GRIP Meeting 2025
Project BED26 TWO 977-04:
Effect of Spacing on Axial Resistance of Auger Cast Pile Foundations

Start Date: Jan. 2023

End Date: Aug. 2025

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PRESENTED BY

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FDOT

1. Summary of benefits, implementation, tasks and objectives
2. Representative technical background
3. Experimental program and results
4. Numerical modeling and results
5. Design charts and concluding remarks

SUMMARY BENEFITS AND OBJECTIVES

- Estimate effect of spacing and load-deformation behaviors in ACP via FEM and physical model testing.
- Influence of proximity of ACPs on foundation performance. If research indicates 2.5D spacing is OK, it could be adopted to make construction faster, use less concrete/steel, and save in costs and time due to smaller pile caps.
- Development of reduction factors for applicable cases implemented in Structures Design Guidelines.
- Quantify effect of overlapping stress bulbs.
- Investigate effect of soil layering, rock strength, and design unit skin friction.
- Investigate relationships among geotechnical variables influencing effect of spacing on the capacity of ACP.
- Develop correlations that can be used in geotechnical practice in Florida.

1. Technical literature review

- Compiled current code guidance, laboratory-scale physical models, and numerical studies.

2. Laboratory-scale experimental program

- Executed two ways:
  End-bearing controlled (EBC) series: engaging both tip and shaft resistance.
  Side-resistance controlled (SRC) series: foam-isolated tips to deactivate end bearing.
- Conducted single-pile, 2x2, and 3x3 tests at $2D$–$4D$ spacings.

3. Numerical modeling framework

- Developed 3-D FEM calibrated with laboratory and field tests.
- Explored stress bulbs, load-sharing, and group-efficiency factors across spacings, pile diameters, and limestone strength.

4. Empirical spacing correlations

- Generated design charts and formulas linking spacing to axial capacity for EBC and SRC conditions.

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

Reduction factors from other DOTs (Caltrans)

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

- Spacing < 3D reduces the effective stresses against both the side and base of the 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**.

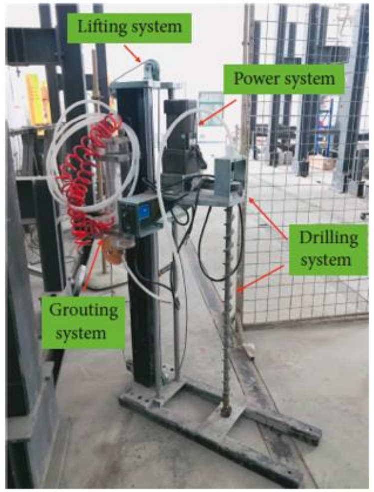
- **FDOT soils and foundations handbook:**

  - 3D and 2.5D spacing for drilled shafts in sand and rock socketed for 1.0 efficiency
- **FHWA, major DOT, Building codes and standards:**

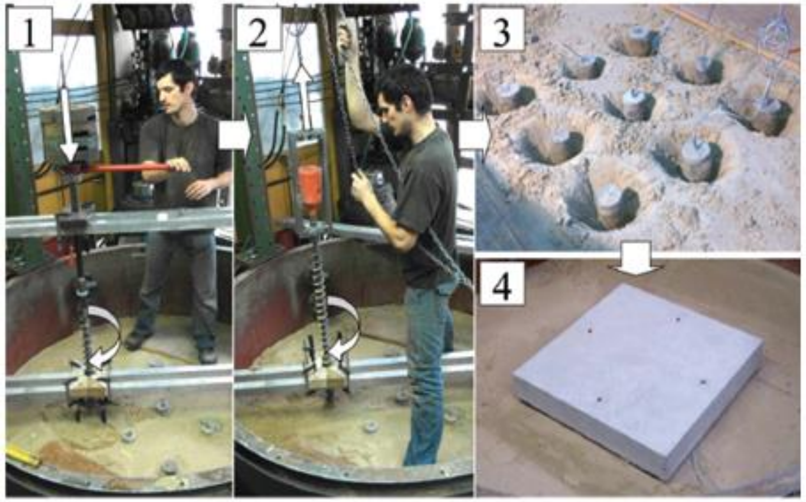
  − Drilled shafts group reduction factors at different spacings, configurations and cap contact

REPRESENTATIVE BACKGROUND: PHYSICAL MODELS

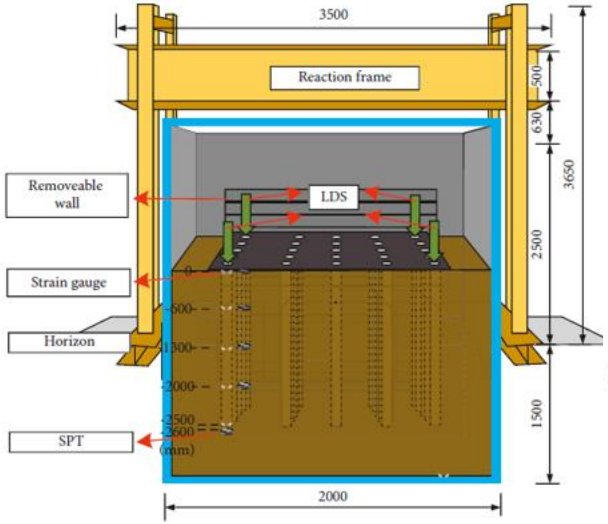
Zhu et al. (2021)



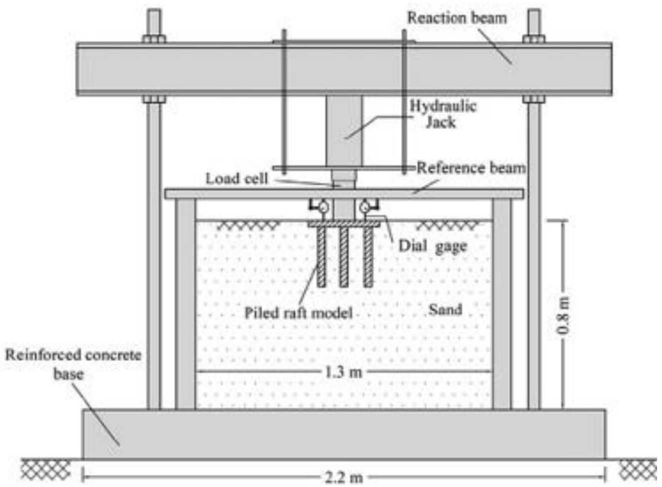
Krasiński and Kusio (2015)



Li et al. (2022)

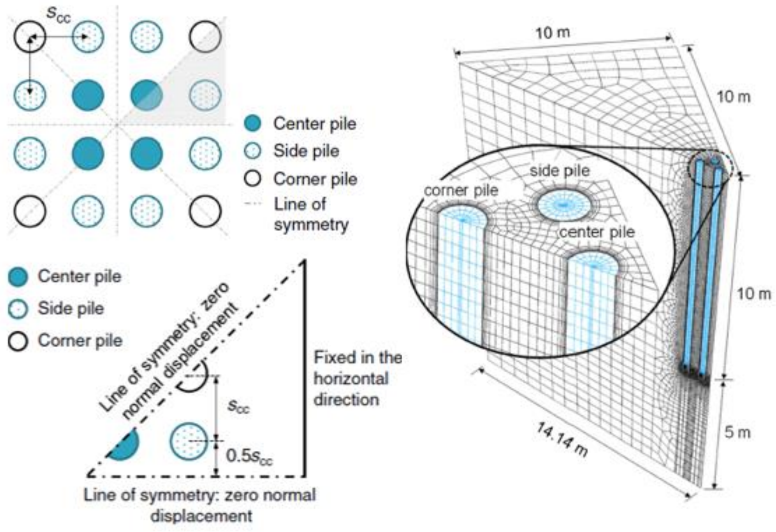


Sharafkhah et al. (2018)

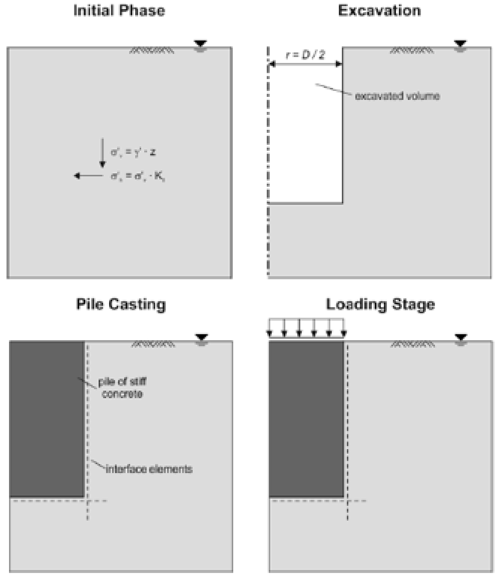


- Constructed piles with **pile-forming equipment** and **grout/slurry delivery**. **Pressure cells and gages** captured side shear and tip response. ACP grouting produced surrounding-soil densification.
- Used **soil containers large enough** to avoid boundary effects on the test.
- Most of the **instrumentation consisted of LVDTs or dial gages** to record displacements at the top of the piles.
- Studies tested **single, 2×2, and 3×3 groups with spacings between $2.6D$–$5.2D$.**
- Loading through hydraulic jacks and reaction beams **under controlled load sequences**.
- Several **prevented cap–soil contact** or evaluated cap configuration.

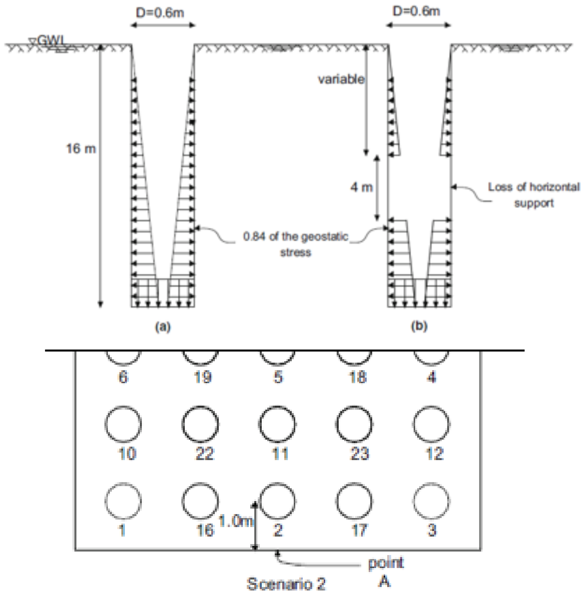
Han et. al. (2019)



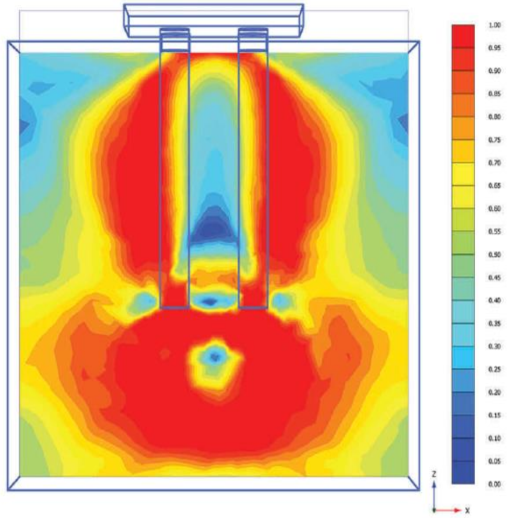
Schmüdderich et al. (2020)



Arab et al. (2020)



Nasrollahzadeh et al. (2019)



- **Installation modeling**: Used simple wished-in-place piles, some simulated excavation or reduced K_0 to capture drilled-shaft installation effects.
- **Soil constitutive laws**: Mohr-Coulomb; some used HS-Small.
- **Pile representation**: Usually linear-elastic solids or embedded-beam elements.
- **Soil-pile interface**: Neglected to save run-time; when included, they used zones with reduced shear strength.
- **Model extent**: Domains typically extended ≥ 25D laterally and 30D below tip to avoid boundary effects.

