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

- Establish side shear vs. MWD specific energy correlations on a number of sites using ISO compliant MWD on ACIP Pile installations for load tested piles
- Validate MWD correlations and developed QA/QC procedures on production piles at each of the sites
- Based on pile load tests and recovered field cores/laboratory strength testing, reassess LRFD phi factors for Auger Cast Piles in South Florida
- Use the MWD specific energy vs. pile side shear correlations from load tests to establish LRFD phi factors for future south Florida axial pile capacity QA/QC

Tasks and Deliverables

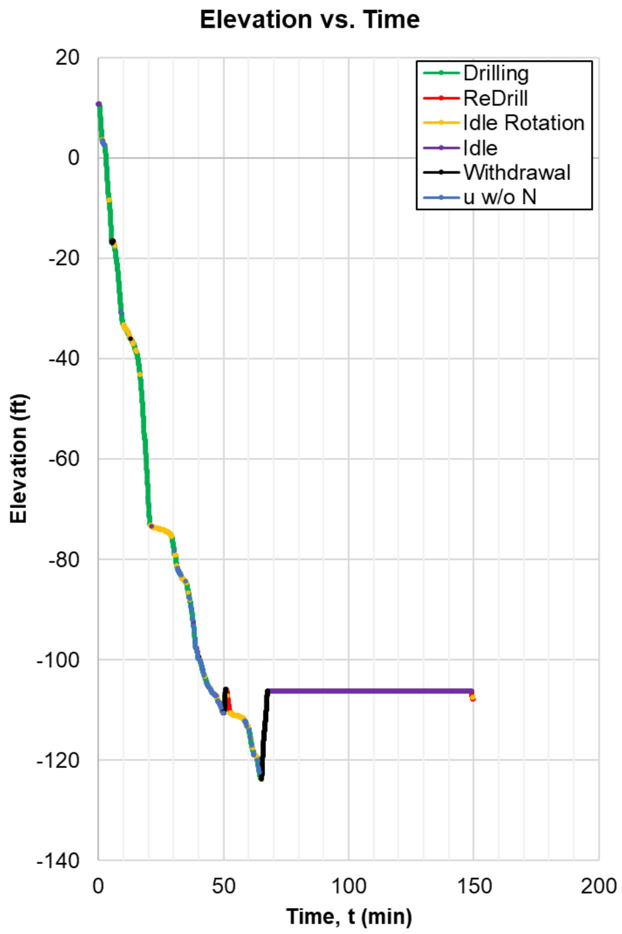
- Deliverable 1 - Establish MWD Data Reduction Criteria and Procedures for ACIP Pile Drill Rigs. (Task 1)
- Deliverable 2 - MWD Specific Energy vs. ACIP Pile Side Shear Relationships (Task 2)
- Deliverable 3 - MWD Correlation Validation for ACIP Production Pile QA/QC (Task 3)
- Deliverable 4 - LRFD Phi 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)

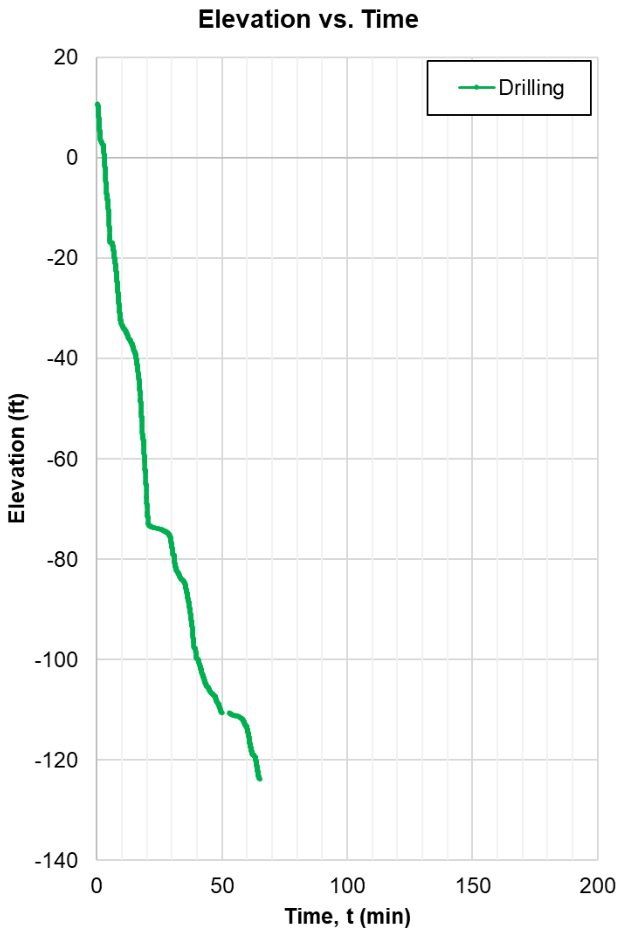
Task 1 – Establish MWD Data Reduction Criteria and Procedures for ACIP Drill Rigs

- 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

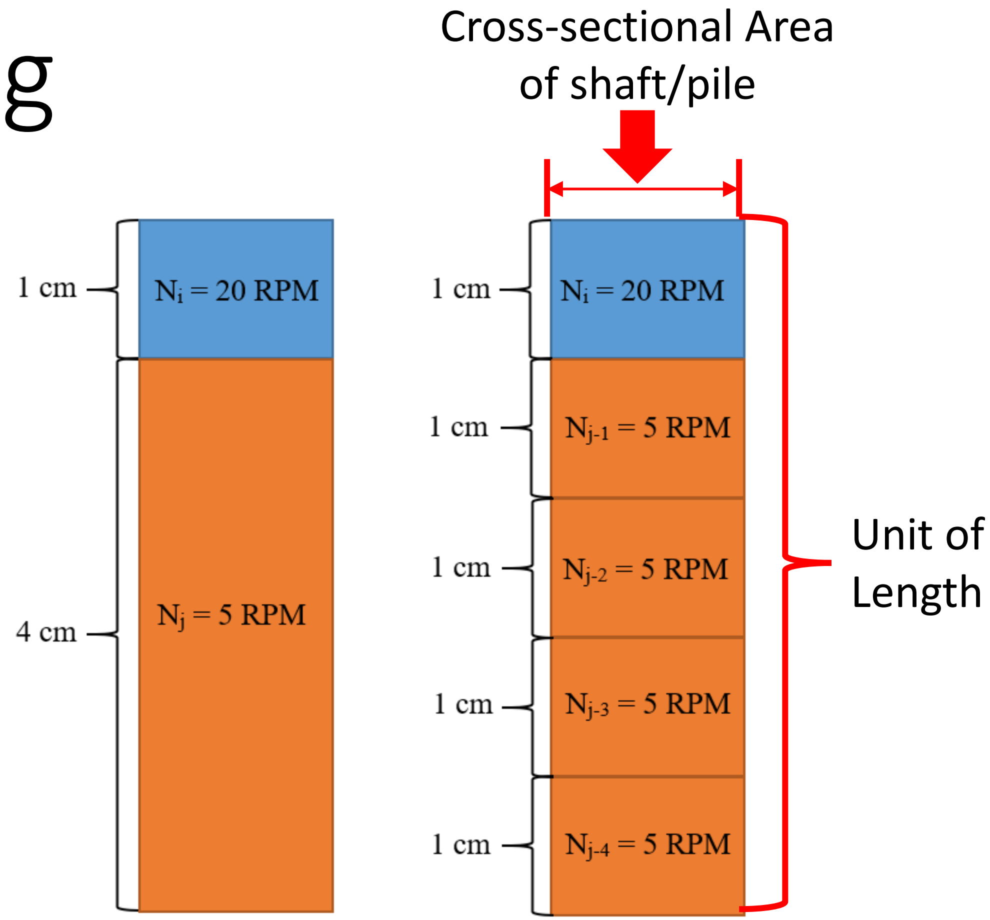
- The drilling operations can include 6 different types of drilling
- **Drilling**
  - Penetration, rotation, torque, and crowd are applied simultaneously
- Withdrawal
  - Auger is being withdrawn (moving upward not downward)
- Re-drill
  - Re-drilling a segment that has been previously drilled (occurs 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 unit volume of rock
- In order to properly average specific energy over a specified length equal individual lengths of measure must be used
  - 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 and depth-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 AME Pile Data

Can enter in ACIP MWD data for up to 10 piles

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	**Enter Pile 1** ⇨	Time	Duration (	Gear Box I	Penetratio	Penetratio	Depth (ft)	Gear Box I	Torque (f	Crowd Pre	Thrust (lb:	**Enter Pile 2** ⇨	Time	Duration (	Gear Box I	Penetratio	Penetratio	Depth (ft)	Gear Box I	Torque (f	Crowd Pre	Thrust (lb:	**Enter Pile 3** ⇨	Time
2	**Pile ID**	5/4/2020 7	0	-293.35	-36.9423	3.048	0	454.5482	0	208.5642		**Pile ID**	4/29/2020	0	14.87	2.821522	0.354419	0.262467	750.4251	0	671.0894		**Pile ID**	5/8/2020
3	**Pile 1**	5/4/2020 7	0.02	-293.26	-36.9751	3.048	0	477.4641	0	201.1673		**Pile 2**	4/29/2020	0.02	18.23	4.625984	0.21617	0.492126	830.3408	0	693.1352		**Pile 3**	5/8/2020
4	**Top of Shaft Elevation (ft)**	5/4/2020 7	0.03	14.75	0	3.048	0	587.9828	0	351.5714		**Top of Shaft Elevation (ft)**	4/29/2020	0.03	18.7	7.57874	0.131948	0.787402	792.9211	0	407.1208		**Top of Shaft Elevation (ft)**	5/8/2020
5	**11.84**	5/4/2020 7	0.05	16.29	0.295276	3.386667	0.032808	551.8684	0	275.8617		**5.00**	4/29/2020	0.05	18.67	8.267717	0.120952	1.049869	784.654	0	452.0825		**10.74**	5/8/2020
6	**Station**	5/4/2020 7	0.07	16.21	0.787402	1.27	0.065617	606.8377	0	252.9457		**Station**	4/29/2020	0.07	18.7	11.54856	0.086591	1.312336	807.4249	0	503.1358		**Station**	5/8/2020
7	**100+00.01**	5/4/2020 7	0.08	16.16	1.181102	0.846667	0.098425	603.3568	0	239.8924		**100+00.01**	4/29/2020	0.08	18.7	15.35433	0.065128	1.607612	775.3715	0	494.2885		**100+00.01**	5/8/2020
8	**Offset (ft)**	5/4/2020 7	0.1	16.16	1.574803	0.635	0.131234	665.1429	0	251.9305		**Offset (ft)**	4/29/2020	0.1	18.67	17.35564	0.057618	1.935696	859.2033	0	414.3727		**Offset (ft)**	5/8/2020
9	**10.0**	5/4/2020 7	0.12	16.29	2.034121	0.491613	0.19685	614.5247	0	246.9992		**10.0**	4/29/2020	0.12	18.63	17.15879	0.058279	2.230971	909.3864	0	397.5483		**10.0**	5/8/2020
10	Pile ID (B#-P#-S#)	5/4/2020 7	0.13	16.43	2.132546	0.468923	0.229659	641.7918	0	243.0832		Pile ID (B#-P#-S#)	4/29/2020	0.13	18.63	16.96194	0.058956	2.427822	809.0203	0	327.4951		Pile ID (B#-P#-S#)	5/8/2020
11	B = Bridge	5/4/2020 7	0.15	16.5	2.001312	0.499672	0.229659	623.372	0	248.5946		B = Bridge	4/29/2020	0.15	18.6	14.4357	0.069273	2.427822	763.1884	0	435.6933		B = Bridge	5/8/2020
12	P = Pier	5/4/2020 7	0.17	16.62	1.935696	0.51661	0.262467	643.5323	0	252.0755		P = Pier	4/29/2020	0.17	18.57	11.05643	0.090445	2.427822	725.1885	0	213.4955		P = Pier	5/8/2020
13	S = Shaft/Pile	5/4/2020 7	0.18	16.78	1.935696	0.51661	0.295276	618.0056	0	246.9992		S = Shaft/Pile	4/29/2020	0.18	18.67	7.316273	0.136682	2.427822	801.4783	0	347.3653		S = Shaft/Pile	5/8/2020
14		5/4/2020 7	0.2	16.91	1.902887	0.525517	0.328084	663.9826	0	245.6939			4/29/2020	0.2	18.7	3.937008	0.254	2.46063	768.5548	0	298.9227			5/8/2020
15		5/4/2020 7	0.22	16.98	1.870079	0.534737	0.360892	661.807	0	247.7244			4/29/2020	0.22	18.67	1.213911	0.823784	2.46063	878.7834	0	379.9988			5/8/2020
16		5/4/2020 7	0.23	17.28	1.968504	0.508	0.393701	634.2499	0	250.9152			4/29/2020	0.23	18.7	0.951444	1.051034	2.526247	798.1425	0	390.5865			5/8/2020
17		5/4/2020 7	0.25	17.46	2.034121	0.491613	0.459318	681.5322	0	242.6481			4/29/2020	0.25	18.67	1.213911	0.823784	2.559055	794.6616	0	329.2356			5/8/2020
18		5/4/2020 7	0.27	17.47	2.034121	0.491613	0.492126	709.2344	0	255.9915			4/29/2020	0.27	18.63	1.541995	0.648511	2.591864	800.6081	0	231.0451			5/8/2020
19		5/4/2020 7	0.28	17.41	2.034121	0.491613	0.524934	669.349	0	268.3197			4/29/2020	0.28	18.6	1.804462	0.554182	2.624672	780.4479	0	310.0906			5/8/2020
20		5/4/2020 7	0.3	17.62	2.132546	0.468923	0.557743	682.2573	0	254.5412			4/29/2020	0.3	18.63	2.001312	0.499672	2.65748	917.7986	0	369.5561			5/8/2020
21		5/4/2020 7	0.32	17.57	2.165354	0.461818	0.590551	717.2114	0	250.9152			4/29/2020	0.32	18.9	2.001312	0.499672	2.690289	917.5085	0	388.701			5/8/2020
22		5/4/2020 7	0.33	17.54	2.165354	0.461818	0.62336	695.1657	0	253.816			4/29/2020	0.33	19.13	2.001312	0.499672	2.723097	959.1343	0	390.4415			5/8/2020
23		5/4/2020 7	0.35	17.62	2.198163	0.454925	0.656168	643.8224	0	263.5335			4/29/2020	0.35	19.37	2.034121	0.491613	2.755906	962.3251	0	332.5714			5/8/2020
24		5/4/2020 7	0.37	17.79	2.26378	0.441739	0.688976	722.8679	0	250.9152			4/29/2020	0.37	19.67	2.099738	0.47625	2.788714	900.6841	0	343.8844			5/8/2020
25		5/4/2020 7	0.38	17.6	2.26378	0.441739	0.754593	716.1962	0	258.0221			4/29/2020	0.38	20	2.132546	0.468923	2.821522	856.8827	0	358.9683			5/8/2020
26		5/4/2020 7	0.4	17.44	2.230971	0.448235	0.787402	685.5932	0	252.9457			4/29/2020	0.4	19.9	2.230971	0.448235	2.854331	845.2797	0	323.8692			5/8/2020
27		5/4/2020 7	0.42	17.49	2.26378	0.441739	0.82021	663.5475	0	270.4953			4/29/2020	0.42	19.9	2.46063	0.4064	2.919948	841.6538	0	364.4797			5/8/2020
28		5/4/2020 7	0.43	17.49	2.296588	0.435429	0.853018	688.0588	0	252.0755			4/29/2020	0.43	19.93	2.755906	0.362857	2.985564	808.8753	0	374.1973			5/8/2020
29		5/4/2020 7	0.45	17.46	2.296588	0.435429	0.885827	691.9749	0	258.6022			4/29/2020	0.45	19.93	3.051181	0.327742	3.051181	997.4243	0	392.9071			5/8/2020
30		5/4/2020 7	0.47	17.58	2.296588	0.435429	0.918635	667.4635	0	269.48			4/29/2020	0.47	19.9	3.346457	0.298824	3.116798	892.8521	0	336.0524			5/8/2020
31		5/4/2020 7	0.48	17.65	2.362205	0.423333	0.984252	715.1809	0	250.7702			4/29/2020	0.48	20.03	3.543307	0.282222	3.149606	924.6153	0	384.0598			5/8/2020
32		5/4/2020 7	0.5	17.62	2.427822	0.411892	1.01706	713.0053	0	259.6175			4/29/2020	0.5	20.13	3.510499	0.28486	3.215223	897.0582	0	345.0447			5/8/2020
33		5/4/2020 7	0.52	17.62	2.427822	0.411892	1.049869	696.326	0	251.0603			4/29/2020	0.52	20.2	3.47769	0.287547	3.28084	924.9054	0	323.4341			5/8/2020
34		5/4/2020 7	0.53	17.66	2.46063	0.4064	1.115486	698.7916	0	253.816			4/29/2020	0.53	20.17	3.444882	0.290286	3.346457	755.6464	0	136.6255			5/8/2020
35		5/4/2020 7	0.55	17.66	2.559055	0.390769	1.148294	712.4252	0	254.2511			4/29/2020	0.55	20.17	3.444882	0.290286	3.412074	918.2337	0	411.472			5/8/2020
36		5/4/2020 7	0.57	17.81	2.559055	0.390769	1.181102	703.1428	0	257.877			4/29/2020	0.57	20.2	3.47769	0.287547	3.444882	864.7148	0	372.6019			5/8/2020
37		5/4/2020 7	0.58	17.82	2.526247	0.395844	1.213911	693.7153	0	252.2206			4/29/2020	0.58	20.2	3.47769	0.287547	3.510499	859.6384	0	322.4188			5/8/2020
38		5/4/2020 7	0.6	17.84	2.559055	0.390769	1.279528	710.1046	0	263.8236			4/29/2020	0.6	20.13	3.47769	0.287547	3.576116	893.5773	0	376.0828			5/8/2020

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

Display Settings 100%

AME Pile Info

- Based on pile selected (discussed later) it will automatically import the data into the Pile Info tab
  - Can scroll through organized raw data for pile selected
- Pile info tab also allows depth referenced data to be dropped into the spreadsheet for analysis

	A	B	C	D	E	F	G	H	I	J
1			Time	Duration (min)	Depth (ft)	Rotational Speed (RPM)	Penetration Rate (ft/min)	Torque Pressure (psi)	Crowd Pressure (psi)	
2	Input		3/25/2020 10:19:59 PM	0.00	0.00	0.0	0.00	132	-355	
3	Engineer		3/25/2020 10:20:00 PM	0.02	0.00	0.0	0.00	129	-369	
4	Michael Rodgers		3/25/2020 10:20:01 PM	0.03	0.00	0.0	0.00	114	-357	
5	Location		3/25/2020 10:20:02 PM	0.05	0.00	0.0	0.00	117	-367	
6	Miami, Florida		3/25/2020 10:20:03 PM	0.07	0.00	0.0	0.00	90	-373	
7	Project		3/25/2020 10:20:04 PM	0.08	0.00	0.0	0.00	127	-372	
8	ACIP MWD		3/25/2020 10:20:05 PM	0.10	0.00	0.0	0.00	134	-368	
9	Drill Bit Diameter (in)		3/25/2020 10:20:06 PM	0.12	0.00	0.0	0.00	116	-352	
10	30.0		3/25/2020 10:20:07 PM	0.13	0.00	0.0	0.00	135	-343	
11			3/25/2020 10:20:08 PM	0.15	0.00	0.0	0.00	123	-338	
12	Do Not Input		3/25/2020 10:20:09 PM	0.17	0.00	0.0	0.00	141	-343	
13	Pile ID		3/25/2020 10:20:10 PM	0.18	0.00	0.0	0.00	115	-355	
14	Sample Data Set		3/25/2020 10:20:11 PM	0.20	0.00	0.0	0.00	129	-368	
15	Top of Pile Elevation (ft)		3/25/2020 10:20:12 PM	0.22	0.00	0.0	0.00	1,681	-364	
16	10.74		3/25/2020 10:20:13 PM	0.23	0.00	0.0	0.00	954	-366	
17	Station		3/25/2020 10:20:14 PM	0.25	0.00	0.0	0.00	1,034	-355	
18	100+00.01		3/25/2020 10:20:15 PM	0.27	0.00	1.2	0.00	1,467	-347	
19	Offset (ft)		3/25/2020 10:20:16 PM	0.28	0.00	12.0	0.00	1,222	-349	
20	10		3/25/2020 10:20:17 PM	0.30	0.00	12.0	0.00	1,286	-358	
21	Pile Length (ft)		3/25/2020 10:20:18 PM	0.32	0.00	15.6	0.00	1,592	-375	
22	134.48		3/25/2020 10:20:19 PM	0.33	0.00	24.0	0.00	1,471	-369	
23	Pile Length (in)		3/25/2020 10:20:20 PM	0.35	0.00	25.2	0.03	1,733	-352	
24	1,613.78		3/25/2020 10:20:21 PM	0.37	0.03	24.0	0.46	1,565	-346	
25	Area of Excavation (ft^2)		3/25/2020 10:20:22 PM	0.38	0.10	28.8	1.84	1,641	-312	
26	4.91		3/25/2020 10:20:23 PM	0.40	0.16	32.4	3.12	1,628	-292	
27	Area of Excavation (in^2)		3/25/2020 10:20:24 PM	0.42	0.20	31.2	3.44	1,760	-260	
28	706.86		3/25/2020 10:20:25 PM	0.43	0.26	33.6	3.54	1,560	-272	
29			3/25/2020 10:20:26 PM	0.45	0.36	32.4	3.87	1,767	-276	
30			3/25/2020 10:20:27 PM	0.47	0.43	31.2	4.23	1,646	-263	
31			3/25/2020 10:20:28 PM	0.48	0.49	34.8	4.53	1,901	-245	

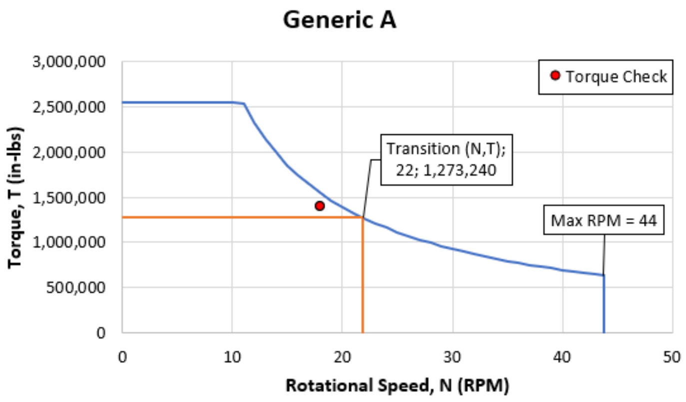
Agreement | AME Pile Info | Enter AME Pile Data | Enter Drill Rig Data | Strength Analysis | Parameters - Layer | Parameters - Threshold | Pile Summary Report | GS-Deep

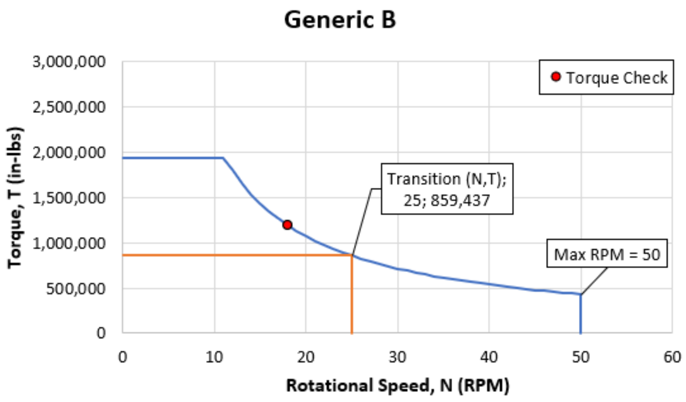
Enter Drill Rig Data

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	Generic A	5,000	10.00	5.00	35,000	160.0	80.0	2	2
2	Generic B	4,500	9.00	4.00	30,000	150.0	75.0	2	

