Implementation of Measuring While Drilling Shafts in Florida (FLMWDS) BDV31-977-91

FDOT GRIP Meeting

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Introduction

- Interest in measuring while drilling, MWD, is growing worldwide as far more data can be obtained from continuously taking measurements during rock drilling.
  - The data collected can be used in the design of foundations and to provide QA/QC during bored shaft/pile construction (e.g., drilled shafts and ACIP piles).
- However, this is a new area, and limited research has been performed on MWD techniques for measuring in situ rock strength, especially in Florida.
- FDOT Contract BDV31-977-20 on measuring rock strength during drilled shaft installations in Florida took the first steps in the delineation of subsurface variability and strength assessment through direct measurements during shaft construction.
  - For every shaft that was drilled/monitored, UF researchers were able to provide a profile of rock strength with a degree of precision that could not be achieved through any current conventional method.
  - The monitoring approach directly addressed the spatial variability in both the horizontal and vertical directions that exist in Florida and significantly increased the quantity of strength data obtained.

Project Background

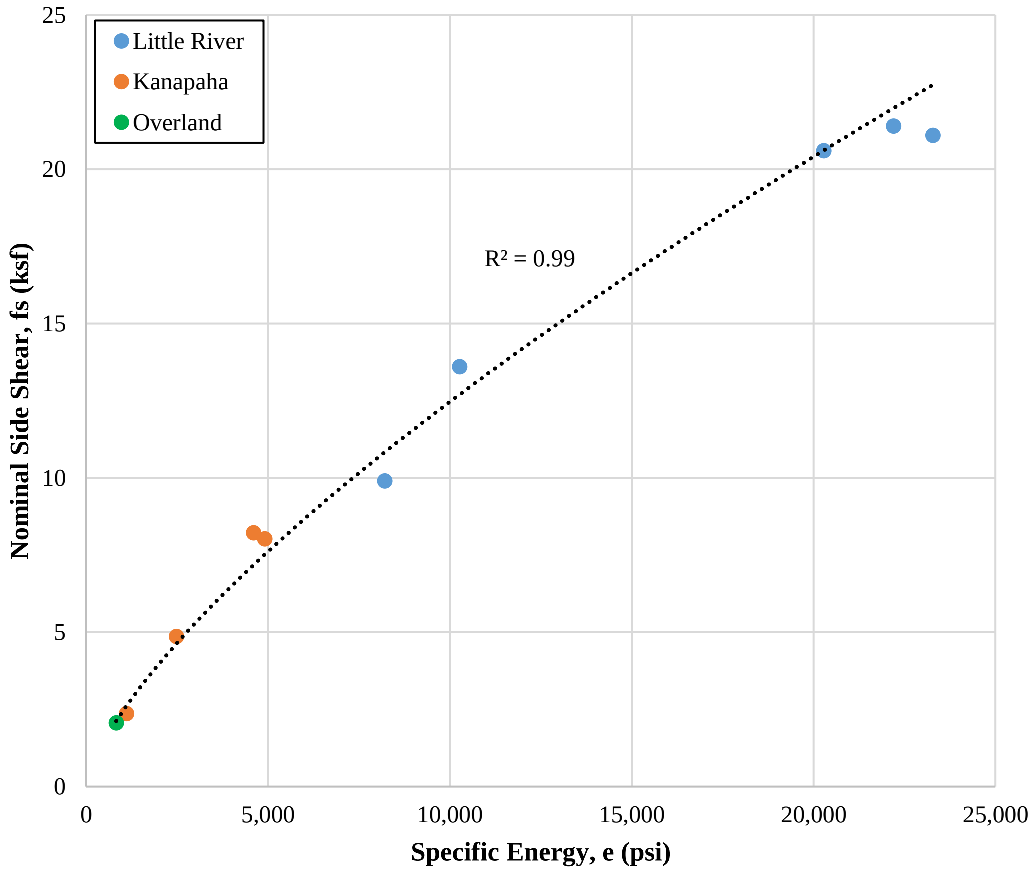
- MWD involves continuously monitoring and recording drilling data during the drilling process
  - Conducted manually or with computerized systems
  - Sensors are placed on the drill rig to monitor a series of drilling parameters in real-time without interference
  - Currently exist on many hydraulic rigs (Bauer, IMT, SoilMec, etc.)
- Monitored data typically are displayed in real-time and often recorded for further analysis
  - Optimize drilling performance
  - Provide detailed records of geological formations
- The International Standards Organization (ISO) recently created standards for geotechnical MWD
  - Specify equipment requirements, operations, and data logging
  - ISO specifications do not cover the assessment of in situ rock strength or geospatial variability

Project Background

- During BDV31-977-20, three separate drilled shaft sites were monitored with variations in the following categories:
  - Limestone formations encountered, drill rigs used to install the shafts, shaft diameters, drilling crews, and rock auger configurations.
- In total, 10 measured (Load test – conventional method) versus predicted (MWD – developed method) data points were obtained with an average error of 0.6% between the measured and predicted.
- The load tests included three of the most widely used methods:
  - Bi-directional Osterberg, Top-down Static, and Statnamic.
- A bias analysis (measured/predicted) showed good agreement but only 10 data points – not sufficient to define CV and LRFD phi

Project Background

- Using the same 10 data points collected in BDV31-977-20, it was recently discovered that the assessment of specific energy also shows excellent correlation with the mobilized unit side shear obtained from load testing
  - Using only rock augers
- Data was collected from three monitored sites, each of which contained a different limestone formation (regional correlation)
- Measuring rock strength through the assessment of specific energy in combination with load testing allows drilled shaft MWD to be used in any rock formation
  - Site-specific correlation
  - Regional correlation (displayed)
  - Possible state-wide correlation



Project Background

- In rock drilling, specific energy is defined as the energy required to remove/excavate a unit volume of rock
  - Must be analyzed in a depth-referenced format (unit volume) w/ individual parameters properly averaged prior to calculating specific energy
  - Time-referenced data are observations collected within a unit volume of rock
    - Must be converted to a unit volume/depth frame of reference
- The specific energy equation Teale developed for non-percussive rotary drilling requires measuring five drilling parameters independently:

$$e = \frac{F}{A} + \frac{2\pi NT}{Au}$$

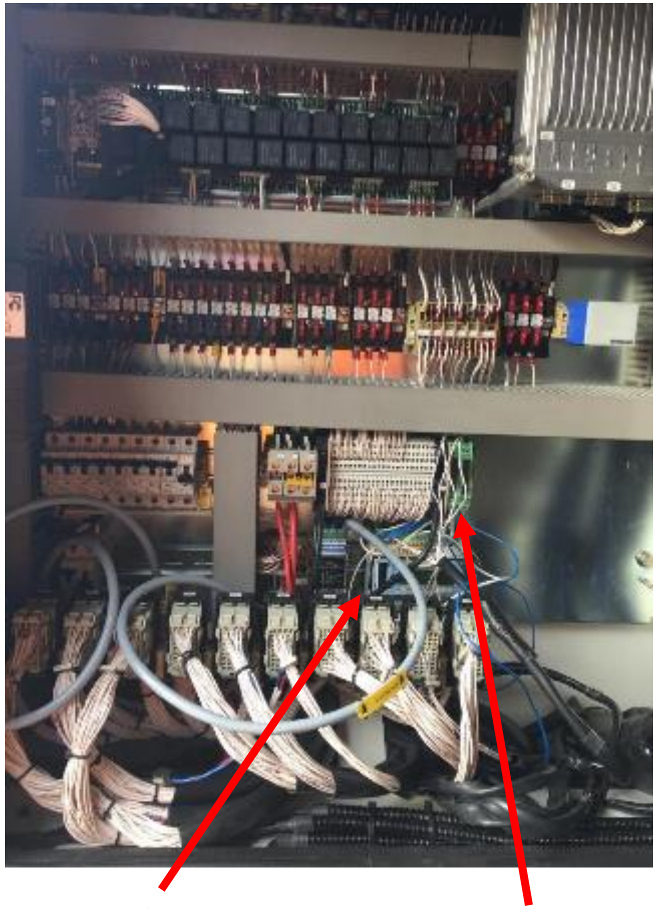
Where:

- e = Specific Energy (psi)
- T = Torque (in-lbs)
- F = Crowd (lbf)
- u = Penetration rate (in/min)
- N = Rotational speed (RPMs)
- A = Cross-sectional area of the excavation (in^2) defined by the bit diameter, d (in)

Project Objectives

- The primary objectives of this research were:
  - Further validate the methods developed in BDV31-977-20
  - Investigate any irregularities in strength prediction (different drilling tools, variable rock formations, etc.) and/or construction monitoring (Lutz, B-tronic, etc.)
  - Further investigate specific energy versus load testing side shear
  - Continue to develop MWD as a QA/QC tool for drilled shaft construction
    - Like the practice of monitoring driven piles with 100% dynamic testing during construction
- The secondary objectives were to:
  - Investigate monitoring mechanically driven drill rigs
    - Unfortunately, all drill rigs used were hydraulically driven
  - Assess the variability of each site using data obtained from core samples and MWD.
- For the research, MWD was conducted at two separate locations, Selmon Parkway and County Road 250 (CR 250)

