Strength Envelopes for Florida Rock and Intermediate Geomaterials
FDOT BDV31-977-51

Principal Managers:
Rodrigo Herrera, P.E.
David Horhota, Ph.D., P.E.
Florida Department of Transportation

Principal Investigators:
Michael McVay, Ph.D.
Xiaoyu Song, Ph.D.
Scott Wasman, Ph.D.
Thai Nguyen, Ph.D.
Kaiqi Wang, Ph.D. Student

University of Florida
Department of Civil and Coastal Engineering

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Presentation Outline

1. Project Description
2. Project Benefits
3. Background of Rock Strength & Bearing Capacity
4. Project Objectives
5. Tasks Outline and Discussion
6. Summary of Research and Conclusions
7. Recommendations
8. Publications

Project Description

This research is separated into three phase project:

Phase 1: Assess strength envelope for Florida Limestone and develop Bearing Capacity Equations of shallow foundations on limestone. (finished)

- Guidelines for laboratory testing for the purposes of developing strength envelope for Limestone
- New design equations for bearing capacity of shallow foundations on Limestone

Phase 2: Validate the new Florida Bearing Capacity Equations derived in the current work by field testing. (expected to last 2 years)

Phase 3: Implementing the validated equations into FB-Multipier. (expected to last 1.5 years)

An updated version of FB-Multipier capable of evaluating shallow foundations would be released after Phase 3.

Project Benefits

I. Qualitative:

Development of design bearing equations for shallow foundations will result in safer and more competitive foundations for bridge piers in case of limestone near the ground surface.

II. Quantitative:

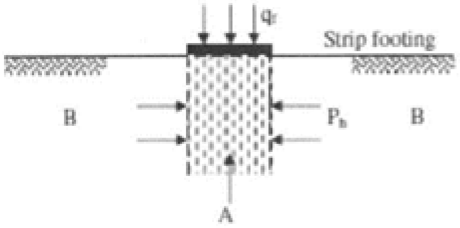
- Better understanding of the strength characteristics of Florida Limestone.
- Value of index testing (e.g. dry unit weight, etc).
- Newer bearing capacity equations for Florida Limestone.
- Recommendations on how to handle less than 100% rock recoveries for strength and bearing capacity.

Background

- Florida has many locations with limestone in the vicinity of the ground surface (e.g. Miami-Dade, Broward, Palm Beach. etc.).
- The FDOT has seen an increase in Design-Build contracts proposing the use of shallow foundations for bridges located on limestone.
- An integral part of shallow design is the estimation of the ultimate contact (bearing) stress, $q_{ult,}$ between the foundation and underlying limestone layer.
- Limited study of Florida Strength Envelope and Bearing Capacity Equations for Shallow Foundations on Rock.

Background

Existing Bearing Capacity Method



Current AASHTO and Federal design (NCHRP 651) methods, give q_{ult} of the form (Carter and Kulhawy, 1988):

$$q_{ult} = (\sqrt{s} \ + (m\sqrt{s} + s)^{0.5})q_u$$

Where

q_u: unconfined compressive strength of the rock

m & s: empirical parameters – associated with Geological Strength Index (GSI)

For instance, (Hoek and Brown, 2002) uses the parameters m & s to assess the major principal stress, $\sigma'_{1,}$ in terms of the minor principal stress, $\sigma'_{3,}$ (e.g. confining stress in triaxial testing) of rock mass at failure:

$$\sigma'_1 = \ \sigma'_3 + qu\left(m_b\frac{\sigma'_3}{q_u} + s\right)^a$$

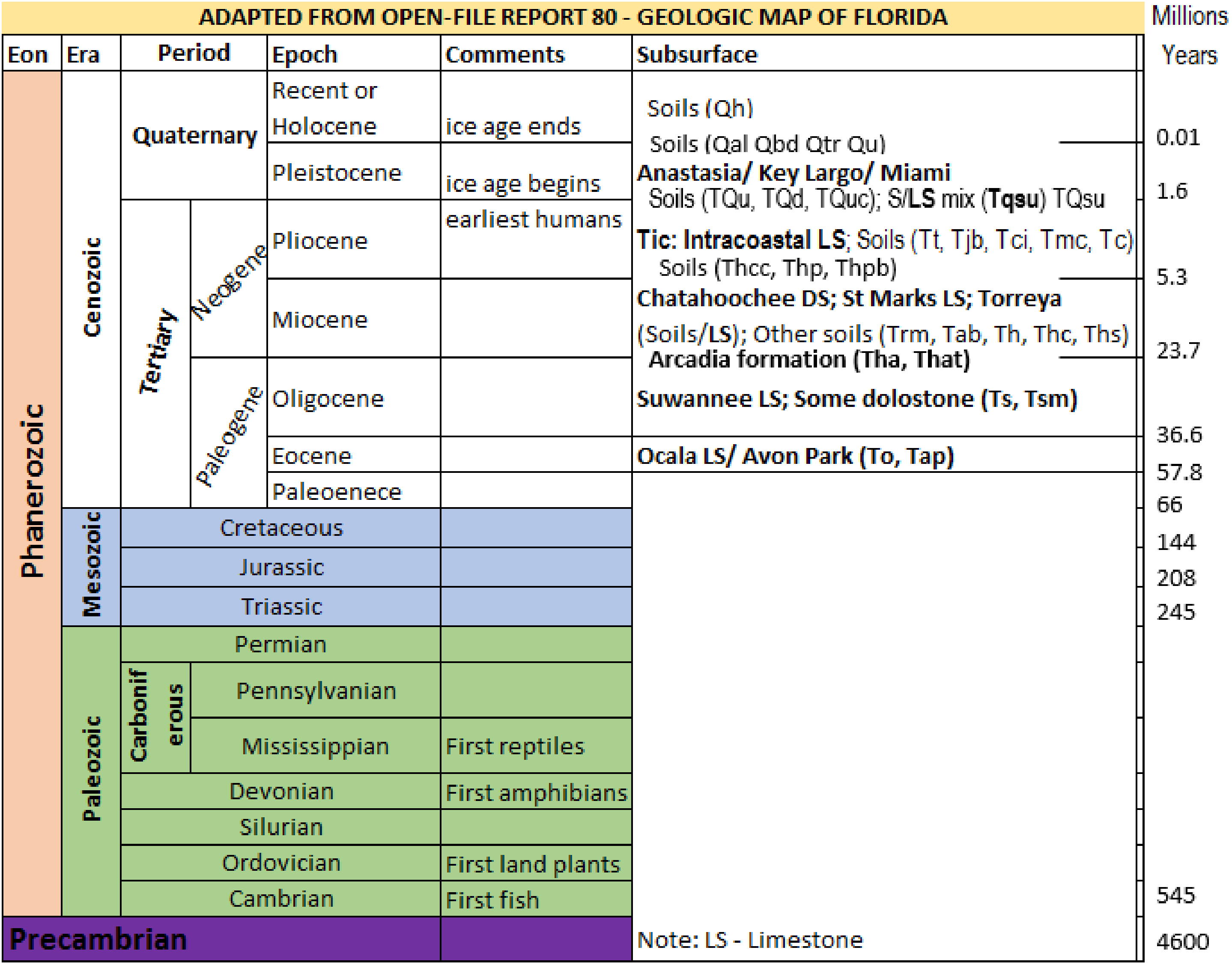
Background

Deficiency of Existing Method

- Hoek-Brown’s GSI (Geological Strength Index) criterion based on joints within rock not intact porous rock.
  - How is GSI Assessed?
- Hoek-Brown’s method was developed empirically and may not be appropriate for Florida Limestone which is highly porous – strength envelope function of stress.
- Strength of the Florida rock under compression or extension loading, may not be consistent with the assumption of current AASHTO and Federal design (NCHRP 651) methods.
- In addition, because of the porous nature of Florida Limestone, the rock may exhibit strain softening as well as crushing which could significantly impact q_{ult}.
- A typical bearing capacity design in Florida should consider the limestone layer overlying sand solution.

Background

Florida Geology:



ADAPTED FROM OPEN-FILE REPORT 80 - GEOLOGIC MAP OF FLORIDA

Eon	Era	Period		Epoch	Comments	Subsurface	Millions Years
Phanerozoic	Cenozoic	Quaternary		Recent or Holocene	ice age ends	Soils (Qh)	0.01
				Pleistocene	ice age begins	Soils (Qal Qbd Qtr Qu) **Anastasia/ Key Largo/ Miami** Soils (TQu, TQd, TQuc); S/**LS** mix (**Tqsu**) TQsu	1.6
		Tertiary	Neogene	Pliocene	earliest humans	**Tic: Intracoastal LS**; Soils (Tt, Tjb, Tci, Tmc, Tc) Soils (Thcc, Thp, Thpb)	5.3
				Miocene		**Chatahoochee DS; St Marks LS; Torreya** (Soils/**LS**); Other soils (Trm, Tab, Th, Thc, Ths) **Arcadia formation (Tha, That)**	23.7
			Paleogene	Oligocene		**Suwannee LS; Some dolostone (Ts, Tsm)**	36.6
				Eocene		**Ocala LS/ Avon Park (To, Tap)**	57.8
				Paleoenece			66
	Mesozoic	Cretaceous					144
		Jurassic					208
		Triassic					245
	Paleozoic	Permian					
		Carboniferous	Pennsylvanian				
			Mississippian		First reptiles		
		Devonian			First amphibians		
		Silurian					
		Ordovician			First land plants		
		Cambrian			First fish		545
Precambrian						Note: LS - Limestone	4600

Background

Florida carbonate rocks

- Limestone (Calcium Carbonate - $CaCO_3$)
  - Calcite (Rhombohedral) $2.70<G_s<2.72$
  - Aragonite (Orthorhombic) $2.85<G_s<2.94$
- Dolostone (Dolomite - $MgCa(CO_3)_2$ ← Calcite +Magnesium-rich water $2.8<G_s<3.0$
- Marls ← Carbonate (35-65%) +soil (clay, silt And sand)

Formations	Number of specimens	% carbonate		% calcite		% aragonite		% dolomite		% quartz	
		range	average	range	average	range	average	range	average	range	average
Ft. Thompson	14	64-80	72	55-78	67	0-15	5			20-36	28
Anastasia	40	66-98	90	50-98	84	0-47	6			2-34	10
Key Largo	39	99-100	99.5	39-95	79	5-61	20			0-1	0.5
poor indurated Miami	12	77-90	84	52-82	70	0-34	14			10-23	16
medium indurated Miami	34	89-98	95	74-97	91	0-22	4			2-11	5
medium to well indurated Miami	14	88-99	96	76-99	91	0-21	5			1-12	4
Arcadia dolostone	26	64-96	84	0-18	2			49-94	82	4-36	16
Hawthorn marl	22	23-77	64	0-40	12			12-73	51	23-77	36
Hawthorn dolostone	49	67-93	81	0-38	12			38-87	69	7-33	19
Hawthorn limestone	7	77-89	84	62-83	76			0-16	8	11-23	16

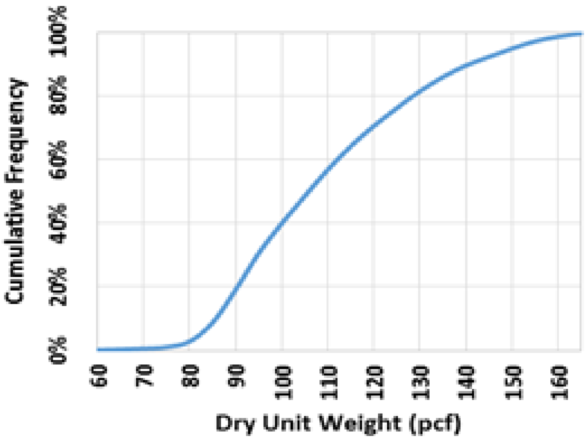
Background

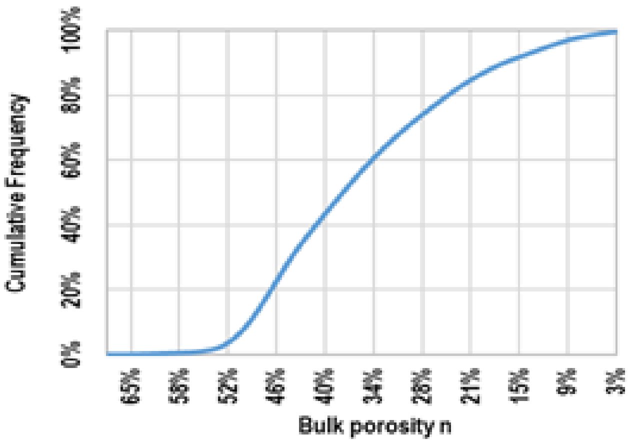
SMO Florida Limestone strength testing (~8500 specimens):

