LRFD Resistance Factors for Auger Cast In-Place (ACIP) Piles

FDOT BDV31-977-12

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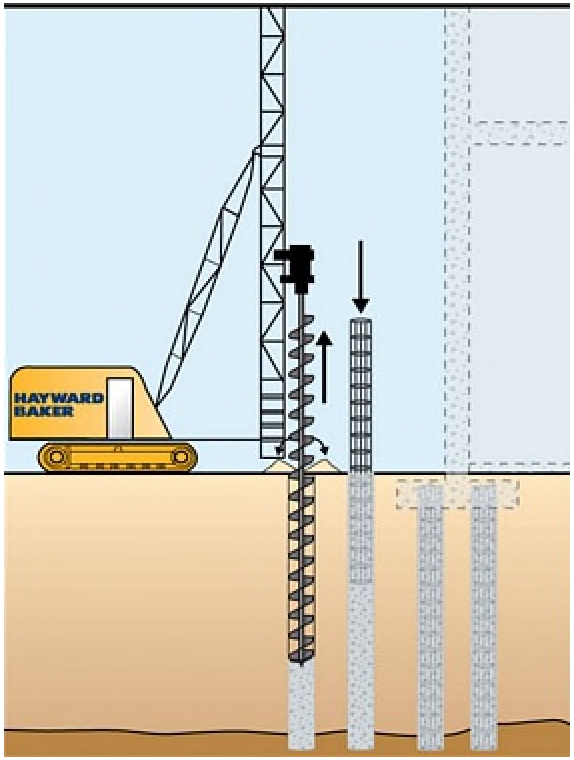
Background: Auger Cast in Place (ACIP) Piles

- Current FDOT use - Sound Walls
- Used in Commercial Sector for High Rises, Condos, etc.
- Other DOTs (e.g. Texas), FHWA (GEC No.8) Recommend for Bridge Foundations



Benefits:

- Minimal Vibrations vs. Pile Driving for Urban Settings
- Much Higher Capacities in Limestone (e.g. South Florida) vs. driven piles
- Cost savings vs. driven piles or drilled shafts

Tasks: Auger Cast in Place (ACIP) Piles

1. Letter of request for ACIP data (load tests, boring and laboratory data)

2. Review of current design methods for ACIPs

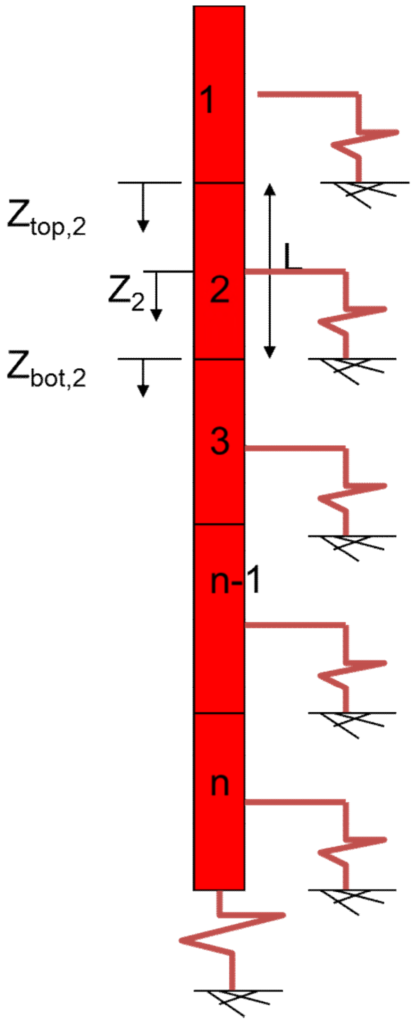
3. Evaluate ACIP design methods and LRFD Φ

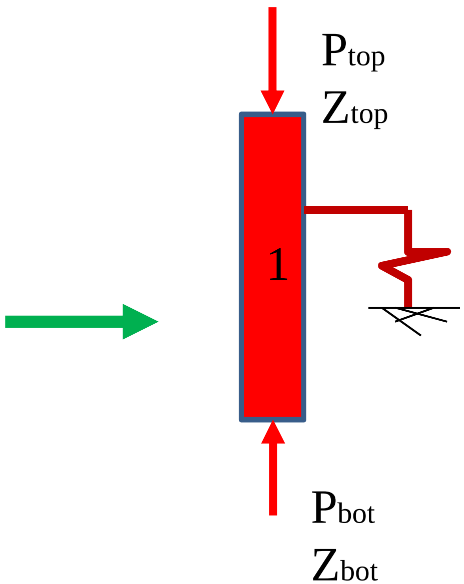
4. Provide recommendations for design and minimum number of load tests

Location	Project Name	Soil Type	Diameter (in)	Embedded Length (ft)	Test Type	Number of Load Test	Water Table Depth (ft)	Instrumentation	Peak Displacement Load Test (in)	Data Provider
Alachua	Alachua-1 TP-2	Clay & IGM	16	64	Static	14	29	Load-Deflection	0.085	Universal Sciences Engineering, Inc.
	Alachua-1 TP-3	Clay & IGM	16	64	Static		31	Load-Deflection	0.125	
	Alachua-1 TP-4	Clay & IGM	16	64	Static		26	Load-Deflection	0.183	
	Alachua-1 TP-5	Clay & IGM	16	64	Static		28	Load-Deflection	0.219	
	Alachua-2 TP-1	Clay	14	42	Static		4.5	Load-Deflection	0.288	
	Alachua-2 TP-2	Clay	14	42	Static		5	Load-Deflection	0.325	
	Alachua-2 TP-3	Clay	14	42	Static		6.5	Load-Deflection	0.295	
	Alachua-2 TP-5	Clay	14	42	Static		5	T-Z & Load-Defl.	0.341	
	Alachua-2 TP-XX-1	No Boring	14	42	Static		None	Load-Deflection	0.777	
	Alachua-2 TP-XX-2	No Boring	14	42	Static		None	Load-Deflection	0.460	
	Alachua-3 TP-1	Clay, Sand & IGM	14	15	Static		12	Load-Deflection	0.549	
	Alachua-5 TP-1	Sand & Clay	14	65	Static		6	T-Z & Load-Defl.	0.600	
	Alachua-5 TP-2	Sand & Clay	14	65	Static		6	T-Z & Load-Defl.	1.000	
	Alachua-5 TP-3	Sand & Clay	14	65	Tension		6	T-Z & Load-Defl.	0.088	
Broward	Broward-1 TP-1	Sand & IGM	18	102	Static	4	5.7	T-Z & Load-Defl.	0.344	Nodarse, A Terracon Company
	Broward-1 TP-2	Sand & IGM	18	102	Tension		5.7	T-Z & Load-Defl.	0.009	
	Broward-1 TP-5	Sand & IGM	30	140	Osterberg		1	O-Cell	0.400	
	Broward-2 TP-1	Sand & IGM	14	40	Static		None	Load-Deflection	0.350	Universal Sciences Engineering, Inc.
Duval	Duval-1 TP 1-2	Sand, Marl & Clay	16	55	Static	4	4.5	Load-Deflection	0.289	Langan Engineering & Environmental Services
	Duval-1 TP 2-2	Sand, Marl & Clay	16	54	Static		4.5	Load-Deflection	0.397	
	Duval-1 TP 3-2	Sand, Marl & Clay	18	54	Tension		4.5	Load-Deflection	0.192	
	Duval-1 TP 3-3	Sand, Marl & Clay	16	54	Static		4.5	Load-Deflection	0.267	
Hollywood	Hollywood-1 TP-1	No Boring	14	50	Static	3	No Boring	Load-Deflection	0.340	DunkelBerger Engineering & Testing
	Hollywood-2 TP-1	No Boring	14	48	Static		No Boring	T-Z & Load-Defl.	0.200	
	Hollywood-2 TP-2	No Boring	14	48	Tension		No Boring	T-Z & Load-Defl.	0.032	
Hillsborough	Hillsborough-2 TP-1	No Boring	14	40	Static	6	None	Load-Deflection	0.079	Applied Foundation Test, Inc.
	Hillsborough-3 TP-1	Sand and Clay	16	60	Static		5.2	T-Z & Load-Defl.	0.548	
	Hillsborough-3 TP-2	Sand and Clay	16	60	Statnamic		5.2	T-Z & Load-Defl.	0.939	
	Hillsborough-3 TP-3	Sand and Clay	16	60	Statnamic		5	T-Z & Load-Defl.	1.176	
	Hillsborough-3 TP-4	Sand and Clay	16	60	Statnamic		5	T-Z & Load-Defl.	0.760	
	Hillsborough-3 TP-5	Sand and Clay	16	67.4	Statnamic		4	T-Z & Load-Defl.	0.653	
Nassau	Nassau-1 TP14	Sand	14	60	Static	3	3.8	T-Z & Load-Defl.	0.385	Amec Foster Wheeler Enviroment & Infrastructure
	Nassau-2 TP-1	Sand	16	39	Static		3	Load-Deflection	0.300	
	Nassua-3 TP-1	Sand	14	65	Static		5	T-Z & Load-Defl.	0.200	
Palm Beach	Palm Beach-1 TP-9	No Boring	16	61	Static	2	None	T-Z & Load-Defl.	0.113	DunkelBerger Engineering & Testing
	Palm Beach-2 TP-8	No Boring	16	61	Static		None	T-Z & Load-Defl.	0.188	
Polk	Polk-1	Clay, Silt & Sand	18	65	Static	1	8.5	Load-Deflection	0.360	Ardaman & Associates, Inc
Santa Rosa	Santa Rosa-1 TP-1	Sand, Cayey Sand	24	47	Static	1	2.5	T-Z & Load-Defl.	0.465	
West Palm	West Palm-1 T2B	Sand	14	40	Tension	3	9	Load-Deflection	0.250	Universal Sciences Engineering, Inc.
	West Palm-1 T8	Sand	14	40	Tension		9	Load-Deflection	0.250	
	West Palm-1 T9B	Sand	14	40	Static		9	Load-Deflection	0.536	

