Measuring While Drilling for Geotechnical Site Characterization and Bored Pile QA/QC

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Florida Geotechnical Design Challenges

- In Florida, our bored piles (drilled shafts and ACIP piles) that support larger structures often rely on a competent length of rock socket to develop the necessary axial capacity required to satisfy the engineering design
- As described by Graham et al. (2013):
  - The subsurface stratigraphy of Florida sites underlain by weathered limestone formations can be highly variable with respect to material layer thicknesses and strengths, even over short horizontal distances
  - These conditions present a challenging environment for the design of drilled foundations in terms of axial performance
- Graham et al. (2013) identified the following contributing factors:
  - Due to the variability in subsurface conditions, it is not always possible to anticipate stratigraphy based on borings even a short distance away, and sometimes even across the footprint of a single foundation unit
  - Highly weathered material is not well suited for typical investigation methods designed for soil or rock
    - SPT borings, CPT soundings, and traditional rock coring – “none of these tests are fully capable of defining the in-situ strengths for design in weathered limestone”
  - It is a challenge to assign material properties to a seemingly erratic stratigraphy that will produce meaningful correlations to the load testing data
- The FDOT has turned to measuring while drilling (MWD) to improve geotechnical design and Bored Pile QA/QC

Introduction to Measuring While Drilling

- MWD is the application of monitoring and recording drilling data during the drilling process
- MWD is conducted using computerized systems with sensors placed on the drill rig to monitor a series of drilling parameters
  - The sensors collect data for each monitored parameter continuously, in real-time, without interfering with the drilling process
- The monitored data typically are displayed in real-time and often recorded for further analysis
- The continuous sampling produces high resolution profiles of individual and compound drilling parameters that can be used to quantify changes in subsurface conditions, assess geo-mechanical properties, as well as optimize drilling operations
- MWD can be used to increase and improve the data collected during site investigation for geotechnical design and as a QA/QC tool during bored pile construction
  - Both applications produce a significant amount of data that can be used to address the problems described by Graham et al. (2013)

Site Investigation MWD – Geotechnical Design

Bored Pile MWD – Construction QA/QC

Introduction to Measuring While Drilling

- Individual drilling parameters are designated by one of three categories:

1. Method-based parameters
   - Parameters that reflect the drilling application including type of drill rig, type of drilling tool, **drill bit diameter**, method of drilled debris removal, and drill rig limitations.
2. Controlled drilling parameters
   - Parameters that are controlled by the drill rig operator including crowd, **rotational speed**, inclination, drilling slurry properties, and fluid injection flow rate.
3. Responsive drilling parameters
   - Parameters that are dependent upon method-based parameters, controlled parameters, and the strata encountered during drilling which includes **torque**, **penetration rate**, vibration, and fluid injection pressure

- Compound drilling parameters
  - A combination of individual drilling parameters that enhance the measurable drilling response due to changes in the strata encountered
  - Compound parameters that focus on responsive drilling parameters provide a more accurate and reliable assessment of in situ geo-mechanical properties, especially in rock
    - **Specific energy**

$$\boldsymbol{Specific\ Energy\ (e) = \frac{F}{A} + \frac{2\pi NT}{Au}}$$

F = Crowd or downward axial force (lbf)

N = Rotational speed (RPM)

T = Torque (in-lbs)

u = Penetration rate (in/min)

A = Cross-sectional area of the excavation (in^2)

Q = Flow rate of injected fluid (GPM)

P = Flow rate injection pressure (psi)

Teale (1965)

- Rotary component of specific energy equation accounts for > 99% of specific energy in rock
- Includes responsive drilling parameters
  - **T** and **u**
- Normalized by method based and controlled parameters
  - **N** and **A**

MWD Assisted Rock Coring in Florida

- Due to the challenges discussed, low core recoveries (REC) and a lack of testable samples recovered are all too common in Florida
  - In many cases, an insufficient amount of data is gathered during the site investigation phase to properly characterize the site for geotechnical design
- However, our recent findings indicate the low recoveries and lack of testable samples recovered may be attributable to the coring techniques implemented rather than the in-situ conditions of Florida limestone
- MWD provides an ideal solution to quantify the effects of drilling techniques on REC and the quality of our core samples, and to provide an increase in the number of strength assessments and data gathered within a rock mass to improve characterization
- In rock coring three possible phases of operation exist (Rodgers et al. 2021):
  - Phase 1 – Inefficient
  - **Phase 2 – Optimized**
  - Phase 3 – Destructive

***Detournay et al. (2008) also identified three operational phases for drag bits**

- In order to optimize drilling operations, core recoveries, and ensure characterization is reflective of the in situ conditions, Phase 2 must be maintained throughout the coring process
- During conventional rock coring, without MWD, maintaining the optimized phase can be quite the challenge
  - Phase 2 is rarely achieved in practice (Detournay et al. 2008)

