Drilled Shaft Resistance Based on Diameter, Torque and Crowd
(Drilling Resistance vs. Rock Strength)
Phase II

BDV31-977-20

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FDOT Geotechnical Research in Progress Final Report
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Topics Covered

- Introduction
- Background
- Objectives
- Project Tasks
  - Tasks 1 - 5
  - Phase I industry survey and results
  - Monitoring equipment and installation
- Summary of research conclusions
- Recommendations

Introduction

- The use of drilled shafts has increased over the past 20 years
- Easy construction in cohesive materials, even rock
- Possible to develop extremely high axial resistance
- Small footprint for single shaft foundations
- Low noise and vibration construction
- Can penetrate below the scour zone

Introduction

Drilled Shaft Limitations:

- No direct measurement of axial resistance during installation as with pile driving
- Generally leads to multiple load tests
  - Challenging and expensive
- Structural integrity requires careful construction, to provide QA and QC
- Non redundant shafts require coring in footprint of every shaft during construction
- Requires thorough site investigation
  - Florida has a high degree of site variability
 - Evident from the spatial profile
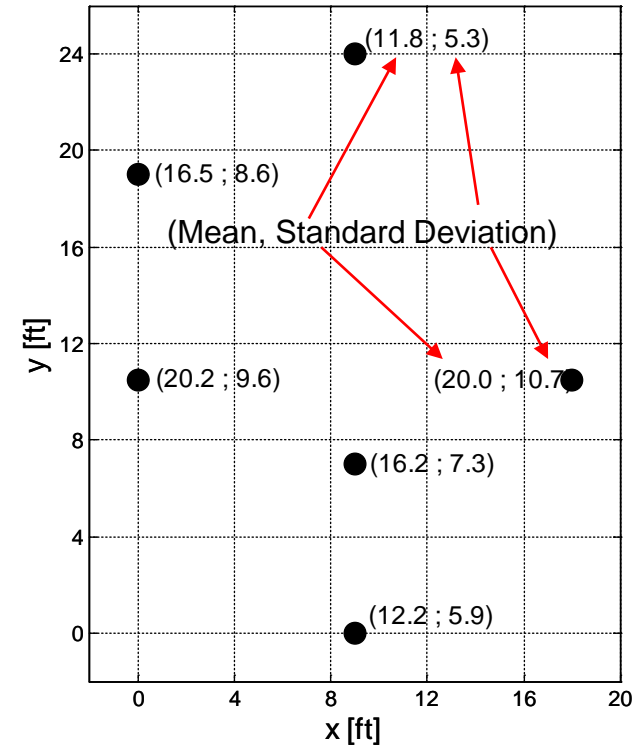
Spatial profile of boring rock strength at 17th Street Bridge Fort Lauderdale

How Do We Resolve These Limitations?

- Develop a method to measure the strength of rock sockets during the construction process, i.e., during drilling
  - Similar to driven piles
  - Provides QA and QC for every drilled shaft installed on a site
    - Alleviates spatial uncertainties
    - Improves the reliability of the design
- Three tasks needed to be competed
  1. Develop relationships for rock strength and drilling parameters in a laboratory drilling environment
  2. Monitor the drilling process in the field using the same drilling parameters recorded from the drill rig
  3. Validate the monitored rock strength estimates using both core testing and load testing as the basis for comparison

Background

- There is great interest in measuring while drilling, MWD, practices
- Many methods in the "Energy Resource" fields have been developed to measure rock strength
  - Most methods are not compatible with drilled shaft installations
    - Bit specific coefficients
    - Mud viscosities and densities
- Karasawa et al.[1,2] and Teale[3] both developed correlations with rock strength using only five drilling parameters
  - Torque, T
  - Crowd or axial force, F
  - Penetration rate, u
  - Rotational speed, N
  - Bit diameter, d

(Karasawa et al.[1])
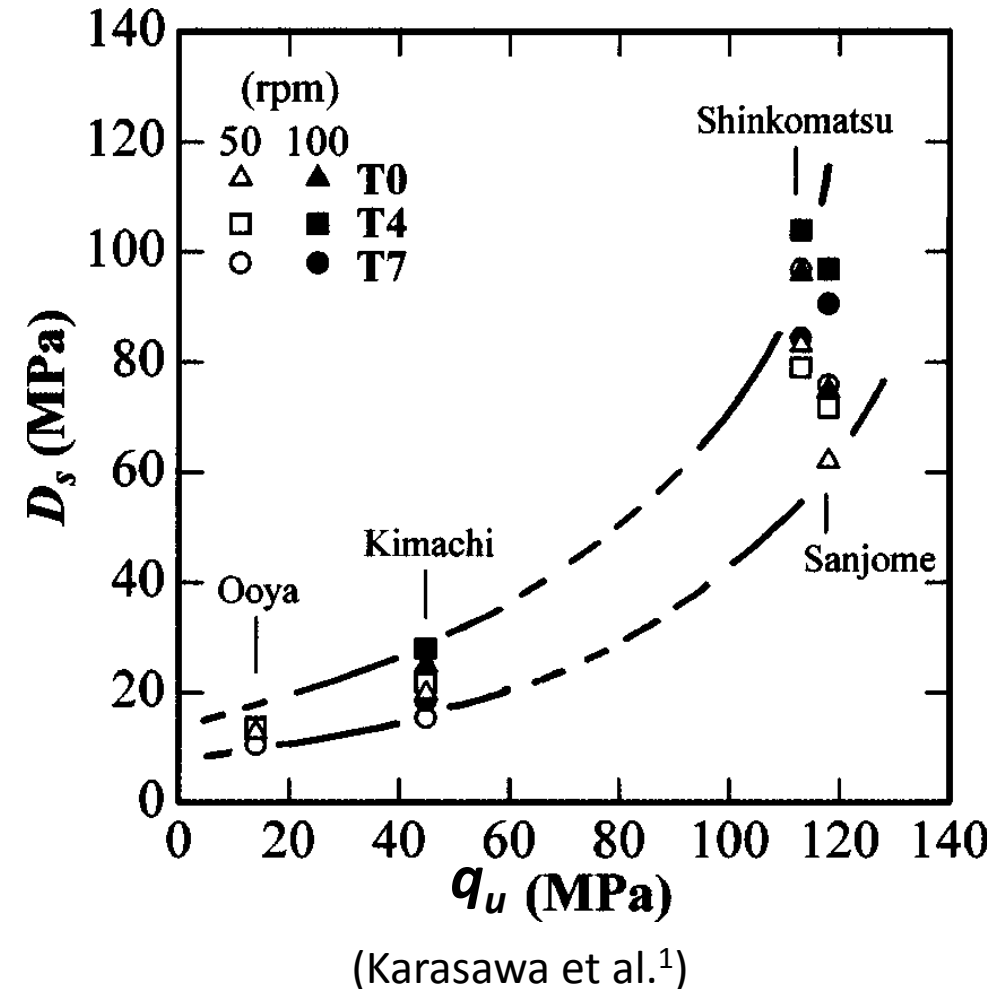
Project Objective

- Develop the first method to measure rock strength in real time during drilled shaft installations
  - Provide a means to quantify the quality and length of rock sockets
  - Ensure the as-built foundation meets or exceeds the engineering design
  - Provide quality assurance to the drilling contractor and foundation engineer
- Take the first steps towards eliminating spatial variability concerns
  - Ultimately leads to increased resistance factors used in design
  - Provides more efficient and cost effective construction practices
    - Reducing the time of completion
    - Reduction in cost per shaft based on reduced uncertainty

Project Tasks

- Task 1 - Continuation of Laboratory Measurements of Drilling parameters on Synthetic limestone.
- Task 2 - Development of Rock Strength from Drilling Parameters
- Task 3 - Preliminary Monitoring of Field Drilling (Pilot Projects)
- Task 4 - Full Scale Drilled Shaft Installation with Capacity Estimated from Drilling Parameters Followed by Static Load Test
- Task 5 – Final Report

Task 1 - Laboratory Drilling

- Developed homogenous synthetic limestone in large scale blocks for drilling
  - Natural Florida limestone has too much variability in strength
  - Not practical to obtain large blocks of natural limestone
- Developed a method to control the drilling process and monitor each of the drilling parameters
  - Bit diameter is logged
  - Rotational speed and penetration rate are set drilling parameters
  - Torque and crowd are continuously monitored and recorded in real time
- Developed a reliable drilling method that is representative of field drilling
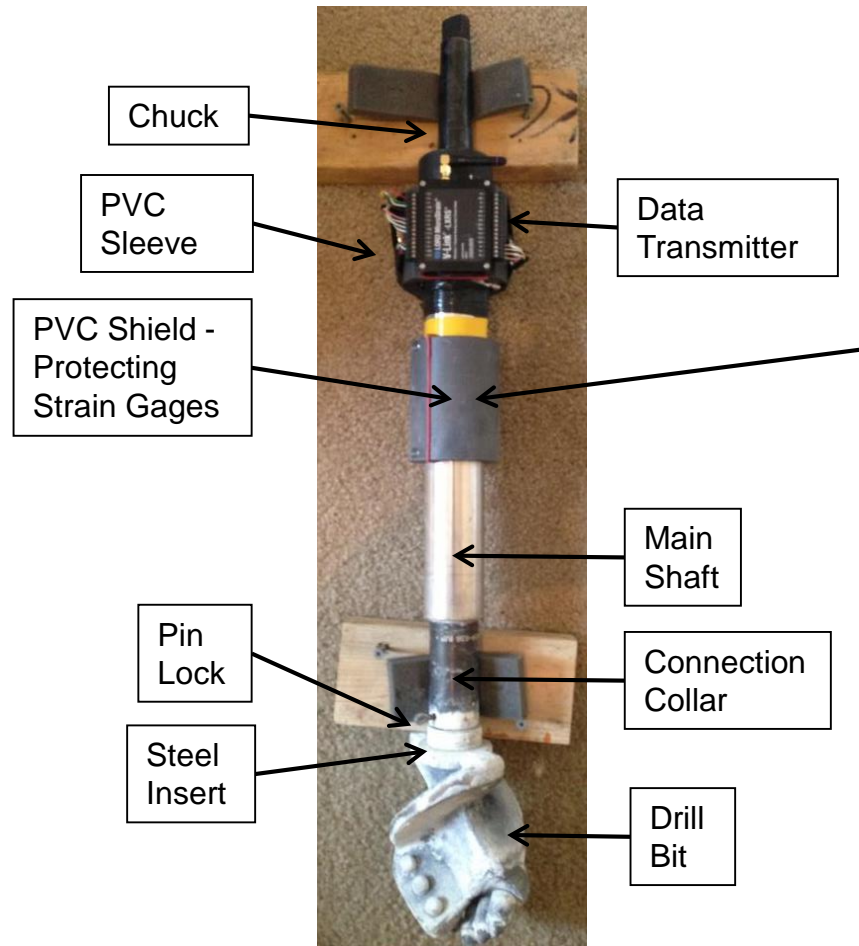 - i.e., wet-hole method

Task 1 - Development of Gatorock

- Synthetic limestone, "Gatorock", used in a number of laboratory experiments
  - Bullock[7], McVay et al.[8], Sheppard et al.[9]
- Simplistic method to model homogenous Florida limestone
  - Controlled compressive strength
    - 10, 20, 40, and 120 tsf
- Created using limestone screenings, cement, and water
- Developed using the guidelines of a CLSM
- Cast into large scale blocks
  - 22.5" x 22.5" x 40"
  - Block strength reference provided using cast cylinders from the same mix
    - Unconfined compression strength
  - Block cores and cast cylinders checked for strength accuracy
    - Block cores generally provided a small increase in strength
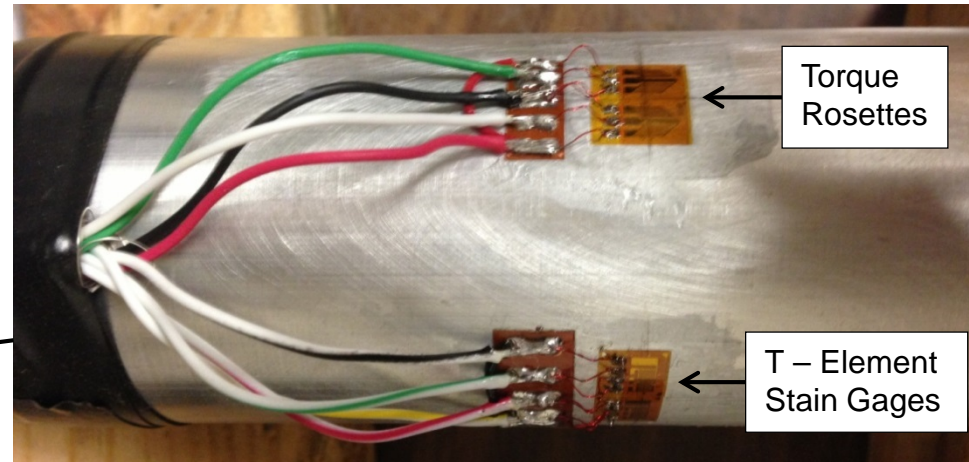   - Conservative approach

Task 1 - Laboratory Drilling Environment

- Laboratory coupler system
  - Measures torque and crowd in real time
  - Setup in full bridge with alternating gauge types every 90 degrees
  - Compensates for bending and temperature effects
- Variable Frequency Drive
  - Controls rotational speed and penetration rate
  - Representative of field drilling
- Wet-hole drilling method
  - Constant circulation of clean water with removal of dirty effluent water
  - Representative of field drilling

