GRIP Meeting 2023
Project BED26 TWO 977-04:
Effect of Spacing on Axial Resistance of Auger Cast Pile Foundations
Start Date: Jan. 2023
End Date: Dec. 2024
Project Manager: Rodrigo Herrera (PM) and Juan Castellanos (Co-PM)

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FDOT

PRESENTATION OUTLINE

- Justification and methodology
- Benefits and implementation
- Background
- Objectives
- Tasks, deliverables, and progress to date
  - Technical background
  - Experimental program
  - Preliminary numerical results

JUSTIFICATION AND METHODOLOGY

- Historically under conventional contracts (i.e., design-bid-build), deep foundations were designed at a spacing of at least three times the pile width center to center, and smaller spacings would only be considered if a pile was rejected during construction and sister piles were required.

- The observed trend in design build projects, particularly the ones with ACP, has been the push for 2.5 diameter spacing resulting in smaller pile caps and hence time and cost savings.

- AASHTO design code is silent on how to address the issue of spacing in rock or intermediate geomaterial (IGM) from a foundation design perspective.

- Research was proposed from a numerical and physical model testing perspectives to ensure the bearing layer is not being over-stressed and to study the effect of pile spacing on settlement and bearing resistance.

BENEFITS (EXPECTED) and IMPLEMENTATION

QUALITATIVE

- Better estimation of the effect of spacing and load-deformation behaviors in ACP.
- Understanding geotechnical mechanisms and influence of proximity of ACP on the performance.

QUANTITATIVE

- Study effects of foundation layout and rock strength on axial resistance of ACP.
- Calibration of bearing capacities using advanced rock models for Florida limestone.
- Study failure mechanisms and influence of pile spacing ratio (S/D), relative stiffness factor (E_{top}/E_{bottom}), and rock strength parameters (e.g., Recovery and RQD) on foundation deformation characteristics.

IMPLEMENTATION

- Potential development of reduction factors for applicable cases in Structures Design Guidelines.
- If the effort indicates the use of 2.5D (or less) spacing is not an issue, it could be adopted by designers more often making construction faster, using less concrete and steel, and generating time and cost savings due to reduced pile caps.

BACKGROUND

- Fundamental question is if axial capacity of ACP constructed in granular soil and Limestone should be reduced as a function of pile spacing.

- Preliminary analyses showed that plunging failure of ACP when socketed in competent strata is almost independent of S/D. But, when a performance-based deformation criterion is used (e.g., Davisson’s method) and given that the load-deformation curves are highly affected by overlapping of stress bulbs, the load-capacity required to satisfy the deflection criterion reduces as S/D reduces.

- AASHTO LRFD for the broader case of drilled shaft foundations claims that: “the bearing resistance in sands is less than the sum of individual capacities due to overlap of shear zones between adjacent shafts and loosening of soil during construction.” These issues need to be evaluated for ACPs.

- A concern in granular materials is that during installation of ACP, there is a reduction of K_0 values due to their installation, further study is needed for the specific conditions in Florida.

OBJECTIVES

- Evaluate effect of spacing on load-settlement behavior of ACP and develop reduction factors for applicable cases.
- Quantify the effect of overlapping stress bulbs among foundation elements.
- Investigate the effect of soil layering (sand-rock, and sand-rock-sand-rock) on the load-settlement behavior of ACP.
- Investigate the effect of rock strength and design unit skin friction developing a limiting demand/capacity ratio of unit skin friction vs. rock strength, beyond which reduction factors are required.
- Investigate relationships among geotechnical variables that influence the problem and develop correlations (formula or charts).

TASKS, DELIVERABLES, AND PROGRESS TO DATE

Tasks 1 and 2: Technical Background and Physical Model Testing

Task 1: Technical background provided in three parts: current recommendations provided by design codes and major DOTs, review of laboratory-based physical model tests, and review of previous numerical modeling strategies.

Deliverable 1: Report on technical background 02/2023

Task 2: Construction of a structural steel soil box to develop physical model tests. Soil box dimensions selected to accommodate a maximum 3 x 3 pile group at 4D center-to-center spacing. Testing matrix will consider variations in soil density and E_{top}/E_{bottom} ratios, S/D, and pile group configuration.

Preliminary testing matrix

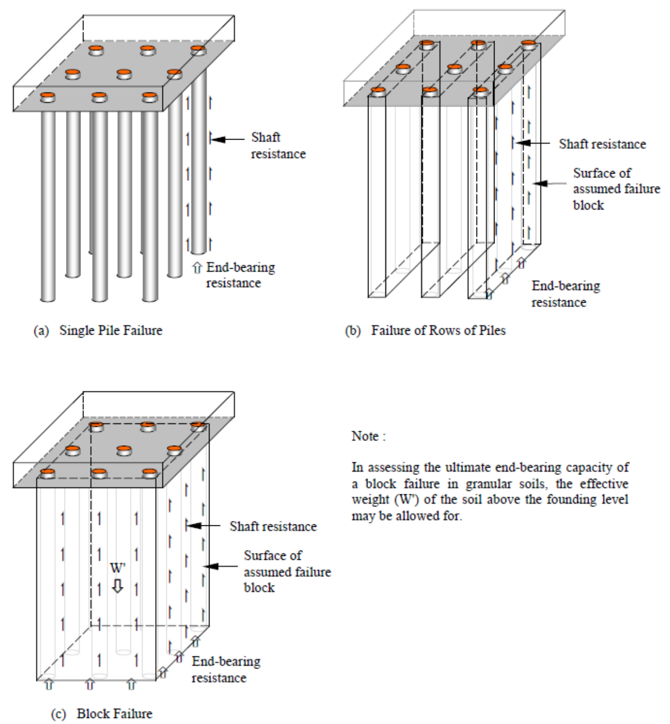
Test #	Soil density	Pile group	Pile spa.
1	50%	Single	N/A
2	75%	Single	N/A
3	50% + Gator Rock	Single	N/A
4	75% + Gator Rock	Single	N/A
5	Gator Rock	Single	N/A
6	50%	2 x 2	2.5
7	75%	2 x 2	2.5
8	50% + Gator Rock	2 x 2	2.5
9	50% + Gator Rock	2 x 2	2
10	50% + Gator Rock	2 x 2	3
11	50% + Gator Rock	2 x 2	4
12	50% + Gator Rock	3 x 3	2.5
13	50% + Gator Rock	3 x 3	2
14	50% + Gator Rock	3 x 3	3
15	50% + Gator Rock	3 x 3	4

Deliverable 2a: Report on details of lab testing program 07/2023

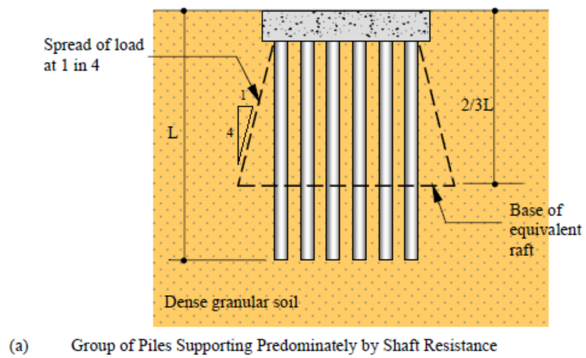
Deliverable 2b: Report with results of lab testing program 12/2023

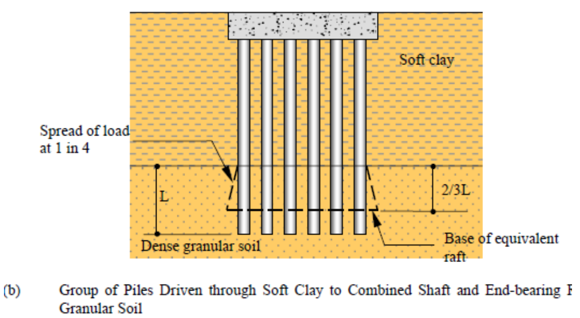
Main variables:

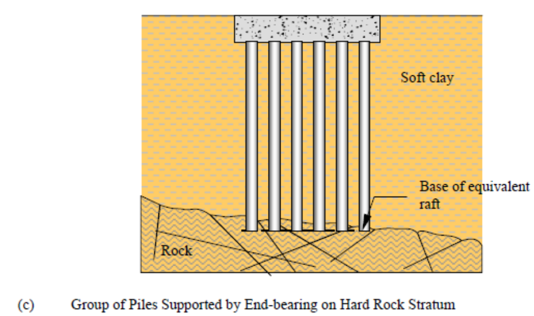
- Spacing of ACP.
- Relative density and degree of saturation of soils.
- Strength of rock and IGM.
- Geometric and material characteristics of ACP.
- Construction sequence during installation.
- Configuration of the pile group.
- ACP installation effects: penetration rate with auger and injection pressure of the concrete material.
- Presence of pile cap (either in firm or no contact with the ground).



Failure Mechanisms of Pile Groups (Fleming et al, 1992)







Equivalent Raft Method depending on soil type (Tomlinson, 1994)

FDOT Developmental Specifications

Dev346ACP (346 ACP Grout)

Dev455ACP (455 ACP)

- Defined here as: "foundation made by rotating a hollow-stem auger into the ground with sufficient crowd to prevent mining of the soil."
- Minimum grouting head of 5 ft or 10% of the length of the pile prior to auger withdrawal.
- Minimum pumping volume of 115% based on the column of the auger hole.

