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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:
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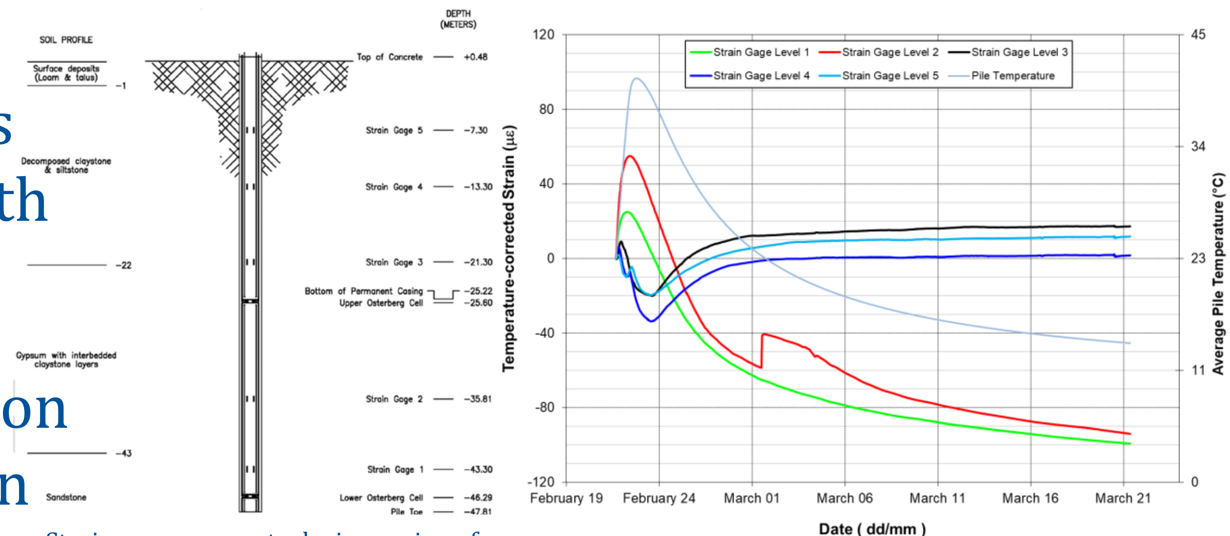
August 14th, 2025

Introduction: Residual Stress in Deep Foundations

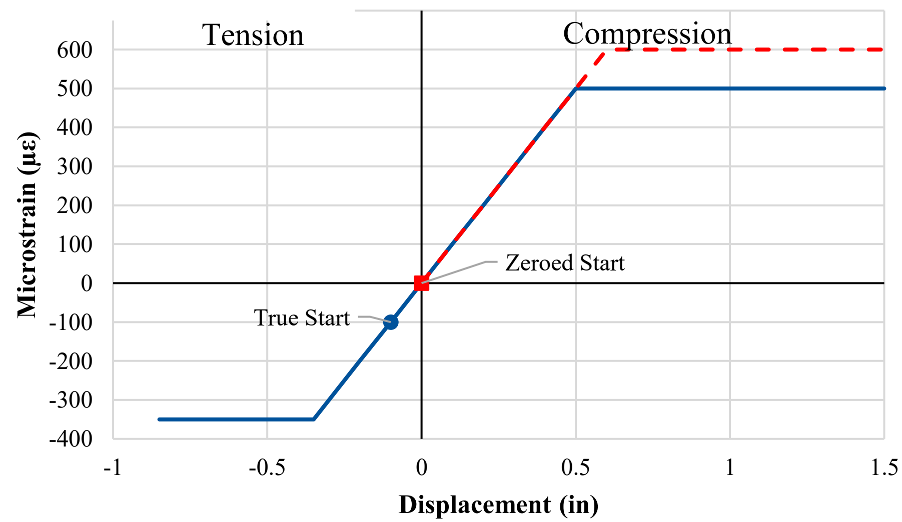
- Residual stresses are tension stresses that develop in the pile/shaft during the grout curing phase; influenced by
  - Length of the pile/shaft - 25 ft vs 125 ft ACP
  - Layering – interbedded layers of soil and rock vs just soil
  - Drilling/grouting with highly variable pile/shaft diameters
  - Grout mix design/selection and volumetric change during curing
- Residual stress leads to
  - Different top down or bottom-up mobilized side shear in a segment of pile/shaft
  - Microcracks of sufficient size (high residual stresses) that result in higher axial strains in pile/shaft further from the applied load than strains closer to the load
  - Shortened pile/shaft integrity (life span)
  - Introduces uncertainty in the MWD QA/QC correlations
- Little work has been done to quantify it and account for it in load test results
- Distributed Fiber Optic Sensing (DFOS) allows cm scale resolution of temperature and strain measurements on single cables

Background – Grout Curing Tension Strain

- Small residual compression strains in shaft segment with steel casing
- Large residual tension strains in segment in soil/rock layer – unpredicted compression
- Zeroing gages for load test leads to erroneous mobilized side friction

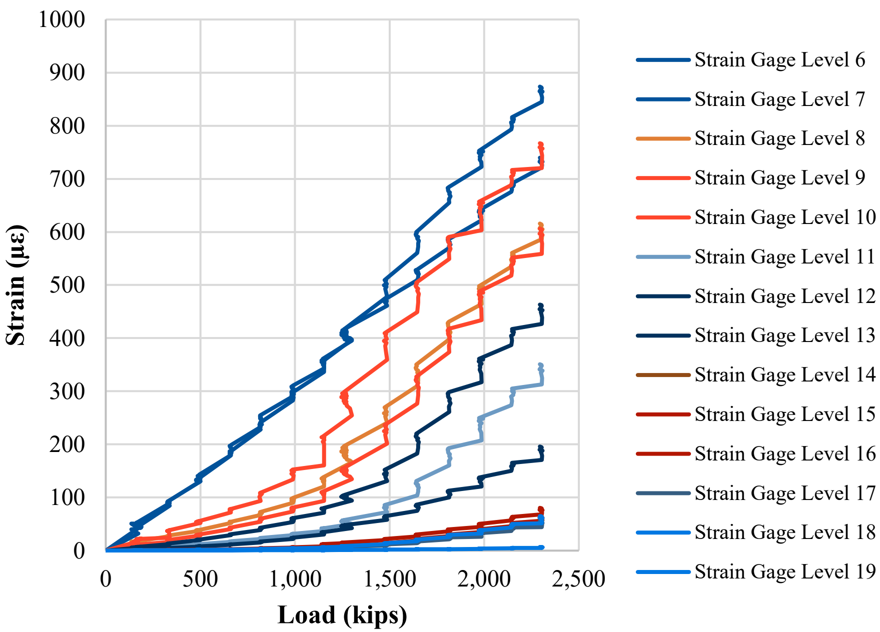


Strain measurements during curing of a drilled shaft



Theoretical load path for strain gage 1

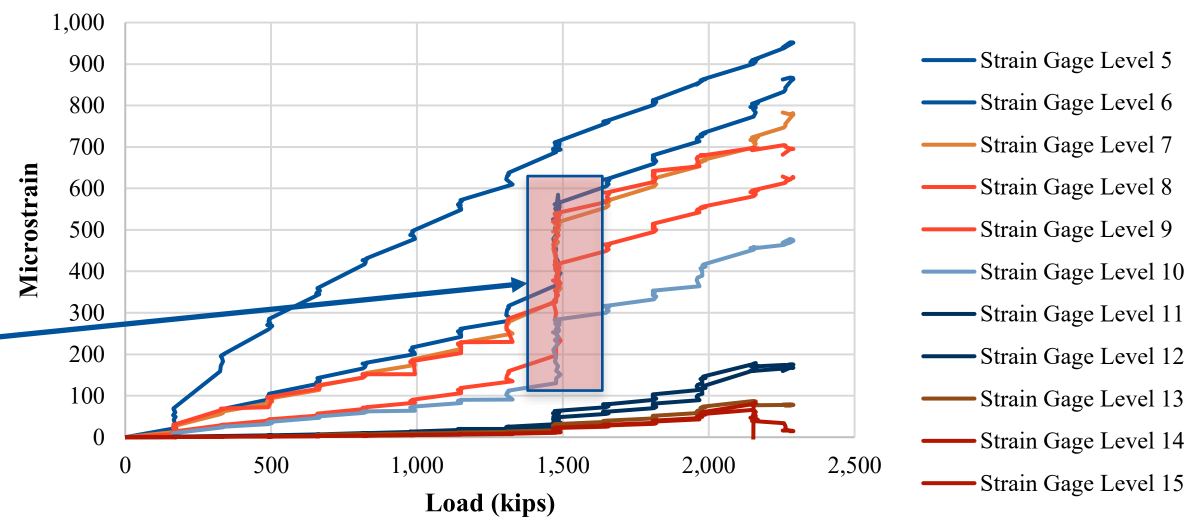
Background – Load Test Observations



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

- Irregular strain profile
- Gauges further from load had higher strains during load test

200 με of micro-fracture closures during 1,500 kips sustained for 1 hr and LTA movement of 0.09 inches



Project Objectives

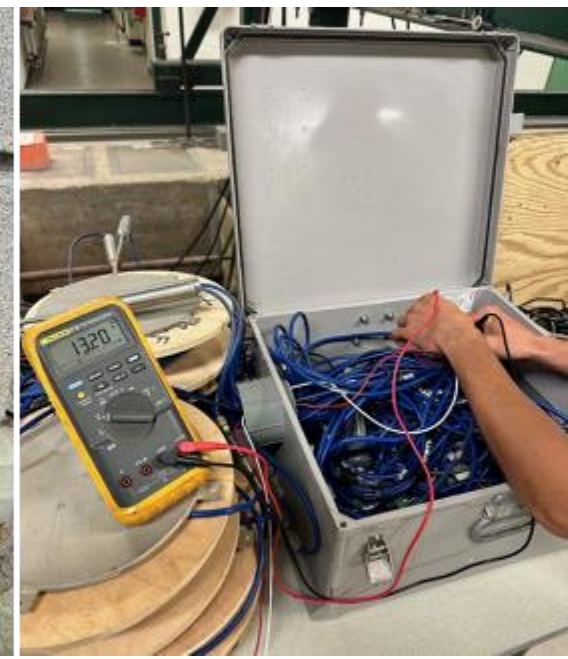
- The project's primary objective is to study the thermal influence on residual stress development in bored piles and identify an appropriate design method for axial capacity of ACIP piles with residual stress while adding to the MWD dataset of South Florida limestone
- We will conduct a test program on 3 ACIP piles that includes:
  - Measuring While Drilling (MWD)
  - Rock core testing for strength and thermal properties
  - Grout mix design study and lab testing of curing temperatures and strains using DFOS
  - Monitoring pile temperatures and strains during curing using DFOS and strain gages
  - Measuring strains during axial load tests using DFOS and strain gages
  - Modeling of curing bored pile
  - Establish T-Z model(s) for bored piles with residual stress.

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

- Distributed Fiber Optic Sensing (DFOS) cables, which are not typically used for bi-directional load tests, will be a requirement for this research
  - Installation plan for cables was developed in collaboration with load test consultants
  - Provides quality assurance for the DFOS cables
- A literature was conducted to gain insight from prior instances where fiber optic cable was placed in various deep foundation types
  - Drilled shafts, ACIP piles, driven piles, micro-piles, etc.
- Developed programming for a DAQ module to be used to collect continuous data from the standard strain gauges placed in the reinforcement cage
  - Provides a better understanding of the pile curing process from conventional gauges
- The research team is working with FDOT officials to collect prior untested samples of soil and rock to be used initially in Task 4
  - Thermal conductivity of various geomaterials will be studied and considered as a variable in understanding the overall pile curing process and performance under load

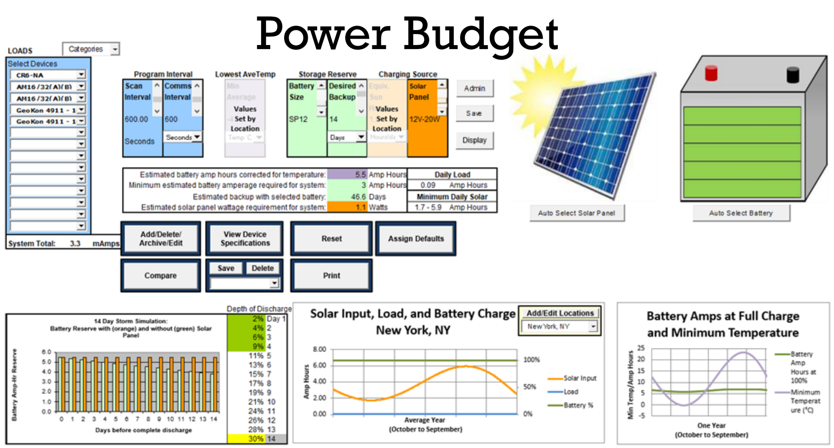
Task 1: Instrumentation Planning, Literature Review, and Sample Collection