Task 1 – Field Monitoring at Selmon Parkway



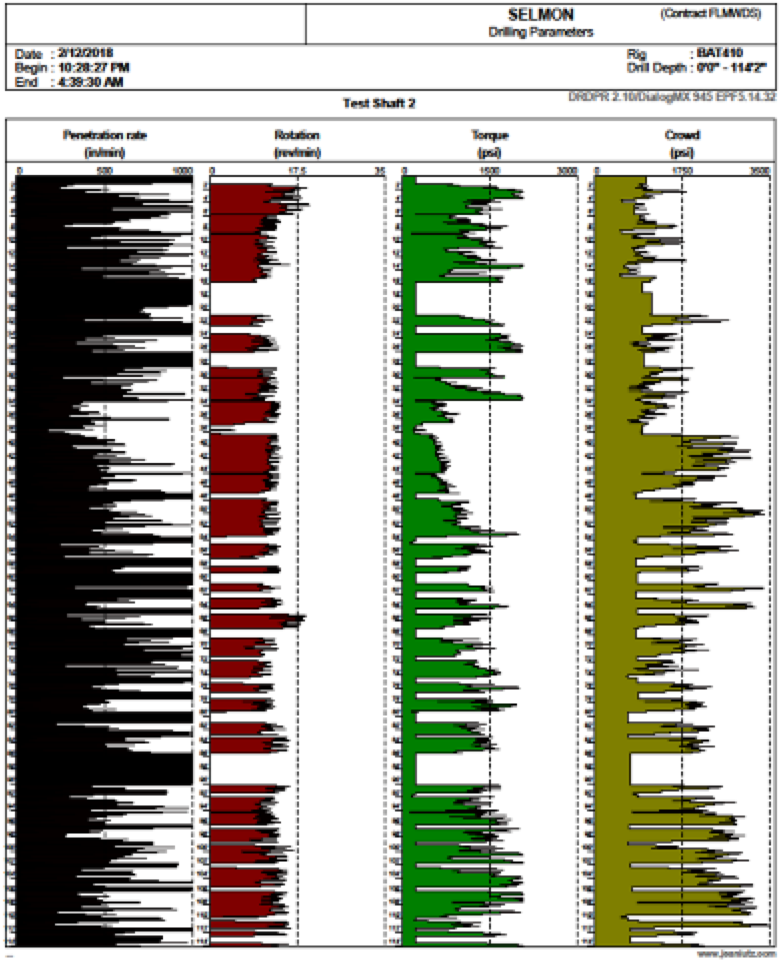
Junction Box
Internal Components

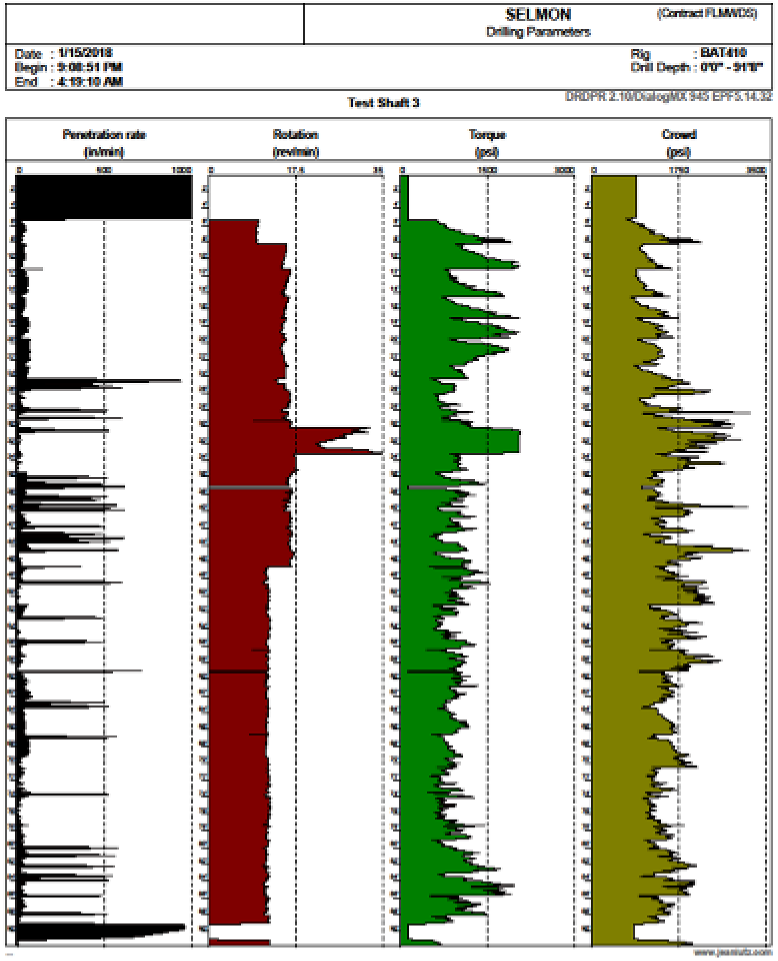
Copy Modules

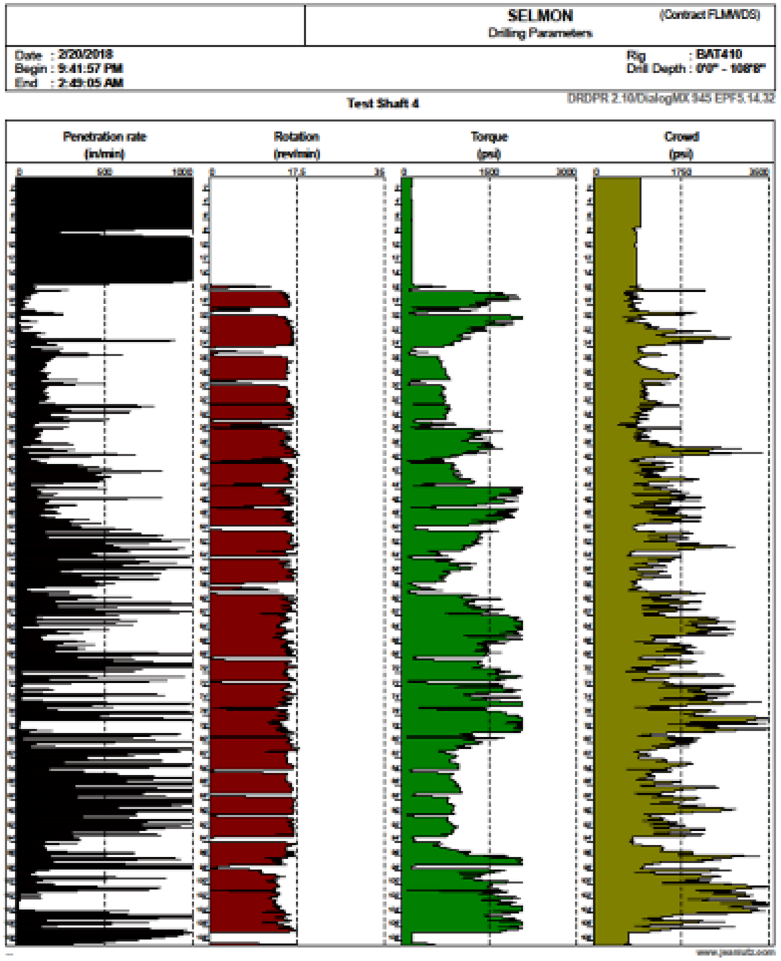
Task 1 – Field Monitoring at Selmon Parkway

Monitoring at a safe distance

Task 1 – Field Monitoring at Selmon Parkway



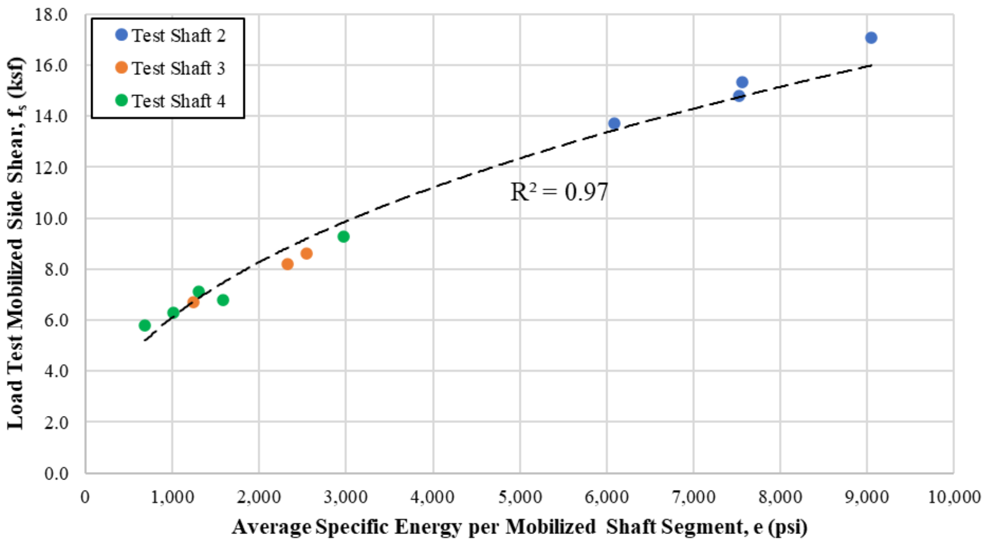




Raw data profiles of drilling parameters

Task 2 – Data Reduction and Analysis at Selmon

- From all three test shafts at Selmon Parkway, 12 data points were collected and used to develop the MWD specific energy—load test side shear correlation
  - Four segments from Test Shaft 2
  - Three segments from Test Shaft 3
  - Five segments from Test Shaft 4
- Excellent correlation was found between specific energy and load test unit side shear using a unique drilling tool (rock drilling bucket)
  - Note sensitivity – 3 orders of magnitude
- The average error between the two methods (load test versus MWD) was negligible
  - Average error = 0.3%

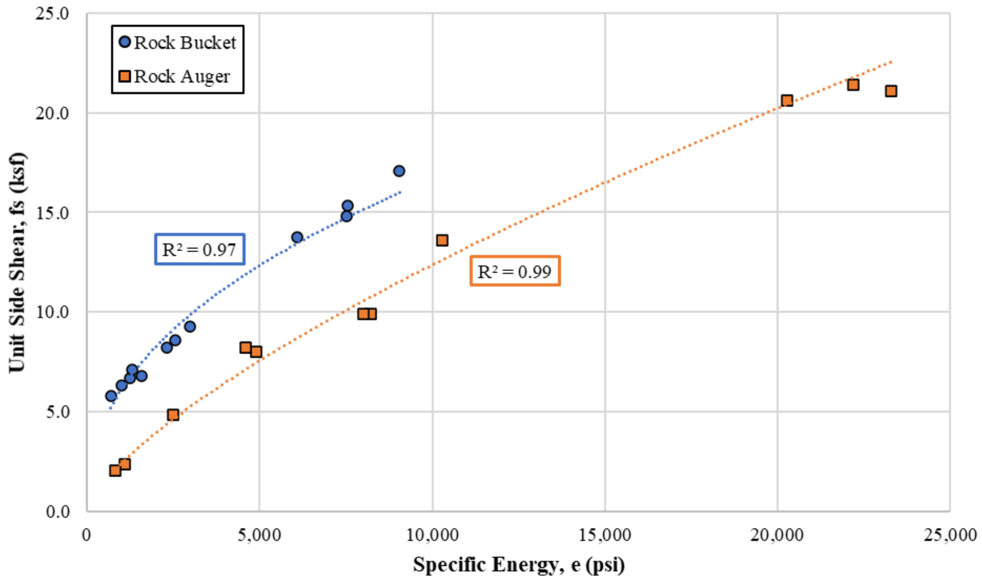


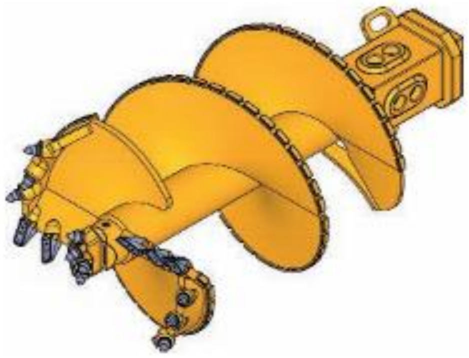
Specific Energy-Side Shear Correlation Summary of Statistics

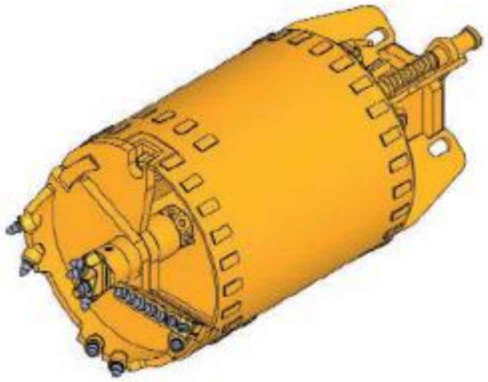
Test Shaft	Segment	EL_{Top} (ft)	EL_{Bot} (ft)	e (psi)	e (ksf)	LT f_s (ksf)	MWD f_s (ksf)	% Error
2	15	-83	-87	7,559	1,089	15.3	14.8	-3.4%
	16	-87	-92	9,051	1,303	17.1	16.0	-6.3%
	17	-92	-96.4	6,086	876	13.7	13.5	-1.7%
	18/Toe	-96.4	-106	7,525	1,084	14.8	14.8	0.0%
3	12	-61	-68.1	2,548	367	8.6	9.2	7.0%
	13	-68.1	-73	1,243	179	6.7	6.7	0.0%
	Toe	-73	-81.3	2,321	334	8.2	8.8	7.3%
4	5	-25	-30	686	99	5.8	5.2	-10.3%
	10	-50	-58	1,013	146	6.3	6.2	-1.6%
	11	-58	-63	1,302	188	7.1	6.9	-2.8%
	12	-63	-67	1,582	228	6.8	7.5	10.3%
	16.2	-88	-93.5	2,969	427	9.3	9.8	5.4%
							Average Error =	0.3%

Task 2 – Data Reduction and Analysis at Selmon

- Prior "e vs q_u" correlation developed in BDV31-977-20 could not be used because rock drilling buckets were used at Selmon Parkway
  - Differences in mechanical efficiency of the drilling tools due to different bit geometries
- Therefore, the researchers had to develop an alternative approach to estimate q_u via MWD while drilling with the rock drilling bucket
  - Required for rock strength assessment and site variability analysis for comparison with core samples (Task 3a)

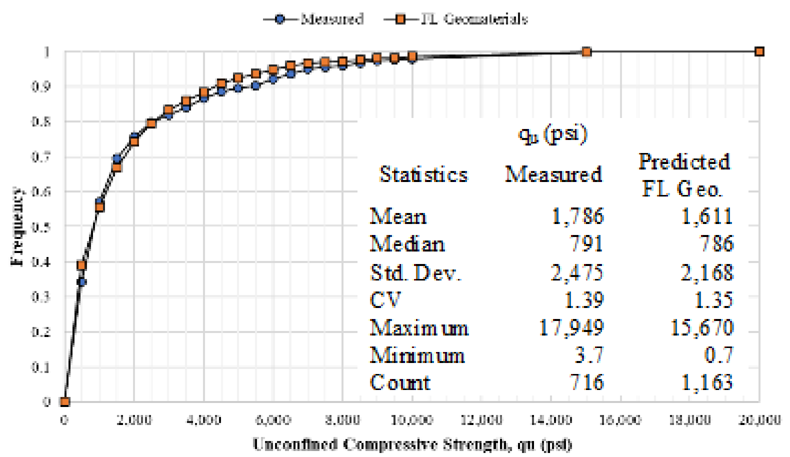



Rock Auger


Rock Drilling Bucket

Task 2 – Data Reduction and Analysis at Selmon

- In BDV31-977-20 excellent side shear estimates were made using the FDOT's Soils and Foundation Handbook recommended side shear equation (McVay et al., 1992) with q_u measured via MWD
- Tensile strength (q_t) was estimated using the FL Geomaterials equation
  - FL Geomaterials EQN defines the relationship between qu and qt
- This provided a means to estimate q_u from f_s using SFH recommendations
- Equation 3-10 was used to estimate q_u based on f_s measured from the load test results and MWD for rock strength assessment – New EQN



