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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

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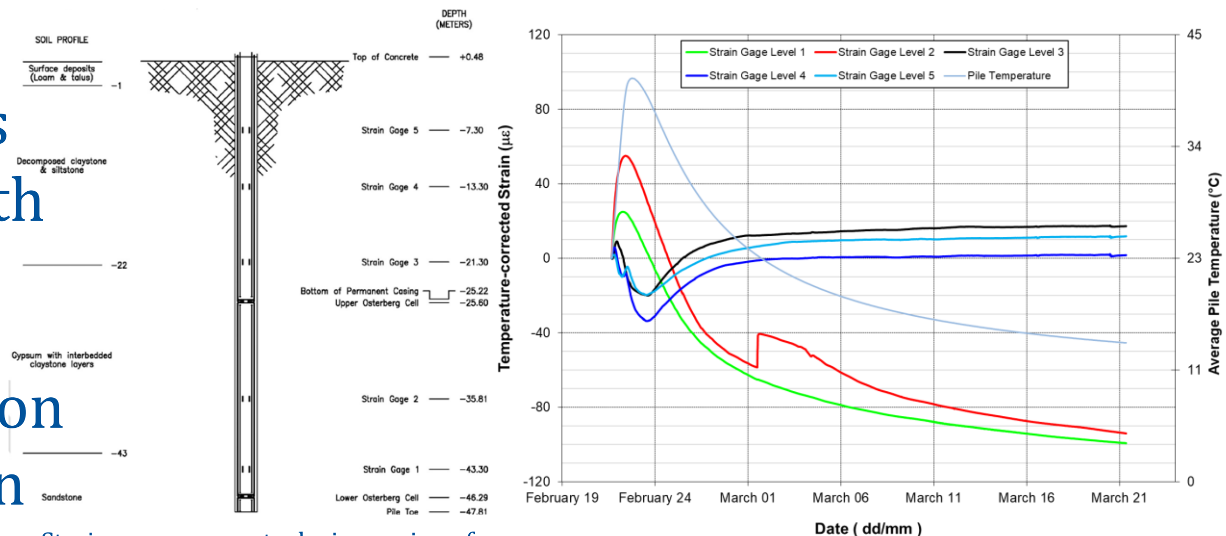
Introduction: Residual Stress in Deep Foundations

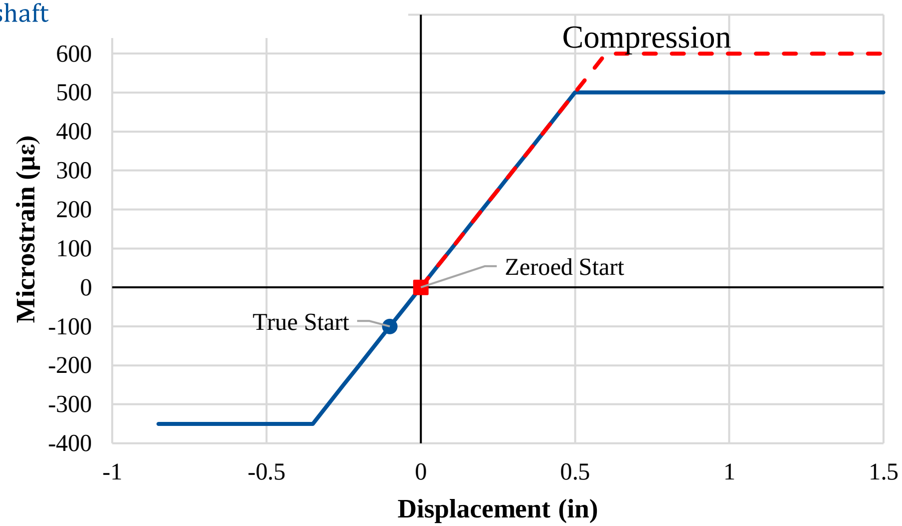
- Residual stresses are tension stresses that develop in the pile/shaft during the grout curing phase; influenced by
  - Length of the pile/shaft - 25 ft vs 125 ft ACP
  - Layering – interbedded layers of soil and rock vs just soil
  - Drilling/grouting with highly variable pile/shaft diameters
  - Grout 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 epistemic uncertainty in the MWD QA/QC – Can be addressed!
- 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



