Herbert Wertheim College of Engineering
UNIVERSITY of FLORIDA

Measuring While Drilling for Florida Site Investigation (FLMWD) BDV31-820-006

FDOT GRIP Meeting

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MWD Introduction

- Measuring while drilling (MWD) is the acquisition of real time data from drilling rig sensors used for several purposes
  - Optimize drilling performance
    - Improve production drilling rates
    - Selection of drilling tool
  - Provide detailed records of geological formations encountered
    - Strength vs. depth assessment
- Predominantly used in the energy resource fields (oil and gas)
- MWD is an emerging application in Geotechnical Engineering
  - Address the drilling process, spatial uncertainty, and material property assessment

ISO MWD Specifications

- ISO standards created for geotechnical purposes in 2016
  - Specifications for monitoring systems, operations, and data logging
- MWD Category A - Class 1 monitoring
  - Max length between sampled measurements is 2.5 cm (Class 1)
  - Allows indicative interpretation of the strata encountered via compound drilling parameter properties (e.g., specific energy)
- Assessment of rock strength and geospatial variability from MWD is a new application with limited work completed

Background

- BDV31-977-20 (drilled shaft MWD) took the first steps in our understanding and delineation of MWD practices for measuring in situ rock strength during drilling
  - Proposed construction monitoring technique (QA/QC – rock strength)
  - MWD implemented post design phase
- Integrate the same approach into SPT coring and drilling procedures used as a site investigation tool
  - MWD implemented prior to the design phase
  - Provides a significant increase in design data, better sample recoveries, better drilling practices, and equipment selection

Objectives

- The objective of this research is to investigate the viability of developing MWD practices for standard Florida site investigation.
- The same methods implemented in BDV31-977-20 will be used to develop the new MWD technique for SPT practices.
- The MWD procedure will include using two drilling tools.
  - Standard core barrel
  - Tri-cone roller bit

Objectives

- Using MWD for both drilling tools will provide continuous information while the hole is being advanced and during standard coring procedures.
- The focus of developing the method will be assessing rock strength anytime rock layers are encountered.
- Investigate quantifying drilling/coring procedures
  - Are we influencing poor recoveries?
  - Can we improve drilling techniques to extract more intact core samples for lab testing?

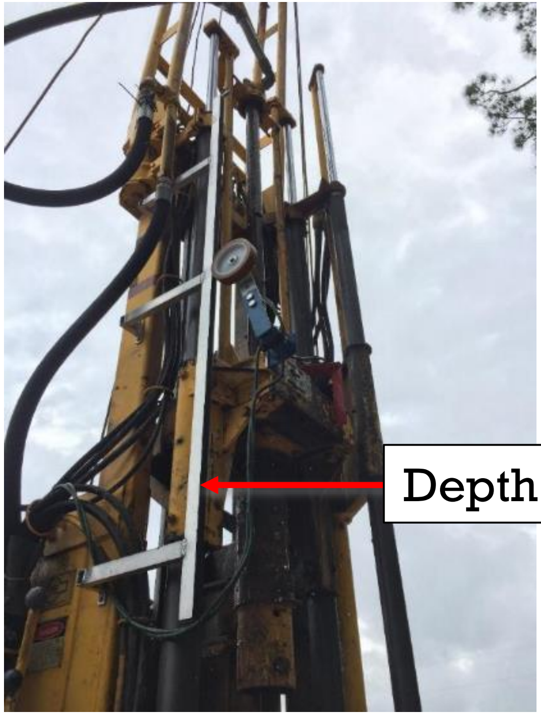
Task Outline

1. Surveying district SPT drillers
2. SPT rig investigation and instrumentation
3. Controlled field testing with Gatorock
4. Full scale field testing at various Florida sites
5. Field testing analysis
6. Draft final report and closeout teleconference
7. Final report

Penetration Rate and Rotational Speed

Depth Sensor RPM Sensor

Depth Sensor Track Installed



Depth Sensor Track

Flowrate and Fluid Injection Pressure

Flow Meter

Pressure Transducer

Instrumented Drill Rod (Torque and Crowd)

- Torque rosettes and T-element strain gauges every 90 degrees
- Full bridge to compensate for bending and temperature
  - Moisture protected coating
- IP 65 waterproof housing for the wireless data transmitter
  - Reduced antenna length
- External battery
  - Improved the battery life by a factor of 10
  - Can monitor all week without having to charge the battery

Creating Gatorock Slabs

Controlled Strength Homogenous Drilling Medium

Real Time Monitoring in a Controlled Environment

Specific Energy

- Energy required to remove a unit volume of rock during drilling
  - Good correlation with q_u in prior FDOT investigation for rock augers

$$e = \frac{F}{A} + \frac{2\pi NT}{Au} = \frac{4F}{\pi d^2} + \frac{8NT}{ud^2}$$

where,

e = Specific Energy (kPa)
F = Crowd or downward axial force (kN)
A = Cross-sectional area of the excavation (m^2)
N = Rotational speed (rpm)
T = Torque (kN-m)
u = Penetration rate (m/min)
d = Bit diameter (m)

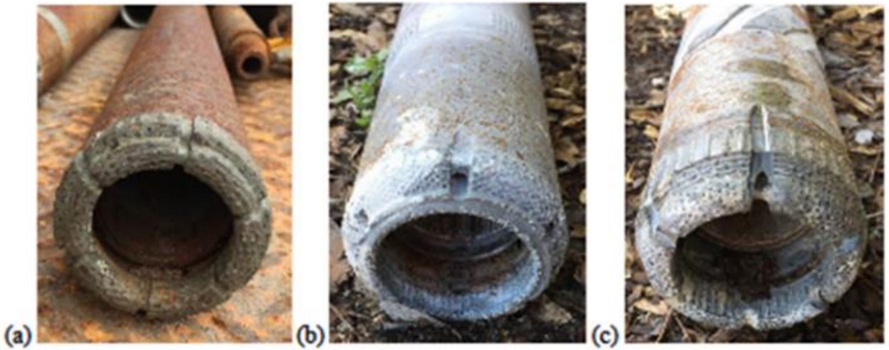
(Teale, 1965)

Additional Drilling Parameters and Terms

- Q = Flow rate (GPM)
- P = Flow rate injection pressure (psi)
- q_u = Unconfined compressive strength
  - Measure of rock strength most often used in design
- u/N ratio = Penetration rate to rotational speed ratio
  - Provides a threshold that must be achieved during drilling to reliably predict rock strength
- T/u ratio = Torque to penetration rate ratio
  - Torque and penetration rate are the best indicators of rock strength
  - When T/u is plotted vs. specific energy, the effects of variable flow rates, rotational speeds, and bit diameters can be investigated directly

Initial MWD Investigation

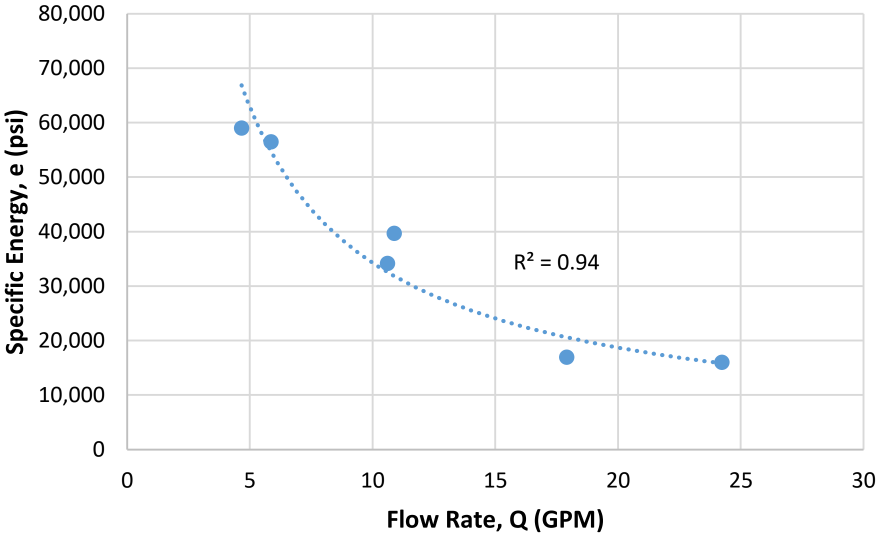
- 3 double wall core barrel cutting surfaces were investigated
  - Different bit geometries
- All surface-set diamond cutting surfaces
  - Based on survey results
- 2 different cutting surface configurations
  a) Pilot profile (NQ – 1.9" Dia. Cores)
  b) Pilot profile (HQ – 2.4" Dia. Cores)
  c) Stepped profile (HQ – 2.4" Dia. Cores)
- 2.5" core barrel selected
  - FDOT SFH guidelines