Location	Project Name	Soil Type	Diameter (in)	Embedded Length (ft)	Test Type	Number of Load Test	Water Table Depth (ft)	Instrumentation	Peak Displacement Load Test (in)	Data Provider
Miami Dade	Miami Dade-1 TP-1	Sand & Limestone	16	43	Static	37	5	Load-Deflection	0.343	Amec Foster Wheeler Environment & Infrastructure
	Miami Dade-1 TP-2	Sand & Limestone	16	43	Tension		5	Load-Deflection	0.208	
	Miami Dade-5 TP-1	Sand & Limestone	14	30	Static		(+) 2.5	Load-Deflection	0.148	
	Miami Dade-5 TP-2	Sand & Limestone	14	30	Tension		(+) 2.5	Load-Deflection	0.270	
	Miami Dade-6 TP-1	Sand & Limestone	14	25	Static		Not measured	Load-Deflection	0.183	
	Miami Dade-6 TP-2	Sand & Limestone	14	40	Static		8	Load-Deflection	0.182	
	Miami Dade-6 TP-3	Sand & Limestone	14	40	Static		8	Load-Deflection	0.303	
	Miami Dade-6 TP-5	Sand & Limestone	14	40	Static		8	Load-Deflection	0.090	
	Miami Dade-6 TP-6	Sand & Limestone	14	40	Static		4	Load-Deflection	0.206	
	Miami Dade-6 TP-7	Sand & Limestone	14	40	Static		Not measured	Load-Deflection	0.060	
	Miami Dade-6 TP-8	Sand & Limestone	14	40	Static		Not measured	Load-Deflection	0.093	
	Miami Dade-6 TP-9	Sand & Limestone	14	40	Static		Not measured	Load-Deflection	0.142	
	Miami Dade-6 TP-10	Sand & Limestone	14	40	Static		Not measured	Load-Deflection	0.572	
	Miami Dade-6 TP-11	Sand & Limestone	14	23	Static		5.5	Load-Deflection	0.073	
	Miami Dade-6 TP-12	Sand & Limestone	14	23	Static		5.5	Load-Deflection	0.346	
	Miami Dade-6 TP-13	Sand & Limestone	14	50	Static		Not measured	Load-Deflection	0.072	
	Miami Dade-6 TP-14	Sand & Limestone	14	58	Static		8	Load-Deflection	0.182	
	Miami Dade-6 TP-15	Sand & Limestone	14	45	Static		7.5	Load-Deflection	0.119	
	Miami Dade-6 TP-16	Sand & Limestone	14	25	Static		5.5	Load-Deflection	0.115	
	Miami Dade-6 TP-17	Sand & Limestone	14	25	Static		5.5	Load-Deflection	0.135	
	Miami Dade-6 TP-18	Sand & Limestone	14	20	Static		4	Load-Deflection	0.115	
	Miami Dade-6 TP-19	Sand & Limestone	14	55	Static		8	Load-Deflection	0.192	
	Miami Dade-6 TP-20	Sand & Limestone	14	30	Static		9	Load-Deflection	0.091	
	Miami Dade-6 TP-21	Sand & Limestone	14	46	Static		12	Load-Deflection	0.110	
	Miami Dade-6 TP-22	Sand & Limestone	14	41	Static		12	Load-Deflection	0.058	
	Miami Dade-6 TP-23	Sand & Limestone	14	58.5	Static		10.5	Load-Deflection	0.560	
	Miami Dade-6 TP-24	Sand & Limestone	14	47	Static		4	Load-Deflection	0.182	
	Miami Dade-6 TP-25	Sand & Limestone	14	56	Static		10	Load-Deflection	0.095	
	Miami Dade-6 TP-26	Sand & Limestone	14	57	Static		10	Load-Deflection	0.296	
	Miami Dade-6 TP-27	Sand & Limestone	14	47	Static		11	Load-Deflection	0.053	
	Miami Dade-6 TP-28	Sand & Limestone	14	65	Static		8	Load-Deflection	0.408	
	Miami Dade-6 TP-29	Sand	14	56	Static		9	Load-Deflection	0.107	
	Miami Dade-6 TP-30	Sand & Limestone	14	56	Static		9	Load-Deflection	0.107	
	Miami Dade-6 TP-31	No Boring	14	44	Static		None	Load-Deflection	0.432	
	Miami Dade-7 TP-1	Sand & Limestone	18	41	Static		4	Load-Deflection	0.064	
	Miami Dade-7 TP-2	Sand & Limestone	18	41	Static		4	Load-Deflection	0.069	
	Miami Dade-8 TP-1	Sand, Silt & Limestone	14	52	Static		1	Load-Deflection	0.300	
	Total # of Test Piles					78	Total T-Z Curve	16		

Pile-Soil Transfer





Minimize $\varepsilon = \sum(\boldsymbol{p_i} - \overline{\boldsymbol{p}}_i)^2$

Subject to $\boldsymbol{y} \in [\boldsymbol{lb}, \boldsymbol{ub}]$

What's known:

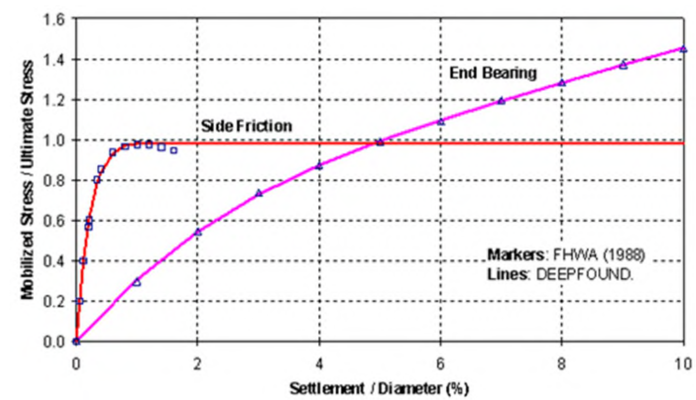
P_{top}; Z_{top}

What's unknown:

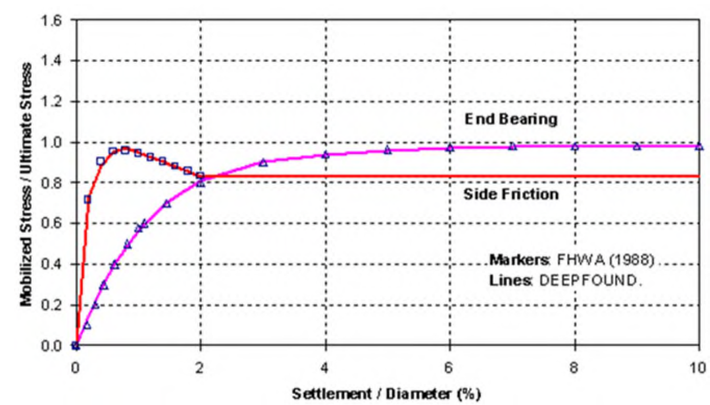
fs; layers, f_{tip}

Assumption:

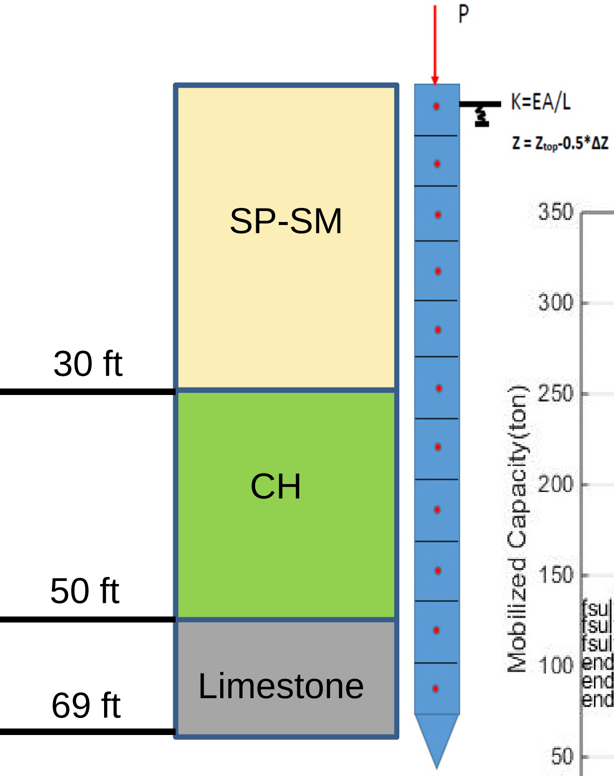
Sand:

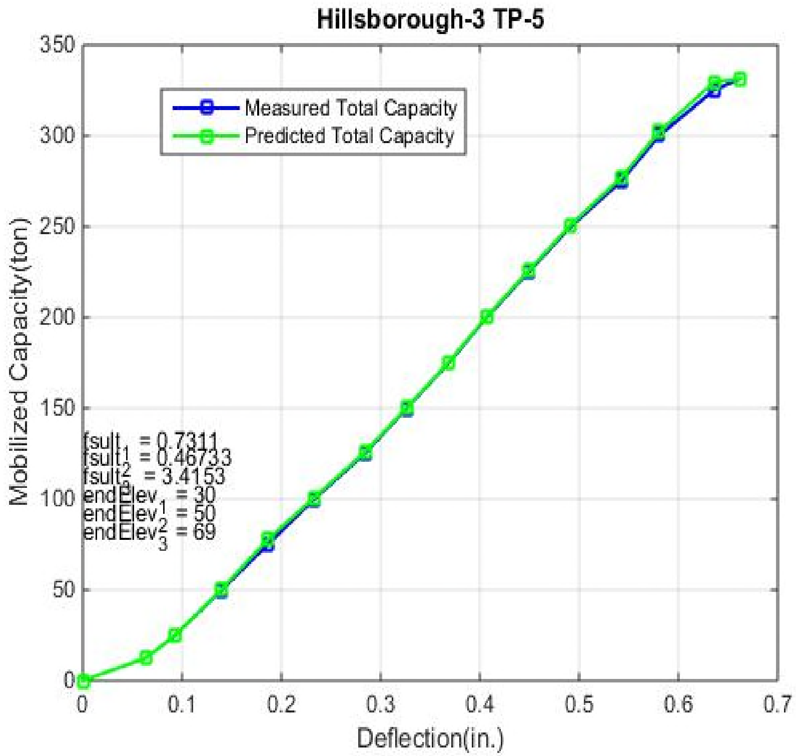


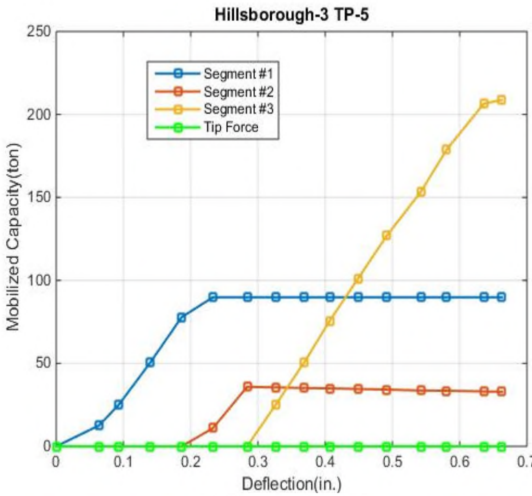
Clay:

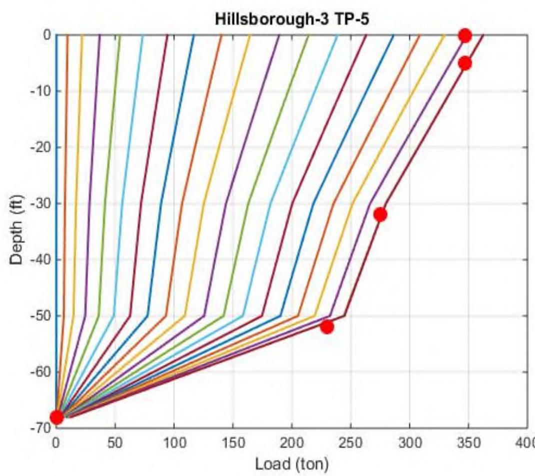


Assessment of Nominal Unit Resistance (Skin & Tip) From Load Tests

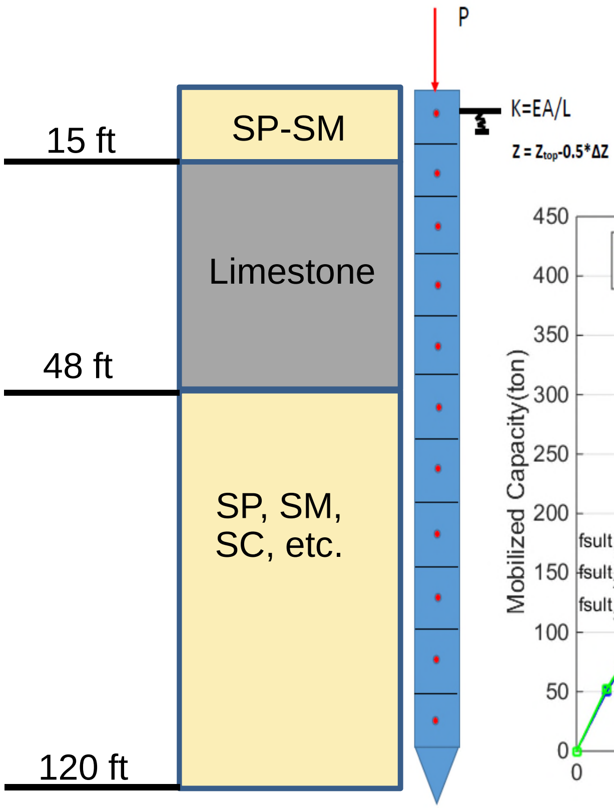


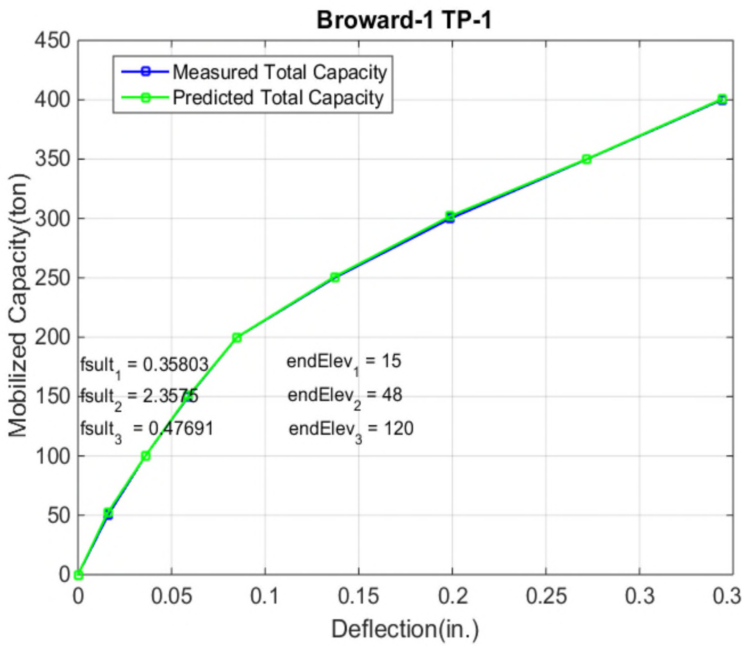


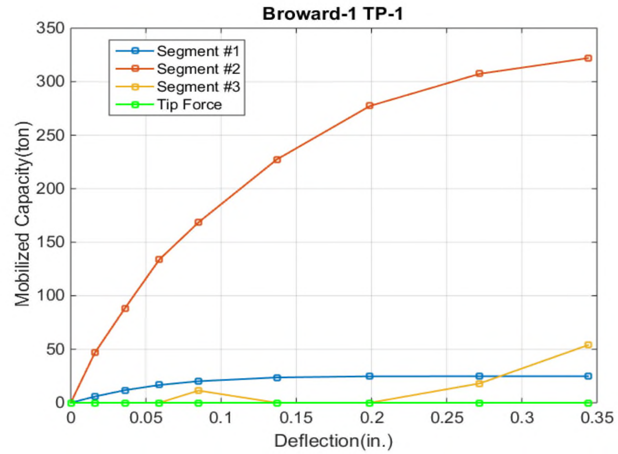


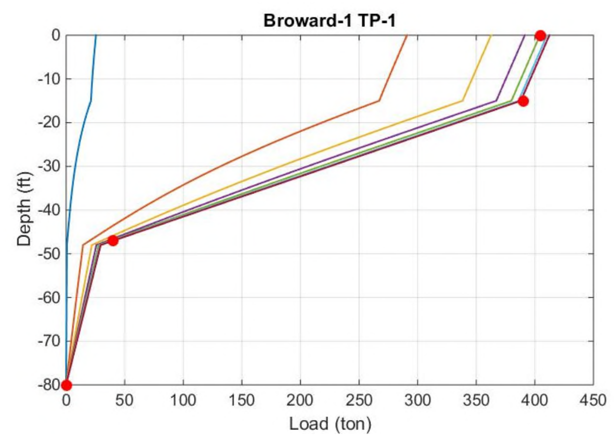


Assessment of Nominal Unit Resistance (Skin & Tip) From Load Tests









Estimated Unit Skin Friction per Soil Layer

Location	Project Name	Soil Type	Diameter (in)	Embedded Length (ft)	Test Type	Water Table Depth (ft)	Instrumentation	Peak Displacement Load Test (in)	Segment #1 (tsf)	Depth range (ft)	Segment #2 (tsf)	Depth range (ft)	Segment #3 (tsf)	Depth range (ft)
Alachua	Alachua-1 TP-2	Clay & IGM	16	64	Static	29	Load-Deflection	0.085	0.652	0~20	0.367	20~40	2.352	40~64
	Alachua-1 TP-3	Clay & IGM	16	64	Static	31	Load-Deflection	0.125	0.896	0~20	0.882	20~40	2.488	40~64
	Alachua-1 TP-4	Clay & IGM	16	64	Static	26	Load-Deflection	0.183	0.489	0~20	0.275	20~40	2.696	40~64
	Alachua-1 TP-5	Clay & IGM	16	64	Static	28	Load-Deflection	0.219	0.600	0~20	0.336	20~40	2.124	40~64
	Alachua-2 TP-1	Clay	14	42	Static	4.5	Load-Deflection	0.288	N/A		N/A		N/A	
	Alachua-2 TP-2	Clay	14	42	Static	5	Load-Deflection	0.325	0.461	0~15	1.609	15~30	1.496	30~42
	Alachua-2 TP-3	Clay	14	42	Static	6.5	Load-Deflection	0.295	0.555	0~15	1.498	15~30	1.493	30~42
	Alachua-2 TP-5	Clay	14	42	Static	5	T-Z & Load-Defl.	0.341	0.596	0~15	1.235	15~30	1.237	30~42
	Alachua-2 TP-XX-1	No Boring	14	42	Static	None	Load-Deflection	0.777	N/A		N/A		N/A	
	Alachua-2 TP-XX-2	No Boring	14	42	Static	None	Load-Deflection	0.460	N/A		N/A		N/A	
	Alachua-3 TP-1	Clay, Sand & IGM	14	15	Static	12	Load-Deflection	0.549	N/A		N/A		N/A	
	Alachua-5 TP-1	Sand & Clay	14	65	Static	6	T-Z & Load-Defl.	0.600	0.498	0~27	1.424	27~65		
	Alachua-5 TP-2	Sand & Clay	14	65	Static	6	T-Z & Load-Defl.	1.000	0.497	0~15	1.453	15~40	3.040	40~50
	Alachua-5 TP-3	Sand & Clay	14	65	Tension	6	T-Z & Load-Defl.	0.088						
Broward	Broward-1 TP-1	Sand & IGM	18	102	Static	5.7	T-Z & Load-Defl.	0.344	0.358	0~15	2.358	15~48	0.477	48~80
	Broward-1 TP-2	Sand & IGM	18	102	Tension	5.7	T-Z & Load-Defl.	0.009						
	Broward-1 TP-5	Sand & IGM	30	140	Osterberg	1	O-Cell	0.400	0.212	0~30	2.069	30~70	2.706	70~95
	Broward-2 TP-1	Sand & IGM	14	40	Static	None	Load-Deflection	0.350	0.331	0~10	0.536	10~32	4.633	32~40
Duval	Duval-1 TP 1-2	Sand, Marl & Clay	16	55	Static	4.5	Load-Deflection	0.289	0.341	0~30	3.197	30~45	0.967	45~55
	Duval-1 TP 2-2	Sand, Marl & Clay	16	54	Static	4.5	Load-Deflection	0.397	0.392	0~30	3.498	30~45	1.026	45~55
	Duval-1 TP 3-2	Sand, Marl & Clay	18	54	Tension	4.5	Load-Deflection	0.192						
	Duval-1 TP 3-3	Sand, Marl & Clay	16	54	Static	4.5	Load-Deflection	0.267	0.279	0~30	3.528	30~45	1.000	45~55
Hollywood	Hollywood-1 TP-1	No Boring	14	50	Static	No Boring	Load-Deflection	0.340	N/A		N/A		N/A	
	Hollywood-2 TP-1	No Boring	14	48	Static	No Boring	T-Z & Load-Defl.	0.200	N/A		N/A		N/A	
	Hollywood-2 TP-2	No Boring	14	48	Tension	No Boring	T-Z & Load-Defl.	0.032	N/A		N/A		N/A	
Hillsborough	Hillsborough-2 TP-1	No Boring	14	40	Static	None	Load-Deflection	0.079	N/A		N/A		N/A	
	Hillsborough-3 TP-1	Sand, and Clay	16	60	Static	5.2	Load-Deflection	0.548	0.543	0~43	0.570	43~55	4.650	55~60
	Hillsborough-3 TP-2	Sand, and Clay	16	60	Statnamic	5.2	T-Z & Load-Defl.	0.939	1.353	0~20	0.990	20~45	1.394	45~60
	Hillsborough-3 TP-3	Sand and Clay	16	60	Statnamic	5	T-Z & Load-Defl.	1.176	0.470	0~25	0.470	25~45	2.310	45~60
	Hillsborough-3 TP-4	Sand and Clay	16	60	Statnamic	5	T-Z & Load-Defl.	0.760	0.778	0~43	0.634	43~58	4.650	58~60
	Hillsborough-3 TP-5	Sand and Clay	16	69	Statnamic	4	T-Z & Load-Defl.	0.653	0.731	0~30	0.467	30~50	3.415	50~69
Nassau	Nassau-1 TP14	Sand	14	60	Static	3.8	T-Z & Load-Defl.	0.385	0.499	0~10	1.377	10~50	1.309	50~60
	Nassau-2 TP-1	Sand	16	39	Static	3	Load-Deflection	0.300	N/A		N/A		N/A	
	Nassua-3 TP-1	Sand	14	65	Static	5	T-Z & Load-Defl.	0.200	0.835	0~10	0.268	10~50	0.838	50~60
Palm Beach	Palm Beach-1 TP-9	No Boring	16	61	Static	None	T-Z & Load-Defl.	0.113	N/A		N/A		N/A	
	Palm Beach-2 TP-8	No Boring	16	61	Static	None	T-Z & Load-Defl.	0.188	N/A		N/A		N/A	
Polk	Polk-1	Clay, Silt & Sand	18	65	Static	8.5	Load-Deflection	0.360	N/A		N/A		N/A	
Santa Rosa	Santa Rosa-1 TP-1	Sand, Cayey Sand	24	47	Static	2.5	CPT Data	0.465	N/A		0.830	0~29	0.185	29~44