Phase 2

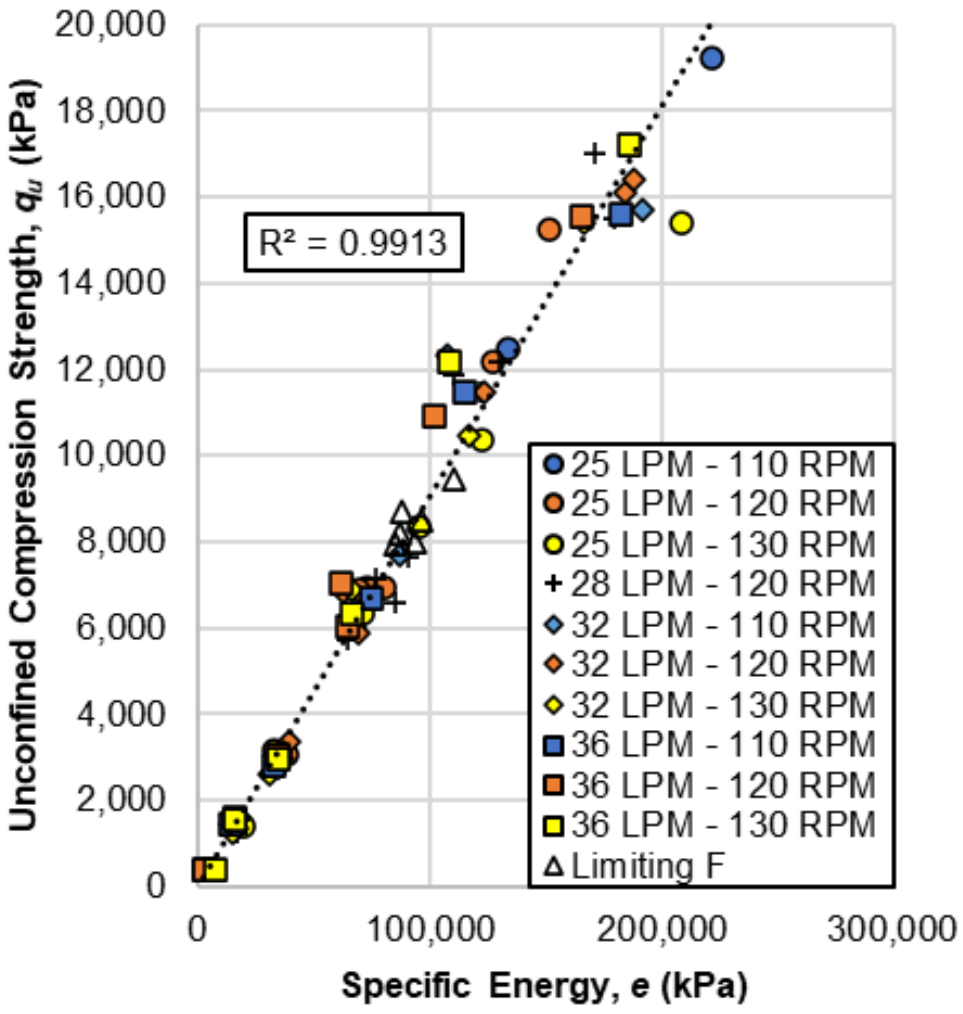
Phase 3

Introduction to Operational Limits

- With MWD, drilling guidelines and procedures can be established to ensure we use our drilling tools in the most efficient manner and only operate in Phase 2
  - Characterization is reflective of the strata encountered and not influenced by our drilling techniques
  - Reliably assess rock strength in situ during drilling with high resolution (cm-scale)
    - Significant added benefit from properly conducting MWD
- In order to measure rock strength in situ and optimize the quantity and quality of the testable core samples collected, certain drilling principles must be understood and followed
  - **Operational Limits** of the drilling tool
- Interdependent relationships exist between each of the drilling parameters and these relationships must be considered to achieve the most efficient drilling practices
- Introduced a new concept of operating within optimal drilling parameter ranges based on the interdependent relationships which are **unique to the geometry of the drilling tool**
- Using MWD, these optimal interdependent drilling parameter ranges can be identified for each drilling tool and maintained throughout the drilling process

Building Correlation for In situ Rock Strength Assessment

- Once we understand the operational limits of Phase 2 for a drilling tool, we can develop correlation between specific energy and rock strength (q_u or UCS)
  - Relating drilling parameters to engineering parameters
  - Allows in situ rock strength assessment
- Data grouped by combinations of variable flow rates and rotational speeds
  - 10 different combinations, 85 core runs total
  - An optimum range of N was determined
    - 110 to 130 RPM
  - N dictated the u based on an efficient u/N range identified for Phase 2
  - Q dictated the range of T and F that could be applied to maintain the efficient u/N range
- Excellent correlation was found between specific energy and q_u
  - $R^2 = 0.99 \rightarrow$ reliable and repeatable results
- REC = 100% for a q_u range of 180 to 2,800 psi
  - ≈80% rock strengths in FL based on historical FDOT data
  - Optimized the number of testable samples sent to the lab
- Can use the regression equation to assess rock strength in situ via specific energy
  - Maintain the operational limits of Phase 2

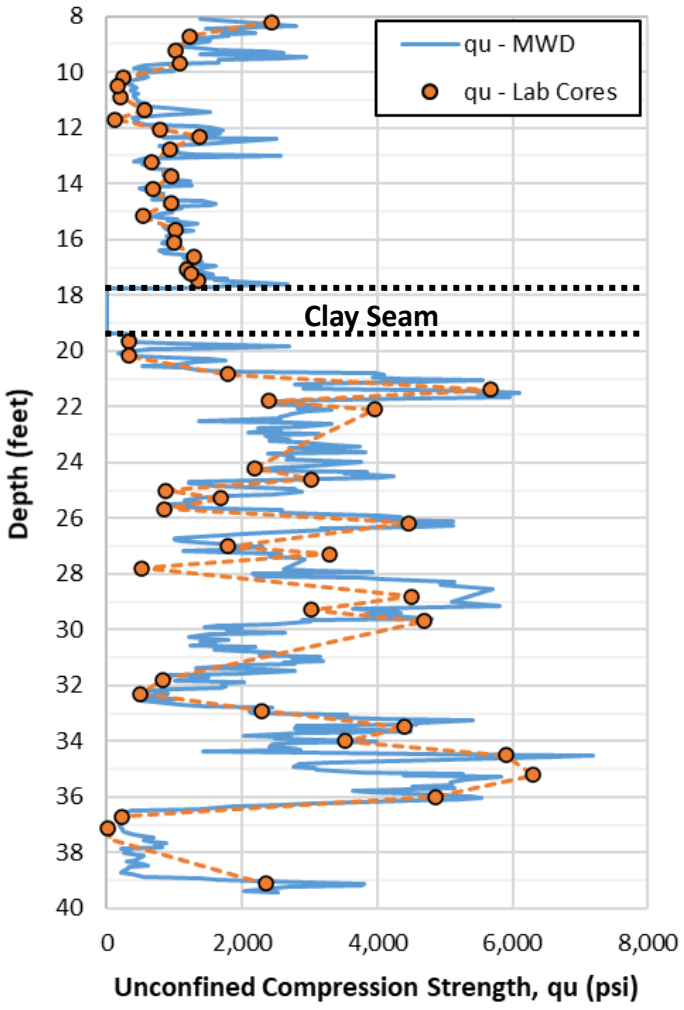


(Rodgers et al. 2021)

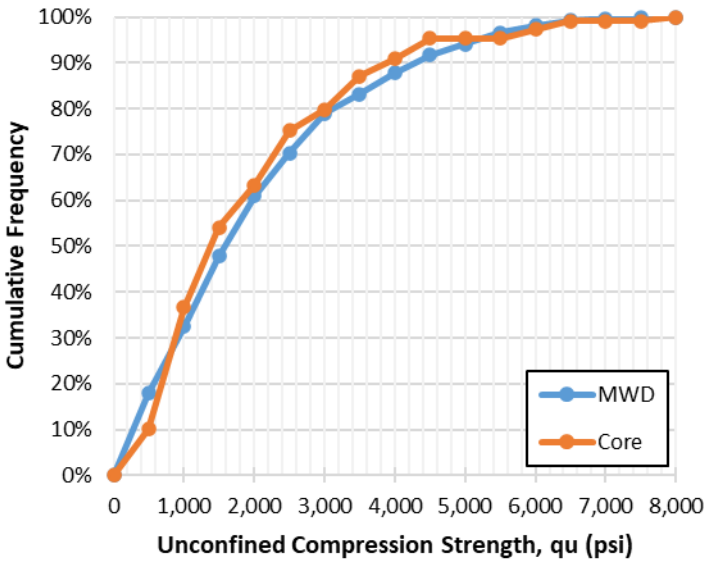
MWD for Site Characterization – Rock Coring

