Evaluation of Static Resistance of Deep Foundations

FDOT BDV31-977-05

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Tasks: FBDEEP Driven Pile Capacity Estimation

1. **Compare FBDEEP Side, Tip and Total H-pile Predictions with DLT data for Florida soils and rock; make recommendations for improvements**

2. **Compare FBDEEP Side, Tip and Total Prestressed Concrete Pile Predictions with DLT data in Florida Limestone; make recommendations for improvements**

3. **Compare FBDEEP Side, Tip and Total for Open Pipe Pile (24”< D< 54”) Predictions with Static and Statnamic Load Test Data; make recommendations for improvements as well as evaluate other methods (API)**

Steel H-Piles

- 1) Pile Driving Hammers
- 2) Subsurface Variabilities
- 3) Plugging Conditions
- 4) Unloading Skin Frictions during Driving

H-Piles – Pile Driving Hammers

From D8-42 with 1.7-kip ram
to very large, i.e. oversize D30-42 with 6.6-kip ram

Usually not abundantly available

Very popular to drive Concrete Piles in Florida (D30, D36)

Large Hammers would result in:

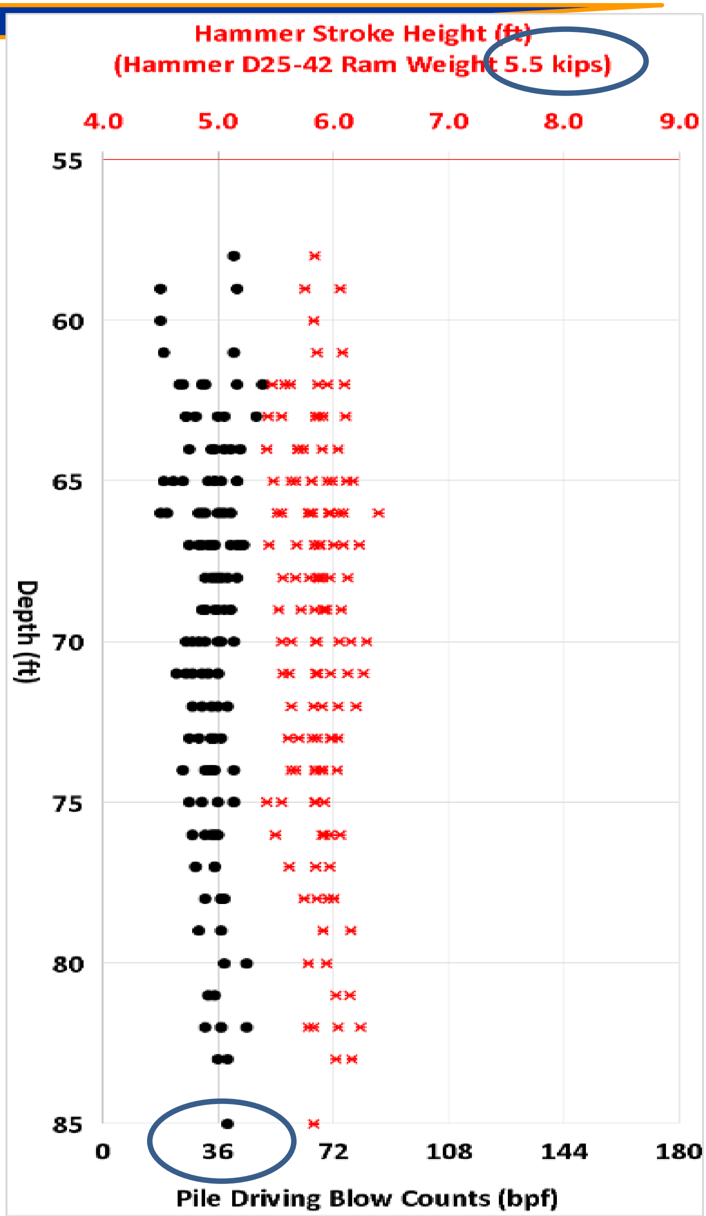
- less than 36 bpf at EOD (typical NBR=240-300 kips for H-piles)
- Easily cut through most soil types

→ pile would be too deep (>100')→ unloading skin friction
→ pile capacities do not appear to increase with depth
→ has to rely on end bearing (keep driving to find end bearing layer)

H-Piles – Pile Driving Hammers

Example:

5.5-kip ram
RMX = 240 to 300 kips
Low blow counts
Low strokes



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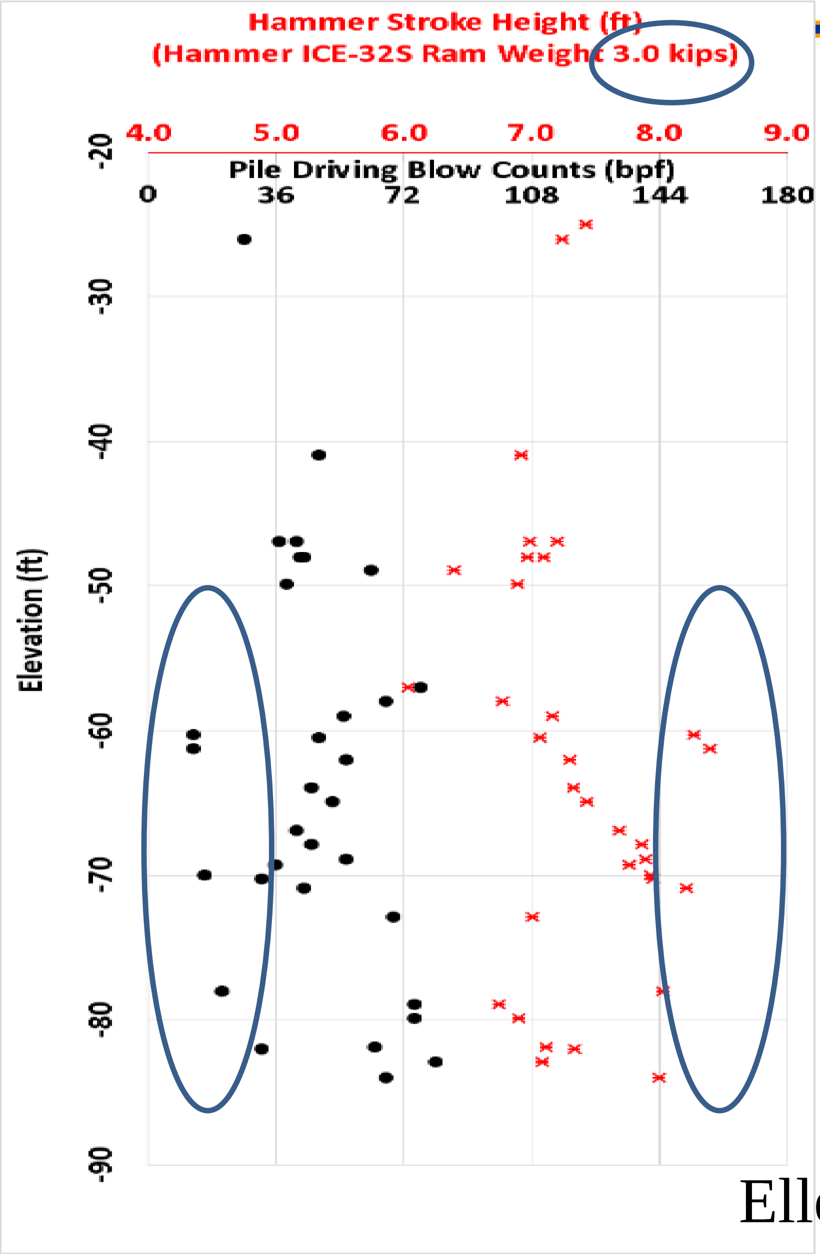
H-Piles – Pile Driving Hammers

Example:

3-kip ram
RMX = 240 to 300 kips
OK blow counts
OK strokes

(some low blow counts when stroke is high)



Eller Drive

H-Piles – Pile Driving Hammers

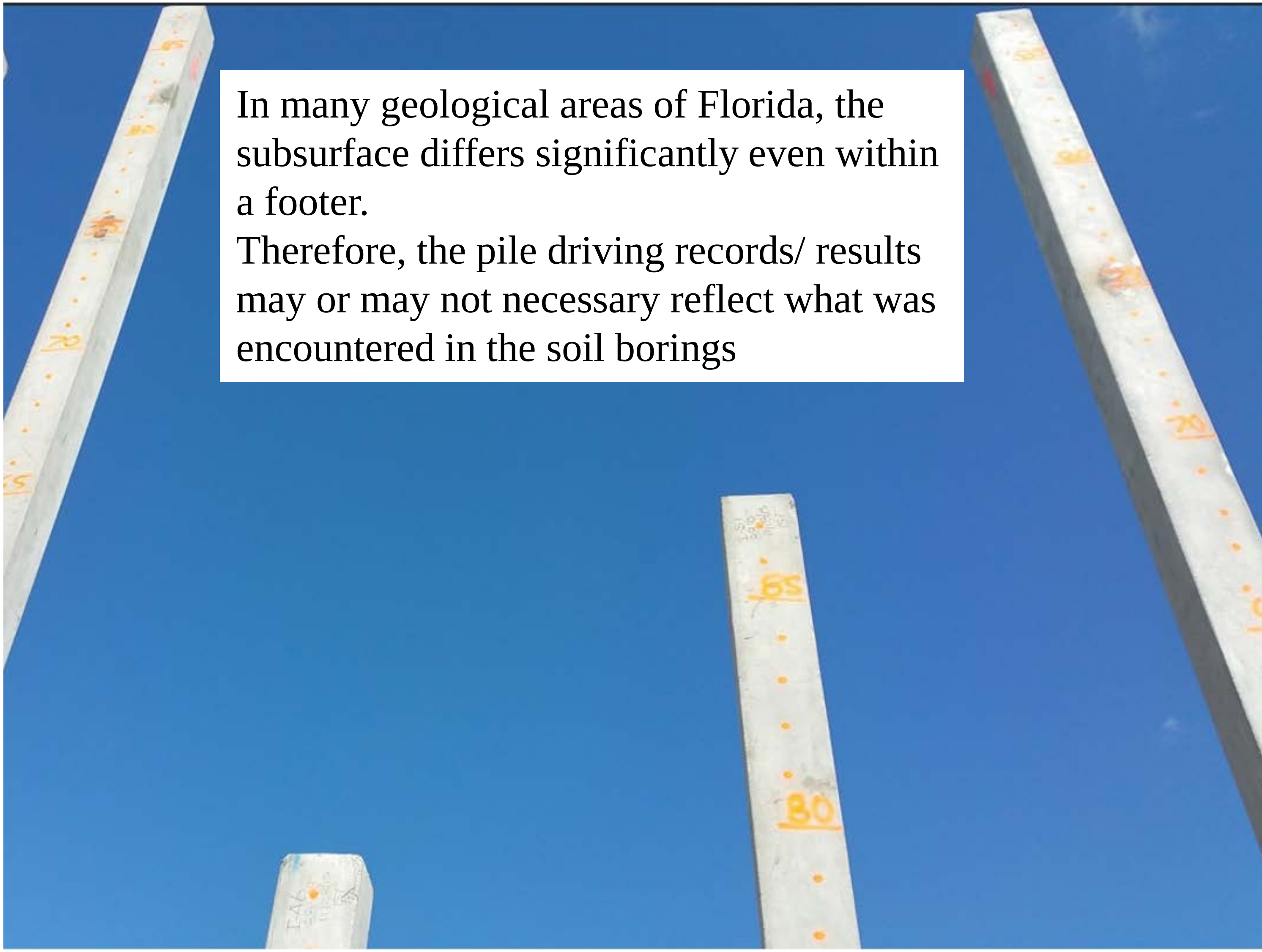
Recommendations:

Smaller Hammers (1.7 to 3.0 kip) are more suitable as H-piles are typically small and NBR is typically less than 400 kips.

