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

#### **GRIP Meeting**

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# Outline

- Introduction
- Project Background
- Project Objectives
- Tasks and Deliverables
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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 siteto-site basis

# Specific energy – side shear relationship for drilled shafts using rock augers



# 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 timereferenced 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</u> <u>individual lengths of measure</u> <u>must be used</u>
  - Length of shaft segment
  - Volume removed (L<sub>Shaft</sub> x A<sub>X-sect</sub>)
- 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:

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

## 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
- Assist in developing a "drilling index" to automatically discern soil from rock
  - Can analyze individual and compound drilling parameters based on layering or specific energy requirements
- 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	В	с	D	E	F	G	н	I J	к	L	М	N	0	P	Q	R	S	Т	U	V	W	X
1 Enter Pile 1	Time	Duration (	Gear Box I	Penetrati	Penetrati	Depth (ft)	Gear Box F	Torque (f Crowd P	re Thrust (Ib	Enter Pile 2 📥	Time	Duration (Ge	ear Box F	Penetratic	Penetratic	Depth (ft)	Gear Box IT	Forque (f	Crowd Pre T	hrust (lb	Enter Pile 3 🖂	<mark>&gt;</mark> Time 🕴
2 Pile ID	5/4/2020	7 0	-293.35	-36.9423	3.048	0	454.5482	0 208.564	2	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	0.02	-293.26	-36.9751	3.048	0	477.4641	0 201.167	3	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	0.03	14.75	0	3.048	0	587.9828	0 351.571	4	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 (f	t) 5/8/2020
5 <b>11.84</b>	5/4/2020	0.05	16.29	0.295276	3.386667	0.032808	551.8684	0 275.861	7	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	0.07	16.21	0.787402	1.27	0.065617	606.8377	0 252.945	7	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	0.08	16.16	1.181102	0.846667	0.098425	603.3568	0 239.892	4	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	0 251.930	5	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	0.12	16.29	2.034121	0.491613	0.19685	614.5247	0 246.999	2	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	0.13	16.43	2.132546	0.468923	0.229659	641.7918	0 243.083	2	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	0.15	16.5	2.001312	0.499672	0.229659	623.372	0 248.594	6	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	0.17	16.62	1.935696	0.51661	0.262467	643.5323	0 252.075	5	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	0.18	16.78	1.935696	0.51661	0.295276	618.0056	0 246.999	2	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	0 245.693	9		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	0 247.724	4		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	0 250.915	2		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	0 242.648	1		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	0.27	17.47	2.034121	0.491613	0.492126	709.2344	0 255.991	5		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	0 268.319	7		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	0 254.541	2		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	0 250.915	2		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	0 253.81	6		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	0 263.533	5		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	0 250.915	2		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	0 258.022	1		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	0 252.945	7		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	0 270.495	3		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	0 252.075	5		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	0 258.602	2		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	0 269.4	В		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	0 250.770	2		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	0 259.617	5		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	0 251.060	3		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	0 253.81	6		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	0 254.251	1		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	0 257.87	7		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	0 252.220	6		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	0 263.823	6		4/29/2020	0.6	20.13	3.47769	0.287547	3.576116	893.5773	0	376.0828			5/8/2020
Agreement	AME Pile I	Info Ent	er AME Pil	e Data	Enter Drill	Rig Data	Strength	Analysis Param	eters - Laye	Parameters - Threshold	Pile Sum	imary Report	GS-E	Deep	$(\div)$					•		Þ
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## 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	Н	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 <sup>2</sup> )	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 <sup>2</sup> )	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 Ent	ter Drill Rig Data Strength Analysis	Parameters - Layer Param	neters - Threshold Pile Summary	Report GS-Deep 🕂		: •	

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## Enter Drill Rig Data

	А	В	С	D	E	F	G	Н	I.	J	К	L	М	Ν	0
1					Torque Spe	ecifications						Crowd Specific	ations		
2	Drill Dig	Pig Type	Maximum Operating	Hydraulic Motor Disp	olacment, V <sub>g</sub> (in³/rev)	Hydraulic Flow	Gear Case	Reduction	# of Motors	Select Drill Rig		Specifications	Drill Rig 1	Drill Rig 2	
3	Drill Kig	Rig Type	Pressure, OP <sub>Max</sub> (psi)	Max	Min	Rate, Q (in <sup>3</sup> /min)	Gear 1	Gear 2		(1 or 2)		F <sub>Max</sub> (lbf)	78,683	89,924	
4	1	Generic A	5,000	10.00	5.00	35,000	160.0	80.0	2	2		OP <sub>Max</sub> (psi)	5,000	4,500	
5	2	Generic B	4,500	9.00	4.00	30,000	150.0	75.0	2	<b>∠</b>		Baseline Pressure, BP (psi)	0	0	
												Crowd Conversion	M     N       pecifications     Drill Rig 1     Drill       78,683     89,5     5,000     4,5       (psi)     0     (0     (0       n     15.74     19.     19.		
6												Coefficient, K <sub>F</sub> (lbf/psi)	15.74	19.98	
7	Drill Rig	Gear	N <sub>min</sub> (RPM)	N <sub>max</sub> (RPM)	T <sub>min</sub> (in-lbs)	T <sub>max</sub> (in-lbs)	Torque Che	ck - Drill Rig 1	Torque Che	ck - Drill Rig 2	.		L     M     N       Crowd Specifications     Drill Rig 1     Drill F       Max (lbf)     78,683     89,5       PMax (psi)     5,000     4,50       Pressure, BP (psi)     0     0       I Conversion     15.74     19.3		
8	1	1	11	22	1,273,240	2,546,479	N (RPM)	P (psi)	N (RPM)	P (psi)			L M N   Crowd Specifications Specifications Drill Rig 1 Drill   F <sub>Max</sub> (lbf) 78,683 89,5   OP <sub>Max</sub> (psi) 5,000 4,5   line Pressure, BP (psi) 0 0   crowd Conversion 15.74 19.		
9		2	22	44	636,620	1,273,240	18	4,500	18	4,500					
10	2	1	11	25	859,437	1,933,733	T (in-lbf)	T (ft-lbf)	T (in-lbf)	T (ft-lbf)					
11	2	2	22	50	429,718	966,866	1,392,606	116,050.5	1,193,662	99,471.8					
13     14     15     16     17     18     19     20     21     22     23     24     25     26     27     28     29     200	3,00 2,50 (sq 2,00 L 1,50 1,00 50	0,000 0,000 0,000 0,000 0,000 0,000 0,000 0 0 0 0	Generic A	• 1 ransition (N,T); 22; 1,273,240 Ma 30 40 eed, N (RPM)	iorque Check	3,000,000 2,500,000 2,000,000 1,500,000 500,000 0 0	Ge 10 20 Rot	Transition (N 25; 859,43 ) 30 30 tational Speed, N (RF	Torque Che Torque Che Max RPM = 5 A0 50 YM)	ck 0 60					
-50	> Agreem	ent AME Pile Info	Enter AME Pile Data	a Enter Drill Rig Da	ata Strength Analy:	sis Parameters - Lay	/er Parameters -	Threshold Pile Su	mmary Report   GS-	Deep 🕘			:	1;	5
													F		