Task 1 - Laboratory Coupler System

Chuck

PVC Sleeve

PVC Shield - Protecting Strain Gages

Data Transmitter

Main Shaft

Pin Lock

Connection Collar

Steel Insert

Drill Bit

Strain Gage Instrumentation

Torque Rosettes

T – Element Stain Gages

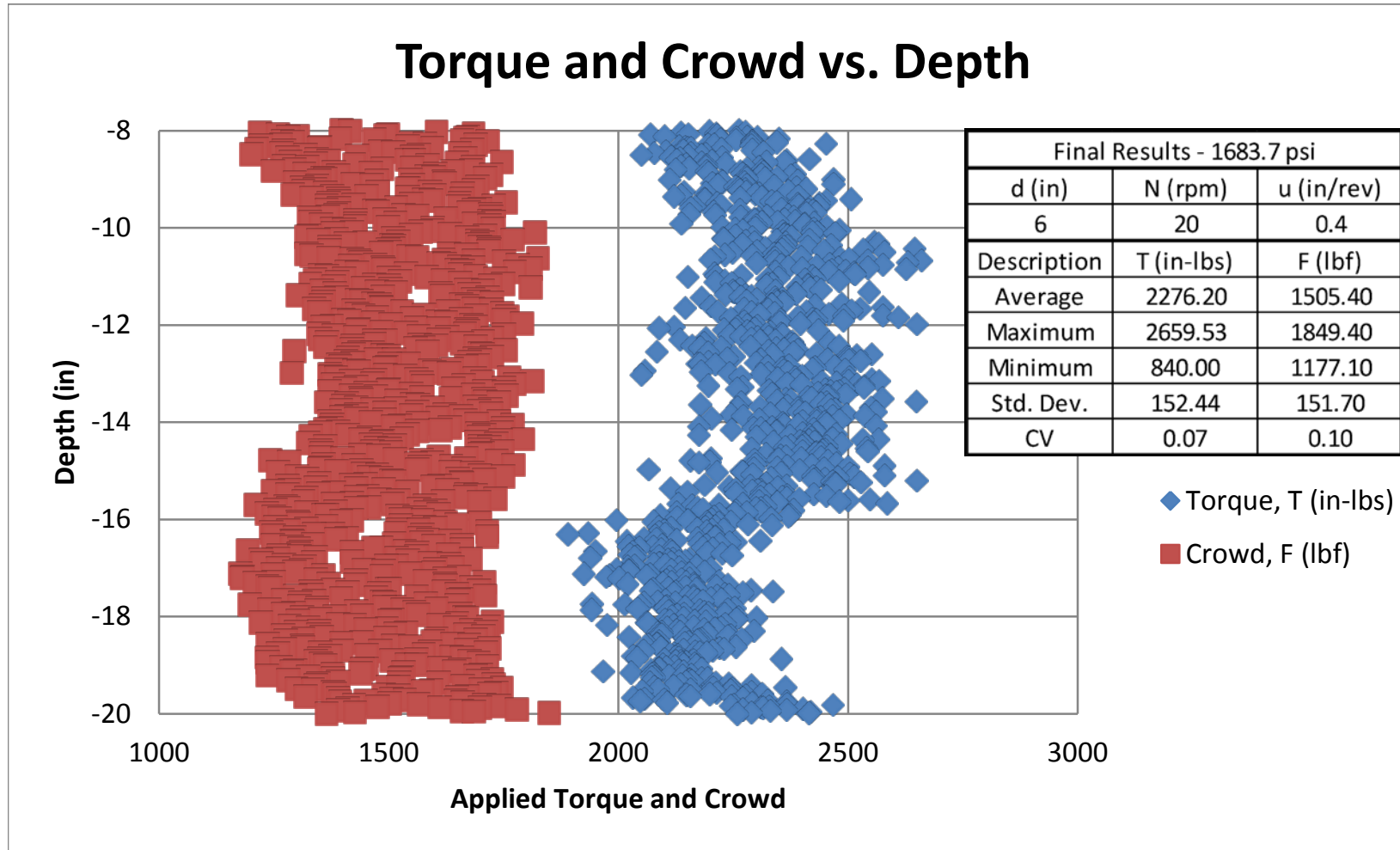Torque Calibration

Crowd Calibration

Task 1 - Laboratory Drilling

- 12 readings are taken per revolution for each gage
  - Average value obtained at each increment of penetration
    - e.g., penetrate 0.008 in/rev
- Readings are then averaged for each gage type per depth increment
  - e.g., readings from both gages for crowd are averaged
  - Compensates for bending
    - One side in compression and one side in tension
- Averages for every depth increment are then combined to produce a final average for torque and crowd for the entire drilling

Clean influent water

Dirty effluent water

Task 1 - Single Laboratory Drilling Result

Torque and Crowd vs. Depth

Final Results - 1683.7 psi		
d (in)	N (rpm)	u (in/rev)
6	20	0.4
Description	T (in-lbs)	F (lbf)
Average	2276.20	1505.40
Maximum	2659.53	1849.40
Minimum	840.00	1177.10
Std. Dev.	152.44	151.70
CV	0.07	0.10

◆ Torque, T (in-lbs)

■ Crowd, F (lbf)

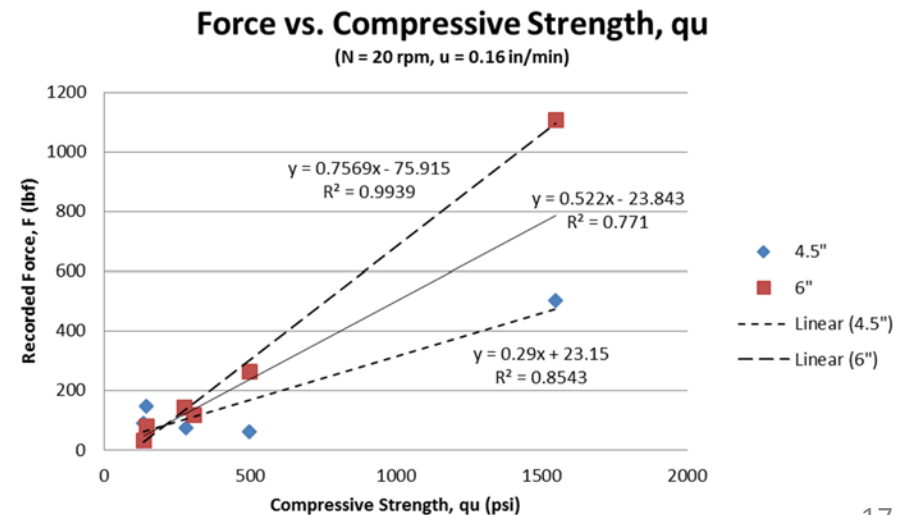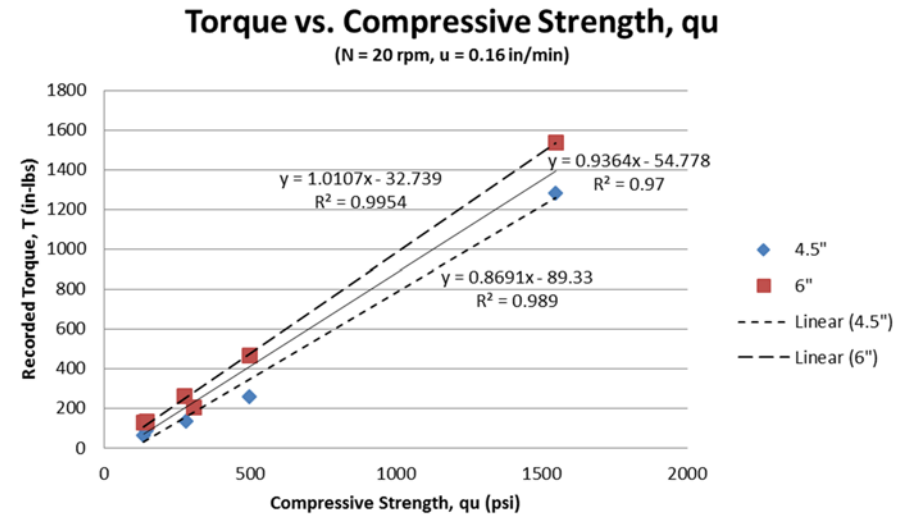# Task 1 - Laboratory Drilling Breakdown

- 81 drilling data points produced in total
- 81 compressive strength data points
  - 43 used the 4.5" bit
  - 38 used the 6" bit
- 64 tensile strength data points
  - 29 used the 4.5" bit
  - 35 used the 6" bit

Task 2 - Laboratory Data Analysis

- q_t vs. q_u
- Effects of bit diameter
- Torque and crowd relationship
- Torque-rotational speed-penetration rate relationship
- Torque and crowd vs. u/N ratios (Karasawa)
- Torque and crowd vs. compressive and split tension strength
- Determined the most reliable drilling parameters
- Compared developed drilling methods
  - Teale and Karasawa
  - Bit diameter, rotational speed, and penetration rate groupings
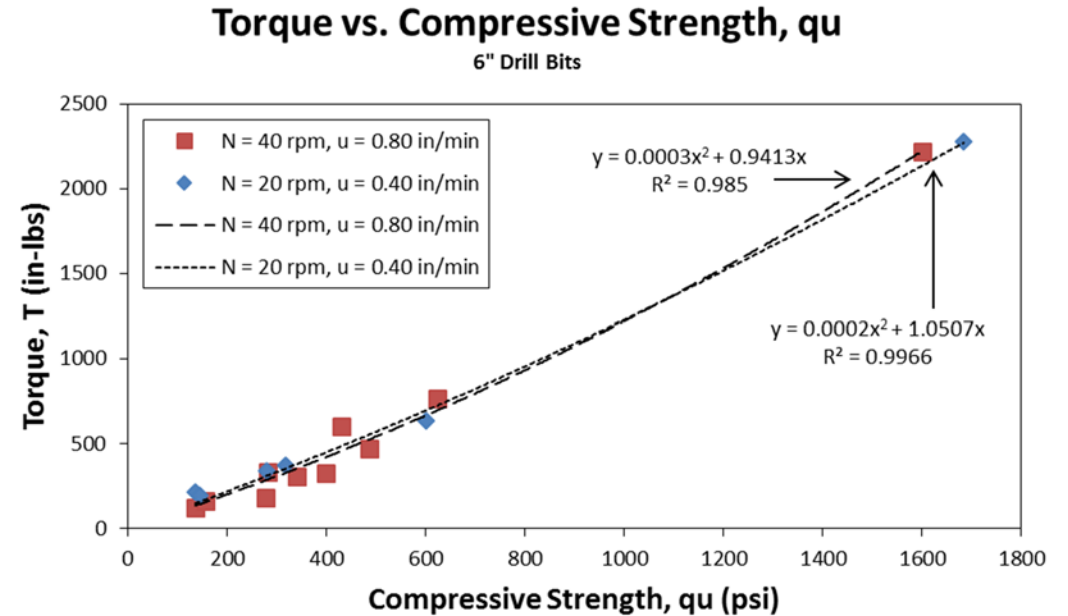 - All drillings parameters

Task 2 - Effects of Bit Diameter

- How does bit diameter affect torque and crowd?
  - Upscaling was a major concern
  - Factor of 10
- Crowd was more affected by changes in bit diameter
- Poorly defined by a single regression line
- Deviation between bit diameter regression lines as strength increased
- Torque was well defined using a single regression line
- Displayed little deviation between bit diameter as strength increased
- Indicated torque is less affected by changes in bit diameter

Torque vs. Compressive Strength, qu
(N = 20 rpm, u = 0.16 in/min)

Force vs. Compressive Strength, qu
(N = 20 rpm, u = 0.16 in/min)

