Drilled Shaft Resistance Based on Diameter, Torque and Crowd
(Drilling Resistance vs. Rock Strength)
BDV 31 977 20

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FDOT Geotechnical Research in Progress Report
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Department of Civil & Coastal Engineering

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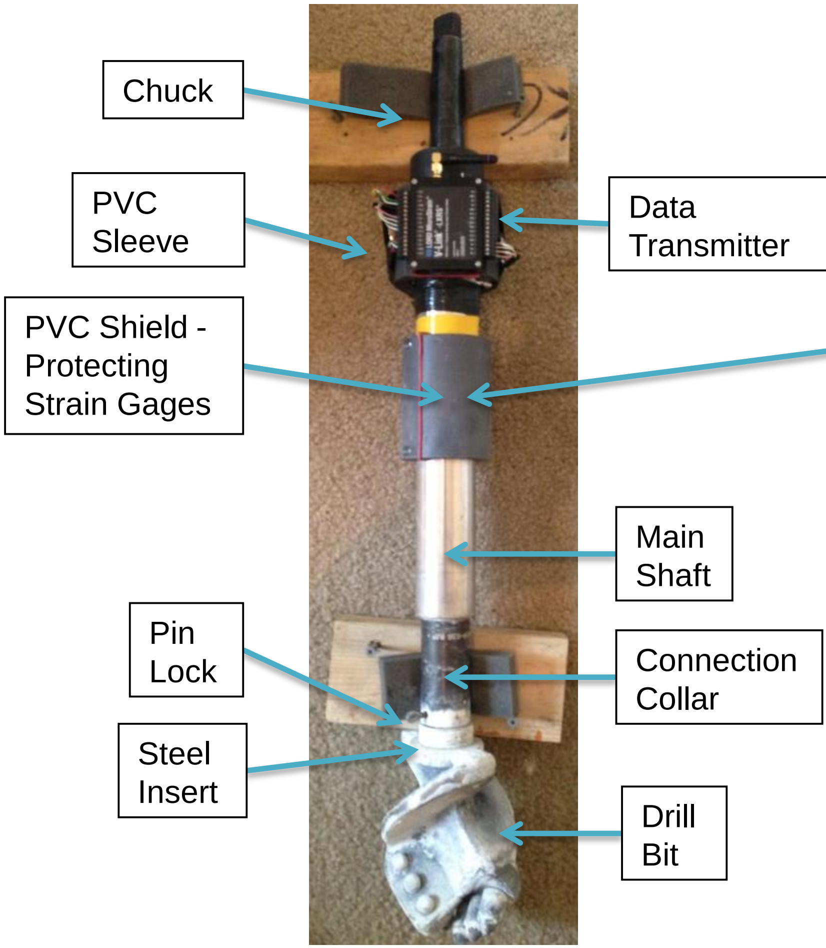
Topics Covered

- Brief review
- Laboratory drilling equation development
  – Karasawa’s equation
  – Teale’s equation
- Pilot project analysis
  – Little River – Quincy, Florida
  – Overland – Jacksonville, Florida
- Kanapaha (Gainesville) site investigation

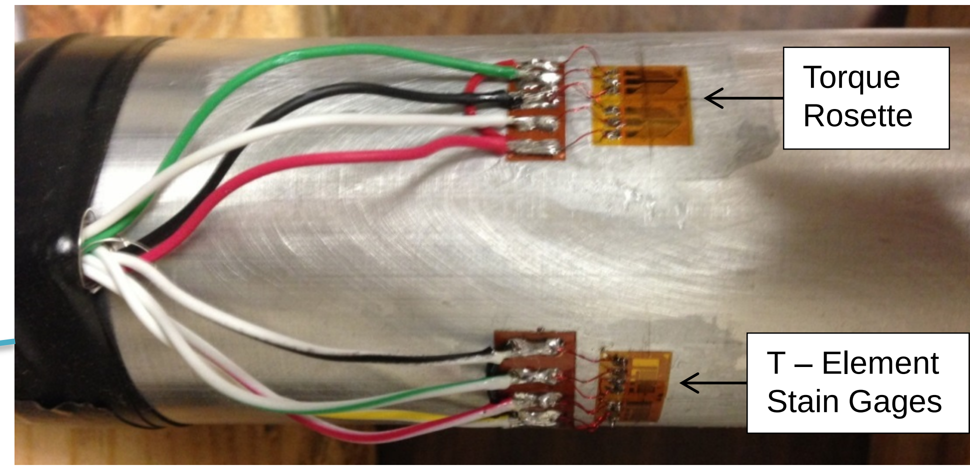
Review

- Developed laboratory drilling environment
  - Drill into large synthetic limestone (Gatorock) blocks measuring 5 drilling parameters in real time
      - Torque, T
      - Crowd or axial force, F
      - Penetration rate, u
      - Roational speed, N
      - Bit diameter, d
  - Drilling results are used for drilling equation development
  - Developed equation is used for field monitoring predictions to estimate drilled shaft capacity in real time
    - Estimates skin friction based on predicted rock strengths
- Acquired field drilling equipment
  - Records the same drilling parameters in the field from the drill rig in real time
  - Field monitoring results are compared to obtained core data and load test results

Laboratory Coupler System



Strain Gage Instrumentation

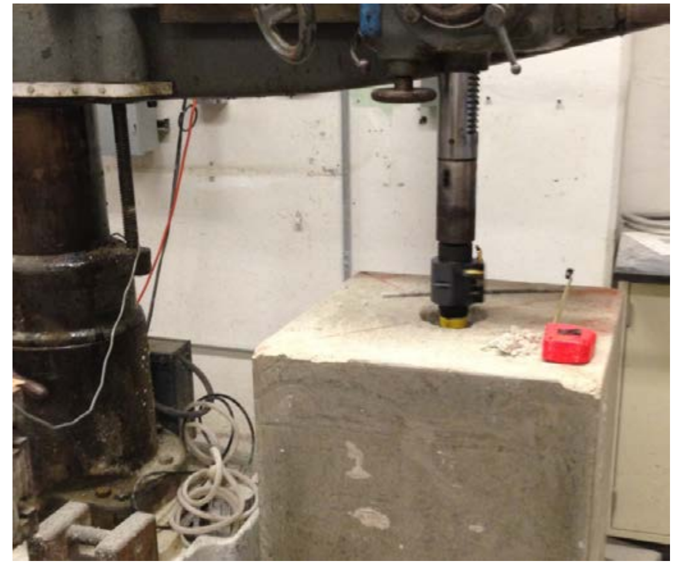


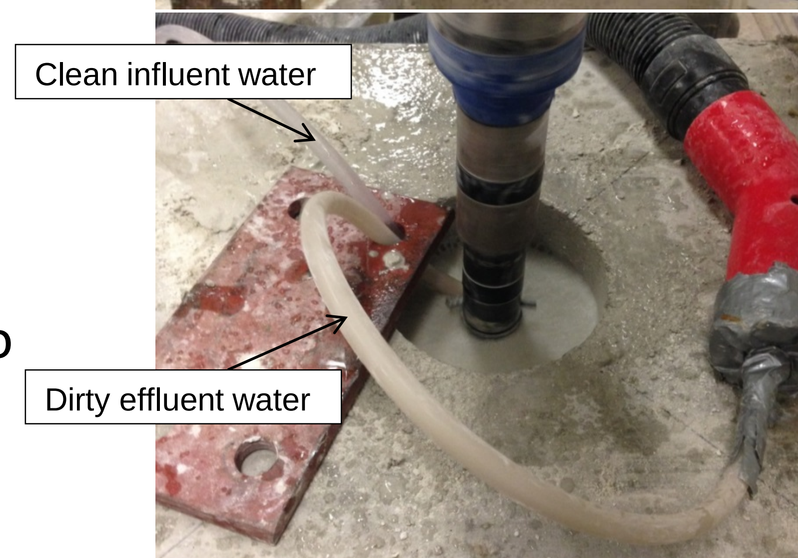
Torque Calibration

Crowd Calibration

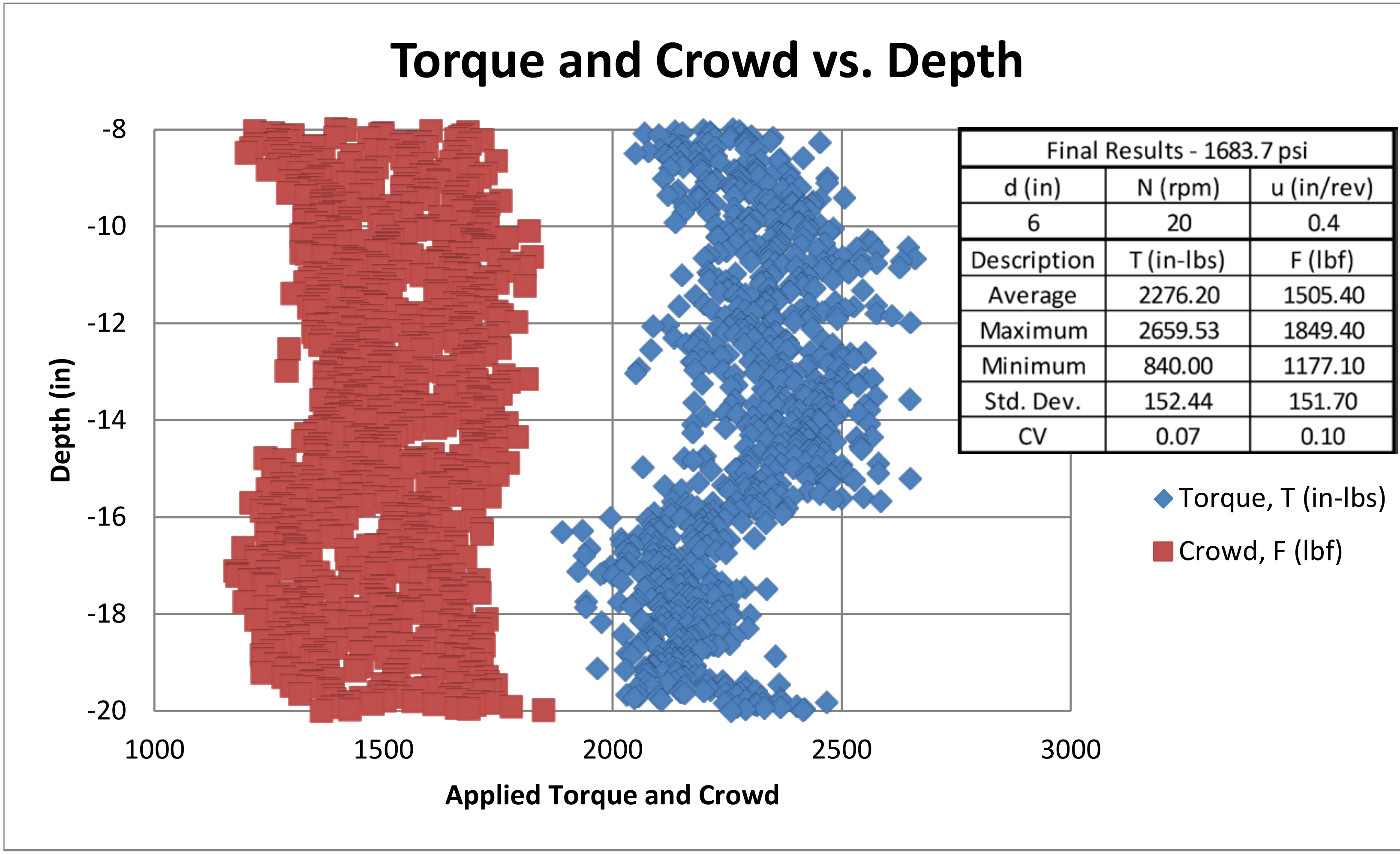
Laboratory Drilling

- 12 readings are taken per revolution for each gage
  - Average value at each increment of penetration
    - i.e. penetrate 0.008 in/rev
- Readings are then averaged for each gage type per depth increment
  - i.e. 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





