Herbert Wertheim College of Engineering
UNIVERSITY *of* FLORIDA

Implementation of Measuring While Drilling Shafts in Florida (FLMWDS)

BDV31-977-91

FDOT GRIP Meeting

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FDOT

POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

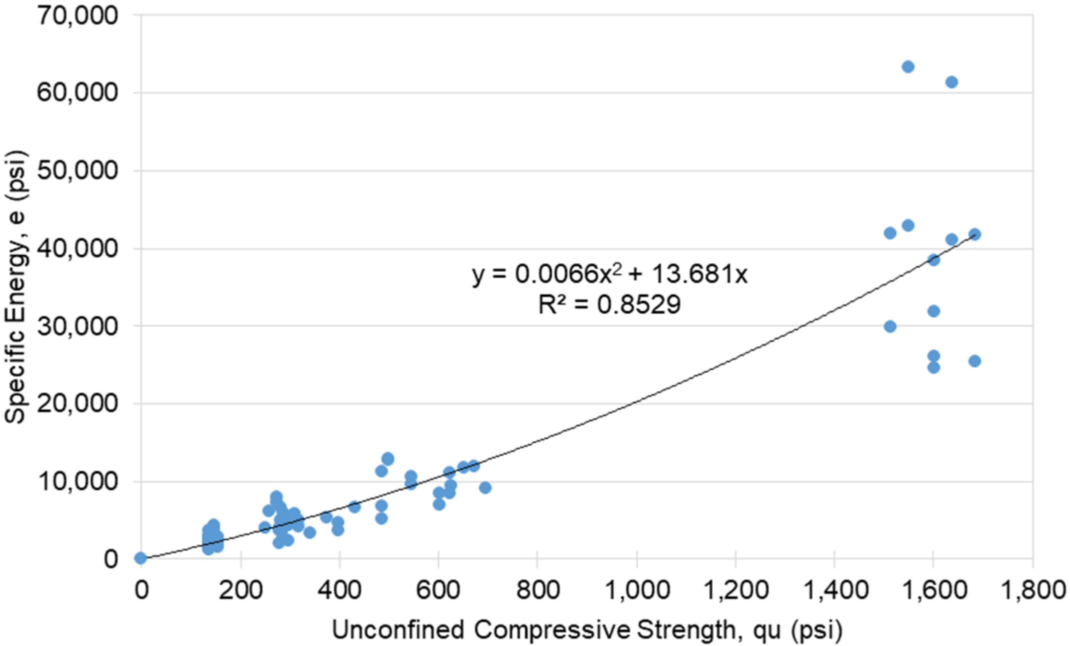
Task Outline

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

Background and Objective

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

Small-scale Drilling with Rock Augers



(Rodgers et al. 2018A)

Florida Rock Field Drilling Equation

Using the equation from the e vs. q_u plot

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

Where,

$y = e$ (psi)
$x = q_u$ (psi)

Setting the equation equal to zero:

$$0.0066x^2 + 13.681x - y = 0$$

Using the Quadratic solution,

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

Substituting terms in for a, b, and c:

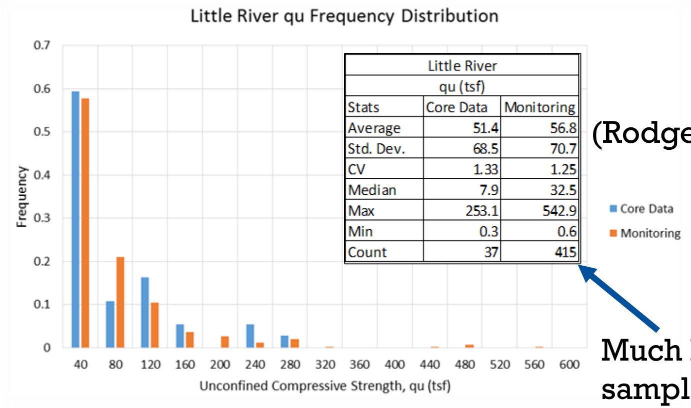
$$q_u = \frac{-13.681 + \sqrt{(13.681)^2 - 4 * (0.0066) * (-e)}}{2 * (0.0066)}$$

Field Drilling Investigation

- During the field drilling investigation, three variations were implemented in the following categories:
  - Drill rigs and drilling crews
  - Shaft/Auger diameters
    - 3 ft, 4 ft, and 5 ft
  - Locations (limestone formations encountered)
  - Slurries
    - Water, bentonite, and polymer
  - Rock auger configurations
    - Unique flights, tooth configurations, and guide shafts
    - All double flight augers
  - Comparative load tests
    - Top-down static, Statnamic, and Bi-directional Osterberg
- In all cases, the results obtained from monitoring the shaft installations (MWD) were in good agreement w/ the results obtained from load testing

Analysis of Rock Strength – Little River, FL

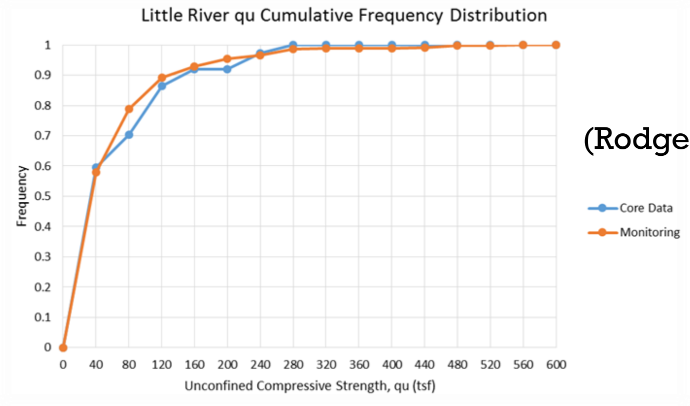
- Good core recoveries
  - Average REC% = 85%
- Large number of core samples
  - 37 q_u core samples available for comparison in monitored depth range
- Monitoring and core sampling produced similar frequency distributions
  - Nearly identical CV values
- Difference in average strength due to site variability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



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

(Rodgers et al. 2018B)

Much larger MWD sampled population

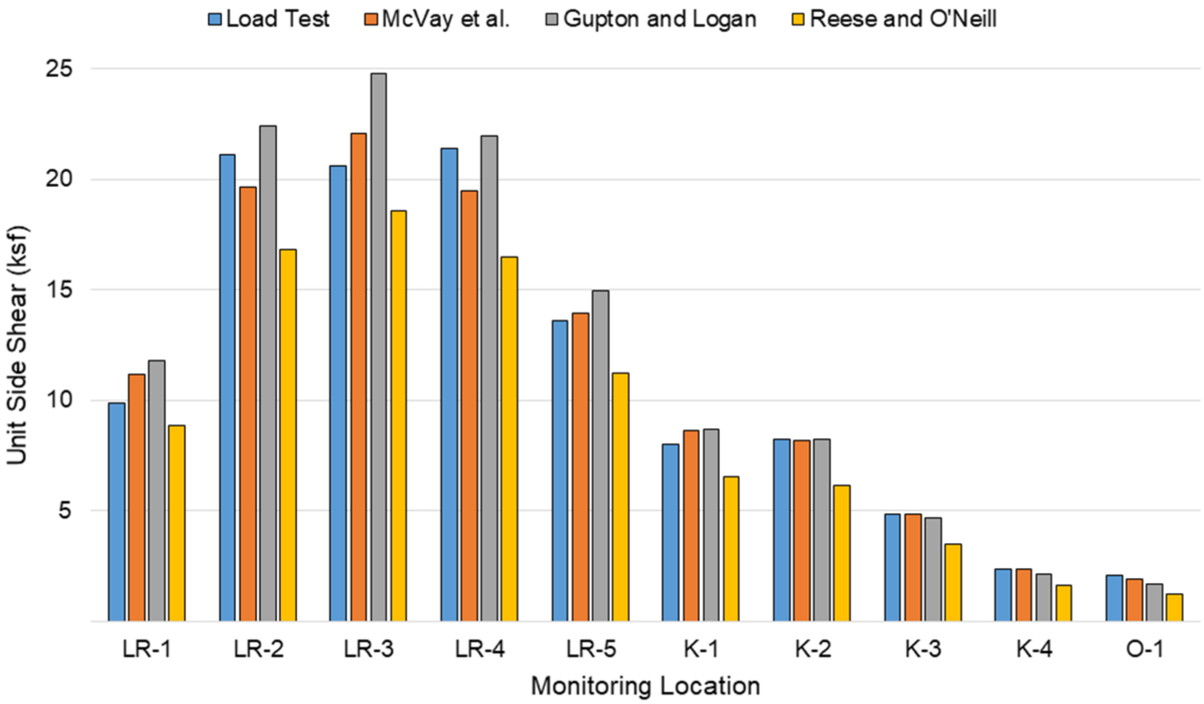


(Rodgers et al. 2018B)