West Palm	West Palm-1 T2B	Sand	14	40	Tension	9	Load-Deflection	0.250						
	West Palm-1 T8	Sand	14	40	Tension	9	Load-Deflection	0.250						
	West Palm-1 T9B	Sand	14	40	Static	9	Load-Deflection	0.536	0.310	0~10	0.471	10~30	0.494	30~40

Green – clay; Yellow – sand; Dark Green – marl; Light Orange – Ocala Limestone; Light Blue – Anastasia Limestone; Light Grey – Miami Limestone

Estimated Unit Skin Friction per Layer

Location	Project Name	Soil Type	Diameter (in)	Embedded Length (ft)	Test Type	Water Table Depth (ft)	Instrumentation	Peak Displacement Load Test (in)	Segment #1	Depth range (ft)	Segment #2	Depth range (ft)	Segment #3	Depth range (ft)
Miami Dade	Miami Dade-1 TP-1	IGM, Sand & FT Limestone	16	43	Static	5	Load-Deflection	0.343	2.100	0~18	0.441	18~35	3.910	35~43
	Miami Dade-1 TP-2	Sand & IGM	16	43	Tension	5	Load-Deflection	0.208						
	Miami Dade-5 TP-1	Sand & IGM	14	30	Static	(+) 2.5	Load-Deflection	0.148	N/A		N/A		N/A	
	Miami Dade-5 TP-2	Sand & IGM	14	30	Tension	(+) 2.5	Load-Deflection	0.270						
	Miami Dade-6 TP-1	IGM & Sand	14	25	Static	Not measured	Load-Deflection	0.183	6.425	5~14	1.500	14~25	N/A	
	Miami Dade-6 TP-2	IGM & Sand	14	40	Static	8	Load-Deflection	0.182	3.153	0~20	0.994	20~40	N/A	
	Miami Dade-6 TP-3	IGM & Sand	14	40	Static	8	Load-Deflection	0.303					N/A	
	Miami Dade-6 TP-5	IGM & Sand	14	40	Static	8	Load-Deflection	0.090	5.380	2~16	0.588	16~40	N/A	
	Miami Dade-6 TP-6	IGM, Sand & FT Limestone	14	40	Static	4	Load-Deflection	0.206	1.737	2~24	0.100	24~35	4.024	35~40
	Miami Dade-6 TP-7	IGM & Sand	14	40	Static	Not measured	Load-Deflection	0.060	N/A		N/A		N/A	
	Miami Dade-6 TP-8	IGM & Sand	14	40	Static	Not measured	Load-Deflection	0.093	N/A		N/A		N/A	
	Miami Dade-6 TP-9	IGM & Sand	14	40	Static	Not measured	Load-Deflection	0.142	3.005	1~24	0.478	24~40	N/A	
	Miami Dade-6 TP-10	IGM & Sand	14	40	Static	Not measured	Load-Deflection	0.572	3.431	5~22	0.404	22~40	N/A	
	Miami Dade-6 TP-11	IGM & Sand	14	23	Static	5.5	Load-Deflection	0.073	3.759	1~8	0.907	8~23	N/A	
	Miami Dade-6 TP-12	IGM & Sand	14	23	Static	5.5	Load-Deflection	0.346	N/A		N/A		N/A	
	Miami Dade-6 TP-13	IGM, Sand & FT Limestone	14	50	Static	Not measured	Load-Deflection	0.072	1.899	1~25	0.504	25~40	4.318	40~50
	Miami Dade-6 TP-14	IGM & Sand	14	58	Static	8	Load-Deflection	0.182	3.009	5~16	0.392	16~58	N/A	
	Miami Dade-6 TP-15	IGM & Sand	14	45	Static	7.5	Load-Deflection	0.119	3.199	3~11	0.616	11~45	N/A	
	Miami Dade-6 TP-16	IGM & Sand	14	25	Static	5.5	Load-Deflection	0.115	3.658	5~14	0.853	14~25	N/A	
	Miami Dade-6 TP-17	IGM & Sand	14	25	Static	5.5	Load-Deflection	0.135	3.315	4~21	0.159	21~25	N/A	
	Miami Dade-6 TP-18	Sand & IGM	14	20	Static	4	Load-Deflection	0.115	1.474	1~8	5.782	8~19	N/A	
	Miami Dade-6 TP-19	IGM, Sand & FT Limestone	14	55	Static	8	Load-Deflection	0.192	3.420	1~9	0.777	9~40	6.176	40~50
	Miami Dade-6 TP-20	IGM & Sand	14	30	Static	9	Load-Deflection	0.091	3.860	1~26	0.583	26~30	N/A	
	Miami Dade-6 TP-21	IGM & Sand	14	46	Static	12	Load-Deflection	0.110	3.008	4~17	0.612	17~46	N/A	
	Miami Dade-6 TP-22	IGM & Sand	14	41	Static	12	Load-Deflection	0.058	N/A		N/A		N/A	
	Miami Dade-6 TP-23	Sand	14	58.5	Static	10.5	Load-Deflection	0.560	0.275	0~58.5	N/A		N/A	
	Miami Dade-6 TP-24	IGM & Sand	14	47	Static	4	Load-Deflection	0.182	3.044	1~20	0.651	20~47	N/A	
	Miami Dade-6 TP-25	IGM & Sand	14	56	Static	10	Load-Deflection	0.095	N/A		N/A		N/A	
	Miami Dade-6 TP-26	IGM, Sand & FT Limestone	14	57	Static	10	Load-Deflection	0.296	2.755	20~32			4.634	32~57
	Miami Dade-6 TP-27	IGM, Sand & FT Limestone	14	47	Static	11	Load-Deflection	0.053	2.072	1~10	0.152	10~22	4.423	22~47
	Miami Dade-6 TP-28	IGM, Sand & FT Limestone	14	65	Static	8	Load-Deflection	0.408	1.564	1~9			7.230	60~65
	Miami Dade-6 TP-29	IGM, Sand & FT Limestone	14	56	Static	9	Load-Deflection	0.107	2.930	0~18	0.916	24~46	4.872	46~56
	Miami Dade-6 TP-30	IGM, Sand & FT Limestone	14	56	Static	9	Load-Deflection	0.107	3.490	1~15	0.659	15~45	4.248	45~56
	Miami Dade-6 TP-31	IGM, Sand & FT Limestone	14	44	Static	Not measured	Load-Deflection	0.432	2.026	1~12	0.137	12~30	4.332	30~40
	Miami Dade-7 TP-1	Sand & IGM	18	41	Static	4	Load-Deflection	0.064	N/A		N/A		N/A	
	Miami Dade-7 TP-2	Sand & IGM	18	41	Static	4	Load-Deflection	0.069	N/A		N/A		N/A	
	Miami Dade-8 TP-1	Sand & IGM	14	52	Static	1	Load-Deflection	0.300	N/A		N/A		N/A	
Total # of Test Piles				78	Total T-Z Curve	16								