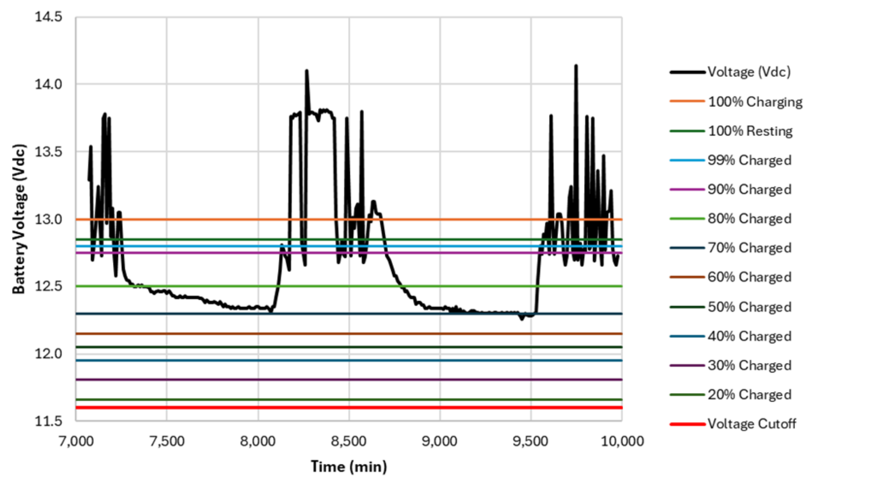
Continuous Data Collection – DAQ Programming

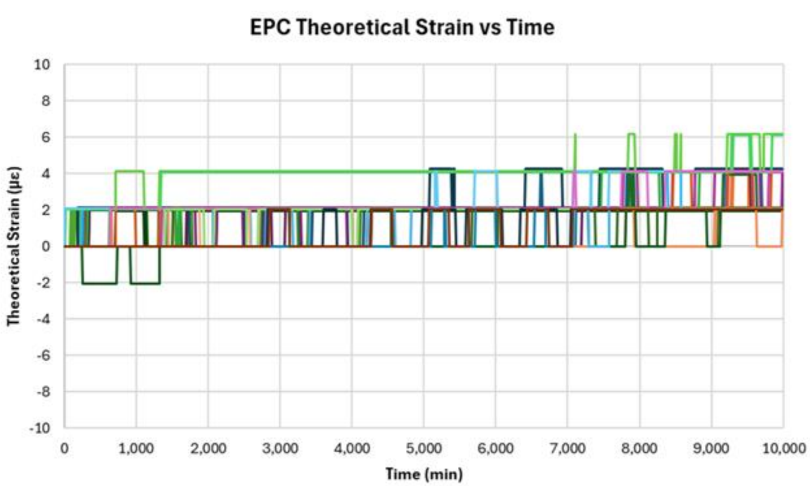


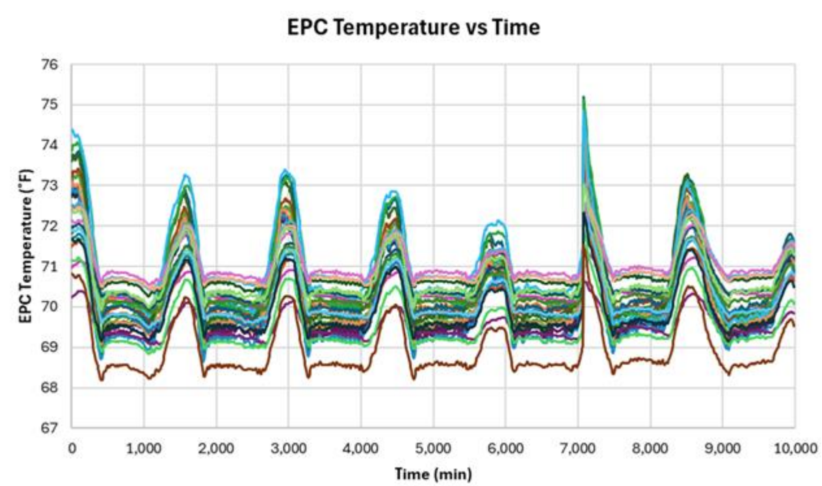
Task 1: Instrumentation Planning, Literature Review, and Sample Collection

Continuous Data Collection Trials – VW Gauges







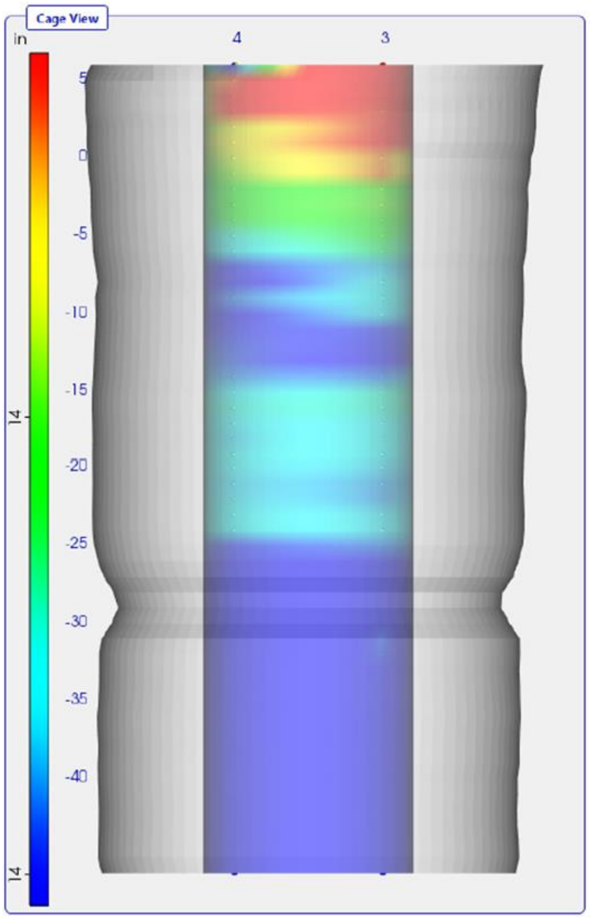


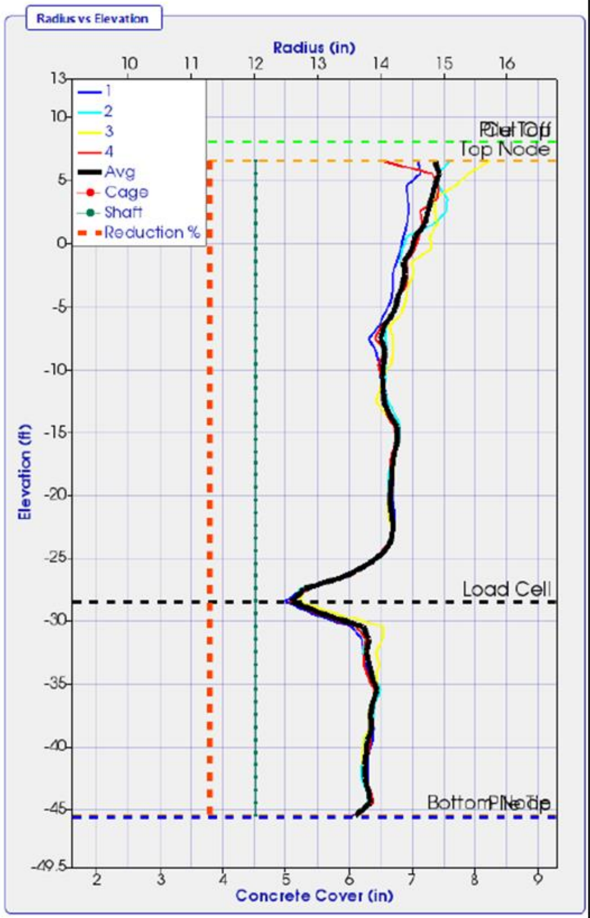
Task 2: MWD Investigation for ACIP Test Piles

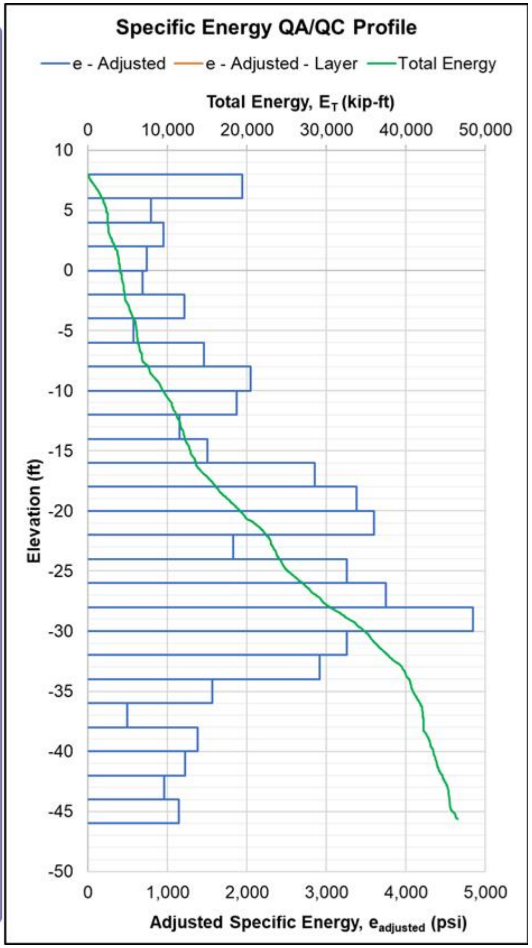
- Task 2 will be comprised of 3 subtasks
- Each subtask includes the completion of MWD during the installation of one load tested ACIP pile to compare MWD with load test results
  - AME data will be transformed into MWD data and assessed
  - MWD data used to determine strength layering via specific energy
  - Provide insight to materials present over the full span of the ACIP piles
- MWD will also be used to investigate variable penetration rates during the drilling process to 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

MWD Observations







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

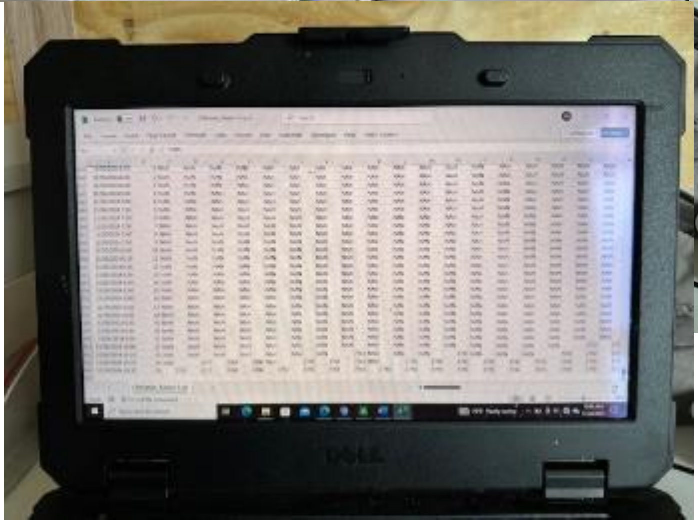
- This task consists of instrumenting and load testing 3 full scale ACIP piles with fiber optic cables and vibrating wire strain gages
  - Axial load tests will be performed on each ACIP pile
  - Data collected from DFOS and VW Strain gages will be compared
  - The DFOS data will also be used to improve 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 @ FIU Bridge Site

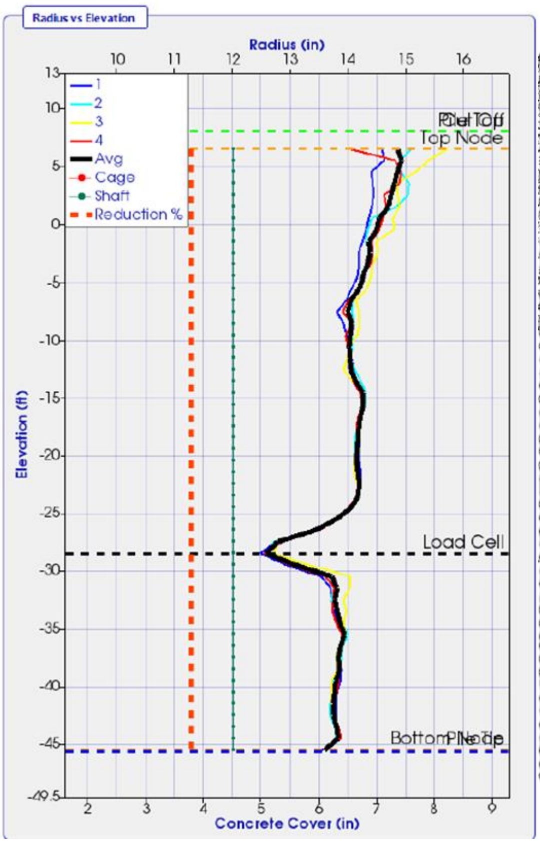
Task 3: Instrumented ACIP Piles for Curing Behavior and Static Load Tests