Crowd Specifications		
Specifications	Drill Rig 1	Drill Rig 2
F_{Max} (lbf)	78,683	89,924
OP_{Max} (psi)	5,000	4,500
Baseline Pressure, BP (psi)	0	0
Crowd Conversion Coefficient, K_F (lbf/psi)	15.74	19.98

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	1,273,240	2,546,479	18	4,500	18	4,500
	2	22	44	636,620	1,273,240	T (in-lbf)	T (ft-lbf)	T (in-lbf)	T (ft-lbf)
2	1	11	25	859,437	1,933,733	1,392,606	116,050.5	1,193,662	99,471.8
	2	22	50	429,718	966,866				





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

Strength Analysis Tab – Specific Energy

Pile	Pile Segment	ΔZ Increment (cm)
5	8	1
e Threshold (psi)	e Reduction (psi/ft)	MWD Assessment
0	0.0	ISO Class 1

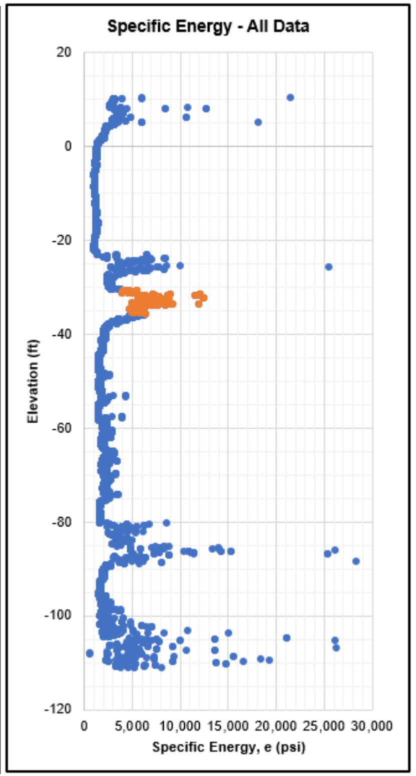
Specific Energy, e (psi) - All Data

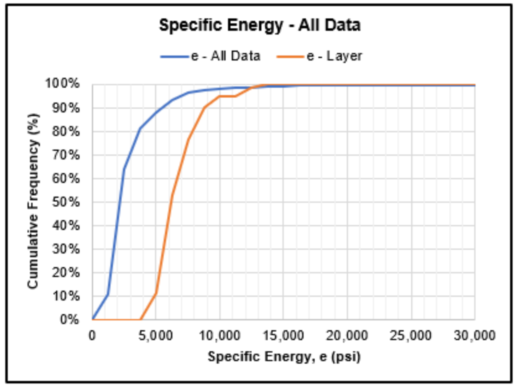
Mean	Median	Standard Deviation	Coefficient of Variation	Maximum	Minimum	Count
3,095	2,134	7,286	2.35	280,309	603	3,702

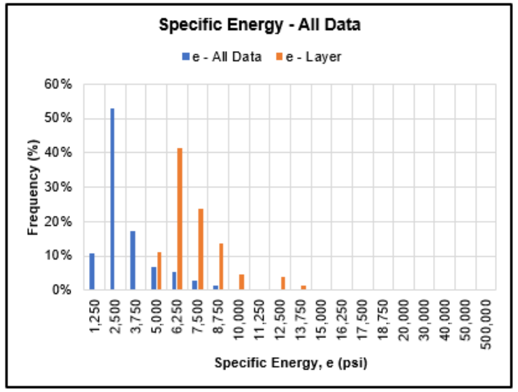
Pile Information

Pile ID	Pile Elevations (ft)		Pile Length (ft)	Layer Elevations (ft)		Drill Bit Diameter (ft)
	Top of Pile	Bottom of Pile		Top	Bottom	
Pile 5	10.29	-111.20	121.49	-30.7	-35.7	2.5

Pile Segments and Elevations			Specific Energy, e (psi) - All Data - Layer Analysis						
Pile Segment	Elevation 1 (ft)	Elevation 2 (ft)	Mean	Median	Std. Dev.	CV	Maximum	Minimum	Count
1	3.60	-0.7	1,812	1,928	355	0.20	2,322	1,329	131
2	-0.7	-5.7	1,267	1,271	64	0.05	1,436	1,104	153
3	-5.70	-10.7	1,128	1,116	38	0.03	1,264	1,072	152
4	-10.7	-15.7	1,263	1,244	55	0.04	1,410	1,184	153
5	-15.70	-20.7	1,271	1,286	118	0.09	1,567	1,108	152
6	-20.7	-25.7	2,996	2,229	2,203	0.74	10,068	1,063	152
7	-25.70	-30.7	3,862	2,903	4,165	1.08	47,387	2,398	153
8	**-30.7**	**-35.7**	**6,586**	**6,033**	**1,784**	**0.27**	**12,529**	**3,947**	**152**
9	-35.70	-40.7	3,213	2,550	1,250	0.39	6,450	2,034	153
10	-40.7	-45.7	1,881	1,951	219	0.12	2,295	1,509	152
11	-45.70	-50.7	1,753	1,652	295	0.17	2,723	1,473	152
12	-50.7	-55.7	1,911	1,790	503	0.26	4,418	1,465	153
13	-55.70	-60.7	1,953	1,857	537	0.27	3,986	1,475	152
14	-60.7	-65.7	2,305	2,242	399	0.17	3,207	1,794	153
15	-65.70	-70.7	2,302	2,244	385	0.17	3,481	1,756	152
16	-70.7	-75.7	2,382	2,323	321	0.13	3,531	1,748	152







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

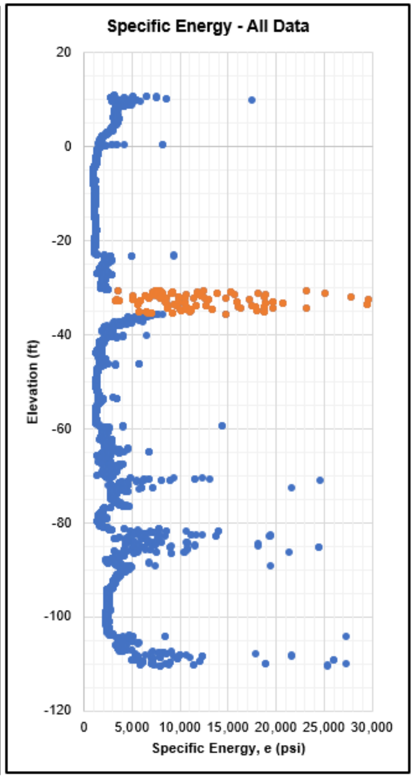
Strength Analysis Tab – Specific Energy

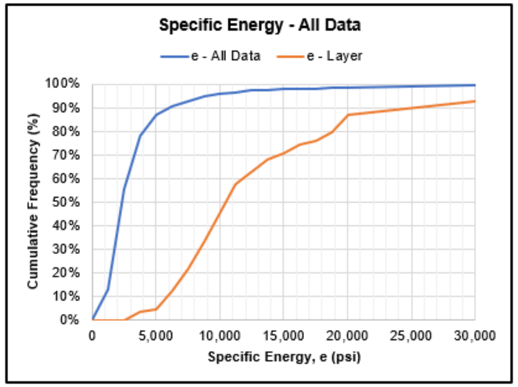
Pile	Pile Segment	ΔZ Increment (cm)
9	8	1
e Threshold (psi)	**e Reduction (psi/ft)**	**MWD Assessment**
0	0.0	ISO Class 1

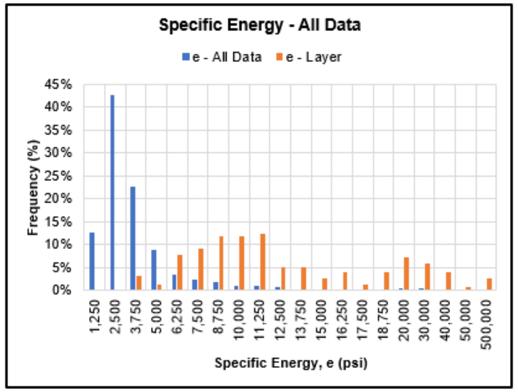
Specific Energy, e (psi) - All Data						
Mean	Median	Standard Deviation	Coefficient of Variation	Maximum	Minimum	Count
3,727	2,376	11,105	2.98	488,901	969	3,699

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	
Pile 9	10.86	-110.63	121.49	-30.7	-35.7	2.5

Pile Segments and Elevations			Specific Energy, e (psi) - All Data - Layer Analysis						
Pile Segment	Elevation 1 (ft)	Elevation 2 (ft)	Mean	Median	Std. Dev.	CV	Maximum	Minimum	Count
1	3.6	-0.7	2,210	1,943	916	0.41	8,251	1,497	131
2	-0.7	-5.7	1,276	1,296	146	0.11	1,509	1,011	152
3	-5.7	-10.7	1,131	1,160	96	0.08	1,264	969	153
4	-10.7	-15.7	1,198	1,195	43	0.04	1,305	1,108	152
5	-15.7	-20.7	1,253	1,258	50	0.04	1,347	1,156	152
6	-20.7	-25.7	1,966	1,963	1,167	0.59	9,420	1,114	153
7	-25.7	-30.7	2,063	2,014	327	0.16	3,558	1,455	152
8	**-30.7**	**-35.7**	**15,797**	**10,541**	**23,714**	**1.50**	**238,445**	**3,295**	**153**
9	-35.7	-40.7	3,950	3,461	1,789	0.45	14,874	1,973	152
10	-40.7	-45.7	1,822	1,803	291	0.16	3,409	1,309	152
11	-45.7	-50.7	1,623	1,398	698	0.43	5,769	1,257	153
12	-50.7	-55.7	1,596	1,492	418	0.26	3,427	1,311	152
13	-55.7	-60.7	1,764	1,309	1,575	0.89	14,407	1,236	153
14	-60.7	-65.7	2,523	2,308	837	0.33	6,814	1,685	152
15	-65.7	-70.7	3,357	2,471	9,269	2.76	116,196	1,432	152
16	-70.7	-75.7	5,047	3,551	6,260	1.24	59,907	2,591	153
Soil	-5.0	-20	1,187	1,202	90	0.08	1,347	969	457





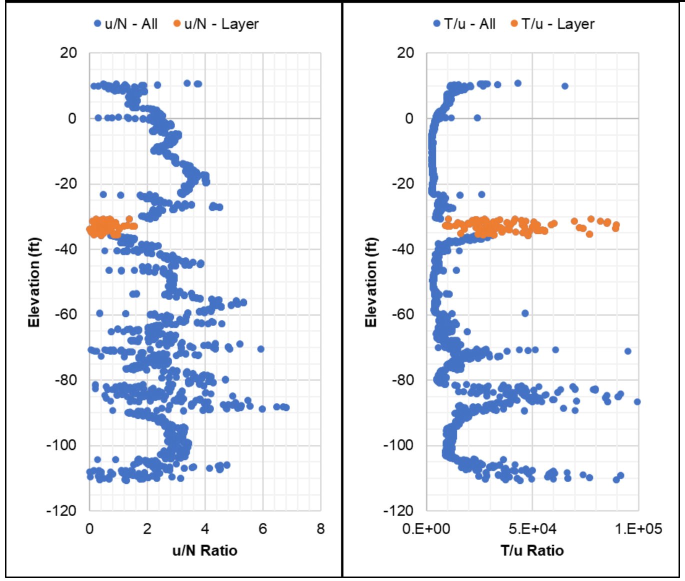


Agreement | AME Pile Info | Enter AME Pile Data | Enter Drill Rig Data | Strength Analysis | Parameters - Layer | Parameters - Threshold | Pile Summary Report | GS-Deep

Parameters – Layer

Rock Layer

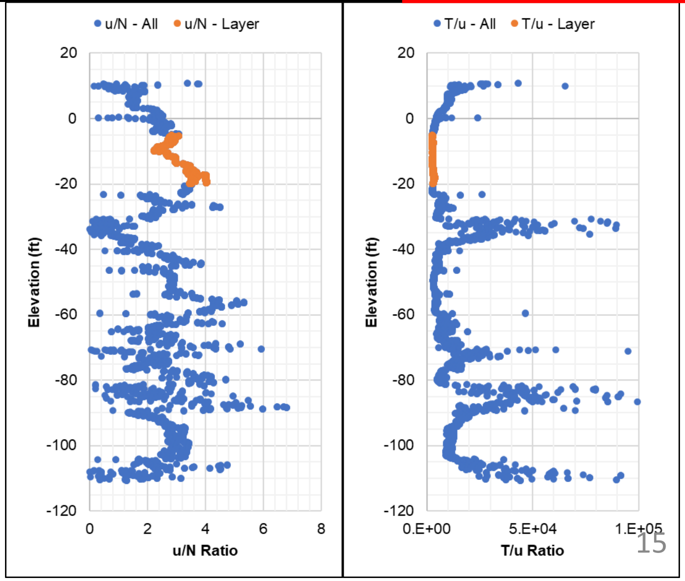
Summary of Statistics - Layer						
Statistics	N (RPM)	T (in-lbs)	u (in/min)	F (lbf)	Compound u/N	Compound T/u
Mean	37.6	605,640	20.4	25,345	0.56	46,852
Median	38.4	583,913	19.3	23,527	0.49	30,684
Stand. Dev.	5.2	99,246	11.4	9,809	0.32	62,421
CV	0.14	0.16	0.56	0.39	0.58	1.33
Maximum	46.8	878,595	56.7	50,508	1.56	604,163
Minimum	25.2	436,783	0.8	1,380	0.02	9,127
Count	153	153	153	153	153	153



Soil Layer

Summary of Statistics - Layer						
Statistics	N (RPM)	T (in-lbs)	u (in/min)	F (lbf)	Compound u/N	Compound T/u
Mean	45.8	405,382	140.8	21,108	3.10	2,857
Median	46.8	381,140	141.7	20,575	2.96	2,761
Stand. Dev.	3.1	83,881	17.2	2,207	0.50	314
CV	0.07	0.21	0.12	0.10	0.16	0.11
Maximum	50.4	580,784	165.4	26,287	4.05	3,872
Minimum	37.2	299,165	111.4	17,663	2.22	2,415
Count	457	457	457	457	457	457

- This information is used to help discern soil/IGM from rock
- Low u/N ratio and high T/u ratio are indicative of rock layering
- High u/N ratio and Low T/u ratio are indicative of soil layering



Strength Analysis – Specific Energy – Above Threshold

Pile	Pile Segment	ΔZ Increment (cm)
9	8	1
e Threshold (psi)	**e Reduction (psi/ft)**	**MWD Assessment**
2,000	0.0	ISO Class 1

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

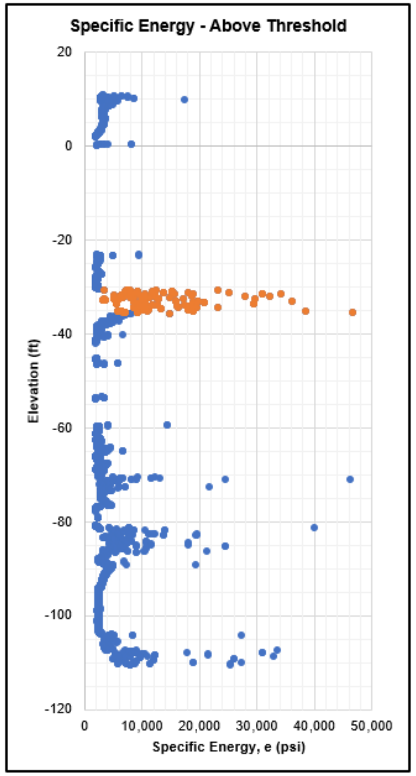
Mean	Median	Standard Deviation	Coefficient of Variation	Maximum	Minimum	Count
5,309	3,195	14,204	2.68	488,901	2,002	2,194

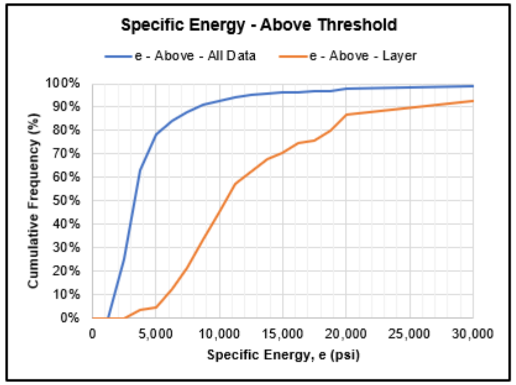
Pile Information

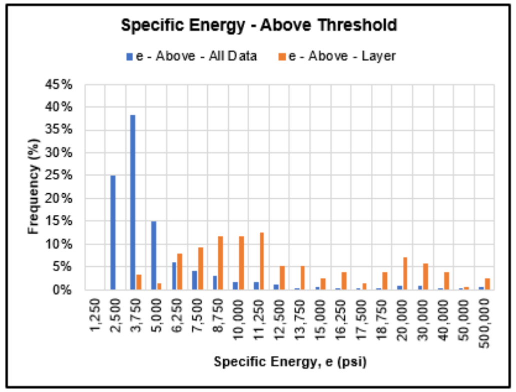
Pile ID	Pile Elevations (ft)		Pile Length (ft)	Layer Elevations (ft)		Drill Bit Diameter (ft)
	Top of Pile	Bottom of Pile		Top	Bottom	
Pile 9	10.86	-110.63	121.49	-30.70	-35.70	2.50

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

Pile Segment	Elevation 1 (ft)	Elevation 2 (ft)	Mean	Median	Std. Dev.	CV	Maximum	Minimum	Count
1	3.6	-0.7	2,786	2,527	1,115	0.40	8,251	2,026	59
2	-0.7	-5.7	0	0	0	0.00	0	0	0
3	-5.7	-10.7	0	0	0	0.00	0	0	0
4	-10.7	-15.7	0	0	0	0.00	0	0	0
5	-15.7	-20.7	0	0	0	0.00	0	0	0
6	-20.7	-25.7	2,779	2,458	1,266	0.46	9,420	2,101	72
7	-25.7	-30.7	2,289	2,292	295	0.13	3,558	2,014	77
8	**-30.7**	**-35.7**	**15,797**	**10,541**	**23,714**	**1.50**	**238,445**	**3,295**	**153**
9	-35.7	-40.7	3,990	3,558	1,785	0.45	14,874	2,162	149
10	-40.7	-45.7	2,201	2,133	240	0.11	3,409	2,015	38
11	-45.7	-50.7	3,548	3,388	1,425	0.40	5,769	2,179	12
12	-50.7	-55.7	2,741	3,111	678	0.25	3,427	2,047	13
13	-55.7	-60.7	3,498	2,487	3,078	0.88	14,407	2,192	29
14	-60.7	-65.7	2,689	2,401	862	0.32	6,814	2,013	121
15	-65.7	-70.7	3,717	2,567	10,279	2.77	116,196	2,015	123
16	-70.7	-75.7	5,047	3,551	6,260	1.24	59,907	2,591	153
Soil	-5.0	-20	0	0	0	0.00	0	0	0





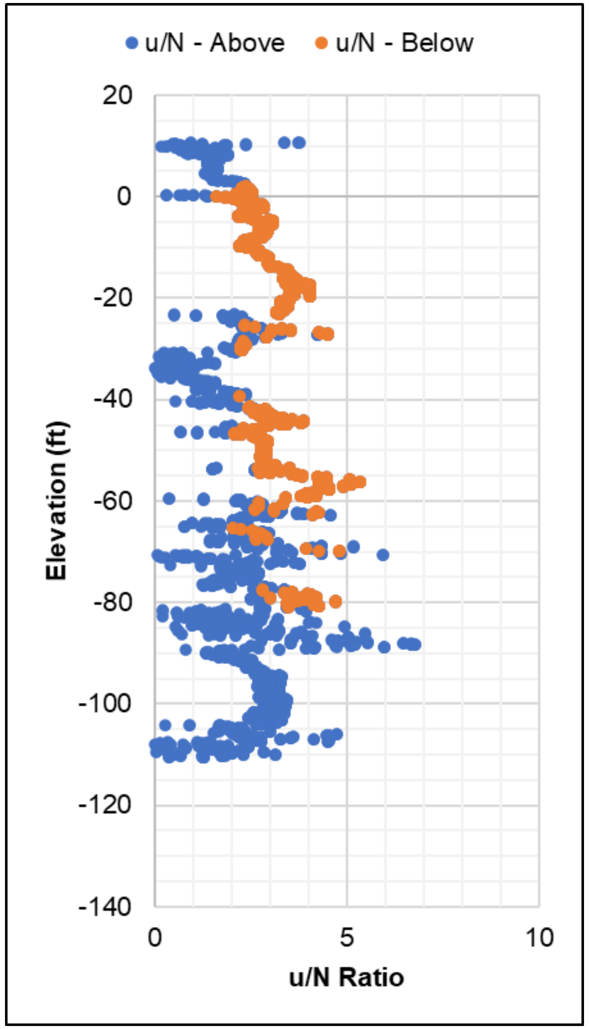


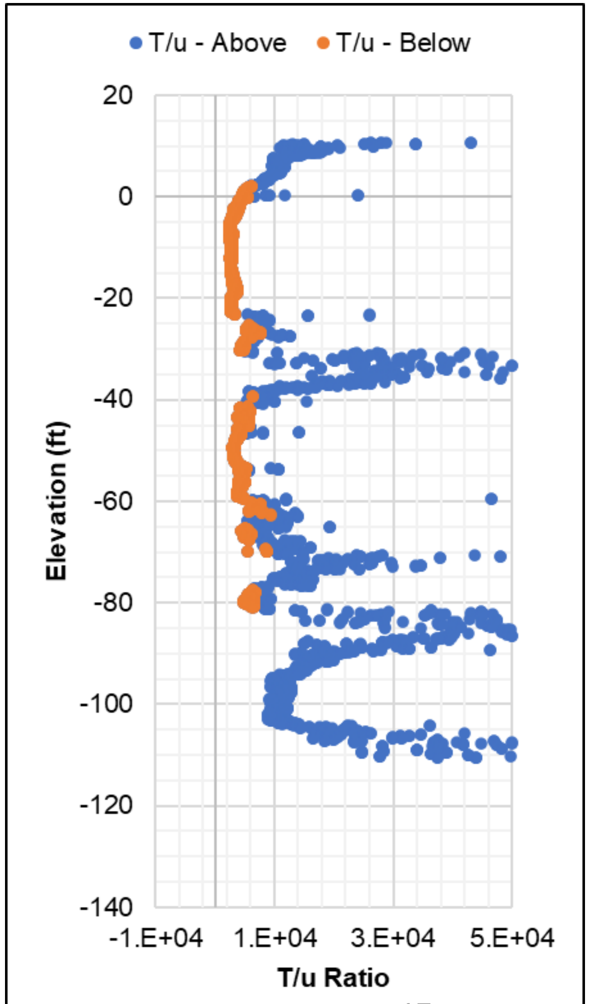
Agreement | AME Pile Info | Enter AME Pile Data | Enter Drill Rig Data | **Strength Analysis** | Parameters - Layer | Parameters - Threshold | Pile Summary Report | GS-Deep

Parameters – Threshold

Summary of Statistics - Above Specific Energy Threshold						
Statistics	N (RPM)	T (in-lbs)	u (in/min)	F (lbf)	Compound u/N	Compound T/u
Mean	29.1	859,247	58.7	9,837	2.18	24,699
Median	28.8	771,657	57.5	8,912	2.14	12,660
Stand. Dev.	8.7	381,776	24.2	13,988	1.05	76,760
CV	0.30	0.44	0.41	1.42	0.48	3.11
Maximum	48.0	2,675,698	110.6	58,724	6.79	2,291,507
Minimum	1.2	293,652	0.4	-27,167	0.02	4,812
Count	2,194	2,194	2,194	2,194	2,194	2,194