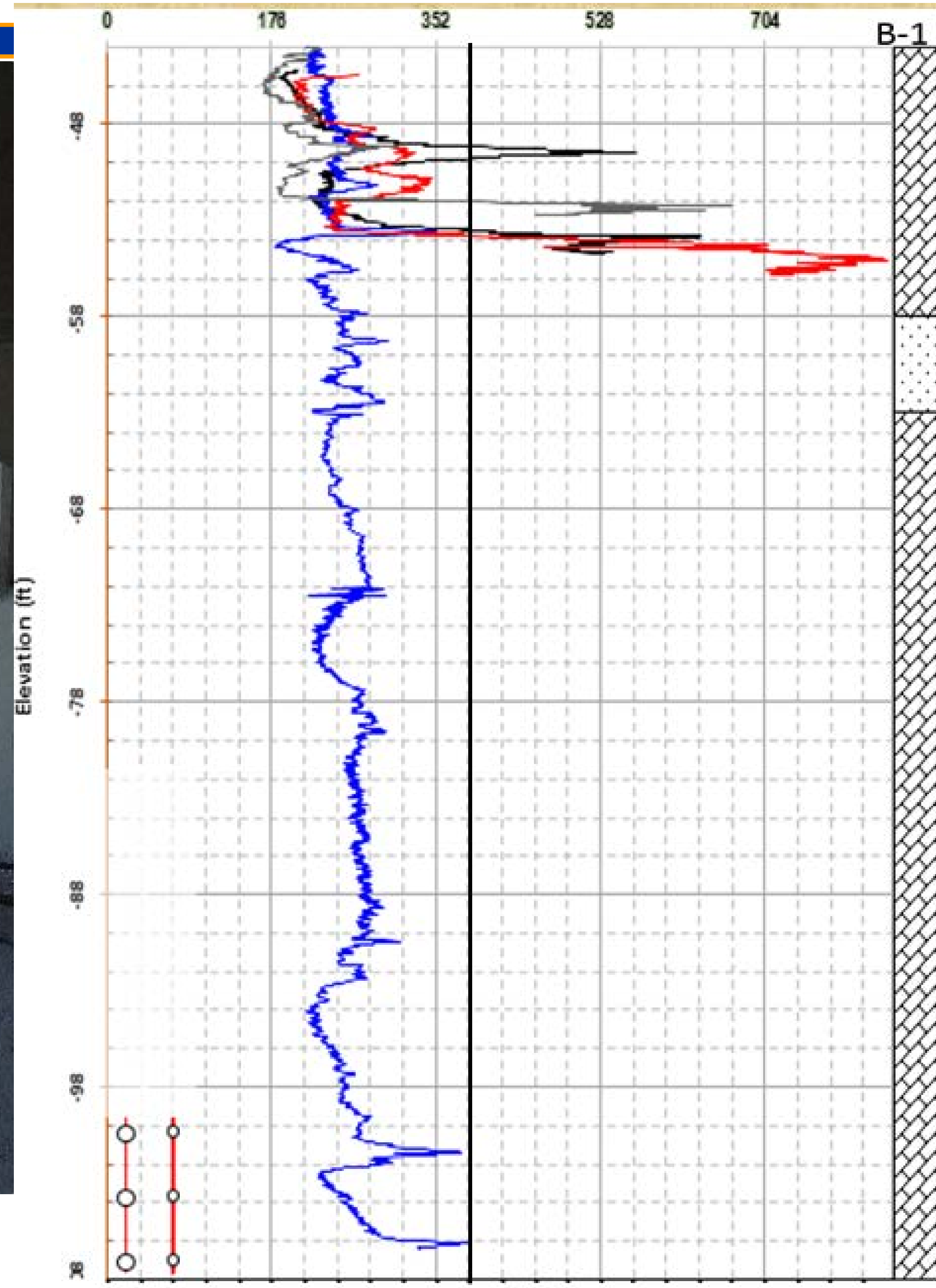
However, Small Hammers are typically not abundantly available

Subsurface Variabilities

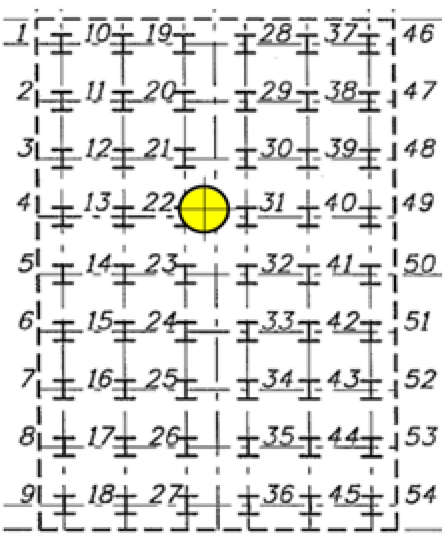
In many geological areas of Florida, the subsurface differs significantly even within a footer.
Therefore, the pile driving records/ results may or may not necessary reflect what was encountered in the soil borings



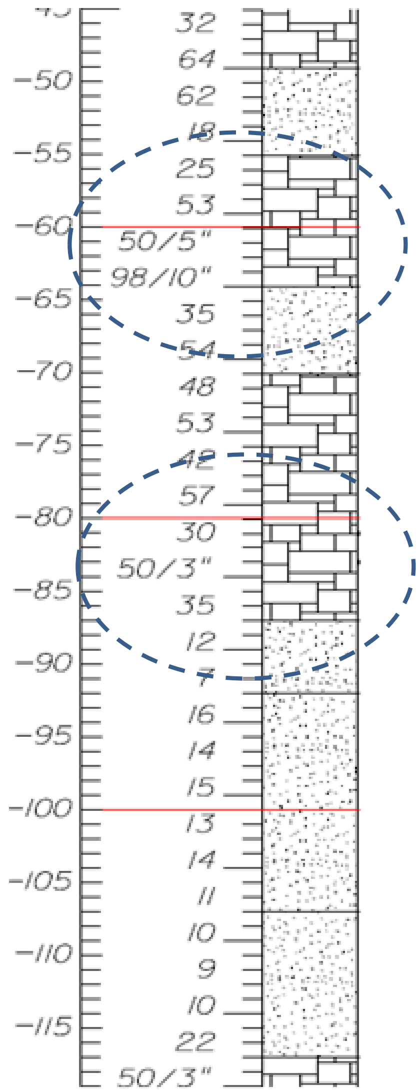
H-Piles – Subsurface Variabilities



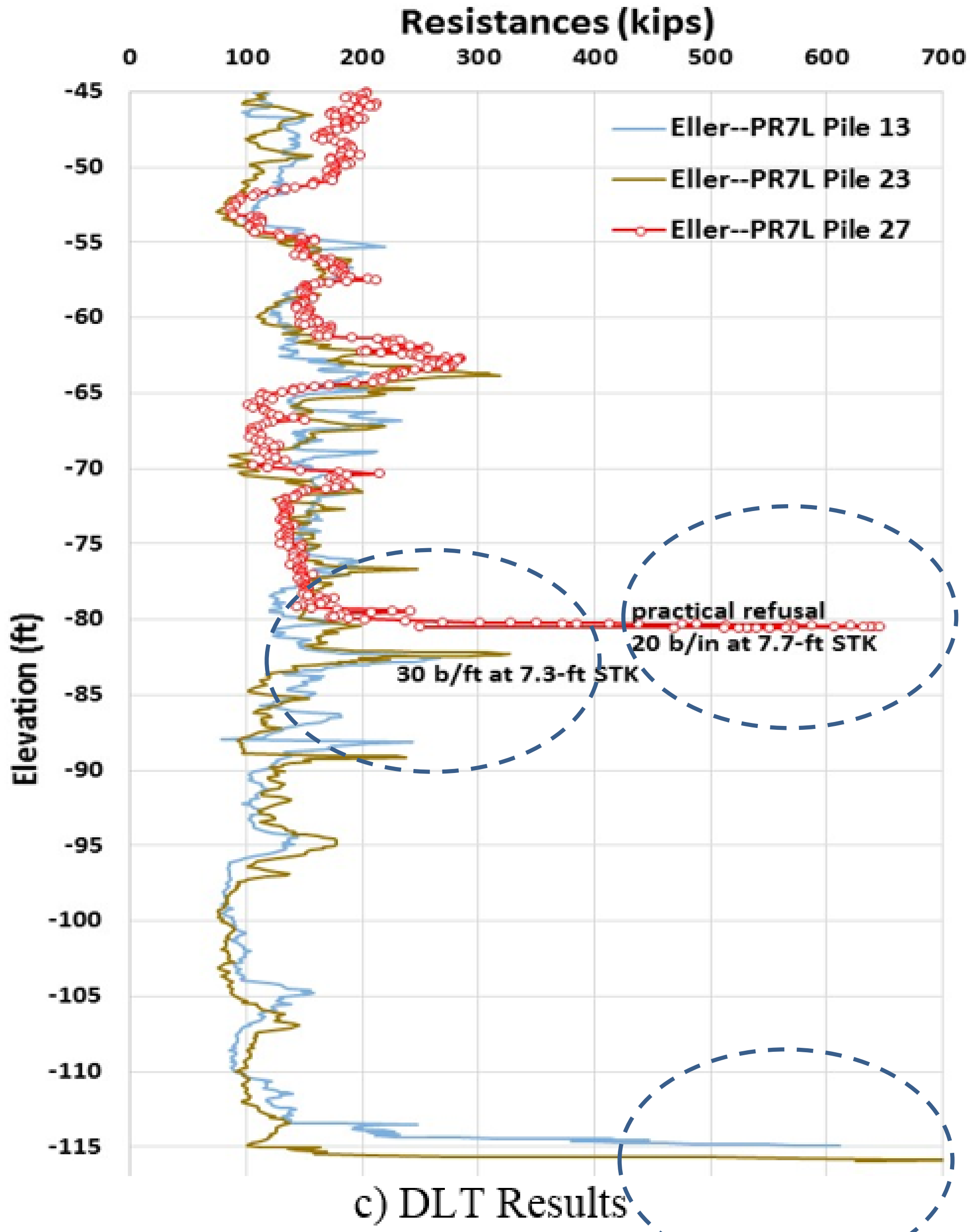
H-Piles – Subsurface Variabilities



a) Boring TB-7L in 2012 within Pier 7L footprint



b) Boring TB-7L SPT N Values



c) DLT Results

H-Piles – Subsurface Variabilities

Boring	Elev. (ft)	SPT N	Hard LS Thickness	DLT EOD Pile behaviors	Comments
7L	-84	50/3”	2.5’	7L-Pile 27 practical refusal, approaching 650 kips	Most competent limestone based on DLT EOD results. However based on Soil Boring, it is not the most competent
	-61	50/5”	10’	300 kips for 1 inch	Less competent limestone based on DLT EOD results. However based on Soil Borings, limestones are more competent than that at elevation -84 ft of boring 7L
9R	-125	50/2”	7.5’	300 kips for 5 inches	
	-145	50/2”	12.5’	400 kips for 1 inch	
8L	-70	41 to 50/4”	15’	180 kips (behaved similar to zones where N=10 to 30)	
8R	-47	50/4”	5’	400 kips for 5 inches	
	-67	50/2”	5’	200 to 450 kips, however at elev -72’	
	-82	50/1”	10’	400 kips for 5 inches	

H Piles Plug – or Unplugged

- **Example in Soft Limestone SPT N=26; L = 30-ft**

  fs = 0.2 tsf

  $Perimeter_{unplug}$ = 7.1 ft — **$Perimeter_{plug}$ = 4.7 ft**

  $F_{s\text{-}unplug}$ = 7.1 * 30 * 0.2 = 43 tons — **$F_{s\text{-}plug}$ = 28 tons**

  qp = 30 tsf

  A_{unplug} = 0.18 ft^2 — **A_{plug} = 1.4 ft^2**

  $Q_{t\text{-}unplug}$ = 5 tons — **$Q_{t\text{-}plug}$ = 42 tons**

  During Driving, due to high acceleration (approx a = 200g), the pile tends to cookie cut the soil (with soil having a large Inertial Force of I = Soil Mass * a keeping the soil mass "motionless" compared to the pile)

  $Ru_{driving} = F_{s\text{-}unplug} + Q_{t\text{-}unplug}$ = 48 tons

  $Ru_{plugged} = F_{s\text{-}plug} + Q_{t\text{-}plug}$ = 70 tons

  Thus, Dynamic Testing may show conservative results

- **For very long (Deep Penetrated) H-piles, another phenomenon may arise:**

  Skin Friction Unloading (will discuss later): Severe Unloading Skin Friction will cause DLT RMX to under-predict

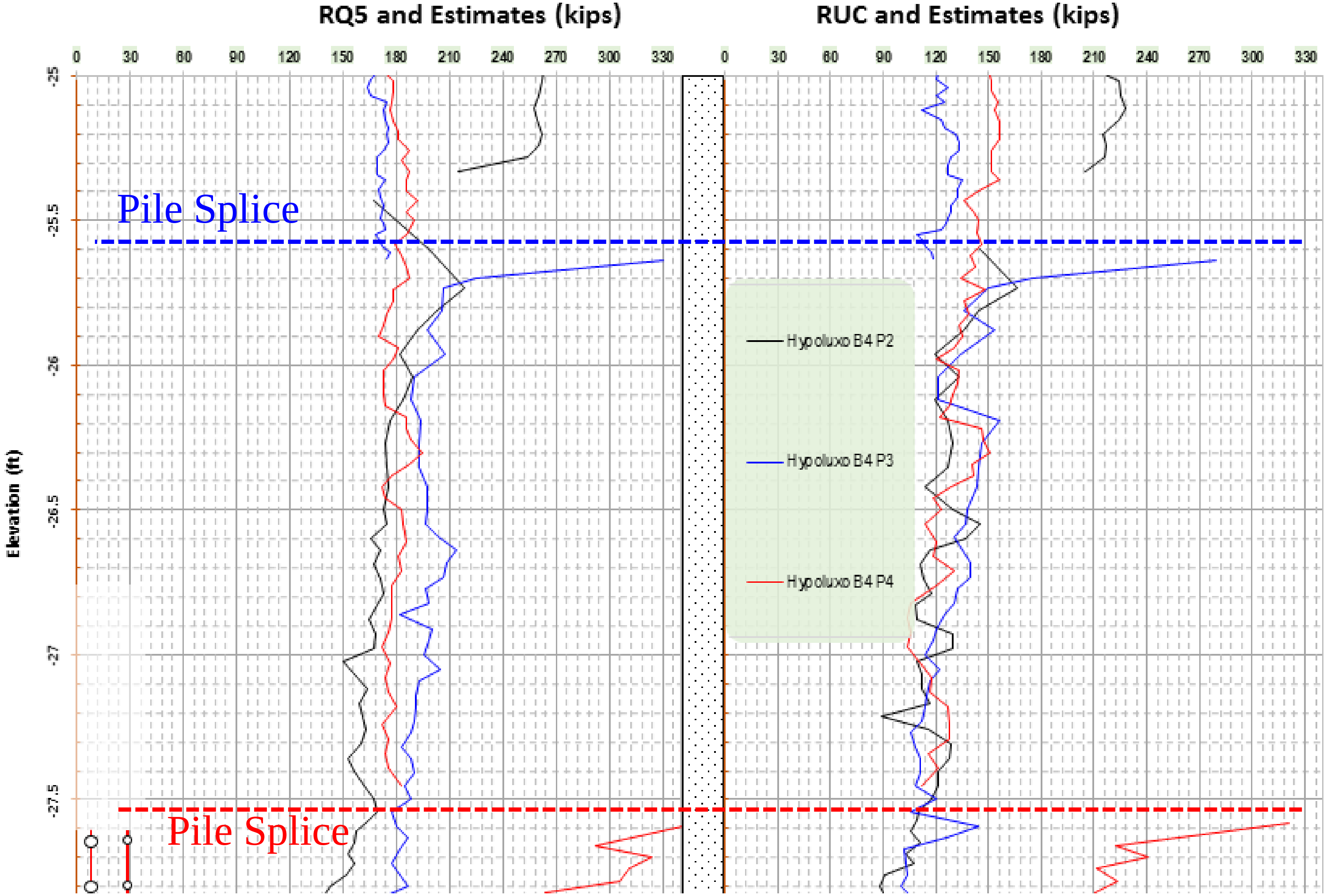
- **For H-piles in between 30 ft and 100 ft, DLT RMX may either under-predict or over-predict depending on Plug Conditions.**