FDOT Soils and Foundation Handbook

Reference 9 is generally applicable to all conditions except for drilled shafts socketed in Florida limestone. Refer to Appendix A for an approved method of determining the side resistance for drilled shafts socketed in Florida limestone. The normal spacing for drilled shafts is 3D. For rock socketed drilled shaft groups with spacing of 2.5D or greater, a group efficiency factor of 1 may be used for axial loads; for shafts tipped in other materials refer to the current AASHTO LRFD Bridge Design Specification. P-y multipliers for lateral loads are in the Structures Design Guidelines. General foundation analysis considerations are further described below.

ACP follow same criteria as drilled shafts

It also specifies a side shear component estimation method for ACP socketed in Florida limestone:

$$f_{su} = REC\left(\frac{1}{2}\sqrt{q_u}\cdot\sqrt{q_t}\right)$$

FDOT Structures Design Guidelines

- Design methods for ACP normally recommended to be the same as drilled shafts.
- Design method for ACP in soils: neglect tip resistance. Several inches needed to mobilize it.
- For ACP socketed in rocks or IGMs: Neglect the side shear of the overburden soil unless strain compatible values could be determined.

Reduction factors from AASHTO LRFD

Shaft Group Configuration	Shaft Center-to-Center Spacing	Special Conditions	Reduction Factor for Group Effects, η
Single Row	2*D*		0.90
	3*D* or more		1.0
Multiple Row	2.5*D*		0.67
	3*D*		0.80
	4*D* or more		1.0
Single and Multiple Rows	2*D* or more	Shaft group cap in intimate contact with ground consisting of medium dense or denser soil, and no scour below the shaft cap is anticipated	1.0
Single and Multiple Rows	2*D* or more	Pressure grouting is used along the shaft sides to restore lateral stress losses caused by shaft installation, and the shaft tip is pressure grouted	1.0

- Spacing < 3D reduces the effective stresses against both the side and base of the existing shaft.
- It does not reduce the shaft group capacity if favorable construction activities.
- Based on limited load test results for small drilled shaft groups for sands above the groundwater table.
- **Does not provide guidelines for design or spacing of ACP nor for IGMs.**

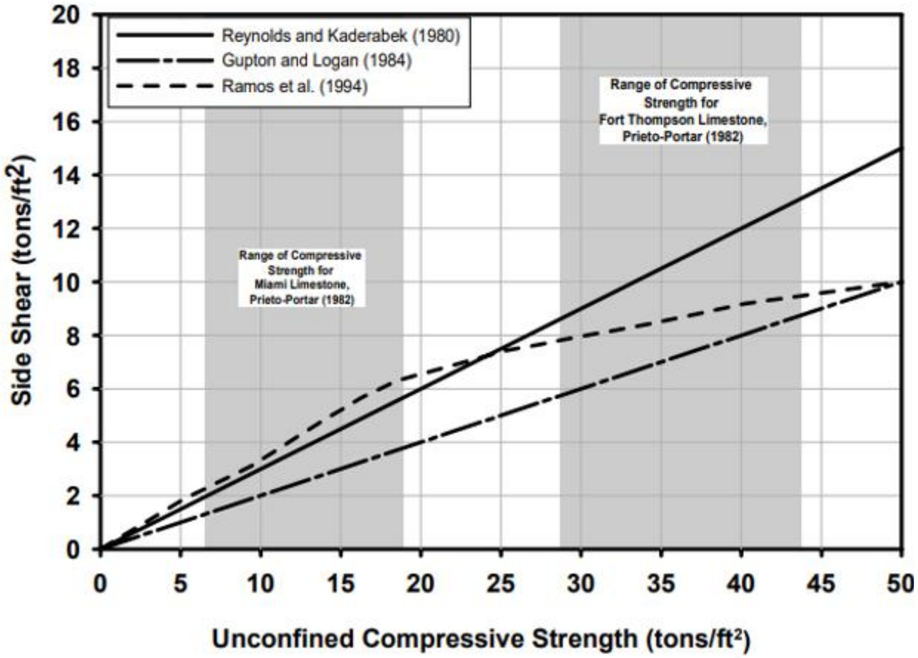
Reduction factors from other DOTs (Caltrans for example).

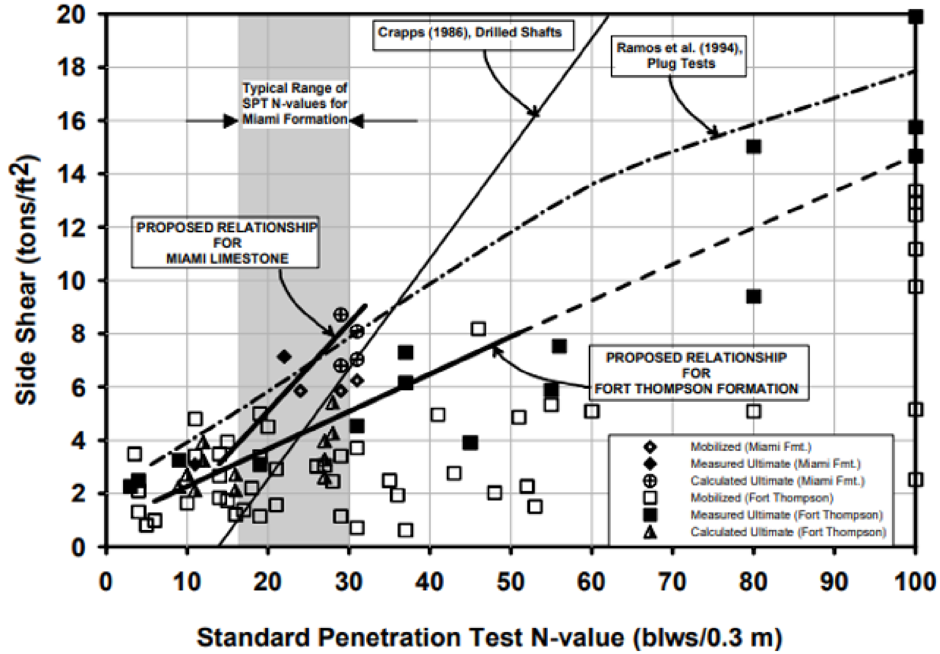
Shaft Group Configuration	Shaft Center-to-Center Spacing	Special Conditions	Reduction Factor for Group Effects, η
Single Row	2.5*D*		0.95
	3*D* or more		1.0
Multiple Row	2.5*D*		0.67
	3*D*		0.80
	4*D* or more		1.0
Single and Multiple Rows	2.5*D* or more	Shaft group cap in intimate contact with ground consisting of medium dense or denser soil, and no scour below the shaft cap is anticipated	1.0
Single and Multiple Rows	2.5*D* or more	Pressure grouting is used along the shaft sides to restore lateral stress losses caused by shaft installation, and the shaft tip is pressure grouted.	1.0

Other DOTs and Agencies: spacings to avoid group effects for single row drilled shafts

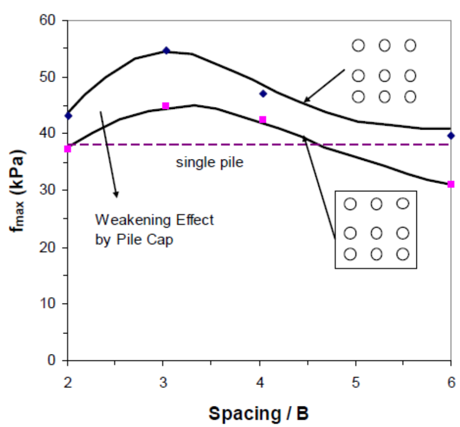
- WSDOT = 3.0D AS 2159-2009 = 2.5D (side)
- WisDOT = 3.0D AS 2159-2009 = 2.0D (end)
- ASCE(1997) = 2.5D JTG 3363-2019 = 2.5D
- IBC = 3.0D JTG 3363-2019 = 2.0D (end)

FHWA correlations for drilled shafts socketed in Florida Limestone

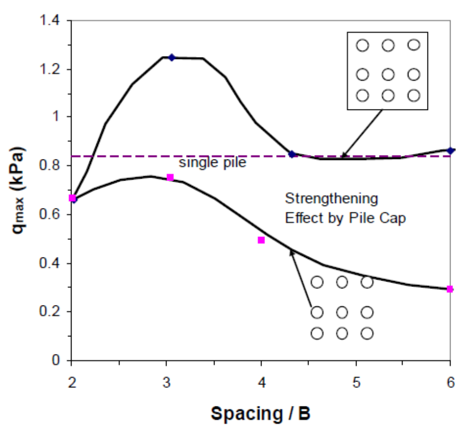




Pile capacity as a function of spacing over diameter (B) from FHWA (2007)

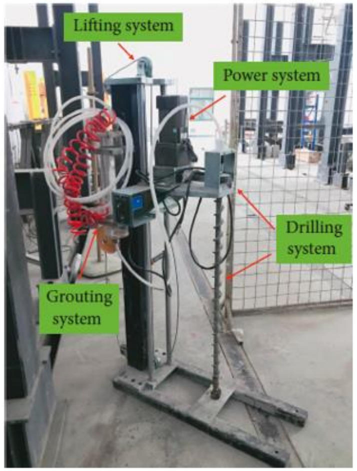


Side shear



End bearing

- End bearing efficiency increases when pile cap contact the soil.
- Opposite occurs for side shear.
- Tests performed under dry conditions.
- Applicable only for drilled shafts.