Yellow – sand; light grey – Miami Limestone or North Florida IGM; dark grey – Fort Thompson Limestone

Findings of Load Test Data and Analysis

1. Review of pile head movements
    - >90% of displacements 0.1” to 0.3”
    - Typical failure (FHWA 5% diameter – 0.5x14”=0.75”) not reached
    - Load Test (ASTM D1143) run to 2 x design load
2. Review load transfer plots (measured/estimated) – typical tip resistance was less than 10% of top load
3. Current practice suggests most ACIP designed for side friction only
4. LRFD assessment occurred for ACIP side resistance only

Design Methods for Auger Cast in Place (ACIP) Piles using Lab Data

Examples of Design in Florida Limestone:

Authors	Design Methodology	Note	Comment
FDOT (1998)	Unit Skin Friction: $f_s = \frac{1}{2} \cdot \sqrt{q_u} \cdot \sqrt{q_t} \cdot REC$ (ksf)	$\boldsymbol{q_u}$= Revised* unconfined compressive strength (tsf); $\boldsymbol{q_t}$= Revised* split tensile strength (tsf); $\boldsymbol{REC}$ = average recovery of rock core.	Florida Limestone
Herrera−q_u (FDOT)	$f_s = C\sqrt{q_u(ksf)}\ x\ REC$ (tsf)	$\boldsymbol{q_u}$= Revised* unconfined compressive strength (tsf); $\boldsymbol{REC}$ = average recovery of rock core. C = Correction factor	Florida Limestone
Ramos et al. (1994)	Unit Skin Friction: for $q_u \leq 1800\ kPa\ (36\ ksf)$ $f_s = 0.5 \cdot q_u$ (kPa or ksf) $f_s = 0.35 \cdot q_u$ (kPa or ksf)(lower bound) for $q_u > 1800\ kPa\ (36\ ksf)$ $f_s = 0.12 \cdot q_u$ (kPa or ksf)	q_u= unconfined compressive strength (kPa or ksf);	

*Revised as per SFH

Design Methods for Auger Cast in Place (ACIP) Piles using Lab Data

Examples of Design in Florida Limestone:

Authors	Design Methodology	Note	Comment
Horvath and Kenney (1979)	Unit Skin Friction: $f_s = 0.67 \cdot \sqrt{q_u}$ (tsf)	q_u= unconfined compressive strength (tsf).	
Williams et al. (1980)	Unit Skin Friction: $f_s = 1.842 \cdot q_u^{0.367}$ (tsf)	q_u= unconfined compressive strength (tsf).	
Reynolds and Kaderabek (1980)	Unit Skin Friction: $f_s = 0.3 \cdot q_u$ (tsf)	q_u= unconfined compressive strength (tsf).	Miami Limestone
Gupton and Logan (1984)	Unit Skin Friction: $f_s = 0.2 \cdot q_u$ (tsf)	q_u= unconfined compressive strength (tsf).	Key Largo, Anastasia, Fort Thompson and Miami limestone formations

Design Methods for Auger Cast in Place (ACIP) Piles using SPT in Limestone

Examples of Design in Florida Limestone:

Authors	Design Methodology	Note	Comment
Frizzi & Meyer (2000)	Unit Skin Friction: $f_s = 0.35 \cdot N_{60} - 1.5$ (tsf) (1) $f_s = 0.14 \cdot N_{60} + 1$ (tsf) (2)	$\mathbf{N_{60}}$ = SPT-*N* value at 60% of hammer efficiency (blows/ foot).	(1) Miami limestone formation; (2) Ft. Thompson limestone formation.
Crapps (IGM)	Unit Skin Friction: $f_s = \sigma_v' \cdot \left[e^{0.0646(N-13.6)}\right]$(ksf)	σ_v'= vertical effective stress (ksf) *N*= blow count (blows/ft).	

Design Methods for Auger Cast in Place (ACIP) Piles using In-situ Data

Examples of Design in Florida Cohesionless Soils:

Authors	Design Methodology	Note	Comment
FHWA 1999 (O'Neill and Reese,1999)	Unit Skin Friction: $f_s = \beta \cdot \sigma_v' < 2.0$ tsf $\beta = 1.5 - 0.135 \cdot Z^{0.5}$ N ≥ 15 $\beta = \frac{N_{60}}{15}(1.5 - 0.135 \cdot Z^{0.5})$ N < 15	σ_v' = vertical effective stress; β = friction factor; Z = depth in feet; N_{60}= SPT-*N* value at 60% of hammer efficiency; N = SPT value at the tip of the pile.	Cohesionless Soils (Sands & Silts)
Zelada and Stephenson (2000)	Unit Skin Friction: $f_s = \beta \cdot \sigma_v' < 1.6$ tsf $\beta = 1.2 - 0.11 \cdot Z^{0.5}$ N ≥ 15 $\beta = \frac{N_{60}}{15}(1.2 - 0.11 \cdot Z^{0.5})$ N < 15	σ_v' = vertical effective stress; β = friction factor; Z = depth in feet; N_{60}= SPT-*N* value at 60% of hammer efficiency; N = SPT value at the tip of the pile.	Cohesionless Soils (Sands & Silts)