Leading Skin Friction Equations

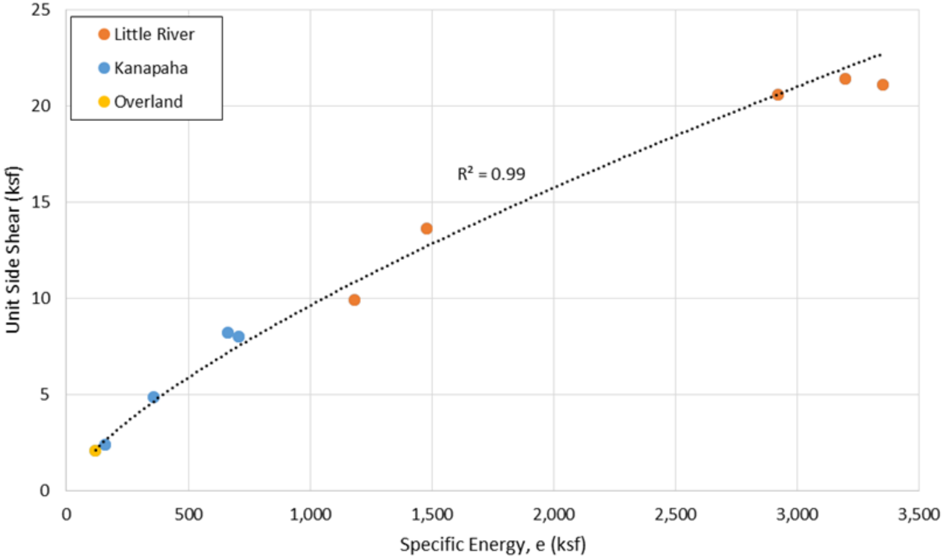
Method	Author	Design Methodology
1	McVay et al.[6]	$f_s = 1/2 \times \sqrt{q_u} \times \sqrt{q_t}$
2	Reese and O'Neill[7,8]	$f_s = 0.15 \times q_u$ (tsf)
3	Horvath and Kenney[8]	$f_s = 0.67 \times \sqrt{q_u}$ (tsf)
4	Williams et al.[9]	$f_s = 1.842 \times {q_u}^{0.367}$ (tsf)
5	Reynolds and Kaderabek[10]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

Comparative Skin Friction Analysis



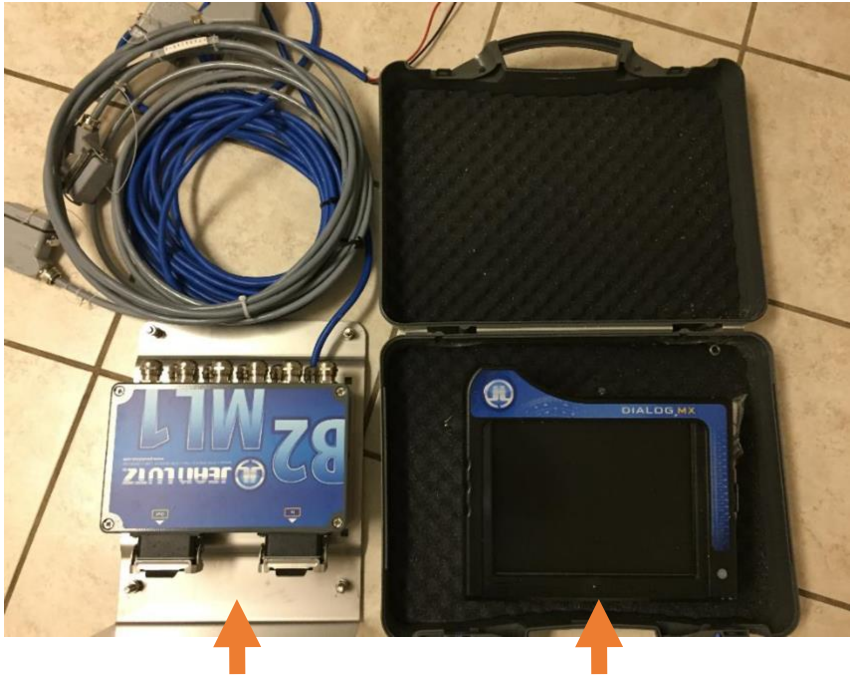
MWD e vs. Load Test Side Shear – Rock Auger

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



New Monitoring Equipment

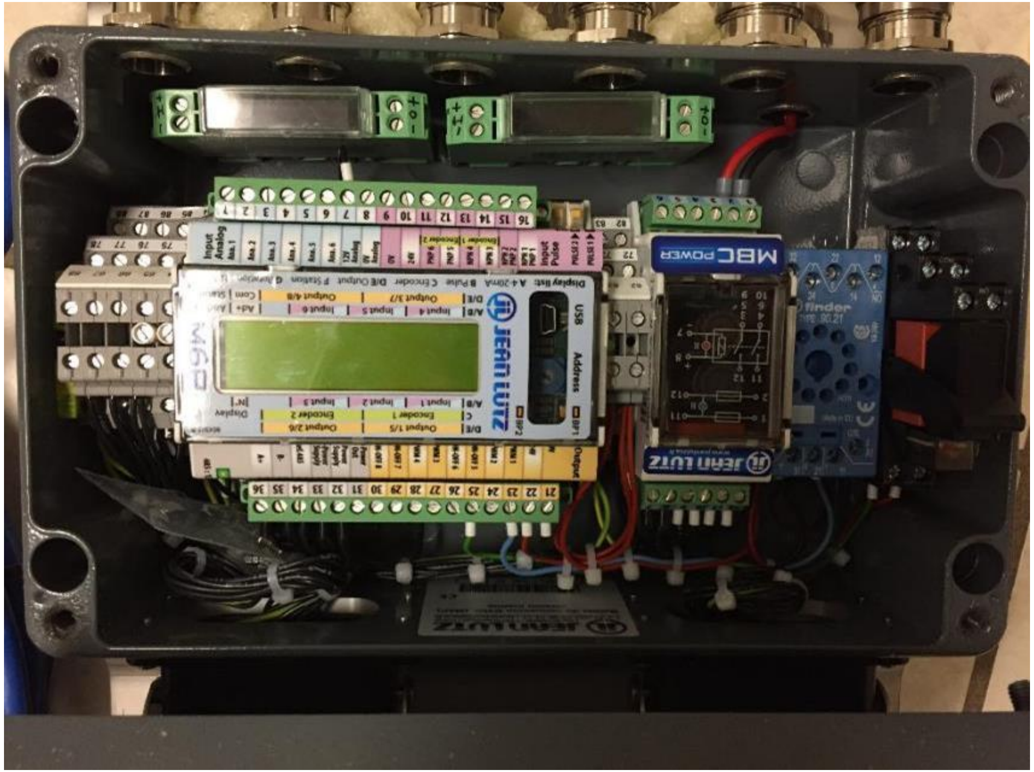
- Acquired new monitoring equipment
  - DIALOG – DAQ module
  - Junction box
  - Extra cable
- Installed on a Liebehrr BAT 410 drill rig
  - First monitored Liebehrr rig
  - Fully hydraulic w/ all sensors installed by the manufacturer
  - Tapped into existing sensors
  - New installation method
- Monitored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