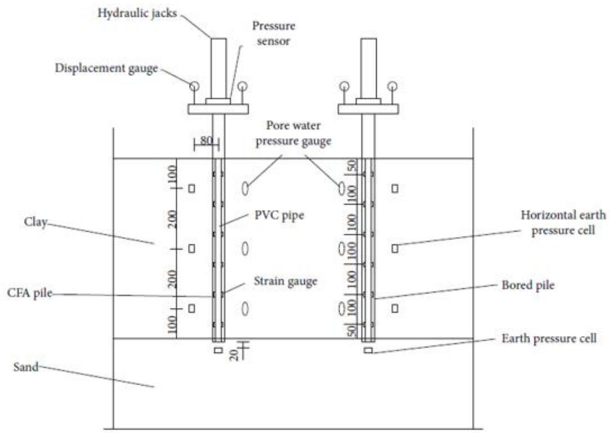


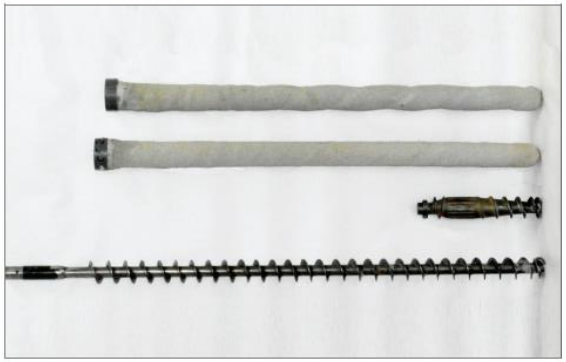
FIGURE 4: Section layout drawing of piles and sensors.

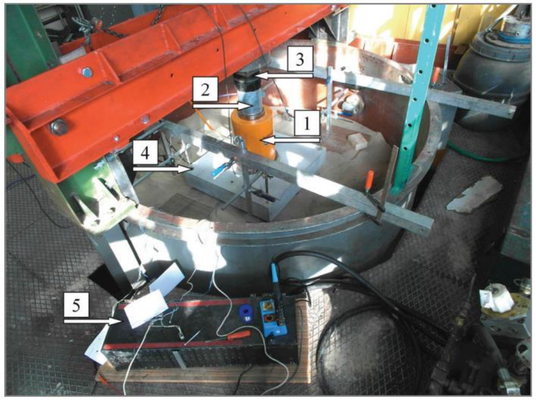
Zhu et al. (2021):

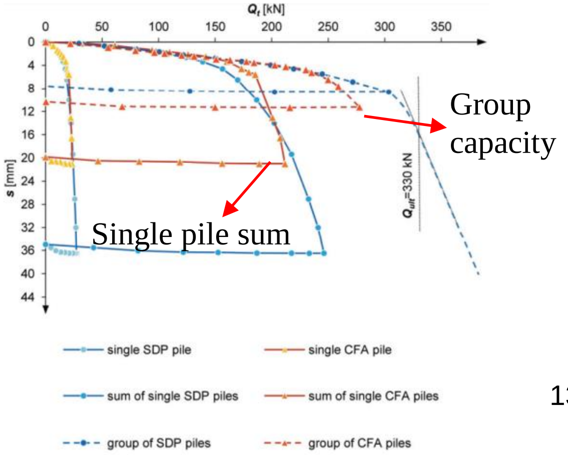
- ACPs installed with a "pile forming equipment" (drilling system).
- Strain gauges were installed to measure shaft and end bearing capacities.
- Loading using hydraulic jacks and deformations measured with displacement gauges

Krasiński and Kusio (2015):

- Continuous Flight Auger (CFA) piles installed in 3x3 groups on a saturated sand.
- Loading using hydraulic jacks and deformations with displacement gauges on the corners of pile group.
- Group capacity was 26% higher than the sum of the single pile capacity (η>1.0)

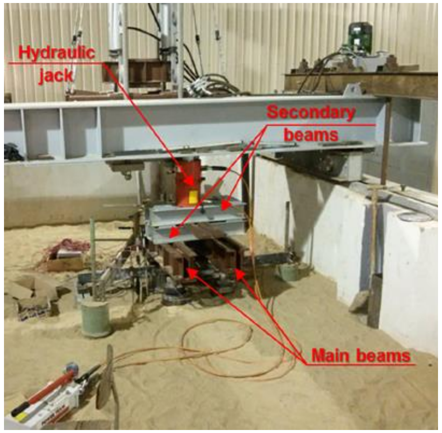


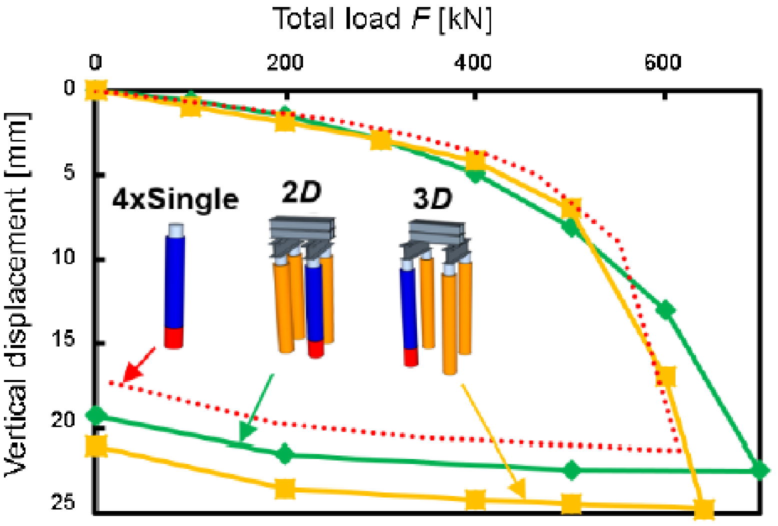




Norkus and Martinkus (2019):

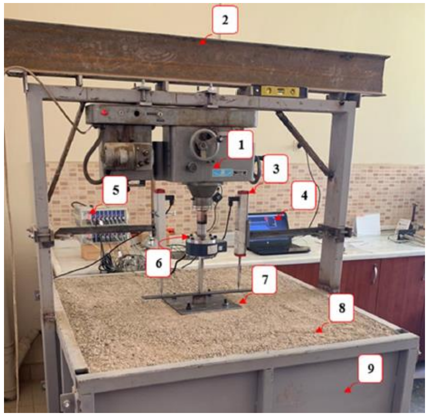
- 2x2 pile groups installed in dense sand at S=2D and S=3D.
- Pile load measurement using hollow load cell on head.
- Construction sequence including the installation effect of individual adjacent pile on the model pile.

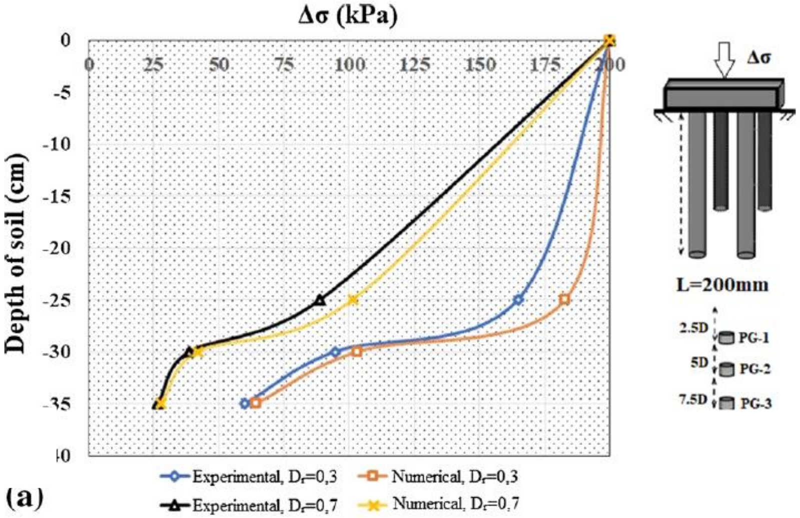




Ateş and Şadoglu (2021):

- 2x2 pile groups inserted with loading press into sand of relative densities of 30% and 70%. S=4D pile spacing.
- Pressure gauges installed at 2.5D, 5.0D, and 7.5D below pile tip to obtain vertical stress increment distribution.
- Vibro-compaction device to obtain the higher relative density.