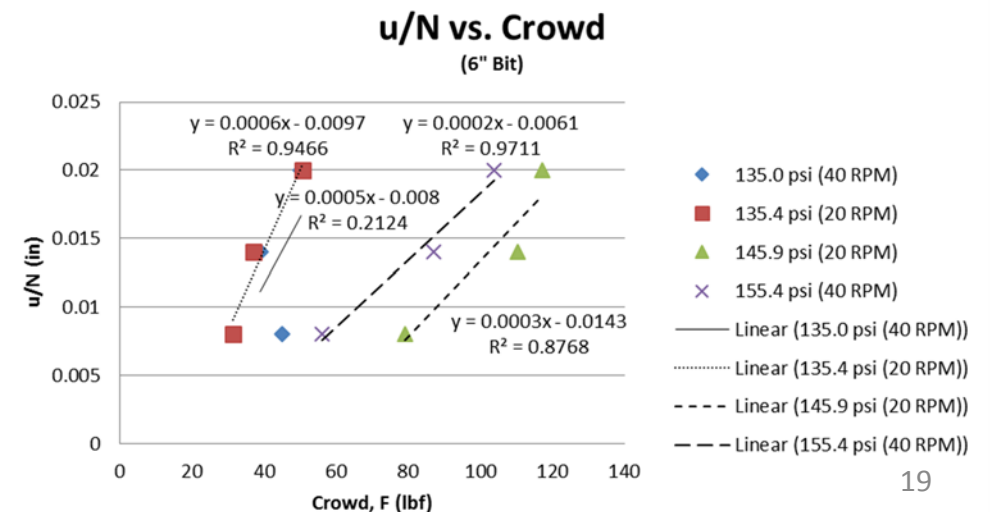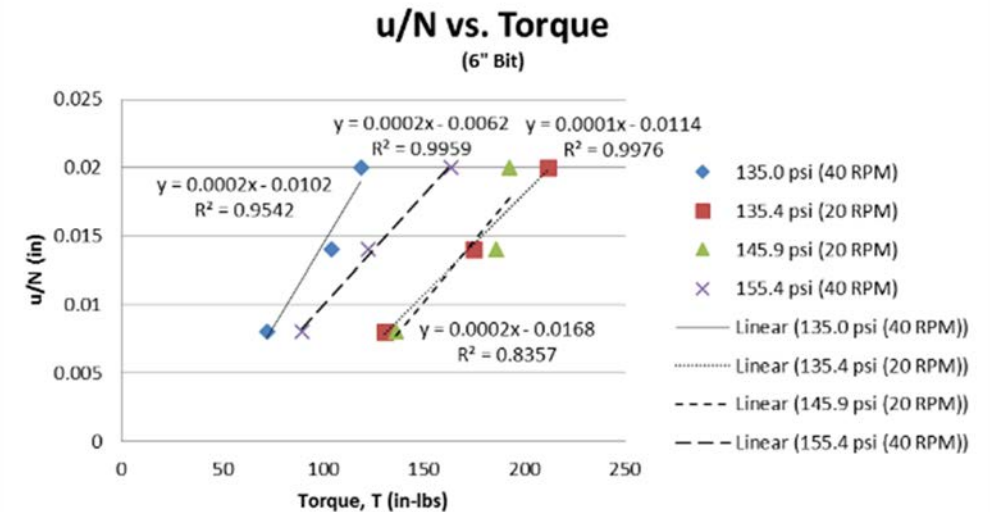# Task 2 - Torque-Rotational Speed-Penetration Rate

- Torque, rotational speed, and penetration rate had a direct relationship
  - Independent of rock strength
- Two groupings created
  - Same bit diameter
  - Different penetration rates
  - Different rotational speeds
- Drilling for the same amount of time
- Volume of excavated material using 20 RPM was half of the volume excavated using 40 RPM
- Both excavations required the same amount of torque

Torque vs. Compressive Strength, qu
6" Drill Bits

Legend:
- N = 40 rpm, u = 0.80 in/min
- N = 20 rpm, u = 0.40 in/min
- N = 40 rpm, u = 0.80 in/min
- N = 20 rpm, u = 0.40 in/min

$y = 0.0003x^2 + 0.9413x$
$R^2 = 0.985$

$y = 0.0002x^2 + 1.0507x$
$R^2 = 0.9966$

Y-axis: Torque, T (in-lbs)
X-axis: Compressive Strength, qu (psi)

$$\frac{N_1 T_0}{u_1} = \frac{N_2 T_0}{u_2}$$

Task 2 - u/N Ratio vs. Torque and Crowd

- Similar to Karasawa et al.[1,2]
- Both showed increasing values as u/N ratios increased
  - In agreement with Karasawa
- Lower rotational speeds provide larger torques
  - In agreement with previous slide
- Torque displayed a good increasing trend as rock strength increased
- Crowd showed more variability with respect to rock strength increase
- Crowd showed little to no correlation with rotational speed

Task 2 - Reliability of Torque and Crowd Conclusions

Torque

- Less dependent on bit diameter

- Direct relationship with rotational speed and penetration rate

- Good trend with rock strength
  - Independent of all other drilling parameters

Crowd

- More dependent on bit diameter

- Poor trend with rotational speed

- Good trend with penetration rate

- A trend with rock strength
  - Independent of all other drilling parameters

Task 2 - Desirable Drilling Equation

- Place more emphasis on drilling parameters that show good correlation with one another and rock strength
  - Torque
  - Rotational speed
  - Penetration rate

- Place less emphasis on crowd
  - More dependent on bit diameter
  - Less correlated to rotational speed and rock strength

- Only use bit diameter to define the area of the excavation
  - Resolves upscaling issues when transitioning to field drilling

Task 2 - Karasawa's Drillability Strength

- Developed through trial and error using 2 previously developed drilling relationships
  - Wolcott and Bordelon[5]
  - Teale[3]
- Groups all drilling parameters together
  - Does not limit the influence of crowd
- Places a large amount of emphasis on bit diameter
  - Bit diameter is cubed
  - Increases bit diameter dependency

$$D_s = \frac{64NT^2}{Fud^3}$$

- Wolcott and Bordelon[5] in combination with Teale[3]

$$D_s = \frac{S_e{}^2}{I_s}$$

Task 2 - Teale's Specific Energy

- Developed for rotary non-percussive drilling
  - Drilled shafts installations
- Separates crowd and torque components
  - Limits the unreliability of crowd
- Groups drilling parameters show good correlation with one another together
  - T, u, and N
- Only uses bit diameter to define the cross-sectional area of the excavation
  - Resolves upscaling issues

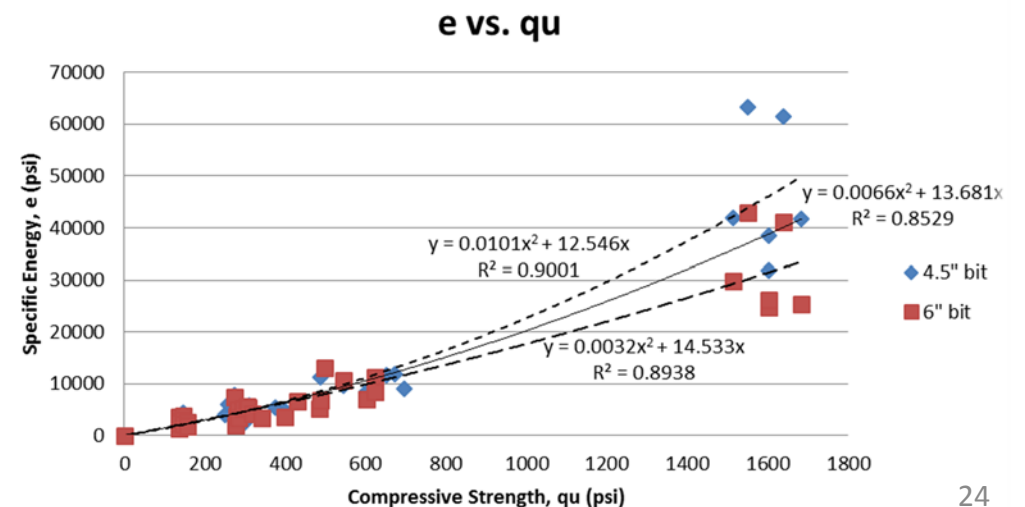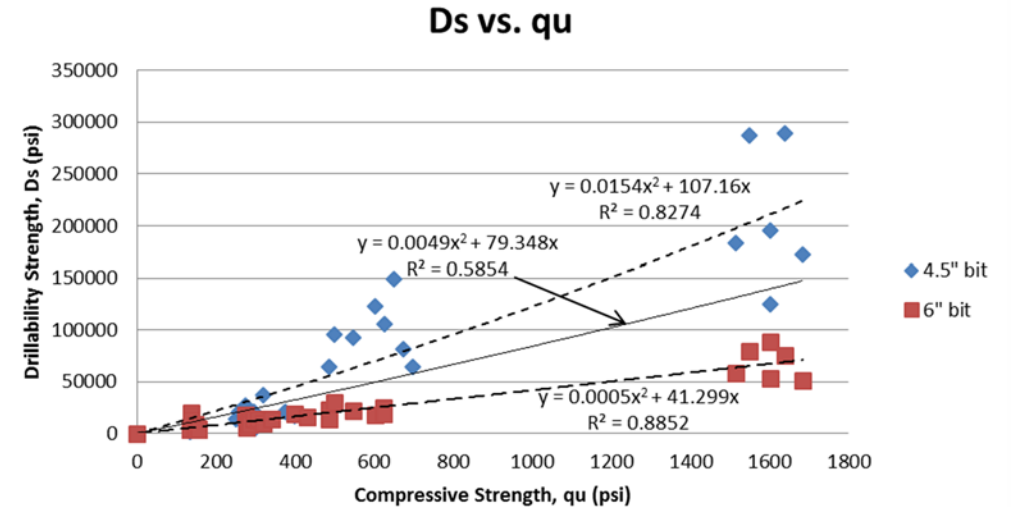$$e = \frac{F}{A} + \left(\frac{2\pi}{A}\right)\left(\frac{NT}{u}\right)$$

- Thrust Component

$$e_t = \left(\frac{F}{A}\right)$$

- Rotary Component

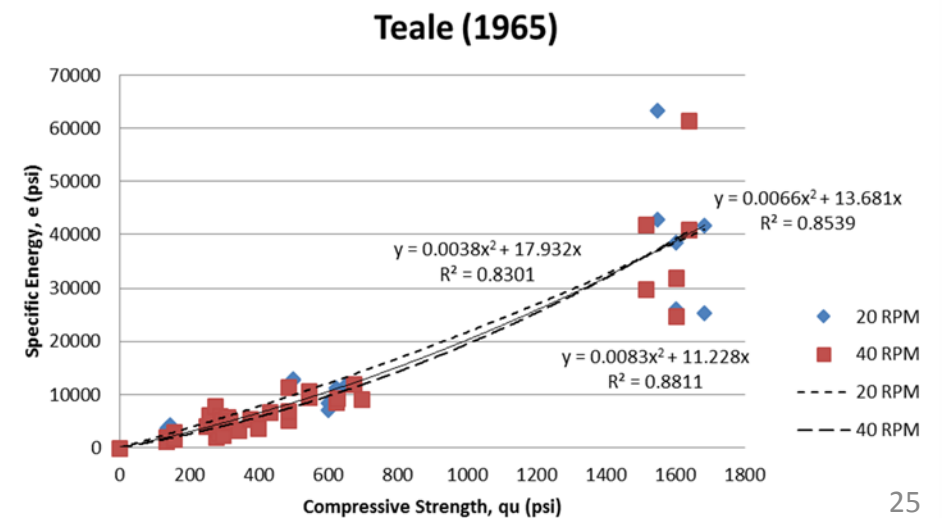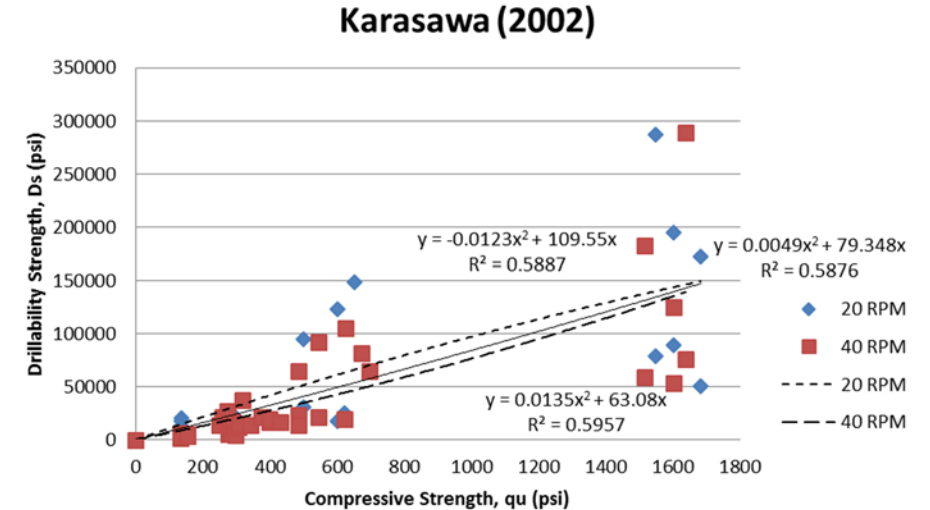$$e_r = \left(\frac{2\pi}{A}\right)\left(\frac{NT}{u}\right)$$

Task 2 - Bit Diameter Groupings

- Drilling results using each method are grouped by bit diameter
- Analyzed each grouping individually
- Analyzed each method as whole
- Teale's method was better
  - Individual bit diameters
  - Both bit diameters as a whole
- $R^2 = 0.8529 > 0.5854$

Ds vs. qu

$y = 0.0154x^2 + 107.16x$
$R^2 = 0.8274$

$y = 0.0049x^2 + 79.348x$
$R^2 = 0.5854$

$y = 0.0005x^2 + 41.299x$
$R^2 = 0.8852$

- ◆ 4.5" bit
- ■ 6" bit

Drillability Strength, Ds (psi) vs. Compressive Strength, qu (psi)

e vs. qu

$y = 0.0066x^2 + 13.681x$
$R^2 = 0.8529$

$y = 0.0101x^2 + 12.546x$
$R^2 = 0.9001$

$y = 0.0032x^2 + 14.533x$
$R^2 = 0.8938$

- ◆ 4.5" bit
- ■ 6" bit

Specific Energy, e (psi) vs. Compressive Strength, qu (psi)

Task 2 - Rotational Speed Groupings

- Drilling results using each method are grouped by rotational speed
- Analyzed each grouping individually
- Analyzed each method as whole
- Teale's method was better
  - Individual rotational speeds
  - Both groupings as a whole
- $R^2 = 0.8539 > 0.5876$


Karasawa (2002)

Teale (1965)

