Assessing Axial Capacities of Auger Cast Piles from Measuring While Drilling BDV31-977-125

GRIP Meeting

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Introduction

- The FDOT has developed and applied measuring while drilling (MWD) of drilled shafts to assess axial shaft capacity quality control.
  - Little River, Kanapaha, Overland, Selmon Expy, and CR-250
- The process involves monitoring the torque, crowd, penetration rate, and rotational speed in real time to obtain specific energy per 1” of penetration which is then correlated to measured shaft side shear from static load tests, rock strength (qu), and SPT N values
- The developed specific energy-side shear correlation is subsequently used for quality assurance (shaft capacities) during the installation of production shafts
  - “qu vs. e” is established or verified on a site-to-site basis

Project Background

- Recently, the FDOT has allowed the use of auger cast (ACIP) piles for bridge piers at I-395 in Miami, West Palm-Boca Raton and Delray, as well as other sites
- Like drilled shafts, ACIP piles require QA/QC of their axial capacities during production pile installation
- ACIP Piles employ an auger bit to remove limestone similar to drilled shafts → It is believed MWD could be used for ACIP axial capacity QA/QC
  - Assess specific energy on at least a 1" scale on planned load tests
  - Establish correlation for ACIP Piles
- Established correlations could then be used as a new method of ACIP QA/QC for production piles
- Since a large amount of data is being collected, LRFD phi assessment of different design methods should be revisited and LRFD for standard design as well as MWD approach should be assessed

Project Objectives

1. Use ISO specified MWD procedures during Auger Cast Pile installations for load tested piles to establish a side shear versus MWD specific energy correlation on a number of sites
2. Validate the MWD correlations and developed QA/QC procedures on production piles at each of the sites
3. Use data obtained from pile load tests, recovered field cores/laboratory strength testing, and SPT testing to reassess LRFD phi factors for Auger Cast Piles in south Florida
4. Use the MWD pile side shear versus specific energy correlations from load tests to establish LRFD phi factors for future south Florida axial pile capacity QA/QC

Tasks and Deliverables

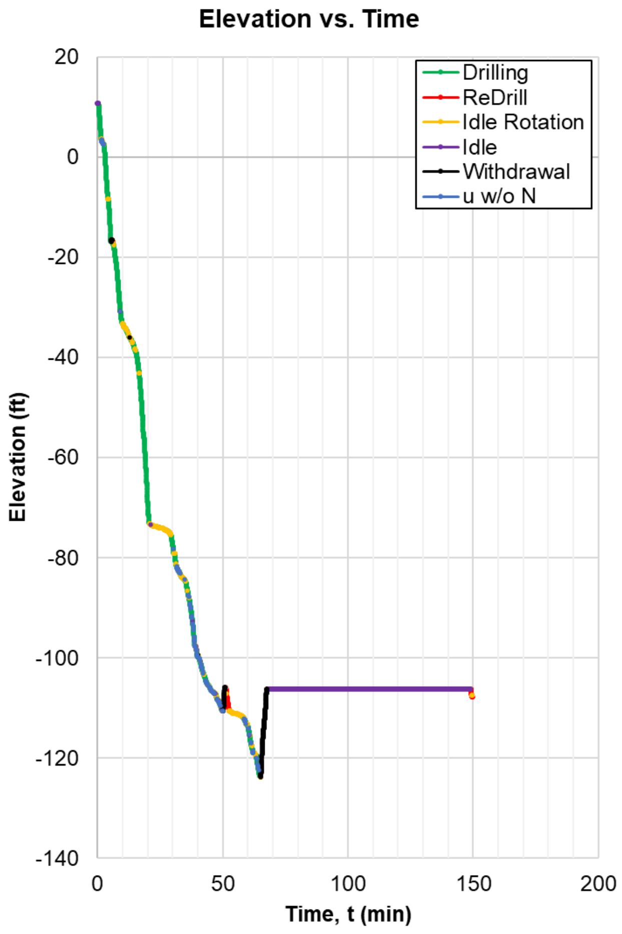
- Deliverable 1 - Establish MWD Data Reduction Criteria and Procedures for ACIP Pile Drill Rigs. (Task 1)
- Deliverable 2 - MWD Specific Energy vs. ACIP Pile Side Shear Relationships (Task 2)
- Deliverable 3 - MWD Correlation Validation for ACIP Production Pile QA/QC (Task 3)
- Deliverable 4 - LRFD Phi Assessment of FDOT Design Methods of ACIP Piles in South Florida (Task 4)
- Deliverable 5 - LRFD Phi Assessment of MWD Specific Energy for ACIP Pile Axial Capacity QA/QC (Task 5)
- Deliverable 6a - Draft Final (Task 6)
- Deliverable 6b - Closeout Meeting (Task 6)
- Deliverable 7 - Final Report (Task 7)

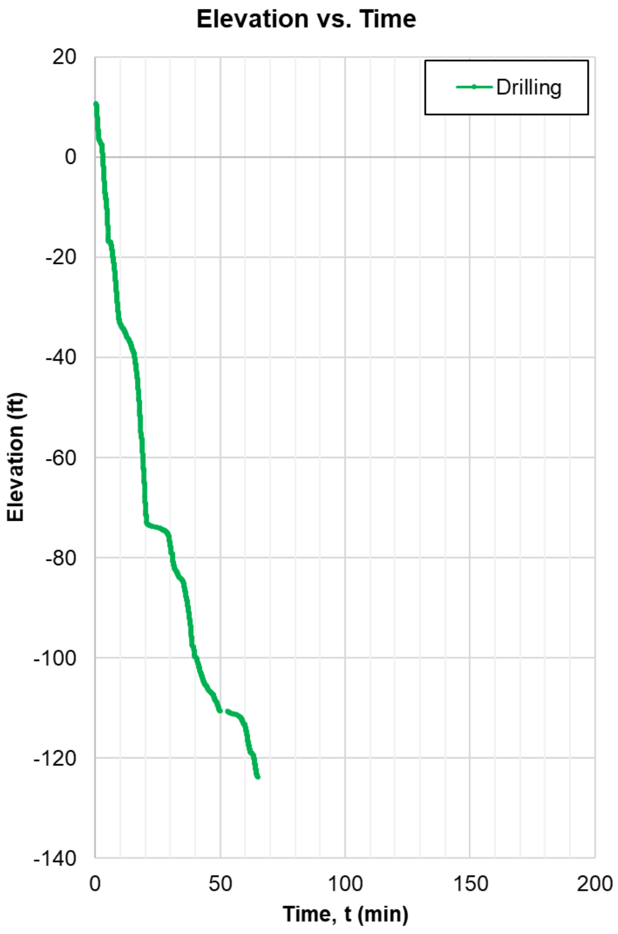
Task 1 – Establish MWD Data Reduction Criteria and Procedures for ACIP Drill Rigs

- The monitoring systems onboard the ACIP pile drill rigs, and the format in which the drilling parameters may be recorded and reported was unknown
  - Time or depth referenced?
- New raw data processing criteria and procedures were developed to produce a workable spreadsheet in which specific energy, rock strength, and shaft capacity may be assessed
- Processing the raw data required a program to be written in which the time-referenced-data is transformed into depth-referenced-data for compatibility with the specific energy equation
  - This increased the complexity of post processing due to the large number of time-referenced raw data points
  - The research effort first focused on properly reducing the raw data in a workable format prior to the assessment of MWD specific energy

Establishing Valid Drilling Data

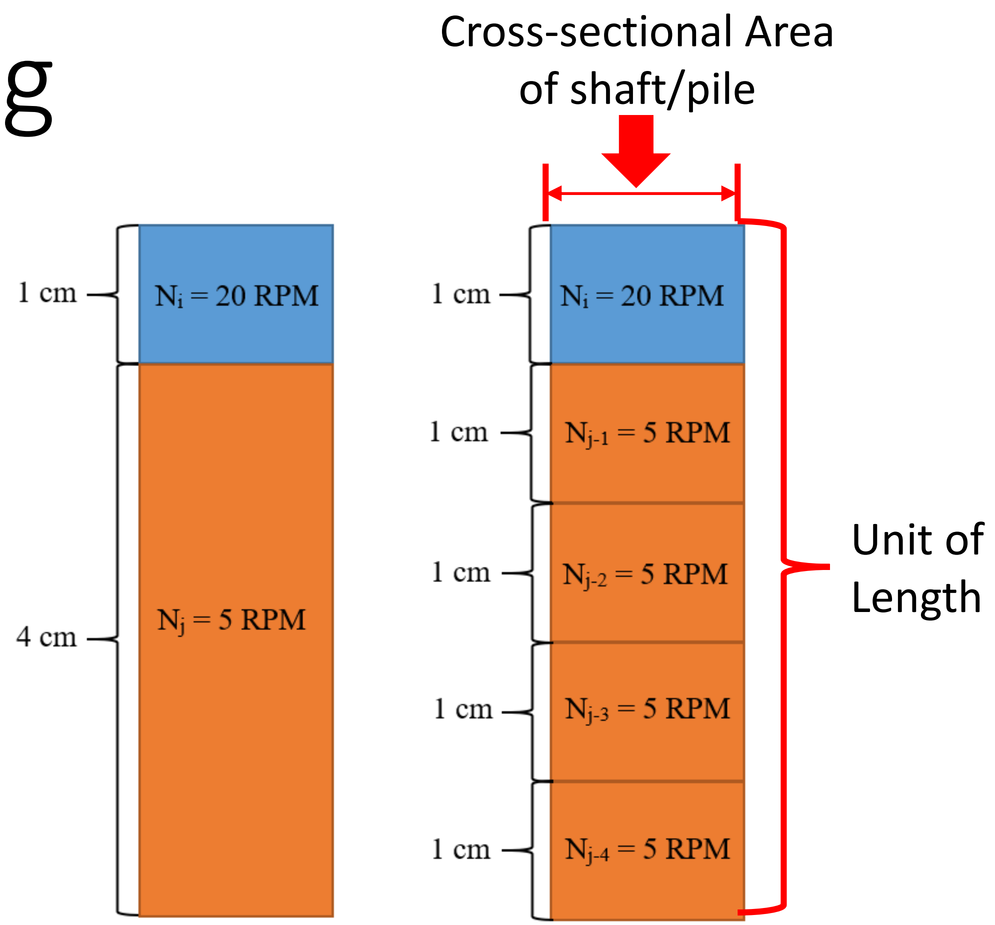
- The drilling operations can include 6 different types of drilling
- **Drilling**
  - Penetration, rotation, torque, and crowd are applied simultaneously
- Withdrawal
  - Auger is being withdrawn (moving upward not downward)
- Re-drill
  - Re-drilling a segment that has been previously drilled (occurs after withdrawal)
- Idle Rotation
  - Rotation is occurring without penetration
- Idle
  - The auger is at rest
- u w/o N
  - Penetration is occurring without rotation (possible void or depth sensor malfunction)
- Only **drilling** data is considered valid and used for specific energy and strength assessment
- Once the valid drilling data points have been established then proper averaging must take place





Proper Averaging

- In rock drilling, specific energy is defined as the energy required to remove/excavate a <u>unit volume of rock</u>
- In order to properly average specific energy over a specified length <u>equal individual lengths of measure must be used</u>
  - Length of shaft segment
  - Volume removed (L_{Shaft} x $A_{X\text{-}sect}$)
- Must use weighted averaging
  - Proportional to the depth increment achieved
  - Cannot be achieved using the time-referenced measurements alone



Incorrect Averaging:

$$N_{avg} = \frac{N_i + N_j}{n} = \frac{20\ RPM + 5\ RPM}{2} = 12.5\ RPM$$

Correct Weighted Averaging:

$$N_{avg} = \frac{N_i + N_{j1} + N_{j2} + N_{j3} + N_{j4}}{n} = \frac{20+5+5+5+5}{5} = 8\ RPM$$

ACIP Analysis Program

- Easy to use and navigate
  - Used simple Microsoft Excel format
- Quickly assess layering within the pile
  - Can assess up to 30 layers within the pile at a time
- Quickly assess rock strengths and pile capacity
  - Automatically provides qu, fs, and capacity for the whole pile and within defined layers
- Capable of assessing time-referenced data
- Quickly adjust analyses based on the drill rig used
- Track drilling operations and efficiency
  - Provides a pile summary report and plots drilling operations vs. time
- Compare multiple piles
  - Can load 10 piles into spreadsheet at a time for quick analyses of a pile group
  - Produces a data page that can be quickly dropped into GeoStat for further analyses

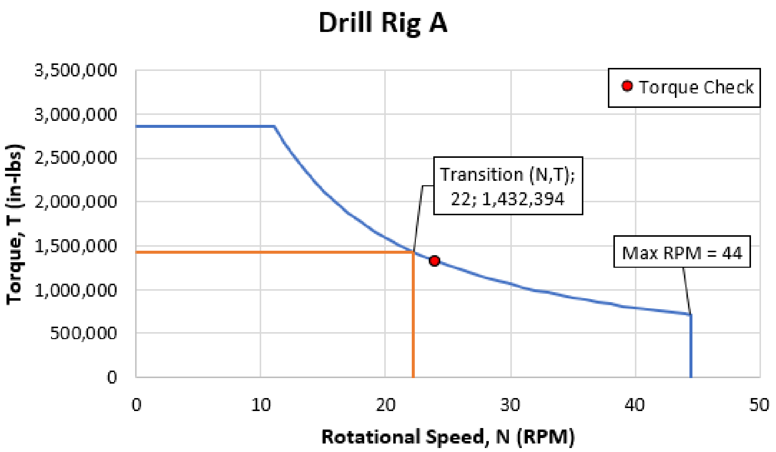
Enter Drill Rig Data

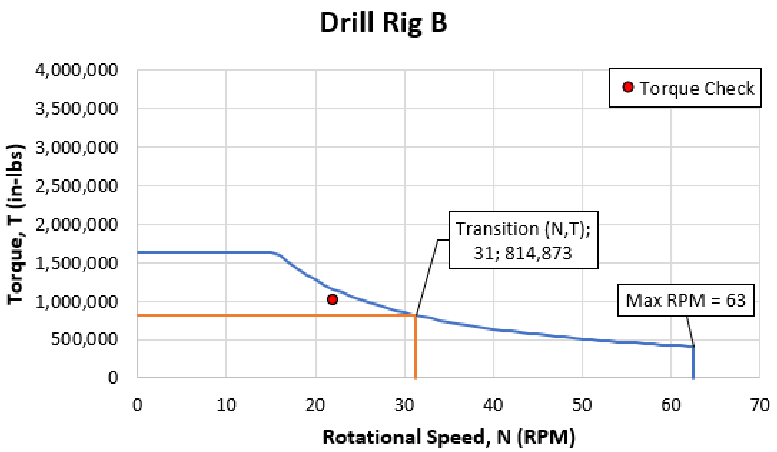
Torque Specifications									
Drill Rig	Rig Type	Maximum Operating Pressure, OP_{Max} (psi)	Hydraulic Motor Displacment, V_g (in^3/rev)		Hydraulic Flow Rate, Q (in^3/min)	Gear Case Reduction		# of Motors	Select Drill Rig (1 or 2)
			Max	Min		Gear 1	Gear 2		
1	Drill Rig A	5,000	10.00	5.00	40,000	180.0	90.0	2	2
2	Drill Rig B	4,000	8.00	4.00	40,000	160.0	80.0	2	

Crowd Specifications		
Specifications	Drill Rig 1	Drill Rig 2
F_{Max} (lbf)	100,000	90,000
OP_{Max} (psi)	5,000	4,000
K_F (lbf/psi)	20.00	22.50

Drill Rig	Gear	N_{min} (RPM)	N_{max} (RPM)	T_{min} (in-lbs)	T_{max} (in-lbs)	Torque Check - Drill Rig 1		Torque Check - Drill Rig 2	
						N (RPM)	P (psi)	N (RPM)	P (psi)
1	1	11	22	1,432,394	2,864,789	24	5,000	22	3,500
	2	22	44	716,197	1,432,394	T (in-lbf)	T (ft-lbf)	T (in-lbf)	T (ft-lbf)
2	1	16	31	814,873	1,629,747	1,326,291	110,524.3	1,012,804	84,400.3
	2	31	63	407,437	814,873				

Baseline Hydraulic Pressures		
Hydraulic Parameter	Drill Rig 1	Drill Rig 2
Torque, T_{BP} (psi)	0	0
Crowd, F_{BP} (psi)	0	0





Agreement | Enter Drill Rig Data | Enter AME Pile Data | AME Pile Info | Enter AME Test Pile Data | AME Test Pile Info | Strength Analysis | Pile Summary Report

Strength Analysis Tab – Specific Energy

Pile	Pile Segment	ΔZ Increment (cm)
6	7	1
e Threshold (psi)	**e Reduction (psi/ft)**	**MWD Assessment**
1,250	0.0	ISO Class 1

Specific Energy, e (psi) - All Data

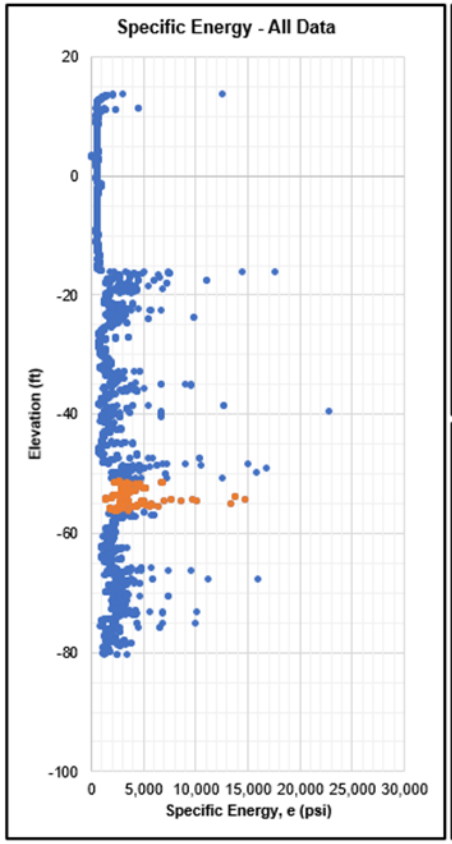
Mean	Median	Standard Deviation	Coefficient of Variation	Maximum	Minimum	Count
2,001	1,594	2,110	1.05	49,698	178	2,867

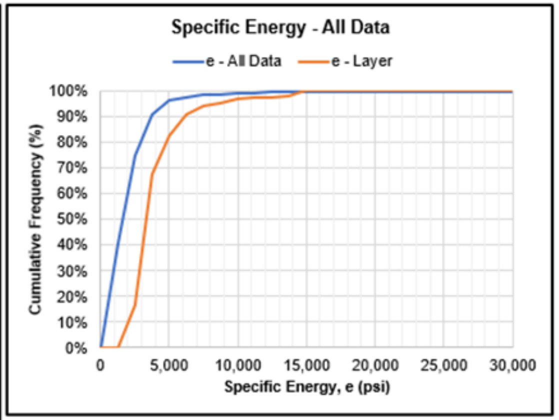
Pile Information

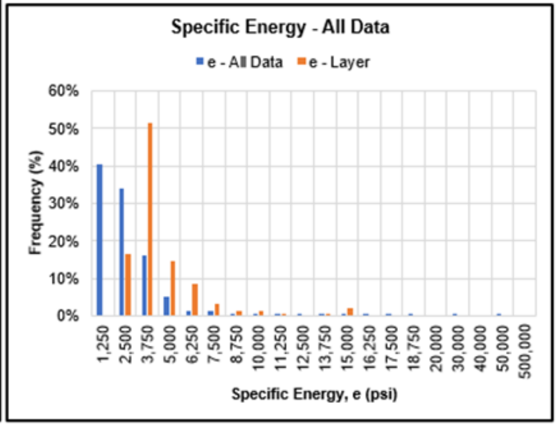
Pile ID	Pile Elevations (ft)		Pile Length (ft)	Layer Elevations (ft)		Drill Bit Diameter (ft)
	Top of Pile	Bottom of Pile		Top	Bottom	
B-16	13.55	-80.54	94.09	-51.5	-56.5	2.5

Pile Segments and Elevations / Specific Energy, e (psi) - All Data - Layer Analysis

Segment	Elevation 1 (ft)	Elevation 2 (ft)	Mean	Median	Std. Dev.	CV	Maximum	Minimum	Count
20	13.55	8.55	1,000	713	1,117	1.12	12,685	561	152
19	8.55	3.55	655	648	41	0.06	783	602	152
18	3.55	-1.45	611	622	119	0.19	825	178	153
17	-1.45	-6.45	709	669	113	0.16	1,056	603	152
16	-6.45	-11.45	641	629	43	0.07	753	545	153
15	-11.45	-16.45	1,132	760	1,961	1.73	17,746	636	152
14	-16.45	-21.45	2,995	2,584	1,743	0.58	11,222	1,281	152
13	-21.45	-26.45	2,423	2,128	1,324	0.55	9,873	1,074	153
12	-26.45	-31.45	1,242	1,051	505	0.41	3,709	789	152
11	-31.45	-36.45	2,527	2,082	1,452	0.57	9,618	913	153
10	-36.45	-41.45	2,251	1,668	2,437	1.08	22,845	857	152
9	-41.45	-46.45	1,628	1,376	693	0.43	4,123	774	152
8	-46.45	-51.45	3,853	3,011	4,609	1.20	49,698	832	152
7	**-51.45**	**-56.45**	**3,929**	**3,209**	**2,245**	**0.57**	**14,812**	**1,424**	**152**
6	-56.45	-61.45	2,338	2,216	877	0.37	6,099	1,252	153
5	-61.45	-66.45	1,975	1,886	750	0.38	5,819	1,080	152
4	-66.45	-71.45	3,057	2,628	1,717	0.56	16,095	1,370	152
3	-71.45	-76.45	3,071	2,482	3,722	1.21	45,336	941	153
2	-76.45	-80.54	1,978	1,780	644	0.33	4,001	1,161	124