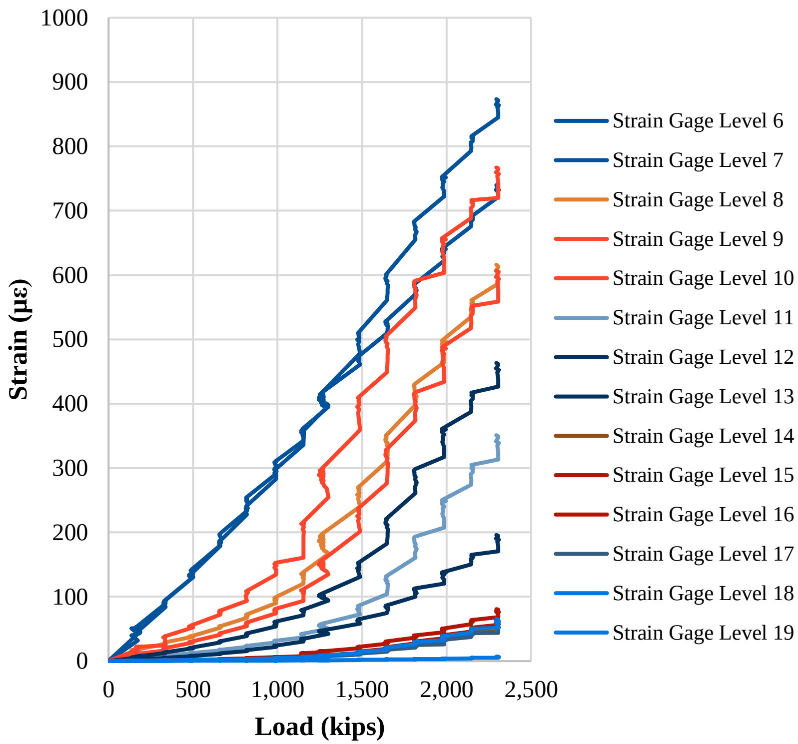
Strain measurements during curing of a drilled shaft



Theoretical load path for strain gage 1

Background – Load Test Observations

- Tension strains neglected in load test data
- Irregular strain profile
- Absolute strain needed

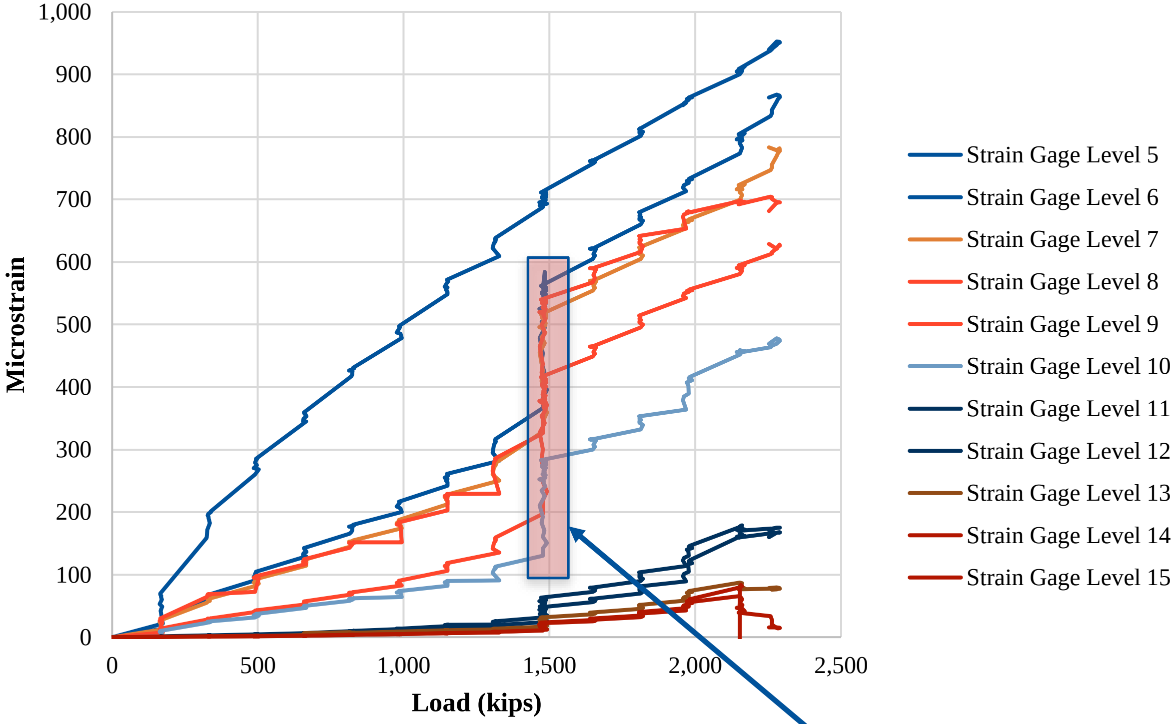


I-395 test pile axial strains as a function of applied load in LTA test

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

Background – Tensile Micro-Fracturing

- Micro-fracturing in concrete during curing may be occurring
- Resulting in highly non-linear pile rigidity (EI)
- Increased pile compression before mobilization
- Increases moisture and oxygen ingress, steel corrosion of piles/shafts in porous limestone