(a)

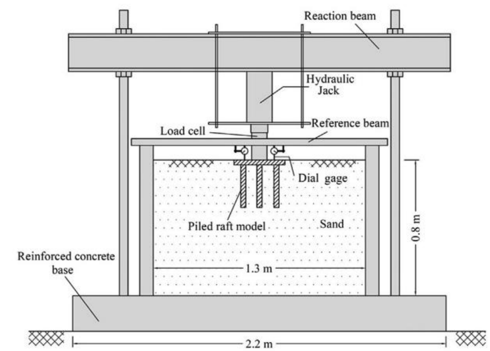
TECHNICAL BACKGROUND (Laboratory-based Physical Model Tests)

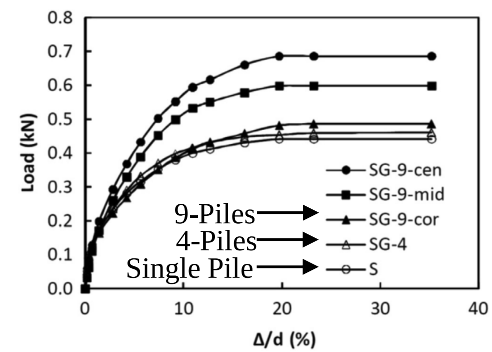
Database of Testing Programs

Author(s)	Applied Load	Pile Type	Pile Installation Method	Soil Layers	Pile Material
Zhu et al. (2021)	Axial	ACP Drilled Shaft	Drilling Rig Soil Sampler	Clay, Sand	Grout, Cast-in-situ
Krasiński & Kusio (2015)	Axial	ACP SDP	Hand Auger	Sand	Concrete, Cast-in-situ
Norkus & Martinkus (2019)	Axial	DP	Jacking	Sand	Steel
Li et al. (2022)	Axial	WIP	Pre-installation	Silty Sand	Plexiglass
Khari et al. (2013)	Lateral	WIP	Pre-installation	Sand	Aluminum
Kim & Yoon (2011)	Lateral	WIP	Pre-installation	Sand	Steel
Vakili et al. (2021)	Lateral	WIP	Pre-installation	Sand	Steel
Sharafkhah & Shooshpasha (2018)	Axial	Drilled Shaft	Hand Auger	Sand	Concrete, Cast-in-situ
Al-Khazaali & Vanapalli (2019)	Axial	WIP	Pre-installation	Sand	Steel
Jeffrey et al. (2016)	Axial	CHD	Drilling Rig	Sand	Grout, Cast-in-situ
Elsamny et al. (2017)	Axial	WIP	Pre-installation	Sand	Concrete, Precast
Goit et al. (2021)	Vertical Load Inclined Pile	WIP	Pre-installation	Sand	Acrylic
Hokmabadi et al. (2015)	Lateral	DP	Driving	Synthetic	Polyethylene
Zhu et al. (2018)	Lateral	DP	Jacking	Sand	Aluminum
Shamsi Sosahab et al. (2019)	Axial	DP	Driving	Sand	Steel
Lande et al. (2021)	N/A	N/A	Drilling Rig	Sand	Steel
Momeni et al. (2017)	Axial	DP	Jacking	Sand	Steel
Ateş & Şadoglu (2021)	Axial	**DP**	**Jacking**	Sand	Composite
Su & Zhou (2015)	Lateral	DP	Jacking	Sand	Aluminum
Faresghoshooni et al. (2021)	Lateral	WIP	Pre-installation	Sand	Polyethylene
Hussain et al. (2019)	Lateral	Micropile	Pushed Manually	Sand	Grout, Cast-in-situ
Munaga & Gonavaram (2021)	Lateral	WIP	Pre-installation	Sand	Aluminum
Kayalvizhi & Muthukkumaran (2021)	Lateral	DP	Driving	Sand	Aluminum
Kong et al. (2019)	Lateral	WIP	Pre-installation	Sand	Concrete, Precast
Koteswara et al. (2019)	Axial	**WIP**	**Pre-installation**	Sand	Aluminum
Kumar & Kumar (2018)	Axial	DP	Jacking	Sand	Steel
Martines et al. (2017)	Axial	DP WIP	Driving Pre-installation	Sand	Steel
Majumder et al. (2022)	Axial	UR	Pre-installation	Sand	Steel
Mohammadi et al. (2020)	Axial	DP WIP	Driving Pre-installation	Sand	Steel
Choi et al. (2017)	Combined	DP	Driving	Sand	Steel
Subanantharaj & Kumar (2018)	Combined	WIP	Pre-installation	Sand	Steel
Omer & Haroglu (2021)	Axial	DP	Jacking	Sand	Aluminum

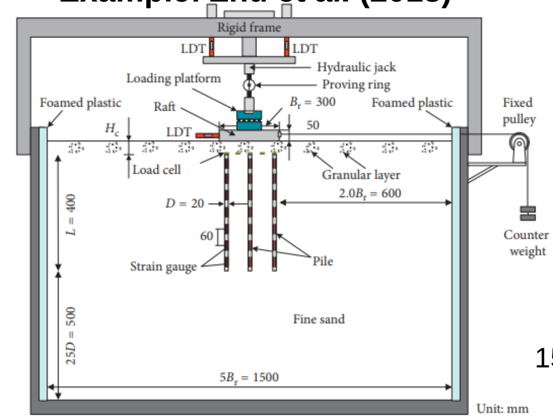
ACP: Auger Cast Piles, SDP: Screw displacement piles, UR = Under-Reamed
DP: Displacement pile, CHD: Continuous Helical Displacement, WIP: Wished-In-Place- Jeffrey et al. (2016)
Pre-installation: "Positioning of the pile before the soil sample is fully prepared,
it is used to simulate the installation of ideal non-displacement piles" Martines et al. (2017)

Example: Sharafkhah and Shooshpasha (2018)



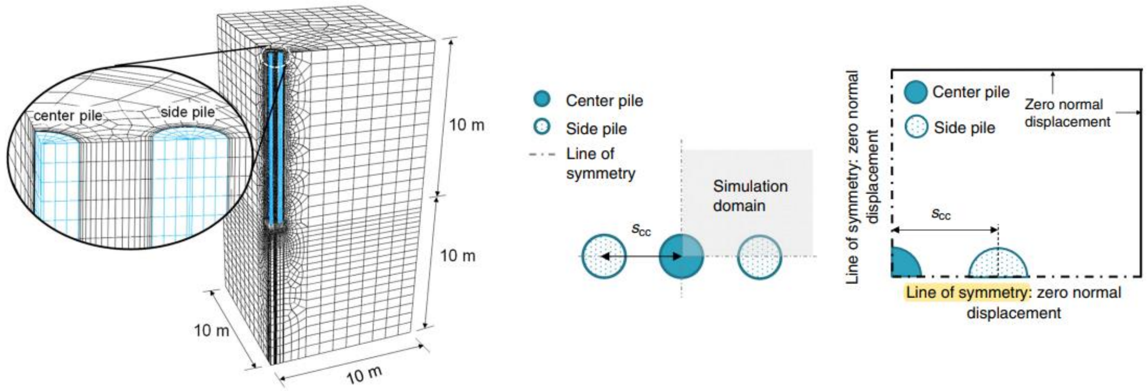


Example: Zhu et al. (2018)



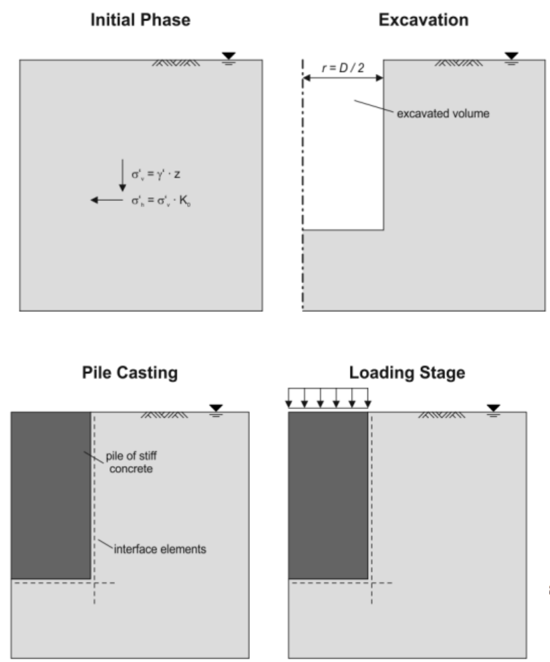
Axial capacity of pile groups
Han et al. (2019):

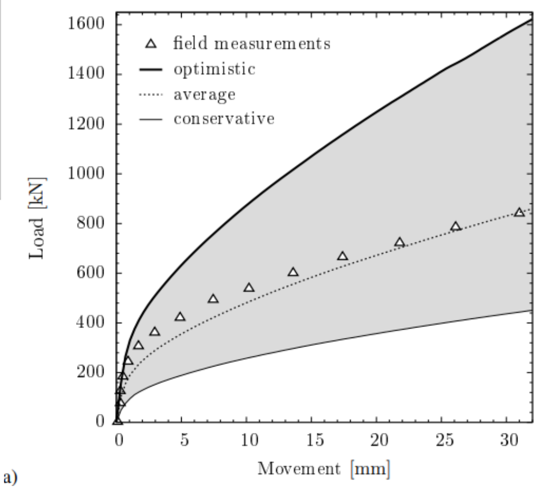
- 3D modeling in ABAQUS
- Soil model: two-surface constitutive model.
- Rigid soil-pile interface.
- Euler stress integration method to deal with large deformations.



Numerical simulation of cast-in-place piles, Schmudderich et al. (2020):

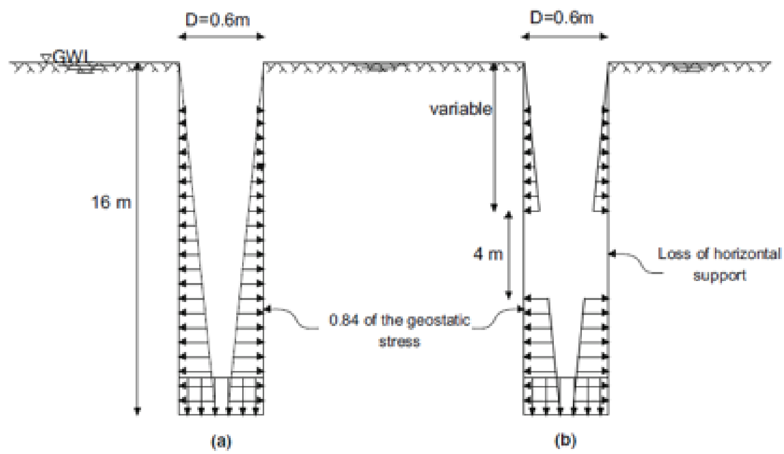
- 2D modeling in PLAXIS.
- HS-Small used to model the soil.
- Linear elastic used for the pile.
- Interface elements around the pile to model soil-pile interaction).

