Measuring While Drilling for Florida Site Investigation (FLMWD)

BDV31-820-006

FDOT GRIP Meeting

Project Manager: David Horhota, Ph.D., P.E.

UF PI: Michael McVay, Ph.D.
UF Co-PI: Michael Rodgers, Ph.D., P.E.

August 9th, 2018

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 (determining operational limits for drilling tools in specific formations)
    - 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 standards created for geotechnical purposes in 2016
  - Guidelines for monitoring systems, operations, and data logging
  - 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
  - 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

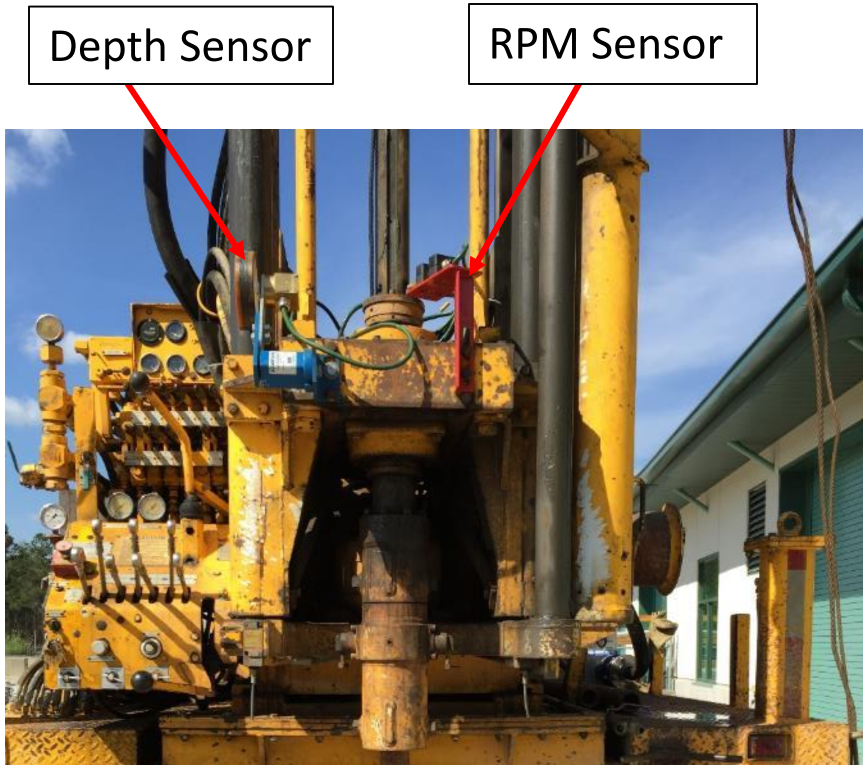
Objectives

- 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

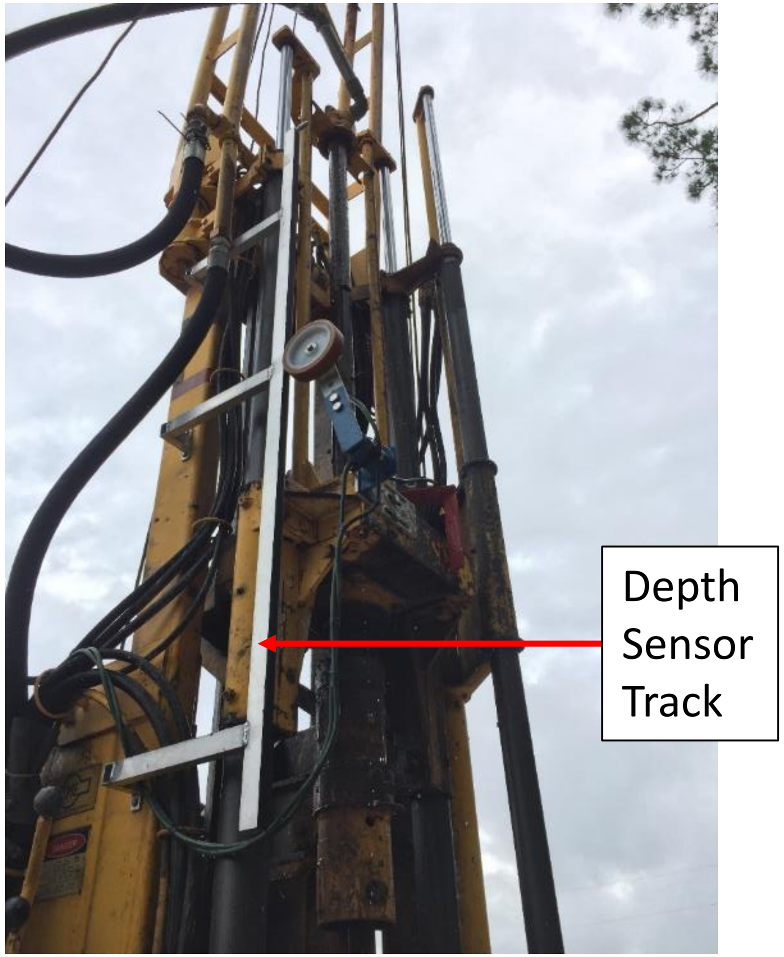
1. Surveying district SPT drillers
2. SPT rig investigation and instrumentation
3. Controlled field testing with Gatorock
4. Full scale field testing at various Florida sites
5. Field testing analysis
6. Draft final report and closeout teleconference
7. Final report

Penetration Rate and Rotation Speed


Depth Sensor

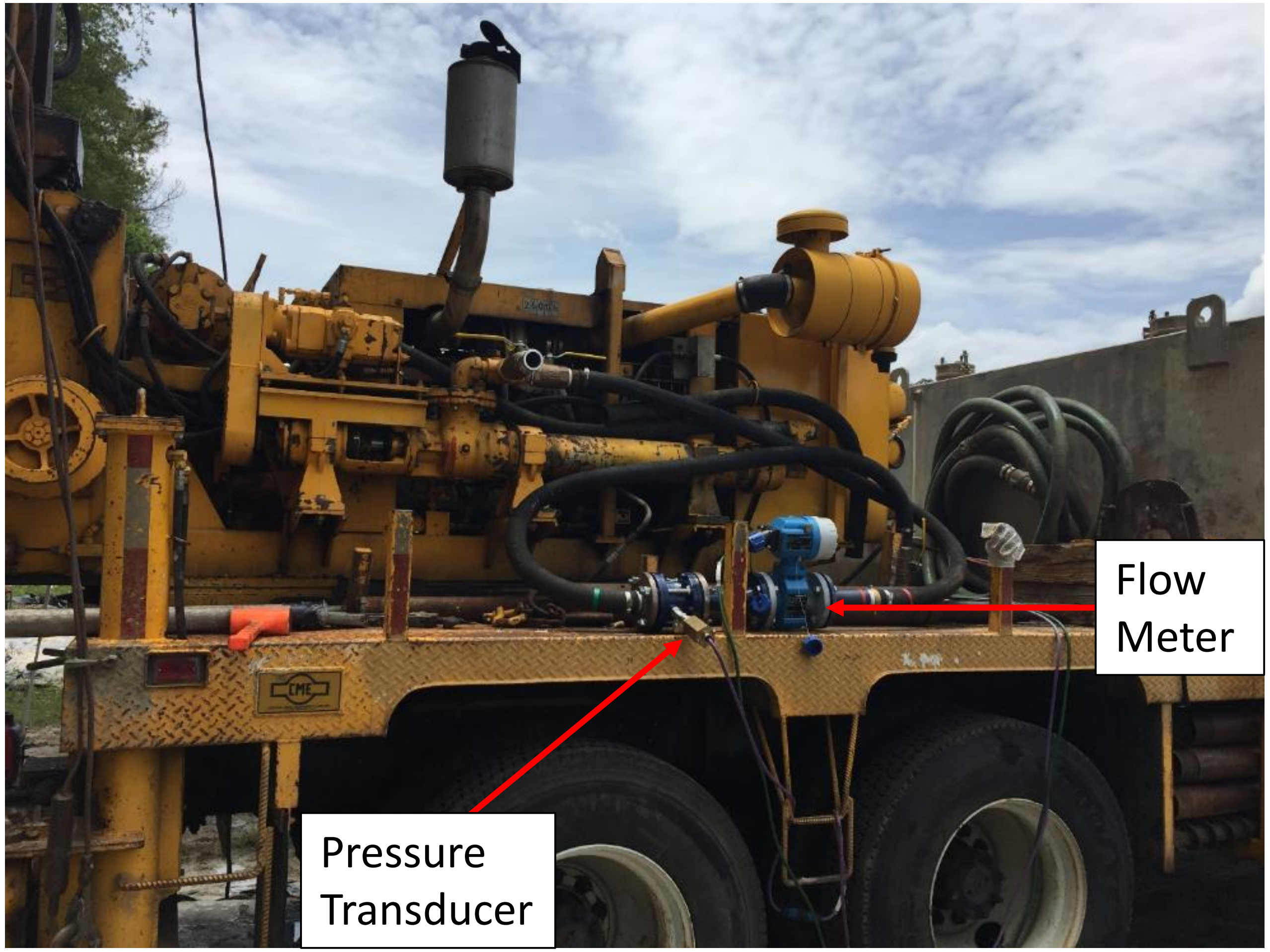
RPM Sensor

Modified Depth Sensor



Depth Sensor Track

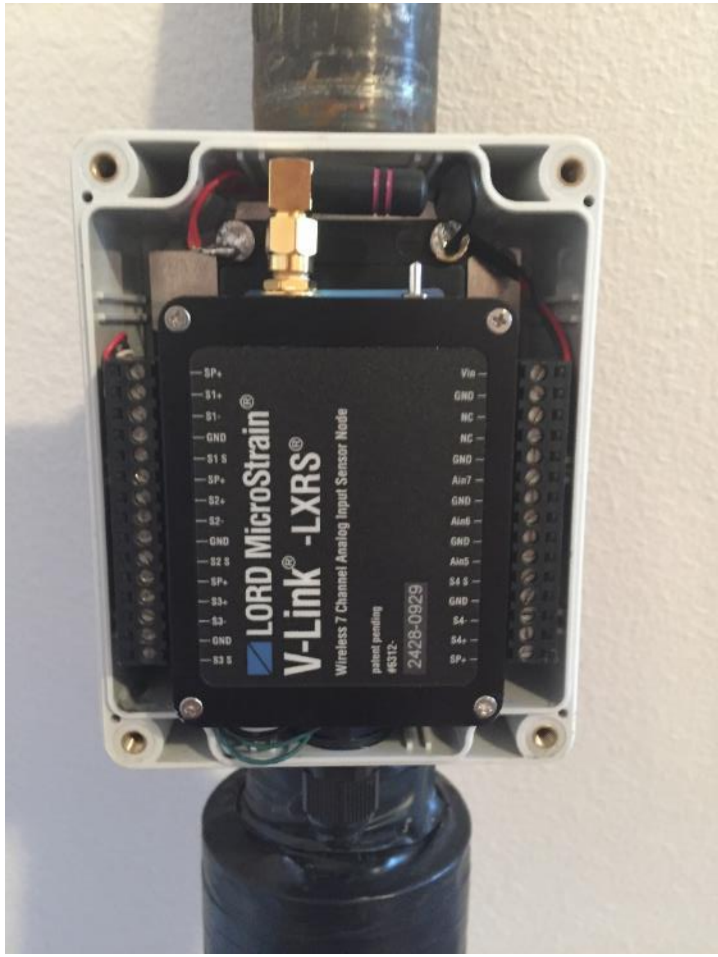
Flowrate and Pressure



Instrumented Drill Rod

- 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

Water Resistant Housing



Creating Gatorock Slabs

Real Time Monitoring

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)