Single Laboratory Drilling Result

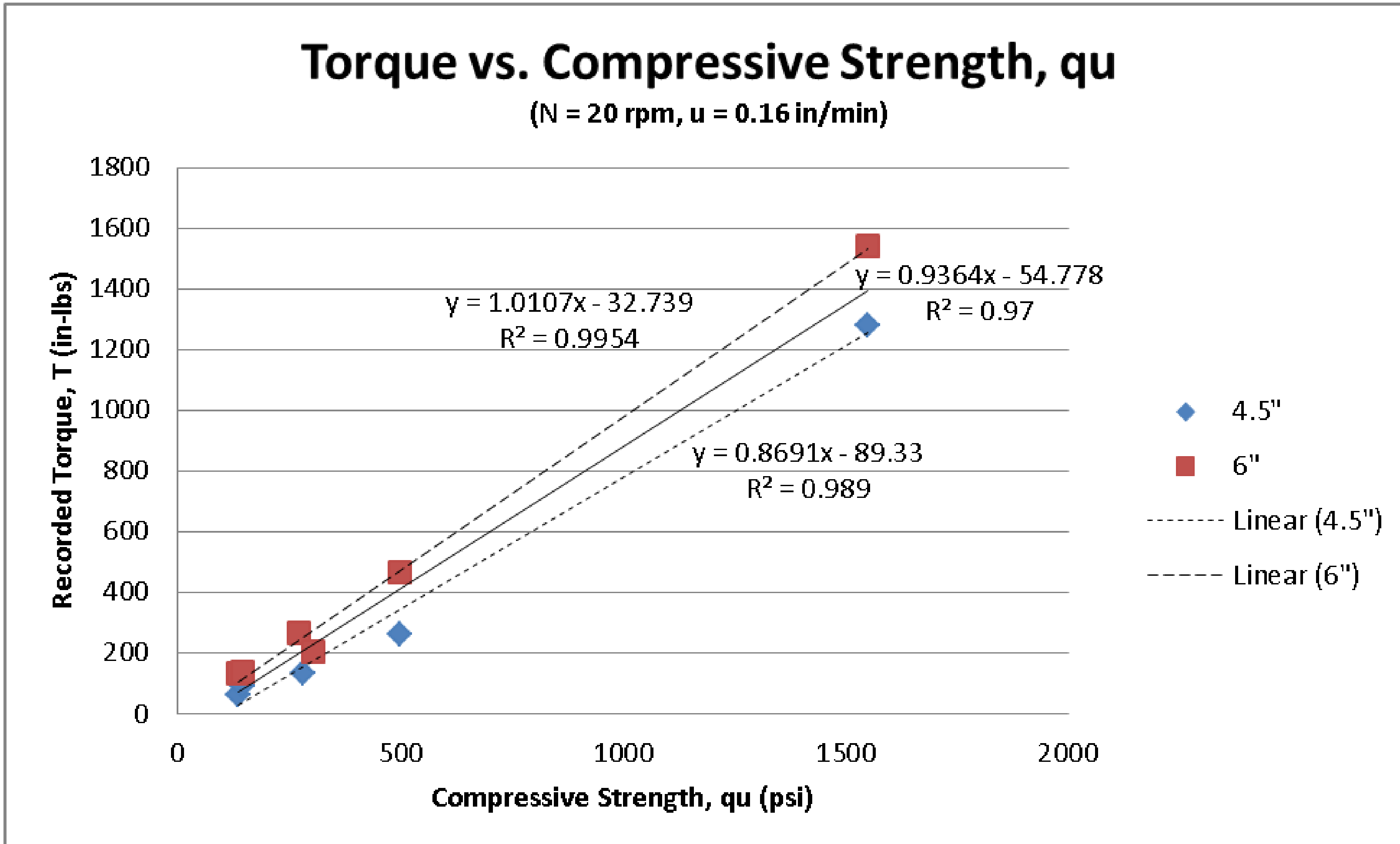


Final Results - 1683.7 psi		
d (in)	N (rpm)	u (in/rev)
6	20	0.4
Description	T (in-lbs)	F (lbf)
Average	2276.20	1505.40
Maximum	2659.53	1849.40
Minimum	840.00	1177.10
Std. Dev.	152.44	151.70
CV	0.07	0.10