Substituting the Florida Geomaterials equation,

$$q_t = 0.436 \times q_u^{0.825} \quad \text{(Eq. 3-7)}$$

into the skin friction equation developed by McVay et al.,

$$f_s = {}^{1}\!/_{2} \times q_u^{0.5} \times q_t^{0.5} \quad \text{(Eq. 3-8)}$$

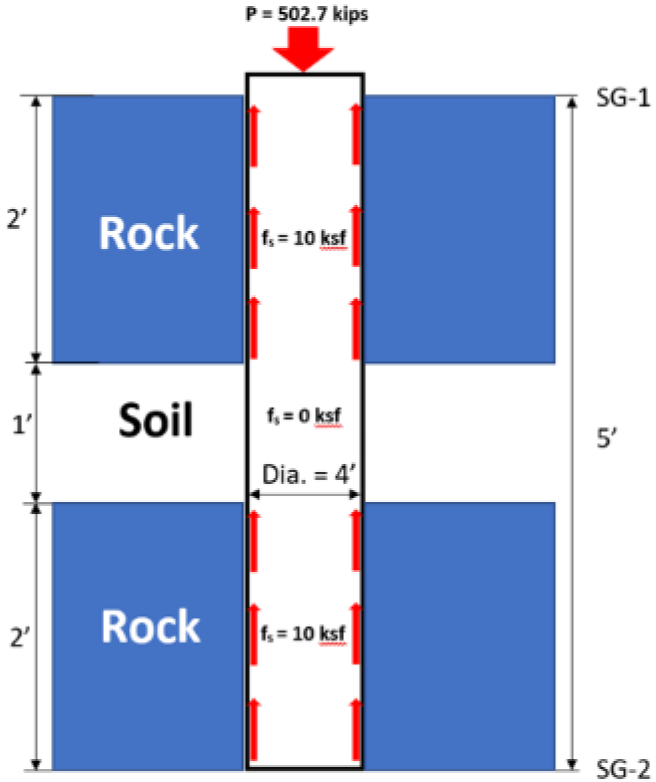
f_s can be solved directly using only q_u,

$$f_s = 0.3302 \times q_u^{0.9125} \quad \text{(Eq. 3-9)}$$

rearrange Equation 3-9 to solve for q_u based on measured f_s,

$$q_u = \left(\frac{f_s}{0.3302}\right)^{\left({}^{1}\!/_{0.9125}\right)} \quad \text{(Eq. 3-10)}$$

Task 2 – Data Reduction and Analysis at Selmon



f_s calculated based on length of segment:

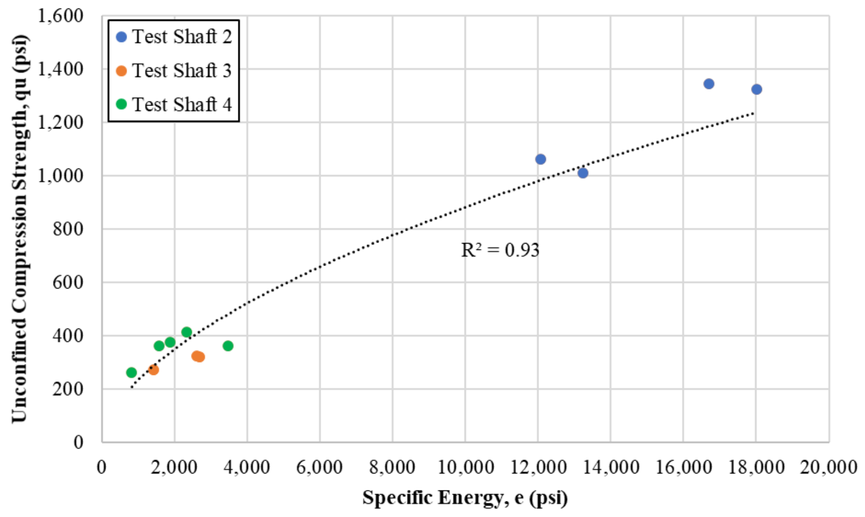
$$f_{s-rock} = \frac{P}{\pi \times D \times L_{segment}} = \frac{502.7\ kips}{\pi \times 4\ ft \times 5\ ft} = 8\ ksf$$

f_s calculated based on length of rock socket:

$$f_{s-rock} = \frac{P}{\pi \times D \times L_{rock}} = \frac{502.7\ kips}{\pi \times 4\ ft \times 4\ ft} = 10\ ksf$$

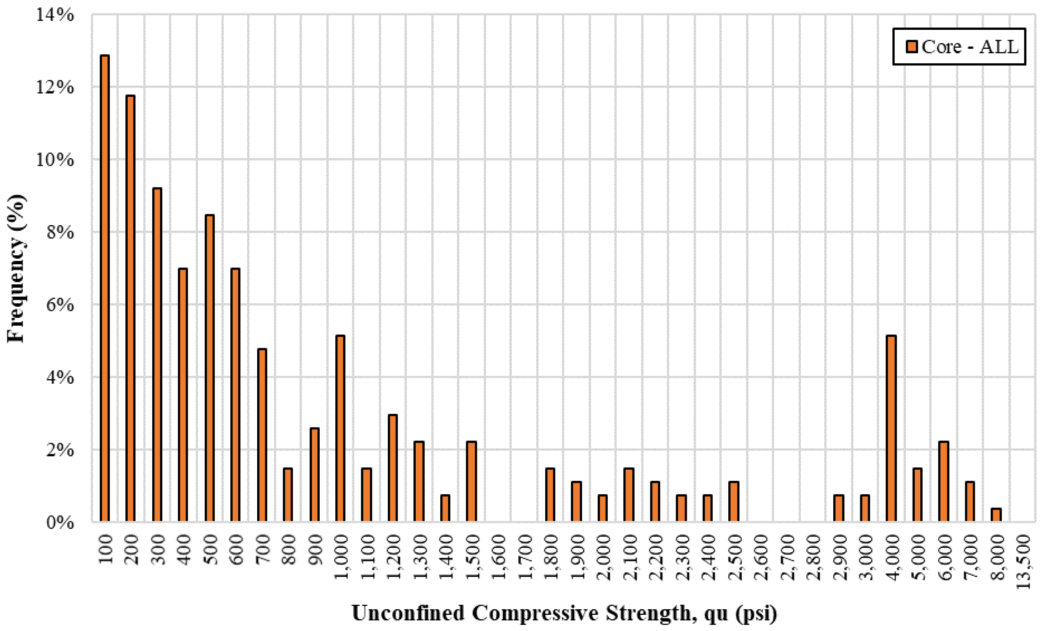
- Developed criteria to remove soil based on drilling parameters
- Produced a new relationship between q_u and specific energy for rock drilling buckets
- The new relationship was then used to assess rock strength and site variability at Selmon Parkway and CR-250; and compared to rock strength obtained from testing core samples

Test Shaft	Segment	e (psi)	LT f_s (ksf)	LT q_u (psi)
2	15	16,687	34.1	1,345
	16	18,015	33.6	1,326
	17	12,068	27.5	1,063
	18/Toe	13,240	26.2	1,010
3	12	2,694	9.2	320
	13	1,423	8.0	274
	Toe	2,620	9.3	326
4	5	821	7.7	264
	10	1,570	10.3	363
	11	1,887	10.7	376
	12	2,329	11.7	416
	16.2	3,461	10.9	364



Task 3a – Core Data and Site Variability Analysis Selmon Parkway

- Examination of all the core data collected at Selmon Parkway revealed there was a significant range (i.e., variability) of rock strengths
- The frequency distribution had a lognormal shape, but also displayed bimodal characteristics
  - Of great interest was bimodal due to layering, zones, or other?



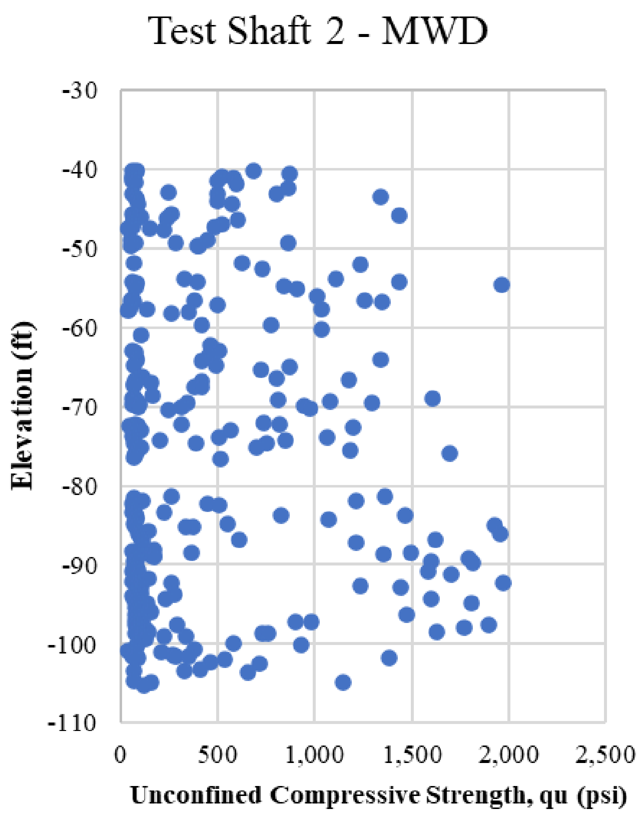
Task 3a – Core Data and Site Variability Analysis Selmon Parkway

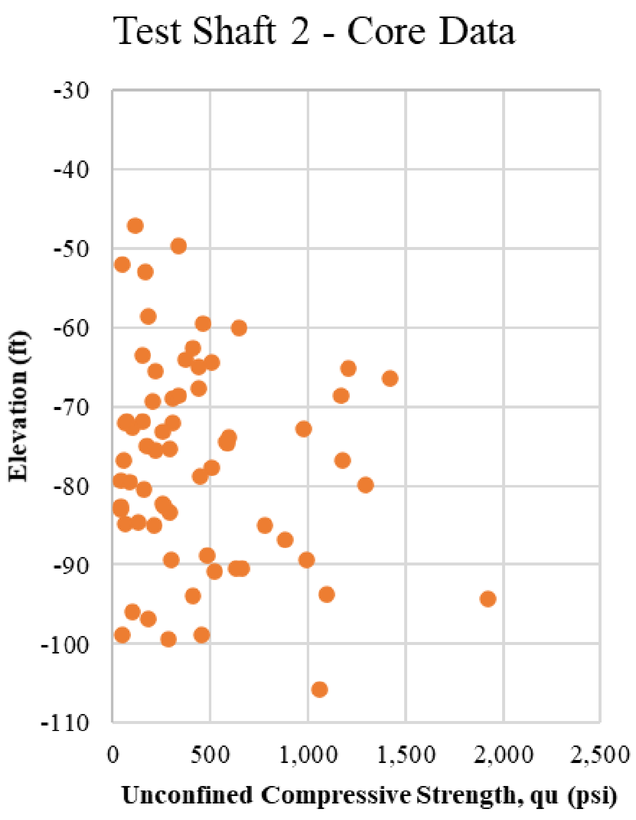
- Limited data available within proximity to the load tested shafts:
  - ≤ 100 feet from test shafts
  - Only 18 rock strength assessments

Stats	qu (psi)
Mean	995
Median	610
Std. Dev.	1,014
CV	1.02
Max	3,905
Min	50
Count	18

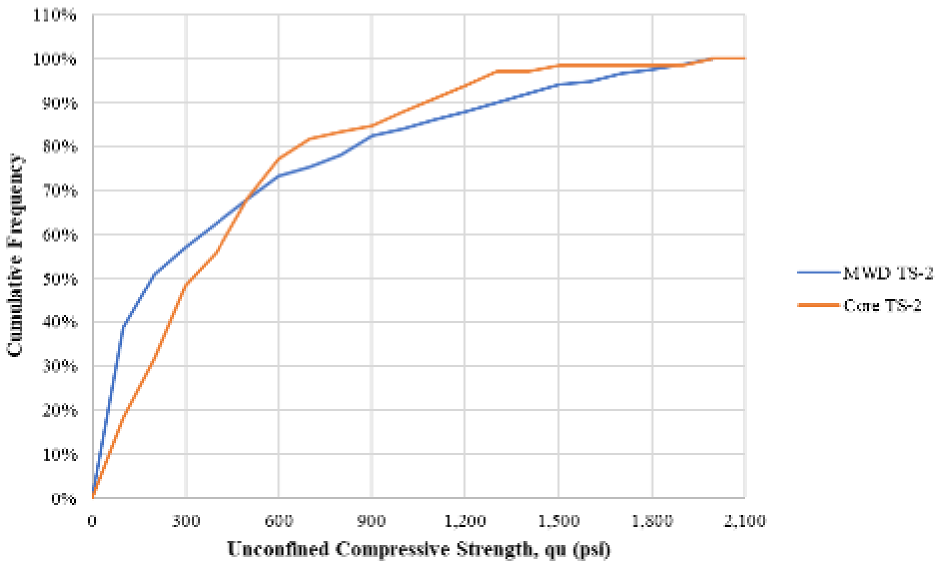
- Due to the limited number of core samples collected within proximity of the Test Shafts, the distance considered for the analyses was expanded to include more core samples
- This required a limit to be placed on the q_u data such that the initial statistics would not be impacted by higher strength outlying values
  - i.e., influence the summary of statistics and variogram analyses for each shaft
- As is the practice of the FDOT, any value outside of 1-standard deviation (1σ = 1,014 psi) from the original mean (q_u = 995 psi) would be eliminated as the core sample distance considered was increased
- At each of Test Shaft locations, a distance of 2,500 feet (≈ ½ mile) was required to generate enough core data to evaluate the statistics, develop frequency and cumulative frequency distribution plots, and perform variogram analyses to compare with MWD

