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

FDOT BED31-977-17

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Aug 17, 2023

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BSI Bridge Software Institute FDOT

Presentation Outline

- Project Background
- Project Objectives
- Deliverable 1: Implementation of Strength Envelopes and Florida Bearing Capacity Analyses in FB-MultiPier
- Future Tasks
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- Project Timeline

Project Background

- FDOT recently investigated the potential use of shallow foundations as an alternative to deep foundations within bridge substructures and funded a three-phase project (2017-2024).
- In Phase I (BDV31-977-51), based on the triaxial strength testing, bilinear strength envelopes were developed for Florida Limestone based on bulk dry unit weight/porosity and formation (e.g., Miami, Ft Thompson, Ocala, etc.). Using 3D finite element approach with bilinear Mohr-Coulomb, bearing capacity equations for single footings based on width, shape, embedment depth and bearing scenario (homogeneous rock or rock-over-sand) were developed.
- In Phase II (BDV31-977-124), three full scale load tests were performed to validate the bearing capacity equations. In addition, intact moduli by formation were developed for load-settlement predictions for homogeneous limestone and heterogeneous (rock over sand) site conditions.
- In Phase III (current phase), the developed Florida bearing capacity equations along with load-settlement predictions (homogeneous & heterogenous) using Winkler Model will be implemented into FB-MultiPier - finite element analysis (FEA) software, for both Service and Strength design for practicing bridge engineers. In addition, lateral resistance of embedded footings, as well as the effects of inclined and eccentric loadings will be investigated and implemented.

Project Objectives

I. TASK 1 – Implementation of bearing capacity equations for Florida limestone for strength design of shallow foundation homogeneous rock or rock-over-sand scenarios.

II. Task II – Implementation of nonlinear Winkler model for load-settlement analysis, i.e., service design of footings on homogeneous Florida rock or rock over sand, resulting in distributions of internal forces and moments throughout bridge substructures for design.

III. Task III – In case of embedded footings and lateral loading – Develop load transfer curves for the interface of rock and footing as well as embedded footing in rock

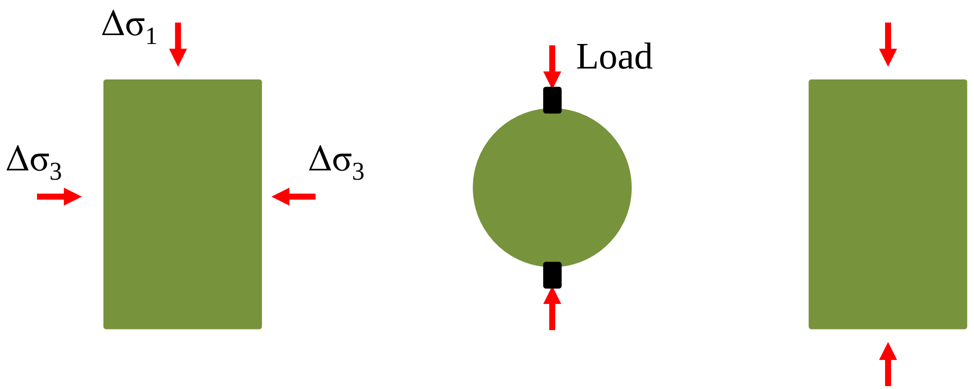
IV. Task IV – In the case of the resultant load being inclined and/or eccentric – modify Winkler and bearing capacity to account for it.

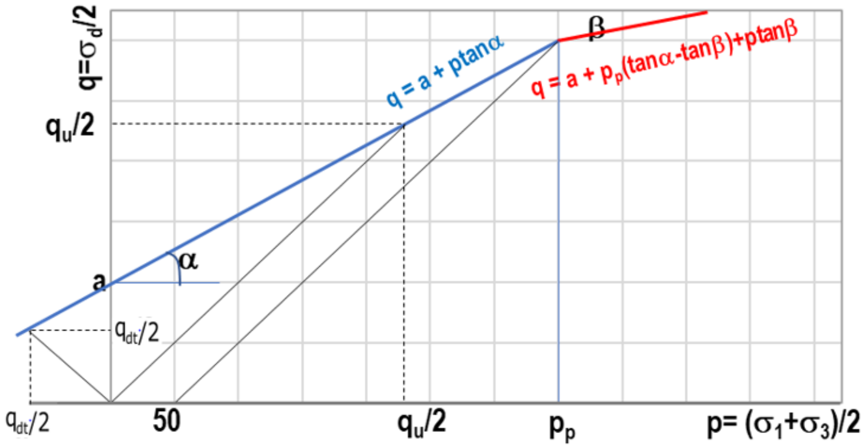
V. Task V – Develop documentation and data sets for the above four thrusts areas within the FB-MultiPier software manual.

Deliverable 1: Implementation of strength envelopes and Florida bearing capacity analyses

Bi-linear strength envelope

- Florida limestone at shallow depths are highly porous (median bulk porosity of 37%), have low bulk dry unit weights and nonlinear strength envelopes.
- Due to the high porosity, Florida carbonate rock (limestone) exhibits matrix crushing (p_p) resulting in a bilinear strength envelope.
- Based on unconfined compression (q_u) tests, Brazilian splitting tensile (BST) tests and triaxial tests under different confining pressure (50 psi and 600 psi) for five different Florida limestone formations (Nguyen et al., 2018 & 2019; McVay et al., 2019), bilinear strength envelops were developed as a function of bulk dry unit weight and formation.





Deliverable 1: Implementation of strength envelopes and Florida bearing capacity analyses

Florida bearing capacity equations

- The bi-linear Mohr-Coulomb elastoplastic model with a non-associated flow rule (matrix crushing) was developed for Florida limestone (McVay et al., 2019; Yang et al., 2023) and implemented – FEA.
- Using the 3D finite element method, numerical simulations were performed for a strip footing on a homogeneous rock subsurface, and bearing capacity equation was developed for bi-linear strength condition.
- Next, the width, shape, and embedment factors were developed based on the FEA simulation results.
- Finally, the rock-over-sand reduction factor was developed based on the rock layer thickness and moduli of rock and sand for the rock-over-sand condition encountered in South Florida.