- 89 feet of rock coring completed at Perry, FL using a double-wall core barrel
  - MWD produced a continuous high-resolution strength (qu) profile to identify layering at each boring location
- Boring 5 strength profile displayed in the center
  - γ_d range =100 to 165 pcf
  - *w%* range = 0.7% to over 20%
  - Core q_u range = 66 to 6,300 psi
    - Basically, the entire range found in FL
  - Mean REC = 92%
- MWD optimized REC and ensured the characterization was reflective of the strata encountered
  - More than doubled the number of testable samples collected per linear foot than conventional rock coring at the same site
  - Recovered far more low strength rock
- MWD and Lab core statistics and strength distributions were in excellent agreement over the full strength range
- MWD increased the number of strength assessments by an order of magnitude
- Greatly improves the information available for design
  - Fills in the gaps where testable samples were unable to be recovered
- Increases confidence in the data used for design
  - In situ MWD assessment and laboratory strength (qu) tests are both in agreement

Boring 5 – Strength Profile



Perry Florida – 5 Borings Summary of Site Statistics - qu (psi)		
Stats	**MWD**	**Lab Cores**
Mean	**1,923**	**1,884**
Median	**1,558**	**1,381**
Std Dev	**1,484**	**1,515**
CV	**0.77**	**0.80**
Max	**7,997**	**7,697**
Min	**41**	**66**
Count	**1,353**	**155**



Rodgers et al. (2021)

The Effects of Phase 3 Drilling

- Quantified these effects by investigating Phase 2 drilling and both loading paths of Phase 3 for various strengths of rock
  - Phase 2 – Operational Limits (OL)
  - Phase 3 – State of Stall (Stall) → reduced u/N
  - Phase 3 – Manual Overcrowd (MOC) → increased u/N from applying more crowd
- Additional T and F beyond the Op. Limits
  - Generates wasted energy
    - Increased frictional resistance
  - Damages core specimens
  - Prevents in situ strength assessment via MWD
- ≈3% difference in MWD qu vs. Core qu
  - Phase 2 produced 10 testable qu samples
  - Both Phase 3 core runs produced zero testable samples and MWD greatly overestimated qu

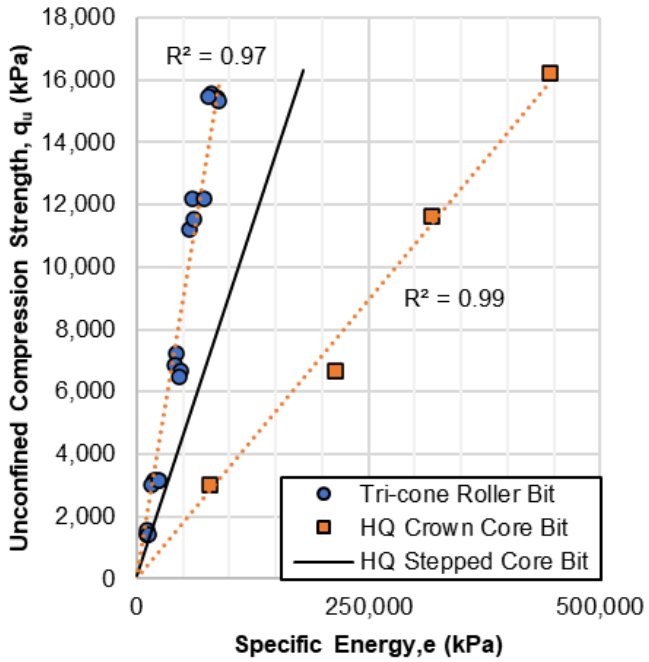
OL – Phase 2 | Stall – Phase 3 | MOC – Phase 3

Drilling Parameter	Average Values Over Entire Core Run (qu ≈ 3,000 kPa)		
	(a) Operational Limits	(b) Stall	(c) Manual Overcrowd
u (cm/min)	17.5	14.5	25.7
N (rpm)	120	116	115
u/N (cm/rev)	0.147	0.124	0.224
T (N-m)	32	149	323
F (N)	992	5,765	12,242
Q (LPM)	30	29	28
e (kPa)	32,302	206,346	235,304
MWD q_u (kPa)	3,100	19,900	22,700
Core q_u (kPa)	3,000	3,000	3,000

(Rodgers et al. 2021)

Maximum Mechanical Efficiency – Bit Geometry

- 3 drilling tools presented
  - Tri-cone roller bit
  - Stepped-profile core bit
  - Crown-profile core bit
- Each tool has a unique bit geometry
  - Shape of the cutting face
  - Size of cutting teeth in comparison to the size of the cutting face
    - Stones per carat (SPC) for core bits
  - Dictates the optimum u/N range
- Unique mechanical efficiency for each drilling tool
- Produces a unique relationship between specific energy and rock strength
  - Relating drilling parameters to engineering parameters commonly used in design
- Tri-cone type bits will be used for MWD in-situ soil assessment



(Rodgers et al. 2021)