### Strength Analysis Tab – Specific Energy

	Α	В	C C	E	F	G	н	I.	J	K L	. М	Ν	0	Р	Q	R	S
1	Pile	Pile Segment	ΔZ Increment (cm)			Specific E	nergy, e (psi	) - All Data						Pile Information	ו		
2	5	8	1	Mean	Median	Standard	Coefficient	Maximum	Minimum	Count	Pile ID	Pile Elev	vations (ft)	Pile Length	Layer Elev	ations (ft)	Drill Bit
3	e Threshold (psi)	e Reduction (psi/ft)	MWD Assessment	wear	weulan	Deviation	of Variation	Maximum	winnun	count	File ID	Top of Pile	Bottom of Pile	(ft)	Тор	Bottom	Diameter (ft)
4	0	0.0	ISO Class 1	3,095	2,134	7,286	2.35	280,309	603	3,702	Pile 5	10.29	-111.20	121.49	-30.7	-35.7	2.5
5																	
6	Pile	Segments and Elevat	tions		Speci	fic Energy, e	(psi) - All Da	ta - Layer An	alysis		s	Specific Energy - A	II Data		Specific En	ergy - All Data	
7	Pile Segment	Elevation 1 (ft)	Elevation 2 (ft)	Mean	Median	Std. Dev.	cv	Maximum	Minimum	Count	20				e - All Da	tae_laver	
8	1	3.60	-0.7	1,812	1,928	355	0.20	2,322	1,329	131				40.00	0 748 84	u 0 2490	
9	2	-0.7	-5.7	1,267	1,271	64	0.05	1,436	1,104	153			•	100%			
10	3	-5.70	-10.7	1,128	1,116	38	0.03	1,264	1,072	152		<b>.</b>	•	90%			
11	4	-10.7	- <mark>1</mark> 5.7	1,263	1,244	55	0.04	1,410	1,184	153	0			5 80%			
12	5	-15.70	-20.7	1,271	1,286	118	0.09	1,567	1,108	152	<b></b>			90 /0%			
13	6	-20.7	-25.7	2,996	2,229	2,203	0.74	10,068	1,063	152				B 60%			
14	7	-25.70	-30.7	3,862	2,903	4,165	1.08	47,387	2,398	153				E 50%			
15	8	-30.7	-35.7	6,586	6,033	1,784	0.27	12,529	3,947	152	-20			.ita 40%			
16	9	-35.70	-40.7	3,213	2,550	1,250	0.39	6,450	2,034	153		Seedle .		1 30%			
17	10	-40.7	-45.7	1,881	1,951	219	0.12	2,295	1,509	152				5 20%			
18	11	-45.70	-50.7	1,753	1,652	295	0.17	2,723	1,4/3	152		206 2		10%			
19	12	-50.7	-00.7	1,911	1,790	503	0.26	4,418	1,465	103	-40			0%	5 0 00 10 000	15 000 20 000	25 000 30 000
20	10	-00.70	-00.7	1,905	1,007	200	0.27	3,900	1,475	152	Ê			ll ř	Specif	ic Energy, e (psi)	20,000 00,000
21	14	-60.7	-63.7	2,303	2,242	399	0.17	3,207	1,794	153	io 🕨						
22	16	-03.70	-70.7	2,302	2,244	321	0.17	3,401	1,730	152	evat	•					
23	10	-10.1	-13.1	2,002	2,020	521	0.15	0,001	1,740	102	шт <sub>-60</sub>	•			Specific En	ergy - All Data	
25											-00				■e - All Da	ta 📕 e - Layer	
26														60%			
27											5						
28											-80			50%			
29														S 40 %			
30													••••	5 20 8			
31											1			ant 30 %			
32											-100			ë 20%			
33												5		10%			
34											• 6		••	10 %			
35														0%			
36											-120			250	750 250 750 000	250 250 250 250 250 250 250 250 250 250	000
37											0	5,000 10,000 15,000 2	20,000 25,000 30,000	- 0	1 6 7 6 5 3 1	11 15 15 17 17	18 20 30 50 50 50 50 50
38												Specific Energy	, e (psi)		Speci	fic Energy, e (psi)	
39																	
40																	
41																	
42									and Theorem 1.1	pile our	- Den et l						4.4
	Agreemen	t AME Pile Info Ei	nter AME Pile Data Ente	er Drill Rig Data	Strength A	naiysis Par	améters - Laye	r Paramete	rs - Threshold	Pile Summa	ry Report	GS-Deep (+)			÷ .		14