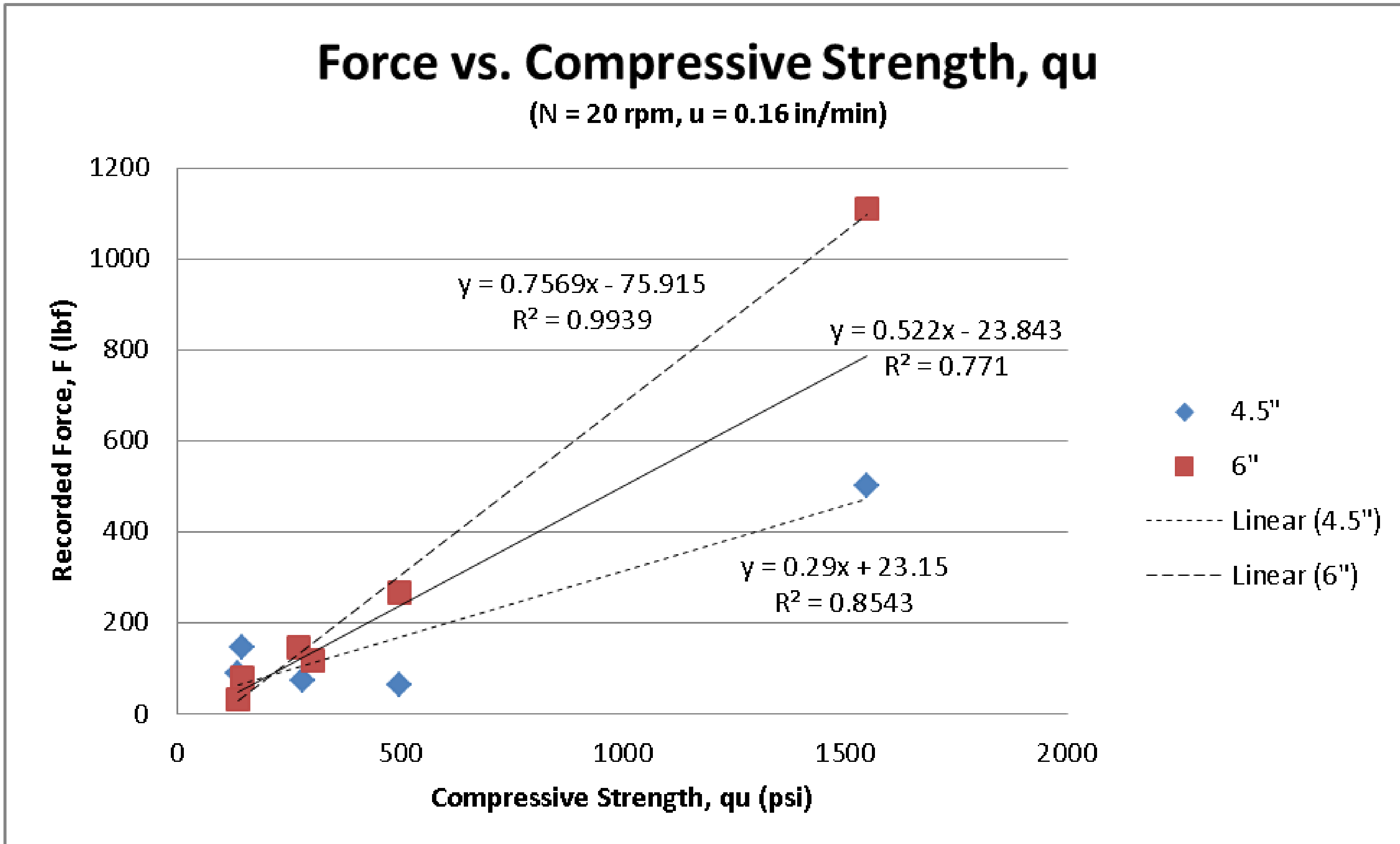
Laboratory Drilling Breakdown

- 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

Effects of Bit Diameter on Torque

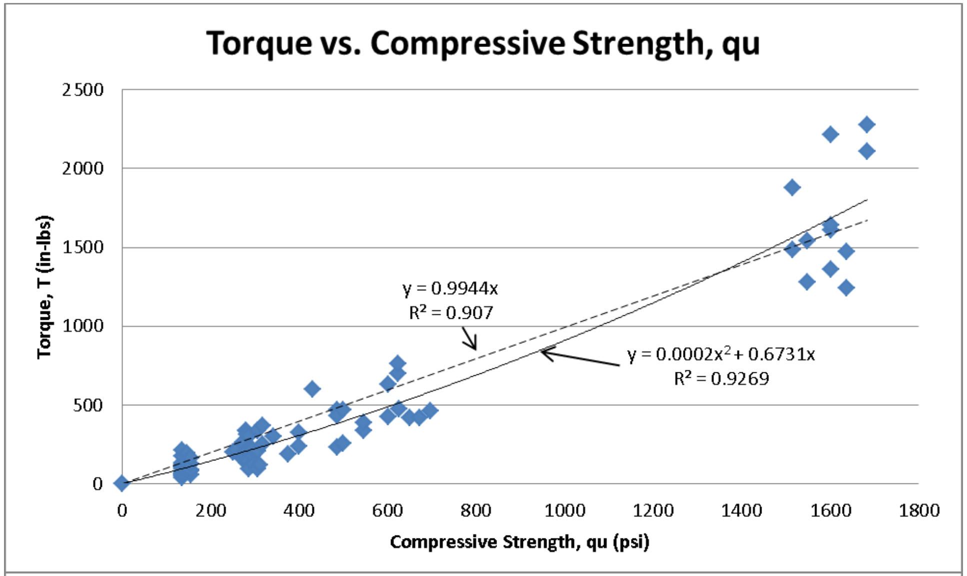


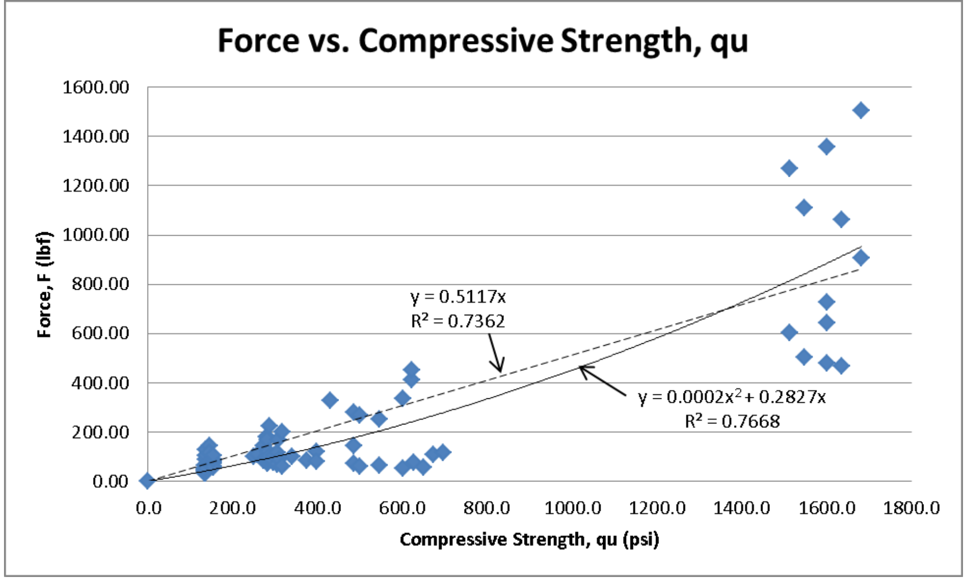
Effects of Bit Diameter on Force



Torque and Force vs qu

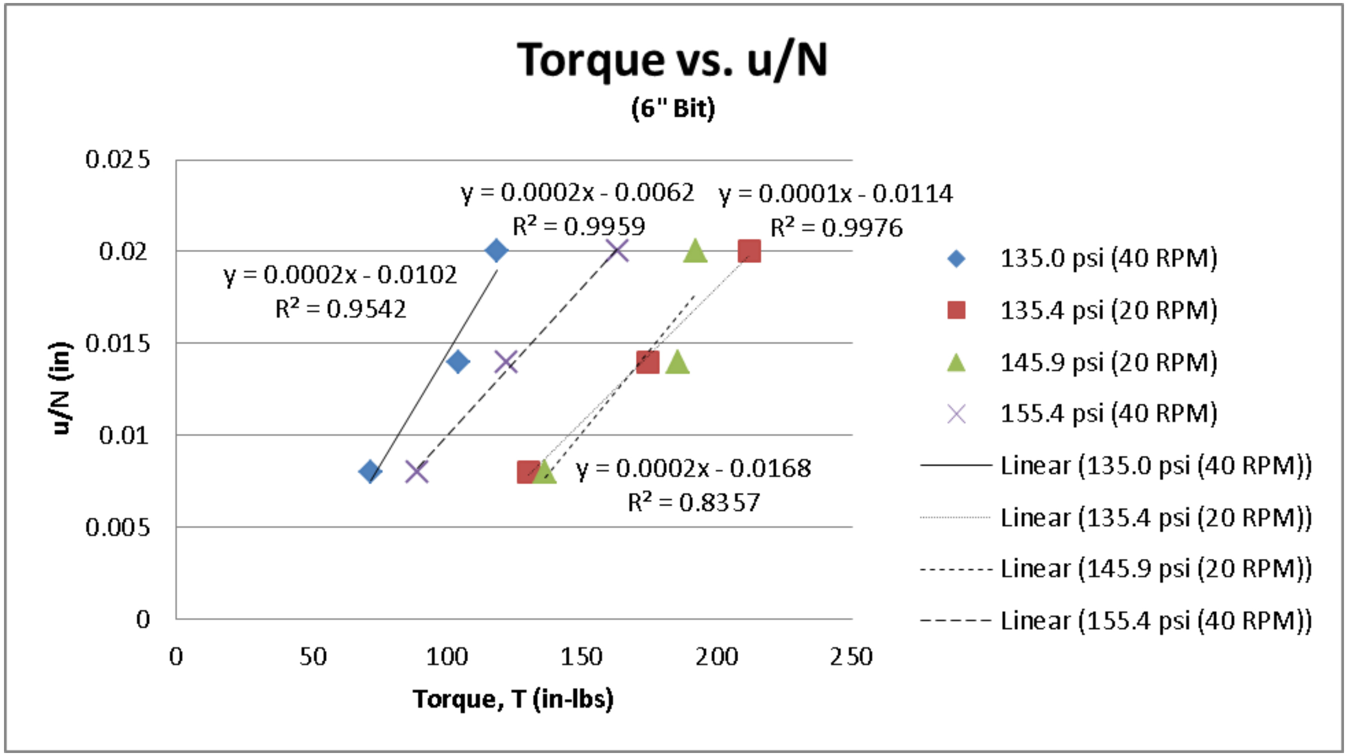
- Torque shows good trending when plotted vs respective compressive strengths
- Force trending is more variable





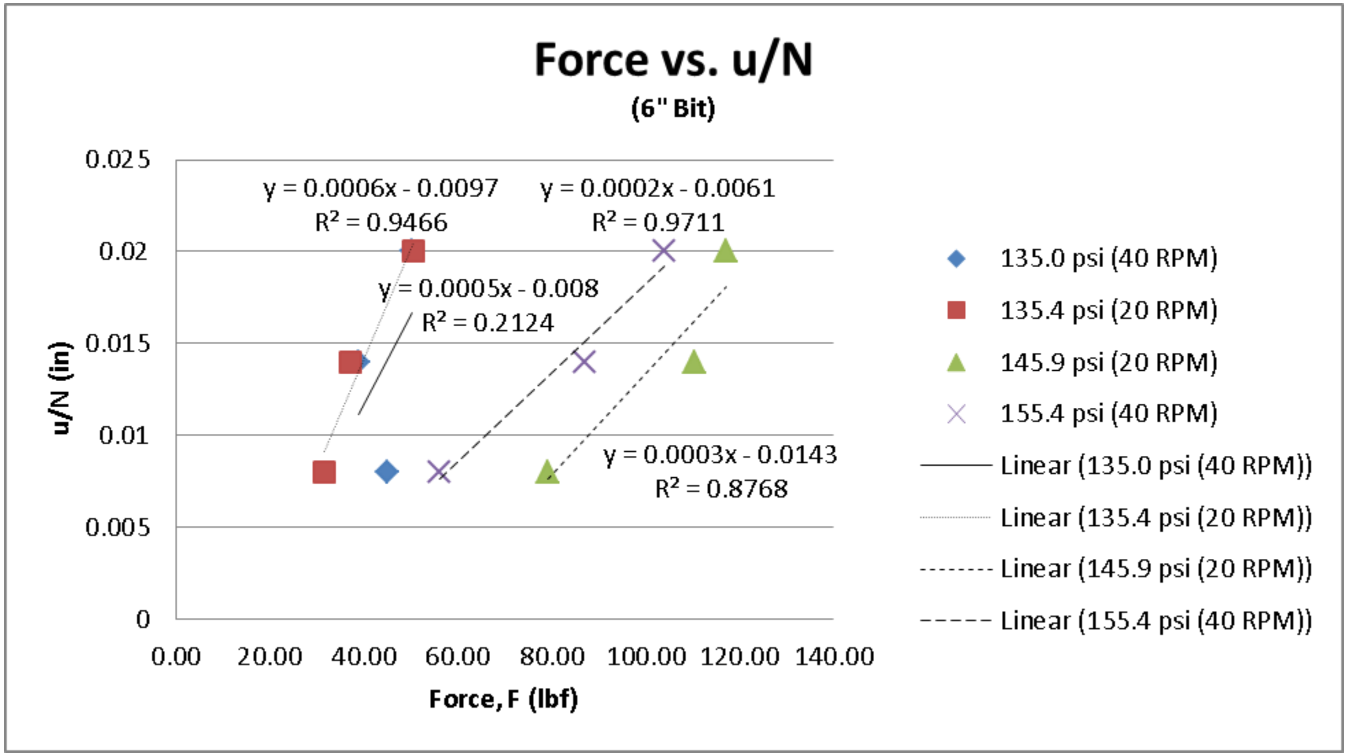
Torque vs u/N

- Torque increases with u/N increase
- Lower RPMs produce the highest torques



Force vs u/N

- Force generally increases with u/N increase
- RPMs plot randomly



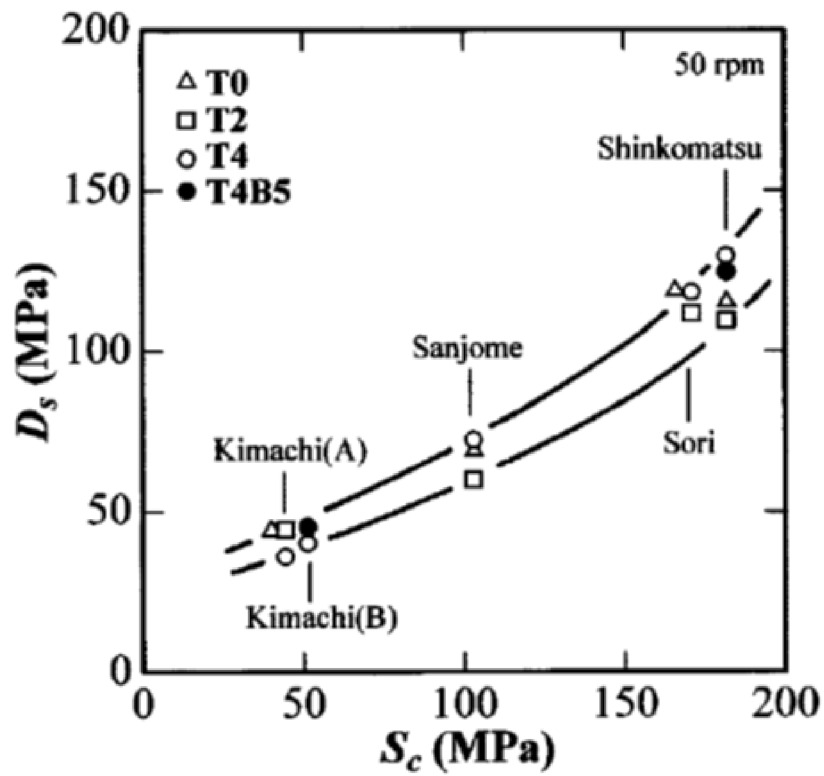
Analysis Conclusions

- Torque
  - Shows less dependency on bit diameter;
  - Shows strong trend with rotational speed;
  - Shows a good trend with penetration rate;
  - Shows a strong trend with compressive strength independent of all other drilling parameters
- Crowd
  - Shows more dependency on bit diameter;
  - Shows poor trend with rotational speed;
  - Shows a trend with penetration rate;
  - Shows a trend with compressive strength independent of all other drilling parameters
- Final drilling equation
  - Place more emphasis on torque, rotational speed and penetration rate
    - Most reliable drilling parameters
  - Should place less emphasis on crowd and bit diameter
    - Upscaling may be an issue
    - Crowd was least reliable drilling parameter and more dependent on bit diameter

Karasawa’s Equation

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

- Karasawa compared:
  - Drillability Strength of rock, D_s
  - Unconfined Compressive Strength, S_c or q_u
- Concerned that too much influence was being placed on bit diameter
  - d^3



***S_c (q_u – unconfined compression)**

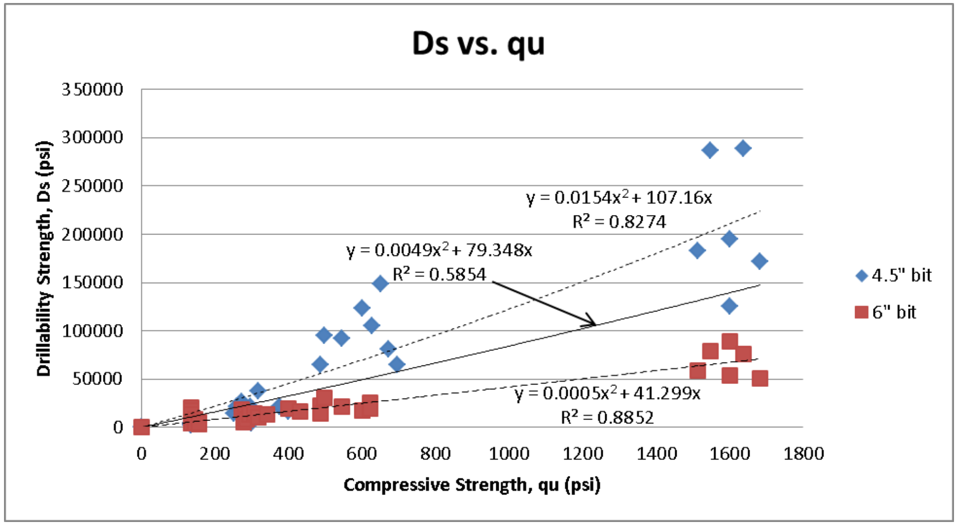
Karasawa, 2002

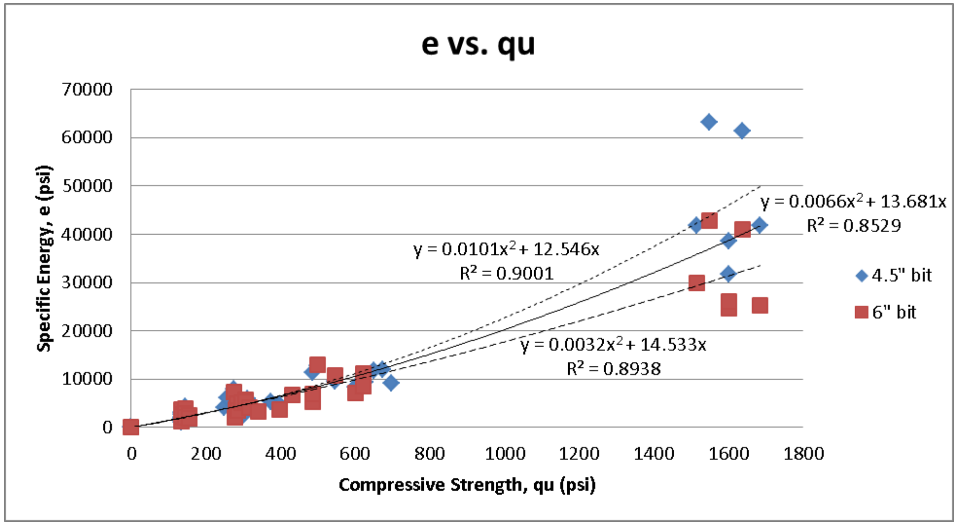
Teale's Equation

- Based on principles of virtual work
    - $W = Fu + 2\pi NT$
- Specific energy, e
    - $e = \frac{F}{A} + \left(\frac{2\pi}{A}\right)\left(\frac{NT}{u}\right)$
- Two drilling components
  - Thrust
    - $e_t = \left(\frac{F}{A}\right)$
  - Rotary
    - $e_r = \left(\frac{2\pi}{A}\right)\left(\frac{NT}{u}\right)$