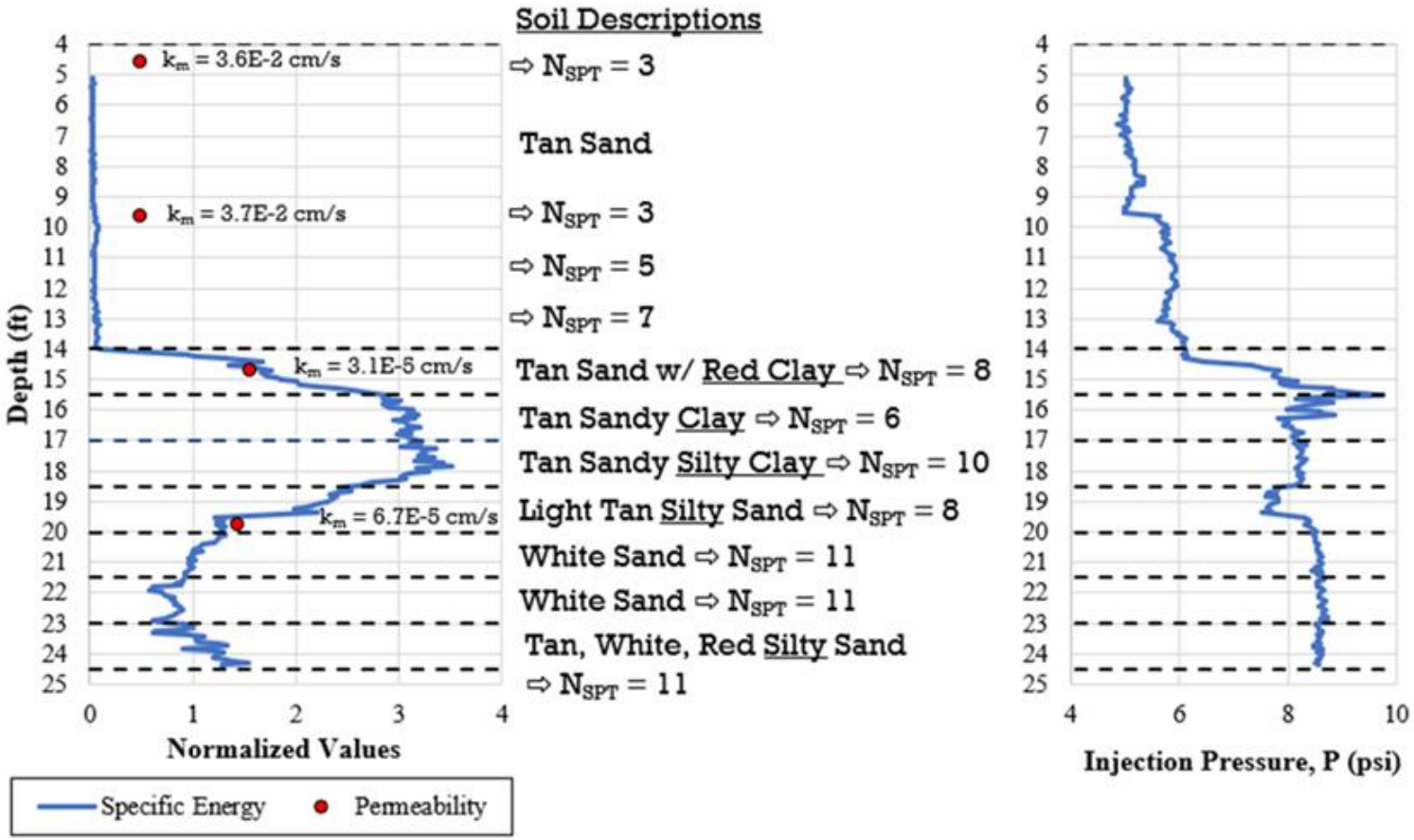
Tri-cone Roller Bit

Stepped-Profile
SPC = 25-35

Crown-Profile
SPC = 115

MWD for Site Characterization – Soil Assessment

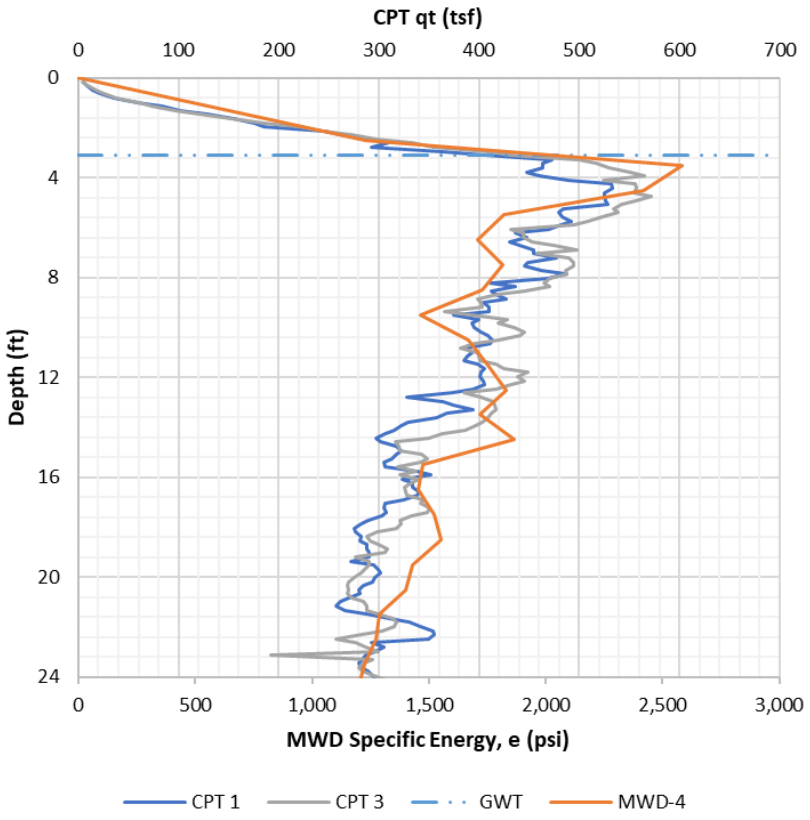
- Tri-cone roller bit used during preliminary study in Trenton Florida
- 25-foot boring completed in under 10 minutes with minimal effort
- MWD indicated low specific energy in cohesionless soil with low SPT blow counts
- MWD indicated increased specific energy in cohesive soil with higher SPT blow counts
- MWD injection pressure increased in lower permeable soils
  - Agreed with comparative permeability tests conducted using the VIP (FM5-614)
- UF and FDOT are currently developing a new MWD "quick method" for in situ soil and rock assessment using similar bit types
  - Ideal application for pre-bid borings
  - Ideal to determine minimum tip elevations for driven piles with variable rock and driving conditions

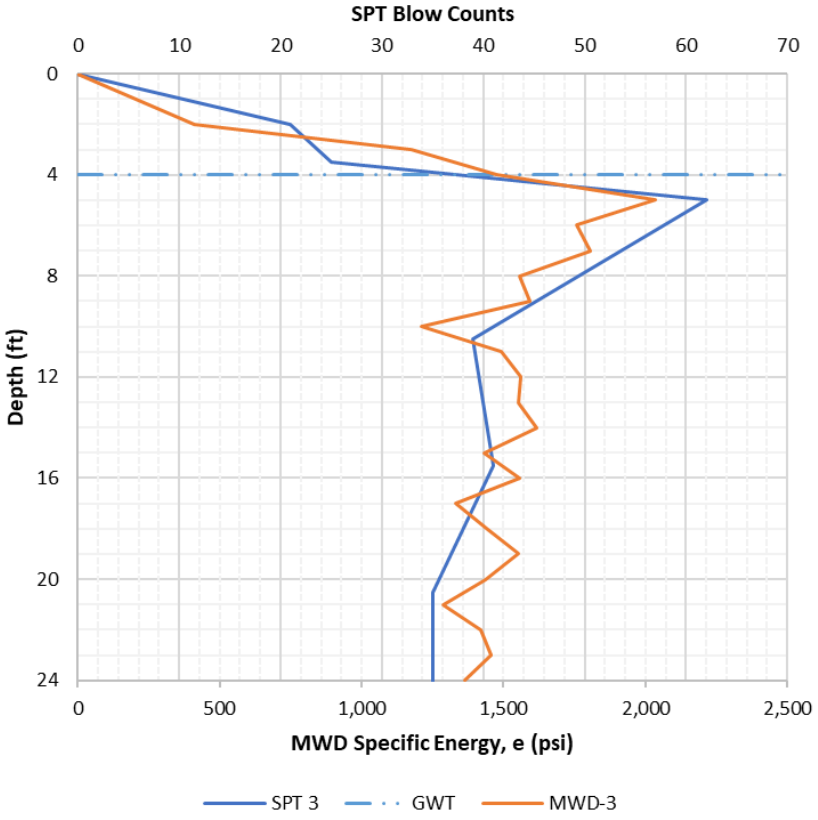


McVay and Rodgers (2019b)

MWD Compared to Conventional Methods

- One of the biggest challenges for developing MWD in-situ soil assessment will be relating drilling parameters to conventional soil engineering parameters commonly used in design
- We are already seeing agreement between MWD and conventional site investigation methods that are commonly used for soil characterization and design – encouraging!