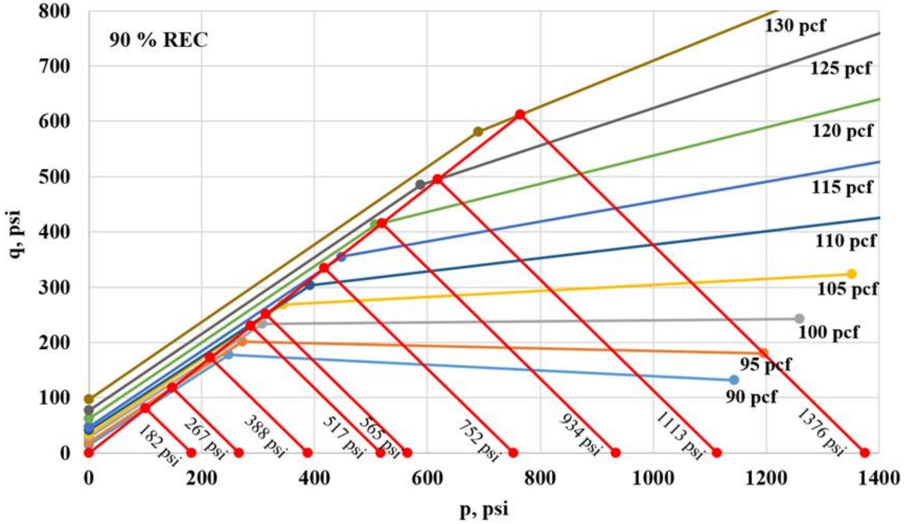
$Q_u = \min(Q_{u1}, Q_{u2}) * \xi / N_R$

Where,

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

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

ξ = Shape factor; N_R = Rock over sand reduction factor; n = width factor; N_q = embedment factor

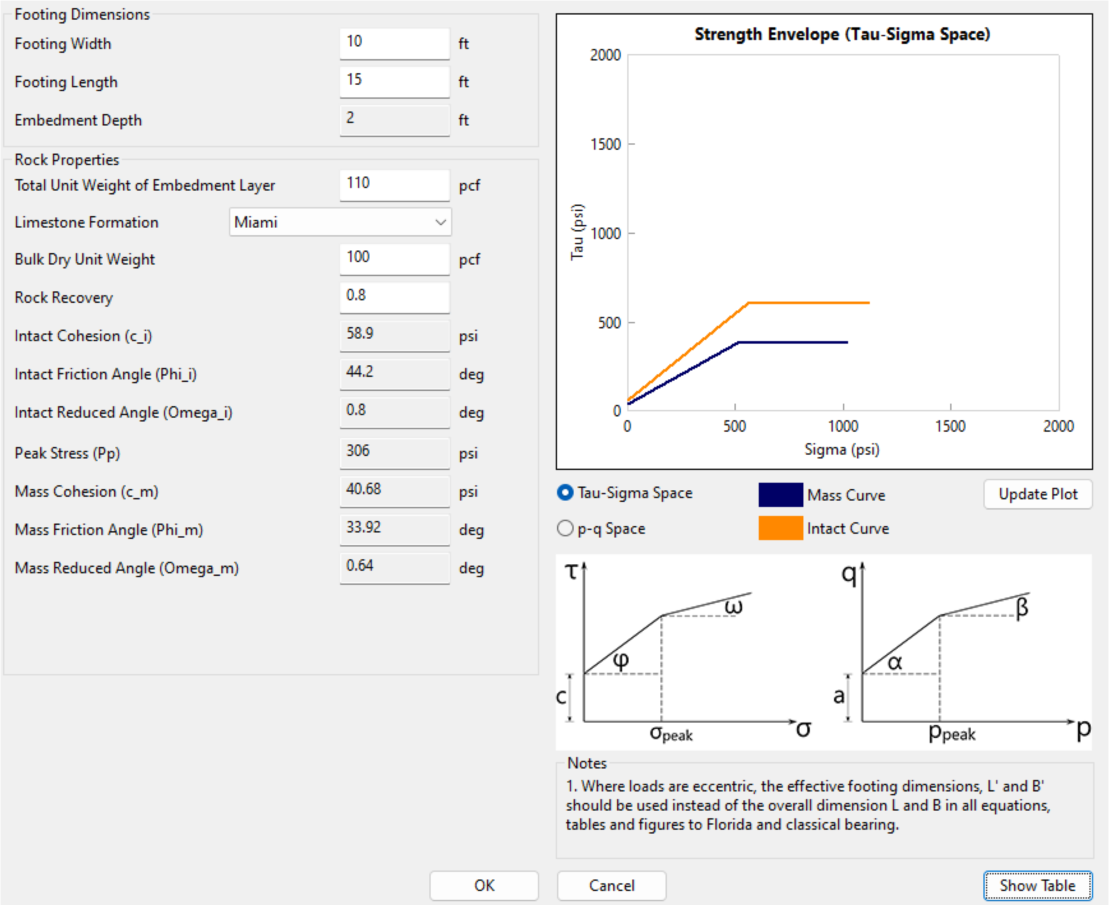


Deliverable 1: Implementation of strength envelopes and Florida bearing capacity analyses

- 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 and considered as an additional option in FB-MultiPier for plane Strain condition (L/B >10).

Deliverable 1: Implementation of strength envelopes and Florida bearing capacity analyses

Case 1: Based on Formation, Bulk dry unit weight and Recovery (Homogeneous)



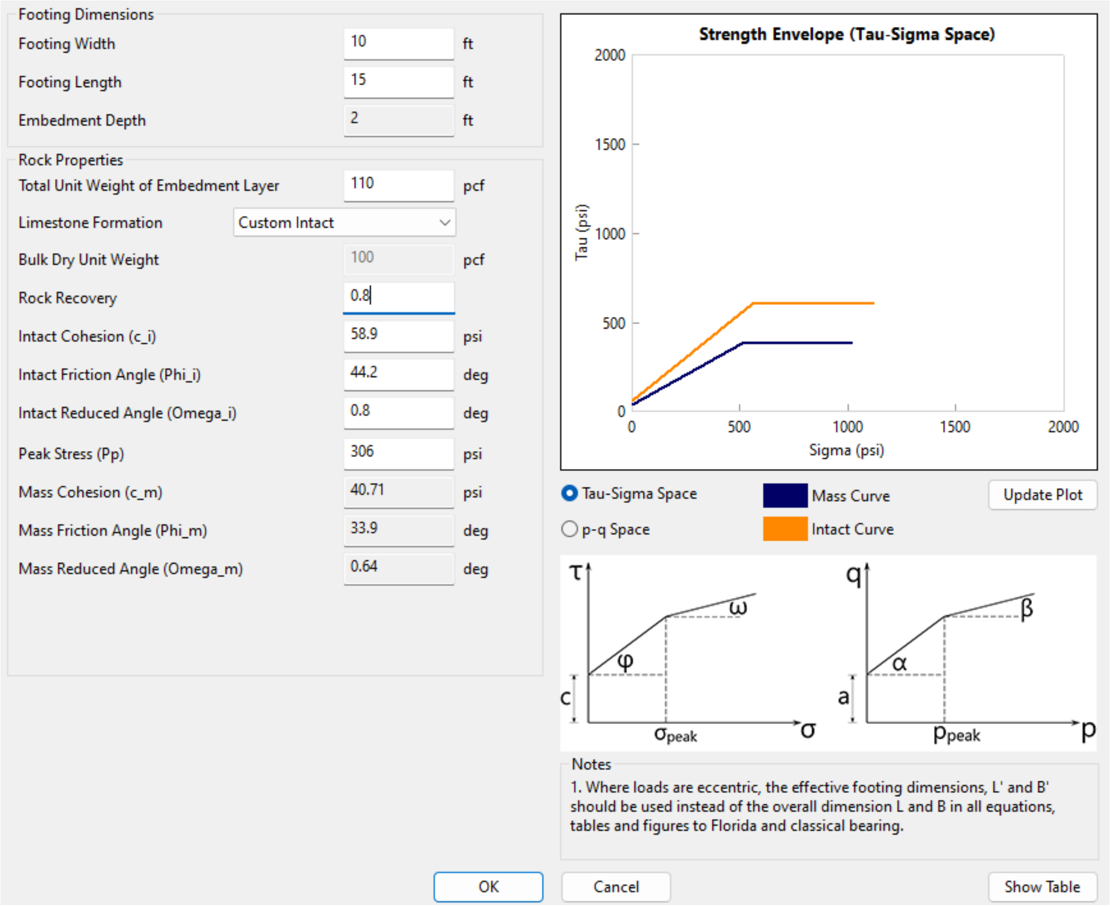
Input parameters:

Footing geometry: Footing width (B), Footing length (L), Embedment depth (D_f)

Rock properties: Formation (Miami, Ft. Thompson, Ocala etc.), Bulk dry unit weight (γ_{dt}), Recovery (REC)

Deliverable 1: Implementation of strength envelopes and Florida bearing capacity analyses

Case 2: Based on Intact strength parameters and Recovery (Homogeneous)



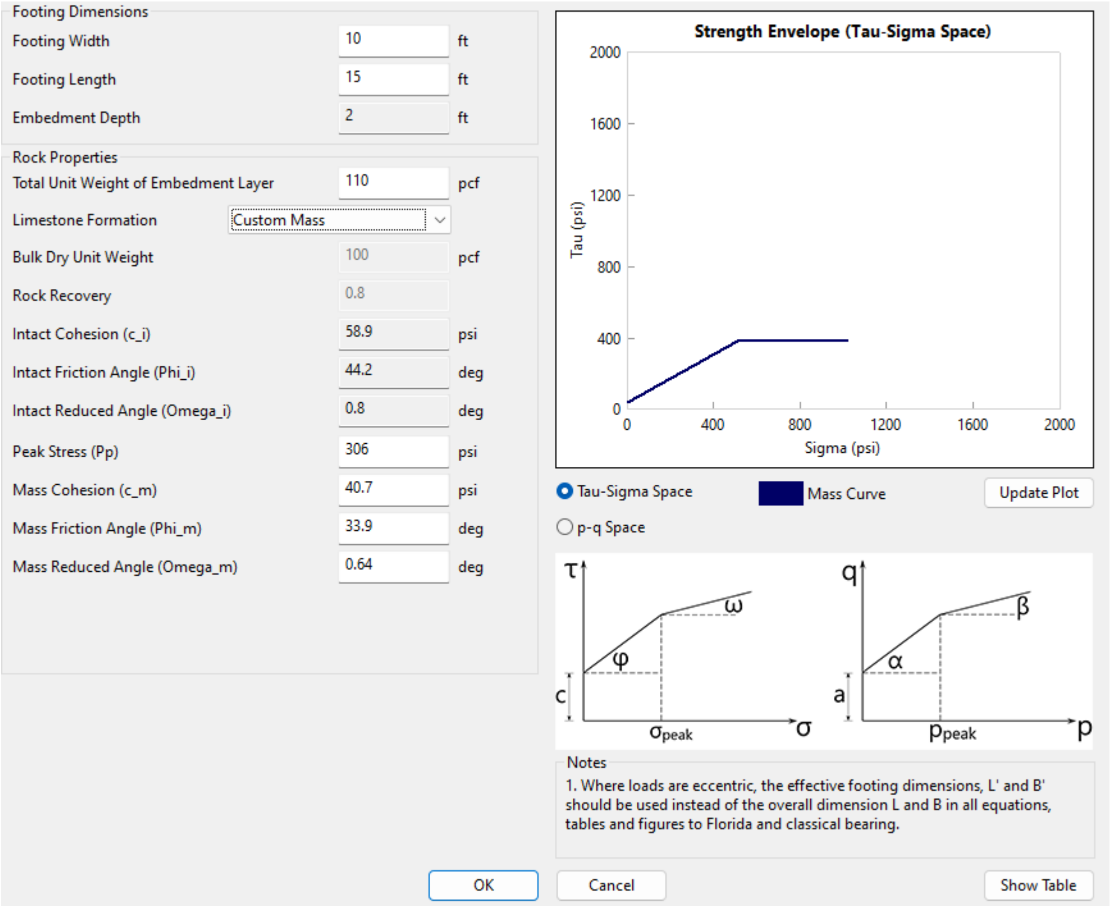
Input parameters:

Footing geometry: Footing width (B), Footing length (L), Embedment depth (D_f)

Rock properties: Intact cohesion (c_i), Intact friction angle (φ_i), Peak stress (p_p), Intact reduced angle (ω_i) and Recovery (REC)

Deliverable 1: Implementation of strength envelopes and Florida bearing capacity analyses

Case 3: Based on Mass strength parameters (Homogeneous)



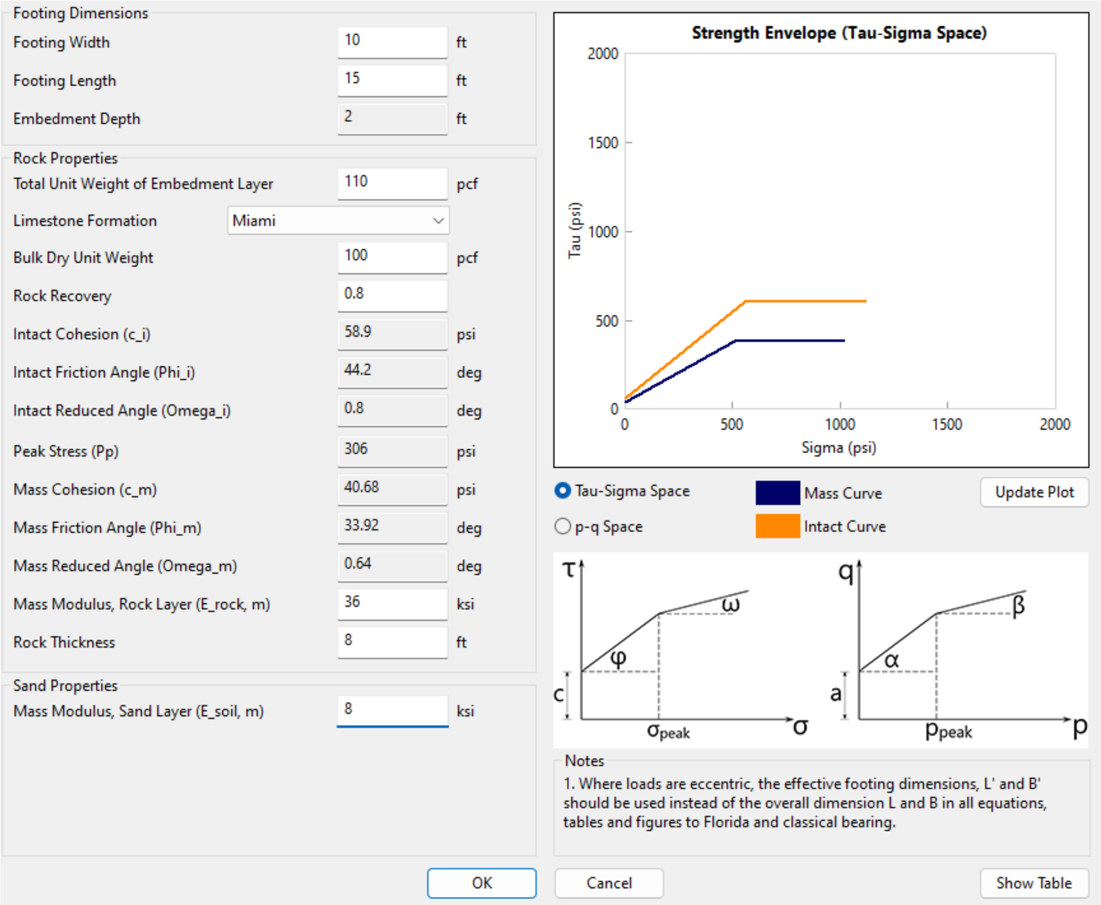
Input parameters:

Footing geometry: Footing width (B), Footing length (L), Embedment depth (D_f)

Rock properties: Mass cohesion (c_m), Mass friction angle (φ_m), Peak stress (p_p), Mass reduced angle (ω_m)

Deliverable 1: Implementation of strength envelopes and Florida bearing capacity analyses

Case 4: Based on Formation, Bulk dry unit weight and Recovery (Rock over sand)



Input parameters:

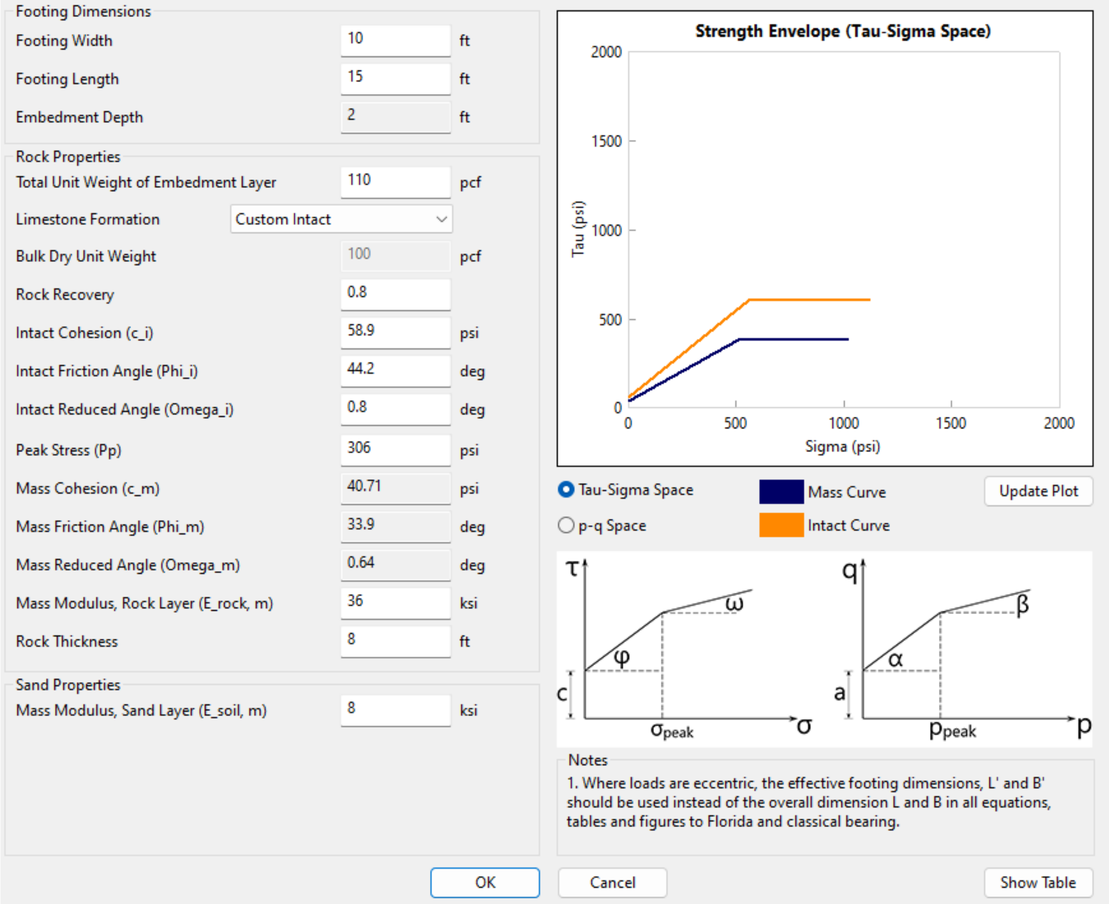
Footing geometry: Footing width (B), Footing length (L), Embedment depth (D_f), Rock layer thickness (T, bottom of footing to top of sand layer)

Rock properties: Formation (Miami, Ft. Thompson, Ocala etc.), Bulk dry unit weight (γ_{dt}), Mass modulus (E_{rock_mass}) and Recovery (REC)

Sand properties: Mass modulus (E_{sand_mass})

Deliverable 1: Implementation of strength envelopes and Florida bearing capacity analyses

Case 5: Based on Intact strength parameters and Recovery (Rock over sand)



Input parameters:

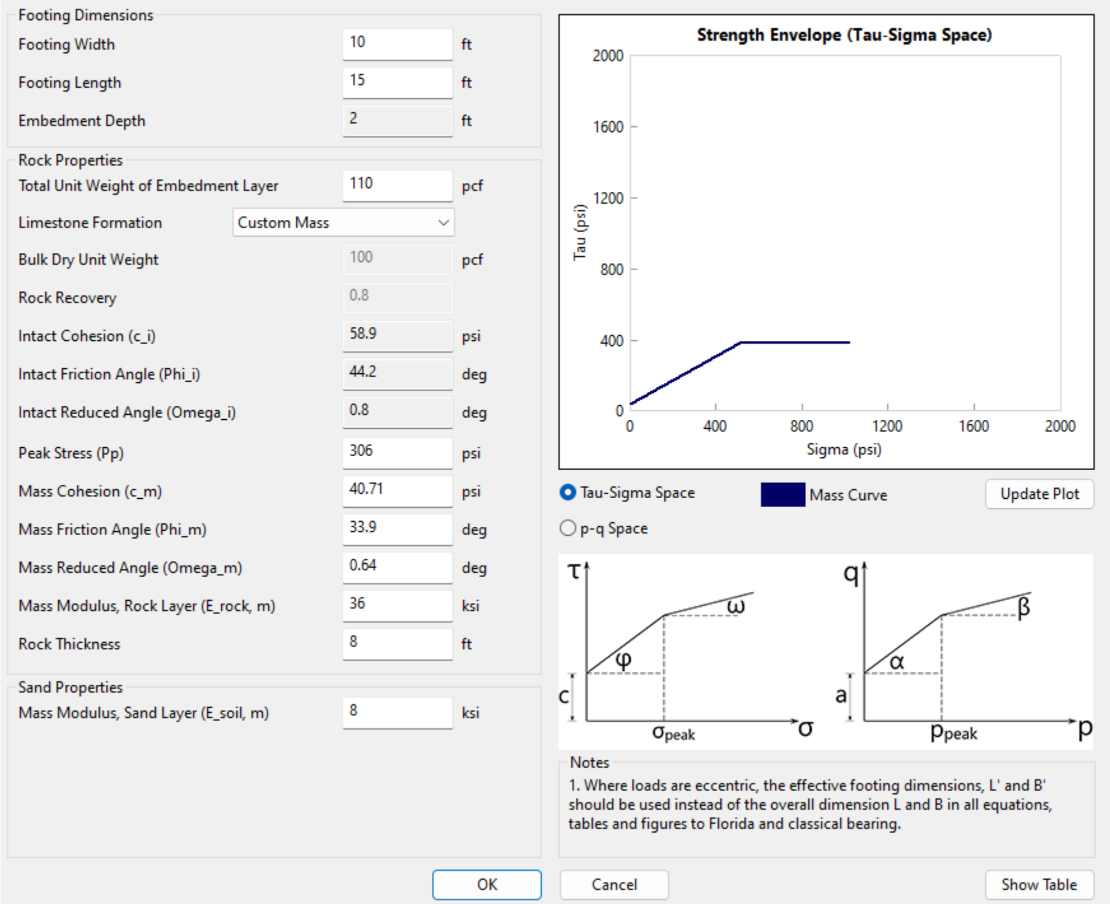
Footing geometry: Footing width (B), Footing length (L), Embedment depth (D_f), Rock layer thickness (T)