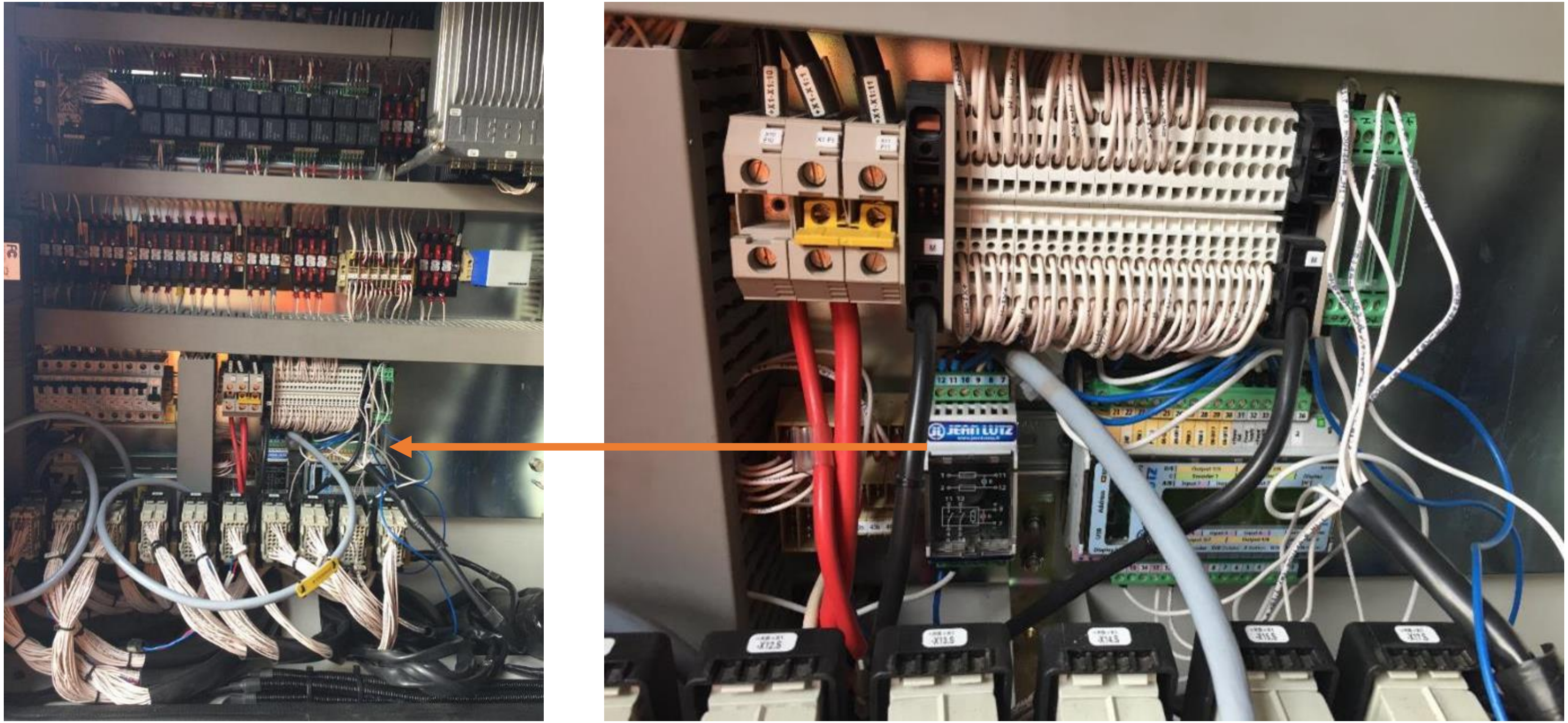
Junction Box

DIALOG

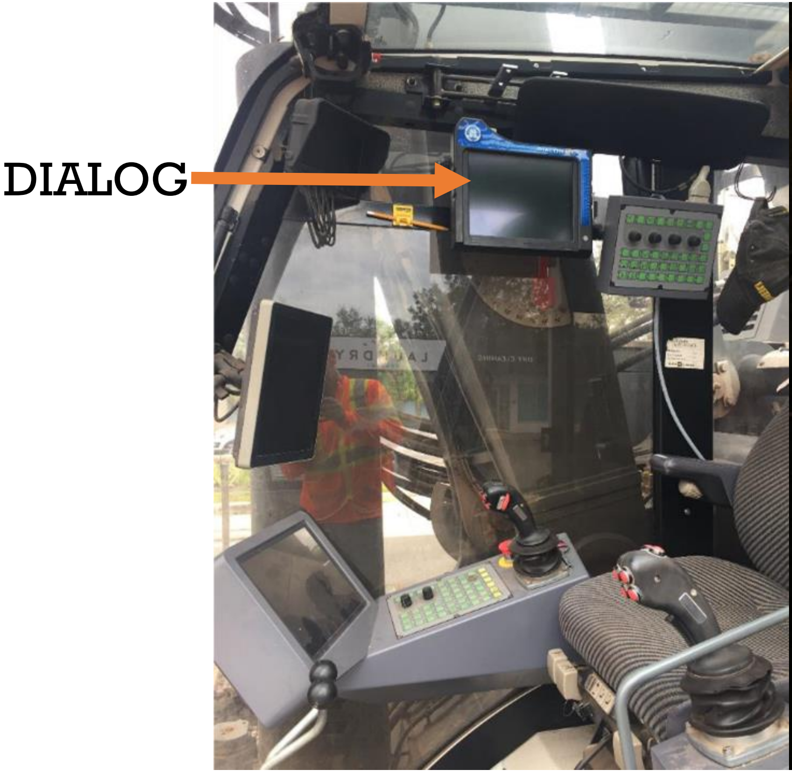
Internal Components of Junction Box



Mounting Components into Electrical Unit



Monitoring from a Safe Distance

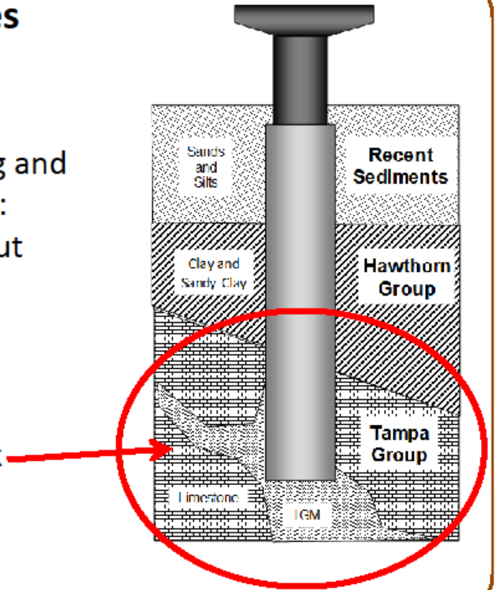


Extreme Variability at Selmon Expy.

Challenges for design and design approach prior to MWD development - 2013

The Challenges For Design

- A means of identifying and Quantifying the strata:
  too hard for SPT, but
  too soft for coring
- Design Process MUST account for variability of the weathered rock bearing formation.



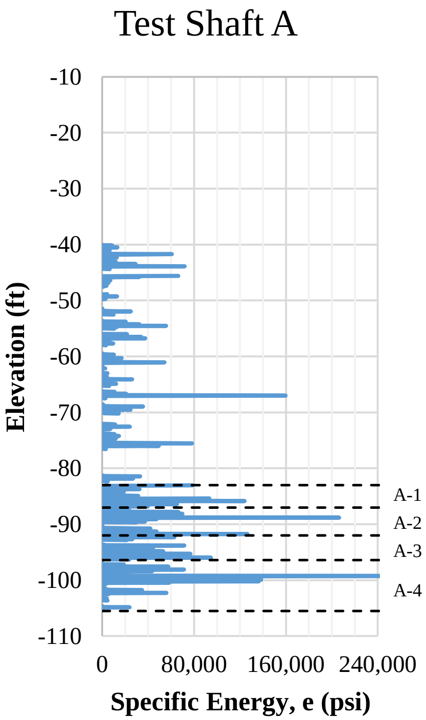
Design of Non-Redundant Foundations in Highly Variable Conditions Requires:

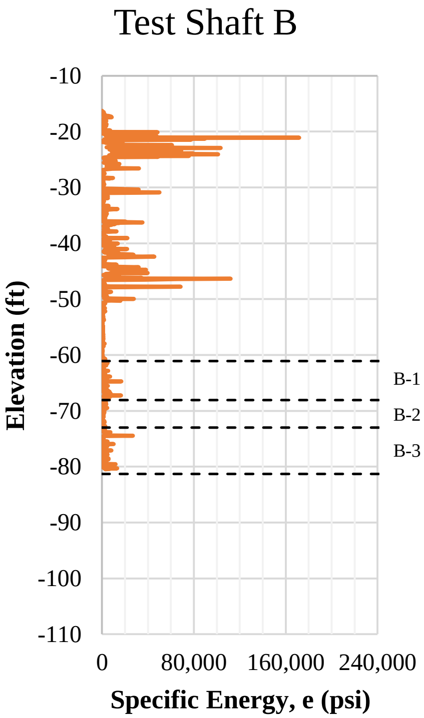
1. Through Investigation: Simple SPT delineation used
   (a) with a large sample population, and
   (b) boring at each location. MWD coring/drilling?
2. Comprehensive load testing across range of conditions.
   (a) Assign Resistances based on material, and
   (b) Resist temptation to delineate into finer segments.
3. Design must be robust to achieve reliability:
   (a) Capture the low end of the performance,
   (b) Then carefully consider your ϕ-factor.
4. Rigorous QC/QA is required, and the designer must remain engaged during construction.

