Herbert Wertheim College of Engineering
UNIVERSITY of FLORIDA

DEPARTMENT OF CIVIL & ENVIRONMENTAL ENGINEERING

FAMU-FSU College of Engineering

DEPARTMENT OF CIVIL AND COASTAL ENGINEERING

Residual Stresses in Florida Bored Piles
BED31-977-28

FDOT GRIP Meeting

FDOT Project Managers:
PM: Rodrigo Herrera, P.E.
Co-PM: Kelly Shishlova, P.E.

UF and FSU Project Investigators:
UF PI: Michael Rodgers, Ph.D., P.E.
FSU Co-PI: Scott Wasman, Ph.D.

August 13th, 2026

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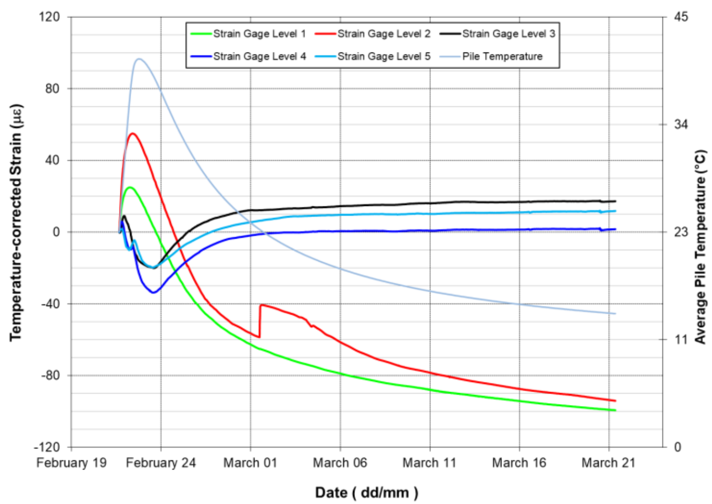
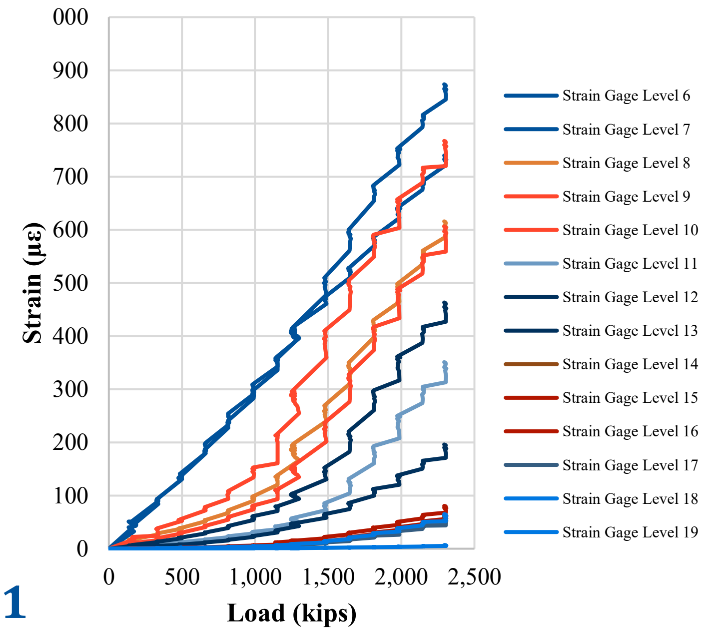
Introduction: Residual Stress in Deep Foundations

- **Residual stresses develop in piles/shafts during grout curing**
  - Influenced by pile length, soil/rock layering, geometry, and grout behavior
- **Residual stress alters pile load-transfer behavior**
  - Changes side-shear mobilization and measured strain response
- **Residual stress can affect load-test interpretation and MWD correlations**
  - May also contribute to cracking and long-term performance concerns
- **Residual stress is rarely quantified during curing and load testing**
  - **Conventional instrumentation and DFOS are combined to define residual-stress development and load-transfer effects**
    - **Conventional gauges provide the basis for analysis**
    - **DFOS provides a higher-resolution view of strain and temperature development**

Background – Grout Curing Tension Strain

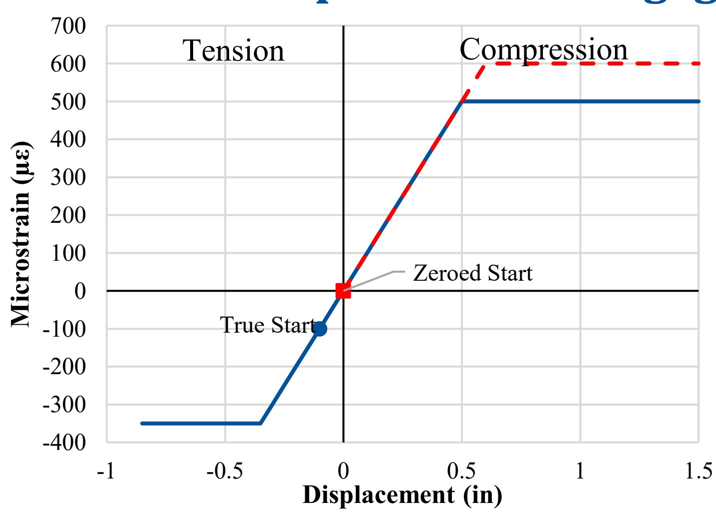
Strain measurements during curing

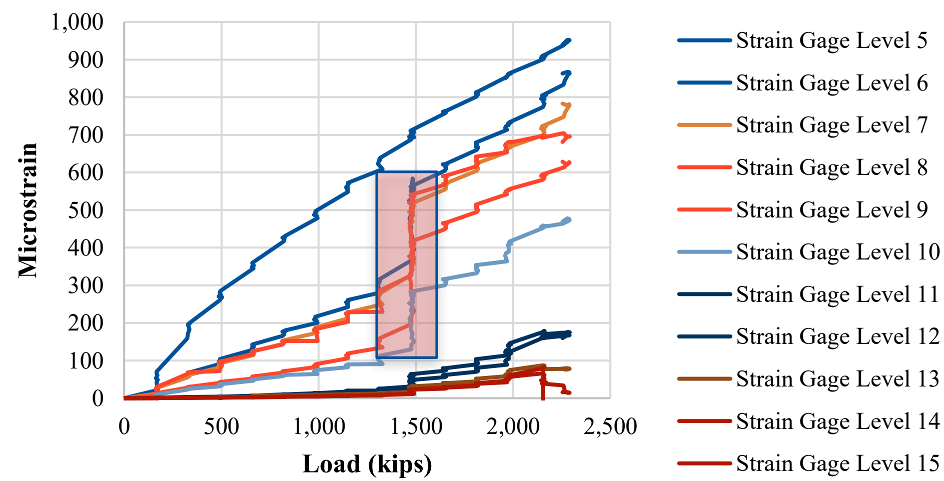




Strain Gauge Level	Maximum Strain (με)
7	873.6
9	767.0
6	739.8
8	615.8
10	606.3
12	463.2
11	350.9
13	196.0
15	80.5
18	65.6
16	65.0
14	60.9
17	55.9
19	6.6

Theoretical load path for strain gage 1





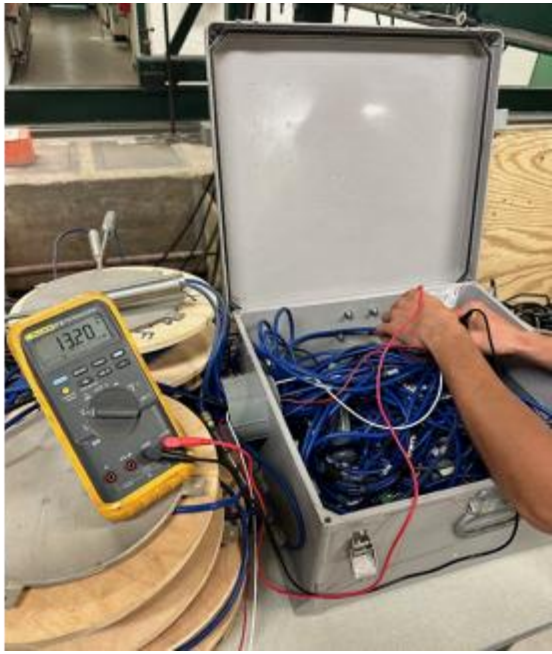
- **Project Objectives**
  - Evaluate thermal effects and residual stress development in ACIP piles
  - Develop axial capacity methods that account for residual stress
  - Expand the South Florida limestone MWD dataset
- **Three-pile test program:**
  - MWD and rock core characterization
  - Grout mix, strength, and thermal testing
  - DFOS and strain-gauge monitoring during curing
  - Instrumented axial load testing
  - Curing analysis and residual-stress T–Z model development

Task 1: Instrumentation Planning, Literature Review, and Sample Collection

- **Reviewed prior fiber-optic applications in deep foundations**
  - Drilled shafts, ACIP piles, driven piles, and micropiles
- **Developed DFOS installation plan for bi-directional load testing**
  - Coordinated with load-test consultants to ensure cable protection and data quality
- **Developed DAQ system for continuous conventional strain-gauge monitoring**
  - Captures pile curing behavior prior to load testing
- **Coordinated collection of existing soil and rock samples for Task 4**
  - Thermal conductivity will be evaluated as a factor in curing and load response

Task 1: Instrumentation Planning, Literature Review, and Sample Collection

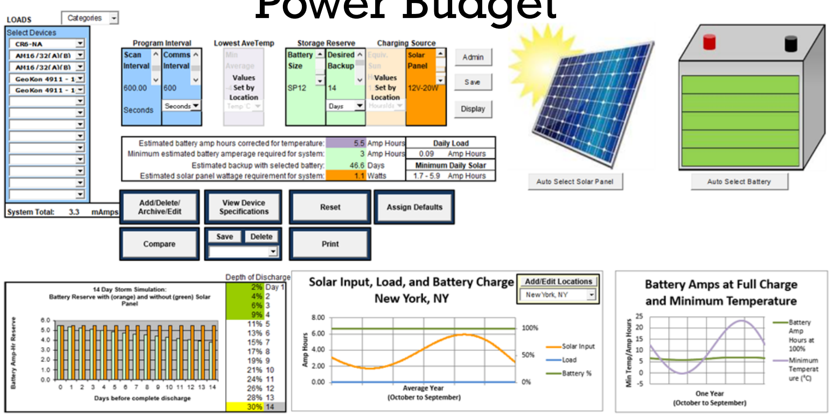
Continuous Data Collection – DAQ Programming

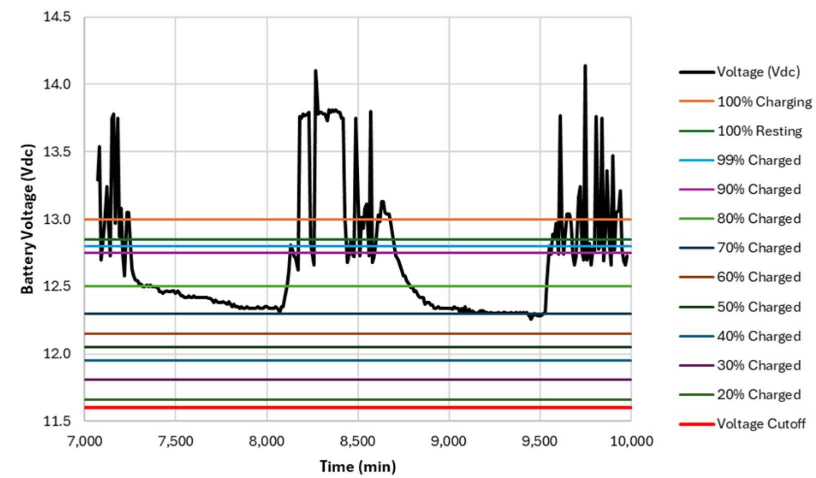


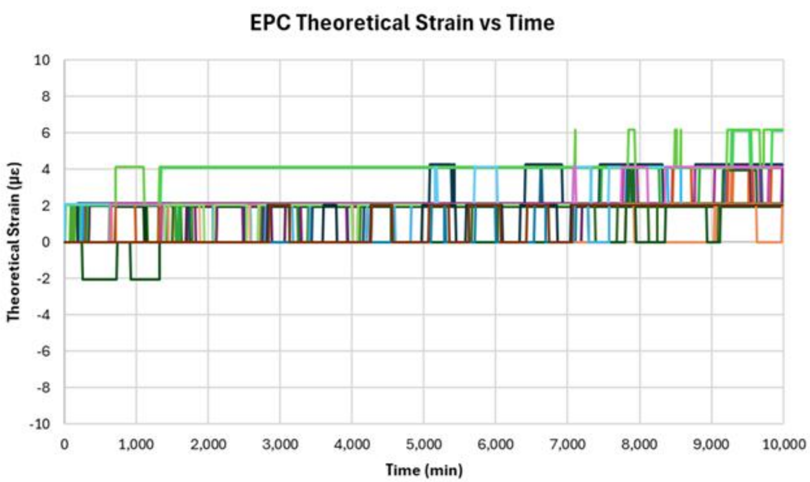
Task 1: Instrumentation Planning, Literature Review, and Sample Collection