SR-836 test pile axial strain as a function of load

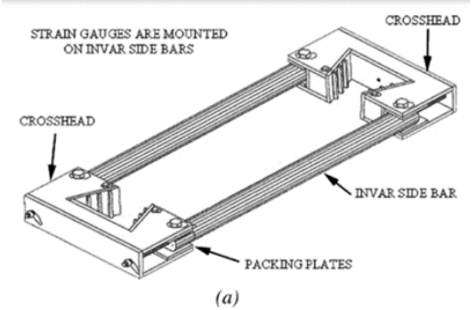
200 με of micro-fracture closures during 1,500 kips sustained for 1 hr and LTA movement of 0.09 inches

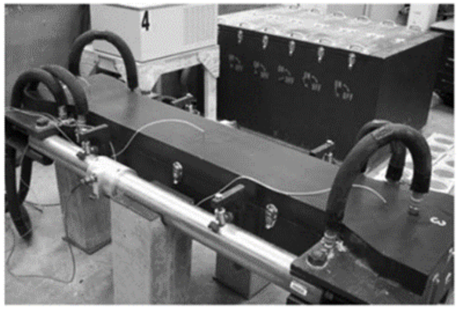
Background – Contributing Factors

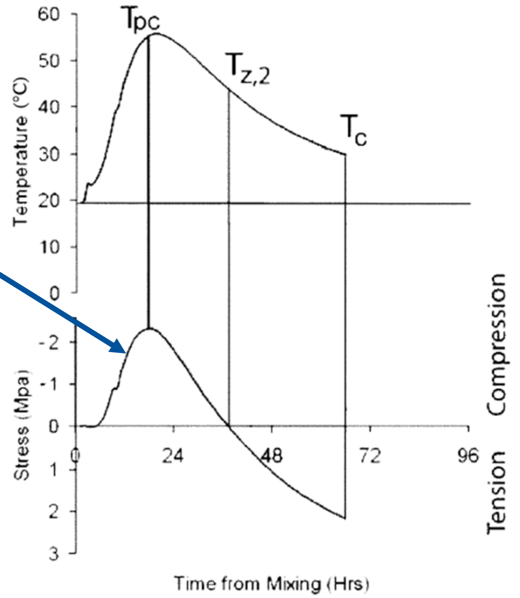
- Geologic layers may contribute to residual stress development
  - MWD profiles indicated multiple shaft segments in low strength soil/rock bounded by higher strength rock layers in Miami-Dade
  - TIP profile in these segments indicated larger shaft radius than design
    - Agreed with MWD strength profiles
  - Large tension strains measured in “bound” pile segments
- Drilling process
  - Drilling penetration rate is high in weaker geomaterials and low in stronger geomaterials
  - TIP profiles show non-uniform and larger diameter holes made with high penetration rates
  - Large residual stresses measured in piles/shaft segments with non-uniform diameter holes (high penetration rates)

Background – Contributing Factors

- Concrete curing process
  - Rigid cracking frame tests simulate concrete specimens cast with two fixed ends
  - As the concrete expands and contracts during curing, strain gauges mounted on an Invar frame measure the stresses
    - Invar -> low thermal expansion
  - Rigid cracking frame tests show similar behavior as weak geomaterial bound by stronger rock layers, permanent casing, or an embedded LTA that serve as the "fixed ends"
    - Strong segments exhibit early tension then minor compression
    - Weak bound segments exhibit early compression then major tension