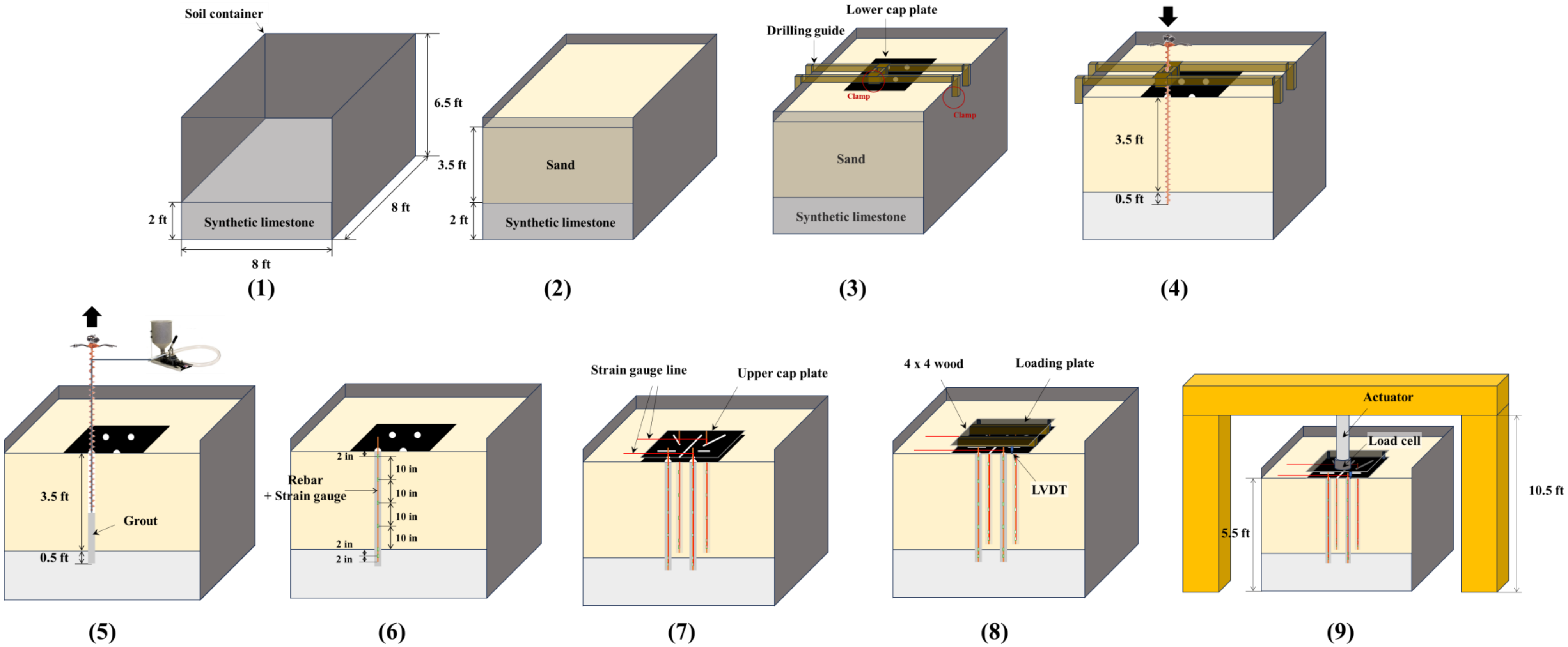
Combined Experimental Program Testing Matrix

Test Type	Pile group	Pile spacing	No. of conclusive tests	Loading mode and installation notes
End-bearing-controlled (EBC)	Single, 2x2, 3x3	$2D$ and $4D$	13 tests: -5 single -4 tests on 2x2 groups -4 tests on 3x3 groups	*Displacement-controlled *Both tip and limestone shaft engaged
Side-resistance-controlled (SRC)	Single, 2x2, 3x3	$2.5D$ and $4D$	15 tests: -3 single -6 tests on 2x2 groups -6 tests on 3x3 groups	*Displacement-controlled *Foam disk at tip to suppress end bearing

Summary of conditions tested

- **Ground condition**
  - Sand: 50% relative density (D_r).
  - Limestone: Synthetic limestone (SL) created using cement, crushed limestone, and water.
- **Pile spacing:** - EBC tests at the tightest practical spacing: $2D$
  - SRC tests at $2.5D$ mirroring Florida Handbook specification.
- **Loading mode:** Displacement control defined to minimize damage to the limestone layer.

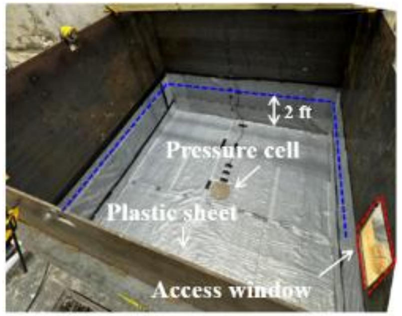
EXPERIMENTAL PROCEDURE



1) Placement of 2 ft-high SL layer.
2) Deposition of 3.5 ft-high sand layer.
3) Installation of the lower cap plate followed by setting up drilling guide.
4) Drilling using the auger and motor.
5) Extraction of auger while applying grouting pressure with pump.
6) Insertion of the instrumented rebar into the grout.
7) Installation of upper cap plate and setup strain gauge lines.
8) Placement of wood spacers and LVDT on the cap plate, connection of loading plate.
9) Installation of reaction frame and actuator to apply load on ACPs.

IMPLEMENTATION EXPERIMENTAL METHOD

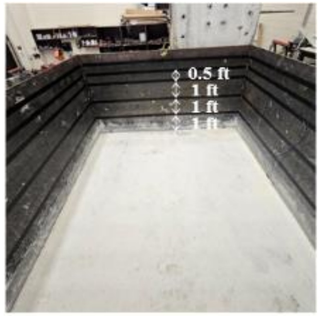
Prepare SL → Deposit sand → Install ACP → Install instruments → Perform test



Installation of plastic sheet and earth pressure cell

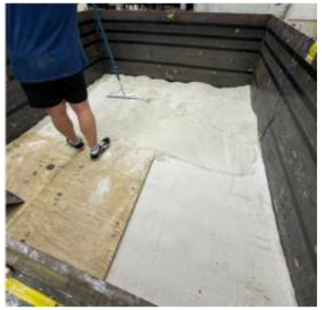
SL placement through access window

Leveling and vibrating to remove air bubbles

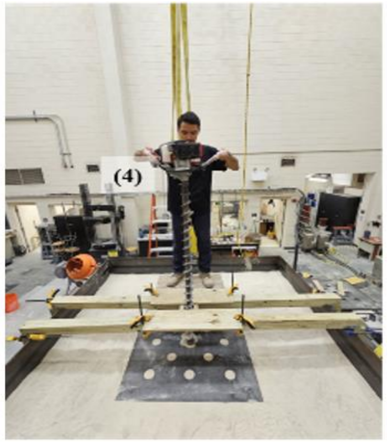


Four layers of sand with total height of 3.5 ft

Placement of sandbags and crane scale

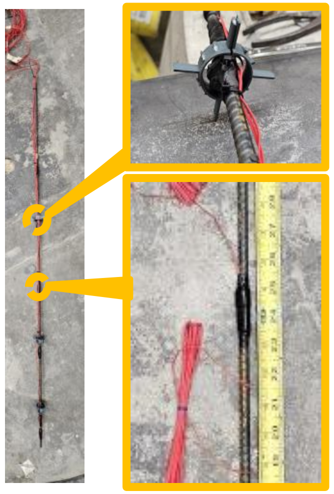


Compacting the sand up to the target level



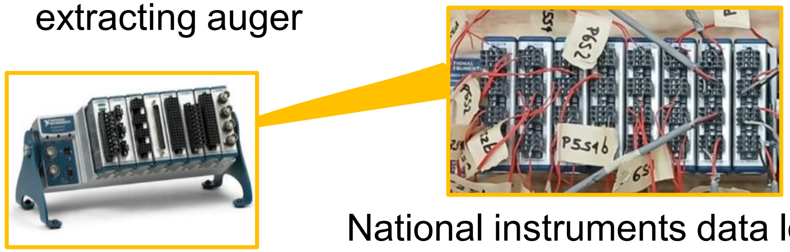
Drilling guide and spacing steel plates

Injection of grout while extracting auger

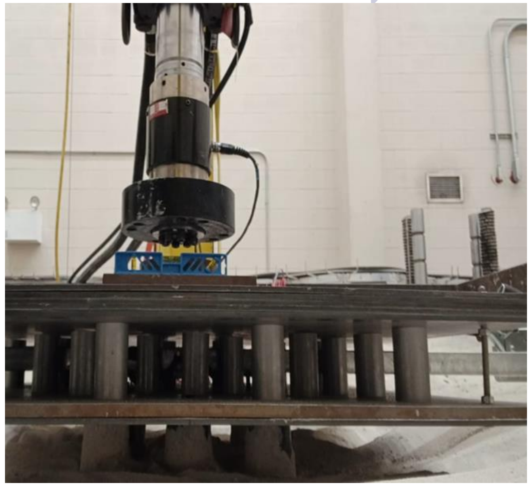


Strain gauge attached to the rebar

Install LVDTs



National instruments data logger

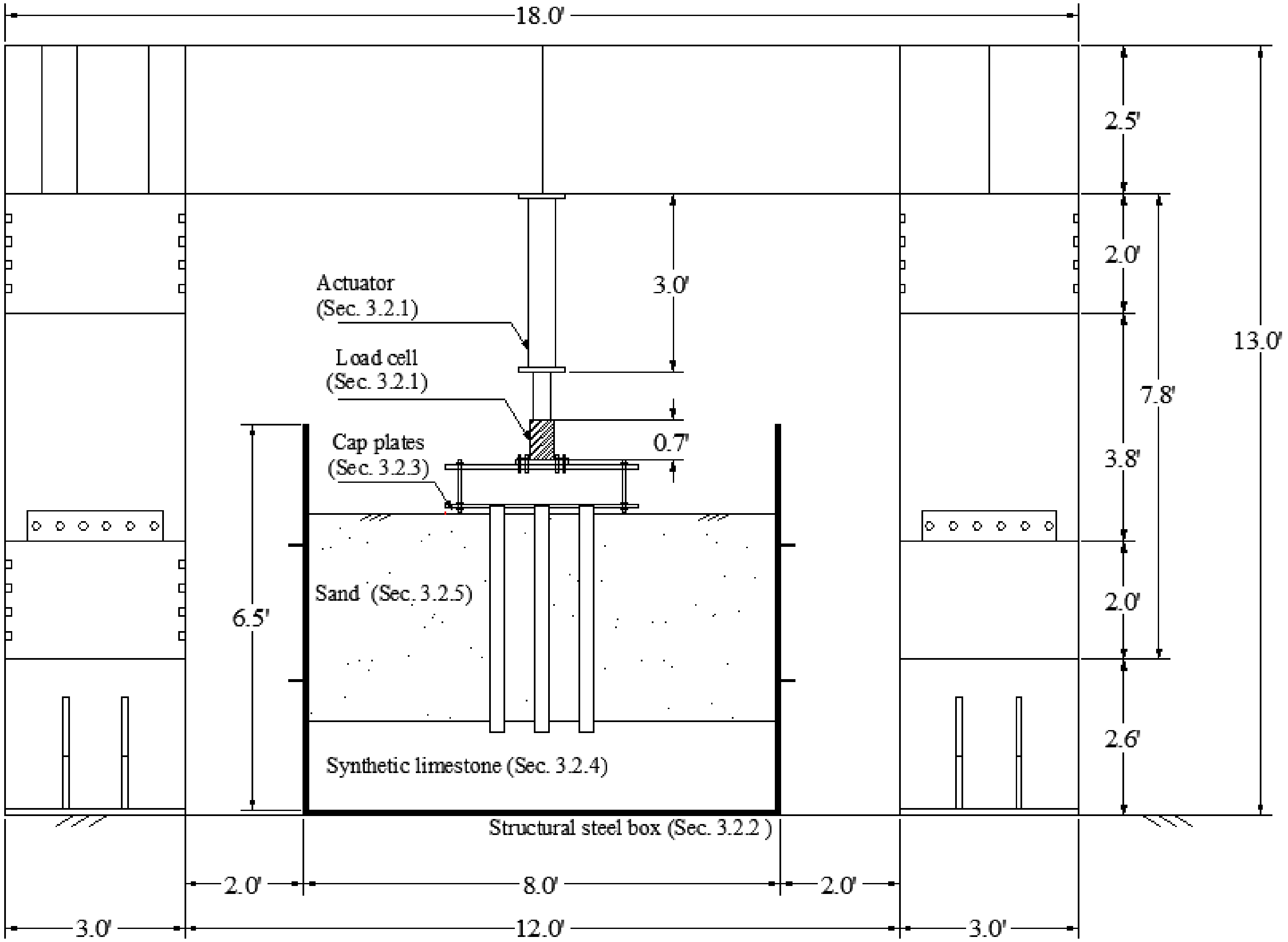


Load test with surrounding sand excavated

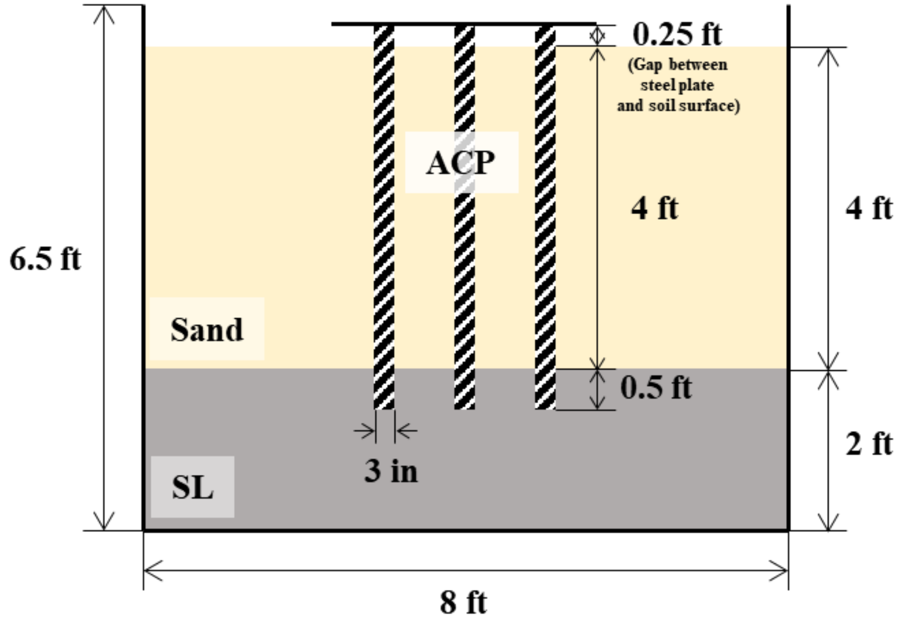
Experimental setup for physical model test

