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
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)

Additional Drilling Parameters and Terms

• $Q$ = 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, $F \approx 1,000 - 1,200$ lbf
  • Varied Flow rate, $Q$ and RPM, $N$
  • $u/N \approx 0.020$ 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
Initial rotational speeds came from using 3rd gear with ½ to ¾ throttle – recommended by surveyed drillers. 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

$F_{\text{max}} \text{ (lbf)} = 62.5 \text{ (lbf/GPM)} \times Q \text{ (GPM)} = \text{Limiting Crowd (lbf)}$

Normalized Crowd Values

$y = 68.45x$
$R^2 = 0.94$

$y = 62.59x$
$R^2 = 0.94$
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 ($F_{\text{max}}$)
- 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

<table>
<thead>
<tr>
<th>Test Matrix 1</th>
<th>N (RPM)</th>
<th>$(u/N)_{\text{min}}$ (in/rev)</th>
<th>$u$ (in/min)</th>
<th>Q (GPM)</th>
<th>$F_{\text{max}}$ (Ibf)</th>
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<tr>
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<td>0.02</td>
<td>2.2</td>
<td>6.5</td>
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<td></td>
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<td>0.02</td>
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<td>406</td>
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<tr>
<td>120</td>
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<td>7.5</td>
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<table>
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<th>$(u/N)_{\text{min}}$ (in/rev)</th>
<th>$u$ (in/min)</th>
<th>Q (GPM)</th>
<th>$F_{\text{max}}$ (Ibf)</th>
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<td>130</td>
<td>0.02</td>
<td>2.6</td>
<td>8.5</td>
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<td>120</td>
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<td>2.4</td>
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</table>

<table>
<thead>
<tr>
<th>Test Matrix 3</th>
<th>N (RPM)</th>
<th>$(u/N)_{\text{min}}$ (in/rev)</th>
<th>$u$ (in/min)</th>
<th>Q (GPM)</th>
<th>$F_{\text{max}}$ (Ibf)</th>
</tr>
</thead>
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<td>2.2</td>
<td>9.5</td>
<td>594</td>
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<td>2.4</td>
<td>9.5</td>
<td>594</td>
<td></td>
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<tr>
<td>130</td>
<td>0.02</td>
<td>2.6</td>
<td>9.5</td>
<td>594</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>0.02</td>
<td>2.4</td>
<td>7.5</td>
<td>469</td>
<td></td>
</tr>
</tbody>
</table>
Additional Correlations

**Torque vs. Force Relationship**

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

- Equation: $y = -0.0006x + 1.2803x$
- $R^2 = 0.96$

**Specific Energy vs. T/u Relationship**

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

- Equation: $y = 114.6x$
- $R^2 = 0.99$
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 $\approx$ 100%
  - RQD $\approx$ 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)

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

*Efficient region can be increased by increasing Flow Rate

(Chen et al. 2016)
Effects of Overcrowding the Drill Bit

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

Drilling outside the operational limits. Fractured rock from overcrowding the drill bit.
UCS ≈ 700 psi
REC = 30%
RQD = 0%
Effects of Overcrowding the Drill Bit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Operational Limits</th>
<th>Overcrowd - Stall</th>
<th>Overcrowd - Manual</th>
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<tr>
<td></td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
</tr>
<tr>
<td>u (in/min)</td>
<td>6.9</td>
<td>5.7</td>
<td>10.1</td>
</tr>
<tr>
<td>N (rpm)</td>
<td>120</td>
<td>116</td>
<td>115</td>
</tr>
<tr>
<td>u/N (in/rev)</td>
<td>0.058</td>
<td>0.049</td>
<td>0.088</td>
</tr>
<tr>
<td>T (in-lbs)</td>
<td>280</td>
<td>1,321</td>
<td>2,858</td>
</tr>
<tr>
<td>F (lbf)</td>
<td>223</td>
<td>1,296</td>
<td>2,752</td>
</tr>
<tr>
<td>Q (gpm)</td>
<td>8.0</td>
<td>7.6</td>
<td>7.4</td>
</tr>
<tr>
<td>e (psi)</td>
<td>4,685</td>
<td>29,928</td>
<td>34,128</td>
</tr>
<tr>
<td>MWD qu (psi)</td>
<td>452</td>
<td>2,888</td>
<td>3,293</td>
</tr>
<tr>
<td>Core qu (psi)</td>
<td>436</td>
<td>436</td>
<td>436</td>
</tr>
</tbody>
</table>
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

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

• 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

<table>
<thead>
<tr>
<th>Stats</th>
<th>( u ) (in/min)</th>
<th>( N ) (rpm)</th>
<th>( u/N ) (in/rev)</th>
<th>( T ) (in-lbs)</th>
<th>( T/u ) (lbf-min)</th>
<th>( 2\pi NT/Au ) (psi)</th>
<th>( F ) (lbf)</th>
<th>( F/A ) (psi)</th>
<th>( Q ) (gpm)</th>
<th>( e ) (psi)</th>
</tr>
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<tbody>
<tr>
<td>Average</td>
<td>1.28</td>
<td>125.8</td>
<td>0.010</td>
<td>1,221.8</td>
<td>960.8</td>
<td>116,478.9</td>
<td>1,051.3</td>
<td>161.2</td>
<td>5.2</td>
<td>116,640.1</td>
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<tr>
<td>Std. Dev.</td>
<td>0.14</td>
<td>0.3</td>
<td>0.001</td>
<td>44.4</td>
<td>82.7</td>
<td>10,256.4</td>
<td>76.0</td>
<td>11.7</td>
<td>0.6</td>
<td>10,246.5</td>
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<tr>
<td>CV</td>
<td>0.110</td>
<td>0.002</td>
<td>0.036</td>
<td>0.086</td>
<td>0.088</td>
<td>0.072</td>
<td>0.072</td>
<td>0.108</td>
<td>0.088</td>
<td>0.088</td>
</tr>
</tbody>
</table>
Assessing Bit Wear with Specific Energy