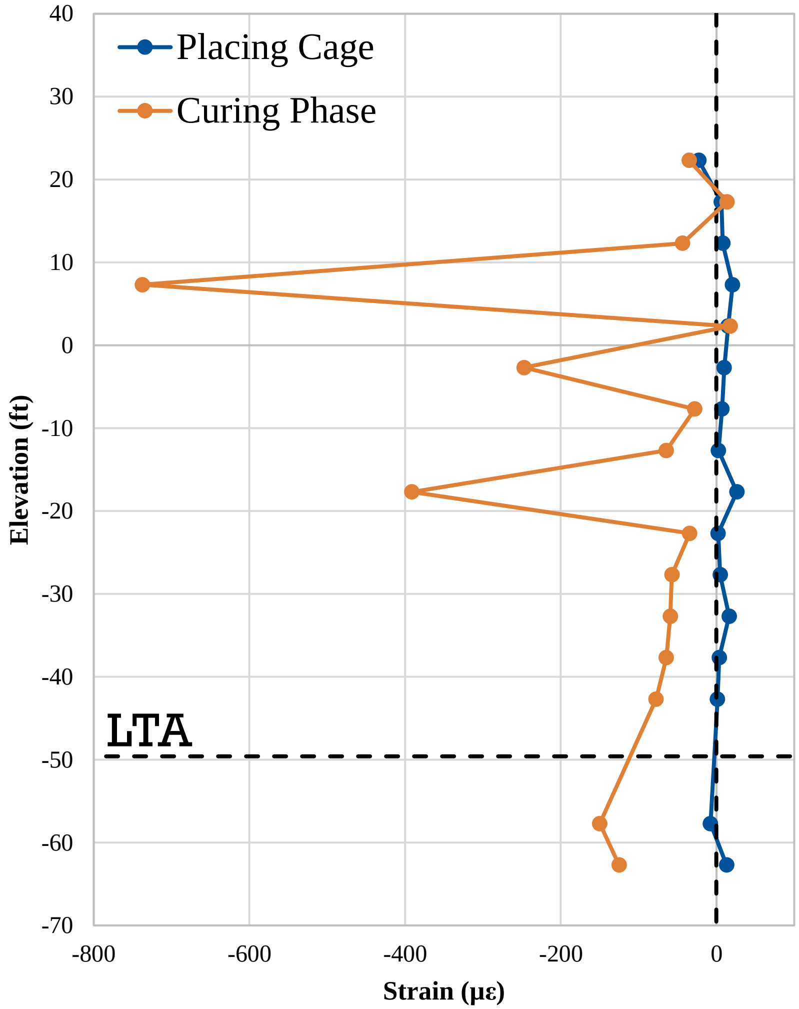




Curing temperature and strains in rigid cracking frame

Background – Contributing Factors

- LT Consultant stated "high tensile curing strains were observed in strain readings" for multiple Miami-Dade load test reports
- UF recorded strain readings at multiple phases prior to load test
  - Cage lying on ground
  - Immediately after cage placement
  - Prior to start of load test
- Limited strain change noticed during cage placement
- Significant strain changes observed during curing phase



Background – Contributing Factors

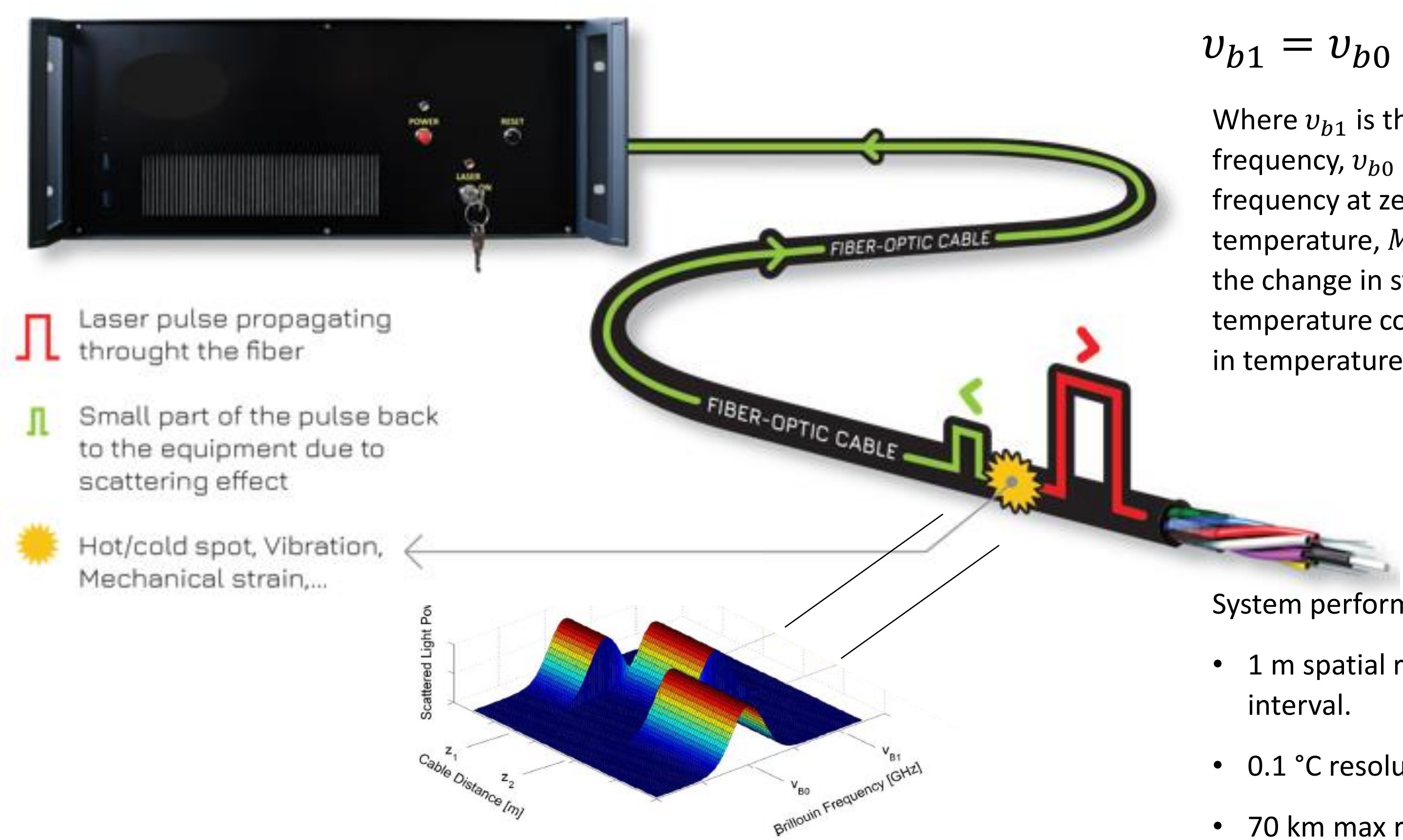
- Geomaterial thermal conductivity and concrete mix
  - Thermal strains influenced by surrounding geomaterial conductive properties
  - Thermal conductivity of geomaterials is a function of mineralogy, dry density, moisture content, gradation, time, temperature
  - Concrete heat of hydration are sensitive to additives in mix design
  - Fast setting-high strength mix designs may be commonly used
  - Geology may need to be considered in mix design for piles/shafts