γ_{dt} = total dry unit weight = dry unit weight in air (ASTM D6473) / cylindrical volume

γ_{st} = unit weight of solids = $G_s \gamma_w$

n = bulk porosity = $1 - \gamma_{dt} / \gamma_{st}$





50% Population – γ_{dt} = 105 pcf

75% Population – γ_{dt} < 123 pcf

50% Population – n = 37%

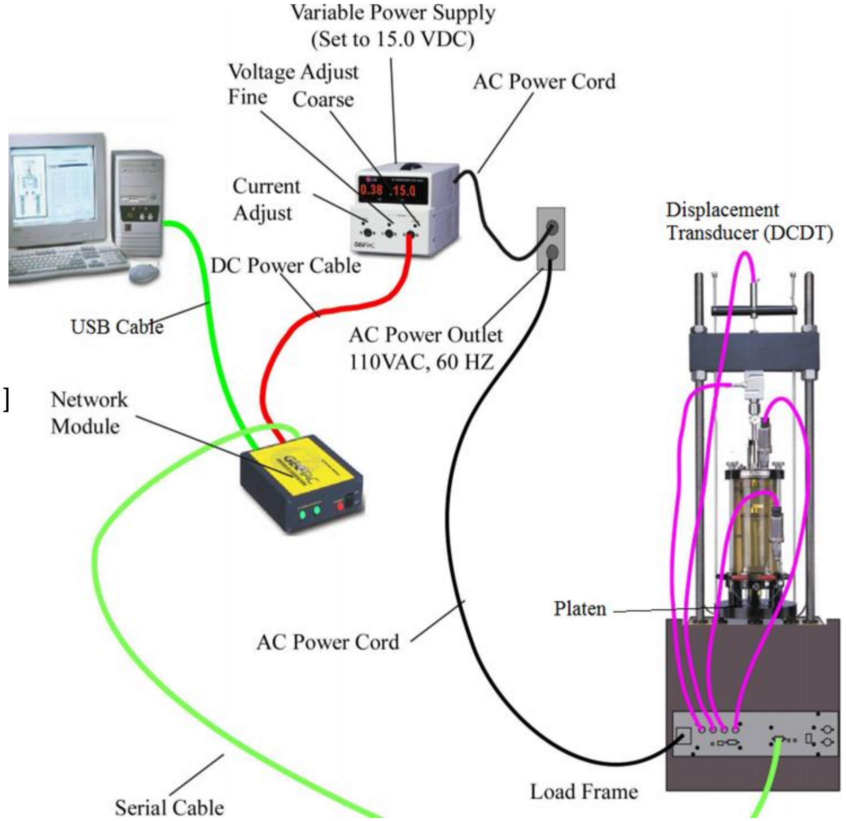
75% Population – n > 28%

Project Objectives

- Acquire and setup a triaxial apparatus at the State Materials Office capable of 1500 psi cell pressure, 40,000 lb axial capacity with instrumentation to monitor applied stress, strain and pore pressure.
- Collect Florida Limestone and marl samples from multiple surface formations (Miami, Anastasia, Fort Thompson, Suwannee, etc.) where shallow foundation for bridge structures could exist.
- Assist SMO technicians in preparing and performing triaxial compression, extension, unconfined compression and split tension testing of Florida Limestone and marl samples.
- Develop strength envelope for compression and extension for Florida Limestone and marl considering index properties.
- Develop a stress-strain model including strain softening if necessary and implement into a Finite Element code to model both the homogeneous and 2 layer (rock over sand) bearing capacity problem.
- Develop bearing capacity equations for both homogeneous and 2 layer (rock over sand) problem for Florida Limestone and marl conditions.

Task 1: Triaxial Rock Testing Equipment

Covered the setup and running of the Trautwein – TruePath Triaxial Testing Equipment for Florida Limestone: sample preparation, applying sample confinement and back pressure, triaxial compression or extension loading, as well as data acquisitio and analysis.

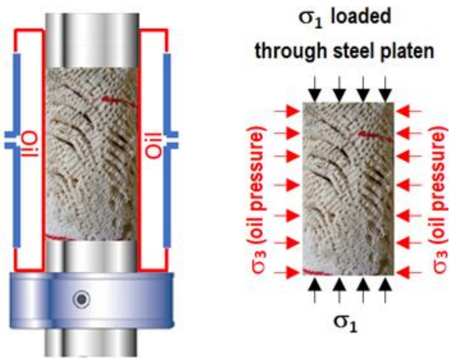


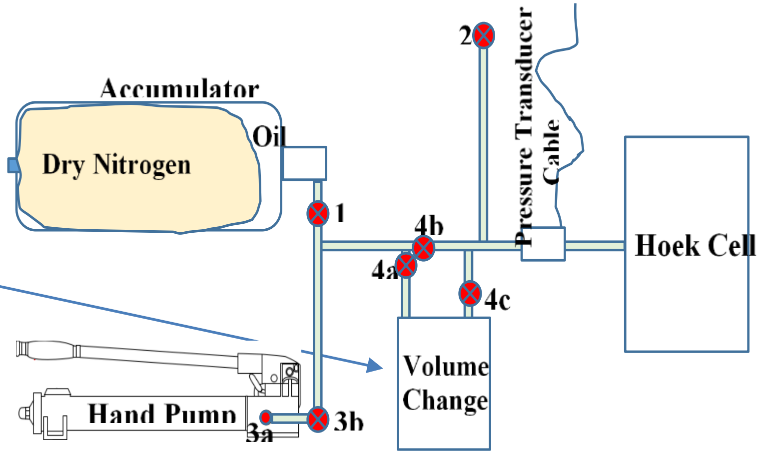
Task 1: Triaxial Rock Testing Equipment

The triaxial system used for this study to test Florida limestone was designed to satisfy the objectives:

- A Hoek cell from RocTest with cell pressure rated for 69 MPa (10,000 psi).
- A 180-kN (40,000-lb) capacity strain-controlled Sigma-1 load frame by GEOTAC.
- GEOTAC Sigma-1 CU SI software and instrumentation for controlling the load frame strain rate and sample monitoring.
- A direct current displacement transducer (DCDT) is attached to the top of the Hoek cell assembly to measure the vertical displacement of the rock specimen during shear.
- A volume change measurement device.

Hoek Cell:



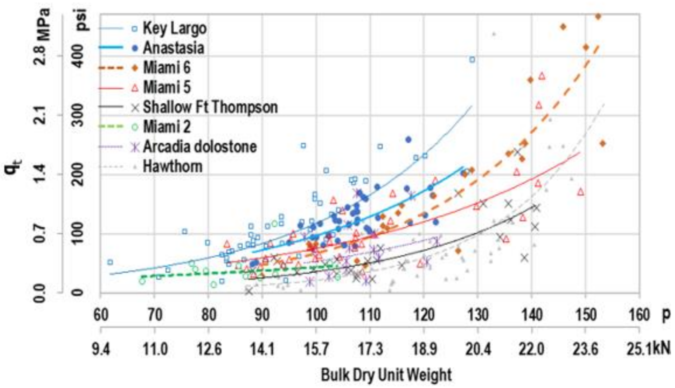


Task 2: Qu and Qt Testing with Index Measurements

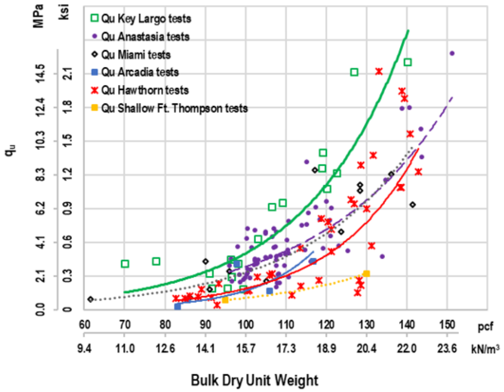
Besides SMO existing data, additional specimens were obtained and tested (q_u and q_t) with a number of Index measurements: 1) Unit Weight, 2) specific gravity, 3) void ratio & porosity, 4) carbonate content, 5) moisture content, and 6) saturation obtained for each specimen. Task 2 focused on identifying the 4 Index tests which best are correlated to rock strength (q_u and q_t) and established correlations between the 4 best index tests for all recorded rock strength data including formation information.

Task 2: Qu and Qt Testing with Index Measurements

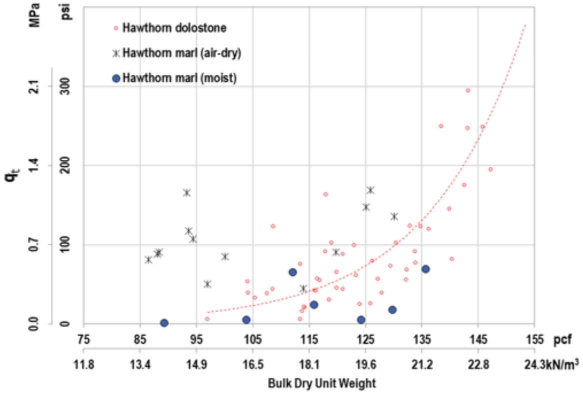
The unconfined strength – both split tension and unconfined compression – are strongly correlated to the material bulk porosity, which is inversely represented by the bulk dry unit weight.



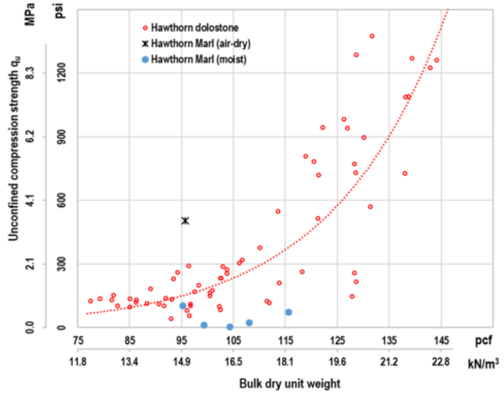
q_t and bulk dry unit weight for different formations



q_u and bulk dry unit weight for different formations



q_t results for marl



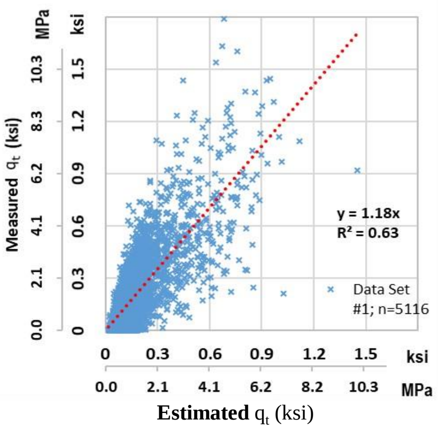
q_u results for marl

Task 2: Qu and Qt Testing with Index Measurements

$q_t\ (psi) = 3.864\ e^{0.03^{\gamma_{dt} B}}$

Where,

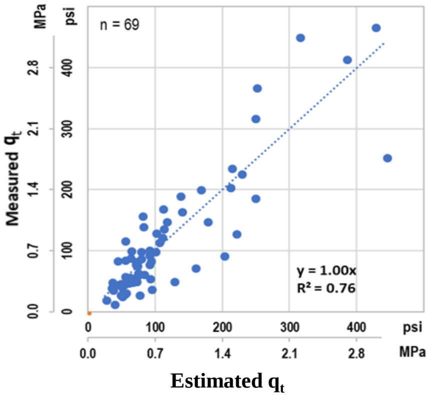
γ_{dt}: Dry unit weight
B = 1 if $\gamma_{dt} < \gamma_{dt0}$
B = $\sqrt{\gamma_{dt}/\gamma_{dt0}}$ if $\gamma_{dt} \geq \gamma_{dt0}$
γ_{dt0} = 22 kN/m^3 (140 pcf)