Rock properties: Intact cohesion (c_i), Intact friction angle (φ_i), Peak stress (p_p), Intact reduced angle (ω_i), Mass modulus (E_{rock_mass}) and Recovery (REC)

Sand properties: Mass modulus (E_{sand_mass})

Deliverable 1: Implementation of strength envelopes and Florida bearing capacity analyses

Case 6: Based on Mass strength parameters (Rock over sand)



Input parameters:

Footing geometry: Footing width (B), Footing length (L), Embedment depth (D_f), Rock layer thickness (T)

Rock properties: Mass cohesion (c_m), Mass friction angle (φ_m), Peak stress (p_p), Mass reduced angle (ω_m) and Mass modulus ($E_{rock\ \_mass}$)

Sand properties: Mass modulus ($E_{sand\ \_mass}$)

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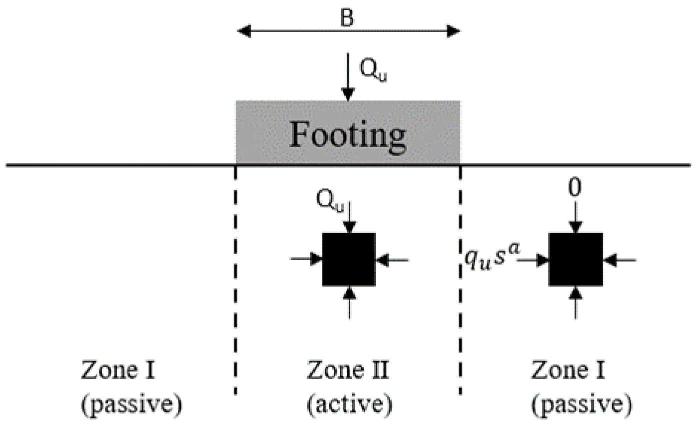
Case 7: Carter and Kulhawy Method



Note, Carter and Kulhawy method (1988) is only used for the case of the strip footing on the ground surface

$$Qu = \left[\sqrt{s} + \sqrt{m\sqrt{s} + s}\right] q_u$$

Where,

$s = e^{(GSI-100)/(9-3D)}$

$m = m_i\, e^{(GSI-100)/(28-14D)}$

GSI = Geological strength index

q_u = unconfined compression strength

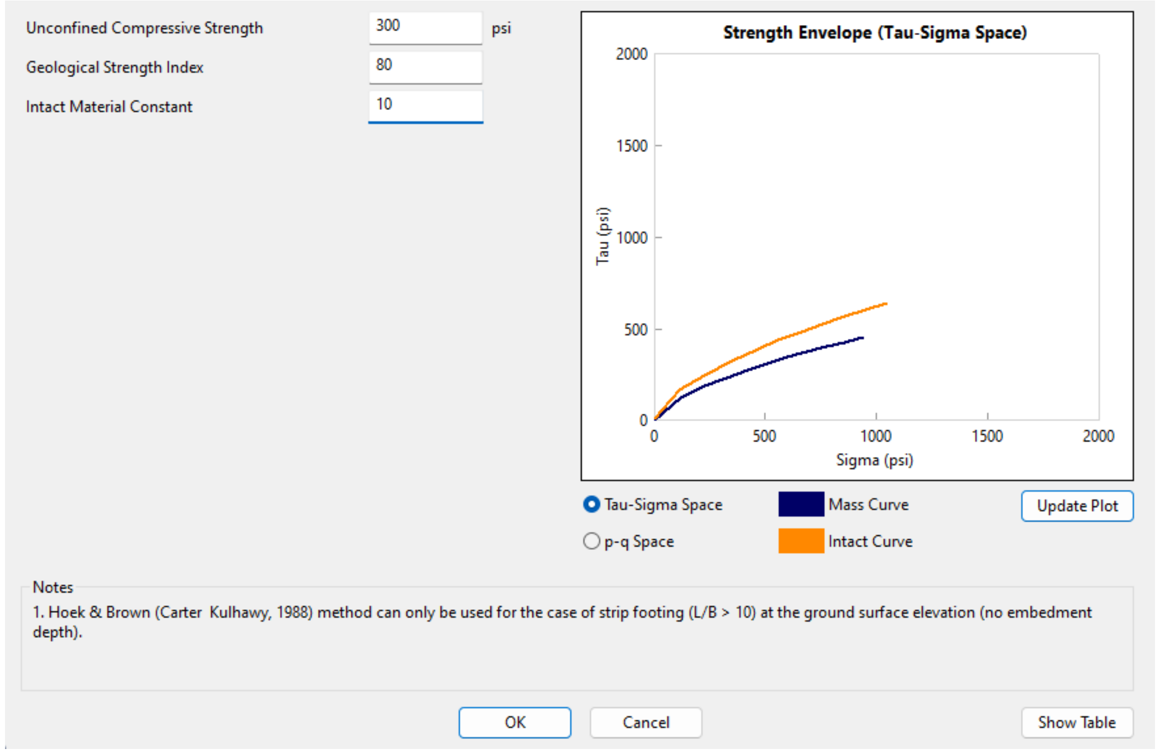
D = disturbance factor, D = 0 represents shallow foundation excavations

m_i = intact frictional strength parameter, assumed as 10

a is approximated as 0.5

Deliverable 1: Implementation of strength envelopes and Florida bearing capacity analyses

Case 7: Carter and Kulhawy Method



Input parameters:

Footing geometry: Footing width (B)