Plug Conditions

Resumed driving (due to splicing) after 7 days:

Blow #0 (of the restrike) show incredible increase in Total Capacity

(Blow #0 is the soft blow in the restrike,
where the stroke height is displayed as 0 feet in Dynamic Testing software)



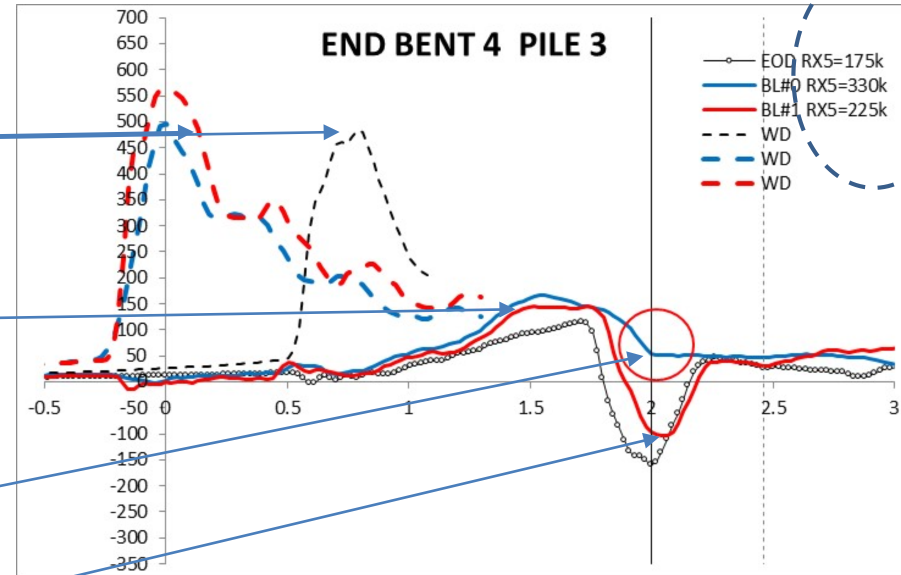
Plug Conditions

Similar Hammer Input Force

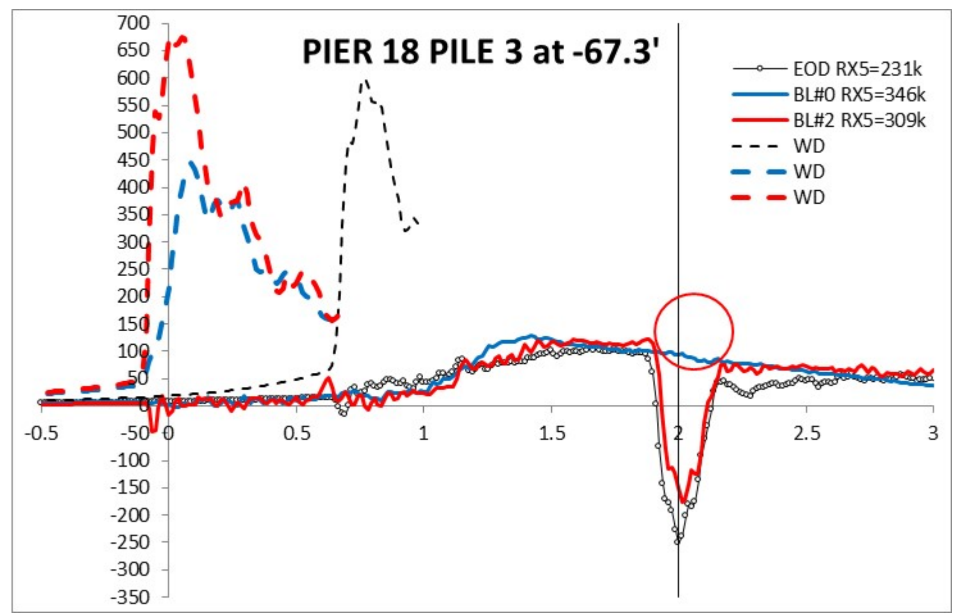
Restrike gain a small amount of Skin Friction (Soil Setup)
BL#1 shows similar Skin Friction as BL#0

Almost no Tension Reflection

Large Tension Reflection



Another Example:



Plug Conditions

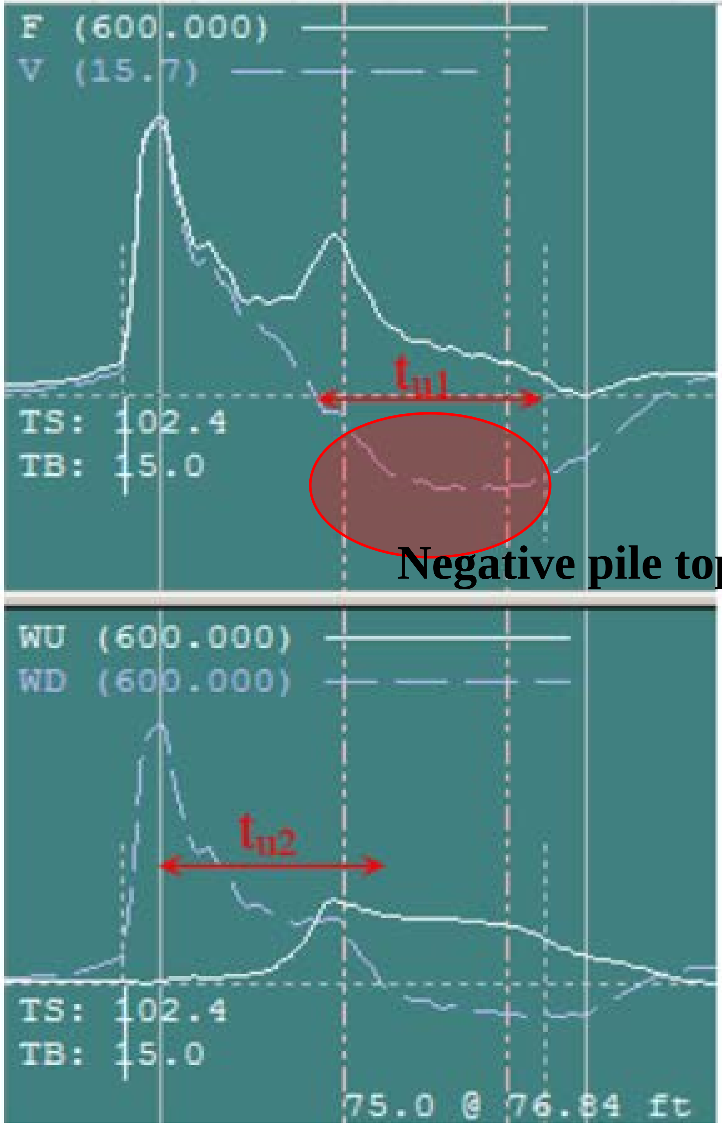
During driving (EOD) the toe area may have been a half plug shape.

Due to setup (freeze) gains on skin frictions after a long wait time, the toe area is a full plugged box shape on BOR Blow #0,

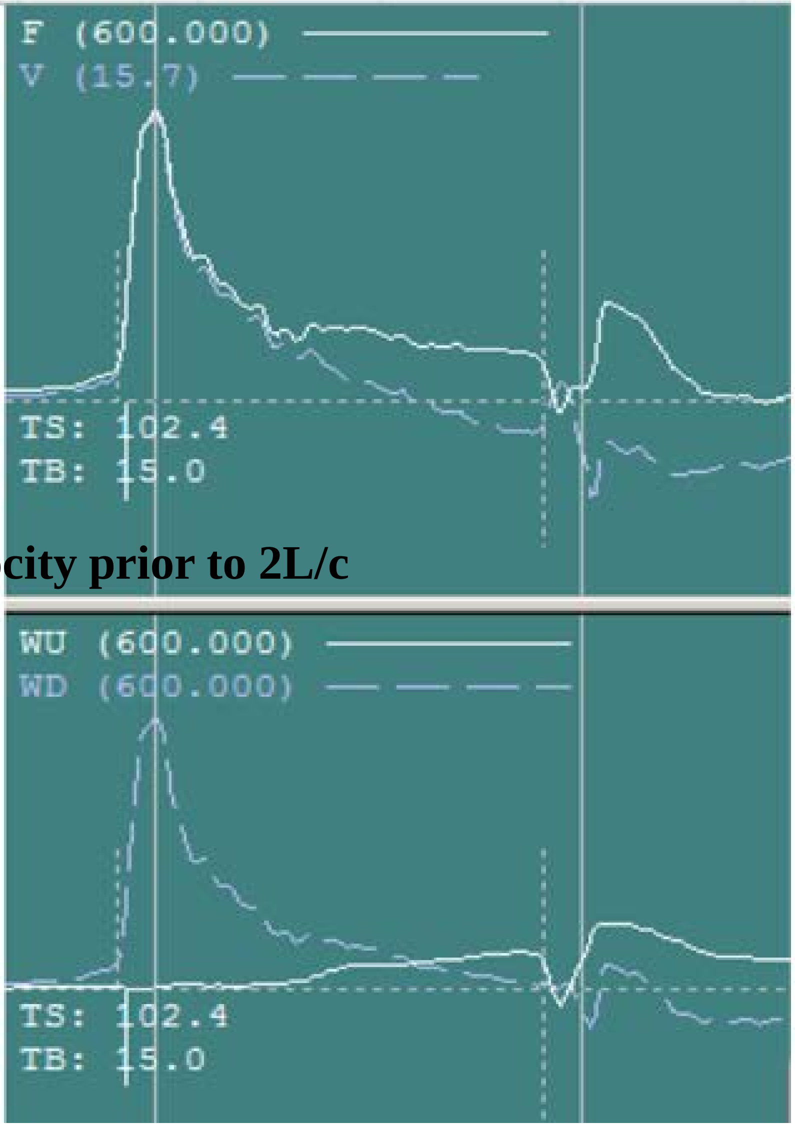
Then the toe area is eroding away almost immediately to a half plug on the next immediate blows

→ reiterates opinions of Hannigan et al. (2006) and Holloway and Beddard (1995) that soil plug depends on hammer dynamic responses, and thus EOD DLT capacities are not the true pile capacities.

Unloading Skin Friction during Driving

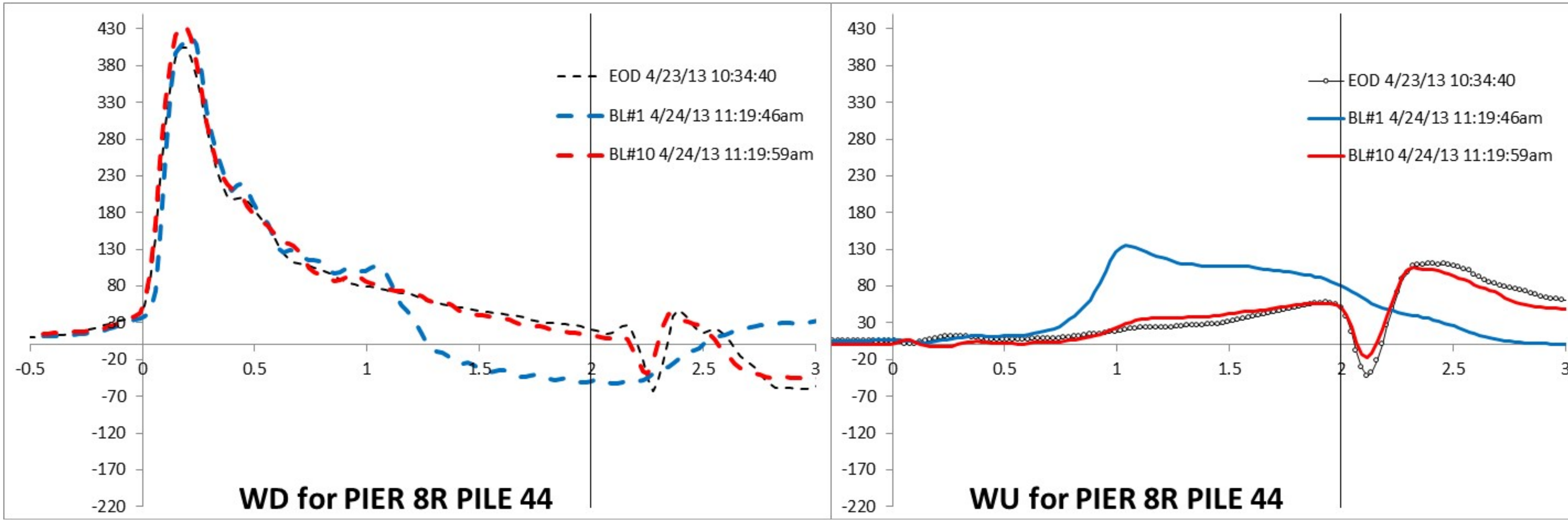


a) Blow #1



b) Blow #10

Soil Setup Disappearance during Driving



EOD, Blows #1 and #10

Soil Freeze Setup can be destroyed almost immediately on H-Pile driving.