## Strength Analysis Tab – Specific Energy

	А	В	C C	E	F	G	н	I.	J	K L	м	N	0	Р	Q	R	S
1	Pile	Pile Segment	ΔZ Increment (cm)			Specific E	inergy, e (psi	) - All Data						Pile Information	ı		
2	9	8	1	Mean	Modian	Standard	Coefficient	Maximum	Minimum	Count	Bile ID	Pile Elev	ations (ft)	Pile Length	Layer Elev	ations (ft)	Drill Bit
3	e Threshold (psi)	e Reduction (psi/ft)	MWD Assessment	wean	Wettan	Deviation	of Variation	waximum	winninum	Count	File ID	Top of Pile	Bottom of Pile	(ft)	Тор	Bottom	Diameter (ft)
4	0	0.0	ISO Class 1	3,727	2,376	11,105	2.98	488,901	969	3,699	Pile 9	10.86	-110.63	121.49	-30.7	-35.7	2.5
5																	
6	Pile	Segments and Elevat	tions		Speci	ific Energy, e	e (psi) - All Da	ta - Layer An	alysis		5	Specific Energy - A	II Data		Specific Er	nergy - All Data	
7	Pile Segment	Elevation 1 (ft)	Elevation 2 (ft)	Mean	Median	Std. Dev.	cv	Maximum	Minimum	Count	20					atae Laver	
8	1	3.6	-0.7	2,210	1,943	916	0.41	8,251	1,497	131						ata — c - Layer	
9	2	-0.7	-5.7	1,276	1,296	146	0.11	1,509	1,011	152				100%			
10	3	-5.7	-10.7	1,131	1,160	96	0.08	1,264	969	153				90%		· · · · · ·	
11	4	-10.7	-15.7	1,198	1,195	43	0.04	1,305	1,108	152	0			లి 80% సా	1		
12	5	-15.7	-20.7	1,253	1,258	50	0.04	1,347	1,156	152	ľ ľ			0 70%	/		
13	6	-20.7	-25.7	1,966	1,963	1,167	0.59	9,420	1,114	153				<b>글</b> 60%	/ /		
14	7	-25.7	-30.7	2,063	2,014	327	0.16	3,558	1,455	152				둔 50%	/ /		
15	8	-30.7	-35.7	15,797	10,541	23,714	1.50	238,445	3,295	153	20			. <u>Å</u> 40%			
16	9	-35.7	-40.7	3,950	3,461	1,789	0.45	14,874	1,973	152	-20			별 30%			
17	10	-40.7	-45.7	1,822	1,803	291	0.16	3,409	1,309	152				5 20%			
18	11	-45.7	-50.7	1,623	1,398	698	0.43	5,769	1,257	153		- V PCR - 1.	8- 1 * * *	10%			
19	12	-50.7	-55.7	1,596	1,492	418	0.26	3,427	1,311	152				0%			
20	13	-55.7	-60.7	1,764	1,309	1,575	0.89	14,407	1,236	153	£ -40			0	5,000 10,000	15,000 20,000	25,000 30,000
21	14	-60.7	-65.7	2,523	2,308	837	0.33	6,814	1,685	152	, L				Speci	fic Energy, e (psi)	
22	15	-65.7	-70.7	3,357	2,471	9,269	2.76	116,196	1,432	152	atio						
23	16	-70.7	-75.7	5,047	3,551	6,260	1.24	59,907	2,591	153	E C				Specific Er	nergy - All Data	
24											-60				e - All D	ata e.laver	
25												C •		45.04			
26	Soil	-5.0	-20	1,187	1,202	90	0.08	1,347	969	457		100 at ate		45%			
27														40%			
28											-80 -	Starts See 2	•	33% © 20%			
29												100.53	• •	e_ 30% ≥ ace			
30												7	•	0 25% 9 20%			
21												(		D 159			
22											-100			L 10%			
34													•	10 % E9/			
35												-953m/	• • • •	5%	In the state of the		
36														0 G G	0 0 0 0 0 0 0	8888888	888888
37											-120			1,2,	3,7 5,0 8,7 8,7 8,7 8,7	2 2 2 2 2 2	800000
38											0	5,000 10,000 15,000 2	20,000 25,000 30,000		-		20.430
39												specific Energy,	e (psi)	11	Spec	cific Energy, e (psi)	
40		1		•										-			
41																	
42																	
	Agreemen	t AME Pile Info E	nter AME Pile Data Ente	er Drill Rig Data	Strength A	nalysis Pa	rameters - Laye	r Paramete	ers - Threshold	Pile Summa	ry Report	GS-Deep 🔶			: [	(	15

### Parameters – Layer

#### Rock Layer

	·	Summary	of Statistics	- Layer		
Statistics	Ν	Т	u	F	Compo	ound
Statistics	(RPM)	(in-lbs)	(in/min)	(lbf)	u/N	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



- 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
- This information will be used to build a "drilling index" to distinguish soil from rock automatically – Similar to CPT

#### Soil Layer

		Summary	of Statistics	- Layer		
Statistics	Ν	Т	u	F	Compo	ound
Statistics	(RPM)	(in-lbs)	(in/min)	(lbf)	u/N	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