Flow Rate Investigation

- Never monitored flowrate before
  - Not required for drilled shafts
- Used NQ pilot profile bit for investigation
  - 1.9” diameter cores
- Similar N and F with variable Q
- Observations
  - u increased with Q increase
  - e decreased with Q increase
  - Increasing Q increases mechanical efficiency
  - Specific energy began stabilizing at higher flow rates

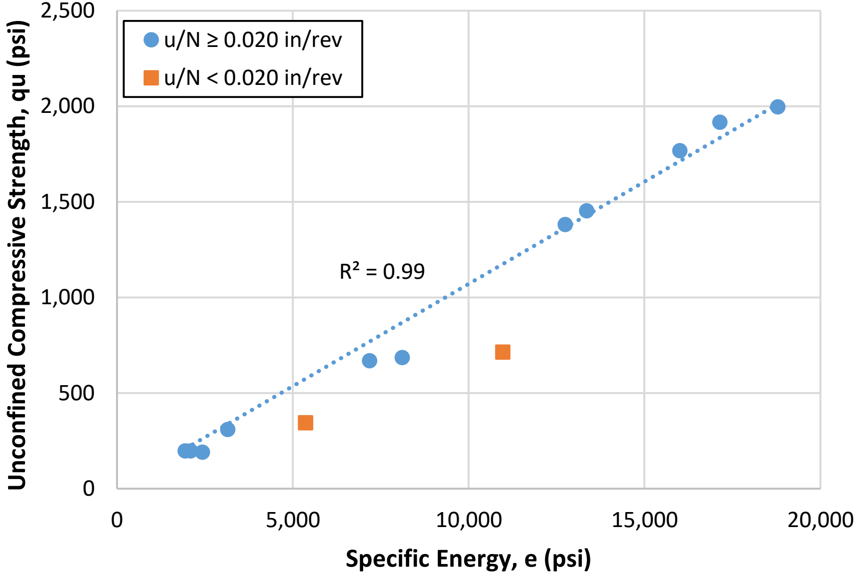
Hole	u (in/min)	N (RPM)	u/N (in/rev)	T (in-lbs)	F (lbf)	F/A (psi)	Q (GPM)	e (psi)
S1-H1	3.2	150	0.021	807	1,055	251	4.7	59,035
S1-H2	3.0	148	0.020	710	853	203	5.9	56,493
S1-H5	7.7	148	0.052	547	790	188	24.2	16,040
S1-H6	9.3	146	0.064	706	978	233	17.9	16,976



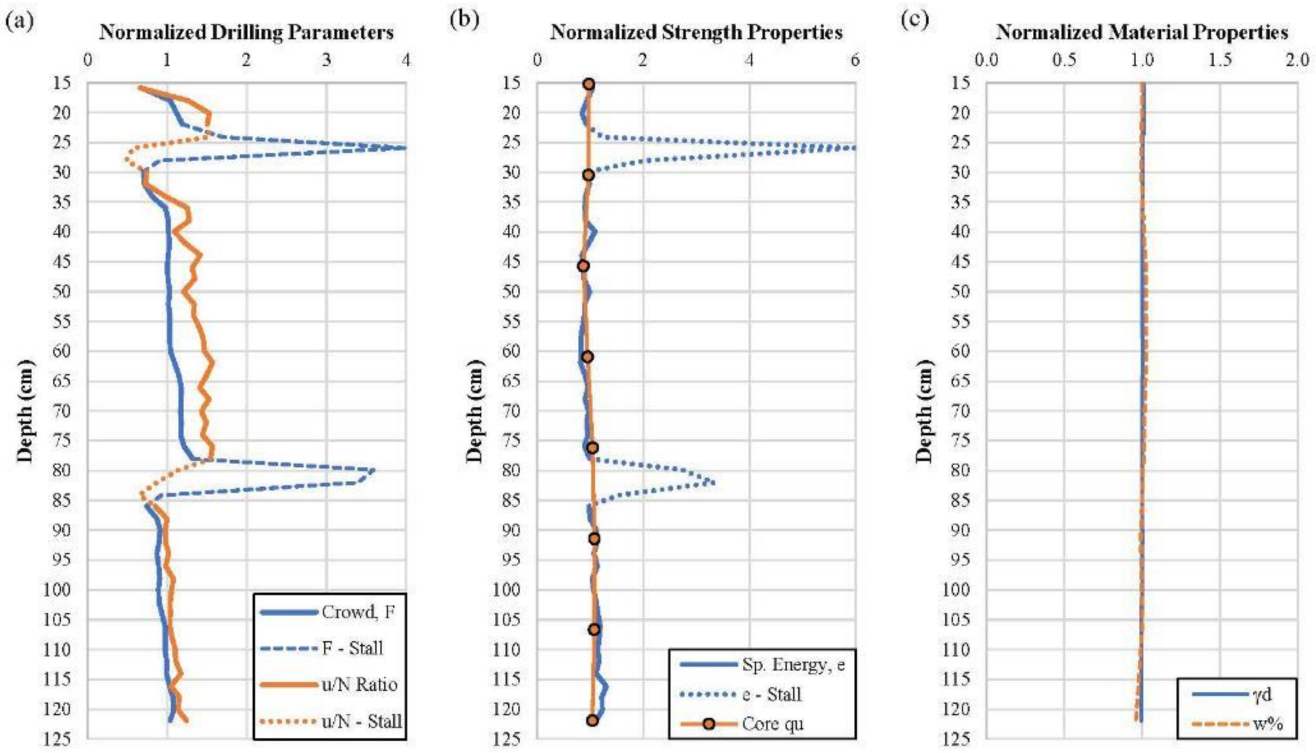
Path to Developing Correlation

- Poor recoveries for low strength Gatorock at the beginning of investigation.
  - Crowd, F ≈ 1,000 - 1,300 lbf
  - Varied Flow rate, Q and RPM, N
  - u/N ≈ 0.020 in/rev for "stepped" core barrel cutting surface
- Regulated crowd to minimum required to achieve u/N > 0.020 in/rev
  - Determined far less crowd was required to achieve the same u/N
  - Low strength REC greatly improved
  - Allowed correlation to be developed

Hole	Bit Configuration	u (in/min)	N (RPM)	u/N (in/rev)	T (in-lbs)	F (lbf)	Q (GPM)	e (psi)	Core UCS (psi)
S2-H7	Stepped	2.6	124.1	0.021	1,407.0	1,278.2	9.7	75,141.7	1,590.0
S1-LC	Stepped	2.9	119.9	0.024	371.5	301.5	7.0	15,061.1	1,767.7