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Unloading Skin Friction during Driving

Impact driving may quickly destroy most of the skin friction setup (freeze) gain of H-pile resistances

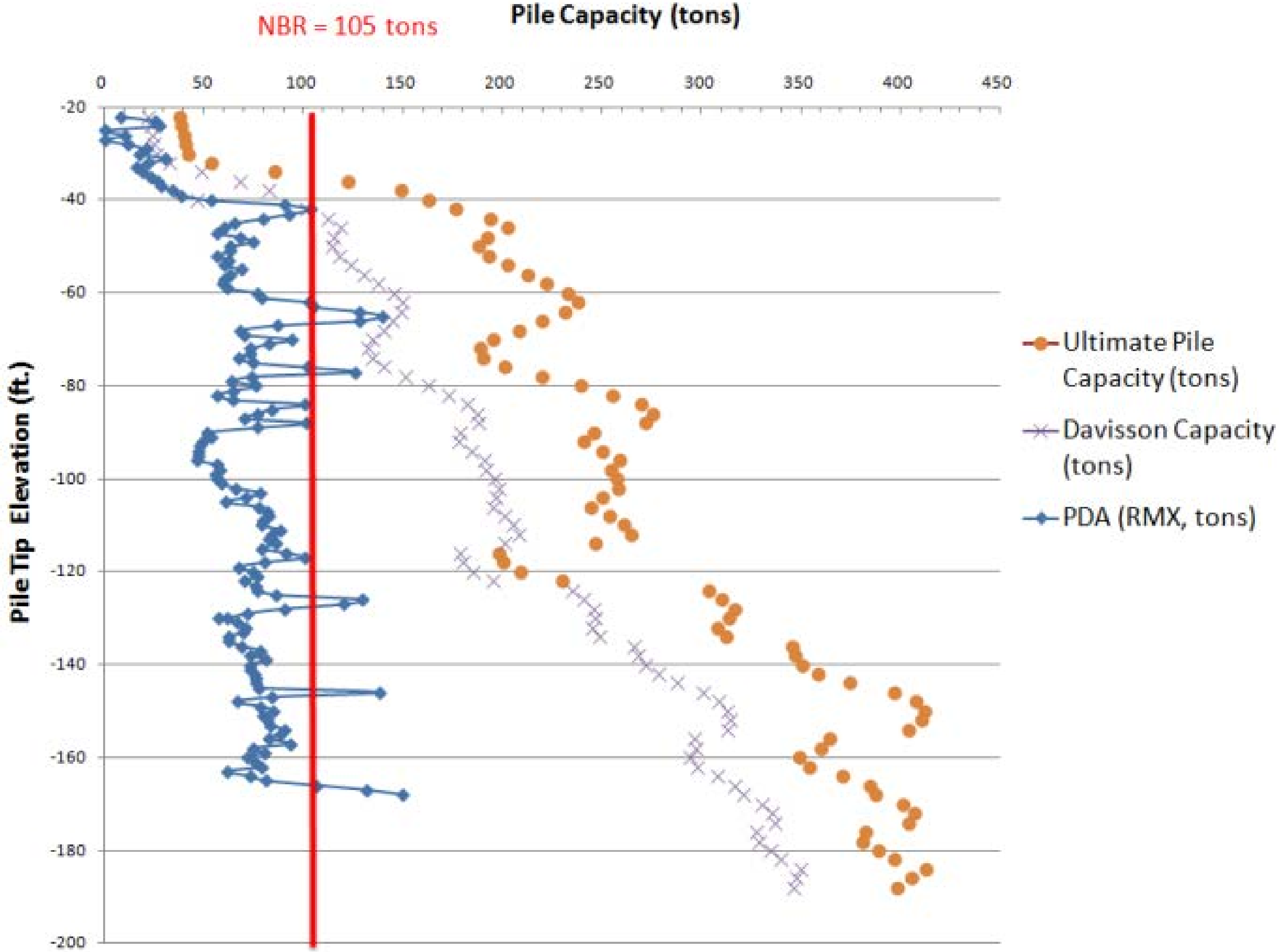
→ Using FDOT Setcheck Criteria for 10 blows would not be able to prove pile capacity (1 blow exceeding NBR, next 5 exceeding 95%, then remaining exceeding 90%)

Unloading make the apparent total skin friction on the DLT RMX results much lower than the actual capacities. The addition of skin friction in the lower depths (as the pile penetrates to deeper depth) is being cancelled out by the unloading skin friction in the upper portion of the pile.

Therefore, if the pile is being driven much deeper, the RMX method capacity appear to not increase with depth until a very competent limestone layer is encountered to provide higher end bearing value.

PDI's PDA Manual Appendix A, Section 4.8: Unloading Skin Friction

Unloading Skin Friction during Driving



H-Piles FB-Deep Formulas

- Highly variable subsurface. Deep pile next to shallow pile.
- Plug conditions vary between Static and Dynamic conditions
- Freeze (setup) as well as the full toe plug could easily be destroyed by around blow #5 of BOR
- Due to skin friction unloading of exceptionally long piles, the DLT results under-predict

→ Discrepancies between DLT RMX results and FB-Deep are not necessary due to inadequacies of the FB-Deep formulas.

→ **Keep all current FB-Deep formulas.**

However, some improvements needed…

H-PILES FB-DEEP IMPROVEMENTS

Plug Conditions:

FB-Deep:

Soil Types 1 & 2:

Always unplugged → Not reasonable as they have high friction during static loading

High friction helps form the plug during static loading.

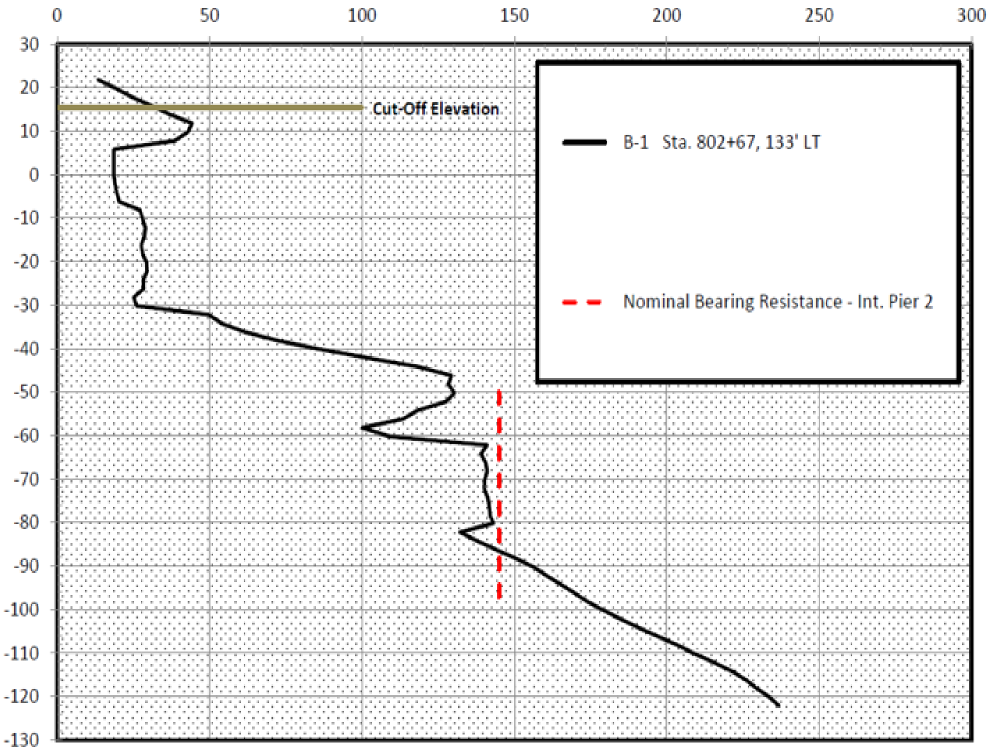
FB-Deep is opposite to recommendations by Tomlinson (1994), Hannigan et al (2006)

Soil Type 2: Furthermore, borderline between Soils 2 and 3 is thin:

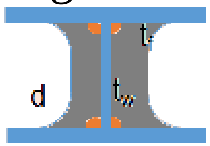
SP-SM (e.g. 12% fine) is Soil 3

SM (e.g. 13% fine) is Soil 2

Soil Type 3: Always Plug

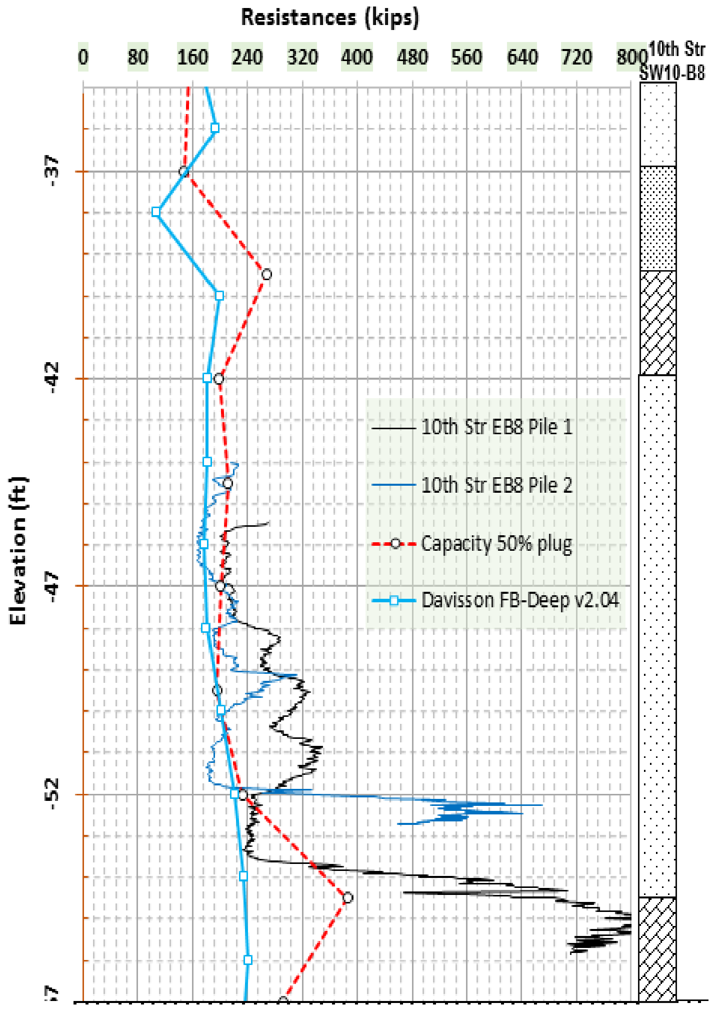


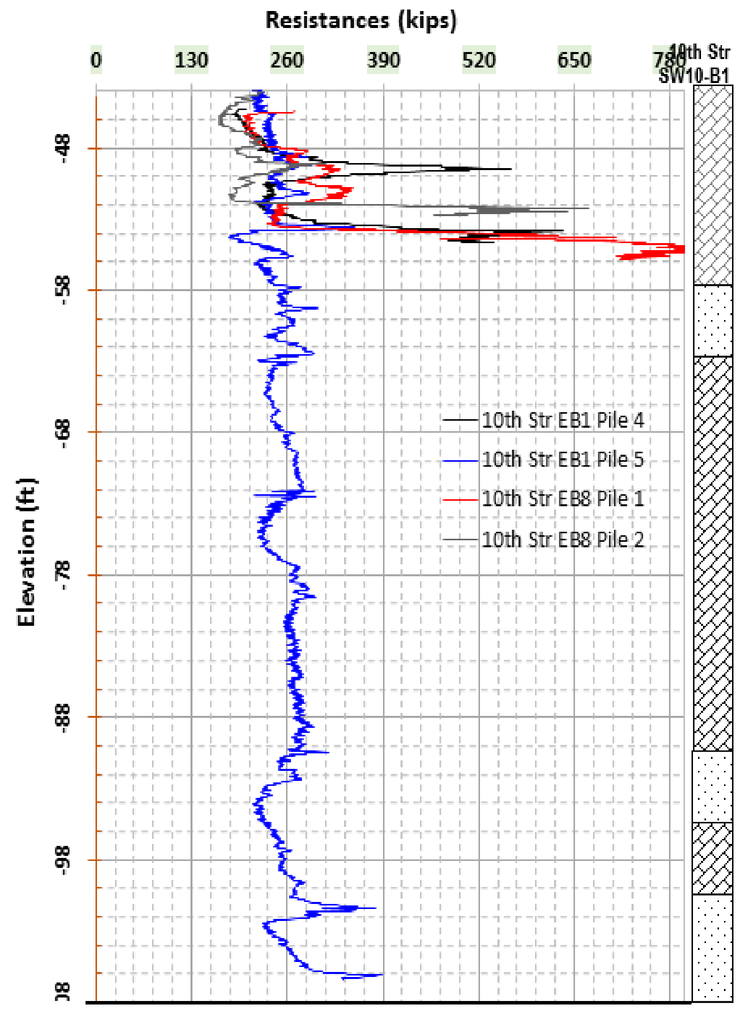
Coyle, H M and Ungaro, R (1991) based on static load tests recommend half plug configuration



We performed analyses "half plug" conf on cases of no "unloading"

H-PILES FB-DEEP IMPROVEMENTS





SPT N limit: FB-Deep users can specify "local-experience" limit, of says 100 (very competent LS) or 35 (inconsistent shelves) instead of default of 60. Furthermore, diminish toe SPT N averaging for H-piles

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H-PILES: SUGGESTIONS

- Getting suitable hammers for H-piles
- EOD RMX resistance is not necessary similar to Long Term Static resistance (plug conditions / setup effects)
- If Soil Borings show high variability → piles can easily go deep (especially with large hammers)

  → Deep penetrated pile may experience unloading of upper skin friction during driving. Thus EOD RMX may not show any increase in skin resistance as pile keep advances.