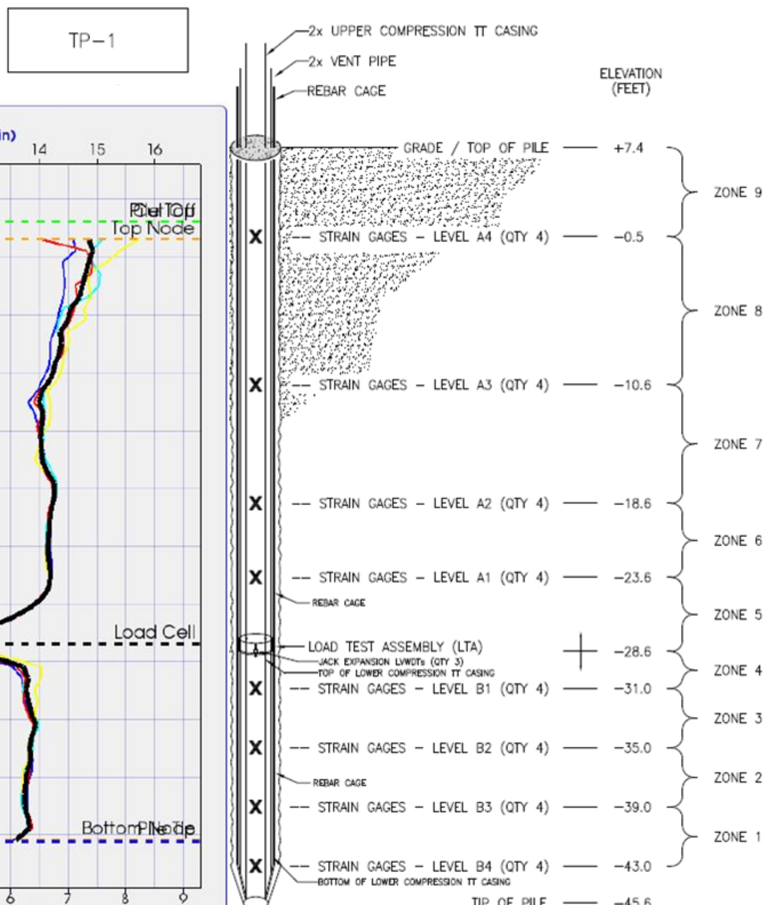
Connecting to DAQ System

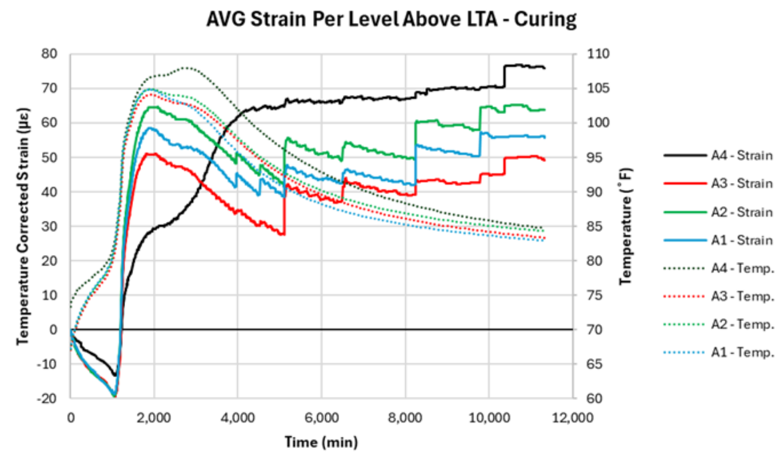


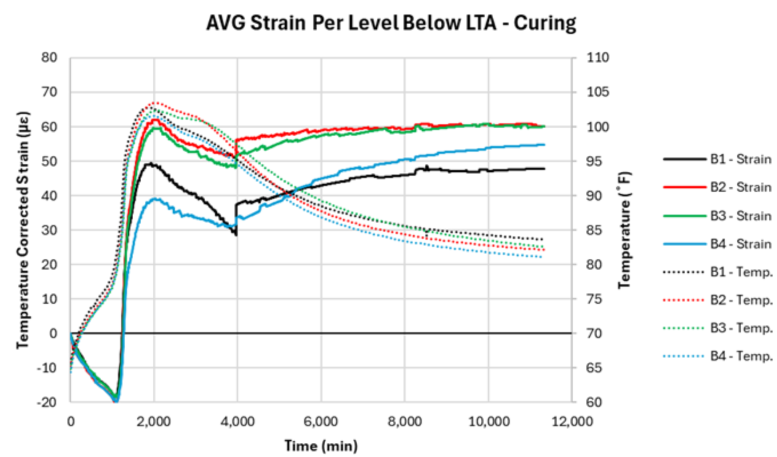
Task 3: Instrumented ACIP Piles for Curing Behavior and Static Load Tests

FIU Bridge Site – TP1 Curing Strains and Temperature



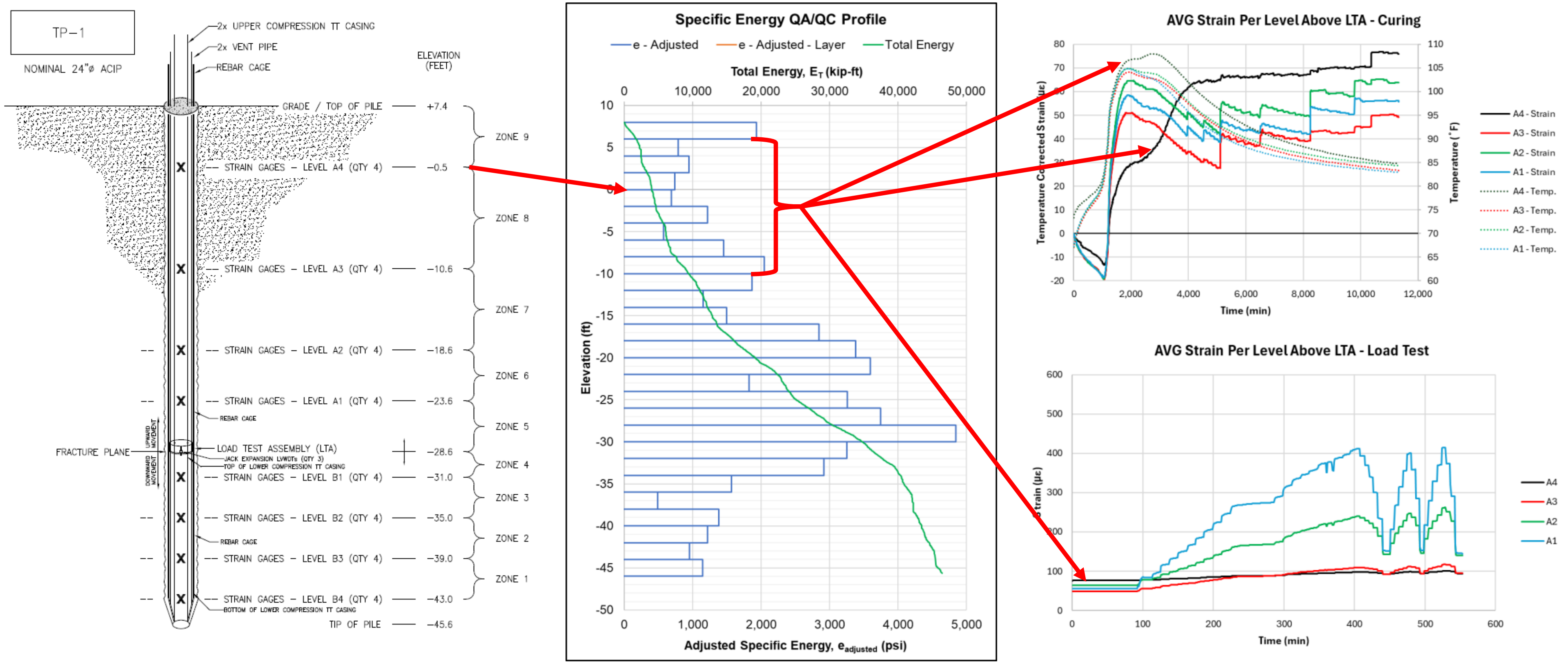






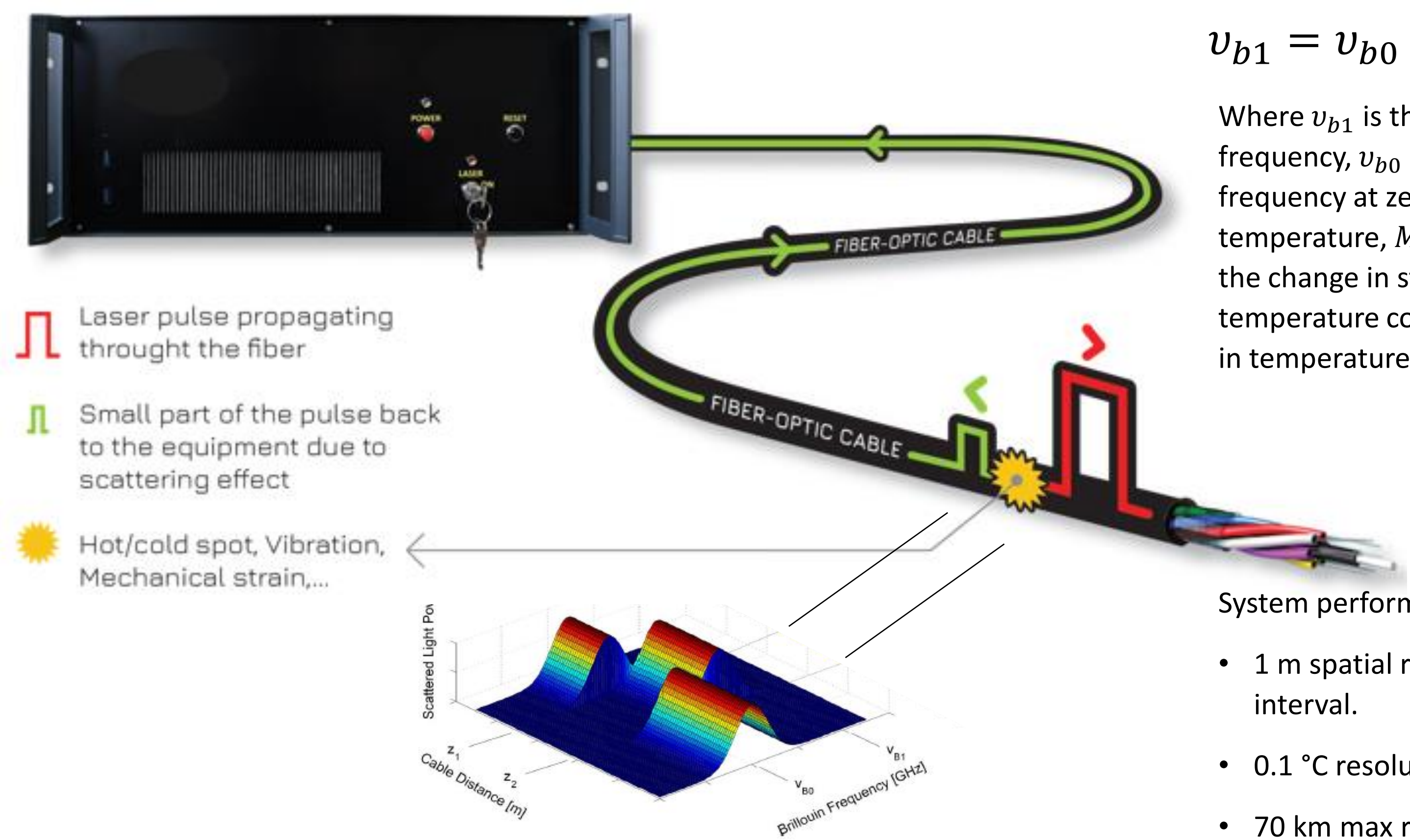
Task 3: Instrumented ACIP Piles for Curing Behavior and Static Load Tests

FIU Bridge Site – TP1 MWD Profile



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

- Distributed Fiber Optic Sensing (DFOS) based on perturbations in the frequency of light passing through glass fiber.



$$\upsilon_{b1} = \upsilon_{b0} + M \cdot \Delta\varepsilon + N \cdot \Delta T$$

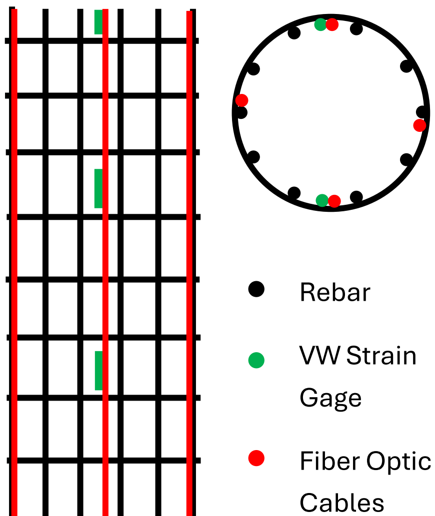
Where υ_{b1} is the change in the Brillion frequency, υ_{b0} is the central peak Brillion frequency at zero strain and constant temperature, M is the strain coefficient, $\Delta\varepsilon$ is the change in strain of the fiber, N is the temperature coefficient, and ΔT is the change in temperature of the fiber.