Agreement | Enter Drill Rig Data | Enter AME Pile Data | AME Pile Info | Enter AME Test Pile Data | AME Test Pile Info | **Strength Analysis** | Pile Summary Report

Strength Analysis – Specific Energy – Above Threshold

Pile	Pile Segment	ΔZ Increment (cm)
6	7	1
e Threshold (psi)	**e Reduction (psi/ft)**	**MWD Assessment**
1,250	0.0	ISO Class 1

Specific Energy, e (psi) - Above Threshold - Entire Pile

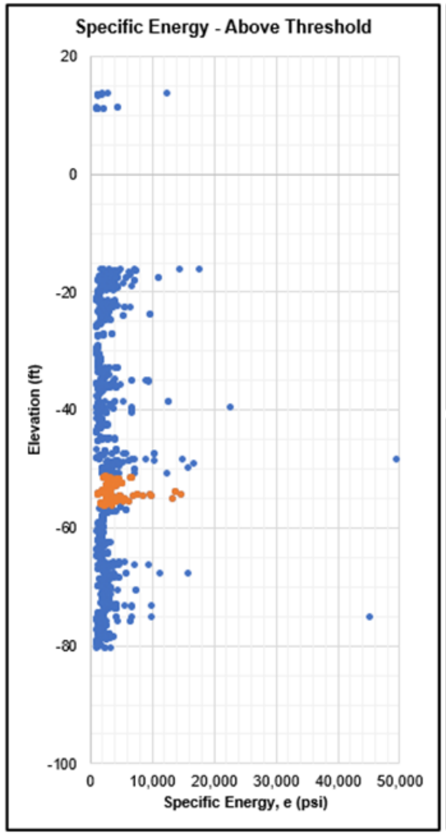
Mean	Median	Standard Deviation	Coefficient of Variation	Maximum	Minimum	Count
2,841	2,303	2,394	0.84	49,698	1,252	1,704

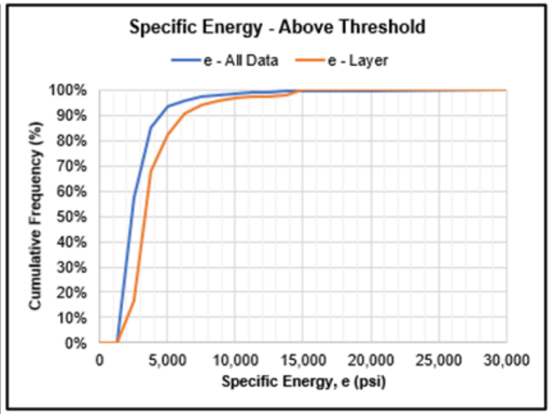
Pile Information

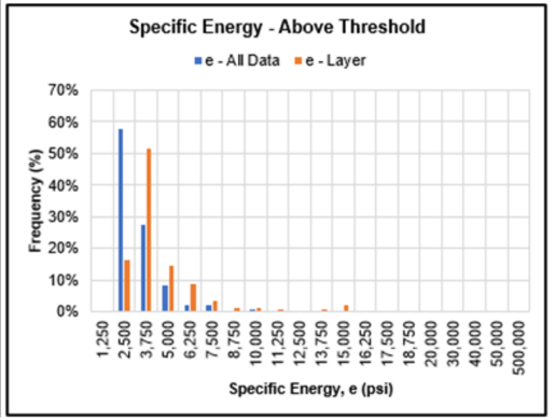
Pile ID	Pile Elevations (ft)		Pile Length (ft)	Layer Elevations (ft)		Drill Bit Diameter (ft)
	Top of Pile	Bottom of Pile		Top	Bottom	
B-16	13.55	-80.54	94.09	-51.45	-56.45	2.50

Pile Segments and Elevations / **Specific Energy, e (psi) - Above Threshold - Layer Analysis**

Segment	Elevation 1 (ft)	Elevation 2 (ft)	Mean	Median	Std. Dev.	CV	Maximum	Minimum	Count
20	13.55	8.55	2,593	1,560	2,575	0.99	12,685	1,273	20
19	8.55	3.55	0	0	0	0.00	0	0	0
18	3.55	-1.45	0	0	0	0.00	0	0	0
17	-1.45	-6.45	0	0	0	0.00	0	0	0
16	-6.45	-11.45	0	0	0	0.00	0	0	0
15	-11.45	-16.45	7,510	6,316	5,807	0.77	17,746	1,887	8
14	-16.45	-21.45	2,995	2,584	1,743	0.58	11,222	1,281	152
13	-21.45	-26.45	2,575	2,252	1,318	0.51	9,873	1,281	137
12	-26.45	-31.45	1,705	1,552	547	0.32	3,709	1,284	58
11	-31.45	-36.45	2,662	2,185	1,445	0.54	9,618	1,319	140
10	-36.45	-41.45	2,716	1,815	2,744	1.01	22,845	1,320	109
9	-41.45	-46.45	2,018	1,937	647	0.32	4,123	1,285	90
8	-46.45	-51.45	4,217	3,198	4,769	1.13	49,698	1,279	135
7	**-51.45**	**-56.45**	**3,929**	**3,209**	**2,245**	**0.57**	**14,812**	**1,424**	**152**
6	-56.45	-61.45	2,338	2,216	877	0.37	6,099	1,252	153
5	-61.45	-66.45	2,114	1,901	723	0.34	5,819	1,321	130
4	-66.45	-71.45	3,057	2,628	1,717	0.56	16,095	1,370	152
3	-71.45	-76.45	3,139	2,501	3,766	1.20	45,336	1,259	148
2	-76.45	-80.54	2,011	1,780	636	0.32	4,001	1,299	119







Agreement | Enter Drill Rig Data | Enter AME Pile Data | AME Pile Info | Enter AME Test Pile Data | AME Test Pile Info | **Strength Analysis** | Pile Summary Report

Strength Analysis – Specific Energy QA/QC

Pile	Pile Segment	Δz Increment (cm)
6	7	1
e Threshold (psi)	**e Reduction (psi/ft)**	**MWD Assessment**
1,250	0.0	ISO Class 1

MWD Auger Cast Pile QA/QC - Production Pile: B-16

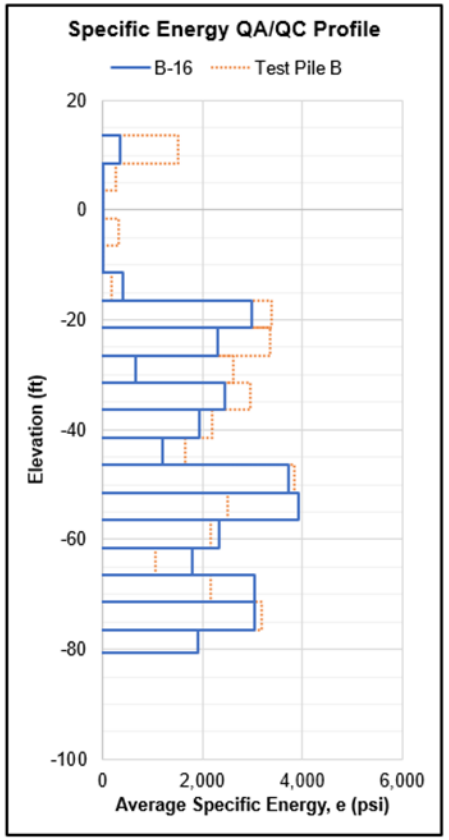
Pile Elevations		e_{above} (psi)	L_{pile} (ft)	L_{rock} (ft)	E_T (kip-ft)	$e_{adjusted}$ (psi)
EL_{TOP} (ft)	EL_{BOT} (ft)					
13.55	-80.54	2,841	94.1	55.9	112,254	1,688

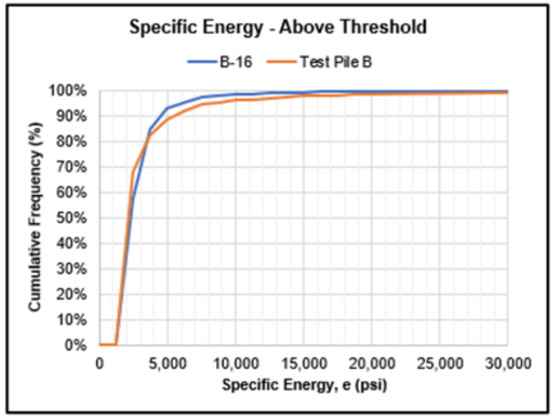
MWD Auger Cast Pile QA/QC - Test Pile: Test Pile B

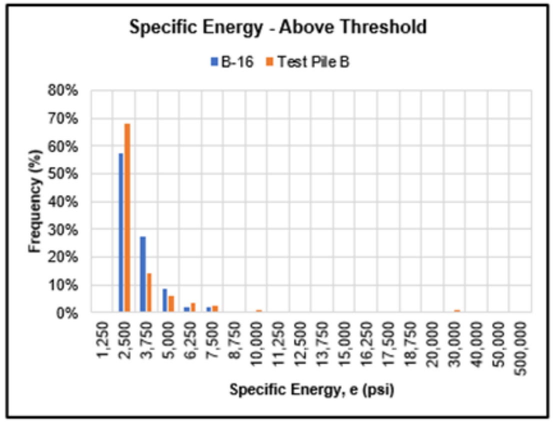
Elevation Range	EL_{TOP} (ft)	EL_{BOT} (ft)	e_{above} (psi)	L_{pile} (ft)	L_{rock} (ft)	E_T (kip-ft)	$e_{adjusted}$ (psi)
Test Pile B	13.50	-94.47	3,538	108.0	79.5	198,736	2,604
B-16	13.55	-80.54	2,665	94.1	65.6	123,601	1,858

Pile Segments and Elevations / **MWD Auger Cast Pile QA/QC - Production Pile - Layer Analysis**

Segment	Elevation 1 (ft)	Elevation 2 (ft)	Count	e_{AVG} (psi)	e_{above} (psi)	L_{layer} (ft)	L_{rock} (ft)	E_T (kip-ft)	$e_{adjusted}$ (psi)
20	13.55	8.55	20	1,000	2,593	5.0	0.7	1,203	340
19	8.55	3.55	0	655	0	5.0	0.0	0	0
18	3.55	-1.45	0	611	0	5.0	0.0	0	0
17	-1.45	-6.45	0	709	0	5.0	0.0	0	0
16	-6.45	-11.45	0	641	0	5.0	0.0	0	0
15	-11.45	-16.45	8	1,132	7,510	5.0	0.3	1,393	394
14	-16.45	-21.45	152	2,995	2,995	5.0	5.0	10,559	2,988
13	-21.45	-26.45	137	2,423	2,575	5.0	4.5	8,182	2,315
12	-26.45	-31.45	58	1,242	1,705	5.0	1.9	2,293	649
11	-31.45	-36.45	140	2,527	2,662	5.0	4.6	8,642	2,445
10	-36.45	-41.45	109	2,251	2,716	5.0	3.6	6,867	1,943
9	-41.45	-46.45	90	1,628	2,018	5.0	3.0	4,213	1,192
8	-46.45	-51.45	135	3,853	4,217	5.0	4.4	13,204	3,736
7	**-51.45**	**-56.45**	**152**	**3,929**	**3,929**	**5.0**	**5.0**	**13,849**	**3,918**
6	-56.45	-61.45	153	2,338	2,338	5.0	5.0	8,295	2,338
5	-61.45	-66.45	130	1,975	2,114	5.0	4.3	6,373	1,803
4	-66.45	-71.45	152	3,057	3,057	5.0	5.0	10,778	3,049
3	-71.45	-76.45	148	3,071	3,139	5.0	4.9	10,773	3,048
2	-76.45	-80.54	119	1,978	2,011	4.1	3.9	5,550	1,918







Agreement | Enter Drill Rig Data | Enter AME Pile Data | AME Pile Info | Enter AME Test Pile Data | AME Test Pile Info | **Strength Analysis** | Pile Summary Report

Pile Summary Report

District Geotech Version

ACIP Pile - MWD Summary Report

Project	Location
I-395	Miami, Florida
Station	**Offset (ft)**
100+00.01	10.00
Top of Pile Elevation (ft)	**Bottom of Pile Elevation (ft)**
13.55	-80.54

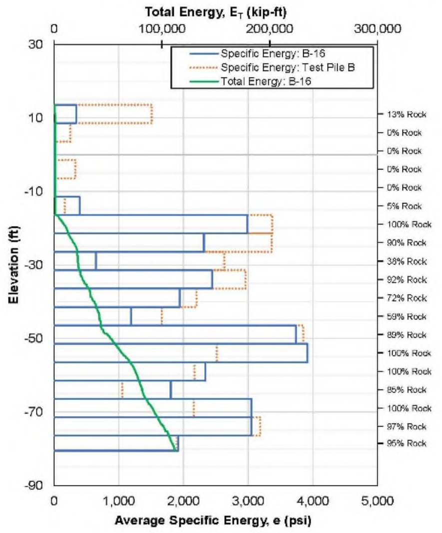
Engineer	Pile ID
Rodgers, McVay, Kelch	B-16
Drill Rig	**Drill Bit Diameter (in)**
Drill Rig B	30
Depth Increment Analyzed (cm)	**ISO-MWD Assessment**
1	Class 1

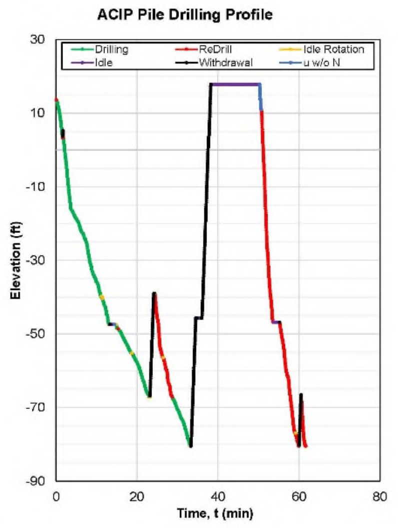
Specific Energy, e (psi) - Summary of Statistics: B-16	
Specific Energy Threshold (psi)	1,250
Mean	2,841
Median	2,303
Standard Deviation	2,394
Coefficient of Variation (CV)	0.84
Maximum	49,698
Minimum	1,252
Number of Data Points	1,704

Specific Energy, e (psi) - Summary of Statistics: Test Pile B	
Specific Energy Threshold (psi)	1,250
Mean	2,665
Median	2,073
Standard Deviation	4,539
Coefficient of Variation (CV)	1.70
Maximum	152,159
Minimum	1,252
Number of Data Points	2,000

ACIP Pile QA/QC	
Pile Length (ft)	94.09
Rock Socket (ft): B-16	55.91
Total Energy (kip-ft): B-16	112,254
Rock Socket (ft): Test Pile B	65.62
Total Energy (kip-ft): Test Pile B	123,601
Total Energy Required	90% of Test Pile
Total Energy Required (kip-ft))	111,241
Design Requirement Inspection	**Passed**

Pile Installation Summary	
Drilling Time (min)	25.7
ReDrill Time (min)	13.4
Idle Rotation Time (min)	2.5
Idle Time (min)	14.0
Withdrawal Time (min)	5.7
Penetration w/o Rotation Time (min)	0.4
Total Time (min)	61.6
Drilling Efficiency (%)	41.6%





Central Office Geotech Version

ACIP Pile - MWD Summary Report

Project	Location
I-395	Miami, Florida
Station	**Offset (ft)**
100+00.01	10.00
Top of Pile Elevation (ft)	**Bottom of Pile Elevation (ft)**
13.55	-80.54

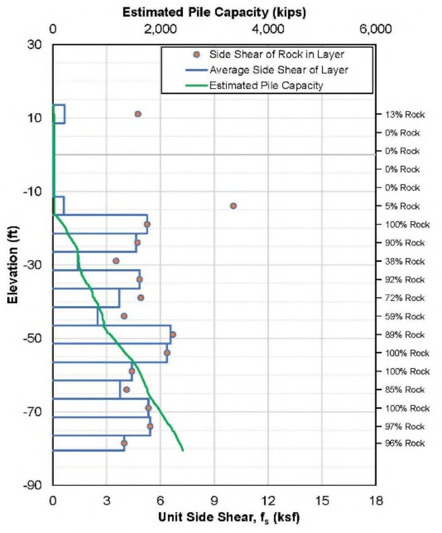
Engineer	Pile ID
Rodgers, McVay, Kelch	B16
Drill Rig	**Drill Bit Diameter (in)**
Drill Rig B	30
Depth Increment Analyzed (cm)	**ISO-MWD Assessment**
1	Class 1

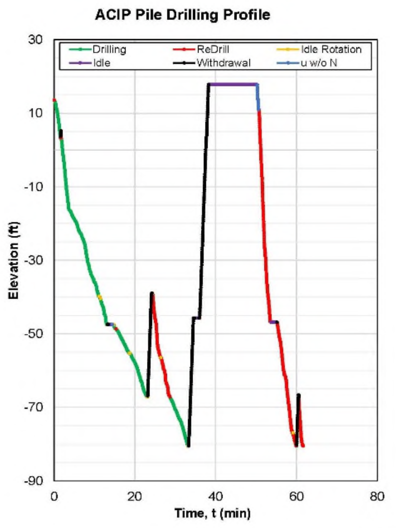
Specific Energy Above Threshold, e (psi)	
Specific Energy Threshold (psi)	1,250
Mean	2,841
Median	2,303
Standard Deviation	2,394
Coefficient of Variation (CV)	0.84
Maximum	49,698
Minimum	1,252
Number of Data Points	1,704

ACIP Pile Capacity QA/QC	
Pile Length (ft)	94.09
Total Rock Socket Length (ft)	55.9
Average Pile Side Shear, f_s (ksf)	3.27
Unfactored Pile Capacity (kips)	2,419
Factored Pile Capacity (kips)	1,451
Factored Design Load (kips)	1,070
C/D Ratio for LRFD Φ = 0.6	1.36
Design Requirement Inspection	**Passed**

Unconfined Compressive Strength Above Threshold, q_u (psi)	
q_u Threshold (psi)	88
Mean	185
Median	157
Standard Deviation	115
Coefficient of Variation (CV)	0.62
Maximum	1,897
Minimum	88
Number of Data Points	1,704

Pile Installation Summary	
Drilling Time (min)	25.7
ReDrill Time (min)	13.4
Idle Rotation Time (min)	2.5
Idle Time (min)	14.0
Withdrawal Time (min)	5.7
Penetration w/o Rotation Time (min)	0.4
Total Time (min)	61.6
Drilling Efficiency (%)	42%





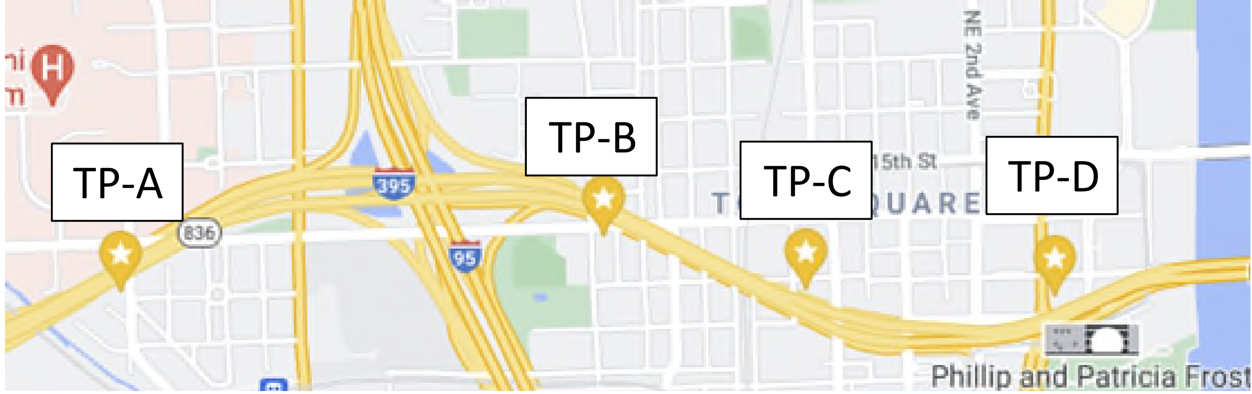
GeoStat Analyses

- Automatically populates rock strength data for Geostat Analyses

	A	B	C	D	E	F	G	H	I	J	K	L
1	This tab must be populated with data prior to loading GS-Deep.											
2												
3	**Depth**	**Soil Type**	**N. Blows**	**Unit Weight**	**Cu**	**qu**	**qt**	**qb**	**Em**	**RQD**	**Socket Roughness**	**Rock Recovery**
4		[1 | 2 | 3 | 4 | 5]								[0.0 to 1.0]	[0 | 1]	[0.0 to 1.0]
5	**ft | m**		**blows/ft | blows/300mm**	**pcf | kN/m^3**	**tsf | kPa**	**tsf | kPa**	**tsf | kPa**	**tsf | kPa**	**ksi | MPa**			
6	0.03	4		114		48.0	6.7			1		1
7	0.07	4		95		15.1	2.6			1		1
8	0.10	4		95		15.1	2.6			1		1
9	0.13	4		88		9.1	1.7			1		1
10	0.16	4		88		9.1	1.7			1		1
11	0.20	4		87		8.9	1.7			1		1
12	0.23	4		85		7.8	1.5			1		1
13	0.26	4		85		7.8	1.5			1		1
14	0.30	4		86		8.0	1.5			1		1
15	0.33	4		86		8.0	1.5			1		1
16	0.36	4		86		8.0	1.5			1		1
17	0.39	4		84		6.9	1.4			1		1
18	0.43	4		84		6.9	1.4			1		1
19	0.46	4		85		7.4	1.4			1		1
20	0.49	4		85		7.4	1.4			1		1
21	0.52	4		85		7.8	1.5			1		1
22	0.56	4		85		7.8	1.5			1		1
23	0.59	4		85		7.8	1.5			1		1
24	0.62	4		84		6.9	1.4			1		1
25	0.66	4		84		6.9	1.4			1		1
26	0.69	4		84		6.9	1.4			1		1
27	0.72	4		83		6.3	1.3			1		1
28	0.75	4		83		6.3	1.3			1		1
29	0.79	4		83		6.3	1.3			1		1
30	0.82	4		81		5.5	1.1			1		1
31	0.85	4		81		5.5	1.1			1		1
32	0.89	4		82		6.2	1.2			1		1
33	0.92	4		82		6.2	1.2			1		1
34	0.95	4		82		6.2	1.2			1		1
35	0.98	4		82		6.2	1.2			1		1
36	1.02	4		81		5.6	1.1			1		1
37	1.05	4		81		5.6	1.1			1		1
38	1.08	4		81		5.6	1.1			1		1

Agreement | AME Pile Info | Enter AME Pile Data | Enter Drill Rig Data | Strength Analysis | Parameters - Layer | Parameters - Threshold | Pile Summary Report | GS-Deep

MWD Specific Energy vs. ACIP Pile Side Shear



- Task 2 - MWD Specific Energy vs. ACIP Pile Side Shear Relationships
  - Develop correlation between MWD specific energy and ACIP unit side shear
  - Requires MWD to be conducted in the footprint of test piles with mobilized segments in order to directly compare specific energy and unit side shear
  - Only 2 of 11 test piles had MWD in the footprint
    - Test Piles A and B
  - Only 3 of 11 test piles had mobilized segments
    - Test Pile A was fully mobilized above the load test assembly (LTA), Test Pile C was fully mobilized above and below the LTA, Test Pile D was mobilized in 2 pile segments above the LTA
  - Required UF to develop correlation with Test Piles C and D using MWD data from adjacent pile groups within proximity to the test pile locations
  - All piles were subject to curing induced residual stresses
    - Required load tests to be reanalyzed in larger layers to reduce the effects of residual stresses
- Task 3 - MWD Correlation Validation for ACIP Production Pile QA/QC
  - Compare MWD data to SPT and rock core data
    - Strength characteristics and layering
  - Modeled Test Piles A and C in MultiPier to compare MWD modeled behavior versus actual pile behavior measured in the field
  - Develop specific energy threshold for QA/QC procedures
    - Removes soil and IGM from consideration in pile capacity estimates
    - Only layers of rock count towards pile capacity
  - Assess the capacity of 50 production piles
    - No pile group data around Test Pile A
    - Assess the capacity of pile groups within proximity to Test Piles B, C, and D

Residual Stresses Identified in Load Test Report

Load test reports stated that high tensile curing strains were observed by comparing pre-installation strain gauge readings to those taken before active loading of the pile at the start of testing. This plus the relatively large strain increases observed during loading indicated that the pile may have experienced curing-induced residual load and subsequent tensile micro-fracturing, resulting in highly non-linear pile rigidity.