Collection of Concrete Piles in Florida Limestone Provided by Districts

Site Information		Insitu Information		Pile Information			
Project Number (Financial)	Project Site	# of Soil Borings	Predominant Soil Type	Dimensions (in)	Length (ft)	# of Piles with CAPWAP	# of BOR CAPWAP Analyses
242484-2-52-01	I-4/SR 408	58	Sand	18 & 24	90-107	112	N/A
210448-2-52-01	San Sebastian Bridge	11	Sand & Clay	24	38-111	111	N/A
211449-1-52-01	CR 229 over South Prong of St Mary's Ri	2	Sand & Clay	18	47-90	9	N/A
209293-2-52-01, 209294-1-52-01, 209294-9-52-01	SR 9B	121	Sand & Some Rock	24	45-119	183	N/A
208166-1-52-01	Plantation Oaks Boulevard over SR23	50	Sand & Rock	18	55-100	10	2
208466-2-52-01	SR 51	6	Clay & Rock	24	73-99	5	0
420809-3-52-01	I-595 Corridor Improvement Project	234	Sand & Rock	18 & 24	30-115	170	38
213304-3-52-01	I-95 Overland Bridge Replacement	133	Sand & Rock	24	22-66	5	2
406813-6-52-01	CR 245 over Olustee Creek	10	Sand & Rock	24	61-69	7	0
210687-3-52-01	SR 200 North of Callahan	11	Clay & Rock	24	36-66	25	9
429551-1-52-01	SR 200 South of Callanha	31	Sand & Rock	24	46-111	33	N/A
	I-95 over Snake Creek						4
249581-1-52-01	SR 826/836	17	Sand & Rock	24 & 30	80-110	177	20
	Total # of Soil Borings:	**684**	**Total # of Piles with CAPWAP Data:**			**847**	**75**
	Total # of Piles with Limestone Bearing Layer & BOR CAPWAP Analysis:					**79**	

Review of PCP Site Data

Site Information		Site Review
roject Number (Financia	Project Site	
242484-2-52-01	I-4/SR 408	Limestone observed at Elev. -60 in boring D-103 (I4 ramp D-D1), but no other borings show limestone and no pile tip into limestone.
210448-2-52-01	San Sebastian Bridge	Limestone observed at Elev. -52 to -59 ft (Thin Layer) in borings B-2,B-4, &B-6 Only. Also, most piles tip above -52 ft (i.e. piles NOT embedded into Limestone).
211449-1-52-01	CR 229 over South Prong of St Mary's Riv	No Limestone.
209293-2-52-01, 209294-1-52-01, 209294-9-52-01	SR 9B	Little to No Limestone Observed (Thin to Very Thin Limestone Layers Observed; Observed in Some Borings Only).
208166-1-52-01	Plantation Oaks Boulevard over SR23	A thin layer of weathered limestone present at Elev. -10 to -25ft.
208466-2-52-01	SR 51	Limestone present but no CAPWAP durng set-check or re-strike.
420809-3-52-01	I-595 Corridor Improvement Project	Limestone present at Elev. -5 to -20ft and Elev. -40 to -60ft.
213304-3-52-01	I-95 Overland Bridge Replacement	Soft clayey sand is located above limestone layer.
406813-6-52-01	CR 245 over Olustee Creek	Limestone present but no CAPWAP during set-check or re-strike.
210687-3-52-01	SR 200 North of Callahan	Piles tip above Gray Limestone Layer(s).
429551-1-52-01	SR 200 South of Callanha	Piles tip above Limestone Layer(s).
	I-95 over Snake Creek	Borings far from piles
249581-1-52-01	SR 826	Most piles tip between elev. -45 and -50 feet where competent/weathered limestone (Miami Ft. Thompson) is located; Weathered limestone with sand observed above it.

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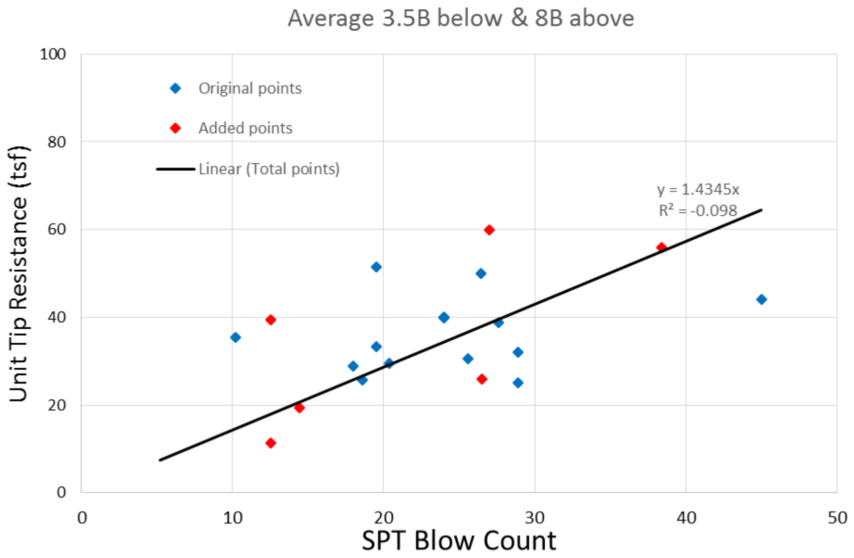
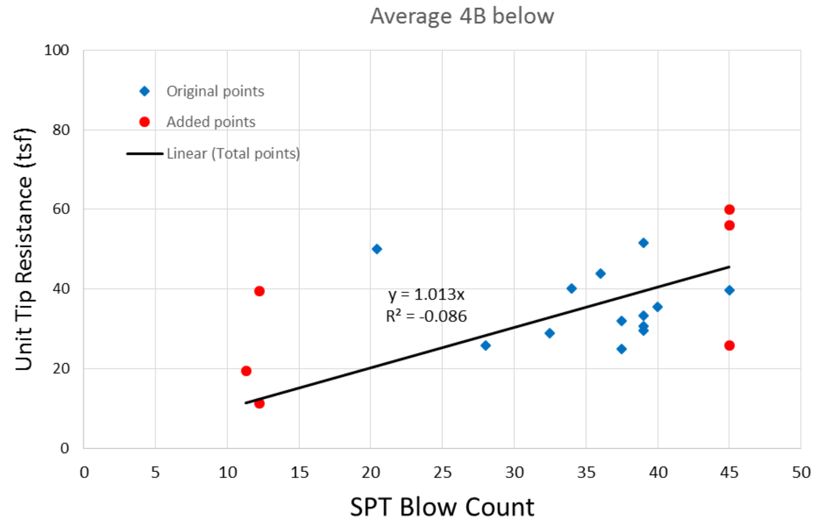
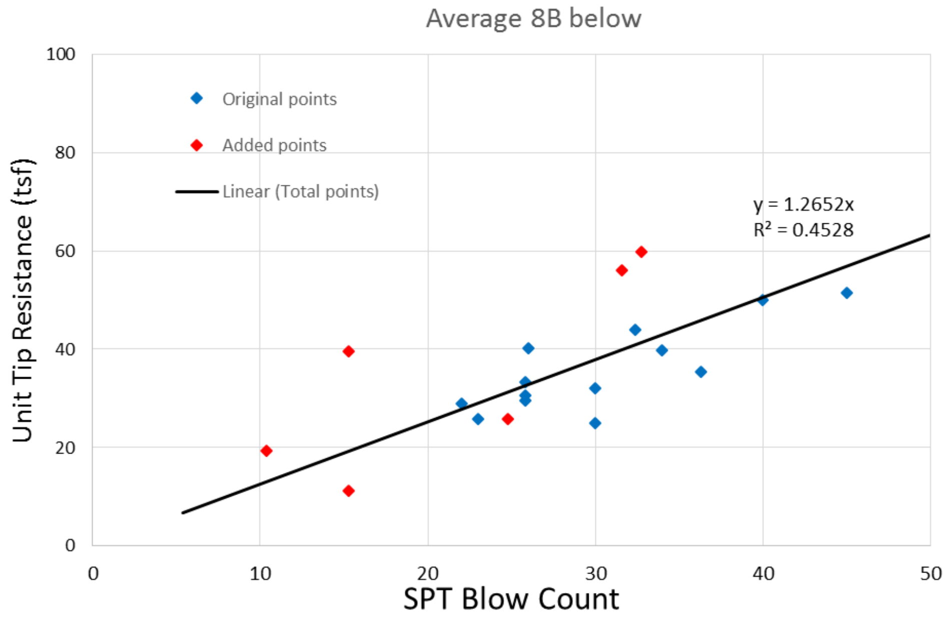
PCP End Bearing–Weathered Limestone with Sand

Project	Bridge #	Pile Name		Nearest Boring	Distance (ft)	Soil Type	Pile Size (in)	Qt (tsf)	Qt (ksf)	Tip_Elev (ft)	Average N (8B below)	Average N (3.5B below &8B above)	Average N Value 4B Below
I 595	000031	Pier 3	Pile 14	BBZ8A-031-8	20	Weathered Limestone with Clean Sand	24	38.75	77.50	-69.06	31.00	27.60	32.40
	000107	End Bent 5	Pile 1	BBZ3-107-4	5	Weathered Limestone with Clean Sand	24	50.00	100.00	-27.03	40.00	26.42	20.40
	000112	Pier 2	Pile 6	B15-N15	39	Weathered Limestone with Clean Sand	24	30.63	61.25	-31.86	25.80	25.60	39.00
			Pile 7	B15-N15	37	Weathered Limestone with Clean Sand	24	51.50	103.00	-31.93	45.00	19.50	39.00
			Pile 8	B15-N15	33	Weathered Limestone with Clean Sand	24	33.25	66.50	-31.89	25.80	19.50	39.00
			Pile 9	B15-N15	30	Weathered Limestone with Clean Sand	24	29.50	59.00	-31.86	25.80	20.40	39.00
		Pier 5S	Pile 1	BW-504	24	Weathered Limestone with Clean Sand	24	35.50	71.00	-42.58	36.30	10.20	40.00
	000123	Pier 3L	Pile 4	BBZ6-123-3	90	Weathered Limestone with Clean Sand	24	44.00	88.00	-60.26	32.40	45.00	36.00
		Pier 4	Pile 6	BBZ6-123-4	25	Weathered Limestone with Clean Sand	24	32.00	64.00	-43.48	30.00	28.91	37.50
			Pile 12	BBZ6-123-4	20	Weathered Limestone with Clean Sand	24	25.00	50.00	-43.48	30.00	28.91	37.50
			Pile 11	BBZ6-123-4	22	Weathered Limestone with Clean Sand	24	28.96	57.92	-34.63	22.00	18.00	32.50
	000119	End Bent 1	Pile 12	BW-601	25	Weathered Limestone with Clean Sand	24	25.82	51.64	-79.42	23.00	18.60	28.00
	860425	End Bent 1	Pile 13	BBZ7-425-1 & -2	100	Weathered Limestone with Clean Sand	24	40.11	80.23	-45.25	26.00	24.00	34.00
		End Bent 5	Pile 12	BBZ7-425-5 & -4	40	Weathered Limestone with Clean Sand	24	39.78	79.56	-7.00	34.00	24.00	45.00
SR 826	Bridge 35	Pier 3	Test Pile 2	B-180	30	Weathered Limestone with Clean Sand	24	25.90	51.8	-43.75	24.80	26.50	45.00
	Bridge 30B	End Bent 3	Test Pile 6	B-30C-1	22	Weathered Limestone with Clean Sand	24	55.97	111.93	-49.78	31.60	38.42	45.00
	Bridge 30A	Pier 2	Test Pile 1	B-30A-2	30	Weathered Limestone with Clean Sand	24	59.88	119.75	-52.90	32.75	27.00	45.00
	Bridge 24B	End Bent 2	Pile 1	B-24-1	15	Weathered Limestone with Clean Sand	24	11.27	22.53	-47.08	15.25	12.50	12.25
			Pile 6	B-24-1	15	Weathered Limestone with Clean Sand	24	39.48	78.95	-47.42	15.25	12.50	12.25
	Bridge 29C	End Bent 2	Pile 11	B-29A-2	25	Weathered Limestone with Clean Sand	24	19.34	39.87	-29.20	10.40	14.40	11.30