$q_t\ (psi) = 2.468\ F_t\ e^{0.03^{\gamma_{dt} B}}\ e^{0.5C}$

Where,

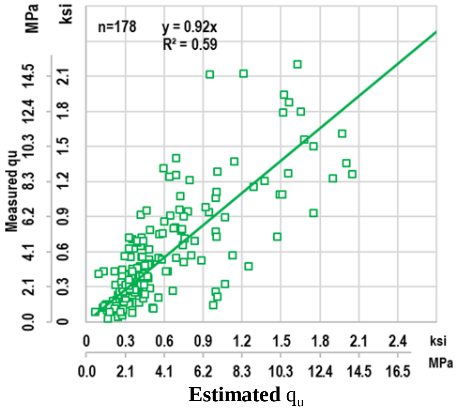
C: Carbonate content, 0.5 ~ 1.0
γ_{dt}: Dry unit weight
F$_t$: Tension formation factor, 0.7 ~ 1.3
B = 1 if $\gamma_{dt} < \gamma_{dt0}$
B = $\sqrt{\gamma_{dt}/\gamma_{dt0}}$ if $\gamma_{dt} \geq \gamma_{dt0}$
γ_{dt0} = 22 kN/m^3 (140 pcf)



$q_u\ (psi) = 5.89\ e^{0.04^{\gamma_{dt} B}}$

Where,

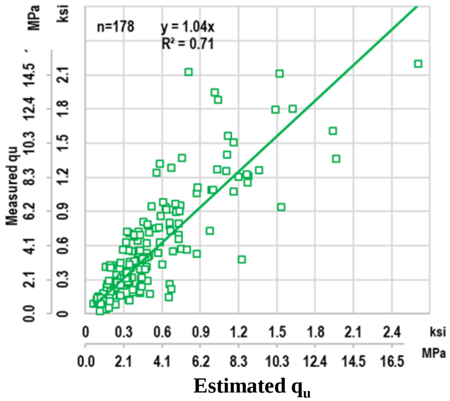
γ_{dt}: Dry unit weight
B = 1 if $\gamma_{dt} < \gamma_{dt0}$
B = $\sqrt{\gamma_{dt}/\gamma_{dt0}}$ if $\gamma_{dt} \geq \gamma_{dt0}$
γ_{dt0} = 22 kN/m^3 (140 pcf)



$q_u\ (psi) = 3.24\ F_u\ e^{0.04^{\gamma_{dt} B}}\ e^{2C/3}$

Where,

C: Carbonate content
γ_{dt}: Dry unit weight
F$_u$: Compression formation factor, 0.7 ~ 1.5
B = 1 if $\gamma_{dt} < \gamma_{dt0}$
B = $\sqrt{\gamma_{dt}/\gamma_{dt0}}$ if $\gamma_{dt} \geq \gamma_{dt0}$
γ_{dt0} = 22 kN/m^3 (140 pcf)



Task 3: Triaxial Testing of Florida Limestone and Intermediate Geomaterials

Triaxial Testing of Samples from Each Formation Considered:

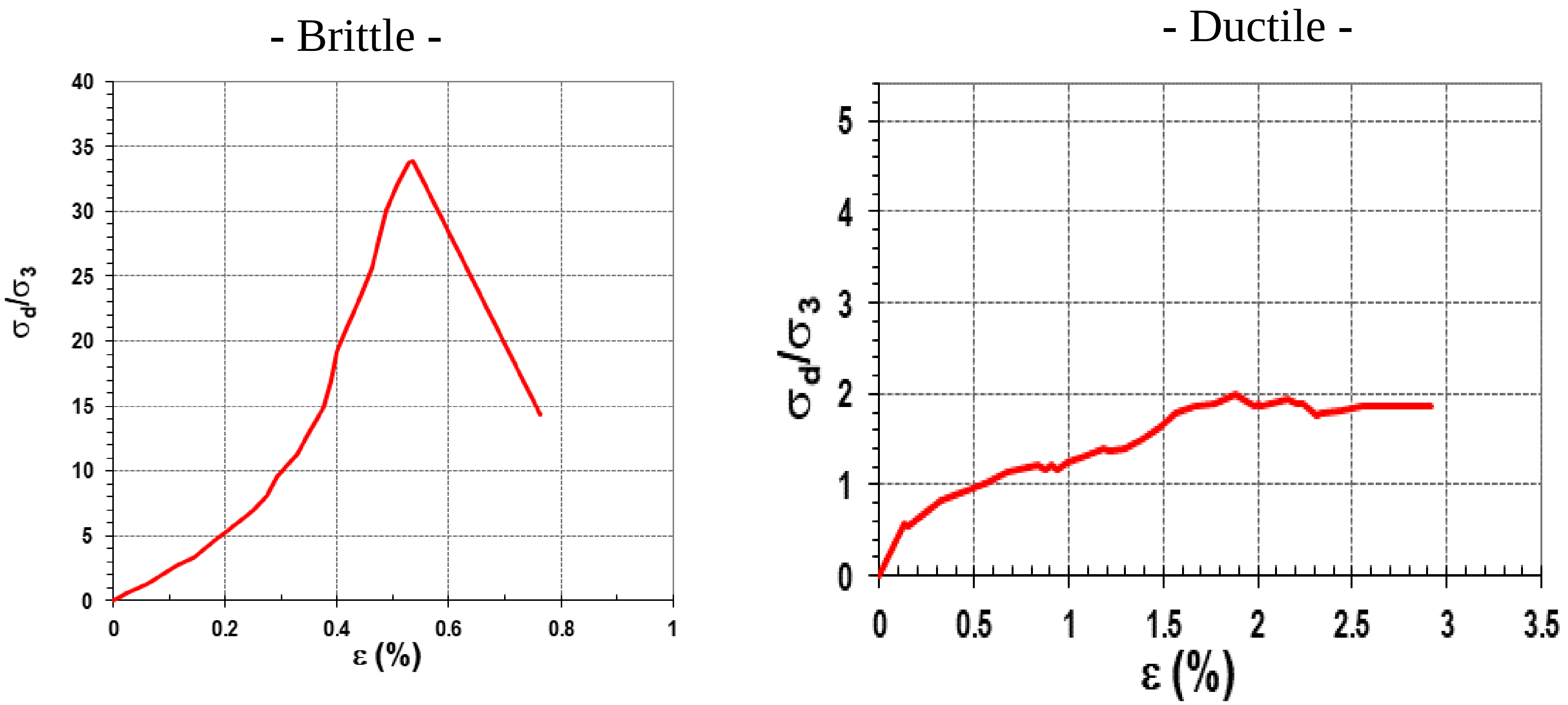
- Strain or Deformation Controlled – Quantify Brittle or Ductile Behavior

- Measurement of Axial and Volumetric Response
  - Assess Poisson Ratio – needed for assessing horizontal stress and stress path for shallow foundation loading

- Multiple Conventional Triaxial compression and extension tests at different cell pressures (25 psi, 50 psi, 130 psi, 200, psi, 300 psi, 600 psi, > 1000 psi) to develop strength envelope

- Differentiate strength results based on dry unit weight and Formation (Miami, Fort Thompson, Key Largo, Anastasia, etc.)

Task 3: Triaxial Testing of Florida Limestone and Intermediate Geomaterials



(a)

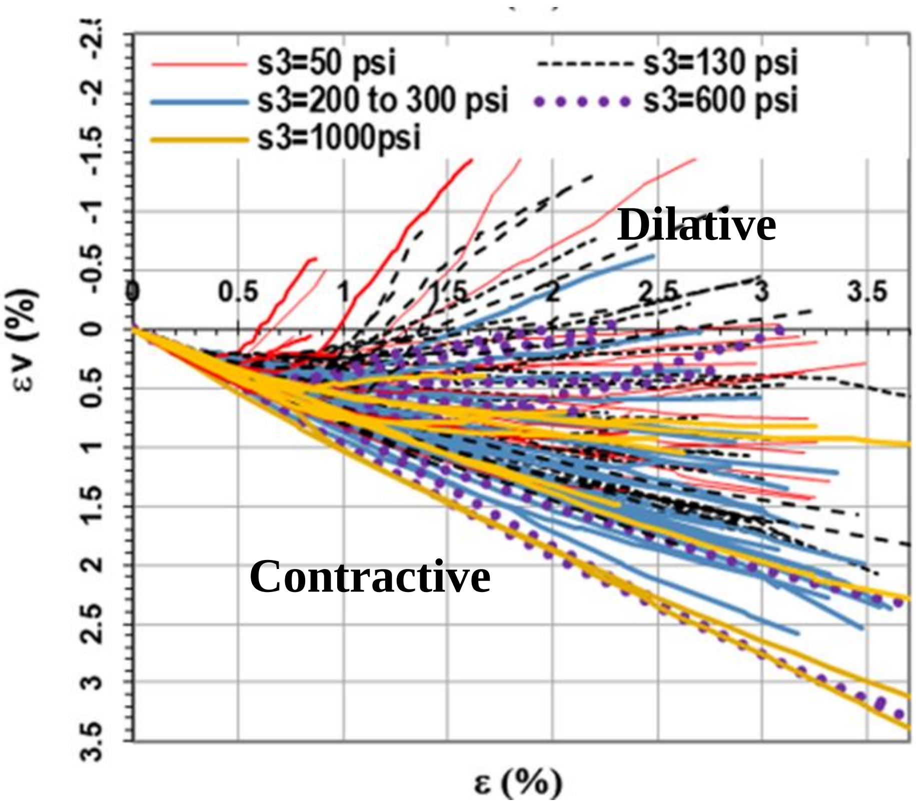
(b)

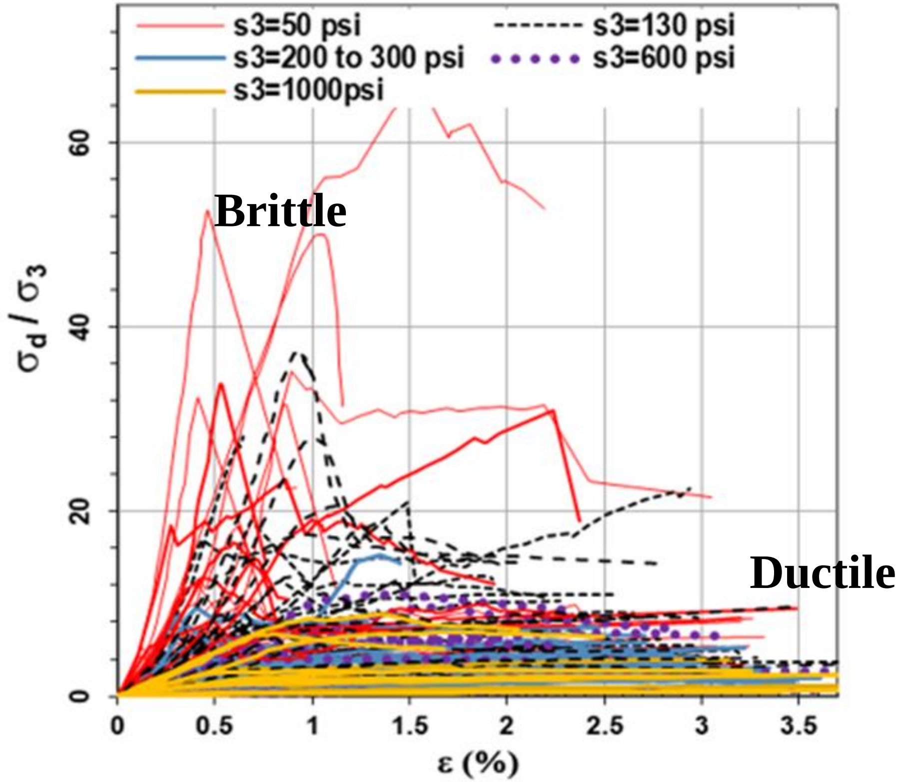
Key Largo formation:

(a) γ_{dt} = 18.9 kN/m^3 = 120 pcf, σ_3 = 345 kPa = 50 psi;