Rock properties: Unconfined compression strength (q_u), Geological strength index (GSI), Intact material constant (m_i)

Bearing stress comparison

Homogeneous – English Units

Footing Geometry	B, ft	10	10	10	10	5	5
	L, ft	15	15	15	15	10	10
	D_f, ft	3	3	3	0	0	0
Depth of Water Table	D_w, ft	0	1.5	5	5	5	5
Formation	-	Miami	Miami	Miami	Miami	Key Largo	Key Largo
Bulk dry unit weight	γ_{dt}, pcf	100	100	100	100	67	67
Total unit weight	γ_{total}, pcf	115	115	115	115	67	67
Recovery	REC, %	80	80	80	80	80	75
FL Bearing	ksf	44.96	46.55	48.14	42.28	19.65	16.69
FBMP	ksf	45.06	46.7	48.34	42.3	19.66	16.7
Error	%	-0.23	-0.32	-0.41	-0.06	-0.06	-0.08

Rock over sand – English Units

Footing Geometry	B, ft	10	10	10	10	10
	L, ft	20	15	15	15	20
	D_f, ft	0	3	3	3	0
Depth of Water Table	D_w, ft	25	1	1	1	25
Formation	-	Miami	Miami	Miami	Miami	Miami
Bulk dry unit weight	γ_{dt}, pcf	135	100	100	100	90
Total unit weight	γ_{total}, pcf	135	115	115	115	90
Recovery	REC, %	1	80	80	80	1
Rock thickness	T, ft	5	8	4	4	20
Mass modulus of rock	E_{rock_mass}, psi	1	36000	36000	36000	1
Mass modulus of sand	E_{sand_mass}, psi	0.03	1200	1200	5000	0.03
FL Bearing	ksf	228.11	35.72	25.25	36.08	65.82
FBMP	ksf	228.11	35.82	25.33	36.19	65.82
Error	%	0	-0.29	-0.29	-0.29	0.01

Homogeneous – SI Units

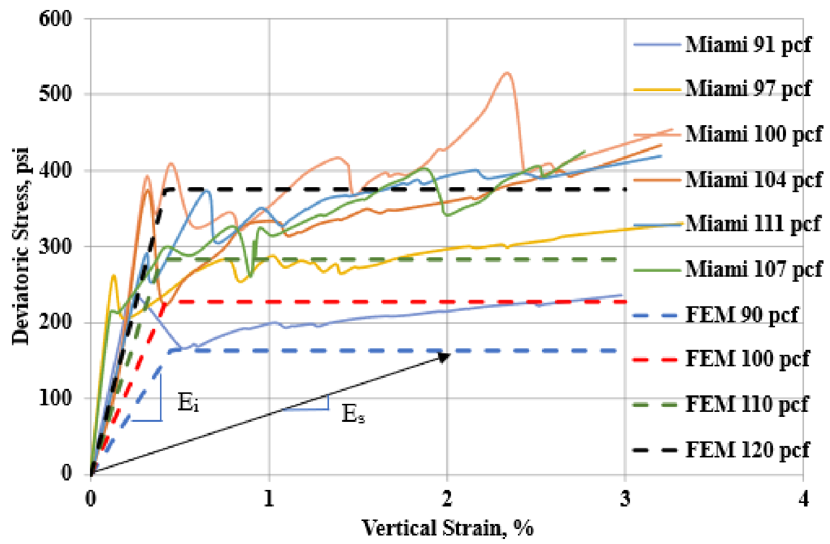
Footing Geometry	B, m	3	3	3	3
	L, m	9	3	3	3
	D_f, m	1	0	1	1
Depth of Water Table	D_w, m	0	0	10	0
Formation	-	Miami	Miami	Miami	Miami
Bulk dry unit weight	γ_{dt}, kN/m^3	17	17	17	17
Total unit weight	γ_{total}, kN/m^3	17.5	17.5	17.5	17.5
Recovery	REC, %	80	80	80	80
FL Bearing	kPa	2857.73	2984.7	3442.37	3180.5
FBMP	kPa	2862.5	2984.7	3442.37	3185.81
Error	%	-0.17	0	0	-0.17

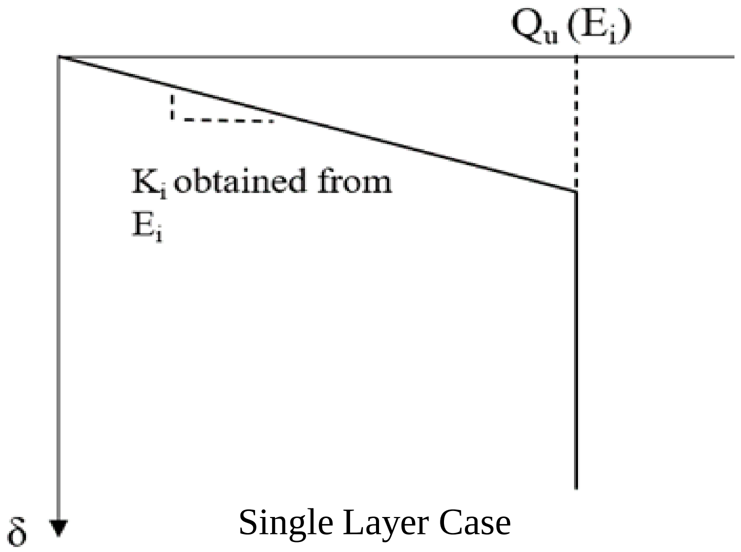
Rock over sand – SI Units

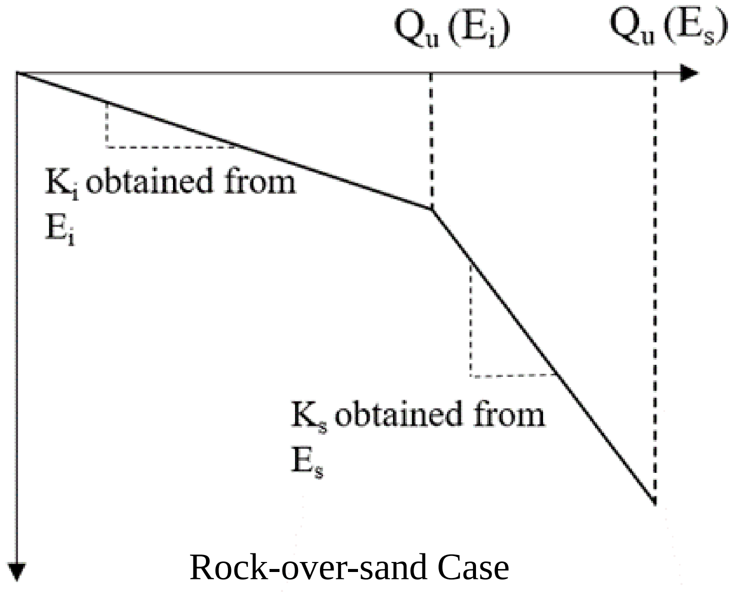
Footing Geometry	B, m	3	3	3
	L, m	9	3	3
	D_f, m	1	1	1
Depth of Water Table	D_w, m	0	0	10
Formation	-	Miami	Miami	Miami
Bulk dry unit weight	γ_{dt}, kN/m^3	17	17	17
Total unit weight	γ_{total}, kN/m^3	17.5	17.5	17.5
Recovery	REC, %	80	80	80
Rock thickness	T, m	12	12	12
Mass modulus of rock	E_{rock_mass}, kPa	36000	36000	36000
Mass modulus of sand	E_{sand_mass}, kPa	5000	5000	5000
FL Bearing	kPa	2862.49	3185.81	3442.37
FBMP	kPa	2862.5	3185.81	3442.37
Error	%	0	0	0

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.