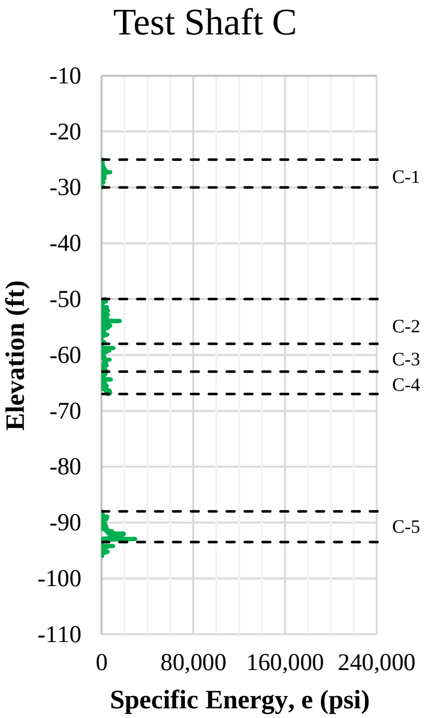
(Dapp et al. 2013)

Drilled Shaft MWD – Selmon Epxy.

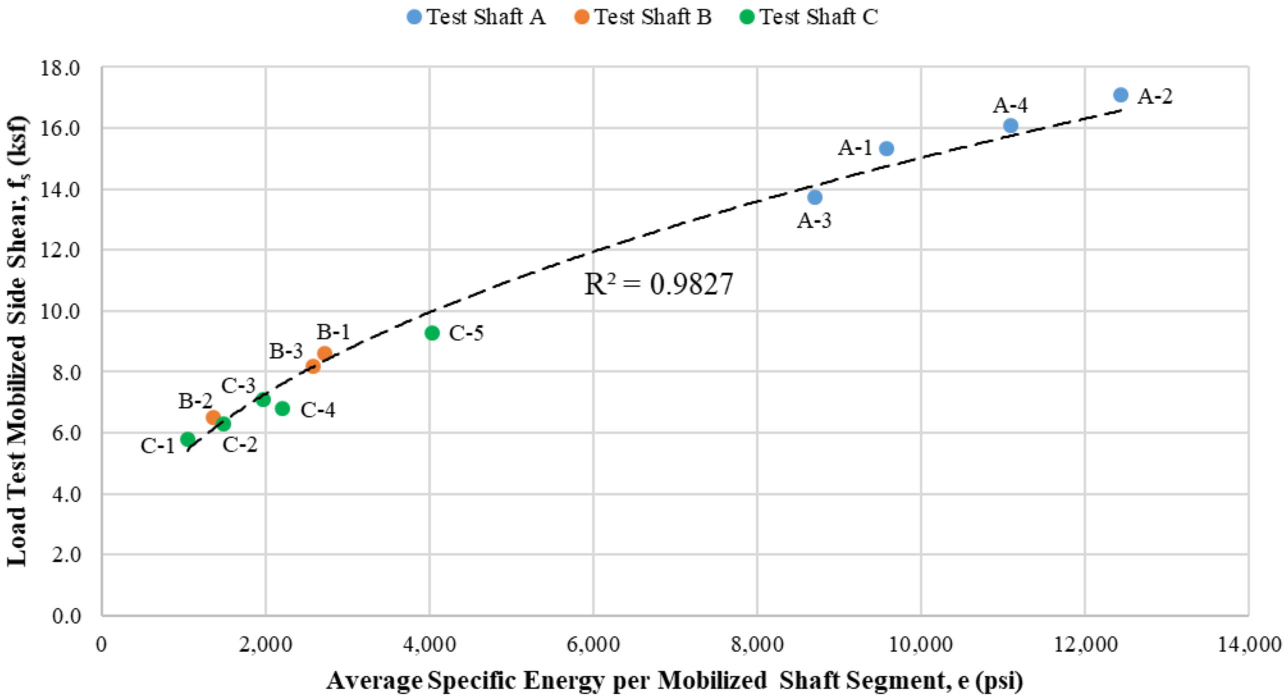
Specific Energy Recorded in Layers of Rock and IGM







e vs. f_s Correlation - Selmon Expy.



Correlation could be used to provide QA/QC during production shaft drilling

Developing q_u Assessment

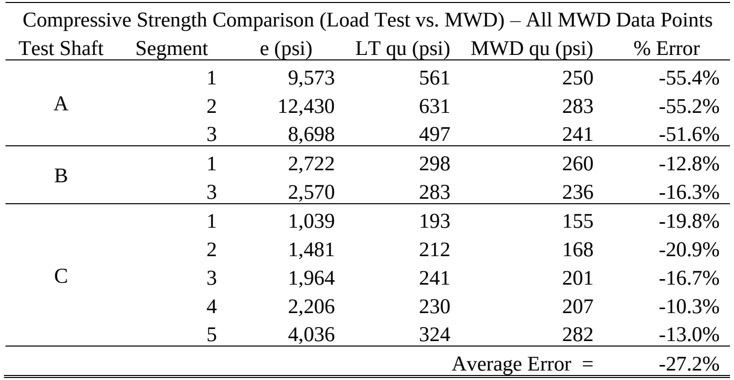
- Prior correlation was for axial shaft capacity based on average specific energy recorded over each mobilized shaft segment using a unique rock drilling bucket
- Needed to analyze MWD q_u vs. Core q_u
  - Could not use rock auger MWD q_u EQN ⇨ Different bit geometry than rock drilling bucket
- Backed out MWD q_u values from f_s using Rodgers et al. (2018c) side shear equation:

$$f_s = 0.3302 \times {q_u}^{0.9125} \rightarrow q_u = \left(\frac{f_s}{0.3302}\right)^{\left({}^{1}/_{0.9125}\right)}$$

  - Combines McVay et al. (1992) side shear equation ($f_s = 1/2\sqrt{q_u}\sqrt{q_t}$) with Rodgers et al. (2018c) Florida Geomaterials equation (q_u – q_t relationship)
- Estimated q_u from load test f_s and each MWD f_s data point for comparison
  - Rock strength should be largest contributor to load test side shear
  - Each shaft segment should provide a reasonable q_u average to compare with MWD q_u estimates

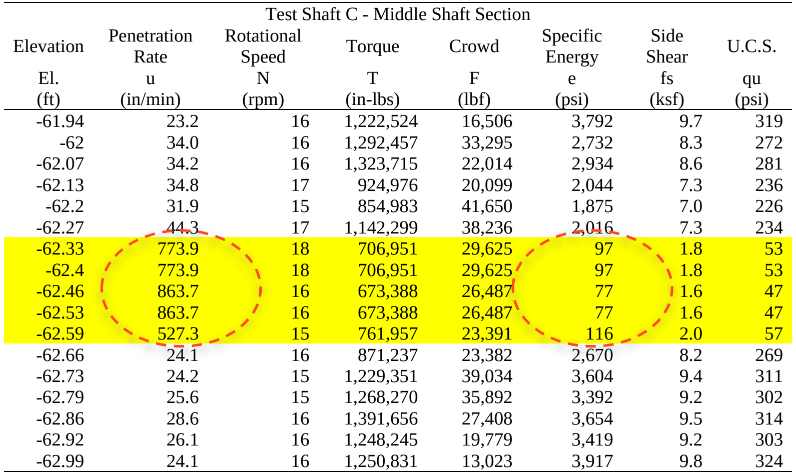
Assessment of MWD q_u

- Load test q_u Avg. derived from measured side shear per mobilized shaft segment
- MWD q_u Avg. from each individual data point backed out from f_s equation
- Why would MWD be so conservative?
  - Soil layers interlaced within rock
    - Not detectable by load testing alone
  - Need to delineate soil from rock to get proper MWD q_u data for core comparisons



Compressive Strength Comparison (Load Test vs. MWD) – All MWD Data Points

Test Shaft	Segment	e (psi)	LT qu (psi)	MWD qu (psi)	% Error
A	1	9,573	561	250	-55.4%
	2	12,430	631	283	-55.2%
	3	8,698	497	241	-51.6%
B	1	2,722	298	260	-12.8%
	3	2,570	283	236	-16.3%
C	1	1,039	193	155	-19.8%
	2	1,481	212	168	-20.9%
	3	1,964	241	201	-16.7%
	4	2,206	230	207	-10.3%
	5	4,036	324	282	-13.0%
				Average Error =	-27.2%