<u>Additional Drilling Parameters and Terms</u>

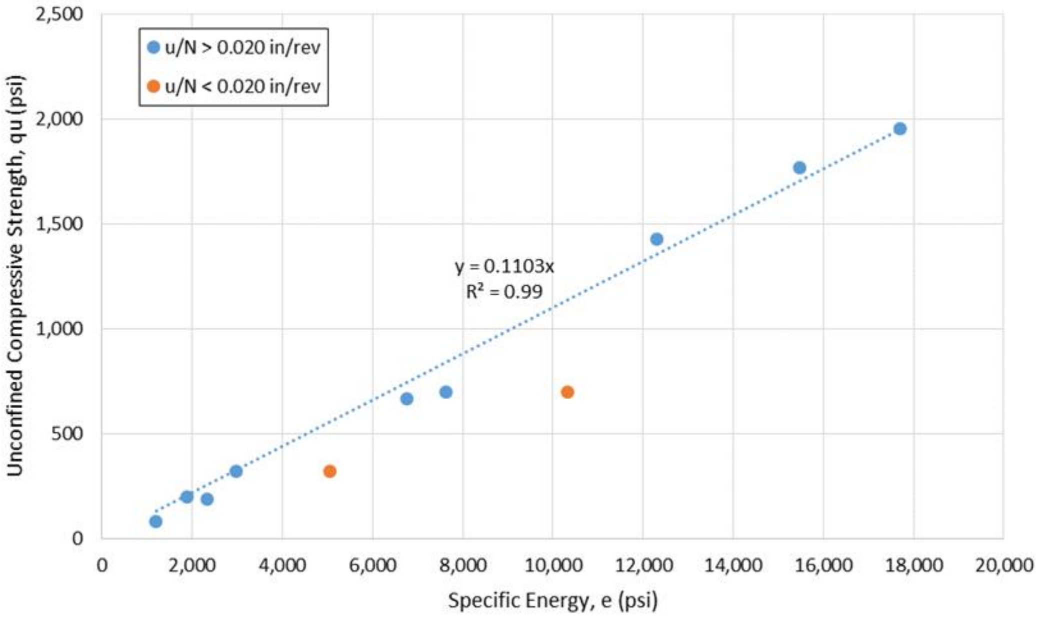
- Q = Flow rate (GPM)
- P = Flow rate injection pressure (psi)
  - Not discussed
- q_u = Unconfined compressive strength
  - Measure of rock strength most often used in design
- u/N ratio = Penetration rate to rotational speed ratio
  - Provides a threshold that must be achieved during drilling to reliably 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

Preliminary SPT MWD Investigation

- 3 double wall core barrels were investigated
- All with diamond studded cutting surfaces
  - Based on survey results
- 2 different cutting surface configurations
  - Stepped
  - Rounded
- 2.4” core barrel selected
  - FDOT SFH guidelines

Preliminary Correlation

- Poor recoveries for low strength Gatorock at the beginning of investigation.
  - Crowd, F ≈ 1,000 - 1,200 lbf
  - Varied Flow rate, Q and RPM, N
  - u/N ≈ 0.020 in/rev for “rounded” 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



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

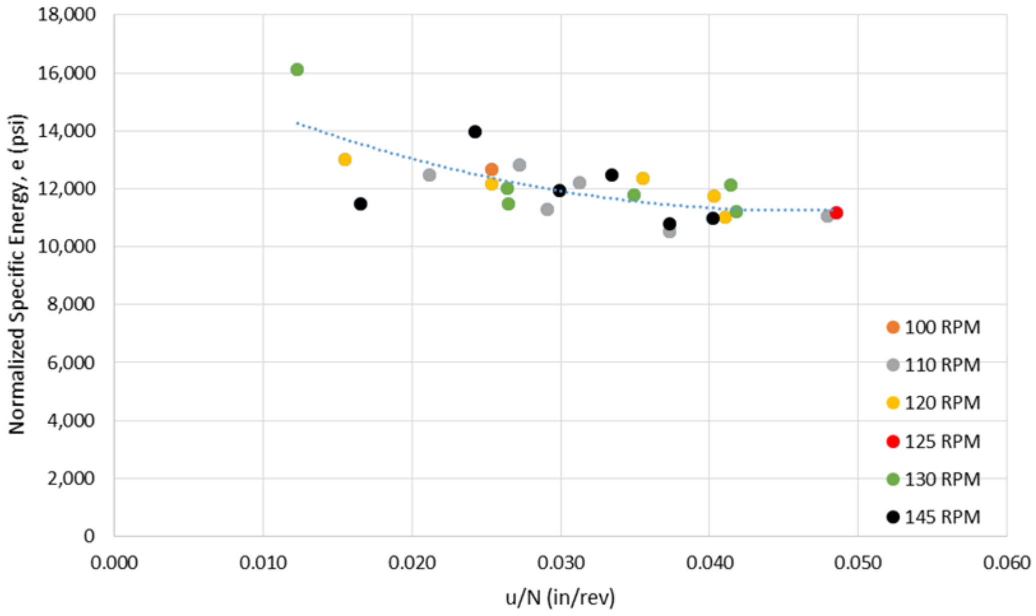
Calibration Study

- Obtained 3 new rounded 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

e vs. u/N Ratio

Rotational Speed Groupings

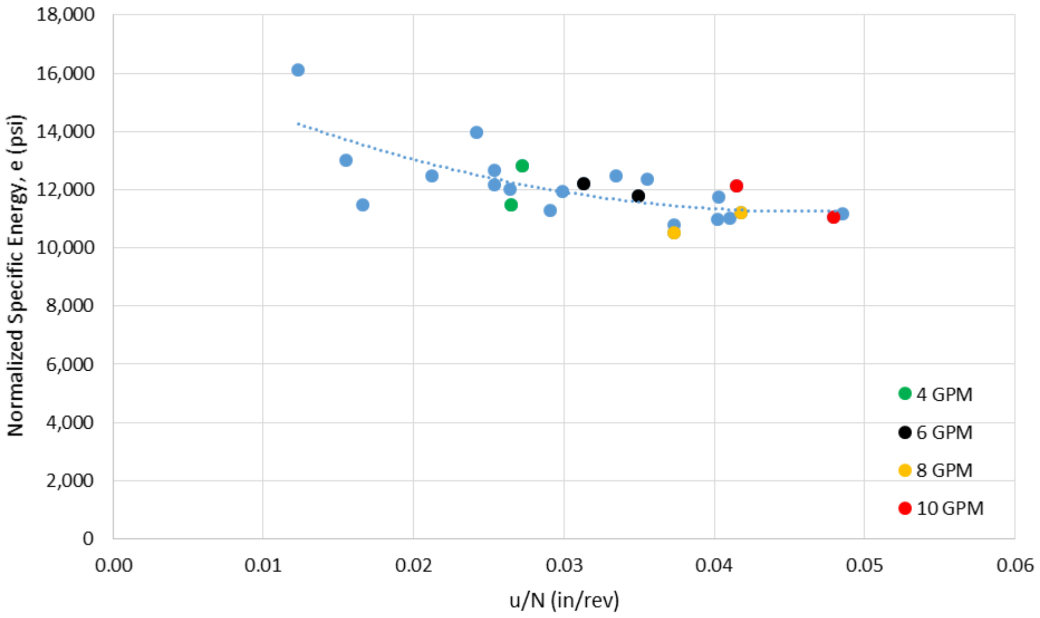
(Investigate Optimal Range)



Initial rotational speeds came from using 3rd gear with ½ to ¾ throttle – recommended by surveyed drillers

Flow Rate Groupings

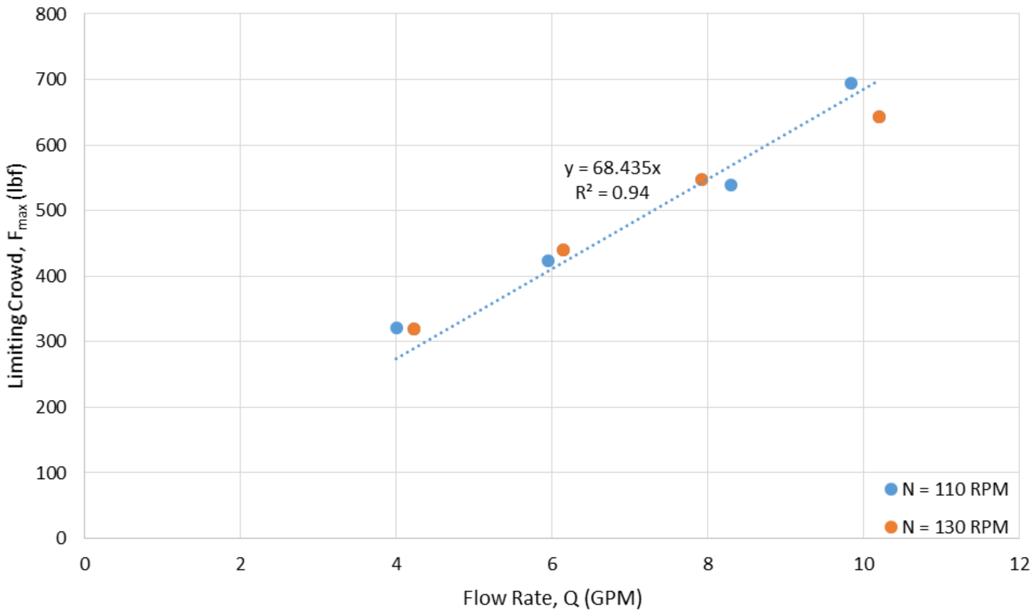
(Limiting Crowd Investigation)