MWD in Controlled Environment



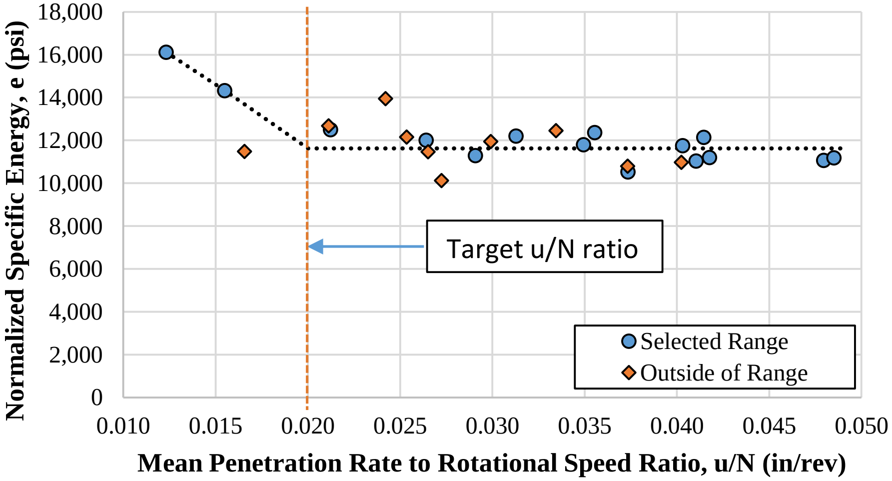
(Rodgers et al. 2019, Figure 13a,b,c)

Operational Limits of Drilling Tools

- We have conducted MWD investigations using multiple drilling tools
  - Rock augers
  - Rock drilling buckets
  - Double wall core barrels
  - Tri-cone roller bits
- In all cases we have determined there are operational limits that must be followed to ensure efficient drilling w/o pulverizing the rock or damaging equipment (i.e. increases e, but wasted energy)
  - u/N ratio (very important)
  - Regulating crowd to prevent stall and pulverizing rock layers
  - Optimizing flowrates (core barrel and tri-cone drilling) – limiting crowd
  - Optimizing rotational speeds

Calibration Study

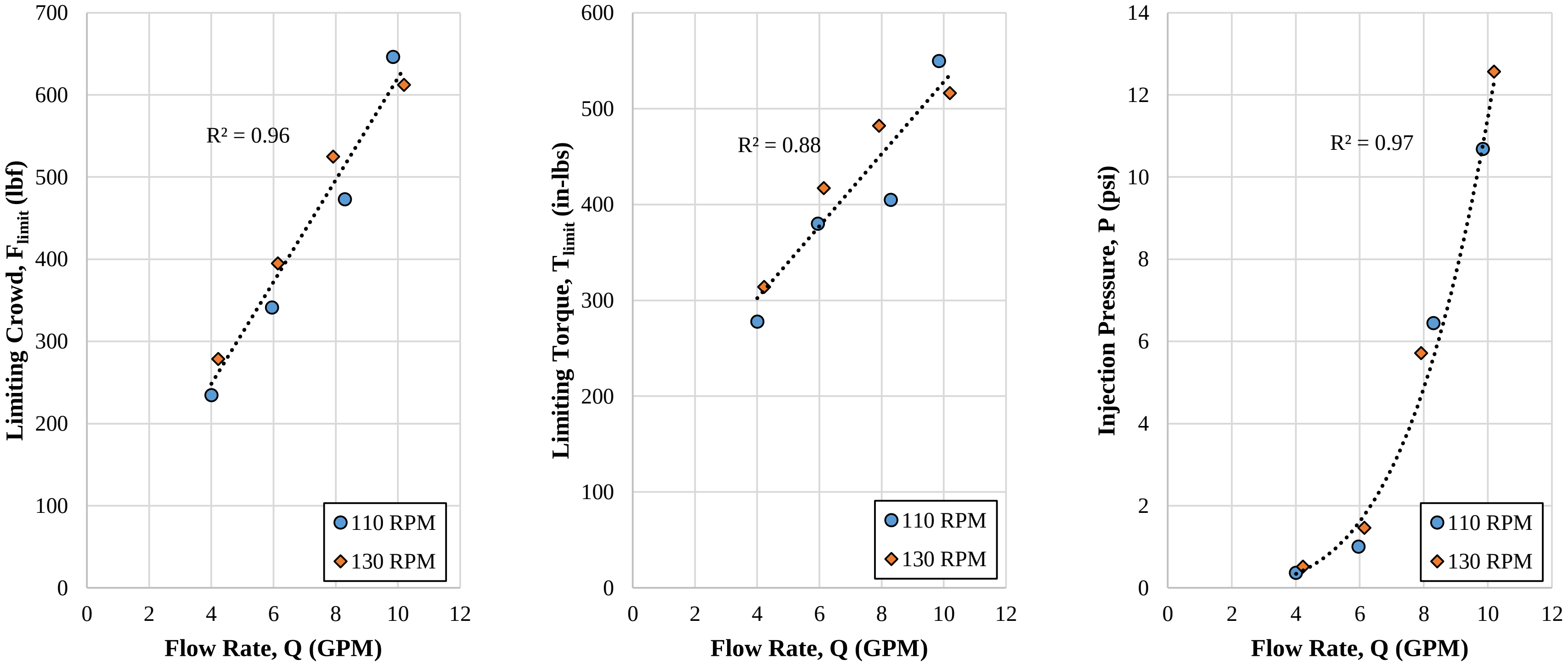
- Obtained 3 new Stepped core barrel cutting surfaces
  - Softer Florida rock
- Poured a median strength Gatorock slab
  - $q_u \approx 1{,}100$ psi
- Conducted 24 drillings using variable drilling parameters
- Investigated drilling parameter relationships to define preliminary operational limits
  - Used to create remaining drilling plan



Limiting Crowd Investigation

- With the understanding that crowd needed to be regulated within a certain range, a study was conducted to determine if flow rate controlled the range.
- Eight core runs were completed in the same strength Gatorock
  - Crowd was pushed to the verge of stall for each core run
- Four flow rates were investigated with two rotational speeds
  - Q = 4, 6, 8, and 10 GPM
- The rotational speeds were 110 and 130 RPM
  - Determined to be the optimum range during calibration study
- Discovered three interdependent relationships with flowrate (Q)

Limiting Crowd Investigation



Drilling Plan - Variable Drilling Parameters

- 3 rotational speeds
  - 110, 120, and 130 RPM
- u/N > 0.020 in/rev
  - 3 target penetration rates
- 4 flow rates
  - 6.5, 7.5, 8.5, and 9.5 GPM
  - 9.5 GPM was max because of limited water on site
- Crowd range estimated based on flow rate
  - Provides limiting crowd (F_{max})
- 6 variable strength Gatorock slabs
  - $q_u \approx$ 50, 200, 450, 975, 1,700, 2,400 psi
- 72 data points from drilling plan
  - 87 data points available for analysis