PCP End Bearing–Weathered Limestone with Sand







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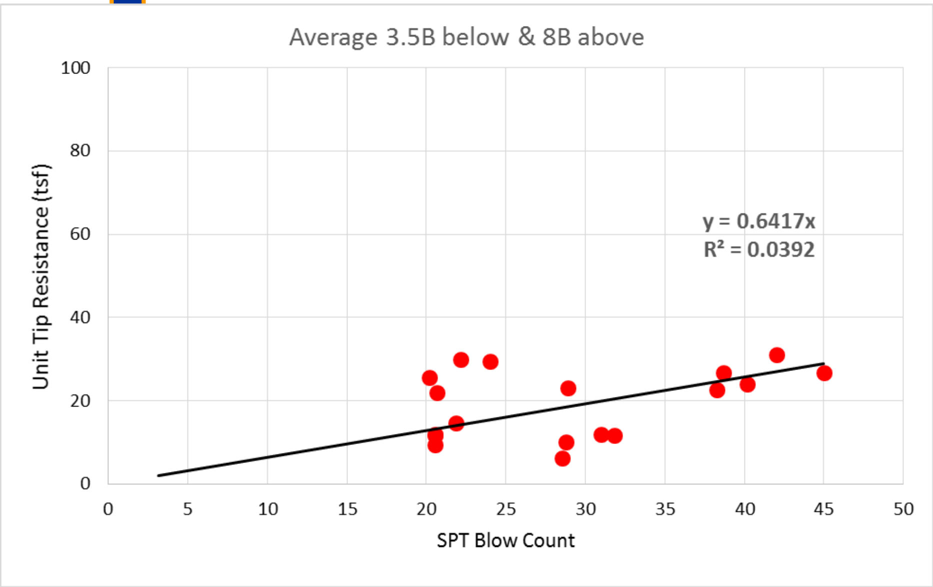
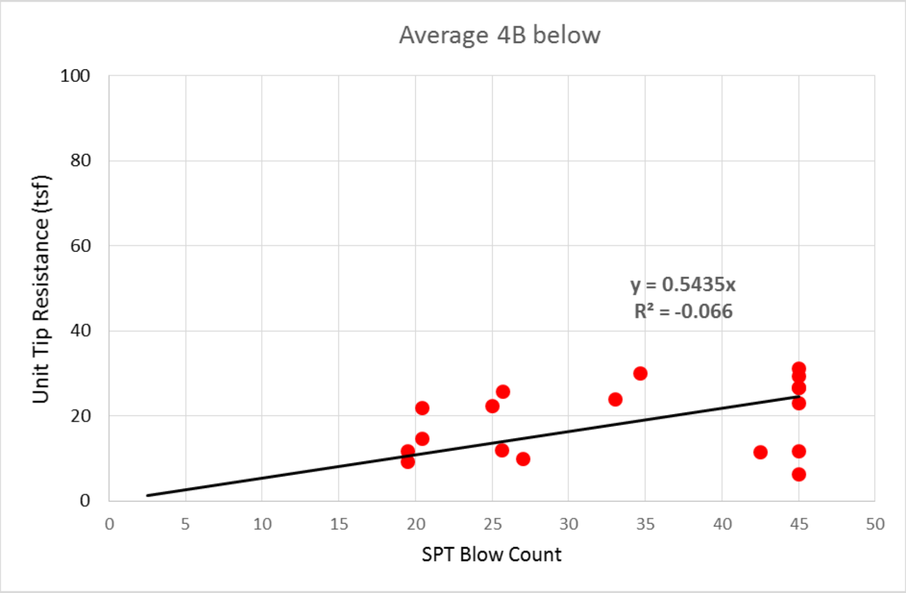
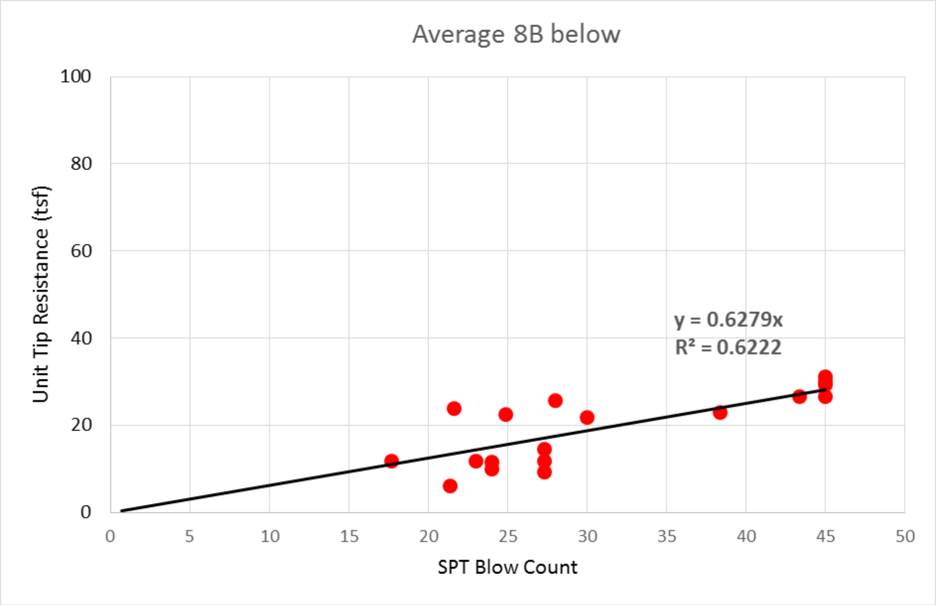
PCP End Bearing–Weathered Limestone with Soil Mixtures







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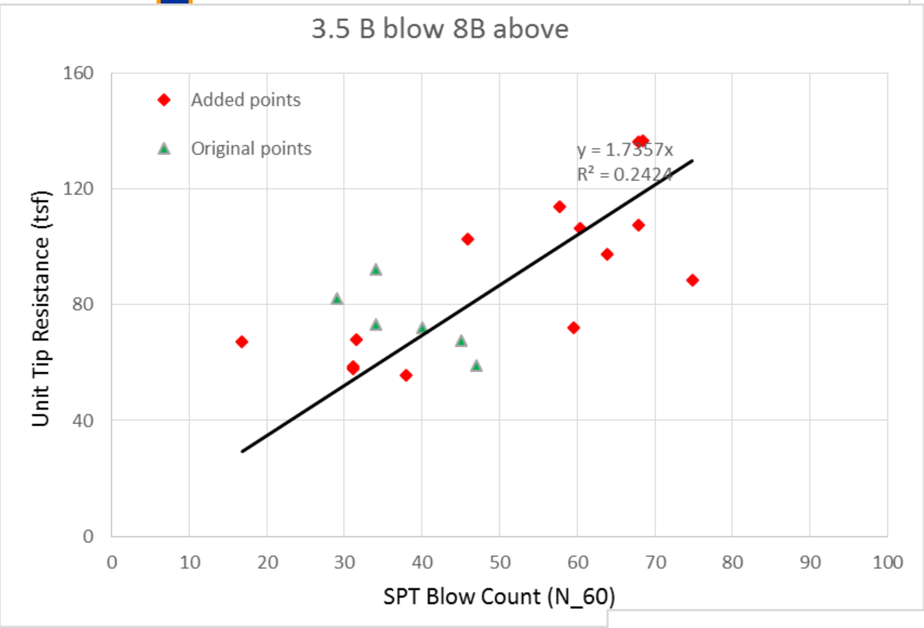
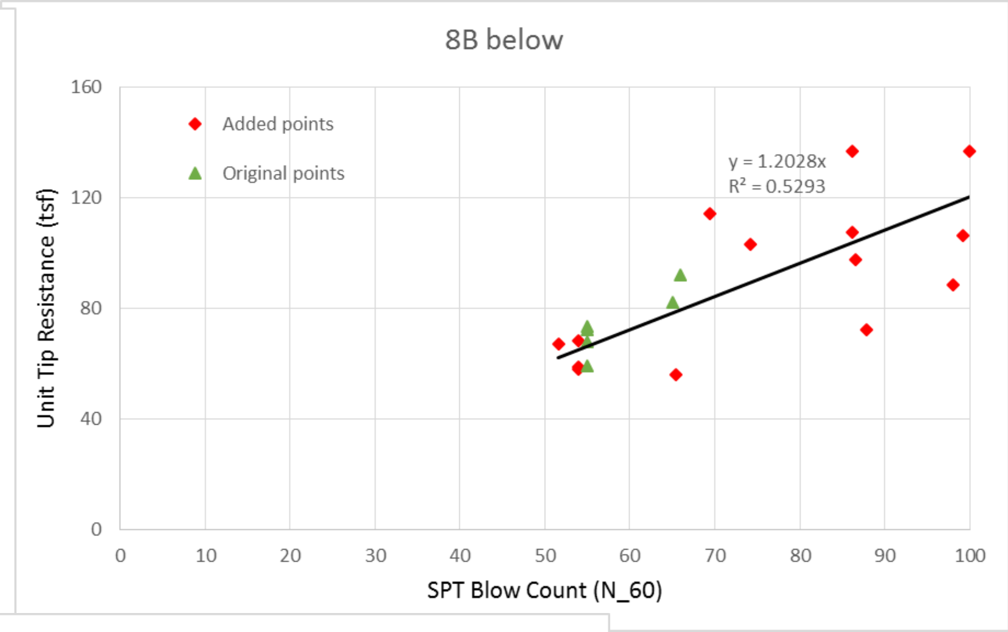
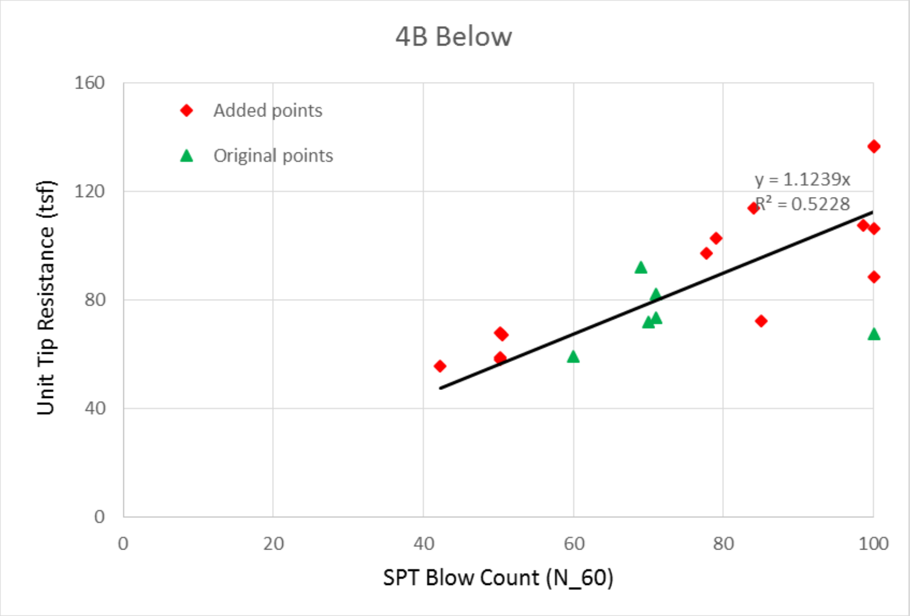
PCP End Bearing in Competent Limestone

Project	Bridge #	Bent Name	Pile No.	Pile Size	Nearest Boring	Qt (ksf)	Qt (Tsf)	Tip_Elev (ft)	Distance (ft)	8B Below	8B Above 3.5B Below	4B Below
SR 826	Bridge 3B	Pier 6	Inst. Pile 9	30	B-2-2	111.67	55.84	-42.19	47.00	65.40	38.00	42.30
	Bridge 7C	Eend Bent 3	Inst. Pile 14	24	B-7C-2	144.40	72.20	-47.09	97.00	87.80	59.60	85.00
	Bridge 9	Bent 10	Inst. Pile 27	24	B-9-7	205.72	102.86	-42.73	42.00	74.20	45.90	79.00
	Bridge 11	Pier 6	Prod Pile 5	24	B-11-4	194.65	97.33	-79.70	0.00	86.60	63.84	77.67
	Bridge 19	Pier 3	Inst. Pile 10	24	B-19-6	134.32	67.16	-45.80	18.00	51.60	16.85	50.60
		Pier 3	Inst. Pile 15	24	B-19-6	115.80	57.90	-46.88	10.00	54.00	31.15	50.30
		Pier 3	Inst. Pile 28	24	B-19-6	136.32	68.16	-47.80	16.00	54.00	31.50	50.30
		Pier 3	Inst. Pile 23	24	B-19-6	117.55	58.78	-47.38	24.00	54.00	31.15	50.30
		End Bent 5	Mon Pile 12	24	B-19-4	215.01	107.51	-46.05	20.00	86.20	67.90	98.66
		End Bent 5	Mon Pile 15	24	B-19-4	212.71	106.36	-45.66	6.00	99.20	60.33	100.00
		End Bent 5	Mon Pile 29	24	B-19-4	273.06	136.53	-46.62	27.00	86.20	67.90	100.00
	Bridge 47	Bent 1	Test Pile 1	24	B-47-1	273.66	136.83	-54.21	15.00	100.00	68.50	100.00
		Bent 2	Test Pile 7	24	B-47-2	176.94	88.47	-48.62	18.00	98.00	74.80	100.00
	Bridge 43	End Bent 2	Test Pile 1	24	B-43-2	227.87	113.94	-46.83	16.00	69.40	57.70	84.00
I-595	000112	Pier 5S	Pile 3	24	BW-504	184.25	92.13	-38.51	25.00	66.00	34.00	69.00
		Pier 5S	Pile 7	24	BW-504	164.50	82.25	-41.48	20.00	65.00	29.00	71.00
		Pier 5N	Pile 3	24	BW-504	144.25	72.13	-56.00	25.00	55.00	40.00	70.00
	860378	End Bent 2L	Pile 1	24	BW-703	118.27	59.13	-43.17	29.00	55.00	47.00	60.00
	000033	End Bent 1	Pile 6	24	BBZ8B-033-1	146.70	73.35	-56.17	34.00	55.00	34.00	71.00
	000031	Pier 8L	Pile 9	24	BBZ8A-031-2	135.25	67.63	-58.90	20.00	55.00	45.00	100.00

PCP End Bearing in Competent Limestone







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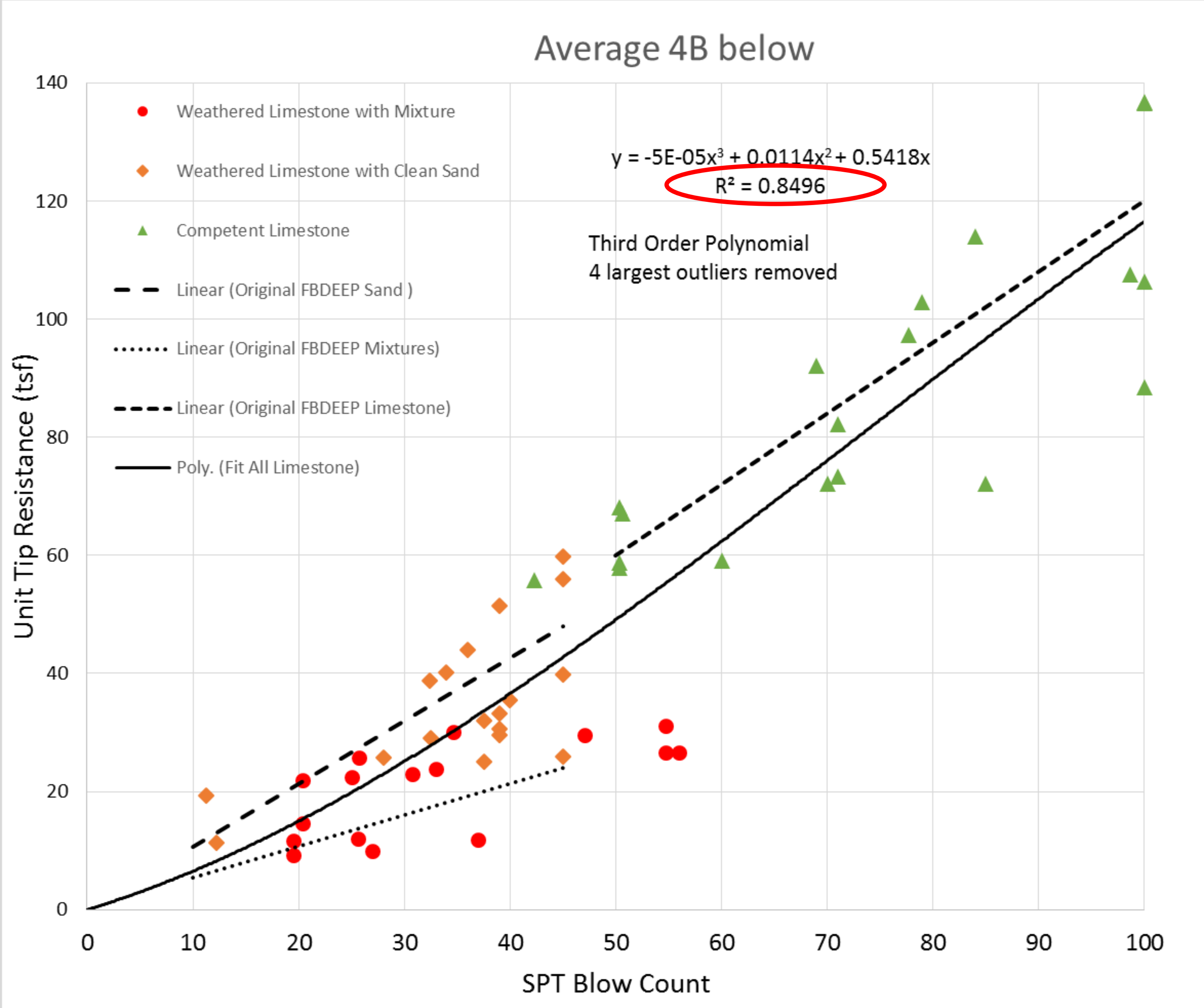
PCP End Bearing in Limestone