System performance:

- 1 m spatial resolution and 10 cm sampling interval.
- 0.1 °C resolution
- 70 km max range
- Wireless communication

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

- In touch with AFT and GRL about upcoming pile installations for better understanding and FO cable installation in the field.
- Pile strain and temp sensing (VW gages and DFOS)



Pile reinforcement cage segment

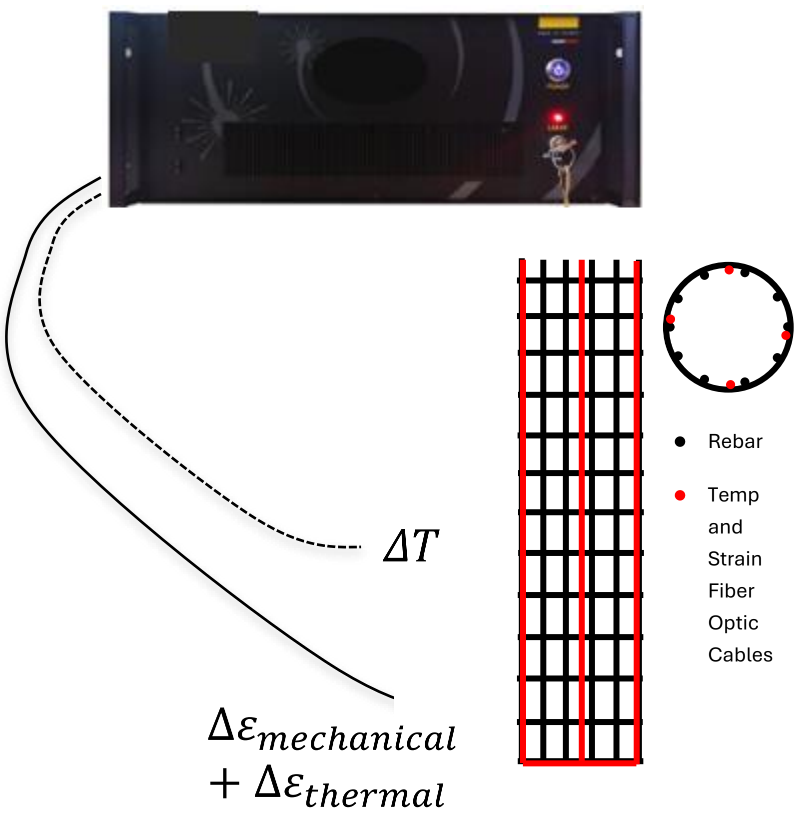
Cable and gage attachment to rebar cage

Pretensioning DFOS cables with cable clamps

Protecting DFOS cables

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

- 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

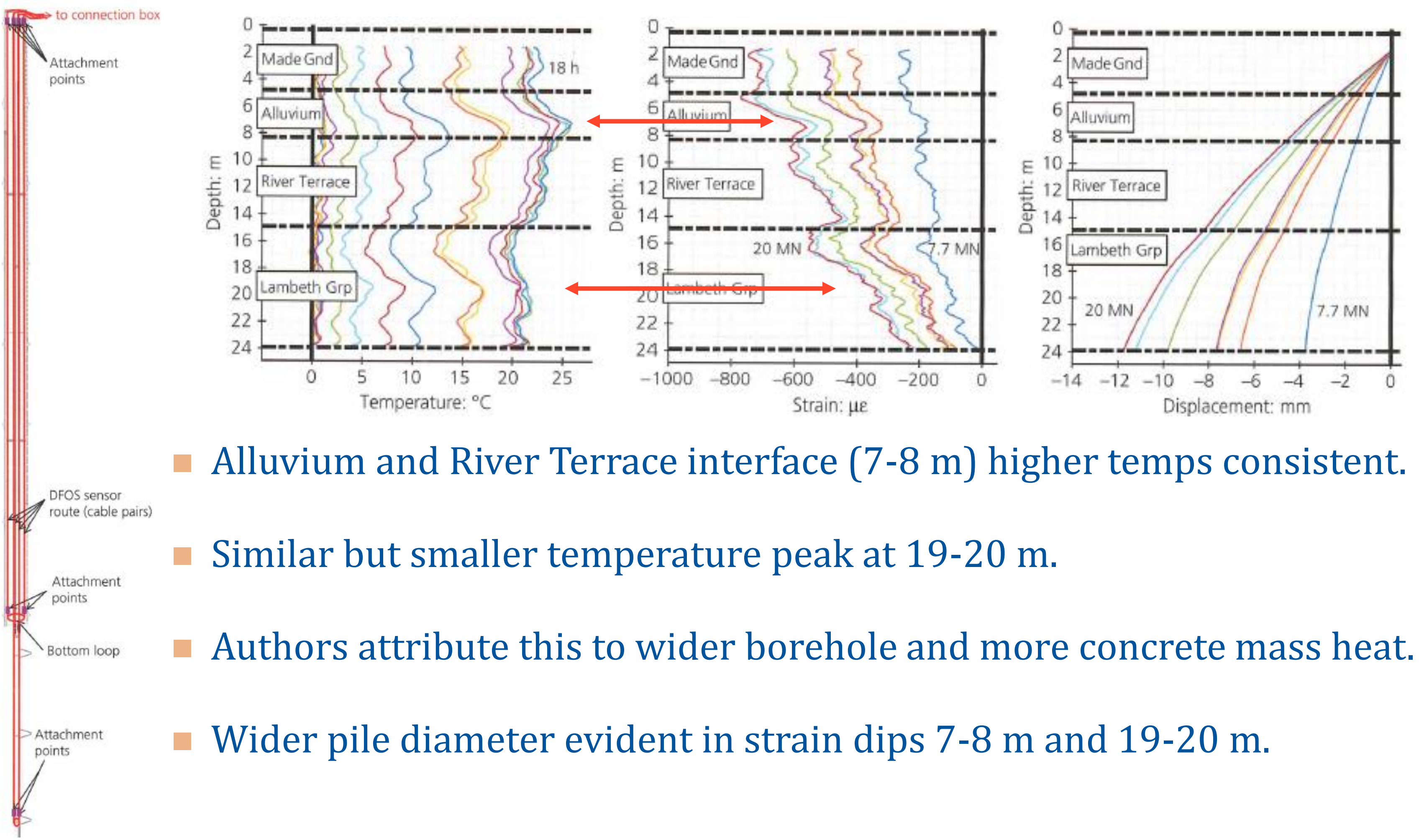
$$F_a(z) = EA \cdot \varepsilon_{M\ or\ T}(z)$$

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

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

- CFA Pile: Thermal and mechanical strains (Bachy Soletanche Ltd, 2015)



- Alluvium and River Terrace interface (7-8 m) higher temps consistent.
- Similar but smaller temperature peak at 19-20 m.
- Authors attribute this to wider borehole and more concrete mass heat.
- Wider pile diameter evident in strain dips 7-8 m and 19-20 m.

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

- Bi-Directional Test (Pelecanos et al., 2017)

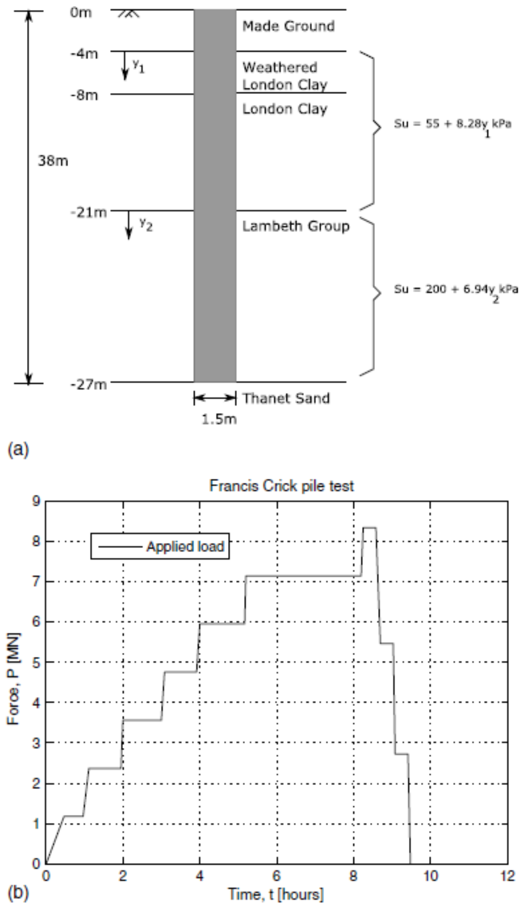
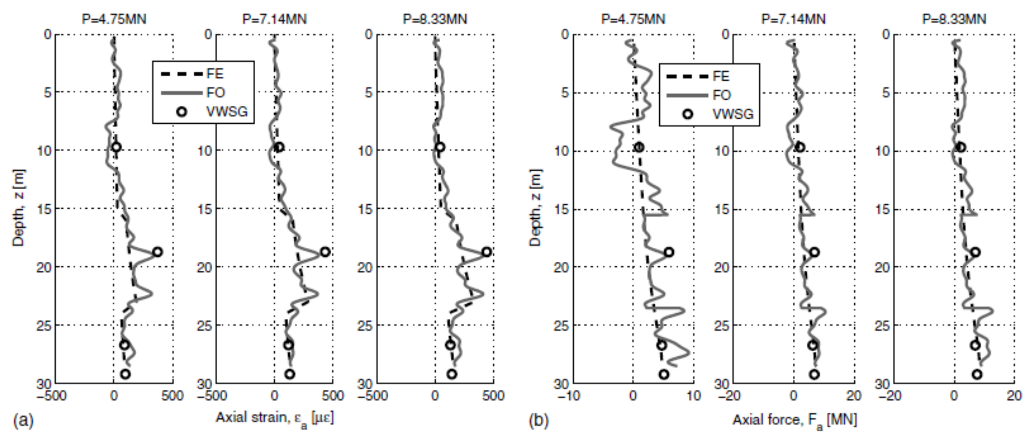
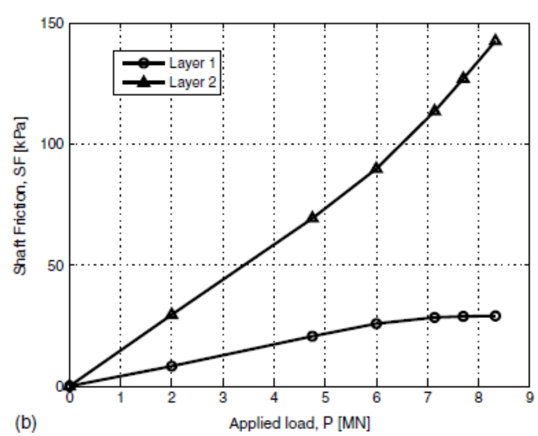
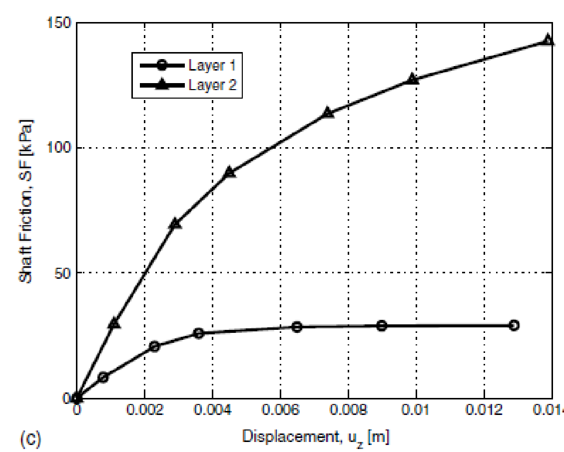


Fig. 11. Description of Case 3—Francis Crick pile load test case: (a) pile geometry and soil stratigraphy; (b) test schedule

