GRIP Meeting 2024
Project BED26 TWO 977-04:
Effect of Spacing on Axial Resistance of Auger Cast Pile Foundations

Start Date: Jan. 2023

End Date: Dec. 2024

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PRESENTED BY

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FDOT

PRESENTATION OUTLINE

MENU

- Review of benefits and implementation
- Review of project objectives
- Tasks, deliverables and progress to date
  - Task 1: Technical background
  - Task 2: Physical model testing
  - Task 3: Numerical modeling
  - Task 4: Correlations and recommendations
- Summary of tasks/deliverables: schedule and progress

REVIEW OF PROJECT BENEFITS AND IMPLEMENTATION

QUALITATIVE

- Better estimation of the effect of spacing and load-deformation behaviors in ACP.
- Understanding the geotechnical mechanisms involved in the performance of ACP which can improve design practices in the State.
- Analysis of the influence of proximity of pile foundations on overall superstructure performance.

QUANTITATIVE

- Quantification of the effects of the foundation layout and rock strength on the axial resistance of ACPs.
- Site-specific analyses and calibration of bearing capacities using advanced rock models for Florida limestone to study the failure mechanisms and influence of pile spacing ratio, relative stiffness factor, and rock strength parameters on foundation deformation characteristics.

IMPLEMENTATION

- Development of reduction factors for applicable cases. Reduction factors could be implemented in Structures Design Guidelines.
- If the effort indicates the use of 2.5D 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.

MAIN OBJECTIVE

Evaluate effect of spacing on load-settlement behavior of ACP through small-scale physical model testing and finite element analysis, and develop reduction factors for applicable cases.

SPECIFIC OBJECTIVES

- Provide guidance on effect of spacing of ACP on load-deformation response.
- Quantify the effect of overlapping stress bulbs among foundation elements.
- Investigate the effect of soil layering on load-settlement behavior of ACP.
- Investigate the effect of rock strength and design unit skin friction.
- Investigate effect of pile diameter on computed load deformation response.
- Develop demand/capacity ratio of unit skin friction vs. rock strength as a function of the proposed reduction factors.
- Investigate relationships among geotechnical variables that influence the effect of spacing on the capacity of ACP.
- Develop correlations or charts.

TECHNICAL BACKGROUND

Deliverable 1: Report on technical background 02/2023 (Delivered)

Non-displacement pile spacing specified by design codes and FDOT guidelines

- FDOT developmental specifications:
  - Dev346ACP (Structural Portland Cement Grout)
  - Dev455ACP (requirements for materials, installation and load testing of ACP)
- FDOT soils and foundations handbook:
  - 3D and 2.5D spacing for drilled shafts in sand and rock socketed for 1.0 efficiency
  - Side shear resistance (f_{su}) drilled shafts socketed in Florida Limestone (McVay's method)
- AASHTO, FHWA, major DOT, Guidelines Building codes and standards:
  - Drilled shafts group reduction factors at different spacings, configurations and cap contact.

Case histories on laboratory based physical model tests

- 32 ACP and case histories on drilled shafts with instrumentation, loading system and installation.

Case histories on numerical modeling of drilled piles

- 17 cases describing modeling stages, constitutive models and soil-pile interface elements used.

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

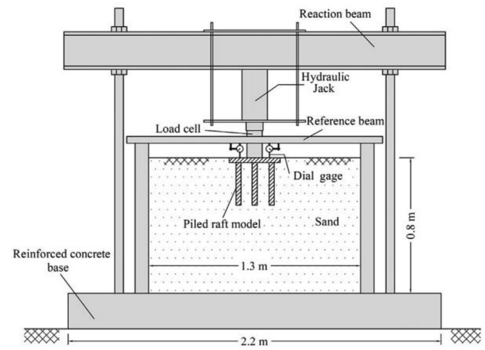
- WSDOT = 3.0D — AS 2159-2009 = 2.5D (side)
- WisDOT = 3.0D — AS 2159-2009 = 2.0D (end)
- ASCE(1997) = 2.5D — JTG 3363-2019 = 2.5D
- IBC = 3.0D — JTG 3363-2019 = 2.0D (end)

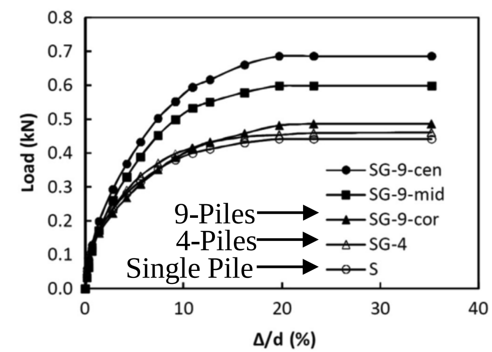
Database of Testing Programs

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

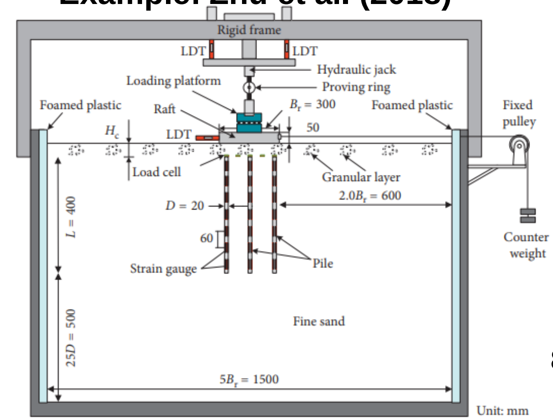
ACP: Auger Cast Piles, SDP: Screw displacement piles, UR = Under-Reamed
DP: Displacement pile, CHD: Continuous Helical Displacement, WIP: Wished-In-Place- Jeffrey et al. (2016)
Pre-installation: "Positioning of the pile before the soil sample is fully prepared,
it is used to simulate the installation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

Example: Sharafkhah and Shooshpasha (2018)



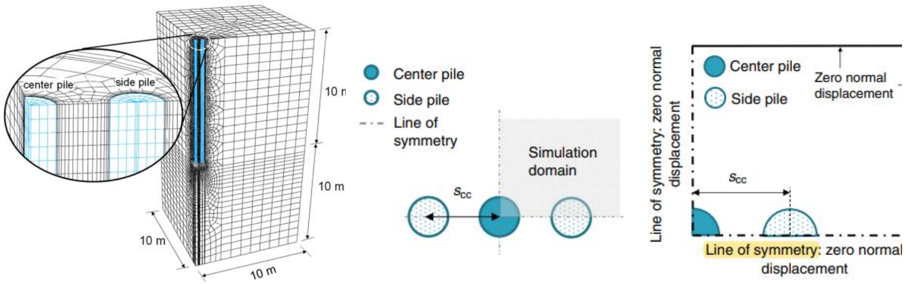


Example: Zhu et al. (2018)



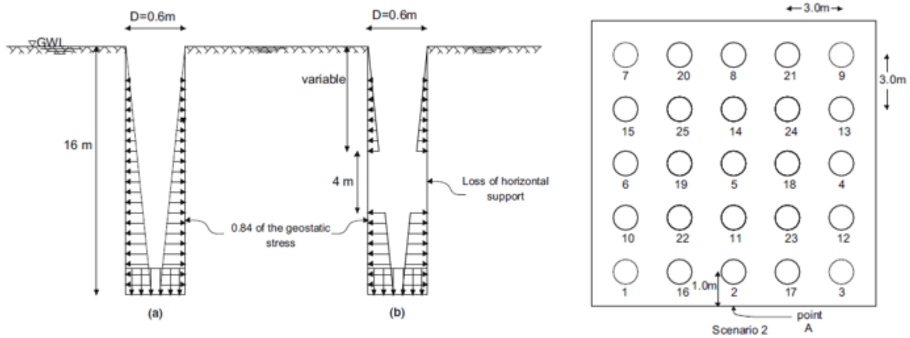
Axial capacity of pile groups Han et al. (2019):

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



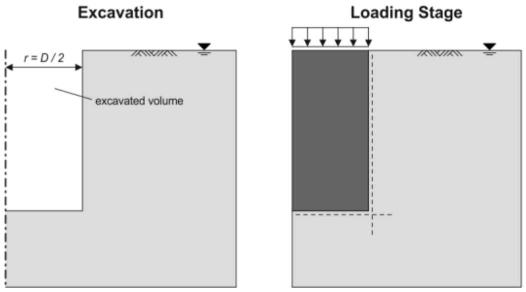
Simulation of Unfavorable CFA Pile Drilling Conditions. Arab et al. (2020):

- 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.



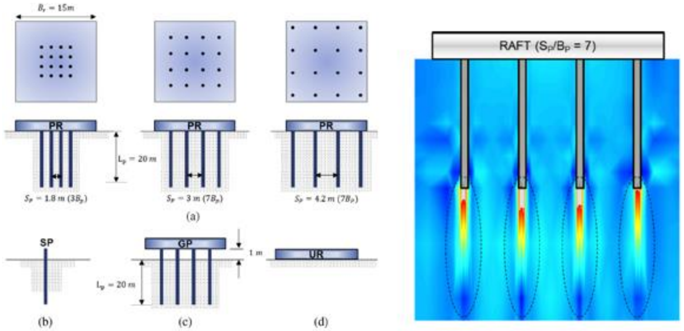
Numerical simulation of cast-in-place piles, Schmudderich et al. (2020):

- 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).



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.



PHYSICAL MODEL TESTING

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

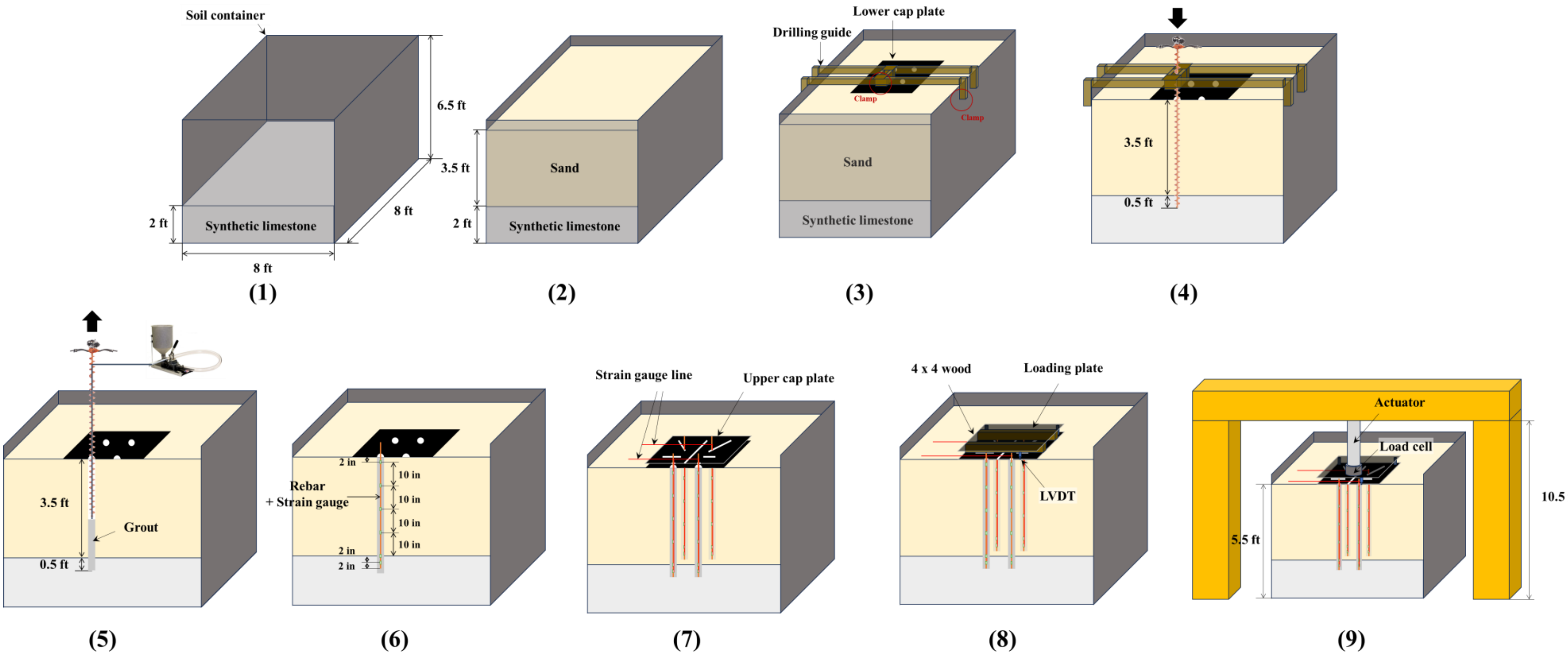
Deliverable 2b: Report with results of lab testing program 12/2023 (Delivered)

EXPERIMENTAL PROGRAM

- **Pile configuration:** Single, 2 x 2, 3 x 3.
- **Ground condition**
  - Sand: 50% and 75% of relative density (D_r).
  - Limestone: Synthetic limestone (SL) created using cement, crushed limestone, and water.
- **Pile spacing for group piles:** 2, 2.5, 3, 4D (D = diameter of ACP).
- **Main experimental condition:** T1 – T9 (50% of D_r + SL)
  - T10 – T15 conditions subject to change based on main experiment results.