N = 110 and 130 RPMs were selected as an ideal range. Drilled final 8 holes using 4 variable flow rates w/ N = 110 & 130 RPM

Limiting Flow Rate – Crowd Correlation

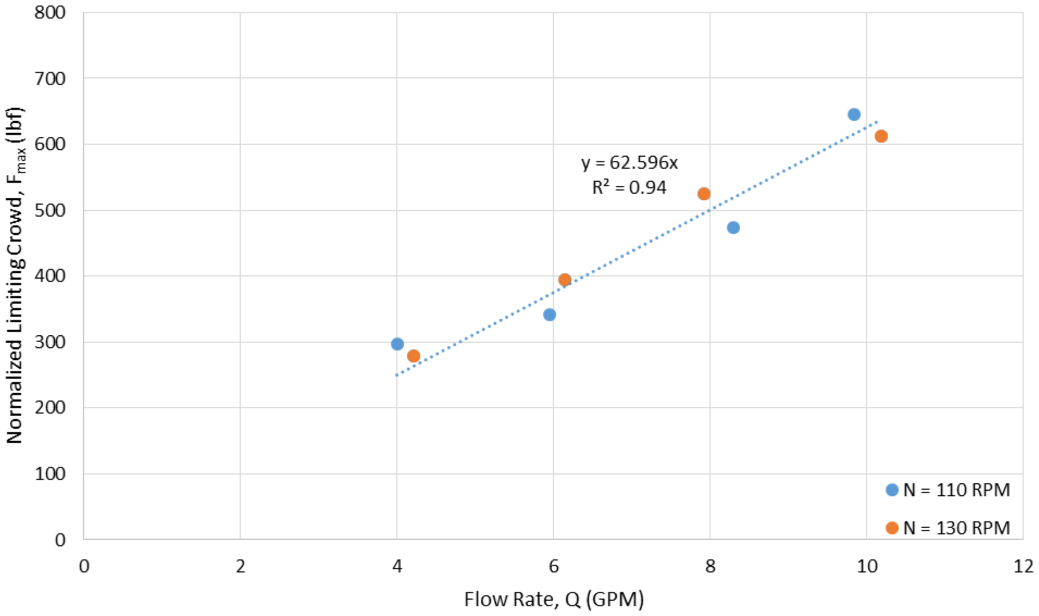
Actual Crowd Values



Increasing Limiting Crowd

Increasing Flow Rate

Normalized Crowd Values



F_{max} (lbf) = 62.5 (lbf/GPM) x Q (GPM) = Limiting Crowd (lbf)

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

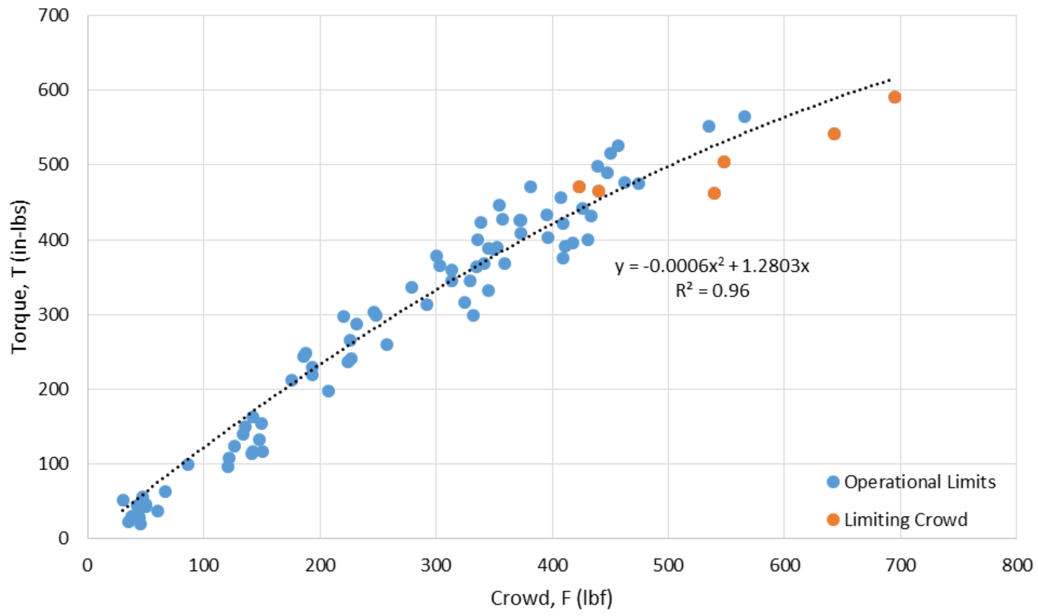
N (RPM)	$(u/N)_{min}$ (in/rev)	u (in/min)	Q (GPM)	F_{max} (lbf)
110	0.02	2.2	8.5	531
120	0.02	2.4	8.5	531
130	0.02	2.6	8.5	531
120	0.02	2.4	7.5	469

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

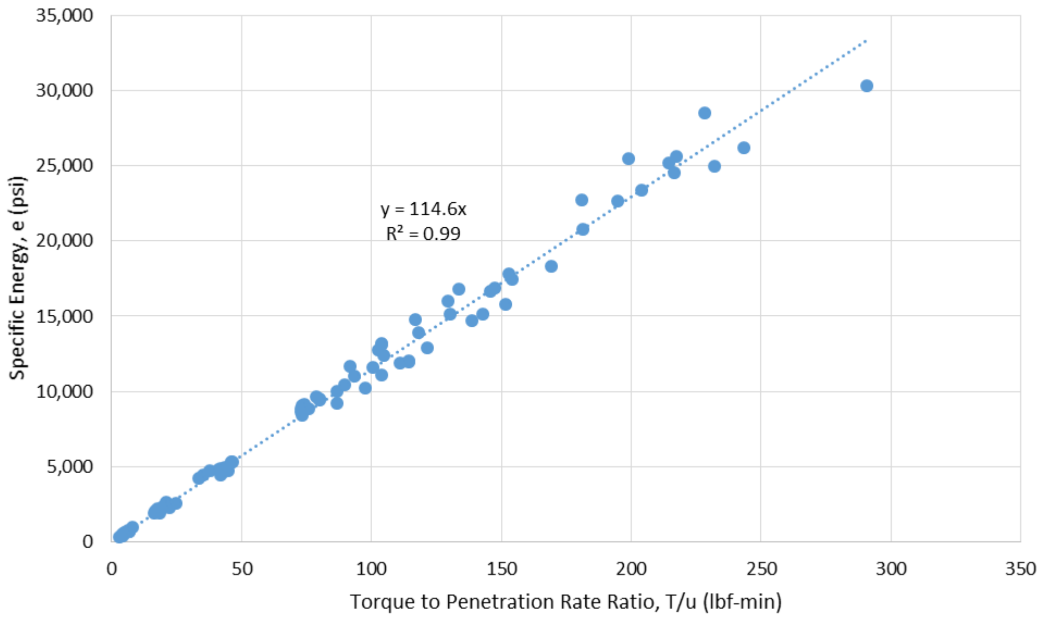
Additional Correlations

Torque vs. Force Relationship



Excellent correlation between crowd and torque regardless of the strength of the rock

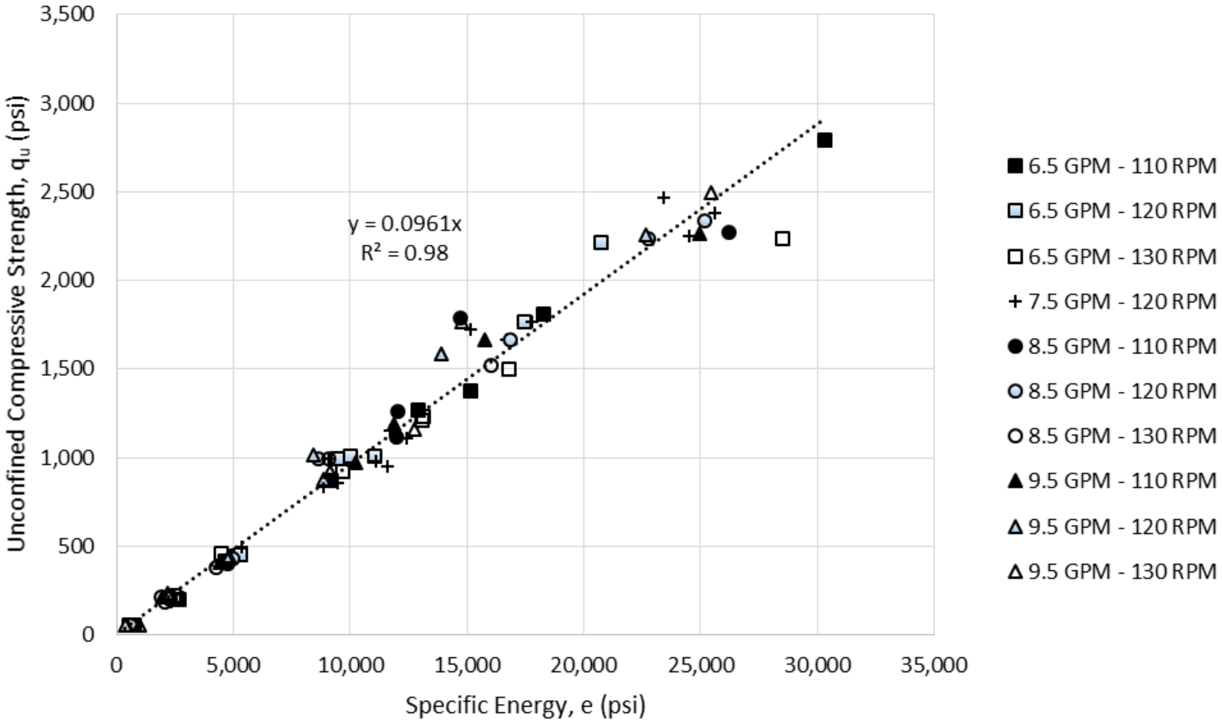
Specific Energy vs. T/u Relationship



Variable drilling parameters within the operational limits have limited effect on strength prediction