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) based on perturbations in the frequency of light passing through glass fiber.



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

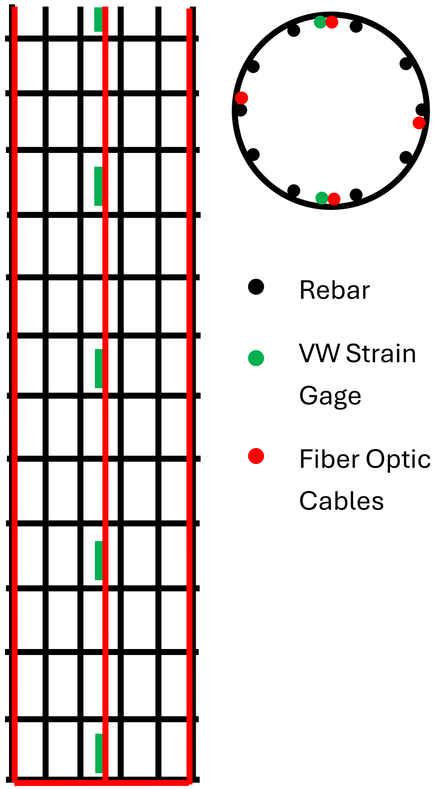
Where υ_{b1} is the change in the Brillion frequency, υ_{b0} is the central peak Brillion frequency at zero strain and constant temperature, M is the strain coefficient, $\Delta\varepsilon$ is the change in strain of the fiber, N is the temperature coefficient, and ΔT is the change in temperature of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

System performance:

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

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

- 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

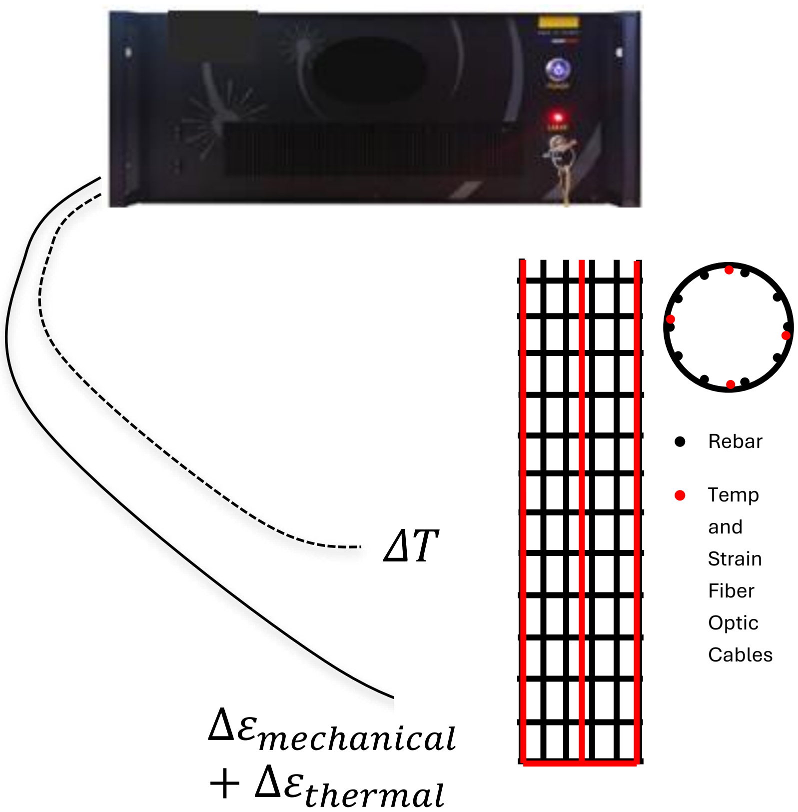
Cable and gage attachment to rebar cage

Pretensioning DFOS cables with cable clamps

Protecting DFOS cables

Task 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

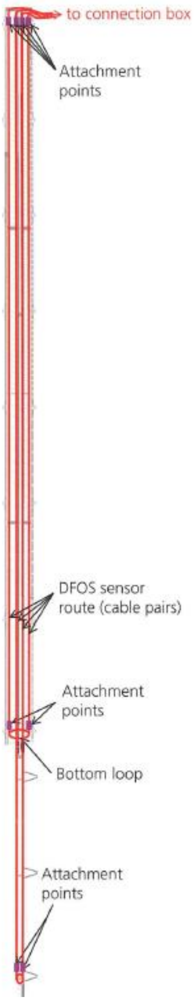
$$F_a(z) = EA \cdot \varepsilon_{M\ or\ T}(z)$$

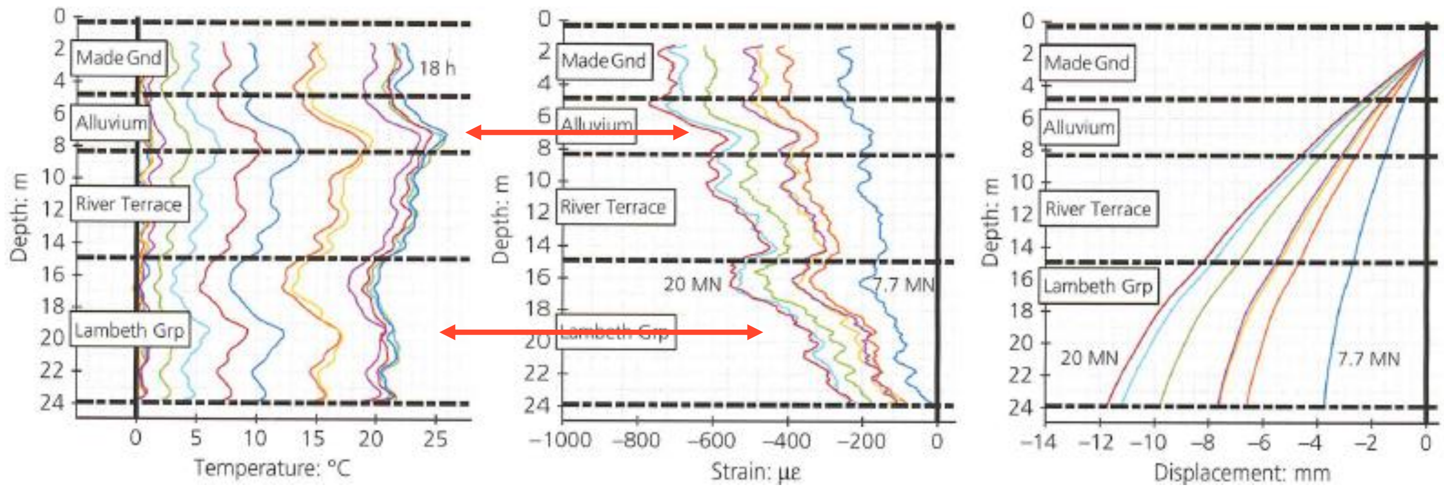
$$u(z) = u(z = z_0) + \int_0^z \varepsilon_{M\ or\ T}(z)dz$$

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 1: Instrumentation Planning, Literature Review, and Sample Collection