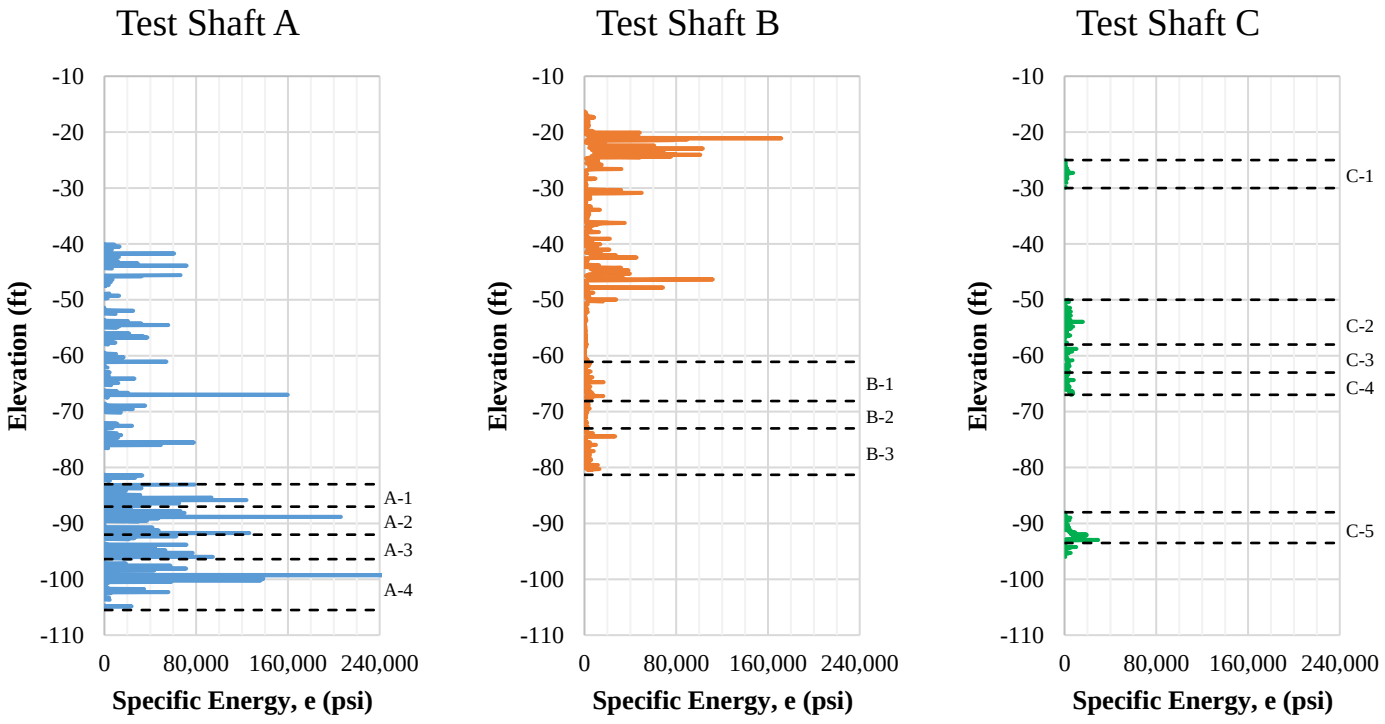


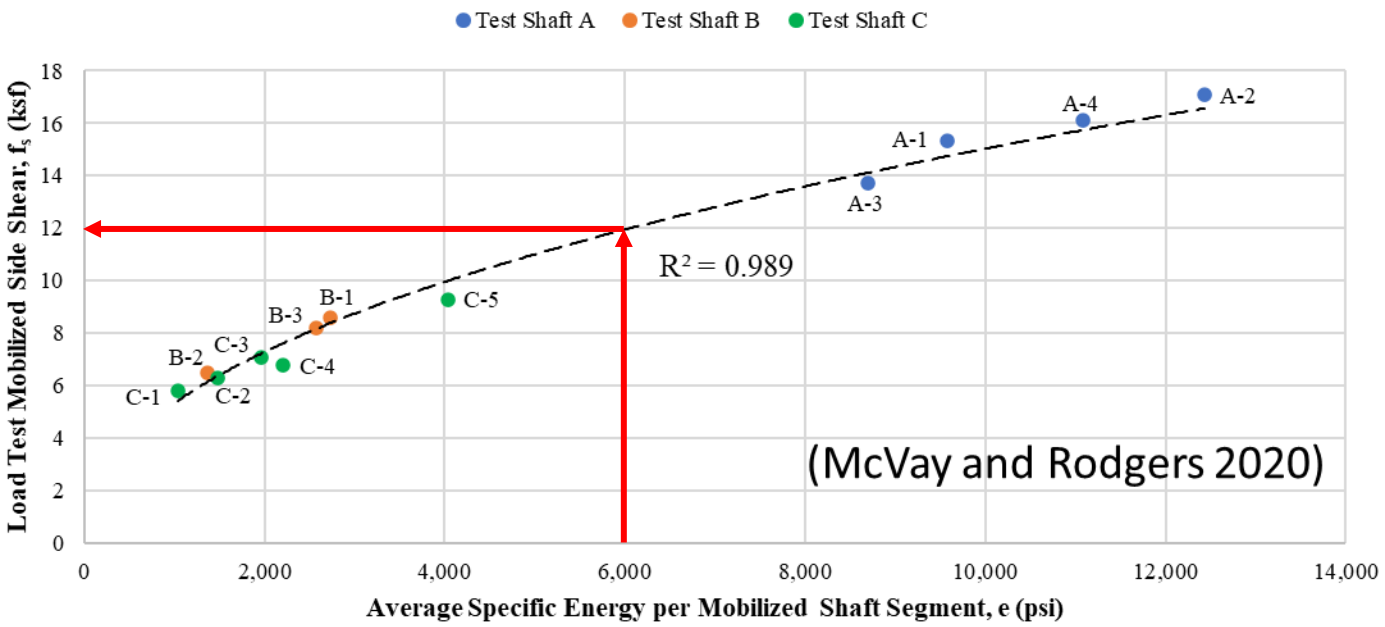
Rodgers, Horhota, and Jones (2024)