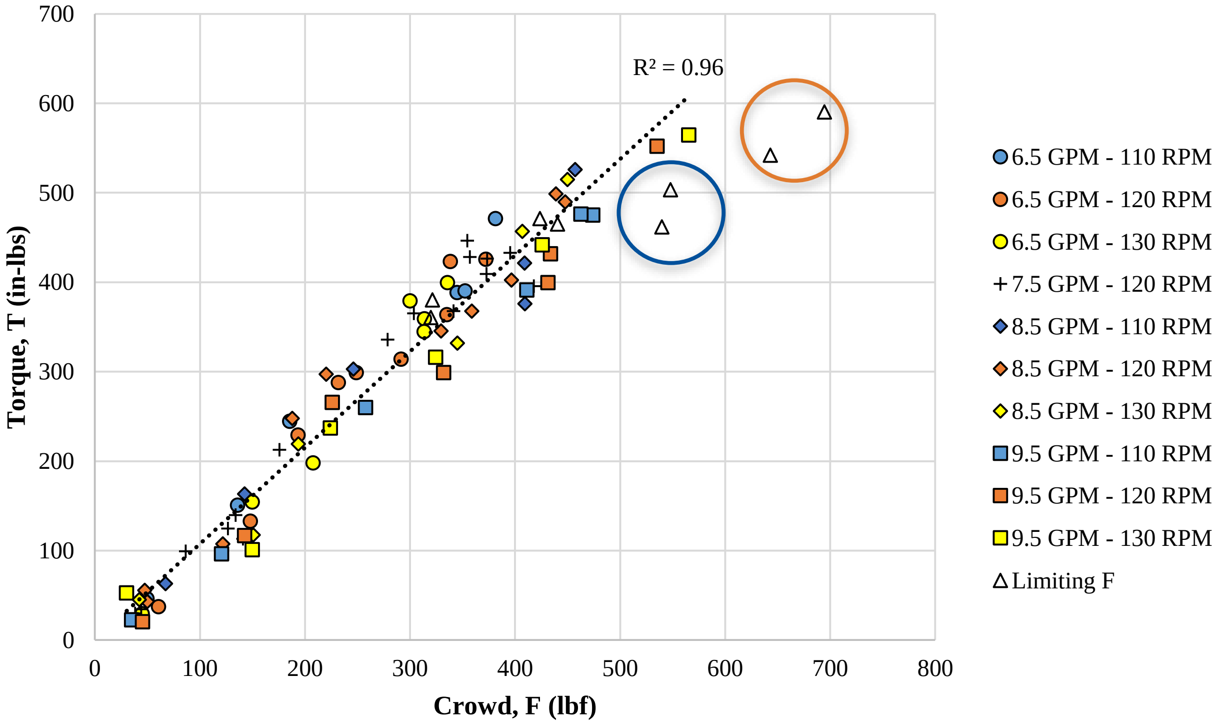
Test Matrix 1				
N (RPM)	$(u/N)_{min}$ (in/rev)	u (in/min)	Q (GPM)	F_{max} (lbf)
110	0.02	2.2	6.5	406
120	0.02	2.4	6.5	406
130	0.02	2.6	6.5	406
120	0.02	2.4	7.5	469

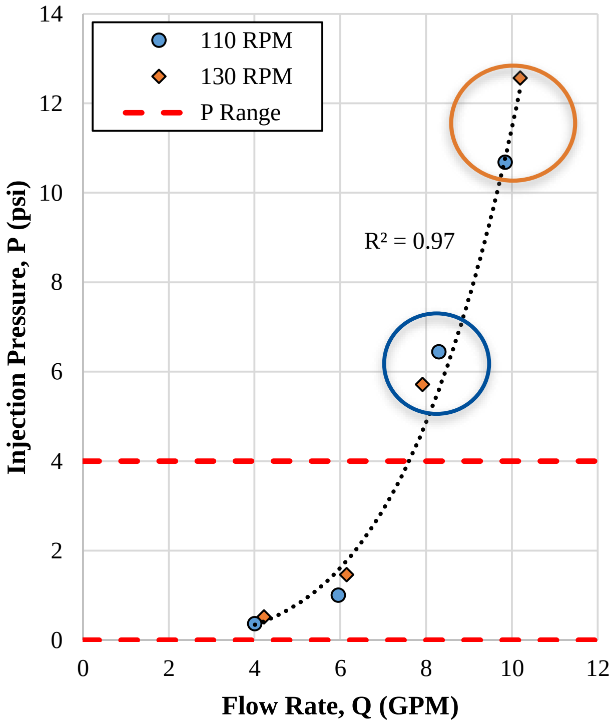
Test Matrix 2				
N (RPM)	$(u/N)_{min}$ (in/rev)	u (in/min)	Q (GPM)	F_{max} (lbf)
110	0.02	2.2	8.5	531
120	0.02	2.4	8.5	531
130	0.02	2.6	8.5	531
120	0.02	2.4	7.5	469

Test Matrix 3				
N (RPM)	$(u/N)_{min}$ (in/rev)	u (in/min)	Q (GPM)	F_{max} (lbf)
110	0.02	2.2	9.5	594
120	0.02	2.4	9.5	594
130	0.02	2.6	9.5	594
120	0.02	2.4	7.5	469

T-F Relationship and Q-P Influence

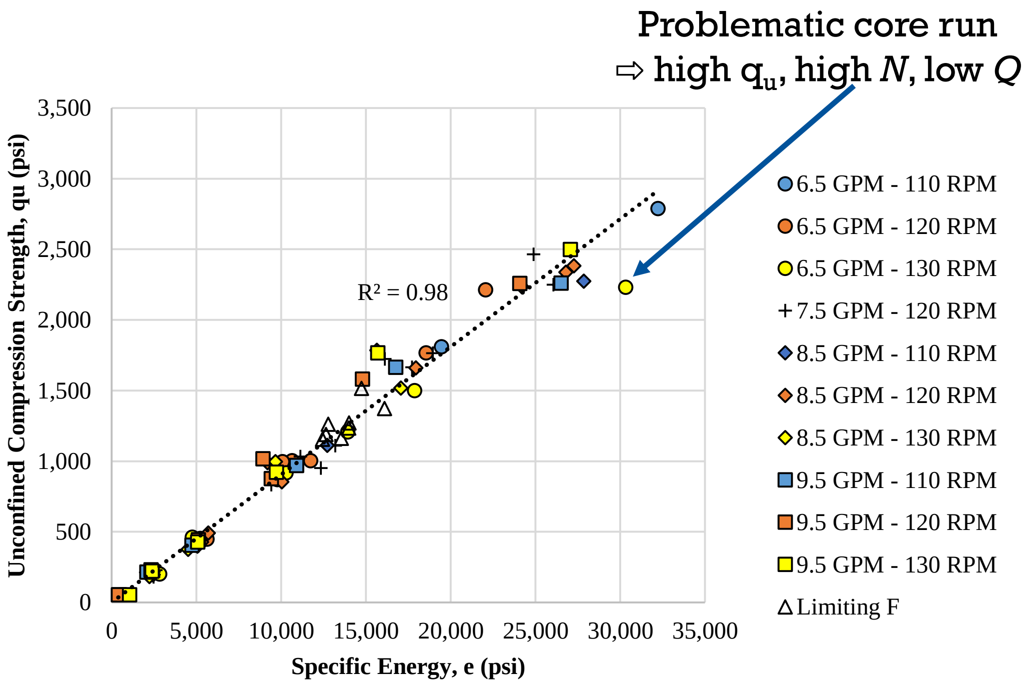
$P \leq 4$ psi for all core runs except four from limiting crowd (F_{limit}) investigation





Specific Energy vs. q_u Correlation

- Data grouped by combinations of variable flow rates and rotational speeds
  - 10 different combinations
- Excellent correlation was found using all 87 data points
  - Range of N and Q
- Nearly perfect RECs and RQDs for a q_u range of 183 psi to 2,788 psi
  - REC ≈ 100%
  - RQD ≈ 100%
- Lowest recovered strength
  - q_u = 24.7 psi