e vs. q_u Correlation

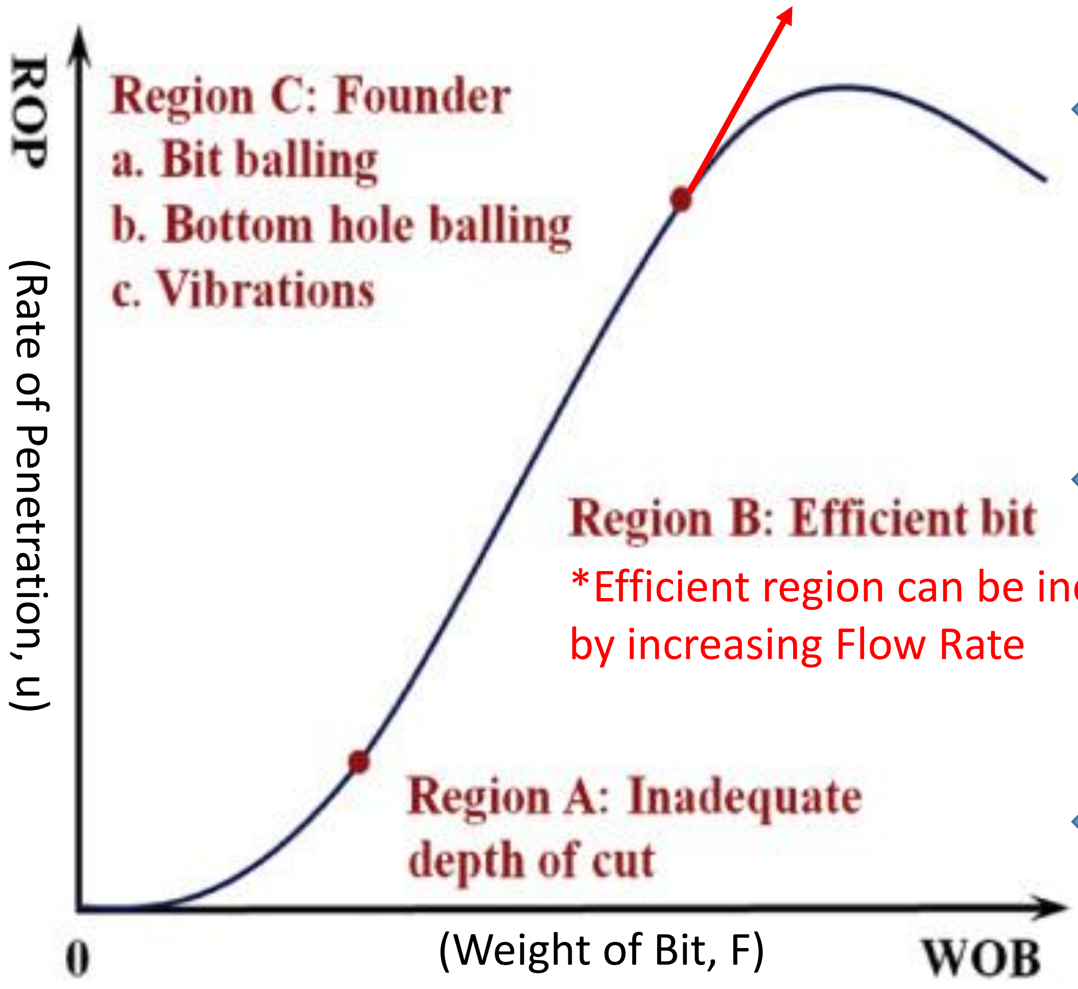
- Data grouped by combinations of variable flow rates and rotational speeds
  - 10 different combinations
- Excellent correlation was found using all 87 data points
  - Range of N and Q
- Nearly perfect RECs and RQDs for a q_u range of 183 psi to 2,788 psi
  - REC ≈ 100%
  - RQD ≈ 100%
- Lowest recovered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



Gatorock Slab 3 - Extremely Weathered Case

- SPT testing was completed
    - N = 24 blows
    - N = 26 blows
- Average q_u of slab was 56 psi from all recovered core samples
    - q_{uAVG} = 39 psi
    - Range of 24.7 psi to 68.2 psi
    - REC = 71%
    - RQD = 55%
- Best recoveries occurred when using higher flow rates
    - Q = 8.5 GPM
    - Q = 9.5 GPM

Drilling Efficiently (Operational Limits)



*Efficient region can be increased by increasing Flow Rate

(Chen et al. 2016)

Increase in specific energy from overcrowding that will pulverize rock cores

- Increases bit wear
- Stall reduces penetration rate
- Increases wasted energy

Minimum specific energy required

- Increases REC and RQD (core barrel)
- Optimized penetration rate w/o pulverizing rock
- Reduces unnecessary bit wear
- Allows strength prediction

Increase in specific energy from breaking rock particles into smaller sizes than necessary for removal

- Low penetration rate

Effects of Overcrowding the Drill Bit

<u>Drilling within the operational limits</u> of the drill bit.
UCS ≈ 700 psi
REC = 100%
RQD = 100%

<u>Drilling outside the operational limits.</u>
Fractured rock from overcrowding the drill bit.
UCS ≈ 700 psi
REC = 30%
RQD = 0%

Effects of Overcrowding the Drill Bit

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

208 psi Gatorock

Stall

Within Operational Limits

The Effects of Significant Bit Wear

- Before significant bit wear
  - u = 3.87 in/min
  - u/N = 0.031 in/rev
  - e = 41,034 psi

Stats	u (in/min)	N (rpm)	u/N (in/rev)	T (in-lbs)	T/u (lbf-min)	2πNT/Au (psi)	F (lbf)	F/A (psi)	Q (gpm)	e (psi)
Average	3.87	123.3	0.031	1,299.7	343.9	40,873.9	1,046.2	160.4	5.5	41,034.4
Std. Dev.	0.62	0.6	0.005	57.9	51.1	6,092.9	46.8	7.2	0.1	6,095.8
CV	0.161	0.004	0.163	0.045	0.149	0.149	0.045	0.045	0.014	0.149

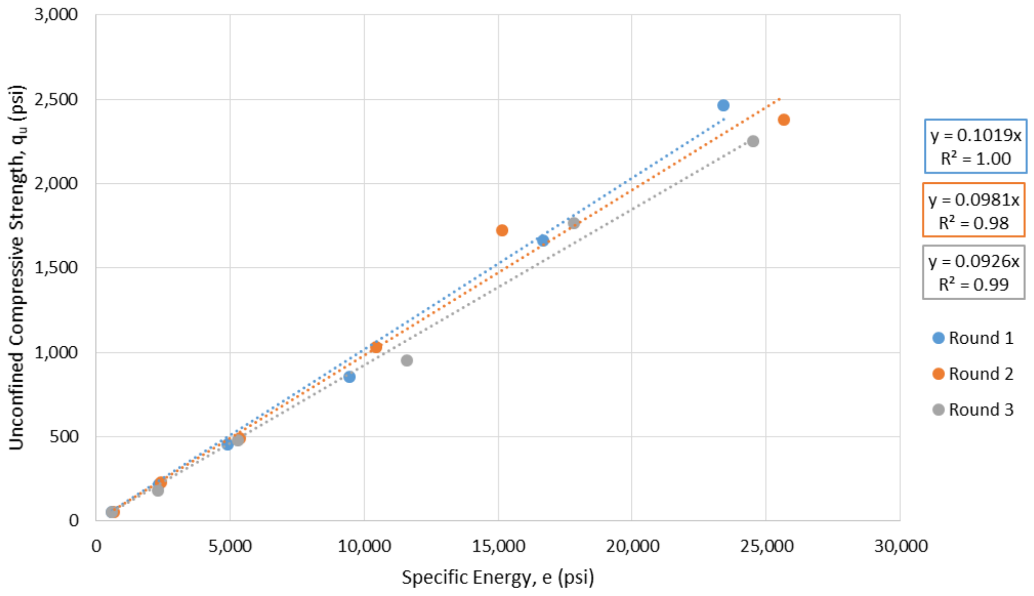
- After significant bit wear
  - u = 1.28 in/min → Penetration rate was reduced by a third
  - u/N = 0.010 → u/N ratio decreased by a third
  - e = 116,640 psi → Required 3 times the amount specific energy

Stats	u (in/min)	N (rpm)	u/N (in/rev)	T (in-lbs)	T/u (lbf-min)	2πNT/Au (psi)	F (lbf)	F/A (psi)	Q (gpm)	e (psi)
Average	1.28	125.8	0.010	1,221.8	960.8	116,478.9	1,051.3	161.2	5.2	116,640.1
Std. Dev.	0.14	0.3	0.001	44.4	82.7	10,256.4	76.0	11.7	0.6	10,246.5
CV	0.110	0.002	0.112	0.036	0.086	0.088	0.072	0.072	0.108	0.088

Missing cutting teeth

Assessing Bit Wear with Specific Energy

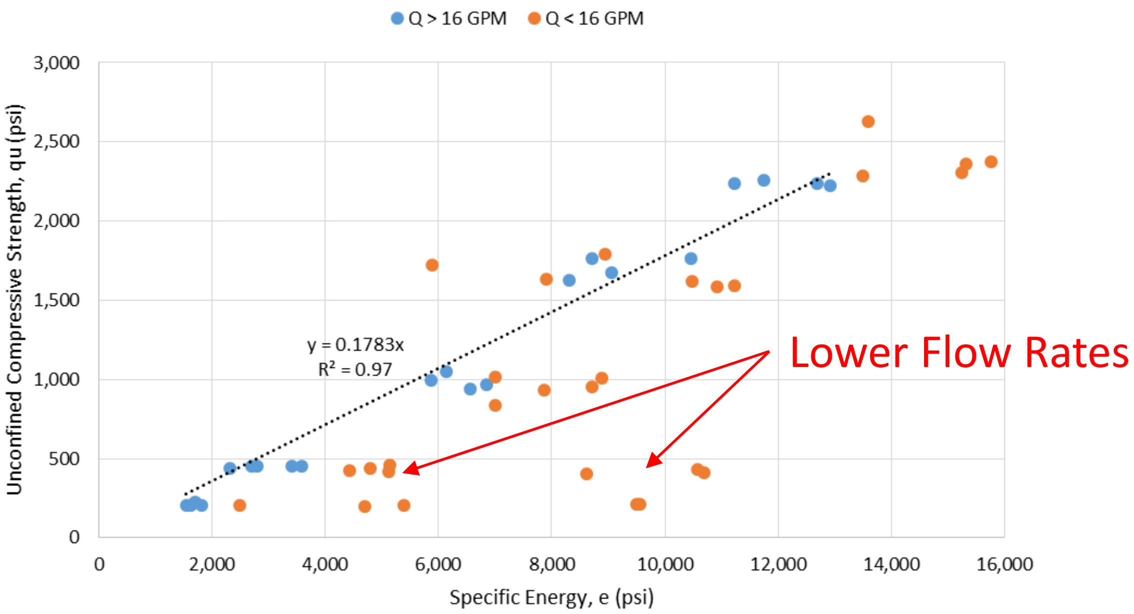
- Continuously tracked the amount of energy experienced by the same drilling tool
- Track through specific energy capacity, P_e
    - $P_e = e * \pi * d * L$
    - Rodgers et al. 2018D
- Better estimate the life of the drilling tool or cutting teeth
- Ensure the drilling tool performs at an optimum level of efficiency



Specific Energy Capacity, P_e		
Round1	Round 2	Round 3
11,676,068	11,689,538	12,495,451

e vs. q_u – Tri-cone Roller Bit

- Completed 49 tri-cone roller bit drillings
- 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



Lower Flow Rates

Why would flow rate have such a great effect on tri-cone roller bit drilling?