PHYSICAL MODEL GEOMETRY AND PILE DIMENSIONS

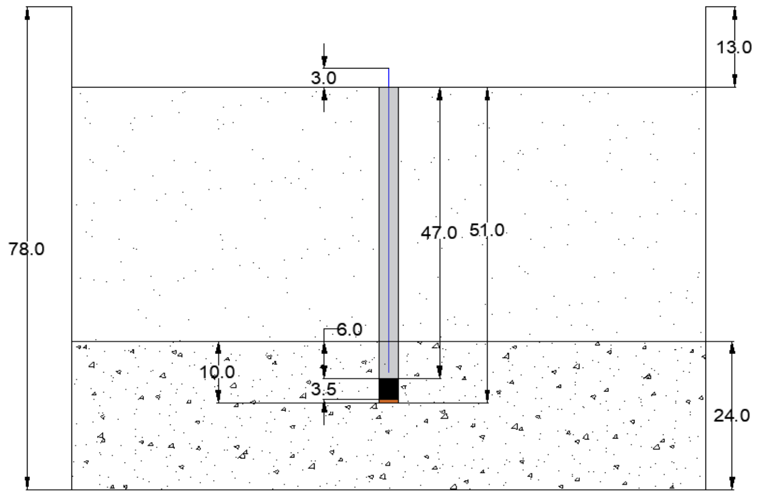
Physical model geometry



End-bearing-controlled piles

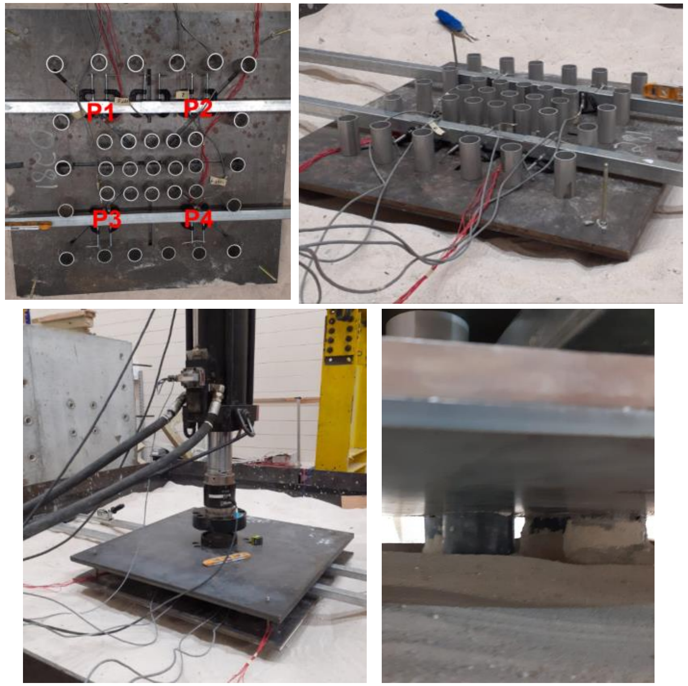


Side-resistance-controlled piles



Single pile

2x2 groups



3x3 groups

Single pile

- **Curing/strength:** 1–2 weeks to achieve 4000–5000 psi grout.
- **Instrumentation:** Strain gages+ LVDTs (pile head, cap edges).
- **Loading setup:** Cap/load plates on 3-in hollow cylinders.

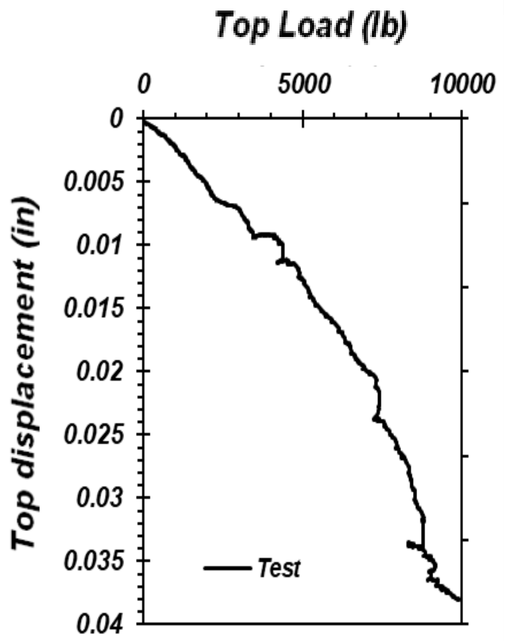
2x2 groups

- **Layout**: 4D shown; 2D built with 12-h delay between adjacent piles.
- **Instrumentation**: LVDTs at pile heads. P1 & P4 wired with gages.
- **Loading setup**: Same hollow cylinders & bolted plate stack; sand excavated below cap.

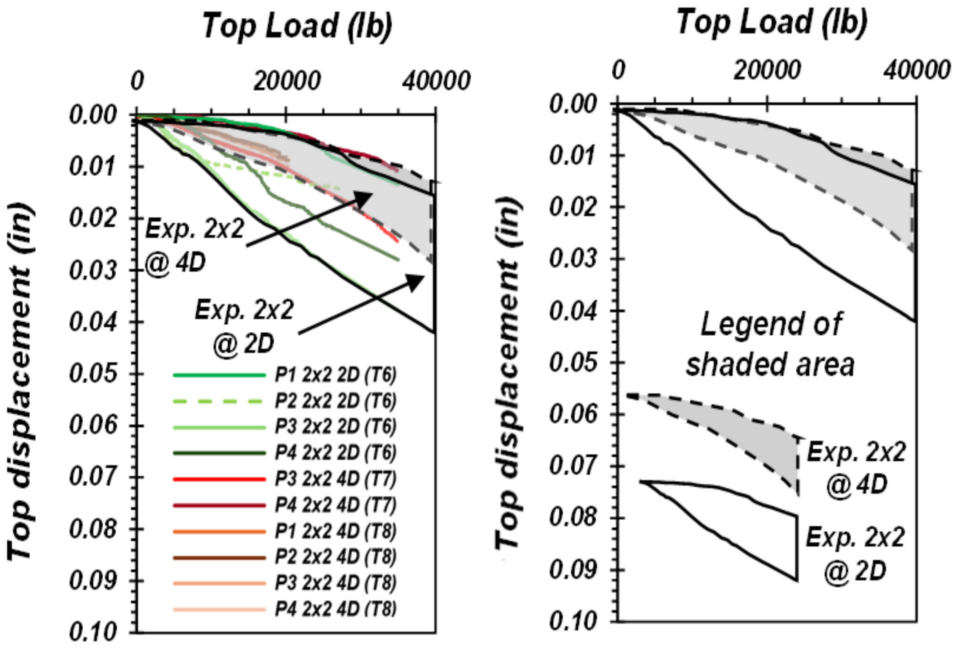
3x3 groups

- **Installation**: Drilling guide. Grout uptake (grout volume ratio) ≈ 1.20 (within spec).
- **Instrumentation**:Center/edge/corner with 6-gage rebars. 4 LVDTs.
- **Loading setup**: Cylinders under cap + sand excavation to avoid cap–sand contact.

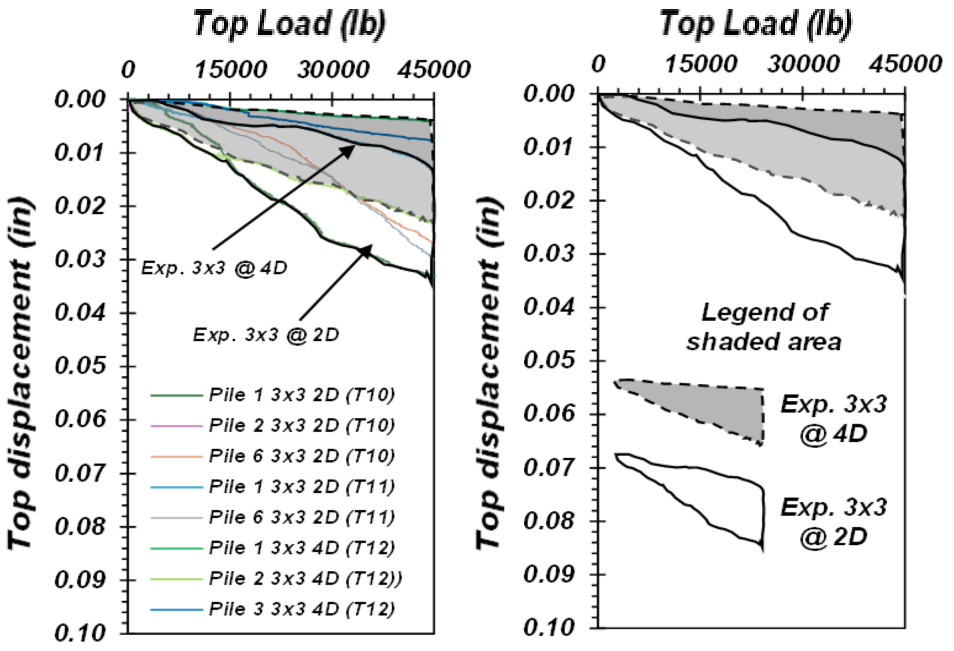
Results single pile



Results 2x2



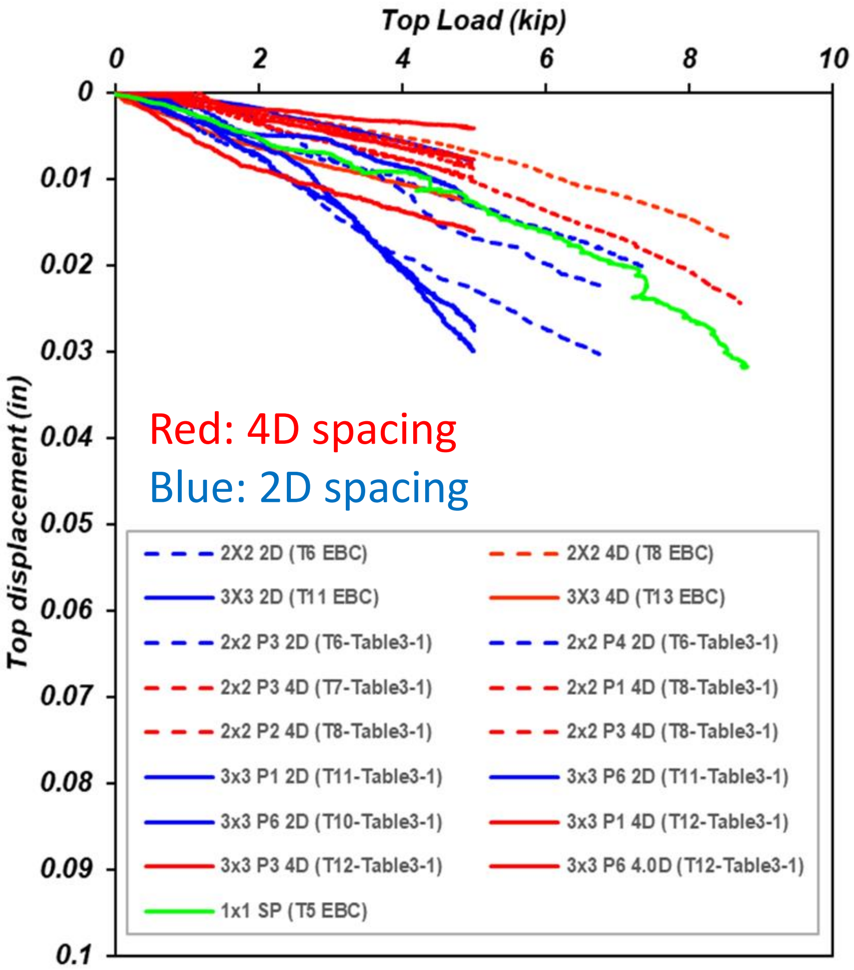
Results 3x3



- **Load limit**: Limited to 10 kip to protect SL (≈500 psi target).
- **Response**: Approx. 0.05 in in deformation to trigger nonlinearity.

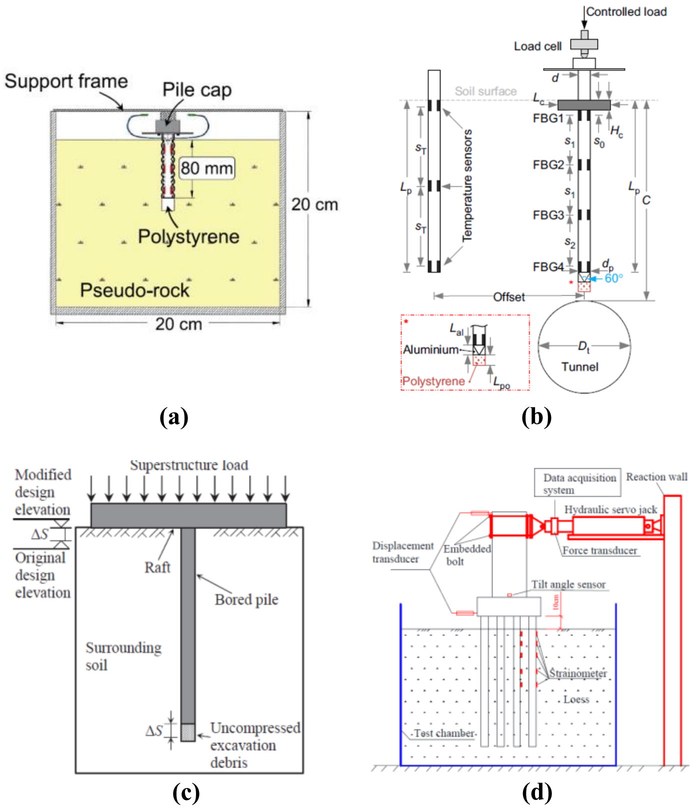
- **Spacing effect**: 2D > 4D settlements at equal load.
- **Envelopes**: Dashed (4D) vs solid (2D) bands show efficiency due to spacing.