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

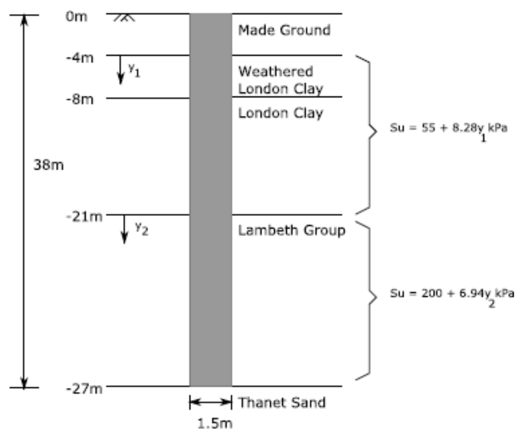




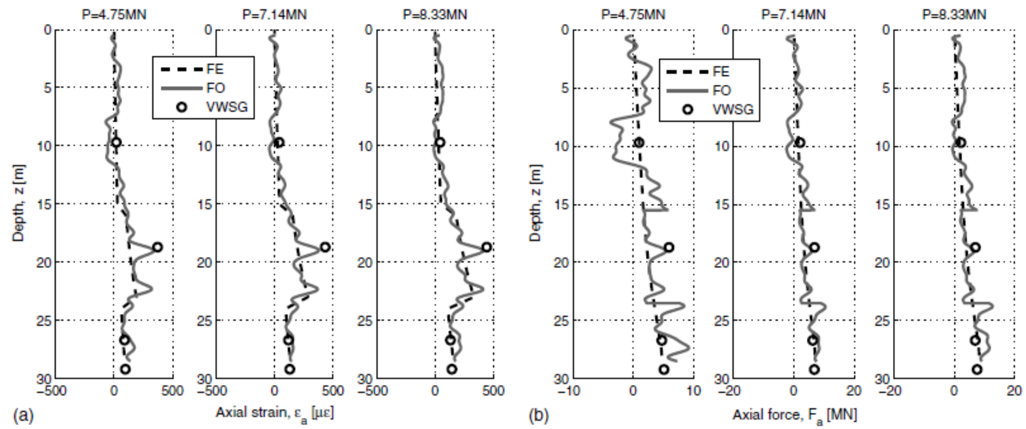
- Alluvium and River Terrace interface (7-8 m) higher temps consistent.
- Similar but smaller temperature peak at 19-20 m.
- Authors attribute this to wider borehole and more concrete mass heat.
- Wider pile diameter evident in strain dips 7-8 m and 19-20 m.

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

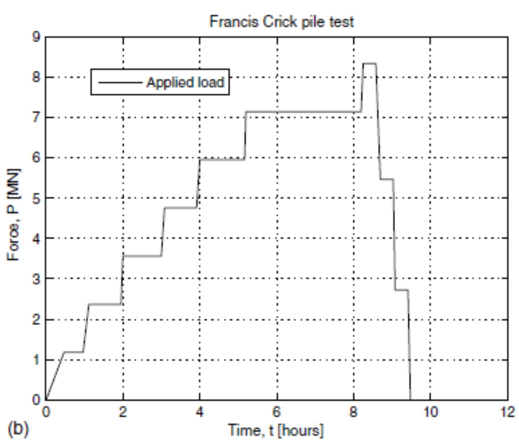
- Bi-Directional Test (Pelecanos et al., 2017)



(a)

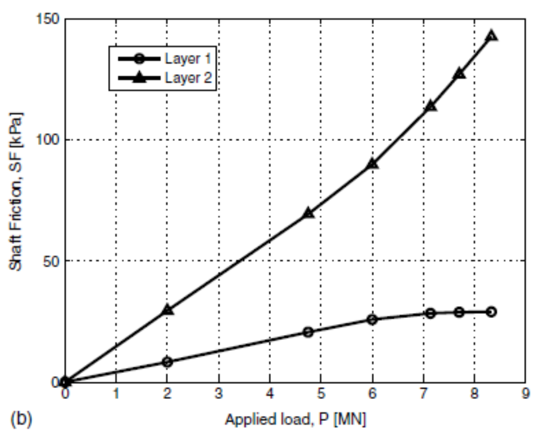


(a) (b)



(b)

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



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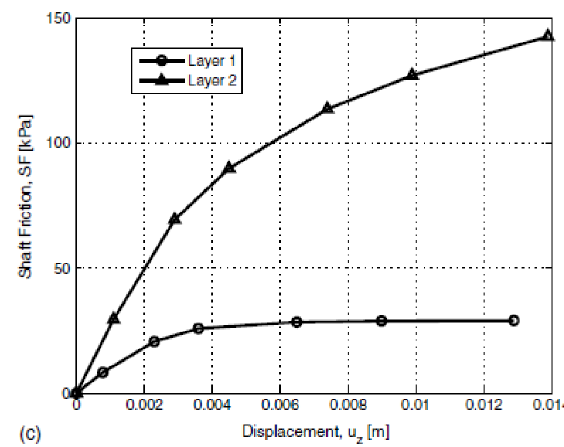


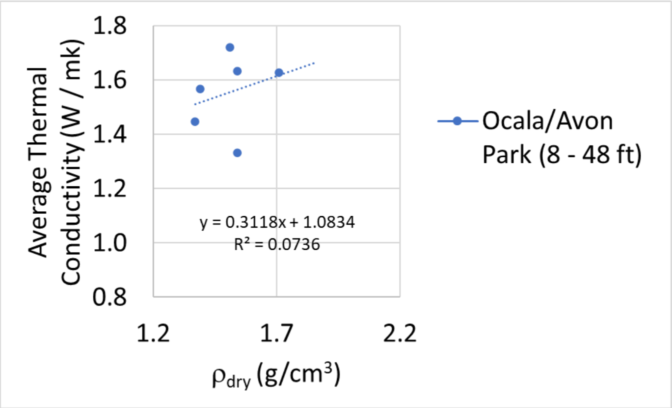
(c)