Effects of Breaking Particles to Smaller Sizes

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**

*Fineness modulus for core barrel cuttings was 2.16

Remaining Tasks

4. Full scale field testing at various Florida sites
5. Field testing analysis
6. Draft final report and closeout teleconference
7. Final report

Thank you!

Jose Hernando
Bruce Swidarksi
Todd Britton
Kyle Sheppard
Travis “Dalton” Stevens
Bill Greenwood
Mike Risher

Implementation of Measuring While Drilling Shafts in Florida (FLMWDS)

BDV31-977-91

FDOT GRIP Meeting

Project Manager: David Horhota, Ph.D., P.E.

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August 9th, 2018

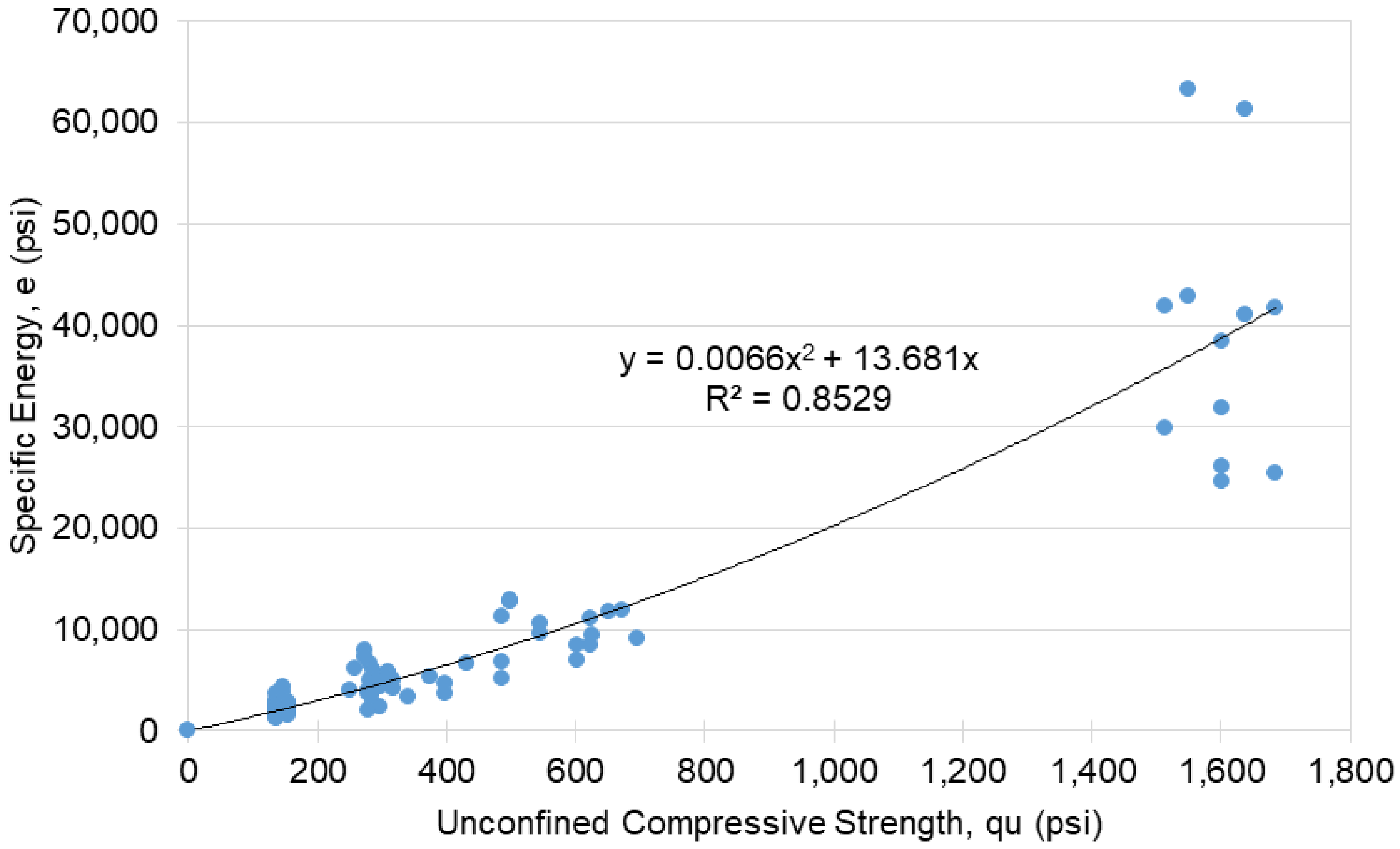
Task Outline

1. Conduct drilled shaft MWD on load tested shafts
2. Data reduction and analysis
3. Core data and site variability analysis
4. Draft Final Report and Closeout Teleconference
5. Final Report

Background and Objective

- Recently, UF and FDOT investigated using real time measurements of drilling parameters (MWD) in determination of specific energy (e) to assess both the quality and length of rock sockets for drilled shafts
- The specific energy required to excavate a shaft was directly correlated to the strength of the drilled rock
- Specific energy allowed engineers to provide real time assessments of compressive, tensile, and shear strength during full scale drilled shaft installations
- Research was verified using extracted core samples and load tests conducted on the monitored shafts.
- The intent of this work is to provide a new method of QA/QC implemented during bored pile construction via specific energy
  - Allowing the engineer to quantify the quality and length of rock sockets

Small-scale Drilling with Rock Augers



(Rodgers et al. 2018A)

Florida Rock Field Drilling Equation

Using the equation from the e vs. q_u plot

$$y = 0.0066x^2 + 13.681$$

Where,

$y = e$ (psi)

$x = q_u$ (psi)

Setting the equation equal to zero:

$$0.0066x^2 – 13.681x – y = 0$$

Using the Quadratic solution,

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Substituting terms in for a, b, and c:

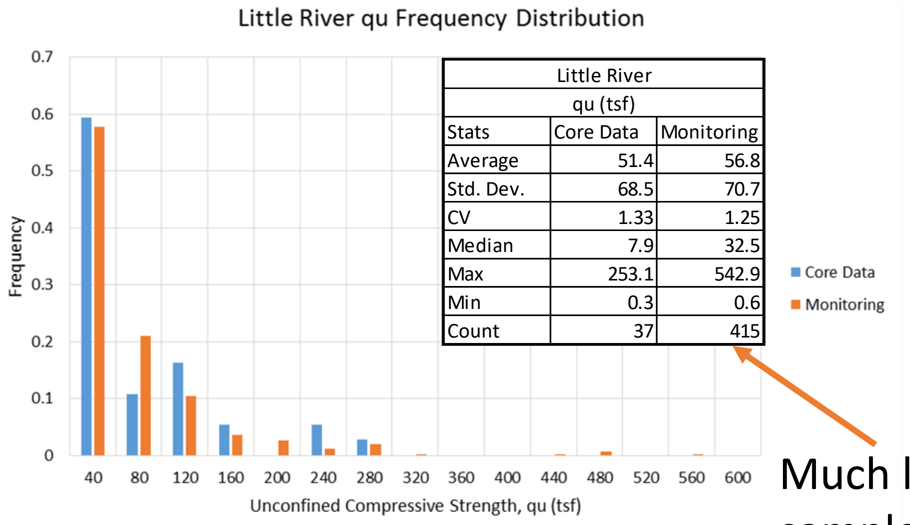
$$q_u = \frac{13.681 + \sqrt{(-13.681)^2 - 4 * (0.0066) * (-e)}}{2 * (0.0066)}$$

Field Drilling Investigation

- During the field drilling investigation, three variations were implemented in the following categories:
  - Drill rigs and drilling crews
  - Shaft/Auger diameters
    - 0.914 m, 1.22 m, and 1.52 m
  - Locations (limestone formations encountered)
  - Slurries
    - Water, bentonite, and polymer
  - Rock auger configurations
    - Unique flights, tooth configurations, and guide shafts
    - All double flight augers
  - Comparative load tests
    - Top-down static, Statnamic, and Bi-directional Osterberg
- In all cases, the results obtained from monitoring the shaft installations (MWD) were in good agreement w/ the results obtained from load testing

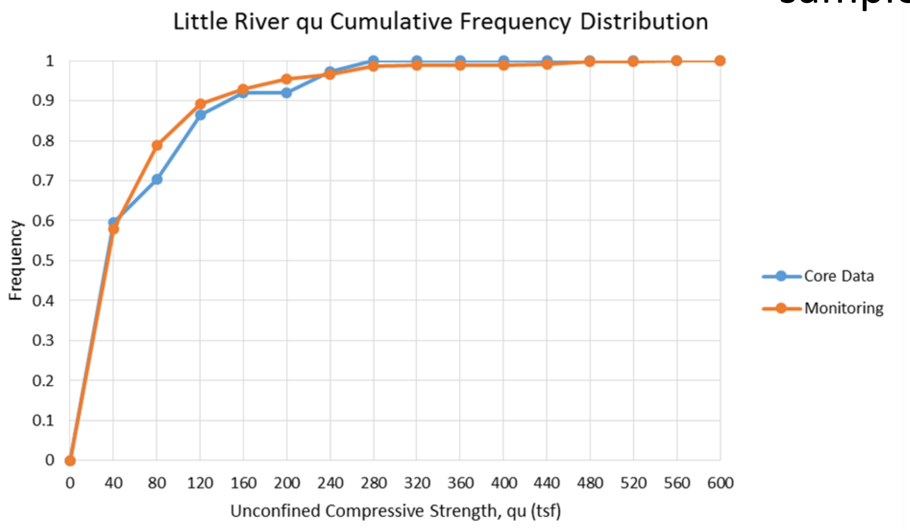
Analysis of Rock Strength – Little River, FL

- Good core recoveries
  - Average REC% = 85%
- Large number of core samples
  - 37 q_u core samples available for comparison in monitored depth range
- Monitoring and core sampling produced similar frequency distributions
  - Nearly identical CV values
- Difference in average strength due to site variability and sampling location
  - 2 of 4 borings completed 80’ away



Little River qu (tsf)		
Stats	Core Data	Monitoring
Average	51.4	56.8
Std. Dev.	68.5	70.7
CV	1.33	1.25
Median	7.9	32.5
Max	253.1	542.9
Min	0.3	0.6
Count	37	415