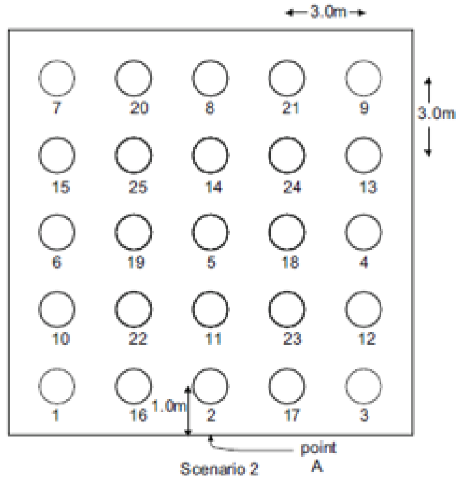




Simulation of Unfavorable CFA Pile Drilling Conditions. Arab et al. (2020):

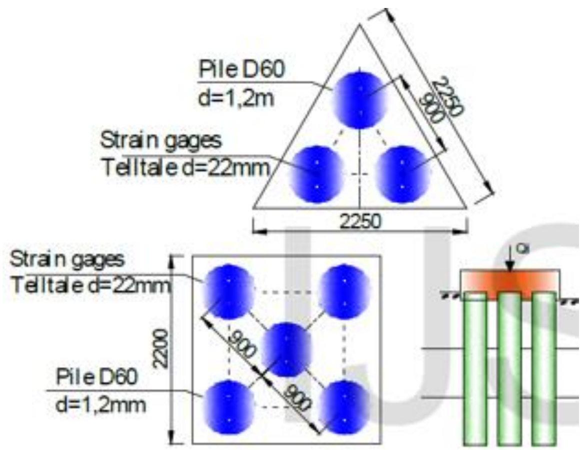
- 3D modeling in ABAQUS.
- Mohr-Coulomb used to represent loose sand behavior.
- Includes the effect of slower rate of penetration vs. rotation.
- Consider the extent of the disturbed zone and number of over-rotations.

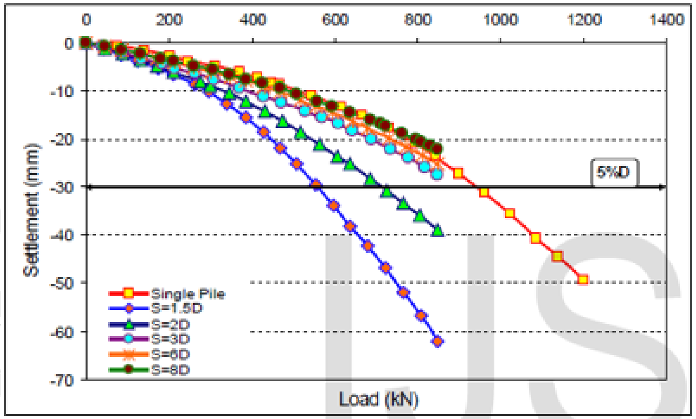




Analysis of pile group efficiency in granular soils. Pham (2016):

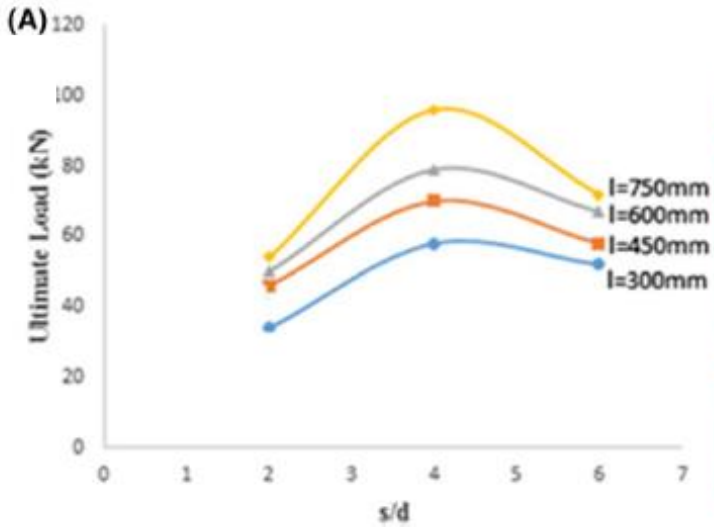
- 3D modeling in PLAXIS.
- Considered the arrangement and spacing effects on axial efficiency.
- Mohr-Coulomb model for all layers.
- Includes cap influence on pile group settlements.

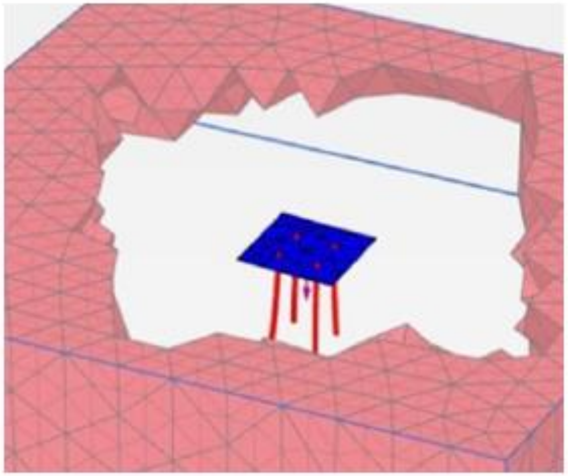




Ultimate Bearing capacity of piled-raft footing. Singh et al. (2020):

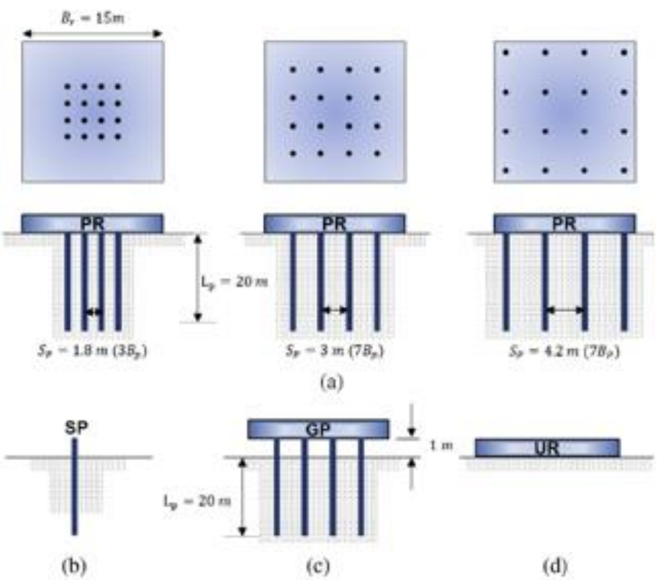
- 3D modeling in PLAXIS
- Mohr-Coulomb material
- Embedded pile element
- Floor element for raft
- Embedded interface elements to represent contacts between materials.

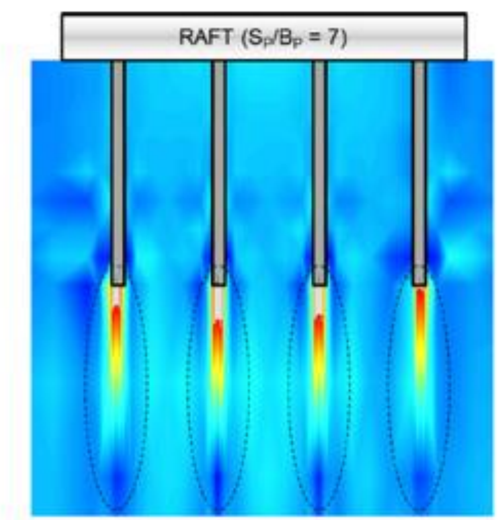




Bearing capacity of pile groups in sand. Lee et al. (2015):

- 3D modeling in PLAXIS to study load-sharing ratios of piled rafts
- Spacings of 3D, 5D and 7D
- Linear elastic materials used to represent piles.





EXPERIMENTAL PROGRAM (Testing Procedure)

Design synthetic limestone → Deposit sand via pluviation → Install sensors in pile and soil → Install ACP → Perform test

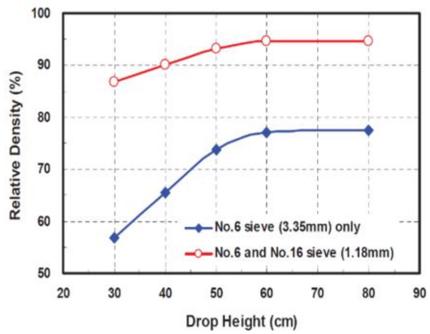
Design synthetic limestone

Designed based on "Gatorock" proposed by UF.

Tested cylinders

Deposit sand via pluviation

Combination of sieve and drop height to achieve 50% and 70% relative densities.