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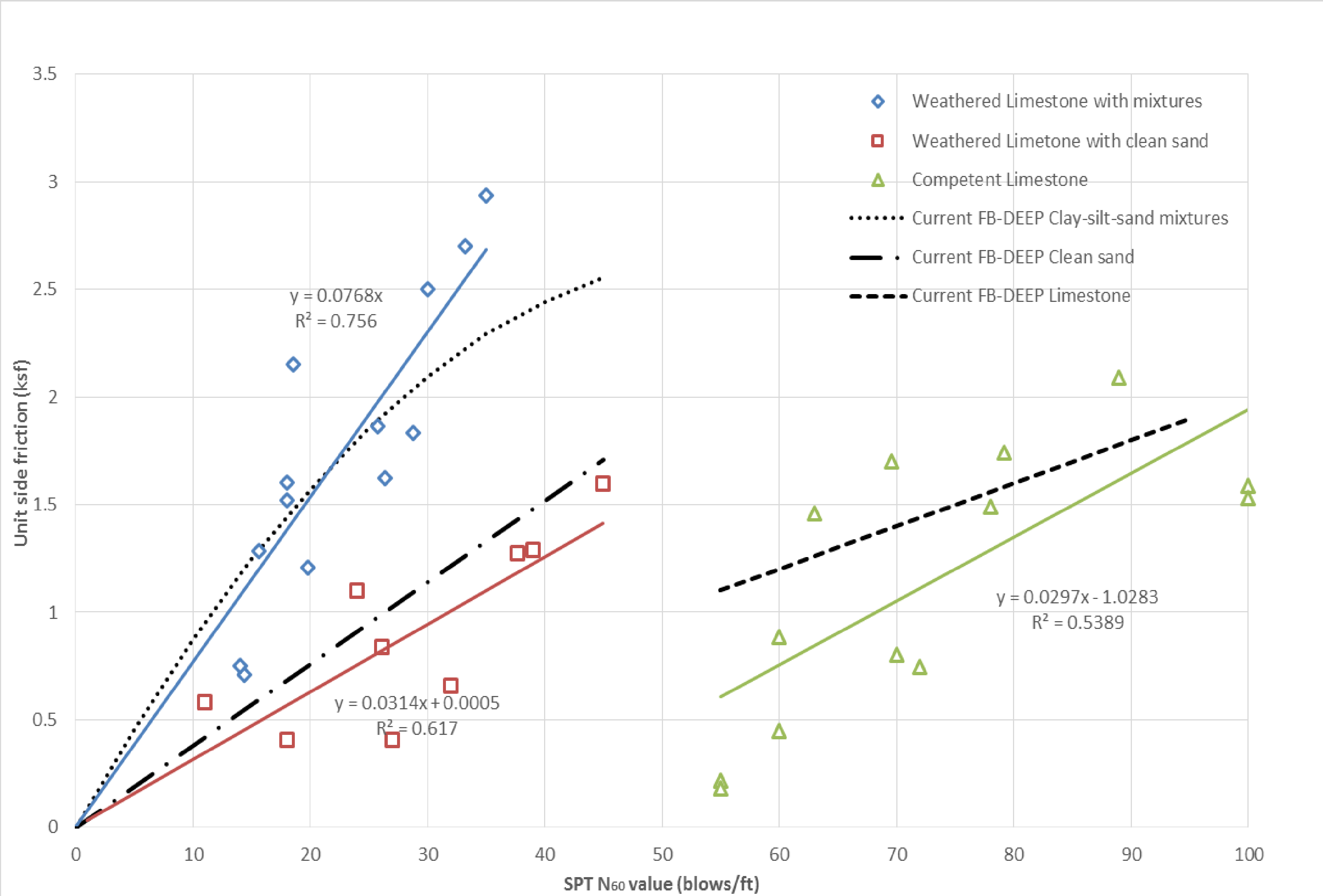
PCP Side Friction in Limestone



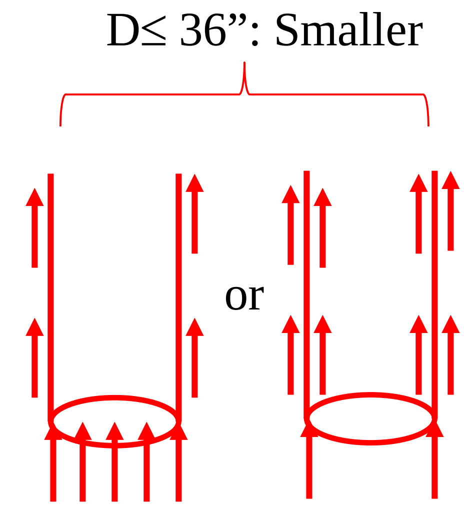
Summary of PCP in Florida Limestone

1. **PCP End Bearing:**
    - **Change Averaging from 3.5B-8B to 4B Below**
    - **Increase Limit of SPT N value to 100 Due to higher measured DLT tip resistances**

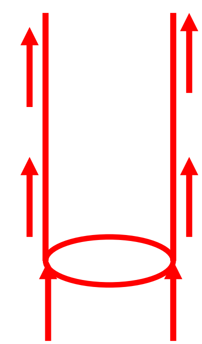
2. **PCP Side Resistance:**
    - **PCPs in Limestone with mixed soils with N <45 is conservative (may wish to model Mixture with soil 2)**
    - **PCP in competent Limestone, Limit of N=60 too conservative increase to N=100**

Open Diameter Pipe Piles 24”<D<54”

Current FBDEEP:



1. **D ≤ 36”**
   - **Qs = unit skin friction x A $_{\text{outside surface area}}$**
   - **Q_{tip} = smaller of unit tip resistance x$A_{\text{tip total}}$ or unit skin friction x A $_{\text{outside}}$ + unit tip resistance x A_{ring}**



2. **D > 36”:**
   - **Qs = unit skin friction x A $_{\text{outside surface area}}$**
   - **Q_{tip} = unit tip resistance x A_{ring}**

Should D≤ 36” Be Used for D>36”?

Open Diameter Pipe Piles 24”<D<54”

Project Name	Pile Name	Diam (in)	Thickness (in)	Plug %	Pile length(ft)	Pile Bottom Depth(ft)	Boring Name	Distance(ft)	Soil Type								Load Test(kips)
									Clay		Sand		Clay-Silt-Sand		Rock		
									Depth Range(ft)	Percentage	Depth Range(ft)	Percentage	Depth Range(ft)	Percentage	Depth Range(ft)	Percentage	
Louisiana Highway 1 Improvements Phase 1B, LA, USA	T-3-1	30	0.63	>0.44 WH	195.00	173.20	BR-002	80.00	34-54	11.43%			0-34&54-175	88.57%			1597.00 [1]
I-880 Port of Oakland Connector Viaduct (Caltrans Bridge No. 33-0612E), CA, USA	TP-9	42	0.63	>0.4 WH	88.30	86.30	eneralized Borir	Unknown	0-13.5&18.5-60&67-90.5	86.74%	13.5-18.5&60-67	13.26%					1253.00 [1]
							UTB-23MR	Unknown	61.25-66.50	5.52%			0-61.25&66.50-95.01	94.48%			963.40 [2]
Woodrow Wilson Bridge over Potomac River, VA & MD, USA	PL-1	54	1.00	>0.9	165.20	132.20	ID_63 UNK	Unknown	2.5-13&43-51&66-137	69.71%	0-2.5&13-41&51-57	26.64%	41-43&57-66	3.65%			2783.00 [1]
							ID_64 UNK	Unknown	0-10.2&25.5-44.5&94.5-104.7&115.5-141.7	46.30%	10.2-20.5&59.5-74.5&84.5-94.5&104.79-115.5	32.70%	20.5-25.5&44.5-59.5&74.5-84.5	21.35%			
	PL-2	42	1.00	>0.9	125.50	107.00	ID_64 UNK	Unknown	0-10.2&25.5-44.5&94.5-104.7	35.02%	10.2-20.5&59.5-74.5&84.5-94.5&104.79-112.5	38.31%	20.5-25.5&44.5-59.5&74.5-84.5	26.67%			2788.00 [1]
							ID_65 UNK	Unknown	84-108	22.22%	7-12&62-67	9.26%	0-7&12-18&23-28&38-62&67-84	54.63%	18-23&28-38	13.89%	
	PL-3	36	1.00	>0.9	96.30	78.00	ID_64 UNK	Unknown	0-10.2&25.5-44.5	34.56%	10.2-20.5&59.5-74.5	29.94%	20.5-25.5&44.5-59.5	35.50%			1597.00 [1]
							ID_65 UNK	Unknown			7-12&62-67	12.35%	0-7&12-18&23-28&38-62&67-81	65.43%	18-23&28-38	22.22%	
Berenda Slough Bridge (Clatrans Bridge No. 41-	TP-1	42	0.63		106.00	103.00	eneralized Borir	50.00			0-60.5&70.5-77	62.62%	60.5-70.5&77-107	37.38%			1618.00 [1]
Gulf Intracoastal Waterway West Closure Complex Test Site 3, LA, USA	TP-9	24	0.50	>0.5	189.83	169.92	ALGS GS-08-2U	150.00					0-177.4	100.00%			811.20 [1]
	TP-11	30	0.63	>0.5 VH	190.00	177.42	ALGS GS-08-2U	150.00					0-179.9	100.00%			1215.00 [1]
Gulf Intracoastal Waterway West Closure Complex, LA, USA	TP-3	30	0.63	>0.5 VH	160.50	141.02	ALGS GS-08-13U	Unknown	0-169.3	100.00%							830.40 [1]
	TP-4	30	0.63	>0.4 WH	170.30	162.50		Unknown	0-169.3	100.00%							1060.00 [1]
	TP-5	30	0.63	>0.35 WH	161.00	140.33		Unknown	0-169.3	100.00%							899.60 [1]
	TP-6	30	0.63	>0.35 WH	150.00	140.25		Unknown	0-169.3	100.00%							830.40 [1]
Lagoon Bridge U.S.68/KY80, KY, USA	TPL-2	30	1.00	>1	97.10	80.10	B-3004 UNK	110.50	0-20.3&54.3-59.3	29.69%			20.3-54.3&59.3-85.2	70.31%			1443.00 [1]
							B-3051 UNK	52.50	18.7-24.2	6.79%					0-18.7&24.2-81	93.21%	
US Highway TH61/Mississippi River, MN,	TP-10	42	0.88	>0.3	194.00	190.00	B-09UNK	Unknown	8-64&99-13	45.26%	0-18&64-99	27.89%			139-190	26.84%	4116.00 [3]
							B-10UNK	Unknown	7-72&97-13	42.11%	0-27&72-97	27.37%			132-190	30.53%	
T.H. 36 over the St. Croix River, MN, USA	P-B-1	24	0.50	conc fill	127.70	86.90	T-205	Unknown			0-89	100.00%					1875.00 [3]
	P-B-2	24	0.63	conc fill	127.40	86.60		Unknown			0-89	100.00%					2190.00 [3]
	P-B-3	42	0.88	.7 conc fill	140.00	140.00		Unknown			0-89	62.68%			89-142	37.32%	4128.00 [3]
	P-B-4	42	0.75	.7 conc fill	140.00	140.00		Unknown			0-89	62.68%			89-142	37.32%	3750.00 [3]
TH 19 over the Mississippi River, MN, USA	TP-3	42	0.88	>0.9	150.00	96.00	T12 UNK	Unknown	57-67	10.20%	0-57&67-98	89.80%					3750.00 [3]
	TP-5	42	0.88	>0.9	170.00	118.00	T12 UNK	Unknown	57-67	7.81%	0-57&67-118	84.38%			118-128	7.81%	3854.00 [3]
							T19 UNK	Unknown			0-121.8	100.00%					

Open Diameter Pipe Piles 24”<D<54”