- **Spacing effect**: 2D > 4D displacements (group and per-pile).
- **Envelopes**: Response depends on load distribution.
- **Response**: Individual pile load varies (as built conditions) and ACP interactions noted due to spacing.



- **Tight spacing causes lower group efficiency:** 2D groups settle more than 4D groups.
- **Modulus verified:** Tangent method E values matched grout cylinder tests.
- **EBC resistance:** Upper sand contributes little to overall response.
- **EBC behavior confirmed:** Settlements and load-transfer fit end bearing dominated ACPs.

Technical Literature



Mostly used materials

a) Soft **polystyrene** plug (Gutiérrez-Ch et al. 2021)

b) Friction pile with **compressible foam** (Tang et al. 2024)

c) Foam **rubber** layer glued to pile tip to simulate debris and delay mobilization (Xu et al. 2018)

d) **Flexible foam** insert at pile base (Zhang et al. 2020)

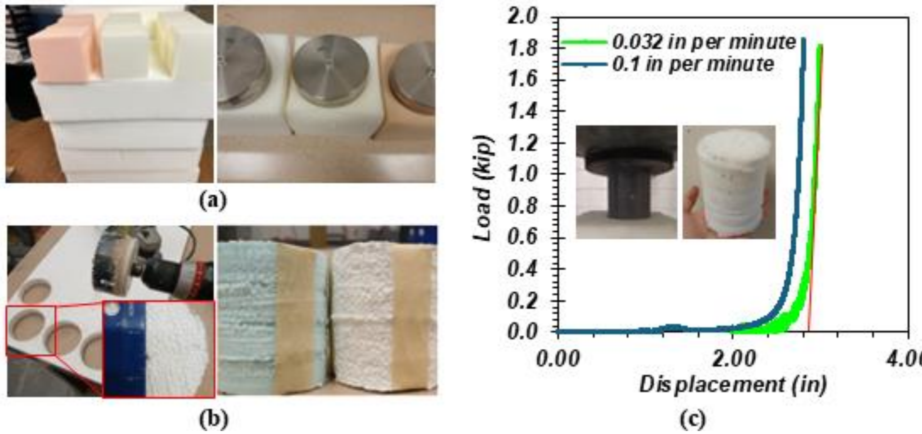
Foam Selection

Goals:

- Large axial **deformation range** before stiffness increased
- **Delay tip resistance** mobilization under testing conditions
- Balance **stability** and **deformability** under loading
- **Support** the pile during **placement.**

Alternatives Evaluated:

- Extruded polystyrene (XPS)
- Expanded polystyrene (EPS)
- Viscoelastic foams with several Indentation Force Deflection (IFD) and density



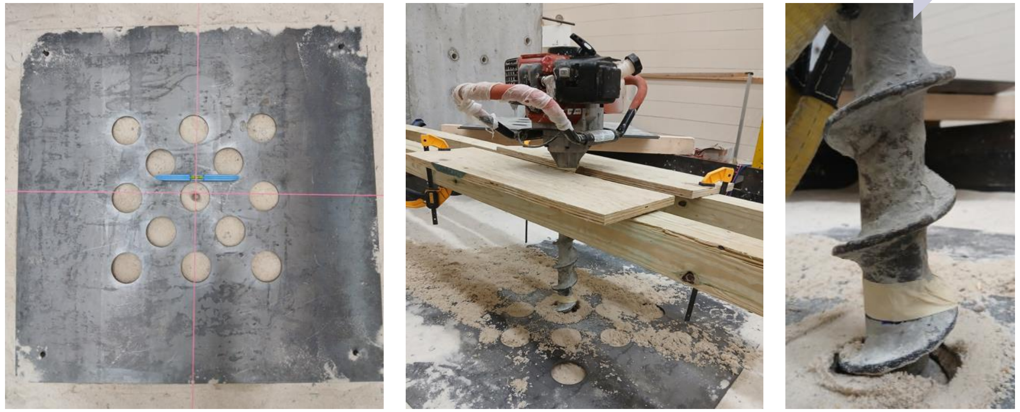
(a) foam samples, (b) preparation of specimens, and (c) uniaxial compression tests of selected ***medium density-low IFD foam.***

Foam installation procedure

Drilling → Foam insertion → Detach foam → Grout pouring

Setup single SRC pile

Level surface → Plate alignment → Aligned drilling → Stop at mark



•**Purpose & prep**: Foam disc wrapped in plastic to block grout; auger depth mark sets placement elevation.

•**Placement**: Lowered with hollow tube, gently seated with rebar. No auger re-entry to minimizes disturbance.

•**Grouting & check**: Foam compressed from 0.5 to 1 in. Tip load delayed, side-resistance controlled.

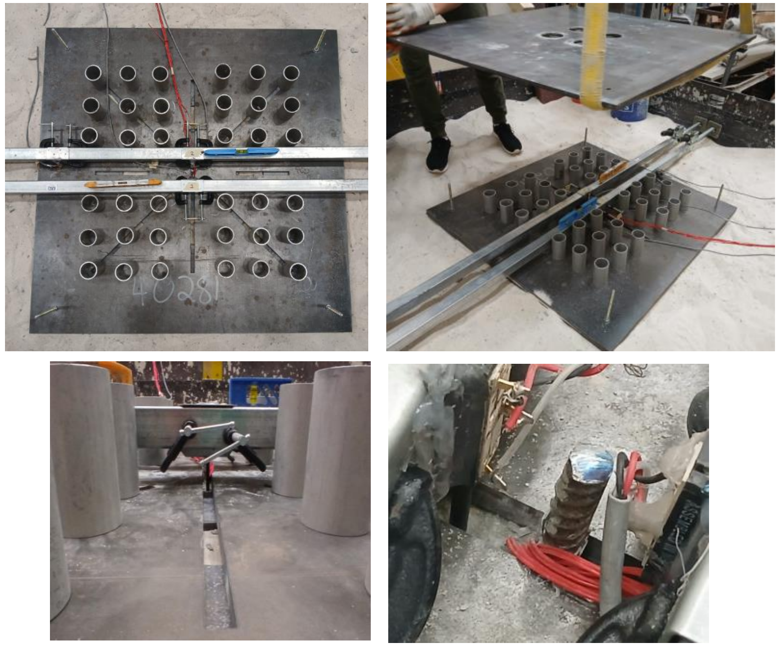
•**Outcome:** Borehole integrity preserved; no early end-bearing mobilization; foam acted as a **cushion** absorbing tip deformation.

•**Curing & strength:** 1–2 weeks to achieve 4000–5000 psi grout.

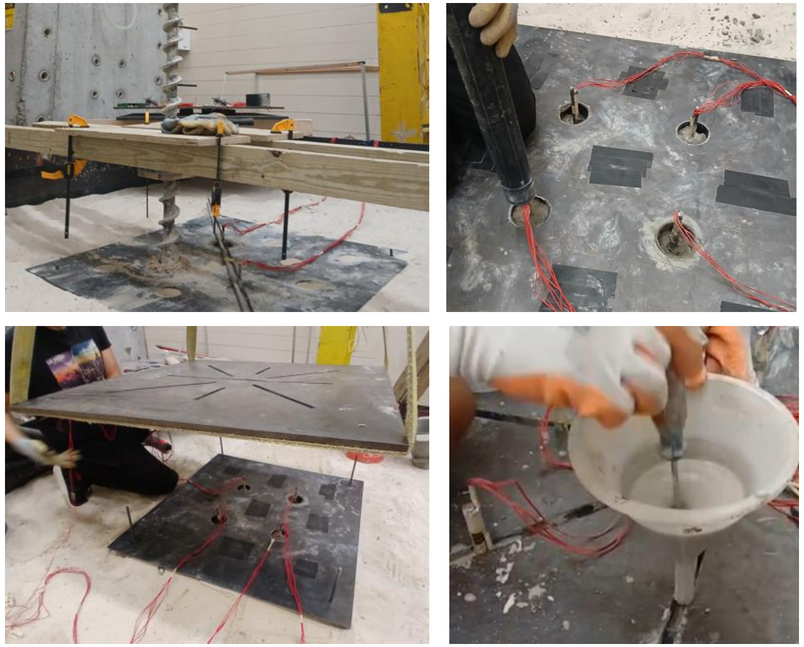
•**Instrumentation:** Strain gages + 3 LVDTs (pile head, cap edges).

•**Loading setup:** Cap/load plates on 3-in hollow cylinders; sand cleared under cap.

Single pile



2x2 groups



3x3 groups

- **Loading setup**: Aluminum cylinders under cap plates. Actuator bears on plates.
- **Instrumentation**: Two symmetric reference bars with LVDTs. Strain gages at pile tops.

- **Surface prep**: Vacuum sand. 1.5 in recess for joint casting.
- **Plate placement**: Pass strain-gage wires & rebars through plate slots.
- **Joint casting**: Fast-setting cement poured to have monolithic head–plate joint.

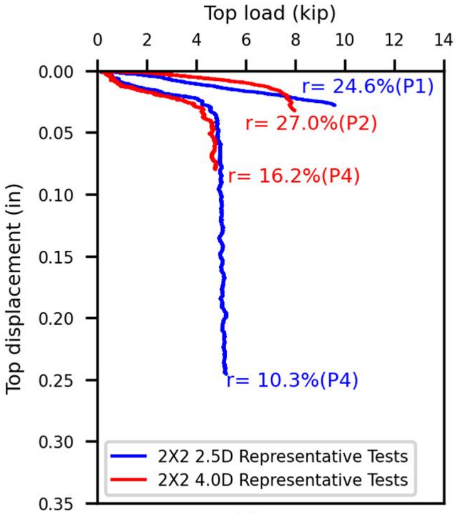
- **Embedment checks**: Measure sand elevation from steel container edge
- **Plate prep**: Set slotted plate; tape unused slots.
- **Clean & cast**: Remove sand from pile heads. Cast rapid-set joint beneath plate.

SRC TESTS: SELECTED RESULTS (2X2 AND 3X3 AT 2.5 AND 4D)

Comparison 2 × 2 group tests at 2.5D and 4.0D:

(a)

(b)



(c)

Conclusions from SRC experiments:

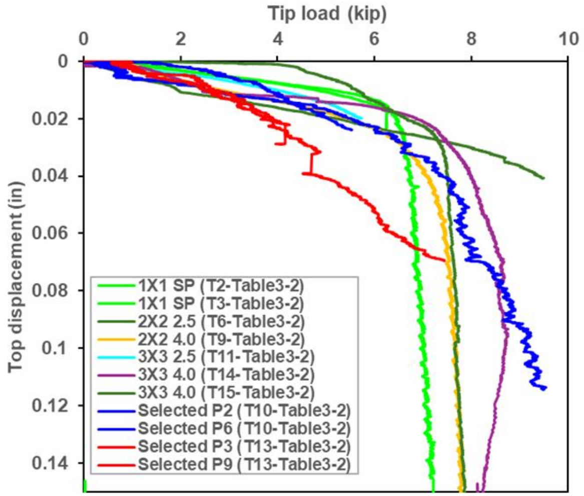
- Comparable piles showed similar stiffness and displacement behavior among spacing configurations (i.e., 2.5D and 4.0D) for SRC program. For EBC program, behavior is more sensitive to S/D considerations.
- Load-deformation mechanisms were controlled by pile-rock interface rather than by spacing-related stress interactions.
- Reducing spacing from 4D to 2.5D did not influence the axial response of ACPs in the SRC program.