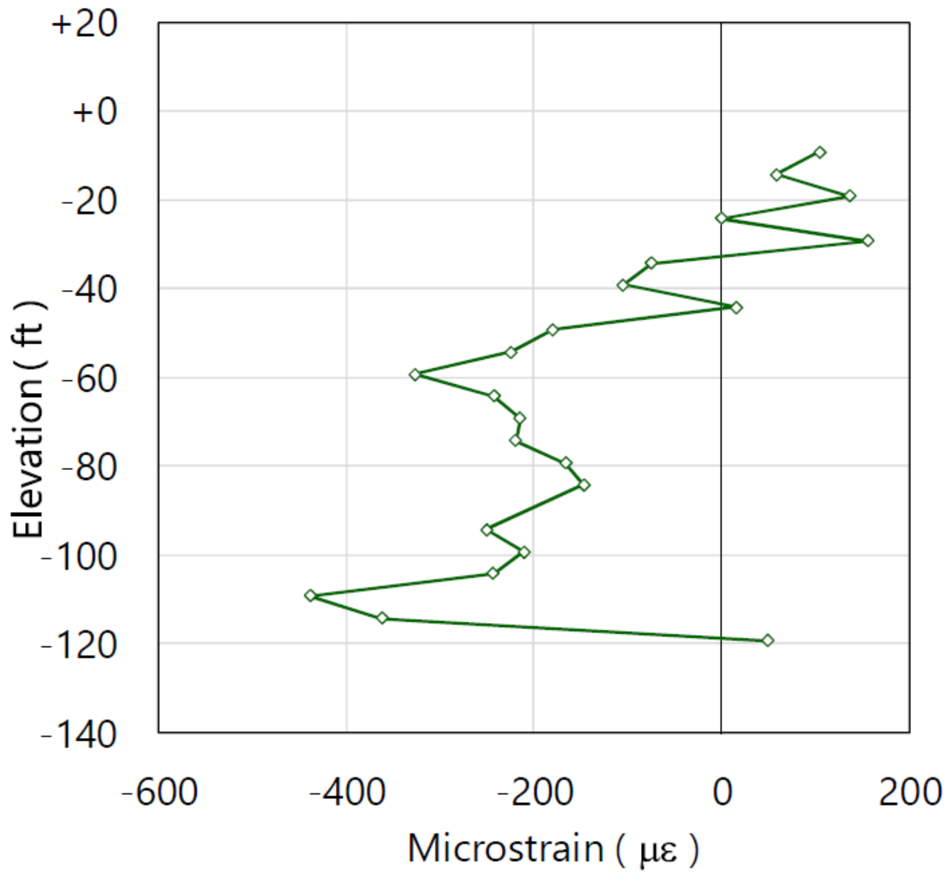
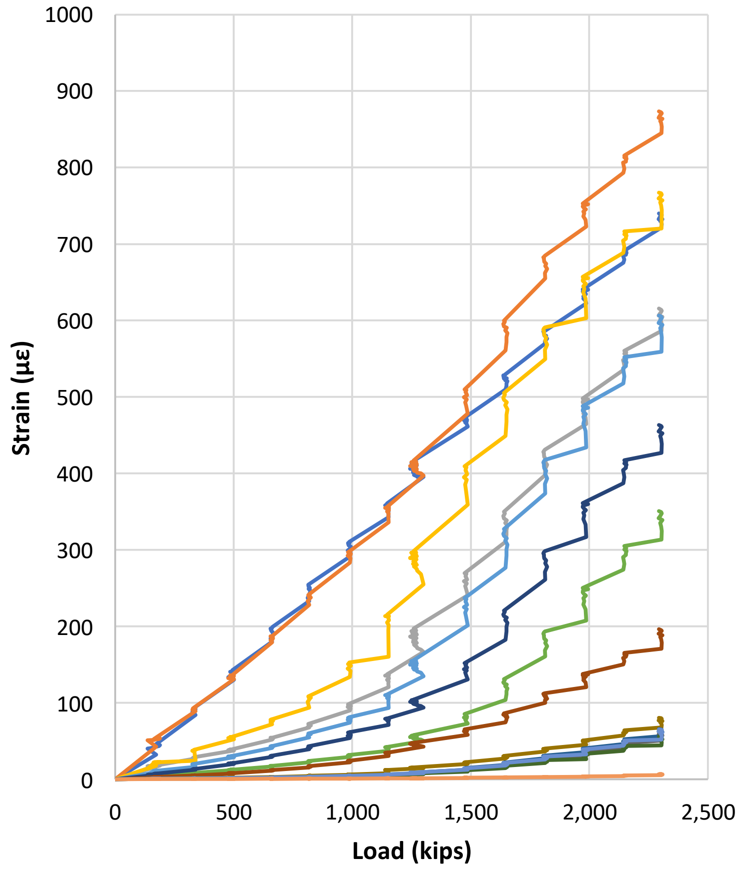
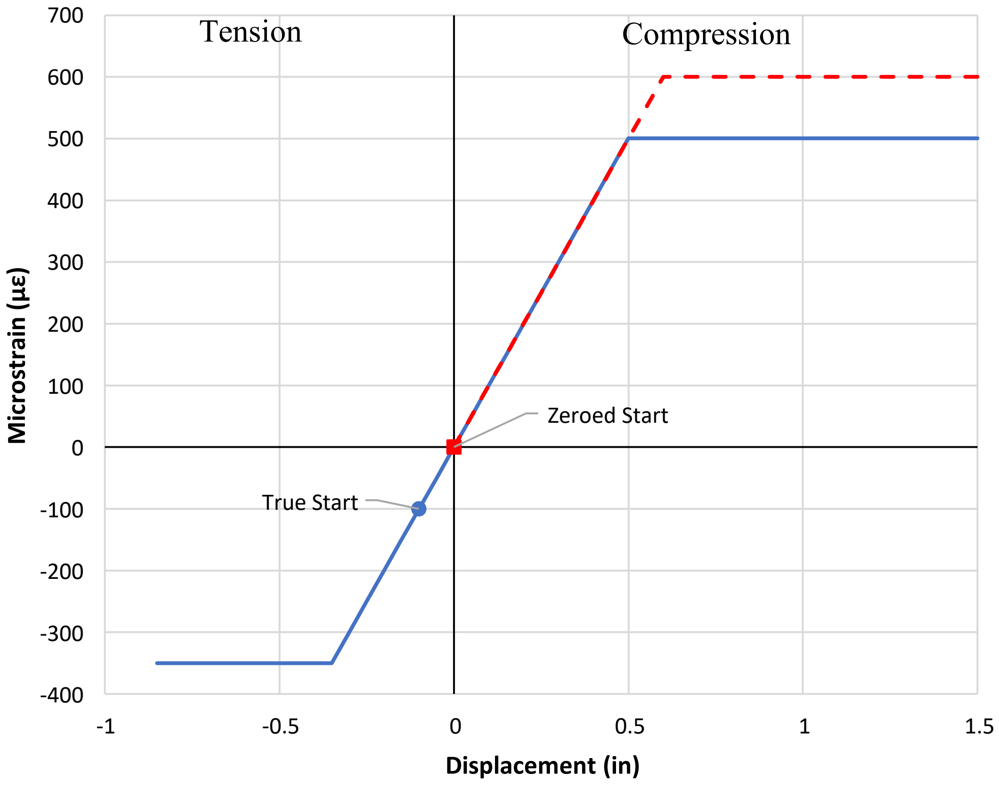


Figure 5: Strain change between installation and start of test (curing strain)

Residual Stresses Present in ACIP Piles

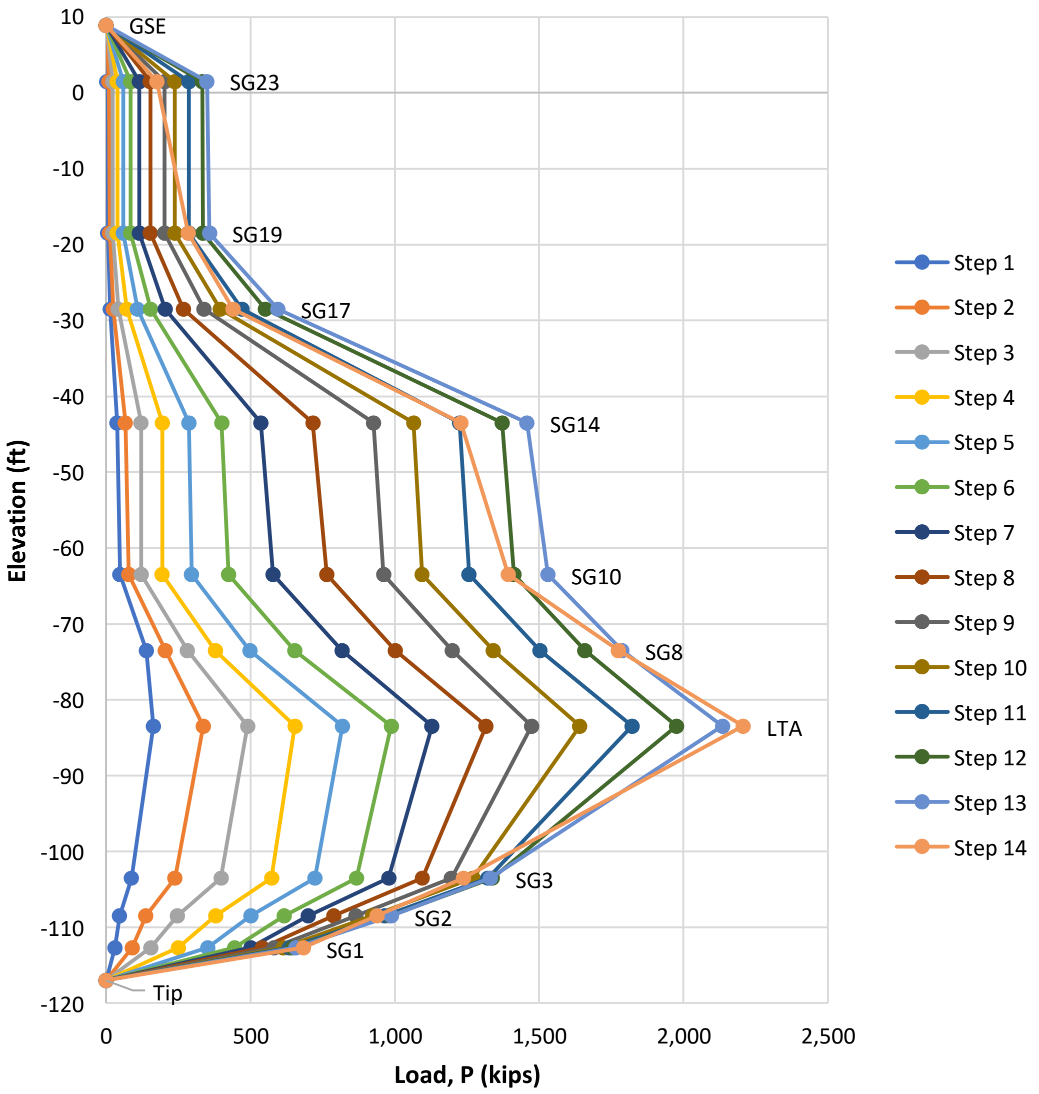


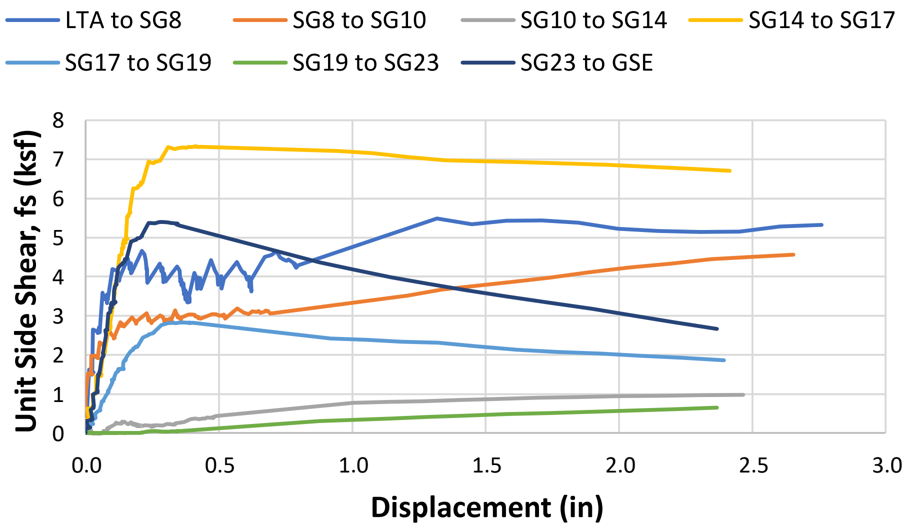
Strain Gauge Level	Maximum Strain (με)
7	873.6
9	767.0
6	739.8
8	615.8
10	606.3
12	463.2
11	350.9
13	196.0
15	80.5
18	65.6
16	65.0
14	60.9
17	55.9
19	6.6

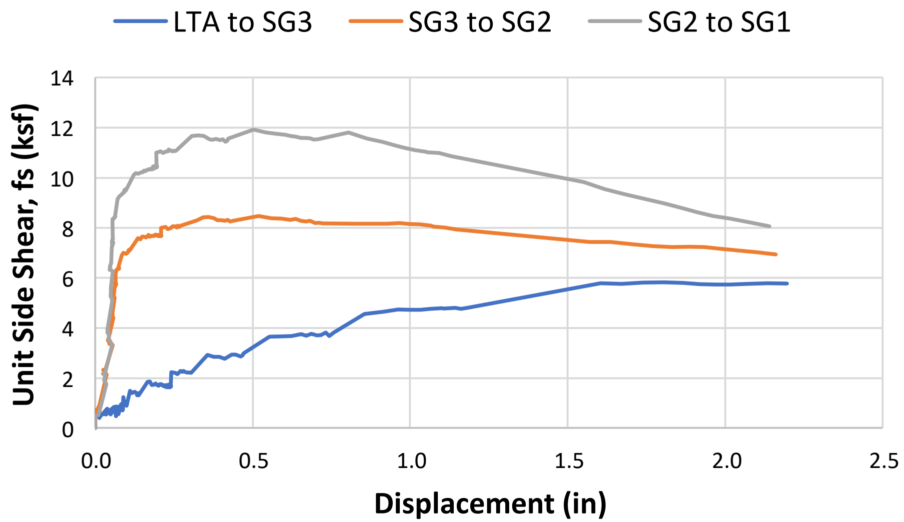


***This effects the layering and T-Z curves generated which need to be accurate in order to build correlation with MWD**

Load Tests Reanalyzed in Larger Layers





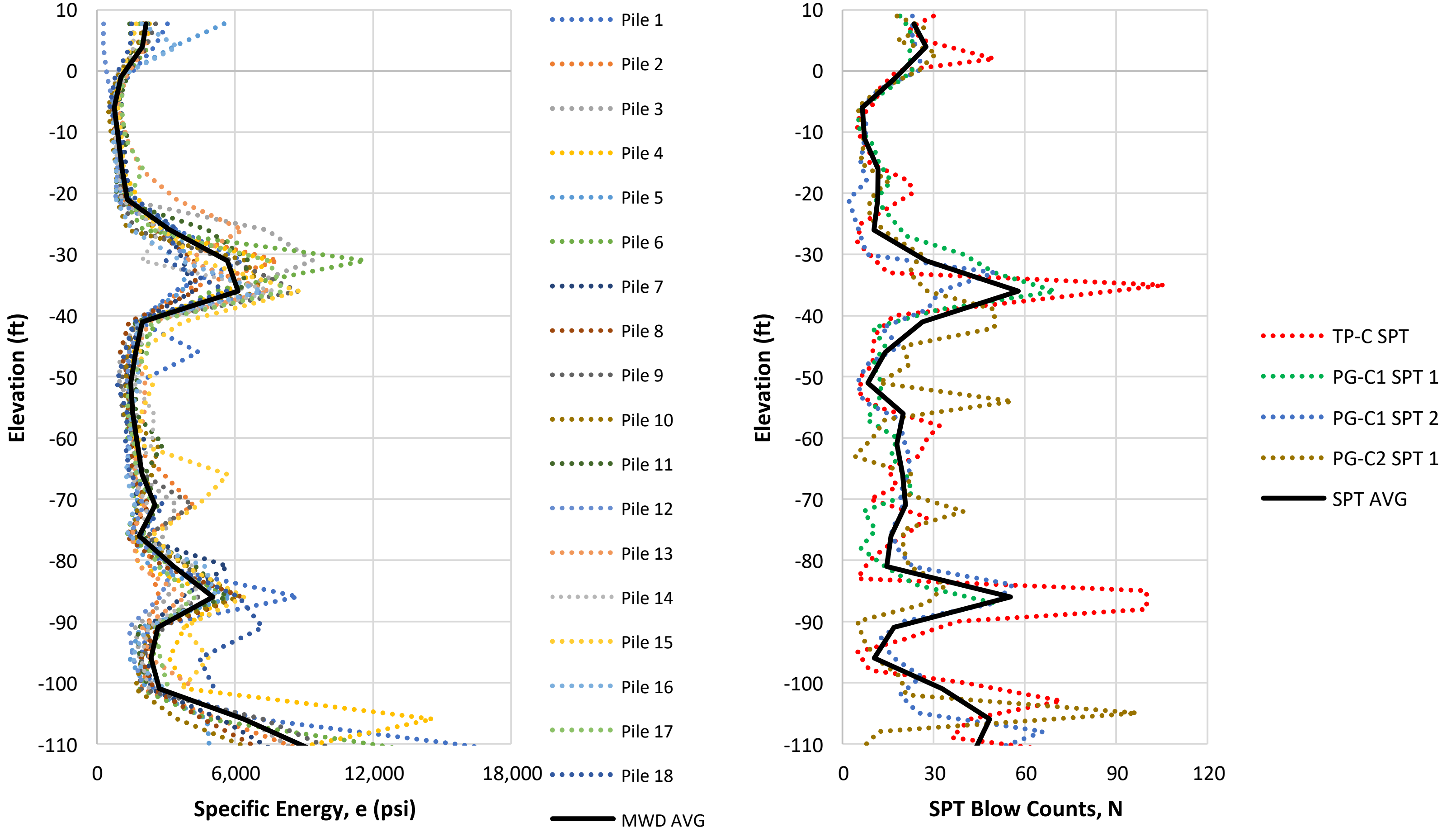


- **Load test report included all raw data which allowed UF to reanalyze the load test in larger layers**

MWD "e" versus SPT "N"

- Compare MWD specific energy to SPT N profile
  - Drilling resistance vs. driving resistance
  - SPT blow counts obtained within the ACIP pile group or within proximity
    - < 100 ft
- MWD profiles resemble the SPT profiles
  - Suggests MWD strengths and layering are correct