- Continuously tracked the amount of energy experienced by the same drilling tool
- Track through specific energy capacity, $P_e$
  - $P_e = e \times \pi \times d \times L$
  - 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, $P_e$

<table>
<thead>
<tr>
<th>Round</th>
<th>Specific Energy (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round 1</td>
<td>11,676,068</td>
</tr>
<tr>
<td>Round 2</td>
<td>11,689,538</td>
</tr>
<tr>
<td>Round 3</td>
<td>12,495,451</td>
</tr>
</tbody>
</table>
• 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
  • $Q > 16 \text{ GPM}$ was optimum

Why would flow rate have such a great effect on tri-cone roller bit drilling?
## Effects of Breaking Particles to Smaller Sizes

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Percent Retained</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>11.3 GPM</td>
</tr>
<tr>
<td># 4</td>
<td>0.1</td>
</tr>
<tr>
<td># 8</td>
<td>0.2</td>
</tr>
<tr>
<td># 16</td>
<td>1.1</td>
</tr>
<tr>
<td># 30</td>
<td>14.6</td>
</tr>
<tr>
<td># 50</td>
<td>61.3</td>
</tr>
<tr>
<td>#100</td>
<td>87.9</td>
</tr>
<tr>
<td>#200</td>
<td>97.6</td>
</tr>
<tr>
<td>Fineness Modulus</td>
<td>2.63</td>
</tr>
<tr>
<td>Specific Energy (psi)</td>
<td>8,878</td>
</tr>
<tr>
<td>Penetration Rate (in/min)</td>
<td>3.82</td>
</tr>
</tbody>
</table>

*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.

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

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

\[
y = 0.0066x^2 + 13.681x
\]

\[R^2 = 0.8529\]

(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,

$y = e \text{ (psi)}$

$x = q_u \text{ (psi)}$

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 $c$:

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

<table>
<thead>
<tr>
<th></th>
<th>Core Data</th>
<th>Monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average $q_u$ (tsf)</td>
<td>51.4</td>
<td>56.8</td>
</tr>
<tr>
<td>Std. Dev. $q_u$ (tsf)</td>
<td>68.5</td>
<td>70.7</td>
</tr>
<tr>
<td>CV</td>
<td>1.33</td>
<td>1.25</td>
</tr>
<tr>
<td>Median</td>
<td>7.9</td>
<td>32.5</td>
</tr>
<tr>
<td>Max</td>
<td>253.1</td>
<td>542.9</td>
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<tr>
<td>Min</td>
<td>0.3</td>
<td>0.6</td>
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<tr>
<td>Count</td>
<td>37</td>
<td>415</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>Core Data</th>
<th>Monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stats</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>20.5</td>
<td>14.1</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>9.9</td>
<td>12.7</td>
</tr>
<tr>
<td>CV</td>
<td>0.481</td>
<td>0.897</td>
</tr>
<tr>
<td>Median</td>
<td>20.4</td>
<td>8.6</td>
</tr>
<tr>
<td>Max</td>
<td>39.1</td>
<td>62.5</td>
</tr>
<tr>
<td>Min</td>
<td>5.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Count</td>
<td>19</td>
<td>430</td>
</tr>
</tbody>
</table>

(Much larger MWD sampled population)

(Rodgers et al. 2018B)
# Leading Skin Friction Equations

<table>
<thead>
<tr>
<th>Method</th>
<th>Author</th>
<th>Design Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>McVay et al.(^6)</td>
<td>(f_s = \frac{1}{2} \times \sqrt{q_u} \times \sqrt{q_t})</td>
</tr>
<tr>
<td>2</td>
<td>Reese and O’Neill(^7,8)</td>
<td>(f_s = 0.15 \times q_u) (tsf)</td>
</tr>
<tr>
<td>3</td>
<td>Horvath and Kenney(^8)</td>
<td>(f_s = 0.67 \times \sqrt{q_u}) (tsf)</td>
</tr>
<tr>
<td>4</td>
<td>Williams et al.(^9)</td>
<td>(f_s = 1.842 \times q_u^{0.367}) (tsf)</td>
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<tr>
<td>5</td>
<td>Reynolds and Kaderabek(^10)</td>
<td>(f_s = 0.3 \times q_u) (tsf)</td>
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<tr>
<td>6</td>
<td>Gupton and Logan(^11)</td>
<td>(f_s = 0.2 \times q_u) (tsf)</td>
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<tr>
<td>7</td>
<td>Carter and Kulhawy(^12)</td>
<td>(f_s = 0.63 \times \sqrt{q_u}) (tsf)</td>
</tr>
<tr>
<td>8</td>
<td>Ramos et al.(^13)</td>
<td>(f_s = 0.5 \times q_u) (&lt; 36 ksf) (f_s = 0.12 \times q_u) (&gt; 36 ksf)</td>
</tr>
<tr>
<td>9</td>
<td>Rowe and Armitage(^14)</td>
<td>(f_s = 1.45 \times \sqrt{q_u}) (tsf) clean sockets</td>
</tr>
<tr>
<td>10</td>
<td>Rowe and Armitage(^14)</td>
<td>(f_s = 1.94 \times \sqrt{q_u}) (tsf) rough sockets</td>
</tr>
</tbody>
</table>
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 Liebherr BAT 410 drill rig
  • First monitored Liebherr 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
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

Difference in required specific energy (operational limits, tool selection, etc.)
Identifying Problematic Drilling Methods
References

Questions?