Comparison of 3 × 3 groups at 2.5D and 4.0D:

(a)

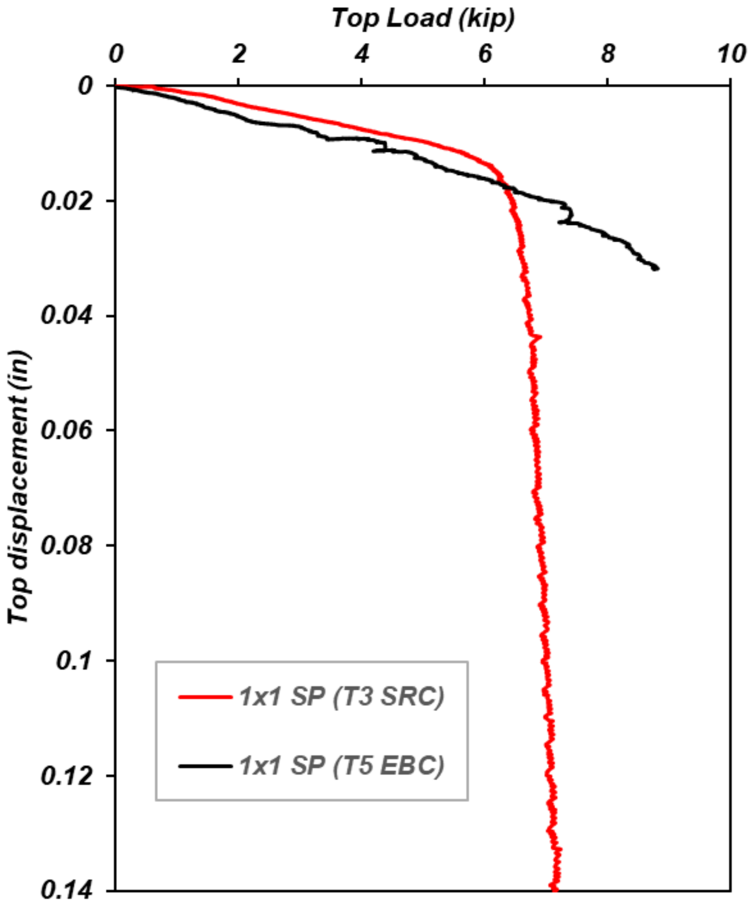
(b)

(c)



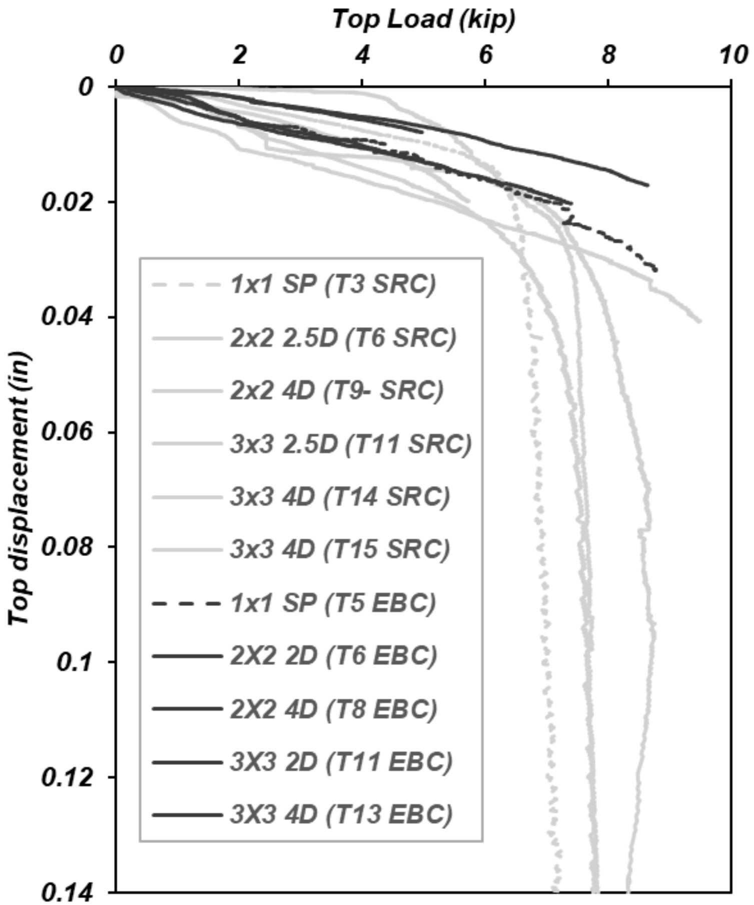
(d)

EBC vs. SRC (*single pile*)



(a)

EBC vs SRC (*groups*)



(b)

(a) *Single pile*: EBC way stiffer than SRC tests. Plunging failure observed in SRC tets.

(b) *Groups*:

SRC = all similar responses regardless of spacing.

EBC = spacing considerations mattered.

•**Observed mechanisms**:

✓ **SRC (gray)** tip resistance minimized, mostly side-resistance at rock socket.

✓ **EBC (black)** concentrated tip resistance, continuously increasing load with no plunging.

Condition	Soil profile	Spacing/Diameter																			
		D=24", 2X2				D=24", 3X3				D=24", 4X4				D=36", 2X2				D=36", 3x3			
End Bearing Controlled	LS/100[a]	*4*[b]	*3*	*2.5*	*2*	*4*	*3*	*2.5*	*2*	4	3	2.5	2	4	3	2.5	2	4	3	2.5	2
	LS/50	*4*	*3*	*2.5*	*2*	*4*	*3*	*2.5*	*2*	4	3	2.5	2	4	3	2.5	2	4	3	2.5	2
	Inter. Layer	4	3	2.5	2	4	3	2.5	2	-	-	-	-	-	-	-	-	-	-	-	-
Side Resistance Controlled	LS/30	4	3	2.5	2	4	3	2.5	2	4	3	2.5	2	4	3	2.5	2	4	3	2.5	2
	LS/50	4	3	2.5	2	4	3	2.5	2	4	3	2.5	2	4	3	2.5	2	4	3	2.5	2
	LS/90	4	3	2.5	2	4	3	2.5	2	4	3	2.5	2	4	3	2.5	2	4	3	2.5	2

Notation: LS/xx where **xx = limestone GSI**; **underlined** cases modeled with **intact & reduced K_0**; **LS = loose sand**; **total simulations = 124**

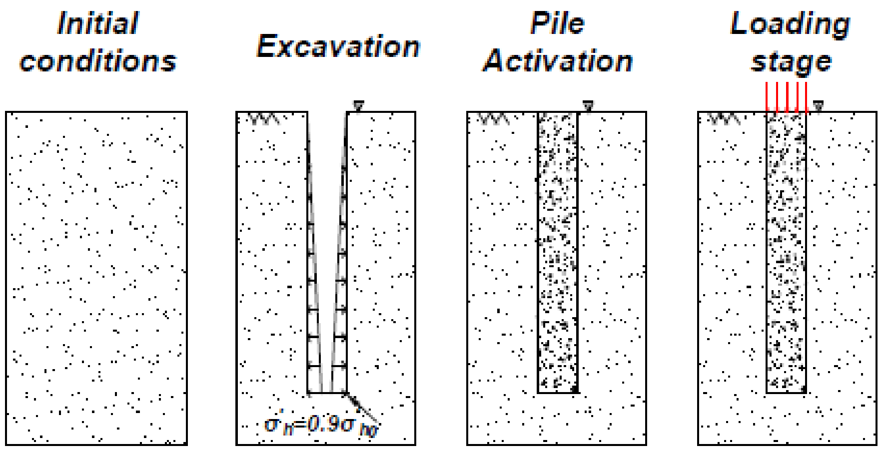
PURPOSE AND METHOD

- **Objective:** quantify spacing and group effects.
- **Tool:** properly calibrated and validated PLAXIS 3D models.
- **Cases modeled:** EBC and SRC cases.
- **Validation:** Laboratory model tests and field bidirectional load tests

MATRIX AND SUBSURFACE CONDITIONS

- **Matrix**: groups 2X2, 3X3, 4X4; pile diam.= 2 ft & 3 ft :124 runs.
- **Profiles**: Sand over limestone with GSI = 100, 90, 50, 30
- **EBC added**: interbedded sand/limestone case for shaft contribution.
- **Constitutive models**: sand = HS-Small; limestone/IGM = calibrated Hoek–Brown.
- **Modeling strategy**: intact vs reduced K_0 to define installation effects.

Reduced-K_o modeling approach



•**Purpose**: Effects of augering and stress relief.

•**Stages**:

(1) K_0 stress initiation

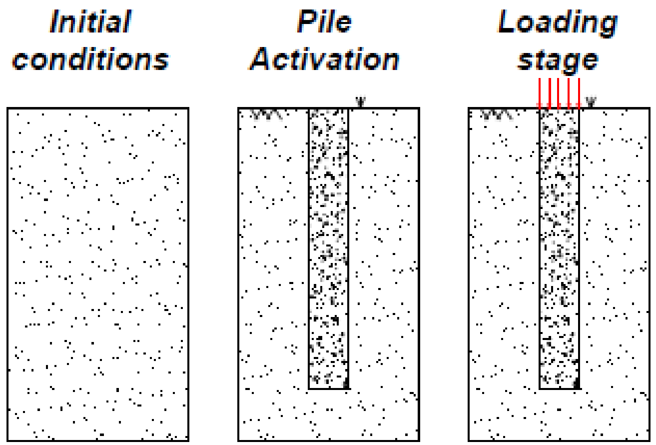
(2) Excavation + radial pressure $\sigma'h = \alpha \cdot \sigma'h_0$

(3) Pile activation and pressure removal

(4) Displacement-controlled loading

•**Effect**: Changes in horizontal confinement produces deformation + partial shear mobilization.

Intact-K_o (wished-in-place) conditions



•**Purpose**: No installation effects.

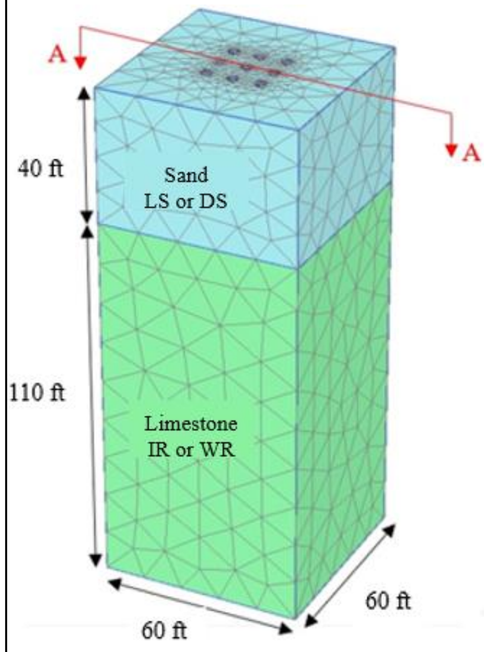
•**Approach**: Activate WIP piles under intact K_0, then run displacement-controlled loading.

•**Use**: Direct comparison with reduced-K_0 to quantify construction effects.

•**Setup**: Geometry, materials, and boundary conditions kept identical to reduced-K_0 cases.

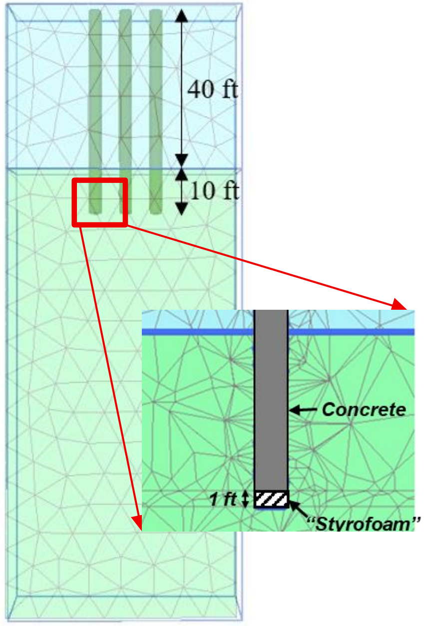
Numerical modeling strategy → **Baseline numerical model geometry** → Selection constitutive model parameters → Validation with physical model tests → Validation with field tests

Overall dimensions and layer names



- **Domain**: 150 ft x 60 ft; ≥ 10D edge; sides restrained, base fixed.
- **Mesh**: 10-node tetrahedral. Medium mesh.
- **Water table** defined at surface
- **Cases:** Single, 2 × 2, 3 × 3, 4 × 4 ACPs

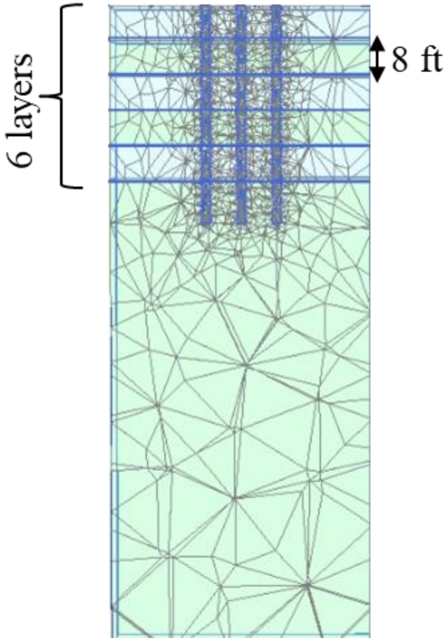
Elevation view, and pile embedment length



- **Profile**:
  - -40 ft LS over 110 ft limestone (GSI 100/90/50/30).
- **Piles**:
  - -Diam.=2 ft,
  - -L=50 ft,
  - -10 ft socket
  - -local mesh refine.

1-ft "Styrofoam" (E≈1.5 psi) under tip **for SRC cases.**

Interbedded sand/limestone cases



- **Cases**:
  - -8 ft interbedded sand/limestone to 40 ft.
- **Used for**:
  - -EBC matrix to check side contribution.