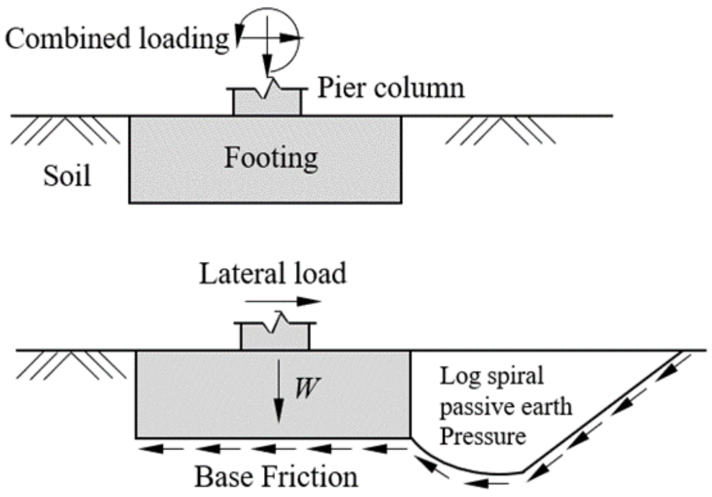


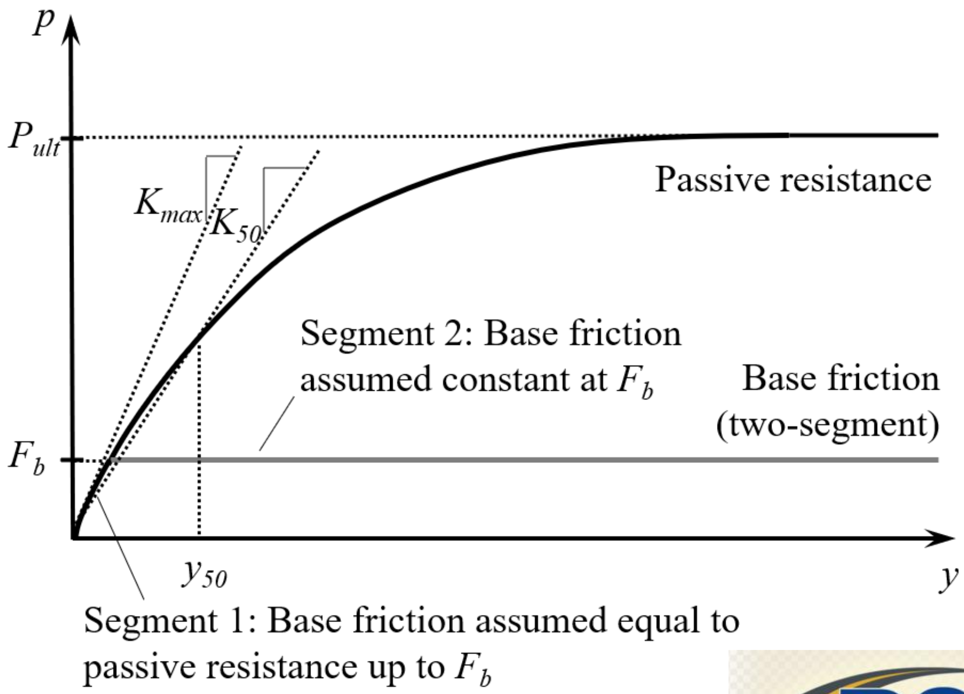
Task 2 – Implement Load-settlement Analysis

Deliverable 2: Upon completion of Task 2, a written report will be submitted that documents pertinent aspects of the implementation, including: the procedures for generating pressure versus (compression-only) vertical displacement relationships under homogenous and rock-over-sand conditions. Also, the Task 2 report will list validation cases (e.g., field load tests from Phase II), variability characterization and settlements, input-associated updates to model files, corresponding engine enhancements, and user interface (UI) enhancements.

Task 3 – Implement Lateral Resistance Models

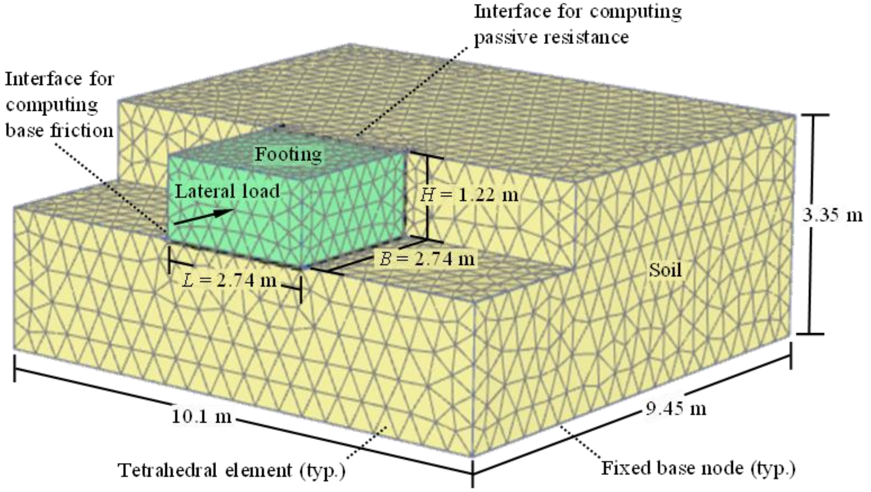
- Inclusion of both vertical and lateral resistance for numerical stability of bridge foundation models.
- Lateral resistance of embedded footings: passive resistance (Rankine, Coulomb and Log-spiral) and base friction (Coulomb friction law).
- Force-displacement relationship for passive resistance: bi-linear, hyperbolic; base friction will mobilize at a similar rate to the passive resistance (two-segment) based on the reviewed load tests and FEMA (2010).
- Formulations will be validated against selected field tests and the robustness will be assessed by conducting a parametric study (using fully-coupled 3D FEA).