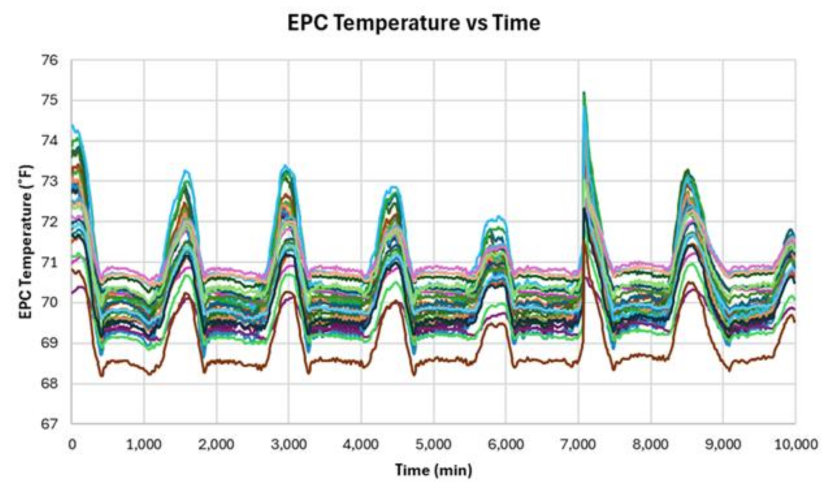
Continuous Data Collection Trials – VW Gauges

Power Budget





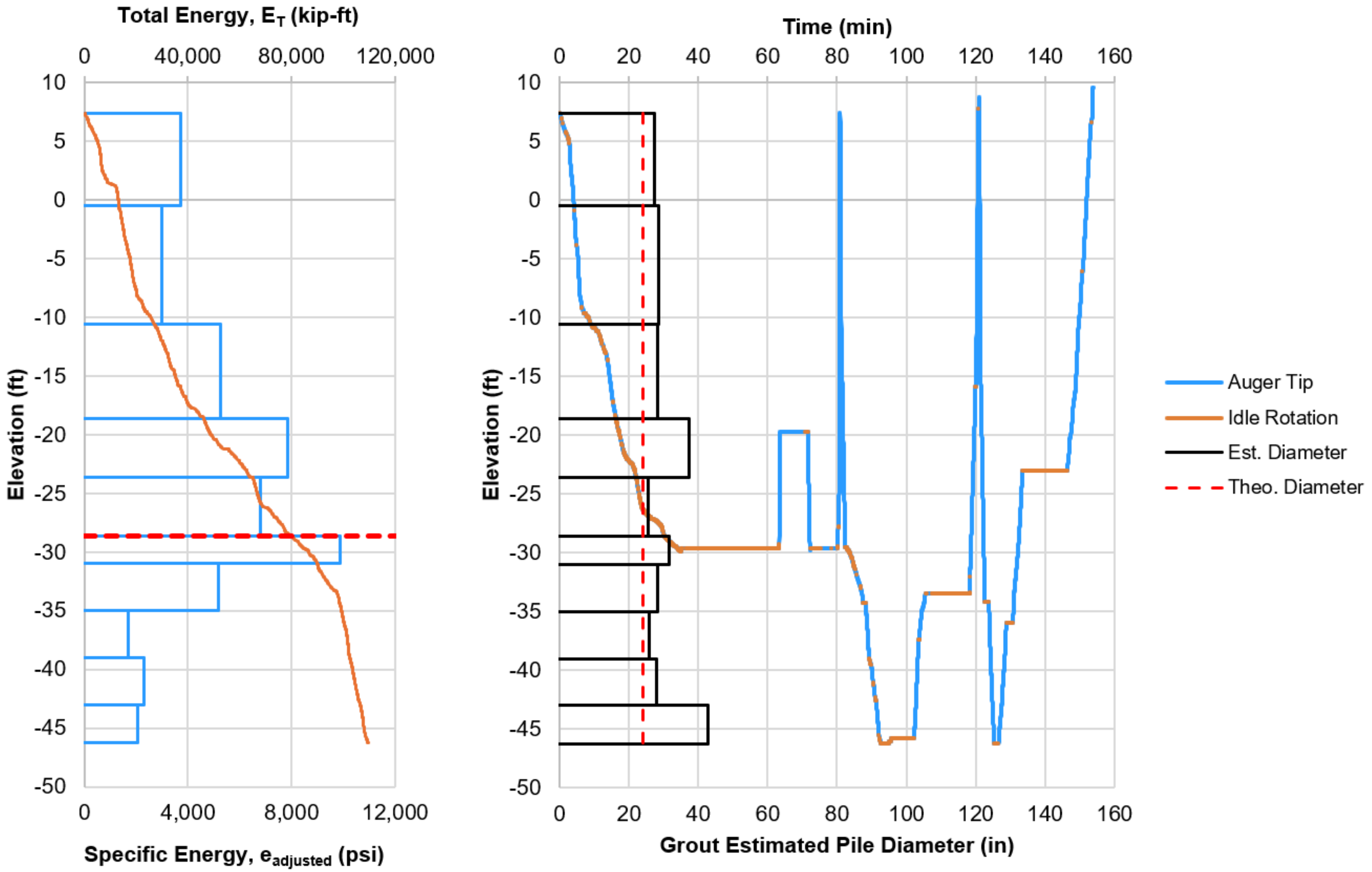




Task 2: MWD Investigation for ACIP Test Piles

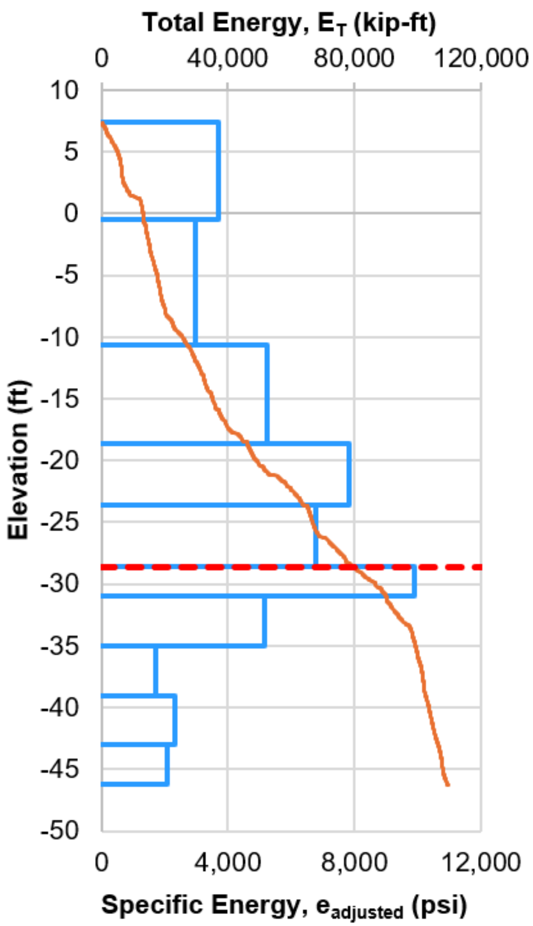
- **Task 2 comprised of 3 subtasks**
- **Each subtask includes the completion of MWD during the installation of one load tested ACIP pile to compare MWD with load test results**
  - MWD data used to determine strength layering via specific energy
  - Provide insight to materials present over the full span of the ACIP piles
- **MWD will also be used to investigate the drilling process**
  - **Assess the influence on pile geometry, pile performance, and the development of residual stresses within the piles**

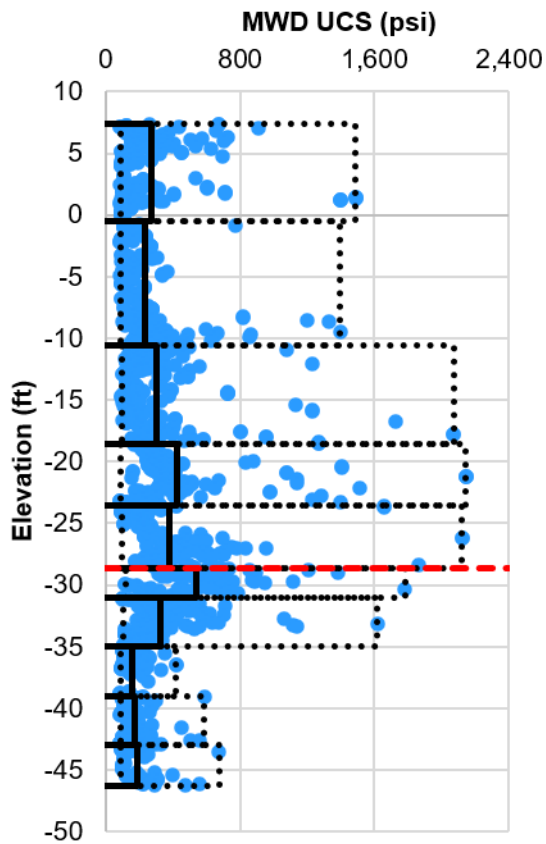
Task 2: MWD Investigation for ACIP Test Piles

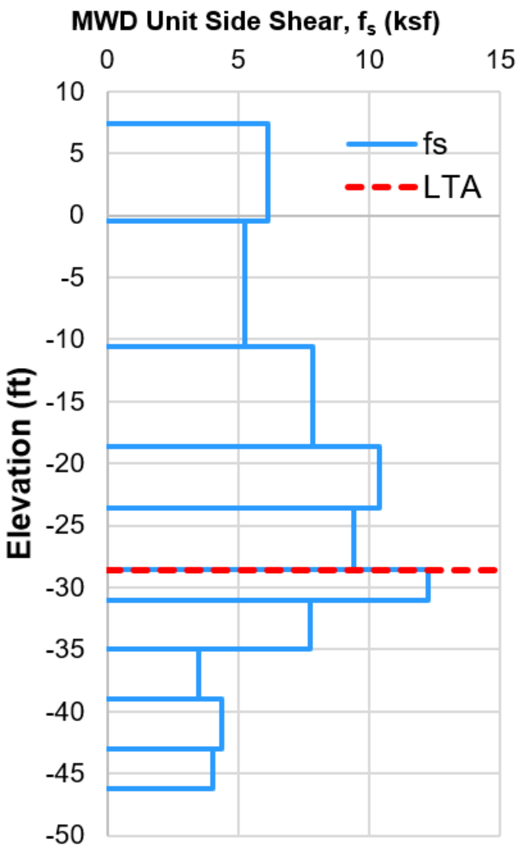


Task 2: MWD Investigation for ACIP Test Piles

Can we validate MWD strength assessments to serve as an independent referee?