Pile groups and SPT borings in proximity to Test Pile C

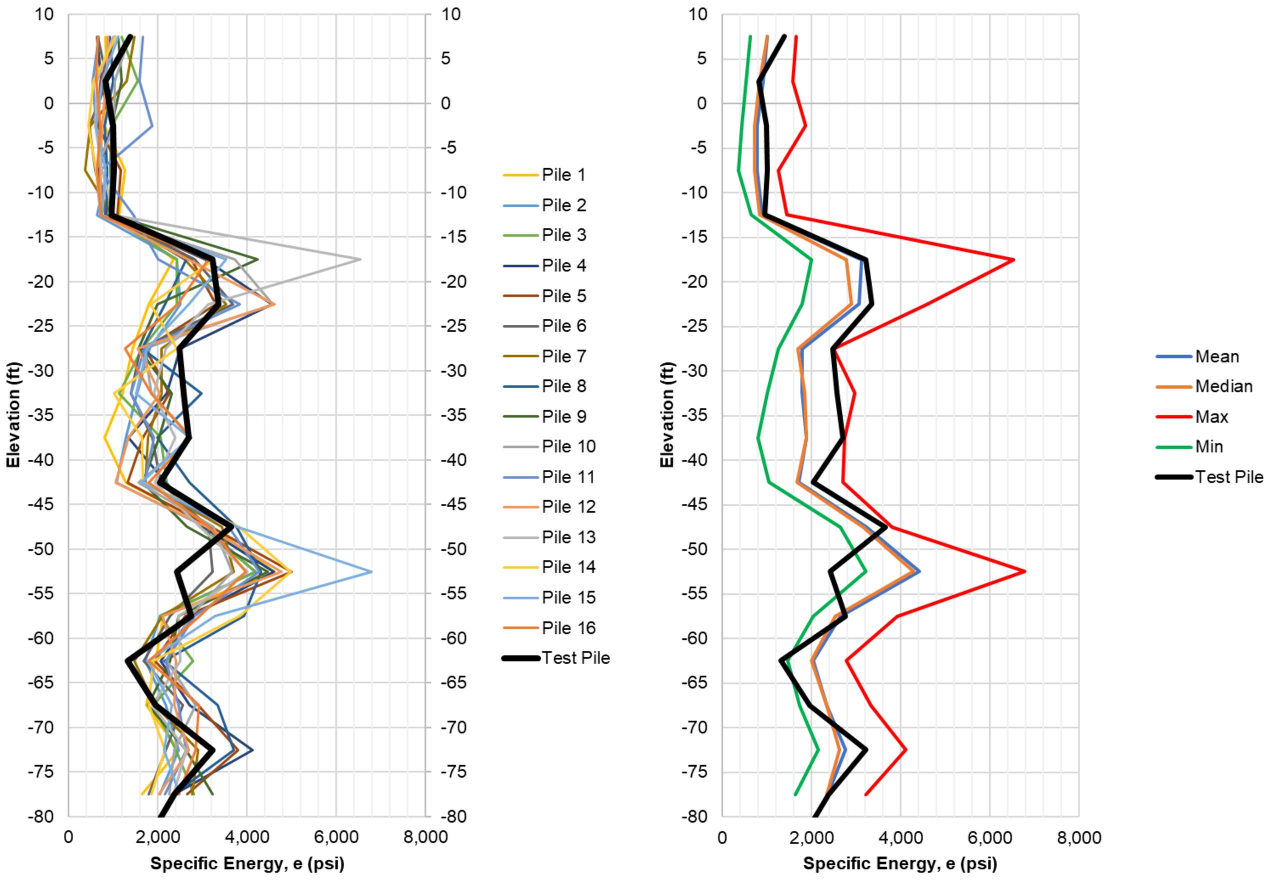


Assessing ACIP Pile Variability Over Short Distances

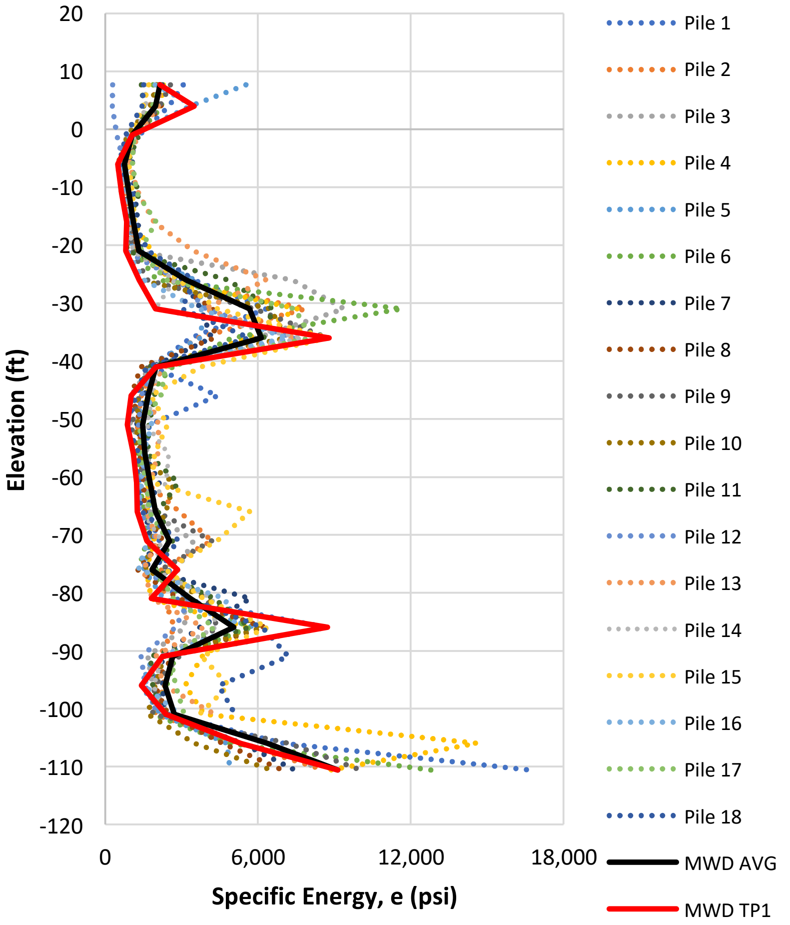
- Can we estimate test pile layering using adjacent pile group data that follows the behavior of measured test piles?
  - Required to get more data points to establish MWD specific energy – ACIP pile side shear correlation
- Compare MWD "e" from pile group to load test MWD within proximity
  - Load test MWD 50' to 85' from adjacent pile group
- Variability observed w/in 32.5' by 32.5' adjacent pile group
- Load test MWD shows similar layering as pile group MWD but does not always follow the mean
  - Test pile specific energy almost always falls within the maximum and minimum specific energy of the pile group
- Indicates MWD profile can be estimated in test pile locations without MWD in the footprint using adjacent pile group data
  - Assessed each pile in group based on original load test layering
  - Calculated mean, median, max, and min for each layer
  - Used these values to develop a theoretical test pile profile for comparison with mobilized unit side shear
  - Compared theoretical profile to SPT, rock cores, and load tests
  - Performed MultiPier simulations to compare modeled behavior to actual pile behavior measured during load tests

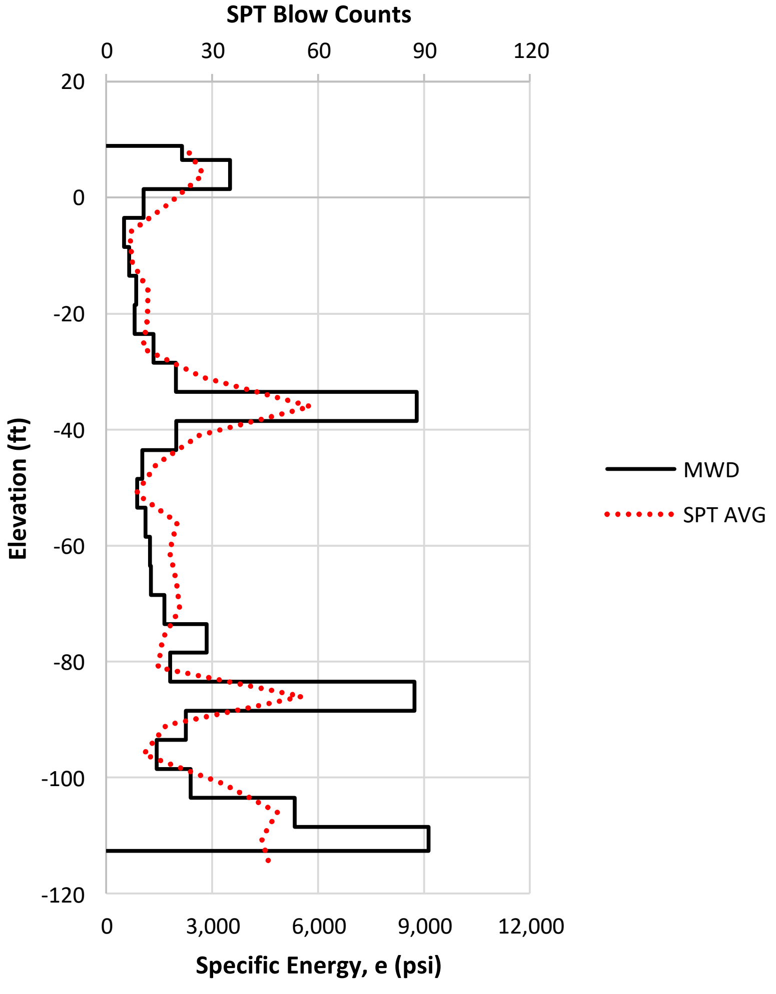
Test Pile B

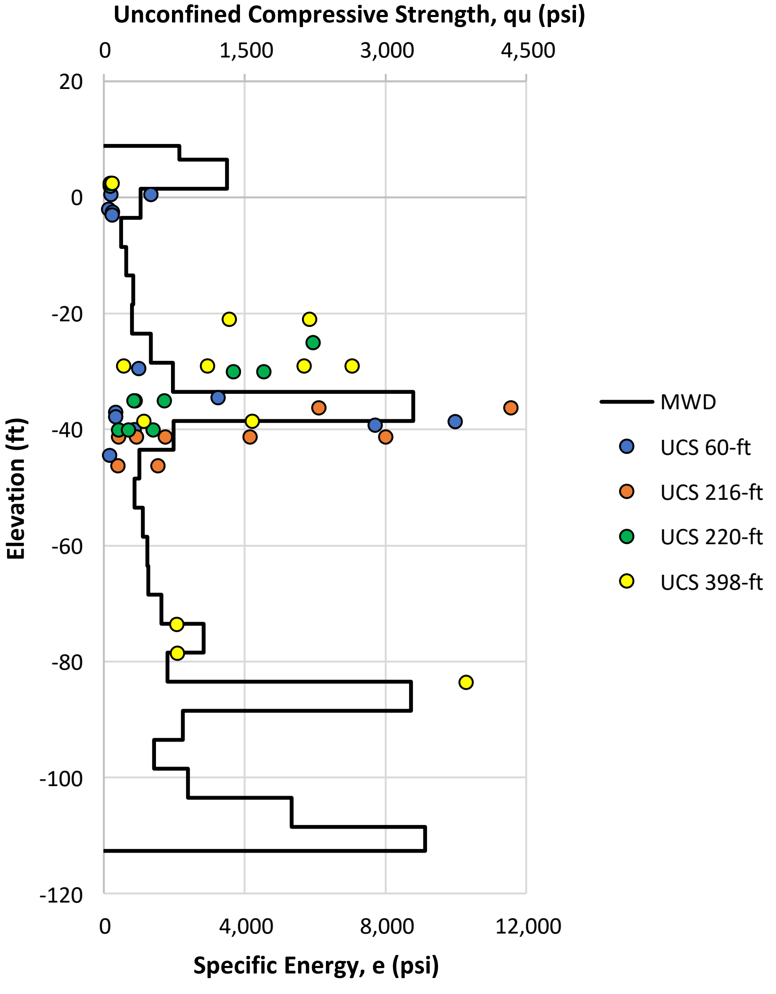
*Not mobilized but had MWD data in footprint and in adjacent pile group



Developing MWD Profiles for Test Piles

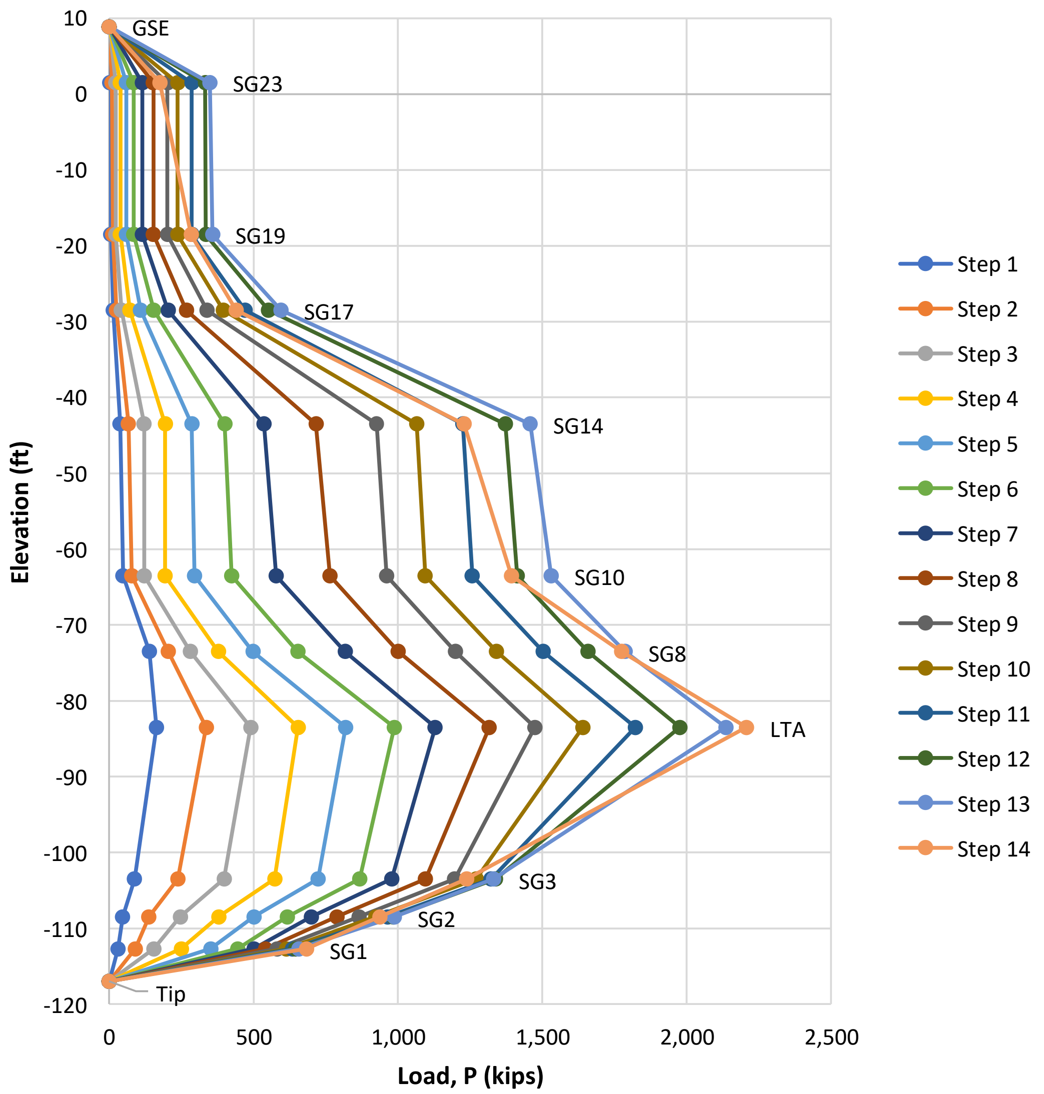






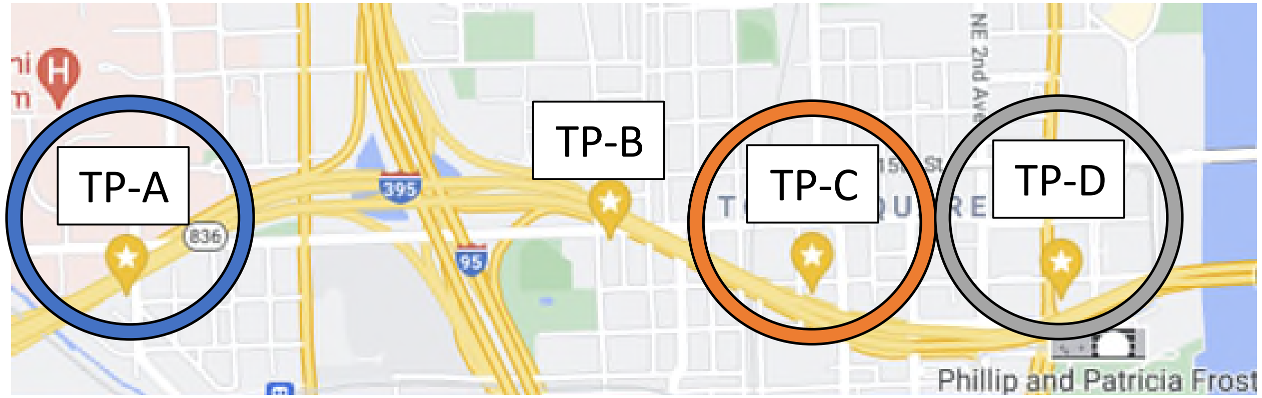
At Test Pile C - MWD, SPT, and Rock Cores all indicate similar layering

Building Correlation



Load test layering agrees with MWD, SPT, and rock cores

Building Correlation



MWD e

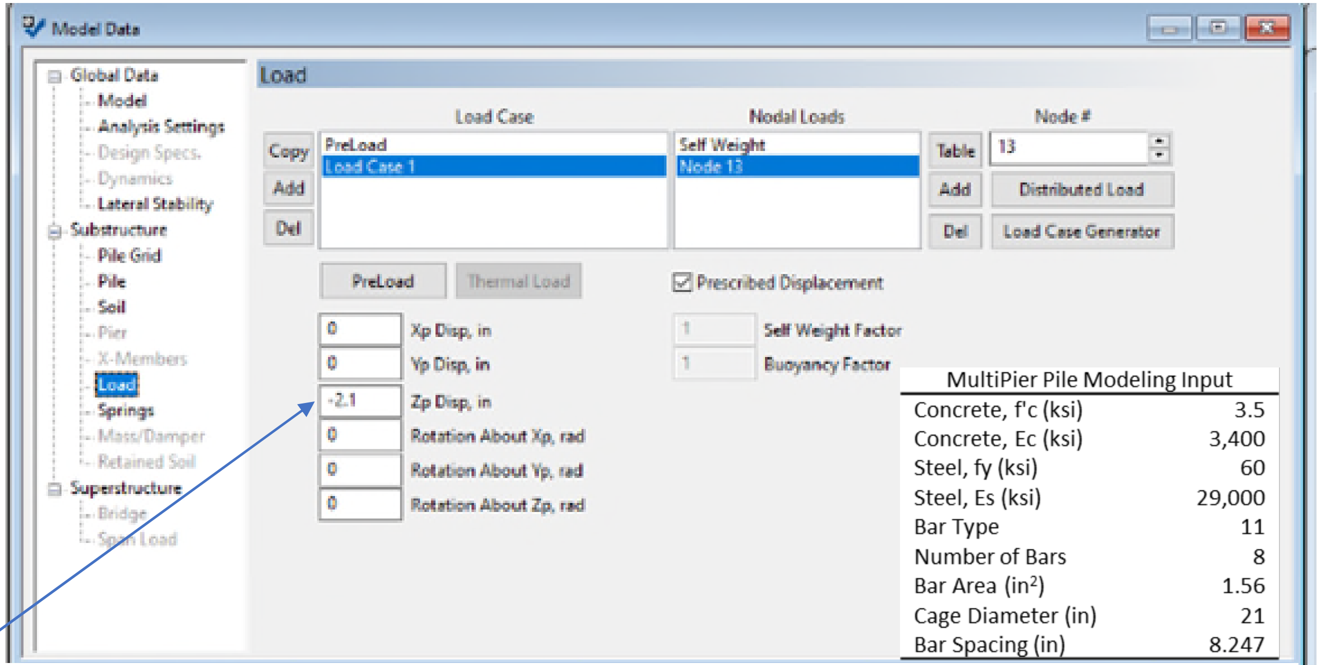
Side Shear

MultiPier Simulations using MWD Data

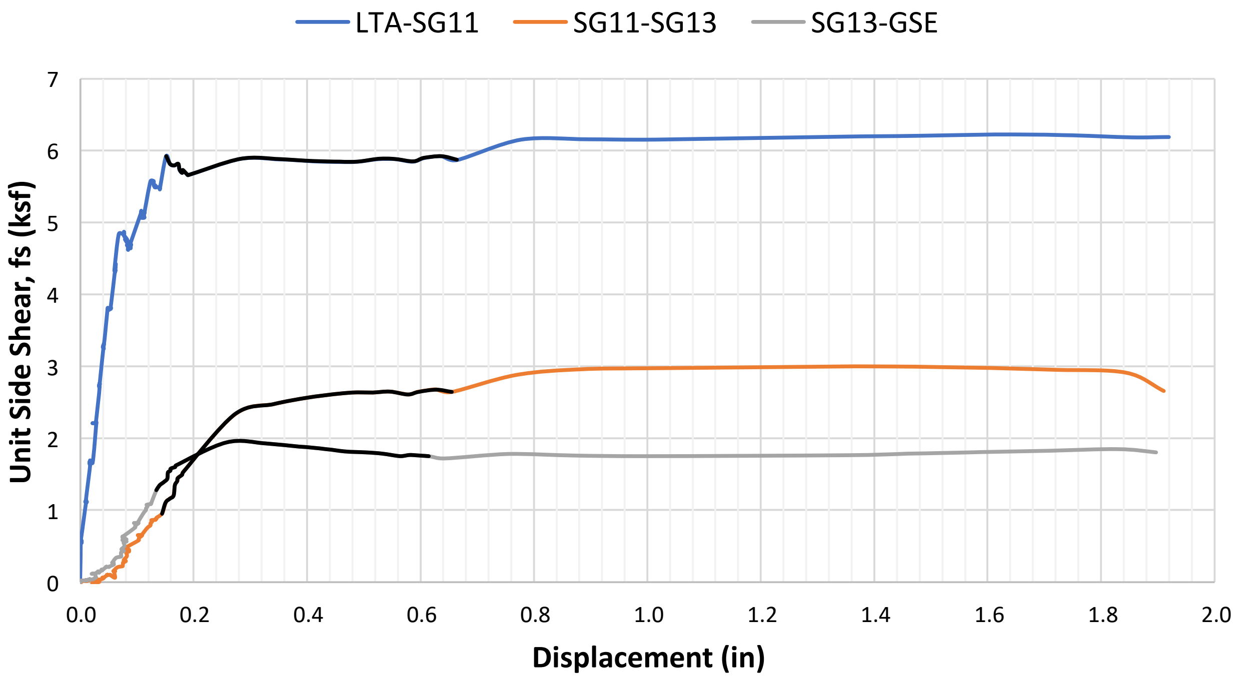
- Modeled Test Piles in MultiPier using MWD data and actual pile properties
  - Load tests were reanalyzed in larger layers
  - MWD was estimated in the footprint of two test piles used to build correlation
  - How well does the modeled pile behavior using the MWD inputs reflect the actual pile behavior measured during load tests?
    - LTA loads and expansion
    - Pile movement based on tell tales
- Modeled upper segments of mobilized Test Piles A and C
  - Upper segments were both fully mobilized
  - Isolated shear → no end bearing effects
  - ACIP pile MWD measures pile side shear