Summary of Statistics - Below Specific Energy Threshold						
Statistics	N (RPM)	T (in-lbs)	u (in/min)	F (lbf)	Compound u/N	Compound T/u
Mean	41.5	488,242	127.5	17,561	3.13	3,946
Median	43.2	463,630	126.0	18,928	2.95	3,639
Stand. Dev.	6.1	127,655	22.3	6,576	0.66	1,270
CV	0.15	0.26	0.17	0.37	0.21	0.32
Maximum	50.4	1,060,084	165.4	54,495	5.33	9,308
Minimum	22.8	293,630	63.0	-1,816	1.59	2,415
Count	1,505	1,505	1,505	1,505	1,505	1,505





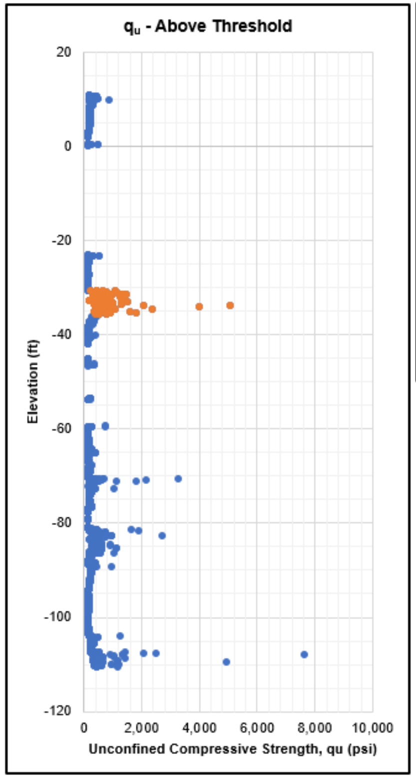
Strength Analysis – Unconfined Compressive Strength

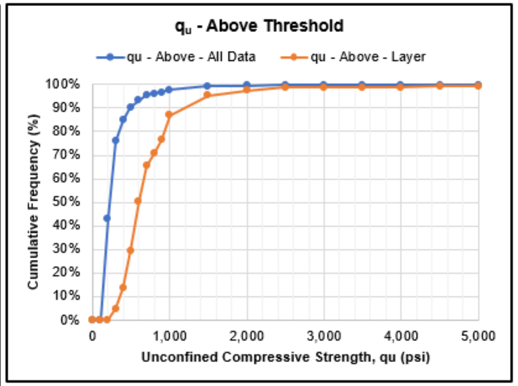
Pile	Pile Segment	ΔZ Increment (cm)
9	8	1
e Threshold (psi)	e Reduction (psi/ft)	MWD Assessment
2,000	0.0	ISO Class 1

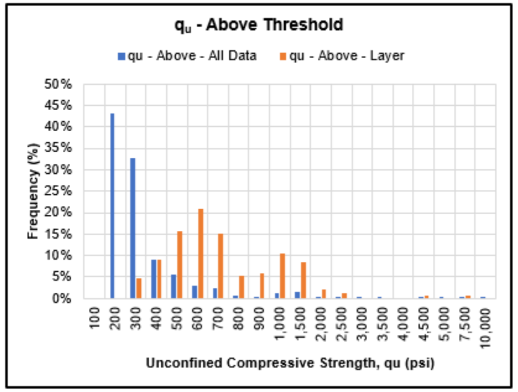
Unconfined Compressive Strength, q_u (psi) - Above Threshold - Entire Pile						
Mean	Median	Standard Deviation	Coefficient of Variation	Maximum	Minimum	Count
295	212	327	1.11	7,632	137	2,194

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	
Pile 9	10.86	-110.63	121.49	-30.70	-35.70	2.50

Pile Segments and Elevations			Unconfined Compressive Strength, q_u (psi) - Above Threshold - Layer Analysis						
Pile Segment	Elevation 1 (ft)	Elevation 2 (ft)	Mean	Median	Std. Dev.	CV	Maximum	Minimum	Count
1	3.6	-0.7	185	171	63	0.34	488	139	59
2	-0.7	-5.7	0	0	0	0.00	0	0	0
3	-5.7	-10.7	0	0	0	0.00	0	0	0
4	-10.7	-15.7	0	0	0	0.00	0	0	0
5	-15.7	-20.7	0	0	0	0.00	0	0	0
6	-20.7	-25.7	184	166	70	0.38	545	144	72
7	-25.7	-30.7	156	156	19	0.12	234	138	77
8	**-30.7**	**-35.7**	**739**	**598**	**564**	**0.76**	**5,063**	**218**	**153**
9	-35.7	-40.7	255	234	99	0.39	788	148	149
10	-40.7	-45.7	150	146	15	0.10	225	138	38
11	-45.7	-50.7	231	224	83	0.36	359	149	12
12	-50.7	-55.7	183	207	42	0.23	226	140	13
13	-55.7	-60.7	221	168	156	0.71	768	149	29
14	-60.7	-65.7	180	163	51	0.28	415	138	121
15	-65.7	-70.7	211	173	285	1.35	3,286	138	123
16	-70.7	-75.7	299	233	237	0.79	2,150	175	153
Soil	-5.0	-20	0	0	0	0.00	0	0	0







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

*Uses drilled shaft rock auger equation developed in Rodgers et al. (2018a, b) to estimate qu

Strength Analysis – Side Shear and Shaft Capacity

Pile	Pile Segment	ΔZ Increment (cm)
9	8	1
e Threshold (psi)	e Reduction (psi/ft)	MWD Assessment
2,000	0.0	ISO Class 1

Side Shear and Shaft Capacity - Above Threshold - Entire Pile

e (psi)	qu (psi)	f_s (ksf)	L_{pile} (ft)	L_{rock} (ft)	P (kips)	*f_s (ksf)
5,309	295	8.3	121.5	72.0	4,719	4.9

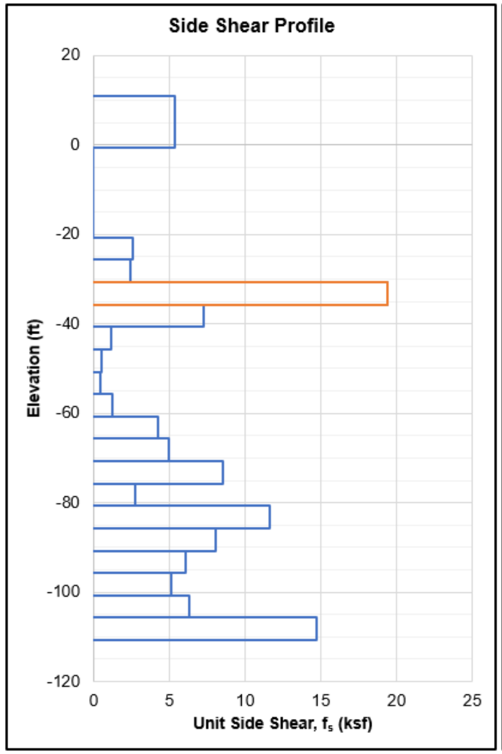
Pile Information

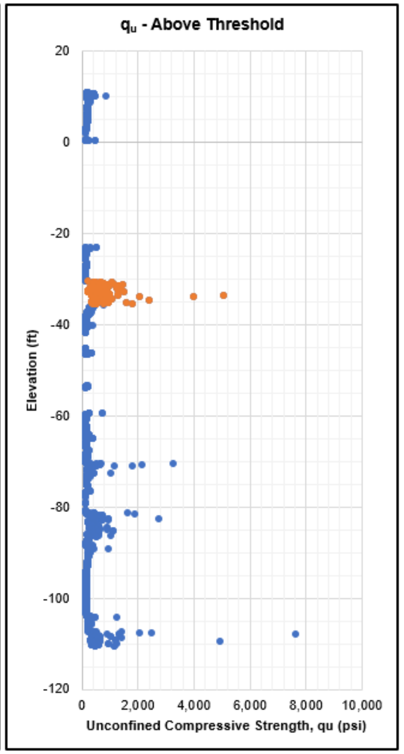
Pile ID	Pile Elevations (ft) Top of Pile	Pile Elevations (ft) Bottom of Pile	Pile Length (ft)	Layer Elevations (ft) Top	Layer Elevations (ft) Bottom	Drill Bit Diameter (ft)
Pile 9	10.86	-110.63	121.49	-30.70	-35.70	2.50

Pile Segments and Elevations / Side Shear and Shaft Capacity - Above Threshold - Layer Analysis

Pile Segment	Elevation 1 (ft)	Elevation 2 (ft)	Count	e_{AVG} (psi)	$q_{u\text{-}AVG}$ (psi)	$f_{s\text{-}AVG}$ (ksf)	L_{rock} (ft)	P (kips)	*f_s (ksf)
1	10.9	-0.7	278	3,555	232	6.8	9.1	488.4	5.4
2	-0.7	-5.7	0	0	0	0.0	0.0	0.0	0.0
3	-5.7	-10.7	0	0	0	0.0	0.0	0.0	0.0
4	-10.7	-15.7	0	0	0	0.0	0.0	0.0	0.0
5	-15.7	-20.7	0	0	0	0.0	0.0	0.0	0.0
6	-20.7	-25.7	72	2,779	184	5.5	2.4	102.6	2.6
7	-25.7	-30.7	77	2,290	156	4.8	2.5	94.3	2.4
8	**-30.7**	**-35.7**	**153**	**15,798**	**739**	**19.4**	**5.0**	**766.2**	**19.4**
9	-35.7	-40.7	149	3,991	256	7.4	4.9	285.6	7.3
10	-40.7	-45.7	38	2,202	150	4.6	1.2	45.0	1.1
11	-45.7	-50.7	12	3,549	231	6.8	0.4	21.0	0.5
12	-50.7	-55.7	13	2,742	183	5.5	0.4	18.5	0.5
13	-55.7	-60.7	29	3,498	221	6.5	1.0	48.3	1.2
14	-60.7	-65.7	121	2,689	180	5.4	4.0	168.7	4.3
15	-65.7	-70.7	123	3,718	211	6.2	4.0	195.4	5.0
16	-70.7	-75.7	153	5,047	299	8.5	5.0	335.9	8.5
17	-75.7	-80.7	71	3,008	199	5.9	2.3	108.7	2.8
18	-80.7	-85.7	145	8,033	444	12.2	4.8	456.3	11.6
19	-85.7	-90.7	152	4,428	279	8.1	5.0	315.6	8.0
20	-90.7	-95.7	152	3,080	205	6.1	5.0	239.0	6.1
21	-95.7	-100.7	153	2,510	170	5.1	5.0	202.9	5.1
22	-100.7	-105.7	152	3,311	215	6.3	5.0	248.4	6.3
23	-105.7	-110.7	151	13,552	560	14.9	5.0	578.1	14.7

*fs = Adjusted side shear based on cumulative length of rock socket





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

*Uses drilled shaft side shear equation developed in Rodgers et al. (2019) to estimate f_s

Strength Analysis – Side Shear and Shaft Capacity

Pile	Pile Segment	ΔZ Increment (cm)
9	Upper	1
e Threshold (psi)	e Reduction (psi/ft)	MWD Assessment
2,000	0.0	ISO Class 1

Side Shear and Shaft Capacity - Above Threshold - Entire Pile

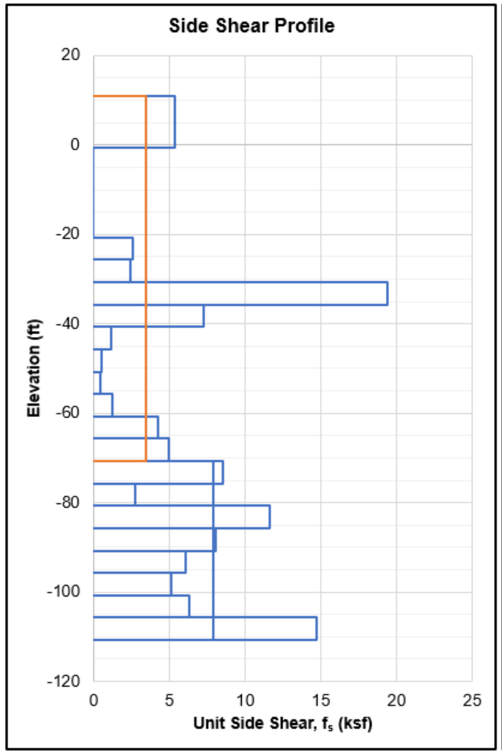
e (psi)	qu (psi)	f_s (ksf)	L_{pile} (ft)	L_{rock} (ft)	P (kips)	*f_s (ksf)
5,309	295	8.3	121.5	72.0	4,719	4.9

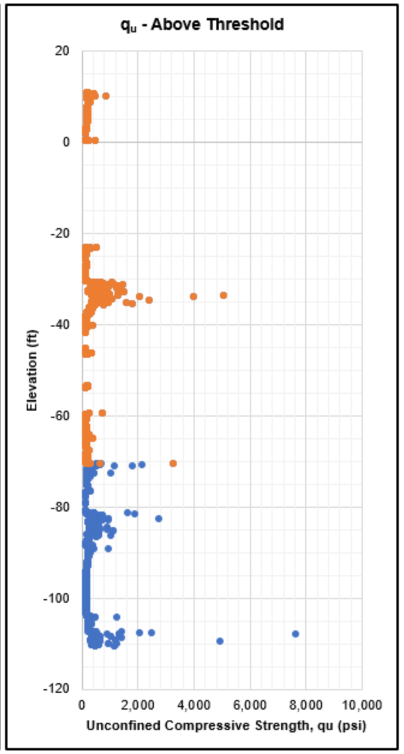
Pile Information

Pile ID	Pile Elevations (ft)		Pile Length (ft)	Layer Elevations (ft)		Drill Bit Diameter (ft)
	Top of Pile	Bottom of Pile		Top	Bottom	
Pile 9	10.86	-110.63	121.49	10.86	-70.70	2.50

Pile Segments and Elevations			Side Shear and Shaft Capacity - Above Threshold - Layer Analysis						
Pile Segment	Elevation 1 (ft)	Elevation 2 (ft)	Count	e_{AVG} (psi)	$q_{u\text{-}AVG}$ (psi)	$f_{s\text{-}AVG}$ (ksf)	L_{rock} (ft)	P (kips)	*f_s (ksf)
1	10.9	-0.7	278	3,555	232	6.8	9.1	488.4	5.4
2	-0.7	-5.7	0	0	0	0.0	0.0	0.0	0.0
3	-5.7	-10.7	0	0	0	0.0	0.0	0.0	0.0
4	-10.7	-15.7	0	0	0	0.0	0.0	0.0	0.0
5	-15.7	-20.7	0	0	0	0.0	0.0	0.0	0.0
6	-20.7	-25.7	72	2,779	184	5.5	2.4	102.6	2.6
7	-25.7	-30.7	77	2,290	156	4.8	2.5	94.3	2.4
8	-30.7	-35.7	153	15,798	739	19.4	5.0	766.2	19.4
9	-35.7	-40.7	149	3,991	256	7.4	4.9	285.6	7.3
10	-40.7	-45.7	38	2,202	150	4.6	1.2	45.0	1.1
11	-45.7	-50.7	12	3,549	231	6.8	0.4	21.0	0.5
12	-50.7	-55.7	13	2,742	183	5.5	0.4	18.5	0.5
13	-55.7	-60.7	29	3,498	221	6.5	1.0	48.3	1.2
14	-60.7	-65.7	121	2,689	180	5.4	4.0	168.7	4.3
15	-65.7	-70.7	123	3,718	211	6.2	4.0	195.4	5.0
16	-70.7	-75.7	153	5,047	299	8.5	5.0	335.9	8.5
17	-75.7	-80.7	71	3,008	199	5.9	2.3	108.7	2.8
18	-80.7	-85.7	145	8,033	444	12.2	4.8	456.3	11.6
19	-85.7	-90.7	152	4,428	279	8.1	5.0	315.6	8.0
20	-90.7	-95.7	152	3,080	205	6.1	5.0	239.0	6.1
21	-95.7	-100.7	153	2,510	170	5.1	5.0	202.9	5.1
22	-100.7	-105.7	152	3,311	215	6.3	5.0	248.4	6.3
23	-105.7	-110.7	151	13,552	560	14.9	5.0	578.1	14.7
Upper	**10.9**	**-70.7**	**1,065**	**5,092**	**287**	**8.1**	**34.9**	**2,234.0**	**3.5**
Lower	-70.7	-110.70	1,129	5,514	302	8.5	37.0	2,484.9	7.9

*fs = Adjusted side shear based on cumulative length of rock socket





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

Pile Summary Report

- Project
- Location
- Engineer
- Pile ID
- Station
- Offset
- Top and bottom Pile Elevation
- Drill Rig Identification
- Pile Diameter
- Pile Length
- Depth Increment Analyzed
- ISO-MWD Assessment Class
- Specific Energy Above the e Threshold Statistics
  - Specific energy threshold, mean, median, standard deviation, CV, maximum, minimum, and number of data points
- Unconfined Compression Strength Above e Threshold Statistics
  - qu threshold, mean, median, standard deviation, CV, maximum, minimum, and number of data points
- ACIP Pile Capacity QA/QC
  - Pile length, total rock socket length, AVG pile side shear, unfactored pile capacity, factored pile capacity, factored design load, C/D ratio, design requirement inspection
- Pile Installation Summary
  - Time spent drilling, redrilling time, idle rotation time, idle time, withdrawal time, penetration without rotation time, total time, drilling efficiency (i.e., drilling time / total time x 100%)
- Strength Profile (discussed later)
- Drilling Profile (discussed later)

ACIP Pile - MWD Summary Report

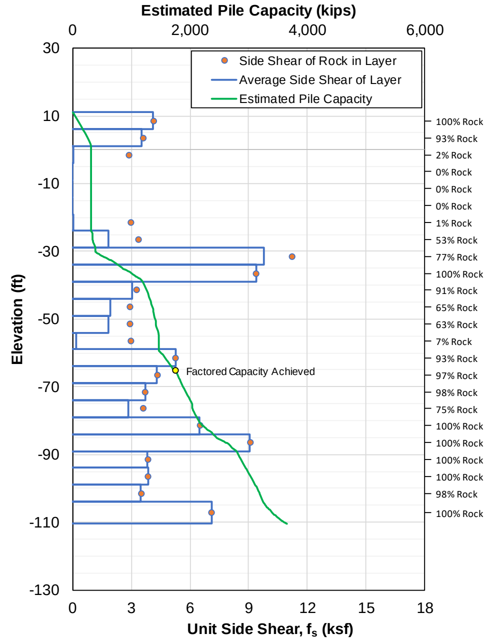
Project	Location	Engineer	Pile ID
UF ACIP MWD	Miami, Florida	Rodgers, McVay, Kelch	Pile Group C - Pile 1
Station	**Offset (ft)**	**Drill Rig**	**Drill Bit Diameter (in)**
100+00.01	10.00	Large Drill Rig	30
Top of Pile Elevation (ft)	**Bottom of Pile Elevation (ft)**	**Depth Increment Analyzed (cm)**	**ISO-MWD Assessment**
11.01	-110.48	1	Class 1

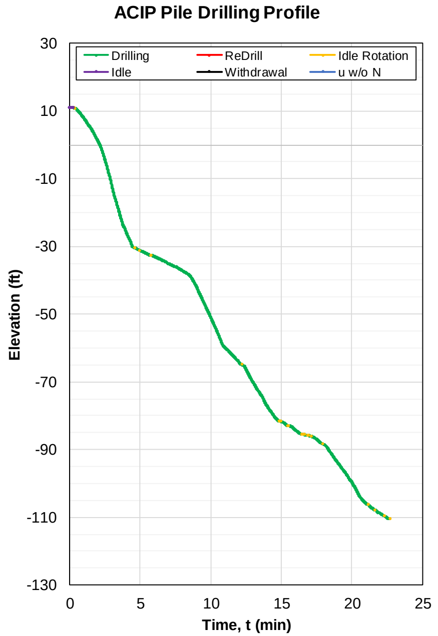
Specific Energy Above Threshold, e (psi)	
Specific Energy Threshold (psi)	1,250
Mean	3,131
Median	1,931
Standard Deviation	5,092
Coefficient of Variation (CV)	1.63
Maximum	124,766
Minimum	1,250
Number of Data Points	2,502

ACIP Pile Capacity QA/QC	
Pile Length (ft)	121.49
Total Rock Socket Length (ft)	82.1
Average Pile Side Shear, f_s (ksf)	3.83
Unfactored Pile Capacity (kips)	3,652
Factored Pile Capacity (kips)	2,191
Factored Design Load (kips)	1,050
C/D Ratio for LRFD Φ = 0.6	2.09
Design Requirement Inspection	**Passed**

Unconfined Compressive Strength Above Threshold, q_u (psi)	
q_u Threshold (psi)	88
Mean	193
Median	133
Standard Deviation	194
Coefficient of Variation (CV)	1.01
Maximum	3,433
Minimum	88
Number of Data Points	2,502

Pile Installation Summary	
Drilling Time (min)	21.8
ReDrill Time (min)	0.0
Idle Rotation Time (min)	0.7
Idle Time (min)	0.3
Withdrawal Time (min)	0.0
Penetration w/o Rotation Time (min)	0.0
Total Time (min)	22.8
Drilling Efficiency (%)	96%





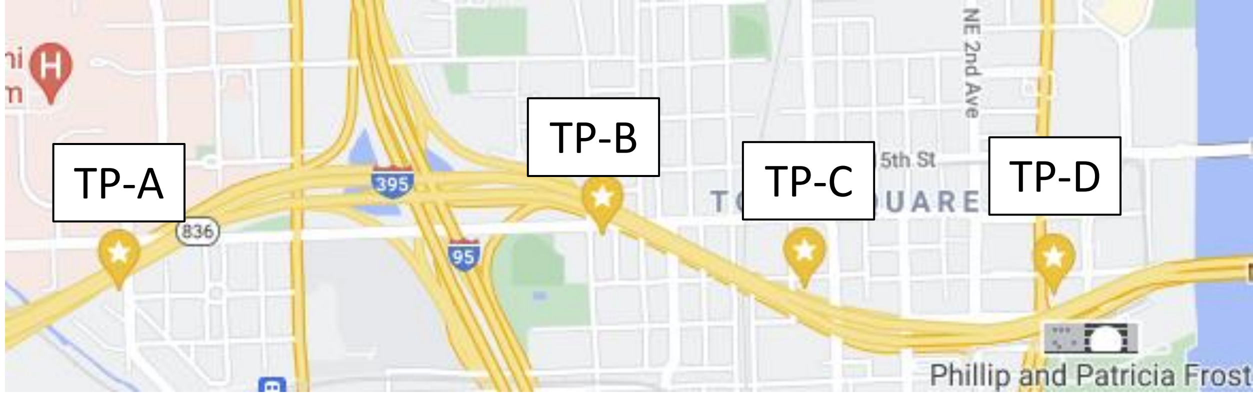
GeoStat Analyses

- Automatically populates rock strength data for Geostat Analyses

	A	B	C	D	E	F	G	H	I	J	K	L	M
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.