Task 2 - Penetration Rate Groupings

- Drilling results using each method are grouped by penetration rate
  - Each rotational speed
- Analyzed each grouping individually
- Analyzed each method as whole
  - Each rotational speed
- Teale's method was better
  - Individual penetration rates
  - Groupings as a whole
    - Each rotational speed
- $R^2 = 0.8556 > 0.5922$
  - Average from both rotational speeds

Karasawa - Penetration Rate Groupings (40 RPM)
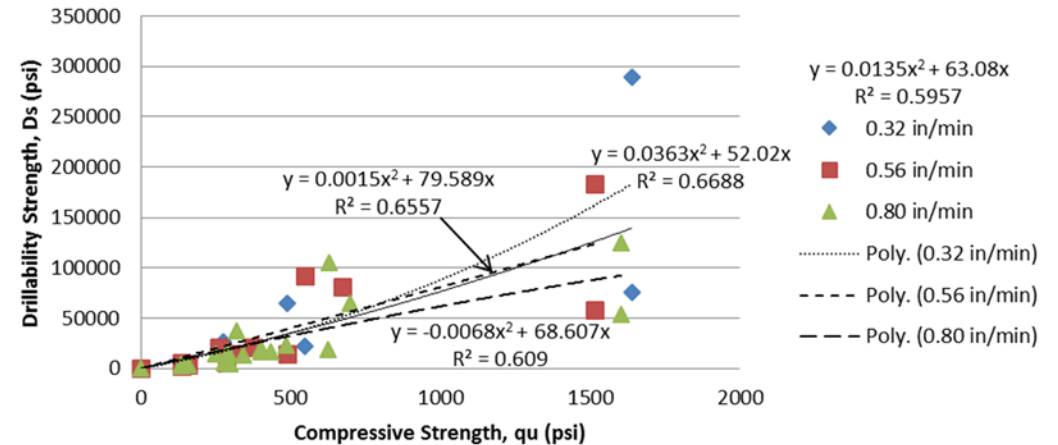
Teale - Penetration Rate Groupings (40 RPM)
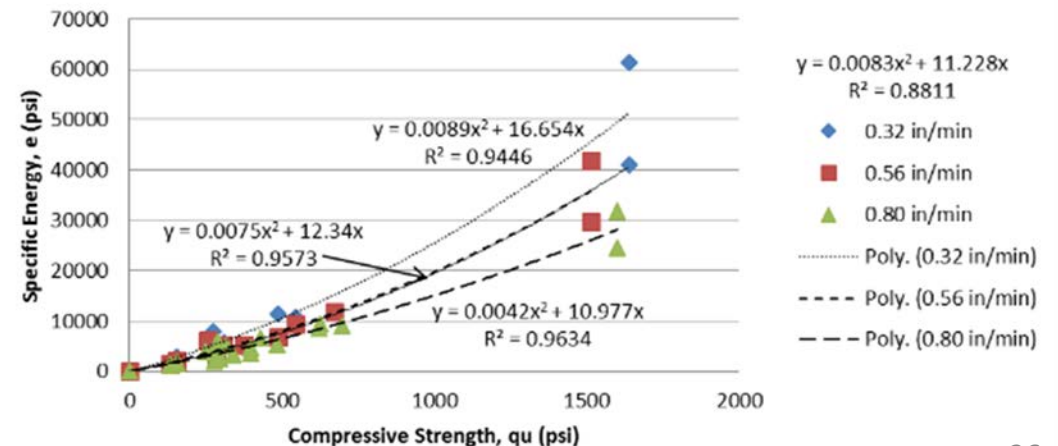
Task 2 - All Drilling Parameters

- Using all drilling data points both methods were compared

- Teale's method consistently outperformed Karasawa's method

- Described more variability
  - Bit diameter
  - Rotational speed
  - Penetration rate

- $R^2 = 0.8529 > 0.5854$

Karasawa - All Drilling Data Points

$y = 0.0049x^2 + 79.348x$
$R^2 = 0.5854$

Teale - All Drilling Data Points

$y = 0.0066x^2 + 13.681x$
$R^2 = 0.8529$
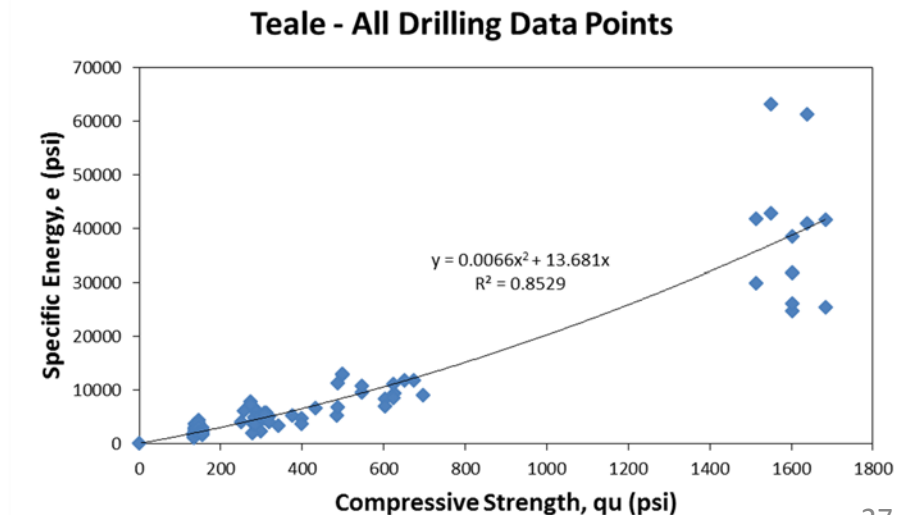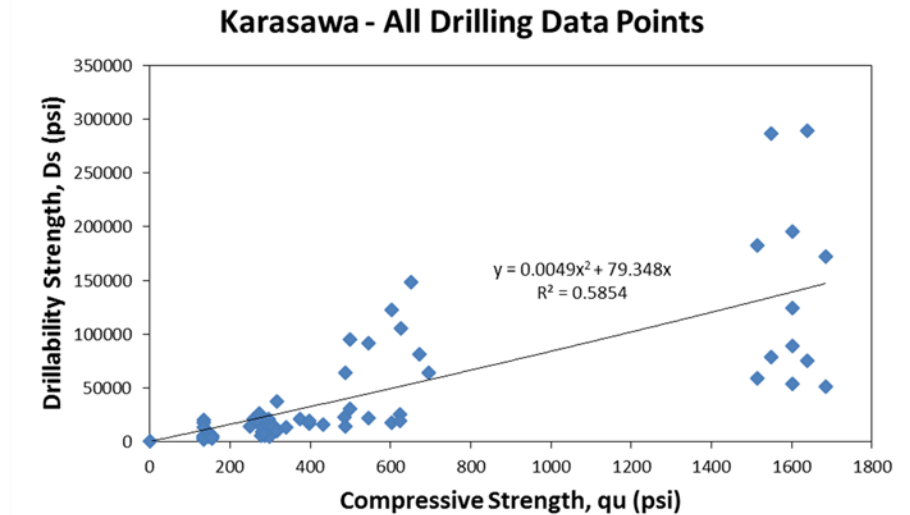
Task 2 - Field Drilling Equation

Using the equation from the e vs. q_u plot

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

Where,

$\quad$ y = e (psi)

$\quad$ 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:

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

Surveying the Industry

- What types of drill rigs are used and who are the manufacturers?
- How are forces torque and crowd applied to the drill bit?
- What are the typical rotational speeds and penetration rates used?
- Are any of the drilling parameters monitored in any way? If so, how?
- What types of tooling are used and what are the typical bit diameters?
- What shaft installation method is used, i.e., dry, wet, cased?

Survey Results

- Hydraulically driven systems
  - Torque and crowd
- Telescopic Kelly systems
- Monitoring equipment available on most rig types
  - Bauer's B-tronic system
  - SoilMec DMS system
- Commercially available monitoring equipment
  - Jean Lutz
- Wet-hole method is used

Monitoring Equipment

- Pressure transducers to measure torque and crowd
  - Tap into hydraulic lines
- Proximity sensor to measure rotational speed
  - Mounted on the rotary table
- Rotary encoder to measure penetration rate
  - Mounted on the main cable winch
- Junction box to receive signals from all sensors
  - Placed near the electrical unit or drill rig battery
  - Provides power to the system
- Data acquisition module to provide graphical display and store data
  - DIALOG
  - Mounted in the cab of the drill rig
  - Transmits data wirelessly

Equipment Installation

Tapping into the depth sensor using a multi-pin connection. The Jean Lutz cable is green.

Depth sensor mounted on the outer rim of the main cable winch. New model replaced old sensor.
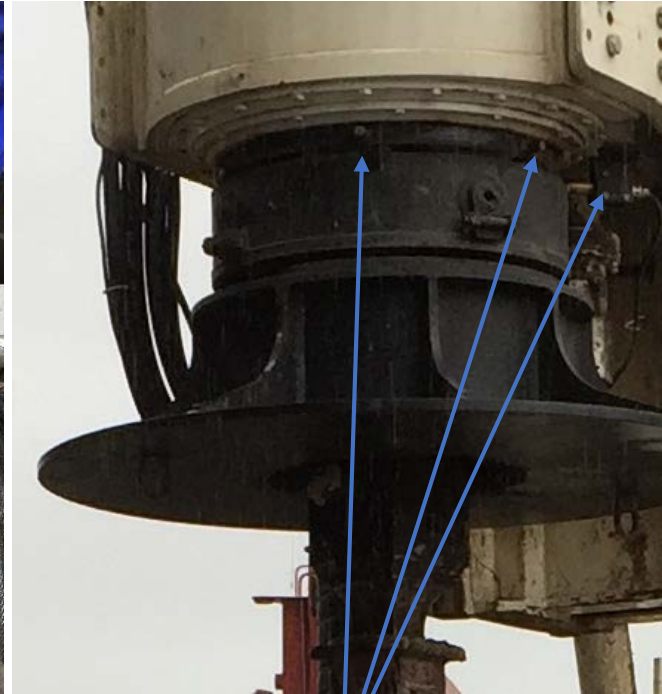
Proximity sensor mounted on the base of the rotary table. Steel bolts mounted on rotary head.
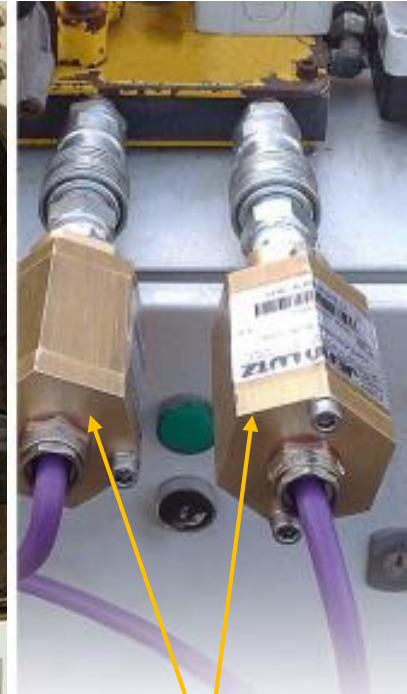
Torque and crowd sensors tapped into hydraulic lines. Location without differential pressure.

Monitoring from a Safe Distance

Cable running to drill rig cab

Junction box mounted near battery

Monitored Locations

- Little River bridge site (Task 3 - Pilot Project 1)
  - Quincy, FL
  - IMT AF250 drill rig used
  - 4' shaft diameter
  - Osterberg load test performed
- Overland bridge site (Task 3 - Pilot Project 2)
  - Jacksonville, FL
  - Bauer BG30 Premium Line drill rig used
  - 5'-6' shaft diameters
  - Statnamic load testing performed
- FDOT's Kanapaha site (Task 4 – Final Load Test)
  - Gainsville, FL
  - SoilMec SR30 drill rig used
  - 3' shaft diameter
  - Top-down static load test performed

Task 3 - Analysis of Rock Strength – Little River

- **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 Frequency Distribution

	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

Little River qu Cumulative Frequency Distribution
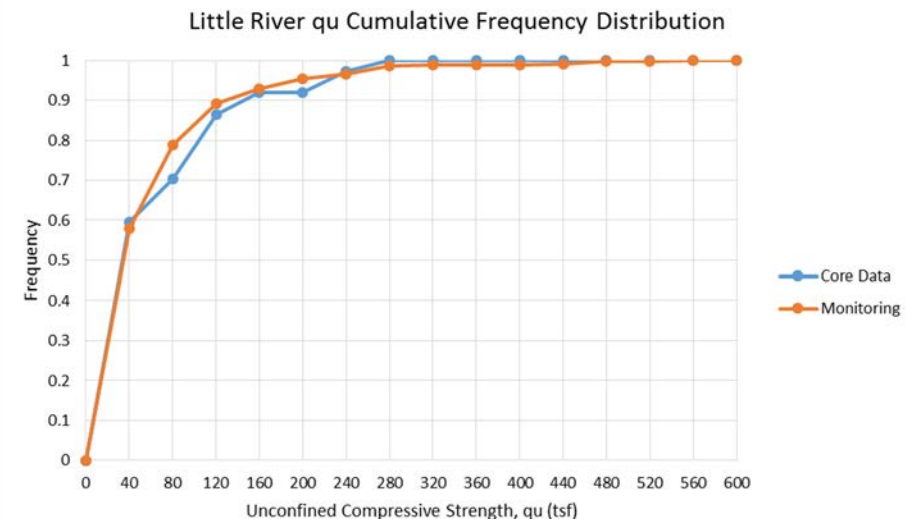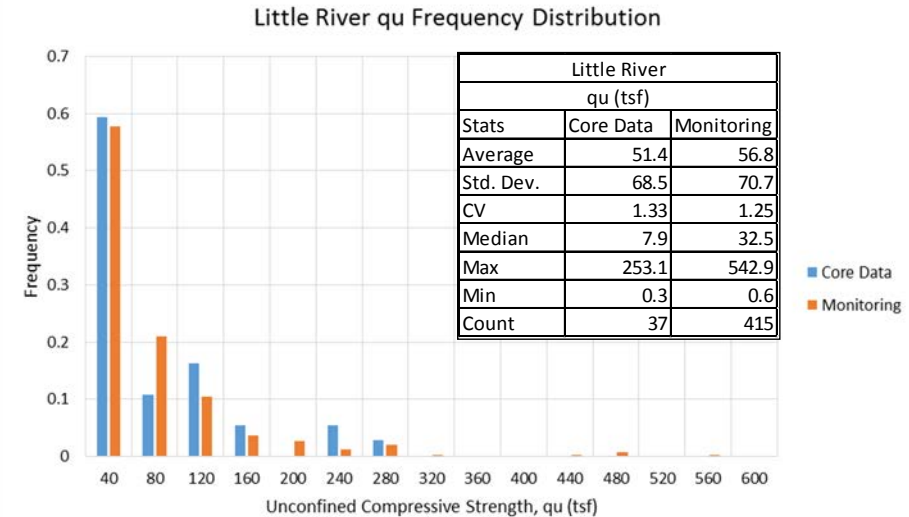
Task 3 - McVay et al.

