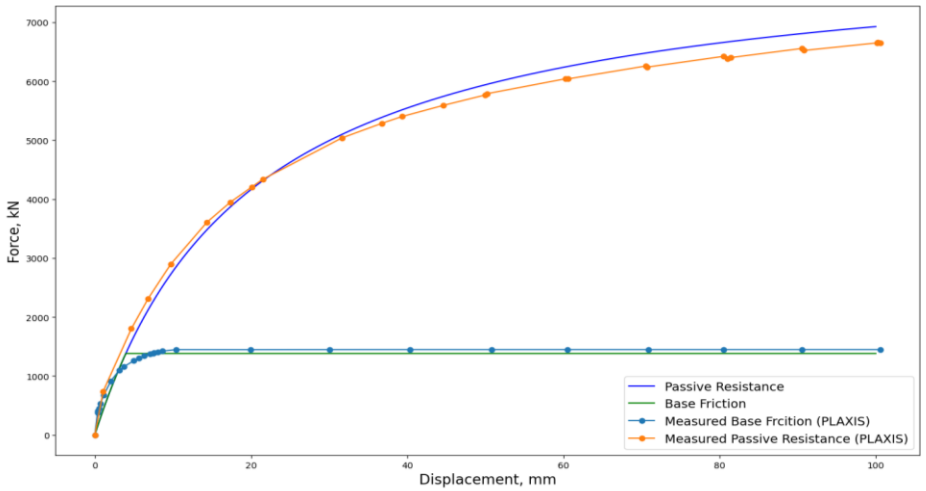
$$R_f = 1 - \frac{P_{ult}}{K_{max} \cdot \Delta_{max}}$$

K_{max} is the initial stiffness

Base Friction Model

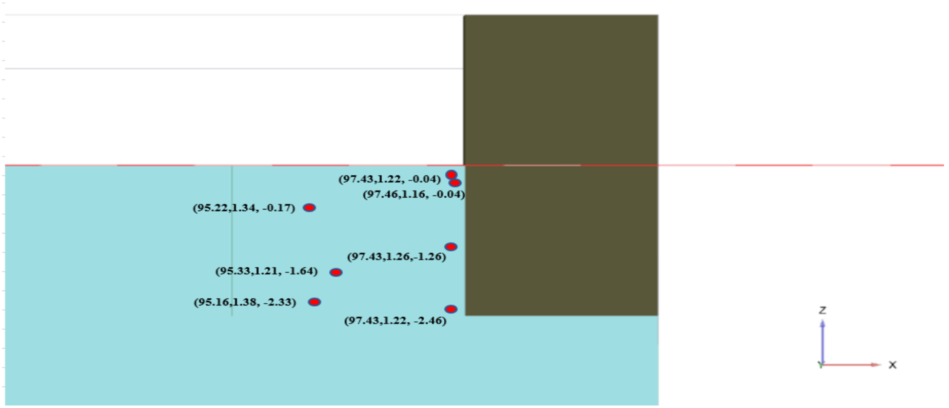
$F = K_{max}\, y \quad y \le y_{\text{intersection with Pult}}$

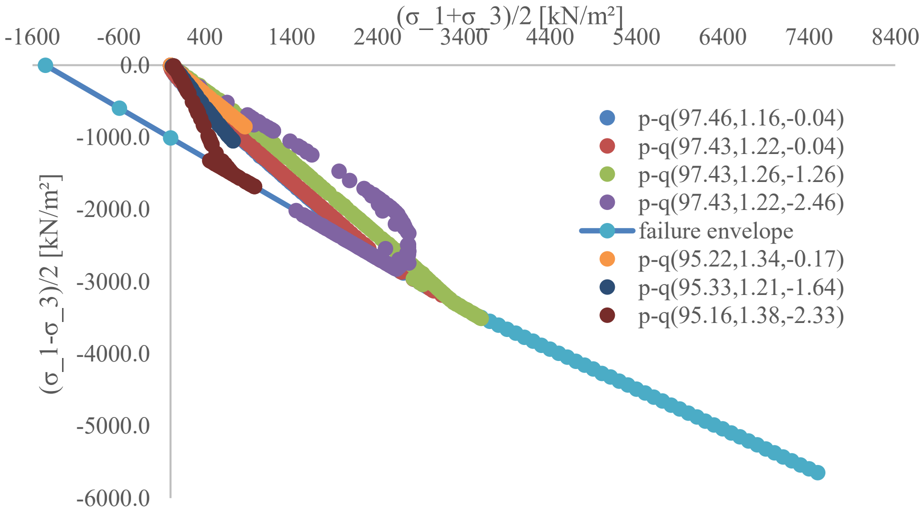
$F = F_{ult} \quad y > y_{\text{intersection with Pult}}$

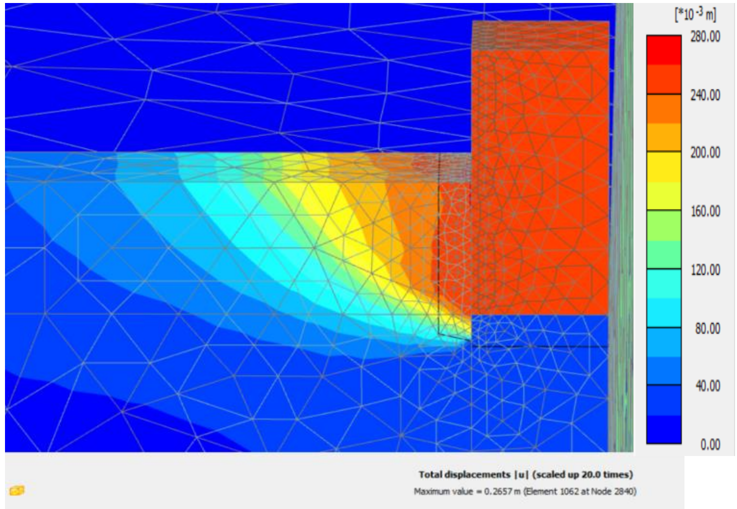


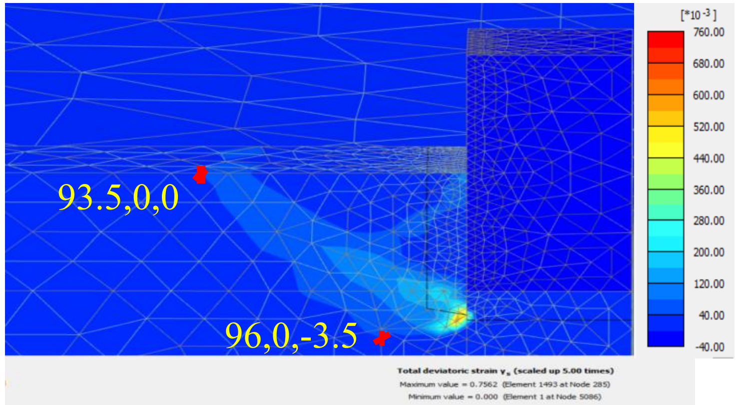
Task 3 – Implement Lateral Resistance

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



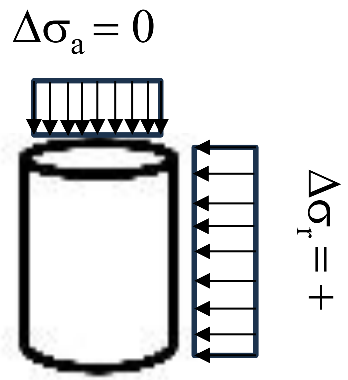






Task 3 – Implement Lateral Resistance

Triaxial Extension Tests on Florida Limestone



- Tests with a range of isotropic stresses encountered in the field (15 psi, 50 psi, and 300 psi).
- Preliminary assessment of passive strength (extension space).
- Limited samples from Ocala, Miami, and Ft Thompson formations.
- Complimentary triaxial compression tests performed at isotropic stress of 50 psi.

Hoek Cell Triaxial Test

Miami Formation

300 psi

Pre-Test Post-Test

Miami Formation

15 psi

Pre-Test Post-Test

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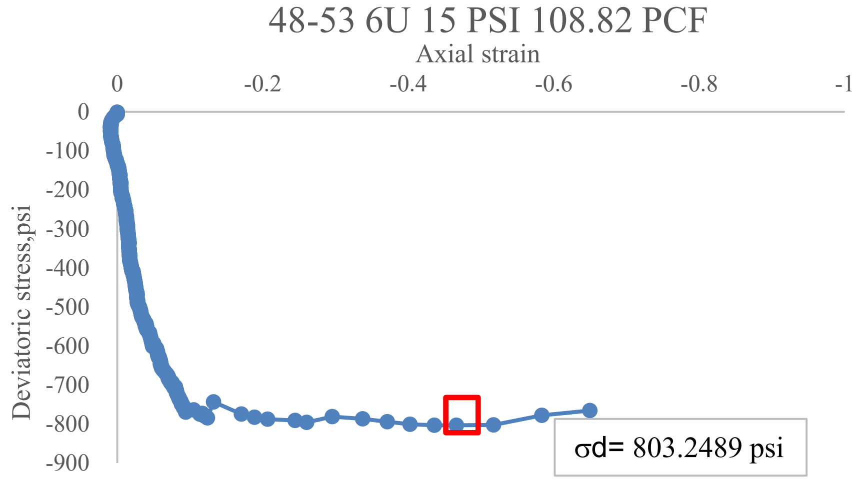
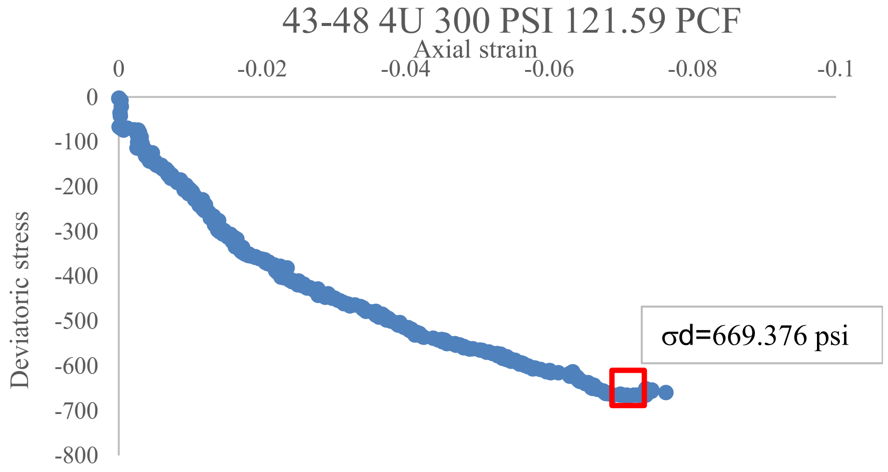
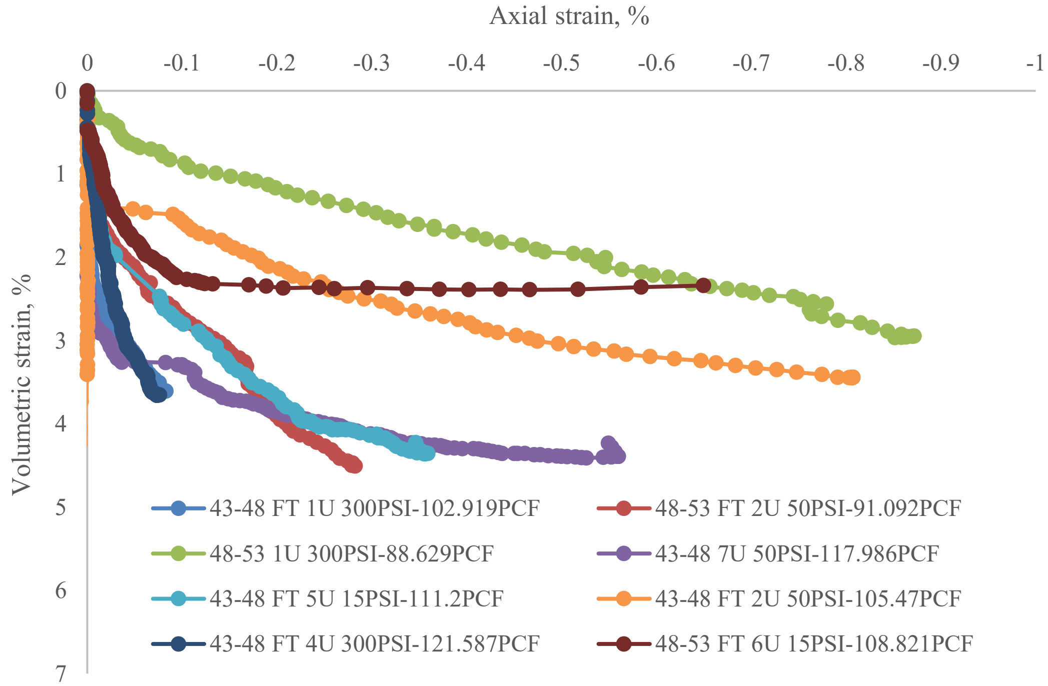
Triaxial Extension Tests: Deviatoric Stress-Strain and Volumetric Strain







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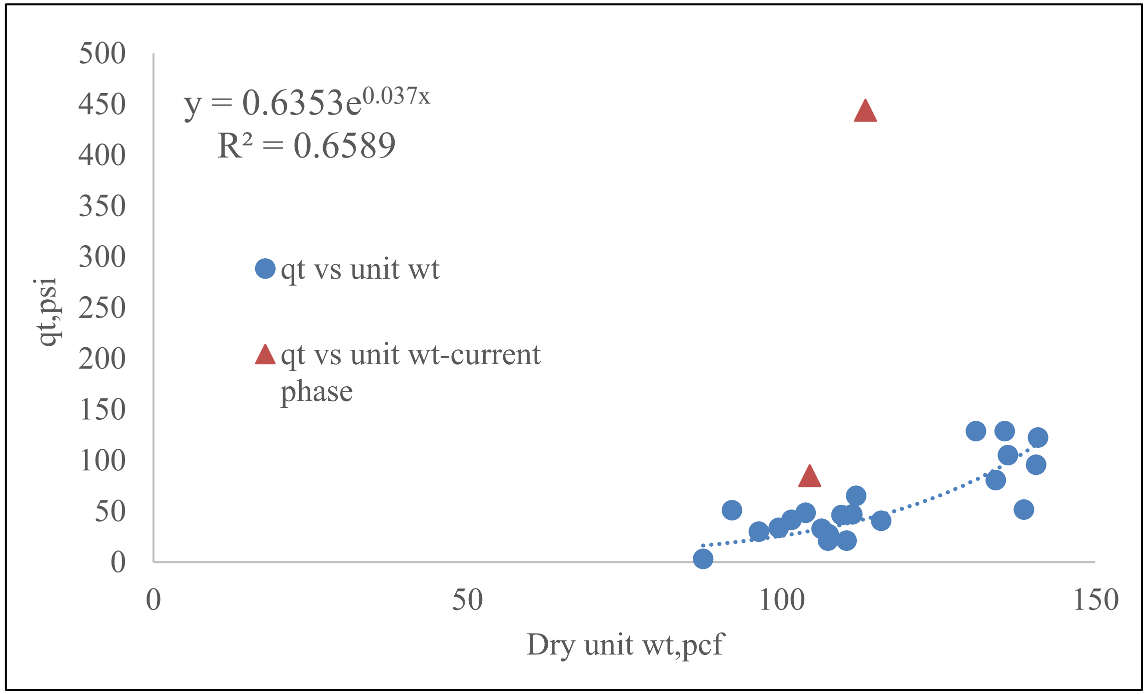
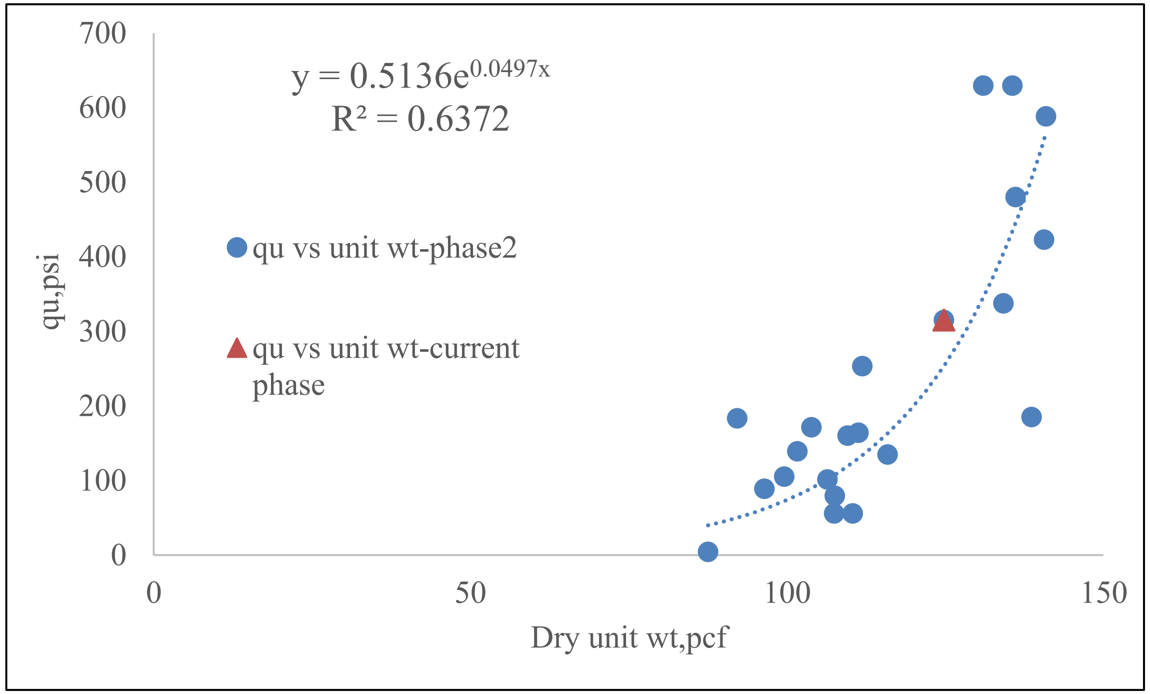
Ft. Thompson q_t and q_u: Current Phase and Phase 1