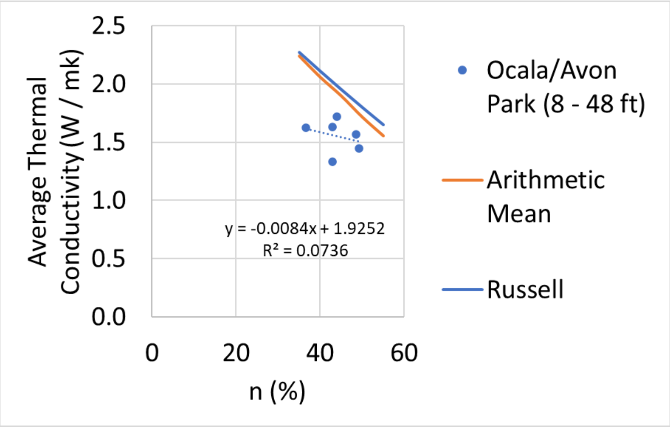
Task 1: Instrumentation Planning, Literature Review, and Sample Collection

- Measure thermal strain and temp of grout cylinders (early age to setup) for approved mix designs.
- In process of collecting cores from Ocala formation, Avon Park, Miami Formation, Ft. Thompson Formation, and Key Largo Formation.
- Volumetric change of limerock during thermal loading
  - Depending on drained or undrained behavior, temp and stress history (OCR), confining pressure, mineralogy, density, 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).
  - Insitu 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

- Thermal conductivity of FL limerock





Arithmetic Mean

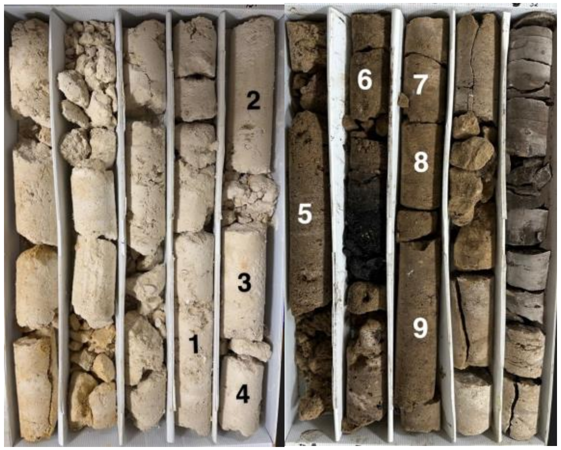
$$k = (1-\phi)k_s + \phi k_a$$

Russell

$$\frac{k_s}{k} = \left(1-\phi^{1/3}\right) + \frac{\phi^{1/3}}{\frac{k_a}{k_s}\phi^{2/3} + 1 - \phi^{2/3}}$$

Where k = thermal conductivity of geomaterial, k_s = thermal conductivity of pure calcite 3.43 W/mk, k_s = 0.024 W/mK thermal conductivity of air, ϕ = porosity.

- **The rock is the Avon Park formation which is limestone and dolostone with gypsum infill. It is identified as having calcite with aragonite to dolomite ratio greater than 1:1. The gypsum has a thermal conductivity around 1.2 (W/ m-k) and aragonite 2.13 (W/m-k) (indicted by darker colored limestone), which could result in the lower thermal conductivity measured here in comparison to pure calcite (3.43 (W/m-k)) and dolomite (5.34 (W/m-k)).**



Cores 8 – 12 ft   Cores 42 – 48 ft

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 using the newly developed analysis tool from FDOT Project BED31-977-09
  - 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 3: Instrumented ACIP Piles for Curing Behavior and Static Load Tests

- This task will consist 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 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 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

Project Benefits - Qualitative

- Previous ACIP pile MWD-load test correlations will be strengthened, or new correlations will be established
- The effect of variable penetration rates during drilling will be identified to provide guidance for future ACIP pile installations
- The effects of irregular pile geometries and geological factors on thermally induced residual stresses will be identified
- Insight to the advantages of DFOS compared to traditional vibrating wire Strain gauges will be gained
- The effects of grout mix designs on thermally induced residual stress will be identified to mitigate future issues
- Better understanding of how to address ACIP pile thermal effects in South Florida soil and rock will be achieved
- Modified T-z models that include residual stress will be established for the soil and geomaterials tested to be used in future ACIP pile design
- Preliminary test standard will be developed for DFOS load test data reductions to provide guidance for future implementation

Project Benefits - Quantitative

- MWD will be conducted on 3 load tested ACIP piles and numerous new MWD-load test data points will be obtained
  - Previous correlations will be strengthened, or new correlations will be established
- 3 load tests will be performed and analyzed using traditional methods and DFOS
  - This will provide insight to the advantages of DFOS compared to traditional methods.
- Numerous rock cores will be collected and tested for strength and material properties as well as thermal conductivity
  - This will provide a better understanding of how to address ACIP pile thermal effects in rock
- Numerous soil samples will be collected and tested for thermal conductivity
  - This will provide a better understanding of how to address ACIP pile thermal effects in soils
- Numerous contributing factors to thermally induced residual stresses in ACIP piles will be identified
  - This will help mitigate future residual stress issues

Thank You!