### Strength Analysis – Specific Energy – Above Threshold

- 4	А	В	СТ	U	V	W	х	Y	Z	AA A	AC		AD	AE	AF	AG	AH	AI A
1	Pile	Pile Segment	ΔZ Increment (cm)		Specific	Energy, e (p	si) - Above T	hreshold - Er	ntire Pile						Pile Informatio	n		
2	9	8	1	Mean	Median	Standard	Coefficient	Maximum	Minimum	Count	Pile		Pile Eleva	tions (ft)	Pile Length	Layer Elev	ations (ft)	Drill Bit
3	e Threshold (psi)	e Reduction (psi/ft)	MWD Assessment		inculuit	Deviation	of Variation			oount	, ne i	-	Top of Pile	Bottom of Pile	(ft)	Тор	Bottom	Diameter (ft)
4	2,000	0.0	ISO Class 1	5,309	3,195	14,204	2.68	488,901	2,002	2,194	Pile	9	10.86	-110.63	121.49	-30.70	-35.70	2.50
5																		
6	Pile	Segments and Elevat	tions		Specific E	nergy, e (psi)	- Above Thr	reshold - Lay	er Analysis		s	pecific	Energy - Above	Threshold		Specific Energy	y - Above Thresh	old
7	Pile Segment	Elevation 1 (ft)	Elevation 2 (ft)	Mean	Median	Std. Dev.	cv	Maximum	Minimum	Count	20					e - Above - All D	, atae_Above	laver
8	1	3.6	i -0.7	2,786	2,527	1,115	0.40	8,251	2,026	59					1000	e - Above - All D	ala — e - Above	- Layer
9	2	-0.7	-5.7	0	0	0	0.00	0	0	0		-	• •		100%			
10	3	-5.7	-10.7	0	0	0	0.00	0	0	0		5			90%			
11	4	-10.7	-15.7	0	0	0	0.00	0	0	0	0	6	•		e 80%	(		
12	5	-15.7	-20.7	0	0	0	0.00	0	0	0	-				0 70%	/		
13	6	-20.7	-25.7	2,779	2,458	1,266	0.46	9,420	2,101	72					₽ <sup>60%</sup>	1 /		
14	7	-25.7	-30.7	2,289	2,292	295	0.13	3,558	2,014	77					E 50%	1 /		
15	8	-30.7	-35.7	15,797	10,541	23,714	1.50	238,445	3,295	153	-20				A10%	1 /		
16	9	-35.7	-40.7	3,990	3,558	1,785	0.45	14,874	2,162	149	-20		•		an 30%	1 /		
17	10	-40.7	-45.7	2,201	2,133	240	0.11	3,409	2,015	38					5 20%	/ /		
18	11	-45.7	-50.7	3,548	3,388	1,425	0.40	5,769	2,179	12		14		•••	10%			
19	12	-00.7	-55.7	2,741	3,111	6/8	0.25	3,427	2,047	13	40	2			0%	5 0 00 40 000	45.000 20.000	25,000, 20,000
20	13	-00.7	-60.7	3,498	2,487	3,078	0.88	14,407	2,192	29	8				l v	5,000 10,000 Spec	ific Energy e (nei)	25,000 30,000
21	14	-60.7	-65.7	2,009	2,401	10.270	0.32	116 106	2,013	121	ы					3466	ine Energy, e (pai)	
22	10	-00.7	-70.7	5,717	2,007	6 260	2.11	50,007	2,015	123	vati							
25	10	-70.7	-13.1	3,047	3,331	0,200	1.24	39,907	2,391	155	e					Specific Energy	y - Above Thresh	old
24											-60					e - Above - All D	ata 📕 e - Above - L	ayer
25	Soil	-5.0	-20	0	0	0	0.00	0	0	0		5			45%			
27	001	-0.0	-20				0.00		, v			100	•••••••••••••••••••••••••••••••••••••••	•	40%			
28												~			35%			
29											-80	1997	121	•	\$ 30%			
30												1.0	37		a 25%			
31												7			9 20%			
32												T			9 15%			
33											-100	L			10%			
34												17		2	5%			
35														•	0%		ورار ار ار او او ا	
36															20	22 22 22 20 20 20 20 20 20 20 20 20 20 2	8 8 8 8 8 8 8	0 0 0 0 0 0 0
37											-120	0 1	0 000 20 000 20 0	0 40 000 50 000	5	3,550,25,0	112511125	18,7 20,0 50,0 00,0
38												0 1	Specific Energy	e (nsi)		Sna	cific Energy e (nei)	
39													opeenie Energy,	e (pai)		ape	cine Lifergy, e (pai)	
40																		
41																		
42					_													
-	Agreemen	t AME Pile Info Er	nter AME Pile Data Ente	r Drill Rig Data	Strength A	nalysis Par	ameters - Laye	er Paramete	ers - Threshold	Pile Summa	ry Report	GS	-Deep 🕘			÷ •		
5		1		-	-			1								F		
																	_	17

### Parameters – Threshold

Su	mmary of	Statistics - A	Above Spec	ific Energy	Threshold	d
Statistics	Ν	Т	u	F	Comp	ound
Statistics	(RPM)	(in-lbs)	(in/min)	(lbf)	u/N	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
Su	mmary of	Statistics - I	Below Spec	ific Energy	Threshold	b
Statistics	mmary of N	Statistics - I T	<mark>Below Spec</mark> u	<mark>ific Energy</mark> F	Threshold Comp	d ound
Su Statistics	mmary of S N (RPM)	<mark>Statistics - I</mark> T (in-Ibs)	<mark>Below Spec</mark> u (in/min)	<mark>ific Energy</mark> F (lbf)	<mark>/ Threshold</mark> Comp u/N	d oound T/u
Su Statistics Mean	mmary of 5 N (RPM) 41.5	Statistics - I T (in-Ibs) 488,242	Below Spec u (in/min) 127.5	ific Energy F (Ibf) 17,561	Threshold Comp u/N 3.13	d ound T/u 3,946
Su Statistics Mean Median	mmary of 5 N (RPM) 41.5 43.2	Statistics - I T (in-Ibs) 488,242 463,630	Below Spec u (in/min) 127.5 126.0	ific Energy F (Ibf) 17,561 18,928	Threshold Comp u/N 3.13 2.95	d oound T/u 3,946 3,639
Statistics Mean Median Stand. Dev.	mmary of 5 N (RPM) 41.5 43.2 6.1	Statistics - I T (in-Ibs) 488,242 463,630 127,655	Below Spec u (in/min) 127.5 126.0 22.3	ific Energy F (Ibf) 17,561 18,928 6,576	Threshold Comp u/N 3.13 2.95 0.66	d ound T/u 3,946 3,639 1,270
Statistics Mean Median Stand. Dev. CV	mmary of N (RPM) 41.5 43.2 6.1 0.15	Statistics - I T (in-Ibs) 488,242 463,630 127,655 0.26	Below Spec u (in/min) 127.5 126.0 22.3 0.17	ific Energy F (lbf) 17,561 18,928 6,576 0.37	Threshold Comp u/N 3.13 2.95 0.66 0.21	d ound T/u 3,946 3,639 1,270 0.32
Statistics Mean Median Stand. Dev. CV Maximum	mmary of 5 N (RPM) 41.5 43.2 6.1 0.15 50.4	Statistics - I       T       (in-lbs)       488,242       463,630       127,655       0.26       1,060,084	Below Spec u (in/min) 127.5 126.0 22.3 0.17 165.4	ific Energy F (Ibf) 17,561 18,928 6,576 0.37 54,495	Threshold Comp u/N 3.13 2.95 0.66 0.21 5.33	d ound <u>T/u</u> 3,946 3,639 1,270 0.32 9,308
Statistics Mean Median Stand. Dev. CV Maximum Minimum	mmary of N (RPM) 41.5 43.2 6.1 0.15 50.4 22.8	Statistics - I       T       (in-lbs)       488,242       463,630       127,655       0.26       1,060,084       293,630	Below Spec u (in/min) 127.5 126.0 22.3 0.17 165.4 63.0	ific Energy F (lbf) 17,561 18,928 6,576 0.37 54,495 -1,816	Threshold Comp u/N 3.13 2.95 0.66 0.21 5.33 1.59	d ound 7/u 3,946 3,639 1,270 0.32 9,308 2,415