Design Methods for Auger Cast in Place (ACIP) Piles using In-situ Data

Examples of Design in Florida Cohesionless Soils:

Authors	Design Methodology	Note	Comment
GEC 10 (Brown, 2010)	Unit Skin Friction: $f_s = \beta \cdot \sigma_v'$ $\beta = Ko \tan\delta$ Ko = (1 – sin φ') OCRsin φ' < Kp $OCR = \frac{\sigma'_p}{\sigma'_v}$ $K_p = \tan^2\left(45° + \frac{\varphi'}{2}\right)$ $\frac{\sigma'_p}{Pa} \approx 0.47(N_{60})^m$	σ_v' = vertical effective stress; σ_p' = vertical effective stress preconsolidation stress; β = friction factor; δ = effective stress angle of friction for the soil-shaft interface; φ' = effective internal angle of friction; Ko = At rest coefficient of horizontal soil stress; K_p = coefficient of passive earth pressure; OCR = overconsolidation ratio; N_{60} = SPT-*N* value at 60% of hammer efficiency (blows/ foot); P_a = atmospheric pressure; m = 0.6 for clean quarzitic sand and m = 0.8 for silty sands to sandy silts	Cohesionless Soils (Sands & Silts)

Design Methods for Auger Cast in Place (ACIP) Piles

Examples of Design in Florida Cohesive Soils:

Authors	Design Methodology	Note	Comment
FHWA 1999 (O'Neill and Reese,1999)	Unit Skin Friction: $f_s = \propto \cdot S_u$ $\propto = 0.55 \; for \; \frac{Su}{Pa} \leq 1.5$ $\propto = \; 0.55 \; to \; 0.45 \; for 1.5 \leq \frac{Su}{Pa} \leq 2.5$	S_u = undrained shear strength of the soil at the pile segment location; $\propto$ = reduction factor; P_a = standard atmospheric pressure.	Cohesive Soils

- Several design methods for cohesive soils use CPT data
- Santa Rosa site provided only source of CPT data

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Review of Site Boring and Laboratory Data

1. Typical site data consisted of SPT, Unified Classification (USCS) and rock strength data

2. Most boring data > 50 ft from load test

3. Insufficient laboratory strength data in one boring to predict a shaft – used site mean data

Miami Limestone Formation Unit Skin Friction

Predicted Unit Skin Friction (Miami Limestone Formation)				
Design Method	Mean-qu **(ksf)**	51.85*	Mean-qu **(ksf)** (+/-) 1-StDev	35.13
	Mean-qt **(ksf)**	13.75	Mean-qt **(ksf)** (+/-) 1-StDev	11.70
	fs (tsf)		**fs (tsf)**	
FDOT	N/A		3.5485	
Herrera_qu (C=1.111)	N/A		3.2610	
Horvath and Kenney (1979)	3.4109		N/A	
Williams et al. (1980)	6.0824		N/A	
Reynolds and Kaderabek (1980)	7.7751		N/A	
Gupton and Logan (1984)	5.1834		N/A	
Reese and O'Neill (1987)	3.8875		N/A	
Rowe and Armitage (1987)	7.3818		N/A	
Carter and Kulhawy (1988)	3.2072		N/A	
Ramos et al. (1994)	3.11		N/A	
Kulhawy et al. (2005)	5.2367		N/A	
Design Method	Mean-SPT (blows/ft)	22.21	Mean-SPT (blows/ft) (+/-) 1-StDev	21.27
	fs (tsf)		**fs (tsf)**	
Herrera_SPT (C=0.15)	N/A		3.1905	
Frizzi & Meyer (2000)	6.2752		N/A	
Ramos et al. (1994)-SPT (Blows/ft)	6.443		N/A	
Crapps (IGM)	1.7795		N/A	
*ACIP piles considered IGM with q_u between 10 ksf and 100 ksf.				

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Fort Thompson Formation Unit Skin Friction

Predicted Unit Skin Friction (Fort Thomspon Limestone Formation)				
Design Method	Mean-qu **(ksf)**	129.91*	Mean-qu **(ksf)** (+/-) 1-StDev	114.77*
	Mean-qt **(ksf)**	32.01	Mean-qt **(ksf)** (+/-) 1-StDev	31.65
	fs (tsf)		**fs (tsf)**	
FDOT	N/A		6.0275	
Herrera_qu (C=1.643)	N/A		4.9795	
Horvath and Kenney (1979)	5.3998		N/A	
Williams et al. (1980)	8.5215		N/A	
Reynolds and Kaderabek (1980)	19.4861		N/A	
Gupton and Logan (1984)	12.9907		N/A	
Reese and O'Neill (1987)	9.7430		N/A	
Rowe and Armitage (1987)	11.6861		N/A	
Carter and Kulhawy (1988)	5.0774		N/A	
Ramos et al. (1994)	7.7944		N/A	
Kulhawy et al. (2005)	8.2903		N/A	
Design Method	Mean-SPT (blows/ft)	51.95	Mean-SPT (blows/ft) (+/-) 1-StDev	35.54
	fs (tsf)		**fs (tsf)**	
Herrera_SPT (C=0.15)	N/A		5.3310	
Frizzi & Meyer (2000)	8.2729		N/A	
Ramos et al. (1994)-SPT (Blows/ft)	12.3898		N/A	
Crapps (IGM)	19.8296		N/A	
*Note outside IGM design values (q_u between 10 ksf and 100 ksf).				

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Cohesionless Unit Skin Friction Bias-All Sites