- FDOT recommended method for drilled shafts socketed into limestone
  - Soils and Foundation Handbook 2015
- Incorporates split tension strength in capacity estimates
  - Allows adjustments to be made based on material formation
  - q_t/q_u ratio
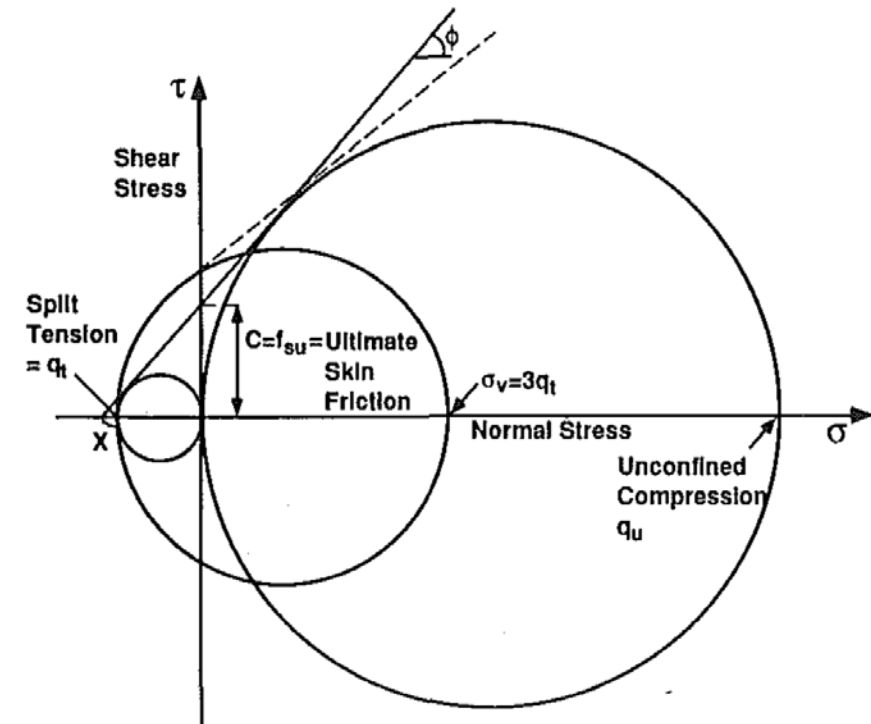
$$f_{su} = c = \frac{1}{2}\sqrt{q_u}\sqrt{q_t}$$

(McVay et al.[13])

Task 3 - q_t Slope Adjustments

- Determined q_t/q_u ratio for the site
- Used core data obtained from each boring to create q_t-q_u pairs
  - Grouped q_t and q_u values within one vertical foot of each other
- Plotted q_t vs. q_u
- Outlying q_t/q_u ratios removed
- Combined all remaining q_t-q_u pairs from every boring and eliminated q_t/q_u outliers
- Determined the site q_t/q_u ratio
- Estimated skin friction

All Borings - 1σ

All Borings - 1σ			
Stats	qt (psi)	qu (psi)	qt/qu
Mean	85.7	636.1	0.1368
Std Dev	146.1	1008.2	0.0334
CV	1.705	1.585	0.244
Count	87	87	87

$y = 0.1375x$
$R^2 = 0.914$
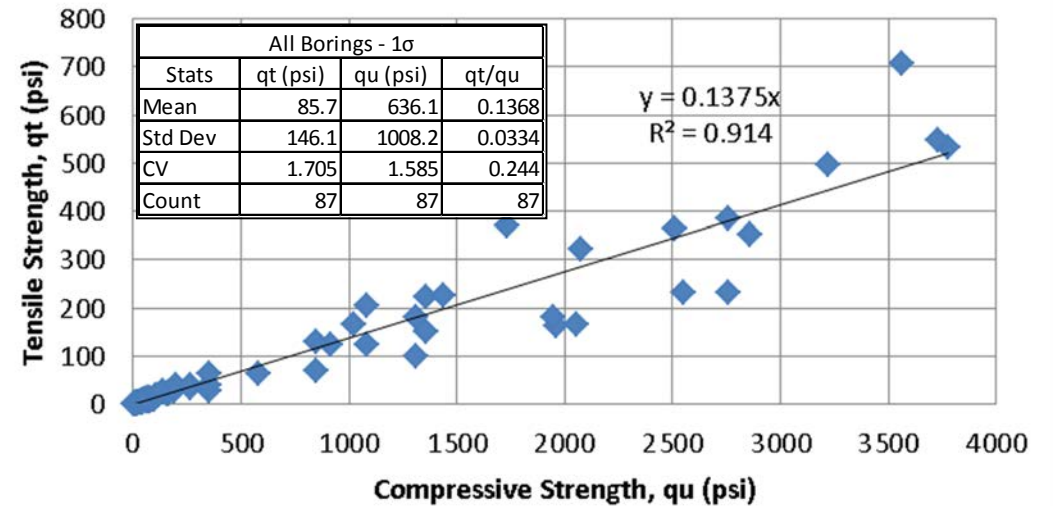
Little River Skin Friction, f_s (ksf)			
Section	Load Test	Monitoring	% Error
SG7 to SG6	21.1	20.8	-1.37%
SG6 to O-cell	20.6	22.9	11.31%
O-cell to SG5	21.4	20.4	-4.81%
SG5 to SG4	13.6	13.9	1.91%
Average	19.2	19.5	1.76%

Task 3 - Pairing Criteria

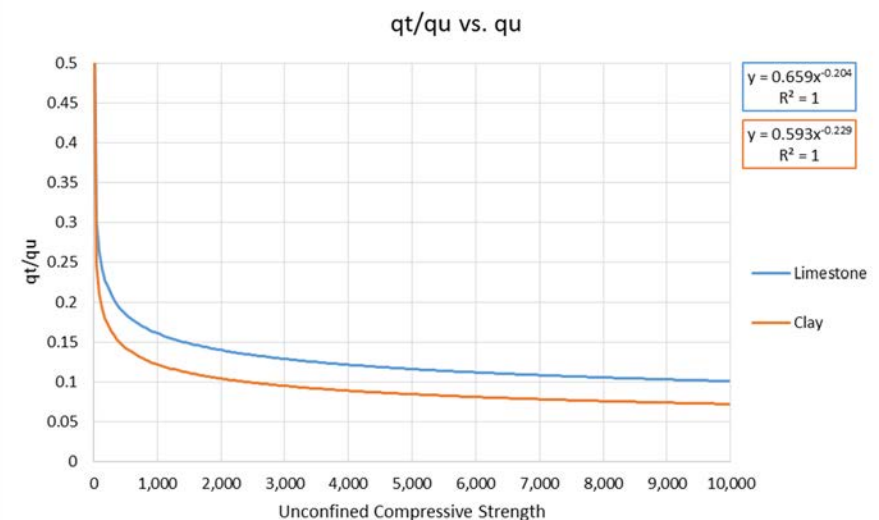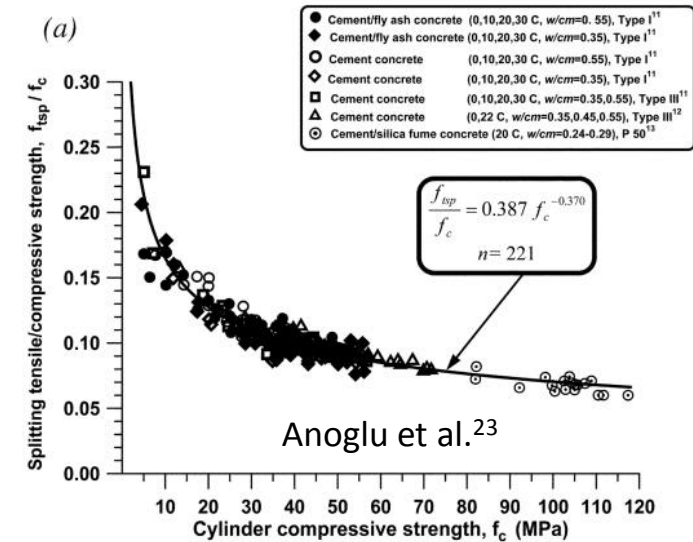- Validity and practicality of the approach was questionable
  - Combines q_t and q_u values from dissimilar materials
- Developed pairing criteria
  - Similar water contents
  - Similar dry unit weights
  - Satisfies Gw = Se condition
- Produced a small amount of valid q_t-q_u pairs
  - Problematic for sites with less available core data
- Led to a more theoretical approach

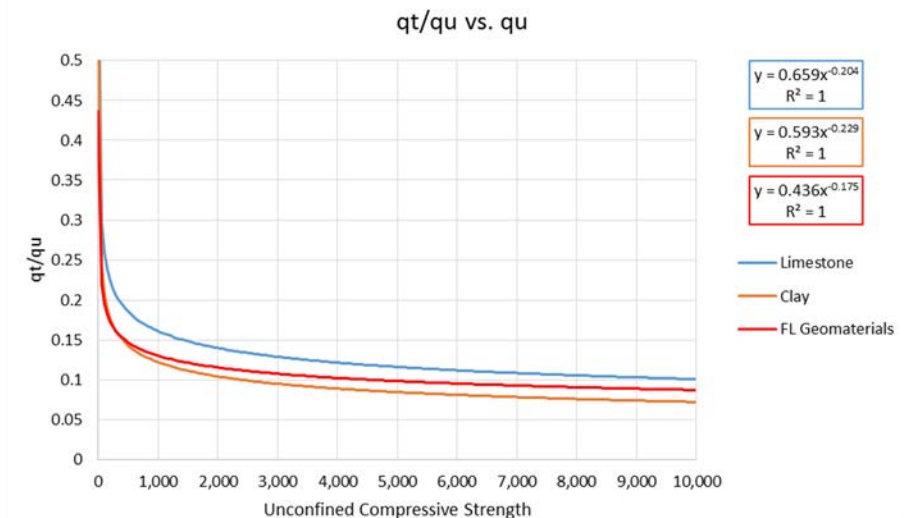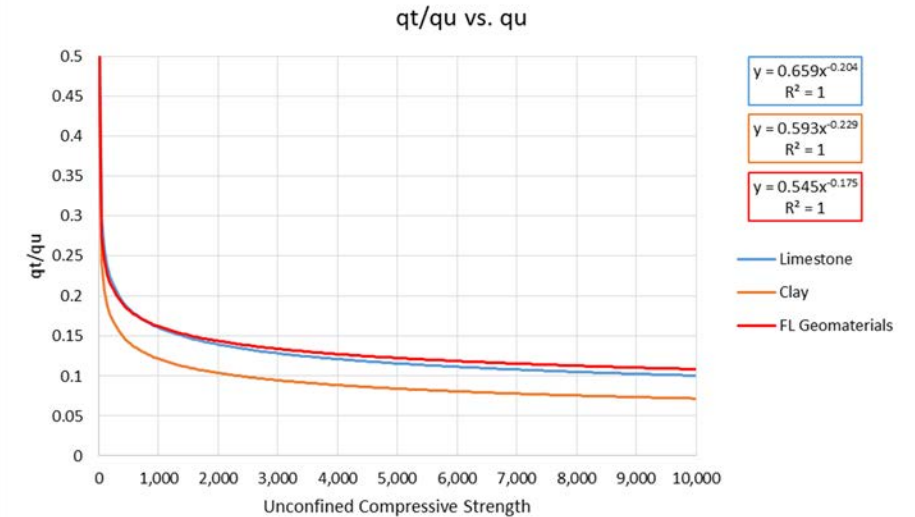| Boring/ Shaft-Core	Sample No.	Test Type	Moisture (%)	Dry Density (pcf)	Max Load (lbs)	S.T. Strength (psi)	q(u) (psi)	Displ. @ Fail. (in)
(38)								
2/1-1	1	T	15.6	106.5	79.3	13.9		0.0344
(48)								
2/1-2	1	T	59.8	63.3	39.6	6.5		0.0863
	2	U	58.2	64.7	128.6		38.1	0.1904
	3	T	60.1	63.2	66.0	8.1		0.0655
	4	U	69.0	59.7	61.1		16.9	0.1679
	5	T	3.2	156.0	9,520.2	975.2		0.0682
	6	T	3.8	135.0	3,180.6	327.3		0.0489
	7	U	5.1	134.4	5,319.1		1,116.9	0.0553
	8	T	7.6	131.5	2,077.8	218.1		0.0335
	9	T	4.8	149.9	1,031.9	107.3		0.0228
	10	T	61.3	63.2	39.3	4.0		0.0624
	11	T	28.8	91.6	54.5	5.2		0.1934

Task 3 - Johnston's Criterion and Anoglu et al.