- **Interfaces**: Cylindrical negative interfaces; sand R_{inter} = 0.8.
- **Loading**: Prescribed displacement (≤ 5 in).
- **Capacity (FDOT/Davisson):** δ = elastic + 0.15 in + D/120.
- **Failure**: If plunging occurs, capacity = plunging load

Numerical modeling strategy → Baseline numerical model geometry → **Selection constitutive model parameters** → Validation with physical model tests → Validation with field tests

Loose sand stratum

- **Sand model**: HS Small.
- **Benefits**: Captures small-strain stiffness and stiffness degradation
- **Use**: Successfully applied to ACP installation in sands (e.g., Schmüdderich et al., 2020).
- **Inputs**: Parameters from Table based on sand relative density.
- **Derivation of parameters**: HS Small parameters correlated to D_r per Brinkgreve et al. (2010)

HS Small properties

Parameter	Units	Loose Sand
D_r	(%)	30
γ_{sat}	pcf	125
ϕ'	^{o}	31.8
ψ	^{o}	1.8
$E_{50}{}^{ref}$	ksi	2.61
$E_{oed}{}^{ref}$	ksi	2.61
$E_{ur}{}^{ref}$	ksi	7.83
$G_0{}^{ref}$	ksi	11.67
m	-	0.61
ν'_{ur}	-	0.2
$\gamma_{0.7}$	$x10^{-4}$	1.7
R_f	-	0.96
R_{inter}	-	0.8

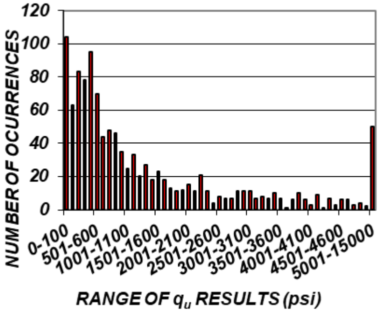
Limestone stratum

- **Rock model**: Hoek–Brown (calibrated model from laboratory unconfined and triaxial tests).
- **Inputs**: (FDOT database): used q_u = 500 psi (typical 100–1000 psi); E_i typical (600–700 ksi).
- **GSI effect**: q_u drops with weathering. GSI of 100/90/50/30 matched 500/286/30/8.5 psi.

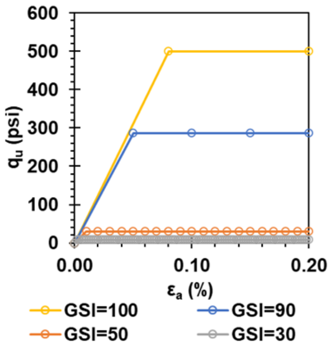
Hoek-Brown properties

Parameter	Units	Limestone
γ_{sat}	pcf	130
GSI	-	30/50/90
E_i	ksi	600
v'	-	0.2
$q_{u,intact}$	psi	500
m_i	-	12

UCS from FDOT database



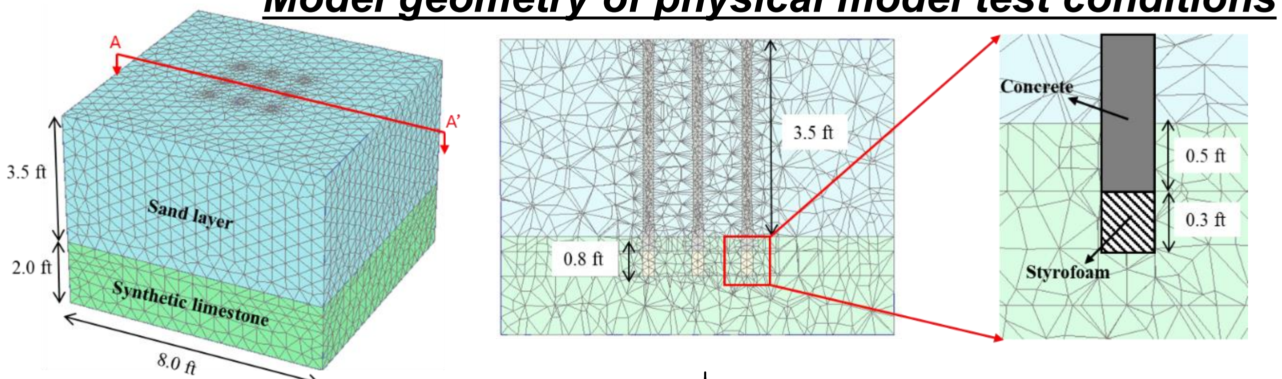
Simulated UCS with H&B params.



VALIDATION WITH PHYSICAL MODEL TESTS

Numerical modeling strategy → Baseline numerical model geometry → Selection constitutive model parameters → **Validation with physical model tests** → Validation with field tests

Model geometry of physical model test conditions



4-in "Styrofoam" under tip for SRC cases (replicate laboratory conditions).

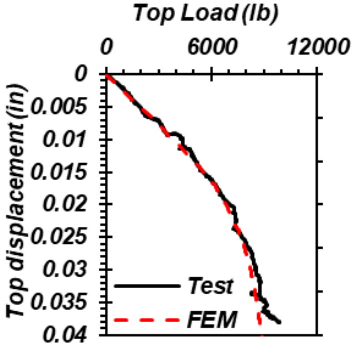
Modeling of EBC physical model tests

- **Load–displacement**: FE matched single-pile (EBC) physical tests.
- **Load transfer**: Sand≈0. Rock socket plus tip resistance for EBC case.
- **Stress bulbs**: 3x3 at 4D shown (widest bulbs) remain inside the domain, confirming minimal boundary effects

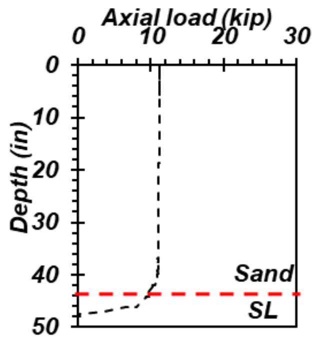
Modeling of SRC physical model tests

- **Load–displacement**: FE matched well SRC tests.
- **Load transfer**: Sand≈0; tip ≈0 (foam isolation); rock socket carries most of load.
- **Stress bulbs**: concentrated around socket, not much interaction. Negligible changes in group efficiency.

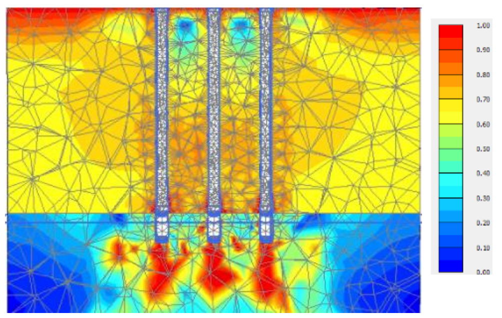
LAB vs. FEM



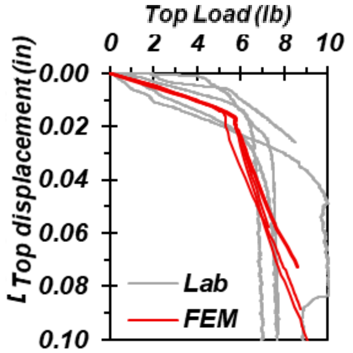
Load transfer



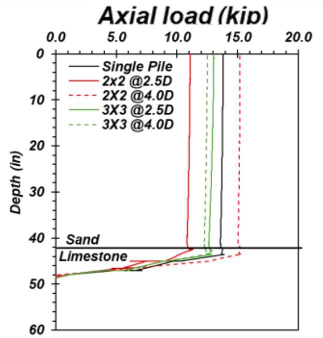
3x3 @ 4D



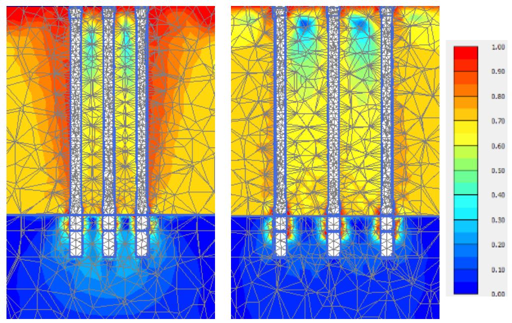
LAB vs. FEM



Load transfer



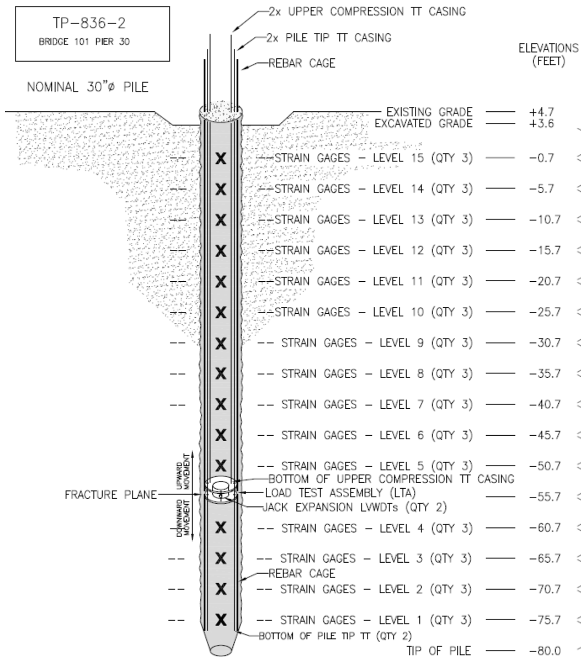
3x3 @ 2.5D *3x3 @ 4D*



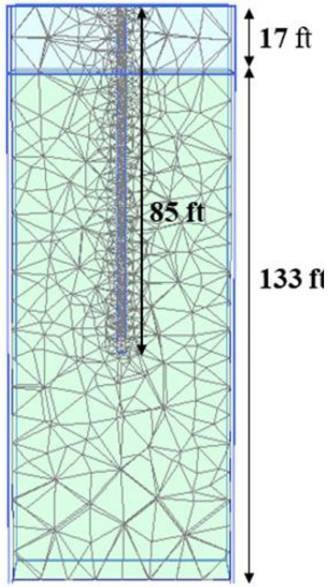
VALIDATION WITH BIDIRECTIONAL LOAD TESTS

Numerical model validation (Full-scale test Miami)

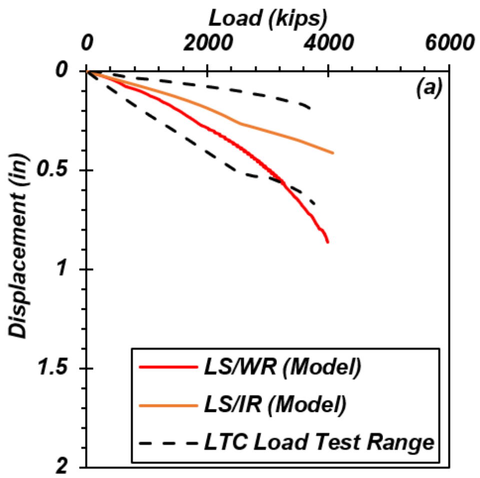
- <u>Field measurements:</u> Bi-directional load test at Bridge No. 101 on SR 836 in Miami, Florida.
- <u>Test pile:</u> 85 ft-long, 30 in-diameter.
- <u>Soil profile:</u> Defined based on SPTs. A 17 ft-thick weathered limestone over a more competent strata.
- <u>FE model:</u> Modeled with a top sand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



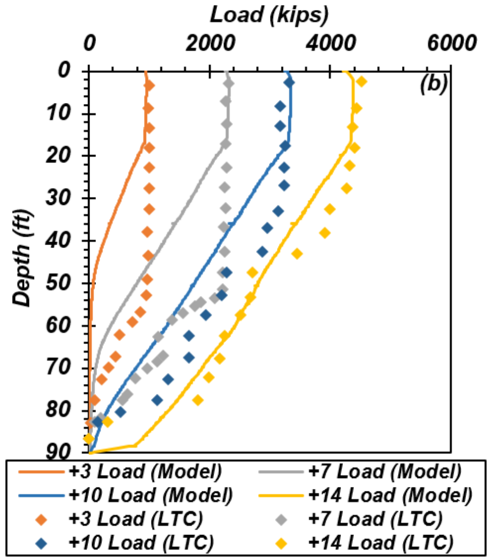
Load test schematic



FEM geometry



Load vs displacement

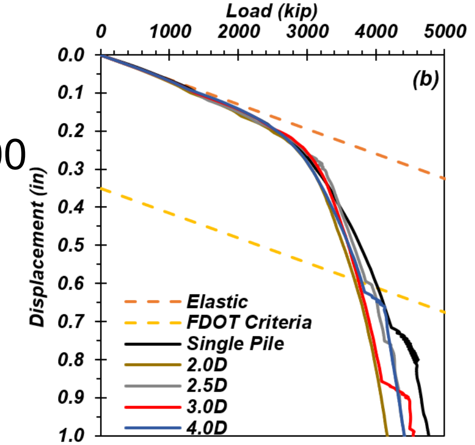


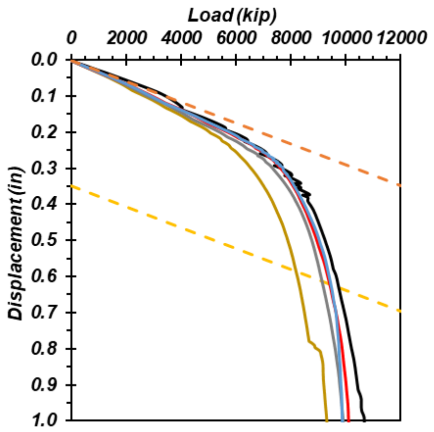
Load transfer mechanism

- **Cases**: single, 2 × 2, 3 × 3, 4 × 4; S/D = 2–4; GSI = 50–100
- **Spacing**: More interactions in 2D than 4D.
- **Sand**: 2D shows more shaft resistance in sand; 4D sand contribution negligible.
- **Takeaway**: Model found S/D influence on axial capacity, 3 × 3 shows more interactions than 2 × 2