Test Shaft C - Middle Shaft Section

Elevation El. (ft)	Penetration Rate u (in/min)	Rotational Speed N (rpm)	Torque T (in-lbs)	Crowd F (lbf)	Specific Energy e (psi)	Side Shear fs (ksf)	U.C.S. qu (psi)
-61.94	23.2	16	1,222,524	16,506	3,792	9.7	319
-62	34.0	16	1,292,457	33,295	2,732	8.3	272
-62.07	34.2	16	1,323,715	22,014	2,934	8.6	281
-62.13	34.8	17	924,976	20,099	2,044	7.3	236
-62.2	31.9	15	854,983	41,650	1,875	7.0	226
-62.27	44.3	17	1,142,299	38,236	2,016	7.3	234
-62.33	773.9	18	706,951	29,625	97	1.8	53
-62.4	773.9	18	706,951	29,625	97	1.8	53
-62.46	863.7	16	673,388	26,487	77	1.6	47
-62.53	863.7	16	673,388	26,487	77	1.6	47
-62.59	527.3	15	761,957	23,391	116	2.0	57
-62.66	24.1	16	871,237	23,382	2,670	8.2	269
-62.73	24.2	15	1,229,351	39,034	3,604	9.4	311
-62.79	25.6	15	1,268,270	35,892	3,392	9.2	302
-62.86	28.6	16	1,391,656	27,408	3,654	9.5	314
-62.92	26.1	16	1,248,245	19,779	3,419	9.2	303
-62.99	24.1	16	1,250,831	13,023	3,917	9.8	324

MWD Elimination Criteria

- Developed data point elimination criteria using penetration rate
  - u = 400 in/min threshold estimate
- Investigated N and F
  - Limited variability for N
- F stats were very similar for u above and below 400 in/min
  - F is not creating increase in u
- Reanalyzed MWD q_u with elimination criteria applied
  - Performed in-depth statistical analysis using new MWD q_u data

Crowd, F (lbf)

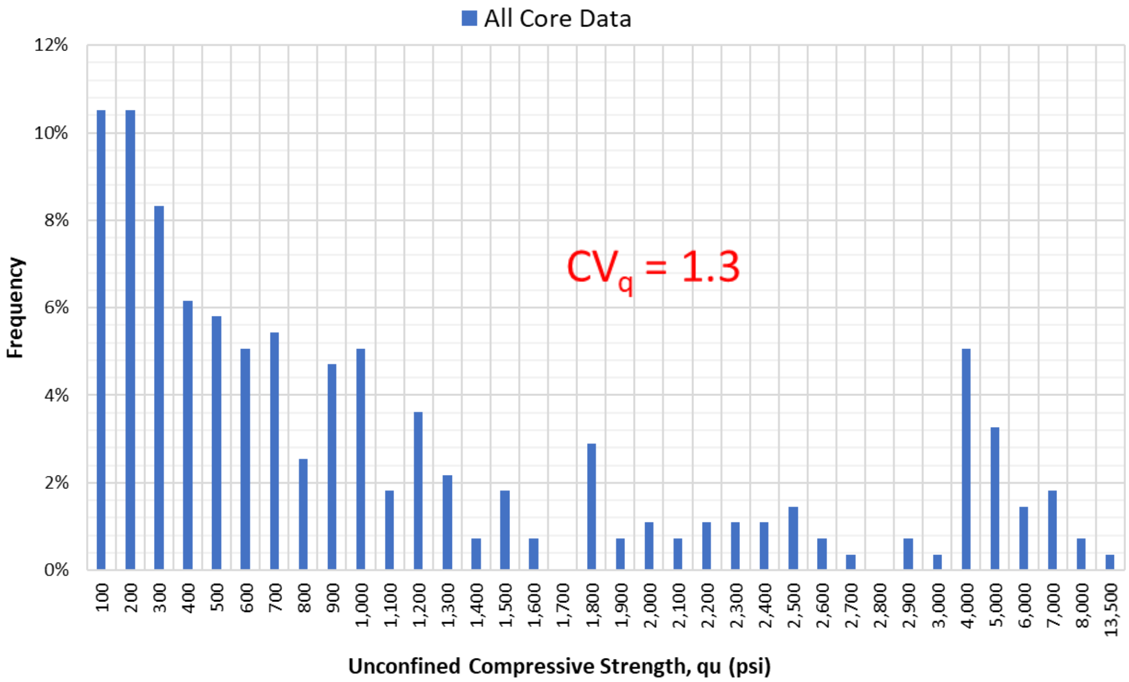
Stats	Test Shaft A		Test Shaft B		Test Shaft C	
	u < 400	u > 400	u < 400	u > 400	u < 400	u > 400
Average	23,858	24,930	12,210	12,048	24,686	20,963
Std. Dev.	12,223	11,897	5,405	6,216	14,456	13,601
CV	0.51	0.48	0.44	0.52	0.59	0.65
Median	23,966	23,955	11,160	9,500	23,595	19,652
Maximum	51,466	51,726	27,202	24,853	55,633	55,010
Minimum	191	404	1,858	3,325	252	209
Count	256	408	264	33	262	128

Compressive Strength Comparison (Load Test vs. MWD)

Test Shaft	Segment	LT qu (psi)	MWD qu (psi)	% Error
A	1	561	541	-3.5%
	2	631	577	-8.6%
	3	497	512	2.9%
B	1	298	258	-13.3%
	3	283	250	-11.7%
C	1	193	165	-14.4%
	2	212	221	4.5%
	3	241	262	8.8%
	4	230	281	22.0%
	5	324	309	-4.9%
			Avg. % Difference =	-1.8%

Selmon Expy. Core q_u Frequency Distribution

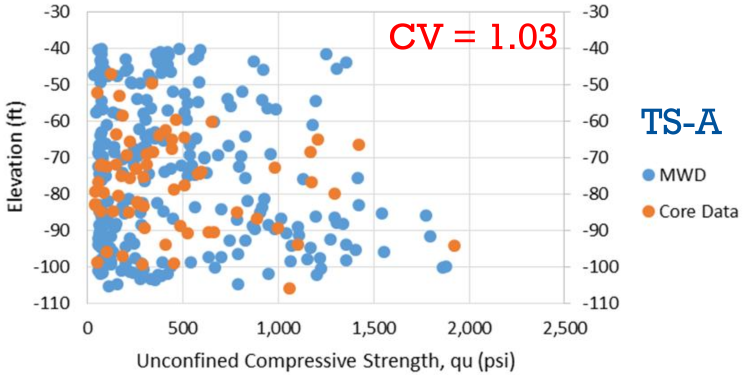
- Strength Data is Bimodal
  - Results in Very High CV
  - ⇒ Low **Φ**
- Not known from Frequency distribution if Variability is Vertical or Horizontal

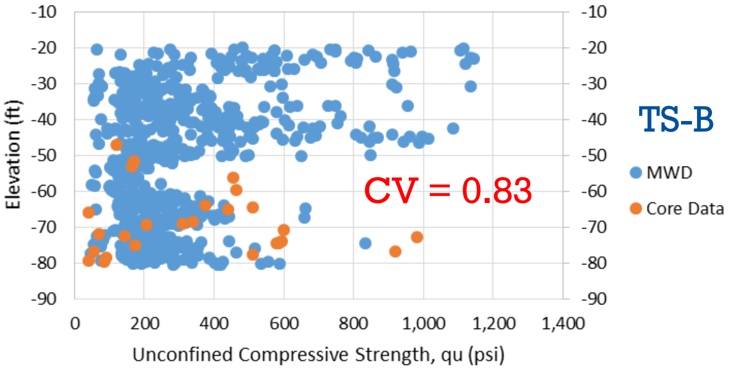


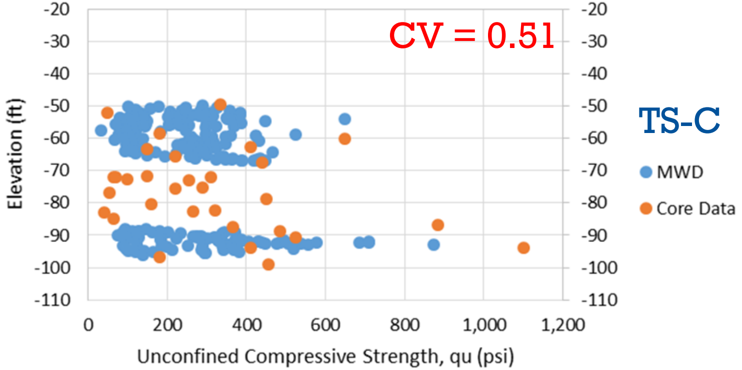
$CV_q = 1.3$

Selmon Expressway

- MWD conducted on 3 test shafts
    - Significant layering at the site
    - MWD variograms developed
- Core data from all borings
    - **$CV_{\text{all data}}$ = 1.3**
    - **High CV → Low LRFD Φ**


TS-A


TS-B


TS-C

Vertical Zonal Anisotropy

Areal View:

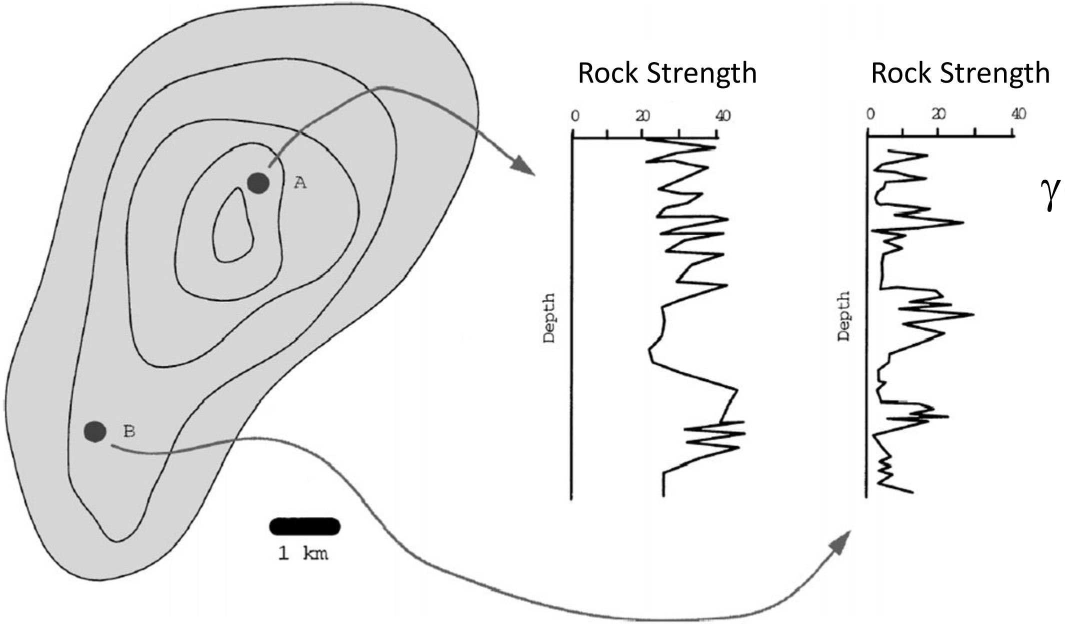
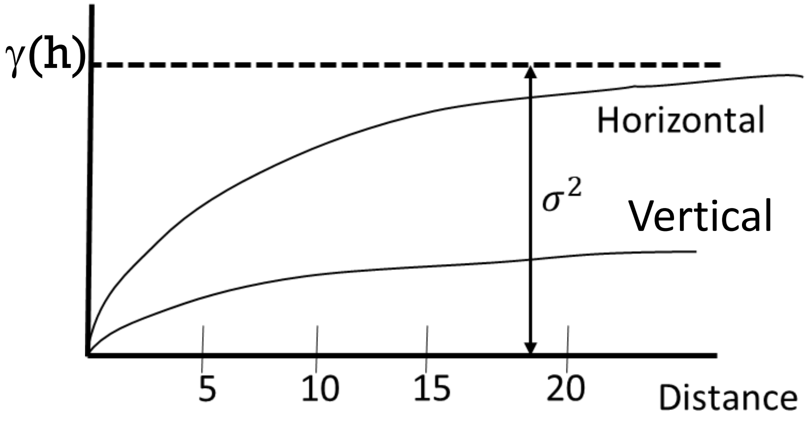


Figure 3. In presence of areal trends (illustrated at the left) each well will not "see" the full range of variability, that is, wells in the higher valued areas (e.g., well A) encounter mostly high values whereas wells in the lower valued areas (e.g., well B) encounter mostly low values. The vertical variogram in this case does not reach the total variability, that is, it shows a *zonal anisotropy*.



Variograms

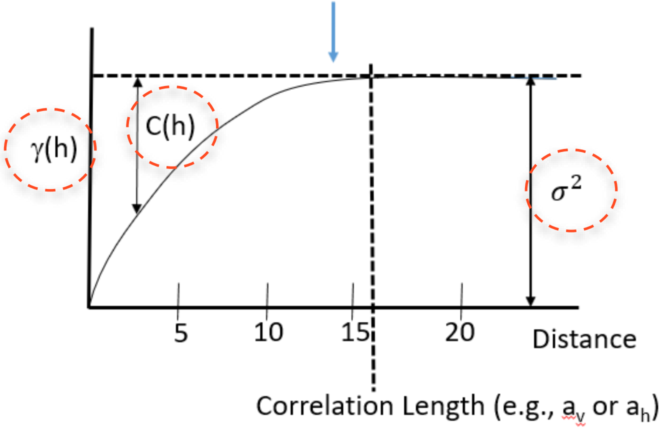
$$\gamma(h) = \frac{1}{2N}\sum_{i=1}^{n}\left(V(t)_i - V(t+h)_i\right)^2 \leftarrow \text{General Equation}$$