Core UCS Range

124 psi to 2,060 psi

Task 2: MWD Investigation for ACIP Test Piles

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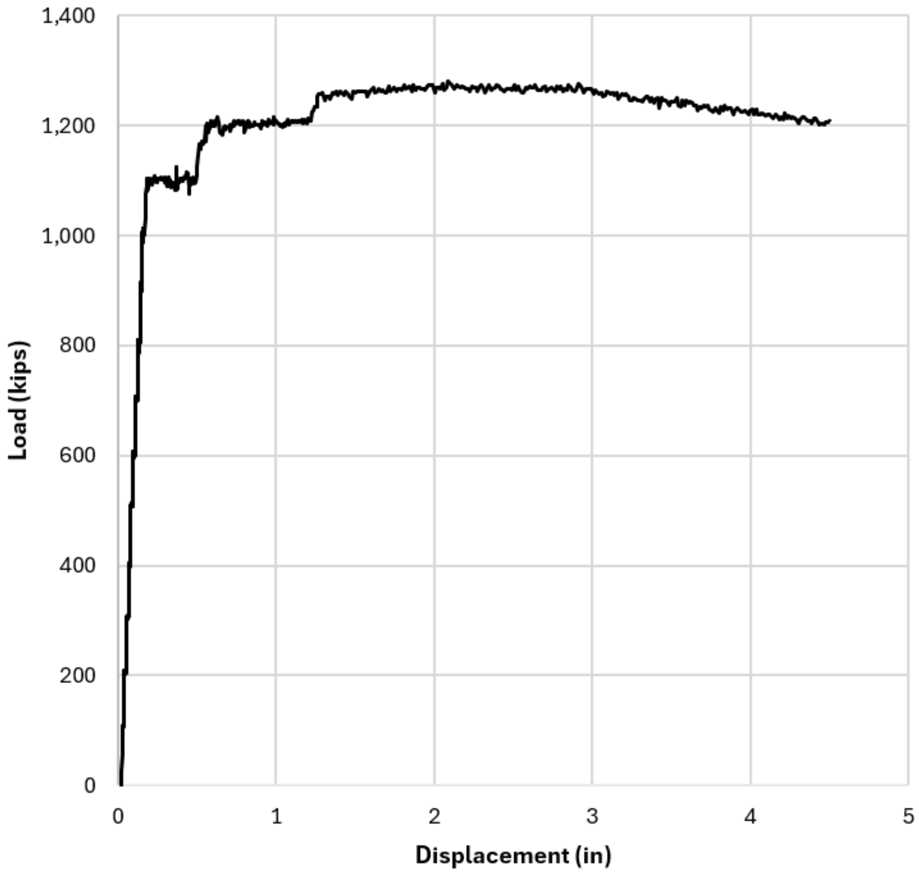
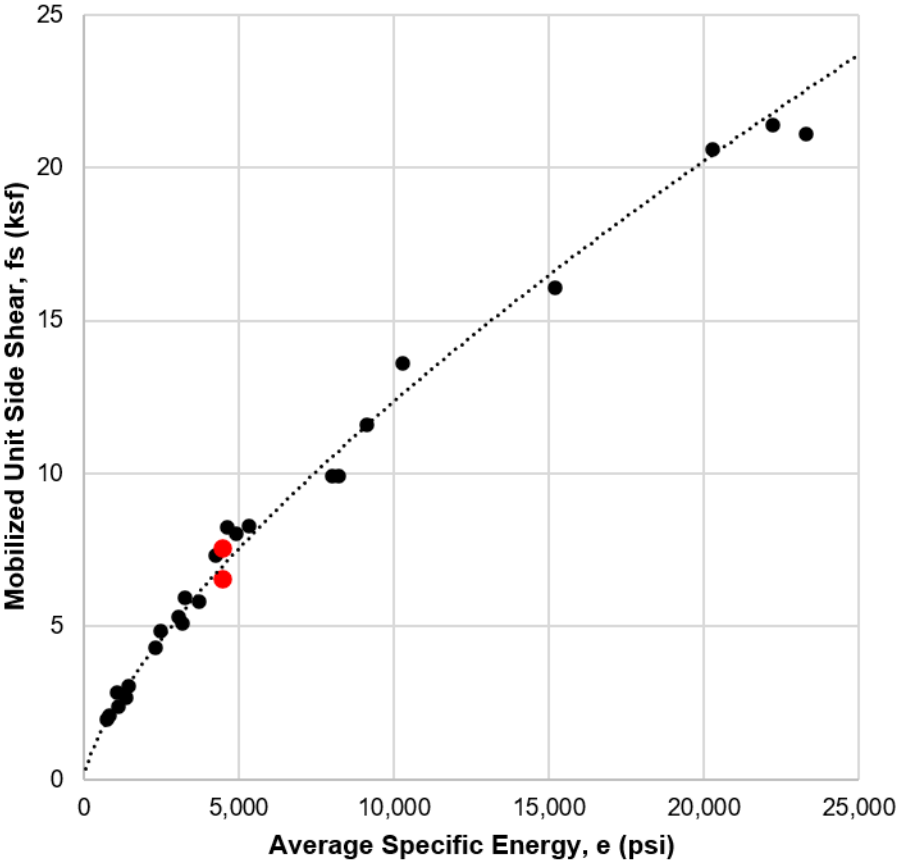




Task 3: Instrumented ACIP Piles for Curing Behavior and Static Load Tests

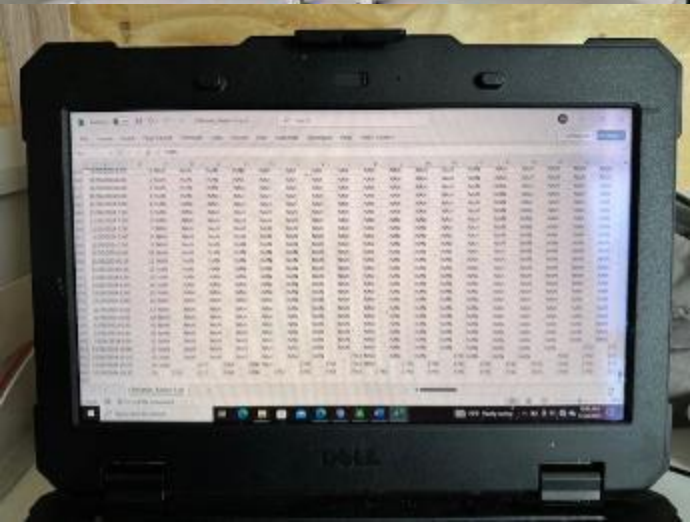
- **This task consists of instrumenting and load testing 3 full scale ACIP piles with fiber optic cables and vibrating wire strain gages**
  - Data collected from DFOS and VW Strain gages will be compared
  - The DFOS data will also be used to improve and/or test MWD correlations for the formations tested in Task 2 and 3
- **Development of a draft test standard for DFOS load test data reductions**