Investigating Drilling Equations

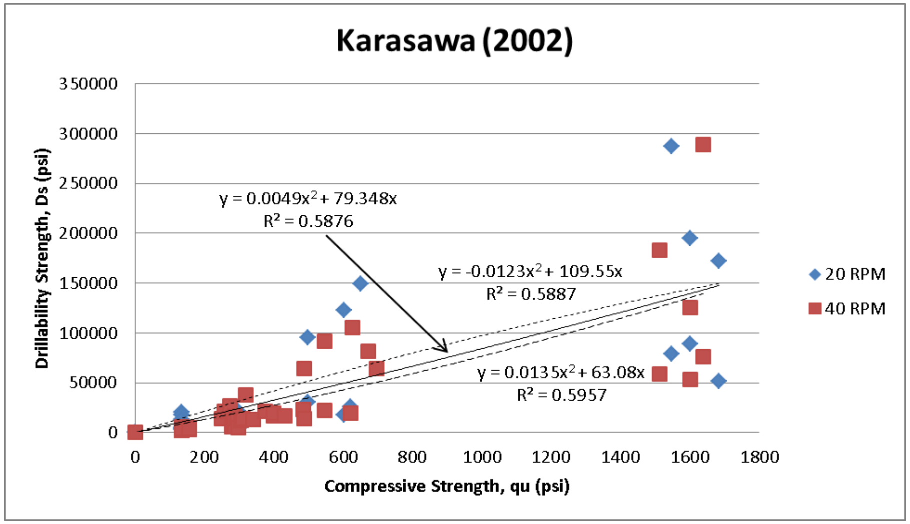
- Compared methods proposed by Karasawa (2002) and Teale (1965)
  - Created equation plots
    - D_s (Karasawa) versus q_u
    - e (Teale) versus q_u
  - Used a 2nd order polynomial regression line for curve fitting
- Compared the equation plots based on set drilling parameters
  - Bit diameter
  - Rotational speed
  - Penetration rate

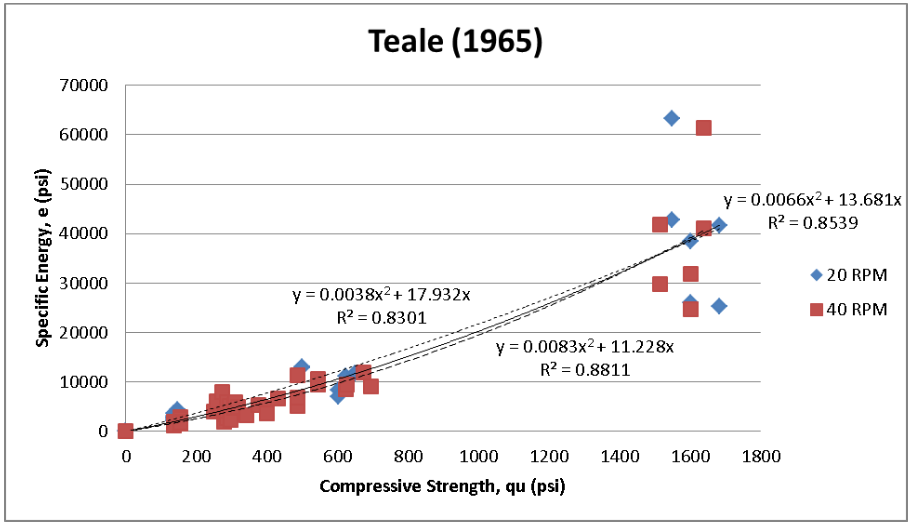




Comparing Teale and Karasawa
(Based on Rotational Speed for Compressive Strength)

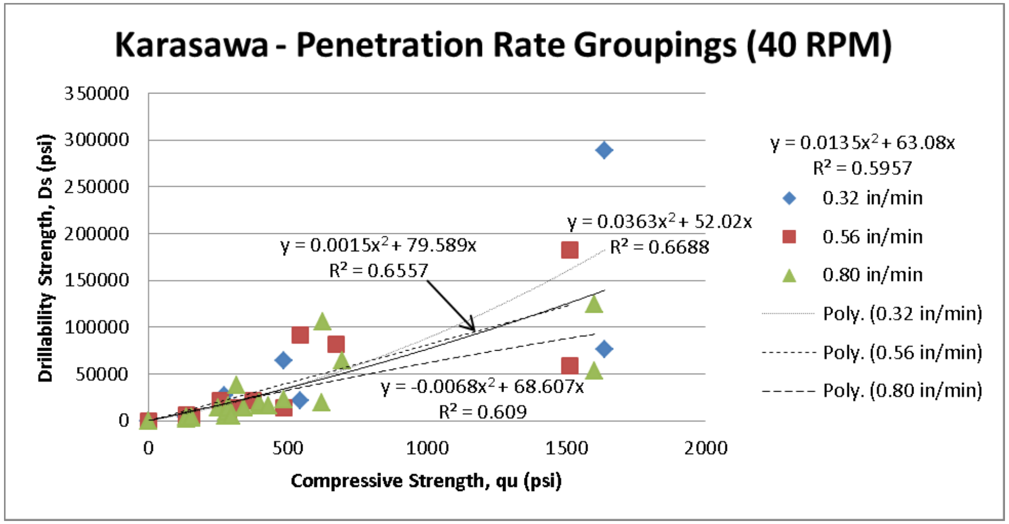
- Each equation is plotted using groupings based on RPMs
- Teale's equation shows far better trending

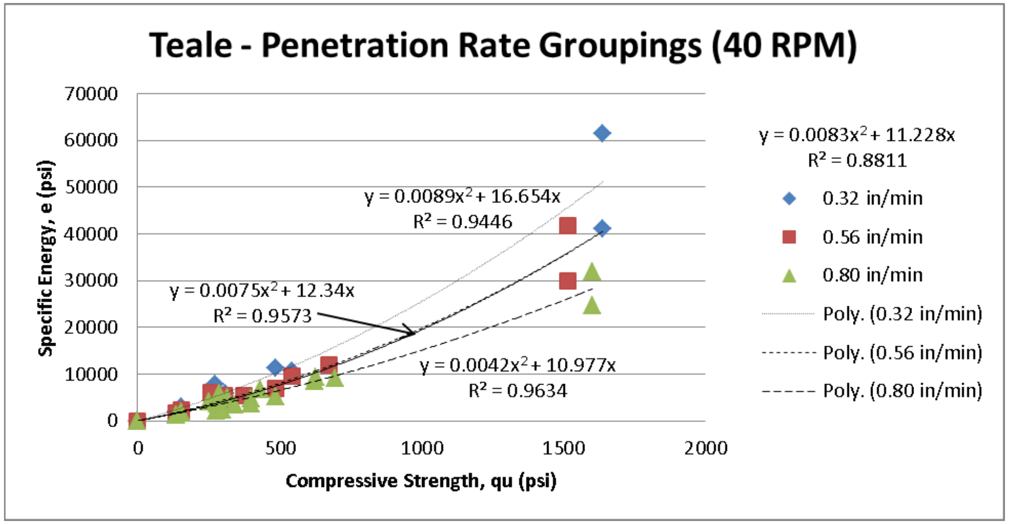




Comparing Teale and Karasawa
(Based on Penetration Rate for Compressive Strength)

- Each equation is plotted using groupings based on penetration rate for each rotational speed
- Teale's equation shows far better trending





Comparison Results

- Teale's equation shows better trending
  - Bit diameter
  - Rotational speed
  - Penetration rate
- Which equation places less emphasis on the problematic drilling parameters?
  - Bit size
    - Teale's equation only uses bit diameter to define the area of the excavation
    - Karasawa's equation places additional emphasis on bit diameter – d^3
  - Force
    - On average, Teale's thrust component only accounts for 0.2% of the reported specific energy values, e, in lab drilling results
- Preliminary monitoring results indicated Karasawa's equation produced large overestimations
- Teale's equation was selected for field monitoring analysis

Field Drilling Equation

Using the equation from the e vs. qu plot

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

Where,

y = e (psi)

x = qu (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:

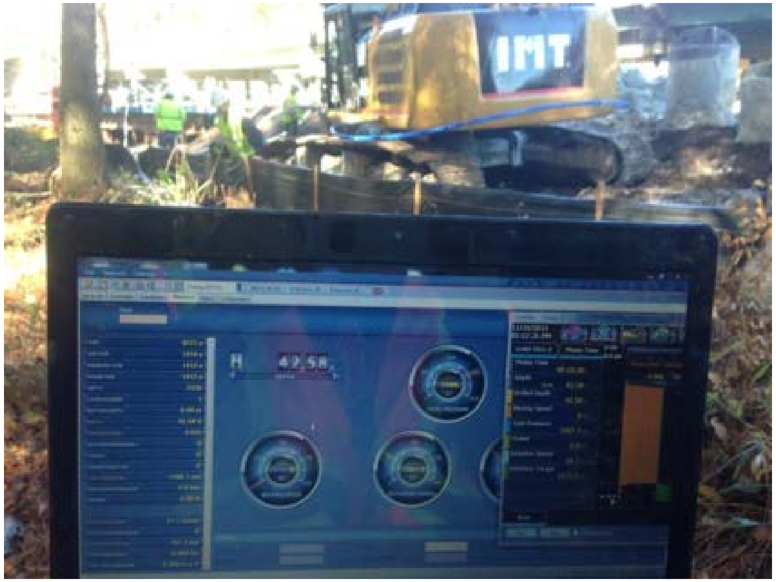
$$q_u = \frac{13.681 + \sqrt{(-13.681)^2 - 4*(0.0066)*(-e)}}{2*(0.0066)}$$

Pilot Projects

- 2 field monitoring locations
- Little River bridge site
  - Quincy, Florida
  - 1 load test
    - O-cell testing
- Overland bridge site
  - Jacksonville, Florida
  - 3 load tests:
    - Statnamic testing
- Provided direct feedback on monitored drilling results compared to conventional test methods

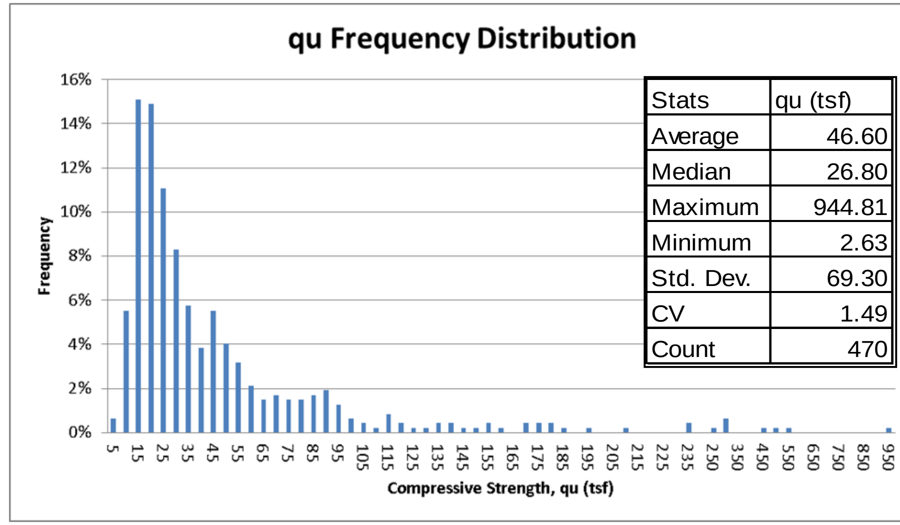
Little River – Quincy, Florida

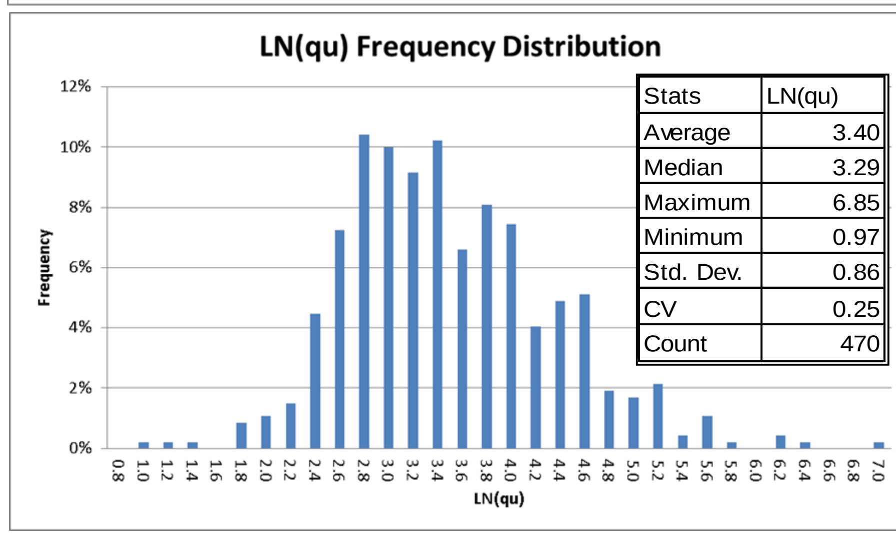
- IMT AF 250 drill rig was used for shaft installation
- Only one sensor had to be installed for monitoring
  - Crowd
- 48 inch diameter shaft installed
- O-cell load test
- Strata was highly variable
  - 3 distinct soil layers
  - High strength rock present
- 33 foot section of the shaft was available for comparison
  - Geomaterial comparable to limestone
  - Rock Auger was used to complete the drilling
  - O-cell results indicated the section was at or close to failure