- **Group efficiency (η)**: $\eta = \dfrac{P_{group}}{\Sigma P_{single}}$

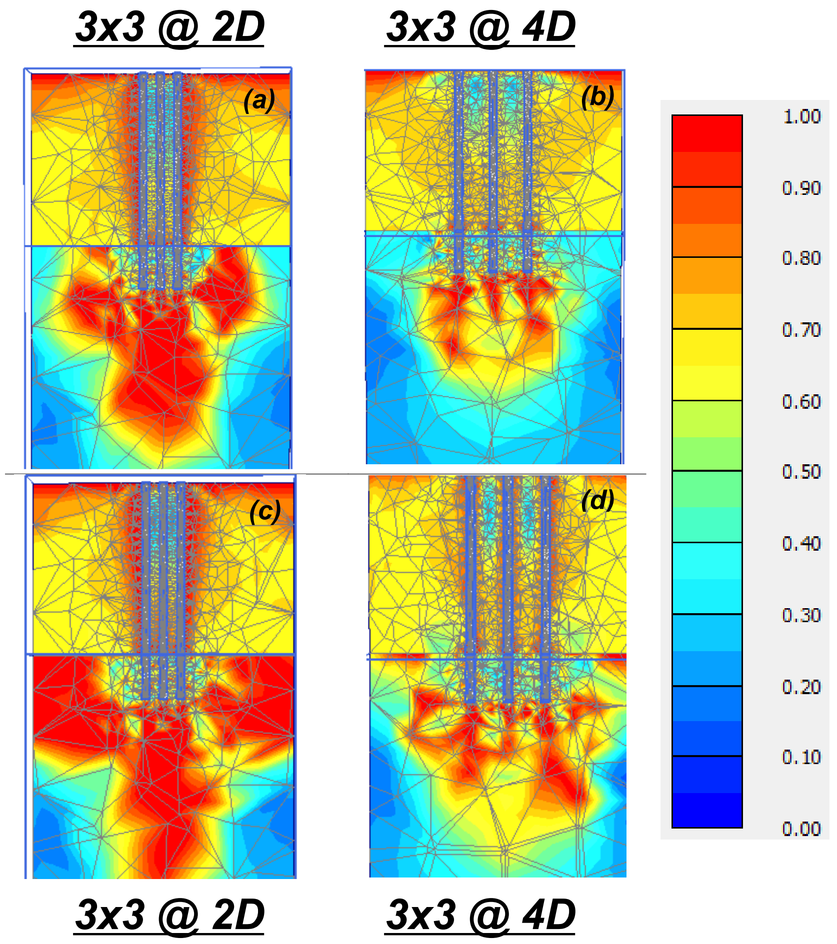
2x2 groups and LS/50





3x3 groups and LS/50

LS/50 for: intact-K_0 conditions



LS/50 for: reduced-K_0 conditions

EBC MODEL RESULTS FOR TWO-LAYER CASE

Baseline numerical model geometry | **EBC model results for two-layer case** | SRC model results for single pile and groups | Efficiency charts

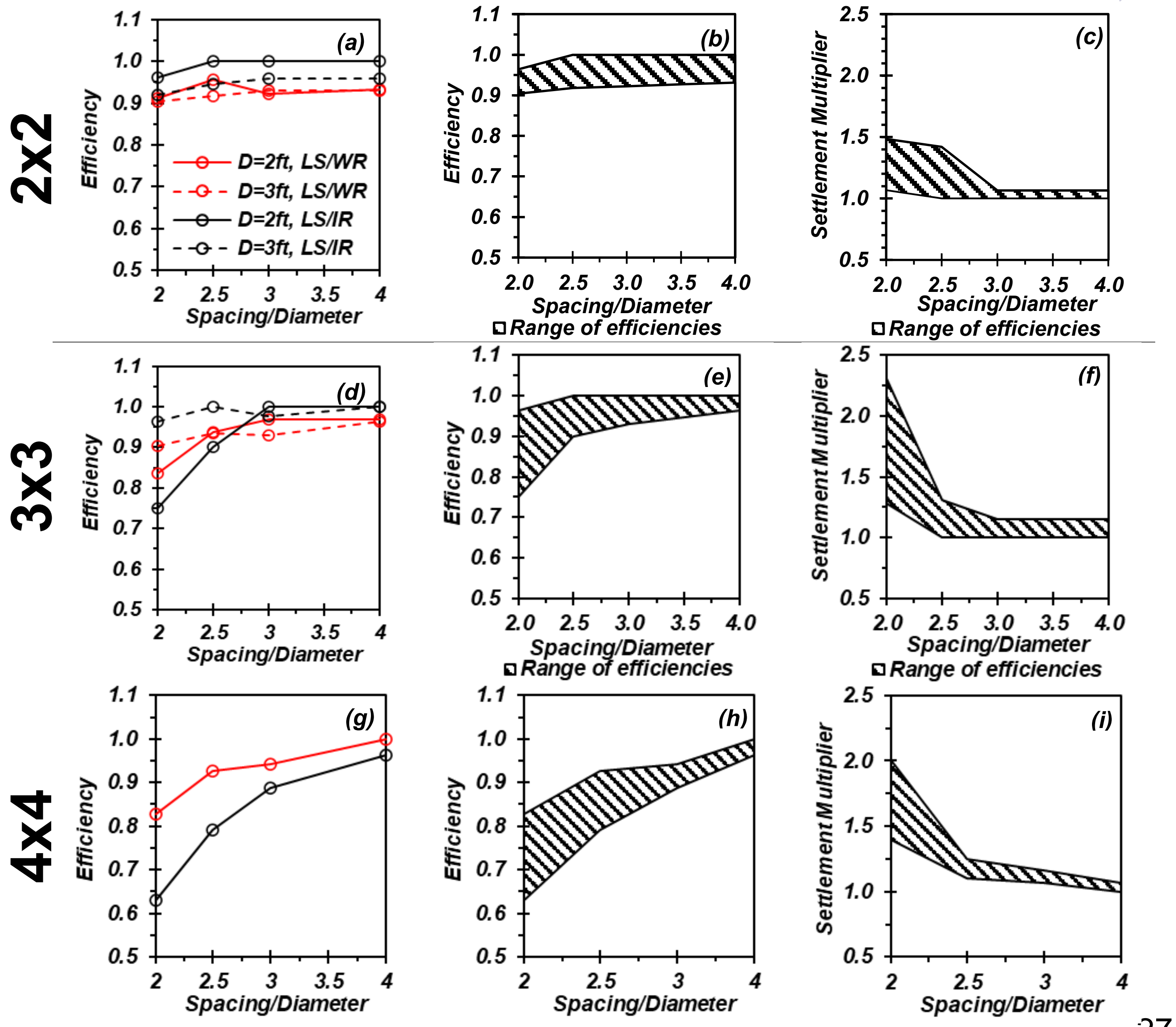
•**Scope**: LS/100 & LS/50; **Output**: η (efficiency) and settlement multiplier.

•**2 × 2**: η ≥ ≈ 0.90 across 2–4D (limited interference).

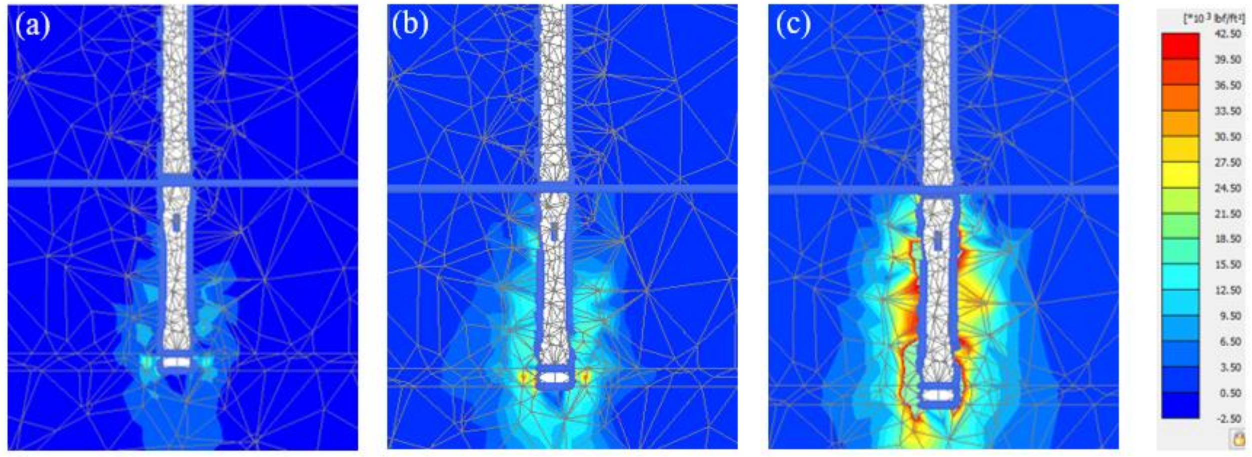
•**3 × 3**: η drops to 0.75 when the spacing is 2D.

•**4 × 4**: η drops to 0.65 when the spacing is 2D.

•**Threshold**: Group effects notable for S/D < 2.5D, consistent with FDOT 2.5D norm.



SRC MODEL RESULTS FOR SINGLE ACP



Mobilized shear stress contours for single ACP and GSI values of: (a) 30, (b) 50, and (c) 90:

- **Avg. side shear** stresses at failure along interface: GSI of 30, 50, and 90 were 7, 10, and 25 ksf.

- **FEM side shear stresses** are reasonable and within expected ranges

- **Stress bulbs** are highly localized around the perimeter of the piles

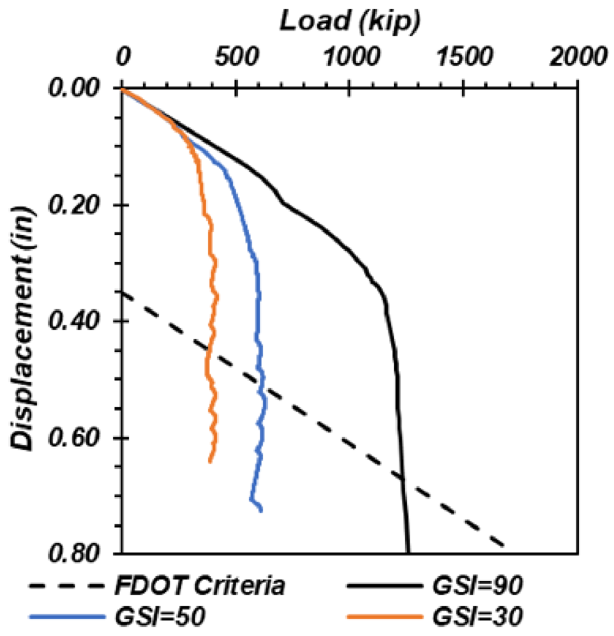
FEM results for single ACP:

- Higher GSI, larger capacity. Clear **plunging** failure.

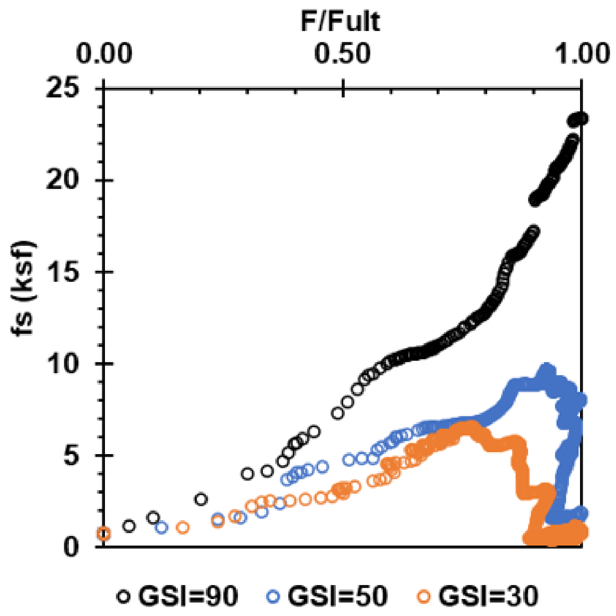
- GSI = 30 and 50 show increase in side shear up to max. of 7 ksf and 10 ksf.