Split Tension Test data-current phase & phase 1



UC Test data-current phase & phase 1



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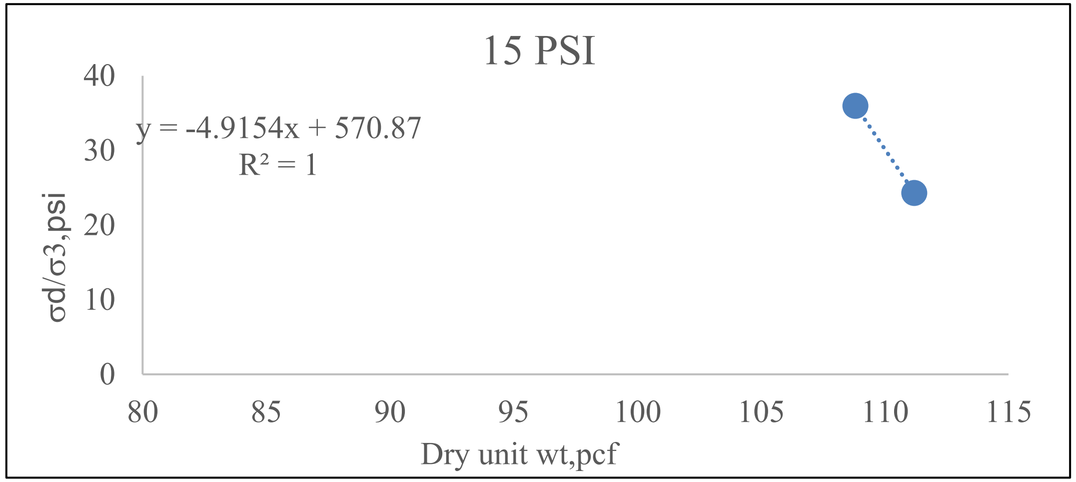
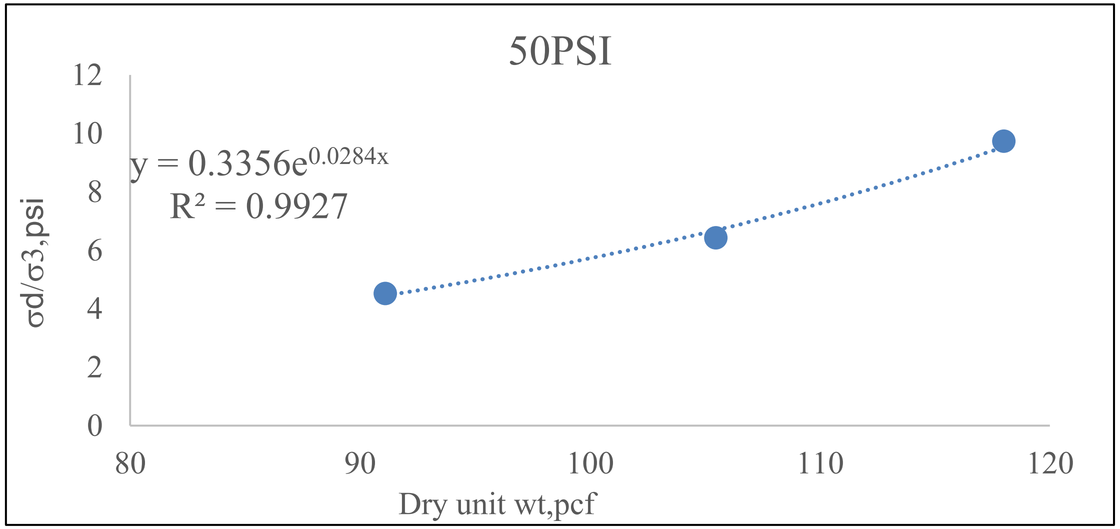
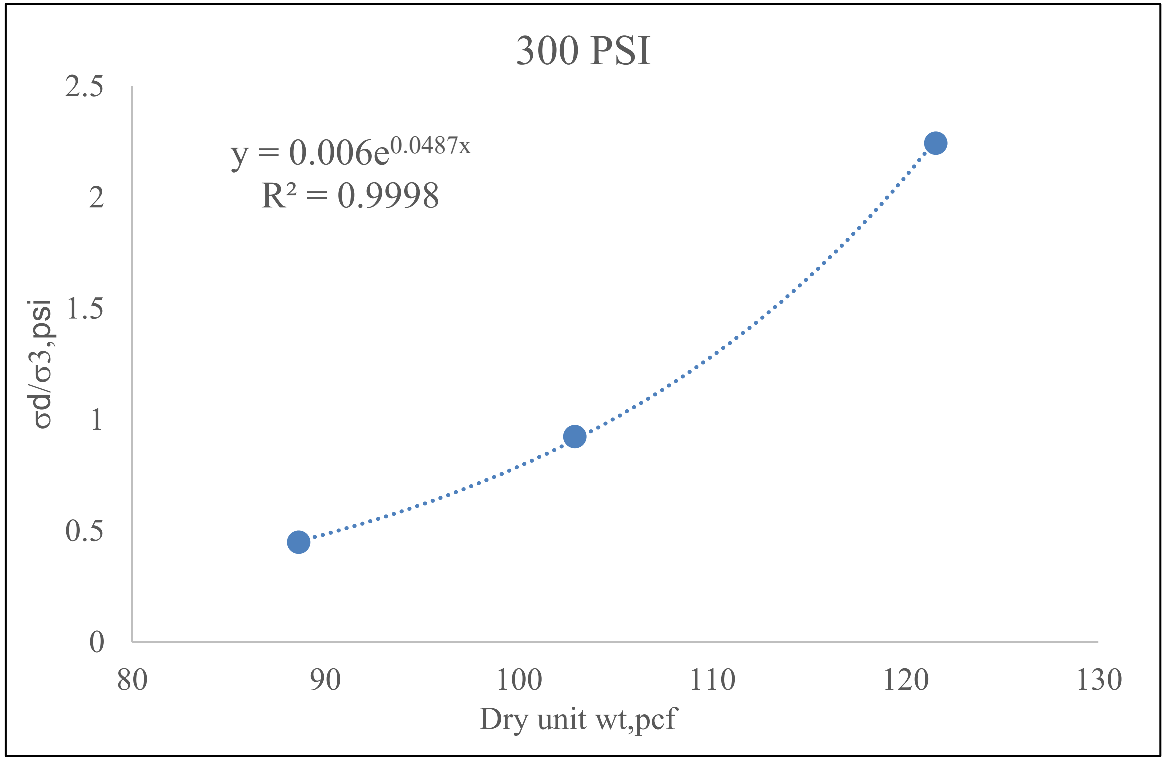
Ft. Thompson Deviatoric Stress – Dry Unit Weight for 15 psi, 50 psi, and 300 psi Confining Stresses







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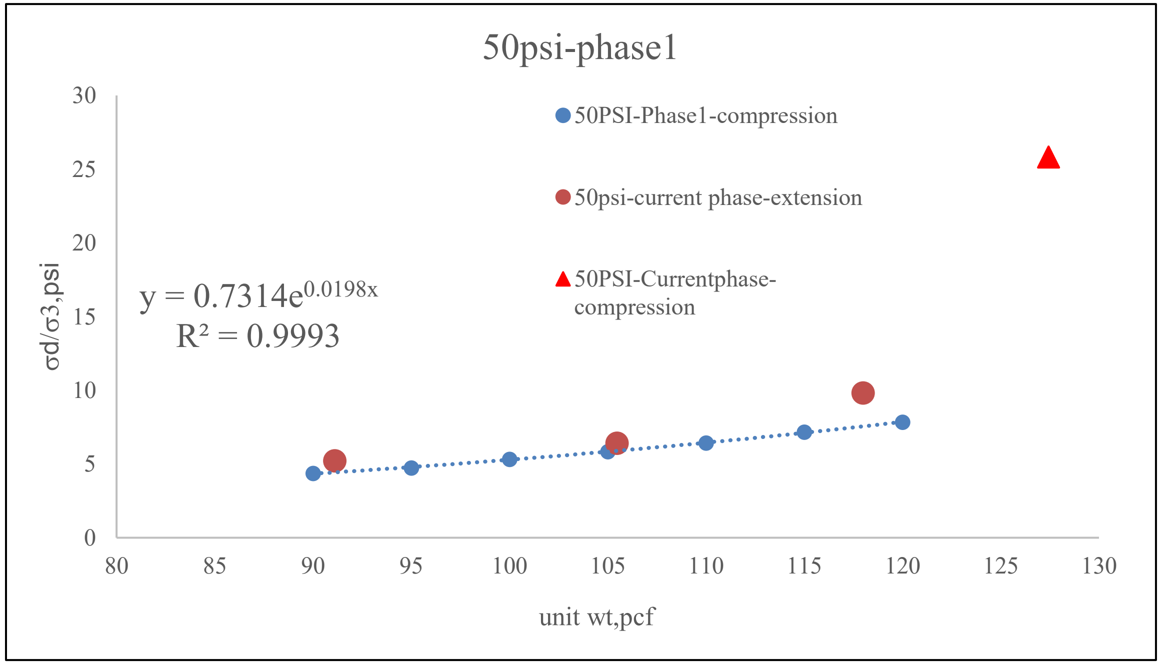
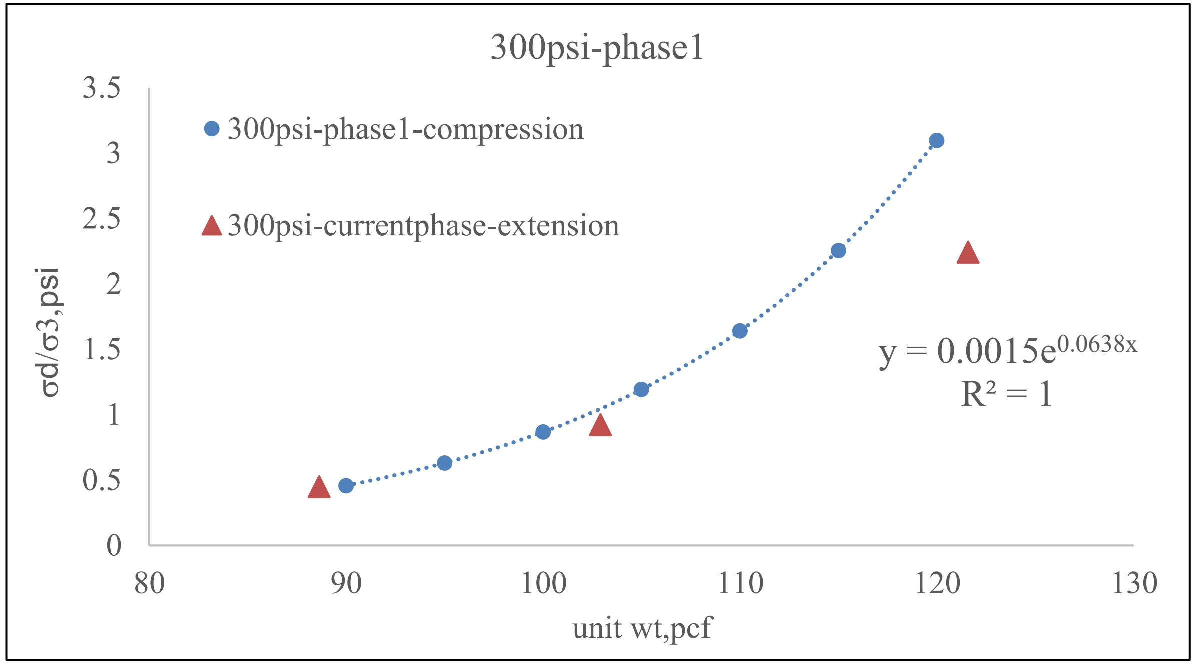
Compression Test data – current & phase-1





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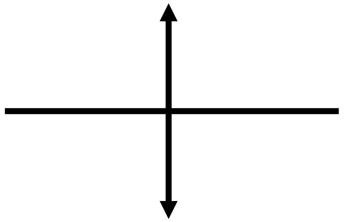
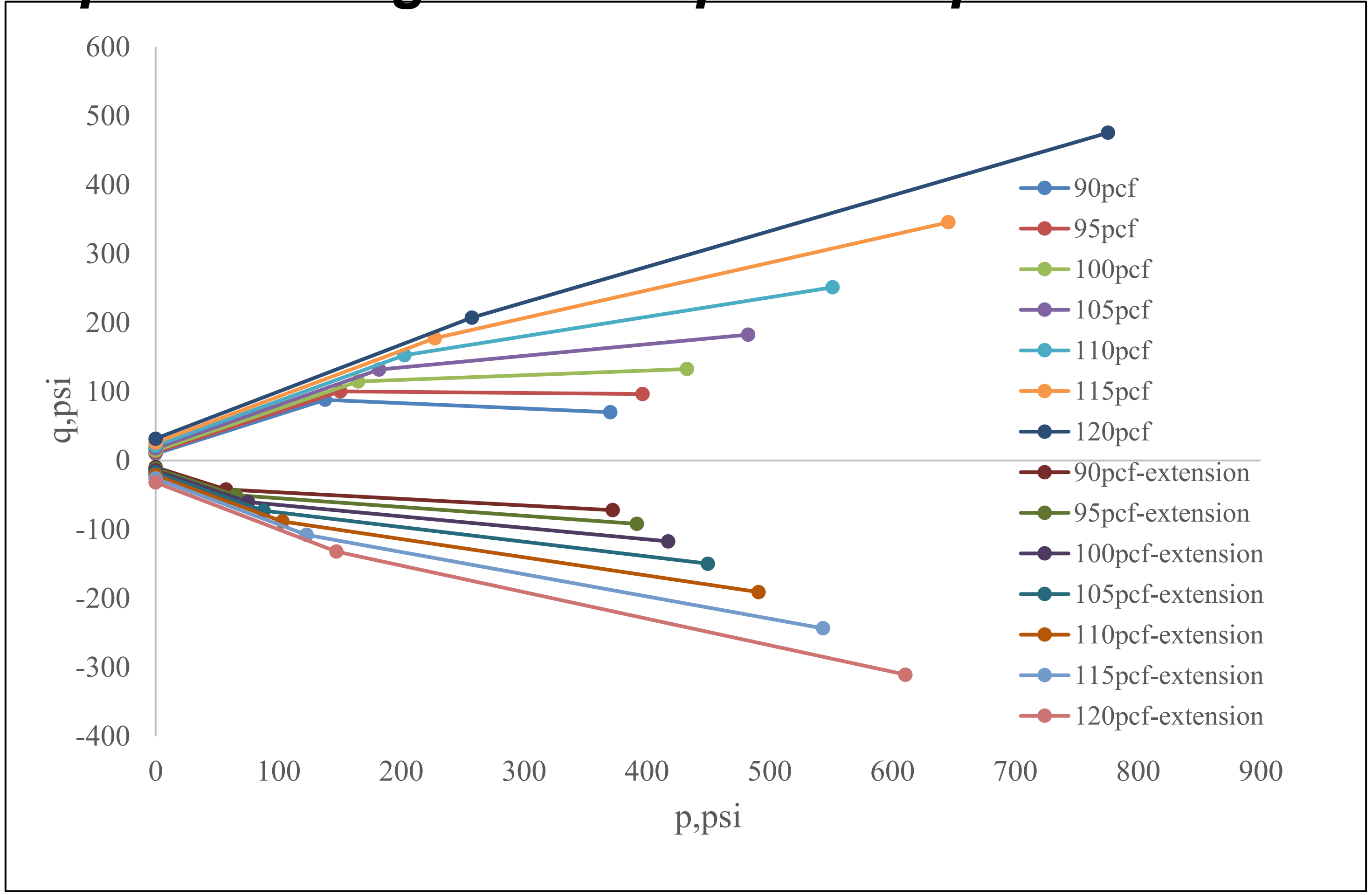
Ft. Thompson Strength Envelopes-Compression and Extension