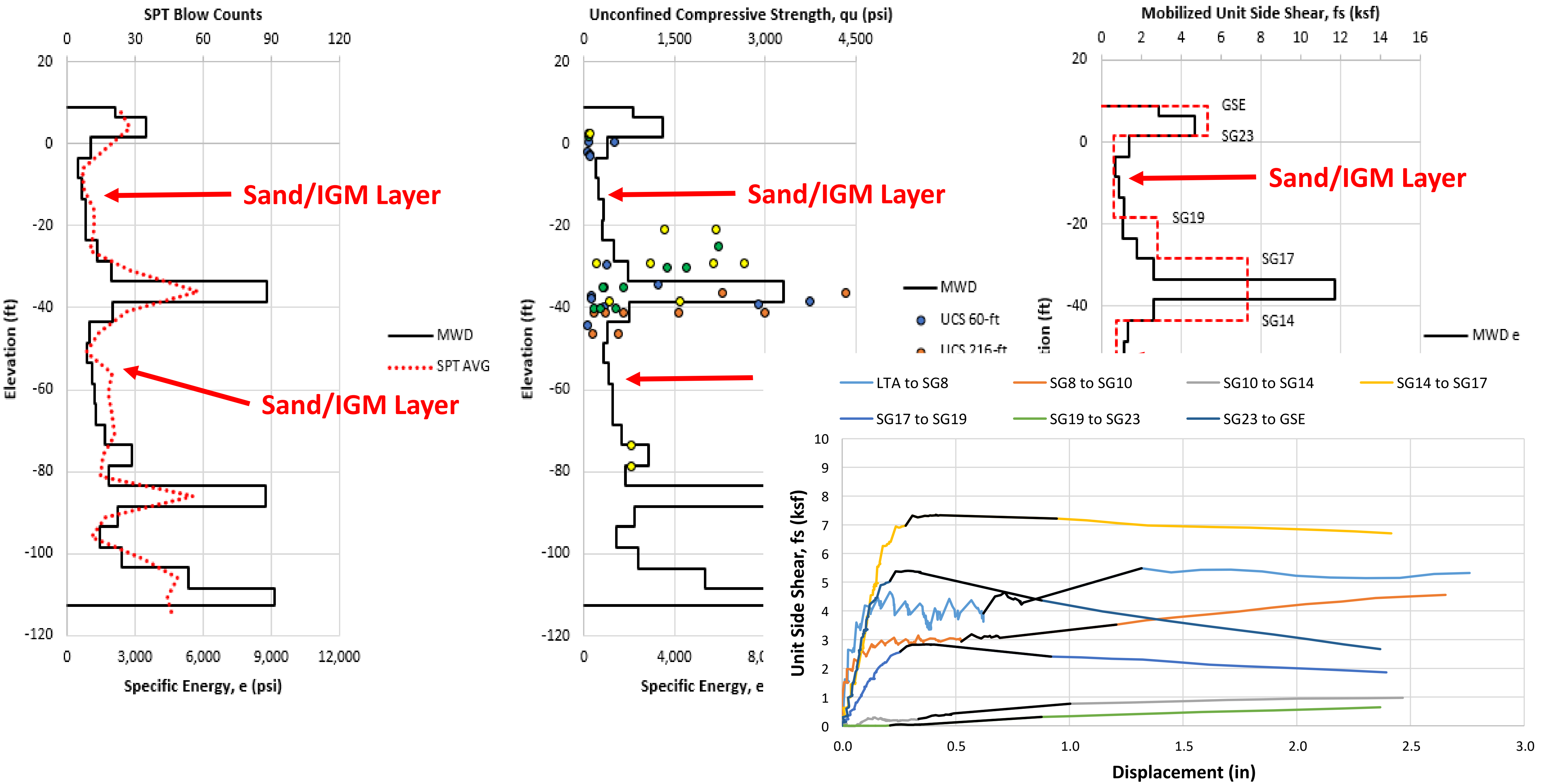
MultiPier Simulations

- Test Pile A was modeled first
  - MWD was conducted in the footprint of TP-A
  - TP-A boring indicated predominately rock
- Modeled qu and fs using MWD data
  - Unit weights estimated based on prior MWD correlations (Rodgers et al. 2019)
- Modeled test pile properties using load test pile rigidity and actual pile steel properties and layout
  - Pile diameters estimated from LT report and TIP data
- Used prescribed displacement based on actual LTA expansion measured during load test
  - 2.1” of upward expansion
- Modeled test pile was fully mobilized at a load of P = 1,921 kips
- Top of pile displacement at full mobilization was 1.87 inches
- Modeled pile behavior was in perfect agreement with the actual pile behavior
  - Pile fully mobilized after a load of P = 1,989 kips
  - Actual top of pile displacement was 1.87 inches



MultiPier Pile Modeling Input	
Concrete, f'c (ksi)	3.5
Concrete, Ec (ksi)	3,400
Steel, fy (ksi)	60
Steel, Es (ksi)	29,000
Bar Type	11
Number of Bars	8
Bar Area (in²)	1.56
Cage Diameter (in)	21
Bar Spacing (in)	8.247





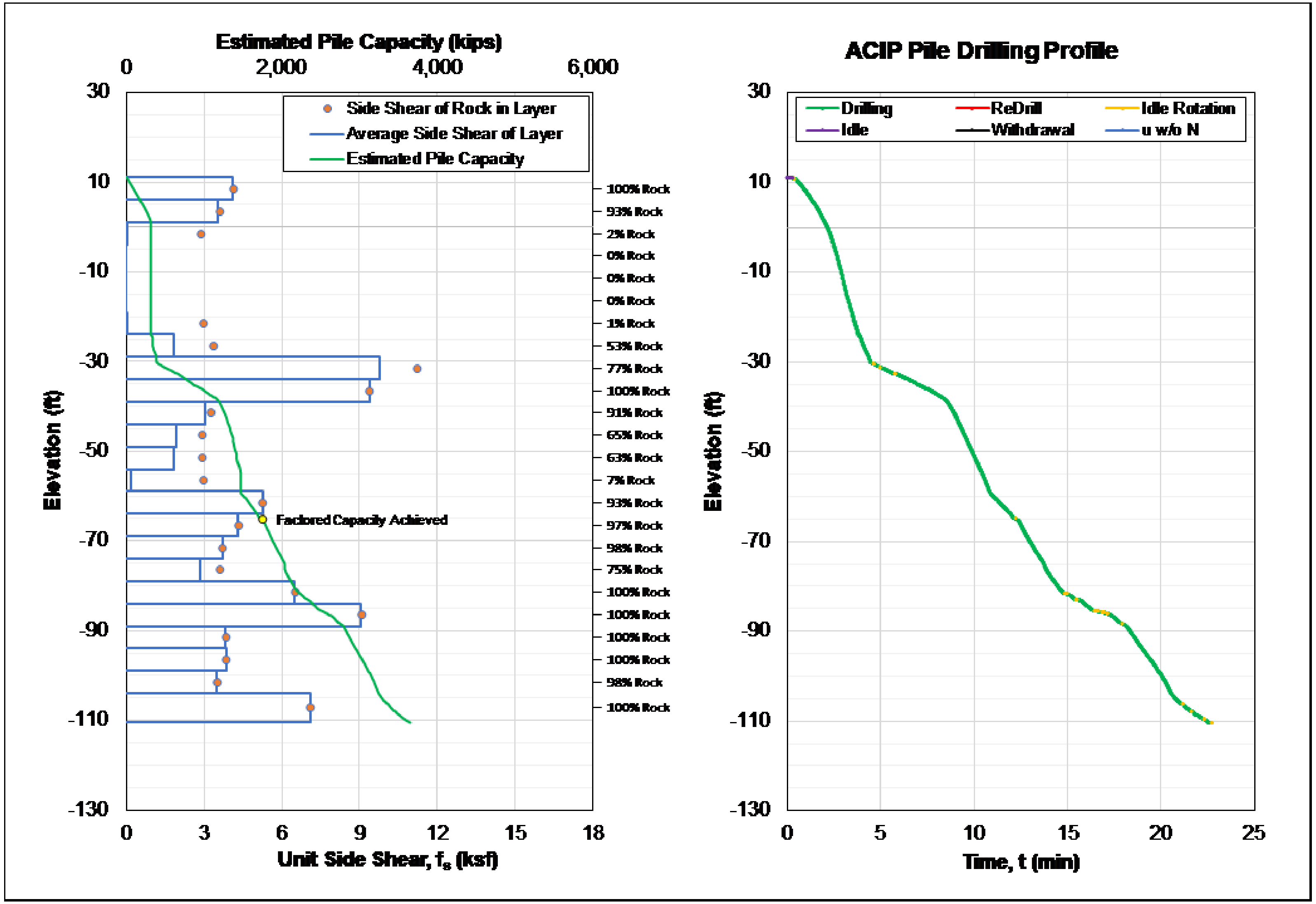
SPT Blow Counts
Elevation (ft)
Specific Energy, e (psi)
MWD
SPT AVG
Sand/IGM Layer
Sand/IGM Layer
Unconfined Compressive Strength, qu (psi)
UCS 60-ft
Sand/IGM Layer
Mobilized Unit Side Shear, fs (ksf)
GSE
SG23
SG19
SG17
SG14
MWD e
Sand/IGM Layer
LTA to SG8
SG8 to SG10
SG10 to SG14
SG14 to SG17
SG17 to SG19
SG19 to SG23
SG23 to GSE
Unit Side Shear, fs (ksf)
Displacement (in)

Determined Specific Energy Threshold for QA/QC

- Developed specific energy threshold for rock for MWD ACIP Pile QA/QC
  - e = 1,250 psi
  - Equates to qu = 88 psi
- Any specific energy value less than 1,250 psi was discounted as rock
  - Does not count towards ACIP pile capacity in developed MWD QA/QC procedure
- Based on MWD and SPT data, modeled pile behavior, and prior MWD research
  - Prior MWD research indicated qu of this strength would not count as competent rock in a true assessment of RQD → easily broken by hand
  - Simulated highly weathered / decomposed rock for MWD coring investigation
    - Core strengths ranged from 24 psi to 96 psi

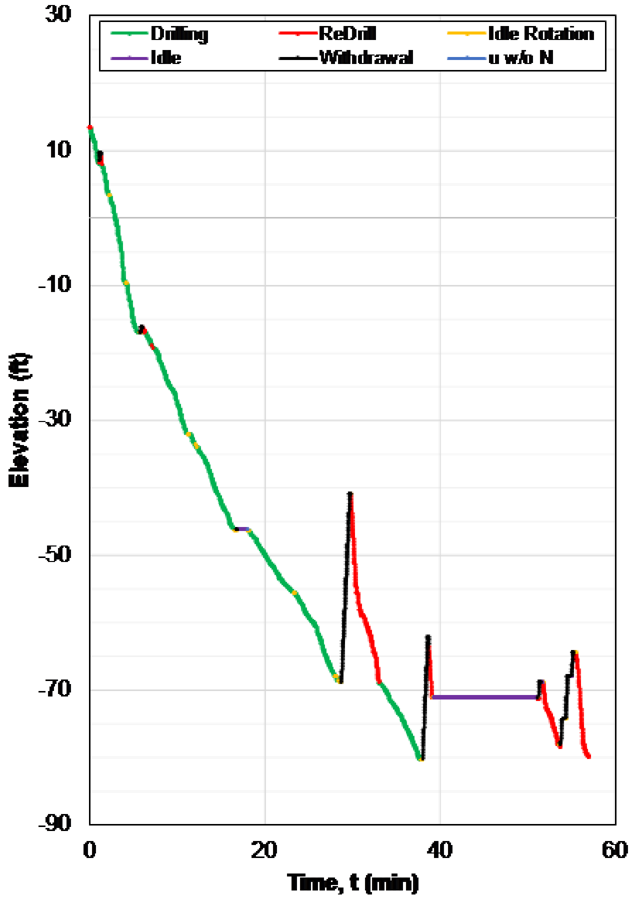
Pile Summary Report Strength and Drilling Profiles

- Indicates the side shear strength of rock in 5-ft layers
  - Orange circles
- Indicates % of rock per layer
  - Based on specific energy threshold of e = 1,250 psi
- Indicates average side shear per layer
  - Blue lines
  - Side shear adjusted based on % rock
    - FDOT methodology (e.g., REC x fs)
- Provides pile capacity depth profile
  - Green line in strength profile
- Indicates when factored pile capacity is achieved
  - Factored Resistance > Factored Load
- Provides drilling profile
- Drilling profile closely resembles strength profile
  - Prior MWD work indicated that torque and penetration rate are the true indicators of rock strength

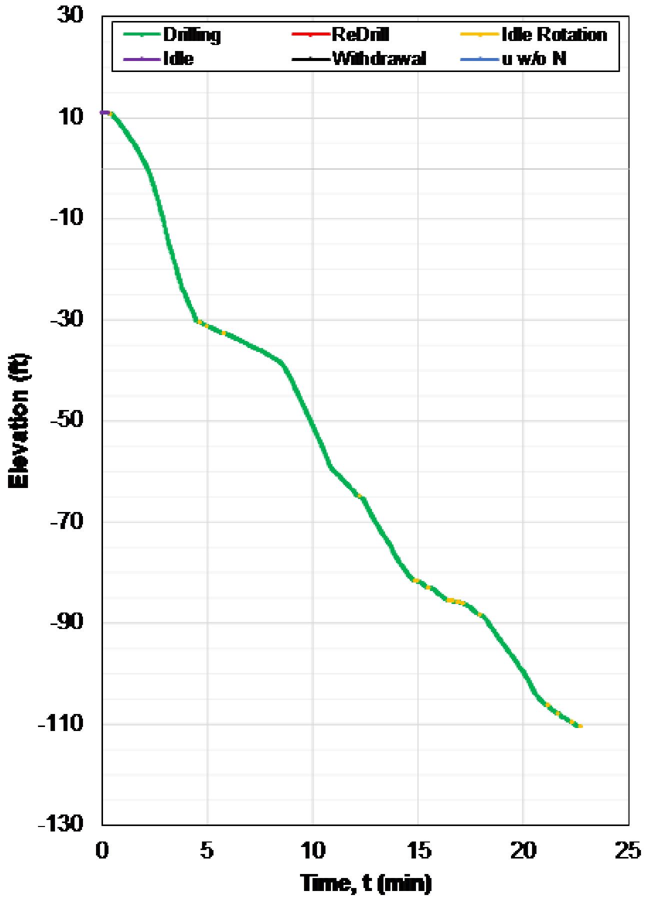


Drill Rig Performance Comparison

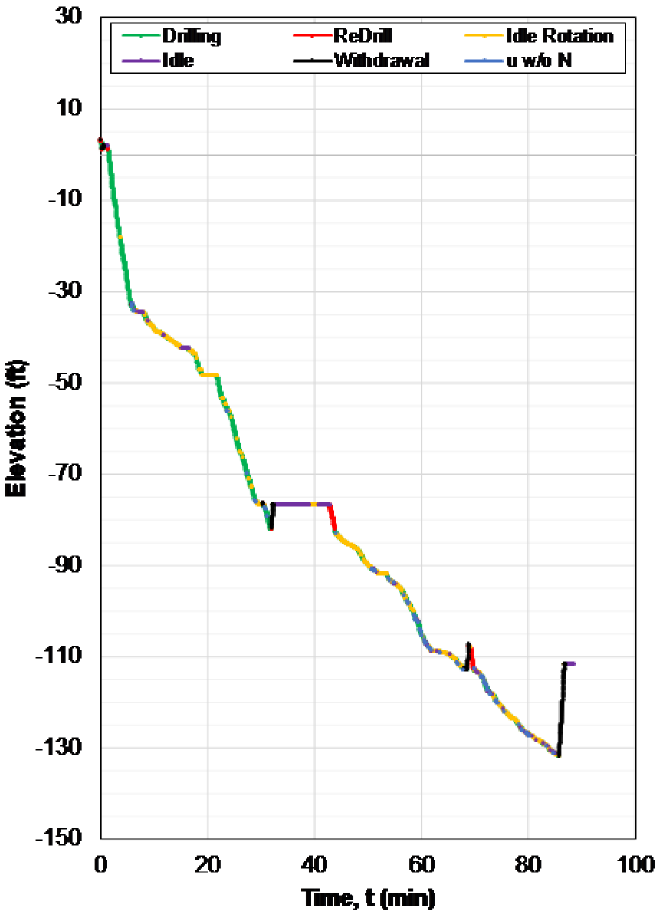
Smaller drill rig in
fs = 3.8 ksf rock



Larger drill rig in
fs = 3.8 ksf rock

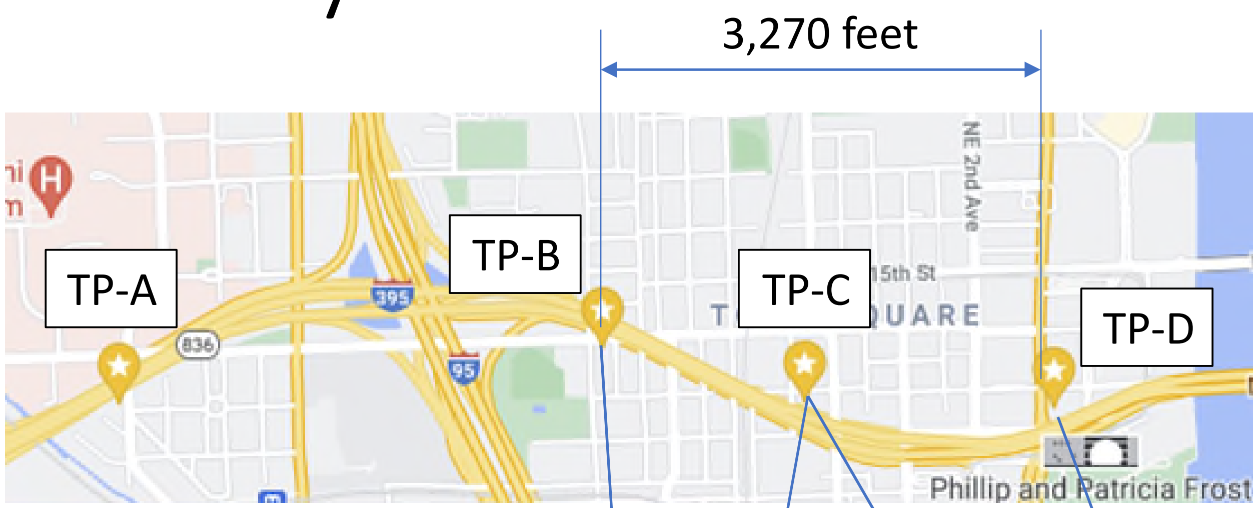


Larger drill rig in
fs = 6.2 ksf rock



QA/QC Summary

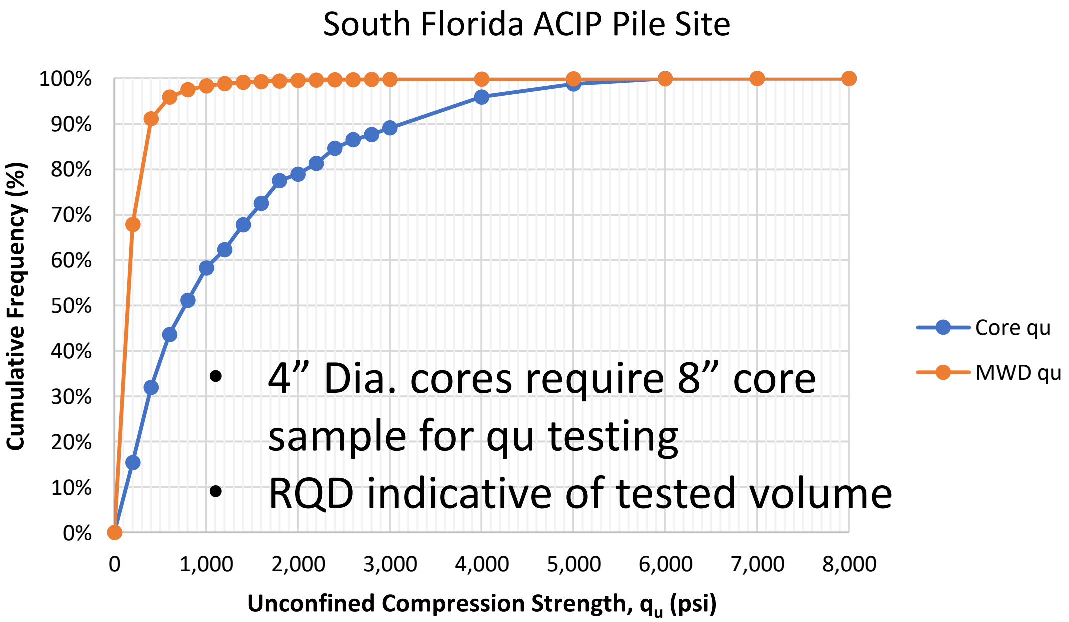
- Assessed the capacity of 50 production piles from 4 different pile groups
- All production piles assessed passed QA/QC inspection
- Observed trends of decreasing rock strength and socket length moving East to West
  - Rock socket per pile length
  - Average pile side shear
  - Factored and unfactored capacity
  - C/D Ratio