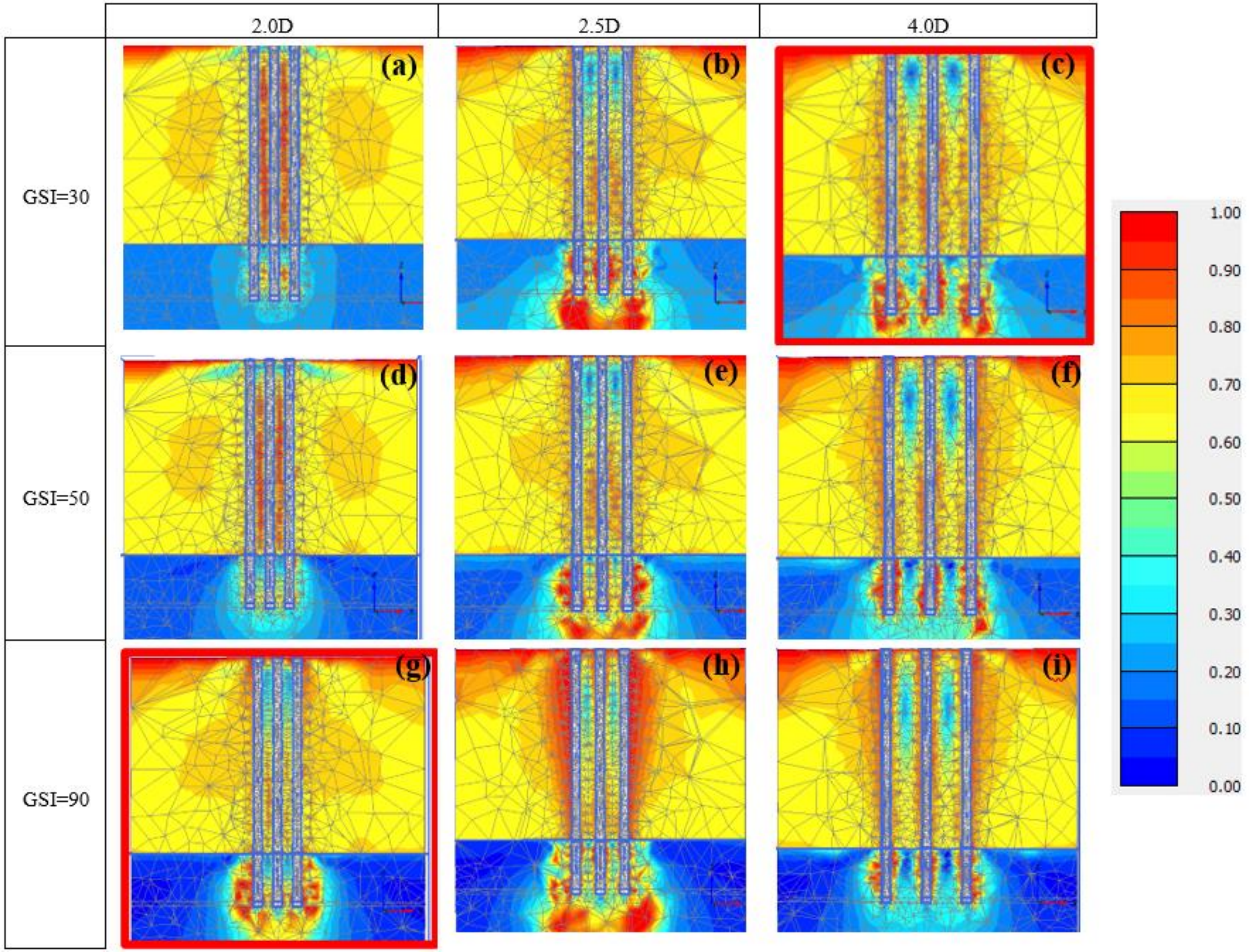
- Side shear increases continuously for GSI of 90. This confirms conclusions by O'Neill and Hassan 1994.

Load-displacement curves



Side shear **development with increasing *top load***





Shear stress contours for GSI of 30, 50, and 90 and S/D ratios:

- For 4.0D spacing: no overlapping of stress bulbs because piles are located far enough, avoiding interaction effects.

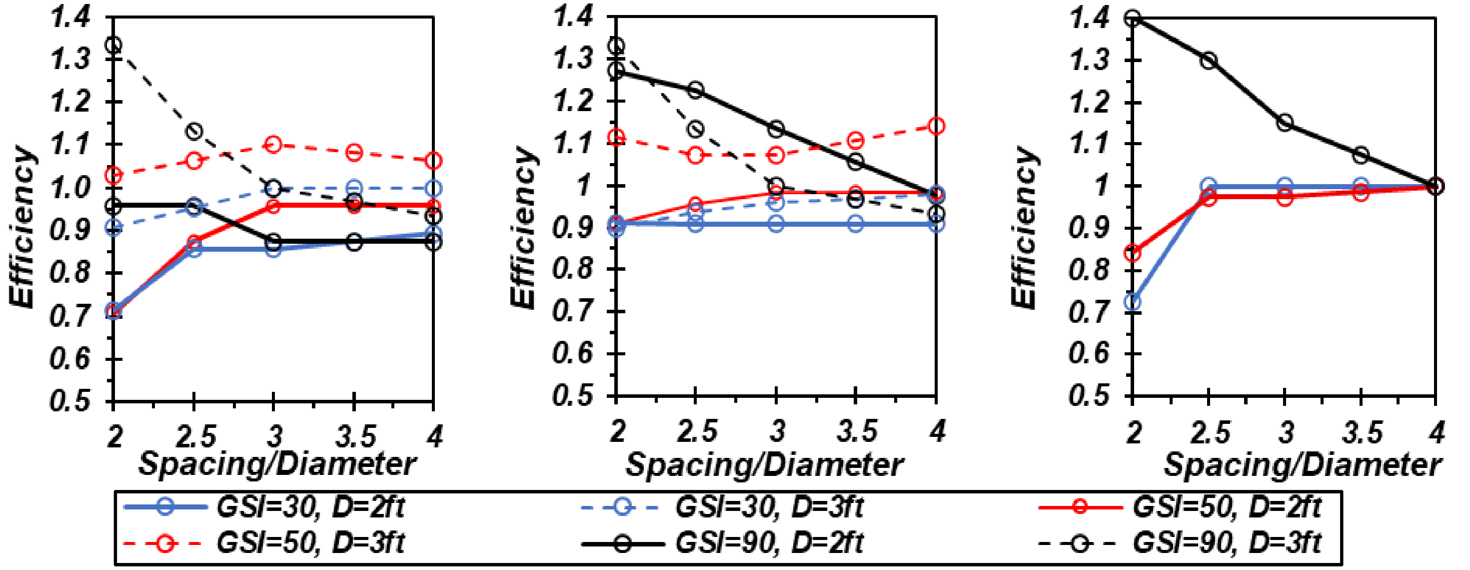
- Stress bulbs overlap more as spacing reduces, causing slight reduction in group efficiency.

- See extreme case: GSI 90 at 2.0D: no significant side shear development among piles (similar to Liu et al. 1985)

EFFICIENCY FACTORS IN SRC CASE

Baseline numerical model geometry → EBC model results for two-layer case → **SRC model results for single pile and groups** → Compilation of efficiency charts

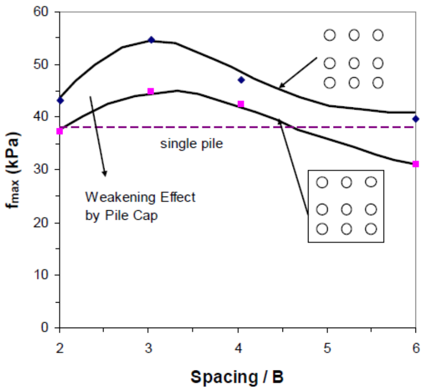
- **Computed efficiencies** vs. S/D for field-scale soil profile and several GSI:
(a) 2x2
(b) 3x3
(c) 4x4



(a) (b) (c)

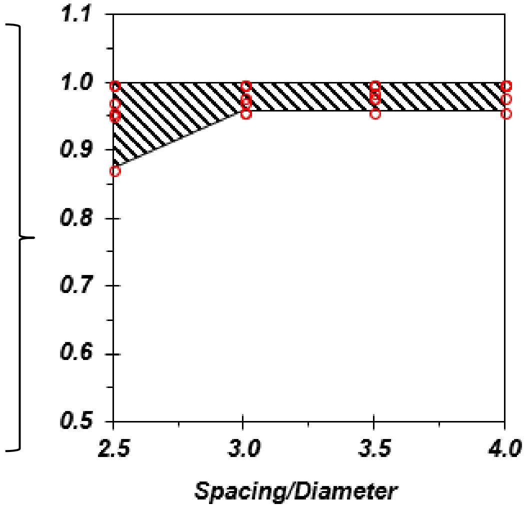
- For extreme tight spacing (2.0D), η ≥ 0.7

- η ≥ 1 for GSI > 90 due to effect of confinement of adjacent piles.



Liu et al. (1985)

Summarized η for S/D > 2.5 for SRC case. Single, 2x2, 3x3, and 4x4 groups.

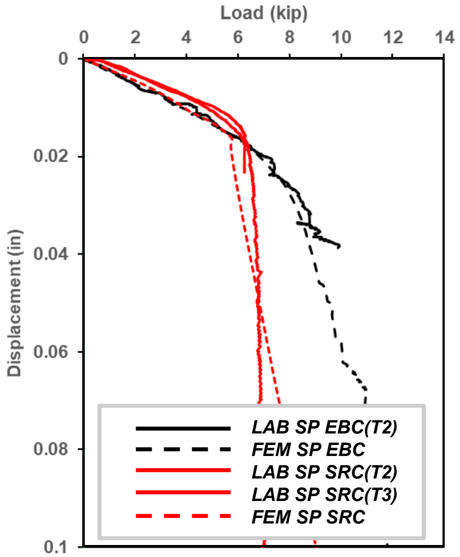


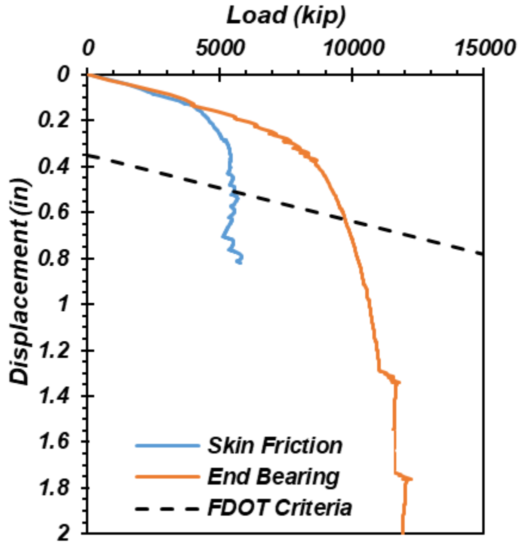
COMPARISON EBC VS. SRC

Baseline numerical model geometry → EBC model results for two-layer case → SRC model results for single pile and groups → **Compilation of efficiency charts**

Load-Deformation Curves

Single ACP Physical Model (**Measured Vs. FEM**)

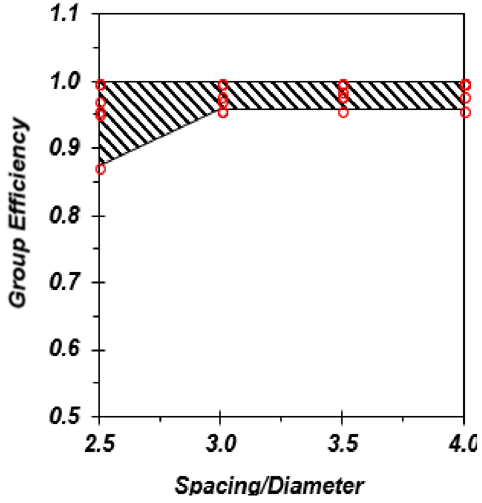


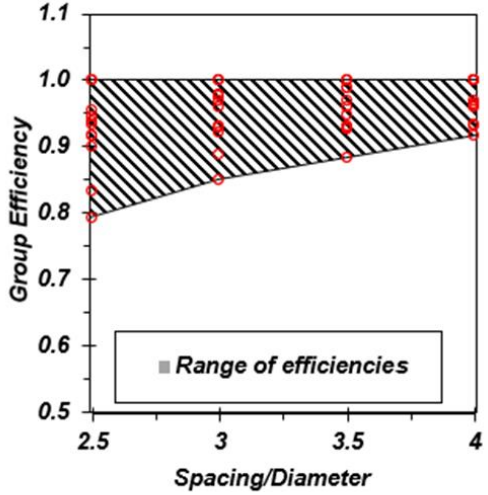


Single ACP **(Field-Scale Models)**

Efficiency Factors

SRC case





EBC case

Summary and justification:

- ACP groups installed in weathered limestone present geotechnical challenges due to the variability of the rock formation and ACP performance based on rock quality. Weathered limestone ranges from soft to moderately hard and causes inconsistent end-bearing conditions across the ACP group. Weathered zones exhibit low RQDs and RECs reducing confidence in end-bearing capacity.

- Construction of ACP groups in weathered limestone may not provide reliable end bearing due to uncontrolled drilling or inadequate cleaning leading to loose materials or voids at pile base, reducing contact and bearing area. ACPs are mainly designed to work based on side resistance at the rock socket.

Selected conclusions from laboratory and numerical results:

- In the laboratory tests, maintaining full penetration and diameter of ACPs was difficult in transition zones from soils to limestone, which generated variability in as-built ACPs. In real conditions, ensuring clean pile bases is also difficult in weathered limestone.

- When response is EBC, ACPs carry more load, leading to non-uniform stress and settlement distribution within the ACP group. Load tests were influenced by variations in the synthetic limestone quality and construction practices in the laboratory, but in general the results are consistent with controlled numerical simulations and with expected results.

- In weak limestone, SRC cases are not as affected by group effects. Under the laboratory and FEM conditions, reducing the spacing from 4D to 2.5D did not significantly influence ACP group behavior for the SRC cases. For EBC cases, behavior is more sensitive to S/D considerations.

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