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

EXPERIMENTAL PROCEDURE



1) Placement of a 2 ft-high SL layer inside the soil container.

2) Deposition of a 3.5 ft-high sand layer on top of the SL layer.

3) Installation of the lower cap plate on the soil surface, followed by setting up the drilling guide.

4) Drilling operation using the auger and motor.

5) Extraction of the auger while applying enough grouting pressure with pump.

6) Insertion of the instrumented rebar into the grout.

7) Installation of the upper cap plate and setup of the strain gauge lines.

8) Placement of wood spacers and LVDT on the cap plate, followed by the connection of the loading plate.

9) Installation of the reaction frame to be used for the servo-hydraulic system to apply load on pile or group of piles.

Prepare synthetic limestone → Deposit sand → Install ACP → Install instruments → Perform test

- Design of SL to have similar properties to typical Florida limestone
  - Target compressive strength = 500 psi ± 300 psi
  - Target unit weight = 120 pcf

- Effect of cement, crushed limestone, and water ratio on compressive strength of SL

$$ratio\ 1 = \frac{W_c}{W_a} \quad \text{and} \quad ratio\ 2 = \frac{W_w}{W_c + W_a}$$

Where, W_c, W_a, W_w are the weight of cement, aggregate, and water, respectively.

	Ratio 1	Ratio 2	W_a (lb)	W_c (lb)	W_w (lb)	q_u (psi)
Batch 1	0.10	0.20	18.19	1.83	4.01	319.2
Batch 2	**0.10**	**0.15**	**19.93**	**1.98**	**3.28**	**498.0**
Batch 3	0.15	0.15	19.16	2.87	3.31	1070.0

- Quantities of each component for physical model test

Volume of SL (V) = 5 yd^3 = 135 ft^3

Target unit weight (γ_t) = 120 pcf

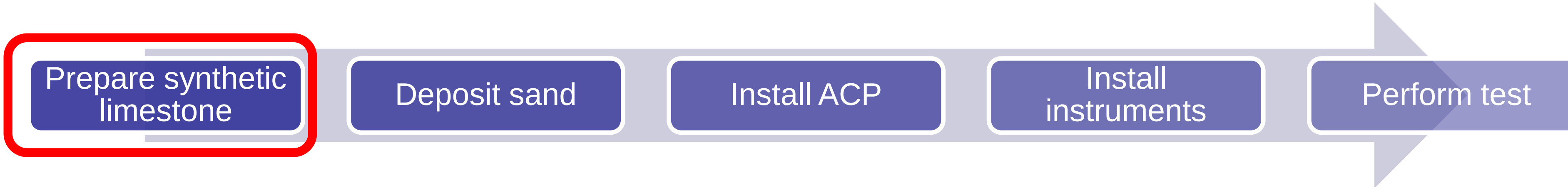
Total weight of SL (W_t) = $V \times \gamma_t$ = 16200 lb

→ Calculate the weight of each component using ratio 1 of 0.1 and ratio 2 of 0.15.

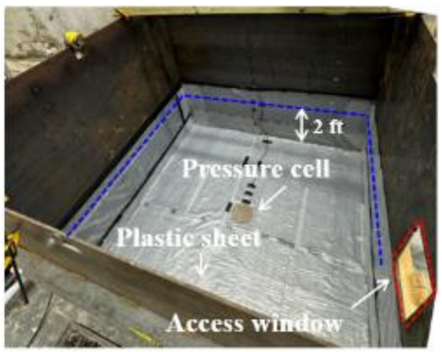
W_a= 14457.45 lb

W_c= 1408.70 lb

W_w= 2241.24 lb



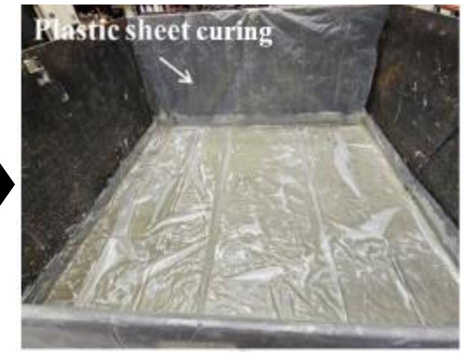
- Installation of the SL layer in the physical model testing facility



Installation of plastic sheet and earth pressure cell

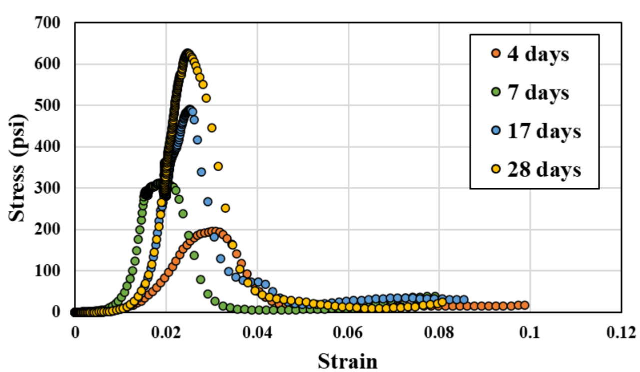
SL placement through access window

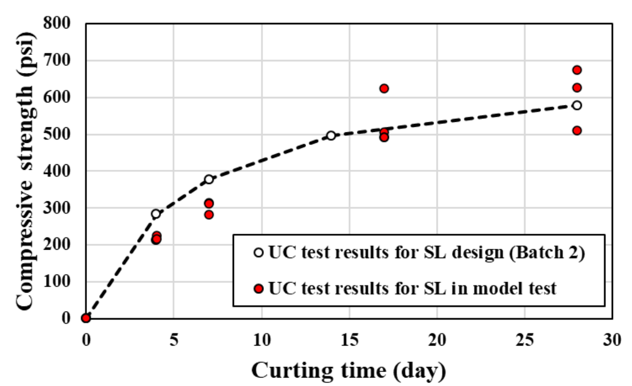
Process of leveling and vibrating to remove air bubbles



Surface cover to maintain moisture during the hydration

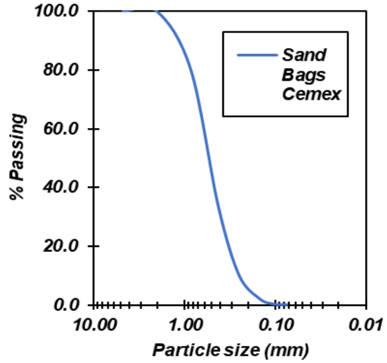
- Material properties of SL layer used for physical model test
  - Average unit weight after 28 days curing = 117 pcf (close to target unit weight)
  - Compressive strength after 14 days = 490 – 674 psi (within the range of target strength)





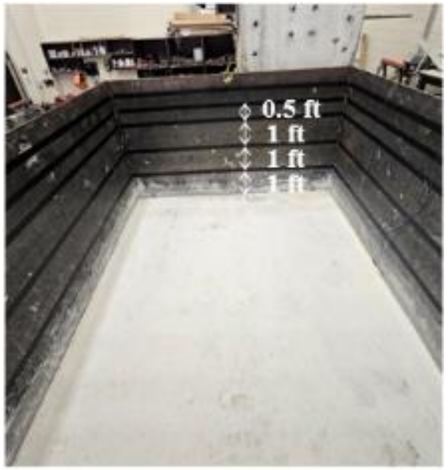
Prepare synthetic limestone → **Deposit sand** → Install ACP → Install instruments → Perform test

- Material properties of sand



Material properties	Value
Uniformity coefficient (C_u)	2.86
Coefficient of curvature (C_c)	0.97
USCS	SP
Specific gravity (G_s)	2.64
e_{max} ($\gamma_{d,\min}$)	0.78 (1.48 g/cm^3)
e_{min} ($\gamma_{d,max}$)	0.47 (1.79 g/cm^3)

- Sand layer installation method: moist compaction method considering volume and unit weight of sand layer



Four layers of sand with total height of 3.5 ft

Placement of the sand using sandbags and crane scale

Compacting the sand up to the target level

Completion of sand compaction process

EXPERIMENTAL METHOD

Prepare synthetic limestone → Deposit sand → **Install ACP** → Install instruments → Perform test

- Drilling equipment auger cast piles

Auger Powerhead Earthquake^{TM} :

-Engine 43cc

-Max rpm = 250

-T(ft-lb) = 1.6

Motor-auger Coupler

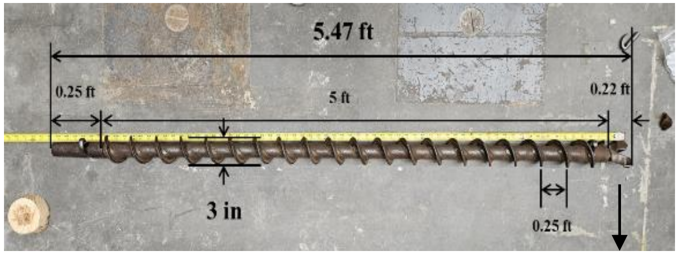
Quick hardening epoxy steel stik:

-Strength 4000 psi

-Set time 5 min

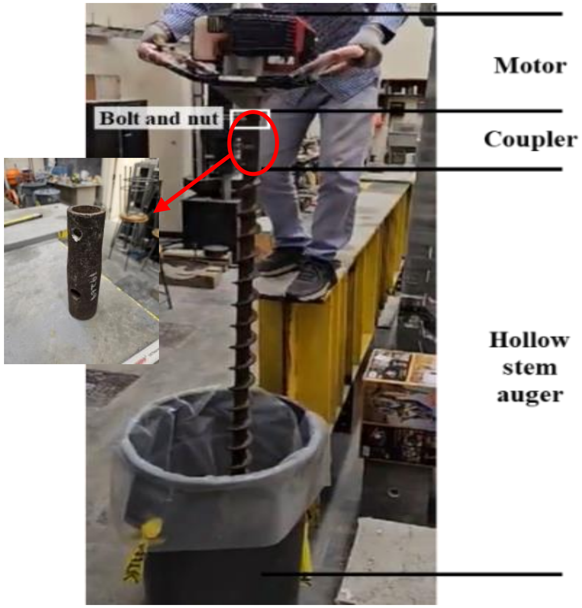
-Cure time 1 hour

Continuous hollow-stem auger -Central Mine Equipment-



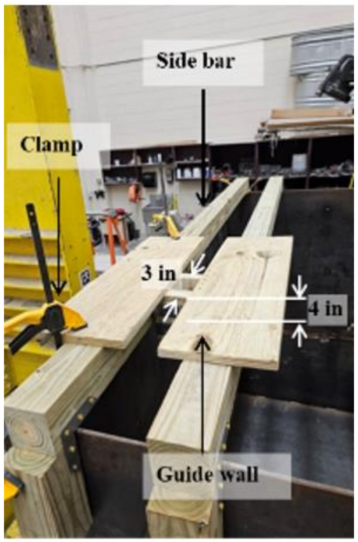
Drill bit

- Preliminary tests for drilling method

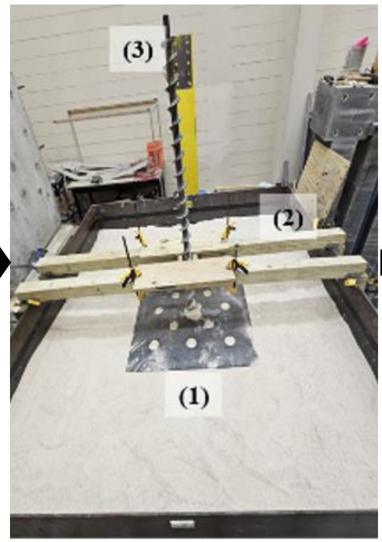


Prepare synthetic limestone → Deposit sand → **Install ACP** → Install instruments → Perform test

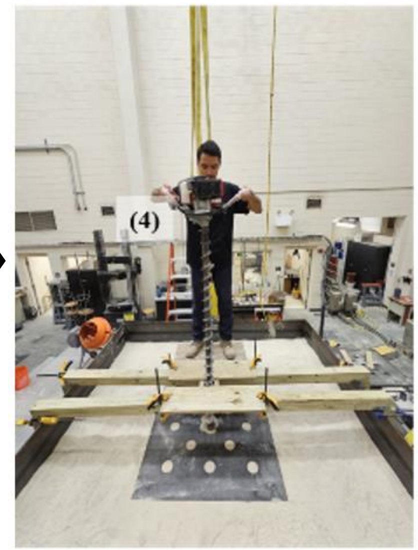
- Drilling procedure of auger cast piles



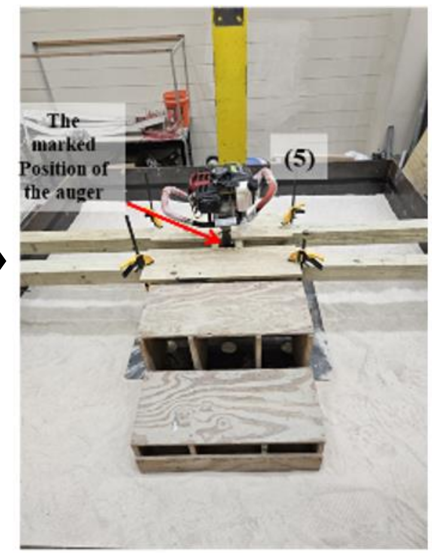
Drilling guide for vertical installation



Installation of cap plate and auger



Installation of the motor head

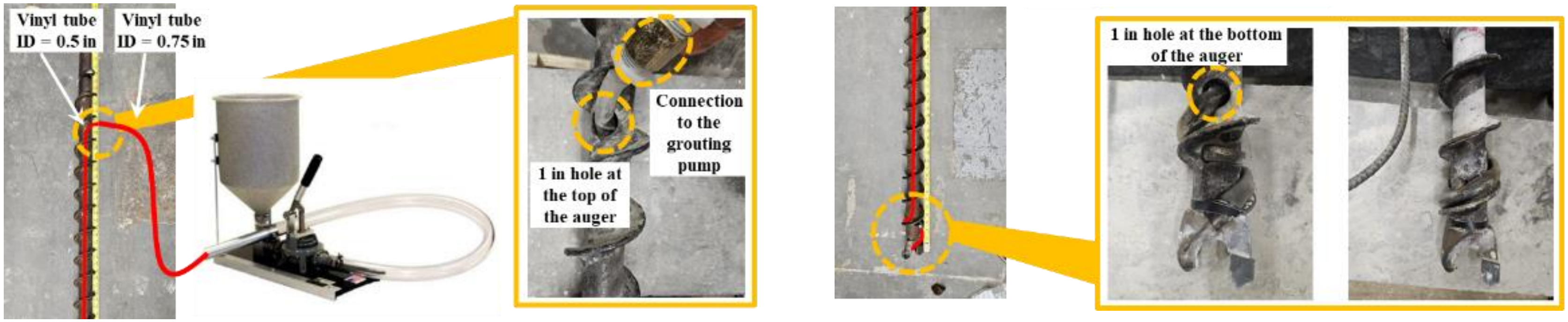


Drilling to design ACP depth

EXPERIMENTAL METHOD

Prepare synthetic limestone → Deposit sand → **Install ACP** → Install instruments → Perform test

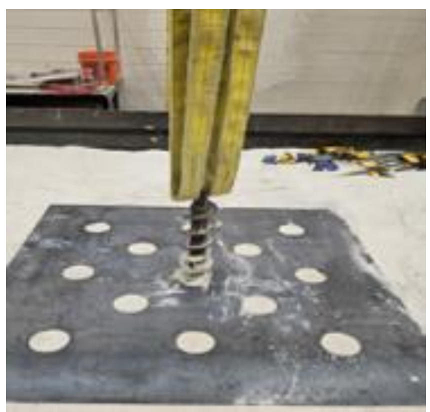
- Grout injection equipment



Top Hollow Auger | Grout Pump | Auger Head | Bottom Hollow Auger | Auger opening for vinyl tube

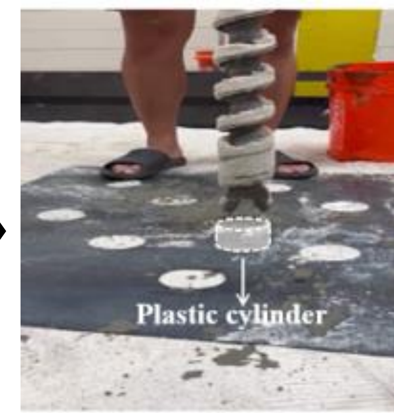
- Grout injection procedure

Removal of motorhead and drilling guide



Connection of crane to the auger

Injection of grout while extracting auger



Insertion of plastic cylinder and injection

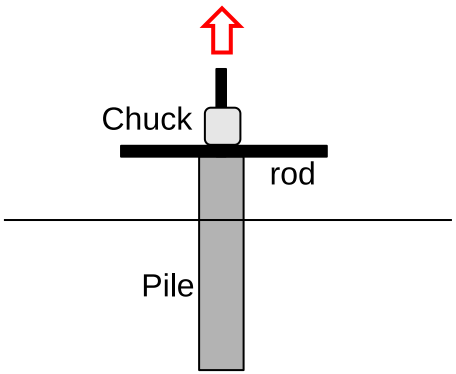
➡ Remove approximately 2 inches of sand below the cap plate after grout curing

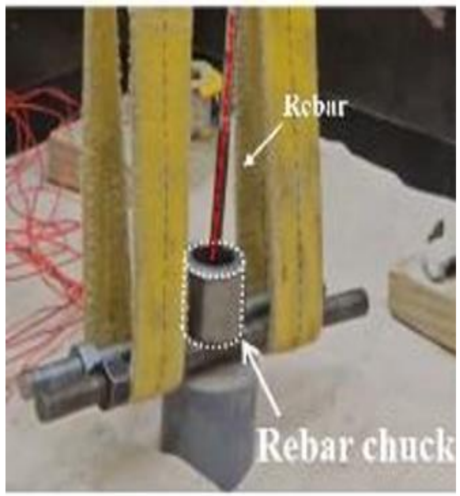
EXPERIMENTAL METHOD

- Prepare synthetic limestone
- Deposit sand
- **Install ACP**
- Install instruments
- Perform test

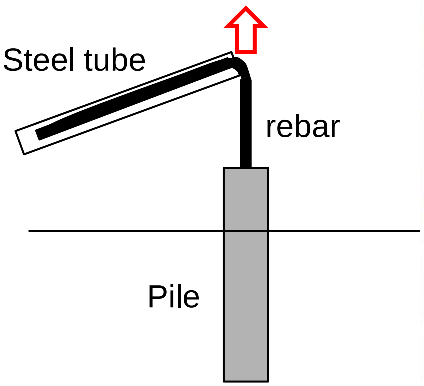
- ACP removal procedure and extracted specimens

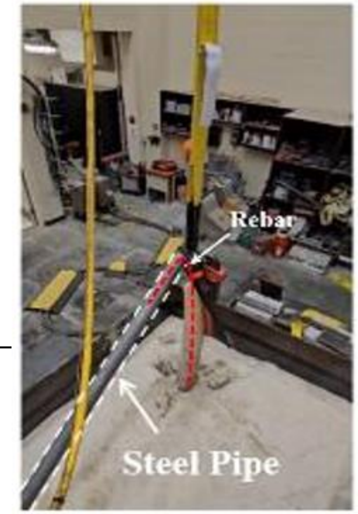
Removal procedure with rebar chuck





Removal procedure with aluminum tube





- Borehole inspection and repair

Borehole Sand Vacuum

Inspection of borehole SL diameter

Synthetic limestone repair

EXPERIMENTAL METHOD

Prepare synthetic limestone → Deposit sand → **Install ACP** → Install instruments → Perform test

- Preliminary tests to verify proposed procedures

Auger Cast Piles:

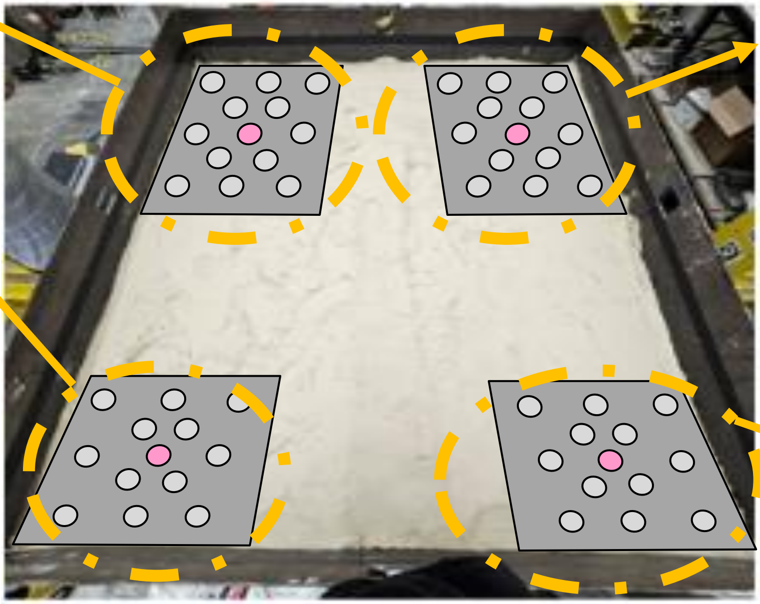
1) Variable grouting rate:
- Diameter increase with depth

2) Controlled grouting rate:
- Uniform diameter through the length

Controlled grouting rate

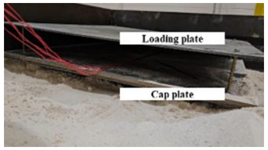
Variable grouting rate

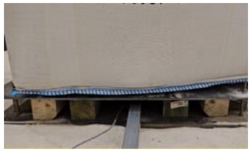
Location of preliminary drilled shafts and Auger Cast Piles

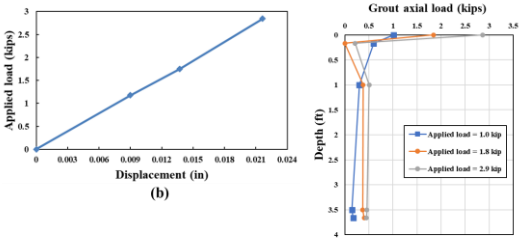


The drilling procedure was performed with the previously described vertical guides, cap plate and drilling platform.