(b) γ_{dt} = 15.7 kN/m^3 = 100 pcf, σ_3 = 3,100 kPa = 450 psi

Task 3: Triaxial Testing of Florida Limestone and Intermediate Geomaterials

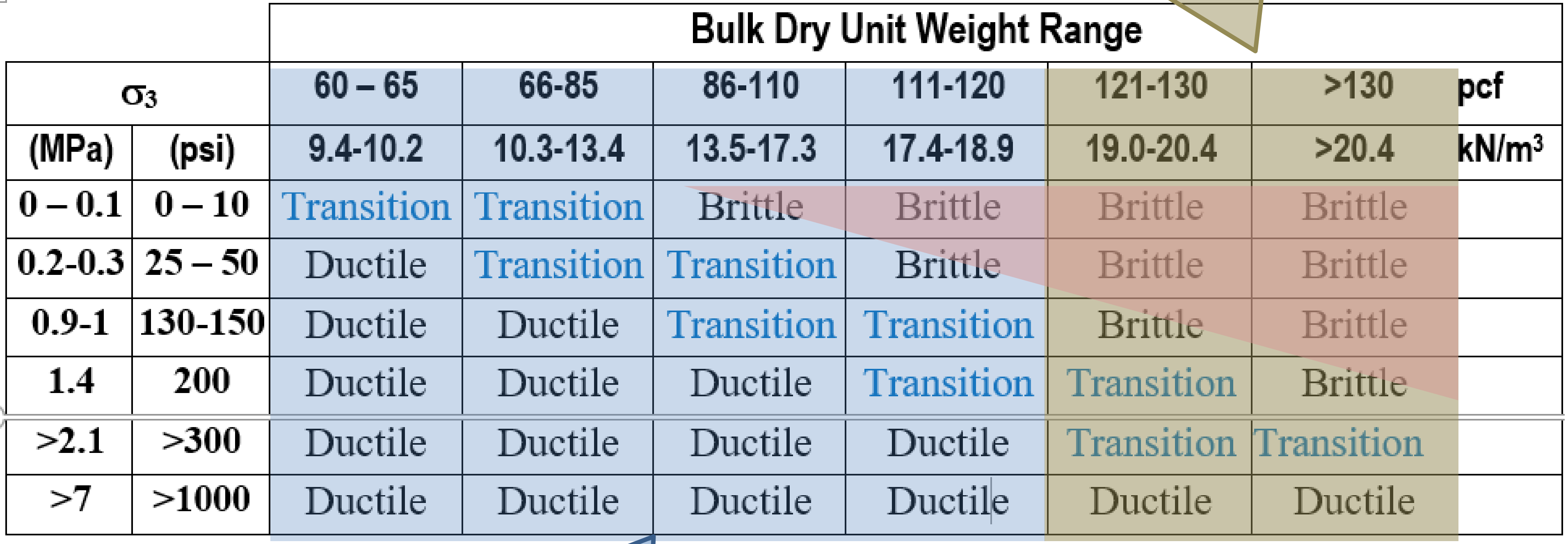




- Brittle stress-strain (rupture) behavior typically associates with dilative volumetric responses.
- Ductile ……associates with …….contractive.

Task 3: Triaxial Testing of Florida Limestone and Intermediate Geomaterials

Not typically encountered for shallow formations

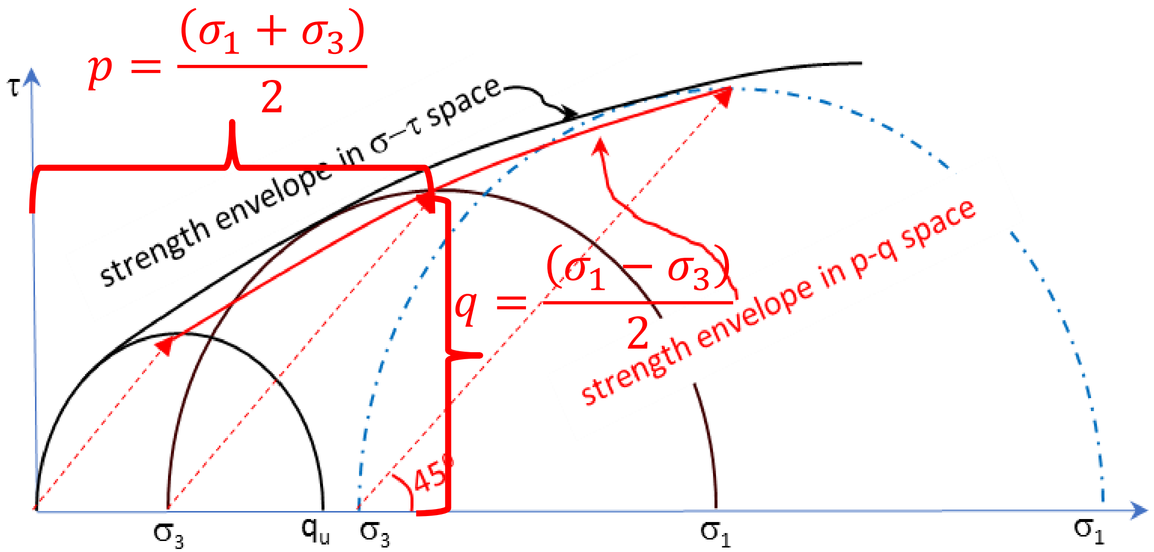


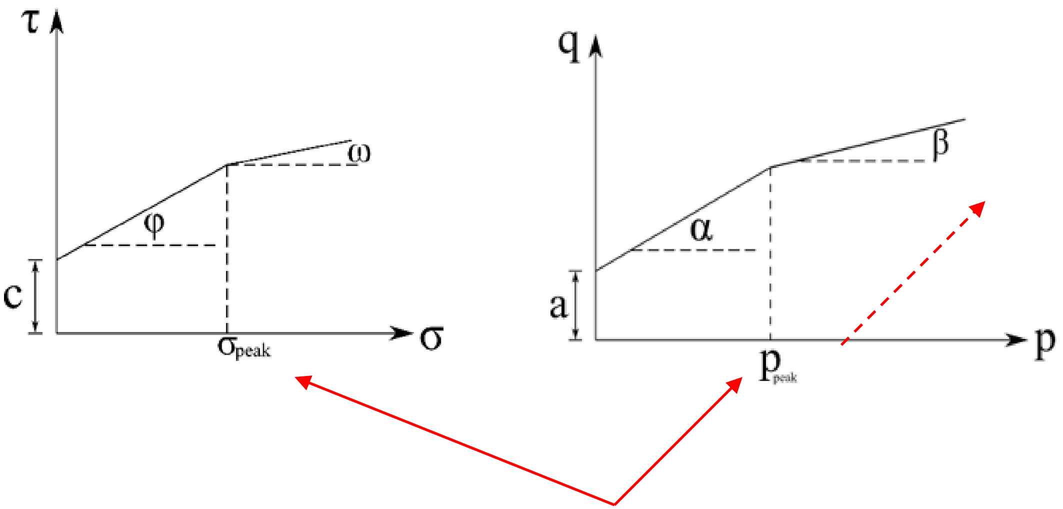
σ_3		Bulk Dry Unit Weight Range						
		60 – 65	66-85	86-110	111-120	121-130	>130	pcf
(MPa)	(psi)	9.4-10.2	10.3-13.4	13.5-17.3	17.4-18.9	19.0-20.4	>20.4	kN/m^3
0 – 0.1	0 – 10	Transition	Transition	Brittle	Brittle	Brittle	Brittle	
0.2-0.3	25 – 50	Ductile	Transition	Transition	Brittle	Brittle	Brittle	
0.9-1	130-150	Ductile	Ductile	Transition	Transition	Brittle	Brittle	
1.4	200	Ductile	Ductile	Ductile	Transition	Transition	Brittle	
>2.1	>300	Ductile	Ductile	Ductile	Ductile	Transition	Transition	
>7	>1000	Ductile	Ductile	Ductile	Ductile	Ductile	Ductile	

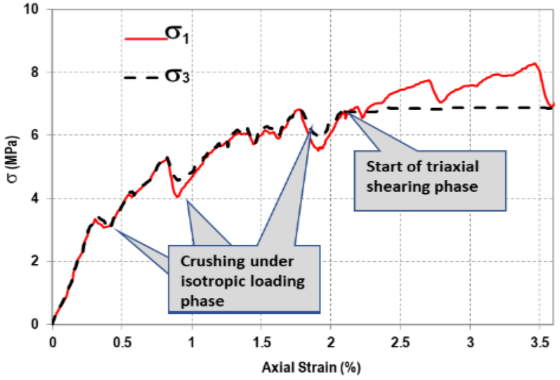
Typically encountered for shallow formations

Some formations (such as Anastasia) would be more predominantly ductile, even in the 121-130 pcf zone.

Task 4: Development of Strength Envelope of Florida Limestone and IGMs

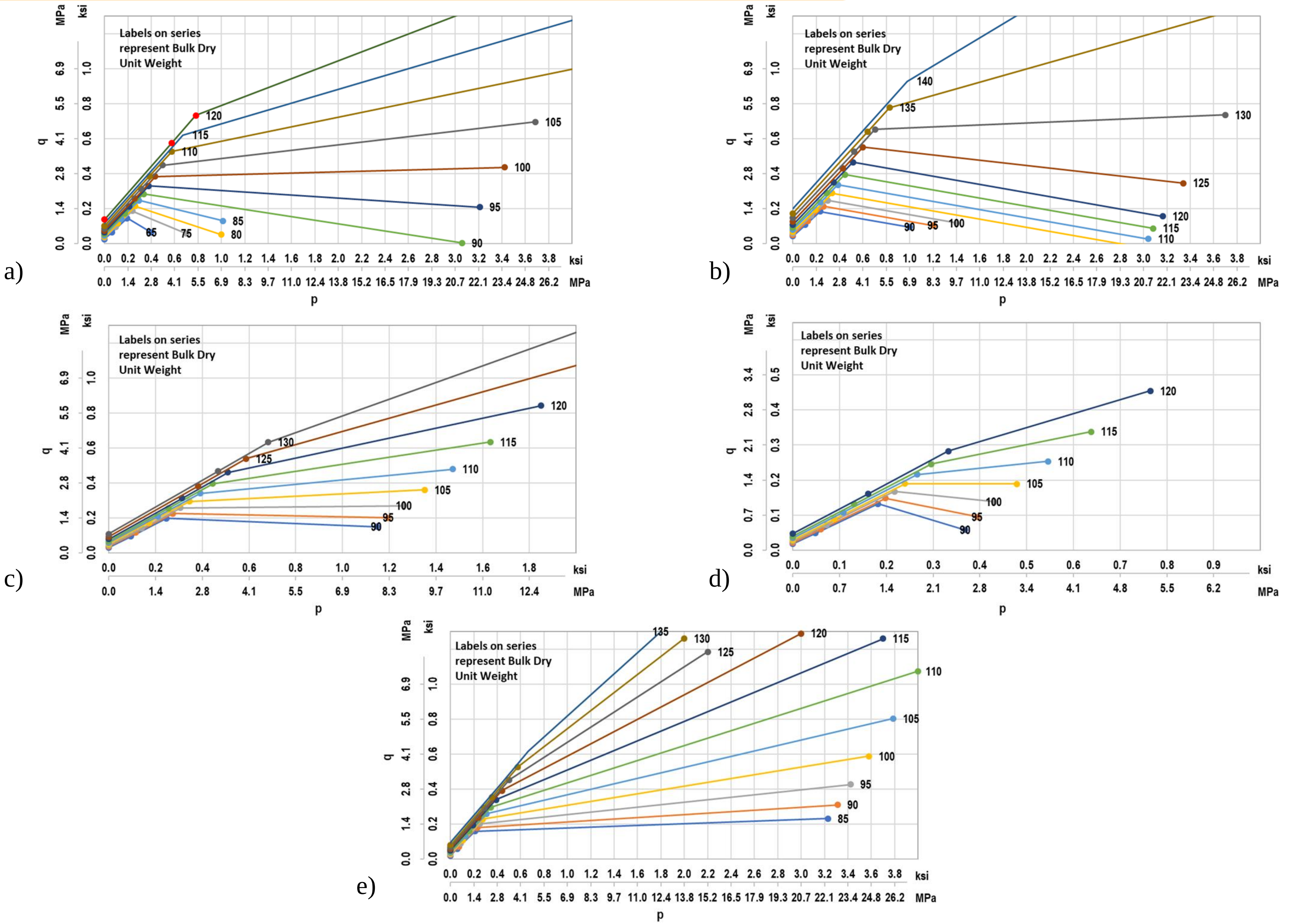






Onset of breakage of cementation, crushing and ductile flow

Task 4: Development of Strength Envelope of Florida Limestone and IGMs



Bilinear strength envelope: a) Key Largo Formation; b) Anastasia Formation; c) Miami Formation; d) Shallow Ft Thompson Formation; e) Hawthorn Formation