- Johnston states q_t/q_u = B/M for drained conditions
  - B and M are material parameters based on q_u
- B is a measure of confinement effectiveness
  - Defines the non-linearity of the Mohr-Coulomb failure envelope
- M represents the relationship between ϕ' and q_u
  - As compressive strength increases, M increases
- Johnston used least squares analysis to derive curve equations
  - Developed 1 B equation
  - Developed 5 M equations for specific materials
  - 1 for carbonate materials (limestone and dolomite)
  - 1 for lithified argillaceous materials (clay and IGM)
- Developed curve equations using Johnston's B equation and M equations for limestone and clay
  - Created data points from 0 to 10,000 psi
  - Increments of 10 psi
  - Plotted q_t/q_u vs. q_u similar to Anoglu

(a)

Cement/fly ash concrete (0,10,20,30 C, w/cm=0. 55), Type I[11]
Cement/fly ash concrete (0,10,20,30 C, w/cm=0.35), Type I[11]
Cement concrete (0,10,20,30 C, w/cm=0.55), Type I[11]
Cement concrete (0,10,20,30 C, w/cm=0.35), Type I[11]
Cement concrete (0,10,20,30 C, w/cm=0.35,0.55), Type III[11]
Cement concrete (0,22 C, w/cm=0.35,0.45,0.55), Type III[12]
Cement/silica fume concrete (20 C, w/cm=0.24-0.29), P 50[13]

$$\frac{f_{tsp}}{f_c} = 0.387\, f_c^{-0.370}$$
$$n = 221$$

Anoglu et al.[23]

qt/qu vs. qu

$y = 0.659x^{-0.204}$
$R^2 = 1$

$y = 0.593x^{-0.229}$
$R^2 = 1$

Task 3 - Florida Geomaterials - q_t/q_u Equation

- Develop a final curve equation representative of OC clay, IGM, and Limestone
  - Florida drilling typically encounters all three materials
- Used Little River q_u Core data
  - All three materials were present
  - Using actual q_u values from each material would reshape the curve
- Developed a correction factor based on CBR and LBR definitions of rock strength for limestone
- $\dfrac{q_{uLBR}}{q_{uCBR}} = \dfrac{800 \text{ psi}}{1{,}000 \text{ psi}} = 0.80$

qt/qu vs. qu

$y = 0.659x^{-0.204}$ $R^2 = 1$
$y = 0.593x^{-0.229}$ $R^2 = 1$
$y = 0.545x^{-0.175}$ $R^2 = 1$

Limestone
Clay
FL Geomaterials

qt/qu vs. qu

$y = 0.659x^{-0.204}$ $R^2 = 1$
$y = 0.593x^{-0.229}$ $R^2 = 1$
$y = 0.436x^{-0.175}$ $R^2 = 1$
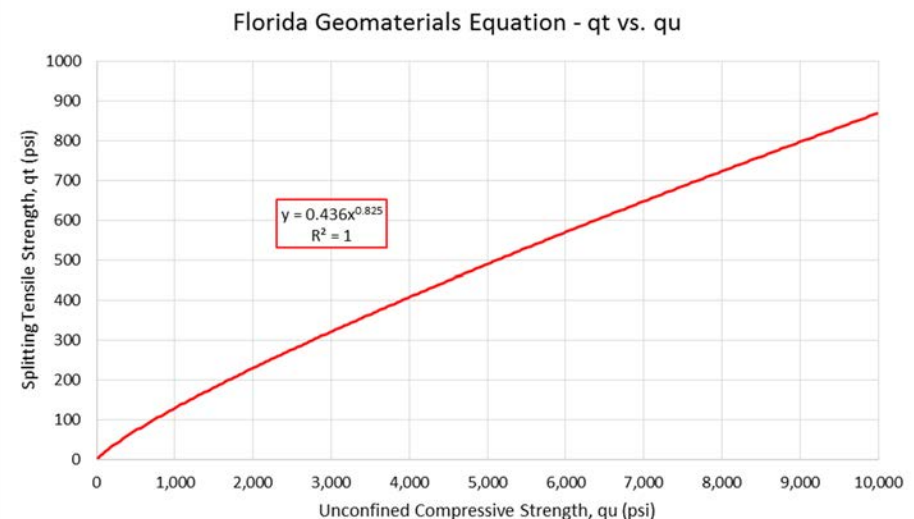
Limestone
Clay
FL Geomaterials

Task 3 - Predicted Split Tension Values

- Used the Florida geomaterials equation and predicted q_t values using q_u data obtained from sites all over Florida

- Assigned the predicted q_t values the same dry unit weight and moisture content as the q_u used to derive each predicted q_t value
  - Pairing criteria parameters

- Plotted the predicted qt values as q_t vs. dry unit weight and moisture content, separately
  - Do the predicted q_t values follow the same trend as the measured q_t values collected from the same Florida sites?

41
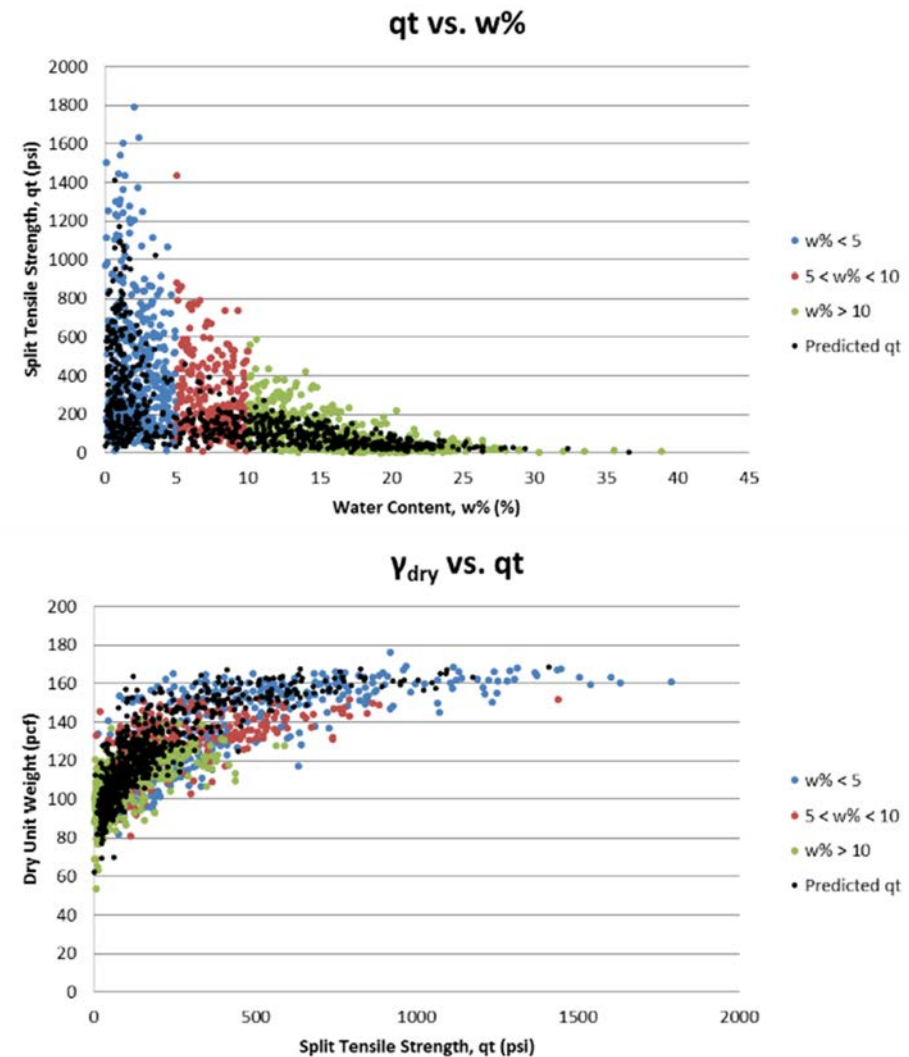
Task 3 - Florida Geomaterials - q_t Equation

- Further investigated the predicted values on the basis of dry unit weight vs. split tension strength
- Grouped values, measured and predicted, within the same dry unit weight range
- Found the mean and standard deviation of the measured q_t values
- Established one standard deviation above and below the mean as an "acceptable" strength range
- Developed the final Florida geomaterials equation to predict q_t directly from q_u

Florida Core Data

$y = 26.443\ln(x) - 16.716$
$R^2 = 0.9732$

$y = 24.104\ln(x) + 5.3756$
$R^2 = 0.9868$

Florida Geomaterials Equation - qt vs. qu

$y = 0.436x^{0.825}$
$R^2 = 1$
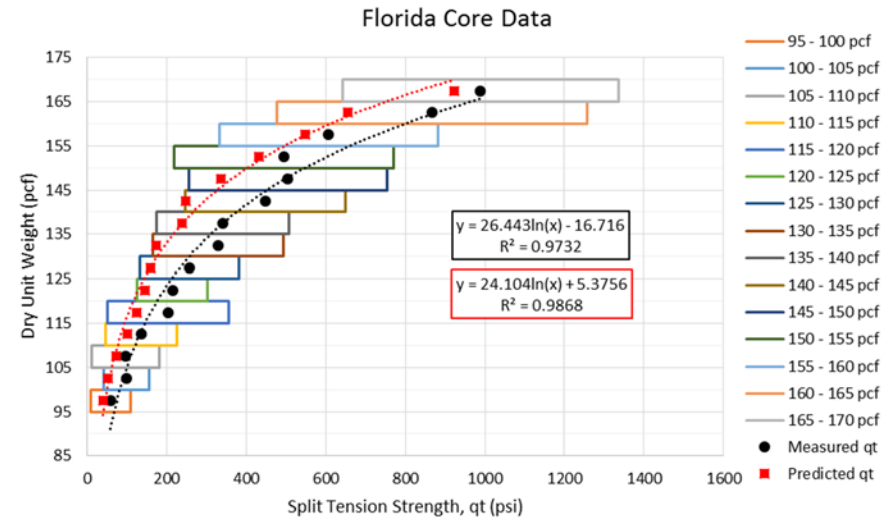
Task 4 – Kanapaha Site Investigation

- From previous site investigation
  - CPT
  - SPT
  - auger borings
  - core borings
- Previous load test data available
  - Townsend, 1993
- The new site investigation included
  - 12 seismic test lines
  - 20+ CPTs
  - 15 core borings
  - 5 SPTs
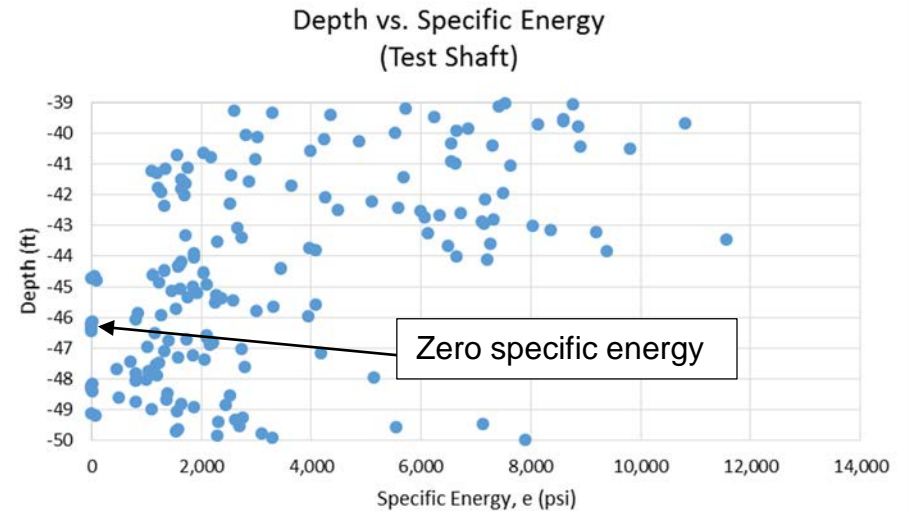- Highly weathered Ocala limestone
  - Ocala Uplift