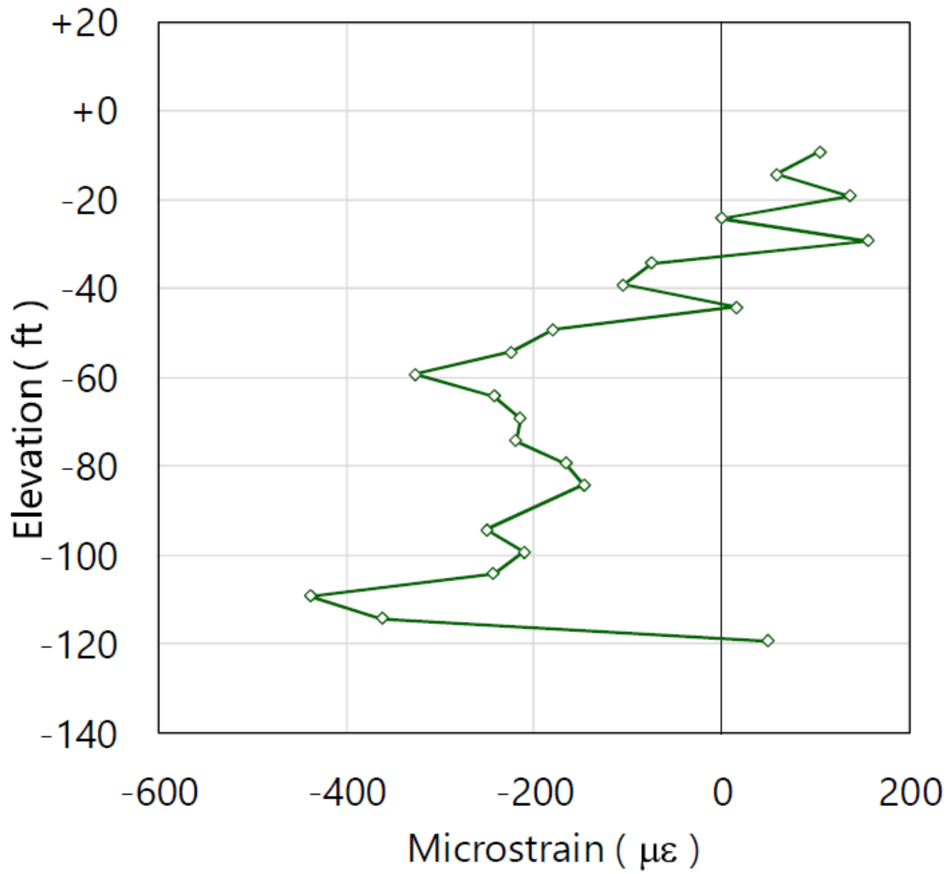
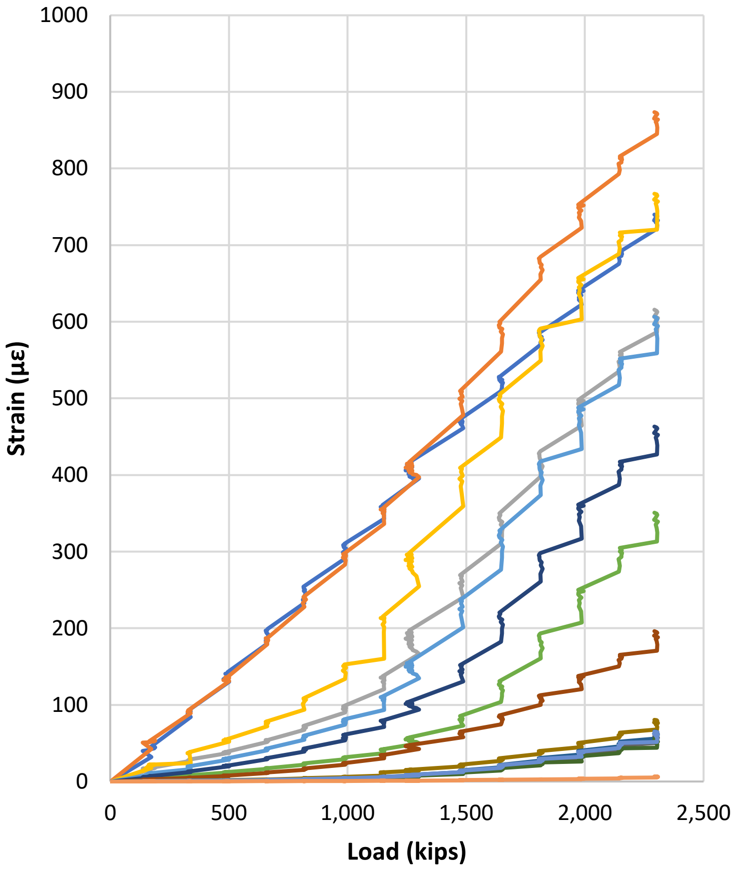
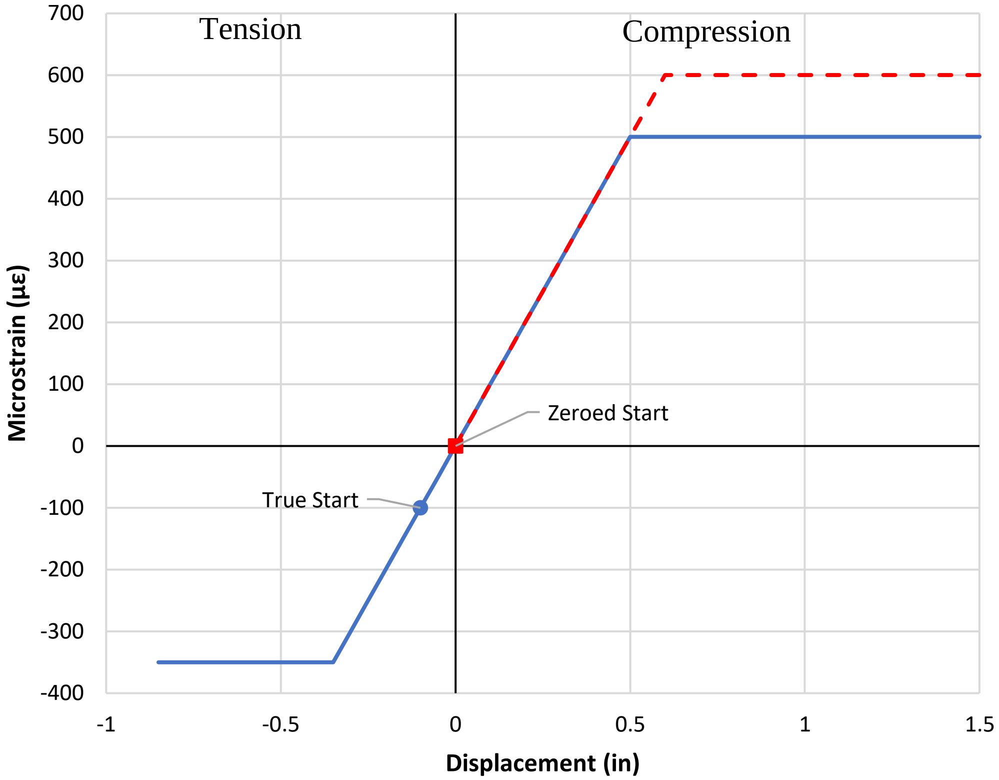


Figure 5: Strain change between installation and start of test (curing strain)

Residual Stresses Present in ACIP Piles

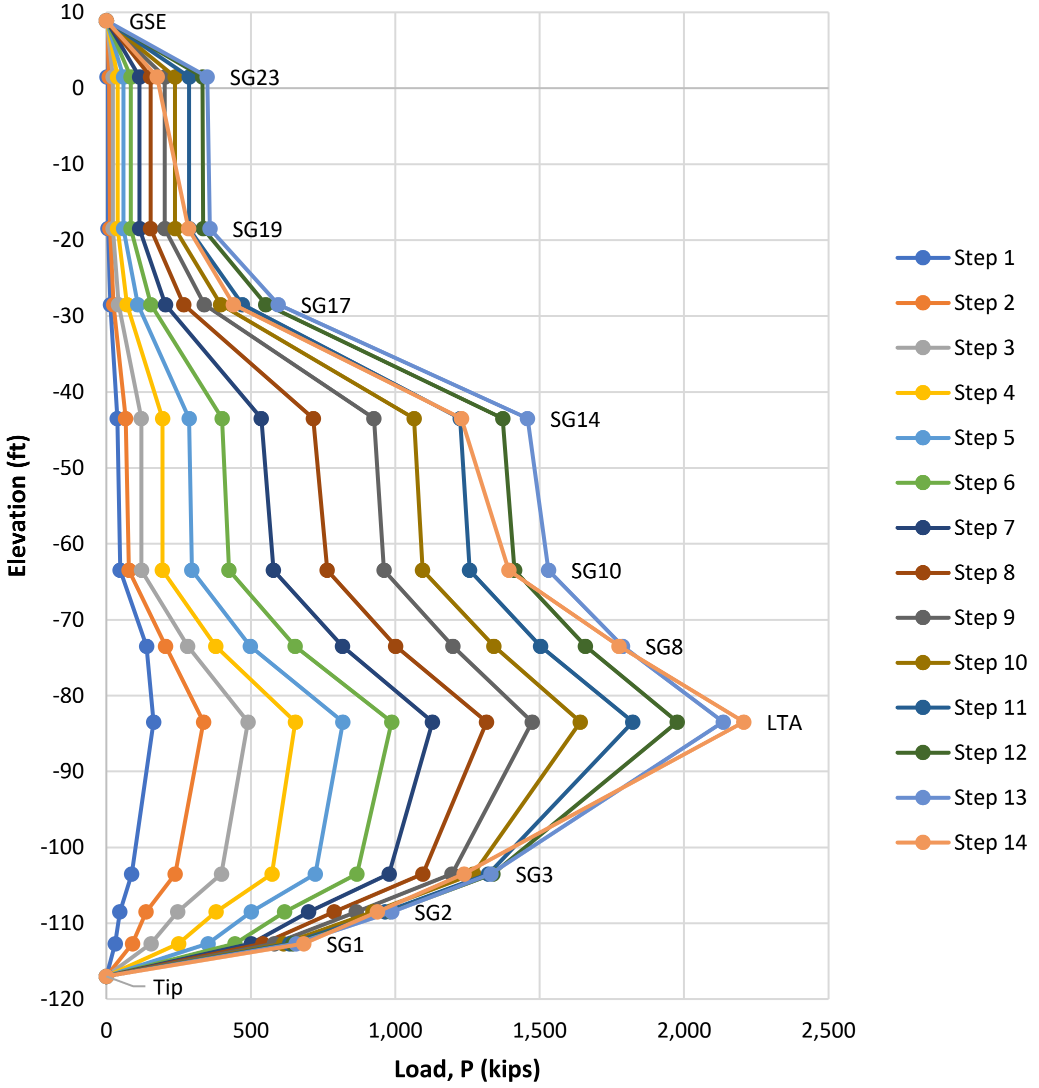


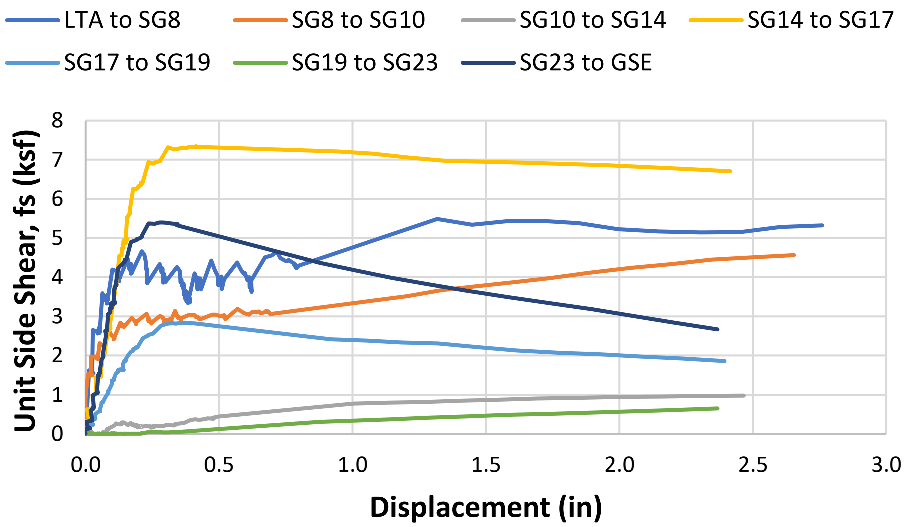
Strain Gauge Level	Maximum Strain (με)
7	873.6
9	767.0
6	739.8
8	615.8
10	606.3
12	463.2
11	350.9
13	196.0
15	80.5
18	65.6
16	65.0
14	60.9
17	55.9
19	6.6

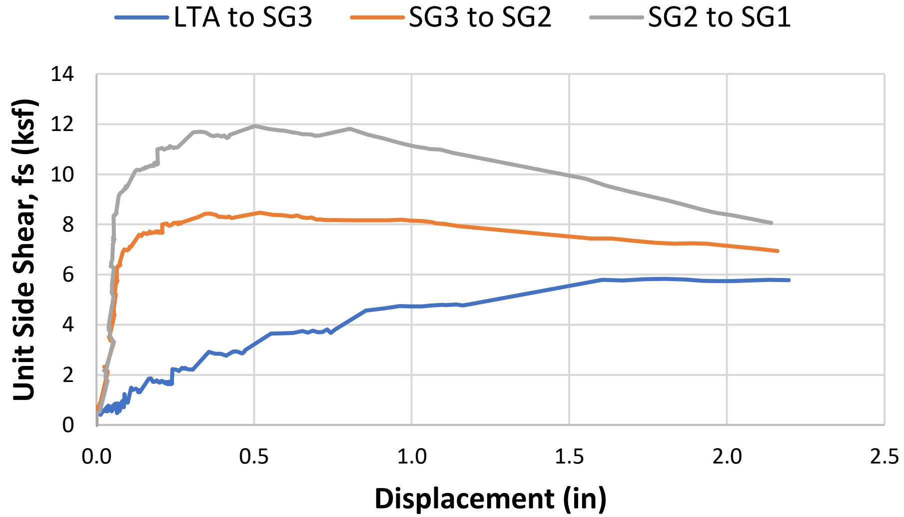


***This effects the layering and T-Z curves generated which need to be accurate in order to build correlation with MWD**

Load Tests Reanalyzed in Larger Layers





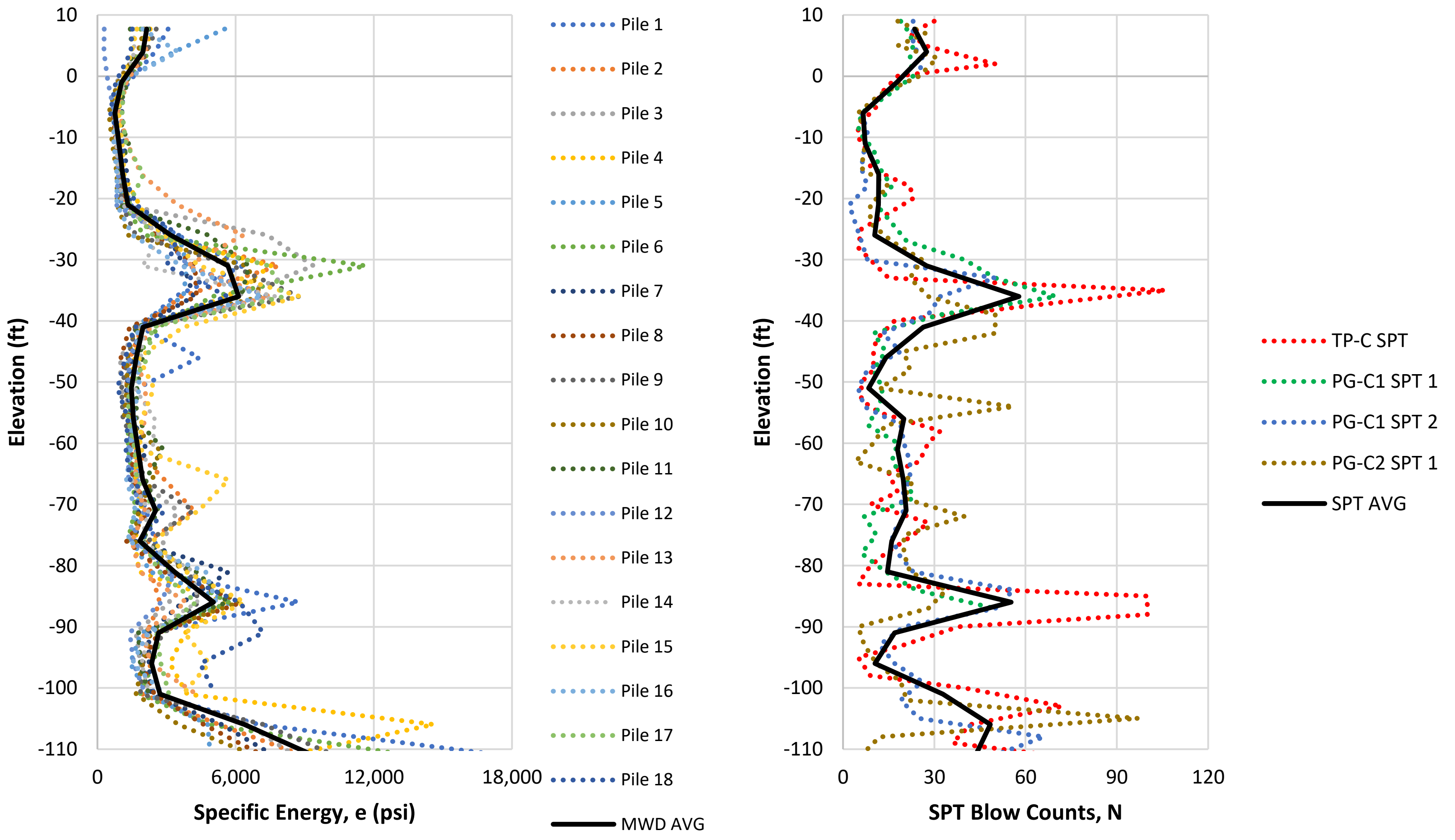


- **Load test report included all raw data which allowed UF to reanalyze the load test in larger layers**

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

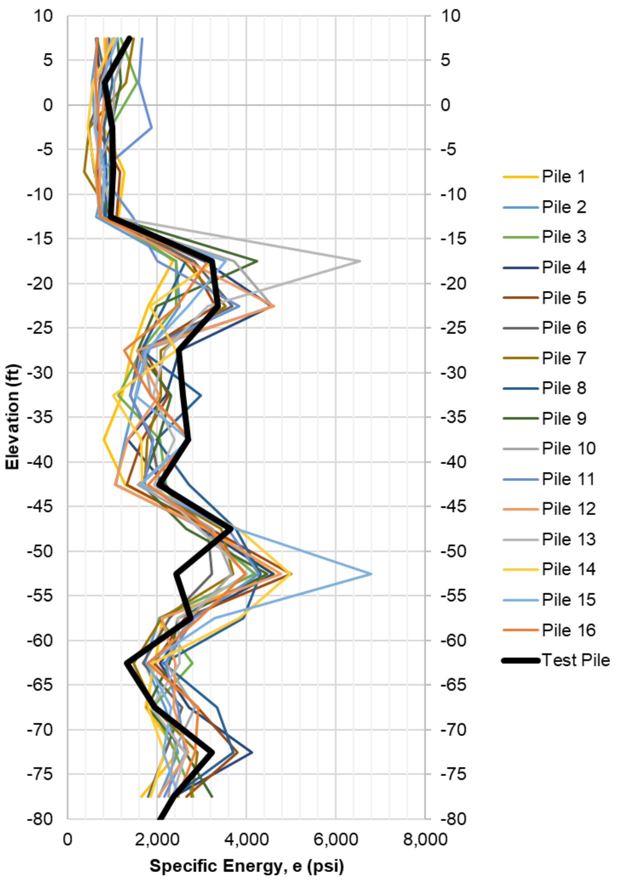


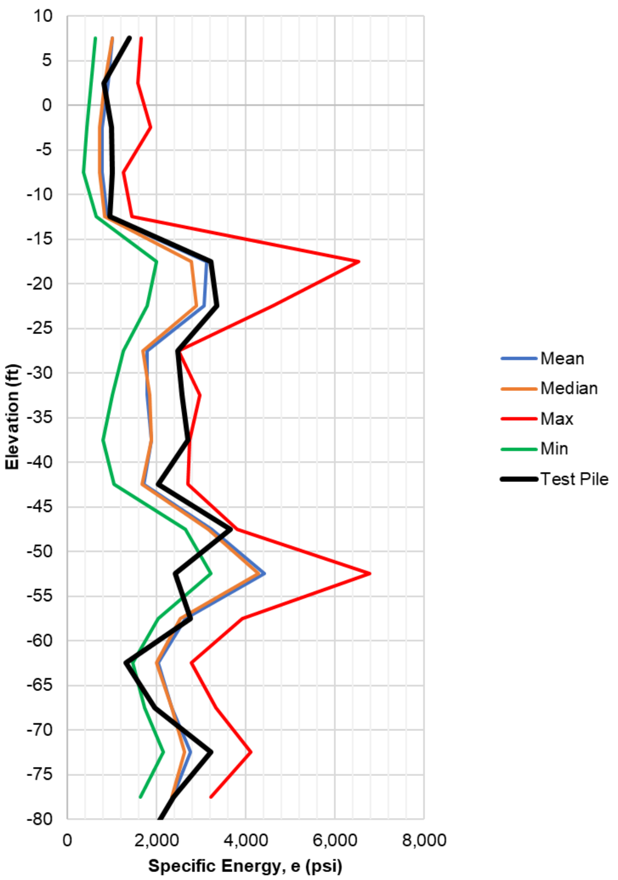
Assessing ACIP Pile Variability Over Short Distances

- 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 25' by 25' 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