MWD for Bored Pile Construction QA/QC

Drilled Shaft MWD

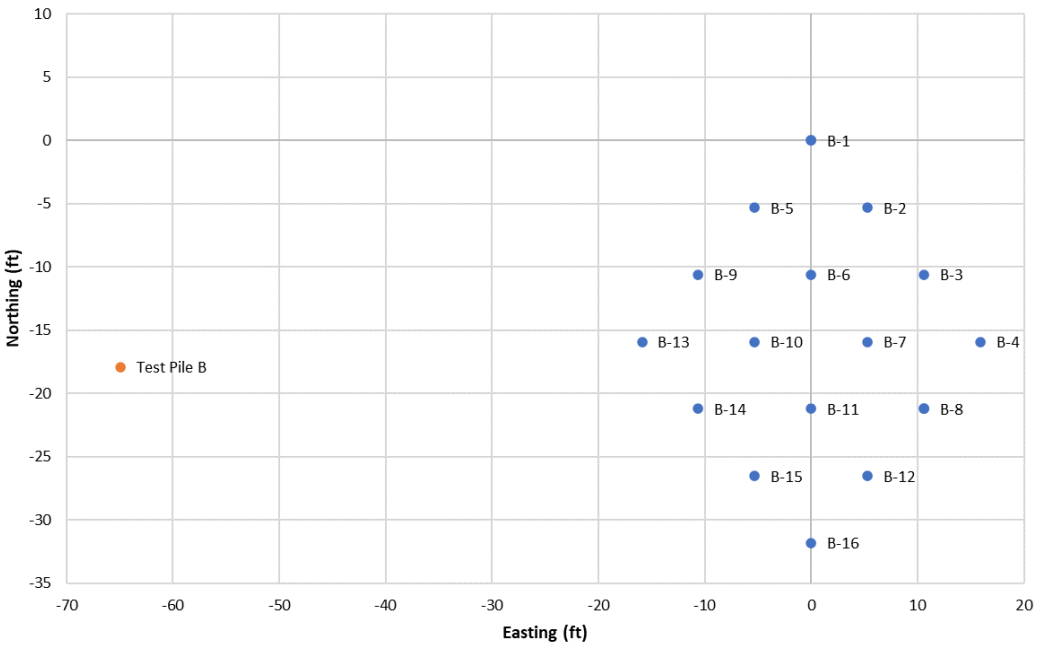
- Specific energy recorded in layers of rock at a Florida bridge site
  - Avg. distance between shafts ≈ 700 yds
- This site was the focus of the Graham et al. (2013) paper
  - "Challenging to produce meaningful correlations to load tests"
- MWD is allowing us to produce a meaningful correlation with load test data that can be translated to untested production shafts via MWD
  - Eliminates spatial uncertainty concerns that arise from Florida's high degree of subsurface variability
    - MWD allows us to assess the subsurface conditions within the footprint of each production shaft location at full-scale
  - Increases the value of load tests when coupled with MWD
    - May encourage more load tests

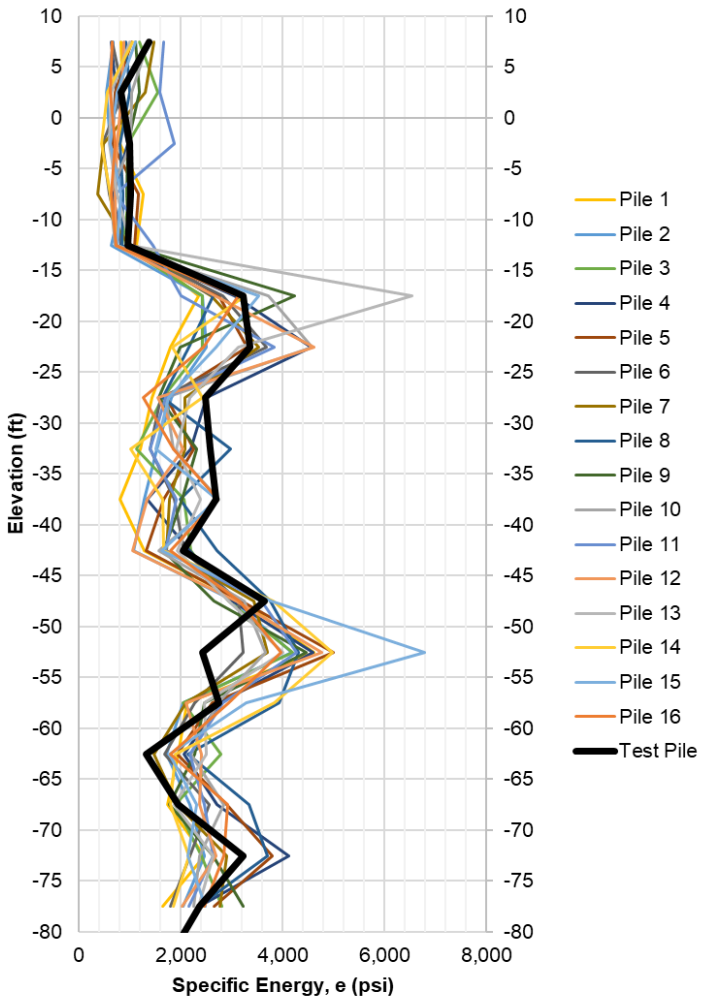


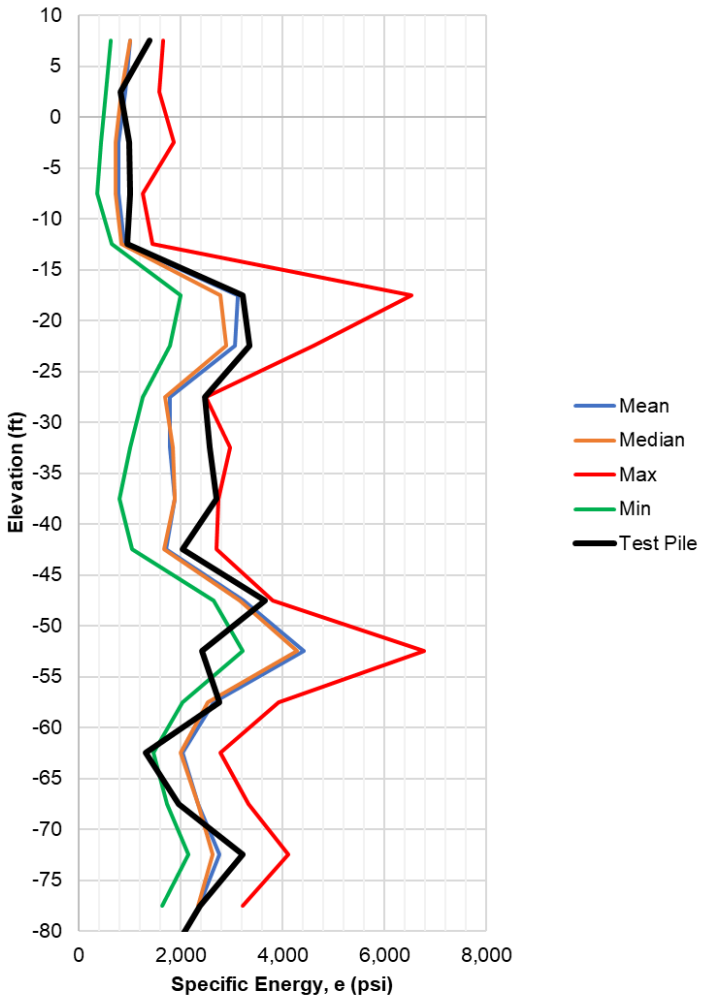


Assessing ACIP Pile Variability Over Short Distances

- Florida limestone formations can be highly variable even over short horizontal distances – Graham et al. (2013)
- ACIP Pile group with 16 piles
  - 32.5’ x 32.5’ pile group footprint
- Variability observed within pile group and compared to Test Pile location
  - Correlated structure also observed
- **UF/FDOT developed and ACIP MWD analysis tool that was useful to quickly evaluate a pile group and determine which pile was selected for verification testing, which was part of the specification language**