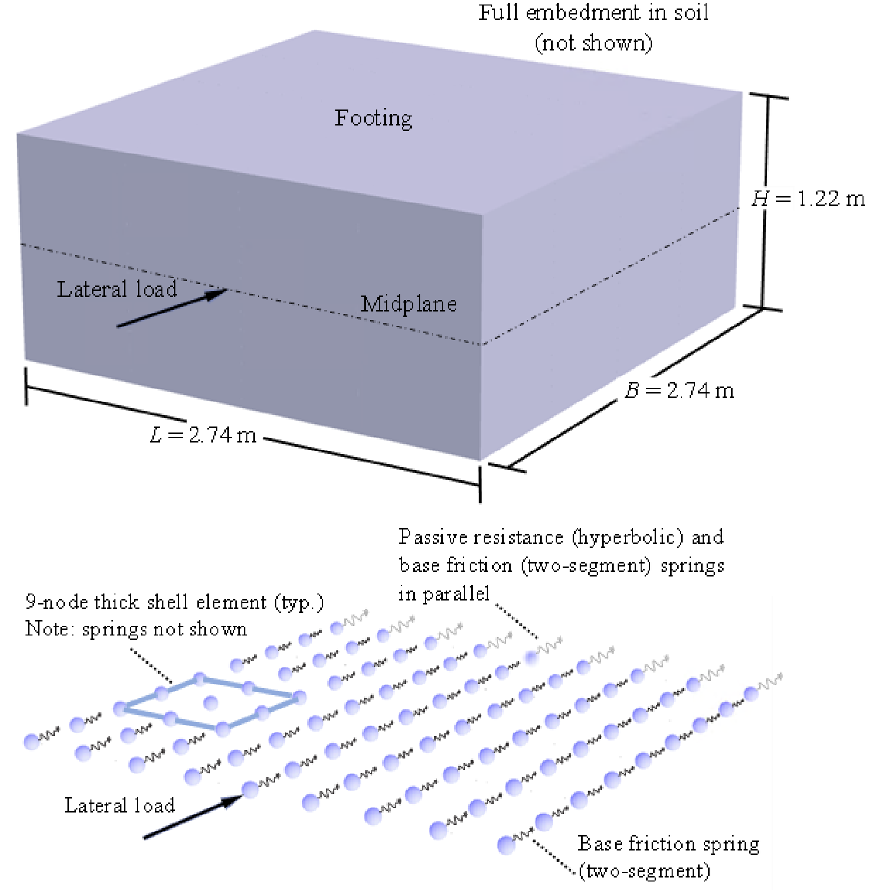


Task 3 – Implement Lateral Resistance

Continuous FEM model



Discrete Winkler model



Task 3 – Implement Lateral Resistance

Deliverable 3: Upon completion of Task 3, a written report will be submitted that includes the literature review, adopted empirical models, force-displacement relationships, lateral nonlinear springs, validation and robustness assessments (e.g., parametric study), corresponding engine enhancements, and UI enhancements.

Task 4 – Investigate Effects of Inclined and Eccentric Loadings

- Development of a conservative means of accounting for load inclination and eccentricity:
  - Review of FDOT BDV31-977-66, Bearing Capacity Factors for Shallow Foundations Subjected to Combined Lateral and Axial Loading.
  - Literature review of rock bearing capacity: discontinuous and continuous rock.
  - Use fully coupled 3D FEA as a cost-effective alternative to physical testing.
  - Parametric study between fully coupled 3D FEA and Winkler model.
  - Trends in footing response will be investigated, identified and used to characterize a conservative modification to vertical bearing spring pressure values (Winkler load-settlement and bearing capacity for FL limestone cases (homogeneous and rock over sand).

Task 4 – Investigate Effects of Inclined and Eccentric Loadings

Deliverable 4: Upon completion of Task 4, a written report will be submitted that documents the adopted approach for incorporating inclined and eccentric loadings. If numerical modeling is necessary, the scope of the parametric study will be documented along with the underlying model configurations, model validation efforts, any identified trends in response quantities, and the approach for conservatively modifying vertical bearing springs.

Task 5 – Develop Software Manual Documentation

- Update the FB-MultiPier Manual to include shallow foundation guidelines:
  - Site characterization (e.g., bulk dry unit weight, rock recovery)
  - Strength assessment with recommended values
  - Immediate settlement with recommended values
  - Validation case

Deliverable 5: Upon completion of Task 5, a written report will be submitted that documents the updates made to the software manual.

Research Publications

FDOT Report:

McVay, M. C., Song, X., Wasman, S. J., Nguyen, T., Wang, K, 2019. Strength envelopes for Florida rock and intermediate geomaterials (No. 00125485). Florida. Department of Transportation.

Rodgers, M., McVay, M., Wasman, S., Tran, K., Yang, K, 2022. Field load testing of shallow foundations in Florida limestone (No. P0147823). Florida. Department of Transportation.

Journal Papers:

Nguyen, T., McVay, M., Song, X., Herrera R., Wasman S., Wang, K., 2019. Strength Envelopes of Florida Carbonate Rocks near Ground Surface. Journal of Geotechnical and Geoenvironmental Engineering. 145(8), 04019034.

Yang, K., McVay, M., Nguyen, T., Wang, K., Song, X., Wasman, S., Rodgers, M., Horhota, D., Herrera, R., 2023. Bearing Capacity of Shallow Foundations on Florida Limestone: a Study of Single Layer and Rock-over-sand Subsurface. Computers and Geotechnics (Accepted, Aug 2023).

Reference

Carter, J. P., Kulhawy, F. H., 1988. Analysis and design of drilled shaft foundations socketed into rock (No. EPRI-EL-5918). Electric Power Research Inst., Palo Alto, CA (USA); Cornell Univ., Ithaca, NY (USA). Geotechnical Engineering Group.

Hoek, E., Brown, E. T., 1980. Empirical strength criterion for rock masses. Journal of the Geotechnical Engineering Division. vol 106-9, pp. 1013–1035.

McVay, M. C., Song, X., Wasman, S. J., Nguyen, T., Wang, K, 2019. Strength envelopes for Florida rock and intermediate geomaterials (No. 00125485). Florida. Department of Transportation.

Nguyen, T., McVay, M., Horhota, D., and Herrera R., 2018. Overview of Carbonate-Rocks and IGMs Supporting Florida Bridges. Proceedings of the 52nd U.S. Rock Mechanics/Geomechanics Symposium. Seattle, Washington.

Nguyen, T., McVay, M., Song, X., Herrera R., Wasman S., Wang, K., 2019. Strength Envelopes of Florida Carbonate Rocks near Ground Surface. Journal of Geotechnical and Geoenvironmental Engineering. 145(8), 04019034.

Project Timeline

Deliverable # / Description of Deliverable as provided in the scope (included associated task #)	Anticipated Date of Deliverable Submittal (month/year)	TO BE COMPLETED BY RESEARCH CENTER (performance monitoring)
Kickoff teleconference	April 2023	
Task 1, Deliverable 1: Implement bearing capacity equations	Aug. 2023	
Task 2, Deliverable 2: Implement load-settlement analysis	Dec. 2023	
Task 3, Deliverable 3: Implement lateral resistance	May 2024	
Task 4, Deliverable 4: Investigate inclined and eccentric loadings	Oct. 2024	
Task 5, Deliverable 5: Update software manual	Dec. 2024	
Task 6, Deliverable 6a: Draft Final report	Jan. 2025	
Task 6, Deliverable 6b: Closeout teleconference	Mar. 2025	
Task 7, Deliverable 7: Final report	Apr. 2025	

Closing Page

Thank You!

Questions & Answers