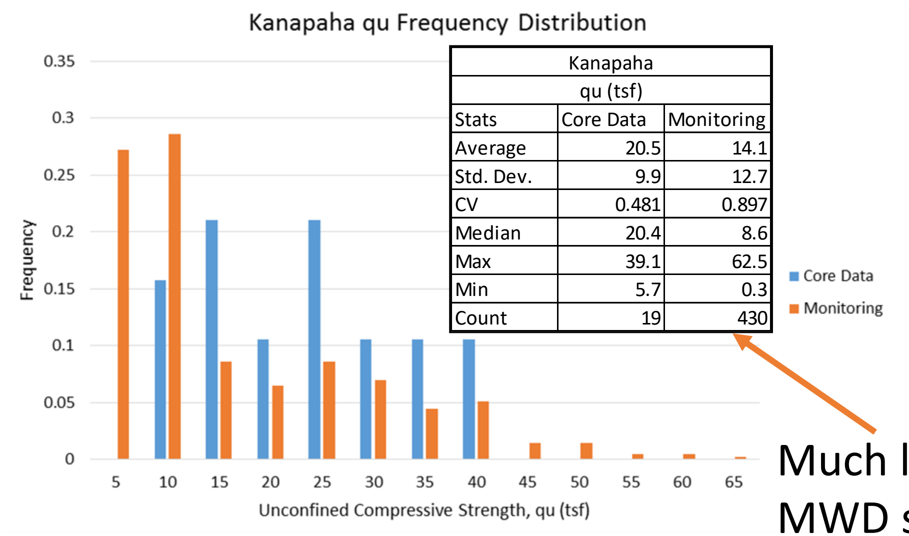
Much larger MWD sampled population



(Rodgers et al. 2018B)

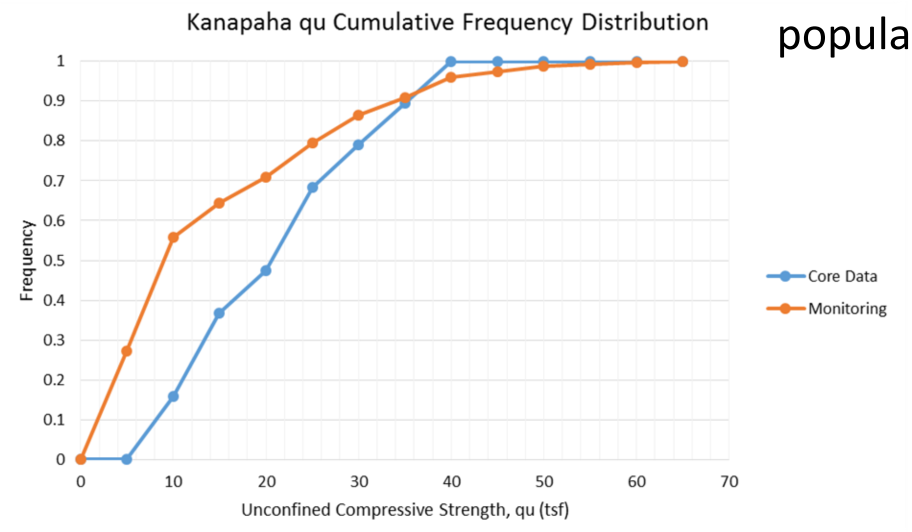
Analysis of Rock Strength – Kanapaha, FL

- 9 borings completed within the monitored depth range
  - 3 in the footprint of the shafts
  - 6 borings within 5’ from the center of the monitored shafts
- Only 19 q_u core samples were obtained
  - Average REC% = 40%
- Frequency distributions indicate core sampling did not pick up the tails of the monitoring distribution
  - Highest and lowest strength material
- Core data CV is nearly half the monitoring CV
  - Core data did not provide the true site variability
- Core data indicated the average rock strength was 40% higher than the monitoring average
  - Poor recoveries
  - Sample size



Kanapaha qu (tsf)		
Stats	Core Data	Monitoring
Average	20.5	14.1
Std. Dev.	9.9	12.7
CV	0.481	0.897
Median	20.4	8.6
Max	39.1	62.5
Min	5.7	0.3
Count	19	430

Much larger MWD sampled population

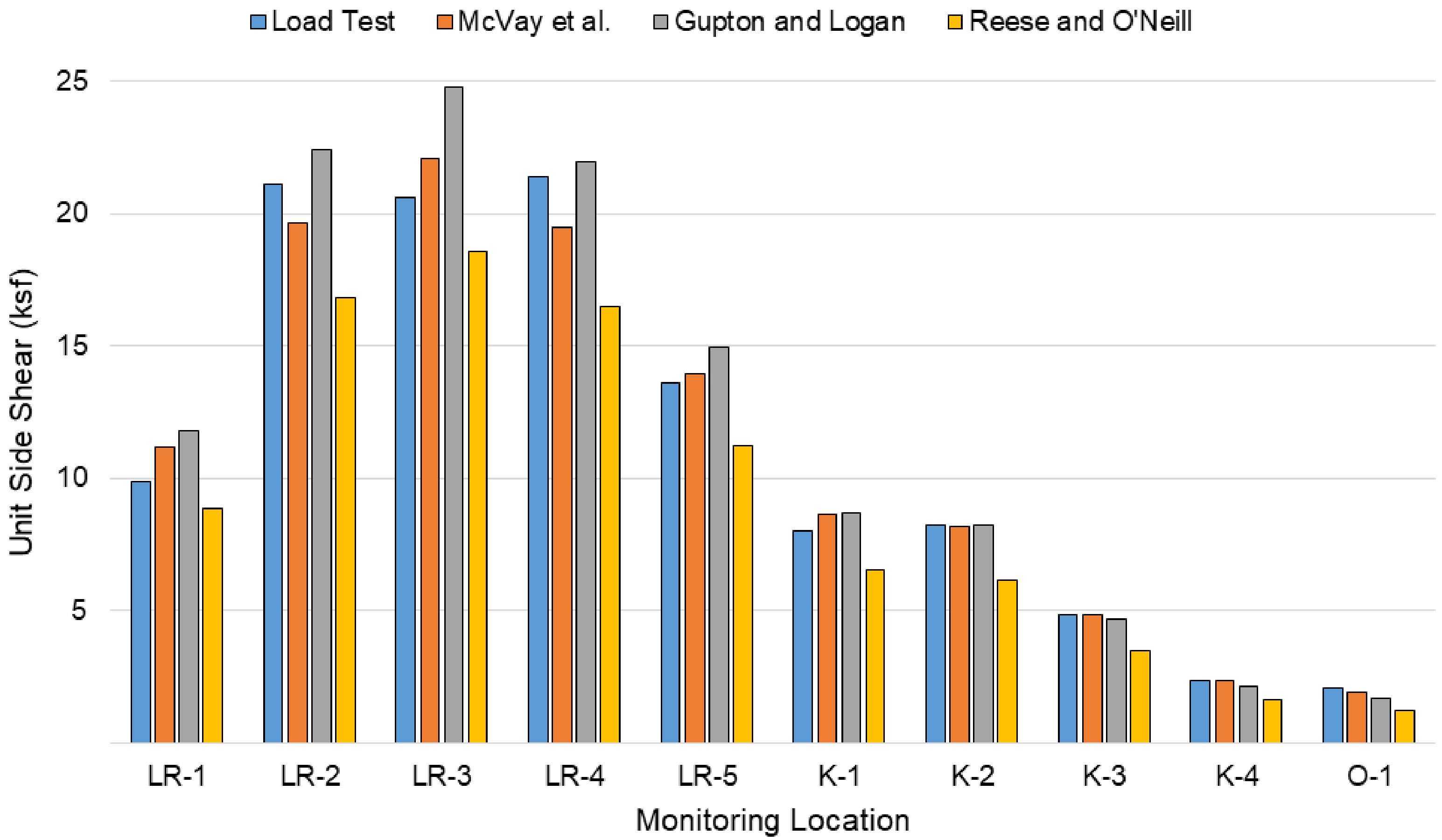


(Rodgers et al. 2018B)

Leading Skin Friction Equations

Method	Author	Design Methodology
1	McVay et al.[6]	$f_s = 1/2 \times \sqrt{q_u} \times \sqrt{q_t}$
2	Reese and O'Neill[7,8]	$f_s = 0.15 \times q_u$ (tsf)
3	Horvath and Kenney[8]	$f_s = 0.67 \times \sqrt{q_u}$ (tsf)
4	Williams et al.[9]	$f_s = 1.842 \times {q_u}^{0.367}$ (tsf)
5	Reynolds and Kaderabek[10]	$f_s = 0.3 \times q_u$ (tsf)
6	Gupton and Logan[11]	$f_s = 0.2 \times q_u$ (tsf)
7	Carter and Kulhawy[12]	$f_s = 0.63 \times \sqrt{q_u}$ (tsf)
8	Ramos et al.[13]	$f_s = 0.5 \times q_u$ (< 36 ksf) $f_s = 0.12 \times q_u$ (> 36 ksf)
9	Rowe and Armitage[14]	$f_s = 1.45 \times \sqrt{q_u}$ (tsf) clean sockets
10	Rowe and Armitage[14]	$f_s = 1.94 \times \sqrt{q_u}$ (tsf) rough sockets

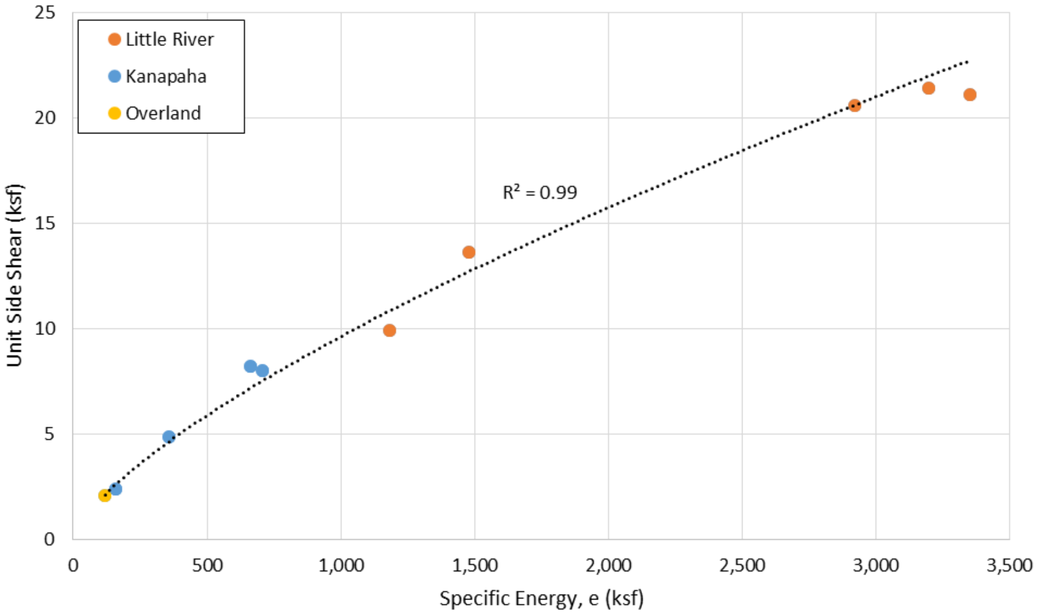
Comparative Skin Friction Analysis



(Rodgers et al. 2018E)