Task 3a – Core Data and Site Variability Analysis Selmon Parkway



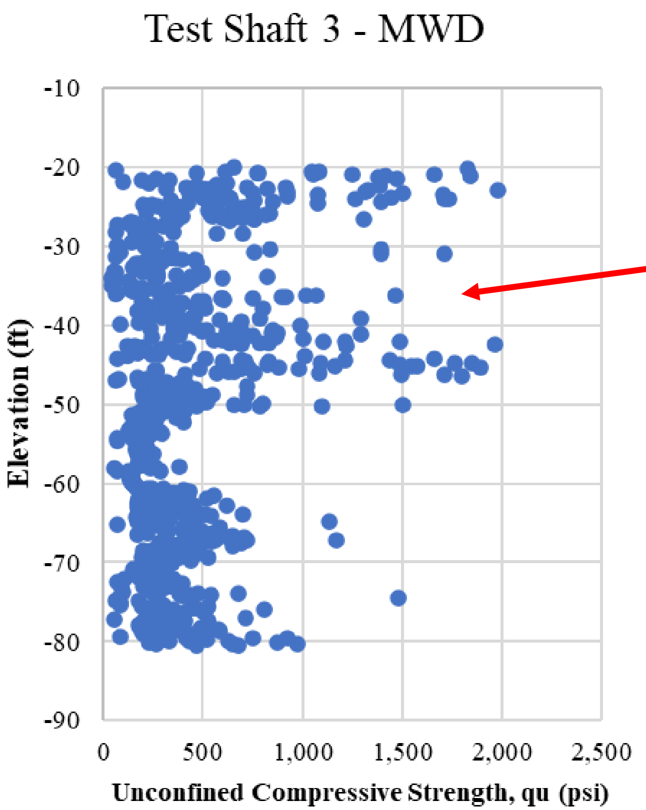


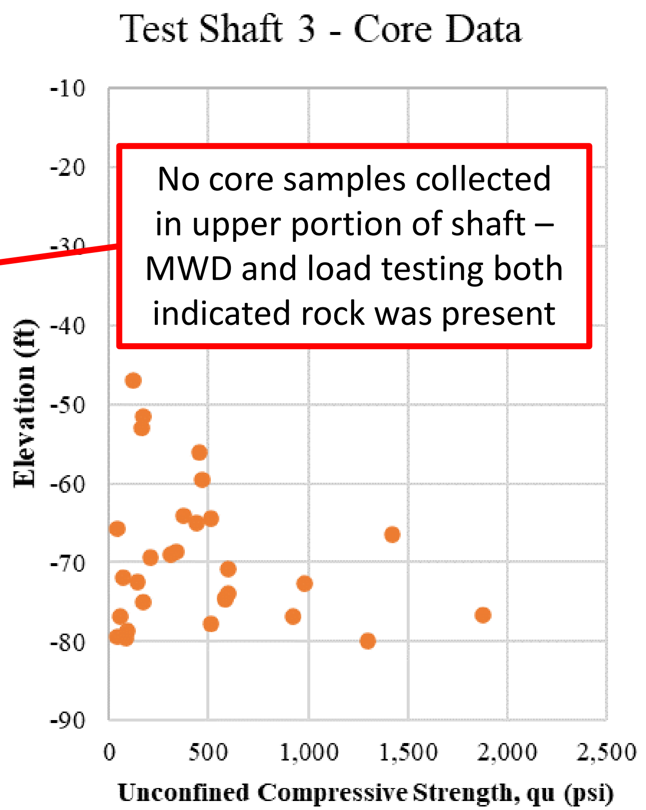
Stats	q_u (psi)	
	MWD	Core
Mean	447	446
Median	172	310
Std. Dev.	505	399
CV	1.13	0.90
Max	1,971	1,920
Min	39	40
Count	289	66



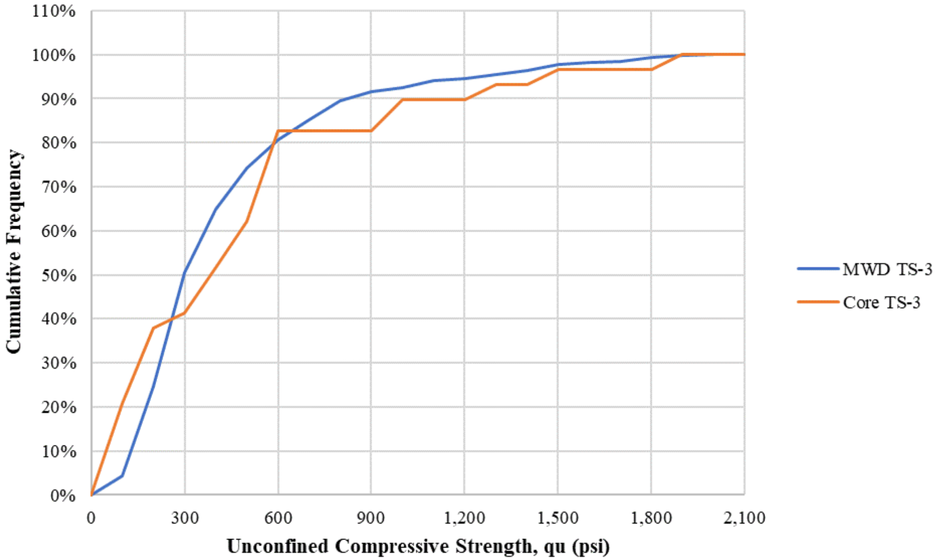
Only 8 core samples collected within 100 feet of Test Shaft 2

Task 3a – Core Data and Site Variability Analysis Selmon Parkway



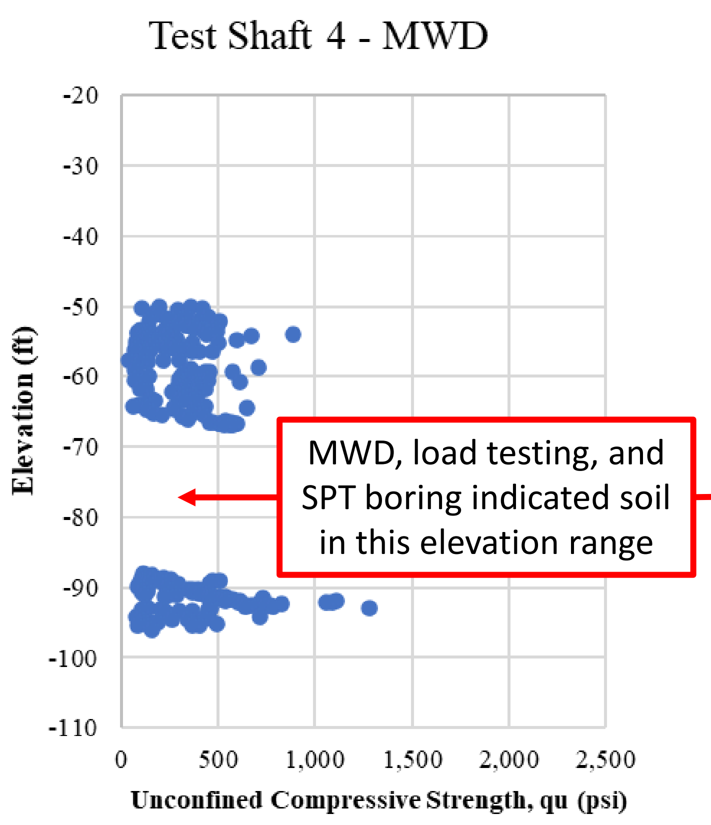


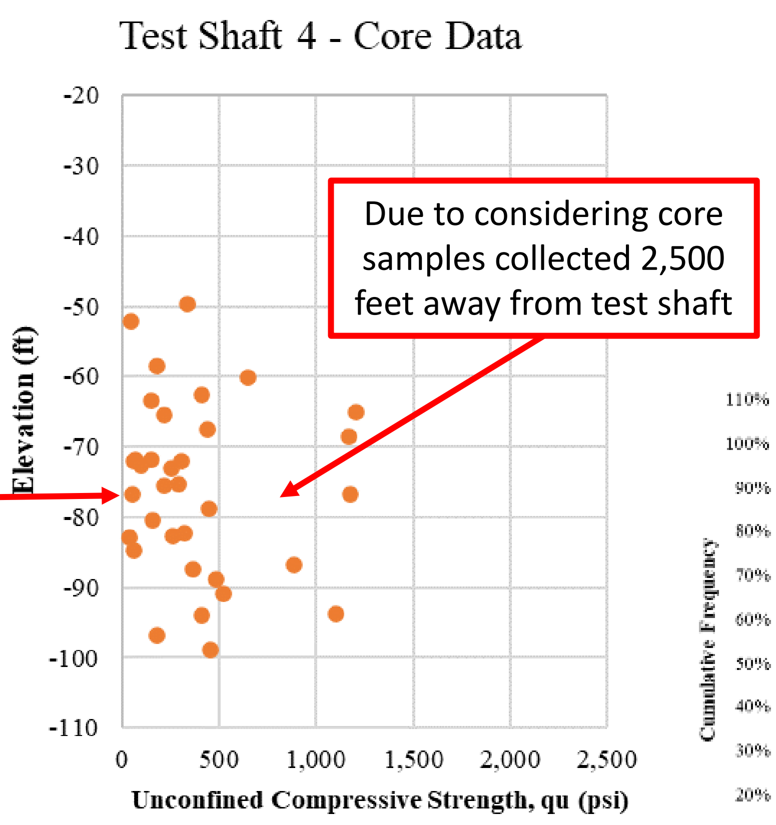
Stats	q_u (psi)	
	MWD	Core
Mean	419	469
Median	297	375
Std. Dev.	346	451
CV	0.83	0.96
Max	1,974	1,875
Min	40	40
Count	798	29



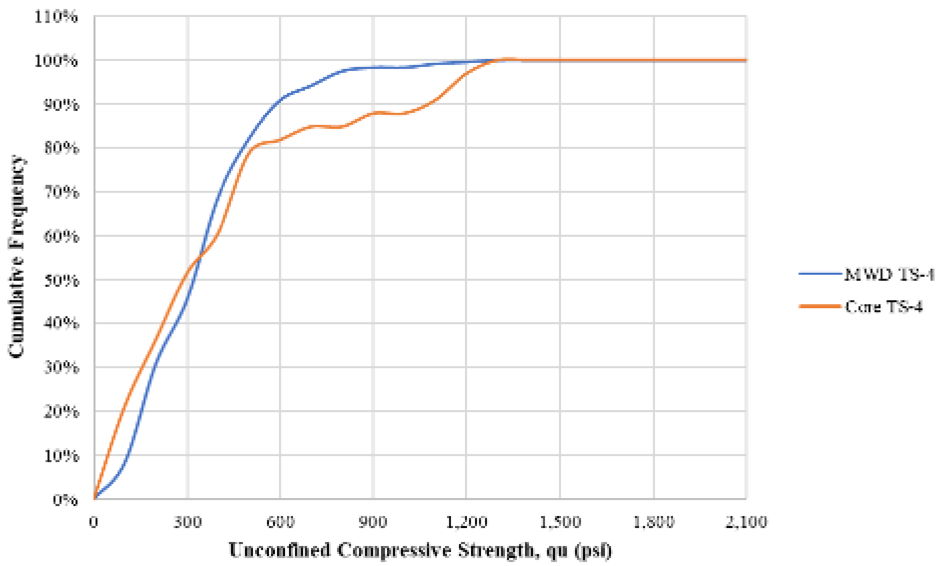
Only 5 core samples collected within 100 feet of Test Shaft 3

Task 3a – Core Data and Site Variability Analysis Selmon Parkway





Stats	q_u (psi)	
	MWD	Core
Mean	338	390
Median	323	290
Std. Dev.	207	347
CV	0.61	0.89
Max	1,282	1,205
Min	40	40
Count	240	33



Only 5 core samples collected within 100 feet of Test Shaft 4

Task 3a – Core Data and Site Variability Analysis Selmon Parkway

- Comparing the statistics of the data (MWD q_u vs. Laboratory q_u) for individual test shafts is important when estimating the capacity of individual shafts, but it does not necessarily address the variability and capacity of production shafts that are located further away
- An evaluation of that behavior is obtained by looking at the variograms of the data
- The data is correlated when C(h) is greater than 0
  - i.e., γ'(h) < 1
- The data is correlated up to a distance "a" from one another

Variogram function:

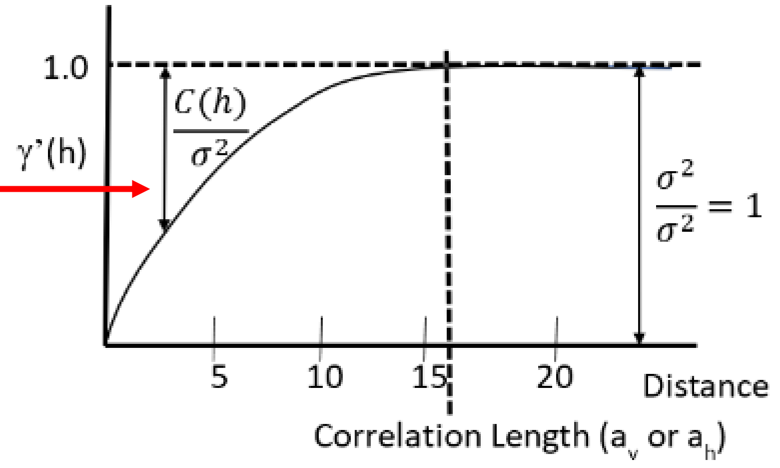
$$\gamma(h) = \frac{1}{2N}\sum_{i=1}^{n}(V(t)_i - V(t+h)_i)^2$$

C(h) is covariance function defined by:

$$C(h) = \sigma^2 - \gamma(h)$$

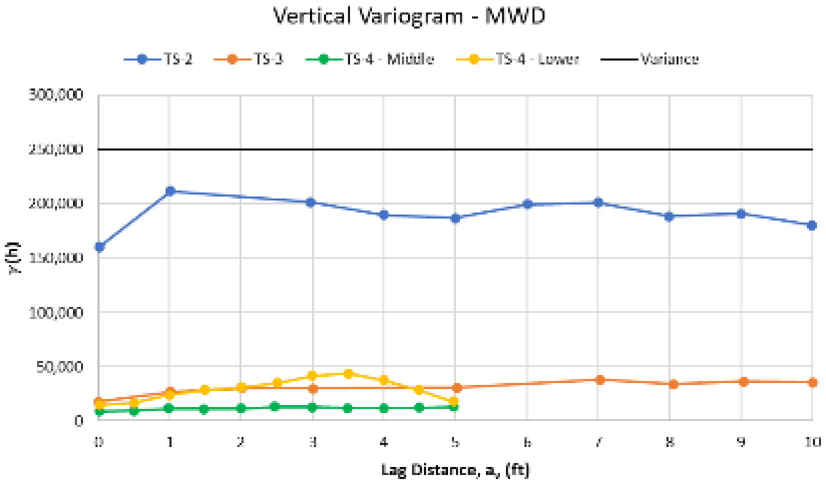
Normalized variogram function:

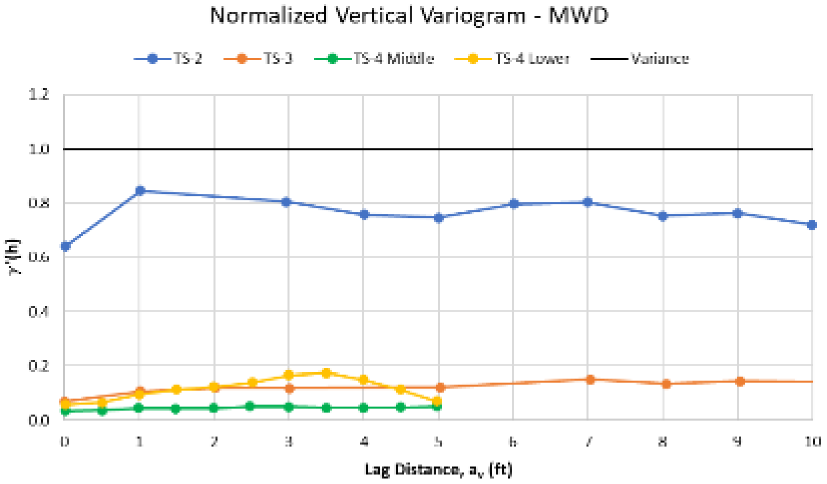
$$\gamma'(h) = \frac{\gamma(h)}{\sigma^2} = \frac{\sigma^2}{\sigma^2} - \frac{C(h)}{\sigma^2} = 1 - \frac{C(h)}{\sigma^2}$$



Task 3a – Core Data and Site Variability Analysis Selmon Parkway

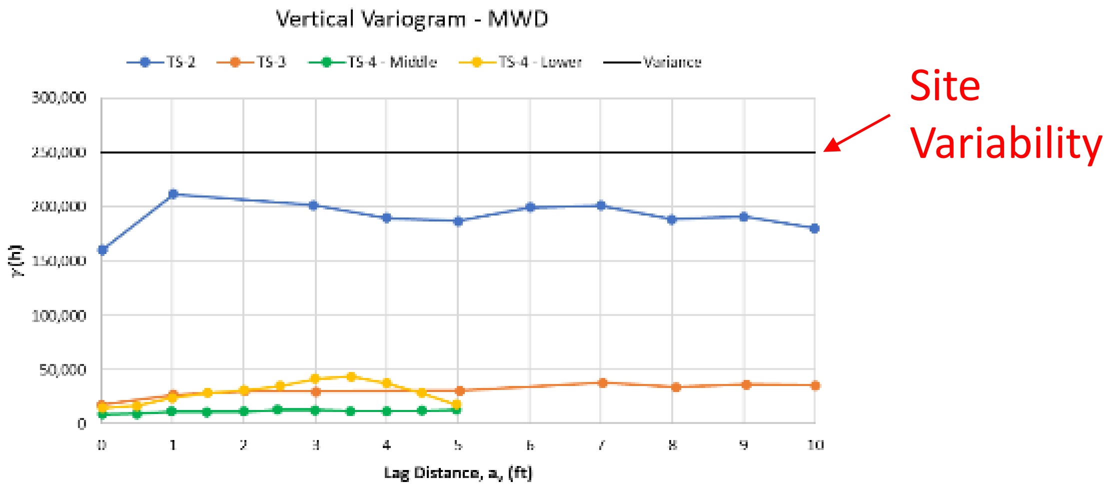
- Prior to MWD monitoring of test shafts to assess strength from specific energy, there never was sufficient data points within individual borings to develop a vertical variogram for a single shaft or boring
- However, with MWD data recorded every two centimeters or less, this is now possible
  - 200 to 800 rock strength data points for each shaft

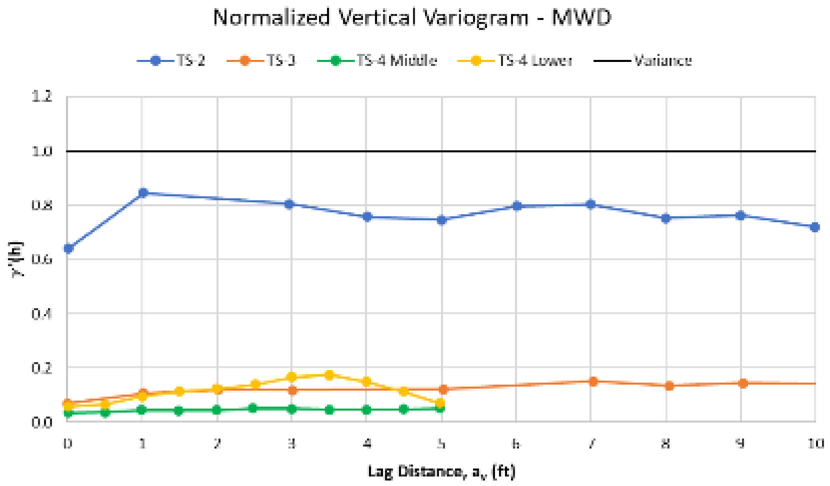




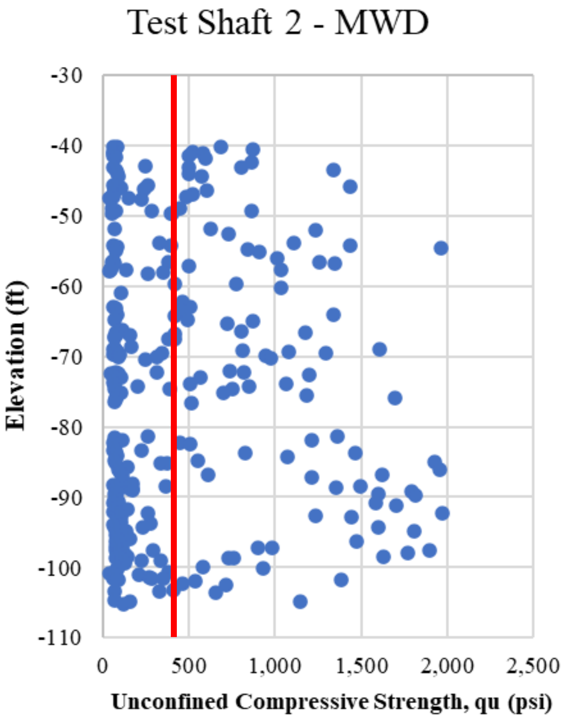
Task 3a – Core Data and Site Variability Analysis Selmon Parkway

- Evident from the variograms, the correlation for Test Shaft 2 compared to Test Shafts 3 and 4 is quite different.
- Test Shaft 2 varies from 0.35 (1 – 0.65) at small distances (a_v < 1 ft) and is approximately 0.20 (1 – 0.80) for larger distances (a_v = 7ft).
- For Test Shafts 3 and 4, the strength correlation is approximately 0.85 (1 – 0.15) for large distances (0 < h < 10 ft)
- This is verified by observing the large range of q_u values about the mean as a function of depth for Test Shaft 2 vs. Test Shaft 4





Task 3a – Core Data and Site Variability Analysis Selmon Parkway



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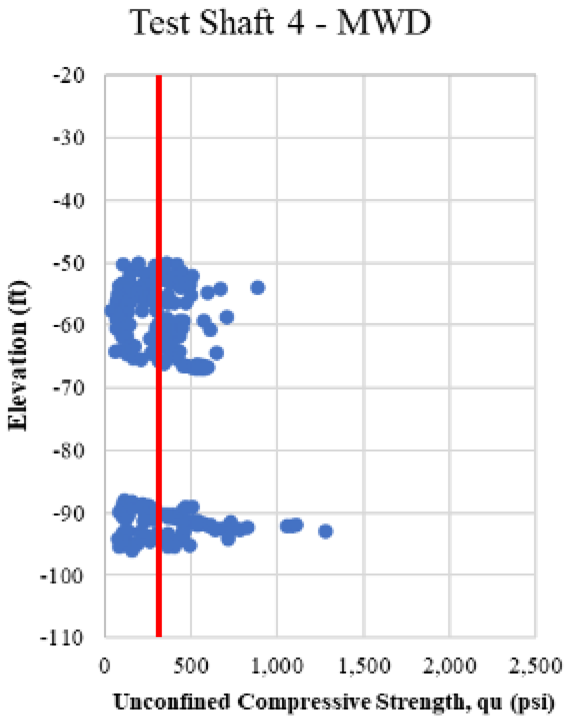

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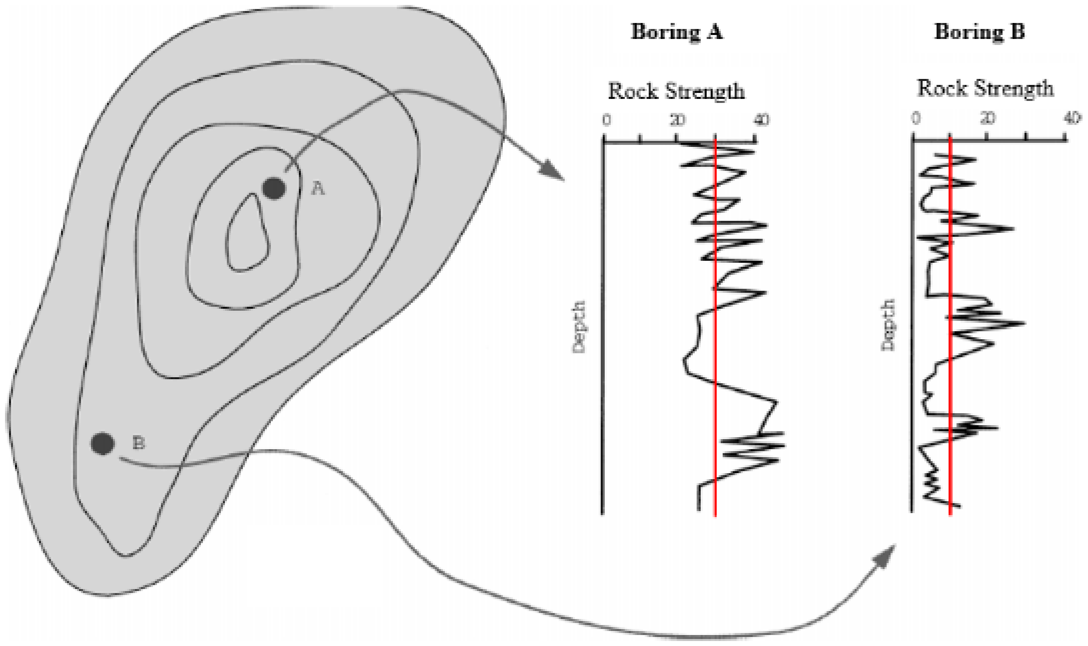
In geostatistics, this is known as an “areal trend”