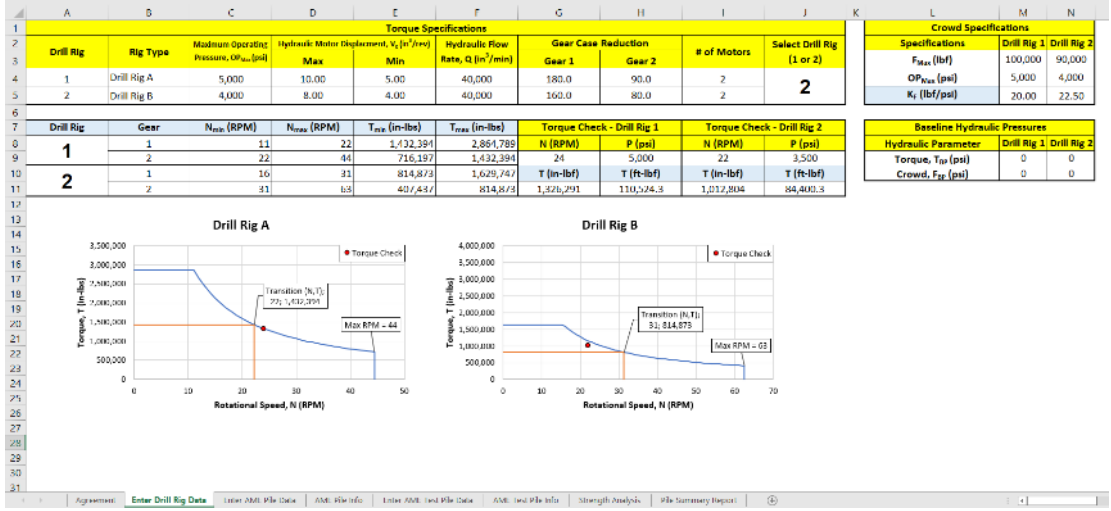




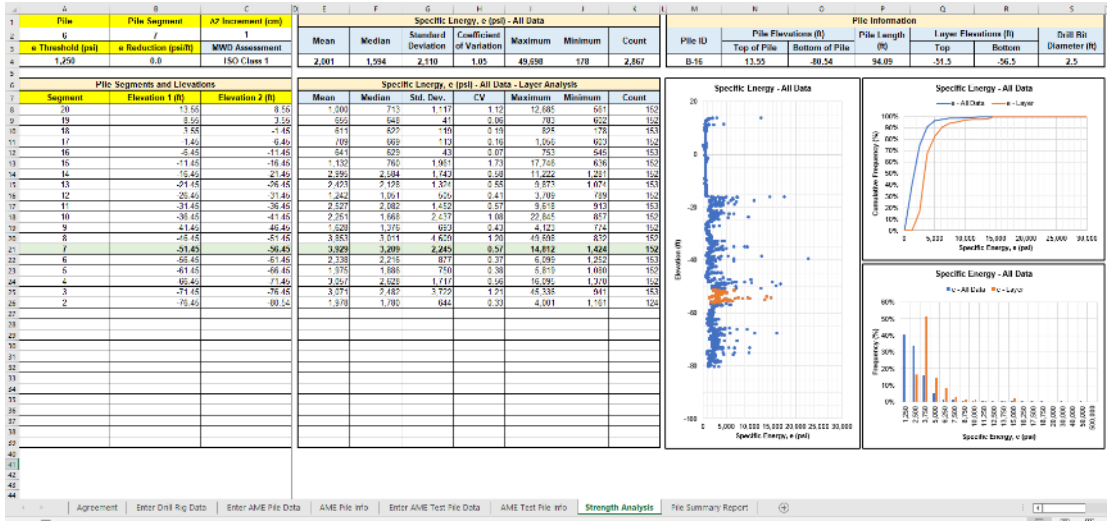


ACIP Pile QA/QC Analysis Tool

Input custom drill rig specs to automatically update the analysis tool to properly assess the pile based on the drill rig used



Specific energy, UCS, and Side Shear Assessments



Rodgers, McVay, and Kelch (2022)

FDOT

ACIP Pile - MWD Summary Report

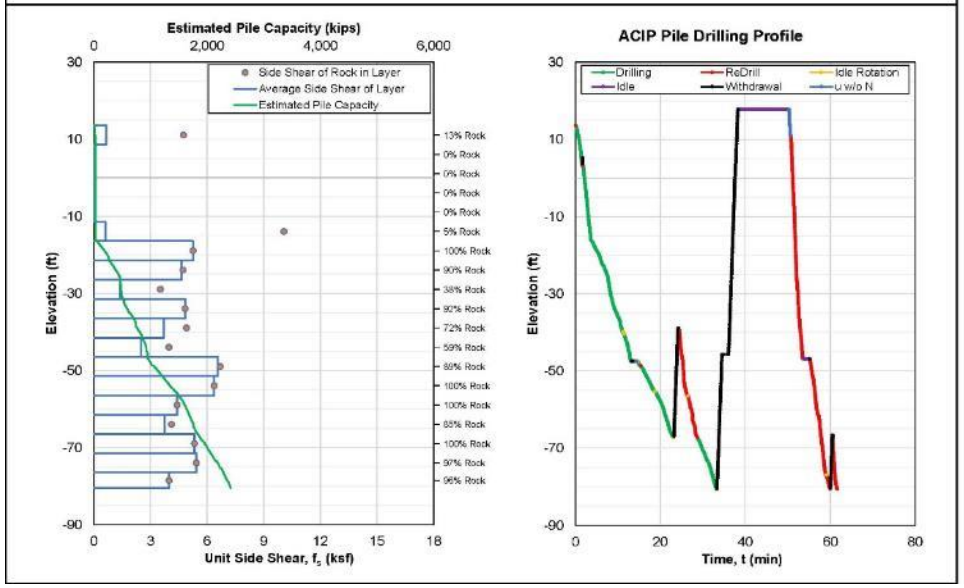
Project	Location	Engineer	Pile ID
		Rodgers, McVay, Kelch	B16
Station	**Offset (ft)**	**Drill Rig**	**Drill Bit Diameter (in)**
100+00.01	10.00	Drill Rig B	30
Top of Pile Elevation (ft)	**Bottom of Pile Elevation (ft)**	**Depth Increment Analyzed (cm)**	**ISO-MWD Assessment**
13.55	-80.54	1	Class 1