MWD e vs. Load Test Side Shear – Rock Auger

- Average specific energy recorded over each mobilized shaft segment
  - Data points recorded every 2 cm of penetration
- Pair average MWD e with the respective unit side shear value obtained from load testing
- Develop correlation directly
- Only requires drilling parameters to be monitored
  - No Florida specific correlations or design equations required
  - Measured drilling resistance vs. load tested axial shaft resistance



(Rodgers et al. 2018E)

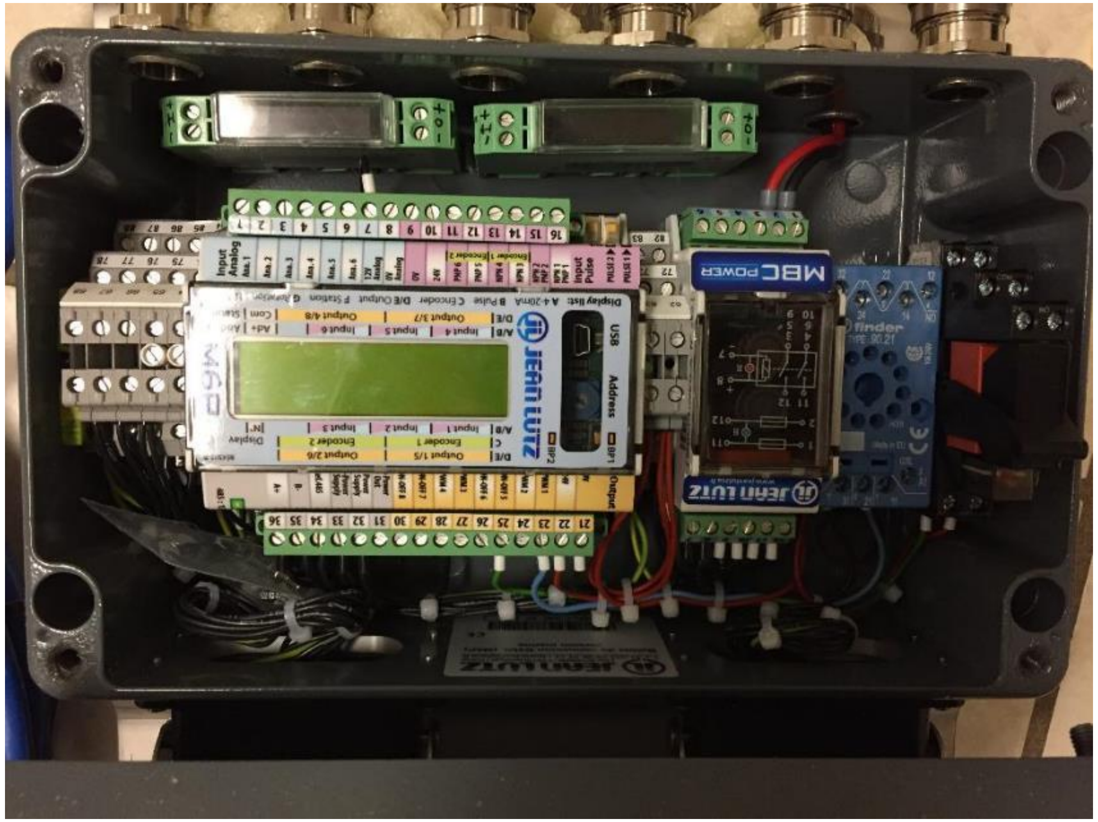
Implementation of Drilled Shaft MWD

- Acquired new monitoring equipment
  - DIALOG – DAQ module
  - Junction box
  - Extra cable
- Installed on a Liebehrr BAT 410 drill rig
  - First monitored Liebehrr rig
  - Fully hydraulic w/ all sensors installed by the manufacturer
  - Tapped into existing sensors
  - New installation method
- Monitored 3 shaft installations at Selmon Parkway (Tampa, FL)
  - New monitored location and limestone formation
- Rock drilling bucket was used
  - New drilling tool

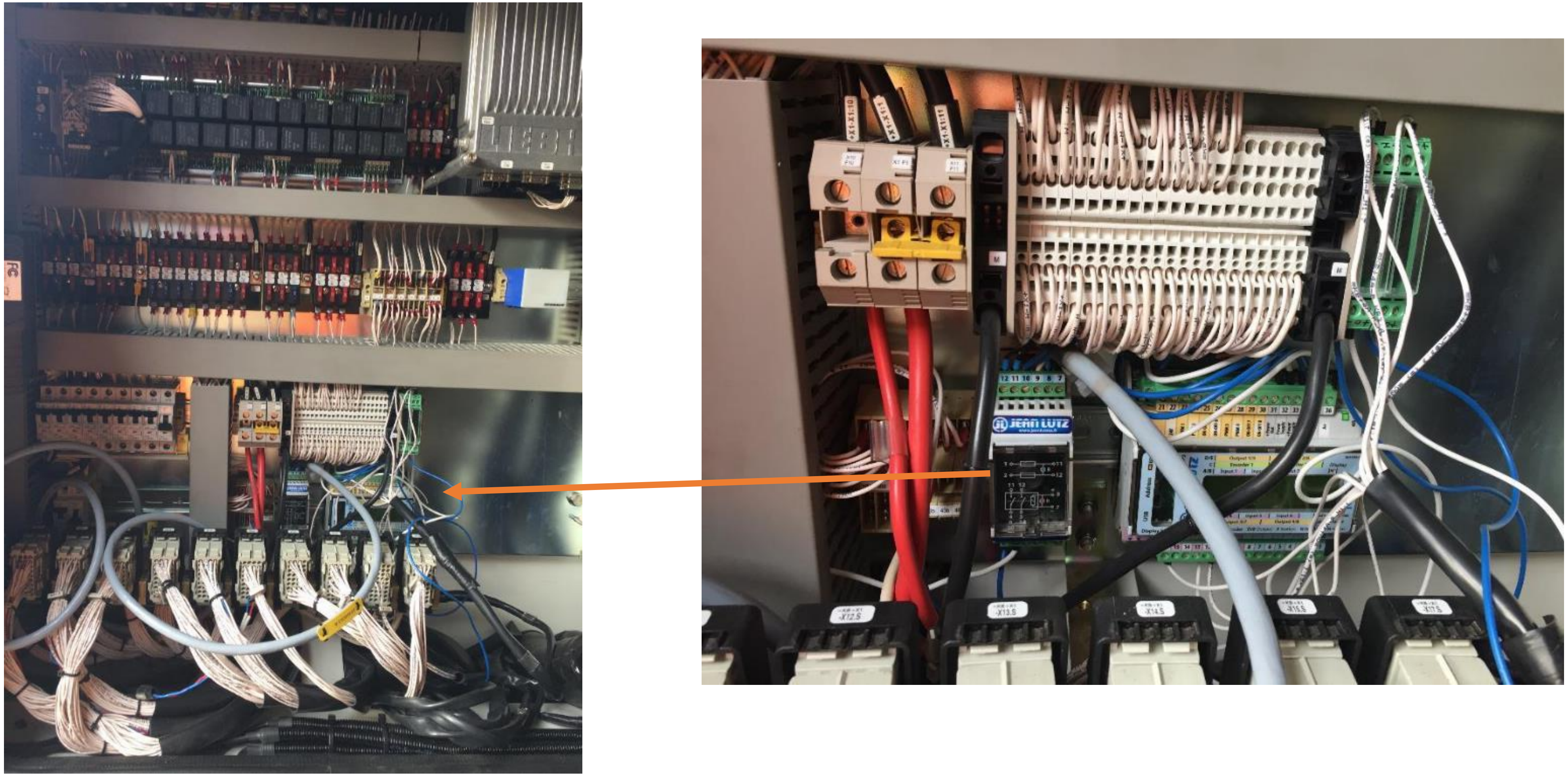
Junction Box

DIALOG

Internal Components of Junction Box



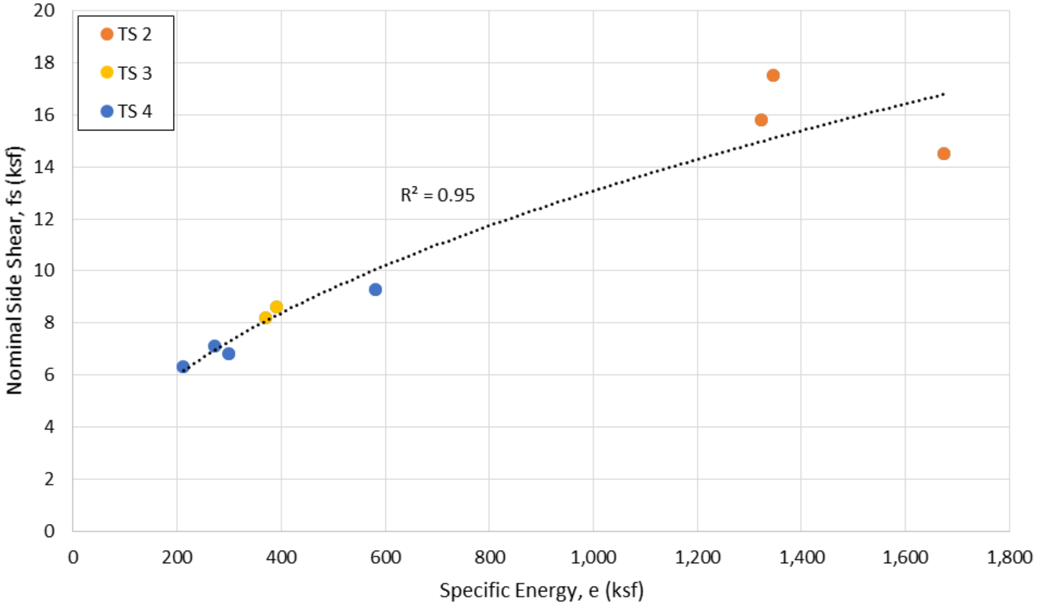
Mounting Components into Electrical Unit