Task 3a – Core Data and Site Variability Analysis Selmon Parkway

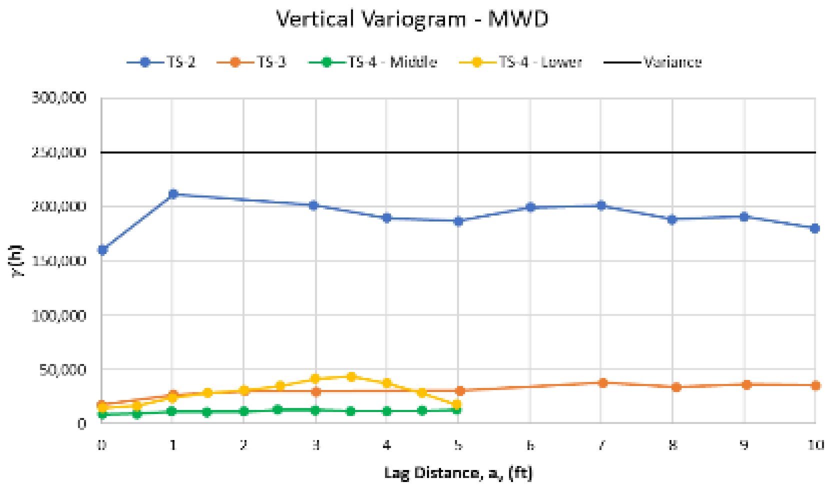
- Boring B shows a mean of approximately 10 and a range of 20
- Boring A shows a mean of approximately 30 and range of 20
- If Borings A and B are combined (i.e., all data), it will show a mean of approximately 20 and a range of 40
- Much higher variance (range) in the case of all data vs. each boring
  - Site should be broken in zones with separate unit side shear
- IF the site is not broken down into zones then much lower LRFD phi required or design side shear

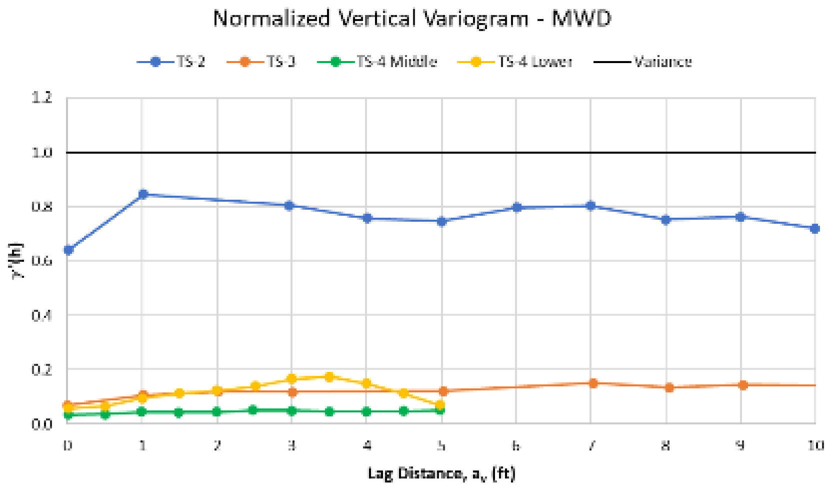
Areal Trends with Zonal Anisotropy



Task 3a – Core Data and Site Variability Analysis Selmon Parkway

- Gringarten and Deutsch (2001) identify areal trends as having an influence on the vertical variogram
- The vertical variogram will not encounter the full variability of petrophysical property
  - γ(h)’ not equal to 1
- There will be positive correlation (variogram below variance or sill) for large distances in the vertical direction.
- This type of behavior is called “zonal anisotropy” and is identified in the data





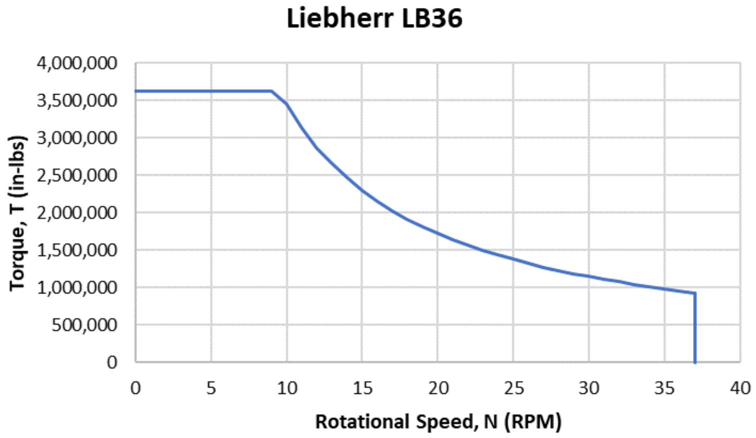
Task 3a – Core Data and Site Variability Analysis Selmon Parkway

- Areal trends (zonal anisotropy) are very important in drilled shaft design and construction
- Generally, geotechnical engineers collect strength data throughout a site and then estimate the shaft capacities based on the mean or median from all the data combined instead of looking at individual boring data
- This is because in all cases there is insufficient data collected within one boring
  - Need MWD performed during site investigation (e.g., BDV31-820-006)
- Many sites are designed with less than 100 data values for the whole site; not the 1,250 data values obtained by monitoring 3 tests shafts with MWD
- The areal trend or zonal anisotropy shown from the MWD qu data also explains the 200% to 300% difference in the measured unit skin friction from the load test reported for Test Shaft 2 vs. Test Shafts 3 or 4

Task 3b – Detailed Report on Converting MWD Data to Shaft Specific Energy and Capacities Estimation

Torque:

- Maximum Torque (T_{max})= 3,628,800 in-lbf
- Maximum Operating Pressure (P_{max}) = 5,076 psi
- Hydraulic Flow Rate (Q) = 42,688.8 in^3/min (constant)



$$T = \frac{PQ}{2\times\pi\times N}$$

Crowd:

- Maximum Crowd (F_{max}) = 89,925 lbs
- Maximum Operating Pressure (P_{max}) = 5,076 psi
- Crowd Threshold Pressure (TP_{Crowd}) = 595 psi

$$K_F = \frac{F_{max}}{P_{max} - TP_{Crowd}} = \frac{89{,}925\ lbf}{5{,}076\ psi - 595\ psi} = 20.1\ \frac{lbf}{psi}$$

$$F\ (lbf) = K_F\left(\frac{lbf}{psi}\right) \times [F_{Pressure}\ (psi) - TP_{Crowd}\ (psi)]$$

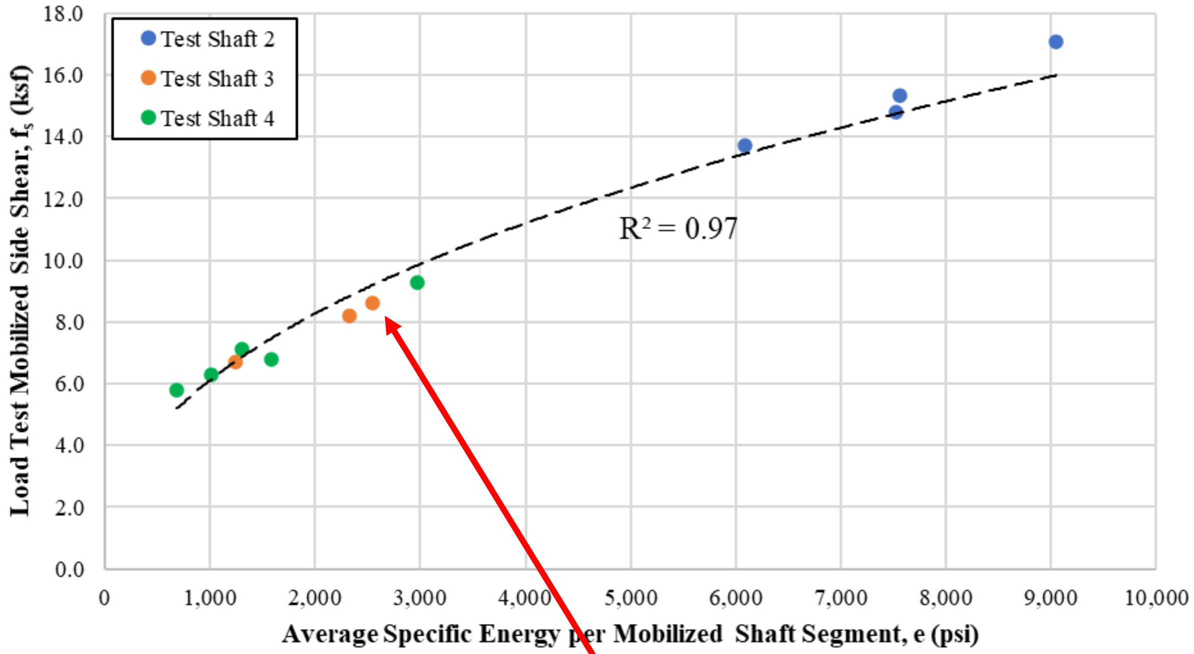
Task 3b – Detailed Report on Converting MWD Data to Shaft Specific Energy and Capacities Estimation

- Jean Lutz software converts time-referenced data to raw depth-referenced data in a columnar format → Paste into Excel
- Using the drill rig specifications the raw data is transformed into data that is compatible with Teale's specific energy EQN

	A	B	C	D	E	F	G	H	I	J	K	L
1	Raw Data								Processed Data			
2	SELMON							Bit Diameter	X-sectional Area	Conversion Inputs		
3	Pile : TS3 0FT							d (in)	A (in^2)	Q (in^3/min)	Crowd (K_F)	
4	Date : 1/15/2018 9:08:51 PM							41.75	1,369	42,688.8	20.1	
5	End : 4:19:10 AM											
6	Pile Length : 91'9"1/8							Segment	Elevation	Load Test fs (ksf)	MWD e_{AVG} (psi)	
7	Volume : 0.000 yds3							12	-61.0 ft to -68.1 ft	8.6	2,548	
8	Diameter : 0"											
9	Overconsumption : 0 %											
10							Elevation	Penetration Rate	Rotational Speed	Torque	Crowd	Specific Energy
11	Depth	Drill. Rate	Rotation	Torque	Thrust			u	N	T	F	e
12	feet	(ft/min)	(rpm)	(psi)	(psi)		(ft)	(in/min)	(rpm)	(in-lbs)	(lbf)	(psi)
992	69.69	0.8315	12.1064	912.9005	1728.844		-61.06	10.0	12.1	512,321.4	17,636.7	2,865.8
993	69.75	1.4819	12.0173	863.8466	1892.97		-61.12	17.8	12.0	488,386.7	20,930.4	1,530.1
994	69.82	1.1332	12.1022	869.6019	1859.051		-61.19	13.6	12.1	488,191.5	20,249.7	2,008.9
995	69.88	3.3767	11.8118	966.1221	2111.701		-61.25	40.5	11.8	555,712.3	25,319.9	762.0
996	69.95	1.2662	[illegible]	1030.875	1915.731		-61.32	15.2	12.0	584,091.7	21,387.2	[illegible]

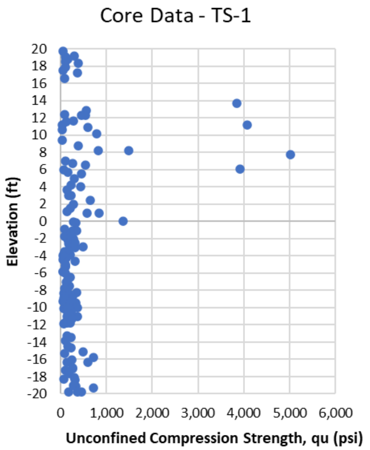
Each raw depth-referenced data point is comprised of several hundred/thousand time-referenced data points

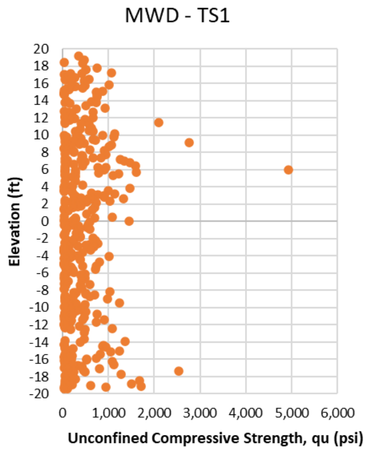
Specific energy is calculated at each depth increment and then an average specific energy is calculated for the shaft segment



Test Shaft 3 – Segment 12:
Elevation Range = -61.0 to -68.1 feet
Load Test Side Shear (f_s) = 8.6 ksf
Average specific energy (e) = 2,548 psi