Little River - Frequency Distribution of Estimated q_u

- Frequency distribution of qu is lognormal
- LN(qu) Frequency distribution produces a normal distribution (symmetric)
  - Confirms raw data log-normal distribution



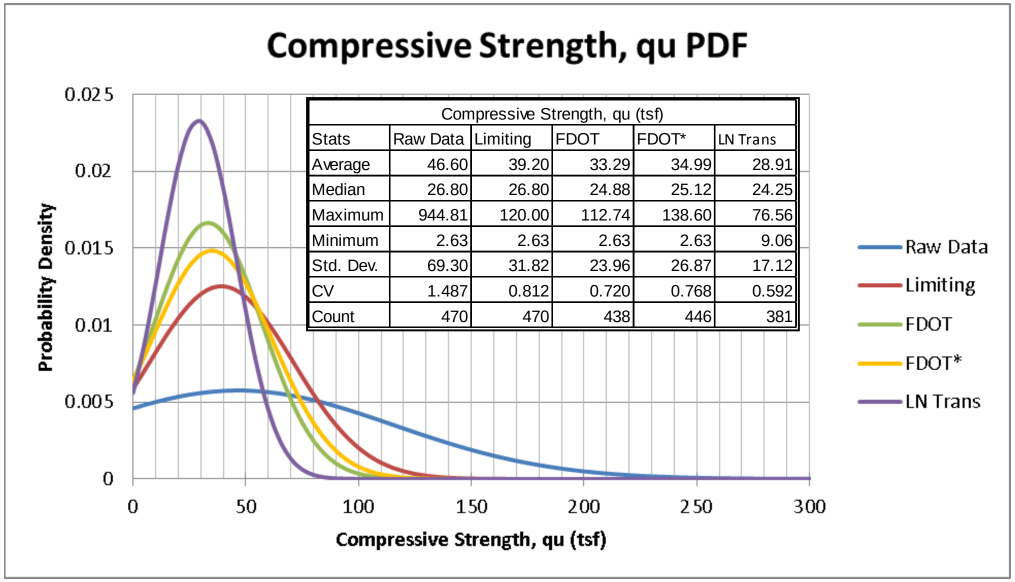


Methods of Analysis

- FDOT Method
  - The mean and standard deviation are found for the entire investigated portion of the shaft (i.e. Elevations +45.6' to +12.6')
  - Values that fall outside of 1σ from the mean are eliminated and a new mean is found with the remaining values
- FDOT* Method
  - Initial averaging is done for each section between strain gages (i.e. zone)
- Limiting Method
  - Limits values based on adhesion constraints
    - qu = 120 tsf, qt = 20 tsf, fs = 25 tsf
    - Values are not eliminated, they're limited to constraining values
- LN Transform Method
  - The log space mean and standard deviation are found using the arithmetic mean and standard deviation from raw data set (El. +45.6 'to +12.6')
  - The data set is then converted to log space using the natural logarithm
  - Values that fall outside of 1σ from the mean in log space are eliminated.
  - The remaining values are then converted back to normal space and a new mean is found.

Methods of Analysis

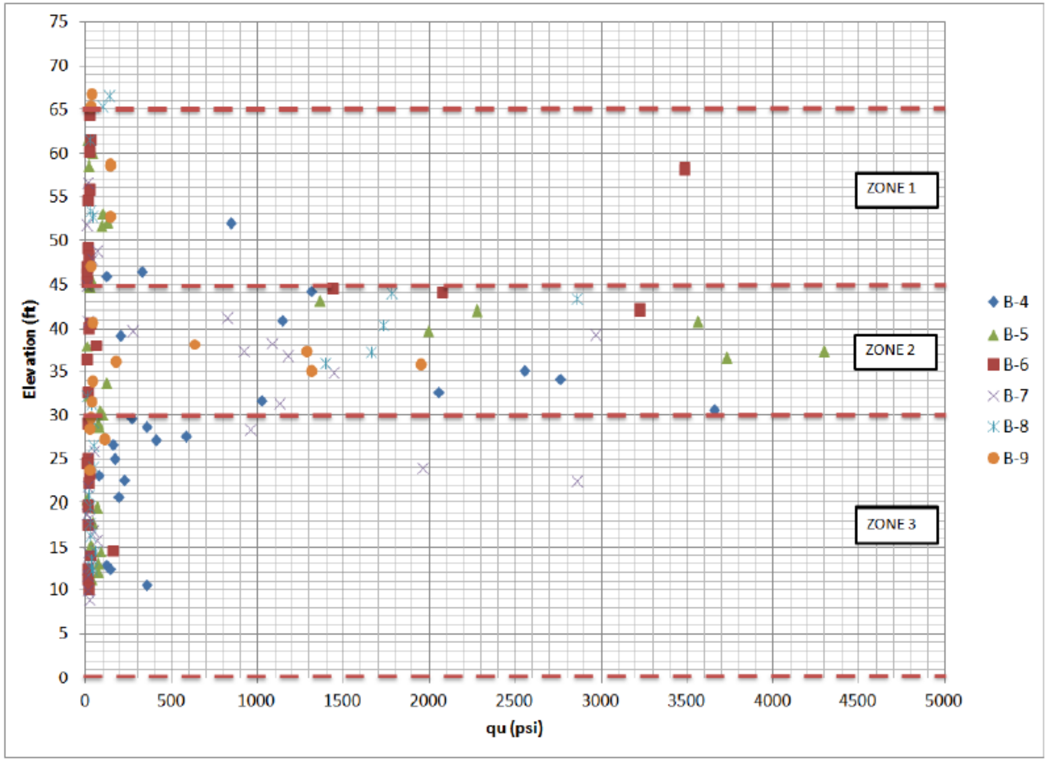
- Raw data shows a wider spread of compressive strengths
- 4 methods reduce the spread of the data closer to the geometric mean
  - FDOT method
  - FDOT* method
  - Limiting method
  - LN Transform method



Compressive Strength, qu (tsf)					
Stats	Raw Data	Limiting	FDOT	FDOT*	LN Trans
Average	46.60	39.20	33.29	34.99	28.91
Median	26.80	26.80	24.88	25.12	24.25
Maximum	944.81	120.00	112.74	138.60	76.56
Minimum	2.63	2.63	2.63	2.63	9.06
Std. Dev.	69.30	31.82	23.96	26.87	17.12
CV	1.487	0.812	0.720	0.768	0.592
Count	470	470	438	446	381

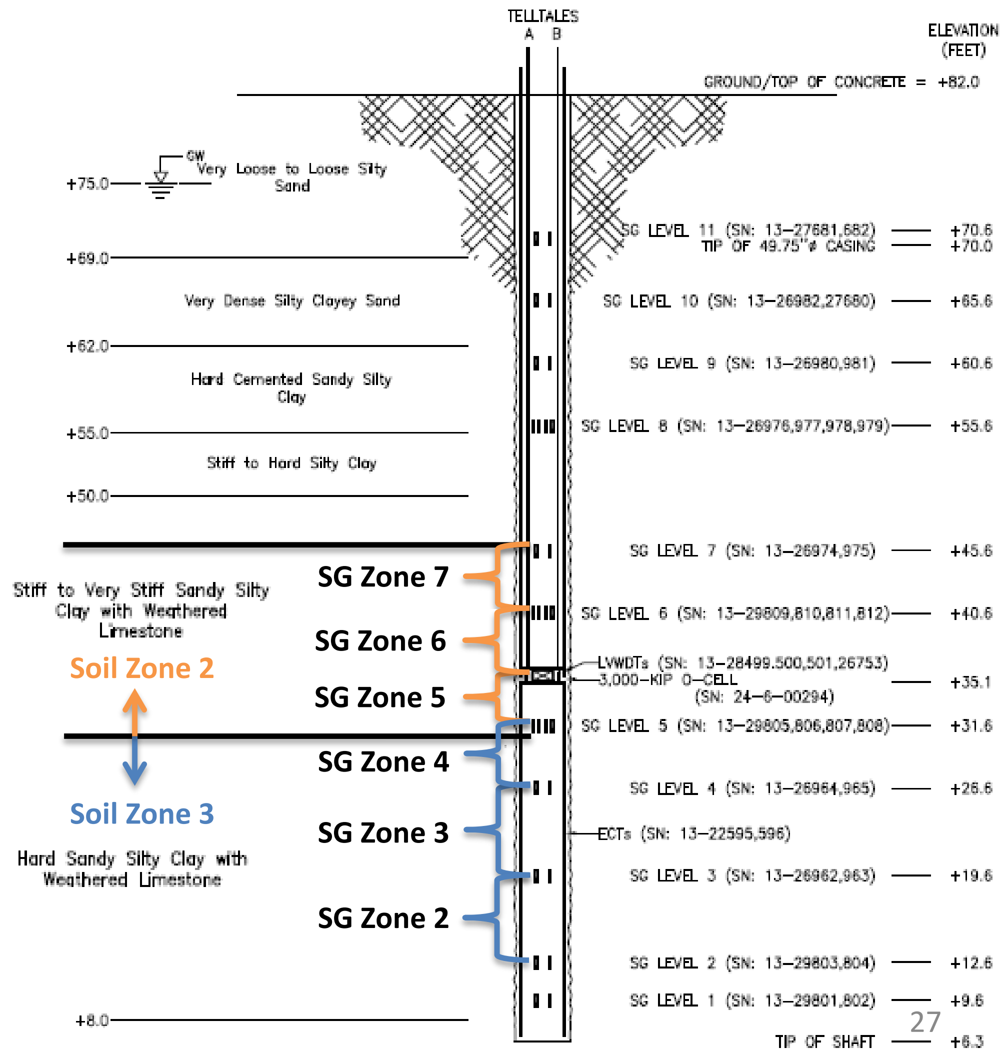
Little River Bridge Site

- Little River had a large degree of variability
- qu stratification indicated 3 distinct layers
  - 2 layers contained limestone formations
    - Zones 2 and 3
- Would qu values obtained from monitoring indicate the same stratification?