Effects of Breaking Particles to Smaller Sizes

Same *N* & *F*
Variable *Q*

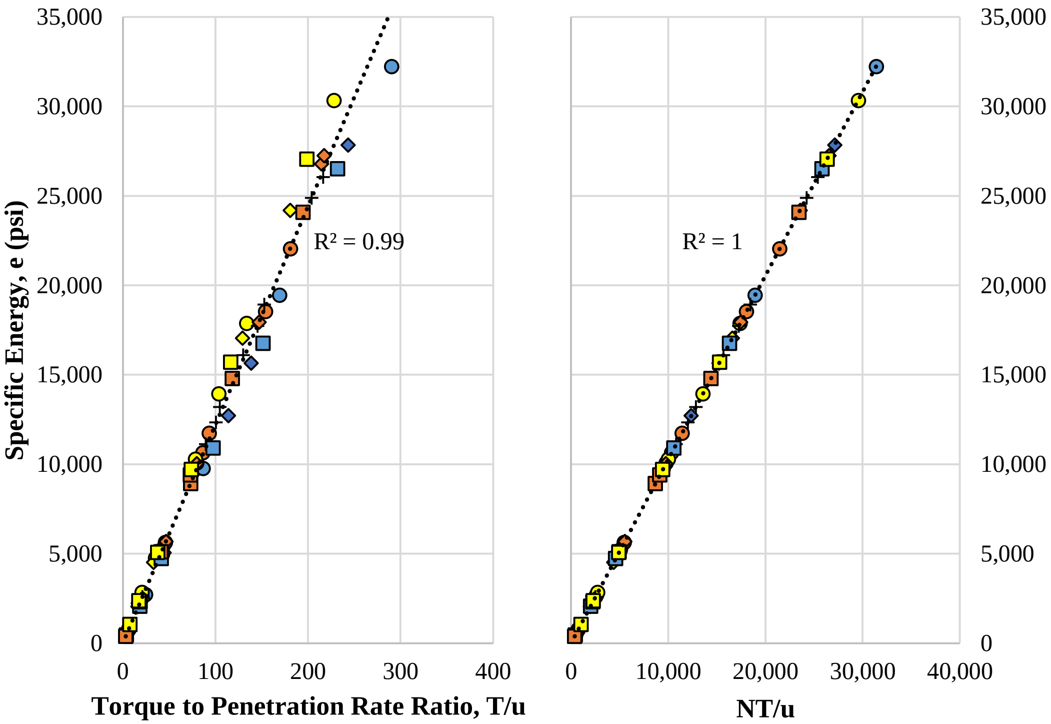
Sieve Size	Percent Retained		
	11.3 GPM	**12.9 GPM**	**16.6 GPM**
# 4	0.1	0.1	0.0
# 8	0.2	0.2	3.4
# 16	1.1	3.0	26.5
# 30	14.6	32.0	55.3
# 50	61.3	71.1	80.1
#100	87.9	91.9	93.5
#200	97.6	98.1	97.9
Fineness Modulus	**2.63**	**2.96**	**3.57**
Specific Energy (psi)	**8,878**	**7,002**	**6,139**
Penetration Rate (in/min)	**3.82**	**3.82**	**4.34**

Collected rock cuttings

Investigation conducted using tri-cone roller bit

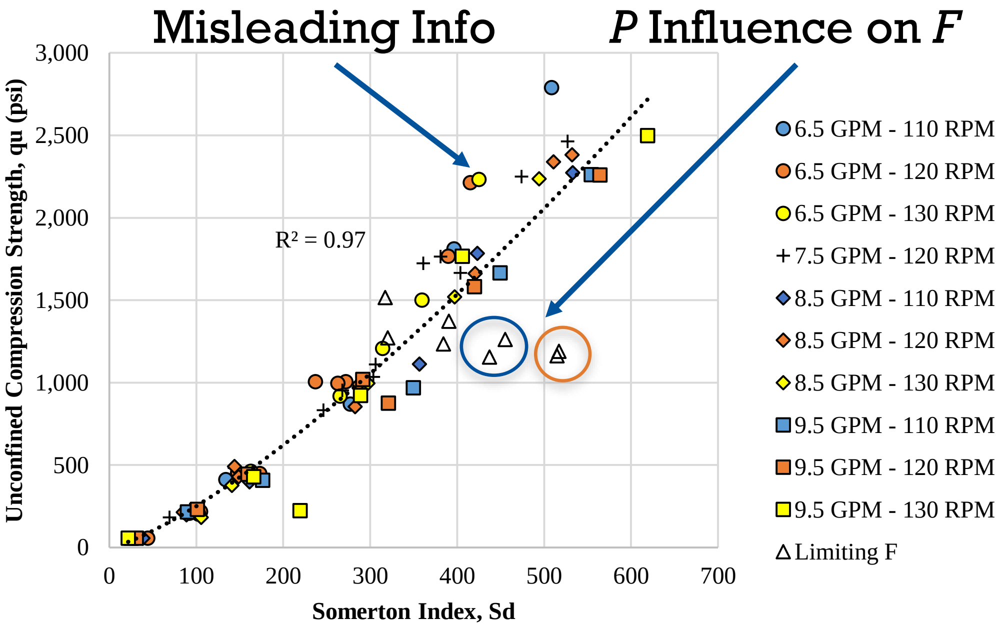
What Drilling Parameters Predict Strength?

- *e* and q_u show excellent correlation
  - *F* is controlled based on *Q* and T_{Limit}
  - *T-F* relationship is variable based on *P*
- *T/u* shows excellent correlation with *e*
- *N* normalizes the *T/u* ratio for direct assessment of *e*
- Verifies *T* and *u* are the true predictors of rock strength



Somerton Index vs. q_u Correlation

- Somerton index is another form of MWD strength assessment
- *F* is a large contributor for strength assessment
- Neglects T for strength assessment
- Reduces the significance of the *u/N* ratio on strength assessment
- Shows good correlation with q_u but provides misleading drilling info and is not ideal for rock strength assessment
- <u>Good correlation because we regulated *F* range and the *P* range was minimal</u>
- Neglects the influence of *P* on *F*
- Neglects the concept of stall and F_{limit}



$$Somerton\ Index\ (S_d) = \frac{F}{A}\left(\frac{N}{u}\right)^{0.5}$$

Effects of Overcrowding on REC & RQD

Operational Limits	
Parameter	Average
u (in/min)	6.9
N (rpm)	120
u/N (in/rev)	0.058
T (in-lbs)	280
F (lbf)	223
Q (gpm)	8.0
e (psi)	4,685
MWD qu (psi)	452
Core qu (psi)	436

Overcrowd - Stall	
Parameter	Average
u (in/min)	5.7
N (rpm)	116
u/N (in/rev)	0.049
T (in-lbs)	1,321
F (lbf)	1,296
Q (gpm)	7.6
e (psi)	29,928
MWD qu (psi)	2,888
Core qu (psi)	436

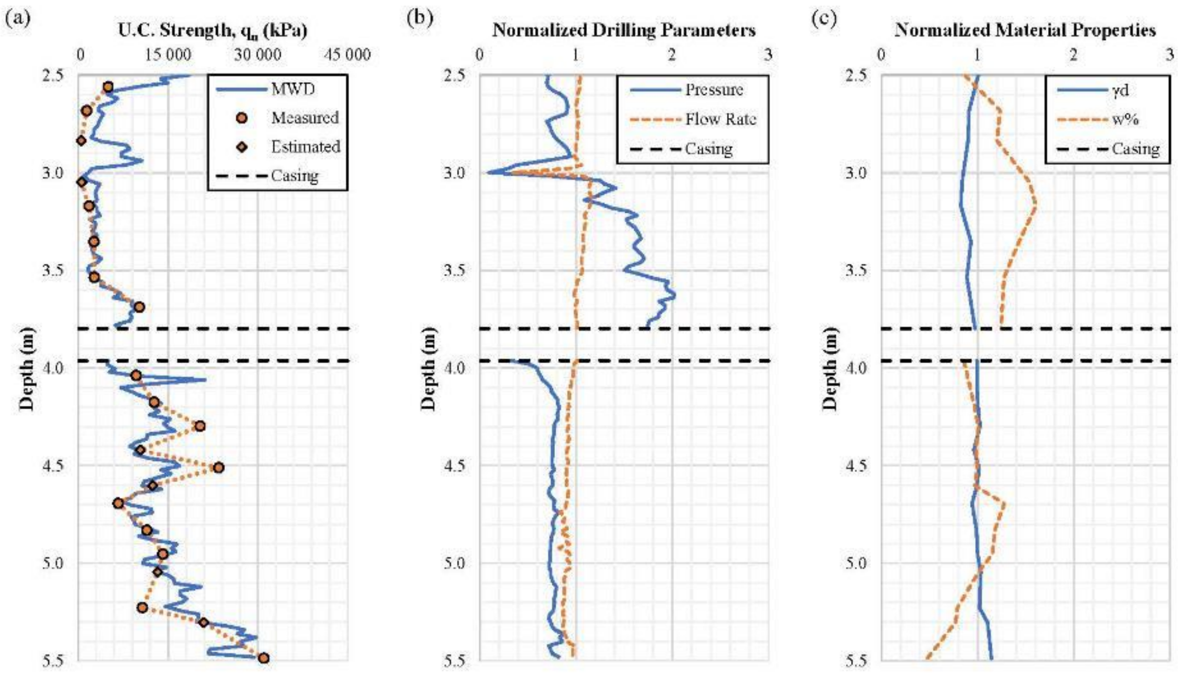
Overcrowd - Manual	
Parameter	Average
u (in/min)	10.1
N (rpm)	115
u/N (in/rev)	0.088
T (in-lbs)	2,858
F (lbf)	2,752
Q (gpm)	7.4
e (psi)	34,128
MWD qu (psi)	3,293
Core qu (psi)	436