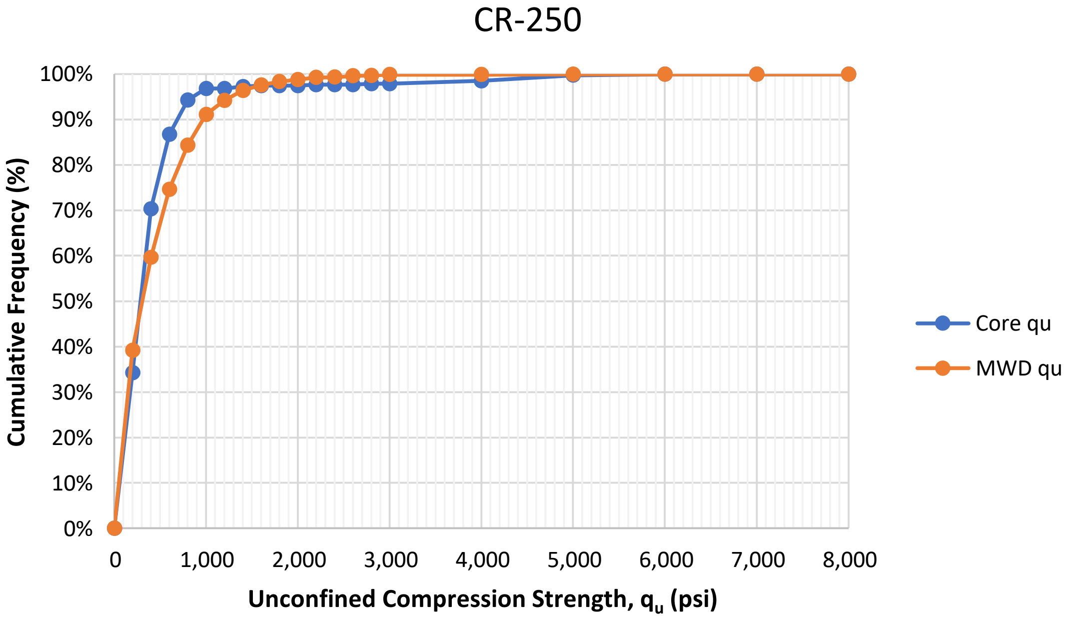
Category	Pile Group Averages			
	PG-B	PG-C2	PG-C1	PG-D
Pile Length (ft)	94.1	111.4	121.5	135.0
Total Rock Socket Length (ft)	56.8	81.0	89.0	99.2
Rock Socket per Pile Length	0.604	0.727	0.733	0.735
Pile Side Shear, fs (ksf)	3.3	4.0	4.2	5.7
Unfactored Pile Capacity (kips)	2,432	3,497	4,018	6,005
Factored Pile Capacity (kips)	1,459	2,098	2,411	3,603
Factored Design Load (kips)	1,070	980	920	1,050
C/D Ratio for LRFD Φ = 0.6	1.4	2.1	2.6	3.4

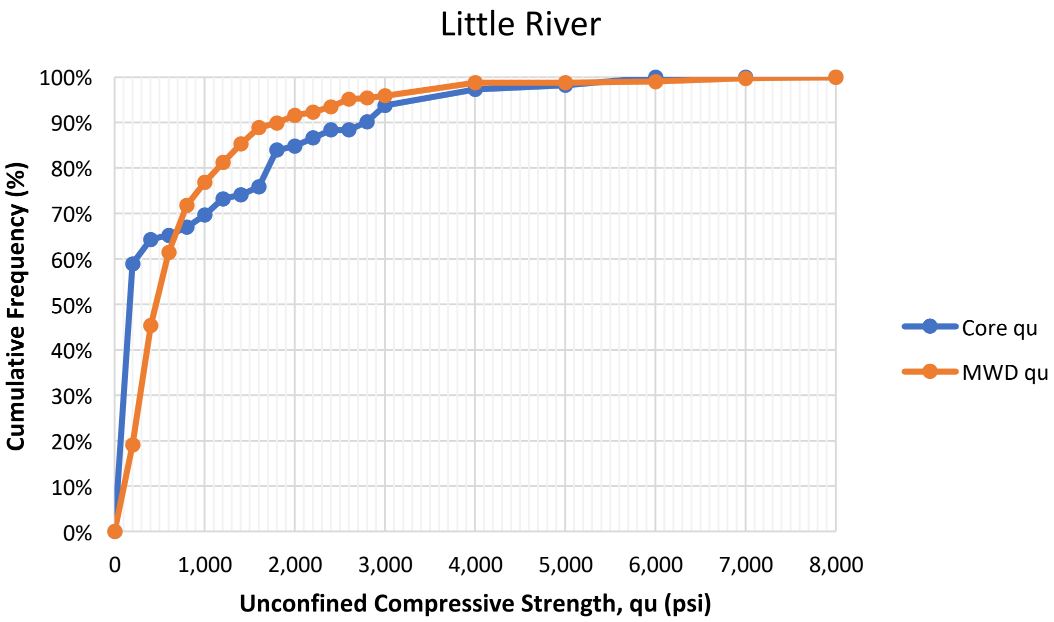
LRFD ϕ Analysis

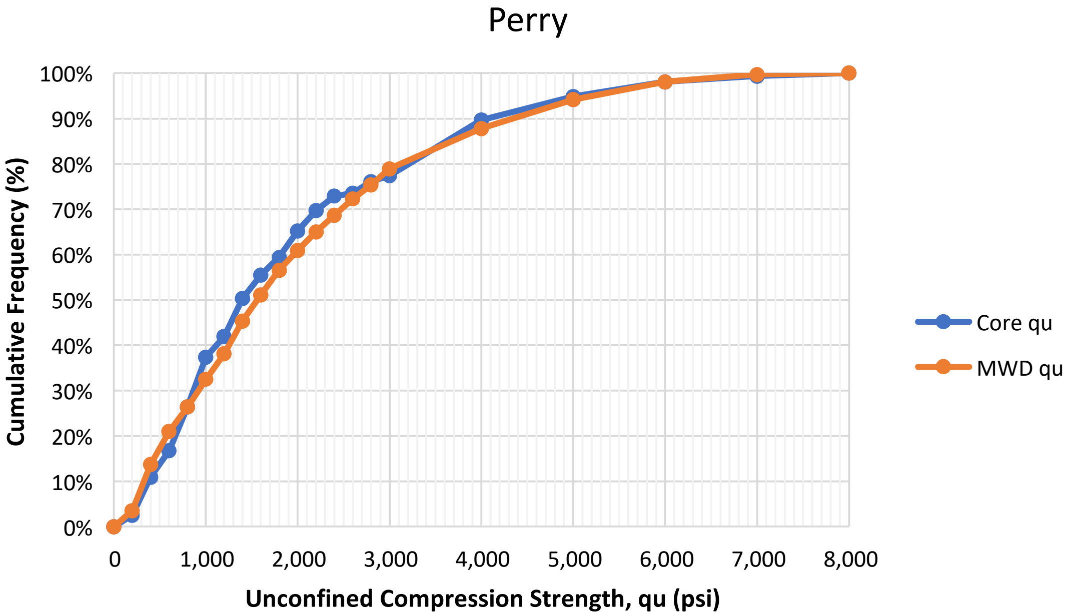
- Task 4 – LRFD Phi Assessment of FDOT Design Methods of ACIP piles in South Florida
  - Lack of core data within the vicinity of test piles
    - Incomplete strength distribution available for LRFD analyses
      - FDOT efforts significantly increased the number of tested cores
    - At deeper depths, the majority of core samples collected were higher strength rock
    - Used RQD to adjust the strength distribution
- Task 5 – LRFD Phi Assessment of MWD Specific Energy for ACIP Pile Axial Capacity QA/QC
  - MWD was assessed as qu strengths outside the footprint of test piles using production pile data within the vicinity (<100 ft)
    - Simulates MWD site investigation and quantifies the true strength distribution and spatial variability effects on capacity estimations
  - MWD QA/QC performed in the footprint of test piles
    - Removes the spatial variability component of pile capacity estimates
    - ϕ ranged from 0.98 to 0.76 for a Beta range of 2 to 4
    - Shows incredible potential for QA/QC



- 4” Dia. cores require 8” core sample for qu testing
- RQD indicative of tested volume

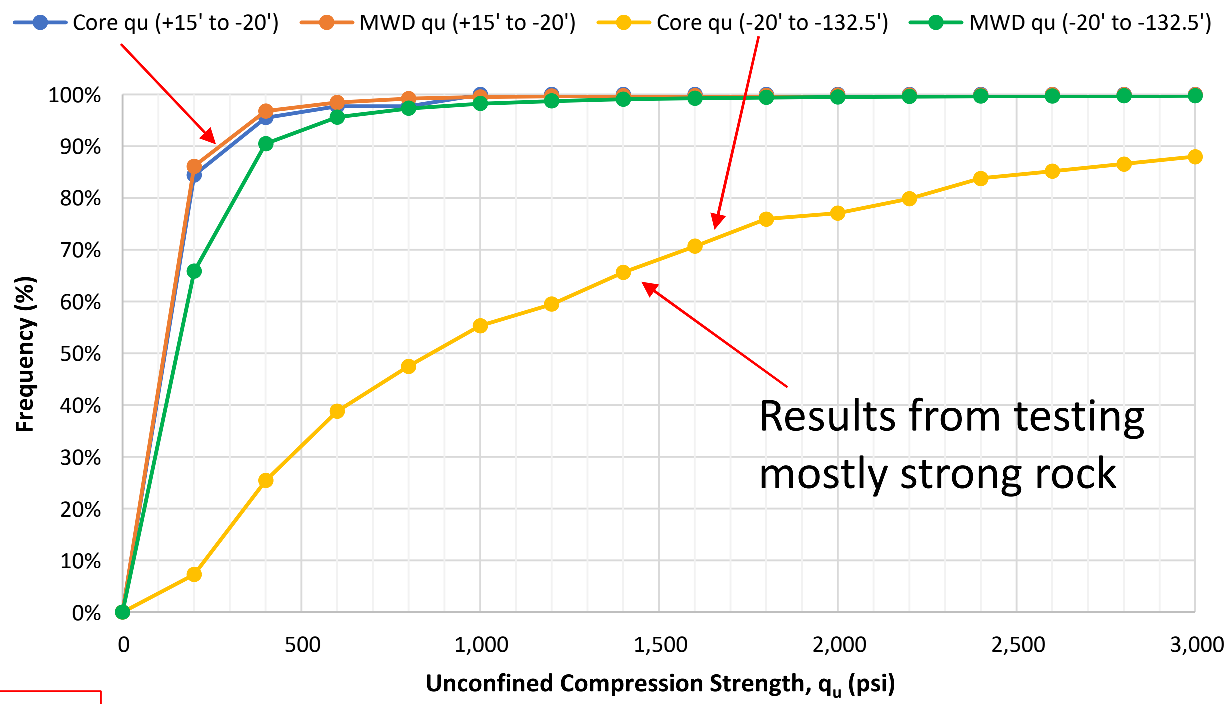






Miami vs. Fort Thompson Formation

- Cumulative frequency distributions were very similar in top 35 feet
  - Further validates MWD strengths
- Core distribution deviates from MWD below El. -20 feet
- Difference in cumulative frequency is due to core size, variable limestone formation, drilling depth, and drilling practices
  - Eccentric rotation
  - Over-crowding the bit
  - Coring outside the operational limits damages core samples and reduces REC and RQD
    - Rodgers et al. 2021 proved this
    - Lower strength rock is more effected
    - Quantified in controlled experiments



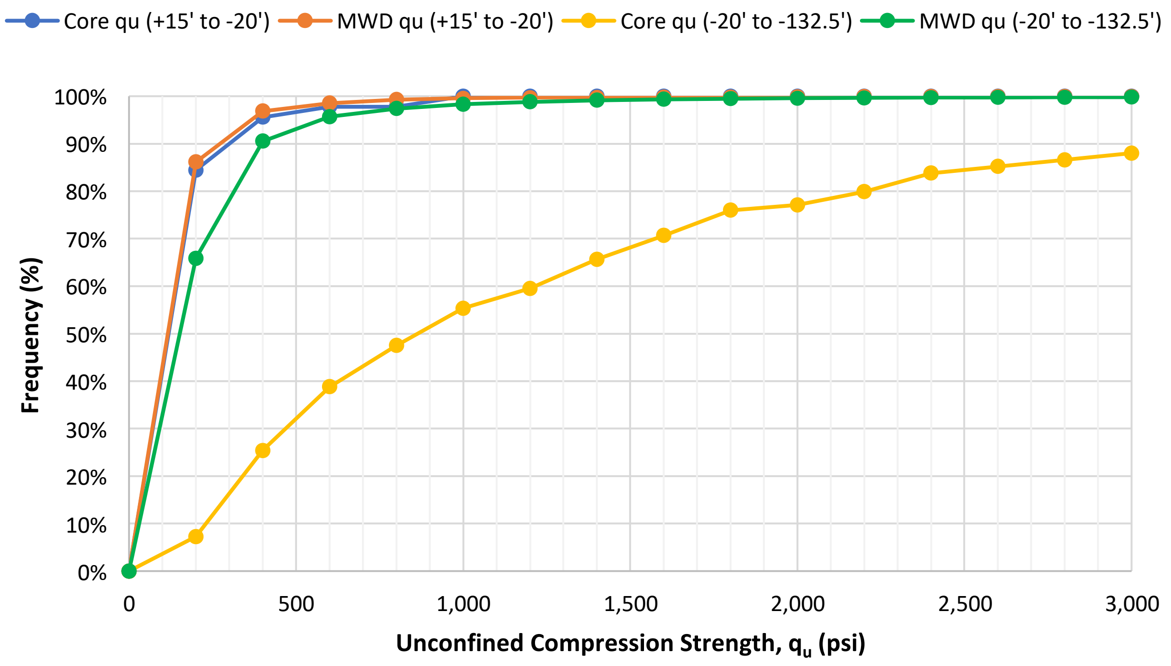
qu ≈ 1,000 psi
REC = 98%
RQD = 38%

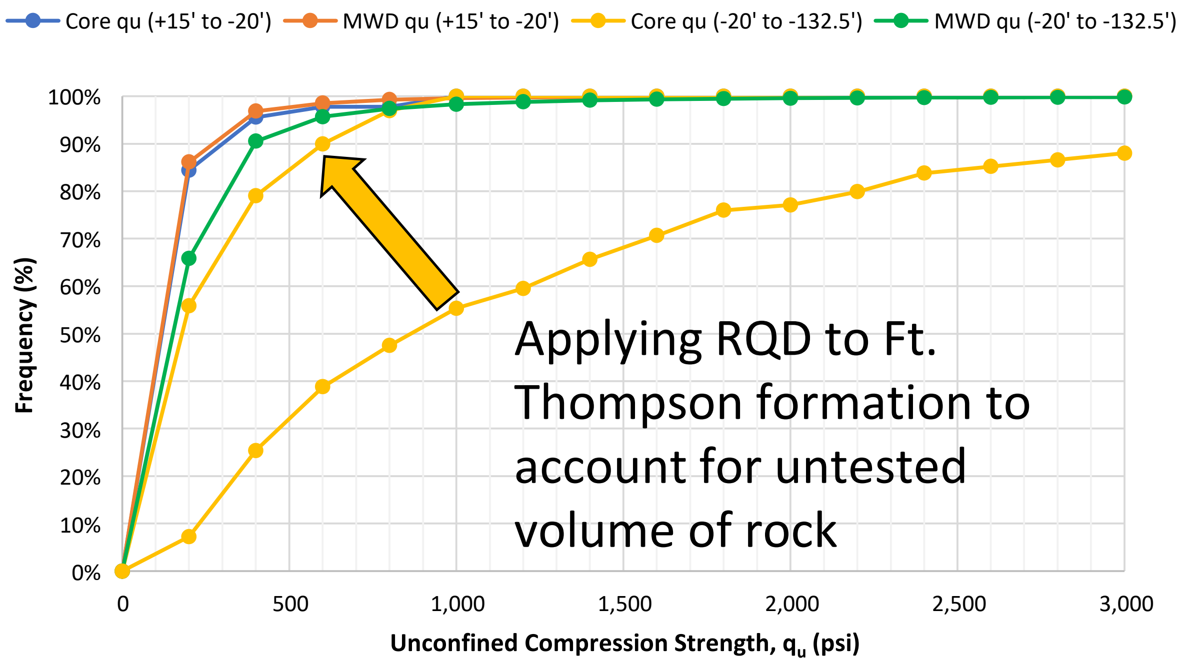
qu ≈ 400 psi
REC = 75%
RQD = 0%

***For rock w/ qu ≈ 200 psi → REC = RQD = 0% when overcrowding**

Applying RQD to Account for Untested Volume

- AVG REC = 42%
- AVG RQD = 19% (81% of volume investigated was not tested)
  - Smallest testable sample size is 4" → RQD is more representative of tested volume
- Applied RQD to Ft. Thompson formation to account for untested volume





Why use RQD instead of REC?

- REC is indicating the volume of rock that was recovered
- RQD is indicating the volume of rock that was tested
- We know from our MWD rock coring project that when we core outside the operational limits, we damage core samples and reduce REC and RQD
  - We are not recovering or testing the entire volume of rock encountered
- We need to account for the strength of the missing volume of rock that was not testable
  - We must assume the missing strengths to be zero
- We also know from the MWD rock coring project that drilling outside the operational limits has a greater effect on lower strength rock
  - We tend to only recover the higher strength rock
- Using REC places more emphasis on the higher strength rock that was recovered and testable
  - In many cases this double counts the higher strength rock which may not provide a proportional strength reduction
- Using RQD places the proper emphasis on the higher strength rock that was testable and anything that wasn't testable is considered zero
  - This provides a proportional strength reduction to account for the missing volume of rock that was not tested

Why use RQD instead of REC?

- AVG REC = 42%
- AVG RQD = 19%
- 42 / 19 = 2.21

$$Average\ Core\ q_u = 1{,}206\ psi$$ 422 qu data points

$$Average\ MWD\ q_u = 223\ psi$$ 120,458 qu data points

- We are multiplying the higher strength rock by 2.21 and then averaging this value with zero from the missing volume
- REC approach:

$$Core\ q_u = (1{,}206\ psi\ * 0.42) + (0\ psi\ * 0.58) = 507\ psi$$

- RQD approach

$$Core\ q_u = (1{,}206\ psi\ * 0.19) + (0\ psi\ * 0.81) = 229\ psi$$

LRFD Analyses

- 10 mobilized load test segments with core data in the vicinity of the ACIP test pile location
  - Signature Bridge, I-395, SR-836
  - $R_{measured} / R_{predicted}$ = Bias (λ_R)
- **3 LRFD Methods**
  - FOSM
    - Styler
    - Pre-Styler
  - Monte Carlo
    - 50,000 trials per simulation
- **6 Reliability Indexes, β**
  - 2, 2.33, 2.5, 3, 3.5, 4
  - 2.33 for redundant piles and shafts
  - 3 for nonredundant piles and shafts
- Q_{DL}/Q_{LL} = 3
  - Based on McVay et al. (2000)
- **18 Design Methods**
  - SPT, Core qu, MWD qu, MWD fs (QA/QC)
- **324 LRFD assessments**
- Developed ϕ vs. β curves for every LRFD and design method for future guidance in South Florida

- SPT Blow Counts
  - Crapps
  - Ramos
  - Frizzi
  - BDV12
- Core qu – Rock core strengths
  - McVay et al.
  - Gupton & Logan
  - Reese & O'Neill
  - FDOT (+/-) 1-StdDev
  - BDV12
  - BDV12 using old C w/ RQD in Fort Thompson
  - BDV12 using new C w/ RQD in Fort Thompson
- MWD qu – Simulate MWD coring outside footprint
  - McVay et al.
  - Gupton & Logan
  - Reese & O'Neill
  - FDOT (+/-) 1-StdDev
- MWD fs - MWD within the footprint
  - ACIP
  - ACIP and DS rock augers
  - All MWD bored piles

FOSM (Pre-Styler)

The resistance factor, ϕ, recommended by AASHTO and FHWA is referred to as the first order second moment (FOSM). According to Barker et al. 1991 and Withiam et al. 1997, using an assumption of log-normal distribution function for resistance (R_n) and bias factors (λ_R, λ_{QD}, and λ_{QL}), the resistance factor, ϕ, can be obtained using the following equation:

$$\Phi = \frac{\lambda_R \left(\gamma_D \frac{Q_D}{Q_L} + \gamma_L\right) \sqrt{\frac{1 + COV_{QD}^2 + COV_{QL}^2}{1 + COV_R^2}}}{\left(\lambda_{QD} \frac{Q_D}{Q_L} + \lambda_{QL}\right) exp\left(\beta_T \sqrt{ln\left[(1 + COV_R^2)\left(1 + COV_{QD}^2 + COV_{QL}^2\right)\right]}\right)}$$

- γ_D = dead load factor = 1.25
- γ_L = live load factor = 1.75
- Q_D/Q_L = dead/live load ratio = 1 to 3
- λ_R = Resistance bias factor
- COV_R = resistance coefficient of variability

- λ_{QD} = dead load bias factor = 1.08
- λ_{QD} = live load bias factor = 1.15
- COV_{QD} = dead load coefficient of variability = 0.128
- COV_{QL} = live load coefficient of variability = 0.180
- β_T = Target reliability index = 2 to 4

Note: The provided values for each LRFD component are based on AASHTO and FHWA recommendations.