Kanapaha Site Investigation Locations
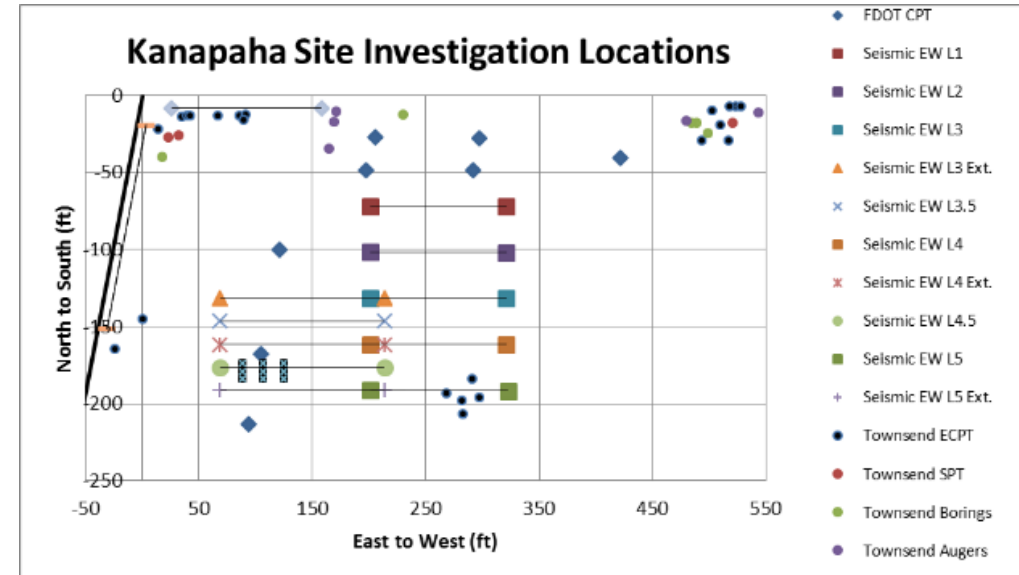
Task 4 - Kanapaha Shaft Construction

Task 4 - Detecting Rig Malfunction

- Rig malfunction occurred at 46 feet
  - Cable was improperly spooled
  - Drill bit was dropped uncontrollably
  - Depth sensor tracked penetration not achieved
  - DAQ recorded zero specific energy
  - Threshold pressure is increased lowering recorded T and F

- Zero bit rotation
  - Only occurs when the bit is lowered into the hole

- Only residual pressures recorded for T and F

- Penetration rate is increasing
  - Indicating acceleration from freefall

- Same specific energy value, 0.25 psi, was repeatedly recorded
  - 1 psi difference in q_u results in a 15 psi difference in specific energy

- Torque, crowd, and penetration rate values are on a different order of magnitude than normal drilling
  - Torque was 2 orders of magnitude lower than normal drilling conditions

Depth vs. Specific Energy
(Test Shaft)

Zero specific energy

Depth	Pen. Rate	Rotation	Torque	Crowd	Sp. Energy	qu
(ft)	u (in/min)	N (rpm)	T (in-lbs)	F (lbf)	e (psi)	(psi)
45.90	16.3	6.43	519716	2525	1268.59	88.9
45.96	5.4	6.53	530608	2926	3946.19	256.7
46.03	27.5	6.61	532757	693	791.67	56.3
46.10	52.0	1.97	73385	408	17.52	1.3
46.16	109.1	0.00	5385	258	0.25	0.0
46.23	114.8	0.00	5507	256	0.25	0.0
46.29	116.5	0.00	5642	257	0.25	0.0
46.36	115.0	0.00	5710	259	0.25	0.0
46.42	149.0	0.00	5365	261	0.26	0.0
46.49	15.6	7.09	410576	1873	1153.92	81.2
46.56	8.6	7.11	407152	1809	2084.81	142.6
46.62	7.9	7.26	370936	1787	2101.55	143.7

$$T = \uparrow k_T \times (Operating\ Pressure - \uparrow Threshold\ Pressure)$$

# Task 4 - Static Load Test Construction

Task 4 - Static Load Test

- ASTM-D1143 quick test performed
  - Standard test procedure
- Max estimated load was 1,000 kips in Design
  - 20 load increments
    - 50 kips
  - Sustained load time increments
    - 0.5, 1, 2, 4, and 8 minutes
- Test shaft was not mobilized at max estimated load
- Increased load increments
  - 100 kips
- Max applied load 1,800 kips
  - Test shaft was fully mobilized
  - Continuous displacement under the sustained max load for 32 minutes
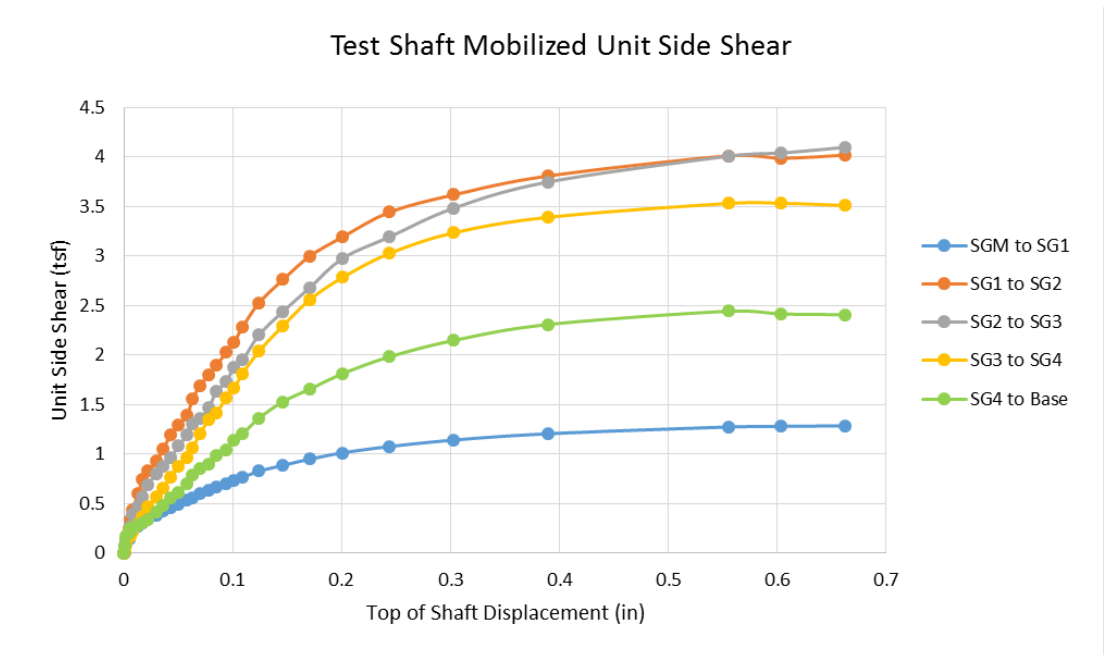- East shaft instrumented section mobilized

Task 4 – Load Test Results

Test Shaft Strain Gauge Distribution
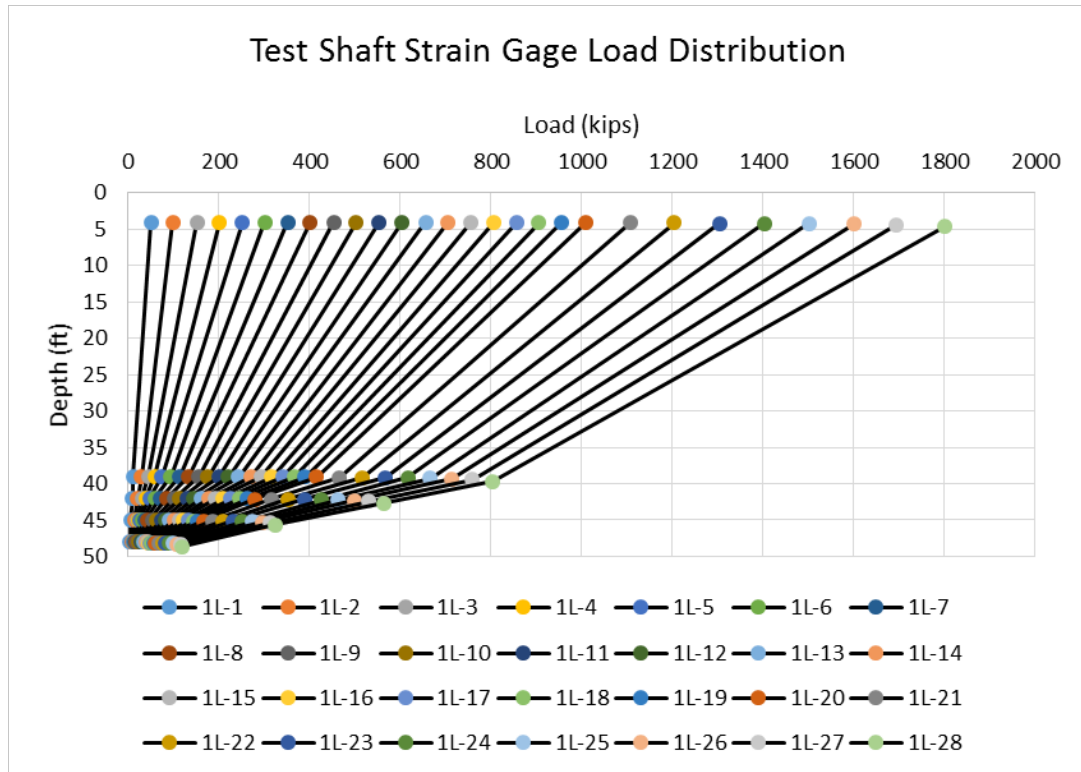
Test Shaft T-Z Curves

Leading Skin Friction Equations

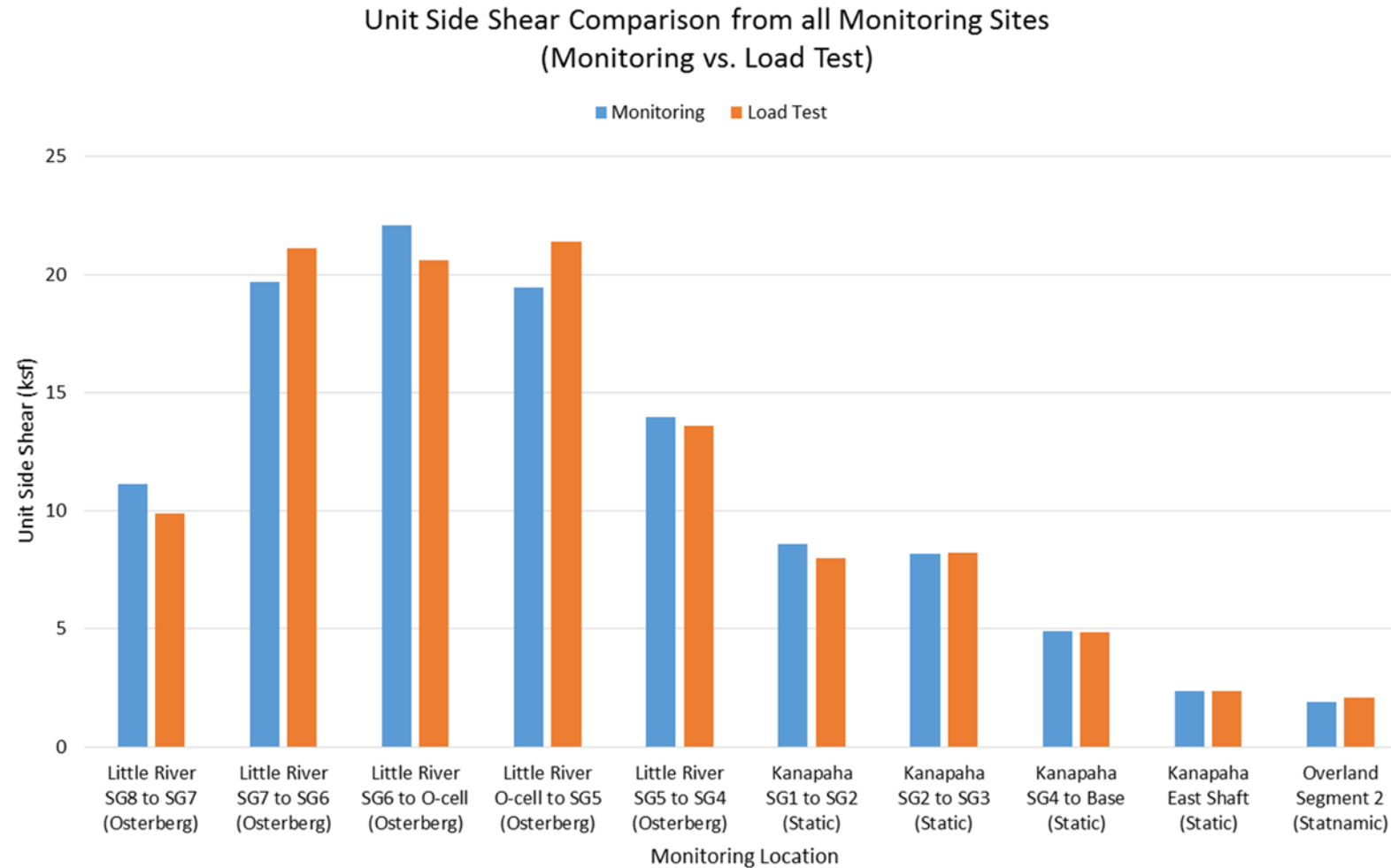| Method	Author	Design Methodology
1	McVay et al.[13]	$f_s = 1/2 \times \sqrt{q_u} \times \sqrt{q_t}$
2a	Reese and O'Neill[14]	$f_s = 0.15 \times q_u$ (tsf), for $q_u \leq 20$ tsf
2b	Horvath and Kenney[15]	$f_s = 0.67 \times \sqrt{q_u}$ (tsf), for $q_u > 20$ tsf
3	Williams et al.[16]	$f_s = 1.842 \times q_u{}^{0.367}$ (tsf)
4	Reynolds and Kaderabek[17]	$f_s = 0.3 \times q_u$ (tsf)
5	Gupton and Logan[18]	$f_s = 0.2 \times q_u$ (tsf)
6	Carter and Kulhawy[19]	$f_s = 0.63 \times \sqrt{q_u}$ (tsf)
7	Ramos et al.[20]	$f_s = 0.5 \times q_u$ (< 36 ksf) $f_s = 0.12 \times q_u$ (> 36 ksf)
8	Rowe and Armitage[21]	$f_s = 1.45 \times \sqrt{q_u}$ (tsf) clean sockets $f_s = 1.94 \times \sqrt{q_u}$ (tsf) rough sockets