Compression
(Bearing Stress)



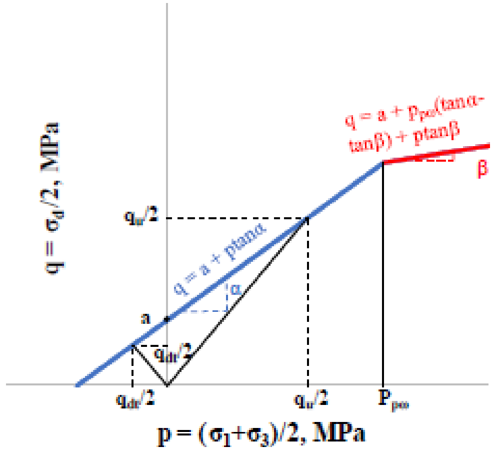
Extension
(Passive Stress)



Task 3 – Implement Lateral Resistance

Ft. Thompson Limestone Strength Envelope Modification Factors

Dry Unit Wt (pcf)	c-ext/c-comp	phi-ext/phi-comp	omega-ext/omega-comp	Pp-ext/Pp-comp	beta-ext/beta-comp	a-ext/a-comp
90	1	1	1.23	0.41	1.23	1
95	1	1	8.17	0.43	8.10	1
100	1	1	2.50	0.46	2.47	1
105	1	1	1.26	0.48	1.25	1
110	1	1	0.93	0.51	0.94	1
115	1	1	0.79	0.54	0.82	1
120	1	1	0.73	0.57	0.77	1
125	1	1	0.70	0.60	0.76	1



- $c_{ext} = F_c * c_{comp}$
- $\phi_{ext} = F_\phi * \phi_{comp}$
- $\omega_{ext} = F_\omega * \omega_{comp}$
- $P_{pext} = F_{Pp} * P_{pcomp}$
- $\beta_{ext} = F_\beta * \beta_{comp}$
- $a_{ext} = F_a * a_{comp}$

- Limited testing suggests reductions in strength envelope parameter Pp.
- Evaluating low dry unit weights for modification to Kp.
- Lime-cement improved clay showed reduced strengths under extension than compression (Ignat et al., 2019).
- Extension and compression $\phi \approx 3\%$ different for different rock types tested (Yu and Ng, 2022).

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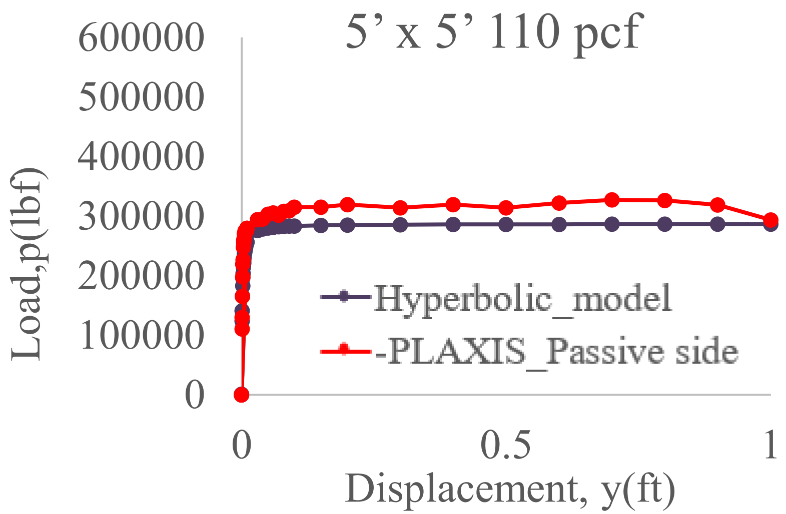
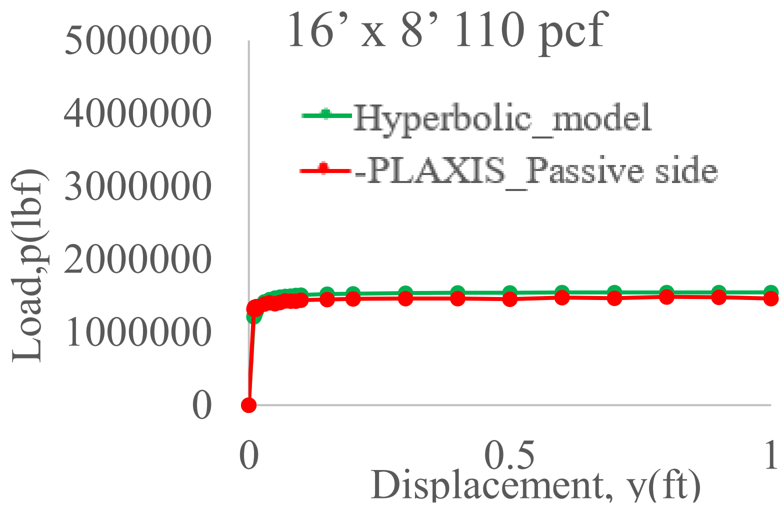
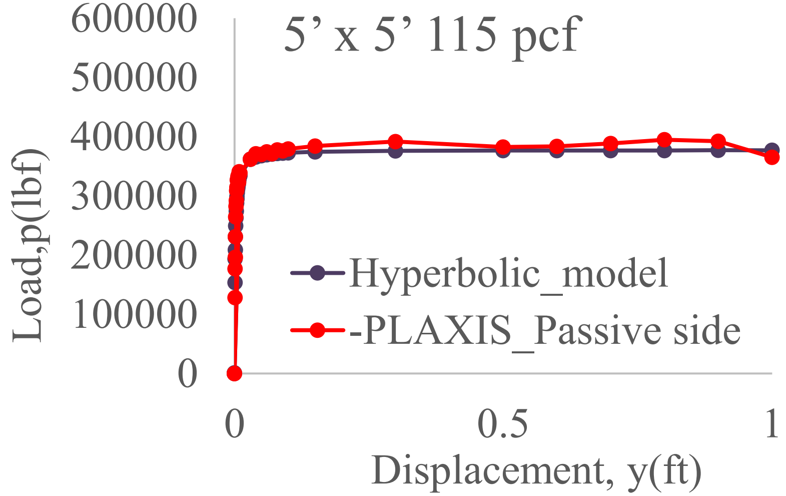
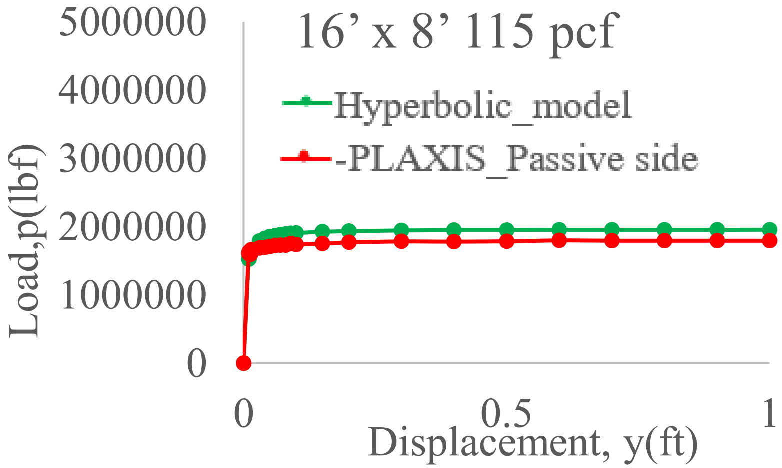
Task 3 – Implement Lateral Resistance

Plaxis Model Passive Load-Deformation in Ft. Thompson Limestone



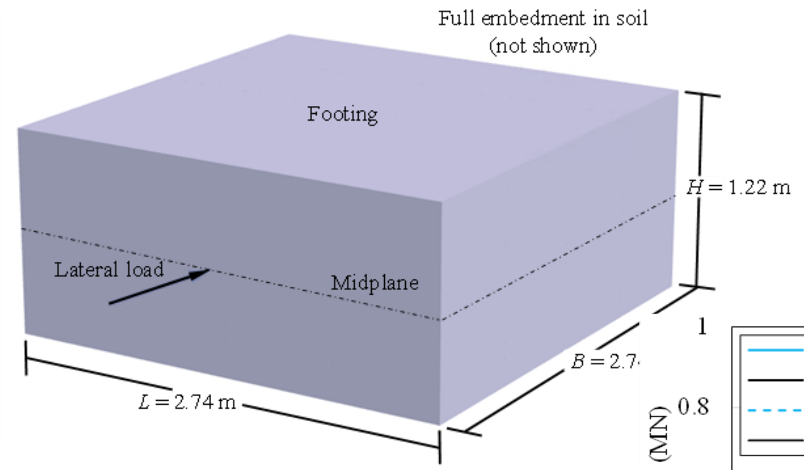


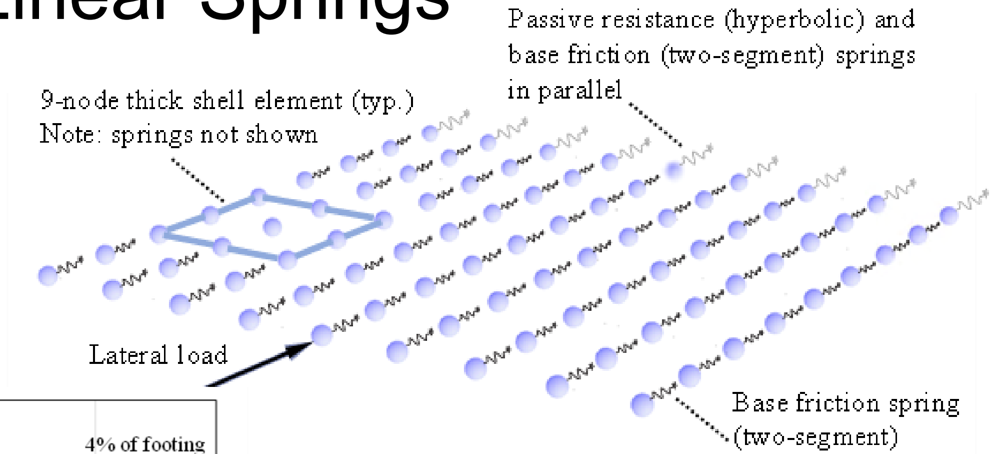


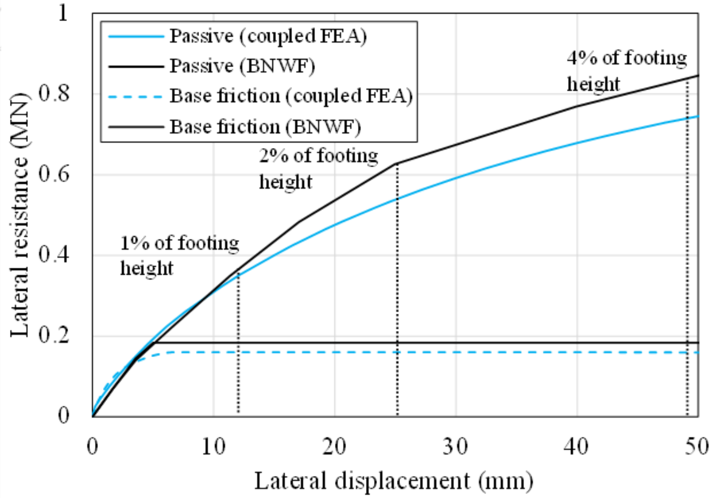


Implement Lateral Resistance in FB-MultiPier

- Shallow Foundation – 9-Node Shell Element
- Soil/Rock Resistance – Discrete Non-Linear Springs