Task 4: Development of Strength Envelope of Florida Limestone and IGMs

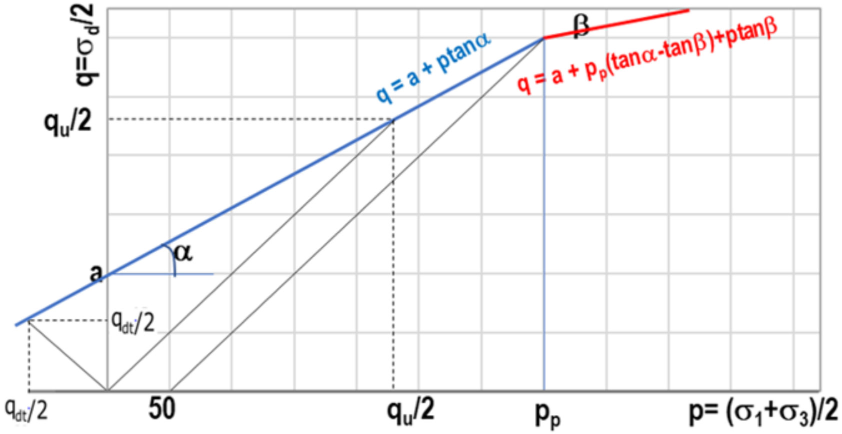
$$c = 0.5\sqrt{q_u q_{dt}}$$

$$\sin\varphi = \frac{q_u - q_{dt}}{q_u + q_{dt}} \text{ or } \tan\alpha = \frac{q_u - q_{dt}}{q_u + q_{dt}} \text{ in p-q diagram}$$

$$c = \frac{a}{\cos\varphi} \text{ or } a = c\cos\varphi$$

$$\sin\varphi = \tan\alpha \text{ and } \sin\omega = \tan\beta$$

$$p_p(psi) = \frac{50 + a}{1 - \tan\alpha} = \frac{50 + c\cos\varphi}{1 - \sin\varphi}$$



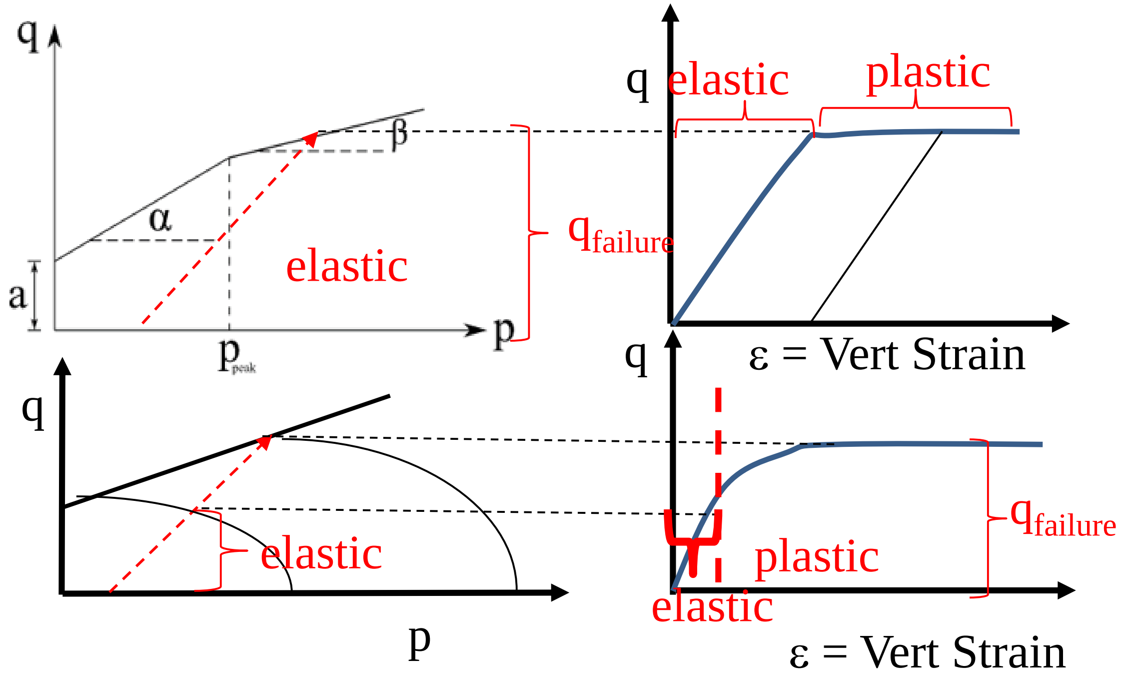
Schematic of bilinear strength envelope for intact rock

Value of 2^{nd} slope (ω) on Florida strength envelopes

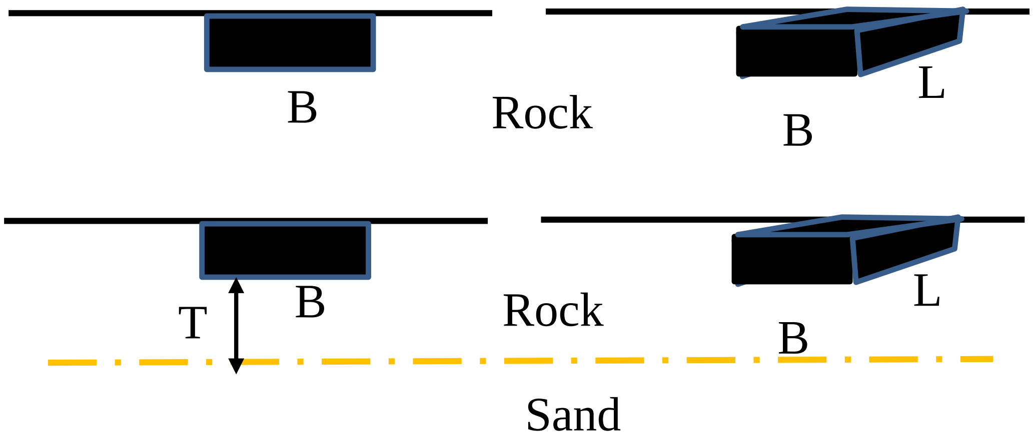
Formation	**ω value for γ_{dt} in pcf**	**ω value for γ_{dt} in kN/m^3**
Key Largo	$0.69\ \gamma_{dt} - 68$	$4.4\ \gamma_{dt} - 68$
Shallow Ft. Thompson	$1.57\ \gamma_{dt} - 165$	$10\ \gamma_{dt} - 165$
Miami	$0.0136\gamma_{dt}^2 - 2.2\ \gamma_{dt} + 85$	$0.55\gamma_{dt}^2 - 14\ \gamma_{dt} + 85$
Anastasia	$0.0691\gamma_{dt}^2 - 16.45\ \gamma_{dt} + 972$ $\omega = -6.7$ for $\gamma_{dt} < 120$ pcf	$2.8\gamma_{dt}^2 - 104.7\ \gamma_{dt} + 972$ $\omega = -6.7$ for $\gamma_{dt} < 19\ kN/m^3$
Hawthorn	$0.011\gamma_{dt}^2 - 1.72\ \gamma_{dt} + 68$	$0.45\gamma_{dt}^2 - 11\ \gamma_{dt} + 68$
Generic Florida formation	$0.79\gamma_{dt} - 90$	$5\gamma_{dt} - 90$

Task 5: Numerical Modeling of Stress Distribution and Bearing Failure of One and Two Layer Systems and Develop Bearing Capacity Equation

- Implement elastic-perfectly plastic material model in FEM code for rock
- Implement elastic-plastic hardening cap model in FEM code for sand (Souza Neto *et al*. 2011)



- Model Strip and Rectangular Footing on Rock
- Model Strip and Rectangular Footing on Rock Overlying Sand



Tasks Outline and Discussion

Validation of Elastic, Perfectly Plastic Model:

Material properties used in validation simulation

	Validation of elastic, perfectly plastic model		3D triaxial test simulation
	Cohesion only material	c - φ material	
Porosity	0.4	0.3	0.3
Dry unit weight	110 pcf	110 pcf	110 pcf
Young's modulus	5,000 psi	43,511 psi	43,511 psi
Poisson's ratio	0.3	0.23	0.23
Friction angle (φ)	0^0	30^0	30^0
2nd slope (ω)	0^0	30^0	0^0
Cohesion intercept	1.72 tsf	1.72 tsf	1.72 tsf

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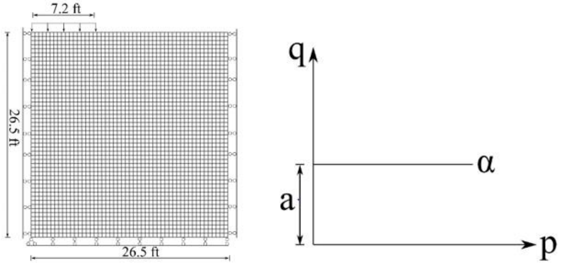
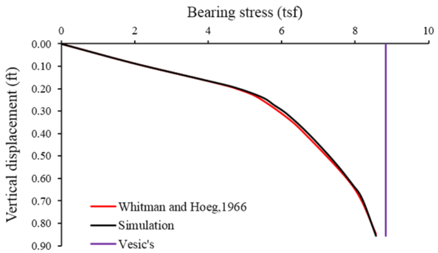
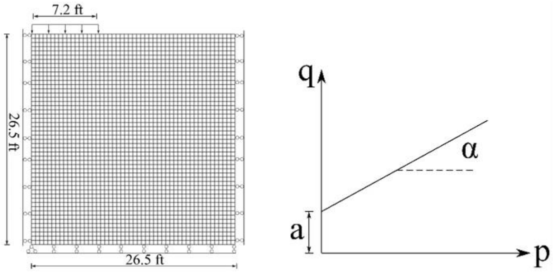
Task 5: Numerical Modeling of Stress Distribution and Bearing Failure of One and Two Layer Systems and Develop Bearing Capacity Equation

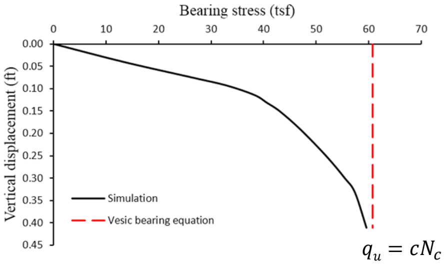
Validation of Elastic, Perfectly Plastic Model:



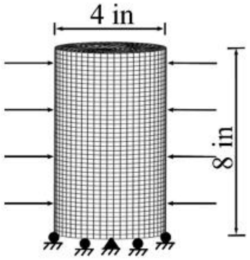


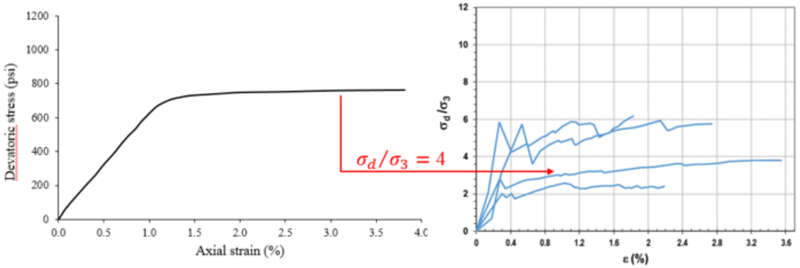
$$q_u = cNc = 1.72 \times 5.14 = 8.84\ tsf$$