Task 3: Instrumented ACIP Piles for Curing Behavior and Static Load Tests

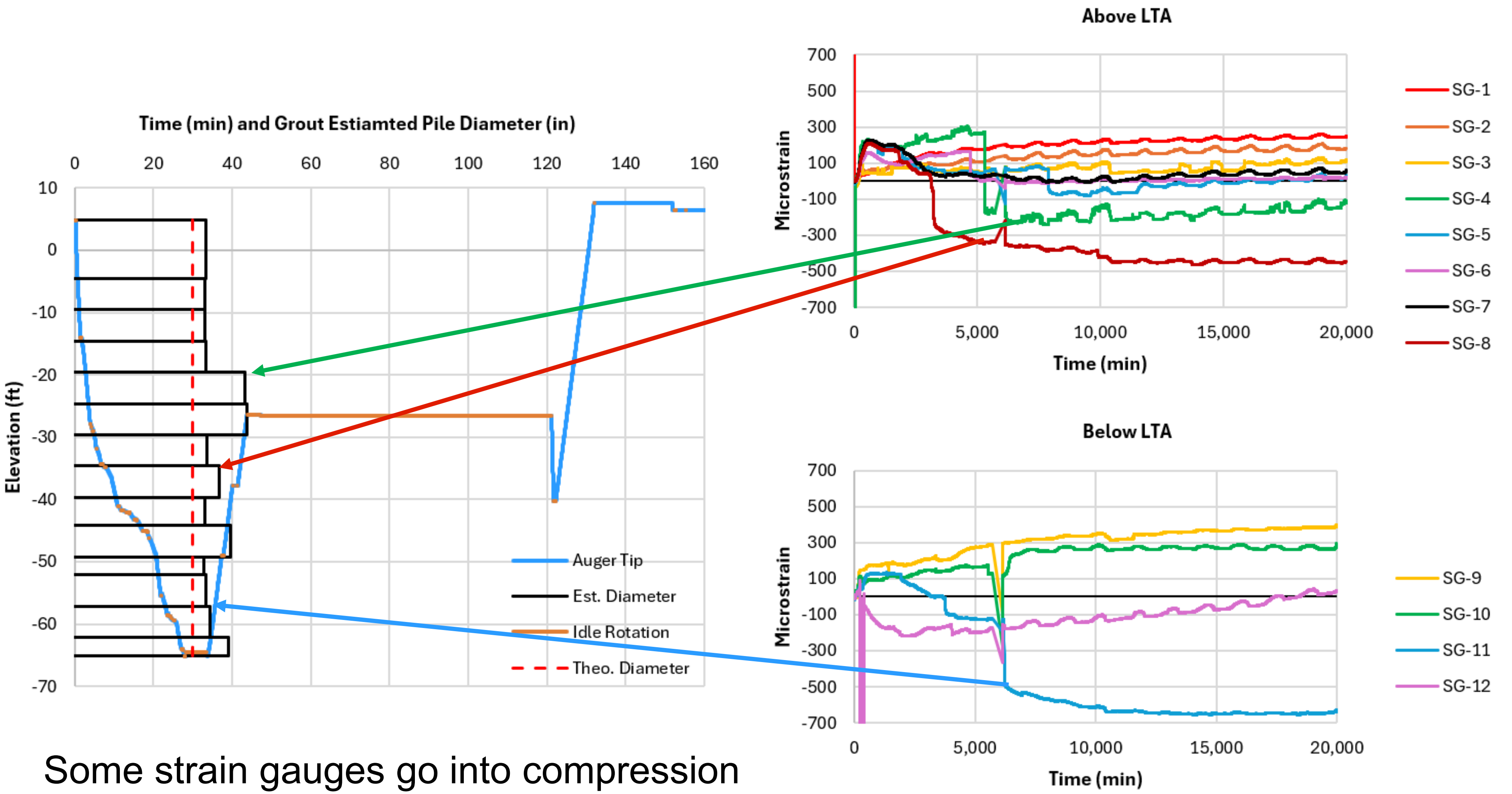
Installing VW Strain Gauges

Task 3: Instrumented ACIP Piles for Curing Behavior and Static Load Tests

Connecting to DAQ System

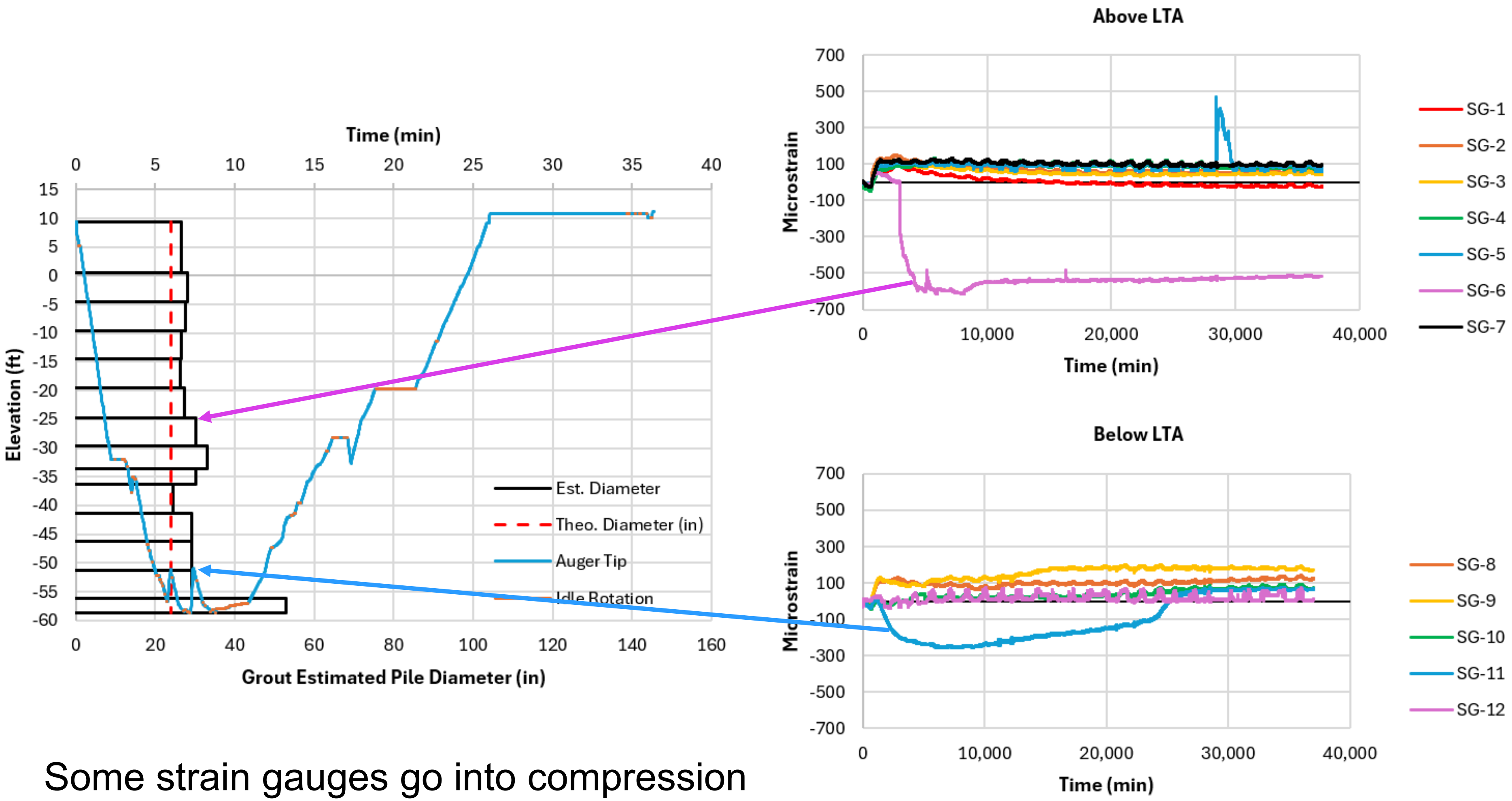


Task 3: Instrumented ACIP Piles for Curing Behavior and Static Load Tests



Some strain gauges go into compression and some go into tension

Task 3: Instrumented ACIP Piles for Curing Behavior and Static Load Tests



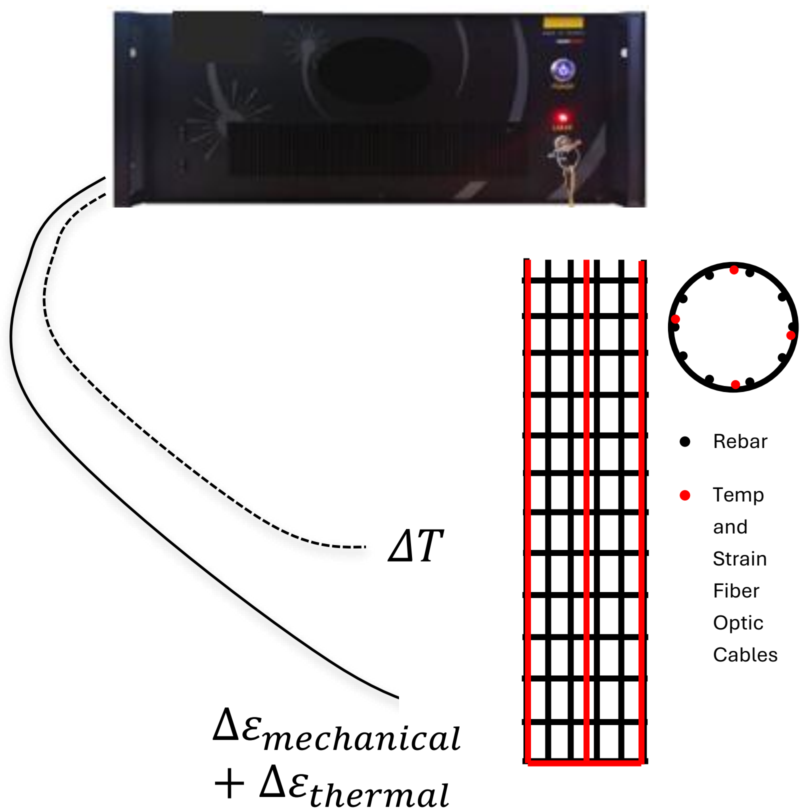
Some strain gauges go into compression and some go into tension

Task 1: Instrumentation Planning, Literature Review, and Sample Collection

- Measure thermal strain and temp of grout cylinders (early age to setup) for approved mix designs
  - 1st FIU Pedestrian bridge pile grout mix
- Cores collected from Ocala formation, Avon Park, Miami Formation, Ft. Thompson Formation, and Key Largo Formation
- Volumetric change of limestone during thermal loading
  - Depending on drained or undrained behavior, temp and stress history (OCR), confining pressure, mineralogy, density, and saturation, soil and rock can contract or expand in response to heating and cooling
  - In general, sedimentary rock, clays, silts and sands that are partially or fully saturated will expand in response to accelerated heating (grout heat of hydration)
    - Excess pore pressure development and decrease in strength (recoverable in some geomaterials and not in others)
  - In situ borehole volume and stresses may be altered due to the thermal loading.
  - Rate of thermal loading influenced by geomaterial thermal conductivity.

Task 1: Instrumentation Planning, Literature Review, and Sample Collection

Distributed Fiber Optic Sensing (DFOS) temp and strain for force and displacements



If fiber optic cables are cast in a pile the force distribution and the axial displacements can be determined as follows

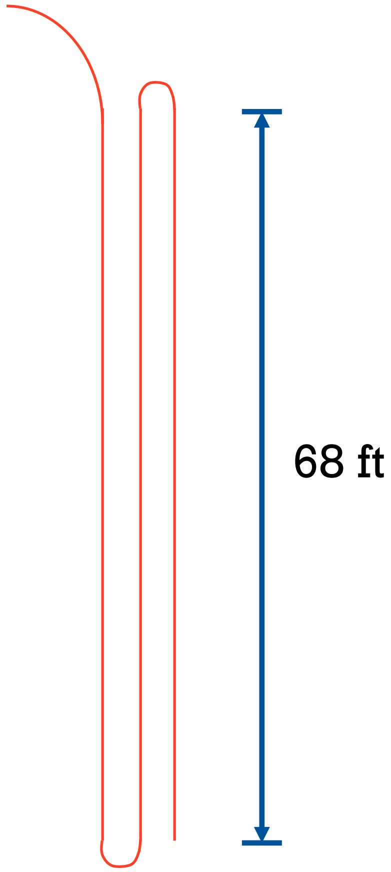
$$F_a(z) = EA \cdot \varepsilon_{M\ or\ T}(z)$$

$$u(z) = u(z = z_0) + \int_0^z \varepsilon_{M\ or\ T}(z)dz$$

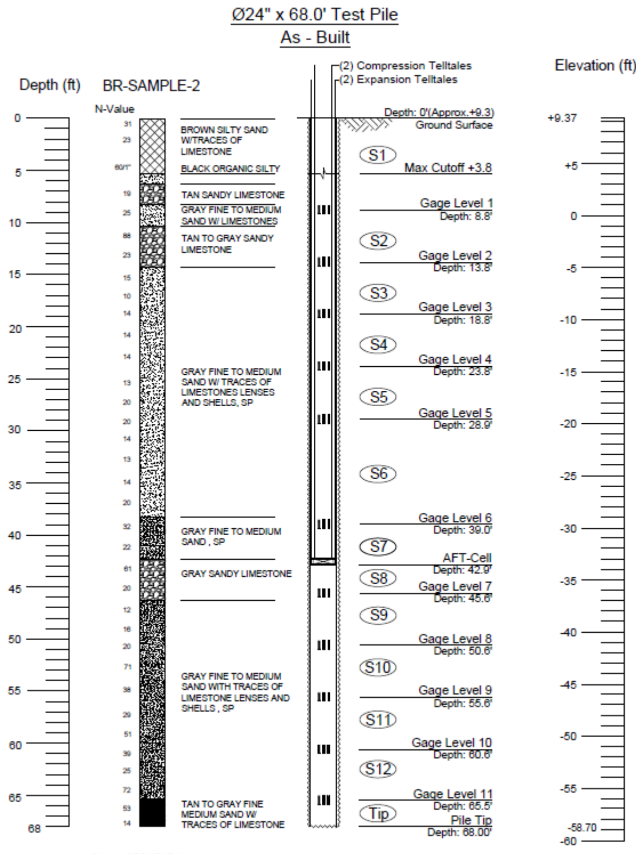
Where EA (E = Youngs modulus and A = pile cross sectional area) is the axial rigidity of the pile, ε_M is the mechanical strain, ε_T is the thermal strain, z is the depth from the top of the pile, z_0 is the absolute vertical displacement at the top of the pile.

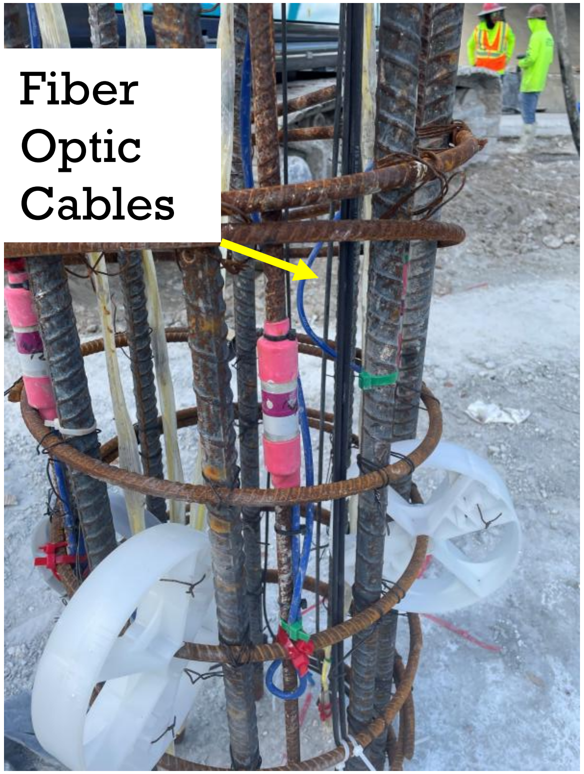
Task 3: Instrumented ACIP Piles for Curing Behavior and Static Load Tests

Fiber Optic Installation-Sawgrass Test Pile



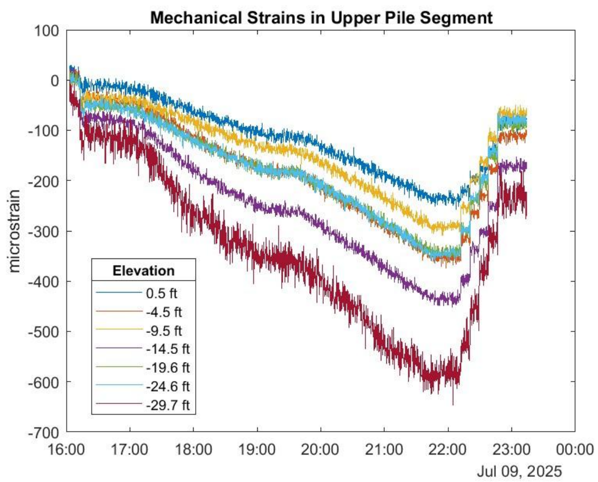
Fiber Optic Cable

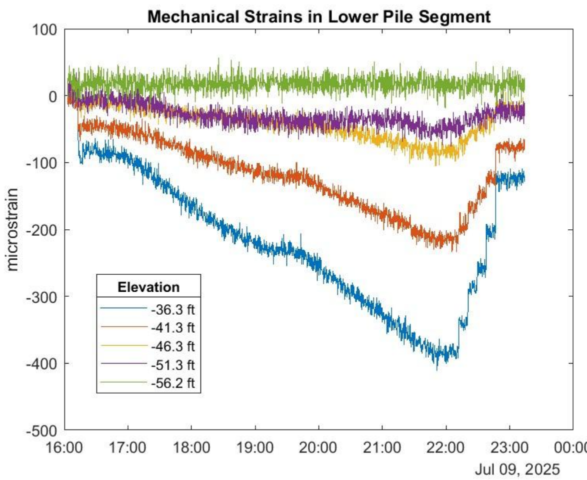


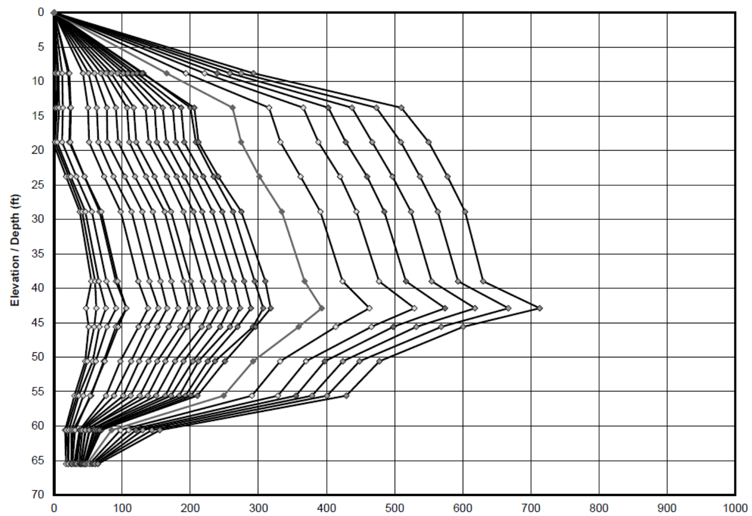


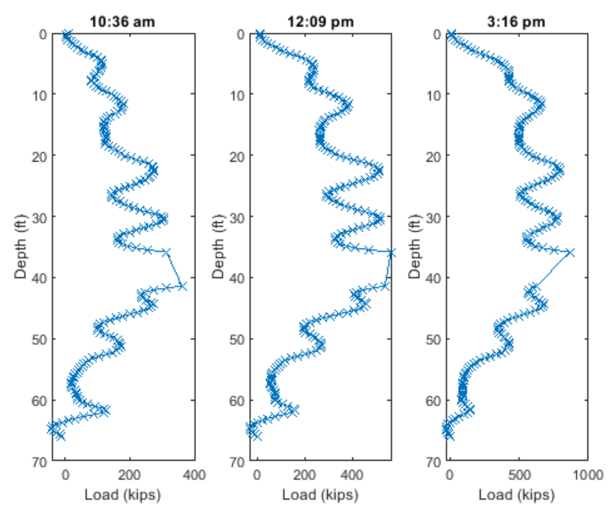
Task 3: Instrumented ACIP Piles for Curing Behavior and Static Load Tests