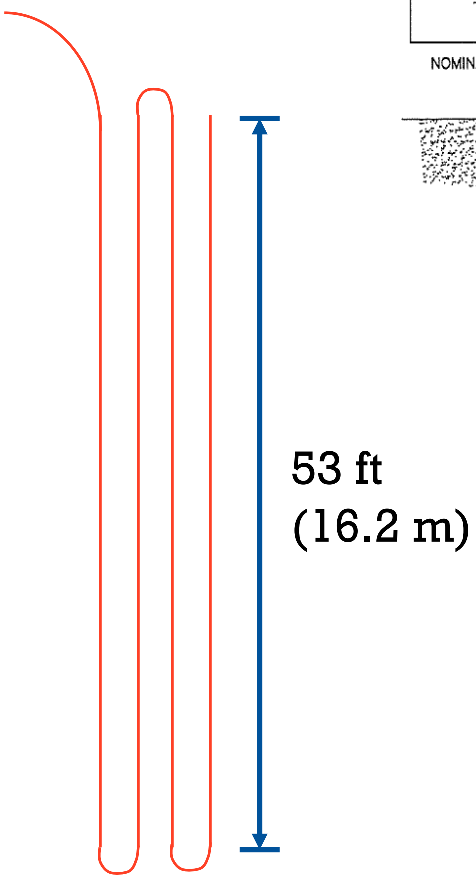




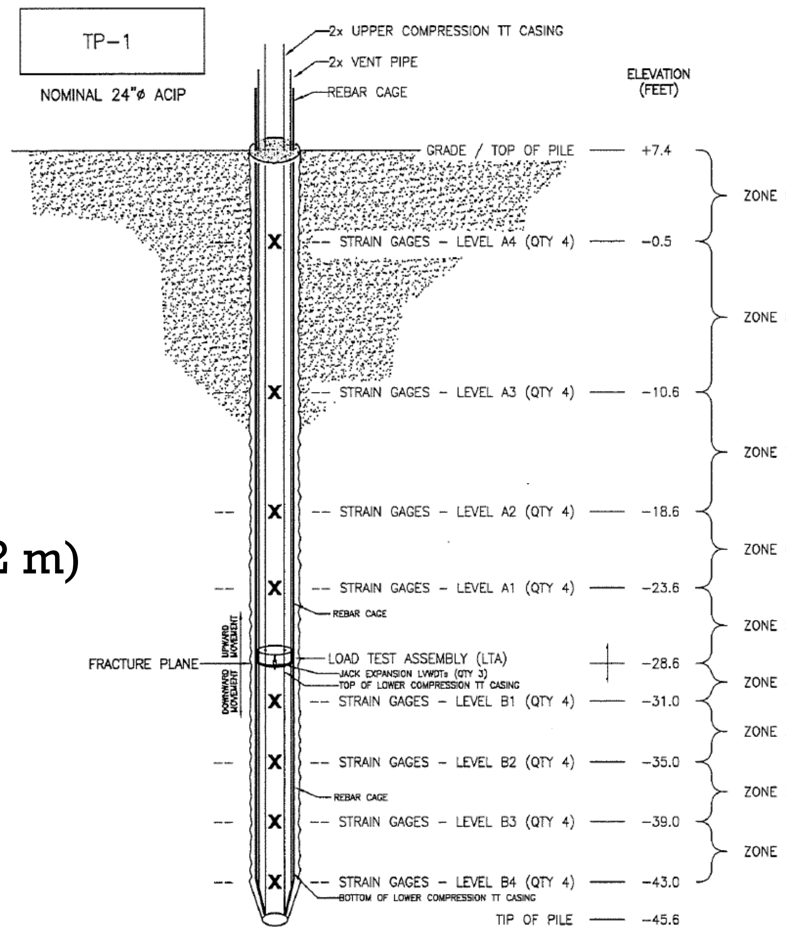


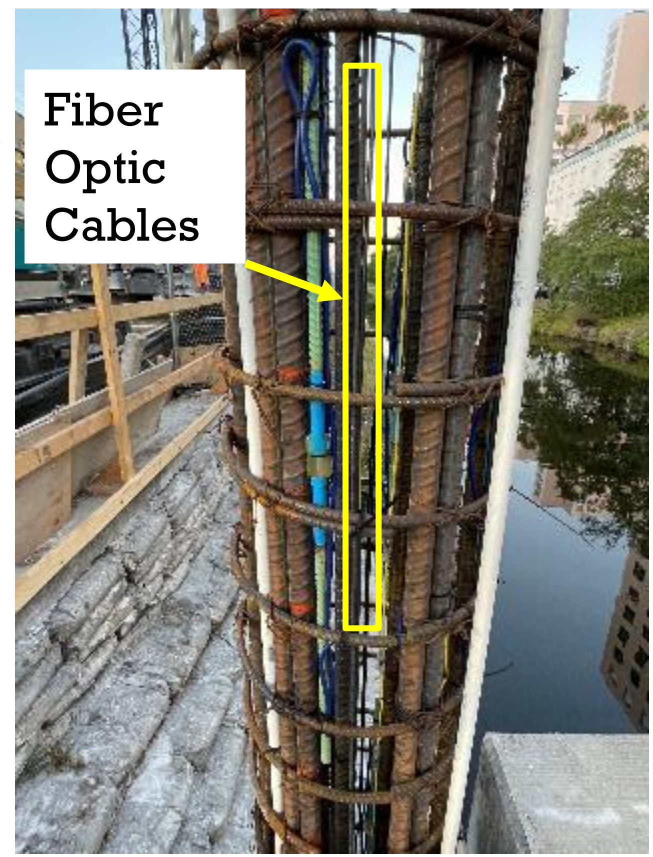
Task 3: Instrumented ACIP Piles for Curing Behavior and Static Load Tests

- Fiber Optic Installation-FIU Pedestrian Bridge Test Pile



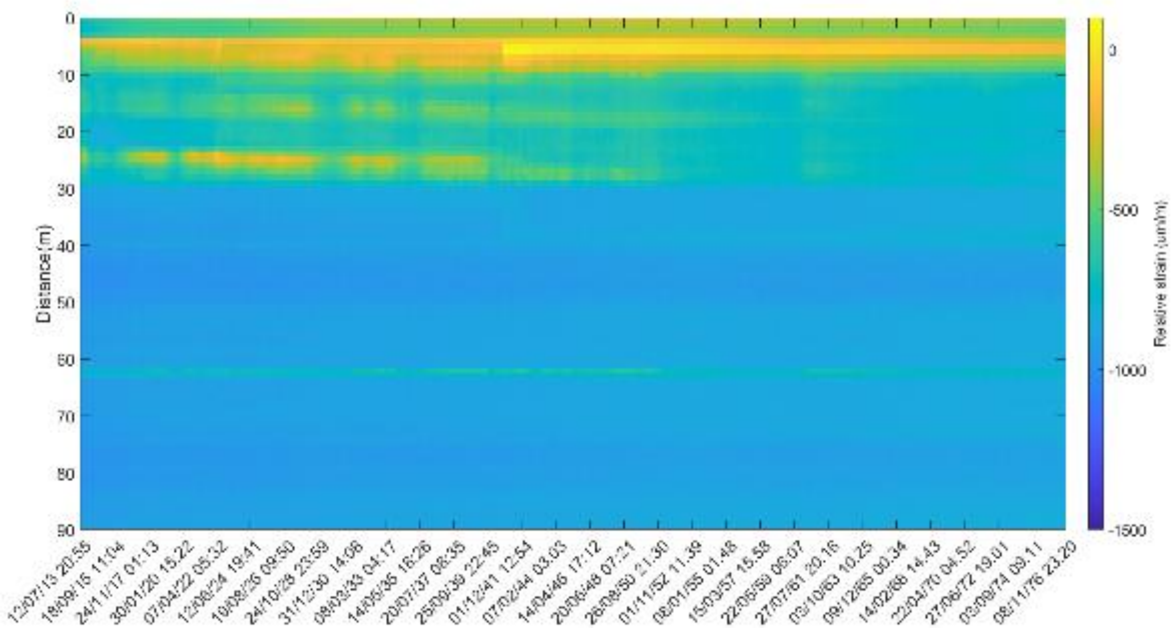
Fiber Optic Cable

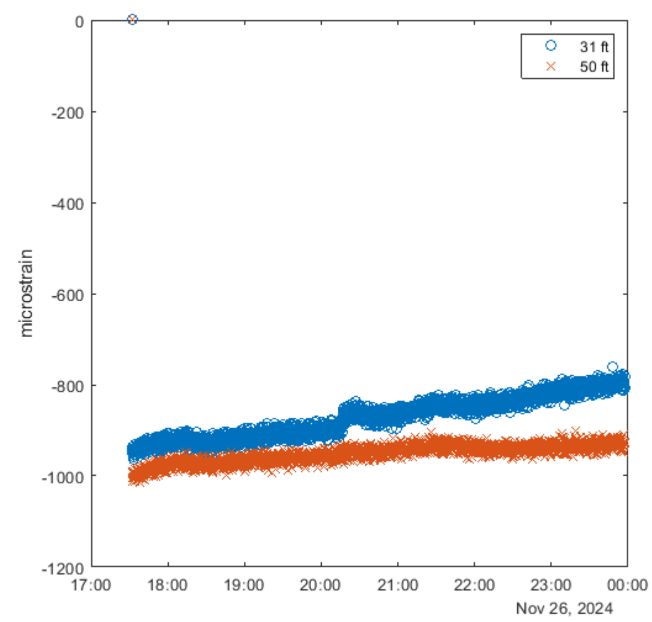




Task 3: Instrumented ACIP Piles for Curing Behavior and Static Load Tests

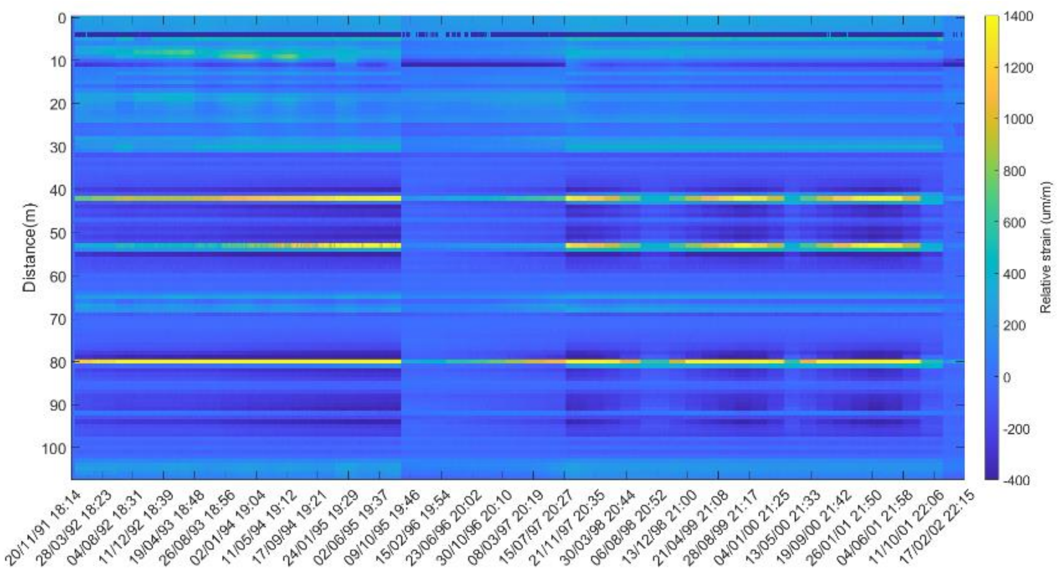
- FIU Pedestrian Bridge Test Pile-Fiber Optic Thermal Strains

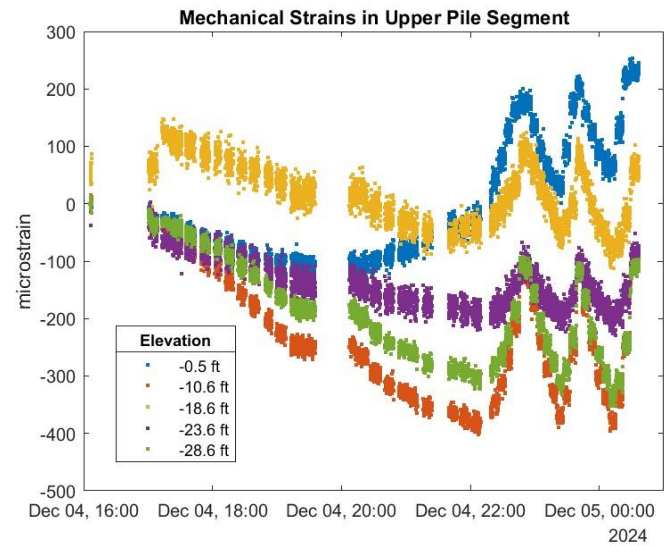




Task 3: Instrumented ACIP Piles for Curing Behavior and Static Load Tests

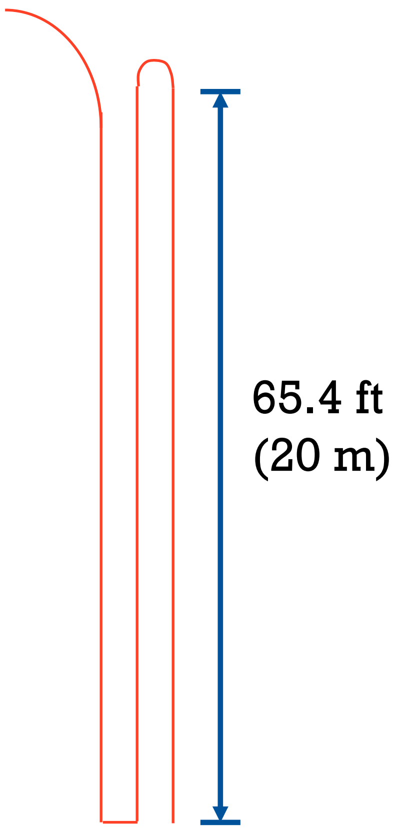
- FIU Pedestrian Bridge Test Pile-Load Test Strains