Comparative Skin Friction Analysis

Location	Section	Load Test	Method 1	Method 2	Method 3	Method 4	Method 5	Method 6	Method 7	Method 8
Little River	SG8 to SG7	9.9	11.2	9.0	14.7	40.8	27.2	8.8	18.6	20.2
	SG7 to SG6	21.1	19.7	8.2	14.0	33.6	22.4	8.1	16.3	18.6
	SG6 to O-cell	20.6	22.1	9.7	15.6	37.2	24.8	9.2	15.3	21.2
	O-cell to SG5	21.4	19.5	8.6	14.3	33.0	22.0	8.3	15.3	19.0
	SG5 to SG4	13.6	14.0	7.3	13.0	22.4	15.0	7.2	12.7	16.5
Kanapaha	TS SG1 to SG2	8.0	8.6	5.5	11.0	13.1	8.7	5.7	8.6	13.0
	TS SG2 to SG3	8.2	8.2	5.3	10.7	12.3	8.2	5.5	8.1	12.6
	TS SG4 to Base	4.9	4.9	3.3	8.7	7.0	4.7	4.1	8.9	9.5
	ES SG1 to SG2	2.4	2.4	1.6	5.5	3.3	2.2	2.4	4.7	5.6
Overland	Segment 2	2.1	1.9	1.3	5.8	2.5	1.7	2.4	4.2	5.6
Average Percent Error		N/A	0.6%	-40.0%	41.6%	78.9%	19.3%	-29.6%	29.6%	62.1%

- McVay et al.[13] provided the best result (Method 1)
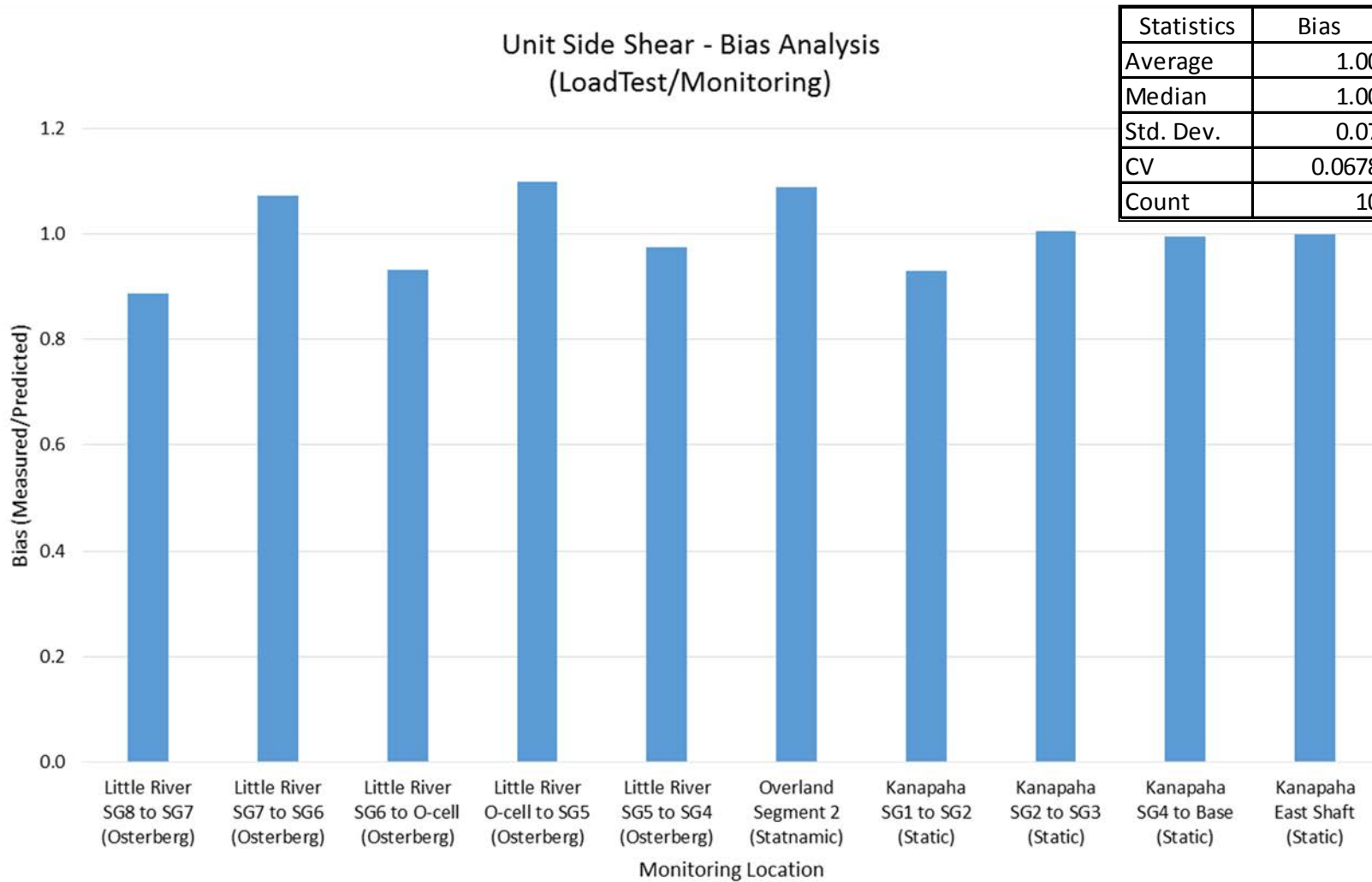- Average percent difference was 0.6% for the entire project

Comparative Skin Friction Analysis

		Comparative Analysis Summary				
Location	Section	Test Type	Thickness (ft)	Measured (ksf)	Predicted (ksf)	% Difference
Little River	SG8 to SG7	Osterberg	10.0	9.90	11.15	12.63%
Little River	SG7 to SG6	Osterberg	5.0	21.10	19.67	-6.78%
Little River	SG6 to O-cell	Osterberg	5.5	20.60	22.09	7.23%
Little River	O-cell to SG5	Osterberg	3.5	21.40	19.46	-9.07%
Little River	SG5 to SG4	Osterberg	5.0	13.60	13.95	2.57%
Kanapaha	SG1 to SG2	Static	3.0	8.02	8.62	7.48%
Kanapaha	SG2 to SG3	Static	3.0	8.22	8.18	-0.49%
Kanapaha	SG4 to Base	Static	2.0	4.86	4.88	0.41%
Kanapaha	East Shaft	Static	5.0	2.36	2.36	0.00%
Overland	Segment 2	Statnamic	5.0	2.06	1.90	-7.77%
Average	All	All	4.7	11.21	11.23	0.62%

Comparative Skin Friction Analysis

Unit Side Shear Comparison from all Monitoring Sites
(Monitoring vs. Load Test)

Bias Analysis

Unit Side Shear - Bias Analysis (LoadTest/Monitoring)

| Statistics	Bias
Average	1.00
Median	1.00
Std. Dev.	0.07
CV	0.0678
Count	10

LRFD Design Benefits

- For a reliability index of β = 3

  - $CV_R = \dfrac{\sqrt{\sigma_{method}^2 + \sigma_{spatial}^2}}{Mean\ Prediction}$

- Reducing the spatial uncertainty leads to an increased Φ-factor

  - $\uparrow \Phi \approx 1 - 1.73 CV_R \downarrow$

- Which leads to a decrease in nominal resistance, R_i, required to sustain the force effect, Q_i

  - $\sum \uparrow \Phi_i \downarrow R_i \geq \sum \eta_i \gamma_i Q_i$

- Direct reduction in socket length

- Direct reduction in cost per shaft
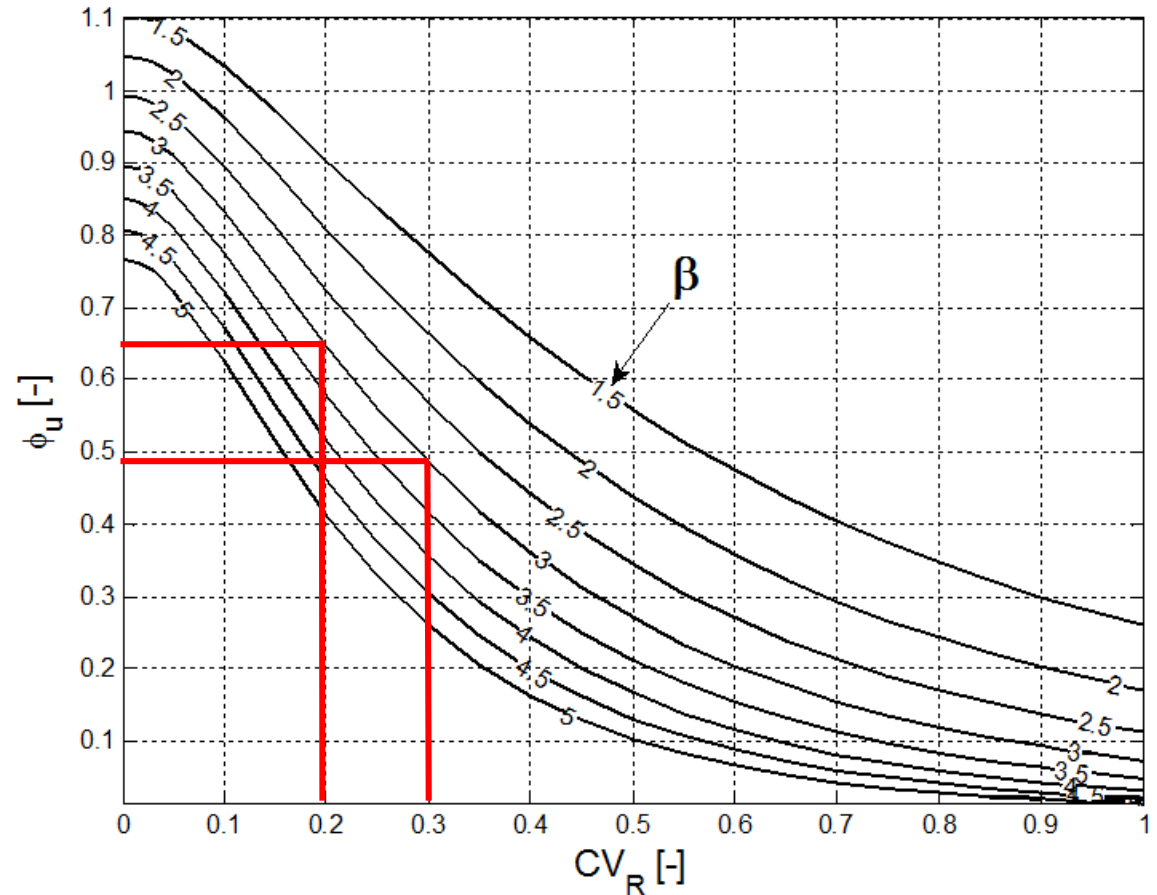
Conclusions

- The developed monitoring method is a viable option to estimating rock strength and drilled shaft capacity in real time
  - Results were in near perfect agreement with conventional methods
  - Monitoring equipment is often standard on new drill rigs and commercially available for rigs without monitoring capabilities
- Provides a means to quantify the quality and length of rock sockets
  - Provides QA and QC for the drilling contractor and foundation engineer
- This research took the first steps towards eliminating spatial variability concerns for structures supported by drilled shafts
  - Will lead to the use of higher LRFD resistance factors
  - Provide more efficient and cost effective construction practices
- Also developed were new relationships between material properties and strength properties of Florida geomaterials
  - Interdependence of q_u and q_t
  - Correlation between q_u and q_t with material properties dry unit weight and moisture content
    - Gives rise to the concept of index testing
    - Provides a better understanding of rock strength when core data is limited

Recommendations

- Conduct more drilled shaft monitoring with load tests to further validate the method
- The concept of Measuring While Drilling (MWD) should be used in more geotechnical engineering applications:
  - ACIP piles where only visual inspection of drilled cuttings occur
  - Used as site investigation tool on the SPT rig for additional design data
    - Provide continuous measurements of rock strength and quantify the quality of the coring procedure
      - Similar to CPT with the ability to penetrate through rock
      - Excellent tool for sites with poor recoveries such as Kanapaha
    - May be used when progressing the hole with a roller bit and during rock coring
  - Lead the way in developing MWD practices
    - Interest is high worldwide for developing MWD practices
- Recreate Johnston's criteria for Florida geomaterials and Gatorock
  - Improve the theoretical equation developed in this research
  - More accurate estimations of q_t and f_s
  - Currently being investigated
- Explore the option of index testing
  - Excellent reference of strength for sites with poor recoveries, i.e., Kanapaha
  - Currently being investigated in BDV31-977-51

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