Sawgrass Pile-Load Test Phase







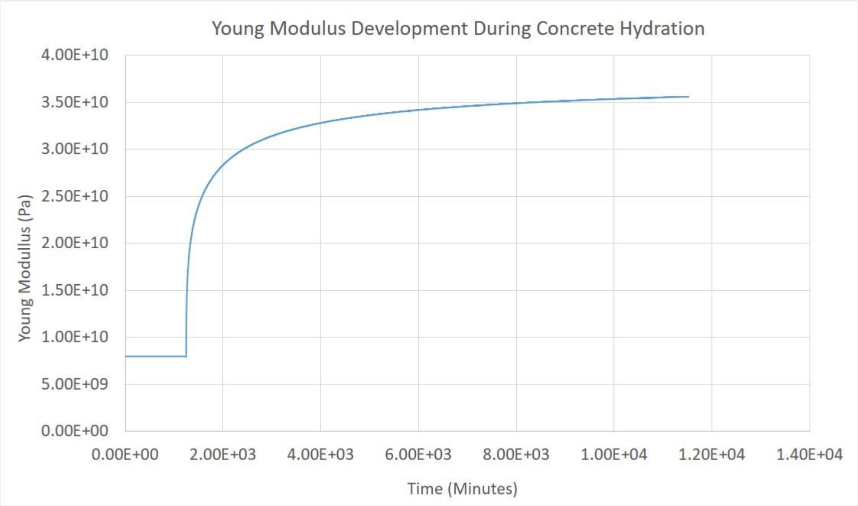


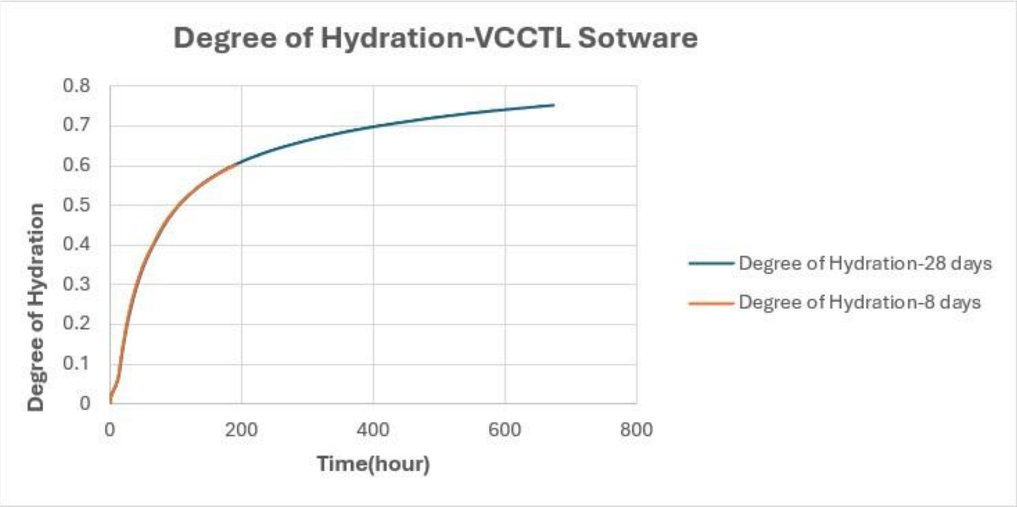
Task 4: Grout Mix and Geomaterial Thermal Investigation

- Investigate modulus and thermal hydration of grout mix designs and thermal properties of FL geomaterials in South FL
  - Identify the grout mix designs used on test piles in Task 3 and obtain core samples during Tasks 1 and 2
  - Thermal conductivity measurements of geomaterials
  - Controlled testing grout mixes with varied additives
  - Measure temperature and thermal stress using DFOS

Task 4: Grout Mix and Geomaterial Thermal Investigation

Grout Mix





$$\beta_{cc}(t) = \exp\left[s\left(1 - \sqrt{\frac{28}{t}}\right)\right]$$

$$\beta_E(t) = [\beta_{cc}(t)]^{0.5}6$$

$$E_{ci}(t) = \beta_E(t)\, E_{c,28}$$

Where:

$\beta_{cc}(t)$, is a function used to describe the strength development with time

t, is the concrete age in days, adjusted to account for temperature during curing

S, is a coefficient that depends on the strength class of cement = 0.25.

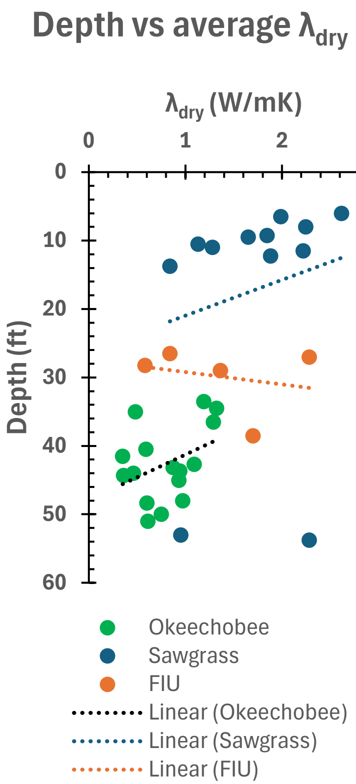
$\beta_E(t)$, is the coefficient which depends on the type of cement (strength class) and the compressive strength

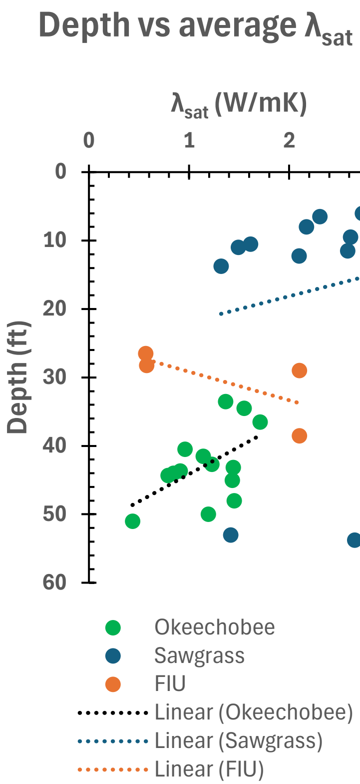
$E_{ci}(t)$, is the modulus of elasticity in MPa at an age t in days

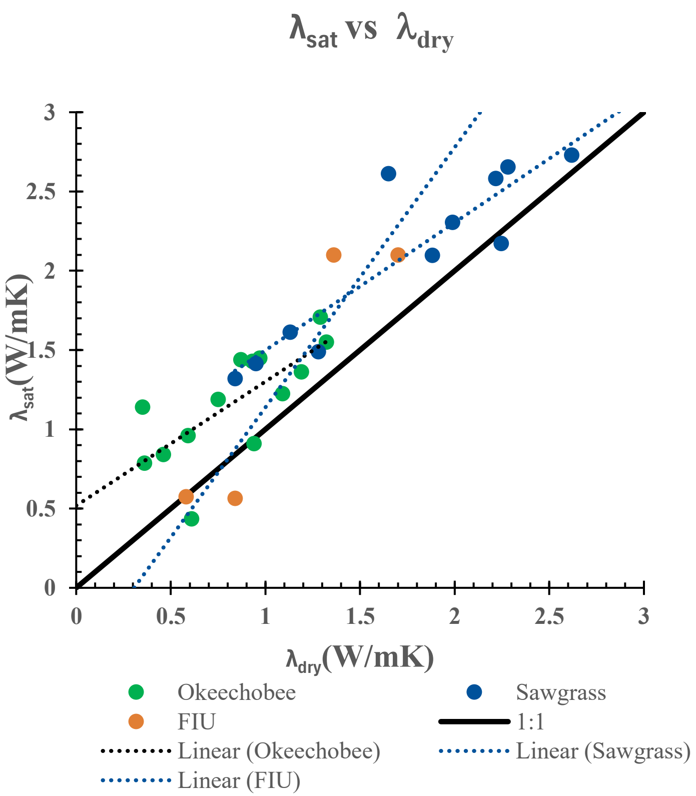
$E_{c,28}$, is the modulus of elasticity in MPa at an age of 28 days