Target relative density based on drop height

Sand pluviator designed at UCF

Install sensors in pile and soil

- Strain gauges to decouple skin and end bearing.
- Pressure cell to verify stresses in the soil.
- Use of geophones to verify soil density.

Strain Gauges

Pressure Cell

Install ACP

- ACP Installed using a hollow stem auger.
- Following FDOT Dev. Specs.
- Class I grout will be used.

3.0 in diameter hollow stem auger

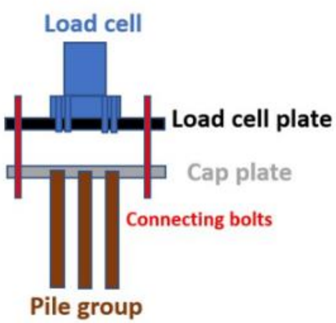
Perform test

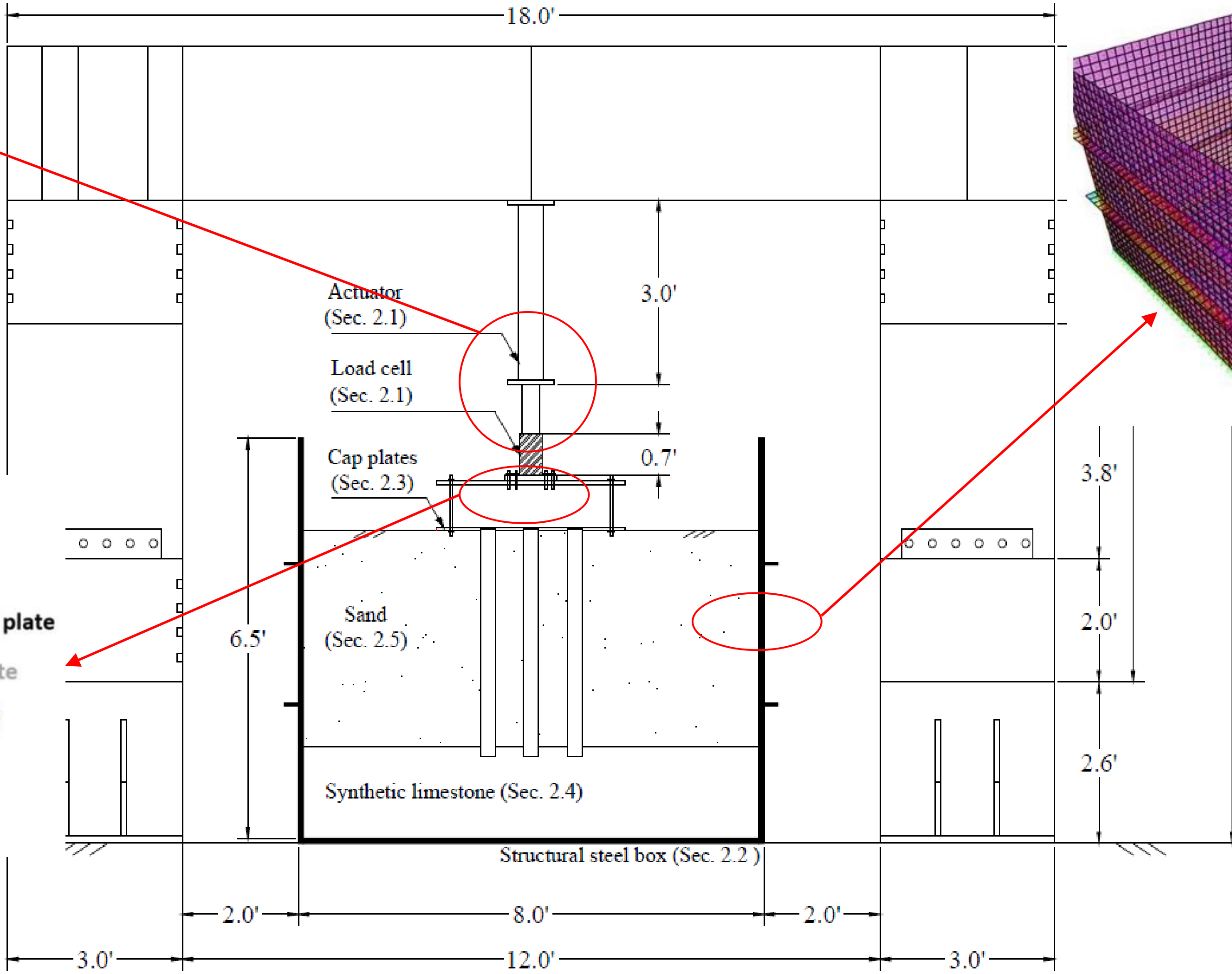
Tests performed following modified quick test requirements from FDOT specs for bridge construction

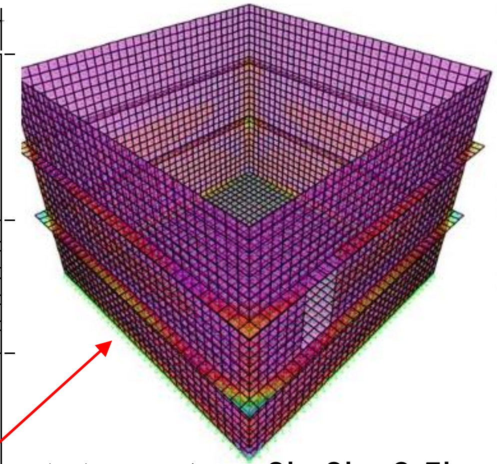
EXPERIMENTAL PROGRAM (Test Setup)

Proposed tests characteristics:

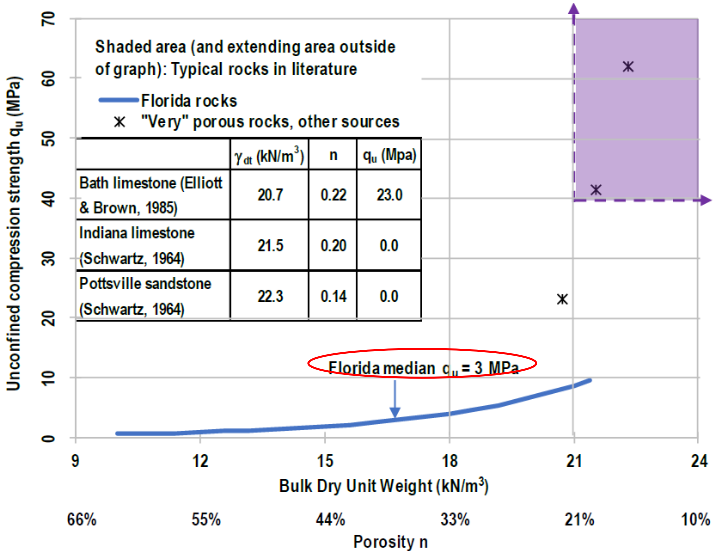
- **Pile dimensions:** 3 in. diam. and ≈ 5ft in length
- **Tested spacings:** 2.0D, 2.5D, 3.0D, and 4.0D.
- **Group configurations**: 2x2 and 3x3 groups
- **Soil conditions**: Medium-dense and dense sands over gatorock. Also, layered and entire sandy soil profiles.
- **Steel box dimensions:** 8'x8' plan view (12D distance to edge).







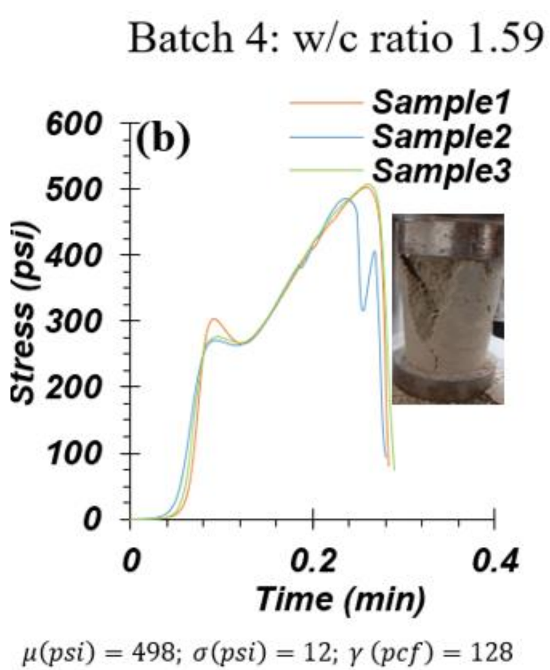
8'x 8' x 6.5' steel box with two levels of stiffeners

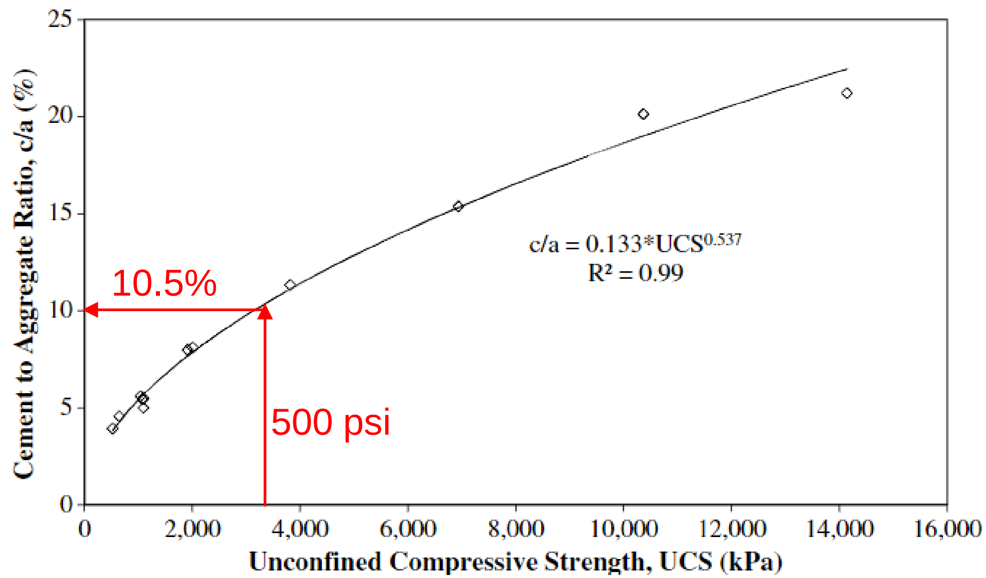


	γ_{dt} (kN/m³)	n	q_u (Mpa)
Bath limestone (Elliott & Brown, 1985)	20.7	0.22	23.0
Indiana limestone (Schwartz, 1964)	21.5	0.20	0.0
Pottsville sandstone (Schwartz, 1964)	22.3	0.14	0.0

Average parameters of Florida Limestones from McVay et al. (2019).