• This information will be used to build a "drilling index" to distinguish soil from rock automatically – Similar to CPT





### Strength Analysis – Unconfined Compressive Strength

- 44	A Dit-	Dillo Commont			AL Comm	Alvi		Above Three	AP	AQ A		AI	AU	Av Dile Informatio	AVV	AA	AT /
1	Pile	Plie Segment		Uncor	inned Comp	Oten dend	igin, q <sub>u</sub> (psi)	- Above mile	shold - Entire	erne		Dile Elev	(ations (ff)	Dila Lanath	II I I I I I I I I I I I I I I I I I I	a (ff)	Deill Dit
2	9 Threehold (nei)	8 Deduction (noi/ft)		Mean	Median	Standard	Coefficient	Maximum	Minimum	Count	Pile ID	Ten of Dile	Valions (IL)	Plie Length		s (IL)	Drill Bit
3	e inresnoid (psi)		WWD Assessment	005	010	Deviation	of variation	7 620	427	0.104	Dile 0	10 00 01 010	Bottom of Pile	(II) 101.40	10p BC	25 70	Diameter (ft)
4	2,000	0.0	150 Class I	295	212	321	1.11	7,632	197	2,194	File 5	10.66	-110.65	121.49	-30.70 -0	35.70	2.50
5	Dile	Commente and Elevati		Unconfi	ned Compre	coive Strengt	the (nei)	hove Three	hold lover	nalysia							
6	File	Segments and Elevati	ons	Unconii	ned Compre	ssive strengt	un, q <sub>u</sub> (psi) - A	bove mies	nolu - Layer A	indiysis		q <sub>u</sub> - Above Thres	shold		q <sub>u</sub> - Above Thre	eshold	
7	Pile Segment	Elevation 1 (ft)	Elevation 2 (ft)	Mean	Median	Std. Dev.	CV	Maximum	Minimum	Count	20				🛏 qu - Above - All Data 🛛 🛁	🗕 qu - Above -	Layer
8	1	3.6	-0.7	185	171	63	0.34	488	139	59				100%			
9	2	-0.7	-5.7	0	0	0	0.00	0	0	0		•		90%	a contraction of the second se		
10	3	-5.7	-10.7	0	0	0	0.00	0	0	0	<b>_</b>			ê 80%	1 1		
11	4	-10.7	-15.7	0	0	0	0.00	0	0	0	0 🏎			2 70%	1 /		
12	5	-15.7	-20.7	0	0	0	0.00	0	0	0				9 60 %	1		
13	6	-20.7	-25.7	184	166	/0	0.38	545	144	72				<u>50%</u>			
14	0	-20.7	-30.7	730	100	19 ECA	0.12	234	138	152				\$ 40%			
15	<b>0</b>	-30.7	-40.7	255	234	00	0.76	788	1/8	1/0	-20			10 30%			
17	10	-40.7	-40.7	150	1/6	15	0.09	225	140	38	r i			E 20%	I		
18	11	-45.7	-40.7	231	224	83	0.10	359	149	12	L			J 10%	¢		
19	12	-50.7	-55.7	183	207	42	0.03	226	140	13	2	P		0%	¢		
20	13	-55.7	-60.7	221	168	156	0.71	768	149	29	40			0	1,000 2,000	3,000	4,000 5,000
21	14	-60.7	-65.7	180	163	51	0.28	415	138	121	E L				Unconfined Compressi	ive Strength, o	ļu (psi)
22	15	-65.7	-70.7	211	173	285	1.35	3,286	138	123	tio						
23	16	-70.7	-75.7	299	233	237	0.79	2,150	175	153	eva				a Above Thre	eshold	
24											<sup>Ш</sup> -60 <b>г</b> .•				40 / 20010 / 1110		
25															■qu - Above - All Data ■c	qu - Above - La	iyer
26	Soil	-5.0	-20	0	0	0	0.00	0	0	0	L			50%			
27											r - R-	• -		45%			
28											-80 🛴			40%			
29														(% 35 % % 20 %			
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35														0%			
27											-120			10	000 20 20 20 20 20 20 20 20 20 20 20 20	200 200	00000000
38											0	2,000 4,000 6,	000 8,000 10,000		-	-0000	0 4 4 3 7 0
39											Un	confined Compressive	e Strength, qu (psi)	11	Unconfined Compress	sive Strength,	qu (psi)
40		I				I I											
41																	
42																	
	Agreement	t AME Pile Info En	ter AME Pile Data Ente	r Drill Rig Data	Strength A	nalysis Para	ameters - Laver	Paramete	rs - Threshold	Pile Summa	Irv Report	GS-Deep			: 1		
	Agreement		Enterne Data Ente	. e.m.rug eatu		, and a second second	anisters cayer	- arantete	in conord	The summe						= m	-