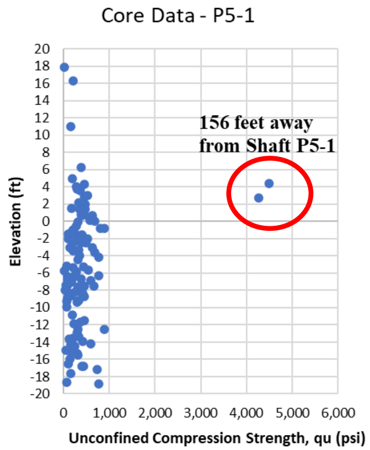
Task 3c – CR-250 Drilled Shaft Installation MWD Monitoring and Data Analysis

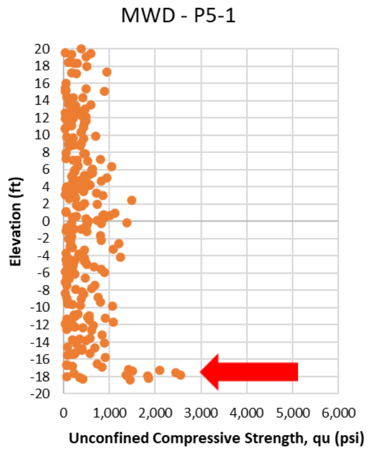




Distance = 200 ft

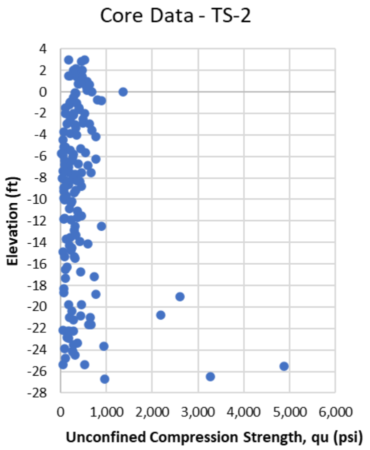
Test Shaft 1 - qu (tsf)		
Stats	Core	MWD
Mean	27.5	27.4
Median	15.3	16.9
Std Dev	52.2	32.9
CV	1.90	1.20
Max	361.5	354.9
Min	2.9	2.3
Count	131	428

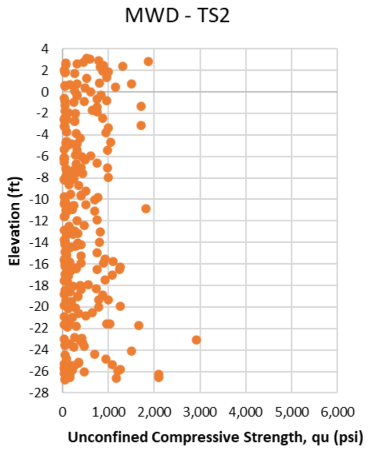




Distance = 200 ft

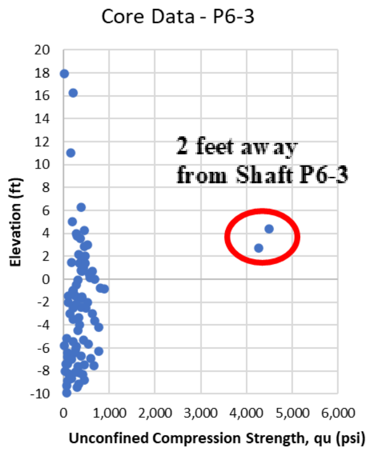
Shaft P5-1 - qu (tsf)		
Stats	Core	MWD
Mean	29.4	30.7
Median	22.6	21.1
Std Dev	41.7	29.3
CV	1.42	0.95
Max	324.0	183.8
Min	1.0	2.4
Count	110	247

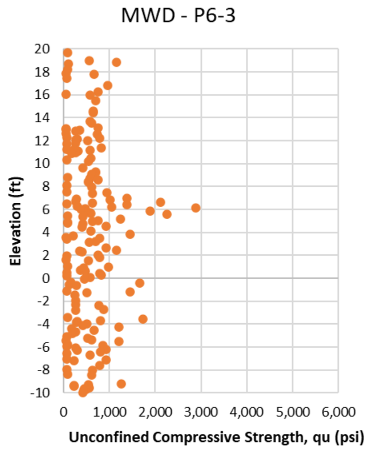




Distance = 200 ft

Test Shaft 2 - qu (tsf)		
Stats	Core	MWD
Mean	29.0	30.1
Median	20.5	18.6
Std Dev	39.3	32.8
CV	1.36	1.09
Max	351.6	210.8
Min	1.2	2.3
Count	152	252



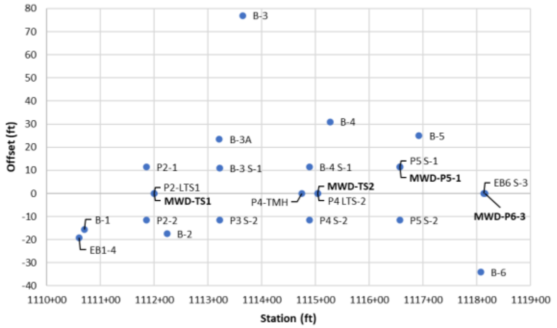


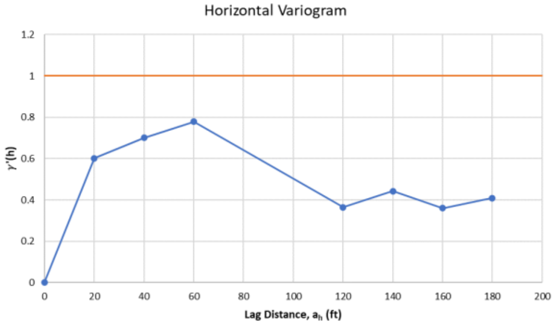
Distance = 400 ft

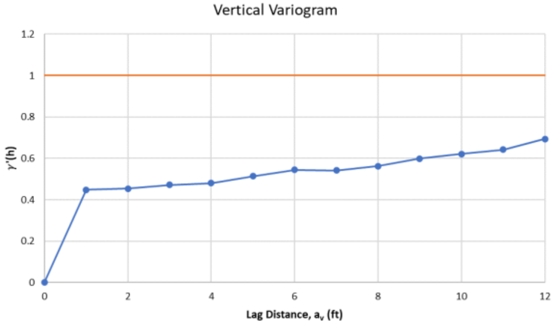
Shaft P6-3 - qu (tsf)		
Stats	Core	MWD
Mean	31.4	38.7
Median	23.7	35.1
Std Dev	47.1	33.1
CV	1.50	0.86
Max	324.0	208.1
Min	1.0	3.4
Count	83	170

Task 3c – CR-250 Drilled Shaft Installation MWD Monitoring and Data Analysis

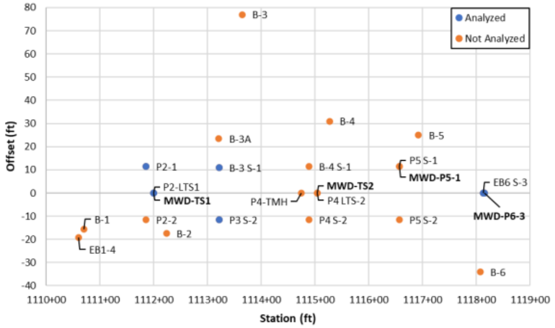
All Data Combined

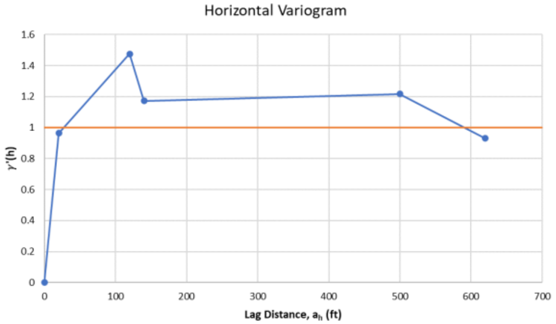


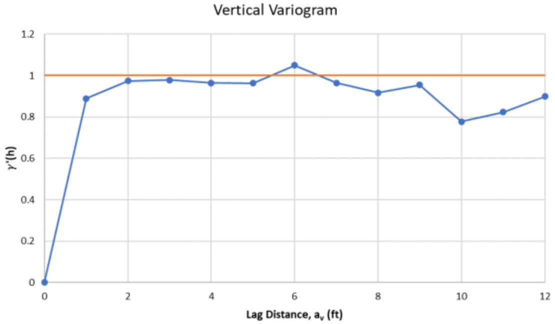




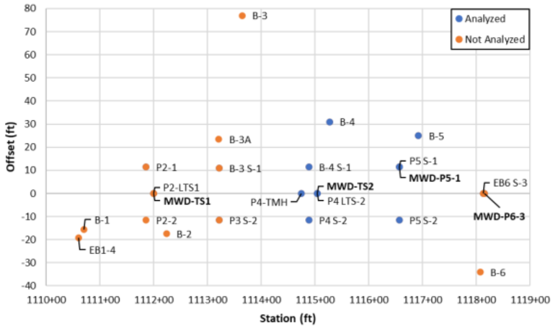
Broken up into Zones

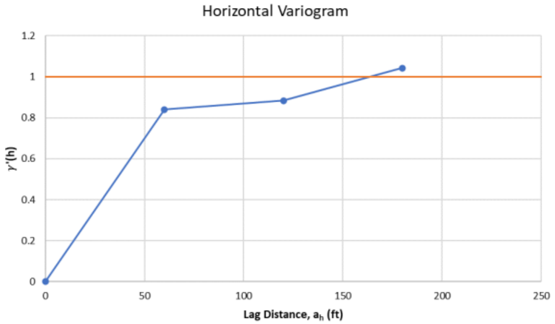


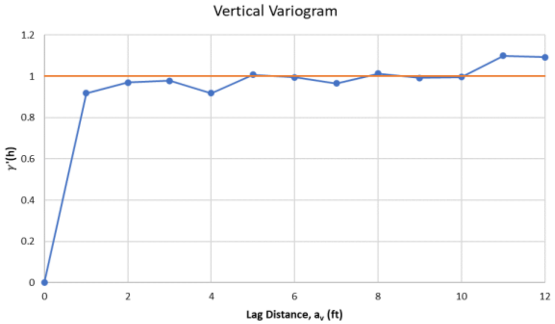




Broken up into Zones







Task 3c – CR-250 Drilled Shaft Installation MWD Monitoring and Data Analysis

- Based on the load test report, limited shaft displacement was achieved in both test shafts
- The peak load measured in each segment typically occurred at a displacement less than 0.07 inches
- With such limited displacement within each segment, it is difficult to assess the load test results using individual load test layers
- However, the total load carried in shear above and below the hydraulic jack can be compared to the estimated loads from the core data and MWD within each segment.
- Test Shaft 1:
  - Above Load Cell – P = 4,444 kips
    - Segments 2, 3, 4, and 5 (Elev. +12.93 to -8.07 ft)
    - Approaching mobilization – Not mobilized
  - Below Load Cell – P = 3,733 kips
    - Segments 6 and 7 (Elev. -8.07 to -18.07 ft)
    - Uncertain of mobilization due to limited displacement

Core Data Load Summary – Test Shaft 1

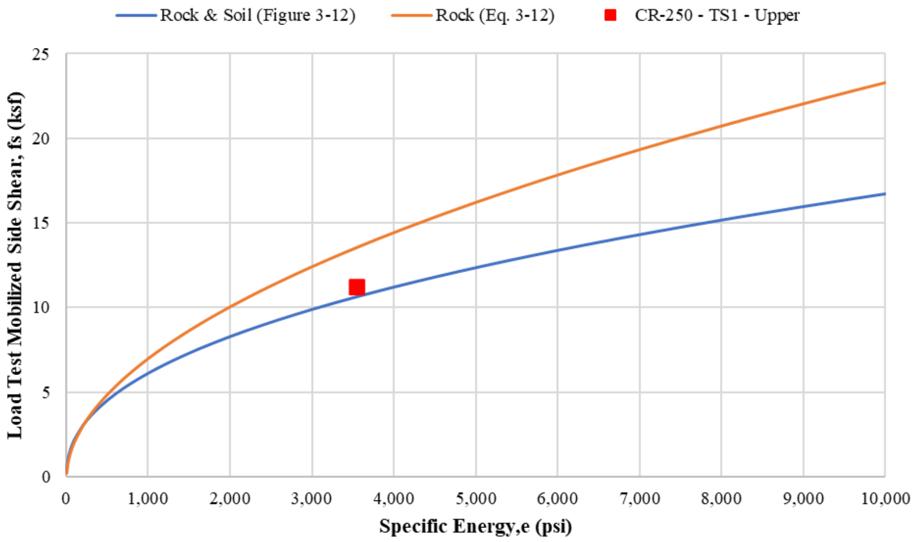
Segment	Location	EL_{Top} (ft)	EL_{Bot} (ft)	ΔZ (ft)	qu (psi)	fs (ksf)	P (kips)
2	Above	12.93	7.93	5.0	691	18.54	1,748
3	Above	7.93	2.93	5.0	859	22.62	2,131
4	Above	2.93	-2.07	5.0	399	11.23	1,059
5	Above	-2.07	-8.07	6.0	163	4.96	561
6	Below	-8.07	-13.07	5.0	185	5.57	525
7	Below	-13.07	-18.07	5.0	266	7.76	731
					Above	P (kips) =	5,499
					Below	P (kips) =	1,256
					Total	P (kips) =	6,756