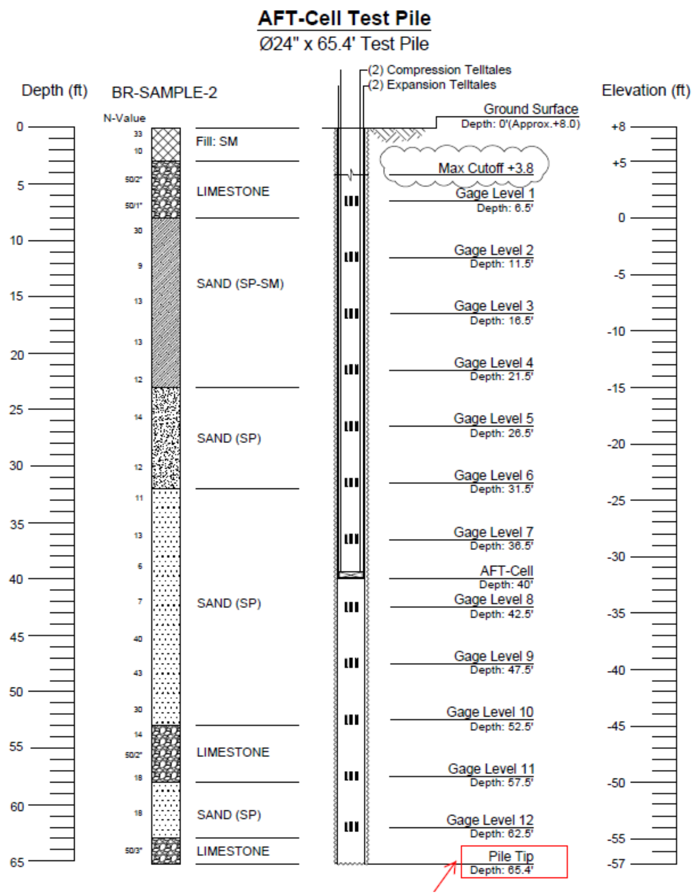


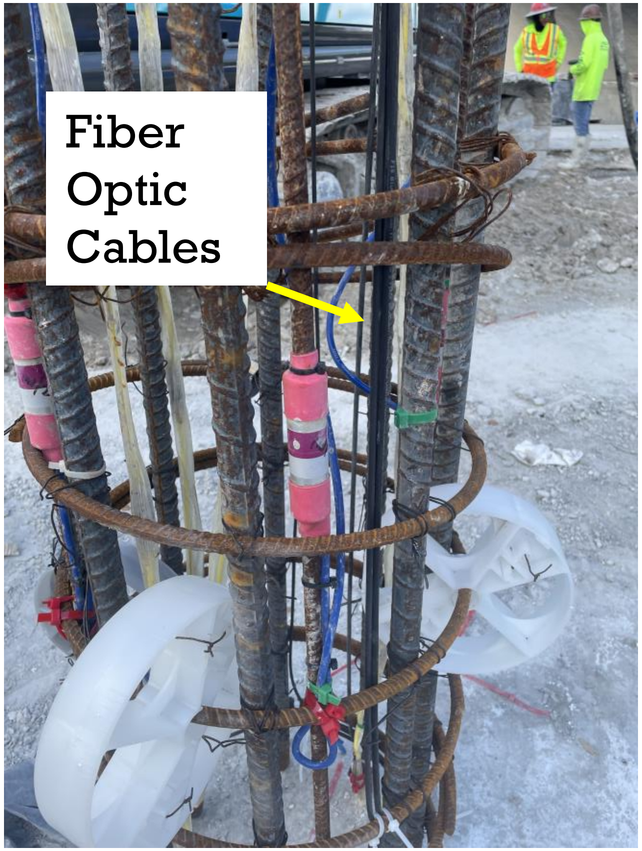
Task 3: Instrumented ACIP Piles for Curing Behavior and Static Load Tests

- Fiber Optic Installation-Sawgrass Expressway Test Pile



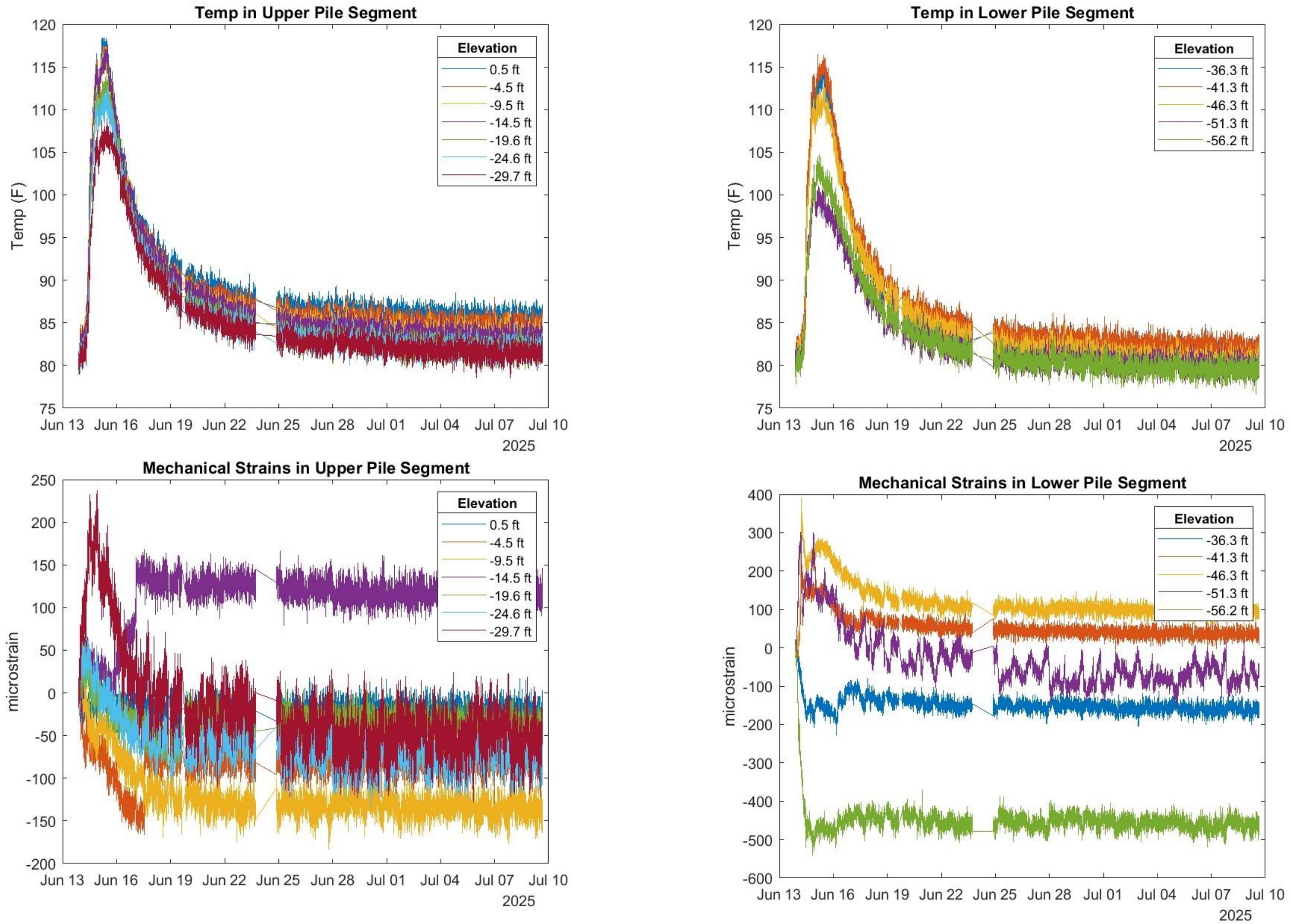
Fiber Optic Cables





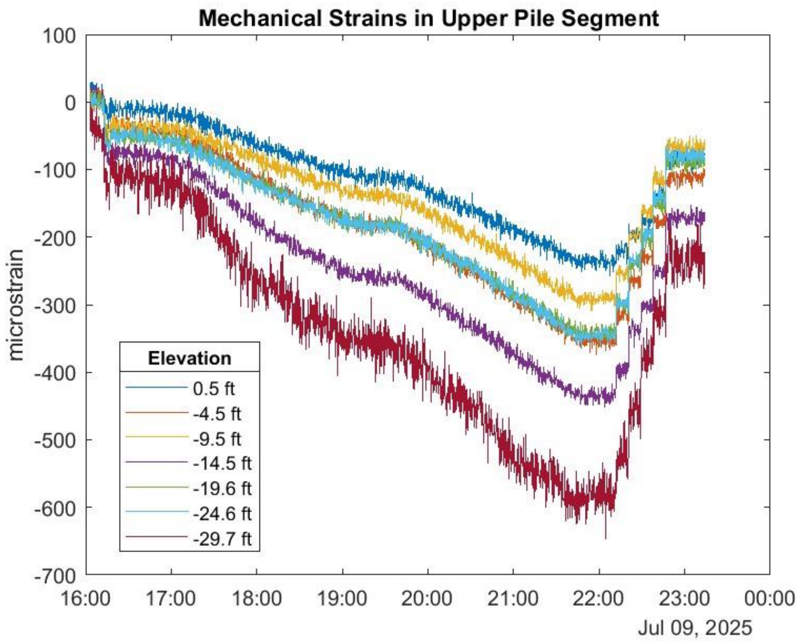
Task 3: Instrumented ACIP Piles for Curing Behavior and Static Load Tests

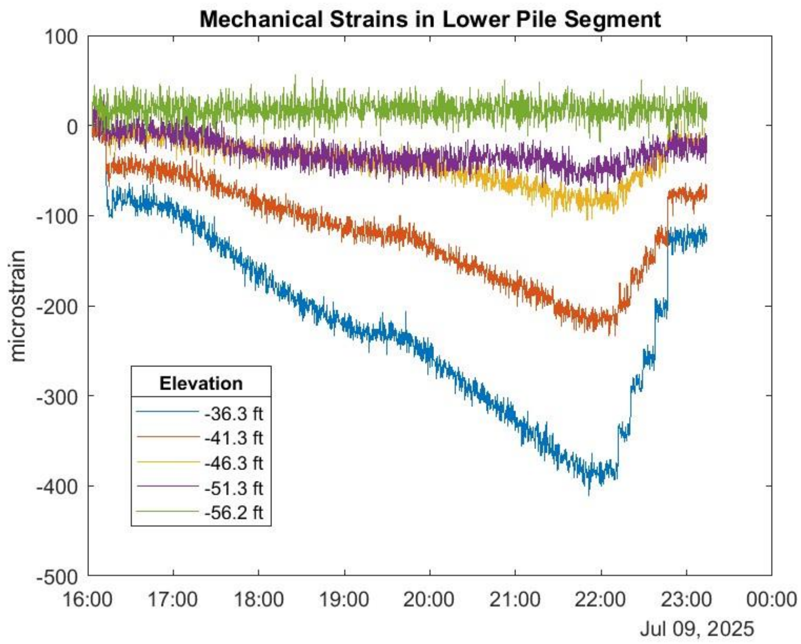
- Sawgrass Expressway Curing Phase-Fiber Optic Temp and Strain



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

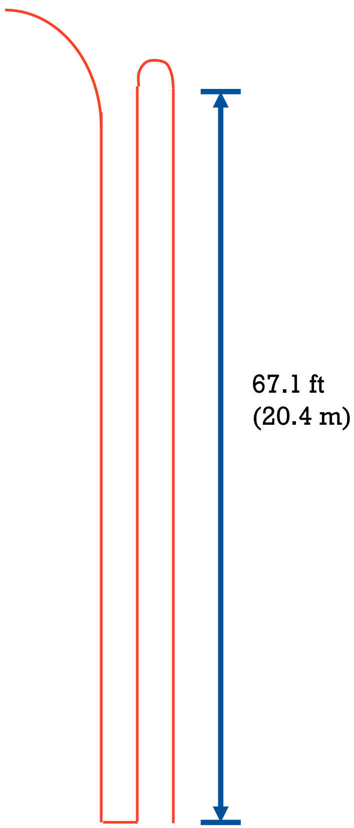
- Sawgrass Expressway Load Test-Fiber Optic Strain