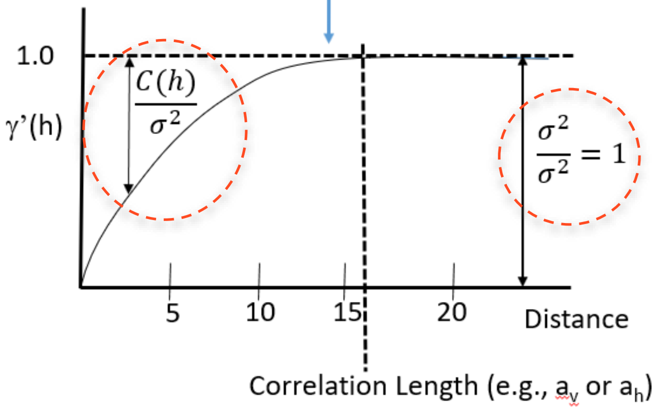
$$\gamma(h) = \sigma^2 - C(h)$$

Normalized by σ^2

Dimensionless in γ-axis

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



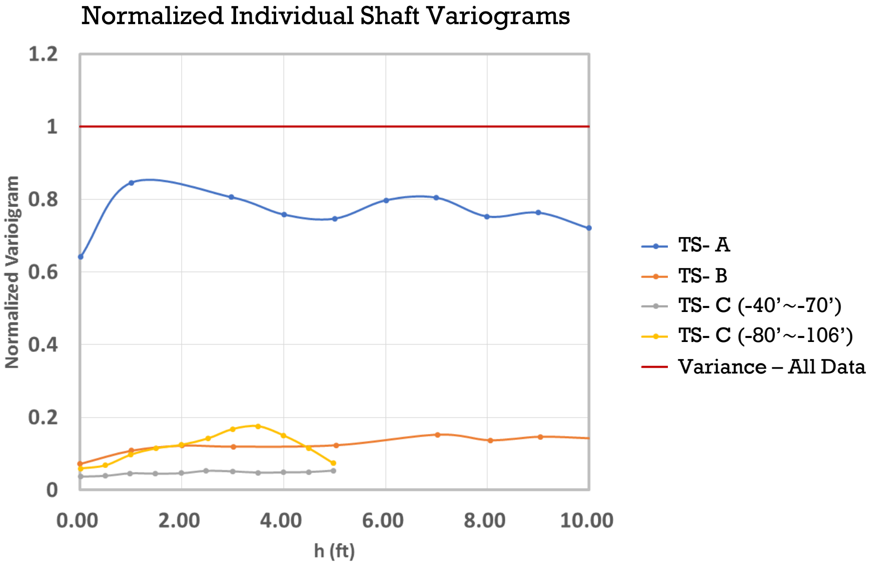


MWD Variograms

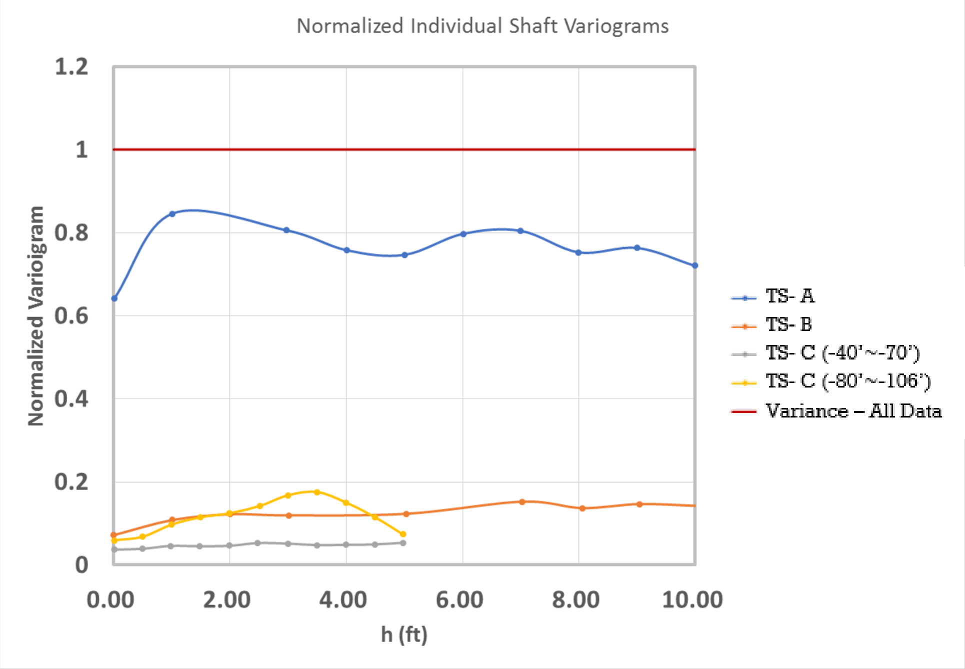
- Areal locations (zones) on the site have very different vertical rock strengths in zones
- Mean strength of rock in each zone is quite different with different CV
  - Very different shaft capacities
- Site should be broken into Areal zones with different axial design for each zone
  - Results in much lower CVs and higher LRFD **Φ** in each zone
- If not broken into zones, but lumped together, the mean strength is too high for many and low for others. Consequently, because of high CV of all the data ---- the LRFD phi with this approach should be very low

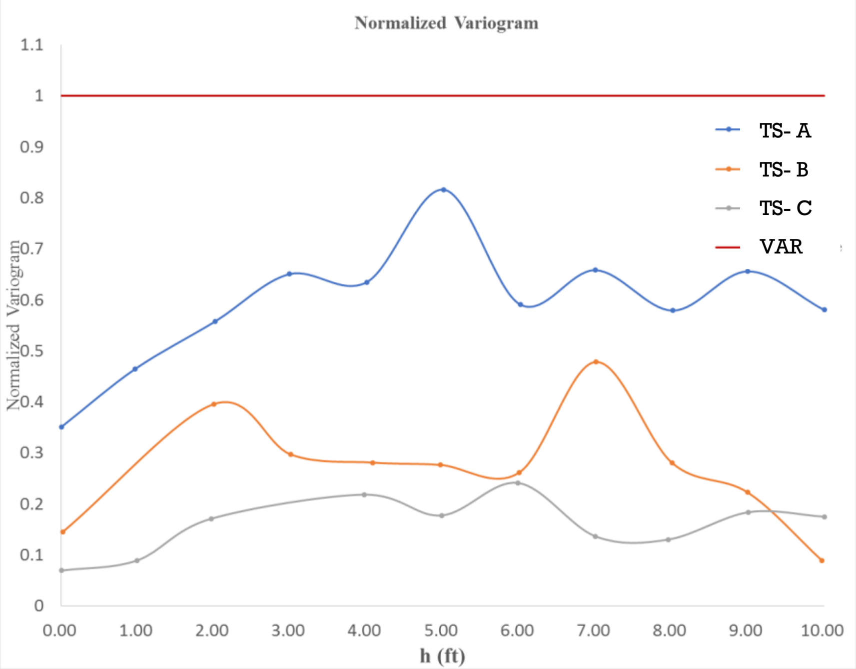
Selmon Expressway MWD Variograms

----Vertical Zonal Anisotropy----



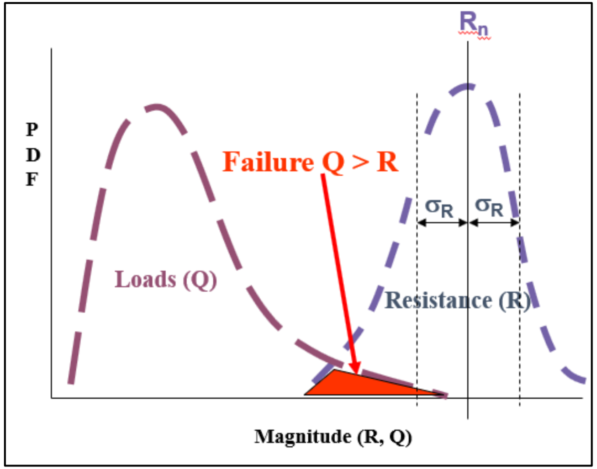
MWD and Core Variograms

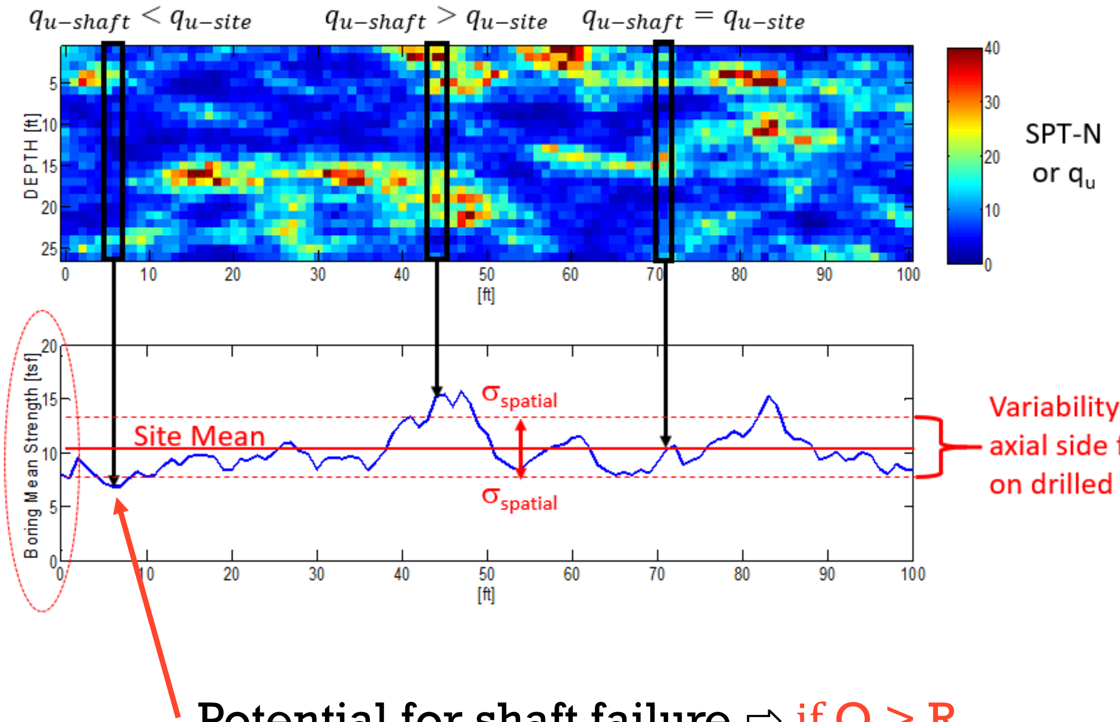




Vertical variograms do not reach total variability ⇨ <u>Vertical Zonal Anisotropy</u>

Shaft Spatial Correlation





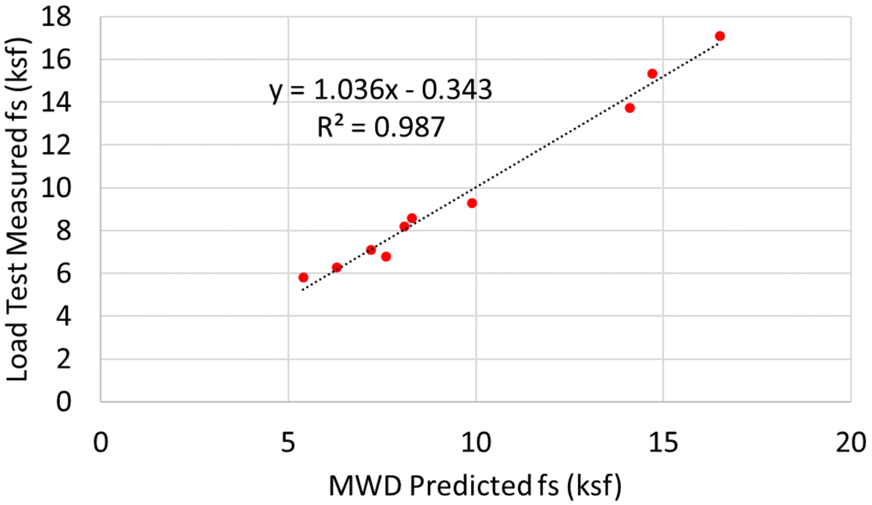
Influence of spatial correlation on mean side friction