Identifying the True Degree of Weathering

Induced Weathered Appearance

True Condition of Rock

MWD in Natural Florida Limestone



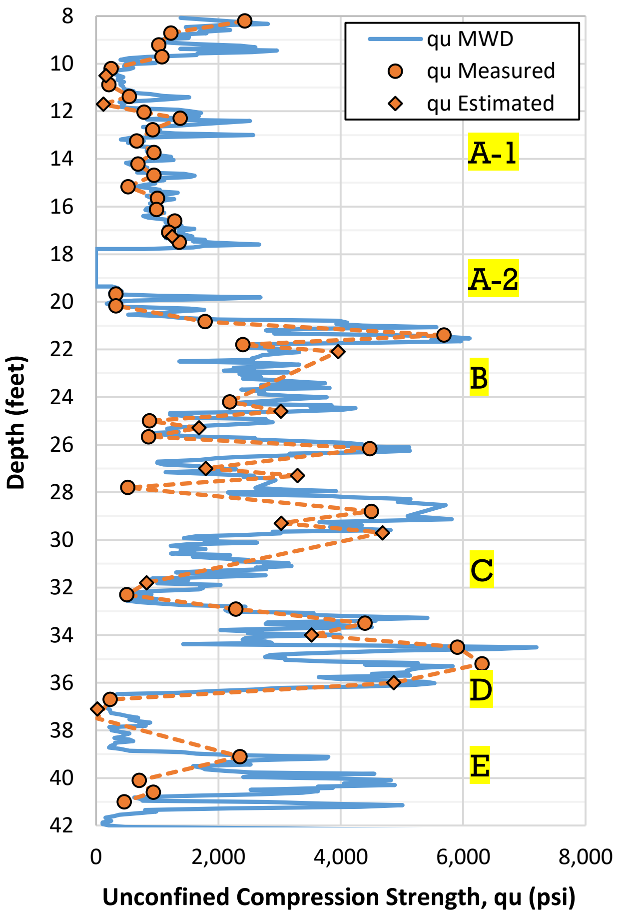
(Rodgers et al. 2019, Figure 14a,b,c and Figure 15a,b)

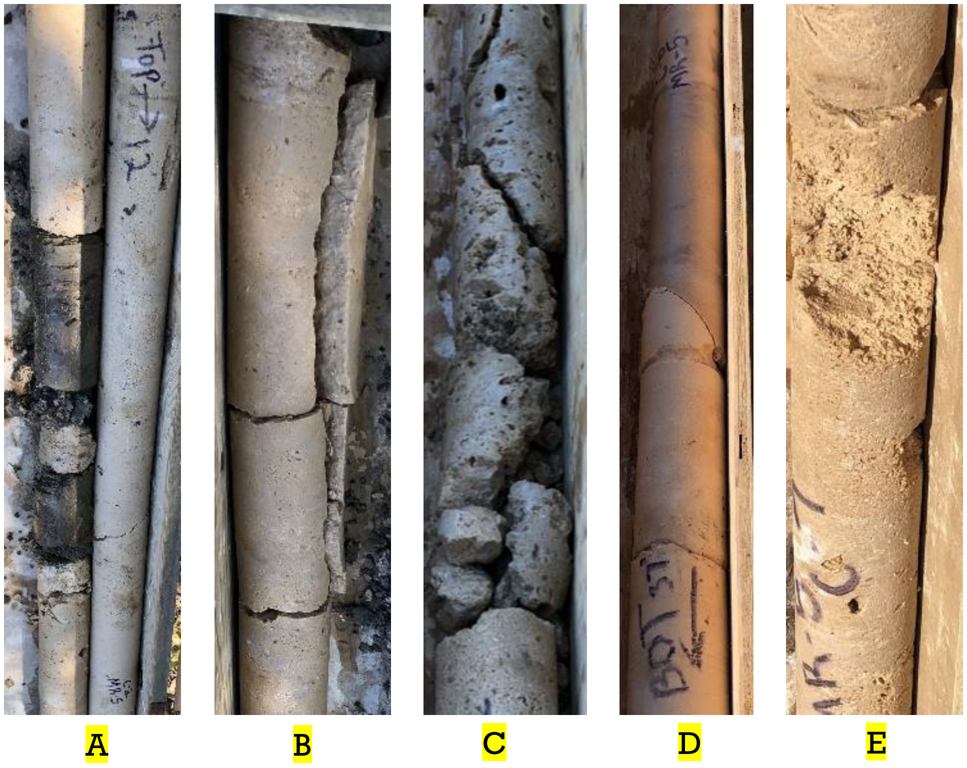
Note: q_u estimates were derived from q_t samples using the methods in Rodgers et al. 2018c.

The Benefits of MWD

- MWD provided a highly detailed profile of rock strength
  - In agreement with core samples
  - 145 MWD strength assessments vs. 21 core strength assessments
- Strength profiles were in agreement with material properties and visual appearance of core samples
- Injection pressure identified natural discontinuities in rock mass
  - Properly quantify missing sections within the recovered core samples
- MWD Benefits Summary
  - Increased the reliability of the measured core strengths
  - Increased the number of strength assessments (identify layering, zones → GS-Deep)
  - Reduced the uncertainty within the rock mass
    - Reduces variability by breaking up rock data into layers and/or zones
  - Ensured REC and RQD reflected the in situ conditions and not improper drilling techniques

Perry, FL - Boring MR5





Average REC from all MR5 core runs was 92%

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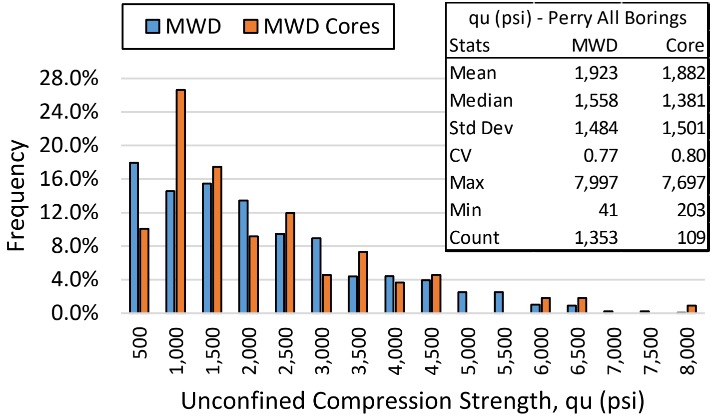
Geosystems Department