Verification of LVDT & strain gauge

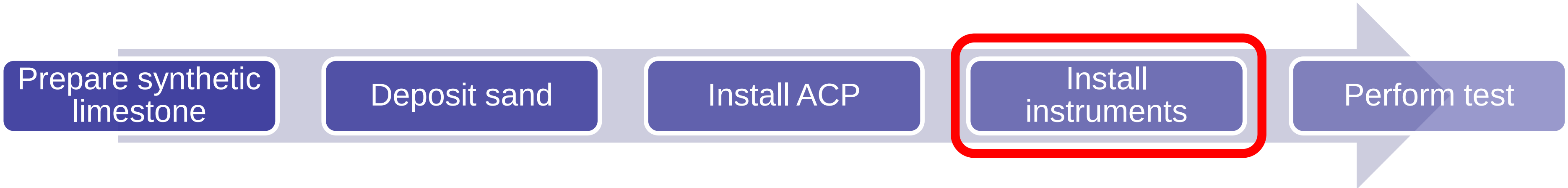




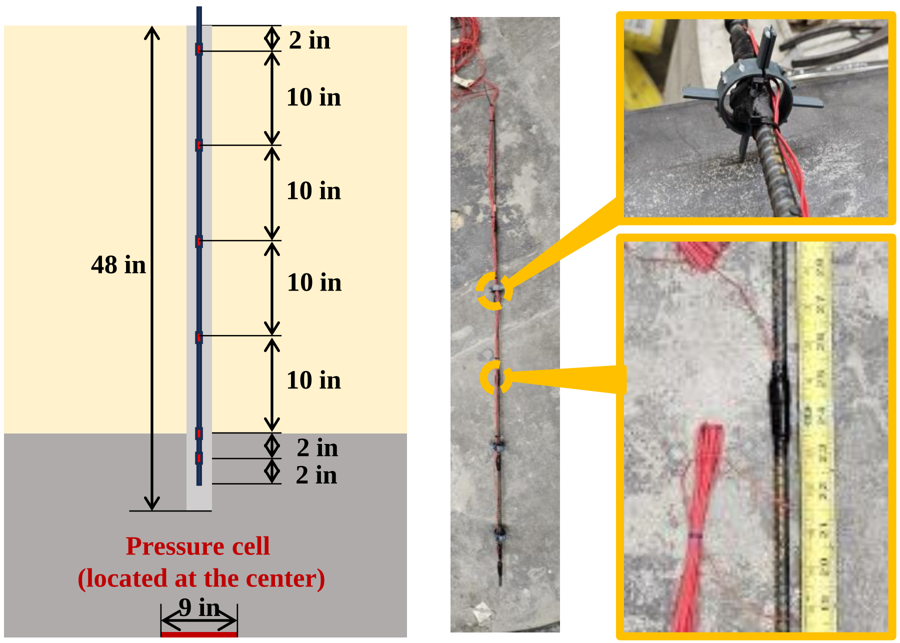


Drilled Shafts:

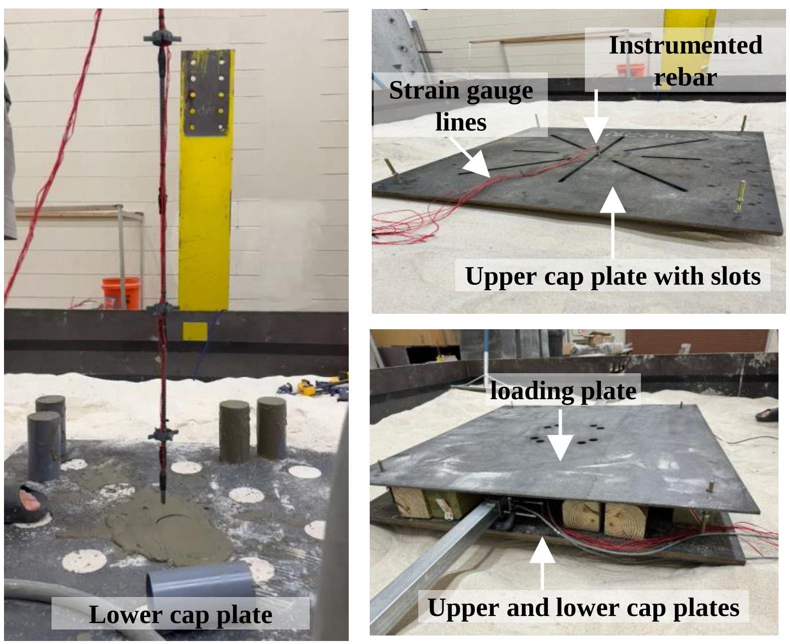
Gravity grouting



- Strain gauge installation
  - Strain gauges manufactured by Kyowa Americas Inc (120 ohms).
  - 6 gauges per ACP, spaced at designed intervals.
  - Installed at ACP center using #3 rebar and spacers.
  - Slots in upper cap plate for strain gauge line extension from ACP head.



Schematic diagram and photographical record of the strain gauge attached to the rebar



Installation of the strain gauges, cap and loading plates

EXPERIMENTAL METHOD

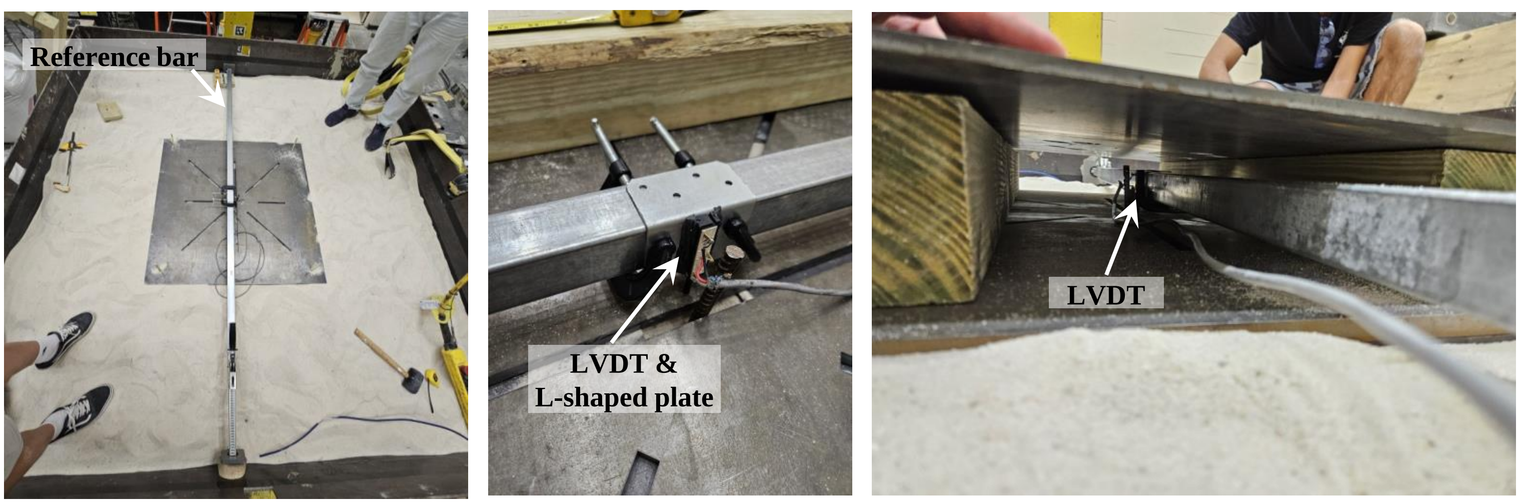
Prepare synthetic limestone → Deposit sand → Install ACP → **Install instruments** → Perform test

- Linear Variable Differential Transformers (LVDTs)
  - LVDTs manufactured by Sensata-BEI Sensors (Max displacement: 1.5 in)
  - Installed at ACP head for accurate load-displacement evaluation
  - Installation method of LVDT:

    1) An adjustable-length bar was fixed to the soil container to serve as fixed reference bar.

    2) The LVDTs were fixed to an L-shaped steel plate clamped to the reference bar.

    → Allows easy position adjustment regardless of ACP location.



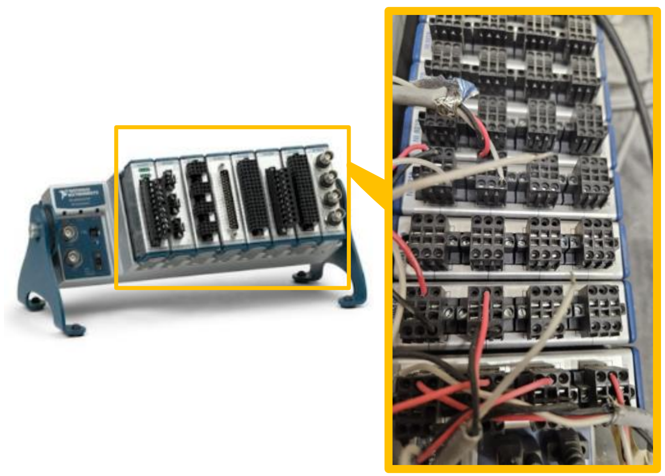
Installation method of the LVDTs with adjustable length bar

EXPERIMENTAL METHOD

Prepare synthetic limestone → Deposit sand → Install ACP → **Install instruments** → Perform test

- Load cell
  - Load cell manufactured by MTS (Max capacity: 110 kips).
  - Installed between the actuator and the loading plate to measure total applied load.
  - Connected to National Instruments data logger along with LVDT and strain gauges (0.1 second measurement intervals)

Load cell installed between the actuator and the loading plate



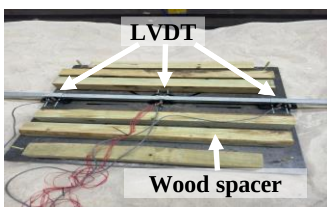
National instruments data logger (DAQ modules and chassis)

- Pressure cell
  - Pressure cell manufactured by Geokon.
  - Installed at bottom of soil container to investigate mostly boundary effects.