2 Site	Pile	Depth (ft)	fs_{EST} (tsf)	$fs_{PRED-FHWA}$ (tsf)	$Bias_{FHWA}$	$fs_{PRED-ZELDA}$ (tsf)	$Bias_{ZELDA}$	*fs_{Brown} (tsf)	*$Bias_{BROWN}$	**fs_{Brown} (tsf)	**$Bias_{BROWN}$
Miami Dade	Miami Dade-1 TP-1	18~35	0.4413	0.4879	0.9046	0.3903	1.1307	0.4808	0.9179	0.4756	0.9279
	Miami Dade-6 TP-21	17~46	0.6123	0.6028	1.0158	0.4823	1.2696	0.6491	0.9433	0.6089	1.0056
	Miami Dade-6 TP-23	0~58.5	0.2750	0.6028	0.4562	0.4823	0.5702	0.6491	0.4237	0.6089	0.4516
	Miami Dade-6 TP-24	20~47	0.6508	0.6028	1.0796	0.4823	1.3494	0.6491	1.0026	0.6089	1.0688
	Miami Dade-6 TP-29	24~46	0.9164	0.6028	1.5203	0.4823	1.9001	0.6491	1.4118	0.6089	1.5050
	Miami Dade-6 TP-30	15~45	0.6590	0.6028	1.0932	0.4823	1.3664	0.6491	1.0153	0.6089	1.0823
Alachua	Alachua-5 TP-1	0~27	0.4980	0.5356	0.9298	0.4285	1.1622	0.8814	0.5650	0.6864	0.7255
	Alachua-5 TP-2	0~27	0.4510	0.5356	0.8420	0.4285	1.0525	0.8814	0.5117	0.6864	0.6571
Broward	Broward-1 TP-1	0~15	0.3580	0.1601	2.2362	0.1281	2.7953	0.1018	3.5167	0.0972	3.6831
	Broward-1 TP-1	48~80	0.4770	0.6513	0.7324	0.5210	0.9155	0.8714	0.5474	0.8295	0.5750
	Broward-2 TP-1	0~10	0.3311	0.4000	0.8278	0.3200	1.0347	1.0461	0.4560	0.9395	0.3524
	Broward-2 TP-1	10~32	0.5364	1.0750	0.4990	0.8604	0.6234	1.0234	0.3235	0.9355	0.5734
Duval	Duval-1 TP 1-2	0~30	0.3410	0.3924	0.8690	0.3140	1.0860	0.3756	0.9079	0.3639	0.9371
	Duval-1 TP 2-1	0~30	0.3920	0.3924	0.9990	0.3140	1.2484	0.3756	1.0437	0.3639	1.0772
	Duval-1 TP 3-3	0~30	0.2790	0.3924	0.7110	0.3140	0.8885	0.3756	0.7428	0.3639	0.7667
Hillsborough	Hillsborough-3 TP-1	0~55	0.5489	0.7242	0.7579	0.5793	0.9475	0.9209	0.5960	0.8006	0.6856
	Hillsborough-3 TP-3	0~45	0.4700	0.5925	0.7932	0.4740	0.9916	0.7534	0.6238	0.6551	0.7174
	Hillsborough-3 TP-4	0~58	0.7407	0.7637	0.9699	0.6109	1.2125	0.9711	0.7627	0.8443	0.8773
	Hillsborough-3 TP-5	0~50	0.6254	0.6584	0.9499	0.5267	1.1874	0.8372	0.7470	0.7278	0.8593
Nassua	Nassau-1 TP14	0~10	0.4990	0.2540	1.9646	0.2030	2.4581	0.371	1.3450	0.2539	1.9653
	Nassau-1 TP14	10~50	1.3773	0.8280	1.6634	0.6620	2.0805	0.9103	1.5130	0.8274	1.6646
	Nassua-3 TP-1	10~60	0.3818	0.4736	0.8062	0.3789	1.0077	0.9103	0.4194	0.8274	0.4614
West Palm	West Palm-1 T98	0~10	0.3100	0.3034	1.0218	0.2427	1.2773	0.4735	0.6547	0.4688	0.6613
	West Palm-1 T98	10~30	0.4710	0.5282	0.8917	0.4226	1.1145	1.017	0.4631	0.9302	0.5063
	West Palm-1 T98	30~40	0.4936	0.7679	0.6428	0.6143	0.8035	1.022	0.4830	0.9348	0.5280
Summary Statistics		Mean			1.0264		1.2829		0.9130		0.9991
		Median			0.9398		1.1748		0.7696		0.8683
		St Dev			0.3950		0.4940		0.5573		0.5967
		CV			0.3849		0.3851		0.6104		0.5972
		count	36	36	36	36	36	36	36	36	36
		min	0.2750	0.1601	0.4562	0.1281	0.5702	0.1018	0.3235	0.0972	0.3524
		max	1.3773	1.0750	2.2362	0.8604	2.7953	1.0461	3.5167	0.9395	3.6831

* Predicted Unit Skin Friction using the Brown Method as Presented in GEC10

** Predicted Unit Skin Friction using the Brown Method as presented in GEC10 with OCR Limited -10 & Angle of internal friction limited -40 degree

$$\text{Bias} = \lambda = \frac{Measured}{Predicted}$$

Summary Statistics:

Bias & CV for prediction methods using rock strengths for Miami Limestone

Statistic	FDOT	Herrera	Horvath	Williams	Reynolds	Gupton	Reese	Rowe	Carter	Ramos	Kulhawy
Mean	1.05	0.851	0.988	0.554	0.564	0.846	1.13	0.456	1.05	1.08	0.648
StDev	0.453	0.282	0.449	0.207	0.267	0.401	0.534	0.208	0.478	0.410	0.295
CV	0.434	0.331	0.454	0.373	0.474	0.474	0.474	0.455	0.455	0.379	0.455

Bias & CV for prediction methods using rock strengths for Fort Thompson Limestone

Statistic	FDOT	Herrera	Horvath	Williams	Reynolds	Gupton	Reese	Rowe	Carter	Ramos	Kulhawy
Mean	0.841	1.01	0.937	0.594	0.557	0.836	1.11	0.433	0.997	0.649	0.615
StDev	0.27	0.35	0.378	0.16	0.278	0.417	0.556	0.15	0.346	0.37	0.213
CV	0.321	0.351	0.403	0.271	0.50	0.50	0.50	0.346	0.347	0.571	0.347

LRFD Φ Using FOSM β =2.33

Cohesionless & Cohesive Soils:

Method	Φ	Φ/λ (%)
	Sand	
FHWA	0.51	0.50
Zelada	0.64	0.50
Brown	0.27	0.30
Brown†	0.31	0.31
	Clay	
FHWA	0.83	53

$$R_{design} = \Phi \cdot R_{measured} = \Phi \cdot \frac{R_{measured}}{\lambda}$$

$$\text{where: } \lambda = \frac{R_{measured}}{R_{predicted}}$$

$$\boxed{R_{design} = \frac{\Phi}{\lambda} \cdot R_{measured}}$$

Rock – Laboratory Data:

Method	Φ	Φ/λ (%)
	Miami Formation	
q_u		
Horvath	0.42	43
Williams	0.29	52
Reynolds	0.23	41
Gupton	0.34	41
Reese	0.46	41
Rowe	0.19	42
Carter	0.45	42
Ramos	0.55	51
Kulhawy	0.28	42
Herrera $\pm\sigma$ q_u	0.48	56
FDOT ($\pm\sigma$ q_u and q_t)	0.47	45

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LRFD Φ Using FOSM β =2.33

Rock – Laboratory Data:

Method	Φ	Φ/λ (%)
Fort Thompson		
q_u		
Horvath	0.45	48
Williams	0.39	66
Reynolds	0.21	38
Gupton	0.32	38
Reese	0.42	38
Rowe	0.24	55
Carter	0.55	55
Ramos	0.21	32
Kulhawy	0.34	55
Herrera $\pm\sigma$ q_u	0.55	55
FDOT ($\pm\sigma$ q_u and q_t)	0.49	58

Rock – In situ SPT N:

Method	Φ	Φ/λ (%)
Miami Formation		
SPT		
Herrera	0.20	21
Frizzi	0.14	19
Ramos	0.20	38

Method	Φ	Φ/λ (%)
Fort Thompson		
SPT N		
Herrera	0.33	51
Frizzi	0.25	37
Ramos	0.13	30

Design Recommendations

- Cohesionless Soils
  - Recommend FHWA (beta, 1991) & Zelada (2000) over Brown (2010)
- Cohesive Soils
  - Recommend FHWA (alpha, 1999) - method is conservative, but good Φ/λ (%)
- Limestone
  - Recommend methods based on laboratory strength data vs. SPT N
  - Miami Formation – recommend Ramos, Herrera, FDOT, Carter and Reese
  - Fort Thompson Formation – recommend Carter, FDOT, Herrera, Horvath, and Reese.

Recommendation: Need For More Load Testing

- Only 2 rock formations with sufficient data for LRFD (Miami and Fort Thompson
  - Other formations needed (Anastasia, Ocala, etc)
- Limited marl or cemented soil tested
  - More data needed from north and south Florida
- Most borings were > 50 ft from load tests and had limited data within any boring
- Only 16 test piles had instrumentation to assess unit side resistance that could be used to validate the Segmental Loading Approach with top movements between 0.1” and 0.6”

Recommendation for Load Testing

- Number: 1 (CV < 0.25) to 3 (CV < 0.5) or more load tests (CV > 0.5) per site depending on length of project and variability.
- Instrument every test pile over multiple segments – obtain skin friction from multiple soil and rock layers for each load test.
- Load each pile to failure or nominal capacity (e.g. Davisson), not 2 x design load – ensures mobilization of ultimate skin friction for soil and rock.
- Ensure that soil boring and rock strength data is available for all load tests within 50 ft and of sufficient quantity to estimate capacity.

Thank You