Task 4: Grout Mix and Geomaterial Thermal Investigation

Thermal Conductivity

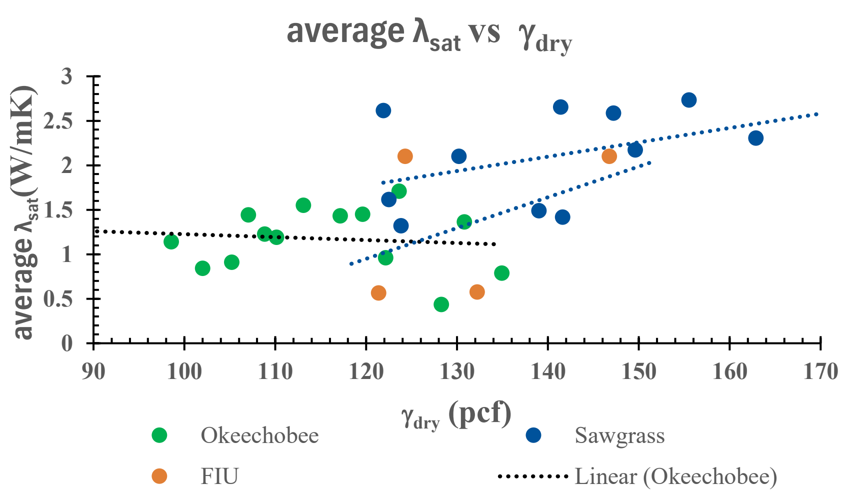


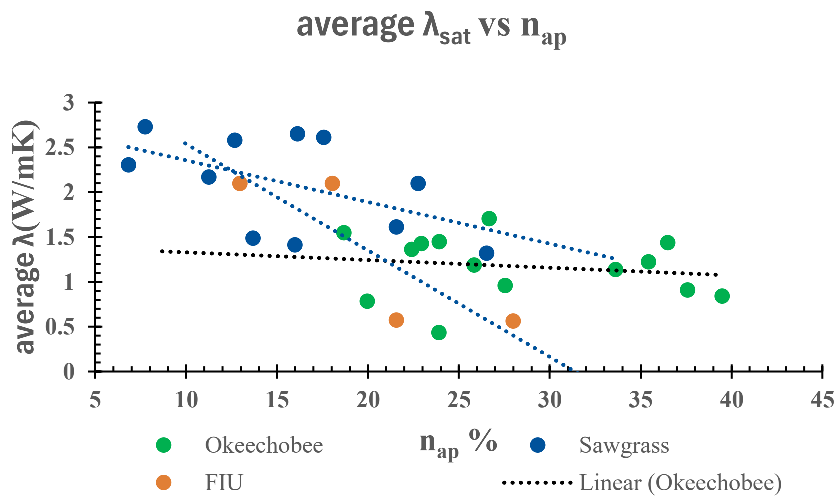


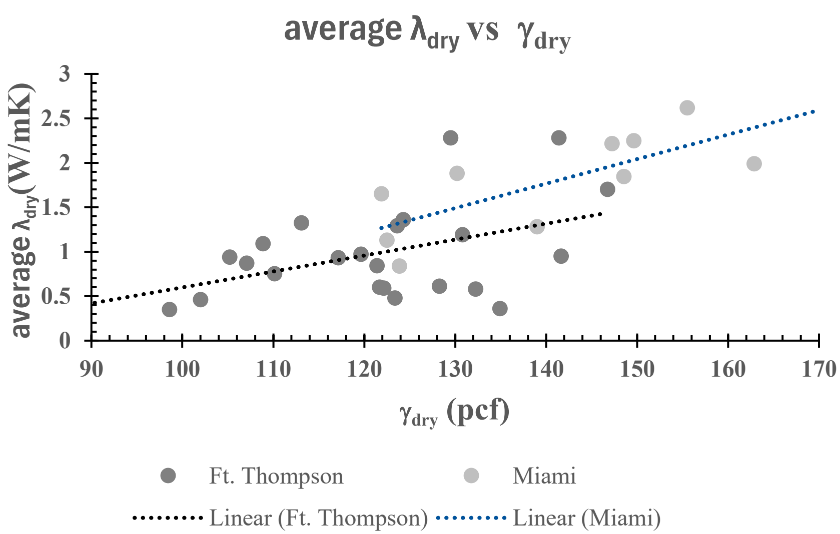


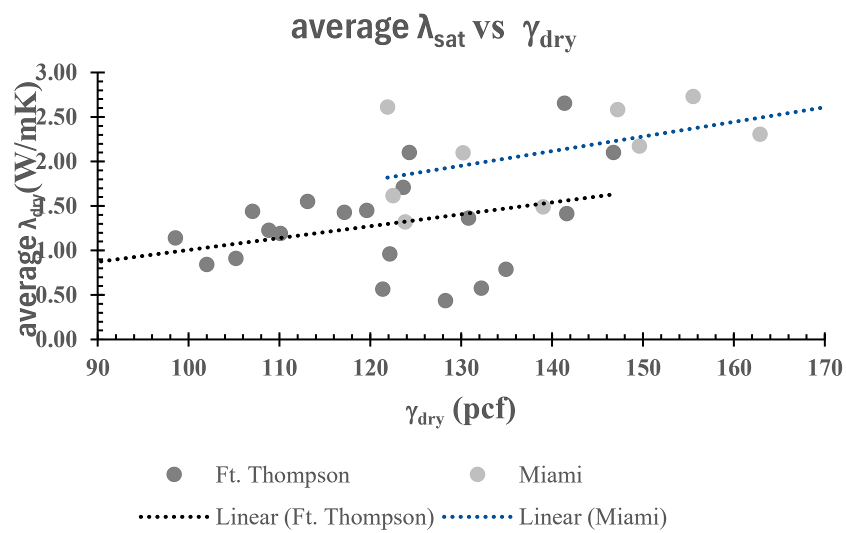
Task 4: Grout Mix and Geomaterial Thermal Investigation

Thermal Conductivity



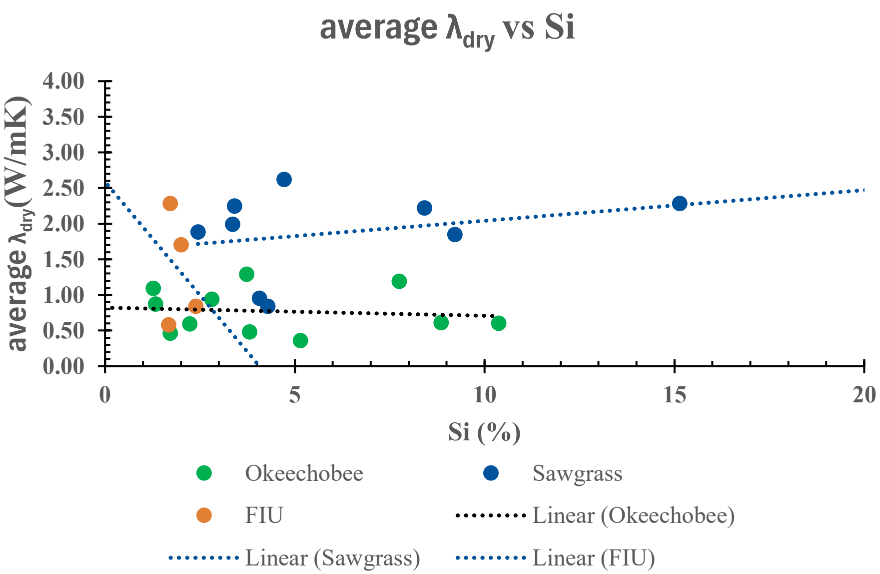


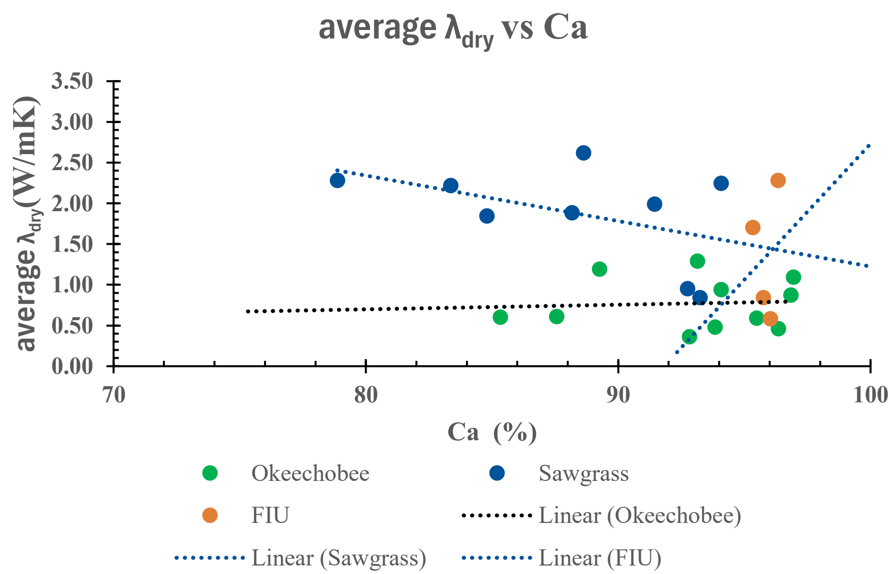




Task 4: Grout Mix and Geomaterial Thermal Investigation

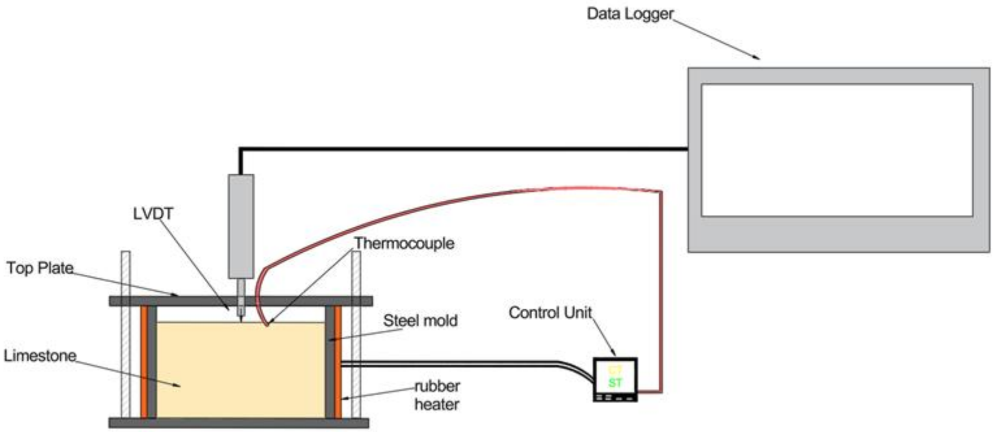
Thermal Conductivity

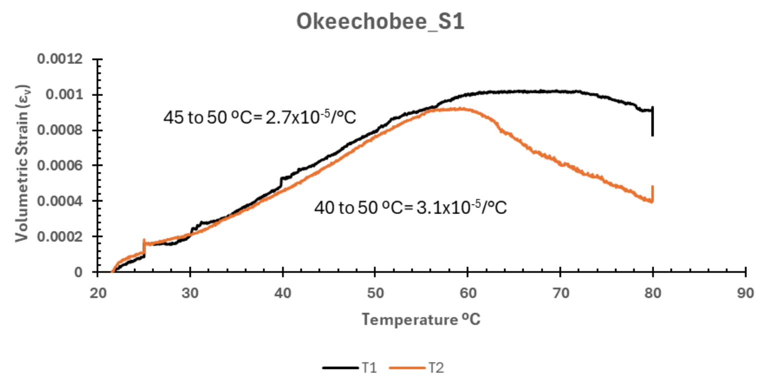




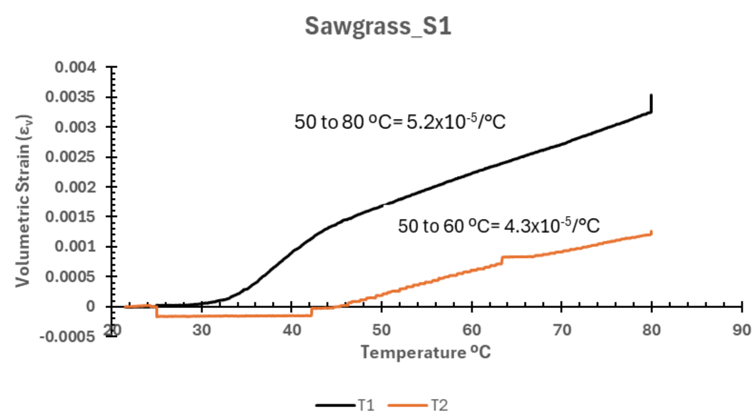
Task 4: Grout Mix and Geomaterial Thermal Investigation

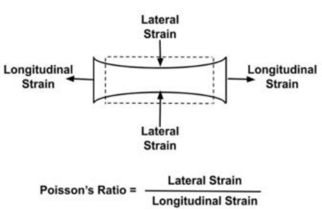
Coefficient of Thermal Expansion





Sample is laterally restrained, data adjusted for expansion of the steel mold





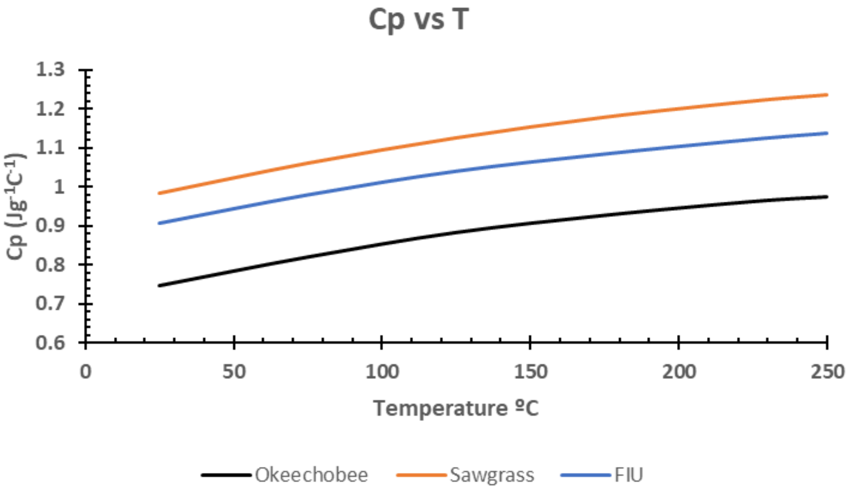
$$\nu = \frac{\varepsilon_x}{\varepsilon_y} = \frac{(\Delta D/D)}{(\Delta H/H)} \therefore \; \Delta D = \frac{D * \Delta H * \nu}{H}$$

$$\frac{\Delta V}{V} = \frac{\left(D - \frac{D * \Delta H * \upsilon_{steel}}{H_{steel\,mold}} - \frac{D * \Delta H * \upsilon_{limestone}}{H_{limestone}}\right)^2 * \frac{\pi}{4} * \Delta H}{(D)^2 * \frac{\pi}{4} * H_{limestone}}$$

Limestone Volumetric CTE 2.4 x10-5/C
(Robertson 1988)