Prepare synthetic limestone → Deposit sand → Install ACP → Install instruments → **Perform test**

- Loading procedure for single ACP test (FDOT, 2021)
  - Maximum test load = 10 kips
  - Load increment at 0.5 kips or displacement-controlled tests
  - Maintaining each load increment for 5 min or a constant rate of displacement
- Summary of experimental setup for physical model test

Space between the cap plate and the soil surface



Placement of wood spacers and LVDT

Installation of loading plate

Installation of cap plate

Drilling

Grouting

T1 (Single ACP)

- **Load-displacement relationship**
  - The stiffness of pile was obtained using initial 5 points of load-displacement curves.
  - Considering the scale of the physical model test, it was necessary to modify performance-based failure criteria (Soils and Foundations manual)
  - Interpreted failure load by modified criteria = 4.8 kips

Failure load criteria (FDOT, 2021)

The load that cause a displacement

$$= \text{Elastic compression} + 0.15 + \frac{1}{120}D \quad \text{(inches)}$$

Displacement to mobilize the skin friction (0.15)

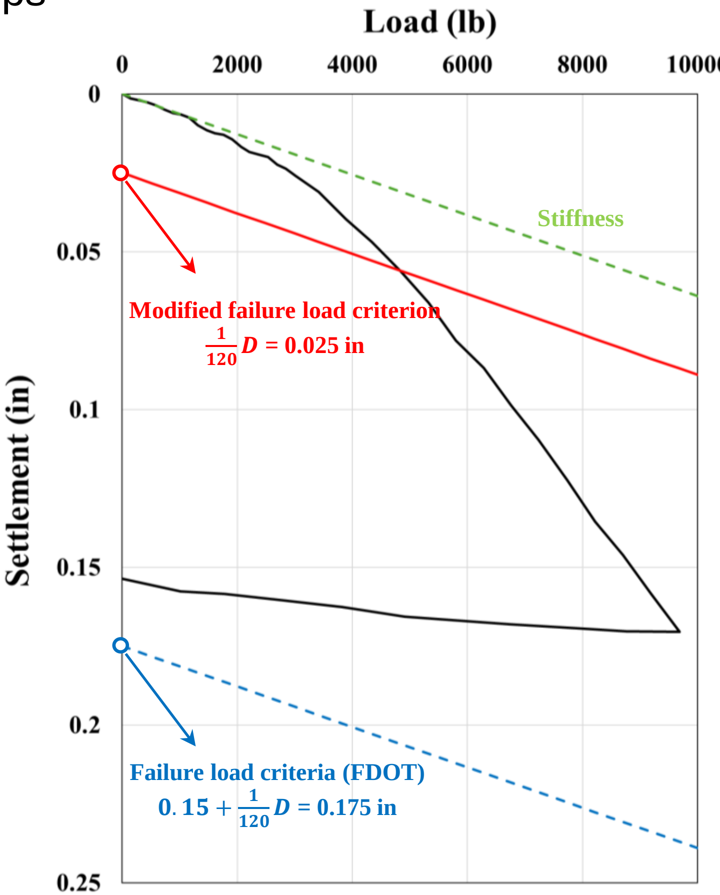
Displacement to mobilize the end bearing ($\frac{1}{120}D$)

Modified failure load criteria

The load that cause a displacement

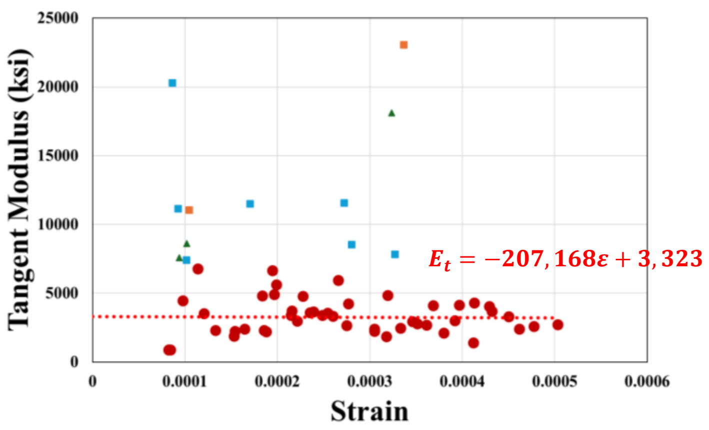
$$= \text{Elastic compression} + \cancel{0.15} + \frac{1}{120}D \quad \text{(inches)}$$

Remove this value due to shallow depth of sand layer compared to the field condition



T1 (Single ACP)

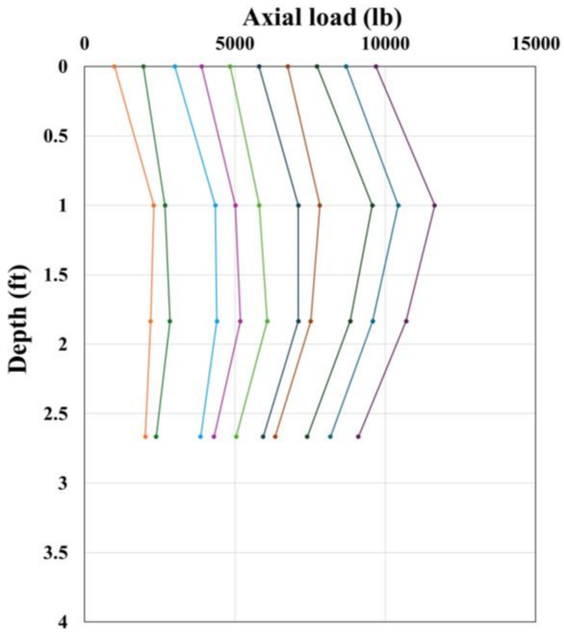
- **Load transfer curve**
  - Two strain gauges installed at the bottom of the ACP failed.
    - The line was installed too tightly, causing damage during the insertion of the strain gauges.
    - In T2, it was possible to measure strains at all depths by adding extra length to the strain gauge.
  - The load transfer curve was evaluated using the tangent stiffness method (Fellenius, 2023).
    - When the shaft resistance above a gauge location is mobilized, the incremental load at the gauge location is the same as the increment of applied load.
    - The tangent modulus at the gauge location can be calculated by $\Delta\sigma_{apply}/\Delta\varepsilon$.



$$E_t = \frac{d\sigma}{d\varepsilon} = -207{,}168\varepsilon + 3{,}323$$

$$\sigma = -103{,}584\varepsilon^2 + 3{,}323\varepsilon$$

$$Axial\ load\ (P) = \sigma A = (-103{,}584\varepsilon^2 + 3{,}323\varepsilon)A$$



T2 (2 x 2 group piles with 4D spacing)

Test #	Loading method	Loading rate	PID gains	Note	Results
1st	Ramp / Load control Dwell / Displacement control	1000 lb/min	1,000 / 500,000	Same with T1	- Load: Oscillation at 4 kips - Displacement: decrease - increase
2nd	Ramp / Load control Dwell / Displacement control	1000 lb/min	1,000 / 500,000	Same with T1	- Load: Oscillation at 4 kips - Displacement: increase
3rd	Ramp / Load control	500 lb/min	1,000 / 500,000	Load control Small loading rate	- Load: No oscillation upto maximum load (4 kips) - Displacement: increase
4th	Ramp / Load control	1000 lb/min	1,000 / 500,000	Load control with large loading rate	- Load: Oscillation after pausing the test (4 kips) - Displacement: increase
5th	Ramp / Load control Dwell / Displacement control	300 lb/min	1,000 / 500,000	Same with T1 Small loading rate	- Load: Oscillation at 4 kips - Displacement: increase
Tuning tests (15 sets)	Ramp and sinewave	-	Various P		
6th	Ramp / Load control Dwell / Displacement control	1000 lb/min	500 / 250,000	Same with T1 Small P gain	- Load: No oscillation / large overshooting - Displacement: increase but slope was small at initial loading step
7th	Ramp / Displacement control	0.03 in/min	500,000	Displacement control small loading rate	N/A
8th	Ramp / Displacement control	0.05 in/min (0.002 in/min for pile)	500,000	Displacement control medium loading rate	- Load: No oscillation / No overshooting - Displacement: decrease - increase
9th	Ramp / Displacement control	0.15 in/min (0.013 in/min for pile)	500,000	Displacement control large loading rate	- Load: No oscillation / No overshooting - Displacement: decrease - increase
10th	Ramp / Load control Dwell / Displacement control	1,000 lb/min	10,000 / 500,000	Same with T1 Large P gain	- Load: Oscillation at 7 kips - Displacement: decrease - increase
11th	Ramp / Load control Dwell / Load control	1,000 lb/min	1,000	Ramp-dwell load control original P gain	- Load: No oscillation / large overshooting - Displacement: decrease - increase
12th	Ramp / Load control Dwell / Load control	1,000 lb/min	10,000	Ramp-dwell load control large P gain	- Load: Oscillation at 7 kips - Displacement: decrease - increase
13th	Ramp / Displacement control	0.15 in/min (0.013 in/min for pile)	500,000	Displacement control large loading rate Increase the thickness of plate	
14th	Ramp / Displacement control	0.15 in/min (0.013 in/min for pile)	500,000	Displacement control large loading rate Increased thickness + Aluminium pipe	

* During pile loading test, actuator vibrations occurred, so multiple experiments were conducted with various loading methods.

NUMERICAL MODELING

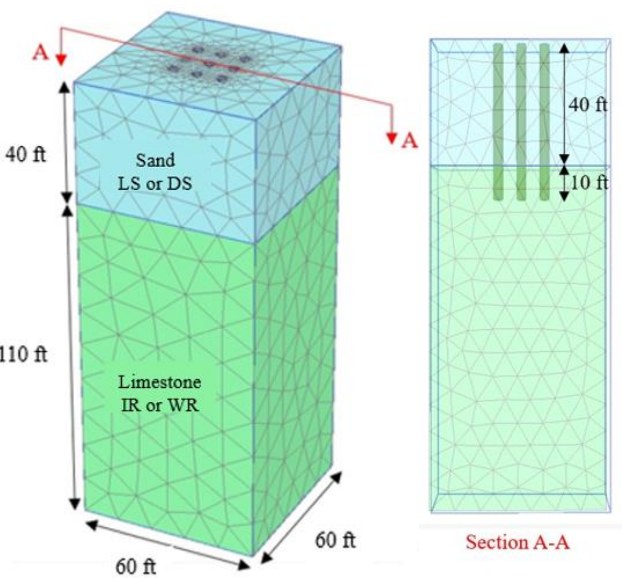
Deliverable 3: Report summarizing numerical modeling results 05/2024 (Delivered)

GENERAL DESCRIPTION OF FE MODEL

Proposed FE 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

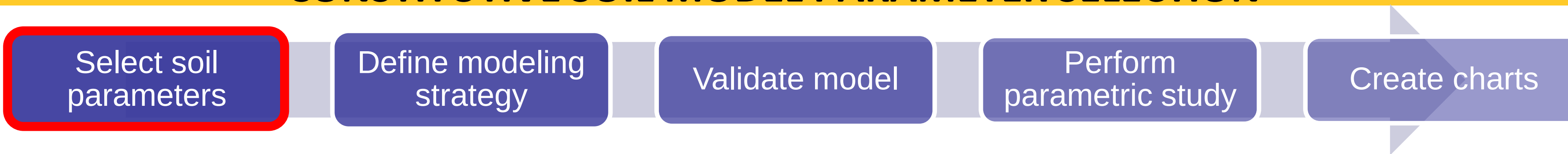
Abbreviations: "S" = soil "LS"= Limestone "qu"= unconf. compression "Spa"= spacing. Est. total cases: 40



Geometry of the 3D FE model

FEM general description

- Geometry: Selected based on records from Bridge No. 101 on SR 836 in Miami, Florida.
- Tested cases: 2x2, 3x3, and 4x4 (additional) pile groups.
- Pile diameter: 2 ft and 3ft.
- Distance to edge: >12D.
- Loading: Prescribed displacement of 5" on top of each pile.
- No cap considered.
- Two sand densities considered of 30% and 75%.
- Two limestone cases considered: intact and weathered cases with GSI of 100 and 50.
- Selected limestone q_u of 500 psi as an average of proposed testing matrix.