Specific Energy Above Threshold, e (psi)	
Specific Energy Threshold (psi)	1,250
Mean	2,841
Median	2,303
Standard Deviation	2,394
Coefficient of Variation (CV)	0.84
Maximum	49,698
Minimum	1,252
Number of Data Points	1,704

ACIP Pile Capacity QA/QC	
Pile Length (ft)	94.09
Total Rock Socket Length (ft)	55.9
Average Pile Side Shear, f_s (ksf)	3.27
Unfactored Pile Capacity (kips)	2,419
Factored Pile Capacity (kips)	1,451
Factored Design Load (kips)	1,070
C/D Ratio for LRFD Φ = 0.6	1.36
Design Requirement Inspection	**Passed**

Unconfined Compressive Strength Above Threshold, q_u (psi)	
q_u Threshold (psi)	88
Mean	185
Median	157
Standard Deviation	115
Coefficient of Variation (CV)	0.62
Maximum	1,897
Minimum	88
Number of Data Points	1,704

Pile Installation Summary	
Drilling Time (min)	25.7
ReDrill Time (min)	13.4
Idle Rotation Time (min)	2.5
Idle Time (min)	14.0
Withdrawal Time (min)	5.7
Penetration w/o Rotation Time (min)	0.4
Total Time (min)	61.6
Drilling Efficiency (%)	42%



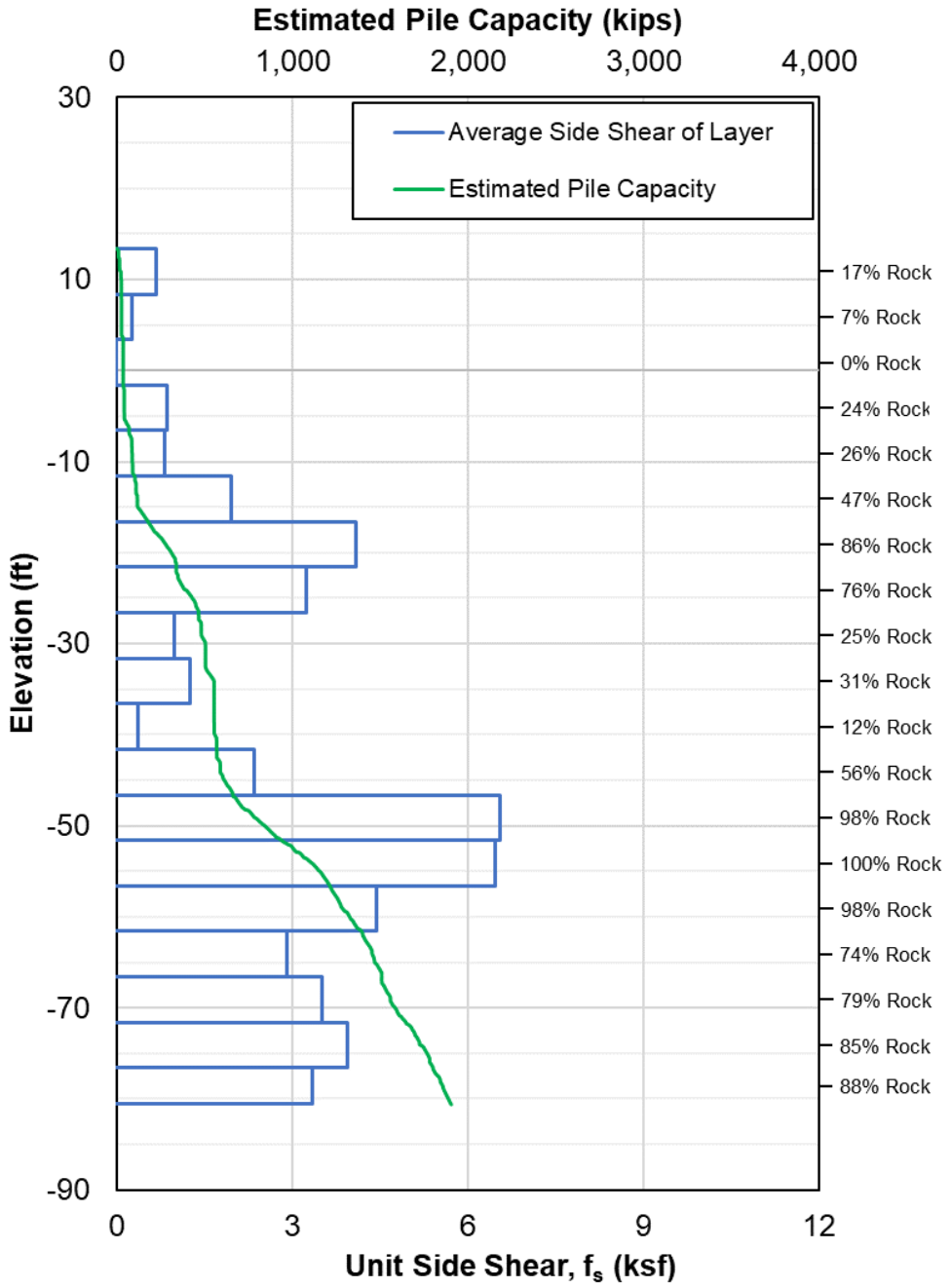
*Current initiative is to make this information readily available to stakeholders in satellite locations to speed up and improve decision making when problematic site conditions are encountered.

Rodgers and Horhota (2024)

ACIP Pile MWD QA/QC
-Unit Side Shear & Pile Capacity-

- When correlation is developed between drilling parameters and engineering parameters, we can directly quantify the length and quality of each rock socket through direct measurement in the footprint of the pile at full scale
- Reduces spatial uncertainty
- Increases reliability of the design
- Can lead to higher LRFD ϕ's used in the future

ACIP Pile Capacity QA/QC	
Pile Length (ft)	94.00
Total Rock Socket Length (ft)	50.6
Average Pile Side Shear, f_s (ksf)	2.58
Unfactored Pile Capacity (kips)	1,904
Factored Pile Capacity (kips)	1,142
Factored Design Load (kips)	1,070
C/D Ratio for LRFD Φ = 0.6	1.07
Design Requirement Inspection	**Passed**



Rodgers, McVay, and Kelch (2022)

Summary

- MWD assisted rock coring can be used to optimize core recoveries and the number of testable samples recovered to ensure rock mass characterization is reflective of the in situ subsurface conditions
  - Excellent strength correlations can be developed when following the operational limits
- MWD can be used to significantly increase and improve the data collected during site investigation to improve characterization
  - Proven in highly variable and weathered Florida limestone
  - In-situ soil assessment is still in development but showing great promise early on
- MWD for bored piles can be used as a QA/QC tool to ensure as-built foundations meet or exceed the demands of the engineering design
  - Encourages increased load testing as the value of each load test is enhanced by MWD
  - Reduces uncertainty and increases reliability
  - Can lead to improved future resistance factors and more cost-effective foundations
- MWD for bored piles can be used to identify problematic shafts/piles during construction which will lead to more efficient and improved decision making in the future when problematic subsurface conditions are encountered

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