FEA and the BNWF force-displacement comparison

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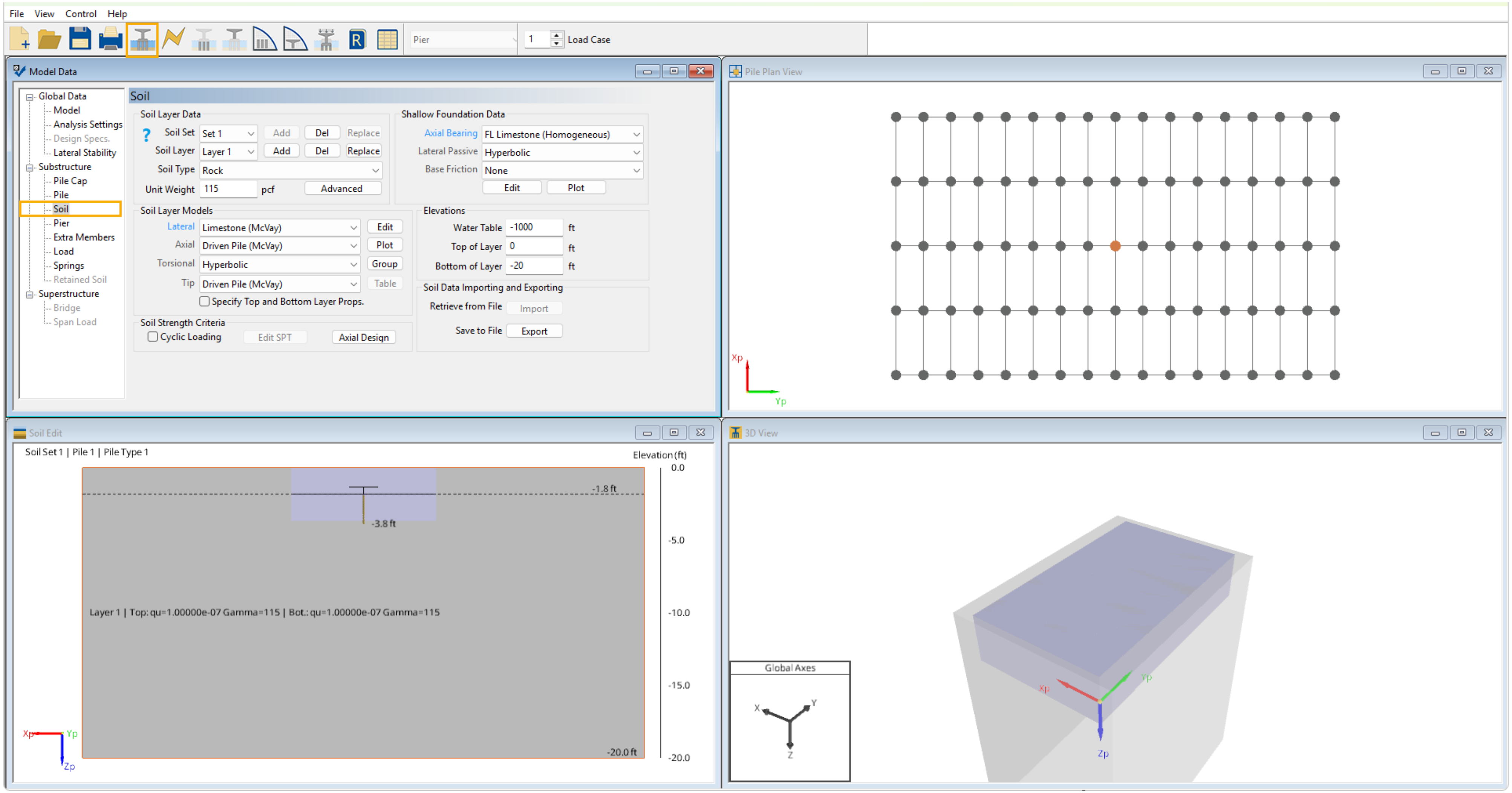
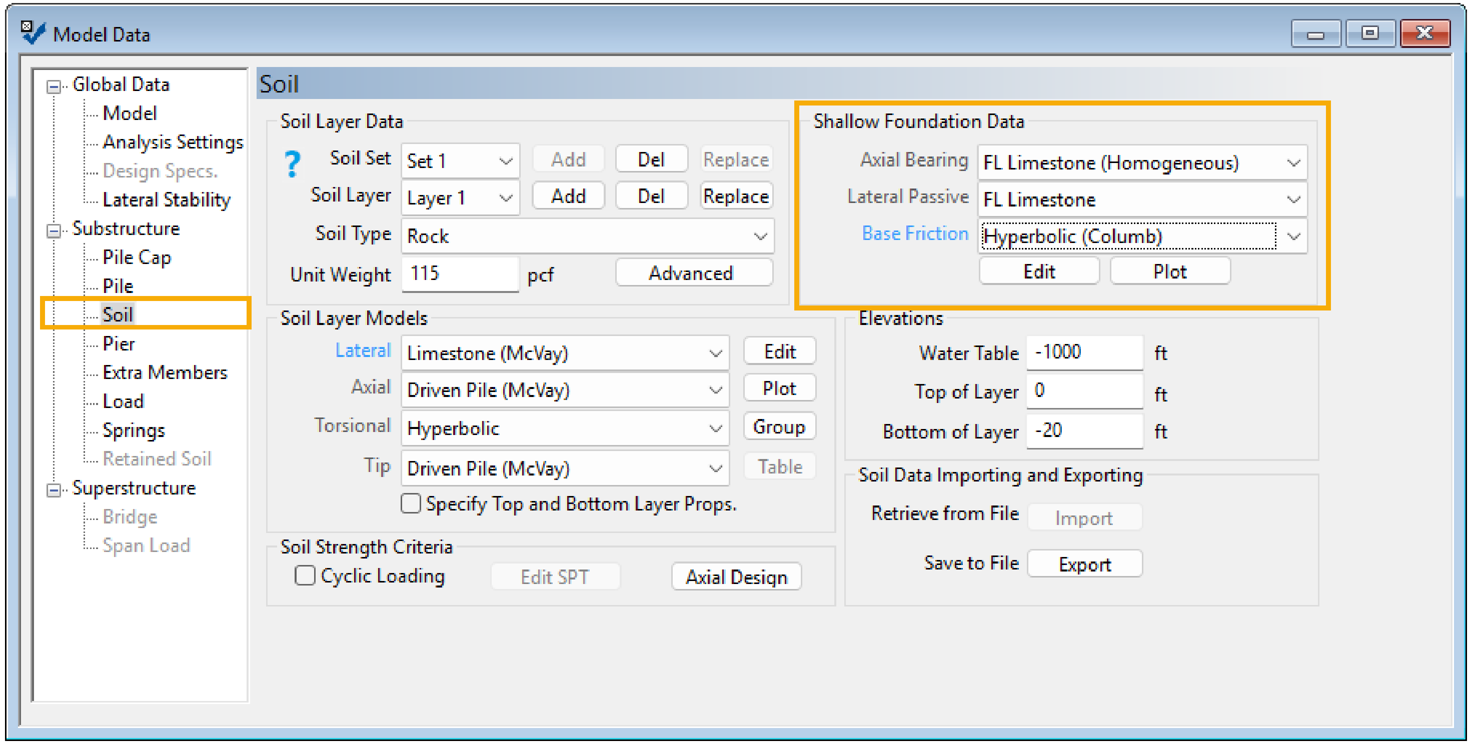
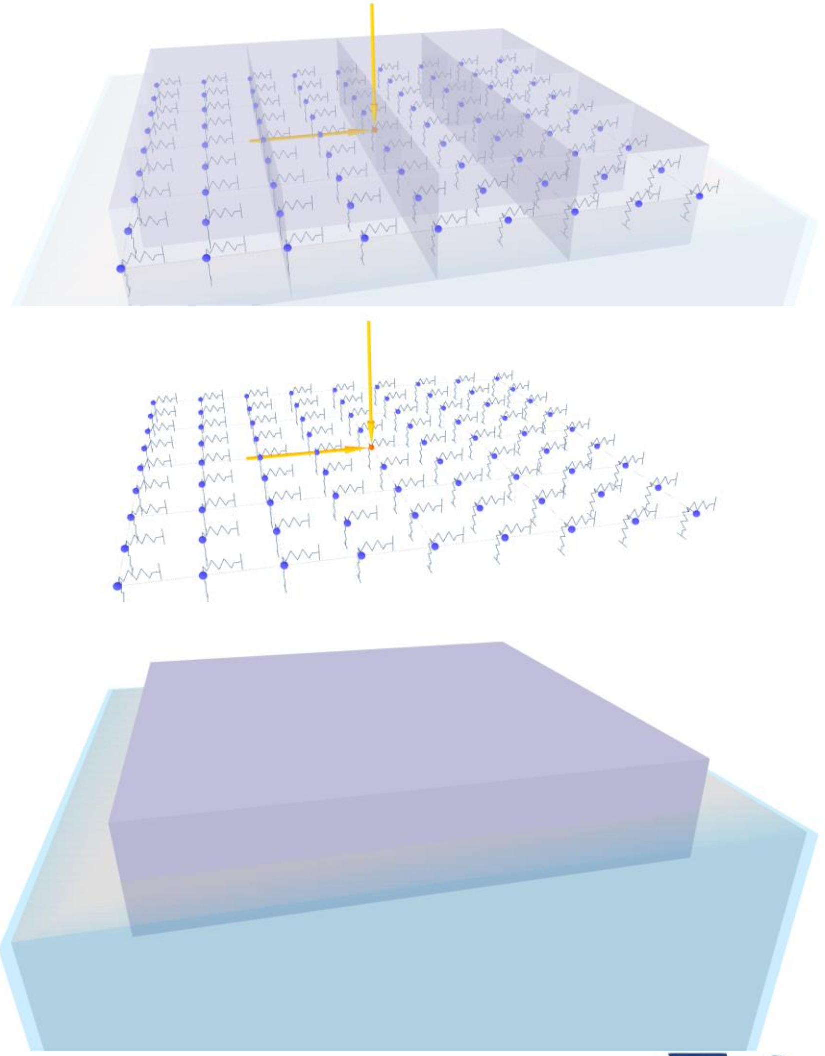
FB-MultiPier Edit Side



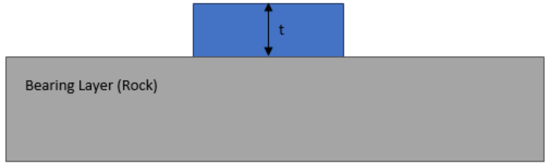
FB-MultiPier Edit Side (Soil Page)

- Lateral Passive Resistance Springs
- Base Friction Resistance Springs

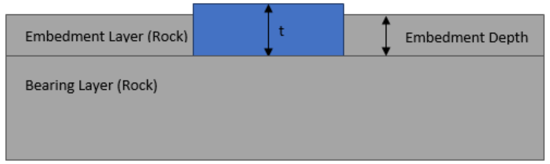




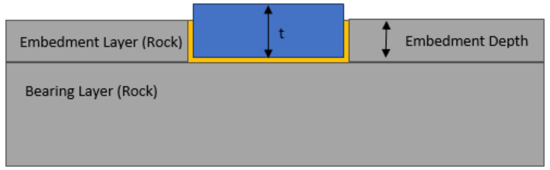
FB-MultiPier Soil Layer Profiles of Interest



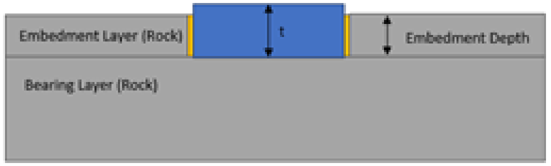
Case 1a. No Embedment, Bearing on Florida Limestone



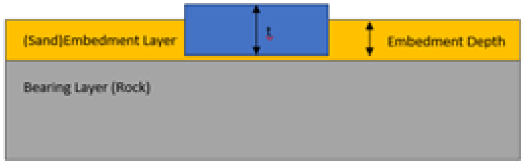
Case 1b. Embedment in Florida Limestone, Bearing on Florida Limestone.



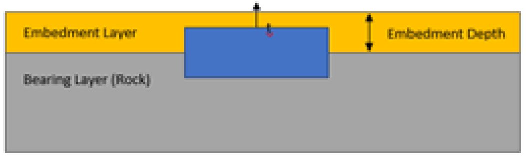
Case 1c. Embedment in Florida Limestone with aggregate backfill around foundation perimeter and ba
while Bearing on Florida Limestone.



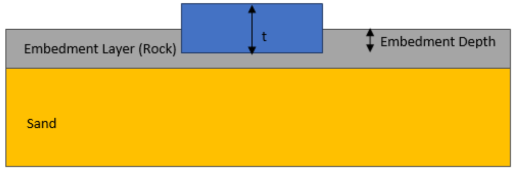
Case 1d. Embedment in Florida Limestone with aggregate backfill around foundation perimeter and Bearing on Florida Limestone.



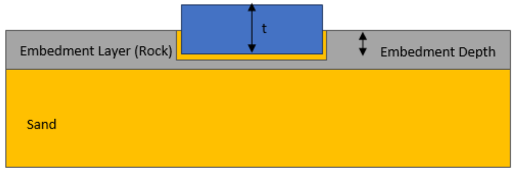
1e. Embedment in Sand underlain by Florida Limestone.



1f. Embedment in Sand, Bearing on Florida Limestone.



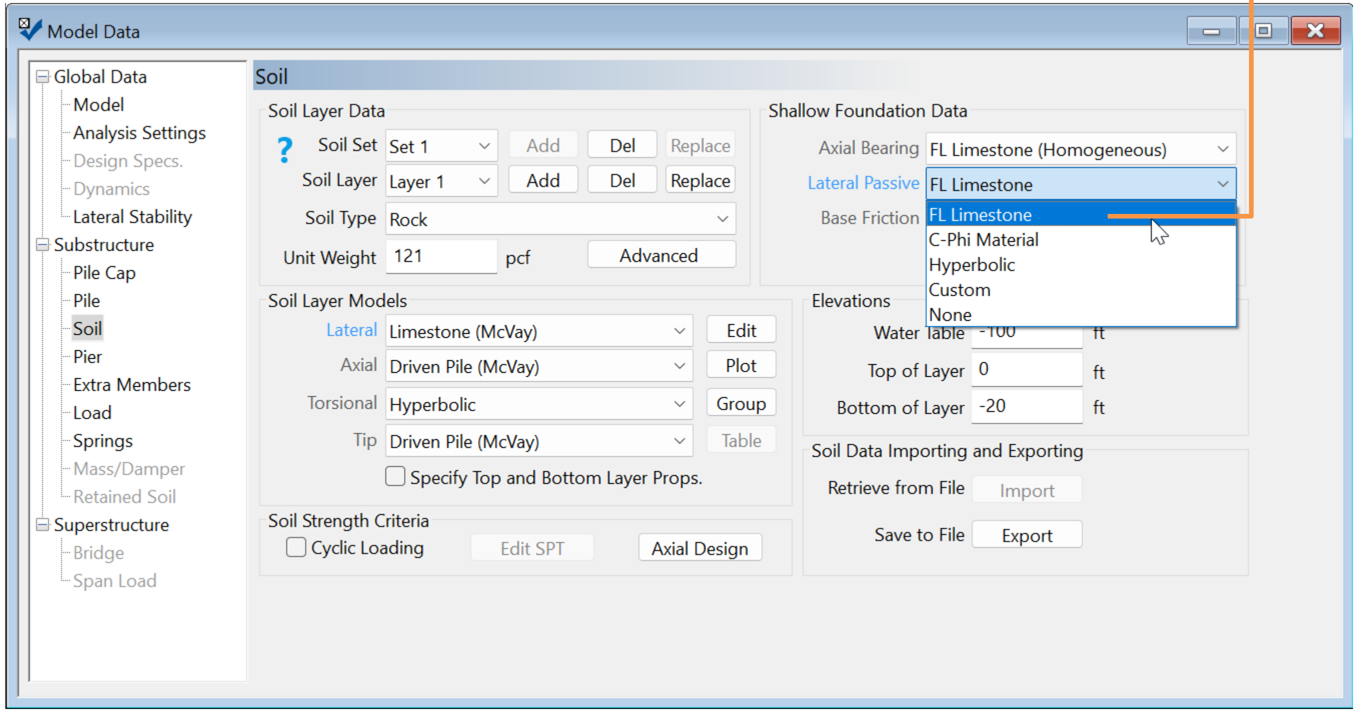
Case 2a. Partial Embedment in Florida Limestone underlain by Sand.

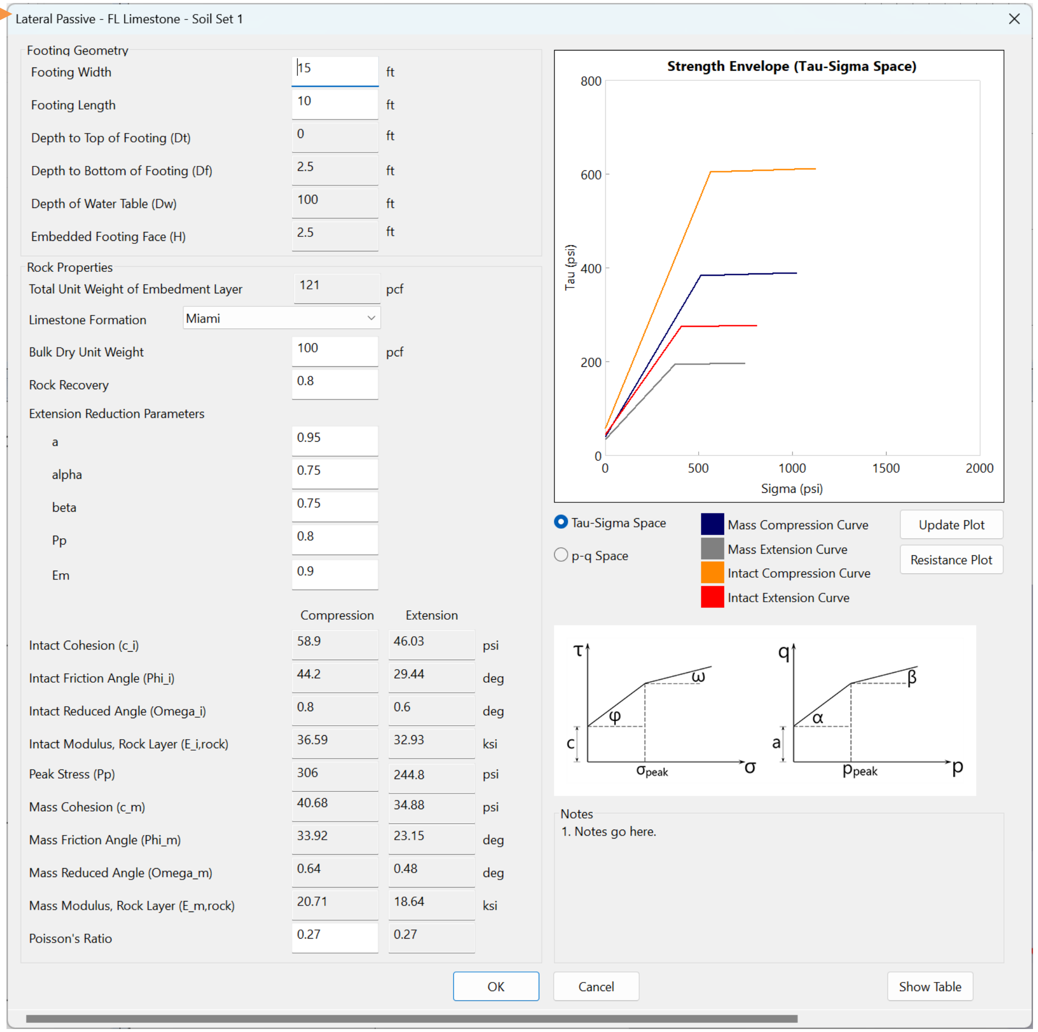


Case 2b. Partial Embedment in Florida Limestone underlain by Sand with sand or aggregate backfill around foundation perimeter and base while Bearing on Florida Limestone.