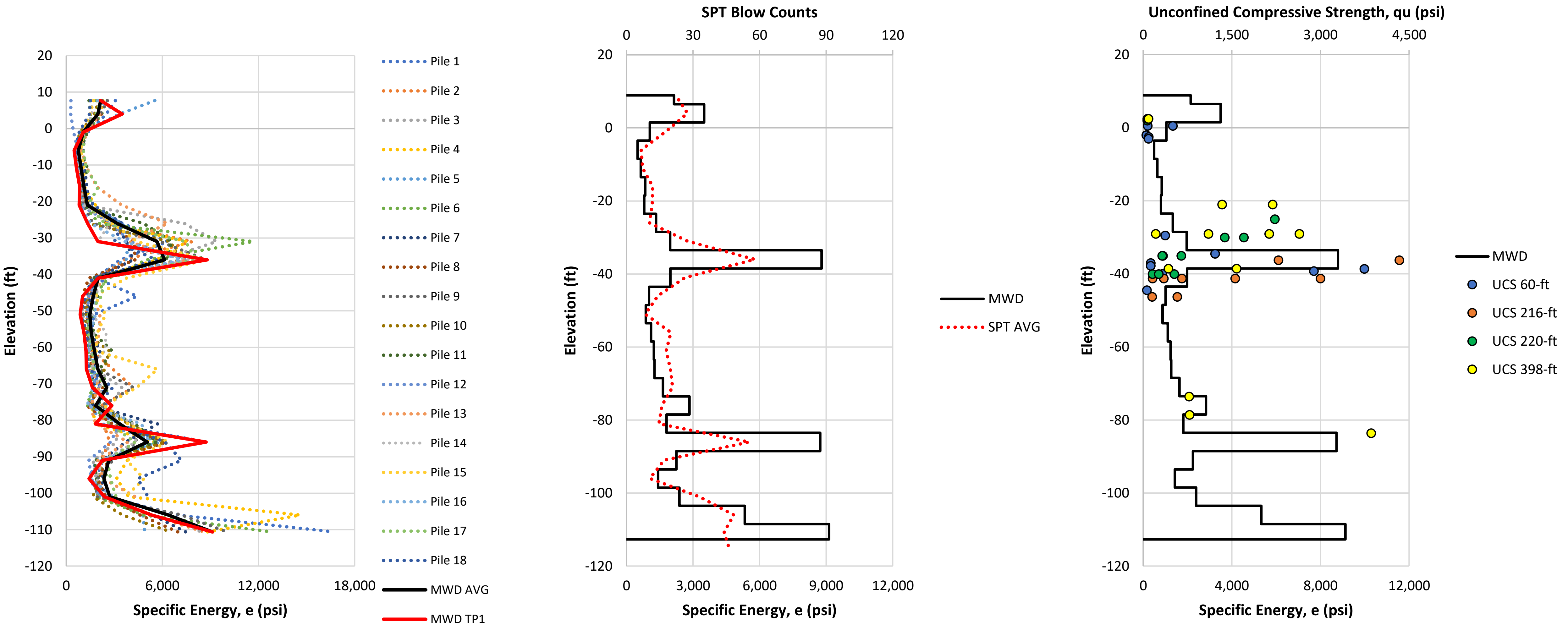
Test Pile B

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



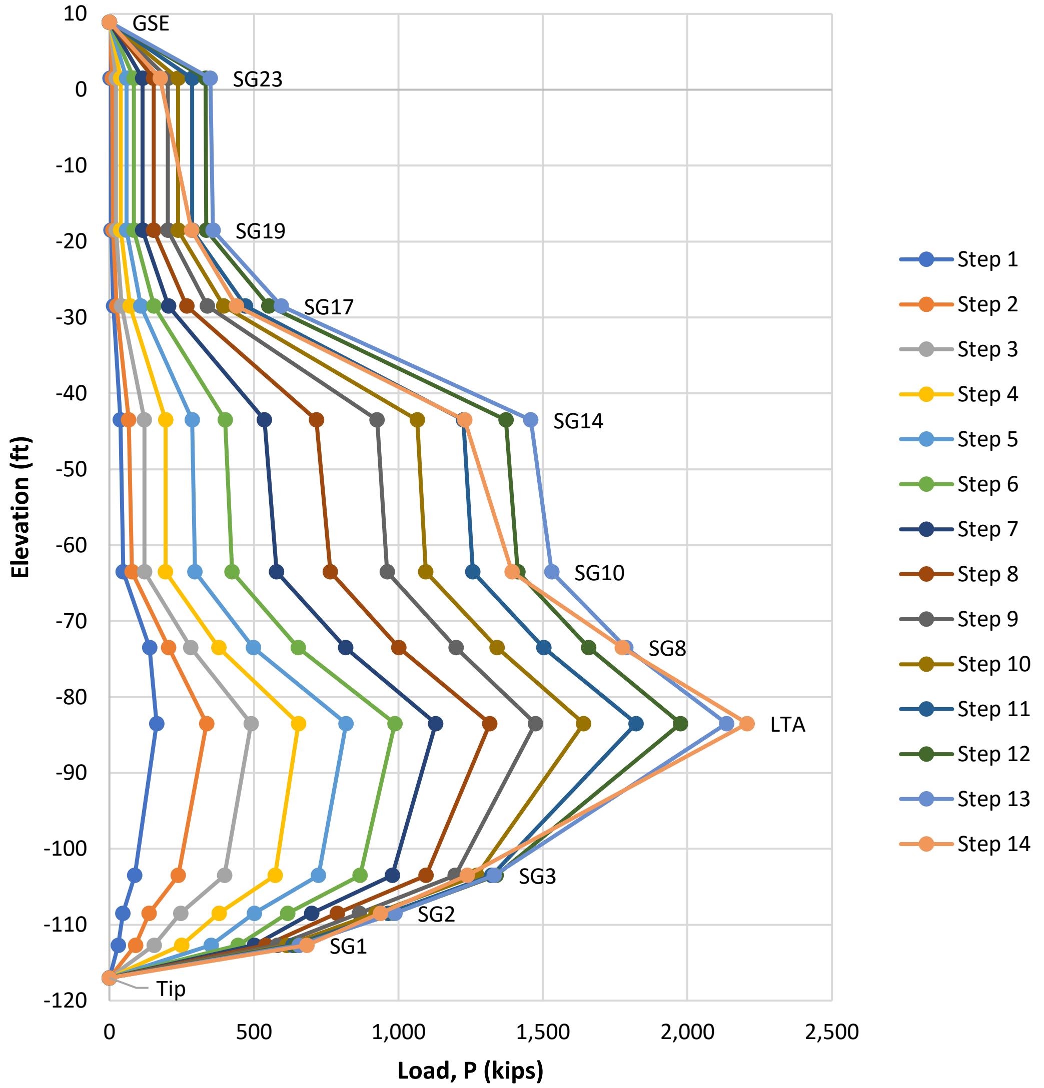


Developing MWD Profiles for Test Piles



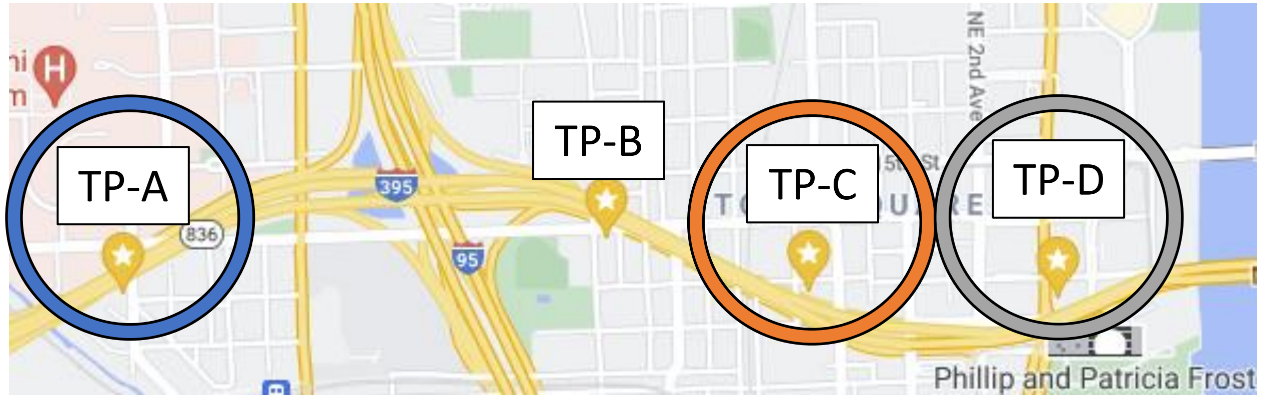
At Test Pile C - MWD, SPT, and Rock Cores all indicate similar layering

Building Correlation



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

Building Correlation



MWD e

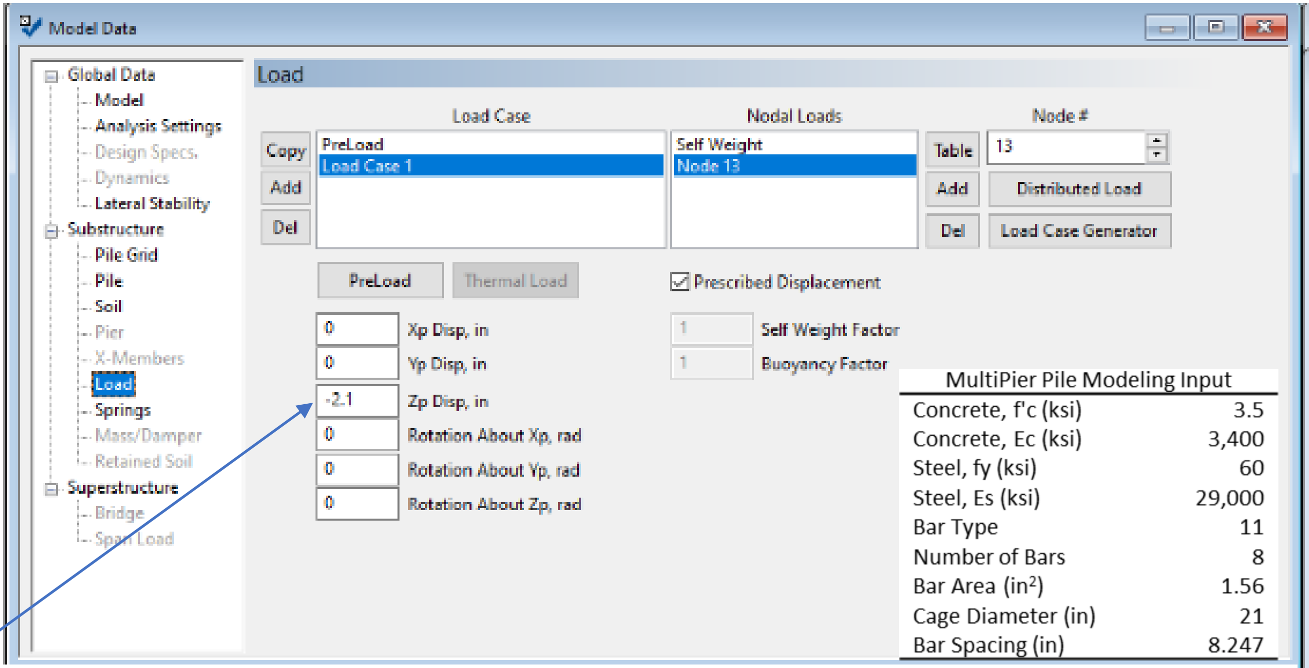
Side Shear

MultiPier Simulations using MWD Data

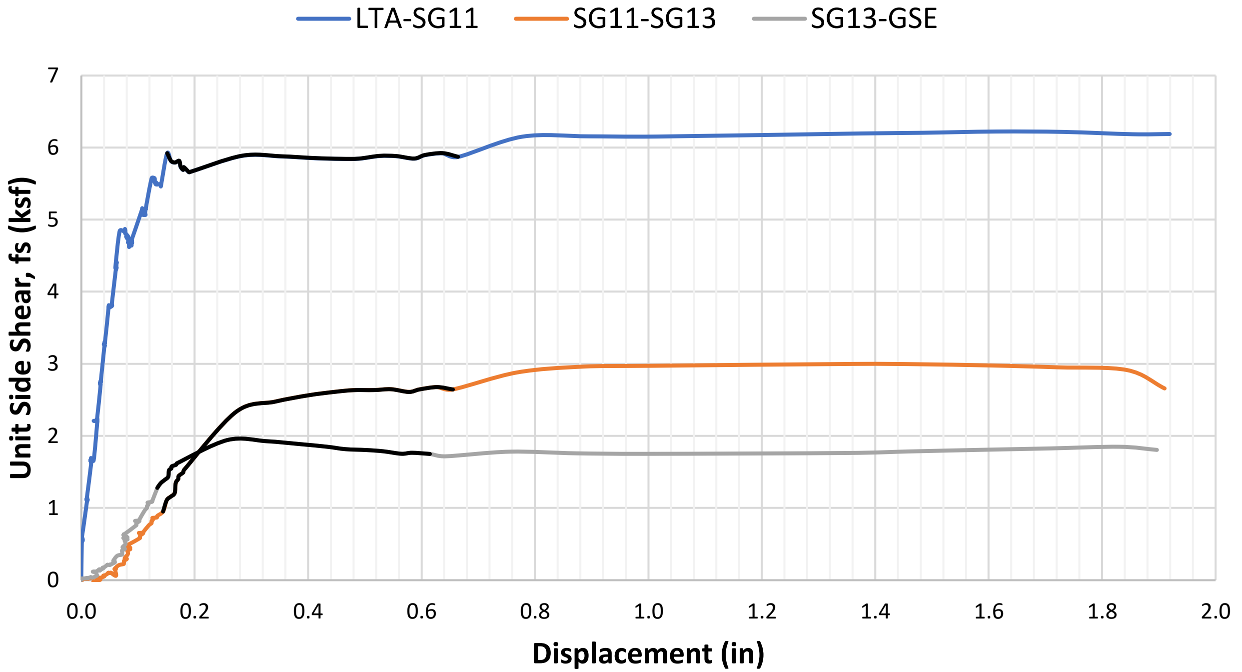
- Modeled Test Piles in MultiPier using MWD data and actual pile properties
  - Load tests were reanalyzed in larger layers
  - MWD was estimated in the footprint of two test piles used to build correlation
  - How well does the modeled pile behavior using the MWD inputs reflect the actual pile behavior 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

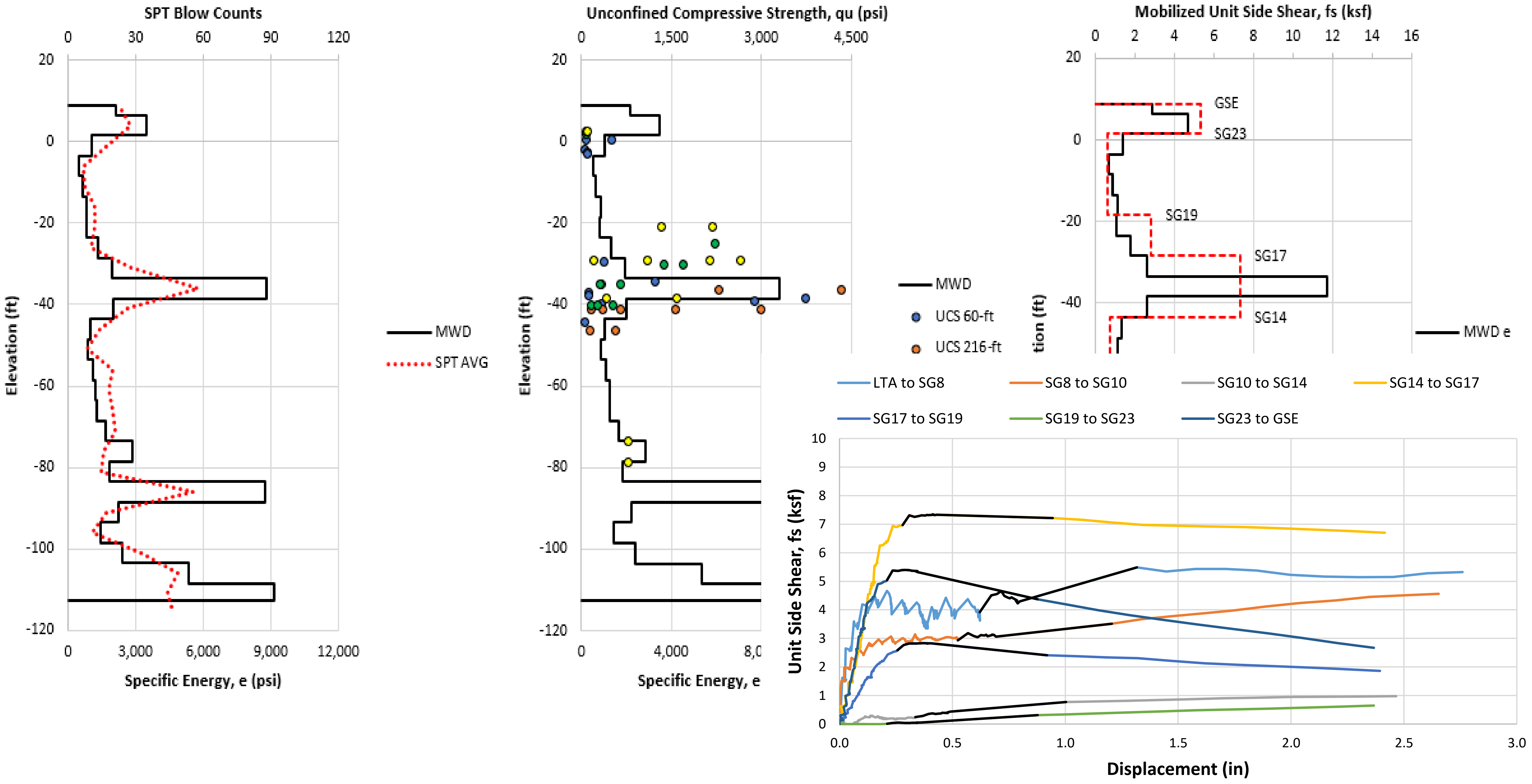
MultiPier Simulations

- 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





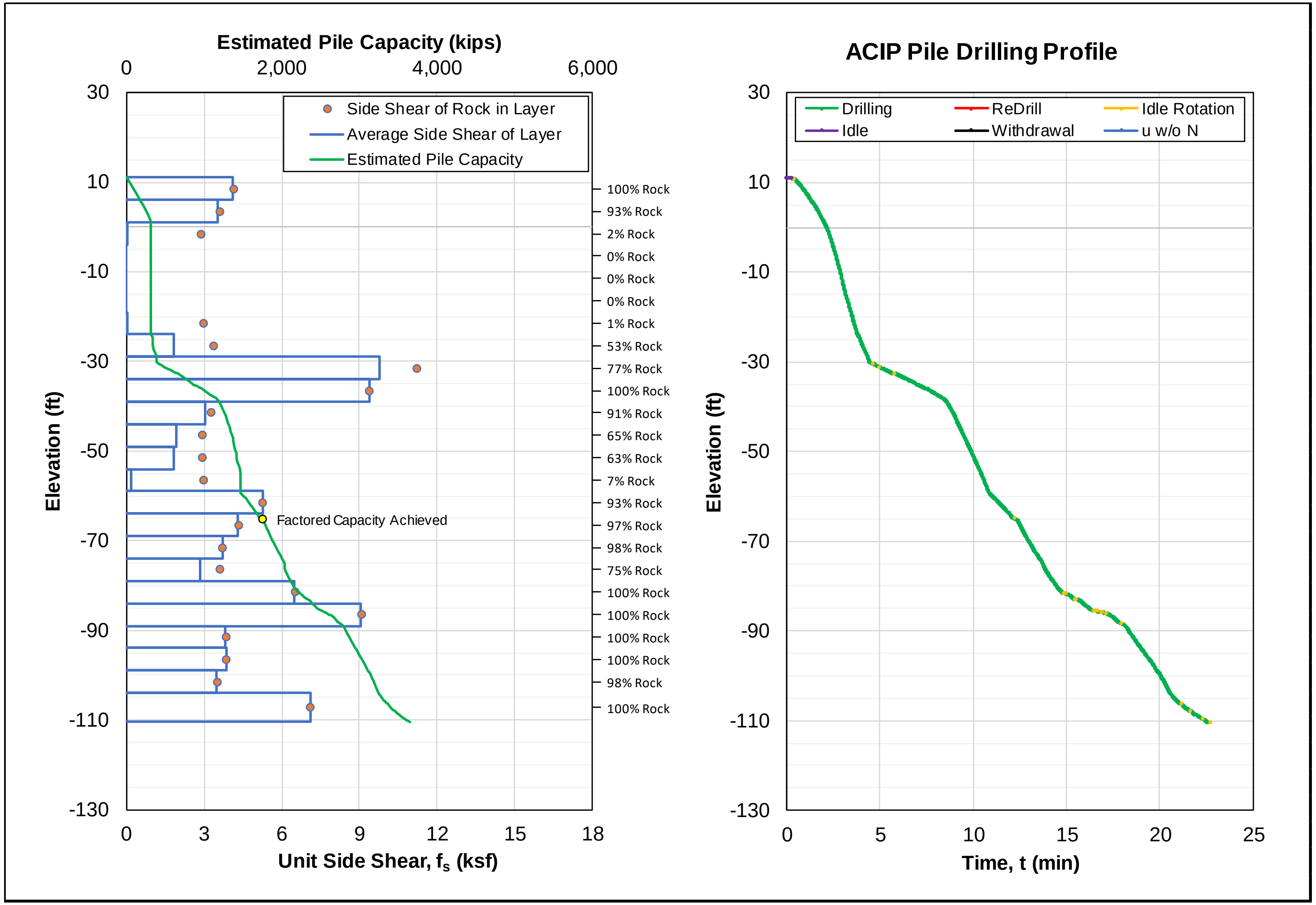
SPT Blow Counts
0
30
60
90
120
20
0
-20
-40
-60
-80
-100
-120
Elevation (ft)
0
3,000
6,000
9,000
12,000
Specific Energy, e (psi)
MWD
SPT AVG
Unconfined Compressive Strength, qu (psi)
0
1,500
3,000
4,500
Elevation (ft)
4,000
Specific Energy, e
MWD
UCS 60-ft
UCS 216-ft
Mobilized Unit Side Shear, fs (ksf)
0
2
4
6
8
10
12
14
16
GSE
SG23
SG19
SG17
SG14
tion (ft)
MWD e
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)
0
1
2
3
4
5
6
7
8
9
10
0.0
0.5
1.0
1.5
2.0
2.5
3.0
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

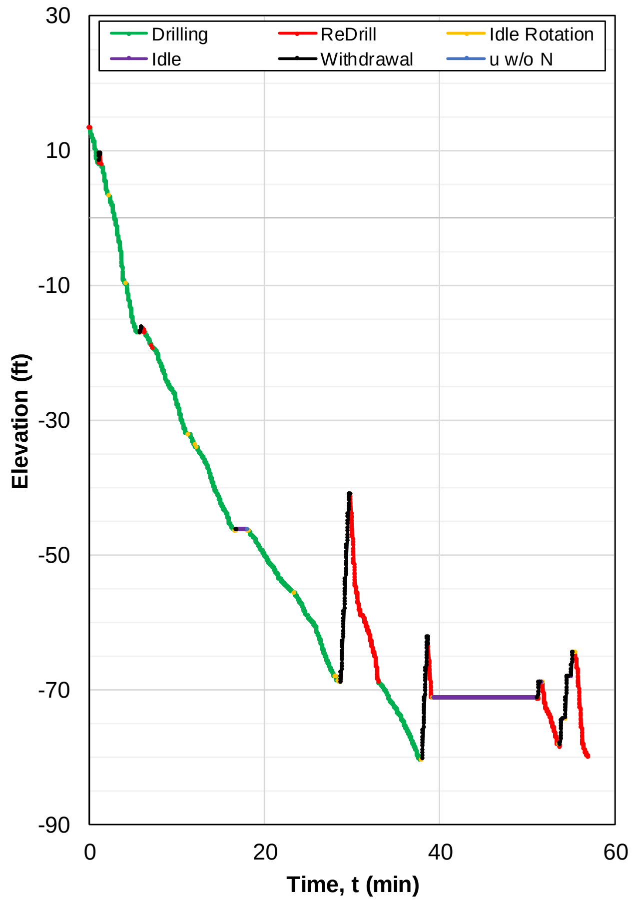
Pile Summary Report Strength and Drilling Profiles