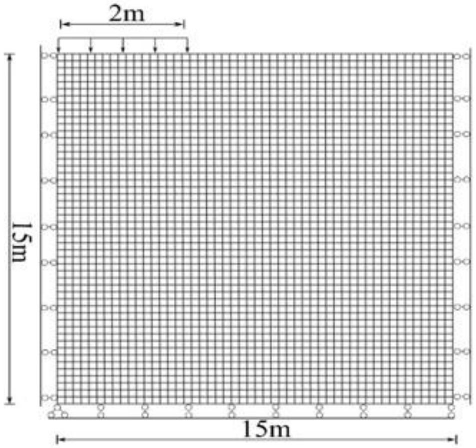
$$q_u = cN_c + 0.5\gamma B N_\gamma$$
$$= 1.72 \times 30.14 + 0.5 \times 100 \times 14.4 \times 22.4$$
$$\times 0.0005 = 60.7\ tsf$$

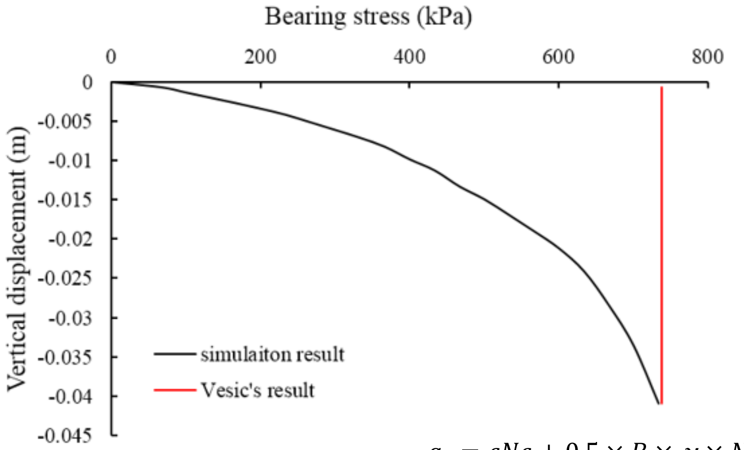




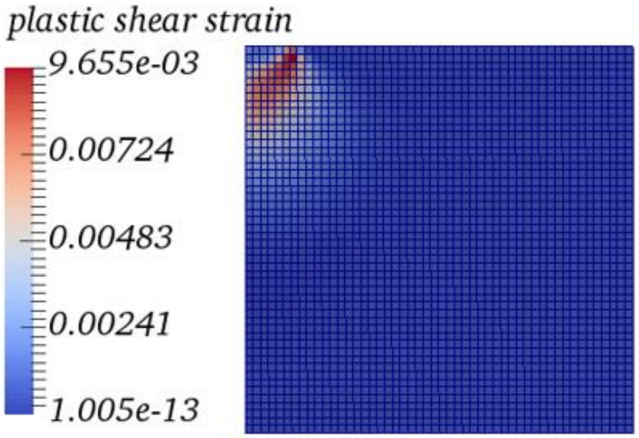
Task 5: Numerical Modeling of Stress Distribution and Bearing Failure of One and Two Layer Systems and Develop Bearing Capacity Equation

Validation of Drucker-Prager-Cap model for soil:



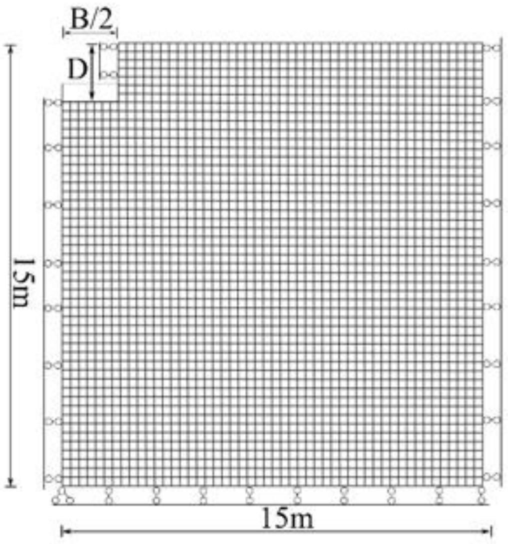


$$q_u = cNc + 0.5 \times B \times \gamma \times N_\gamma$$
$$= 0 + 0.5 \times 4 \times 16.5 \times 22.4 = 739.2\ kPa$$

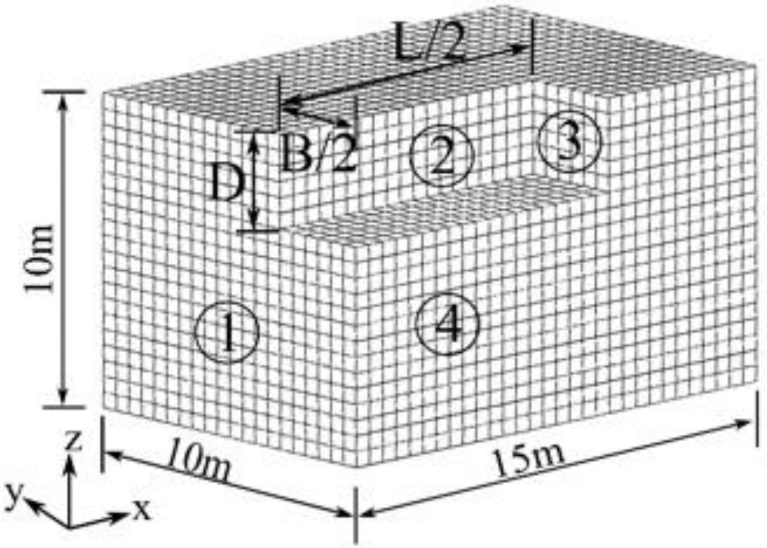


Task 5: Numerical Modeling of Stress Distribution and Bearing Failure of One and Two Layer Systems and Develop Bearing Capacity Equation

Parametric Studies:



$B/L = 0$ and $D \geq 0$



$B/L > 0$ and $D \geq 0$

Task 5: Numerical Modeling of Stress Distribution and Bearing Failure of One and Two Layer Systems and Develop Bearing Capacity Equation

	p-q diagram						τ-σ diagram					
No.	a (MPa)	a (tsf)	α (°)	β (°)	p_p (MPa)	p_p (tsf)	c (MPa)	c (tsf)	φ (°)	ω (°)	σ_p (MPa)	σ_p (tsf)
93	0.1	1.04	38	-5	1.5	15.66	0.160	1.67	51.38	-5.02	2.77	28.92
94	0.1	1.04	38	0	1.2	12.53	0.160	1.67	51.38	0.00	2.24	23.39
95	0.1	1.04	38	0	1.3	13.57	0.160	1.67	51.38	0.00	2.42	25.26
96	0.1	1.04	38	0	1.5	15.66	0.160	1.67	51.38	0.00	2.77	28.92
97	0.1	1.04	38	5	1.2	12.53	0.160	1.67	51.38	5.02	2.24	23.39
98	0.1	1.04	38	5	1.3	13.57	0.160	1.67	51.38	5.02	2.42	25.26
99	0.1	1.04	38	5	1.5	15.66	0.160	1.67	51.38	5.02	2.77	28.92
100	0.1	1.04	38	10	1.2	12.53	0.160	1.67	51.38	10.16	2.24	23.39
101	0.1	1.04	38	10	1.3	13.57	0.160	1.67	51.38	10.16	2.42	25.26
102	0.1	1.04	38	10	1.5	15.66	0.160	1.67	51.38	10.16	2.77	28.92
103	0.1	1.04	38	15	1.2	12.53	0.160	1.67	51.38	15.54	2.24	23.39
104	0.1	1.04	38	15	1.3	13.57	0.160	1.67	51.38	15.54	2.42	25.26
105	0.1	1.04	38	15	1.5	15.66	0.160	1.67	51.38	15.54	2.77	28.92
106	0.1	1.04	38	20	1.2	12.53	0.160	1.67	51.38	21.34	2.24	23.39
107	0.1	1.04	38	20	1.3	13.57	0.160	1.67	51.38	21.34	2.42	25.26
108	0.1	1.04	38	20	1.5	15.66	0.160	1.67	51.38	21.34	2.77	28.92
109	0.5	5.22	27	-20	2	20.88	0.581	6.07	30.63	-21.34	3.52	36.75
110	0.5	5.22	27	-20	2.5	26.10	0.581	6.07	30.63	-21.34	4.27	44.58
111	0.5	5.22	27	-20	3	31.32	0.581	6.07	30.63	-21.34	5.02	52.41
112	0.5	5.22	27	-15	2	20.88	0.581	6.07	30.63	-15.54	3.52	36.75
113	0.5	5.22	27	-15	2.5	26.10	0.581	6.07	30.63	-15.54	4.27	44.58
114	0.5	5.22	27	-15	3	31.32	0.581	6.07	30.63	-15.54	5.02	52.41
115	0.5	5.22	27	-10	2	20.88	0.581	6.07	30.63	-10.16	3.52	36.75
116	0.5	5.22	27	-10	2.5	26.10	0.581	6.07	30.63	-10.16	4.27	44.58
117	0.5	5.22	27	-10	3	31.32	0.581	6.07	30.63	-10.16	5.02	52.41
118	0.5	5.22	27	-5	2	20.88	0.581	6.07	30.63	-5.02	3.52	36.75
119	0.5	5.22	27	-5	2.5	26.10	0.581	6.07	30.63	-5.02	4.27	44.58
120	0.5	5.22	27	-5	3	31.32	0.581	6.07	30.63	-5.02	5.02	52.41
121	0.5	5.22	27	0	2	20.88	0.581	6.07	30.63	0.00	3.52	36.75
122	0.5	5.22	27	0	2.5	26.10	0.581	6.07	30.63	0.00	4.27	44.58
123	0.5	5.22	27	0	3	31.32	0.581	6.07	30.63	0.00	5.02	52.41
124	0.5	5.22	27	5	2	20.88	0.581	6.07	30.63	5.02	3.52	36.75
125	0.5	5.22	27	5	2.5	26.10	0.581	6.07	30.63	5.02	4.27	44.58
126	0.5	5.22	27	5	3	31.32	0.581	6.07	30.63	5.02	5.02	52.41
127	0.5	5.22	27	10	2	20.88	0.581	6.07	30.63	10.16	3.52	36.75
128	0.5	5.22	27	10	2.5	26.10	0.581	6.07	30.63	10.16	4.27	44.58
129	0.5	5.22	27	10	3	31.32	0.581	6.07	30.63	10.16	5.02	52.41
130	0.5	5.22	27	15	2	20.88	0.581	6.07	30.63	15.54	3.52	36.75
131	0.5	5.22	27	15	2.5	26.10	0.581	6.07	30.63	15.54	4.27	44.58
132	0.5	5.22	27	15	3	31.32	0.581	6.07	30.63	15.54	5.02	52.41
133	0.5	5.22	27	20	2	20.88	0.581	6.07	30.63	21.34	3.52	36.75
134	0.5	5.22	27	20	2.5	26.10	0.581	6.07	30.63	21.34	4.27	44.58
135	0.5	5.22	27	20	3	31.32	0.581	6.07	30.63	21.34	5.02	52.41
136	0.5	5.22	31	-20	2	20.88	0.626	6.54	36.93	-21.34	3.7	38.63
137	0.5	5.22	31	-20	2.5	26.10	0.626	6.54	36.93	-21.34	4.5	46.98
138	0.5	5.22	31	-20	3	31.32	0.626	6.54	36.93	-21.34	5.3	55.33
139	0.5	5.22	31	-15	2	20.88	0.626	6.54	36.93	-15.54	3.7	38.63
140	0.5	5.22	31	-15	2.5	26.10	0.626	6.54	36.93	-15.54	4.5	46.98
141	0.5	5.22	31	-15	3	31.32	0.626	6.54	36.93	-15.54	5.3	55.33
142	0.5	5.22	31	-10	2	20.88	0.626	6.54	36.93	-10.16	3.7	38.63
143	0.5	5.22	31	-10	2.5	26.10	0.626	6.54	36.93	-10.16	4.5	46.98
144	0.5	5.22	31	-10	3	31.32	0.626	6.54	36.93	-10.16	5.3	55.33
145	0.5	5.22	31	-5	2	20.88	0.626	6.54	36.93	-5.02	3.7	38.63
146	0.5	5.22	31	-5	2.5	26.10	0.626	6.54	36.93	-5.02	4.5	46.98
147	0.5	5.22	31	-5	3	31.32	0.626	6.54	36.93	-5.02	5.3	55.33