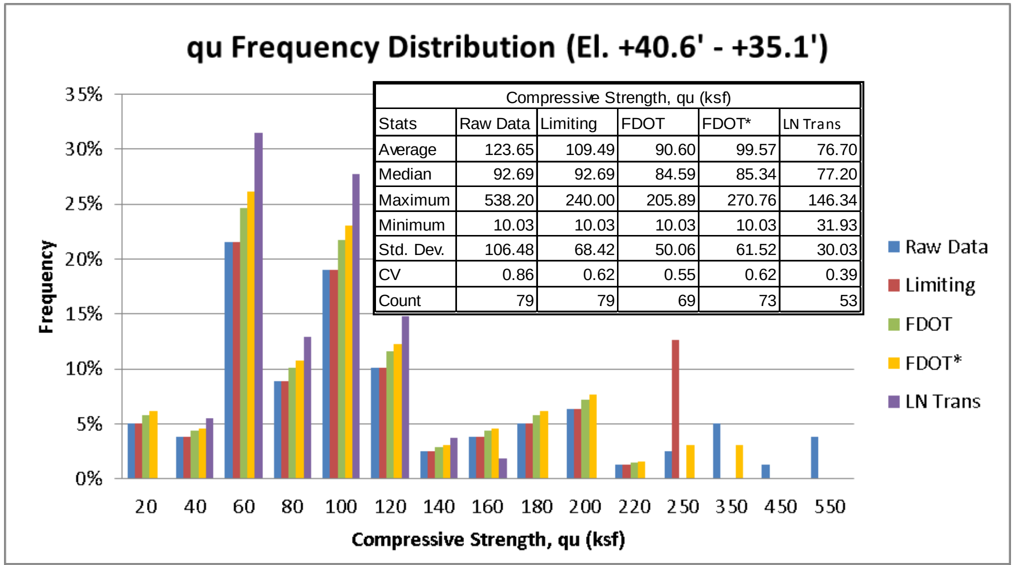
Little River – Shaft Investigation

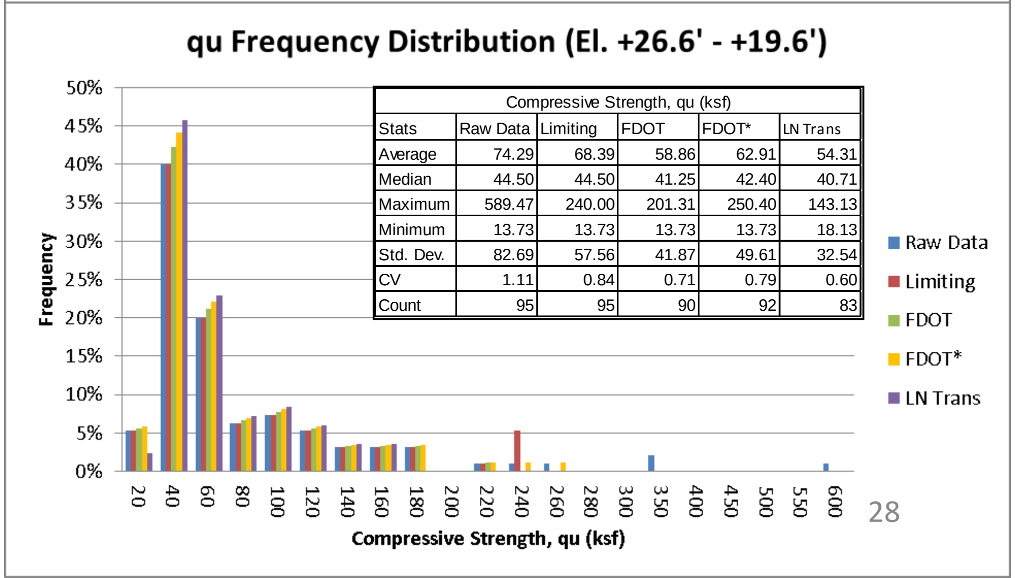
- Soil Zone 2
  - qu stratification indicates the highest compressive strengths
- Soil Zone 3
  - qu stratification indicates lower compressive strengths
- SG Zones 7 through 4
  - Mobilized or close to mobilization
- SG Zones 2 and 3
  - Further away from mobilization



qu Stratification

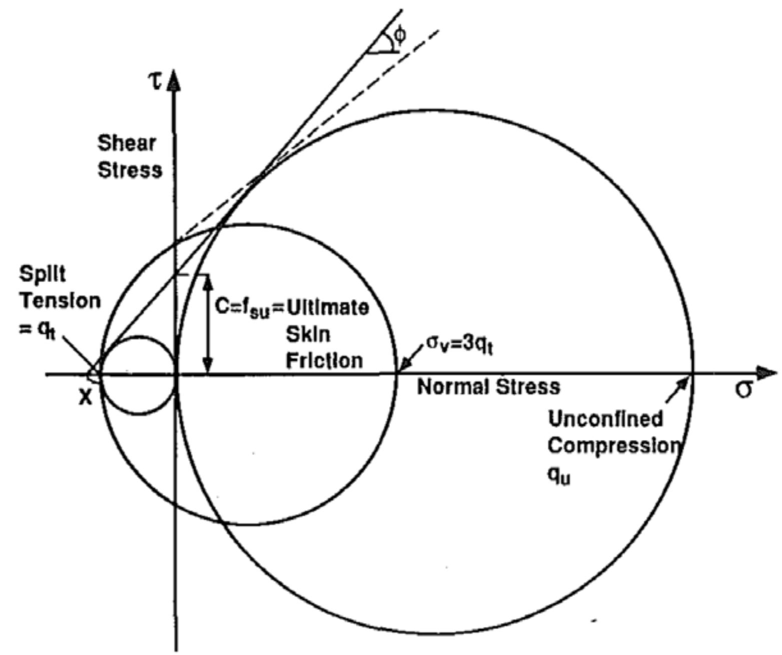
- Monitoring results indicated the same qu stratification as the core data
  - More high end qu values indicated in Zone 2
  - Less than 10% of the zone 2 values were 280 psi or less
  - Half of the zone 3 values were 280 psi or less
- Majority of values fell within the compressive strength range used for lab drilling
  - 140 psi to 1667 psi
  - 20 ksf to 240 ksf





Estimating Shaft Capacity

- FDOT recommended method for drilled shafts socketed into limestone
  - Soils and Foundation Handbook 2015
- Incorporates split tensile strength in capacity estimates
  - Allows adjustments to be made based on limestone formation
  - qt/qu ratio

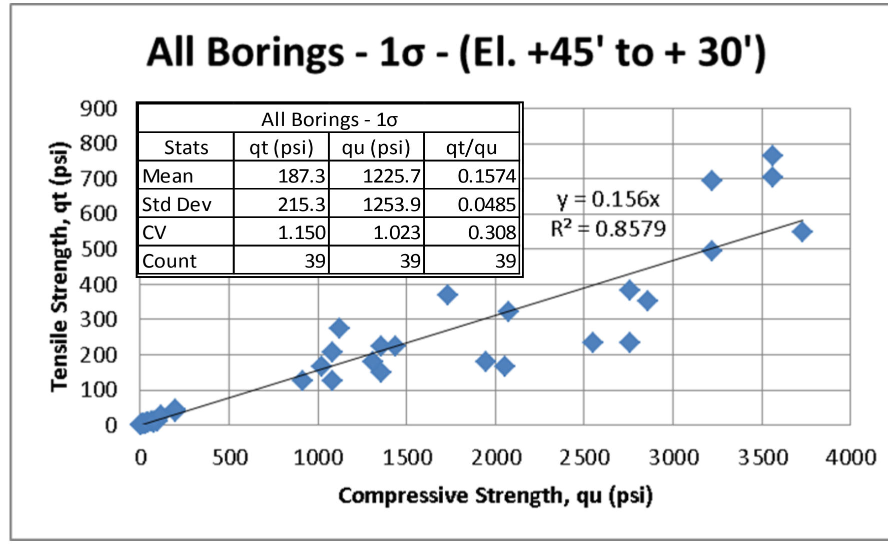


$$f_{su} = \mathrm{c} = \frac{1}{2}\sqrt{q_u}\sqrt{q_t}$$

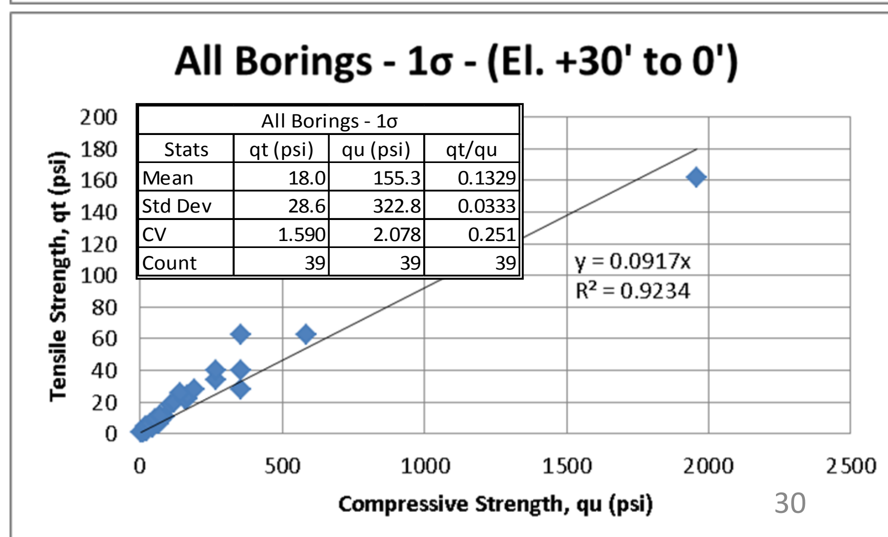
(McVay et al, 1992)

qt Assessment

- qt-qu pairs were created for Little River from available core data
- qu and qt values that fall within 1 vertical foot of one another are paired together
  - Same core run
- The mean and standard deviation of the data set are found
- qt/qu ratios that fall outside of 1 standard deviation from the mean are eliminated
  - Remaining qt-qu pairs are plotted
- This was done to determine the qt/qu slope for each soil zone
  - General qt/qu range thought to be 0.1 to 0.3



All Borings - 1σ			
Stats	qt (psi)	qu (psi)	qt/qu
Mean	187.3	1225.7	0.1574
Std Dev	215.3	1253.9	0.0485
CV	1.150	1.023	0.308
Count	39	39	39



All Borings - 1σ			
Stats	qt (psi)	qu (psi)	qt/qu
Mean	18.0	155.3	0.1329
Std Dev	28.6	322.8	0.0333
CV	1.590	2.078	0.251
Count	39	39	39

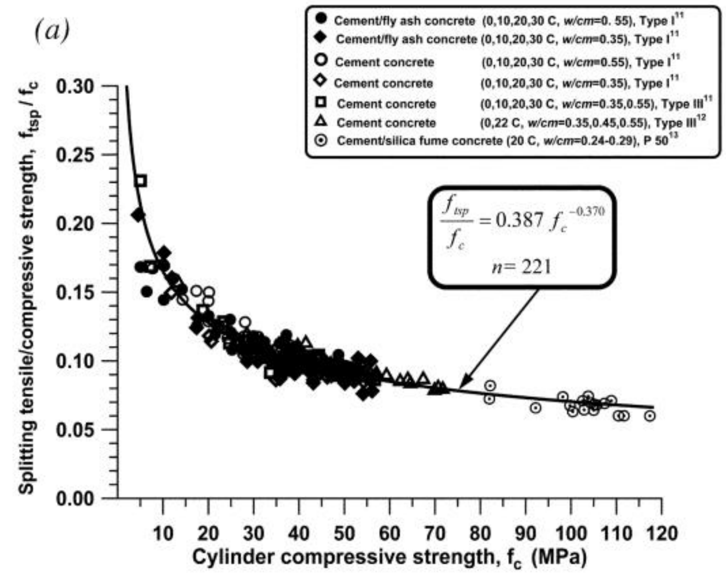
Are the qt Adjustments Valid?

- Creates qt-qu pairs using dissimilar geomaterials
- Developed pairing criteria
  - Similar dry unit weights
    - Similar rock mass constituents
  - Similar moisture contents
    - Similar void structure
    - Porosity and void ratio
  - Satisfies Gw = Se condition
    - Assume degree of saturation, S = 1
- Produced very few pairs
  - Less than 5 pairs per segment were available at Overland
    - 4 additional cores were taken within 10 feet of the shaft
- Does not provide real time assessment of tensile strength or skin friction
- Turned to literature for alternative methods – Johnston Criterion

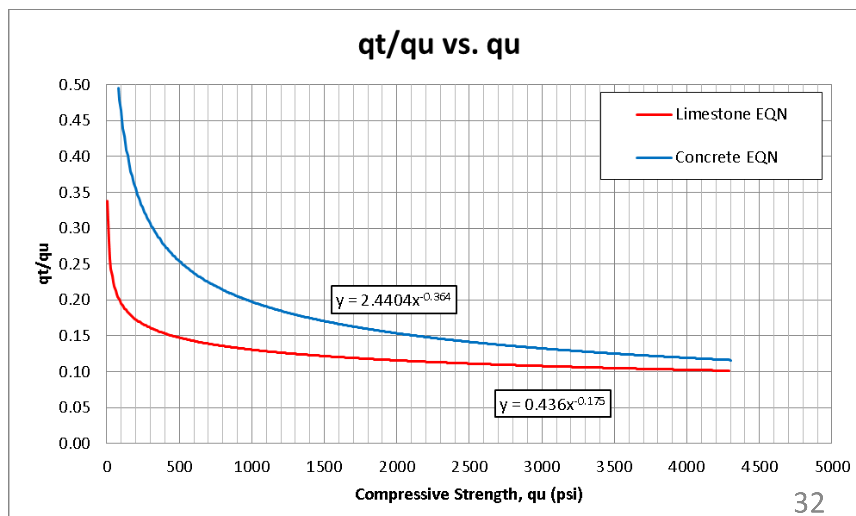
Boring/ Shaft-Core	Sample No.	Test Type	Moisture (%)	Dry Density (pcf)	Max Load (lbs)	S.T. Strength (psi)	q(u) (psi)	Displ. @ Fail. (in)	Strain @ Fail. (%)
(38)									
2/1-1	1	T	15.6	106.5	79.3	13.9		0.0344	
(48)									
2/1-2	1	T	59.8	63.3	39.6	6.5		0.0863	
	2	U	58.2	64.7	128.6		38.1	0.1904	3.67
	3	T	60.1	63.2	66.0	8.1		0.0655	
	4	U	69.0	59.7	61.1		16.9	0.1679	3.34
	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	1.08
	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	