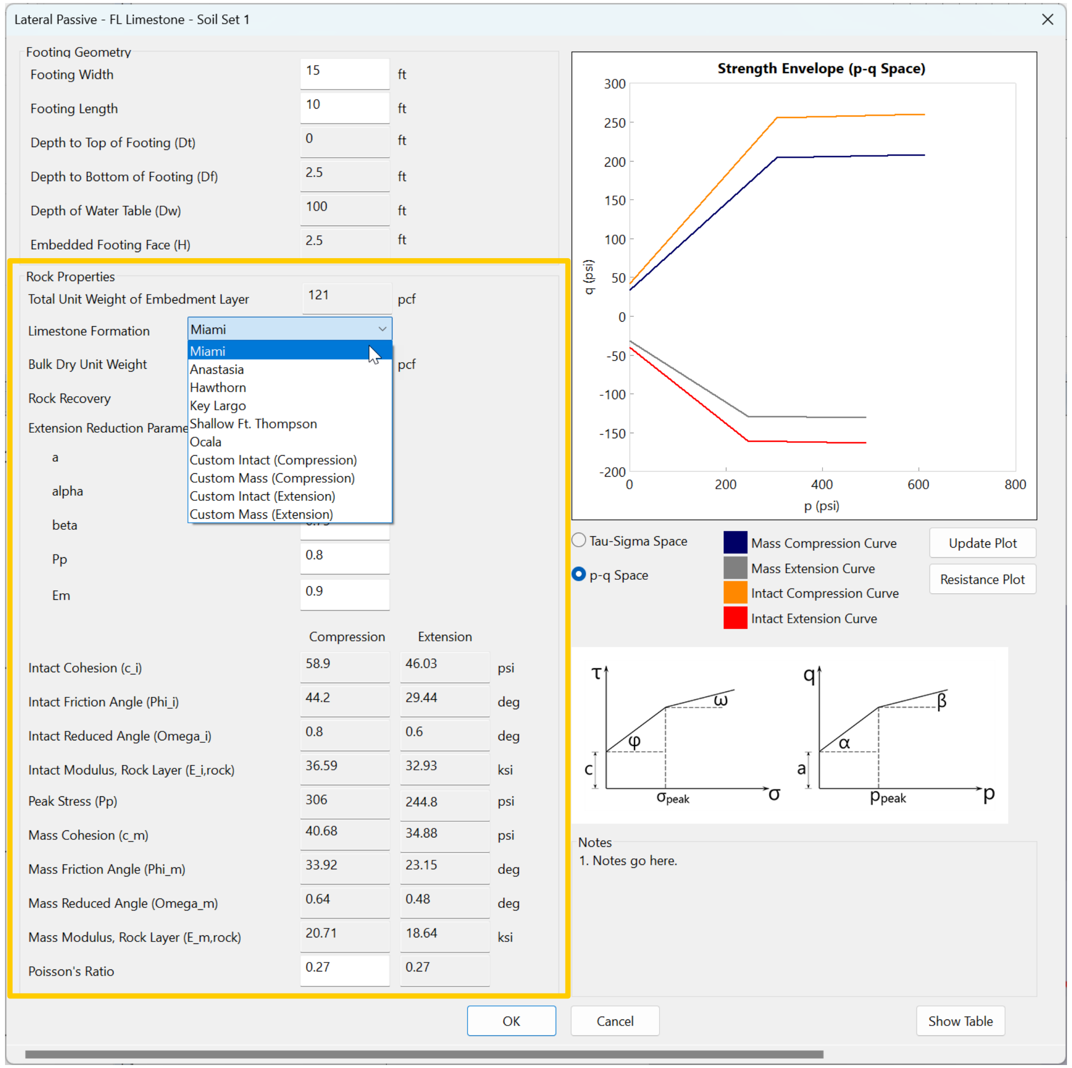
Case	Bearing Model	Passive Model	Friction Model
1a	FL Limestone (Homogeneous)	None	Hyperbolic (Columb)
1b	FL Limestone (Homogeneous)	FL Limestone	Hyperbolic (Columb)
1c	FL Limestone (Homogeneous)	None	Hyperbolic (Columb)
1d	FL Limestone (Homogeneous)	None	Hyperbolic (Columb)
1e	FL Limestone (Homogeneous)	C-Phi Material	Hyperbolic (Columb)
1f	FL Limestone (Homogeneous)	C-Phi Material	Hyperbolic (Columb)
2a	FL Limestone (Rock over Sand)	FL Limestone	Hyperbolic (Columb)
2b	FL Limestone (Rock over Sand)	None	Hyperbolic (Columb)

Lateral Passive - FL Limestone

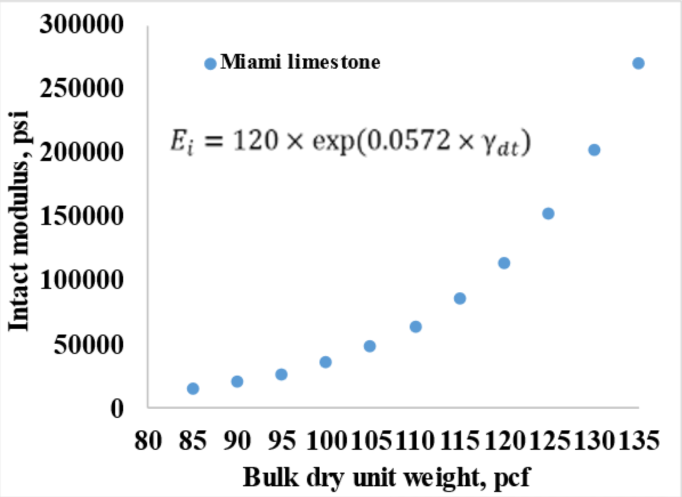




Lateral Passive - FL Limestone

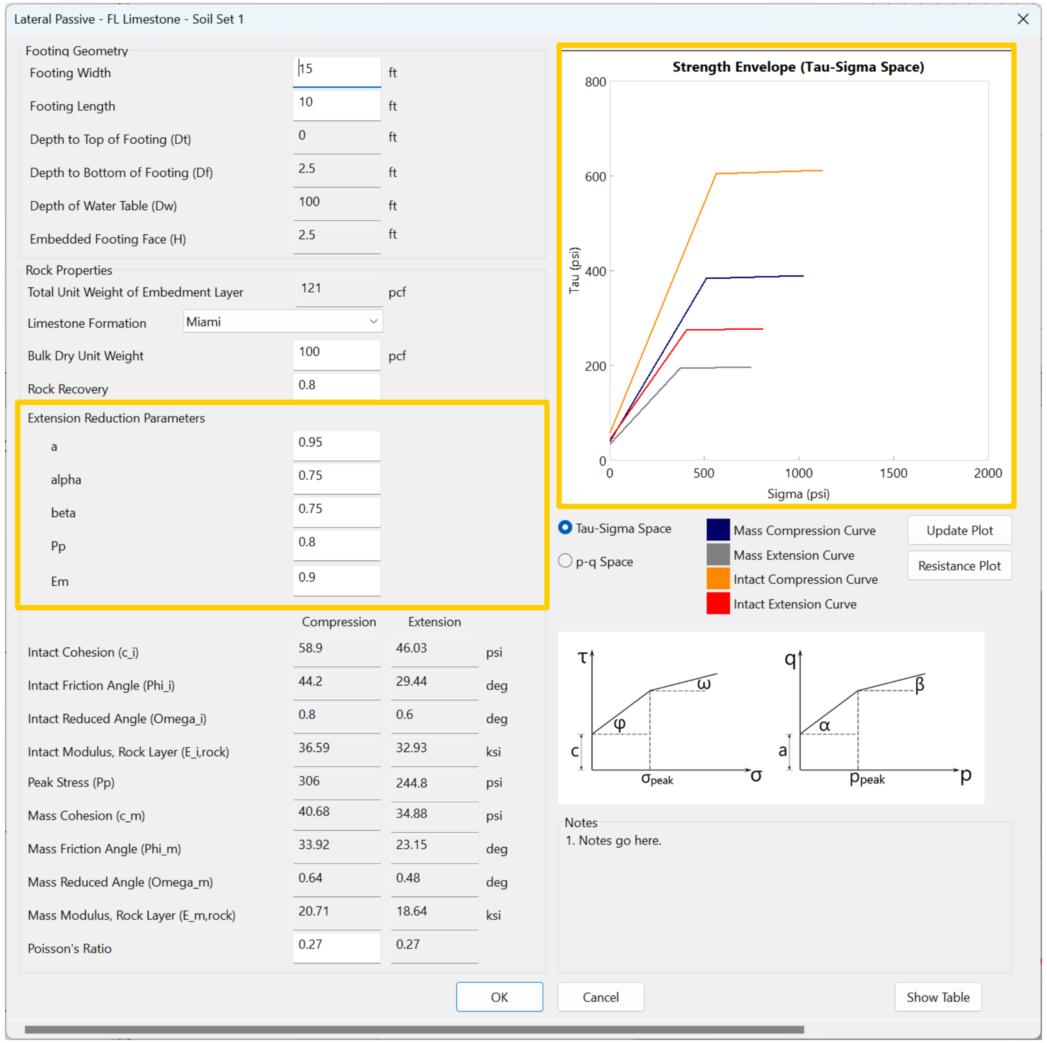


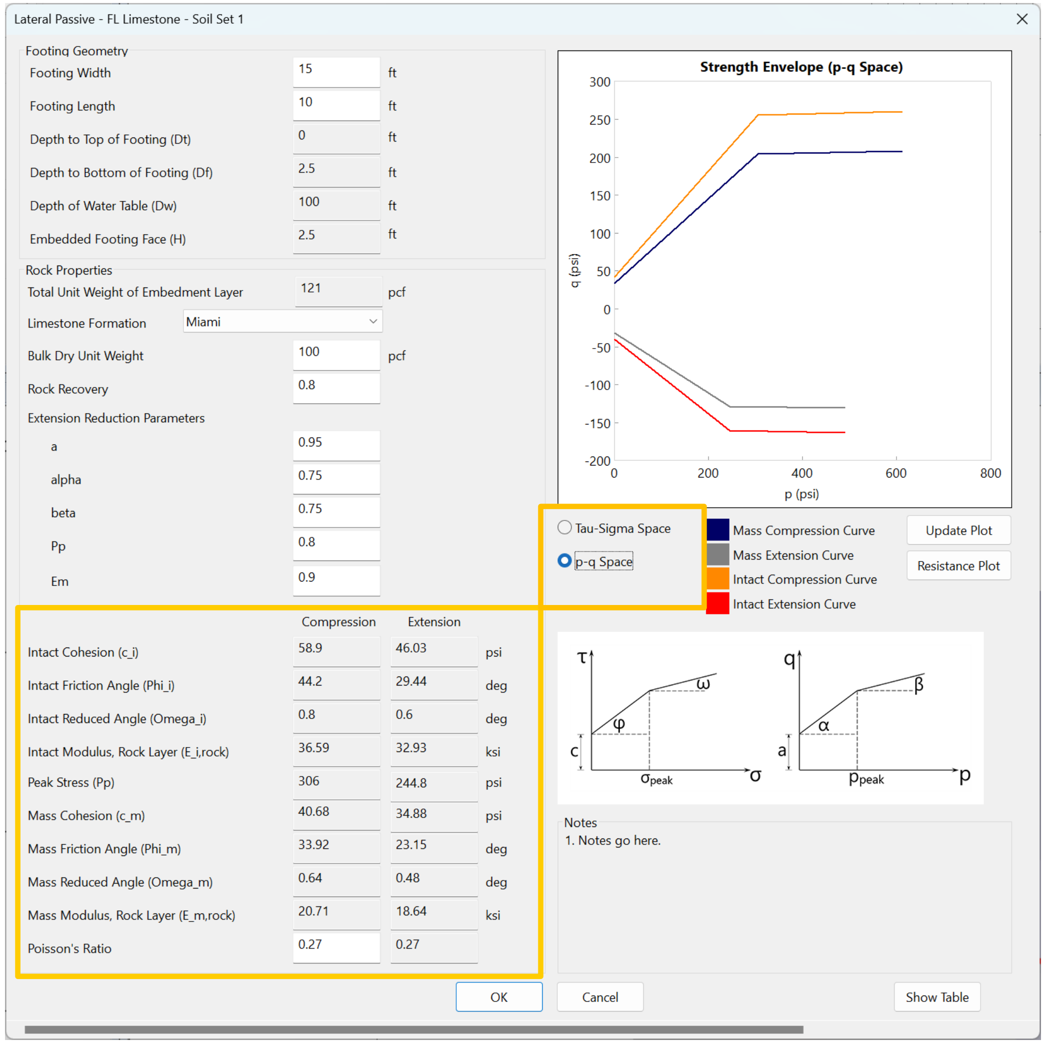
Formation	γ_{dt}, pcf	c_i, psi	φ_i, °	$\sigma_{peak\ i}$, psi	ω_i, °	a_i, psi	α_i, °	Pp, psi	β_i, °
Miami Limestone	90	42.0	42.2	444	-3.0	31.1	33.9	247	-3
	95	49.9	43.2	498	-1.4	36.4	34.4	274	-1.4
	100	58.9	44.2	562	0.8	42.2	34.9	306	0.8
	105	70.9	45.3	640	3.7	49.9	35.4	345	3.7
	110	84.1	46.4	730	7.3	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



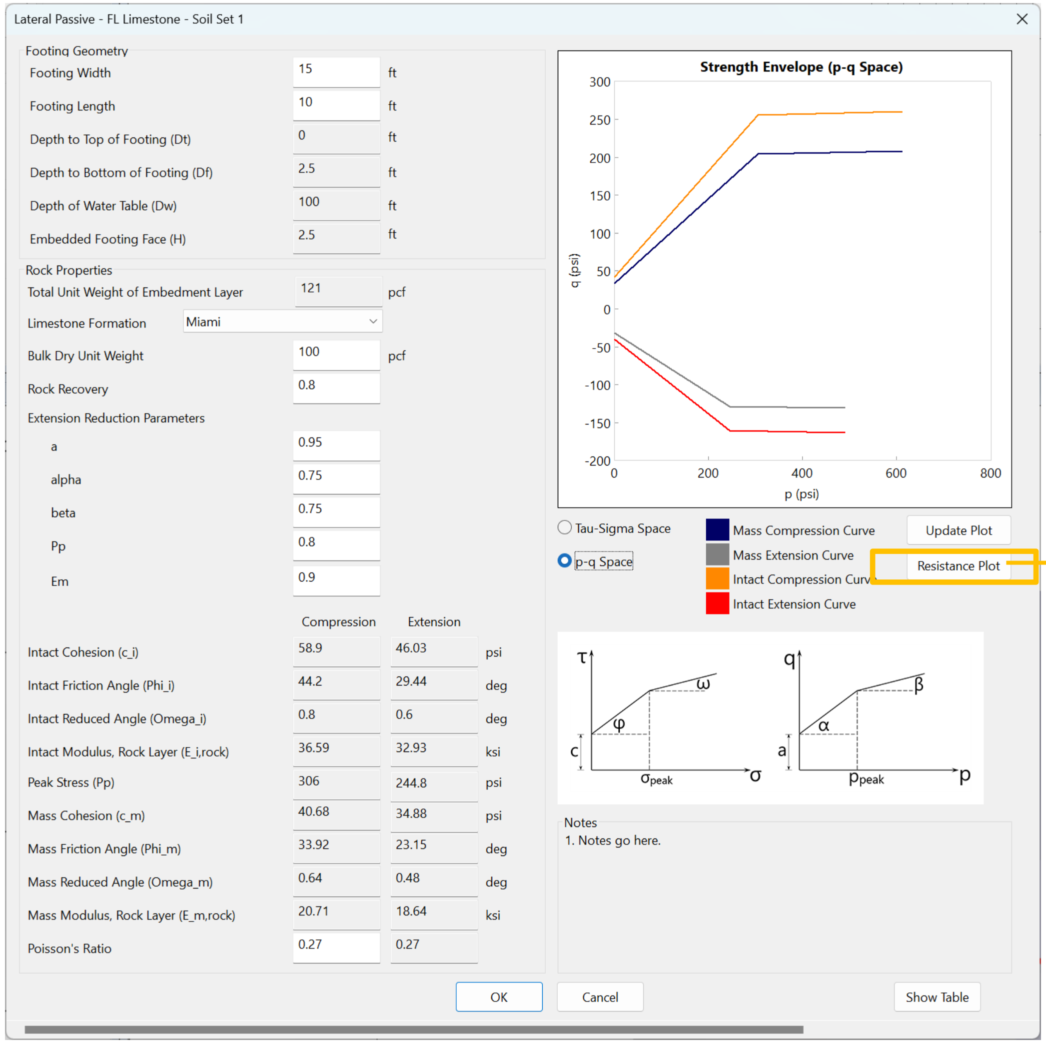
- 3000 Unconfined Compression test
- 225 Triaxial Test