- Target unconfined compression strength of 500 psi based on Florida Limestone's median.
- Procedure following standards for low strength materials (ACI, 1994).
- Mix proportioning following procedure by Cepero et al. (2002) and McVay et al. (2019) at UF.
- Defined water/cement ratio (W/C)=1.59.
- Defined cement/limestone ratio (C/A)= 9.74%.
- Proportions matched values proposed by Rodgers et al. (2018) for C/A of 10.5% for a 500 psi strength.





Gatorock mix design C/A versus unconfined compressive strength (Rodgers et al 2018)

Task 3: Numerical Modeling

<u>Task 3</u>: Develop numerical models validated with results from Task 2. Develop charts of load deformation responses to propose load-reduction factors as a function of: spacing, diameter, soil stratification, and design unit skin friction vs. rock strength.

Selection of constitutive soil and rock models depend on: soil type and density, confinement pressures, strength-stress-strain characteristics of the underlying rock, and characteristics of the ACP.

Models to be used are those implemented into commercial computer codes and with published record of calibrations with field and laboratory testing.

Models preliminarily considered for sands: Hardening Soil with Small Strain Stiffness (HSSMALL), Pressure Dependent Multi-Yield Plasticity Model (PDMYM), Hypoplasticity model.

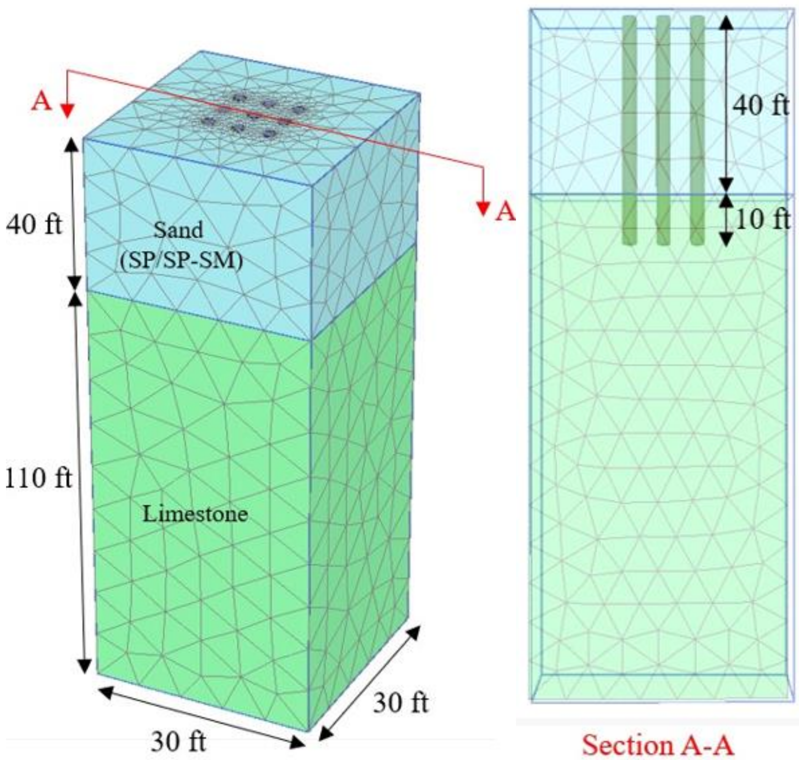
Models preliminarily considered for rock: Mohr-Coulomb, Hoek-Brown with softening, Drucker Prager, and McVay et al. (2019). Verification is needed that the selected model captures the triaxial tests presented in FDOT-BDV31-977-51.

Numerical modeling platforms: OpenSees and Plaxis.

Deliverable 3: Report summarizing numerical modeling results <u>05/2024</u>

Model Characteristics:

- 150 ft-tall and 60 ft-squared base model.
- Tested cases: 2x2 and 3x3 pile groups. No cap considered.
- Pile diameters and distance to edge: 2ft and 12D.
- Prescribed displacement of 5.0 in. on top of each pile.
- Soil profile: sand over limestone.
- Two sand densities considered: 30% and 75%.
- Two limestone cases considered: intact and weathered cases using GSI of 100 and 50.
- Selected limestone q_u: 500 psi (average of proposed testing matrix).



Geometry of the 3D FE model

List of soil cases considered in this numerical study.

Soil Conditions	$D_{r,Sand}$	E_{sand}	GSI_{rock}	$q_{u\,rock}$	E_{rock}	E_{sand}/E_{rock}
	%	ksi	-	psi	ksi	-
A	30	1.92	100	500	600	0.003
B	75	4.99	100	500	600	0.008
C	30	1.92	50	30	301	0.006

Parameters used for the HS small model

Parameter	Units	Loose Sand	Dense Sand
D_r	(%)	30	75
γ_{sat}	pcf	125	130
ϕ'	°	31.8	37.4
ψ	°	1.8	7.4
E_{50}^{ref}	ksi	2.61	6.53
E_{oed}^{ref}	ksi	2.61	6.53
E_{ur}^{ref}	ksi	7.83	19.58
G_0^{ref}	ksi	11.67	16.11
m	-	0.61	0.47
ν'_{ur}	-	0.2	0.2
$\gamma_{0.7}$	$x10^{-4}$	1.7	1.3
R_f	-	0.96	0.91
R_{inter}	-	0.8	0.8

Sandy soil parameters

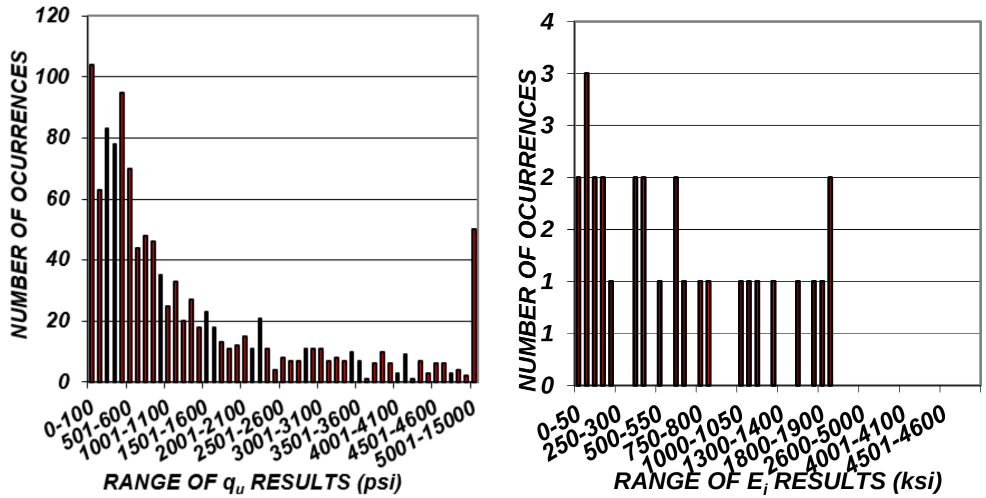
- HS Small model.
- Target relative densities of 30% and 75%.
- Parameters selected based on correlations with D_r by Brinkgreve et al. (2010) for sandy soils.

Limestone parameters

- Hoek and Brown model.
- Both q_u and E_i were obtained as average values of a database provided by FDOT.
- An intact rock with a GSI of 100 was considered to achieve an exact q_u of 500 psi.

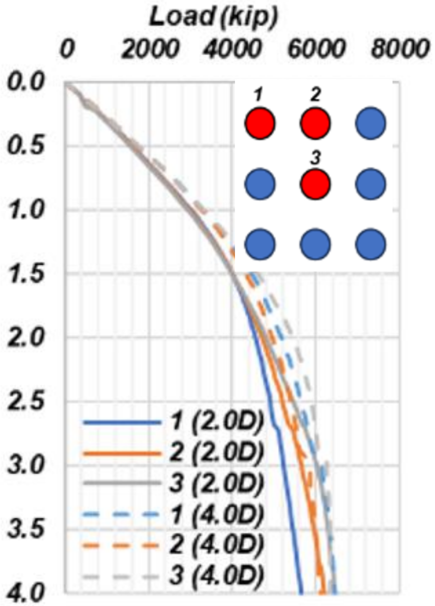
Parameters used for Hoek-Brown model

Parameter	Units	Intact Rock	Weathered Rock
γ_{sat}	pcf	130	130
GSI	-	100	50
E_i	ksi	600	600
ν'	-	0.2	0.2
$q_{u,intact}$	psi	500	500
m_i	-	12	12



Summary of laboratory testing database in terms of: (a) unconfined compr. strength and (b) elastic modulus.