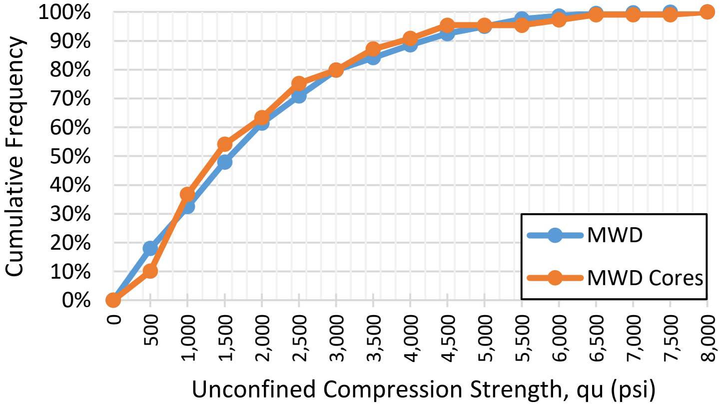
Site Statistics – Perry, FL

- 5 Borings ⇨ 89 feet of rock coring
  - q_u sample recovered every 10" of rock coring
- Large material property range
  - γ_d range ≈100 pcf to 165 pcf
  - *W%* range ≈ 0.5% to 22%

  } **Full FL range**
- Large strength range
  - Core q_u range ≈ 200 psi to 7,700 psi
  - MWD q_u range ≈ 40 psi to 8,000 psi
- Excellent agreement between MWD and rock cores
  - Strength profiles and statistics
  - 1,353 MWD data points vs. 109 from coring



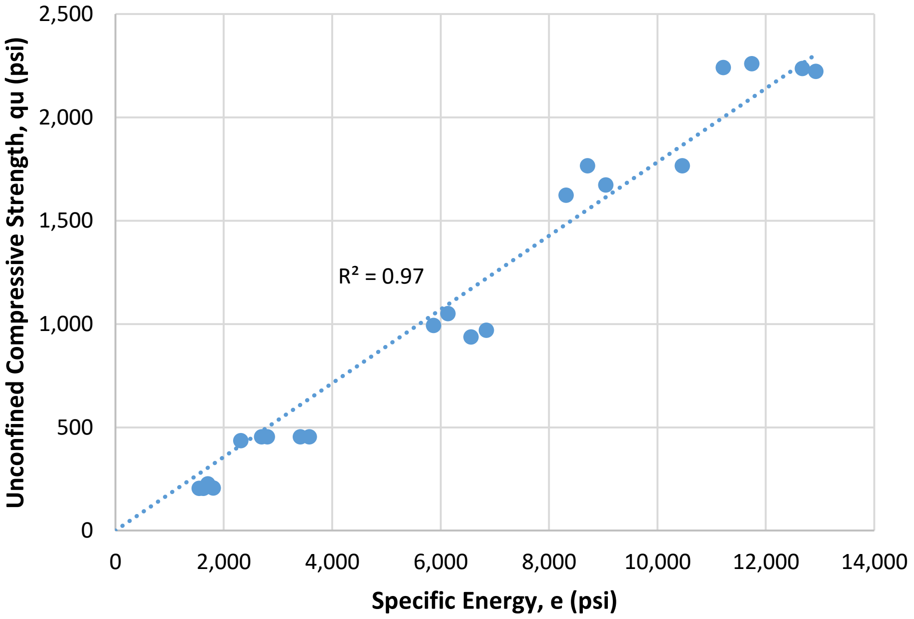
qu (psi) - Perry All Borings		
Stats	MWD	Core
Mean	1,923	1,882
Median	1,558	1,381
Std Dev	1,484	1,501
CV	0.77	0.80
Max	7,997	7,697
Min	41	203
Count	1,353	109



Tri-cone Roller Bit MWD

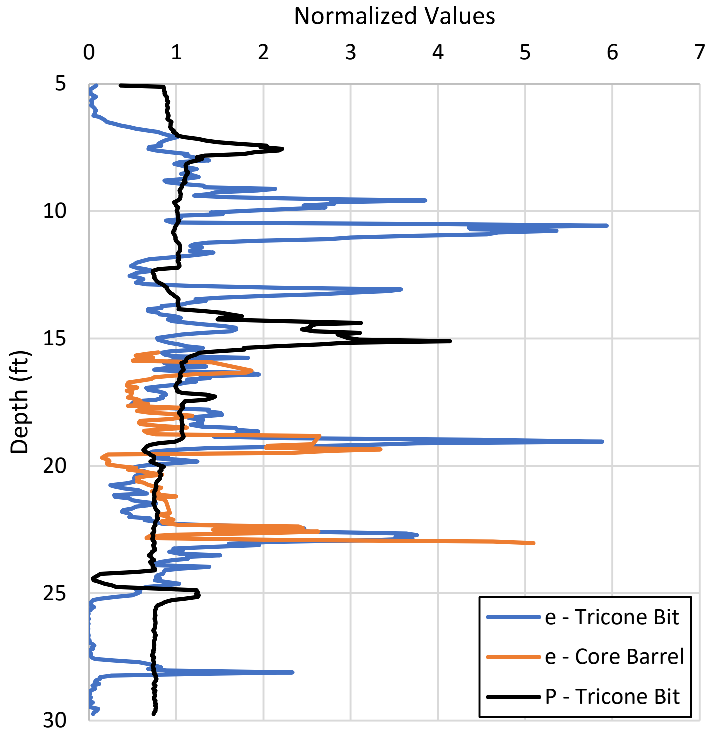
- Completed 49 tri-cone roller bit drillings
  - 25 data points used to develop correlation
- Average compressive strength was determined from cores recovered in adjacent holes
- Optimal *N* range 75 to 100 RPMs
  - In agreement with surveyed drillers
    - 2nd gear – higher throttle
    - 3rd gear – lower throttle
- *u/N* threshold is estimated to be around 0.030 in/rev
- The key component to reliable correlation was flow rate
  - *Q* > 16 GPM was optimum

All data points presented had a Q ≥ 16 GPM

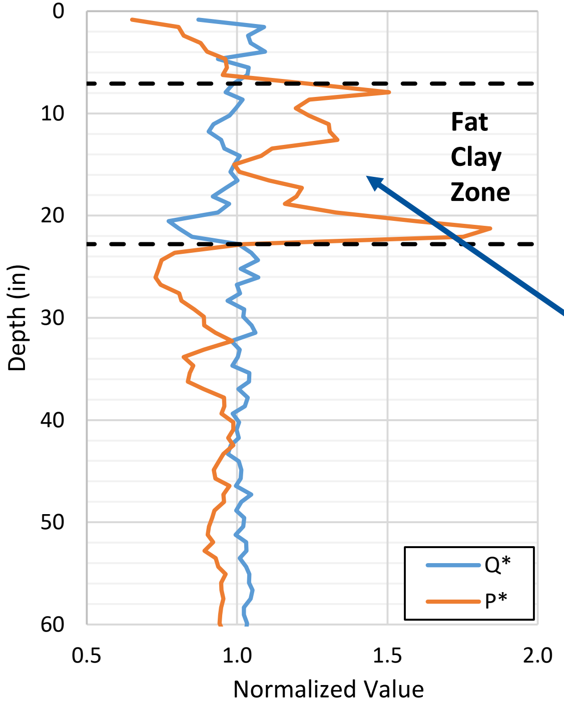


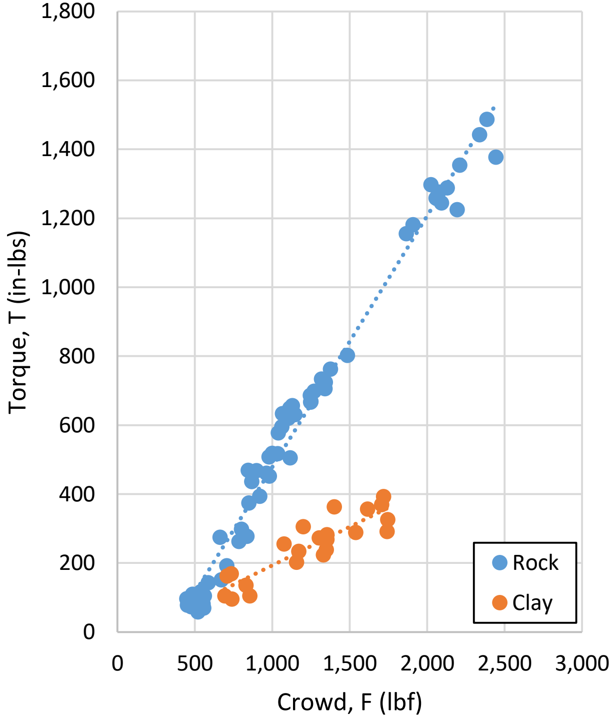
Tri-cone vs. Core Barrel

- Adjacent borings were completed in Newberry, FL
- Normalized specific energy profiles are quite similar
- Injection pressure spiked in a few locations
  - Limited change in *e*
- Can *P* be used to discern clay from rock?
  - Observed using core barrel too