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

### Strength Analysis – Side Shear and Shaft Capacity

4	A	В	C A	G BA	BB	BC	BD	BE	BF	BG	Bł Bl	BJ	BK	BL	BM	BN	BO
	Pile	Pile Segment	ΔZ Increment (cm)		Side Shear	and Shaft Ca	pacity - Abov	e Threshold	- Entire Pile				F	Pile Information	n		
2	9	8	1	e (nsi)	au (psi)	f (kef)	I (ff)	L . (ft)	P (kinc)	*f (kcf)	Pile ID	Pile El	evations (ft)	Pile Length	Layer El	evations (ft)	Drill Bit
3	e Threshold (psi)	e Reduction (psi/ft)	MWD Assessment	e (psi)	qu (psi)	15 (K31)	Epile (14)	Frock (IL)	г (кірэ)	15 (K31)	File ID	Top of Pile	Bottom of Pile	(ft)	Тор	Bottom	Diameter (ft)
1	2,000	0.0	ISO Class 1	5,309	295	8.3	121.5	72.0	4,719	4.9	Pile 9	10.86	-110.63	121.49	-30.70	-35.70	2.50
	Pile	Segments and Elevati	ions	S	ide Shear an	d Shaft Capa	acity - Above	Threshold - I	ayer Analysi	s		Side SI	near Profile			q <sub>u</sub> - Above Thresh	old
	Pile Segment	Elevation 1 (ft)	Elevation 2 (ft)	Count	e <sub>AVG</sub> (psi)	q <sub>u-AVG</sub> (psi)	f <sub>s-AVG</sub> (ksf)	L <sub>rock</sub> (ft)	P (kips)	*f₅ (ksf)	20				20		
	1	10.9	-0.7	278	3,555	232	6.8	9.1	488.4	5.4	20						
	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					- I		
_	4	-10.7	-15.7	0	0	0	0.0	0.0	0.0	0.0	0				ο 🖕		
	5	-15.7	-20.7	0	0	0	0.0	0.0	0.0	0.0	Ŭ						
_	6	-20.7	-25.7	72	2,779	184	5.5	2.4	102.6	2.6							
	/	-25.7	-30.7	152	2,290	106	4.8	2.5	94.3	2.4							
	0	-30.7	-35.7	153	3 001	739	7.4	5.0	285.6	7.0	-20	_			-20		
-	9 10	-30.7	-40.7	149	2 202	200	1.4	4.9	200.0	1.0					r		
	11	-40.7	-40.7	12	3 549	231	6.8	0.4	21.0	0.5							
	12	-40.7	-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	₽ -40				-40		
	14	-60.7	-65.7	121	2,689	180	5.4	4.0	168.7	4.3					E I		
	15	-65.7	-70.7	123	3,718	211	6.2	4.0	195.4	5.0	율				tion		
	16	-70.7	-75.7	153	5,047	299	8.5	5.0	335.9	8.5	eva 🕇				eva –		
	17	-75.7	-80.7	71	3,008	199	5.9	2.3	108.7	2.8	ū -60 🔜				ш -60 <b>г</b>		
	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					L.		
_	20	-90.7	-95.7	152	3,080	205	6.1	5.0	239.0	6.1					<b>.</b> .		
	21	-95.7	-100.7	153	2,510	170	5.1	5.0	202.9	5.1	-80				-80	••	
_	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	-				· · ·		
											-100				-100		
-																	
											_				<b>1</b> 22	• • •	•
											100						
											-120	5	10 15 7	20 25	-120		
											0	Unit	Ride Shear f /keft	20 20	0	2,000 4,000 6,00	00 8,000 10,000
												Unit	side sileal, is (KSI)		Unco	nined Compressive	strength, qu (psi)
				*fs	= Adjusted s	ide shear ba	sed on cumu	lative length	of rock soc	ket							
ſ	Agreement	t AME Pile Info En	ter AME Pile Data Ente	er Drill Rig Data	Strength A	nalysis Par	rameters - Layer	Paramete	rs - Threshold	Pile Summa	ary Report	S-Deep (	Ð			•	
	-	1		-				1		1							