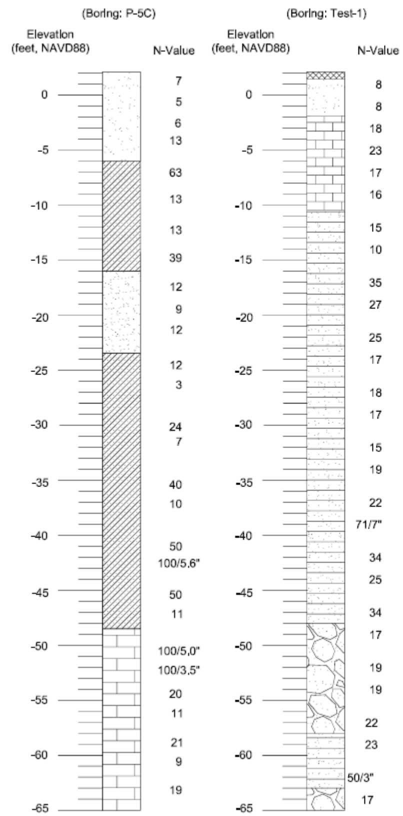


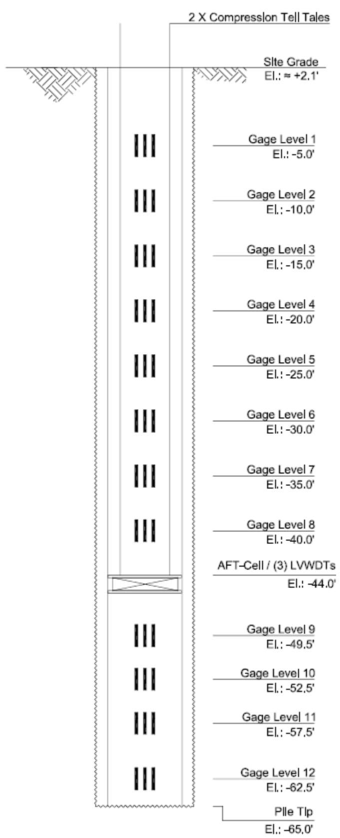
Task 3: Instrumented ACIP Piles for Curing Behavior and Static Load Tests

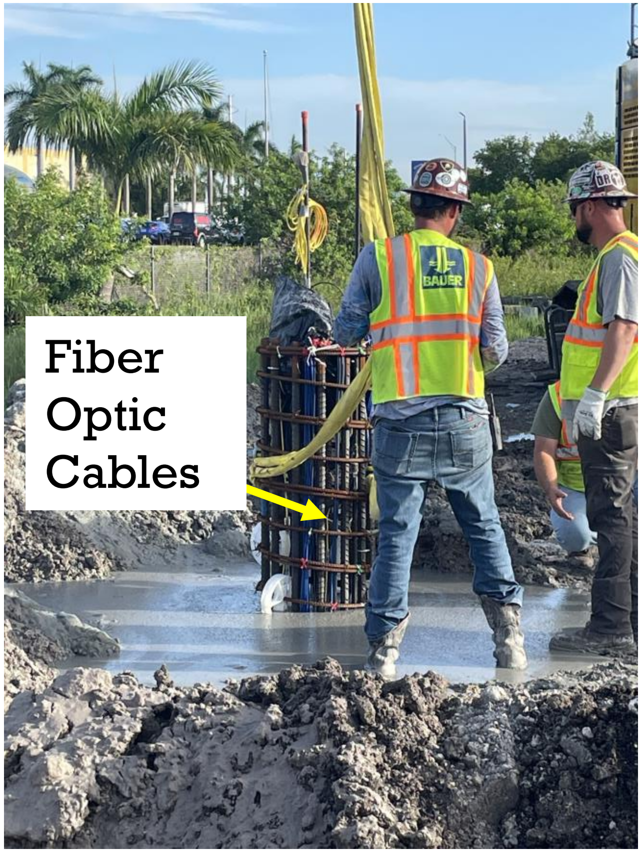
- Fiber Optic Installation-Okeechobee/Palmetto Test Pile



Fiber Optic Cables







Task 4: Grout Mix and Geomaterial Thermal Investigation

- This task will include controlled laboratory testing of grout mix designs and the thermal conductivity 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

Thermal Parameters of Rock (from lab tests):

- Thermal Conductivity:

Samples	Test	λ (W/mK)	R (mK/W)	Average λ	Average Starting T (C°)
1	1	1.431	0.699	1.448	16.07
	2	1.465	0.683		
	3	1.44	0.694		
	4	1.455	0.687		
5	1	1.88	0.532	1.908	16.5
	2	1.906	0.525		
	3	1.905	0.525		
	4	1.94	0.515		
7	1	0.869	1.151	0.879	17.78
	2	0.806	1.241		
	3	0.902	1.109		
	4	0.937	1.067		
10*	1	1.61	0.621	1.609	20.87
	2	1.631	0.613		
	3	1.631	0.613		
	4	1.562	0.640		
11*	1	1.562	0.640	1.648	19.2
	2	1.646	0.608		
	3	1.701	0.588		
	4	1.682	0.595		

Task 4: Grout Mix and Geomaterial Thermal Investigation

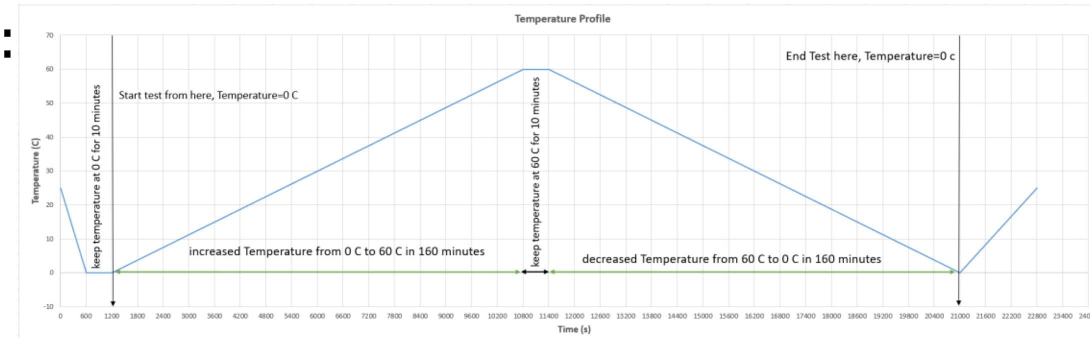
Thermal Parameters of Rock (from lab tests):

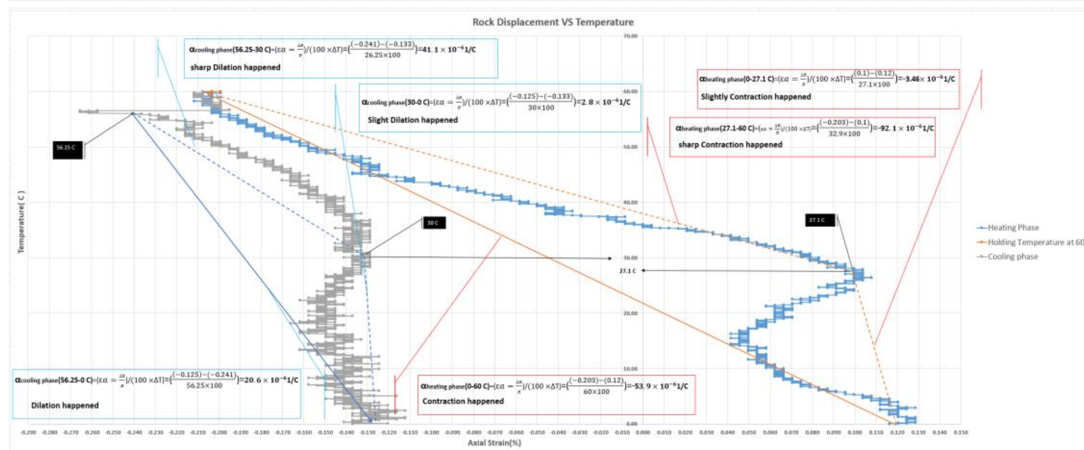
Linear Thermal Expansion:

•**Objective**: Measure linear thermal expansion of rock samples under controlled conditions.

•**Setup**:

- **Oedometer Cell**: 1D expansion and contraction.
- **LVDT**: Installed to record vertical displacement accurately.
- **Chamber Heat System**: Provides controlled thermal loading to simulate temperature variations.





Rock Test	α (0 C to 27.1 C)-slight Contraction	α (27.1 C to 60 C)-sharp contraction	αaverage (0 C to 60 C)-in total Contraction happened
Heating phase	3.46× 10^{-6} 1/C	92.1× 10^{-6} 1/C	53.9× 10^{-6} 1/C

Rock Test	α (56.25 C to 30 C)-sharp Dilation	α (30 C to 0 C)-slight dilation	αaverage (56.25 C to 0 C)- in total Dilation happened
Cooling phase	41.1× 10^{-6} 1/C	2.8× 10^{-6} 1/C	20.6× 10^{-6} 1/C

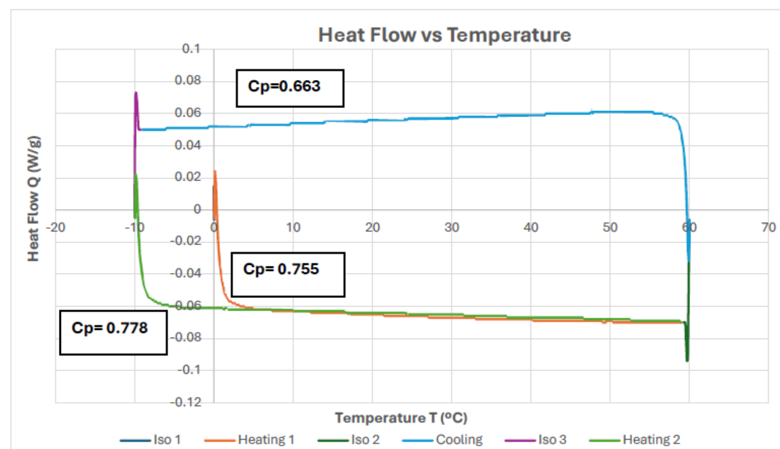
Task 4: Grout Mix and Geomaterial Thermal Investigation

Thermal Parameters of Rock (from lab tests):

- Specific heat capacity through calorimetric testing:

Specific heat for each phase

Phase	Cp (J/g*Cº)	T (Cº)
Heating 1	0.778	0 to 60
Cooling	0.663	60 to -10
Heating 2	0.755	(-10 to 60)



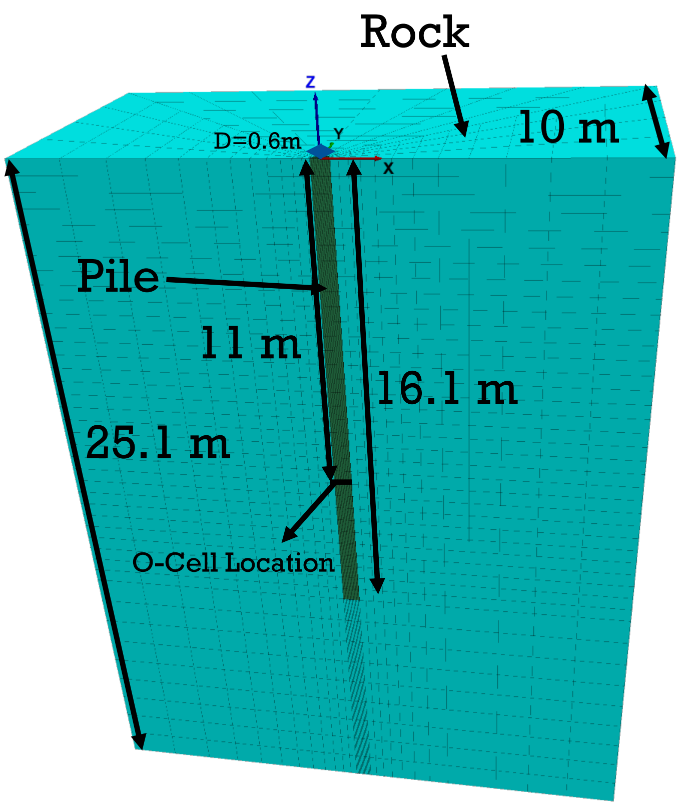
Task 5: ACIP Pile Load Test Analysis and Load Transfer Function for FBMP Model

- 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

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

FLAC 3D Model:

- Pile Diameter: 0.6 m
- Pile Length: 16 m
- Model Length : 25 m
- Model Width : 10 m
- The mesh size near the pile was small, gradually increasing with distance from the pile.
- Hydration phase followed by loading phase.