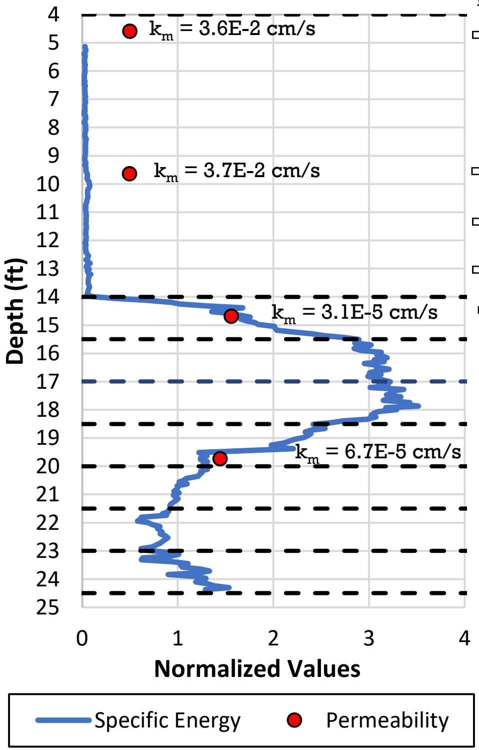


Discerning Clay from Rock





Soil Identification via Tri-cone MWD



Soil Descriptions

⇨ N_{SPT} = 3

Tan Sand

⇨ N_{SPT} = 3

⇨ N_{SPT} = 5

⇨ N_{SPT} = 7

Tan Sand w/ Red Clay ⇨ N_{SPT} = 8

Tan Sandy Clay ⇨ N_{SPT} = 6

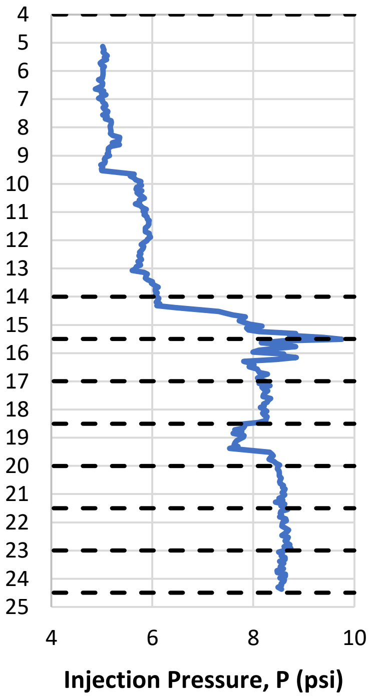
Tan Sandy Silty Clay ⇨ N_{SPT} = 10

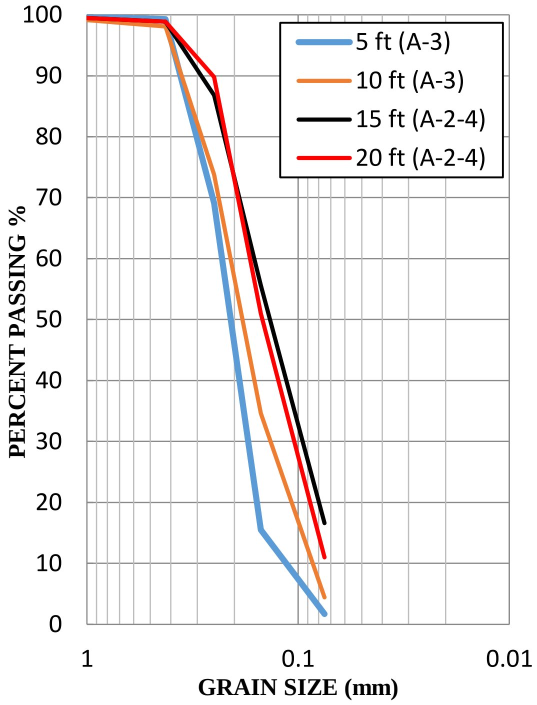
Light Tan Silty Sand ⇨ N_{SPT} = 8

White Sand ⇨ N_{SPT} = 11

White Sand ⇨ N_{SPT} = 11

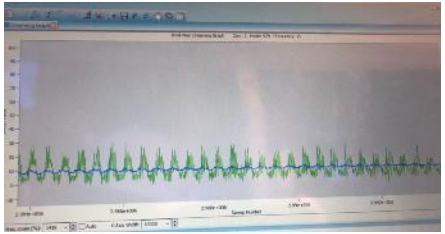
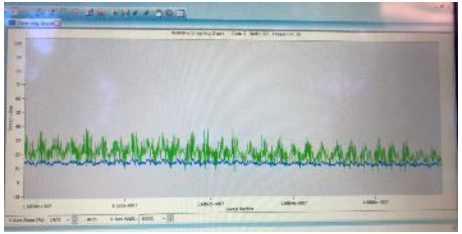
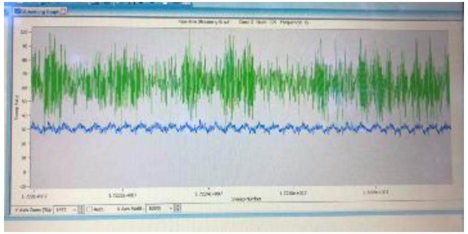
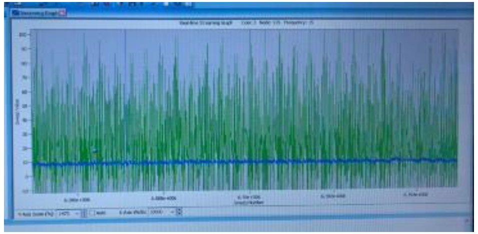
Tan, White, Red Silty Sand ⇨ N_{SPT} = 11





Note: MWD data collected in 10 minutes → very quick assessment

Vibrational Signatures of Florida Rock




Extremely Soft Limestone
γ_d = 100 pcf
$w\%$ = 22%

Fresh Limestone
γ_d = 110-130 pcf
$w\%$ = 7-20%

Banded Limestone/Dolestone
γ_d = 130-160 pcf
$w\%$ = 4-12%

Banded Limestone/Chert
γ_d = 140-145 pcf
$w\%$ = 4-5%

The Future of MWD

- MWD could be used to provide strength assessments and material identification for a precise profile of the strata encountered
  - Specific energy can provide excellent rock strength assessment when drilling within the operational limits of the drilling tool
  - Injection pressure can be used to detect naturally voided sections
  - Injection pressure can be used to discern clay from rock
  - Rock and soil have different T/F relationships
  - Rock and soil have different vibrational signatures
- Propose developing an operational index to discern different materials similar to CPT but with the ability to penetrate rock
  - Tri-cone MWD provides a very quick method of assessment

Recommendations

- We have learned a tremendous amount about SPT coring/drilling and Florida limestone in general throughout this brief study
- Continue to investigate MWD coring
  - Natural Florida limestone and Gatorock
  - Investigate more bit types
- Pursue the development of Tri-cone MWD as a new quick method of assessment and material identification
  - Investigate multiple bit types
  - Properly develop guidelines and methods for this new application
- Develop an operational index for both tool types to begin identifying materials
  - Incorporate monitored vibration as a new drilling parameter
- Pursue more MWD applications as our knowledge of drilling practices and Florida strata continue to improve with each project

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Thank you D-2 and D-3 drilling crews!

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