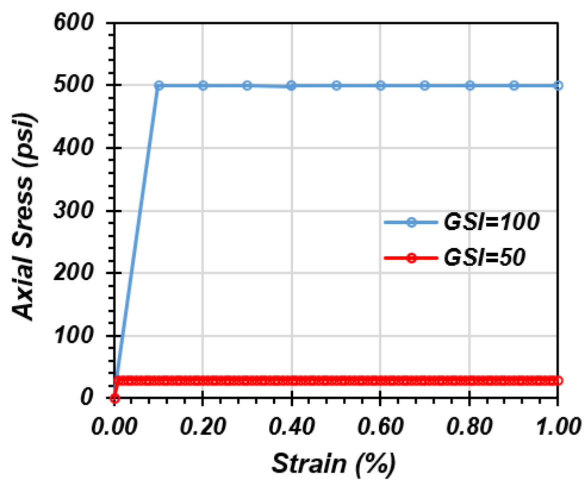
Parameter	Units	Loose Sand	Dense Sand
D_r	(%)	30	75
γ_{sat}	pcf	125	130
ϕ'	°	31.8	37.4
ψ	°	1.8	7.4
E_{50}^{ref}	ksi	2.61	6.53
E_{oed}^{ref}	ksi	2.61	6.53
E_{ur}^{ref}	ksi	7.83	19.58
G_0^{ref}	ksi	11.67	16.11
m	-	0.61	0.47
ν'_{ur}	-	0.2	0.2
$\gamma_{0.7}$	$x10^{-4}$	1.7	1.3
R_f	-	0.96	0.91
R_{inter}	-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

Sandy soil parameters

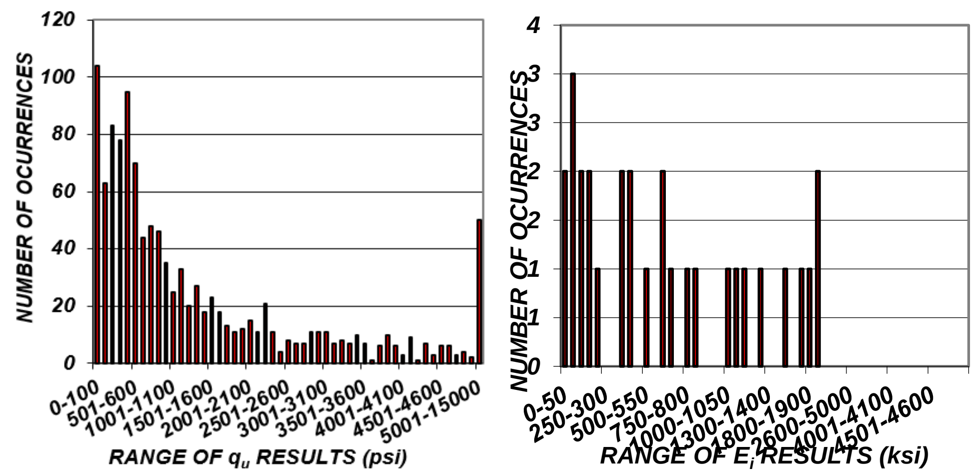
- HS Small model used to simulate the sand.
- Target relative densities of 30% and 75%.
- Parameters selected based on correlations with D_r by Brinkgreve et al. (2010) for sandy soils.

Limestone parameters

- Hoek and Brown model was considered.
- Both q_u and E_i 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.

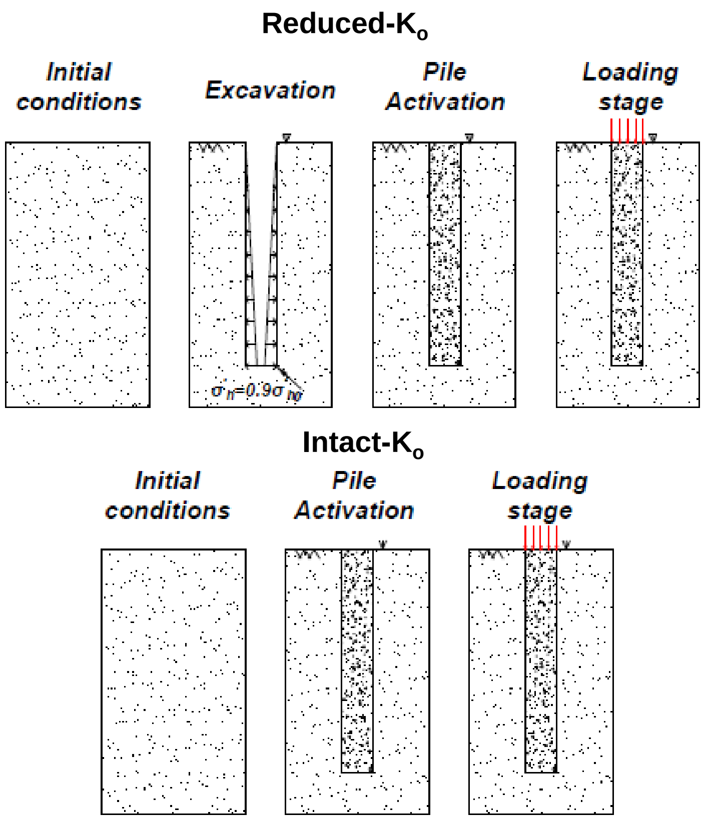


Unconfined compression strength of intact and weathered limestones (IR and WR, respectively)



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

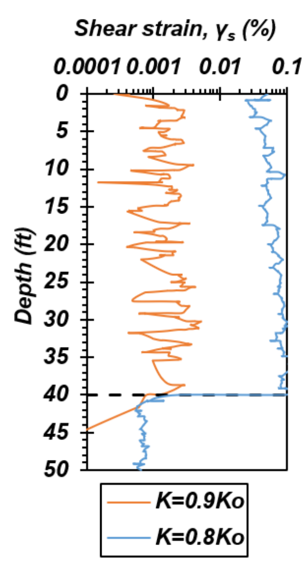
Select soil parameters → **Define modeling strategy** → Validate model → Perform parametric study → Create charts



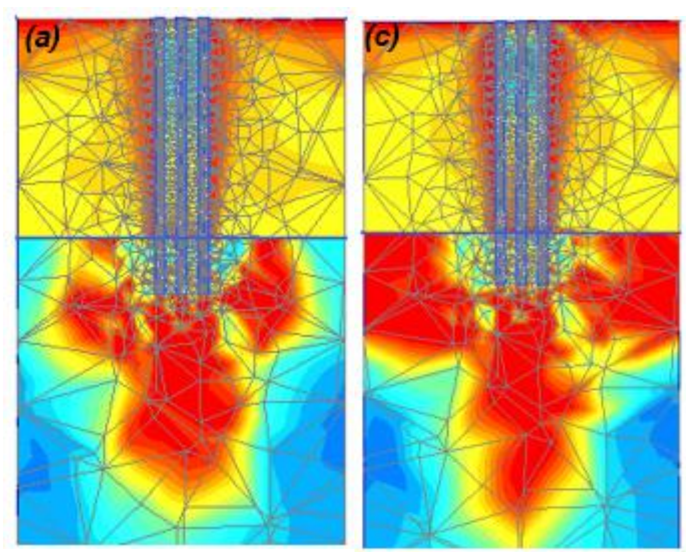
Modeling strategy

- Drilling disturbs the soil in the field, reducing confinement.
- Two strategies: Intact and reduced-K_o conditions.
- Boundary pressures applied at excavation stage.
- Degree of K_o reduction of 10% selected based on expected shear strains of 0.001%.
- Relative shear strain contours showed considerable disturbance vs intact conditions

Two proposed modeling strategies



Shear strain levels close to ACP excavation



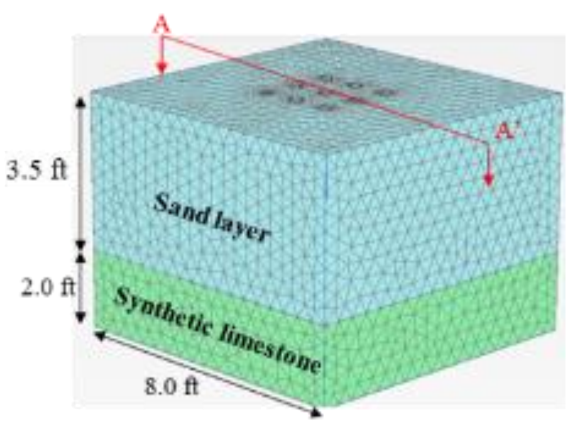
Relative shear stress contours for intact and reduced-K_o, respectively

Select soil parameters → Define modeling strategy → **Validate model** → Perform parametric study → Create charts

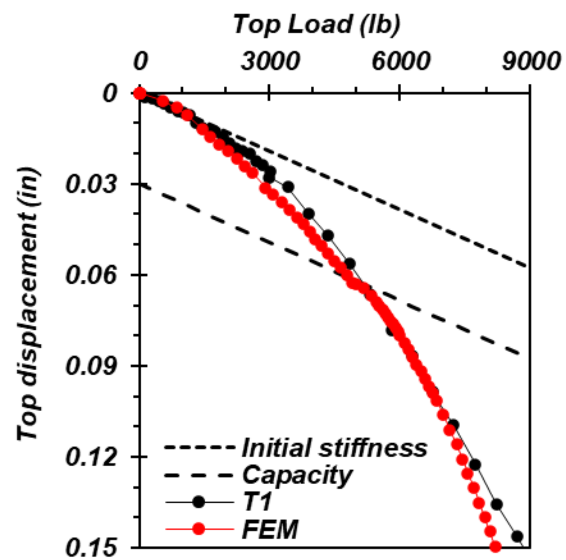
1st Numerical model validation (Laboratory test on T1)

- Laboratory measurements: Validate the FEM with the results from T1.
- Soil profile: Defined based on experimental conditions. E_i defined within range of FDOT database. GSI assumed based on conditions of the SL in the tank.
- FE model: Modeled with a top sand over a limestone with q_u of 500 psi
- Results: Load vs deformation matched measured response. Stress bulbs contours ($\tau_{relative}$) show no boundary effects on T1 at the bearing capacity load.

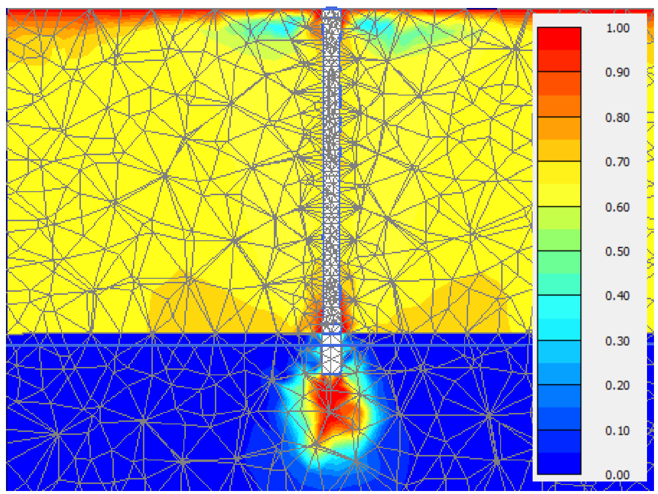
Parameter	Units	Weathered Rock
γ_{unsat}	pcf	130
GSI	-	70
E_i	ksi	31
v'	-	0.2
$q_{u,intact}$	psi	500
m_i	-	12