Simulated 324 Different Set of Strength Properties, and Modulii

Footings:
3 Different Widths (B), 3 L/B,
3 Depths, and Multiple Depths between Footing and underlying soil
> 10,000 Simulations

Task 5: Numerical Modeling of Stress Distribution and Bearing Failure of One and Two Layer Systems and Develop Bearing Capacity Equation

Bearing Capacities (Tsf)

	B=6.6 ft; D=0 ft				B=13.2 ft; D=0 ft				B=6.6 ft; D=3.3 ft				B=13.2 ft; D=6.6 ft			
#	Strip B/L=0	L/B=10 B/L=0.1	L/B=5 B/L=0.2	square	Strip v=0.2	Strip v=0.1	L/B=10 B/L=0.1	L/B=5 B/L=0.2	square	L/B=10 B/L=0.1	L/B=5 B/L=0.2	square	Strip B/L=0	L/B=10 B/L=0.1	L/B=5 B/L=0.2	square
113	30.59	31.53	33.41	38.11	46.46	31.74	32.57	34.45	39.46	38.84	41.13	47.08	37.38	40.30	42.70	48.86
114	30.59	31.53	33.41	38.11	54.29	31.74	32.57	34.45	39.46	38.84	41.13	47.08	37.38	40.30	42.70	48.86
115	30.59	31.53	33.41	38.11	39.99	31.74	32.57	34.45	39.46	38.84	41.13	47.08	37.38	40.30	42.70	48.86
116	30.59	31.53	33.41	38.11	46.98	31.74	32.57	34.45	39.46	38.84	41.13	47.08	37.38	40.30	42.70	48.86
117	30.59	31.53	33.41	38.11	55.02	31.74	32.57	34.45	39.46	38.84	41.13	47.08	37.38	40.30	42.70	48.86
118	30.59	31.53	33.41	38.11	41.03	31.74	32.57	34.45	39.46	38.84	41.13	47.08	37.38	40.30	42.70	48.86
119	30.59	31.53	33.41	38.11	48.02	31.74	32.57	34.45	39.46	38.84	41.13	47.08	37.38	40.30	42.70	48.86
120	30.59	31.53	33.41	38.11	55.33	31.74	32.57	34.45	39.46	38.84	41.13	47.08	37.38	40.30	42.70	48.86
121	30.59	31.53	33.41	38.11	42.07	31.74	32.57	34.45	39.46	38.84	41.13	47.08	37.38	40.30	42.70	48.86
122	30.59	31.53	33.41	38.11	49.17	31.74	32.57	34.45	39.46	38.84	41.13	47.08	37.38	40.30	42.70	48.86
123	30.59	31.53	33.41	38.11	56.17	31.74	32.57	34.45	39.46	38.84	41.13	47.08	37.38	40.30	42.70	48.86
124	30.59	31.53	33.41	38.11	43.43	31.74	32.57	34.45	39.46	38.84	41.13	47.08	37.38	40.30	42.70	48.86
125	30.59	31.53	33.41	38.11	50.01	31.74	32.57	34.45	39.46	38.84	41.13	47.08	37.38	40.30	42.70	48.86

Task 5: Numerical Modeling of Stress Distribution and Bearing Failure of One and Two Layer Systems and Develop Bearing Capacity Equation

Bearing Equations:

1. Because of the bilinear strength envelope used for Florida carbonate rock, the ultimate bearing capacity for Strip Footing on Top of Rock:

$$Q_u = \min(Q_{u1}, Q_{u2})$$

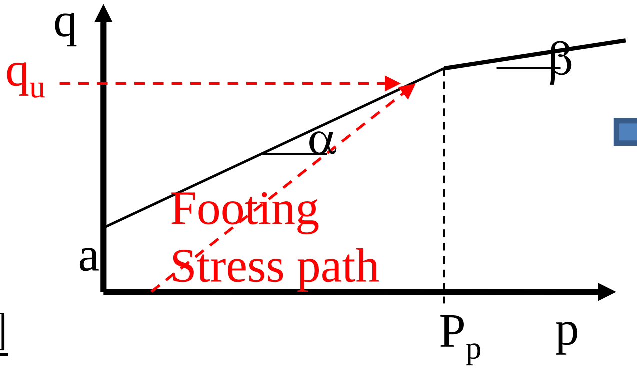
$$Q_{u1} = c\,N_c$$

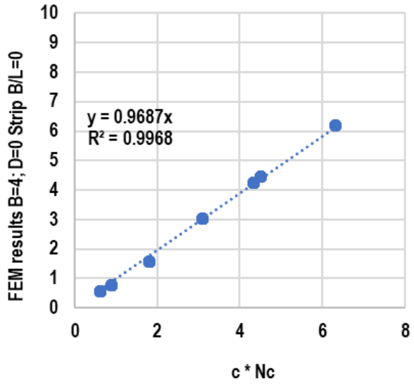
$$Q_{u2} = c\,N'_c + p_p\,N_\gamma$$

$$N_c = \frac{1.8\ \cos\varphi}{0.8 - \sin\varphi}$$

$$N'_c = \frac{1.8\ \cos\varphi}{0.8 - \sin\omega}$$

$$N_\gamma = \frac{1.8\ [\sin\varphi - \sin\omega]}{0.8 - \sin\omega}$$



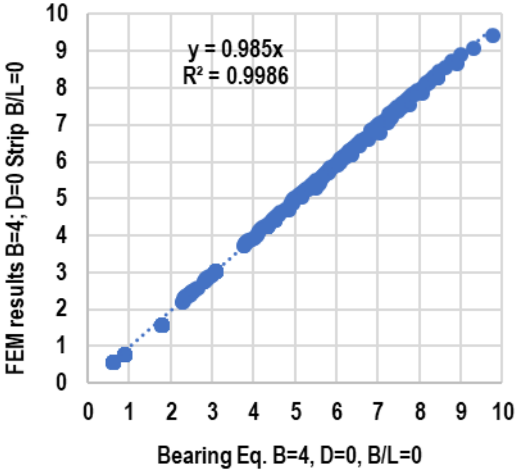


p – q vs. τ - σ :

$$\sin\varphi = \tan\alpha$$

$$\sin\omega = \tan\beta$$

$$c = \frac{a}{\cos\varphi}$$



Bearing equations for the strip footing are well summarized.

Task 5: Numerical Modeling of Stress Distribution and Bearing Failure of One and Two Layer Systems and Develop Bearing Capacity Equation

Bearing Equations:

2. The depth of the footing contributes q N_q to the bearing capacity, with q = $\gamma' * D$.

FEM results of D = 0 and D = 2 were compared in order to correlate the N_q parameter:

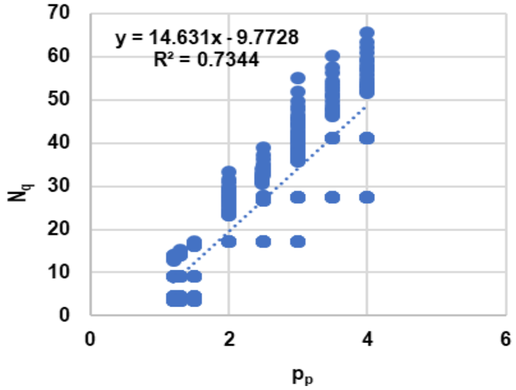
$$N_q = \left(1.5 * \frac{p_p}{\sigma_a} - 10\right) * (3 * \sin\varphi - 1)$$

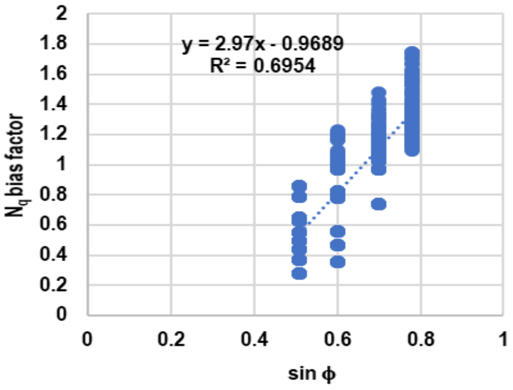
σ_a = Sea level standard atmospheric pressure

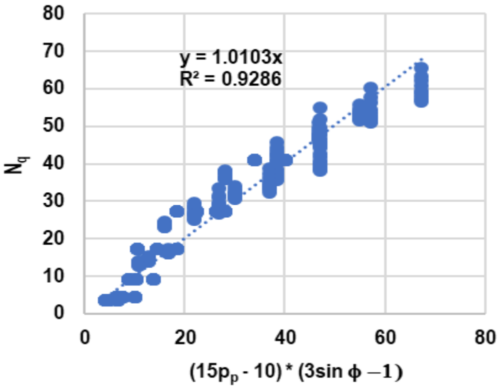
$$Q_u = \min\,(Q_{u1}, Q_{u2})$$

$$Q_{u1} = c\,N_c + qN_q$$

$$Q_{u2} = c\,N'_c + p_p\,N_\gamma + qN_q$$







Task 5: Numerical Modeling of Stress Distribution and Bearing Failure of One and Two Layer Systems and Develop Bearing Capacity Equation

Bearing Equations:

3. Two different geometries were modelled in FEM analyses: B = 2 m and B = 4 m, to modify bearing equations using different width; FEM analyses were performed using footings with different shapes: B/L = 0 (strip footing), B/L = 0.1, 0.2 and 1.0 (square), the shape factor could be obtained:

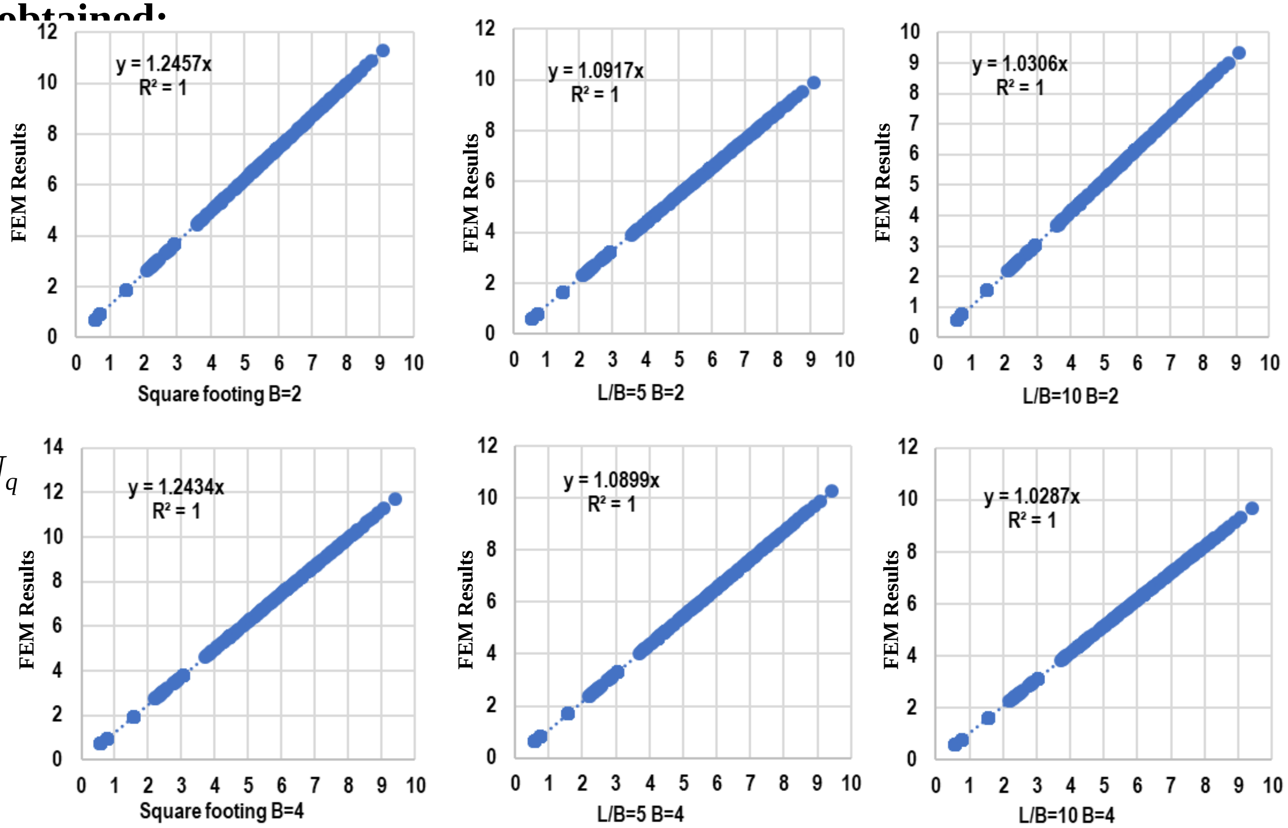
$$n = \left(\frac{4}{B}\right)^{-0.055}$$