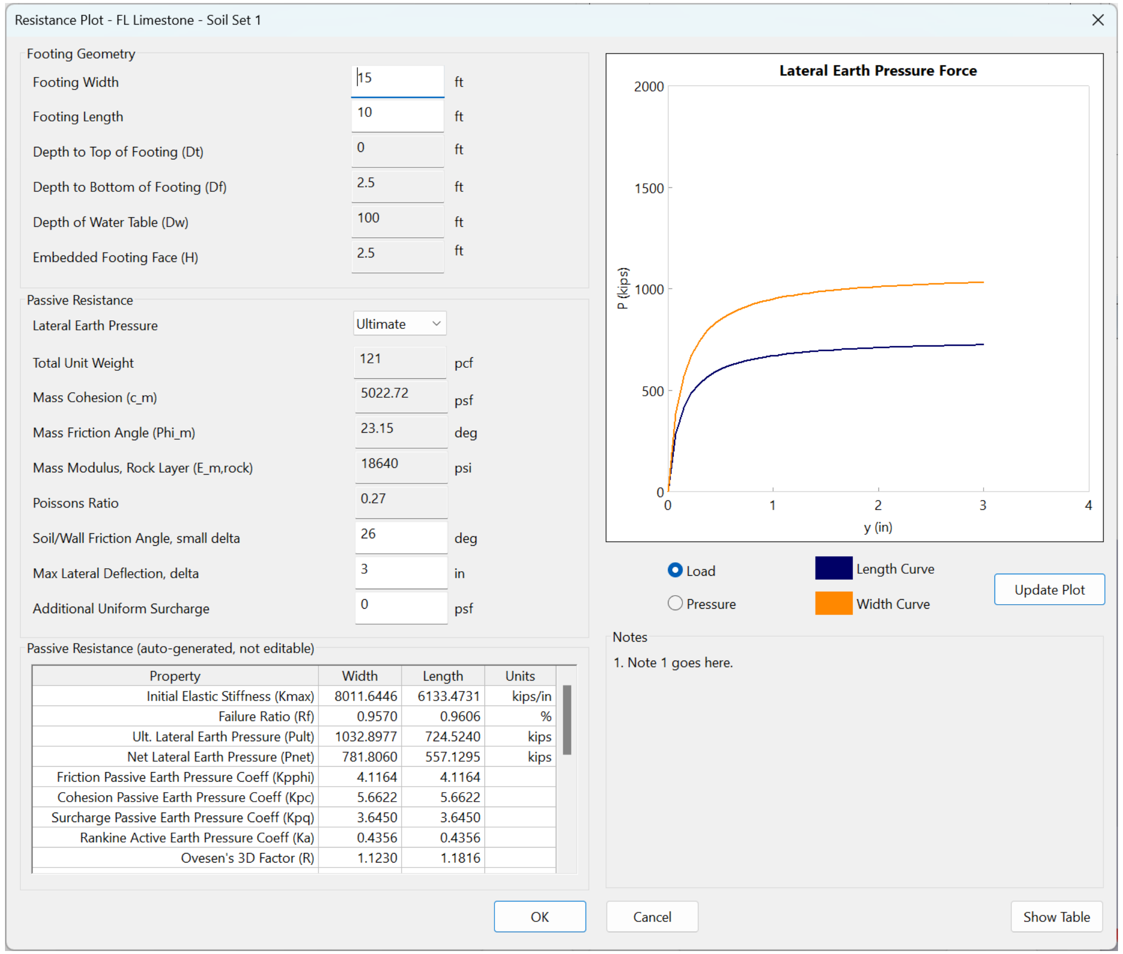
Lateral Passive - FL Limestone





Lateral Passive - FL Limestone





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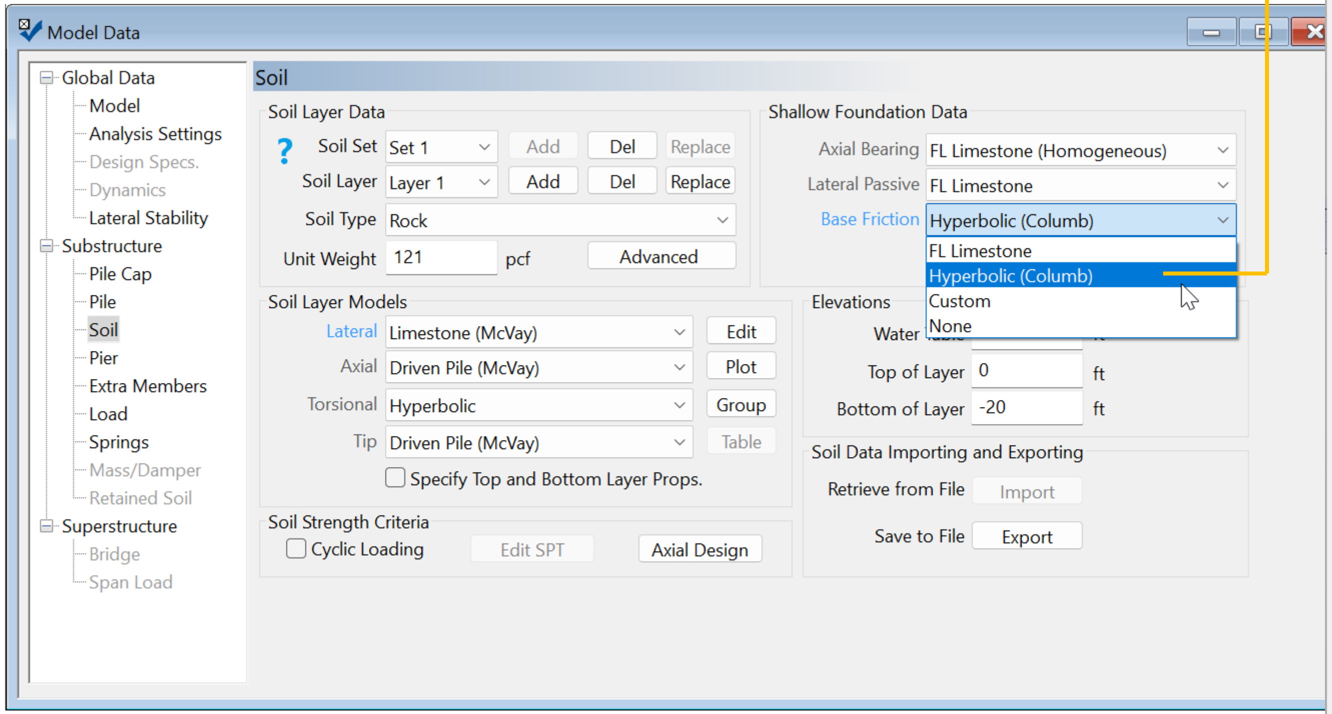
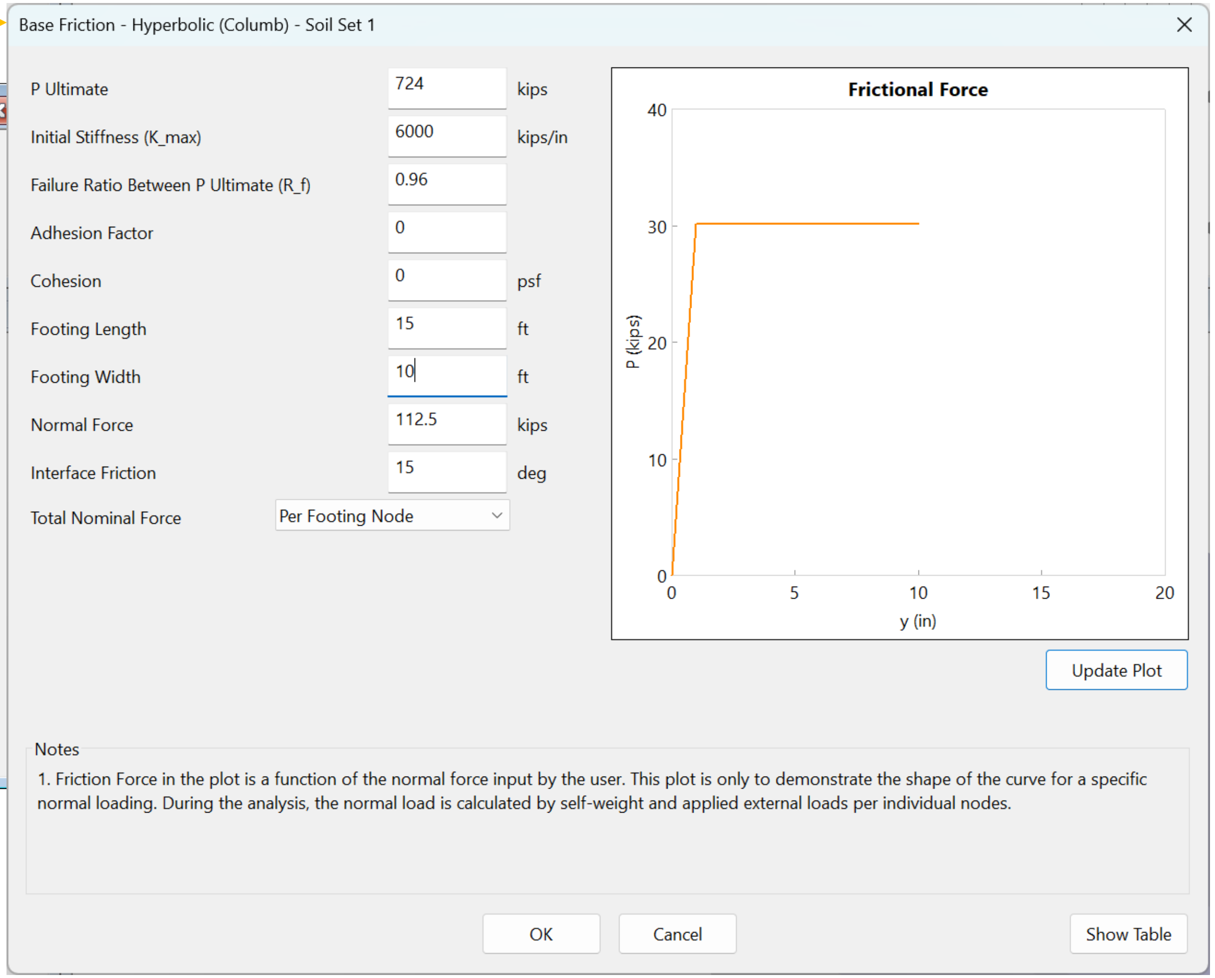
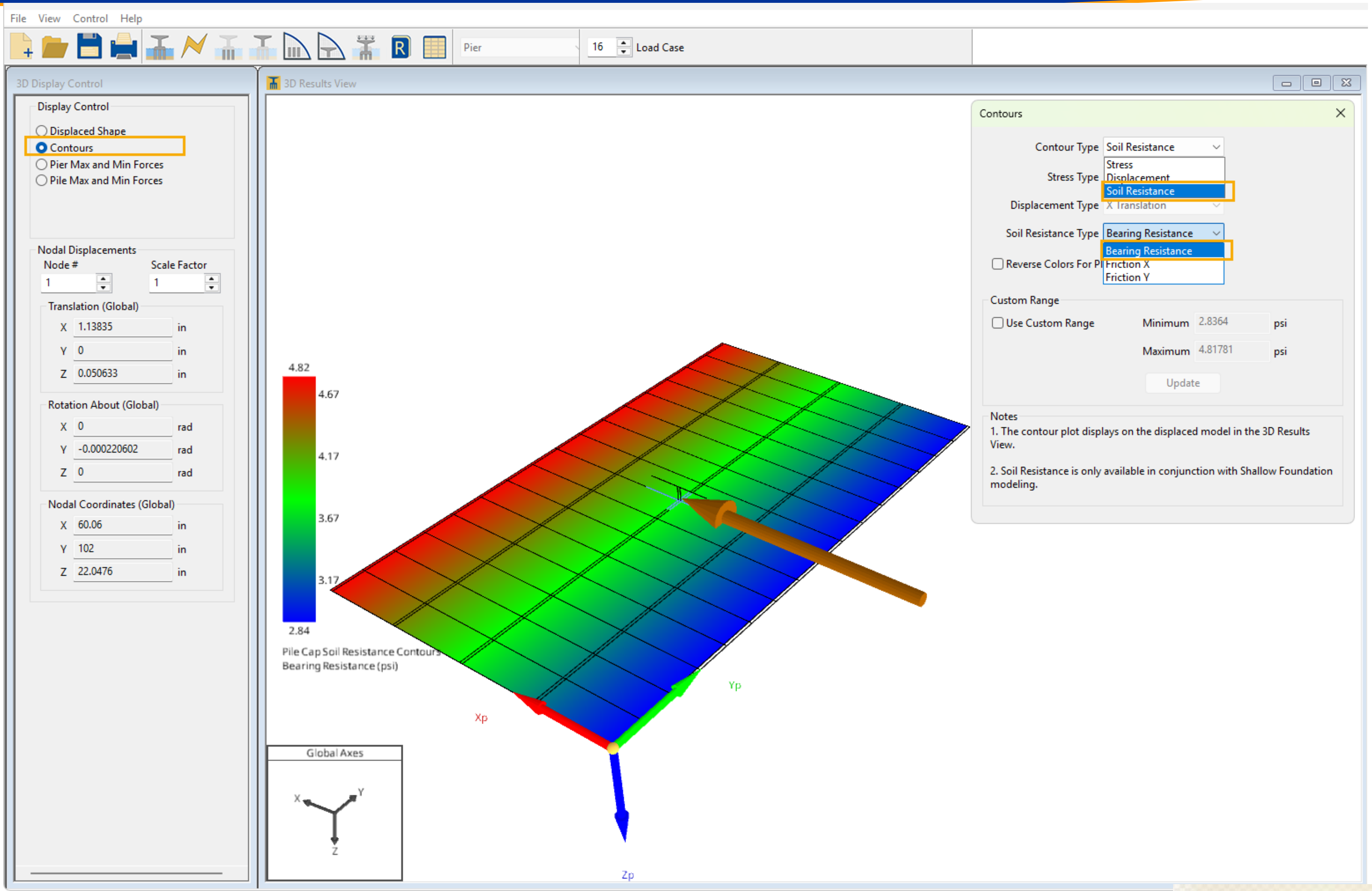
Base Friction – Hyperbolic (Columb)