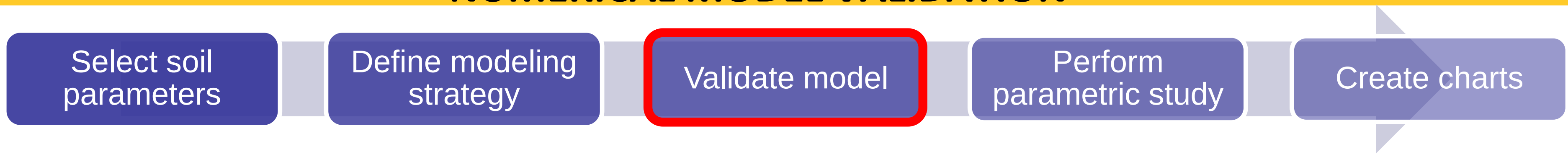
FEM geometry



Load vs displacement

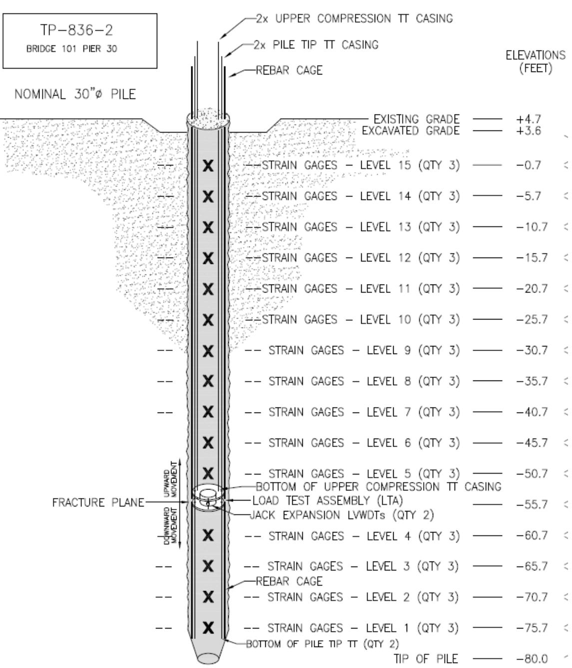


Stress bulbs

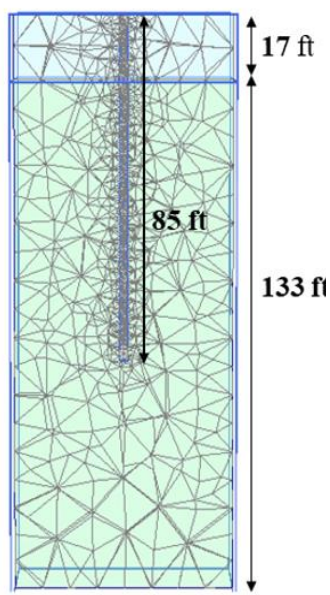


2nd Numerical model validation (Full-scale test in Miami)

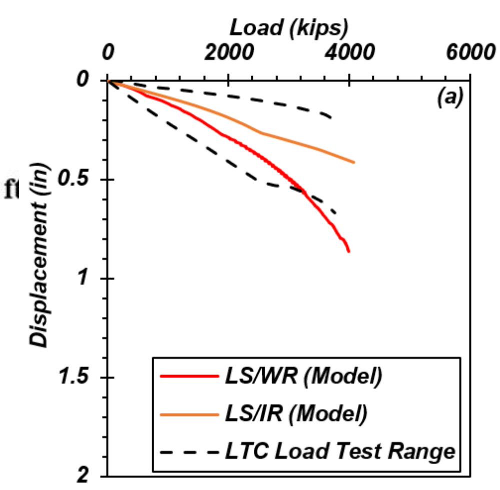
- Field measurements: Bi-directional load test at Bridge No. 101 on SR 836 in Miami, Florida.
- Test pile: 85 ft-long, 30 in-diameter.
- Soil profile: Defined based on SPTs. A 17 ft-thick weathered limestone over a more competent strata.
- FE model: Modeled with a top sand over a limestone in two scenarios (IR or WR).
- Results: Load vs deformation within measured range. Load transfer mechanism similar to measured as well.



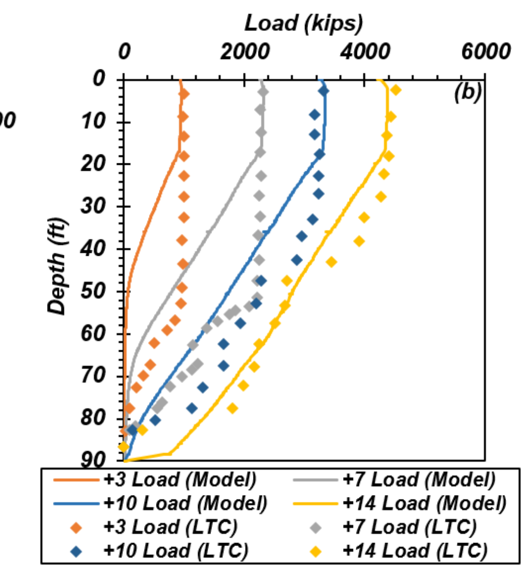
Load test schematic



FEM geometry

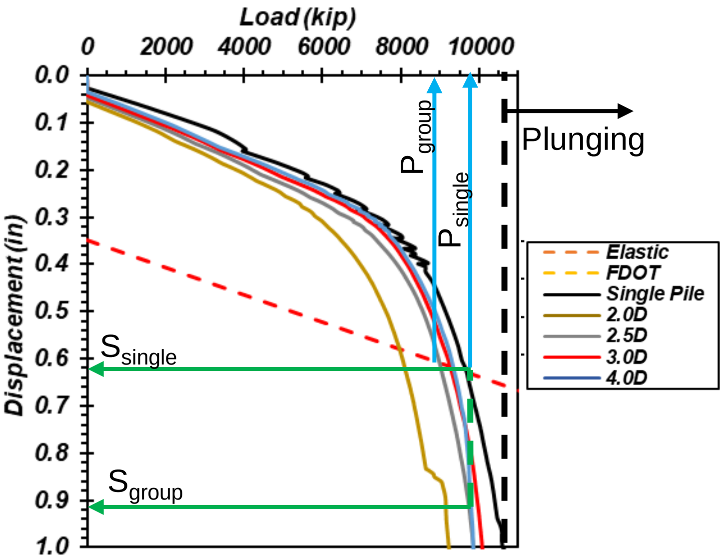


Load vs displacement



Load transfer mechanism

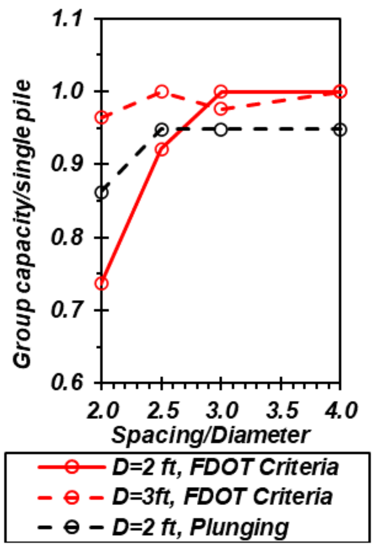
RESULTS OF NUMERICAL MODEL



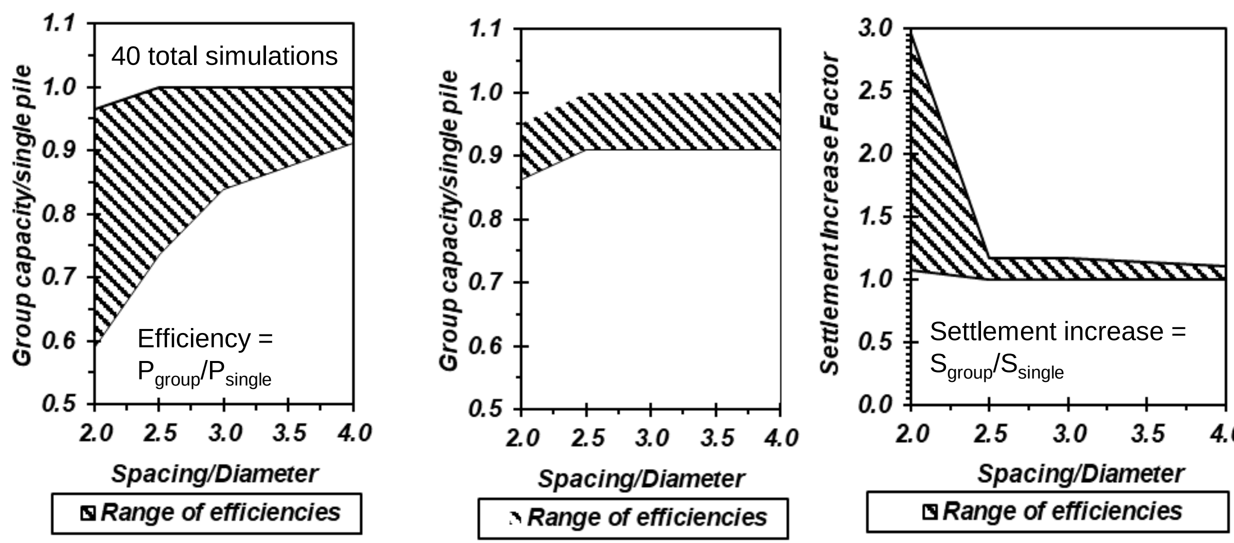
Typical computed load vs displacement curves

Numerical model results

- Most cases of sand over limestone completed.
- This includes 2x2, 3x3, 4x4 groups, and 2 ft and 3 ft diameters for a total of 40 numerical simulations.
- Efficiency curves are developed based on FDOT criteria, plunging failure, and settlement increase at similar load levels.
- Group efficiencies of approximately 70% at 2.5D agree with suggested values by AASHTO and Caltrans.
- For a stiff bearing strata (i.e., rock) pile capacity is governed by settlements not plunging. (Might be different in full soil profiles, pending to be investigated)



Example: LS/IR, 3x3 group efficiencies comparisons



Range of computed efficiencies by FDOT criteria, plunging, and settlement increase, respectively

PROGRESS ON FEM ANALYSIS MATRIX

FEM analysis matrix

Soil profile	D=24", q_u=250 psi				D=24", q_u=750 psi				D=36", q_u=250 psi				D=36", q_u=750 psi			
	Spacing/Diameter															
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 “q_u”= unconf. compression D= Diameter. Est. total cases: 40

Up to date FEM analysis matrix

- The updated FEM matrix considers 2x2, 3x3, and 4x4 group configurations. 4x4 group added to the initial testing matrix.
- An average q_u of 500 psi was used. Value chosen based on FDOT records and McVay, et al. (2019).
- Research team is now in a “production” stage, thus remaining cases are expected to be finished soon.