- 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

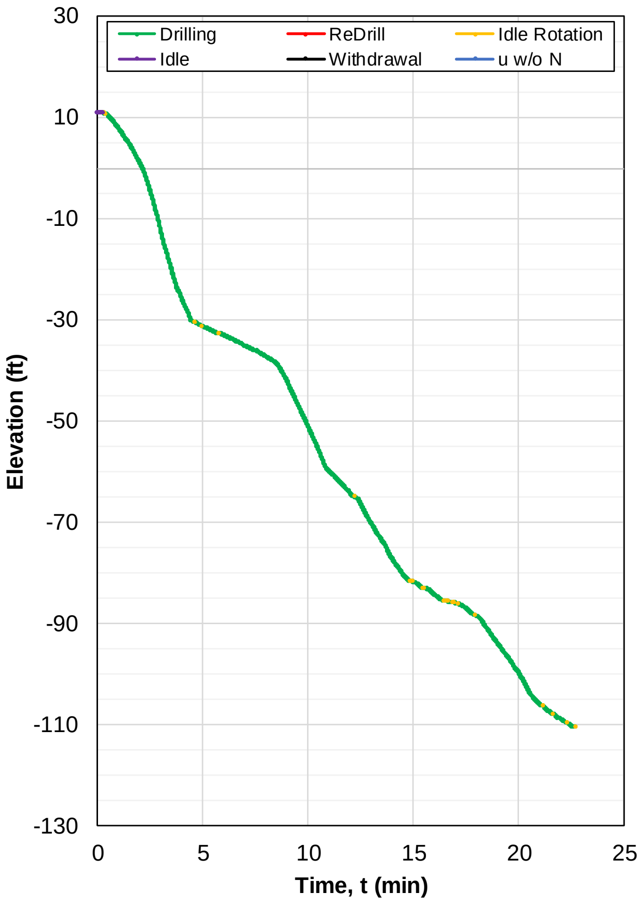


Drill Rig Performance Comparison

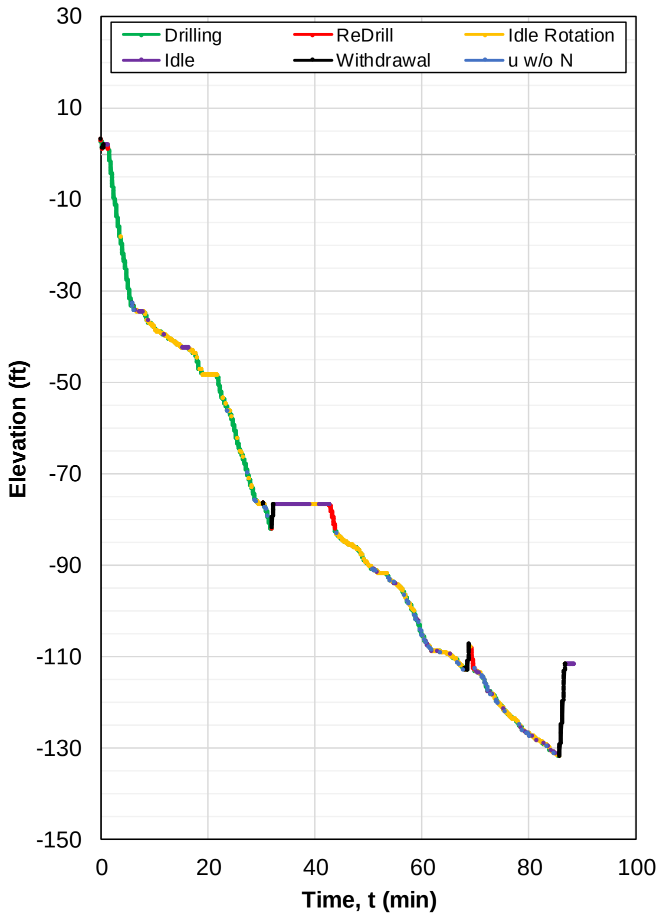
Smaller drill rig in
fs = 3.8 ksf rock



Larger drill rig in
fs = 3.8 ksf rock

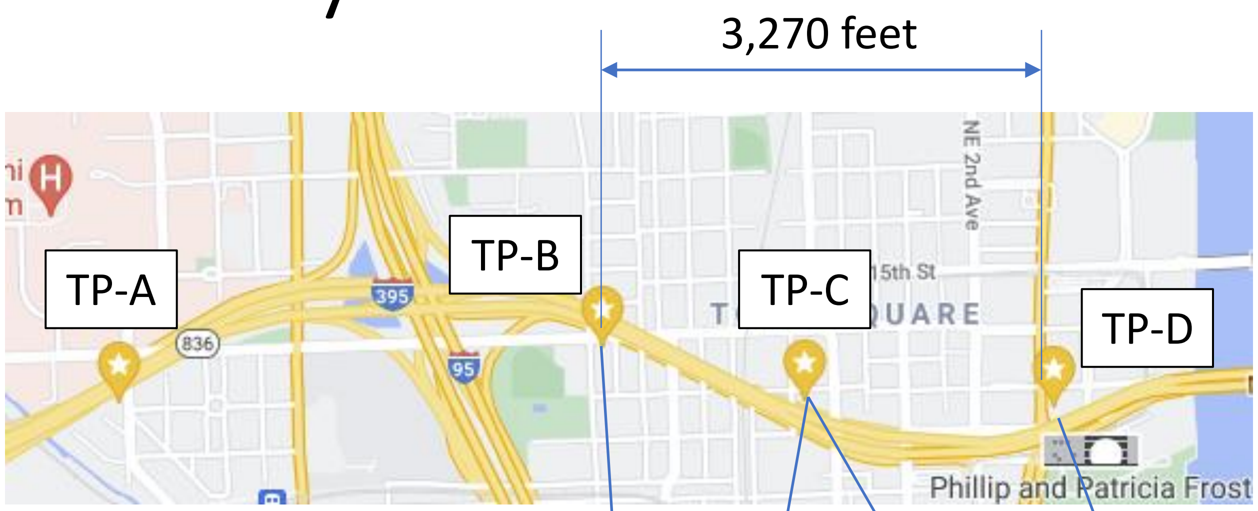


Larger drill rig in
fs = 6.2 ksf rock



QA/QC Summary

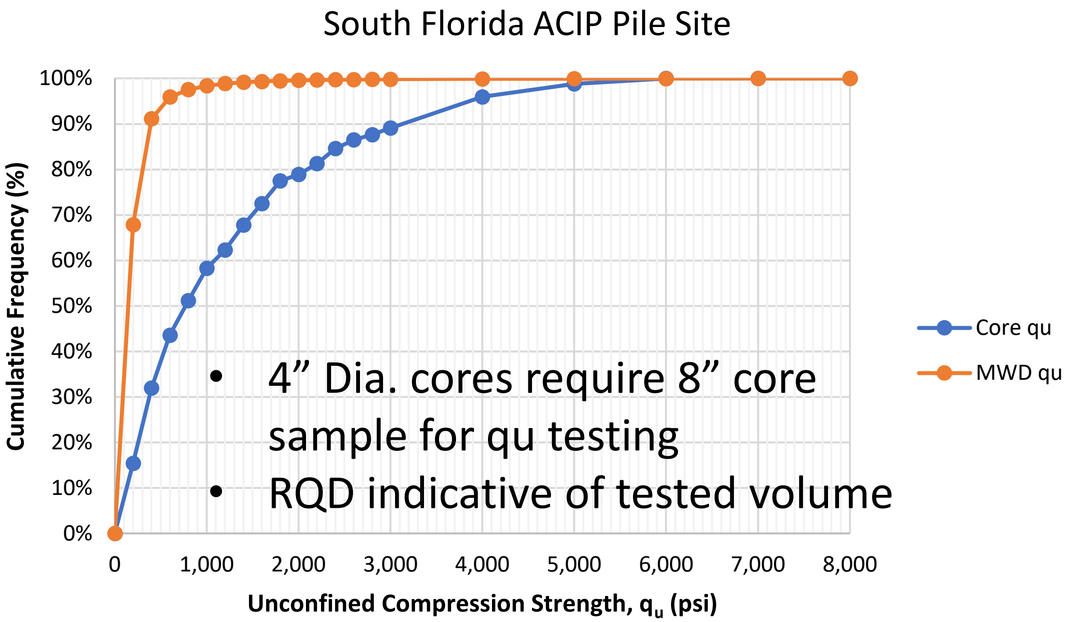
- Assessed the capacity of 50 production piles from 4 different pile groups
- All production piles assessed passed QA/QC inspection
- Observed trends of decreasing rock strength and socket length moving East to West
  - Rock socket per pile length
  - Average pile side shear
  - Factored and unfactored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

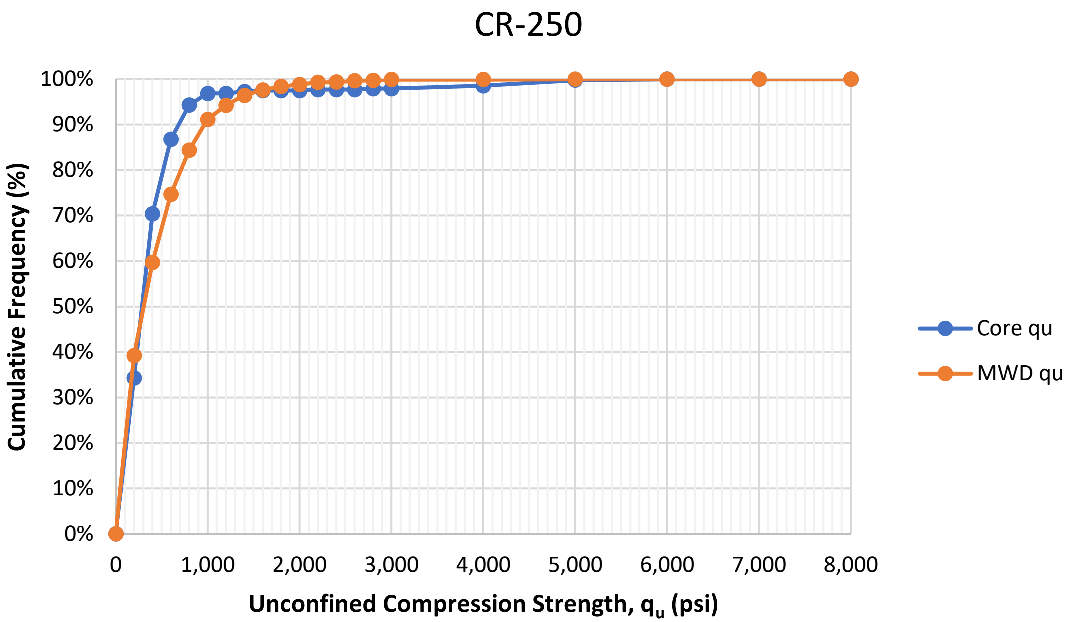


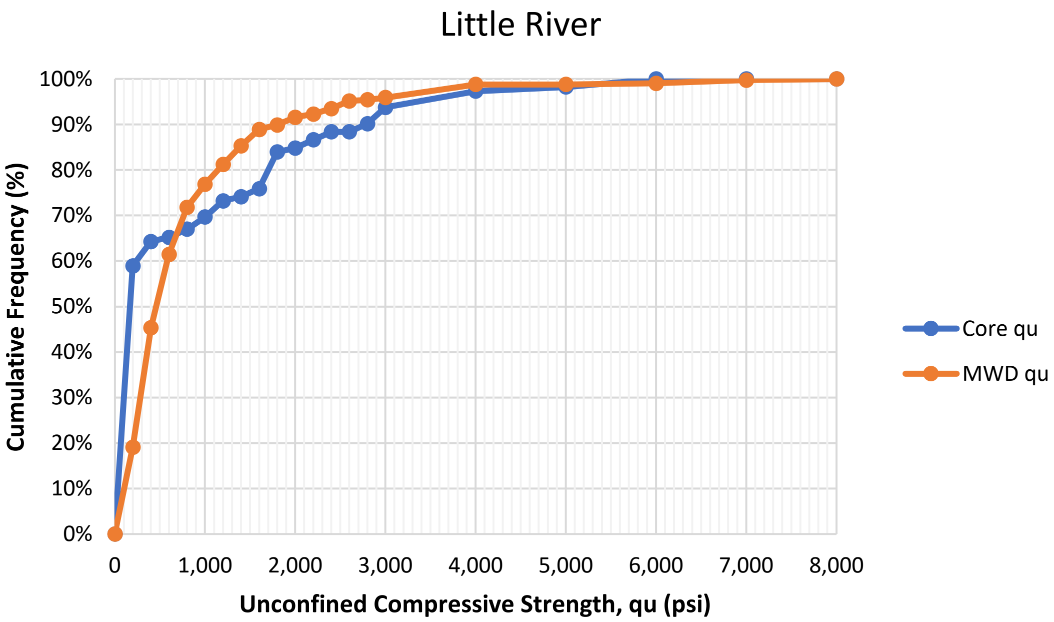
Category	Pile Group Averages			
	PG-B	PG-C2	PG-C1	PG-D
Pile Length (ft)	94.1	111.4	121.5	135.0
Total Rock Socket Length (ft)	56.8	81.0	89.0	99.2
Rock Socket per Pile Length	0.604	0.727	0.733	0.735
Pile Side Shear, fs (ksf)	3.3	4.0	4.2	5.7
Unfactored Pile Capacity (kips)	2,432	3,497	4,018	6,005
Factored 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 $\Phi = 0.6$	1.4	2.1	2.6	3.4

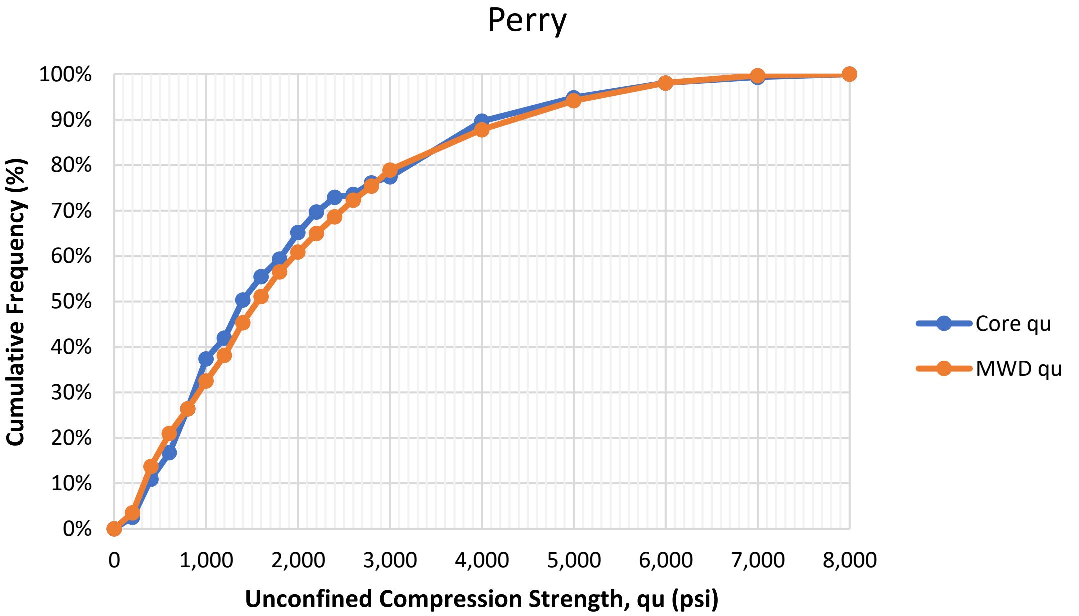
LRFD ϕ Analysis

- 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


South Florida ACIP Pile Site
Cumulative Frequency (%)
Unconfined Compression Strength, q_u (psi)
Core qu
MWD qu
• 4” Dia. cores require 8” core sample for qu testing
• RQD indicative of tested volume

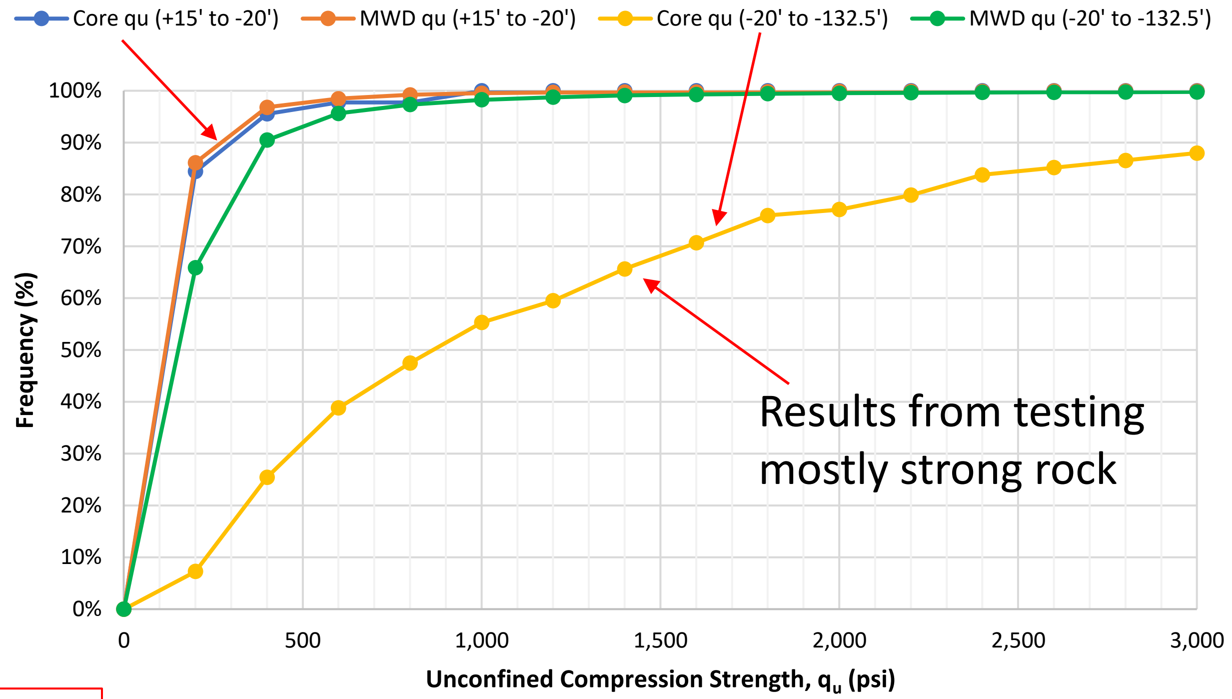

CR-250
Cumulative Frequency (%)
Unconfined Compression Strength, q_u (psi)
Core qu
MWD qu


Little River
Cumulative Frequency (%)
Unconfined Compressive Strength, qu (psi)
Core qu
MWD qu


Perry
Cumulative Frequency (%)
Unconfined Compression Strength, qu (psi)
Core qu
MWD qu

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



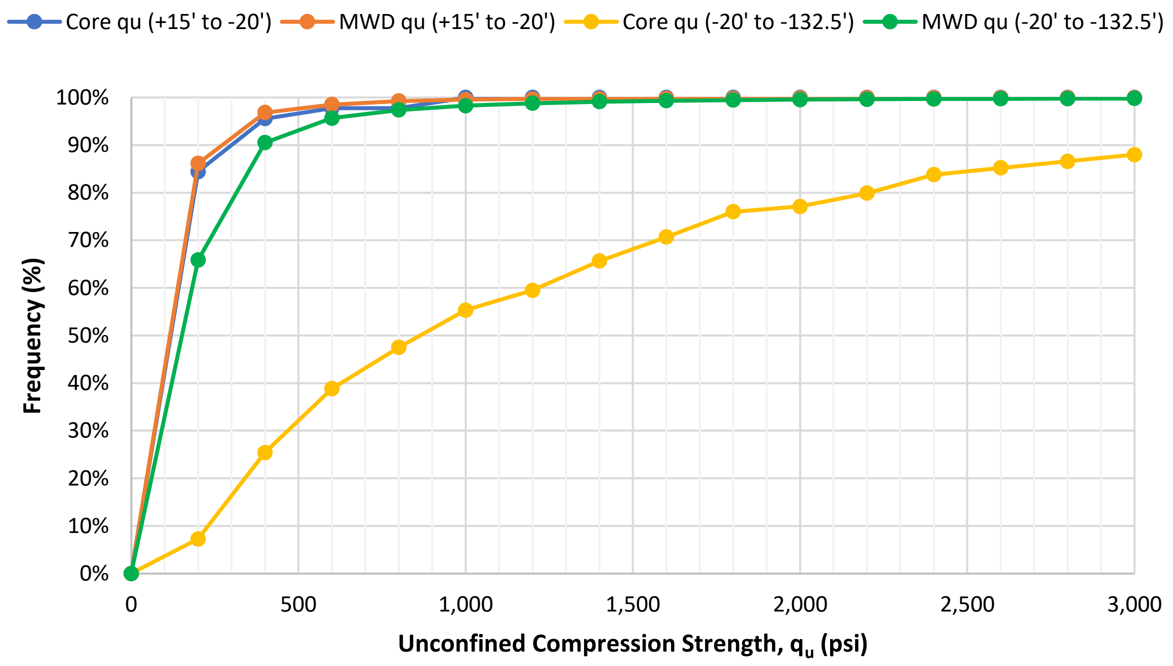
qu ≈ 1,000 psi
REC = 98%
RQD = 38%

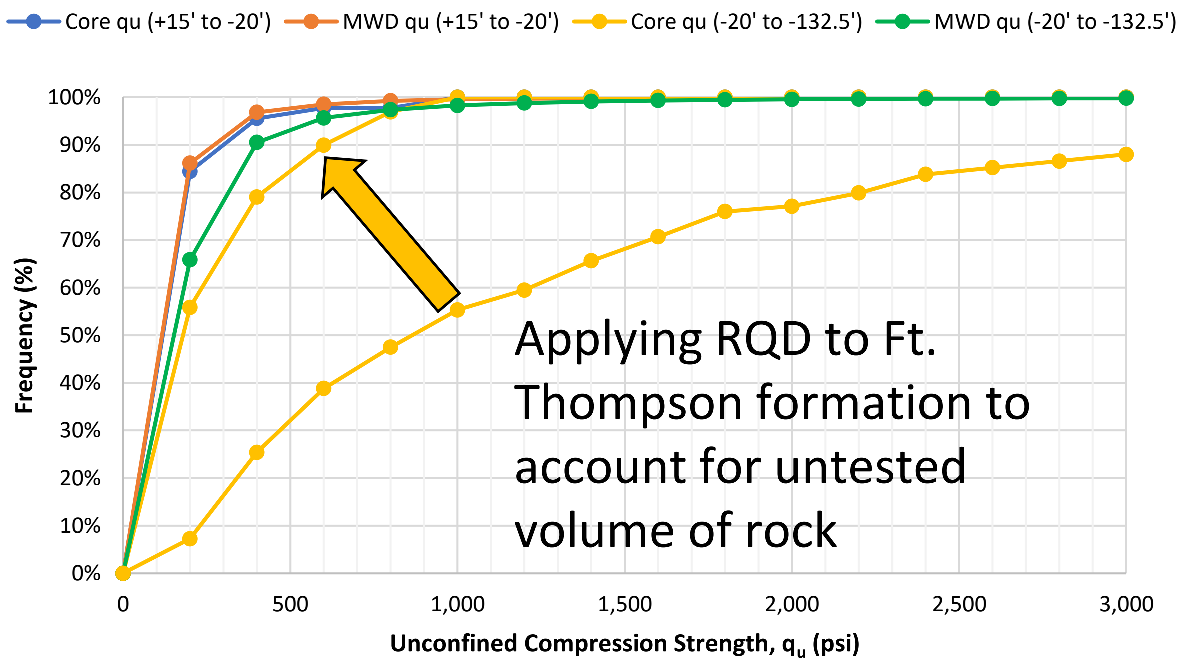
qu ≈ 400 psi
REC = 75%
RQD = 0%

***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)
- 19 Design Methods
  - SPT, Core qu, MWD qu
- 342 LRFD assessments
- Developed ϕ vs. β curves
- SPT Blow Counts
  - Crapps
  - Ramos
  - Frizzi
  - Herrera
- Core qu – Rock core strengths
  - McVay et al.
  - Gupton & Logan
  - Reese & O'Neill
  - FDOT (+/-) 1-StdDev
  - Herrera
  - Herrera using old C w/ RQD in Fort Thompson
  - Herrera 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
  - Herrera
- 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)

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

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

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

- 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 Analyses

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%
		Herrera	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%
	Herrera qu	Herrera Old C w/ REC	0.14	27%
		Herrera Old C w/ RQD	0.53	51%
		Herrera New C w/ RQD	0.58	52%
		Herrera w/ MWD qu	0.27	48%
	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%
		Herrera	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%
	Herrera qu	Herrera Old C w/ REC	0.14	29%
		Herrera Old C w/ RQD	0.59	57%
		Herrera New C w/ RQD	0.65	57%
		Herrera w/ MWD qu	0.30	53%
	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%
		Herrera	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%
	Herrera qu	Herrera Old C w/ REC	0.13	26%
		Herrera Old C w/ RQD	0.57	55%
		Herrera New C w/ RQD	0.62	55%
		Herrera w/ MWD qu	0.29	51%
	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%

$$\beta = 2.33$$

SPT LRFD Methods

- Crapps:

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

- Ramos:

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

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

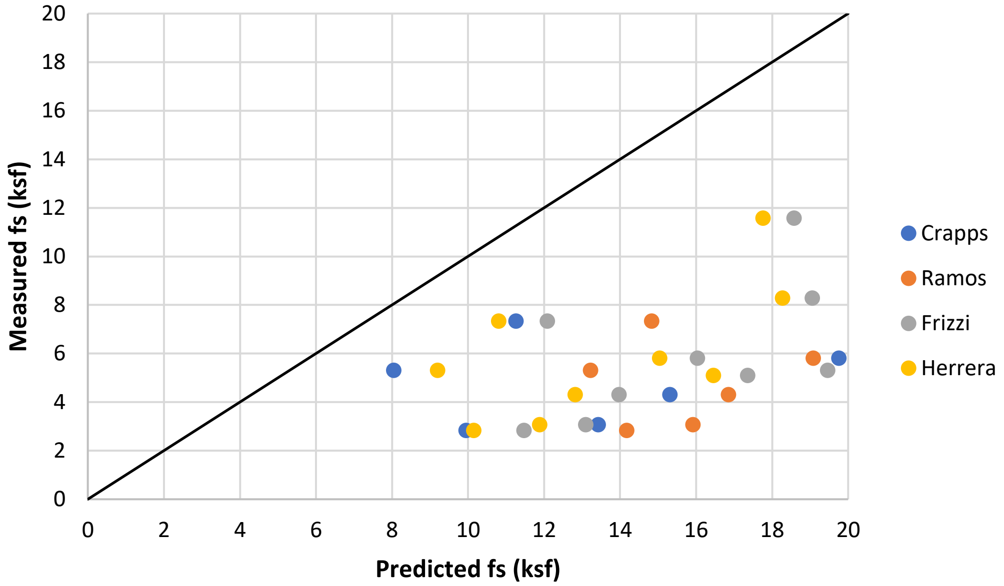
- Frizzi:

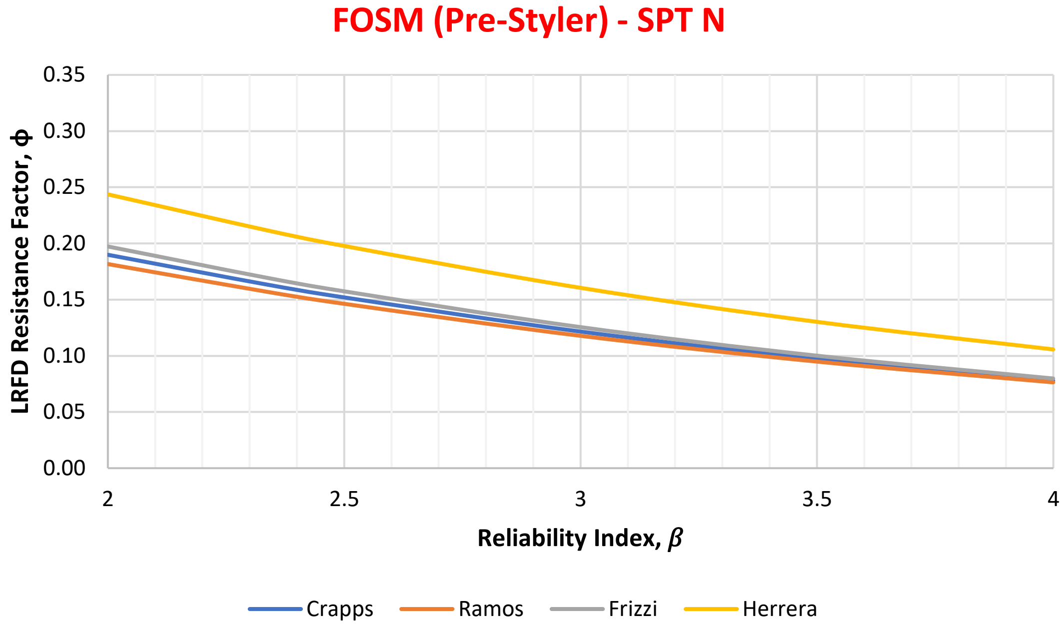
$$f_s = (0.35 * N - 1) * 2\ (ksf/tsf)$$

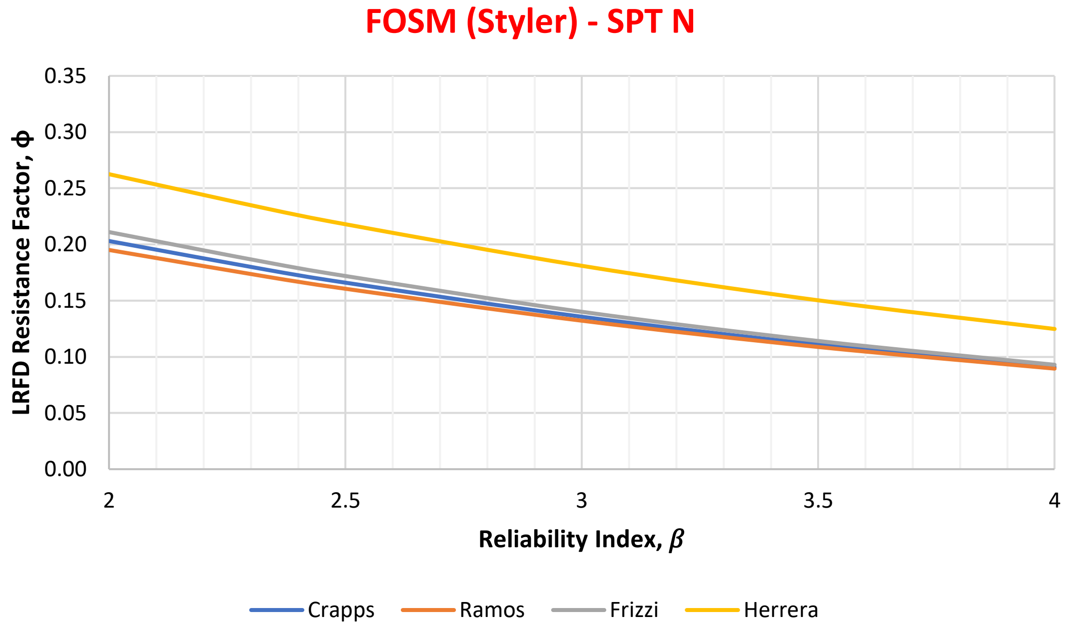
- Herrera:

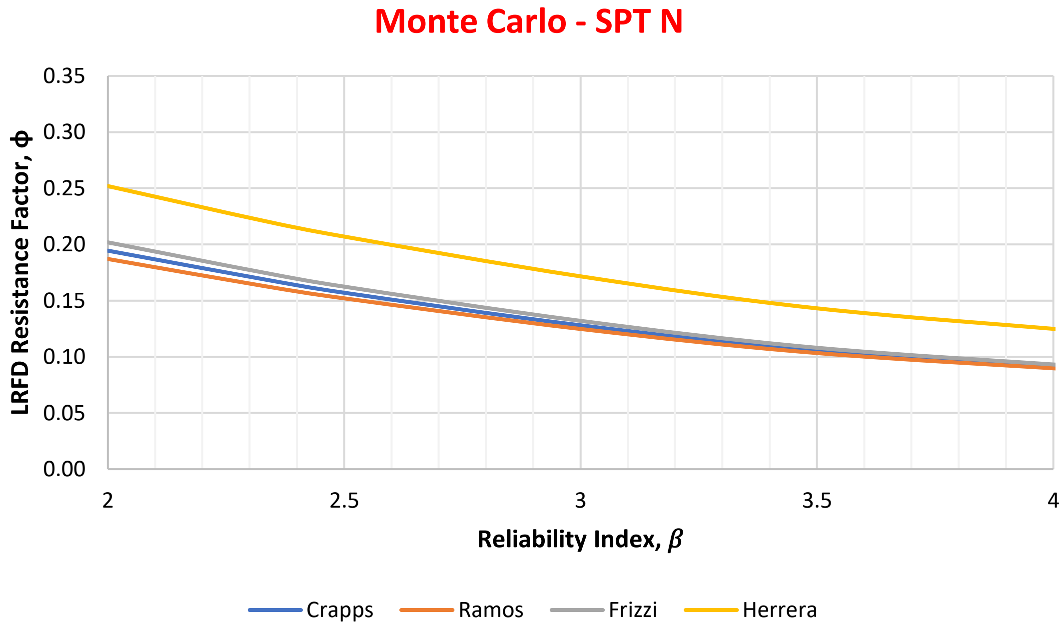
$$f_s = 0.15 * N * 2\ (ksf/tsf)$$

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:

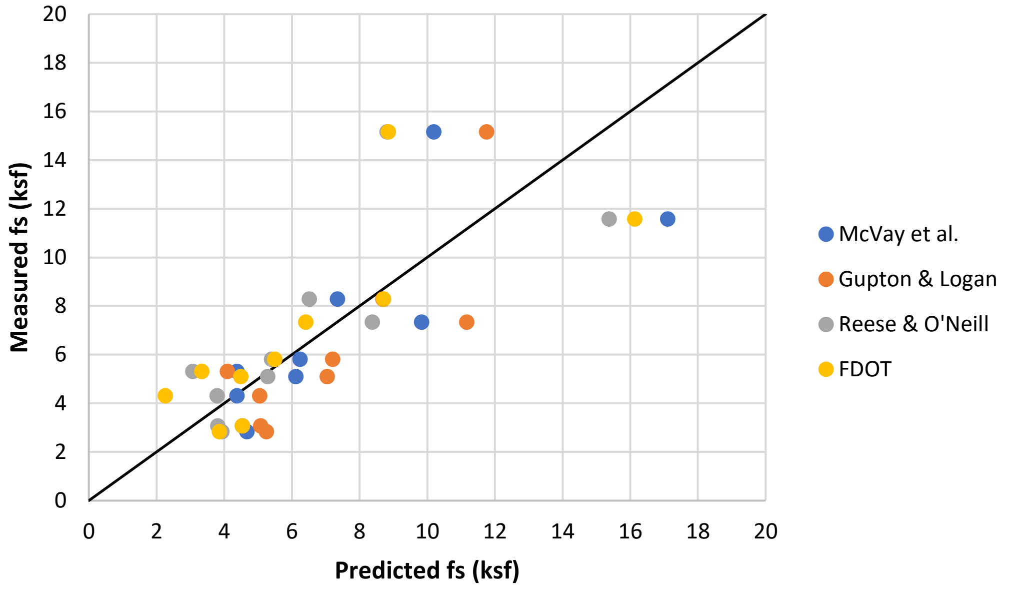
$$f_s = 0.15 * q_u * RQD * 2\ (ksf/tsf)$$

- FDOT:

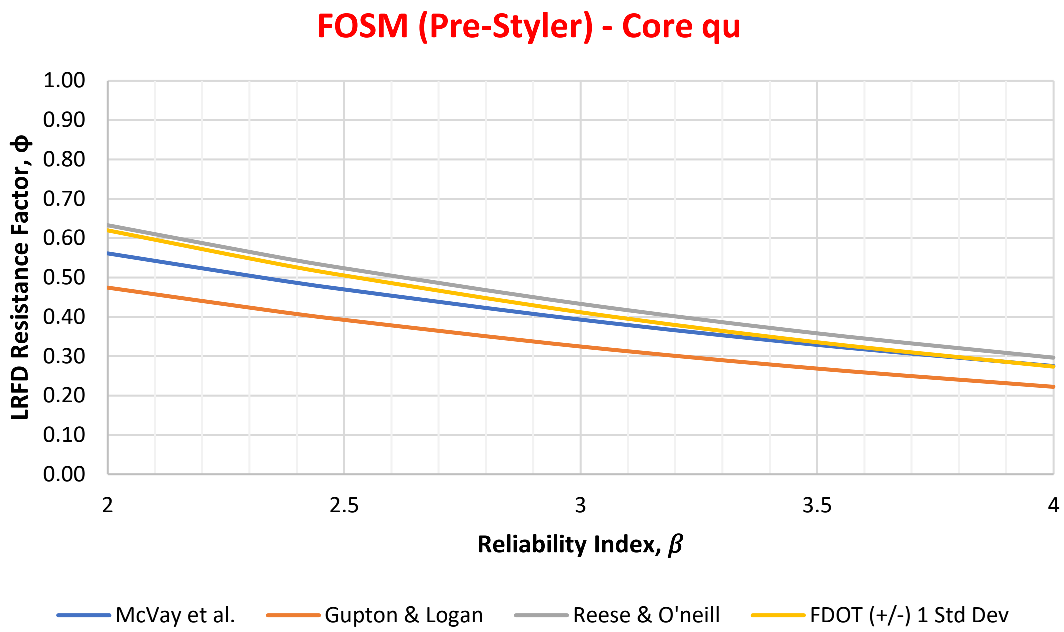
$$\pm 1\ Standard\ Deviation\ from\ mean\ q_u\ removed$$

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

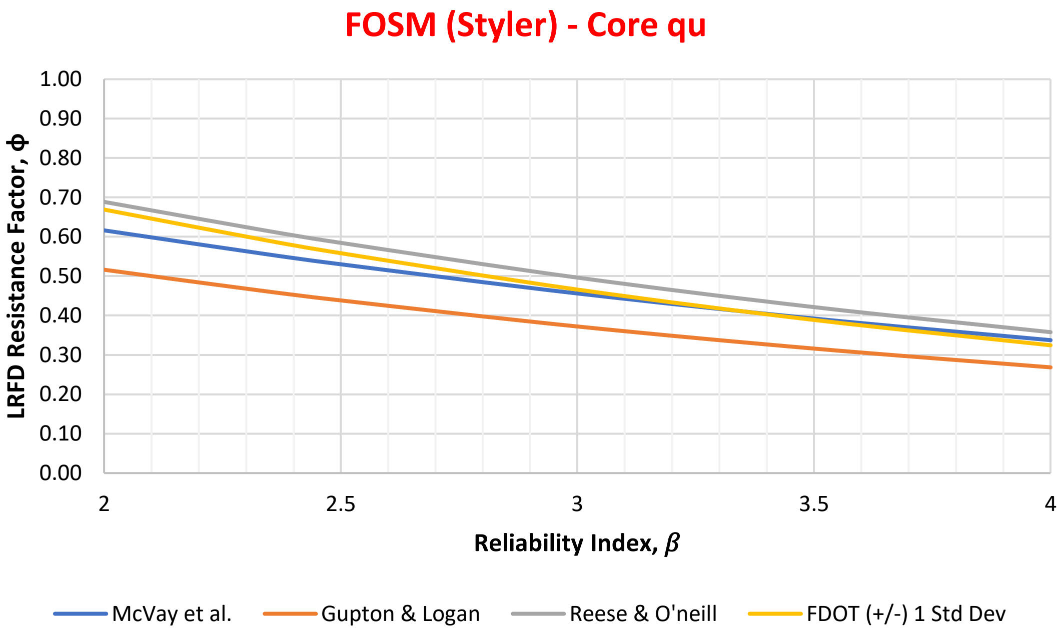
Core qu



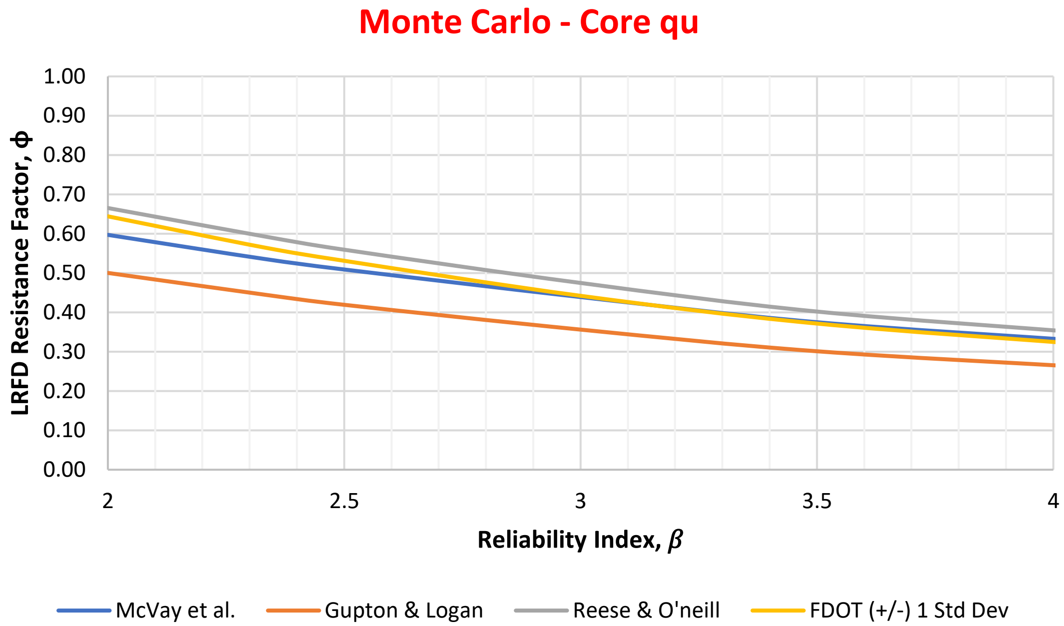
Measured fs (ksf)
Predicted fs (ksf)
McVay et al.
Gupton & Logan
Reese & O'Neill
FDOT



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



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



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

Herrera qu LRFD Methods

- Herrera:

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

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

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

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

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

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

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

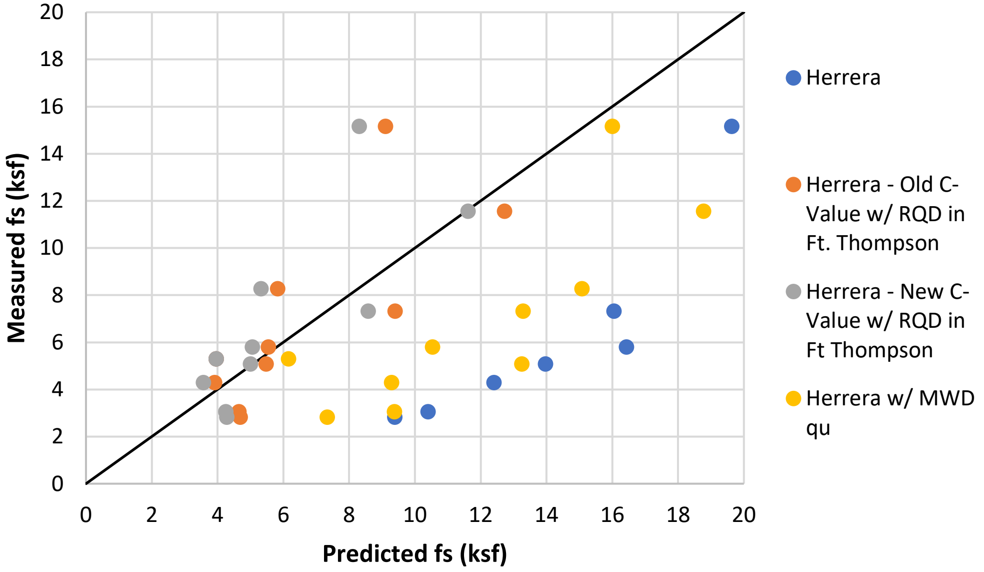
$$f_s = 1.500 * \sqrt{q_u} * RQD * 2\ (ksf/tsf) \rightarrow Fort\ Thompson\ Formation$$

- Herrera using MWD q_u:

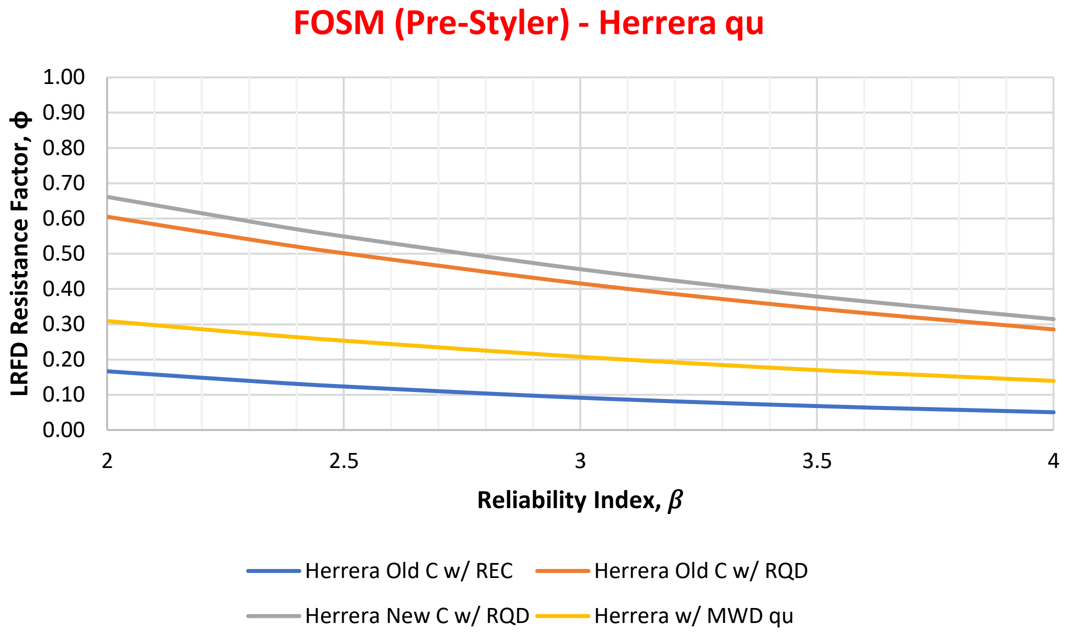
$$f_s = 1.111 * \sqrt{q_{u-MWD}} * REC_{MWD} * 2\ (ksf/tsf) \rightarrow Miami\ Formation$$

$$f_s = 1.643 * \sqrt{q_{u-MWD}} * REC_{MWD} * 2\ (ksf/tsf) \rightarrow Fort\ Thompson\ Formation$$

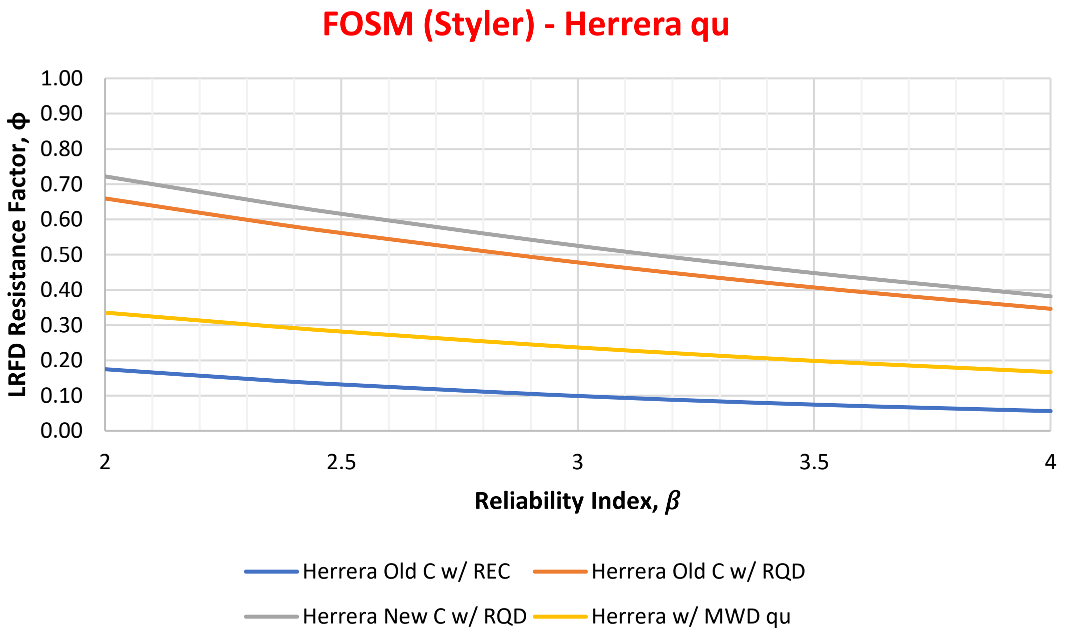
Herrera qu



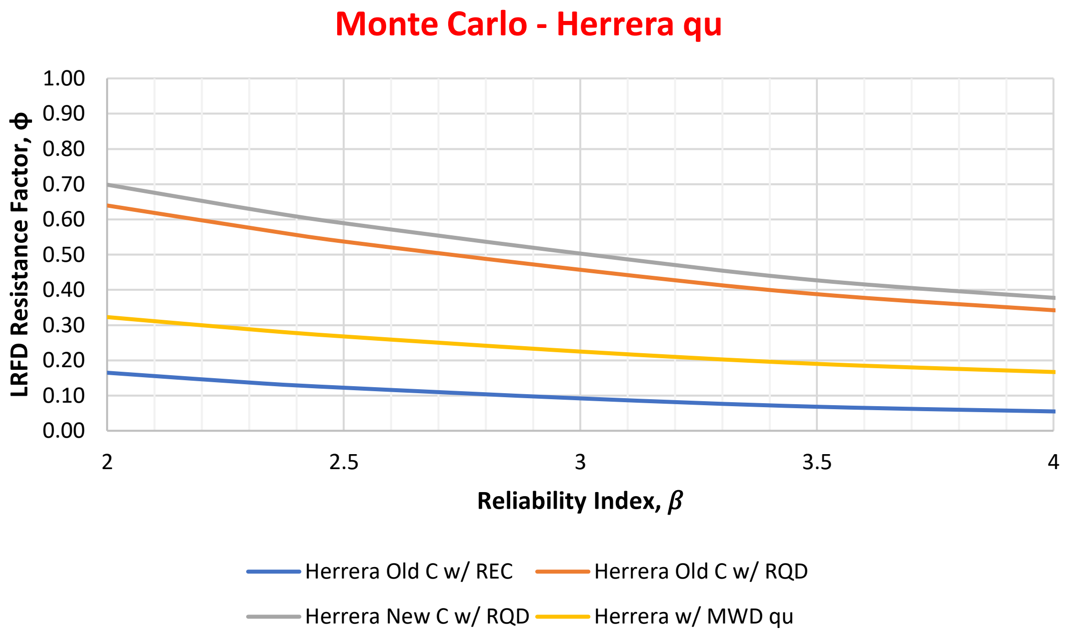
Measured fs (ksf)
Predicted fs (ksf)
Herrera
Herrera - Old C-Value w/ RQD in Ft. Thompson
Herrera - New C-Value w/ RQD in Ft Thompson
Herrera w/ MWD qu