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

Rock Thermal Parameters used in FLAC 3D:

Model	Thermal conductivity	Specific Heat Capacity	Linear thermal-expansion coefficient (αt):
Isotropic	1.5 W/mK	800 J/(kg K)	-37×10^{-6} K^{-1}

- The rock sample (low initial moisture content) exhibited contraction during the heating phase and dilation during the cooling phase.
- An average linear thermal expansion coefficient of -37×10^{-6} K^{-1} was determined from both phases.

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

Pile Parameters in Hydration Phase:

Model(Mechanical)	Density	bulk-reference	shear-reference	constant-c	constant-a	hydration-minimum	tension-reference	hydration-difference-minimum
Hydration-Drucker-Prager	2500 kg/m3	13.9e9 pa	10.4e9 pa	0.4 (no unit)	0.6 (no unit)	0.20 (no unit)	2.0e6 pa	1e-4 (no unit)

Model(thermal)	Thermal conductivity	Linear thermal-expansion coefficient (αt)	Maximum amount of generated heat (Q_{Ce}^{max})	Specific heat ($C_{p,1}$)	Cement concentration (C)	constant-jonasson-b	constant-jonasson-t1	Universal gas constant (R)	Temperature-reference	hydration-grade-maximum	hydration-temperature-maximum	constant-energy-1(Activation energy: $E_{A'1}$)	constant-energy-dt (Slope of energy change (dEA,T))	constant-conductivity-1
Hydration	2 W/m K	10^{-5} K^{-1}	13.7e5 J/kg	0.2 J/(kg K)	330 kg/m^3	-1.114 (no unit)	7.2e4 1/S	8.314 J/mol	293 K	1.0 (no unit)	1e4 (no unit)	33.5 J/mol	1.47 J/mol/K	2.0 (no unit)

Pile Parameters in Loading Phase:

Model	Bulk Modulus	Shear Modulus	Density
Linear Elasitic	13.9e9 pa	10.4e9 pa	2500 kg/m3

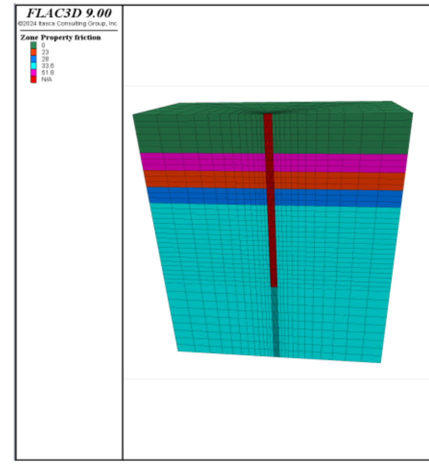
Task 5: ACIP Pile Load Test Analysis and Load Transfer Function for FBMP Model

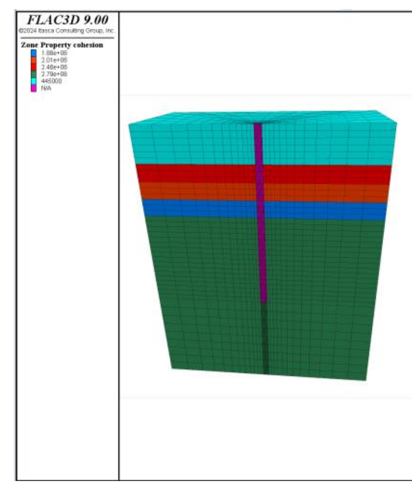
Interface Parameters:

- Interface Parameters was defined for each layer (5 interfaces).

- Interface parameters = 67%(2/3)C and ϕ.

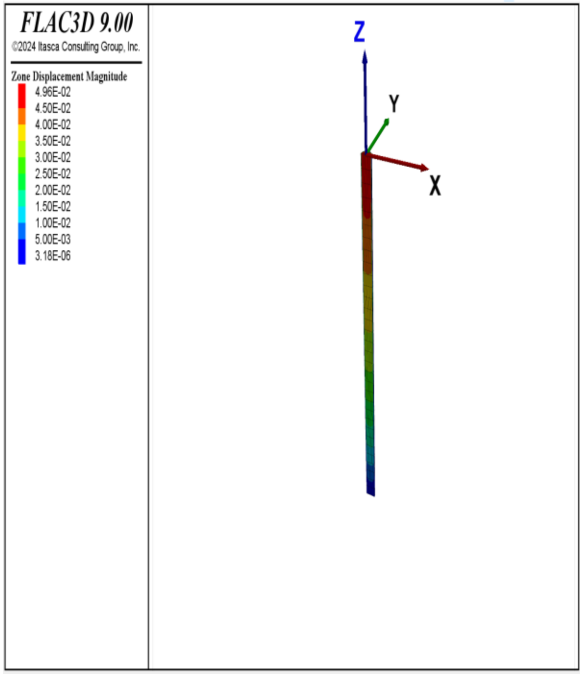
Zone	Normal Stiffness (Kn)-Pa	Shear Stiffness (Ks)-Pa	C(pa)	Φ(degree)
C-0,C-1(side)	1e8	1e8	2.937e5	0
C2(side)	1e9	1e9	1.62e6	40
C3(side)	1e9	1e9	1.326e6	15.6
C4(side)	1e9	1e9	1.24e6	19.34
C-5,C-6(side),Base	1e9	1e9	1.84e6	23.67



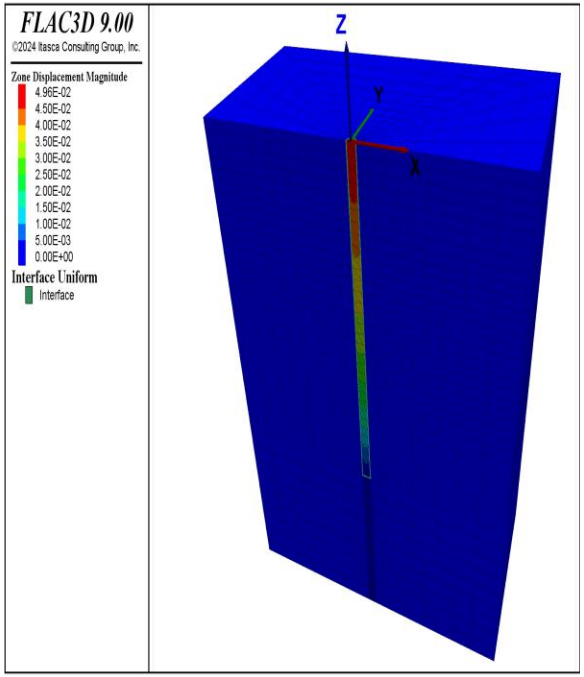


Task 5: ACIP Pile Load Test Analysis and Load Transfer Function for FBMP Model

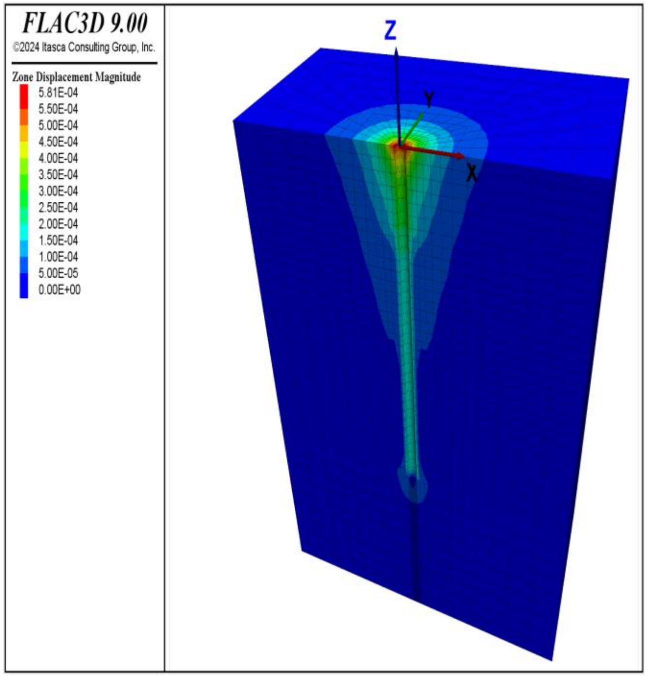
Hydration Phase Results (24 hr hydration)



Pile Magnitude Displacement



Pile and Rock Magnitude Displacement

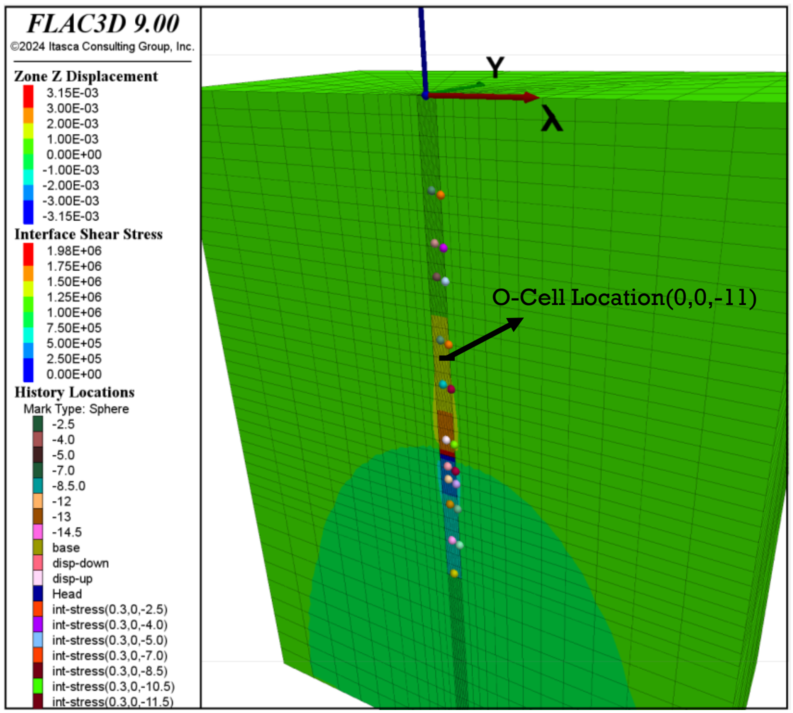


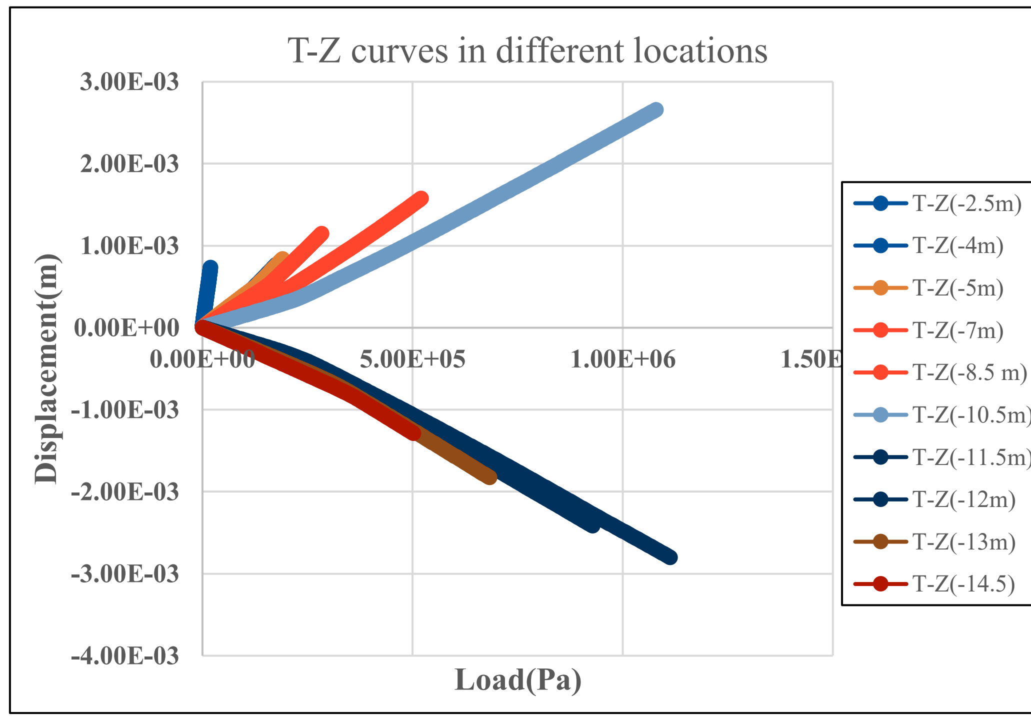
Rock Magnitude Displacement

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

Mechanical Loading (Bidirectional Loading, O-Cell)

1-Mechanical phase(O-Cell Loading): restore from initial phase





Thank You!