Soil profile	$D = 24", q_u = 500\ psi$				$D = 36", q_u = 500\ psi$			
	Spacing/Diameter							
S	4			2				
R	4			2				
S/R/S/R	4	3	2.5	2	4	3	2.5	2
S/R	4	3	2.5	2	4	3	2.5	2

50% completed (S, R, S/R/S/R)

Completed cases and calibrations (S/R)

SUMMARY OF TASKS/DELIVERABLES: SCHEDULE AND PROGRESS

SUMMARY OF TASKS/DELIVERABLES: SCHEDULE AND PROGRESS

TASK AND ASSOCIATED DELIVERABLE	DATE
Kickoff teleconference	01/2023
Deliverable 1: Technical report presenting the technical background	02/2023
Deliverable 2a: Report on details of the laboratory testing program: (i) pile installation, (ii) soil and rock properties, (iii) Gatorock strength, and (iv) detail plan on load transfer along pile length.	07/2023
Deliverable 2b: Report summarizing the results of the laboratory small-scale tests.	12/2023
Deliverable 3: Report summarizing the results of the finite element numerical models and parametric studies of the variables involved in the problem.	05/2024
Deliverable 4: Technical report summarizing proposed correlations and recommendations on 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

PRESENTED BY

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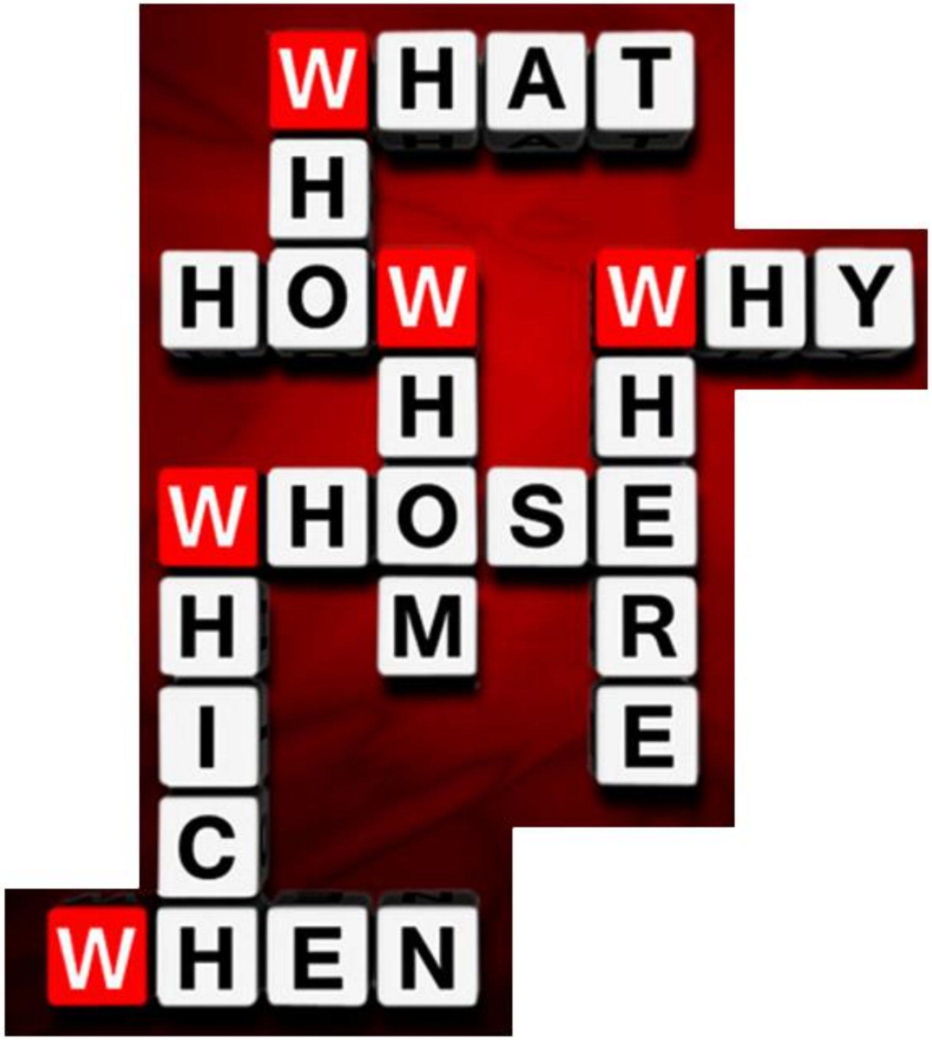
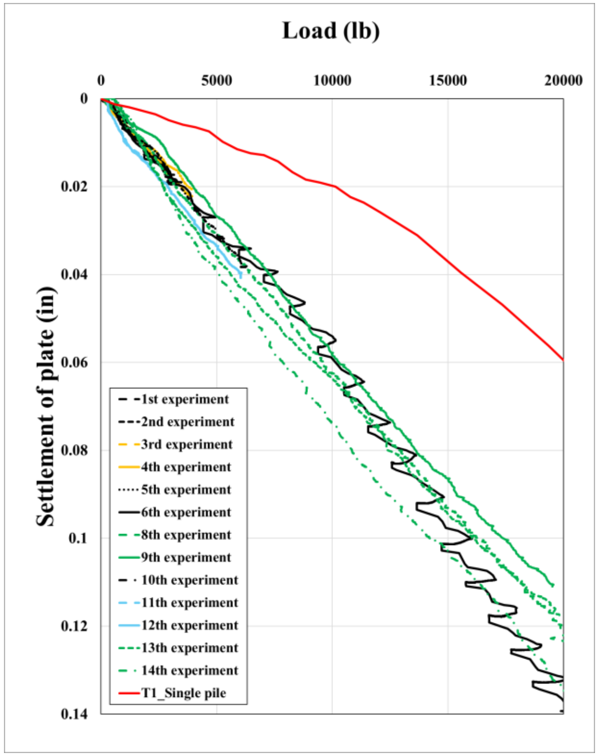


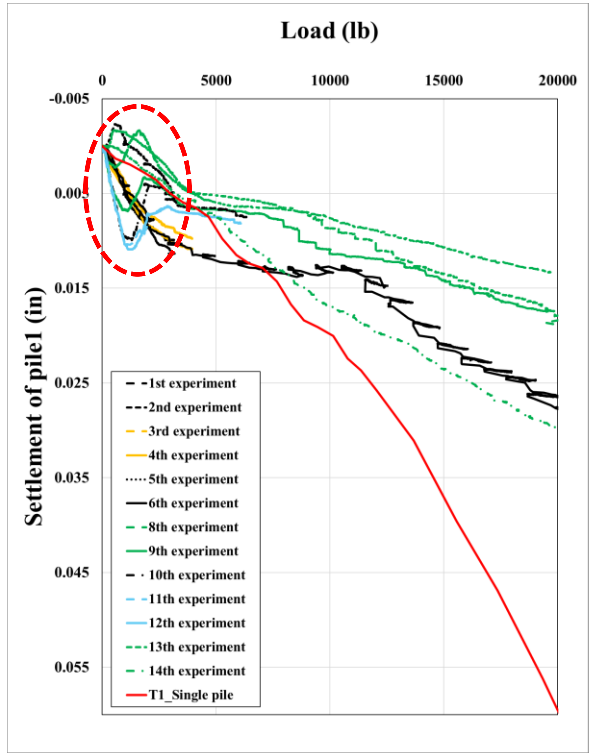
SUPPLEMENTAL SLIDES

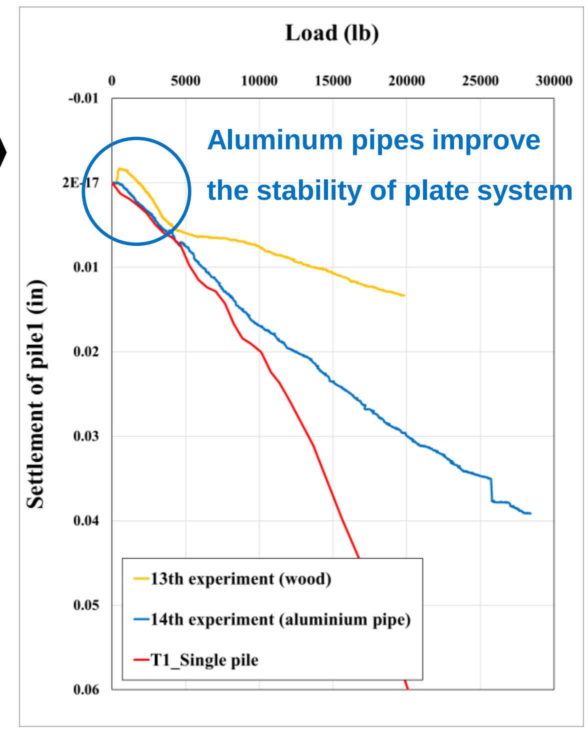
T2 (2 x 2 group piles with 4D spacing)

Load-displacement of plate



Load-displacement of ACP head

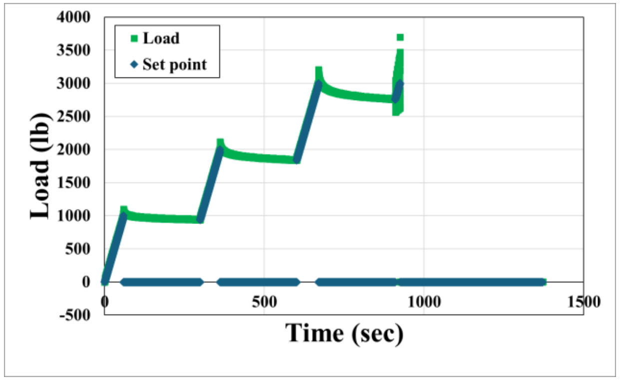


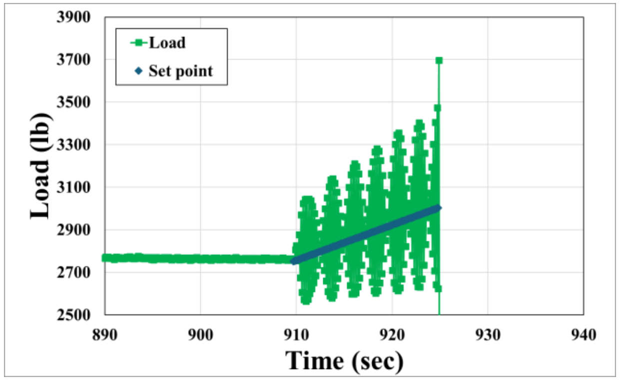


- Plate displacement increases with load.
- Pile head displacement shows instability under small loads.
- Likely caused by unstable behavior of the cap plate and loading plate at the ACP head.

T2 (2 x 2 group piles with 4D spacing)

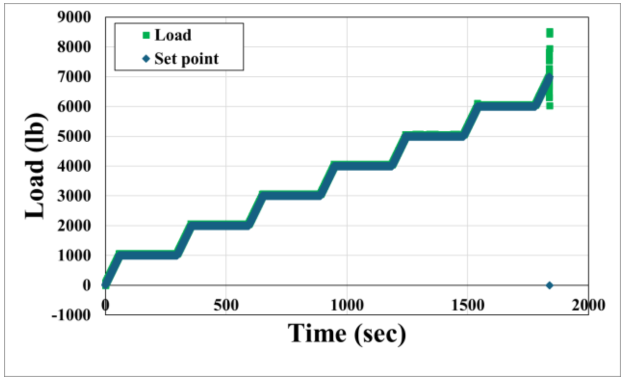
1) Ramp-Dwell
(Load & position control)

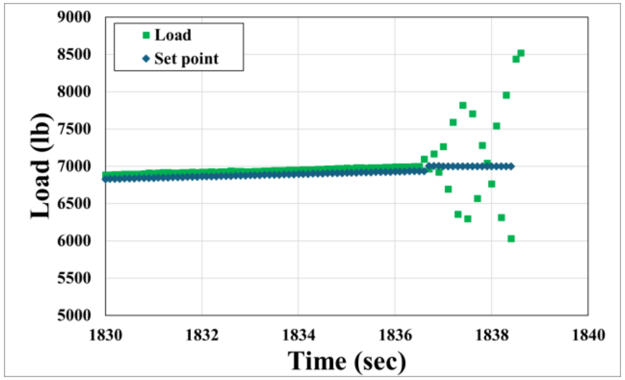




Oscillation of the actuator

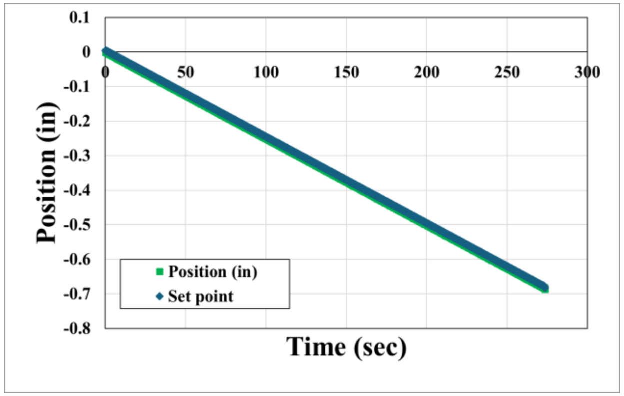
2) Ramp-Dwell
(Load control)





Oscillation of the actuator

3) Ramp
(Position control)



No oscillation of the actuator
Stable experiment