FOSM (Pre-Styler) - Herrera qu
LRFD Resistance Factor, ϕ
Reliability Index, β
Herrera Old C w/ REC
Herrera Old C w/ RQD
Herrera New C w/ RQD
Herrera w/ MWD qu



FOSM (Styler) - Herrera qu
LRFD Resistance Factor, ϕ
Reliability Index, β
Herrera Old C w/ REC
Herrera Old C w/ RQD
Herrera New C w/ RQD
Herrera w/ MWD qu



Monte Carlo - Herrera qu
LRFD Resistance Factor, ϕ
Reliability Index, β
Herrera Old C w/ REC
Herrera Old C w/ RQD
Herrera New C w/ RQD
Herrera w/ MWD qu

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:

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

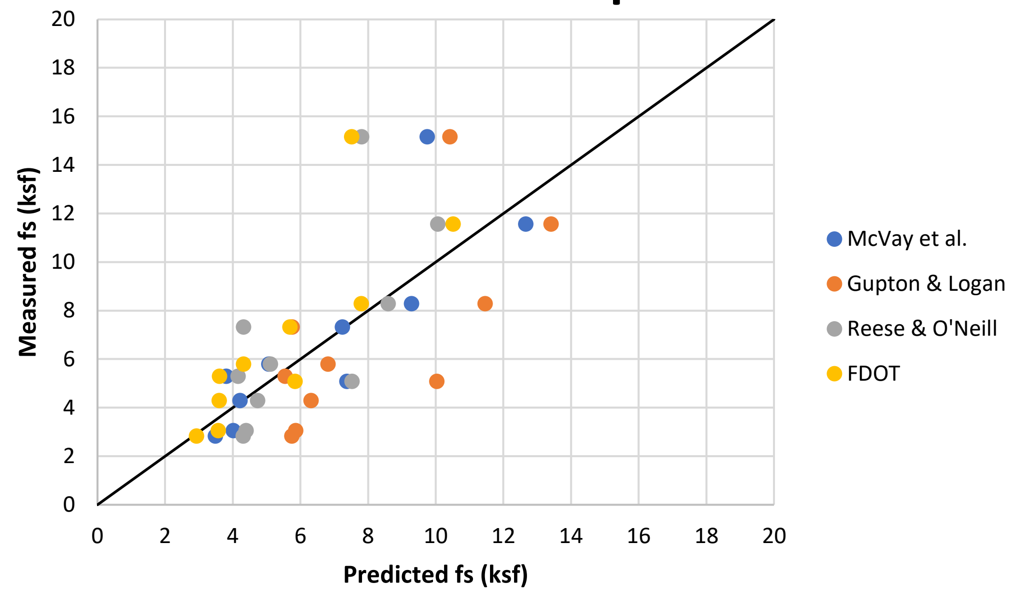
- FDOT:

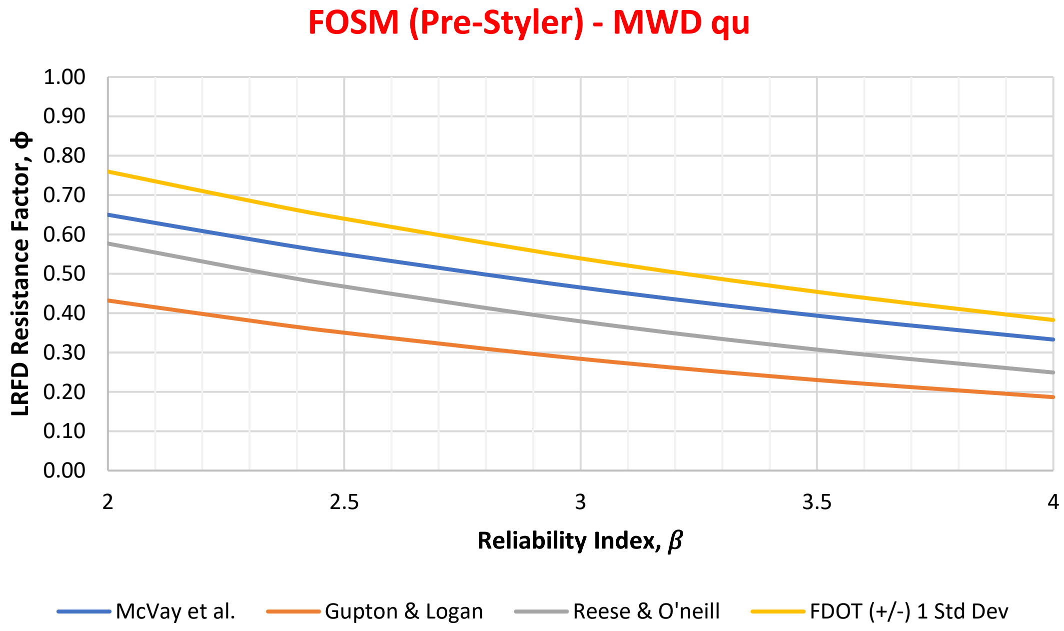
$$\pm 1\ Standard\ Deviation\ from\ mean\ q_u\ removed$$

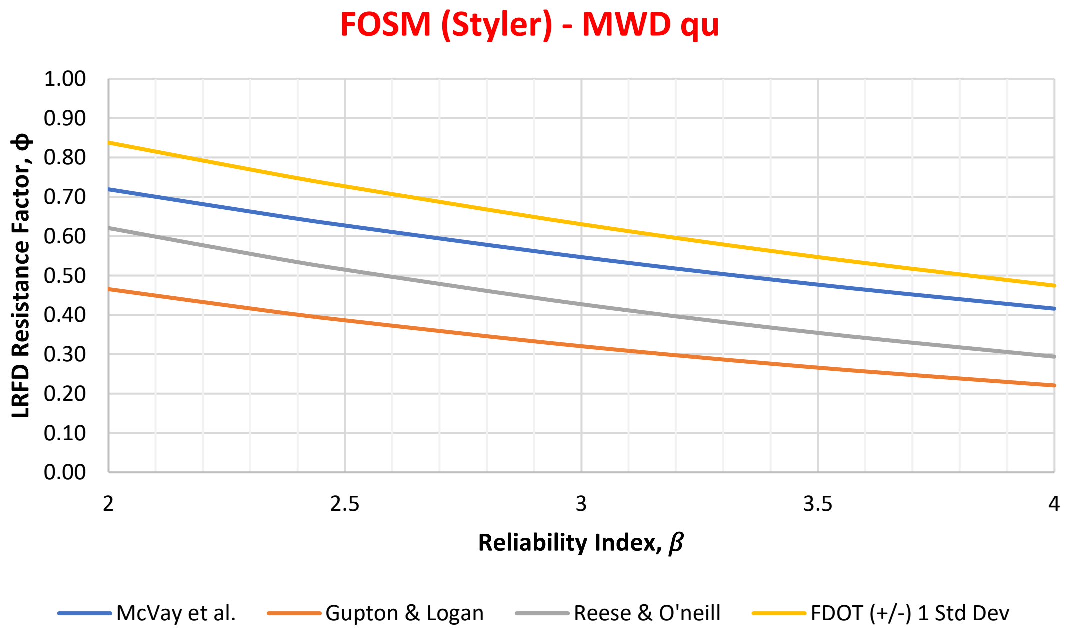
$$f_s = 1/2 * \sqrt{q_u} * \sqrt{q_t} \; * REC \rightarrow FL\ Geomaterials\ EQN\ used\ to\ estimate\ q_t$$

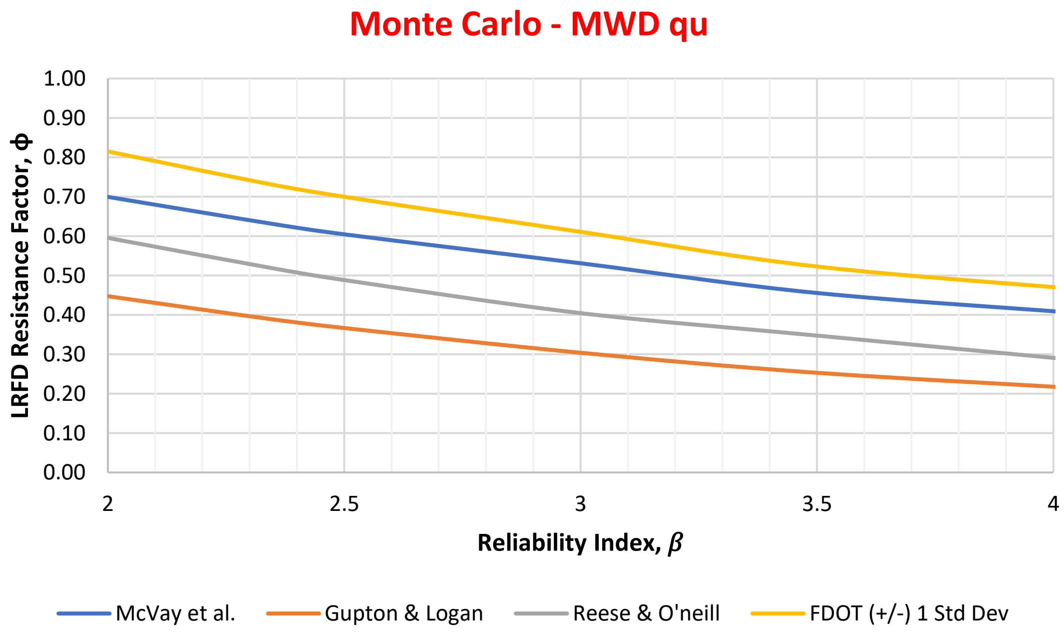
- Within 100 ft or less of test piles
- Number of data points is significantly improved per unit length due to higher resolution profiling – vertically and horizontally

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

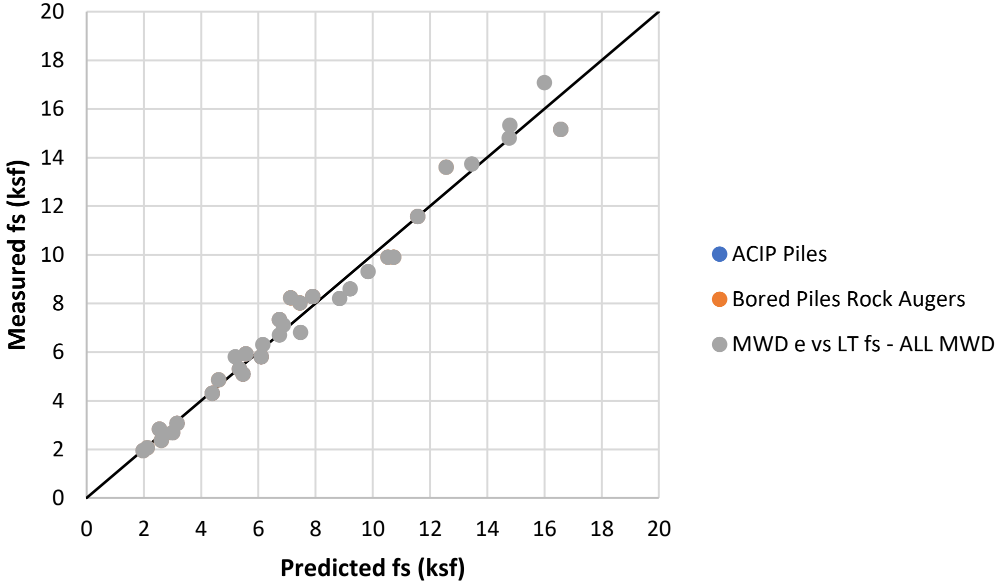

FOSM (Styler) - MWD qu
LRFD Resistance Factor, ϕ
Reliability Index, β
McVay et al.
Gupton & Logan
Reese & O'neill
FDOT (+/-) 1 Std Dev

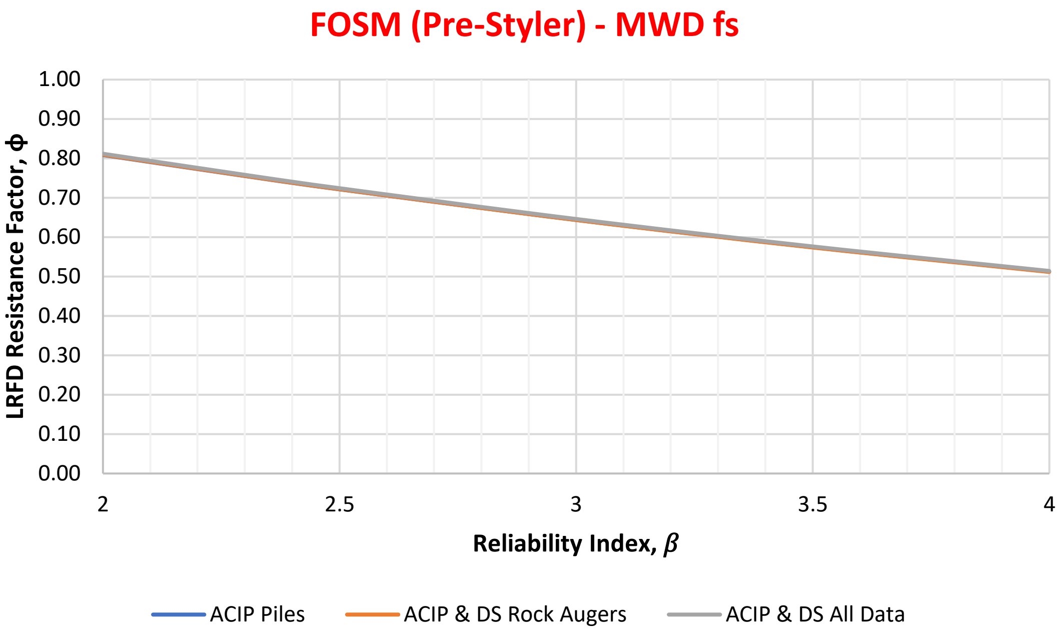

Monte Carlo - MWD qu
LRFD Resistance Factor, ϕ
Reliability Index, β
McVay et al.
Gupton & Logan
Reese & O'neill
FDOT (+/-) 1 Std Dev

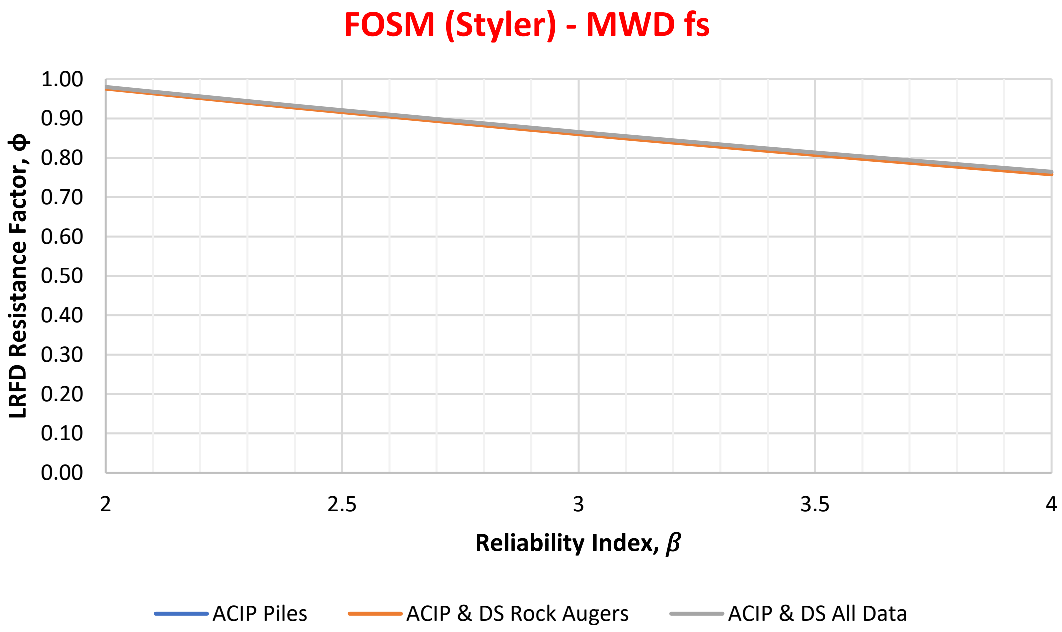
MWD fs

- 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


Measured fs (ksf)
Predicted fs (ksf)
0
2
4
6
8
10
12
14
16
18
20
ACIP Piles
Bored Piles Rock Augers
MWD e vs LT fs - ALL MWD


FOSM (Pre-Styler) - MWD fs
LRFD Resistance Factor, ϕ
Reliability Index, β
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
2
2.5
3
3.5
4
ACIP Piles
ACIP & DS Rock Augers
ACIP & DS All Data


FOSM (Styler) - MWD fs
LRFD Resistance Factor, ϕ
Reliability Index, β
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
2
2.5
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3.5
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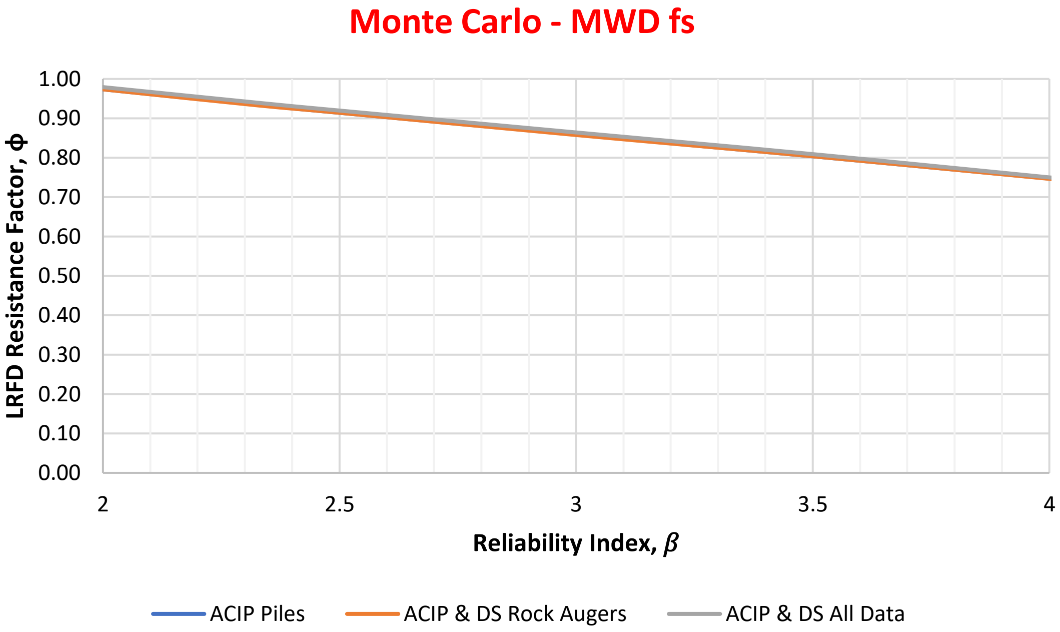
ACIP Piles
ACIP & DS Rock Augers
ACIP & DS All Data


Monte Carlo - MWD fs
LRFD Resistance Factor, ϕ
Reliability Index, β
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
2
2.5
3
3.5
4
ACIP Piles
ACIP & DS Rock Augers
ACIP & DS All Data

Conclusions

- MWD is viable for ACIP pile QA/QC
  - Specific energy has excellent sensitivity vs pile side shear
  - MWD strength assessment and layering was in agreement with SPT, rock cores, and load test data
  - MWD modeled pile behavior reflected the actual load test pile behavior
- MWD generated 285 times more qu data than rock cores collected within the same investigated area
  - High resolution profiling
  - Provides better understanding of the strength distribution and layering at the site
- ACIP analysis spreadsheet was successfully developed
  - Assessment of rock strength, side shear, and pile capacity vs depth, drilling vs time profile that identifies where time was wasted for future optimization
  - 1-cm resolution profiling
- Based on the comparison of MWD qu and laboratory qu,
  - Core strengths compare well with MWD qu in the top 35 feet at the site
  - Core strengths at deeper depths (35 feet and below), MWD qu indicates much lower qu strengths compared to core qu
- This required LRFD Phi assessment to use RQD instead of REC for the rock at lower depths
  - Comparison of rock cumulative frequency using RQD resulted in good correlation with MWD to account for missing volume
- Load testing suggests that residual stresses are developed in South Florida for ACIP piles
  - Recommend monitoring strains after the pile is cast and prior to load testing to assess residual stresses
  - All load test reports should require that the sum of the estimated side shear loads equal the applied load from the LTA for each load step

Conclusions

- LRFD Assessment was performed using site specific data with LRFD methods, FOSM Pre-Styler, FOSM Styler, and Monte Carlo
  - Methods employing rock cores show similar results as drilled shafts (FDOT, McVay, G&L, Reese and O'Neill) but higher than the original ACIP report
  - Methods that employed SPT produced the lowest phi values similar to the original ACIP report (McVay et al.), this is attributed to poor correlation between SPT blow counts and rock strength
  - MWD methods resulted in the highest phi values due to excellent correlation between specific energy, rock strength, side shear, and pile capacity
    - Significant increase in data collected and high-resolution profiling with rock strengths as low as 90 psi
  - MWD in the footprint (QA/QC procedure) provided LRFD phis above 0.8 for Beta equal to 3.5 or less (failure of 1 in 5,000)

Recommendations

- Conduct more MWD research for South Florida ACIP piles
  - Need more data to further validate the results of this research
- Collect more MWD data in the footprint of load tested ACIP piles
- Investigate using MWD coring practices in South Florida to assist with recovering more samples in formations that are difficult to core
  - MWD will provide a significant increase strength data available for design
- Investigate residual stresses that develop in South Florida ACIP piles
  - This needs to be resolved to get higher resolution load test layering
- Sampling frequencies should be increased for AME equipment
  - Currently 1 sample per second
- Develop an ACIP pile analysis program that is capable of handling greater sampling frequencies than the spreadsheet
  - Build off the programming that was developed in the ACIP pile spreadsheet

UF Load Test Recommendations

- In general, strain gauge readings should be taken immediately before (and after) every event of the piling work and not just during the actual load test. Continuous measurements would be the ideal approach. However, continuous measurements may not be feasible, currently. Therefore, readings should be conducted at the following times:

1. After installation of the gauges while the reinforcement cage is laying on the ground (to ensure all gauges are functioning)
2. Just prior to placing the instrumented cage into the ground (to validate the gauges are still working prior to cage placement)
3. **When the cage has been placed into the grouted hole and the gauges have adjusted to the ground or initial grout temperature (within 1-hour)**
4. Immediately before starting the load test
5. After load test analysis is complete, the reported side shear in each level should be converted to load and compared to the applied load. This will ensure the measured loads within the pile do not exceed the applied load. This should be done for each load step
6. Strain gauge data that was used to generate T-Z curves should be multiplied by segment length to obtain segment deformations that are then summed over the full pile length and compared with pile top movement, LTA movement, and tell-tale movement. The error should be within 10%

- If these measurements are not taken at the recommended intervals, and residual stresses are present within the pile, you should break up the load test into larger layers using stable strain gauge locations

Remaining Tasks

- LRFD phi assessment of FDOT design methods of ACIP piles in South Florida
- LRFD phi assessment of MWD specific energy for ACIP pile axial capacity QA/QC
- Draft Final
- Closeout Meeting
- Final Report

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.
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- 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.