FOSM (Styler)

$$\Phi = \frac{\lambda_R \left(\gamma_D \frac{Q_D}{Q_L} + \gamma_L\right) \sqrt{\frac{1 + COV_{QD}^2 + COV_{QL}^2}{1 + COV_R^2}}}{\left(\lambda_{QD} \frac{Q_D}{Q_L} + \lambda_{QL}\right) exp\left(\beta_T \sqrt{ln[(1 + COV_R^2)(1 + COV_{QD}^2 + COV_{QL}^2)]}\right)}$$

$$COV_Q^2 = \frac{\left(\lambda_{QD} \cdot \frac{Q_D}{Q_L} \cdot COV_{QD}\right)^2 + \left(\lambda_{QL} \cdot COV_{QL}\right)^2}{\left(\lambda_{QD} \cdot \frac{Q_D}{Q_L}\right)^2 + 2 \cdot \frac{Q_D}{Q_L} \cdot \lambda_{QD} \cdot \lambda_{QL} + \lambda_{QL}^2}$$

$$\phi = \frac{\lambda_R \left(\gamma_D \cdot \frac{Q_D}{Q_L} + \gamma_L\right) \cdot \sqrt{\frac{1 + COV_Q^2}{1 + COV_R^2}}}{\left(\lambda_{QD} \cdot \frac{Q_D}{Q_L} + \lambda_{QL}\right) \cdot exp\left(\beta \cdot \sqrt{ln\left((1 + COV_R^2) \cdot (1 + COV_Q^2)\right)}\right)}$$

- COV_Q is the coefficient of variation with respect to loading as stipulated by Styler (2006) where COV_{QD} is combined with COV_{QL} into one COV term
- The first-order second-moment (FOSM) LRFD ϕ using the Styler (2006) representation of COV_Q has been shown to be within 3% of the first order reliability method (FORM) LRFD ϕ (Styler 2006)

Monte Carlo

$$g = \emptyset R - \gamma_{LL} LL - \gamma_{DL} DL$$

- γ_{LL} and γ_{DL} are live and dead load factors
- R is the nominal resistance bias
- LL and DL are the live load and dead load bias, respectively
- All of which are described as random variables
- Each of the random variables (R, DL, and LL) were modeled with a lognormal distribution (better PDF match than normal dist.)
- AASHTO live and dead load summary statistics were employed

Monte Carlo

$$g = \emptyset\, R - \gamma_{LL}\, LL - \gamma_{DL}\, DL$$

- The assessment of LRFD phi for associated target reliability index was performed as follows:

- Select a resistance factor ϕ;
- Independently randomly generate N (50,000) trial values of LL, DL and R using Monte Carlo with bias summary statistics
- For each trial value of LL, DL and R, the function $g(x_i)$ (shown above) was evaluated;
- Based on all the trials, the number of cases in which $g(x_i) \leq 0$ was tallied and the probability of failure was computed as,

$$P_f = \frac{count\ (g(x_i))}{N}$$

- Using the inverse of the standard normal cumulative function, ϕ, the reliability index, $\beta = \phi^{-1}(P_f)$ is found;
- If the reliability index, β, is less than or larger than the target values, β_T (e.g., 2.33, 3.0, etc.), the resistance factor ϕ is adjusted upward or downward until $|\beta - \beta_T| < tolerance$

LRFD Analysis Summary

LRFD Analysis - ACIP Piles - South Florida Limestone - β = 2.33				
LRFD Method	Category	Design Method	ϕ	ϕ / λ
FOSM Pre-Styler	SPT - N	Crapps	0.16	42%
		Ramos	0.16	44%
		Frizzi	0.17	41%
		BDV12	0.21	45%
	Core qu	McVay et al.	0.50	54%
		Gupton & Logan	0.42	51%
		Reese & O'neill	0.56	51%
		FDOT (+/-) 1 Std Dev	0.54	47%
		BDV12 Old C w/ REC	0.14	27%
		BDV12 Old C w/ RQD	0.53	51%
		BDV12 New C w/ RQD	0.58	52%
	MWD qu	McVay et al.	0.58	57%
		Gupton & Logan	0.38	45%
		Reese & O'neill	0.50	45%
		FDOT (+/-) 1 Std Dev	0.68	56%
	MWD fs	ACIP Piles	0.75	75%
		ACIP & DS Rock Augers	0.75	75%
		ACIP & DS All Data	0.75	75%

LRFD Analysis - ACIP Piles - South Florida Limestone - β = 2.33				
LRFD Method	Category	Design Method	ϕ	ϕ / λ
FOSM - Styler	SPT - N	Crapps	0.18	46%
		Ramos	0.17	47%
		Frizzi	0.18	45%
		BDV12	0.23	50%
	Core qu	McVay et al.	0.56	60%
		Gupton & Logan	0.46	56%
		Reese & O'neill	0.62	56%
		FDOT (+/-) 1 Std Dev	0.59	51%
		BDV12 Old C w/ REC	0.14	29%
		BDV12 Old C w/ RQD	0.59	57%
		BDV12 New C w/ RQD	0.65	57%
	MWD qu	McVay et al.	0.66	64%
		Gupton & Logan	0.41	49%
		Reese & O'neill	0.55	49%
		FDOT (+/-) 1 Std Dev	0.76	63%
	MWD fs	ACIP Piles	0.94	94%
		ACIP & DS Rock Augers	0.94	94%
		ACIP & DS All Data	0.94	94%

LRFD Analysis - ACIP Piles - South Florida Limestone - β = 2.33				
LRFD Method	Category	Design Method	ϕ	ϕ / λ
Monte Carlo	SPT - N	Crapps	0.17	43%
		Ramos	0.16	45%
		Frizzi	0.18	43%
		BDV12	0.22	47%
	Core qu	McVay et al.	0.54	58%
		Gupton & Logan	0.45	54%
		Reese & O'neill	0.59	54%
		FDOT (+/-) 1 Std Dev	0.57	49%
		BDV12 Old C w/ REC	0.13	26%
		BDV12 Old C w/ RQD	0.57	55%
		BDV12 New C w/ RQD	0.62	55%
	MWD qu	McVay et al.	0.64	62%
		Gupton & Logan	0.39	47%
		Reese & O'neill	0.52	47%
		FDOT (+/-) 1 Std Dev	0.74	60%
	MWD fs	ACIP Piles	0.93	94%
		ACIP & DS Rock Augers	0.93	93%
		ACIP & DS All Data	0.94	94%

β = 2.33 – Redundant Foundations

SPT LRFD Methods

- Crapps:

$$f_s = 0.8 * N - 10.4, \qquad for\ N \geq 11$$

- Ramos:

$$f_s = 0.4 * N + 4, \qquad for\ 60 \geq N \geq 5$$

$$f_s = 0.2 * N + 16, \qquad for\ N > 60$$

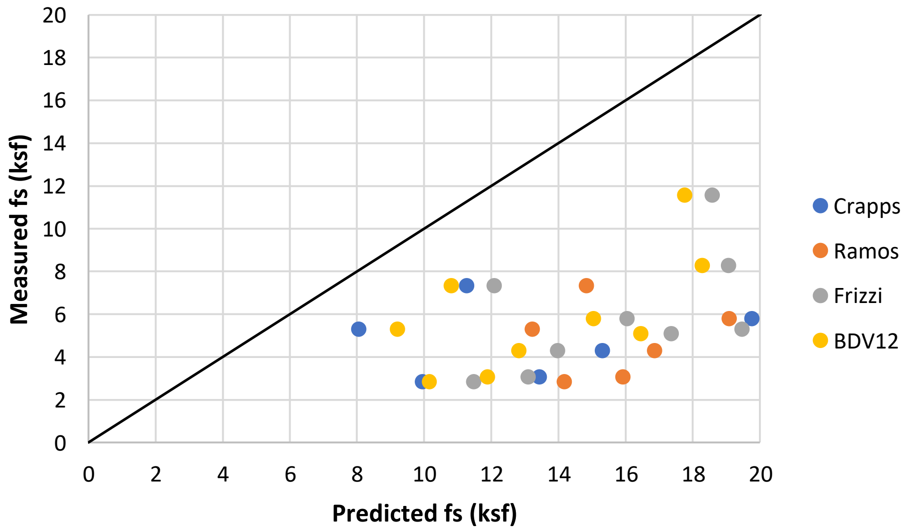
- Frizzi:

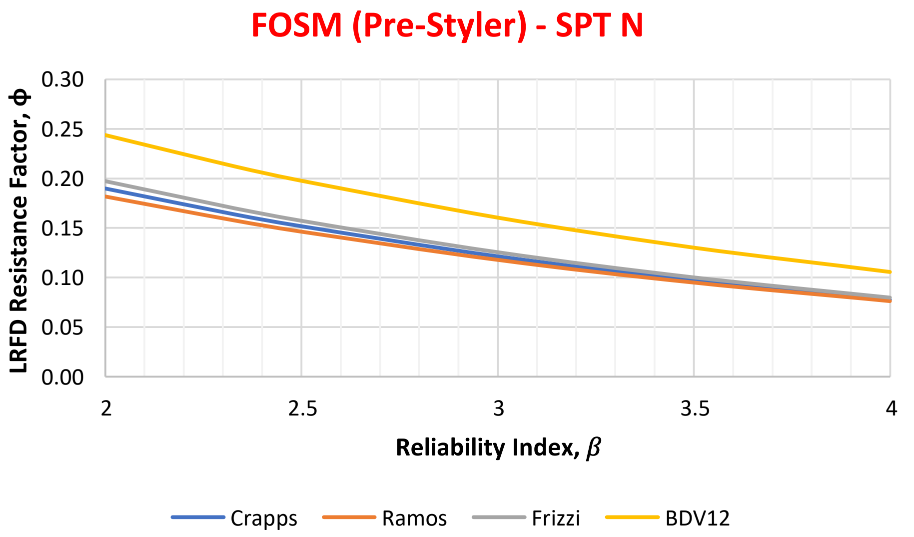
$$f_s = (0.35 * N - 1) * 2\ (ksf/tsf)$$

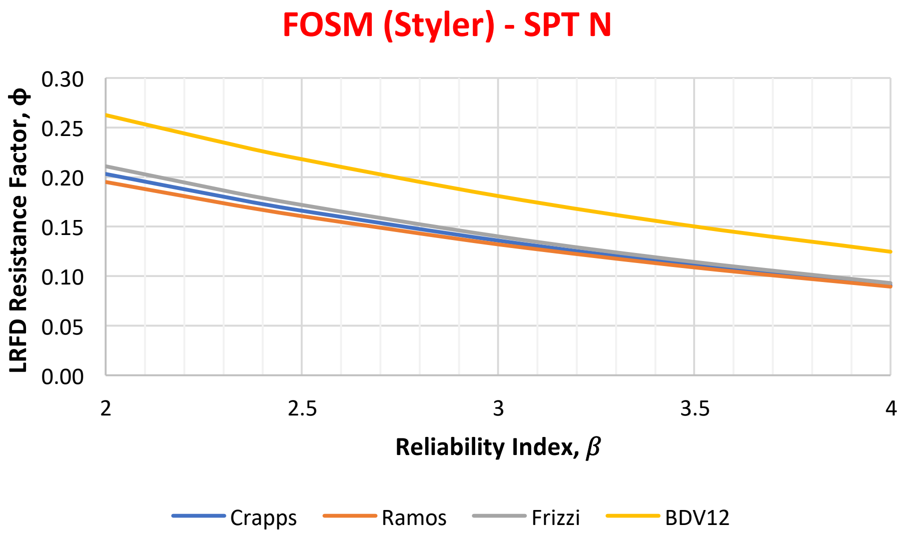
- BDV12:

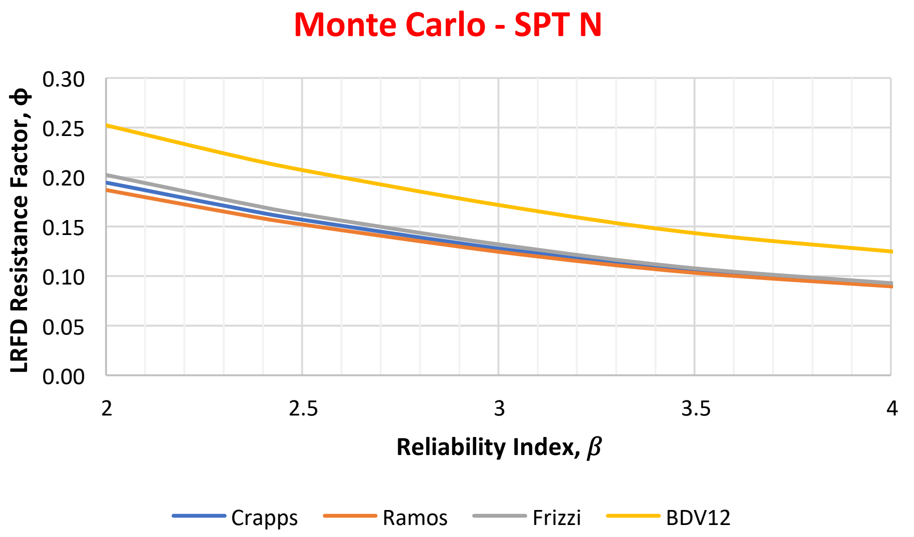
$$f_s = 0.15 * N * 2\ (ksf/tsf)$$

SPT Blow Counts









Core qu LRFD Methods

Note: For all methods RQD was only used in Fort Thompson formation to account for untested volume of rock. REC and RQD were not used in Miami formation because the distribution did not require adjustment

- McVay et al.:

$$f_s = 1/2 * \sqrt{q_u} * \sqrt{q_t} \; * RQD \rightarrow FL\ Geomaterials\ EQN\ used\ to\ estimate\ q_t$$

- Gupton and Logan:

$$f_s = 0.2 * q_u * RQD * 2\ (ksf/tsf)$$

- Reese and O’Neill:

$$f_s = 0.15 * q_u * RQD * 2\ (ksf/tsf)$$

- FDOT:

$$\pm 1\ Standard\ Deviation\ from\ mean\ q_u\ removed$$

$$f_s = 1/2 * \sqrt{q_u} * \sqrt{q_t} \; * RQD \rightarrow FL\ Geomaterials\ EQN\ used\ to\ estimate\ q_t$$

BDV12 Core qu LRFD Methods

- BDV12 using Old C w/ REC:

$$f_s = 1.111 * \sqrt{q_u} * REC * 2\ (ksf/tsf) \rightarrow Miami\ Formation$$

$$f_s = 1.643 * \sqrt{q_u} * REC * 2\ (ksf/tsf) \rightarrow Fort\ Thompson\ Formation$$

- BDV12 using Old C w/ RQD in Fort Thompson:

$$f_s = 1.111 * \sqrt{q_u} * REC * 2\ (ksf/tsf) \rightarrow Miami\ Formation$$

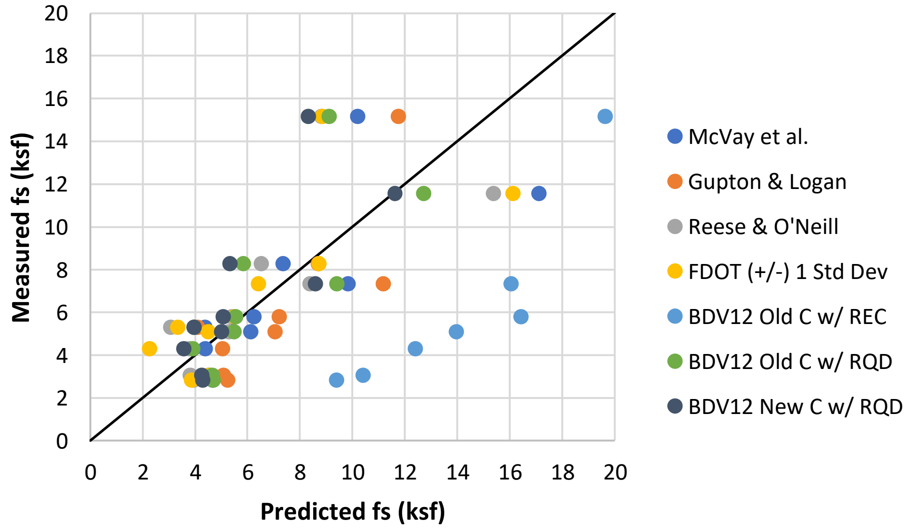
$$f_s = 1.643 * \sqrt{q_u} * RQD * 2\ (ksf/tsf) \rightarrow Fort\ Thompson\ Formation$$

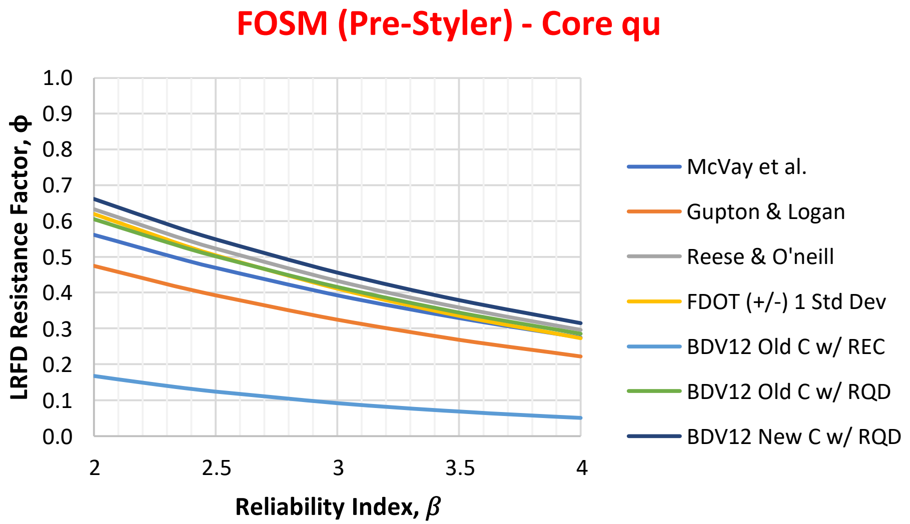
- BDV12 using New C w/ RQD in Fort Thompson :

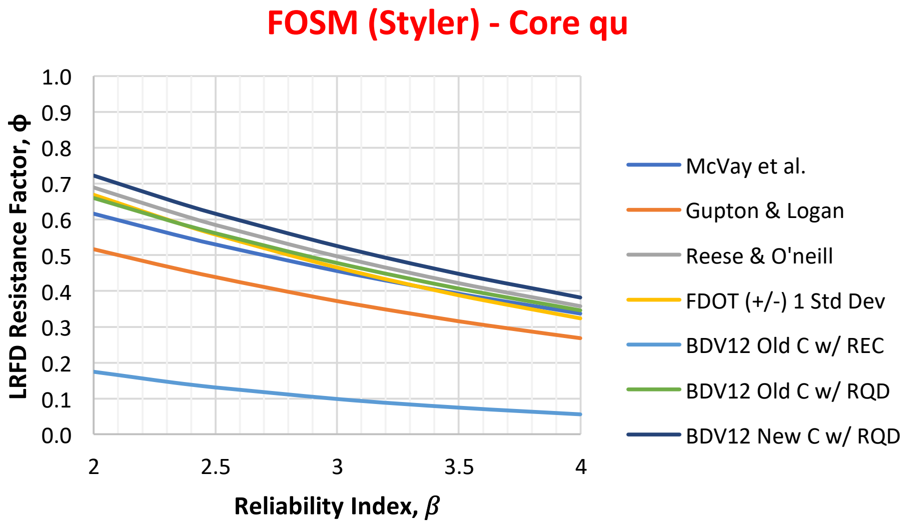
$$f_s = 1.111 * \sqrt{q_u} * REC * 2\ (ksf/tsf) \rightarrow Miami\ Formation$$

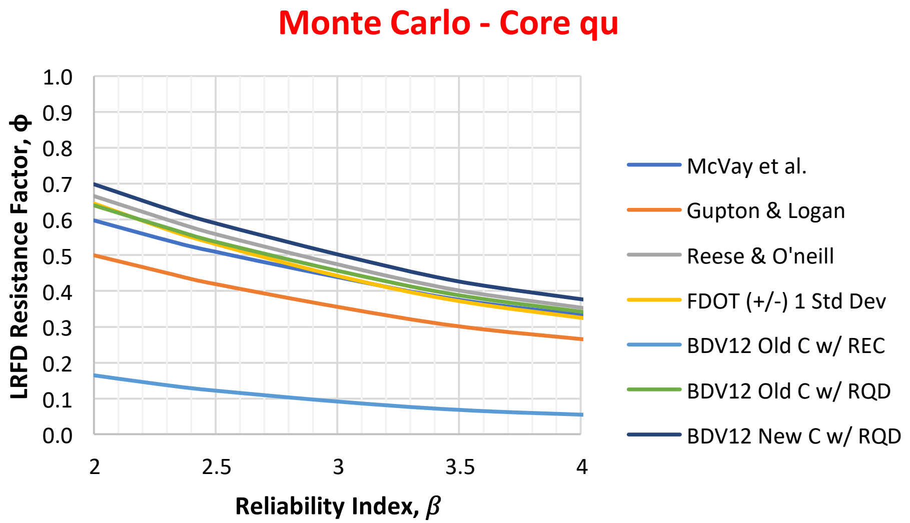
$$f_s = 1.500 * \sqrt{q_u} * RQD * 2\ (ksf/tsf) \rightarrow Fort\ Thompson\ Formation$$