Variability of mean axial side friction on drilled shafts

Potential for shaft failure ⇨ if Q > R

MWD – Selmon Expressway

Skin Friction, fs (ksf)		
Location	Measured	Predicted
TS - A	15.3	14.7
	17.1	16.5
	13.7	14.1
TS - B	8.6	8.3
	8.2	8.1
TS - C	5.8	5.4
	6.3	6.3
	7.1	7.2
	6.8	7.6
	9.3	9.9
Mean	9.8	9.8
Std Dev.	3.844	3.684
Count	10	10



$$\hat{R} = 1.036p - 0.343$$
$$R^2 = 0.987$$
$$b = 1.036$$
$$a = -0.343$$
$$\sigma_m = 3.844$$
$$\sigma_\varepsilon^2 = 0.192$$

$$\sigma_\varepsilon^2 = \sigma_m^2(1 - R^2) = 3.844^2(1 - 0.987) = 0.192$$

$$CV_R = \frac{\sqrt{b^2 \cancelto{0}{\sigma_s^2} + \sigma_\varepsilon^2}}{bp + a} \rightarrow \text{Low } CV_R \rightarrow \text{High } \Phi$$

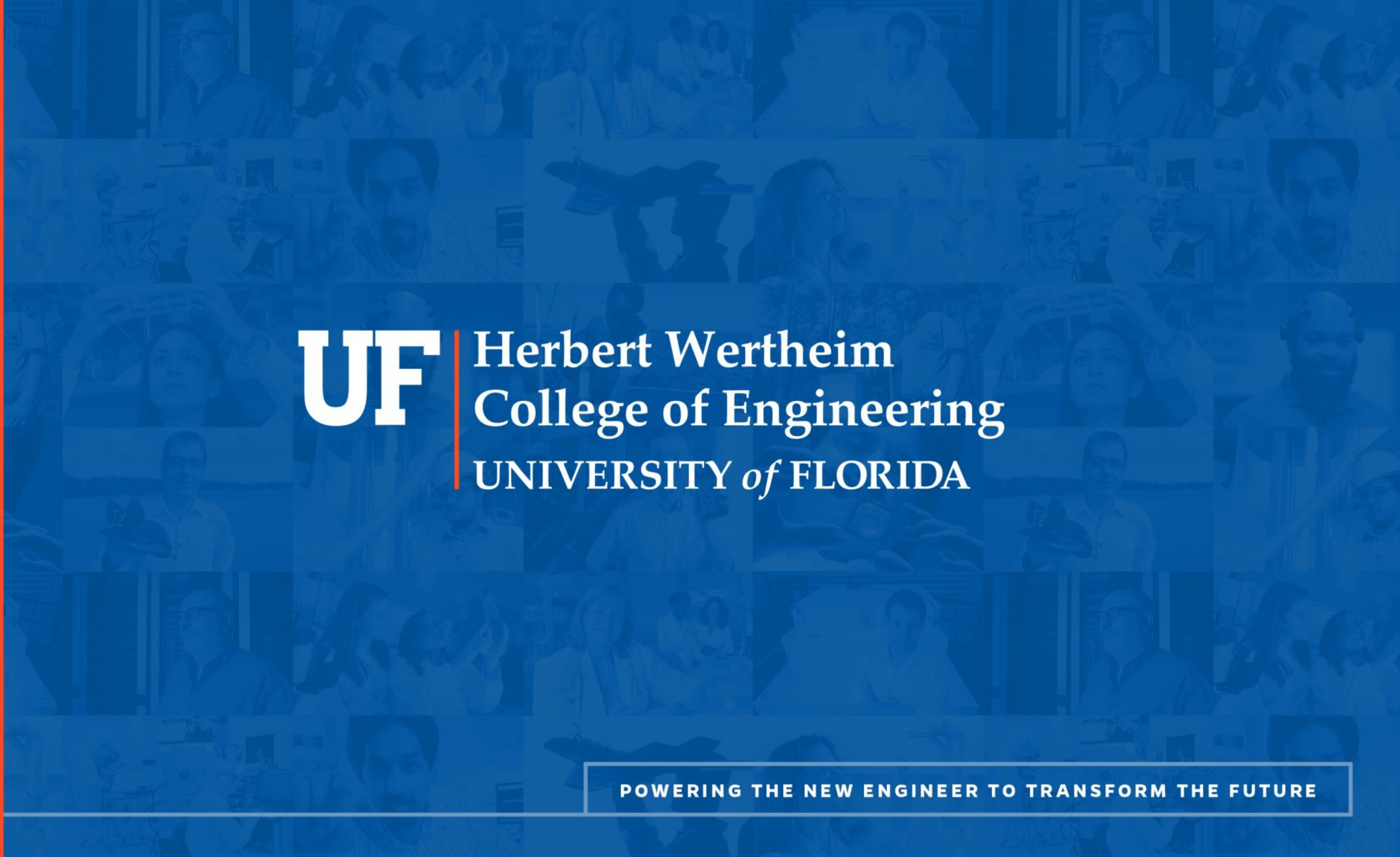
$b^2\sigma_s^2$ = Bias corrected spatial uncertainty
σ_ε^2 = Uncertainty of method (e.g., load test)
$bp + a$ = Bias corrected prediction (i.e., $\hat{R}$)

Remaining Tasks

- Monitor final site
  - CR-250 Bridge is a potential final site
    - Conduct drilled shaft MWD – 4 shafts (2 load tested shafts)
    - MWD data reduction and analysis
    - Core data and site variability analysis (core data being collected)
- Draft Final Report and Closeout Teleconference
- Final Report

References

- Carter JP, Kulhawy FH. Analysis and Design of Foundations Socketed into Rock. *Research Report 1493-4, Geotechnical Engineering Group*. Ithaca; NY: Cornell University; 1987.
- Chen X., Gao D., Guo B., Feng Y. 2016. Real-time optimization of drilling parameters based on mechanical specific energy for rotating drilling with positive displacement motor in the hard formation. Journal of Natural Gas Science and Engineering. Volume 35, Part A, Pages 686-694.
- Gupton C, Logan T. Design Guidelines for Drilled Shafts in Weak Rocks of South Florida. *Proceedings of the South Florida Annual ASCE Meeting*. ASCE: 1984.
- Horvath RG, Kenney TC. Shaft Resistance of Rock-Socketed Drilled Piers. *Symposium on Deep Foundations, ASCE National Convention*. Atlanta; GA: 1979. 182-214.
- McVay M, Townsend F, Williams R. Design of Socketed Drilled Shafts in Limestone. *ASCE Journal of Geotechnical Engineering*. 1992;118:10:1626-1637.
- Ramos HR, Antorena JA, McDaniel GT. Correlations between the Standard Penetration Testing (SPT) and the Measured Shear Strength of Florida Natural Rock. *Proceedings from FHWA International Conference on Design and Construction of Deep Foundations*. Orlando; FL: 1994. 699-711.
- Reese LC, O'Neill MW. Drilled Shafts: Construction Procedures and Design Methods, Design Manual. *US Department of Transportation, Federal Highway Administration*. McLean; VA: 1987.
- Reynolds RT, Kaderabek TJ. Miami Limestone Foundation Design and Construction. *ASCE*. New York; NY: 1980.
- Rodgers M., McVay M., Ferraro C., Horhota D., Tibbetts C., Crawford S. 2018A. Measuring Rock Strength While Drilling Shafts Socketed Into Florida Limestone. ASCE Journal of Geotechnical and Geoenvironmental Engineering.doi.org/10.1061/(ASCE)GT.1943-5606.0001847
- Rodgers M., McVay M., Horhota D., Hernando J. 2018B. Assessment of Rock Strength from Measuring While Drilling Shafts in Florida Limestone. Canadian Geotechnical Journal. doi.org/10.1139/cgj-2017-0321
- Rodgers M., McVay M., Horhota D., Sinnreich J., Hernando J. 2018C. Assessment of Shear Strength from Measuring While Drilling Shafts in Florida Limestone. Canadian Geotechnical Journal. doi.org/10.1139/cgj-2017-0629
- Rodgers M., McVay M., Horhota D. 2018D. Monitoring While Drilling Shafts in Florida Limestone. IFCEE 2018: Installation, Testing, and Analysis of Deep Foundations. GSP 294.
- Rowe RK, Armitage HH. 1987. A Design Method for Drilled Piers in Soft Rock. *Can Geotech J*. 1987;24(1):126-142.
- Teale R. 1965. The Concept of Specific Energy in Rock Drilling. International Journal of Rock Mechanics and Mining Sciences. 2:57–73.
- Williams AF, Johnston IW, Donald IB. The Design of Socketed Piles in Weak Rock. *Proc Int Conf on Struct Foundations in Rock*, (Netherlands): 1980. 327-347.



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