MWD Data Load Summary – Test Shaft 1

Segment	Location	EL_{Top} (ft)	EL_{Bot} (ft)	ΔZ (ft)	qu (psi)	fs (ksf)	P (kips)
2	Above	12.93	7.93	5.0	499	13.76	1,297
3	Above	7.93	2.93	5.0	711	19.02	1,793
4	Above	2.93	-2.07	5.0	411	11.53	1,087
5	Above	-2.07	-8.07	6.0	285	8.27	936
6	Below	-8.07	-13.07	5.0	345	9.83	926
7	Below	-13.07	-18.07	5.0	473	13.12	1,236
					Above	P (kips) =	5,113
					Below	P (kips) =	2,163
					Total	P (kips) =	7,275

Task 3c – CR-250 Drilled Shaft Installation MWD Monitoring and Data Analysis

- Load Test – MWD Correlation QA/QC
- Could use side shear relationship from Selmon Parkway for shaft QA/QC
  - Conservative due to soil layering included in developed MWD correlation
  - All TS-1 geomaterial excavated was rock
- Test Shaft 1:
  - Above load cell
  - Segments 2, 3, 4, and 5
    - Elev. +12.93 to -8.07 ft
    - Upper segment in isolated Shear
  - P = 4,444 kips (from LT side shear)
  - f_s = 11.23 ksf (from load test)
  - e_{AVG} = 3,549 psi (from MWD)
  - Plot data point
  - If full mobilization occurred, the data point would have fallen near or on the rock EQN



$$CV_R = \frac{\sqrt{b^2\sigma_s^2 + \sigma_\varepsilon^2}}{bp + a}$$

- $\sigma_s^2 = 0$ w/ MWD
- Lower CV_R
- Higher LRFD Φ

Production Shaft P5-1 (6 ft Dia.)	Production Shaft P6-3 (4 ft Dia.)
Factored design load = 2,218 kips	Factored design load = 1,138 kips
e_{AVG} = 2,273 psi (from MWD)	e_{AVG} = 2,788 psi (from MWD)
f_s = 8.8 ksf (from MWD)	f_s = 9.6 ksf (from MWD)
MWD Side Shear Load (R_n) = 5,121 kips	MWD Side Shear Load (R_n) = 2,927 kips
ΦR_n = 0.5 * 5,121 kips = 2,560 kips	ΦR_n = 0.5 * 2,927 kips = 1,463 kips
Capacity/Demand = 1.15	Capacity/Demand = 1.29
ΦR_n = 0.7 * 5,121 kips = 3,584 kips	ΦR_n = 0.7 * 2,927 kips = 2,049 kips
Capacity/Demand = 1.62*	Capacity/Demand = 1.80*
*Possibly reduce production shaft length when monitored via MWD	*Possibly reduce production shaft length when monitored via MWD

Task 3c – CR-250 Drilled Shaft Installation MWD Monitoring and Data Analysis

- Total Specific Energy MWD QA/QC
- Set a minimum value for total specific energy that must be achieved within the rock socket of the production shafts
  - Specific energy is a measure of rock strength
- QA/QC method was discussed in Rodgers et al. (2018c)
  - Referred to as “specific energy capacity”
  - Changed name to eliminate confusion
- Developed for sites where limited information was gained from load testing or load testing did not occur
- Can use data from the upper segment of Test Shaft 1 to develop a minimum e_{Total} requirement for the CR-250 site.

Total Specific Energy Equation

- $e_{total}(kips) = e_{avg}(psf) \times \pi \times D(ft) \times L(ft) \times \frac{1\ kip}{1{,}000\ lbf}$

where,

- e_{avg} = average specific energy recorded over the rock socket segment (psf)
- D = diameter of the drilling tool (ft)
- L = length of the rock socket segment (ft)

Total Specific Energy for Upper Segment of TS-1

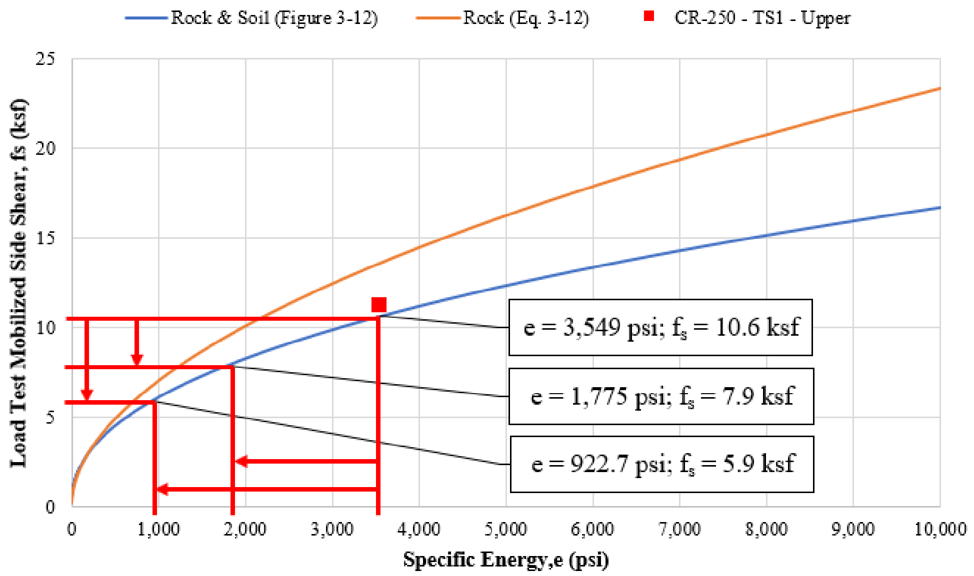
$$e_{total}(kips) = 511{,}056\ psf \times \pi \times 6\ ft \times 21\ ft \times \frac{1\ kip}{1{,}000\ lbf}$$

e_{total} = **202,294 kips**

$$P_{TS-1} = 4{,}444\ kips \sim e_{total} = 202{,}294\ kips$$

Task 3c – CR-250 Drilled Shaft Installation MWD Monitoring and Data Analysis

- Total Specific Energy MWD QA/QC
  - Shaft P5-1 **required** e_{Total}
  - $e_{total\ P5-1} = \frac{P_{5-1}}{P_{TS-1}} \times e_{total\ TS-1} = \frac{2{,}218\ kips}{4{,}444\ kips} \times 202{,}294\ kips = 100{,}965\ kips$
  - Shaft P5-1 **measured** e_{Total}
  - $e_{total\ P5-1}$ = 191,520 kips → **Nearly double the e_{Total} requirement**
  - Shaft P6-3 **required** e_{Total}
  - $e_{total\ P6-3} = \frac{P_{6-3}}{P_{TS-1}} \times e_{total\ TS-1} = \frac{1{,}138\ kips}{4{,}444\ kips} \times 202{,}294\ kips = 51{,}803\ kips$
  - Shaft P5-1 **measured** e_{Total}
  - $e_{total\ P6-3}$ = 122,810 kips → **More than double the e_{Total} requirement**
- This approach to drilled shaft QA/QC is conservative as a reduction in specific energy (e) equates to a smaller reduction in shaft side shear (f_s)



- $e_{P5-1} = \left(\frac{2{,}218\ kips}{4{,}444\ kips}\right) \times 3{,}549\ psi = 1{,}775\ psi$
- ≈ **50%** reduction in e_{AVG}
- $\%\ reduction\ in\ f_{s\ P5-1} = \left(1 - \frac{7.9\ ksf}{10.6\ ksf}\right) \times 100\% = \mathbf{25\%}$
- $e_{P5-1} = \left(\frac{1{,}138\ kips}{4{,}444\ kips}\right) \times 3{,}549\ psi = 922.7\ psi$
- ≈ **74%** reduction in e_{AVG}
- $\%\ reduction\ in\ f_{s\ P5-1} = \left(1 - \frac{5.9\ ksf}{10.6\ ksf}\right) \times 100\% = \mathbf{44\%}$

Research Conclusions

- Correlation can be developed between specific energy and the rock strength of Florida limestone using rock drilling buckets
- The mechanical efficiency of a rock drilling bucket differs from that of a rock auger
  - A unique relationship is shared between specific energy and rock strength for each unique drilling tool (e.g., rock auger vs. rock drilling bucket vs. core barrel).
- MWD provides highly detailed records of the geological conditions encountered at a site
  - The significant increase in strength assessments collected via MWD within a single sampled location allows a correlation structure to be obtained from a single boring or shaft for an individual pier
  - This cannot be achieved using any other current conventional method

Research Conclusions

- Performing variogram analyses with the high resolution MWD data allows areal trends such as zonal anisotropy and layering to be identified.
  - Quantify true site variability → break data into zones and layers → reduce chance of shaft failure
  - Reduces CV value and increases LRFD Φ → reduce cost per shaft
- MWD provides a means to quantify the quality and length of rock sockets during the drilling process which ensures the as-built foundations meet/exceed the design parameters, providing QA/QC to the drilling contractor and foundation design engineer
- MWD data collected from the method shafts could be used to make an informed engineering decision for the design of test shafts
- Performing MWD during drilled shaft installations reduces the spatial uncertainty at each shaft location and reduces the spatial issues associated with zones/layering
  - Should not be using the same mean strengths to estimate shaft side shear
  - MWD data collected at Selmon Parkway and CR-250 showed that zones existed

Research Recommendations

- Further research should be conducted for drilled shaft MWD
  - 10 rock auger data points and 12 rock drilling bucket data points
  - Due to the differences in mechanical efficiency each tool provides, the collection of data points for each drilling tool must be treated separately
  - More data should be collected for both drilling tools at full-scale to further investigate the MWD approach
- Investigate the use mechanically driven drill rigs in future drilled shaft projects that utilize the rig type
  - Was not able to be completed during this research effort
- Technical specifications for MWD should be added to all future FDOT contracts in which drilled shafts or piles are to be installed
  - Ensures that QA/QC issues related to layering and zones (e.g., Selmon) are addressed
  - Specifications should be based on the established ISO (2016) standards and findings from each of the FDOT's MWD research efforts

Research Recommendations

- Further research should be conducted for geotechnical site investigation MWD applications (e.g., BDV31-820-006).
  - Current methods of geotechnical site characterization are inadequate to address the high degree of subsurface variability often encountered throughout the state of Florida
  - MWD approach resolves the lack of geotechnical data collected, allows a correlation structure to be developed from a single sampled location, and provides a method to properly identify areal trends that can lead to shaft failure
  - BDV31-820-006 demonstrated that MWD is not only viable for geotechnical site investigation, it is highly advantageous compared to the current practice that may have poor recoveries
  - FHWA recently identified MWD as the leading advanced method of geotechnical exploration (A-GaME) currently in development – Florida is leading the way!
- Continuing to pursue MWD for site investigation would:
  - Develop continuity between MWD site investigation and MWD construction monitoring
  - Provide insight to the upscaling effect from assessing small scale core samples for design compared to the measured capacity of full-scale bored piles
  - Increase of data should lead to a better understanding of layers and zones which leads to a reduction in CV, increased LRFD resistance factors, and a reduction in cost per shaft
    - Identifies where load testing should occur, and what loads should be applied to achieve mobilization

Project Benefits - Qualitative

- The quality of every rock socket can be assessed on a site
- All drilling operations are logged which can be used to optimize drilling procedures
- Can build a vertical correlation structure from single sampled location
- Provides proper assessment of site variability
  - Can break a site into layers and zones
- Ensures every shaft meets/exceeds the demand of the engineering design
- Generates highly detailed records of geological conditions throughout the state of Florida
- Provides excellent insight to make engineering decisions when load test results are questionable or difficult to interpret
- Can be used to remove uncertainty when site investigation data is conflicting or draws concern
  - Selmon contractor contacted FDOT/UF for assistance when boring data was conflicting, however, MWD equipment had been removed from the drill rig and therefore manual MWD (not recommended) was performed – Had the equipment been left on the rig MWD could have resolved the issue

Project Benefits - Quantitative

- Significant increase in strength assessments collected on a site
  - Sufficient data for geostastical analysis
  - Can properly perform variogram analysis
- Allows a site to be broken down into zones and layers which reduces the CV, increases the LRFD phi, and reduces the cost per shaft
- Reducing shaft lengths will reduce time of completion and cost
- Small overhead cost to implement MWD whereas the savings from MWD implementation could be significant
- Increases the value of load testing
  - Allows the load test results to be translated to the production shafts

Thank you!

- Keith Ellis
- Ben Watson
- Jose Hernando