Core qu


Measured fs (ksf)
Predicted fs (ksf)
McVay et al.
Gupton & Logan
Reese & O'Neill
FDOT (+/-) 1 Std Dev
BDV12 Old C w/ REC
BDV12 Old C w/ RQD
BDV12 New C w/ RQD


FOSM (Pre-Styler) - Core qu
LRFD Resistance Factor, ϕ
Reliability Index, β
McVay et al.
Gupton & Logan
Reese & O'neill
FDOT (+/-) 1 Std Dev
BDV12 Old C w/ REC
BDV12 Old C w/ RQD
BDV12 New C w/ RQD


FOSM (Styler) - Core qu
LRFD Resistance Factor, ϕ
Reliability Index, β
McVay et al.
Gupton & Logan
Reese & O'neill
FDOT (+/-) 1 Std Dev
BDV12 Old C w/ REC
BDV12 Old C w/ RQD
BDV12 New C w/ RQD


Monte Carlo - Core qu
LRFD Resistance Factor, ϕ
Reliability Index, β
McVay et al.
Gupton & Logan
Reese & O'neill
FDOT (+/-) 1 Std Dev
BDV12 Old C w/ REC
BDV12 Old C w/ RQD
BDV12 New C w/ RQD

MWD qu LRFD Methods

Note: For all methods REC is estimated percentage of rock from MWD pile summary report where rock below 88 psi is discounted toward capacity

- McVay et al.:

$$f_s = 1/2 * \sqrt{q_u} * \sqrt{q_t} \ * REC \rightarrow FL\ Geomaterials\ EQN\ used\ to\ estimate\ q_t$$

- Gupton and Logan:

$$f_s = 0.2 * q_u * REC * 2\ (ksf/tsf)$$

- Reese and O'Neill:

$$f_s = 0.15 * q_u * REC * 2\ (ksf/tsf)$$

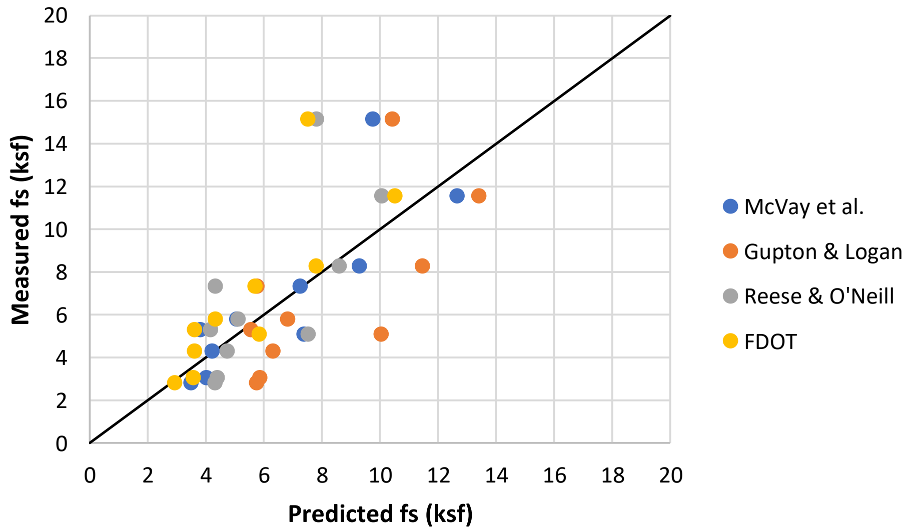
- FDOT:

$$\pm 1\ Standard\ Deviation\ from\ mean\ q_u\ removed$$

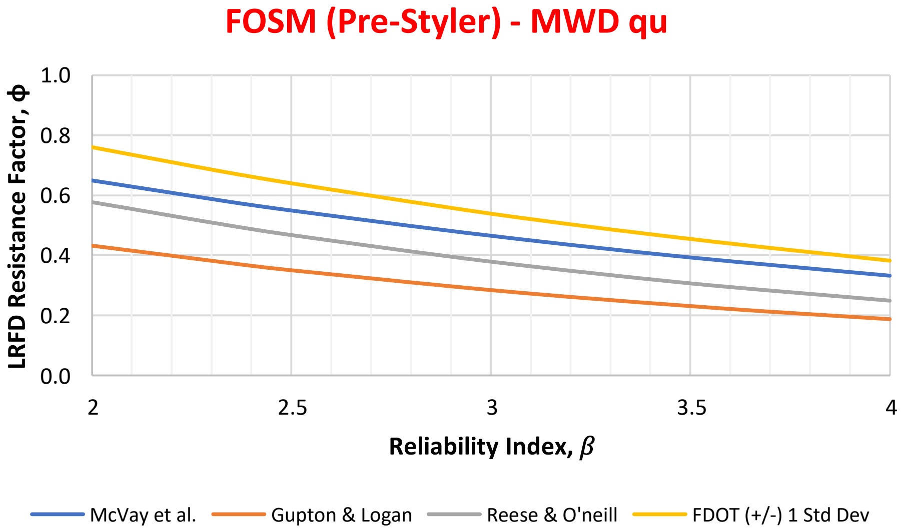
$$f_s = 1/2 * \sqrt{q_u} * \sqrt{q_t} \ * REC \rightarrow FL\ Geomaterials\ EQN\ used\ to\ estimate\ q_t$$

- Within 100 ft or less of test piles
- Number of data points is significantly improved per unit length due to higher resolution profiling – vertically and horizontally

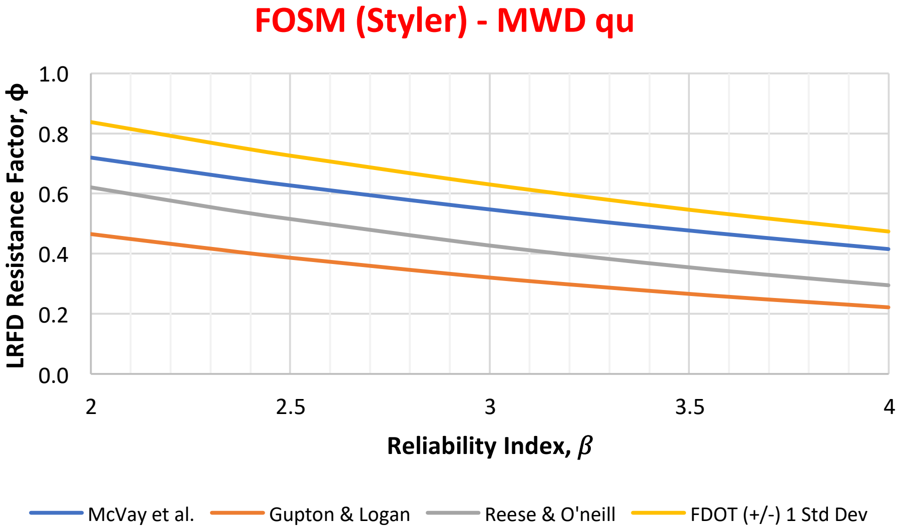
MWD qu



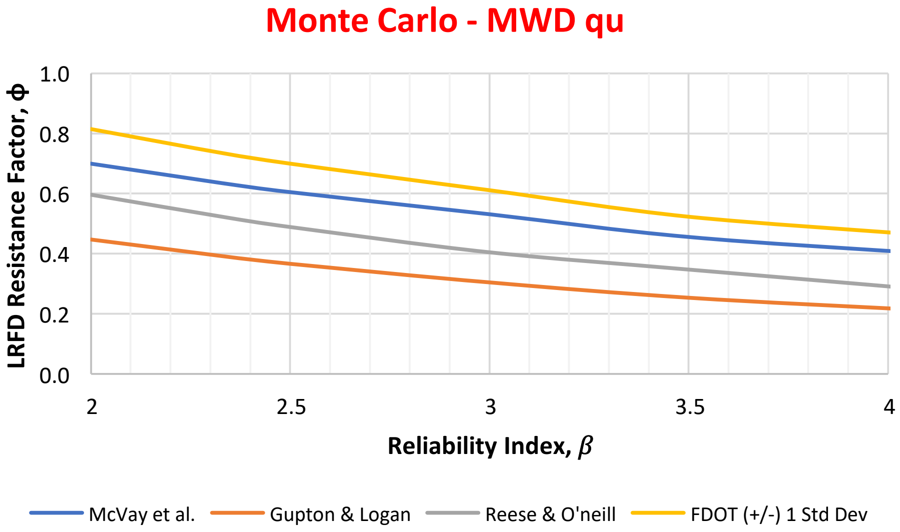
Measured fs (ksf)
Predicted fs (ksf)
McVay et al.
Gupton & Logan
Reese & O'Neill
FDOT



FOSM (Pre-Styler) - MWD qu
LRFD Resistance Factor, ϕ
Reliability Index, β
McVay et al.
Gupton & Logan
Reese & O'neill
FDOT (+/-) 1 Std Dev



FOSM (Styler) - MWD qu
LRFD Resistance Factor, ϕ
Reliability Index, β
McVay et al.
Gupton & Logan
Reese & O'neill
FDOT (+/-) 1 Std Dev

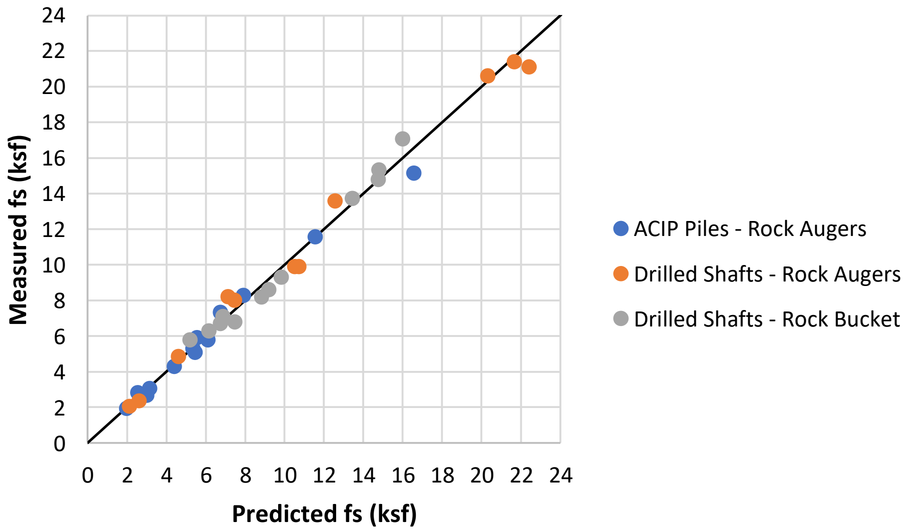


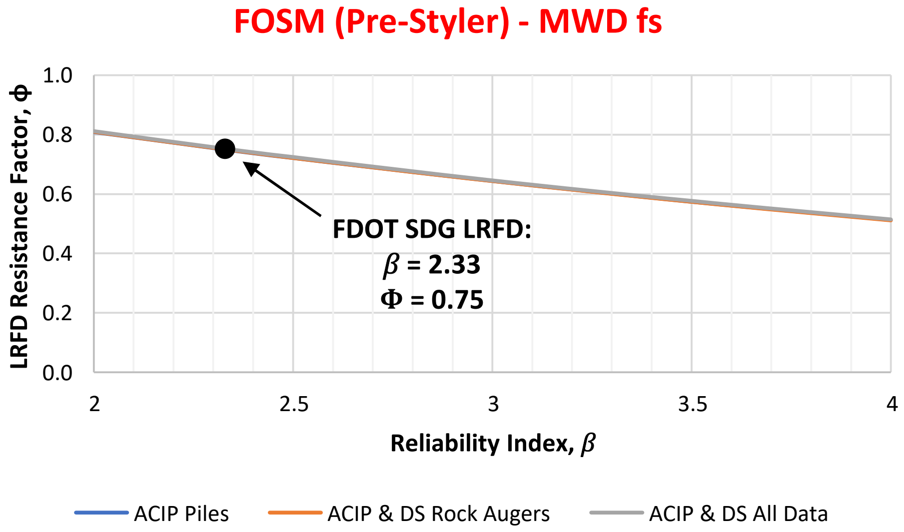
Monte Carlo - MWD qu
LRFD Resistance Factor, ϕ
Reliability Index, β
McVay et al.
Gupton & Logan
Reese & O'neill
FDOT (+/-) 1 Std Dev

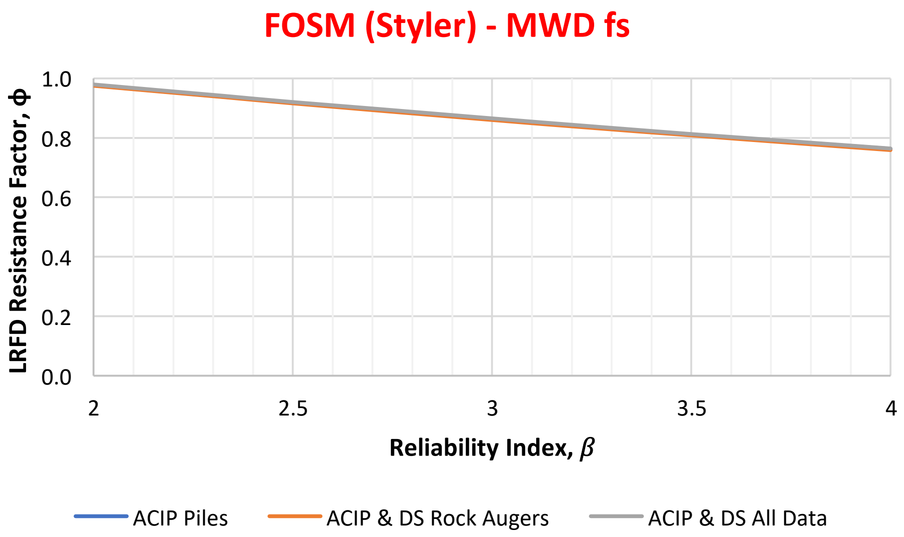
MWD fs

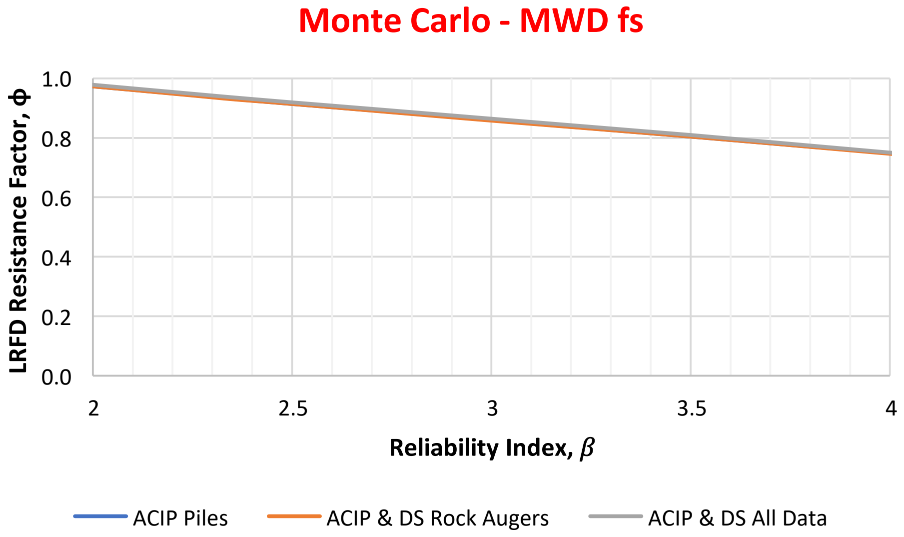
- MWD conducted in the footprint of test piles
  - Removes the influence of spatial variability (zonal, layering, etc.)
  - Considers only the influence of the method and method error
  - Strength assessment every 1-cm
  - Superior QA/QC
- ACIP Piles
  - 13 data points
- ACIP and Drilled Shafts w/ rock augers
  - 24 data points
- ACIP and Drilled Shafts w/ rock augers and rock buckets
  - 36 data points
  - Assess the overall MWD approach

MWD fs – QA/QC Procedure









Conclusions

- Multiple ACIP analysis spreadsheets were successfully developed that transform time-referenced AME data into depth-referenced-data that provides compatibility with Teale's specific energy equation for in situ MWD assessment
  - Each version of the spreadsheet will provide superior ACIP pile QA/QC during future installations in South Florida limestone
- MWD generated 299 times more rock strength data than rock core sampling within the same investigated area and elevation range
  - Illustrates the superior profiling MWD can provide during a site investigation and the additional subsurface information that can be gathered from monitoring every pile on a site.
  - MWD can provide a much better understanding of the subsurface conditions, strength distribution, and layering present at a site
- Rock coring at greater depths in South Florida may be prone to operating outside of the operational limits
  - Diminishes core recoveries (REC) and rock quality designation (RQD)
  - Reduces the number of core samples available for laboratory testing
  - Skews the mean strength toward the higher end
  - Indicates MWD coring should be conducted in South Florida limestone

Conclusions

- Using RQD to adjust the rock core strength distribution at lower depths improved the LRFD ϕ assessment compared to using REC which is common practice
  - RQD under the conditions present properly accounted for the untested volume of rock at the site whereas REC overestimated the untested volume of rock by more than a factor of two
  - Compare tested volume of rock to investigated volume of rock
- Load testing suggested that residual stresses are developed in South Florida limestone for ACIP piles
  - Residual stresses **MUST** be quantified and properly accounted for prior to future ACIP Pile MWD correlations being developed
- LRFD ϕ assessment was performed using site specific data with LRFD methods FOSM (Pre-Styler), FOSM (Styler), and Monte Carlo simulations
  - Methods that employed rock cores indicated similar results as drilled shafts but higher ϕ values than the original ACIP pile results
  - Methods that employed SPT data produced the lowest ϕ values, similar to the original ACIP pile report
  - MWD resulted in higher ϕ values compared to the conventional methods
  - When MWD was conducted in the footprint of the piles (QA/QC procedure), the highest ϕ values were achieved because spatial variability was eliminated
    - Requires multiple load tests with full mobilization and site-specific correlations to be developed

Conclusions

- MWD is viable for ACIP pile QA/QC
  - MWD specific energy was in agreement with:
    - Layering identified by the SPT borings
    - Rock core strength range and layering
    - Load test results as an excellent correlation was developed between unit side shear and specific energy
  - MWD data were able to provide accurate test pile models that showed the same behavior as the actual load tested piles
  - MWD indicated the strength of rock decreased moving East-to-West which agreed with the trends of rock cores and load tests
  - Drilling profiles also showed the same trends as the estimated pile capacities and indicated stronger rock takes longer to drill which is the expected trend
  - MWD methods produced the highest LRFD ϕ values
  - MWD was able to assist in determining the proper strength distribution obtained from traditional rock core sampling

Recommendations

- Conduct more MWD research for South Florida ACIP piles as more data is needed to further validate the results of this research effort
- Collect more MWD data in the footprint of mobilized load tested ACIP piles to increase the data set acquired during this research
- Investigate using MWD coring practices in South Florida to assist with recovering more samples in formations that are difficult to core

Recommendations

- Sampling frequencies should be increased for South Florida AME equipment in order to obtain more than one time-based sampled measurement per recorded depth increment
  - Current sampling frequency (1-Hz) was found to be adequate when drilling in stronger layers of limestone as the drilling rate tends to slow down in the stronger layers
  - Future ACIP pile MWD efforts should focus on delineating lower strength limestone and soil which will require a higher sampling frequency to ensure multiple readings are provided per recorded depth increment, regardless of the geomaterial encountered
  - UF researchers anticipate that monitoring vibration as an additional drilling parameter will assist in the delineation of soil and rock in the future MWD efforts, which will likely require a minimum sampling frequency of 100 Hz
- Develop an ACIP pile MWD analysis program that is capable of handling higher sampling frequencies than the current spreadsheets
  - Current spreadsheets are great for 1-Hz sampling rate but testing the higher recommended sampling frequency with a simulated data set resulted in the program crashing
  - The proposed software should be developed based on the programming that was developed for the ACIP pile spreadsheet, as the current analysis program performed exceptionally well with the given data set sizes

Recommendations

- Residual stresses that develop in South Florida ACIP piles should be further investigated
  - Residual stresses were identified in every load tested pile by the UF research team as well as the load test consultant who originally reduced the load test
  - Ignoring the effect of residual stresses in future South Florida piles will lead to inaccurate strength layering and design related issues
  - Residual stress needs to be resolved to get accurate high resolution load test layering and to build correlation with MWD
- In regard to load testing in South Florida limestone, strain gauge readings should be taken immediately before (and after) every event of the piling work and not just during the actual load test
  - UF provided detailed recommendations to the FDOT on when readings should be taken for the most accurate assessment

Questions?

- 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, 144(3). doi: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, 55(8): 1154-1167. doi:10.1139/cgj-2017-0321.
- Rodgers M., McVay M., Horhota D., Sinnreich J., Hernando J. 2019. Assessment of Shear Strength from Measuring While Drilling Shafts in Florida Limestone. Canadian Geotechnical Journal. doi:10.1139/cgj-2017-0629.
- Rodgers M., McVay M., Horhota D., Hernando J., Paris J. 2020. “Measuring While Drilling in Florida Limestone for Geotechnical Site Investigation.” Canadian Geotechnical Journal. doi.org/10.1139/cgj-2019-0094.
- Rodgers M., McVay M., Horhota D., Hernando J., Paris J. 2021. “Operational Limits of Measuring While Drilling in Florida Limestone for Geotechnical Site Characterization.” ASCE Journal of Geotechnical and Geoenvironmental Engineering. doi:10.1061/(ASCE)GT.1943-5606.0002688
- Teale, R. 1965. The concept of specific energy in rock drilling. International Journal of Rock Mechanics and Mining Science, 2(1), 57–73.