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

## Strength Analysis – Side Shear and Shaft Capacity

4	A	В	C A	A BA	BB	BC	BD	BE	BF	BG	Bł Bl		BJ	BK	BL	BN	4 1	BN	BO
	Pile	Pile Segment	ΔZ Increment (cm)		Side Shear a	nd Shaft Ca	pacity - Abov	e Threshold	- Entire Pile					F	Pile Informati	on			
	9	Upper	1	o (nci)	au (nci)	f (kef)	1 (ft)	1 (64)	P (kinc)	*f (kcf)	Bile ID		Pile Elev	ations (ft)	Pile Length	Lay	er Eleva	ions (ft)	Drill Bit
	e Threshold (psi)	e Reduction (psi/ft)	MWD Assessment	e (psi)	qu (psi)	1 <sub>5</sub> (K31)	Epile (IL)	Frock (III)		15 (K31)	File IL	· 1	Top of Pile	Bottom of Pile	(ft)	То	ρ	Bottom	Diameter (ft)
	2,000	0.0	ISO Class 1	5,309	295	8.3	121.5	72.0	4,719	4.9	Pile 9	)	10.86	-110.63	121.49	10.5	36	-70.70	2.50
	Pile	Segments and Elevati	ons	S	ide Shear and	d Shaft Capa	acity - Above	Threshold - I	ayer Analysi	s			Side She	ar Profile		1	<b>q</b> <sub>u</sub> - /	Above Thres	hold
	Pile Segment	Elevation 1 (ft)	Elevation 2 (ft)	Count	e <sub>AVG</sub> (psi)	q <sub>u-AVG</sub> (psi)	f <sub>s-AVG</sub> (ksf)	L <sub>rock</sub> (ft)	P (kips)	*f₅ (ksf)	20					20			
	1	10.9	-0.7	278	3,555	232	6.8	9.1	488.4	5.4	20					1			
	2	-0.7	-5.7	0	0	0	0.0	0.0	0.0	0.0			_			1			
	3	-5.7	-10.7	0	0	0	0.0	0.0	0.0	0.0						1	<b>[</b>		
_	4	-10.7	-15.7	0	0	0	0.0	0.0	0.0	0.0	0					0	L		
_	5	-15.7	-20.7	0	0	0	0.0	0.0	0.0	0.0	Ŭ					1			
	6	-20.7	-25.7	72	2,779	184	5.5	2.4	102.6	2.6						1			
_	/	-25.7	-30.7	11	2,290	156	4.8	2.5	94.3	2.4						1			· · · · · · · · · · · · · · · · · · ·
	ŏ 0	-30.7	-35.7	153	10,798	739	19.4	5.0	766.2	19.4	-20					-20			
	9	-30.7	-40.7	149	2,991	200	1.4	4.9	200.0	1.3						1	r		
	11	-40.7	-43.7	12	2,202	231	4.0	1.2	40.0	0.5						1			
	12	-40.7	-55.7	12	2 7/2	183	5.5	0.4	18.5	0.5						1	27 ···		
	13	-55.7	-60.7	29	3 498	221	6.5	1.0	48.3	12	₽ -40					-40			
	14	-60.7	-65.7	121	2 689	180	5.4	4.0	168.7	4.3	E E					(#)			
	15	-65.7	-70.7	123	3,718	211	6.2	4.0	195.4	5.0	Ę					tion	<b>_</b>		
	16	-70.7	-75.7	153	5.047	299	8.5	5.0	335.9	8.5	i va	Ц				eva	•		(
	17	-75.7	-80.7	71	3,008	199	5.9	2.3	108.7	2.8	<b>₩</b> -60		_			-60 -60			
	18	-80.7	-85.7	145	8,033	444	12.2	4.8	456.3	11.6			<u> </u>						
	19	-85.7	-90.7	152	4,428	279	8.1	5.0	315.6	8.0						1			
	20	-90.7	-95.7	152	3,080	205	6.1	5.0	239.0	6.1						1	<b>1</b> • • •		
	21	-95.7	-100.7	153	2,510	170	5.1	5.0	202.9	5.1	-80					-80			
	22	-100.7	-105.7	152	3,311	215	6.3	5.0	248.4	6.3							<b>1</b>	•	
	23	-105.7	-110.7	151	13,552	560	14.9	5.0	578.1	14.7						1	5.		
																1			
											-100					-100			
	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						1	22		•
																1			
_											-120					-120			
												0	5 10	0 15 2	20 25		0 2,000	4,000 6,0	00 8,000 10,000
													Unit Sid	de Shear, f₅ (ksf)		1	Unconfine	1 Compressive	Strength, qu (psi)
				*fc	= Adjusted si	da shaar ba	ased on cumu	lative length	of rock soc	ret						<u> </u>			
				15	- Aujusted Si	ue sileai Da	ised on cumu	auve lengu	TOTTOCK SOCI										
¢.,	Agreemen	nt AME Pile Info En	ter AME Pile Data Ente	er Drill Rig Data	Strength Ar	nalvsis Pa	rameters - Laver	Paramete	rs - Threshold	Pile Summ	arv Report	GS-De	ep (+)				: 4		
	- Stating			j - ata															

# Pile Summary Report

- Project
- Location
- Engineer
- Pile ID
- Station
- Offset
- Top of Pile Elevation
- Drill Rig Identification
- Pile Diameter
- Pile Length
- Depth Increment Analyzed
- ISO-MWD Assessment Class
- Summary of Statistics for Specific Energy Above the e Threshold
  - Mean, median, standard deviation, CV, maximum, minimum, and number of data points
- Quality of Rock Socket Summary
  - Specific energy threshold value, total rock socket length based on the e Threshold, and the total specific energy based on the e Threshold
- Pile Installation Time Summary
- Side Shear and Shaft Capacity Estimates



#### ACIP Pile - MWD Summary Report

Project	Location	Engineer	Pile ID				
ACIP MWD	Miami, Florida	Michael Rodgers	Sample Data Set				
Station	Offset (ft)	Drill Rig	Drill Bit Diameter (in)				
100+00.01	10.00	Generic B	30				
Top of Pile Elevation (ft)	Pile Length (ft)	Depth Increment Analyzed (cm)	ISO-MWD Assessment				
10.74	134.48	1	Class 1				
Summary of Statistics - Specific	Energy Above Threshold, e (psi)	Pile Installation - Time Summary					
Mean	4,347	Drilling Time (min)	43.2				
Median	1,811	ReDrill Time (min)	2.3				
Standard Deviation	10,268	Idle Rotation Time (min)	16.3				
Coefficient of Variation (CV)	2.36	Idle Time (min)	82.2				
Maximum	345,556	Withdrawal Time (min)	3.4				
Minimum	23	Penetration w/o Rotation Time (min)	2.2				
Number of Data Points	3,992	Total Time (min)	149.7				
Quality of Rock	Socket Summary	Side Shear and Shaft Capacity Estimates					
Specific Energy Threshold (psi)	0	q <sub>u</sub> Threshold (psi)	0				
Fotal Rock Socket Length (ft)	131.0	Average Side Shear, fs (ksf)	6.73				
Total Specific Energy (kips)	643,949	Total Shaft Capacity, P (kips)	6,919				



Notes:

Enter notes in this section

### GeoStat Analyses

• Automatically populates rock strength data for Geostat (GS-Deep) Analyses

	A	В	С	D	E	F	G	н	- I	J	К	L	N
1	This tab r	nust be populate	d with data prior to loadi	ng GS-Deep.									
2													
3	Depth	Soil Type	N. Blows	Unit Weight	Cu qu	I	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/300mr	n pcf   kN/m^3	tsf   kPa tsf	i <b>k</b> Pa	tsf   kPa	tsf   kPa	ksi   MPa				
6	0.03	4		114	l I	48.0	6.7				1		1
7	0.07	4		95	5	15.1	L 2.6				1		1
8	0.10	4		95	5	15.1	L 2.6				1		1
9	0.13	4		88	8	9.1	l 1.7				1		1
10	0.16	4		88	8	9.1	l 1.7				1		1
11	0.20	4		87	1	8.9	1.7				1		1
12	0.23	4		85	j	7.8	3 1.5				1		1
13	0.26	4		85	5	7.8	3 1.5				1		1
14	0.30	4		86	i	8.0	1.5				1		1
15	0.33	4		86	i	8.0	1.5				1		1
16	0.36	4		86	i	8.0	1.5				1		1
17	0.39	4		84	L .	6.9	1.4				1		1
18	0.43	4		84	4	6.9	1.4				1		1
19	0.46	4		85	5	7.4	1.4				1		1
20	0.49	4		85	5	7.4	1.4				1		1
21	0.52	4		85	5	7.8	3 1.5				1		1
22	0.56	4		85	5	7.8	3 1.5				1		1
23	0.59	4		85	;	7.8	3 1.5				1		1
24	0.62	4		84	L	6.9	9 1.4				1		1
25	0.66	4		84	L	6.9	9 1.4				1		1
26	0.69	4		84	L	6.9	9 1.4				1		1
27	0.72	4		83	•	6.3	3 1.3				1		1
28	0.75	4		83	}	6.3	3 1.3				1		1
29	0.79	4		83		6.3	3 1.3				1		1
30	0.82	. 4		81	L	5.5	5 1.1				1		1
31	0.85	4		81	L	5.5	5 1.1				1		1
32	0.89	4		82	2	6.2	2 1.2				1		1
33	0.92	4		82	2	6.2	2 1.2				1		1
34	0.95	4		82	2	6.2	2 1.2				1		1
35	0.98	4		82	2	6.2	2 1.2				1		1
36	1.02	4		81		5.6	5 1.1				1		1
37	1.05	4		81	l l	5.6	5 1.1				1		1
38	1.08	4		81	L	5.6	5 1.1				1		1
		Agreement	AME Pile Info Ente	er AME Pile Data	Enter Drill Rig	Data :	Strength Analysis	s Param	neters - Layer	Parameters - Threshold	Pile Summary Report	GS-Deep 🕂	

## MWD "e" versus SPT "N"

- Compare MWD specific energy to SPT blow count profile
  - Drilling resistance vs. driving resistance
  - SPT blow counts obtained within the ACIP pile group or within proximity (≈50 ft)
- MWD profiles resemble the SPT profiles
  - Indicates MWD layering is correct
- Layering and strengths are different for each pile group
  - Separated by  $\approx$  2,200 feet



## Variability Over Short Distances

- Compare MWD "e" from pile group to load test MWD within proximity
  - Load test MWD 50' to 85' from adjacent pile group
- Variability observed within the 25' by 25' pile group
- Load test MWD shows similar layering as pile group MWD but does not always follow the average



# MWD versus Core Strengths (qu)

- Rock cores tested in unconfined compression (qu) are compared to MWD qu estimates.
  - ≈ 40,000 MWD qu strength assessments within 25' by 25' pile group
  - 23 core samples collected
- Some piles more closely resemble the core strength layering
  - Piles 1 and 5 separated by 7.5' center to center



Pile 1

Pile 5

3.000

Test Pile Core

## MWD "e" versus Load Test Side Shear

- Recently obtained 1<sup>st</sup> mobilized load test with MWD data
  - Pile segments above load cell were fully mobilized
    - 2.1" of displacement
  - Allows MWD to be directly compared to load test results to build or verify correlation
- Highly non-linear rigidity observed in pile and reported in load test results
- Difficult to compare smaller layers
  - Need to analyze the load test in larger layers to compensate for the highly non-linear rigidity
- Can compare whole upper pile segment to MWD
- Can break load test results into 3 larger layers w/ similar pile geometries for comparison with MWD
  - Komurka and Robertson (2020)
- Indicates drilled shaft rock auger equation may be valid for ACIP piles that use rock augers
  - Potential state-wide correlation for rock augers



# Load Test MultiPier Simulation using MWD Data

- Modeled the Test Pile in MultiPier using MWD strengths ( $q_u$  and  $f_s$ ) for each of the load test layers
  - Loaded the pile tip to simulate a load cell at midspan
  - Modeled pile diameters for each segment based on TIP results
- Used a prescribed displacement of 2.1"
  - Actual load test mobilized 2.1"
- Modeled pile was fully mobilized by a load of P = <u>2,128 kips</u>
- Load test reported the pile displaced ½ inch (0.35" to 0.84"@ LTA, 0.14" to 0.62" @ TOP) in 10 minutes while sustaining a load of 2,148 kips → Likely mobilized entire pile
  - $P = 2,253 \text{ kips} \rightarrow 2.1^{"} \text{ of displacement}$
  - 1.3" of displacement in 10 min under final load
- Supports the use of the drilled shaft rock auger equation for ACIP piles in rock



# Remaining Tasks

- Continue to establish the MWD specific energy vs. ACIP pile side shear relationship
- Validate the MWD correlation for ACIP production pile QA/QC
- 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?

- Komurka V. and Robertson S. 2020. Results and lessons learned from converting strain to internal force in instrumented static loading tests using the incremental rigidity method. ASCE Geo-Congress, GSP 315.
- 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.
- Teale, R. 1965. The concept of specific energy in rock drilling. International Journal of Rock Mechanics and Mining Science, 2(1), 57–73.