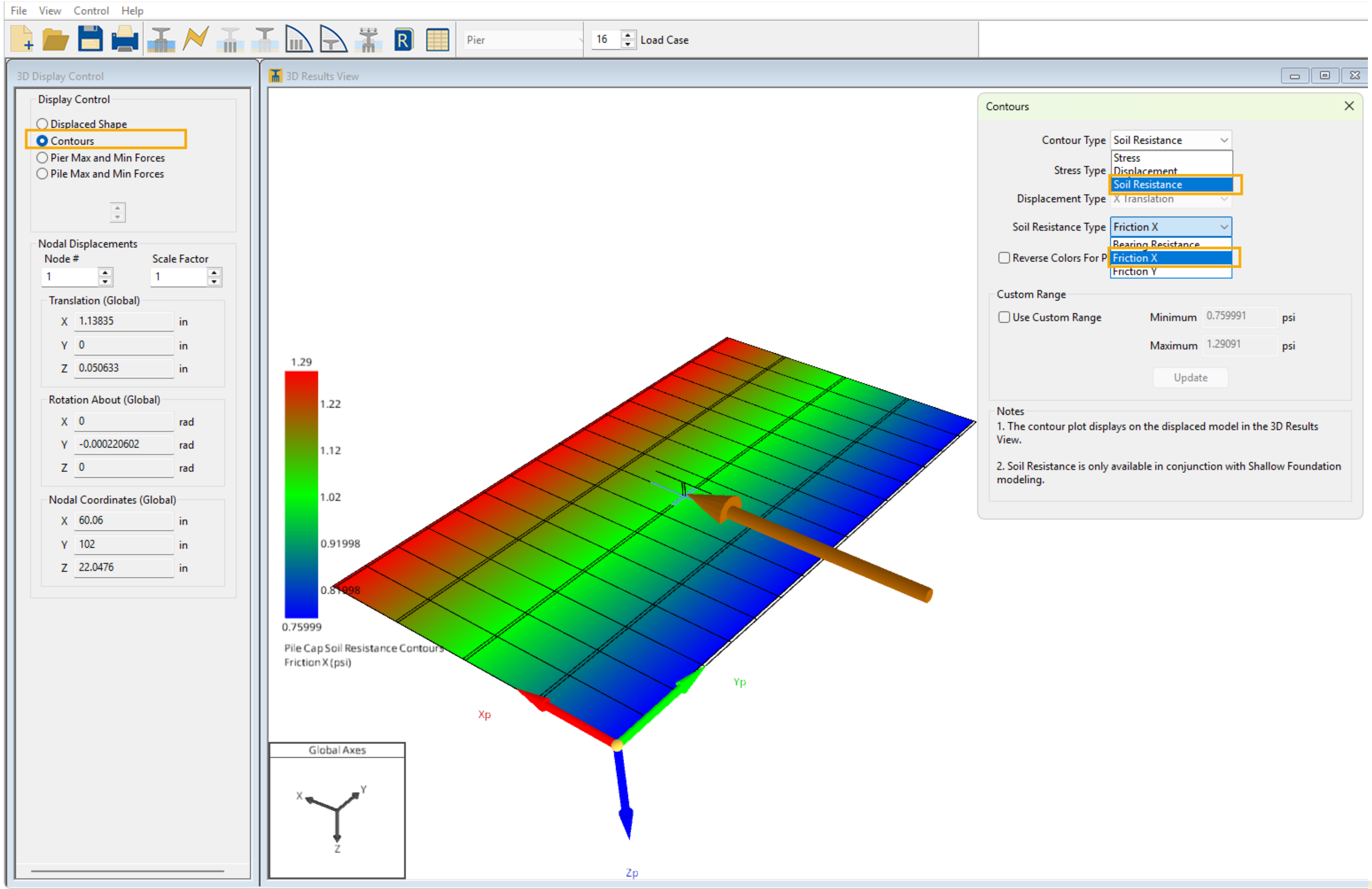




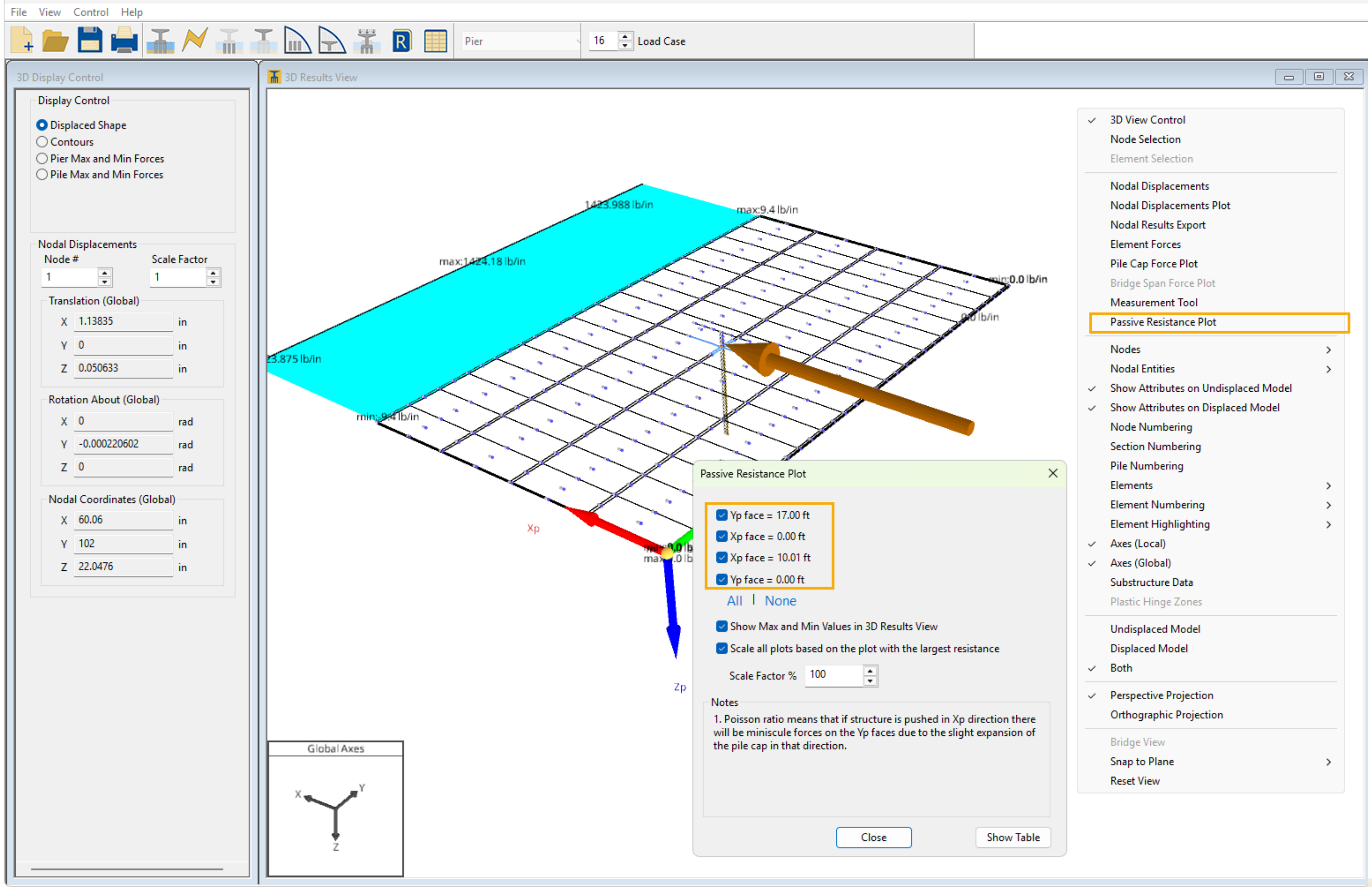
FB-MultiPier - 3D Results – Bearing Resistance Contour



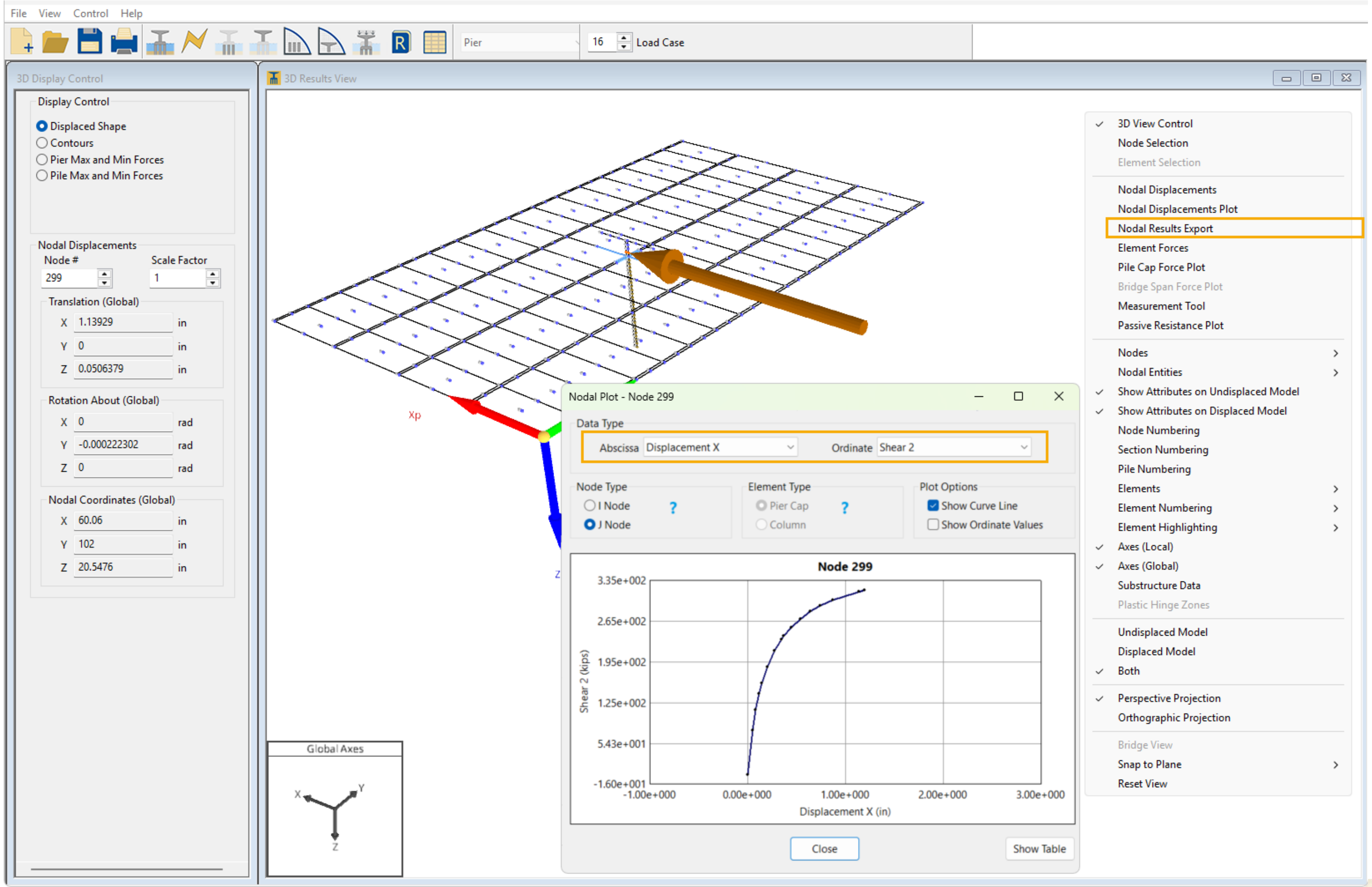
FB-MultiPier - 3D Results – Base Friction Contour



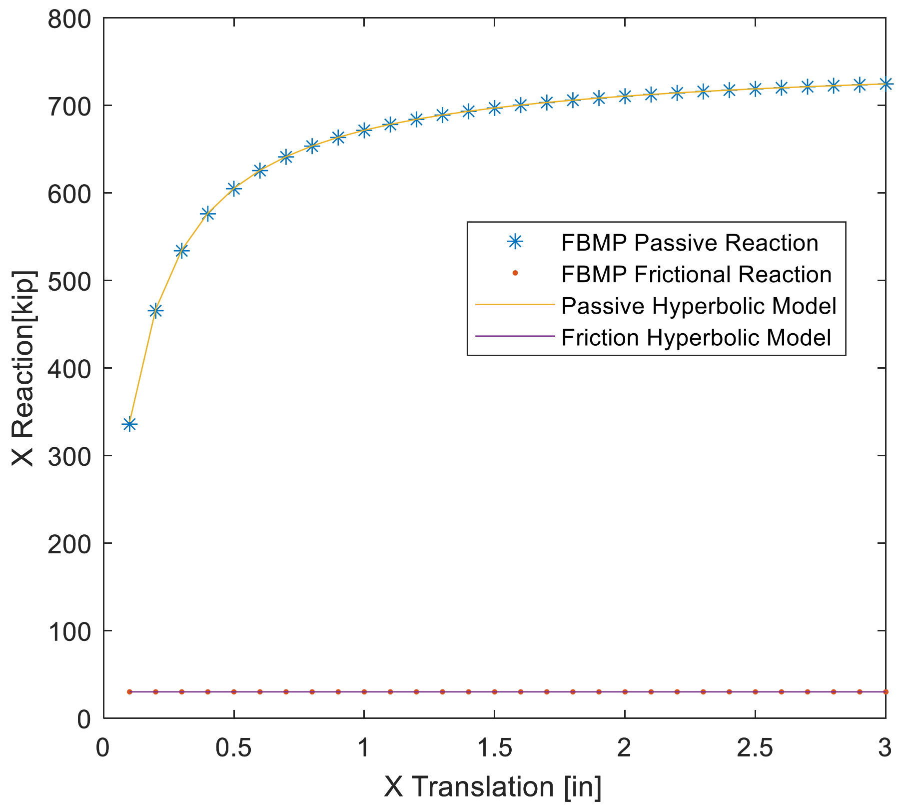
FB-MultiPier - 3D Results – Lateral Passive Contour

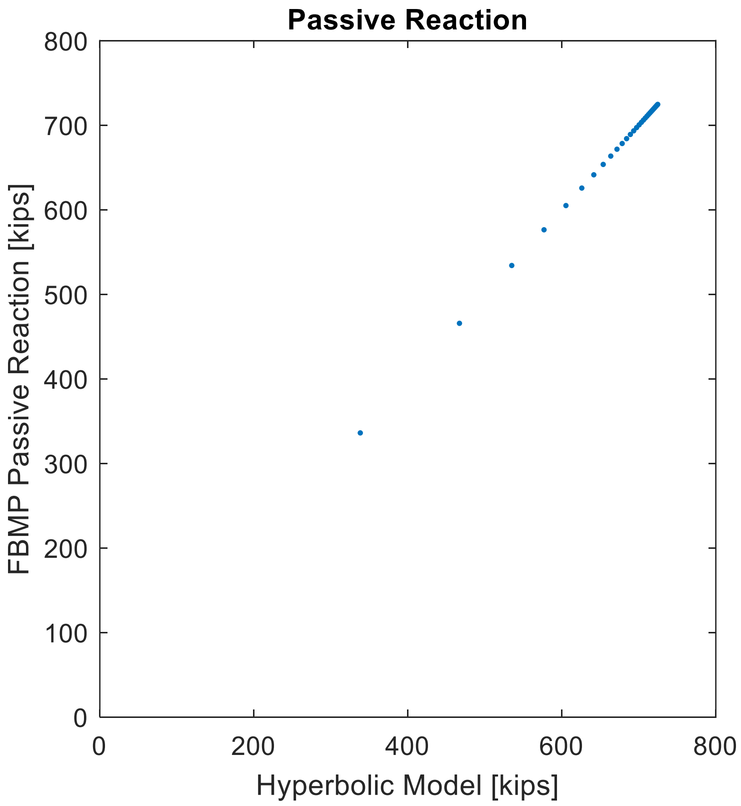


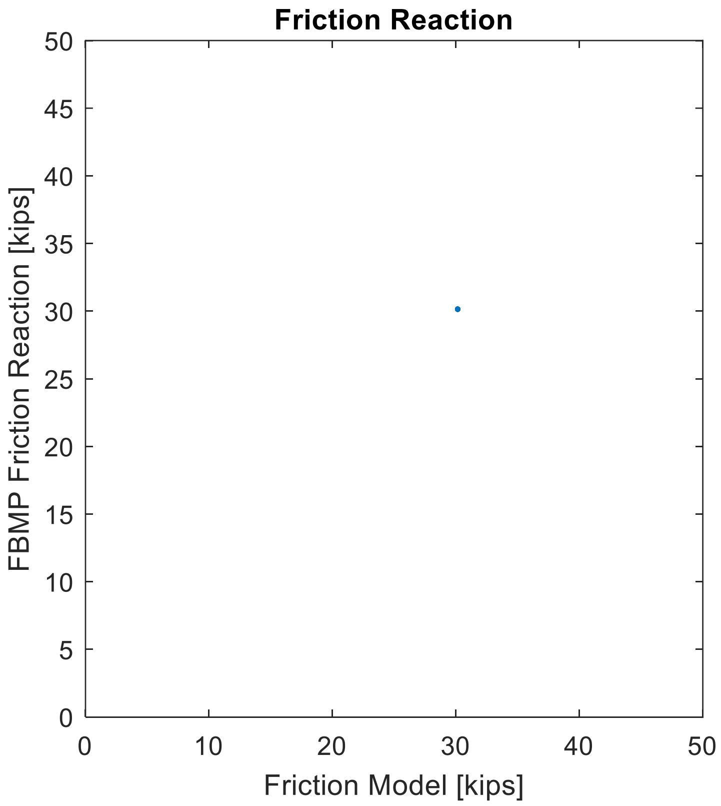
FB-MultiPier - 3D Results – Nodal Plot



FB-MultiPier Validation







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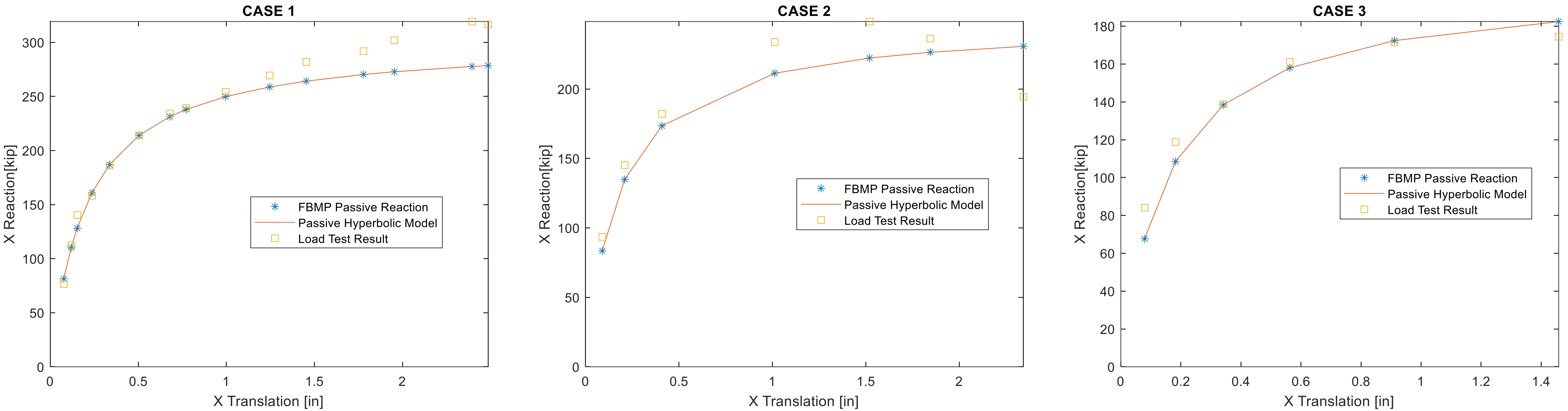
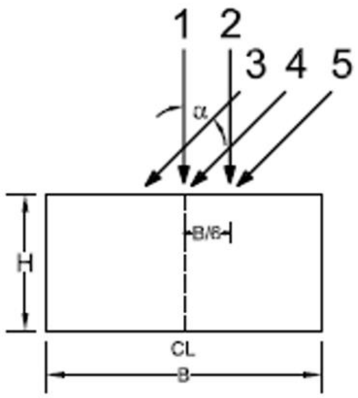
FB-MultiPier Validation – Granular Material



(Rollins and Cole, 2006)

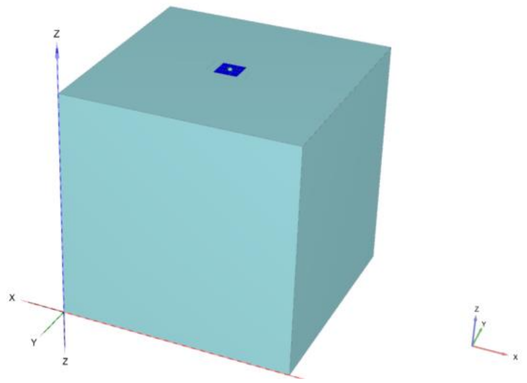
Task 4 – Investigate Effects of Inclined and Eccentric Loading

- Investigate load inclination and eccentricity effects on FL Limestone BC with Plaxis models.
- Based on FEM results, identify methods (modified Vesić, Meyerhof, etc.) for conservative modification to vertical bearing spring pressure values.
- Anticipated issues: lack of current research.