$$\xi = 1 + 0.245\left(\frac{B}{L}\right)^{0.66}$$

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

$$Q_{u1} = n\, c\, N_c + qN_q$$

$$Q_{u2} = n\,[c\, N'_c + p_p\, N_\gamma] + qN_q$$

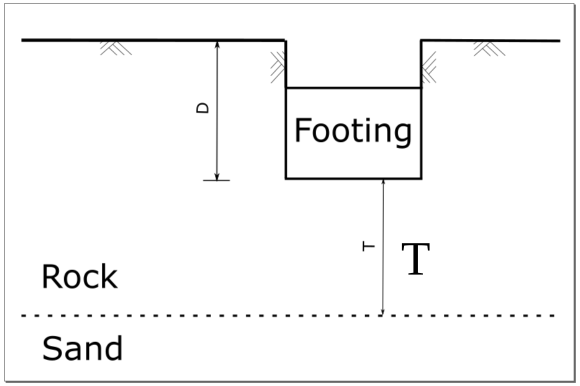


Note: The ratio on the figure = (Bearing capacity of non-strip footing) / (Bearing capacity of strip footing)

Task 5: Numerical Modeling of Stress Distribution and Bearing Failure of One and Two Layer Systems and Develop Bearing Capacity Equation

Bearing Equations:

4. Based on the bearing ratio results the Rock-Over-Sand reduction factor N_R was determined:



$Q_{u,\ Rock\text{-}Over\text{-}Sand} = Q_{u,\ Rock}/N_R$

N_R: Reduction factor compared to rock only subsurface

$N_R = 0.86 \times R^{-0.25}$ if $R < 0.3$

$N_R = 1.2 - 0.1R$ if $R \geq 0.3$

$R = 0.093\ T^2(E_{soil}/E_{rock})$, limit R to 2.0

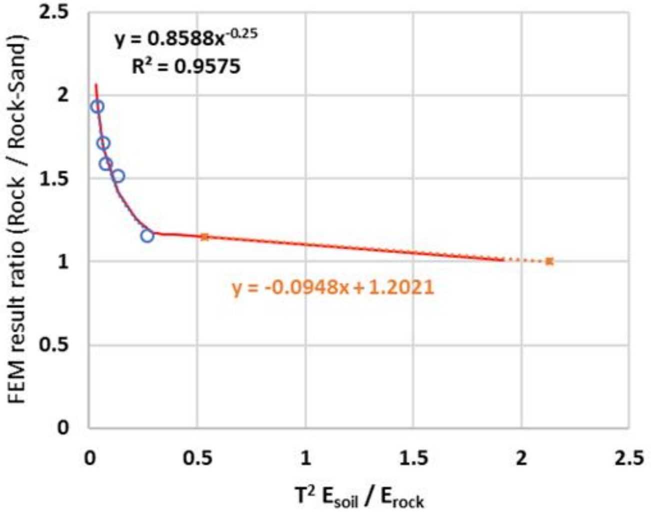
T: Rock thickness in feet {if T is in m, then $R = T^2(E_{soil}/E_{rock})$

E_{soil}/E_{rock} = Modulus ratio of soil and rock layers

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

$Q_{u1} = n\, c\, N_c + qN_q$

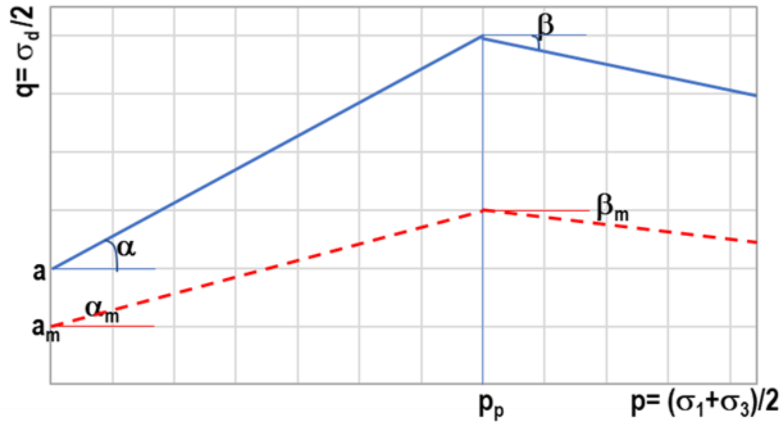
$Q_{u2} = n\, [c\, N'_c + p_p\, N_\gamma] + qN_q$



Task 5: Numerical Modeling of Stress Distribution and Bearing Failure of One and Two Layer Systems and Develop Bearing Capacity Equation

Bearing Equations:

5. Recovery-adjusted Strength Envelope:



$$q_m = q * REC$$

$$a_m = REC*a = REC*0.5\sqrt{q_{uw}q_{tw}}\cos(\arcsin\frac{q_{uw}-q_{tw}}{q_{uw}+q_{tw}})$$

$$\tan\alpha_m = REC*\tan\alpha = REC\frac{q_{uw}-q_{tw}}{q_{uw}+q_{tw}}$$

$$\tan\beta_m = REC*\tan\beta = REC*\sin\omega$$

$$p_{pm} = p_p$$

$$q_{ult} = (\sqrt{s} + (m\sqrt{s} + s)^{0.5})q_u$$

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

$$Q_{u1} = n\, c\, N_c + qN_q$$

$$Q_{u2} = n\, [c\, N'_c + p_p\, N_\gamma] + qN_q$$

Analysis #	GSI	REC
#a	81	100%
#b	71	85%
#c	62	70%
#d	53	55%
#e	41	40%
#f	29	25%

Summary & Conclusions of Research

- Florida carbonate rock (limestone, dolostone, marls) formations are relatively young (10,000 yrs to 57 million yrs)
- Each formation has different carbonate content, as well chemical content (Calcium vs. Magnesium) and crystal structure (calcite vs. aragonite)
- 75% of rocks' total dry unit weight, $\gamma_{dt} < 123$ pcf and porosity, $n > 28\%$
- Rock strength is controlled by index measurements (dry unit weight), carbonate content, formation and stresses (e.q. triaxial, footing, etc.)
- Rock's stress-strain response is generally ductile [f (γ_{dt} , σ_3)], but brittle for high unit weights and low confining stresses
- Strength Envelopes for of Florida rock is impacted by its high porosity, i.e. crushing
  - From triaxial test results; the strength envelopes show significant downward slopes beyond the point of the peak strength, at much steeper rate than the envelopes for brittle rocks
  - Strength envelope and Florida Bearing Capacity Equations may be adjusted by rock recovery ratio, REC.
  - Guidelines to establish the strength envelope for other rock formations in Florida were presented in the Appendix F of Final Report.

Summary & Conclusions of Research

- Split tension and Unconfined compressive strength of Florida Rock function of dry unit weight γ_{dt}. (R^2 =0.59)

$$q_t\,(psi) = 3.864\, e^{0.03\gamma_{dt} B} \qquad q_u\,(psi) = 5.89\, e^{0.04\gamma_{dt} B}$$

$B = 1$ if $\gamma_{dt} < \gamma_{dt0}$

$B = \sqrt{\gamma_{dt}/\gamma_{dt0}}$ if $\gamma_{dt} \geq \gamma_{dt0}$

$\gamma_{dt0} = 22\ \mathrm{kN/m^3}$ (140 pcf)

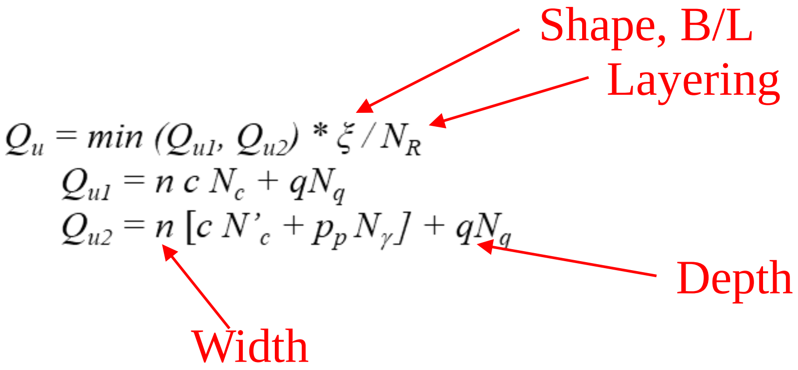
- Split tension and Unconfined compressive strength of Florida Rock function of dry unit weight γ_{dt}, Carbonate content, C, and Formation Factor, F ($R^2 > 0.7$)

$$q_t\,(psi) = 2.468\, F_t\, e^{0.03\gamma_{dt} B}\, e^{0.5C} \qquad q_u\,(psi) = 3.24\, F_u\, e^{0.04\gamma_{dt} B}\, e^{2C/3}$$

- Besides q_u *and* q_t triaxial testing required to establish strength envelop beyond onset of crushing, Pp – upward downward slope β (p –q) or ω (τ - σ)

Summary of Research Conclusions

- Florida Bearing Capacity Equations were developed based on the bilinear strength envelope, which can be applied to any footing shape, any depth, and any rock thickness (which is applicable where a caprock is usually encountered atop a thick sand layer, such as the case in south Florida):



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

$$Q_{u1} = n\, c\, N_c + qN_q$$

$$Q_{u2} = n\, [c\, N'_c + p_p\, N_\gamma] + qN_q$$

- Strength envelope and Florida Bearing Capacity Equations could be adjusted by rock recovery ratio, REC.

Recommendations

- Other Florida Limestone formations need to have their own strength envelopes established as function of dry unit weights; assess carbonate content and formation factor (crystal structure) for q_u and q_t.
- Use porosity as an index property to describe the Florida carbonate rock.

n_v	0 to 5%	5 to 10%	10 to 15%	15 to 20%	>20%
Vug porosity	No vug, relatively smooth rock	Slightly vuggy	Vuggy to Very vuggy	Very vuggy	Extremely vuggy

- Due to the magnitude of bearing capacity stresses – field validation of Bearing Capacity Equations is warranted.

Further research

Next phase will focus on field testing to validate the equations derived in the current work：

1. Validate the Florida bearing capacity equations based on field load tests including different rock formation, embedment and layering (rock over sand).
2. Validate load – settlement response of shallow foundation.
3. Develop LRFD Resistance Factors for Bearing Capacity Predictions.

Phase III – Implementation of BC and settlement equations into FB-Multipier.

Publications

FDOT Report BDV31-977-51, ***Strength Envelopes for Florida Rock and Intermediate Geomaterials***, May 2019

Nguyen, McVay, Song, Wasman, Rodgers, Horhota, Herrera, and Wang, **"Strength And Index Measurement of South Florida Carbonate Rock,"** *ASCE IFCEE*, **GSP 294**, 2018, https://doi.org/10.1061/9780784481585.006

Nguyen, McVay, Song, Wasman, Herrera, and Wang, **"Strength Envelopes of Florida Carbonate Rocks near Ground Surface,"** *ASCE Journal of Geotechnical and Geoenvironmental Engineering, 2019,*
https:// DOI: 10.1061/(ASCE)GT.1943-5606.0002069

"Bearing Capacity of Shallow Foundation in Florida Carbonate Rocks" – In progress

Closing Page

Thank You!

Q & A