Task 4: Grout Mix and Geomaterial Thermal Investigation

Specific Heat Capacity (heat storage capacity)

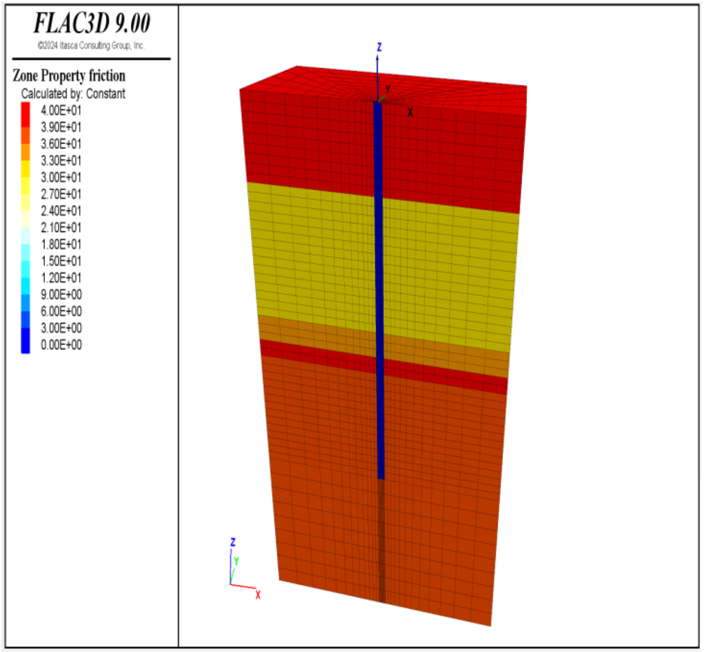


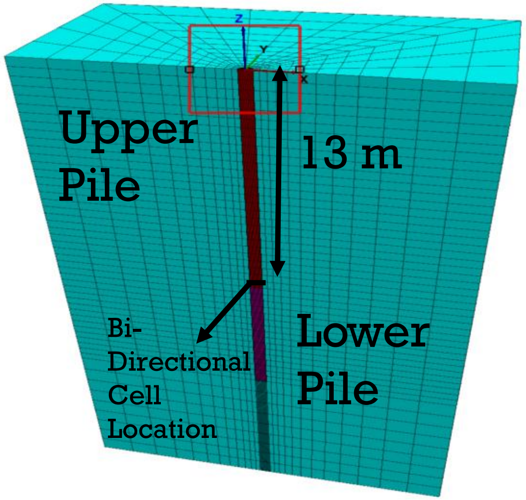
$$c_p = A + BT + CT^{-2}$$

Task 5: ACIP Pile Load Test Analysis and Load Transfer Function for FBMP Model

- Task 5 will involve analyzing the complete set of data from Tasks 1-4, establishing the residual stresses in the test piles, and revising existing T-z models for bored piles to account for the effect of residual stresses
  - Modified T-z models that include residual stress will be established for the soil and geomaterials tested
  - Models will be developed in FB-Multipier (FBMP) based on the load tests and FLAC models

Sawgrass Pile Project:

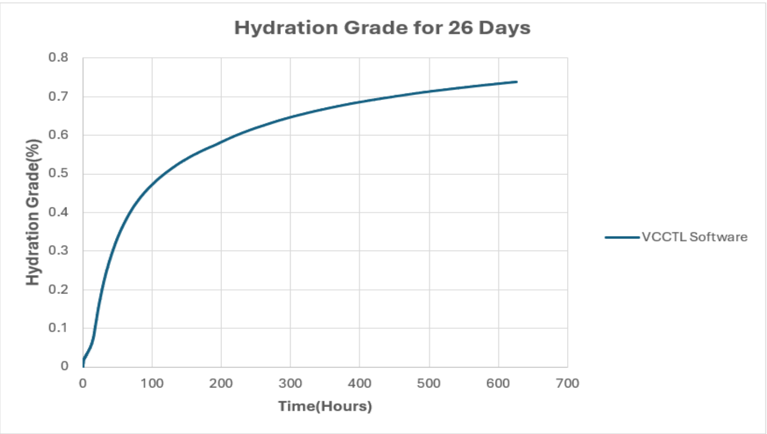




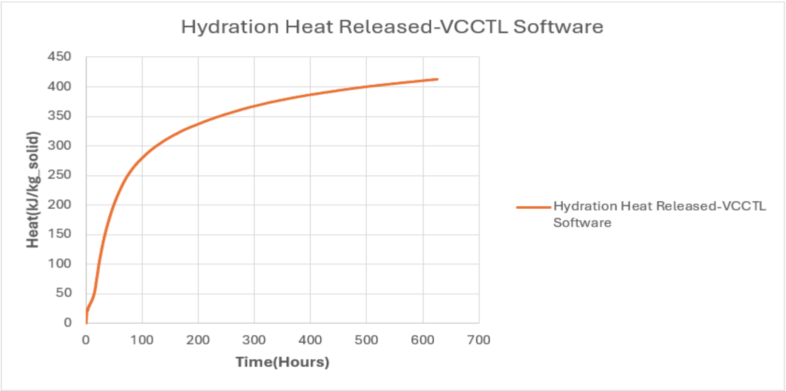
Mechanical Properties Assigned to the Rock Layers in the FLAC3D Model

Layer	Segment(s)	Depth Range (m)	Bulk Modulus, K (Pa)	Shear Modulus, G (Pa)	Cohesion (Pa)	Friction Angle (°)	Tensile Strength (Pa)
L1(IGM II)	S1, S2	0.0 to -4.5	1.56×10^8	1.17×10^8	6.89×10^5	40	7.76×10^5
L2(Snad)	S3, S4, S5, S6	-4.5 to -11.5	1.09×10^7	8.15×10^6	1.50×10^5	32	—
L3(Sand)	S7	-11.5 to -13.0	1.84×10^7	1.38×10^7	1.50×10^5	35	—
L4(IGM II)	S8	-13.0 to -14.0	4.19×10^8	3.14×10^8	1.27×10^6	40	9.86×10^5
L5(Sand)	S9, S10, S11, S12, Tip	-14.0 to -30.0	2.37×10^7	1.78×10^7	1.50×10^5	37	—

Sawgrass Pile Project:



The degree of hydration versus time predicted by VCCTL for 26 days



The hydration heat release versus time predicted by VCCTL for 26 days

Limestone thermal properties used in the FLAC3D hydration model.

Linear Thermal Expansion(K^{-1})	Heat conductivity (W/mK)	Specific Heat (J/(kg K))
-37E-6	1.5	910

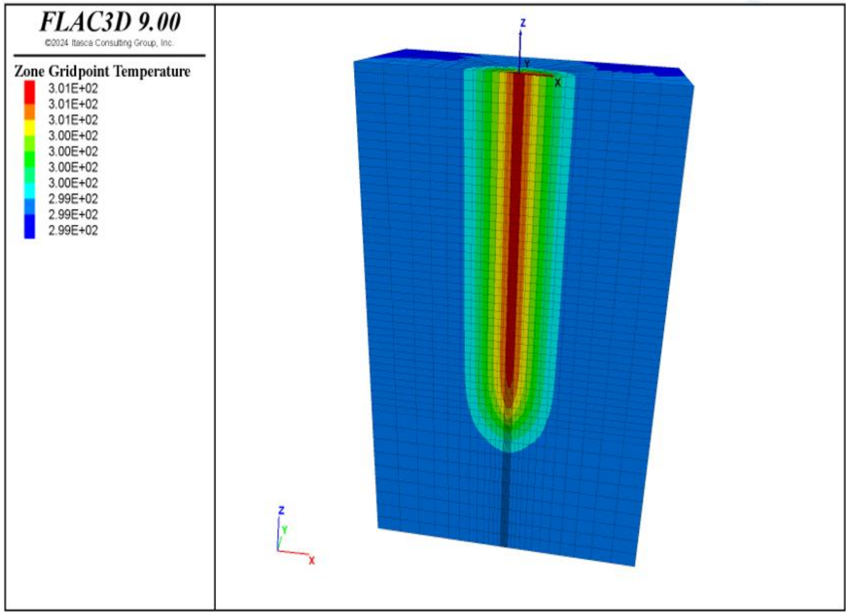
Drucker-Prager Model Parameters Used in the Analysis.

Model (Mechanical)	Density (kg/m3)	Bulk Reference (pa)	Shear Reference (pa)	Constant c (no unit)	Constant a (no unit)	Hydration Minimum (no unit)	Tension Reference (pa)	Hydration Difference Minimum (no unit)
Hydration Drucker Prager	2204	18.48E+9	13.86E+9	0.07	0.22	0.25	5.11E+06	1.00E-4

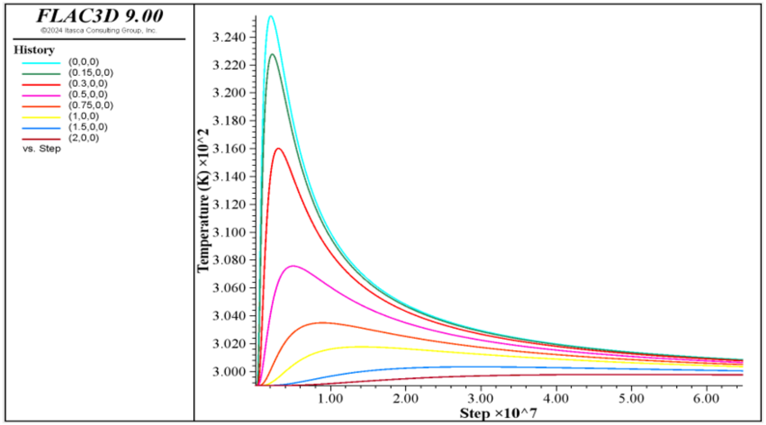
Parameters of Hydration model Used in the Analysis.

Model(thermal)	Hydration
Thermal conductivity	2 W/mK
Linear thermal-expansion coefficient (αt)	$15\times10^{-6}K^{-1}$
Maximum amount of generated heat (Q_{Ce}^{max})	3.9e5 J/kg
Specific heat ($C_{p,1}$)	0.2 J/(kg K)
Cement concentration (C)	700 kg/m^3
Constant-jonasson-b	-1.114 (no unit)
Constant-jonasson-t1	7.2e4 1/S
Universal gas constant (R)	8.314 J/mol
Temperature-reference	293 K
Hydration-grade-maximum	1.0 (no unit)
Hydration-temperature-maximum	1e4 (no unit)
Constant-energy-1 (Activation energy: E_{A1})	33.5 kJ/mol
Constant-energy-dt Slope of energy change (dEA,T)	1.47 J/mol/K
Constant-conductivity-1	2.0 (no unit)

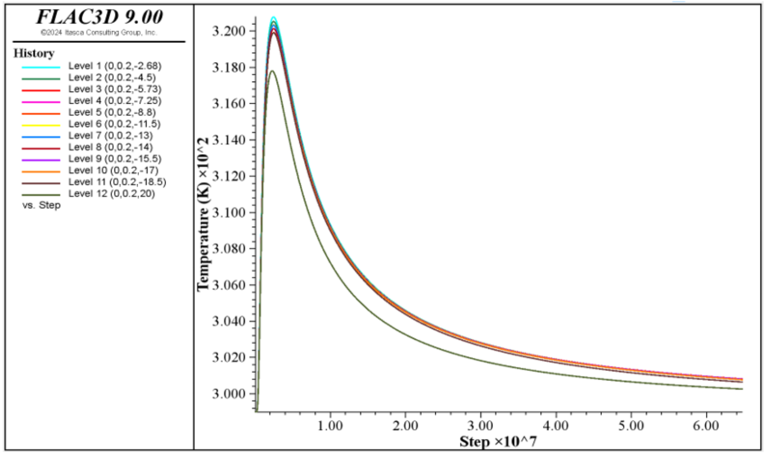
Sawgrass Pile Project:



Temperature Change at the End of the 26-Day Hydration Period

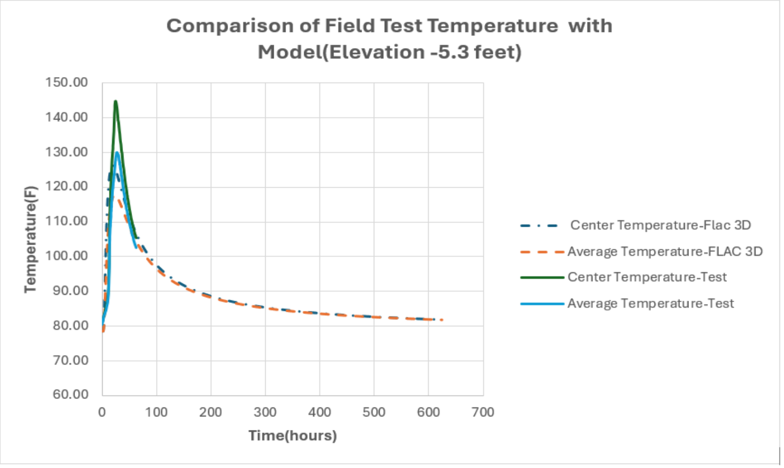


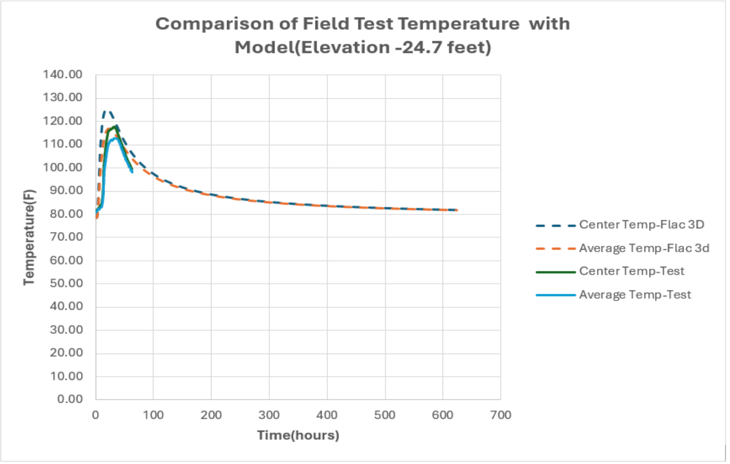
Temperature History Curves During 26-Day Hydration Phase in different locations Along the Pile and Surrounding Rock Strata

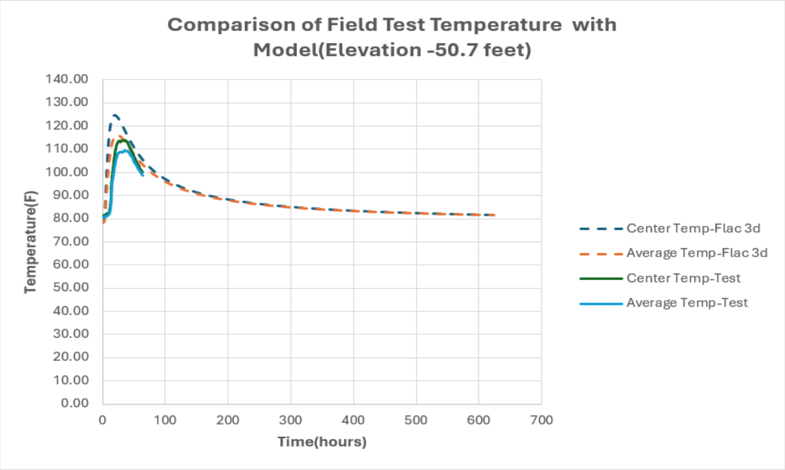


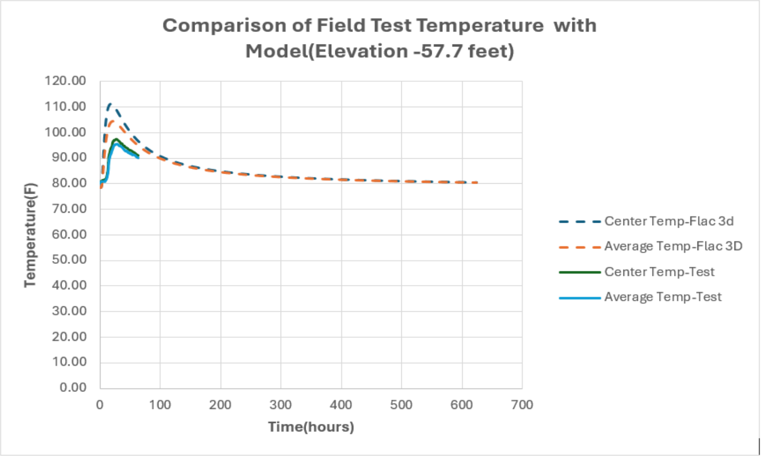
Temperature History Curves During 26-Day Hydration Phase in Different Locations Along the Pile

Sawgrass Pile Project:

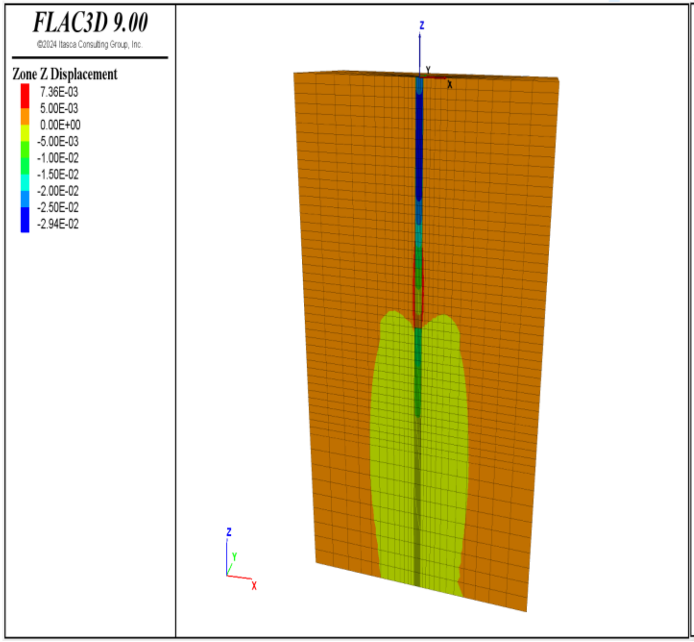




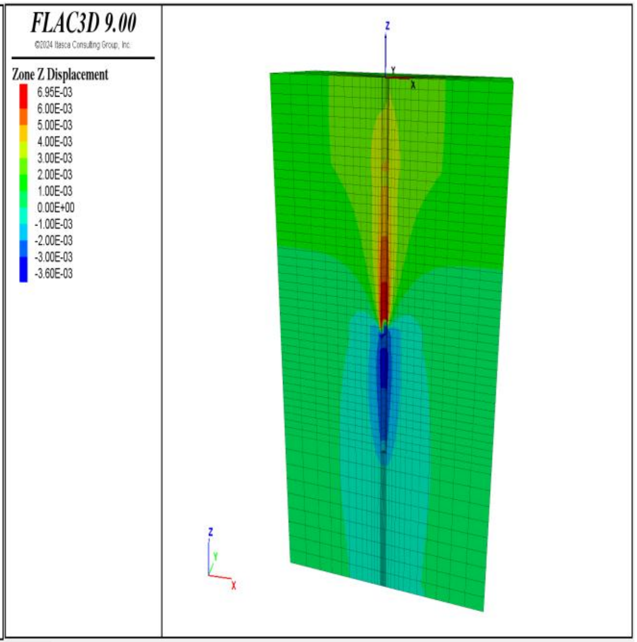




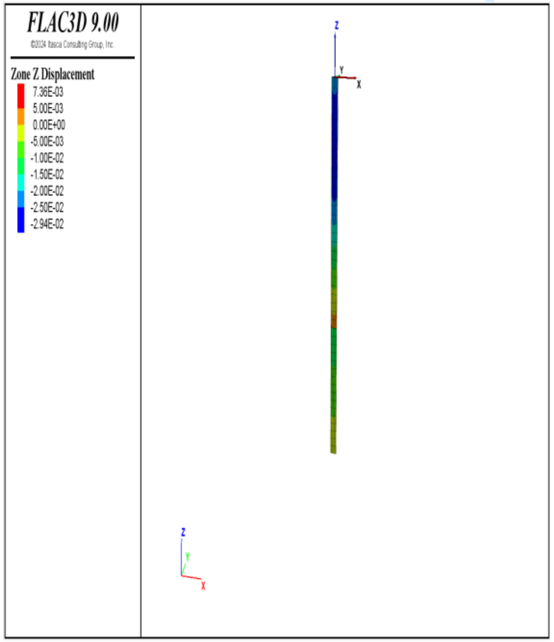
Sawgrass Pile Project:



Vertical (Z-Axis) Displacement of the Pile and Surrounding Rock During Bidirectional Loading

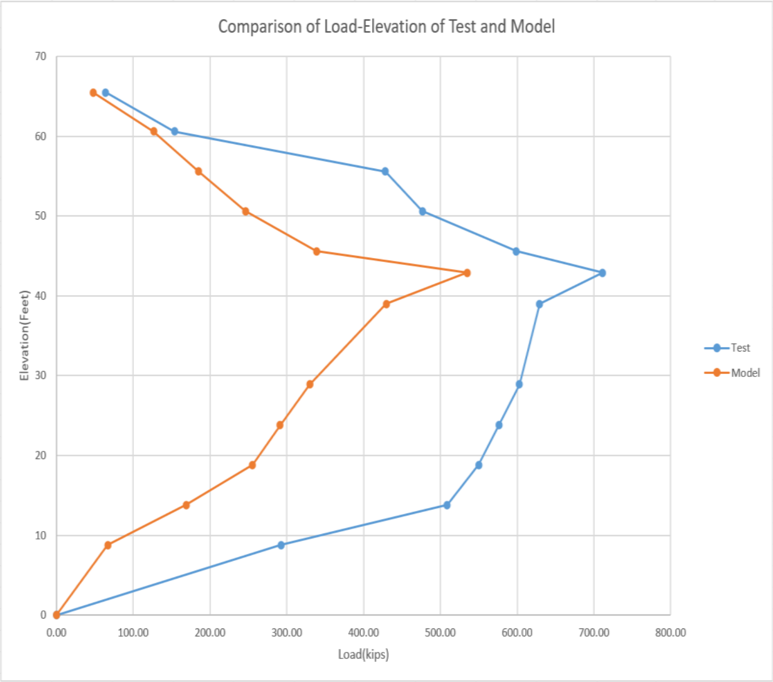


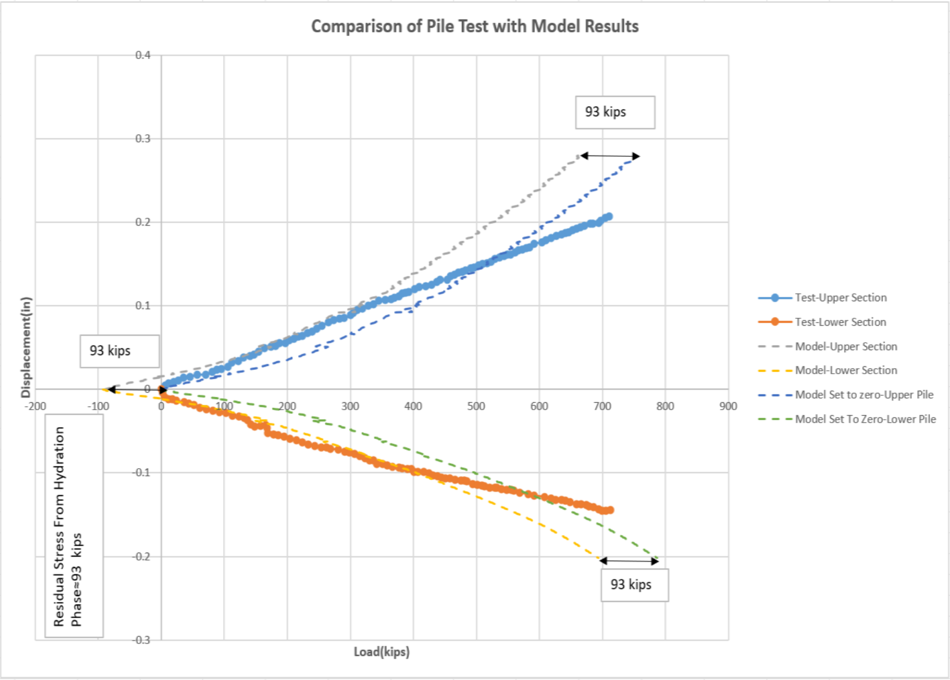
Vertical (Z-Axis) Displacement of the Surrounding Rock During Bidirectional Loading



Vertical (Z-Axis) Displacement of the Pile During Bidirectional Loading

Sawgrass Pile Project:





Thank You!