Johnston Criterion

- States qt/qu = B/M for drained conditions
- As compressive strength approaches zero B = 1
  - B = 1 indicates a normally consolidated clay
- M represents the relationship between ϕ’ and qu
  - As compressive strength increases, M increases
- Johnston developed B and M from 100 data sets including results from lightly OC clay to very hard rock
  - 1700 individual tests
  - Each data set included
    - At least 3 triaxial tests
    - Split tension testing
    - Direct tension testing
- Used least squares analysis to derive curve equations
  - Developed 1 general equation
  - Developed 5 specific material equations
  - 1 for carbonate materials (limestone)



Anoglu (2006)



Johnston Criteria

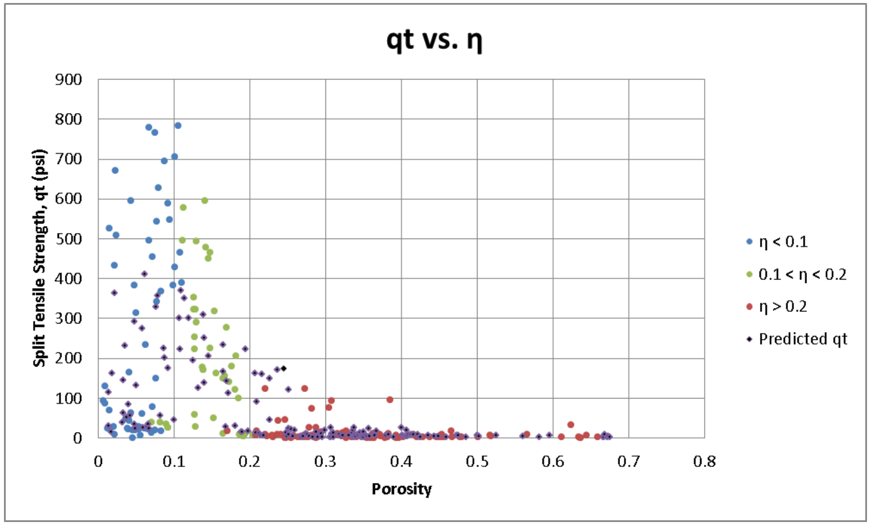
- Provides a qt/qu range of 0.09 to 0.29 for material strengths 10 to 10,000 psi
  - In agreement with FDOT and UF estimated range
- Used Johnston equation for limestone and predicted qt values using qu data at Little River
- Predicted qt values are then designated the same dry unit weight and moisture content as the qu value from which they came
- These predicted qt values are plotted as qt versus dry unit weight and moisture content, separately
  - Do the predicted values follow the same trend as the measured values?
- Same procedure was completed using core data from all of Florida

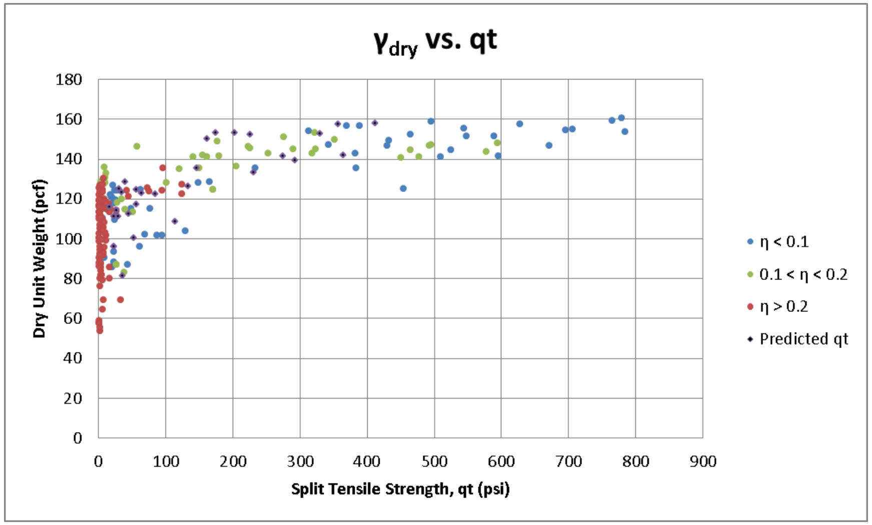
Florida Core Data Sites

- 17th Street Causeway
- Acosta Bridge Research (Modulus)
- BR720153 SR-9 (I-95) Overland
- CR-326 @ Waccasa River
- HEFT / SR 874 PD&E
- I-295 Buckman Bridge
- I-295 Dames Point Bridge
- I-95 @ I-295 Cloverleaf
- I-95 Fuller Warren Bridge
- Jewfish Creek
- MIC- People Mover Project
- NW 12th Ave (SR 933) Miami River Bridge
- NW 36th Street Bridge
- Pump Station at Bal Harbour (96th St & Indian Creek)
- Radio Tower Everglades Academy (Florida City)
- SR-10 @ CSX RR (Beaver St. Viaduct), Duval Co.
- SR-20 @ Lochloosa Creek, Alachua Co.
- SR-25 @ Santa Fe River
- SR30/US98 @ Aucilla River (District 3)
- SR-9 (I-95) Overland Bridge
- US-90 Victory Bridge (District 3)
- Verona Ave Bridge Over Grand Canal
- Wall At Service Road South of Snake Creek

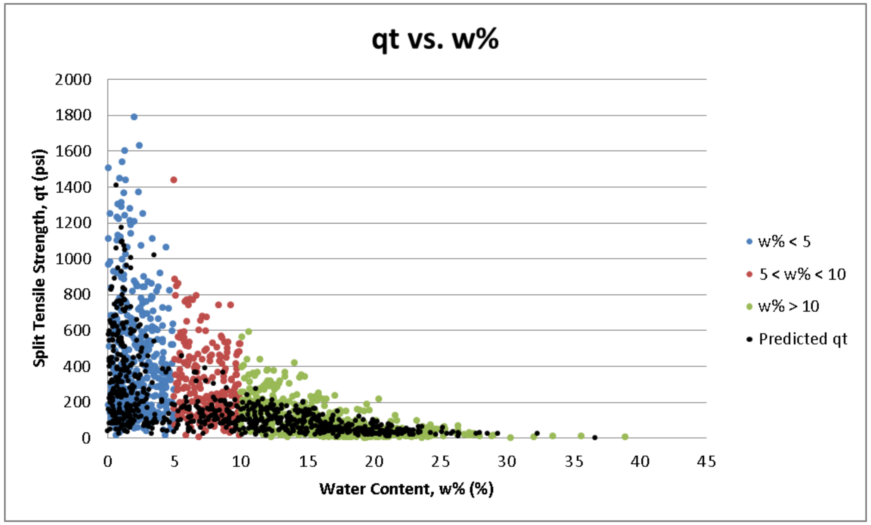
Predicted Split Tensile Values

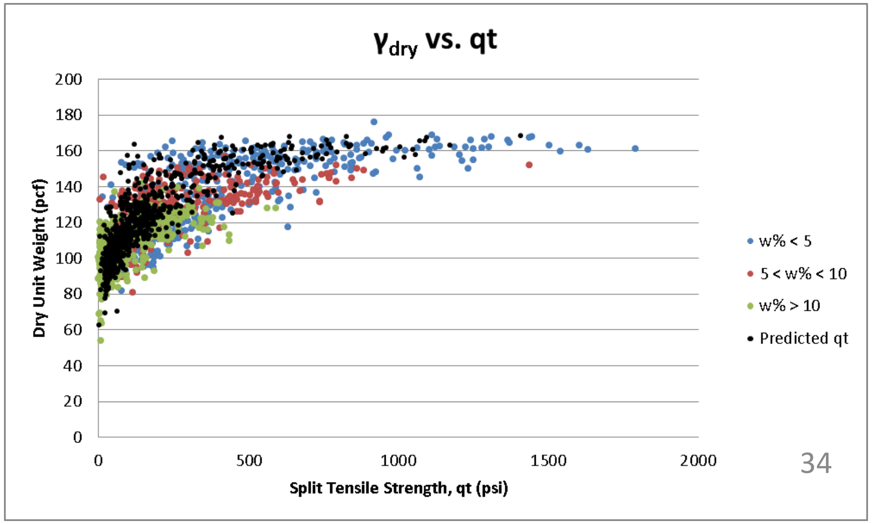
Little River, Quincy Florida





All of Florida





Little River Analysis – Raw Data

Arithmetic Mean (Raw Data)										
Shaft Section (Strain Gage Levels)	Elevation Range (ft)		Measured Mean (O-cell) (ksf)	Predicted Mean (Monitoring) (ksf)	Percent Difference	Predicted Median (Monitoring) (ksf)	Predicted Minimum (Monitoring) (ksf)	Predicted Standard Deviation (Monitoring)	Predicted CV (Monitoring)	Count
SG7 to SG6	45.60	40.60	21.1	19.67	-6.79%	9.77	2.42	25.88	1.32	73
SG6 to O-cell	40.60	35.1	20.6	22.09	7.21%	17.38	2.28	17.10	0.77	79
O-cell to SG5	35.10	31.6	21.4	19.46	-9.08%	12.32	3.56	24.33	1.25	52
SG5 to SG4	31.60	26.6	13.6	13.95	2.60%	9.85	4.06	11.11	0.80	67
SG4 to SG3	26.60	19.6	9.7	13.77	41.95%	8.90	3.04	13.46	0.98	95
SG3 to SG2	19.60	12.6	9.9	13.89	40.28%	8.34	1.27	27.47	1.98	104
Average - SG7 to SG4			19.04	18.83	-1.11%	Note: The highlighted sections are zones where T-Z curve and strain gage load distribution data indicate full side shear mobilization has not been achieved. Zones that are not highlighted indicate side shear has been mobilized or is approaching mobilization.				
Total Load (kips) - SG7 to SG4			4545	4495	-1.11%					
Average - SG7 to SG2			15.12	16.71	10.50%					
Total Load (kips) - SG7 to SG2			6269	6928	10.50%					

- Top 4 zones have reached or are close to full side shear mobilization
  - Indicated by T-Z curves and Strain gage load distribution
- Highlighted zones are further away from side shear mobilization
- 1% difference between the O-cell and predicted monitoring results
- Monitoring provides a slight underestimation which is desired

Little River Analysis – Limiting Method

Limiting Ultimate Values										
Shaft Section (Strain Gage Levels)	Elevation Range (ft)		Measured Mean (O-cell) (ksf)	Predicted Mean (Monitoring) (ksf)	Percent Difference	Predicted Median (Monitoring) (ksf)	Predicted Minimum (Monitoring) (ksf)	Predicted Standard Deviation (Monitoring)	Predicted CV (Monitoring)	Count
SG7 to SG6	45.60	40.60	21.1	16.10	-23.72%	9.77	2.42	13.71	0.85	73
SG6 to O-cell	40.60	35.1	20.6	20.47	-0.63%	17.38	2.28	12.58	0.61	79
O-cell to SG5	35.10	31.6	21.4	16.84	-21.31%	12.32	3.56	12.66	0.75	52
SG5 to SG4	31.60	26.6	13.4	13.65	1.88%	9.85	4.06	9.95	0.73	67
SG4 to SG3	26.60	19.6	9.7	13.09	34.99%	8.90	3.04	10.49	0.80	95
SG3 to SG2	19.60	12.6	9.9	11.46	15.75%	8.34	1.27	9.49	0.83	104
Average - SG7 to SG4			18.98	16.86	-11.21%	Note: The highlighted sections are zones where T-Z curve and strain gage load distribution data indicate full side shear mobilization has not been achieved. Zones that are not highlighted indicate side shear has been mobilized or is approaching mobilization.				
Total Load (kips) - SG7 to SG4			4533	4025	-11.21%					
Average - SG7 to SG2			15.09	14.91	-1.16%					
Total Load (kips) - SG7 to SG2			6257	6184	-1.16%					

- Provides a good conservative estimate
- 1% difference over the entire 33' span of the shaft
  - Includes zones that are not fully mobilized