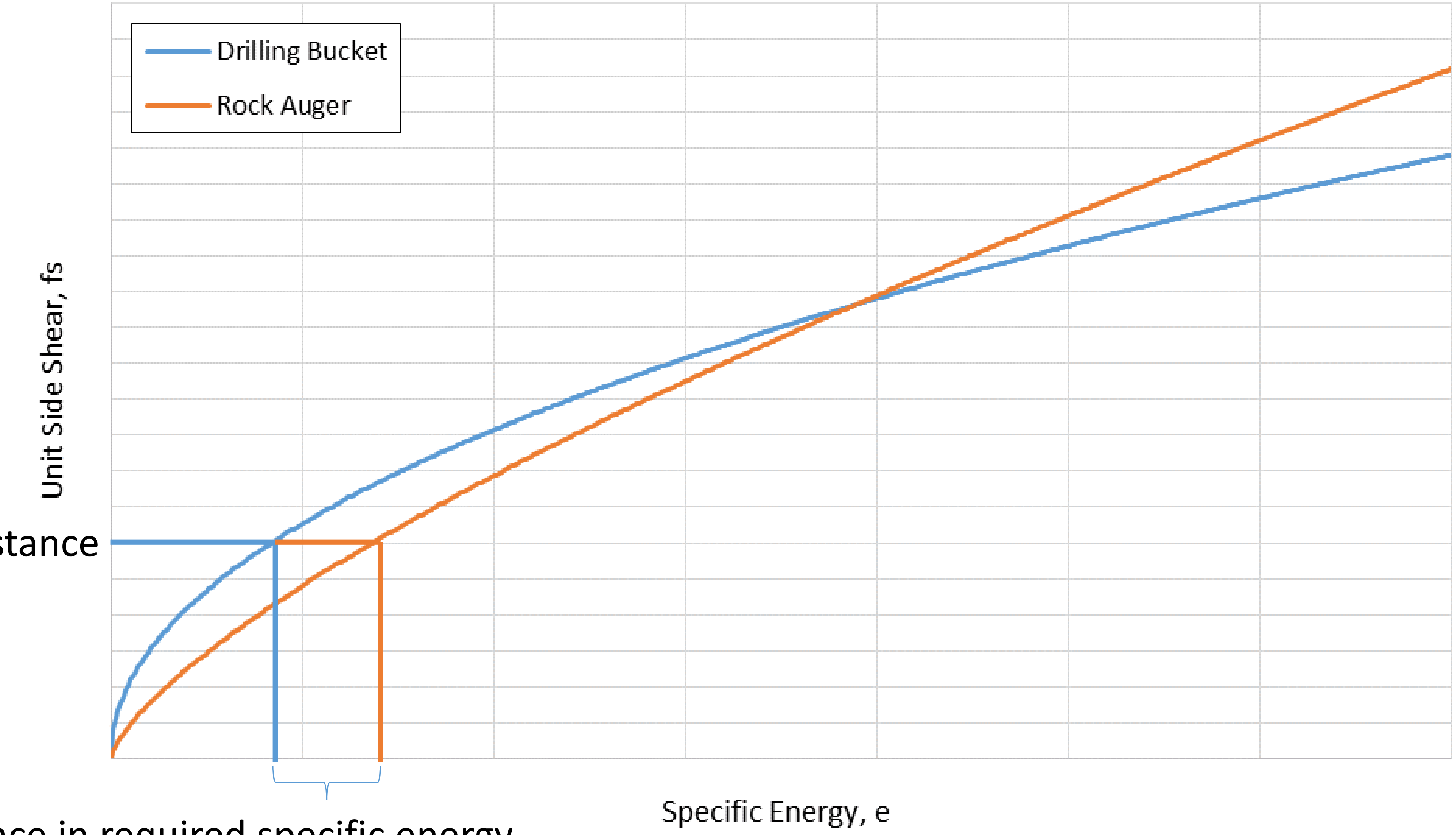
Monitoring from a Safe Distance

e vs. Side Shear – Rock Drilling Bucket

- Monitored 3 test shafts
  - O-cell testing
- The same rock drilling bucket was used for all shafts
  - Entire drilling (soil and rock)
- Good correlation was developed for the unique drilling tool in layers of rock
- Developed relationship could be used to quantify the quality of production shaft rock sockets



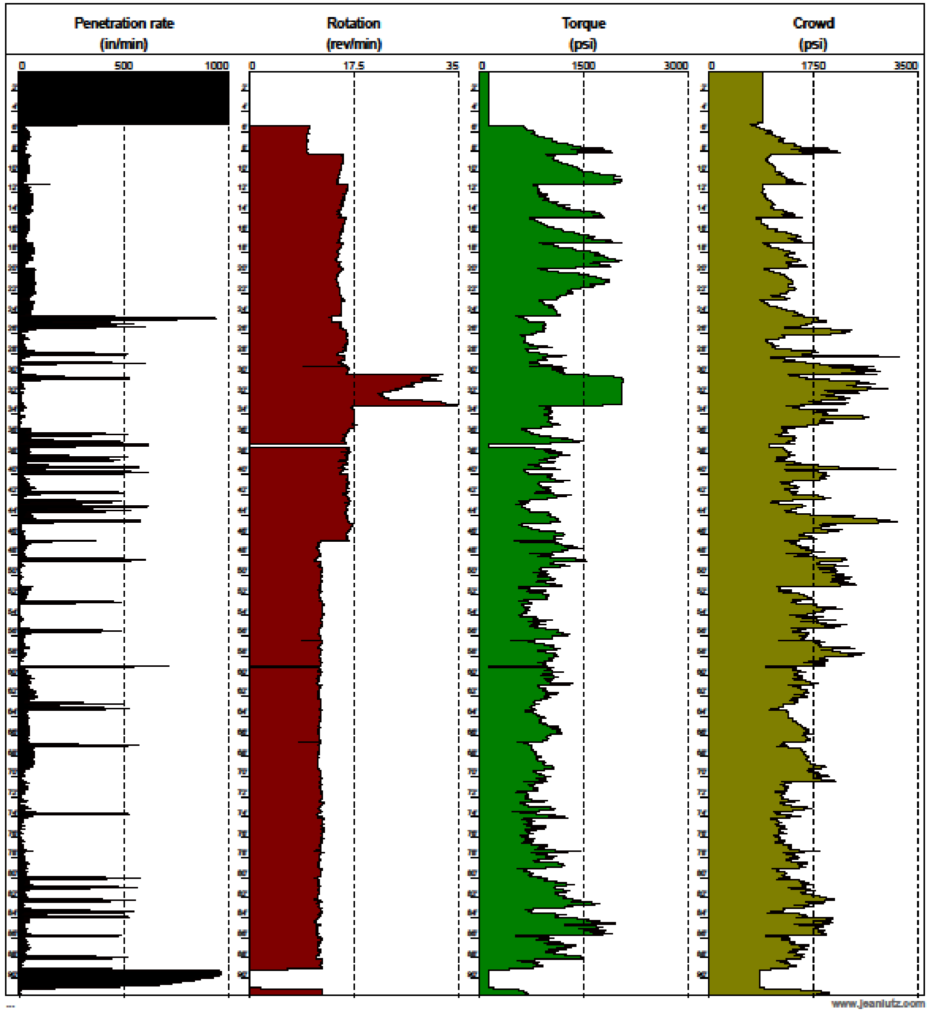
Bit Selection from Specific Energy

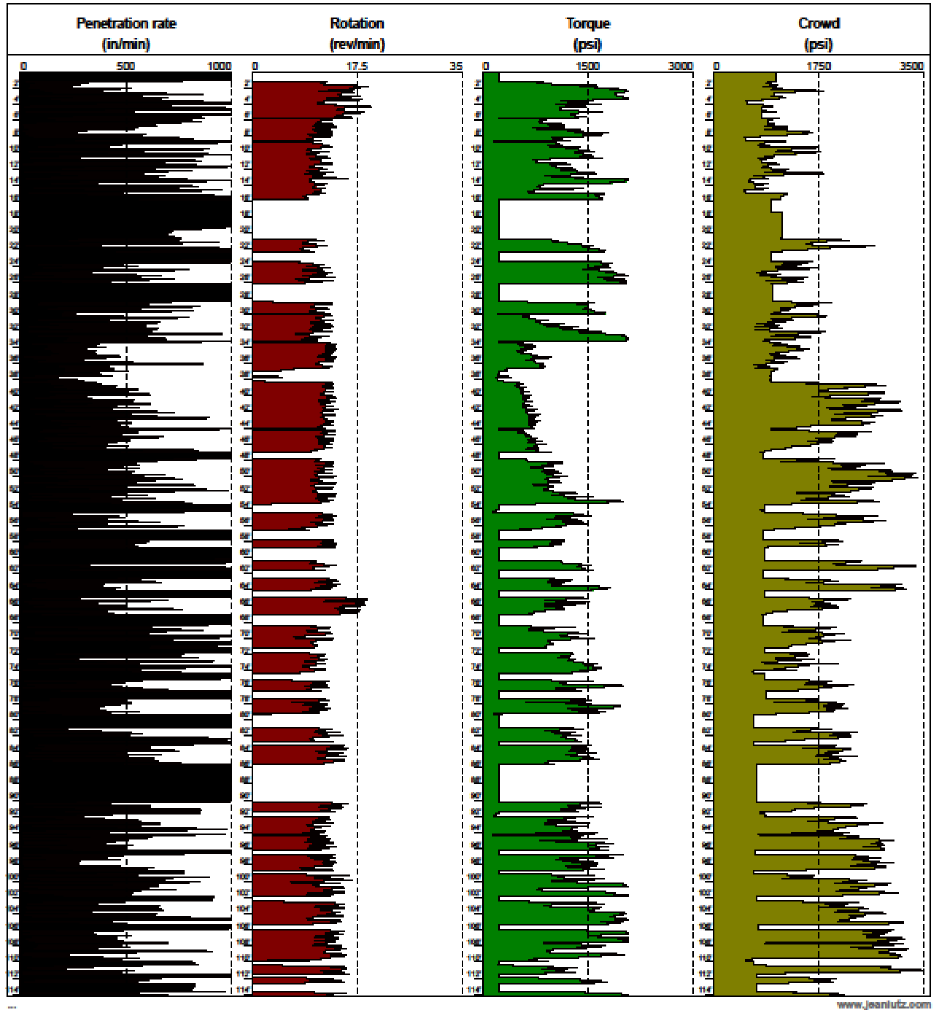


Shaft Resistance

Difference in required specific energy
(operational limits, tool selection, etc.)

Identifying Problematic Drilling Methods





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Questions?

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