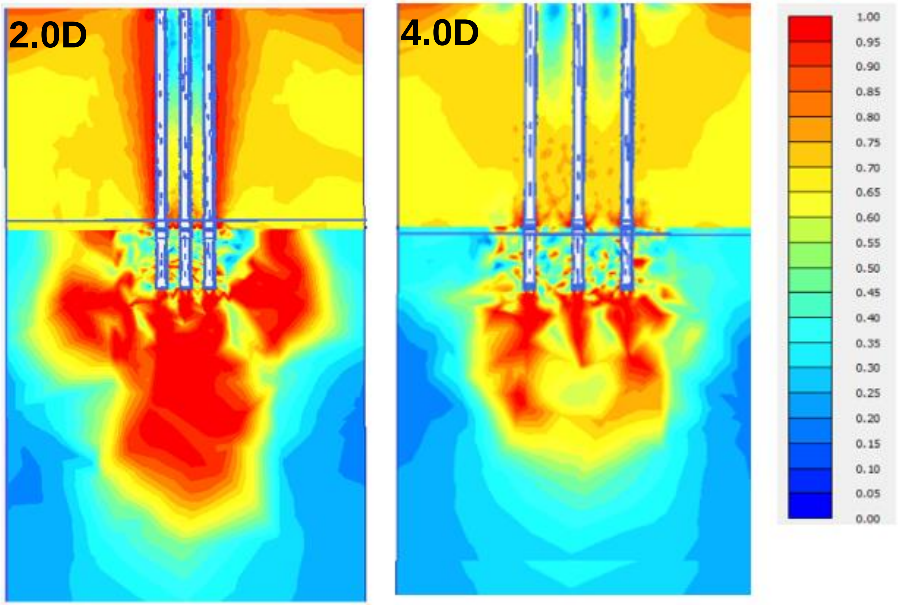
Load vs. displacement curves for piles at three different locations in the pile group



Observations:

- Center piles presented a stiffer behavior than rest of the group. Results match Vesic (1969) observations in the center of a group.
- Corner piles plunged first for a 2D spacing. Edge piles plunged first for a 4D spacing.
- Confinement from surrounding piles affects the response as a function of spacing.

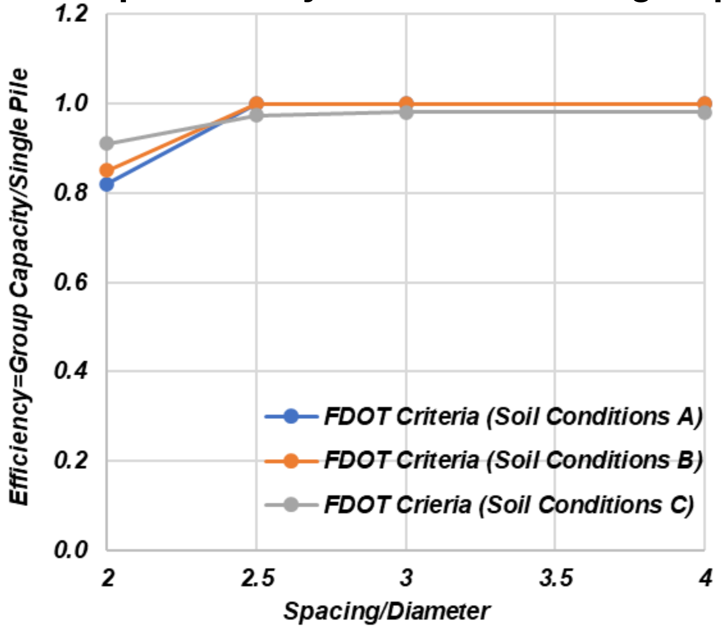
Relative shear stresses



Observations:

- The depth of influence at 2D is larger due to overlapping of stress bulbs.
- Side shear of the sand was mobilized at 2D.
- Computed displacements largely affected by strength of limestone.

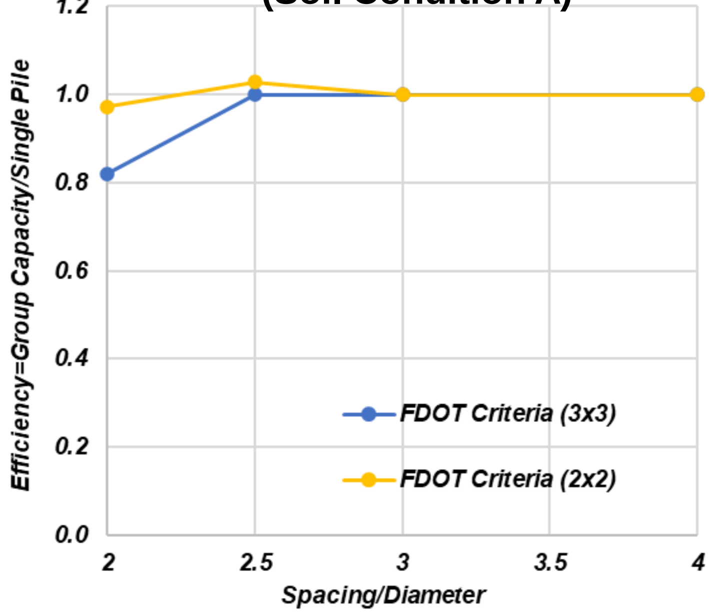
Group efficiency variation for 3x3 groups



Observations:

- Capacity was defined based on FDOT performance criteria (i.e., deformation equal to the elastic compression plus 0.15 inches plus 1/120 of the pile diameter).
- Negligible group effects for $S \geq 2.5D$ for all soil conditions.
- As the stiffness ratio increased, the group efficiency decreased.
- Efficiency decreases up to approximately 80% for the lower stiffness ratios when the spacing is $2D$.

Group efficiency variation for 2x2 and 3x3 groups (Soil Condition A)



Observations:

- Efficiency presented for soil condition A for both 2x2 and 3x3 groups.
- Similar to the 3x3 case, no spacing effects for $S \geq 2.5D$.
- Efficiency increased for the 2x2 group compared to a 3x3, indicating more disturbance when more piles are installed in the group.

Task 4: Correlations and Recommendations

<u>Task 4</u>: Develop empirical correlations (formula or charts). Develop charts showing potential reduction factor of pile load-capacity as a function of S/D vs. design unit skin friction to rock strength ratio for various rock strengths. This is in light of the results from Tasks 2 and 3.

Other correlations will be investigated in terms of relative density, bearing capacity of the underlying rock, elastic moduli ratio (i.e., E_{top}/E_{bottom}), geometric and material characteristics of ACP, construction sequence during installation, configuration of the pile group, installation effects including penetration rate and injection pressure of concrete, and presence of pile cap.

Anticipated FEM analysis matrix

Soil profile	Pile diam. 24", qu = 250 psi				Pile diam. 24", qu = 750 psi				Pile diam. 36", qu = 250 psi				Pile diam. 36", qu = 750 psi			
	Spa. (d/D)	Spa. (d/D)	Spa. (d/D)	Spa. (d/D)	Spa. (d/D)	Spa. (d/D)	Spa. (d/D)	Spa. (d/D)	Spa. (d/D)	Spa. (d/D)	Spa. (d/D)	Spa. (d/D)	Spa. (d/D)	Spa. (d/D)	Spa. (d/D)	Spa. (d/D)
S	4			2									4			2
LS	4			2									4			2
S/LS/S/LS	4	3	2.5	2	4	3	2.5	2	4	3	2.5	2	4	3	2.5	2
S/LS	4	3	2.5	2	4	3	2.5	2	4	3	2.5	2	4	3	2.5	2

Abbreviations: "S" = soil "LS"= Limestone "qu"= unconf. compression "Spa"= spacing. Est. total cases: 40

Deliverable 4: Report summarizing correlations and recommendations <u>09/2024</u>

SUMMARY OF TASK/DELIVERABLE SCHEDULE

TASK AND ASSOCIATED DELIVERABLE	DATE
Kickoff teleconference	01/2023
Deliverable 1: A technical report presenting the results of the technical background on the effect of spacing on capacity of auger cast piles.	02/2023
Deliverable 2a: Report on details of the laboratory testing program: pile installation, (ii) soil and rock properties for physical model tests, (iii) measurements of gator rock strength, and (iv) detail plan on load transfer along pile length during physical model tests and on the comparison of group effects with single pile and control cases.	07/2023
Deliverable 2b: A technical report summarizing the results of the laboratory small-scale physical model tests.	12/2023
Deliverable 3: A technical report summarizing the results of the finite element numerical models and parametric studies of the variables involved in the problem. The results from laboratory tests will be used to validate the numerical modeling results.	05/2024
Deliverable 4: A technical report summarizing the proposed correlations and recommendations regarding the effect of spacing on the capacity of auger cast piles.	09/2024
Deliverable 5a Draft final report.	11/2024
Deliverable 5b: Closeout teleconference meeting and PowerPoint presentation	12/2024
Deliverable 6: Final report	12/2024

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