Little River Analysis – FDOT* Method

FDOT* Method (Each Section)										
Shaft Section (Strain Gage Levels)	Elevation Range (ft)		Measured Mean (O-cell) (ksf)	Predicted Mean (Monitoring) (ksf)	Percent Difference	Predicted Median (Monitoring) (ksf)	Predicted Minimum (Monitoring) (ksf)	Predicted Standard Deviation (Monitoring)	Predicted CV (Monitoring)	Count
SG7 to SG6	45.6	40.6	21.1	12.25	-41.93%	8.85	2.42	8.61	0.70	65
SG6 to O-cell	40.6	35.1	20.6	17.66	-14.26%	16.12	6.57	8.06	0.46	65
O-cell to SG5	35.1	31.6	21.4	15.00	-29.92%	12.04	3.56	10.48	0.70	49
SG5 to SG4	31.6	26.6	13.4	10.28	-23.29%	8.16	4.06	5.25	0.51	57
SG4 to SG3	26.6	19.6	9.7	10.34	6.62%	8.12	3.04	5.89	0.57	86
SG3 to SG2	19.6	12.6	9.9	10.01	1.10%	8.17	1.27	6.18	0.62	100
Average - SG7 to SG4			18.98	13.80	-27.28%	Note: The highlighted sections are zones where T-Z curve and strain gage load distribution data indicate full side shear mobilization has not been achieved. Zones that are not highlighted indicate side shear has been mobilized or is approaching mobilization.				
Total Load (kips) - SG7 to SG4			4533	3296	-27.28%					
Average - SG7 to SG2			15.09	12.26	-18.71%					
Total Load (kips) - SG7 to SG2			6257	5086	-18.71%					

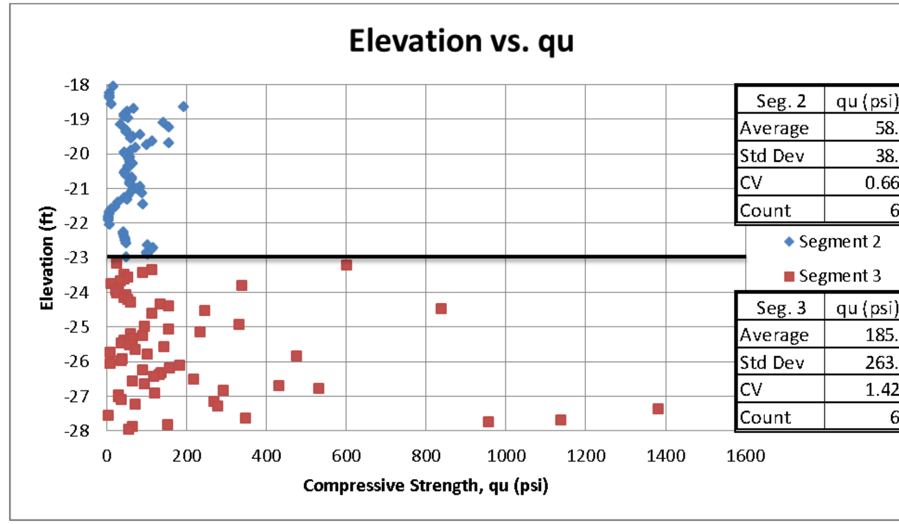
- Provides a more conservative estimate
  - Streamlined result
- FDOT and LN Transform methods produced the largest underestimates
  - Eliminated from future analysis

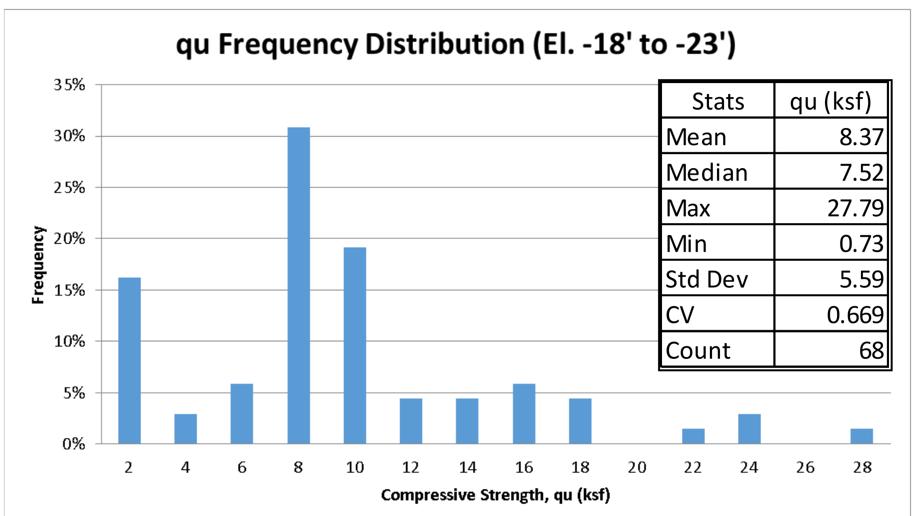
Overland – Jacksonville, Florida

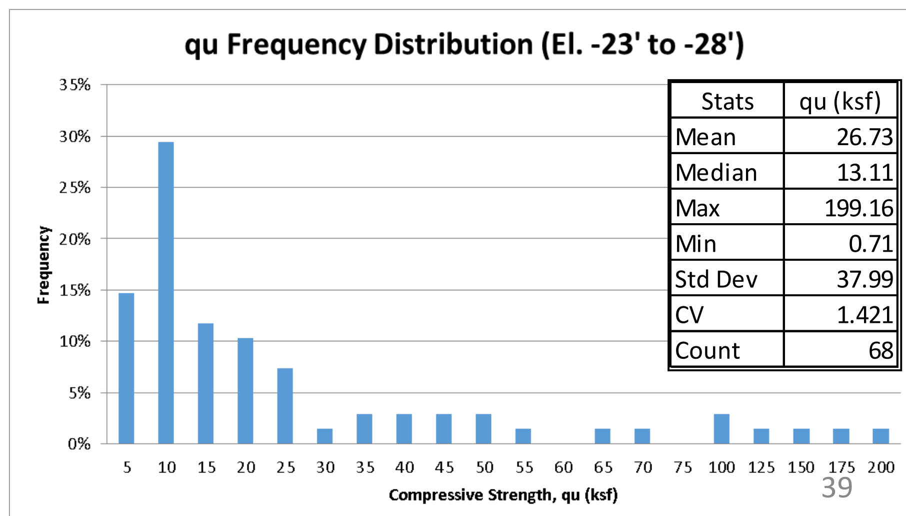
- Bauer BG30 drill rig was used for shaft installation
- No sensors had to be installed for monitoring
  - Copied signal from built in sensors
- 60 inch diameter shafts installed
- 3 Statnamic load tests
- Strata was less variable
  - 2 distinct soil layers
  - Very low strength rock present
- Only 2 strain gage segments available for comparison
  - Geomaterial comparable to limestone
  - Rock Auger was used to complete the drilling
  - Statnamic results indicated the section was at or close to failure

Overland Field Monitoring of qu

- Segment 1
  - Average qu = 58.1 psi
  - Segment was fully mobilized
- Segment 2
  - Average qu = 185.6 psi
  - Segment was not fully mobilized







Overland Analysis

Segment	Status	Statnamic	Raw Data		FDOT*		Limiting	
		fs (ksf)	fs (ksf)	% Diff	fs (ksf)	% Diff	fs (ksf)	% Diff
2	Fully Mobilized	2.06	1.90	-7.73	1.88	-8.56	1.90	-7.73
3	Approaching Mobilization	4.68	5.30	13.34	3.72	-20.53	5.30	13.34

- Segment 2 is the only portion of all 4 shafts, including Little River, where full side shear mobilization was confirmed by T-Z curves
- Results show a 7.7% difference between measured and predicted skin friction for segment 2
  - 0.16 ksf difference
- Very low strength material
  - Very little core data was able to be recovered at these depths
  - 4 borings within 10 feet of the shaft only produced 4 qt samples and 2 qu samples for segment 2

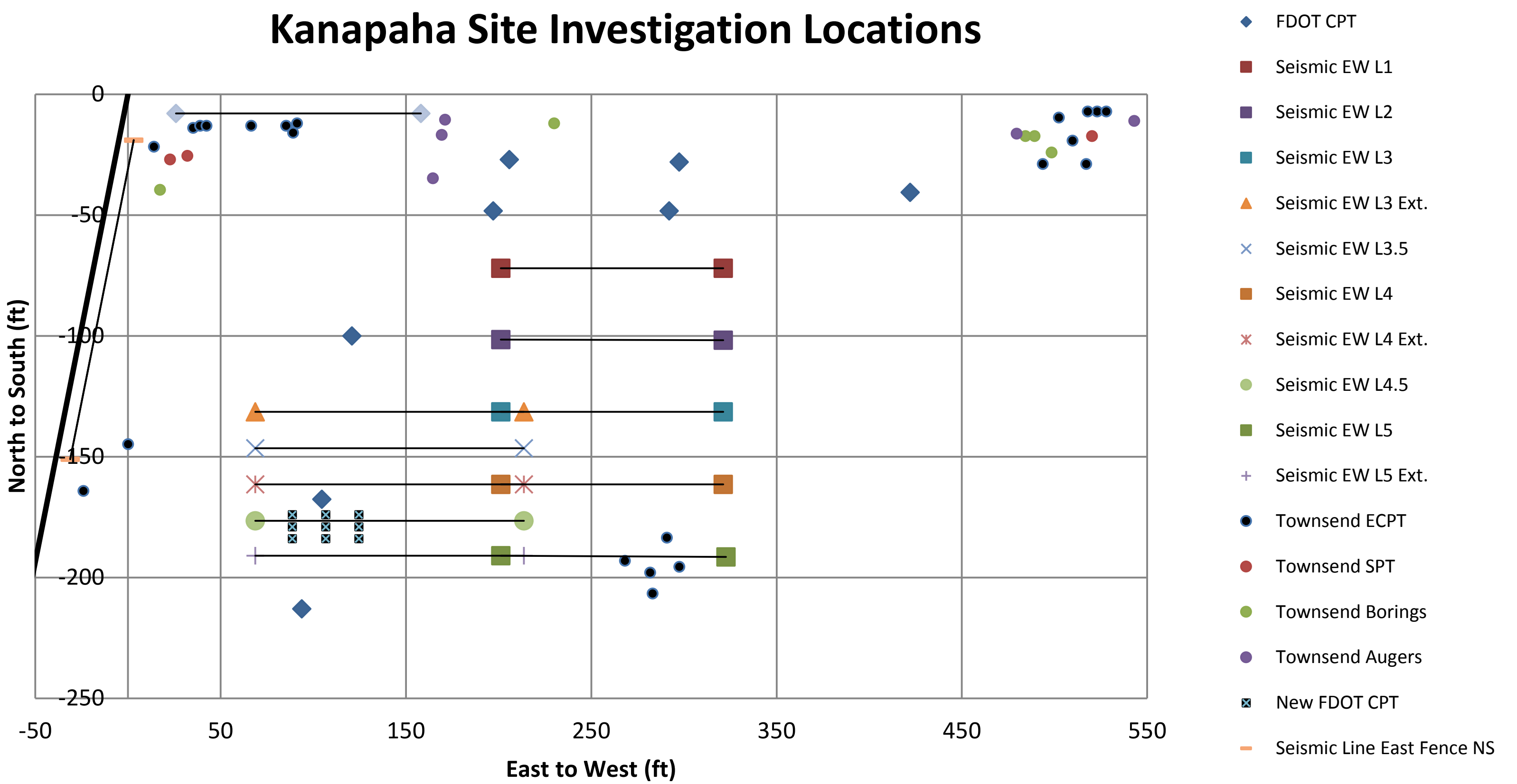
Pilot Project Results

- Indicated qu stratification at both locations
- Accurately estimated skin friction in both locations where T-Z curves indicated full side shear mobilization had been achieved or was closely approaching
- Little River was highly variable throughout with very high rock strengths present
- Overland was less variable with very low rock strength present
- Monitoring was successful even with changing conditions
  - 2 different rig types
  - 2 different drilling crews
  - 2 different bit diameters
- Produced promising results heading into the final load test at Kanapaha in Gainesville, Florida
  - Highly weathered limestone
    - Poor recoveries
  - Highly variable soil/rock conditions

Kanapaha – Final Load Test

- FDOT Kanapaha site will be used for the final load test
- Static load test
  - 3 foot diameter shafts
  - 45 – 55 feet of embedment depth
  - Test and reaction shafts will be instrumented
- Large amount of site investigation completed
  - 42 CPT's
  - 7 SPT's
  - 5 core borings
  - 5 auger borings
  - 12 seismic lines
- Very little intact rock has been recovered
  - Excellent location to show the value of monitoring efforts

Kanapaha Site Investigation Locations



Kanapaha Limestone

Typical Limestone Recovered

Recovered 08/12/2015

Future Plans

- Determine ideal location at Kanapaha for final load test
- Design test and reaction shafts based on core findings
- Perform static load test
  - Make monitoring predictions for skin friction
- Analyze load test results
- Compare the results
- Draft final report

Questions?