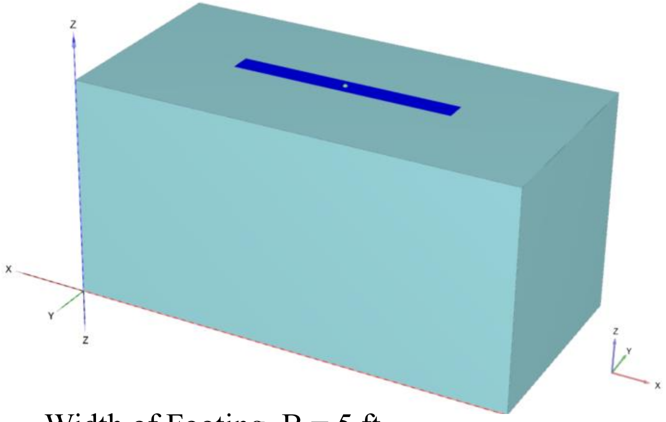
Load Case 1 - concentric, Load Case 2 - eccentric, Load Case 3 - eccentric-inclined (inclination-7 degrees), horizontal component positive (+), to the direction of the eccentricity, Load Case 4 - inclined (inclination-7 degrees) and Load Case 5 - eccentric-inclined (inclination-7 degrees), horizontal component negative (−), to the direction of the eccentricity as presented by Meyerhof (1953).

Square footing (L/B=1):



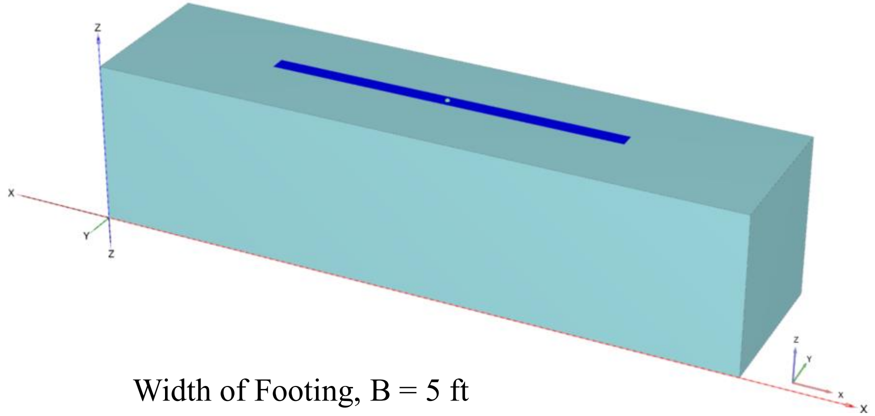
Length and Width of Footing, L=B = 5 ft
Soil body = 50’x50’x50’

Rectangular footing (L/B=10):



Width of Footing, B = 5 ft
Length of Footing, L = 50 ft
Soil body = 100’x50’x50’

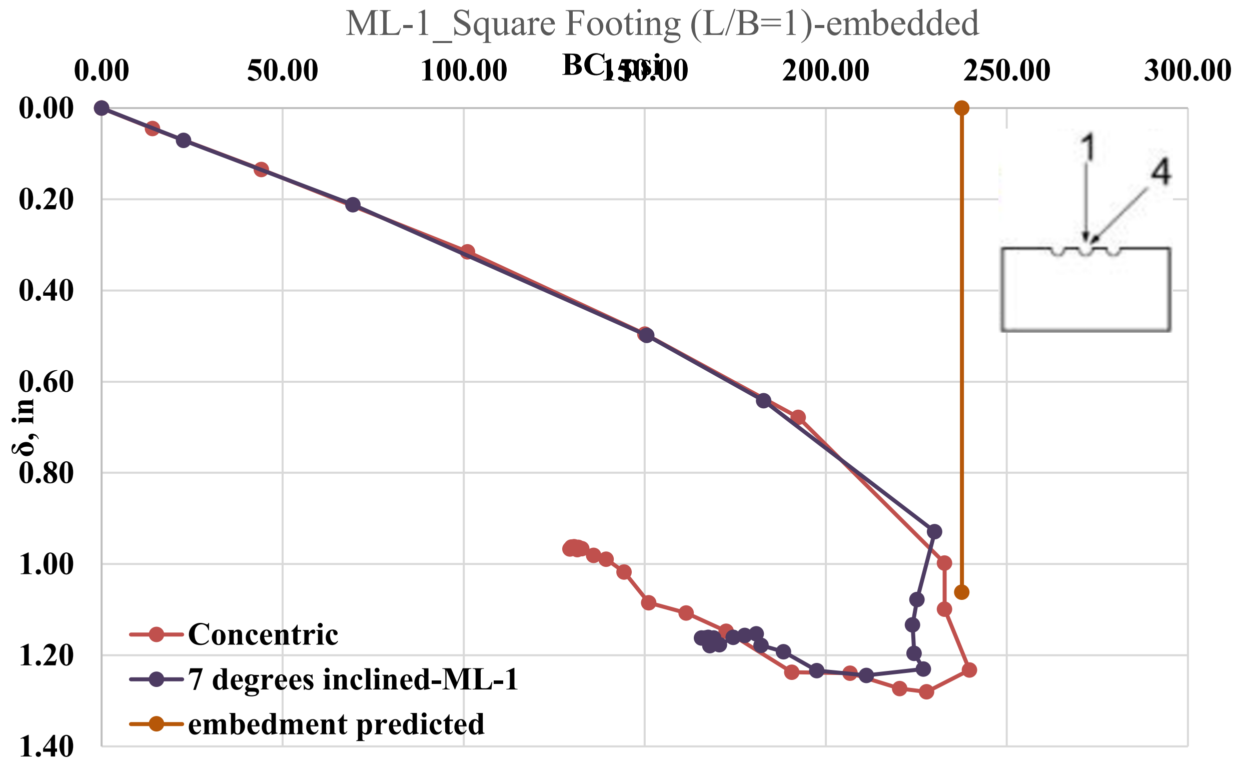
Strip footing (L/B>20):

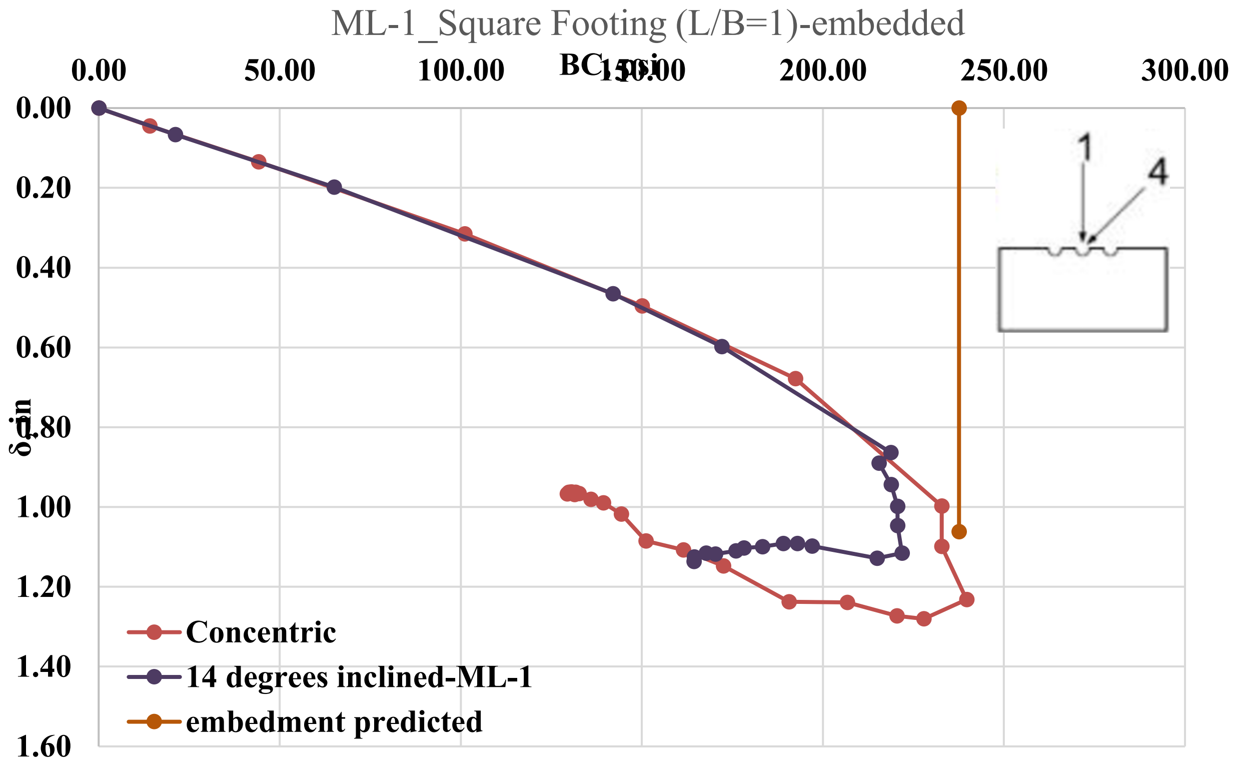


Width of Footing, B = 5 ft
Length of Footing, L = 110 ft
Soil body = 200’x50’x50’

Task 4 – Investigate Effects of Inclined and Eccentric Loading

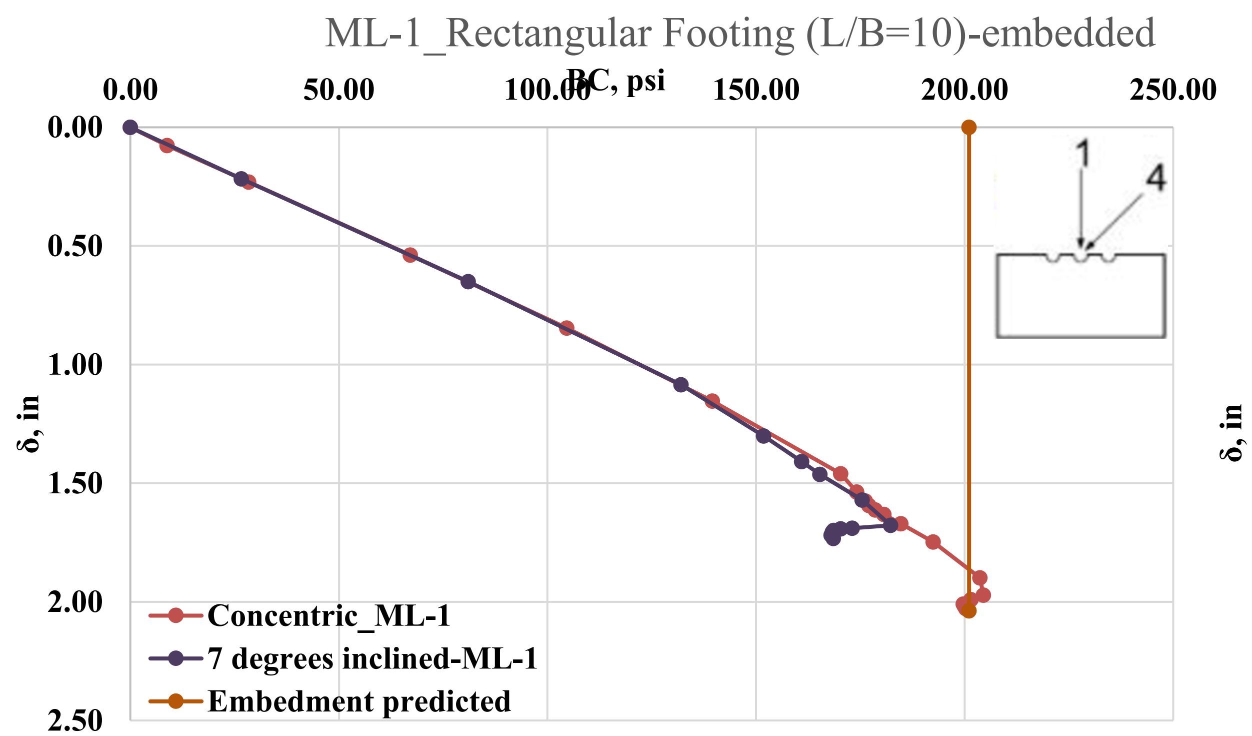
Miami Limestone: L/B = 1 and Fully Embedded with Inclined Loading

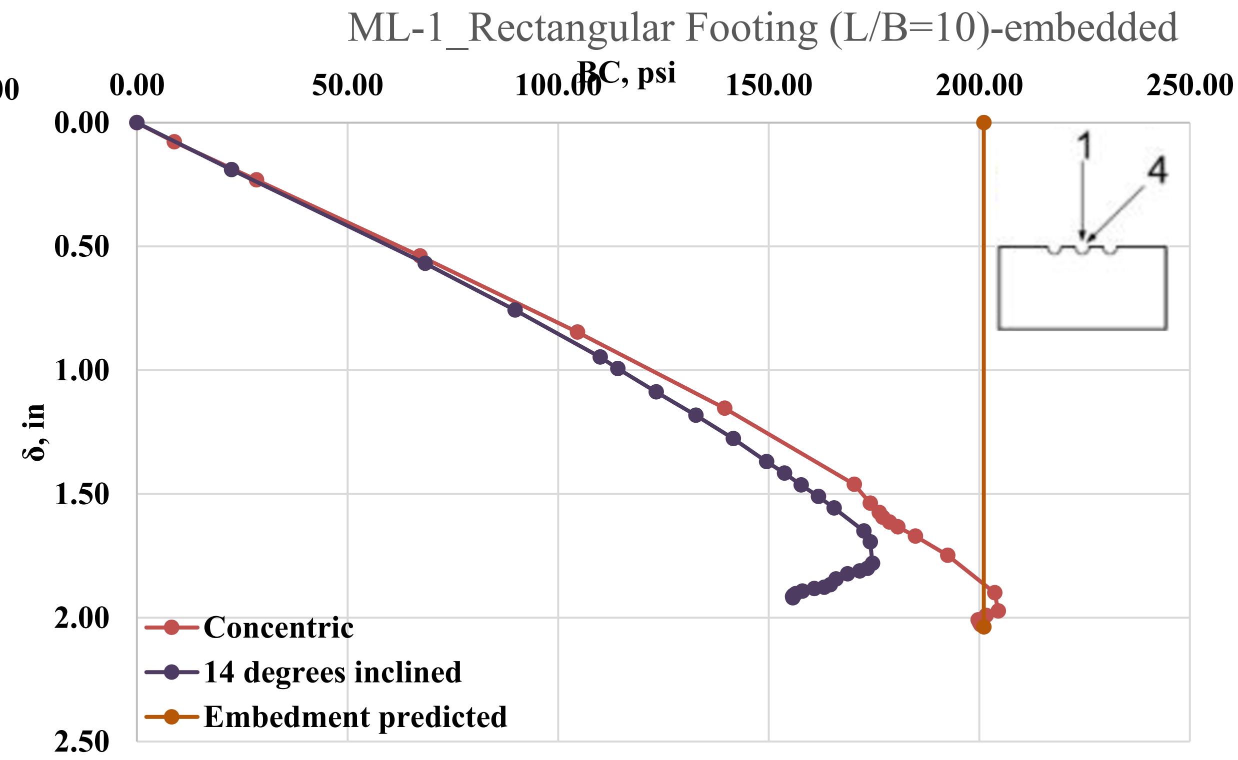




Task 4 – Investigate Effects of Inclined and Eccentric Loading

Miami Limestone: L/B = 10 and Fully Embedded with Inclined Loading





Closing Page

Thank You!

Questions & Answers