Project Name	Pile Name	Diam (in)	Thickness (in)	Plug %	Pile length(ft)	Pile Bottom Depth(ft)	Boring Name	Distance(ft)	Soil Type: Clay Depth Range(ft)	Clay Percentage	Sand Depth Range(ft)	Sand Percentage	Clay-Silt-Sand Depth Range(ft)	Clay-Silt-Sand Percentage	Rock Depth Range(ft)	Rock Percentage	Load Test(kips)
T.H 43 over the Mississippi River, MN, USA	TP-1	42	0.75	>0.75	141.40	136.90	T-103	40.00			0-122	87.71%			122-139.1	12.29%	3720.60 [3]
Port of Oakland Connector Viaduct Maritime On/Off-Ramps (Caltrans Bridge No. 33-612E), CA, USA	IP3-10NC	42	0.75	>0.54	98.00	95.00	UTB-161	5.50	16.2-51.2&71.2-81.2&86.2-	47.53%	0-16.2&81.2-86.2	32.32%	51.2-71.2&91.2-105.2	20.15%			800.00 [1]
	IP6-17NC	42	0.75	>0.59	103.00	101.00	UTB-24A	12.20	0-66.5	60.45%			84-110	23.65%	66.5-84.0	15.90%	1000.00 [1]
	IP9-27NC	42	0.63		97.00	93.00	UTB-05	13.40	0-22.5&49-90&95-99.5	58.86%			22.5-49&90-95	41.14%			1288.00 [1]
Legislative Route 795 section B-6 Philadelphia, PA, USA	TP-C	30	0.50	>0.92	64.20	62.00	PLT-C	250.00	41.25-56.5	23.46%	0-41.25&56.5-65	76.54%					1499.30 [1]
	TP-D	30	0.50	>0.87	86.20	84.00	B-620	200.00	0-16&34.5-48.5&52.25-74.5	60.93%	16-34.5&48.5-52.25&74.5-85.75	39.07%					895.78 [1]
	TP-E	30	0.50	>0.83	96.00	94.00	PLT-E	200.00	51-81.25	31.68%	0-5.5&20.5-51&81.25-95.5	52.62%	5.5-20.5	15.71%			1282.00 [1]
Jin Mao Building, Shanghai, China	ST-1	36	0.79		262.47	289.19	Generalized Boring	Unknown	0-95.14	23.39%	118.11-206.69&249.34-406.824	60.48%	95.14-118.11&206.69-249.34	16.13%			3447.00 [1]
	ST-2	36	0.79		262.47	259.51		Unknown	0-95.14	23.39%	118.11-206.69&249.34-406.824	60.48%	95.14-118.11&206.69-249.34	16.13%			3796.80 [1]
Hokkaido, Japan	TP-1	40	0.87	0.85	134.51	131.23	B-1	Unknown			0-47.9&66.44-83.79	46.80%	47.9-66.44&83.79-139.44	53.20%			3528.00 [1]
Chiba, Japan	TP-2	31.5	0.64	0.98	157.48	133.07	B-2	Unknown	89.98-118.16	6.49%	0-54.19&71.13-89.98	55.76%	54.19-71.13	13.14%	118.16-130.98	24.61%	1855.00 [1]
Kwangyang Substitute Natural Gas (SNG) Plant, KOREA	TP-2	28	0.28	No info	127.00	122.70	BH1	Unknown			0-154.2	100.00%					407.00 [1]
	TP-3	36	0.31	No info	172.21	166.83	BH1	Unknown			0-154.2	81.71%	154.2-187	18.29%			674.00 [1]
Port of Toamasina Offshore Jetty, Republic of Madagascar	4B	40	0.87	>0.95	213.26	147.97	NP-02	12.00	127.95-133.4	3.62%			0-127.95&133.4-149.6	96.38%			2205.00 [1]
	12A	40	0.87	>0.64 VH	213.26	143.04	NP-04	32.00	87.93-104.66	11.64%			0-87.93&104.66-143.7	88.36%			2029.00 [1]
	SP05	48	0.87	>0.94	213.26	117.45	BH-SP	20.00	75.5-87	9.72%			0-75.5&87-118	90.28%			1213.00 [1]
San Mateo-Hayward Bridge (Caltrans Bridge No. 35-0054), CA, USA	TP-Site A	42	6.88		138.62	115.85	95-3	250	0-56.2&114.5-121.5	52.02%			56.2-114.5	47.98%			1544.74 [1]
	TP-Site B	42	6.88		133.86	126.31	95-7	125	0-13.5&83.5-87.5&95.5-117.5	29.81%	43.5-63.5	15.09%	13.5-43.5&63.5-83.5&87.5-95.5&117.5-132.5	55.09%			1681.66 [1]

Current FBDEEP Open Pipe Predictions

Project Name	Pile Name	Diameter (in)	Boring Name	Predicted Capacity (kips)			Measured Capacity (kips)			Capwap Capacity (kips)		
				Side Friction	Tip Resistance	Total Capacity	Side Friction	Tip Resistance	Total Capacity	Side Friction	Tip Resistance	Total Capacity
Louisiana Highway 1 Improvements Phase 1B, LA, USA	T-3-1	30	BR-002	1482.00	270.00	1752.00	1163.80	433.20	1597.00	843.00	115.00	958.00
I-880 Port of Oakland Connector Viaduct (Caltrans Bridge No. 33-0612E), CA, USA	TP-9	42	Generalized Boring	754.00	15.00	769.00			1253.00			
			UTB-23MR	1234.52	18.62	1253.14			963.40			
Woodrow Wilson Bridge over Potomac River, VA & MD, USA	PL-1	54	ID_63 UNK	1900.00	52.00	1952.00	2000.00	783.00	2783.00			
			ID_64 UNK	2572.00	50.50	2622.50	2000.00	783.00	2783.00			
	PL-2	42	ID_64 UNK	1555.00	44.20	1599.20	2000.00	788.00	2788.00			
			ID_65 UNK	1816.00	17.16	1833.16	2000.00	788.00	2788.00			
	PL-3	36	ID_64 UNK	811.16	406.50	1217.66			1597.00			
			ID_65 UNK	976.40	410.40	1386.80			1597.00			
Berenda Slough Bridge (Clatrans Bridge No. 41-0009R),CA, USA	TP-1	42	B-1(Generalized Boring)	1022.84	15.74	1038.58			1618.00			
Gulf Intracoastal Waterway West Closure Complex Test Site 3, LA, USA	TP-9	24	ALGSGS-08-2U	1354.66	158.44	1513.10			811.20	1152.00	49.00	1201.00
	TP-11	30	ALGSGS-08-2U	1784.00	186.30	1970.30			1215.00	1286.00	130.00	1416.00
Gulf Intracoastal Waterway West Closure Complex, LA, USA	TP-3	30	ALGSGS-08-13U	730.00	80.64	810.64			830.40	867.00	72.00	939.00
	TP-4	30		1012.00	100.70	1112.70			1060.00	1080.00	25.00	1105.00
	TP-5	30		720.00	80.00	800.00			899.60	814.00	42.00	856.00
	TP-6	30		722.00	80.30	802.30			830.40	876.00	74.00	950.00
Lagoon Bridge U.S.68/KY80, KY, USA	TPL-2	30	B-3004 UNK	814.00	241.42	1055.42	1174.79	268.71	1443.00	593.00	74.00	667.00
			B-3051 UNK	672.00	266.40	938.40	1174.79	268.71	1443.00			
US Highway TH61/Mississippi River, MN, USA	TP-10	42	B-09UNK	1539.34	25.58	1564.92			4166.00			
			B-10UNK	1565.00	39.22	1604.22			4166.00			
T.H. 36 over the St. Croix River, MN, USA	P-B-1	24	T-205	409.58	204.46	614.04			1875.00	181.00	884.00	1065.00
	P-B-2	24		409.58	204.00	613.58	343.00	1847.00	2190.00	217.00	1029.00	1246.00
	P-B-3	42		815.40	52.74	868.14	983.00	3145.00	4128.00	797.00	2352.00	3149.00
	P-B-4	42		815.40	52.74	868.14	746.00	3044.00	3790.00	1014.00	2271.00	3285.00
TH 19 over the Mississippi River, MN, USA	TP-3	42	T12 UNK	997.72	34.78	1032.50	1100.00	2650.00	3750.00			
	TP-5	42	T12 UNK	1238.32	37.92	1276.24	1550.00	2200.00	3750.00			
			T19 UNK	924.00	42.80	966.80	1550.00	2200.00	3750.00			
T.H. 43 over the Mississippi River, MN, USA	TP-1	42	T-103	1172.61	26.35	1198.96			3720.60	1225.00	1610.00	2835.00
Port of Oakland Connector Viaduct Maritime On/Off-Ramps (Caltrans Bridge No. 33-612E), CA, USA	TP3-10NCI	42	UTB-161	666.64	13.24	679.88			800.00	655.00	296.00	951.00
	TP6-17NCI	42	UTB-24A	966.00	17.26	983.26			1000.00	806.00	246.00	1052.00
	TP9-27NCI	42	UTB-05	1204.00	17.80	1221.80			1288.00			
Legislative Route 795 section B-6 Philadelphia, PA, USA	TP-C	30	PLT-C	730.40	185.36	915.76			1499.30			
	TP-D	30	B-620	871.78	129.48	1001.26			895.78			
	TP-E	30	PLT-E	980.26	145.22	1125.48			1282.00			
Jin Mao Building, Shanghai, China	ST-1	36	Generalized Boring	2629.00	370.84	2999.84	2502.35	946.22	3447.00			
	ST-2	36		2944.30	381.80	3326.10	3085.28	566.74	3796.80			
Hokkaido, Japan	TP-1	40	B-1 Or Generalized Boring	1624.00	27.18	1651.18	3089.00	441.00	3528.00			
Chiba, Japan	TP-2	31.5	B-2(Generalized Boring)	1137.10	310.60	1447.70	1278.00	618.75	1855.00			
Kwangyang Substitute Natural Gas (SNG) Plant, KOREA	TP-2	28	BH1 Or Generalized Boring	219.00	64.00	283.00			407.00			
	TP-3	36	BH1 Or Generalized Boring	407.04	89.44	496.48			674.00			
Port of Toamasina Offshore Jetty, Republic of Madagascar	4B	40	NP-02	1532.00	23.00	1555.00			2205.00	619.35	400.00	1019.35
	12A	40	NP-04	1785.11	25.50	1810.61			2029.00	156.02	388.00	544.02
	SP05	48	BH-SP	1388.82	57.24	1446.06			1213.00	380.40	348.00	728.40

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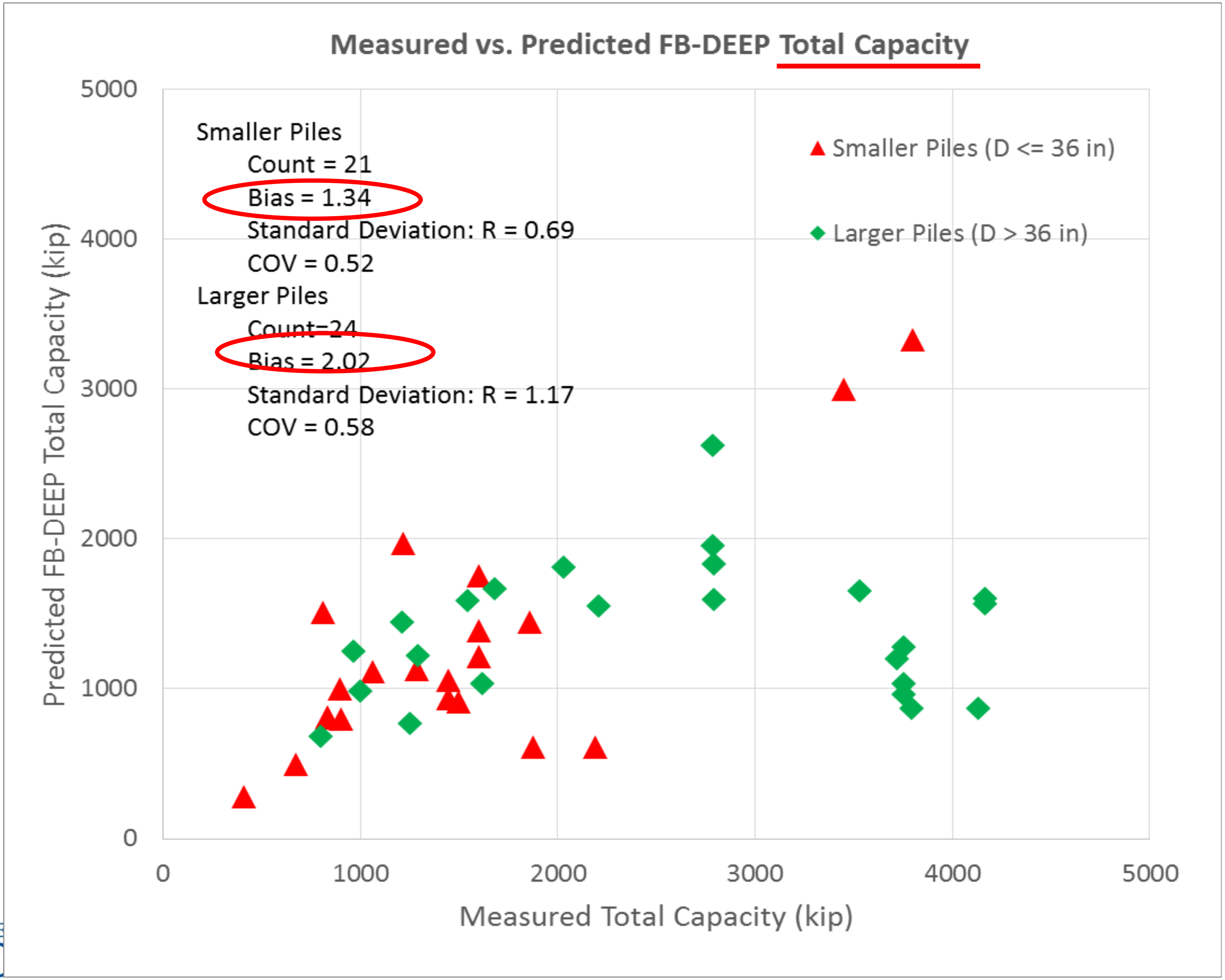
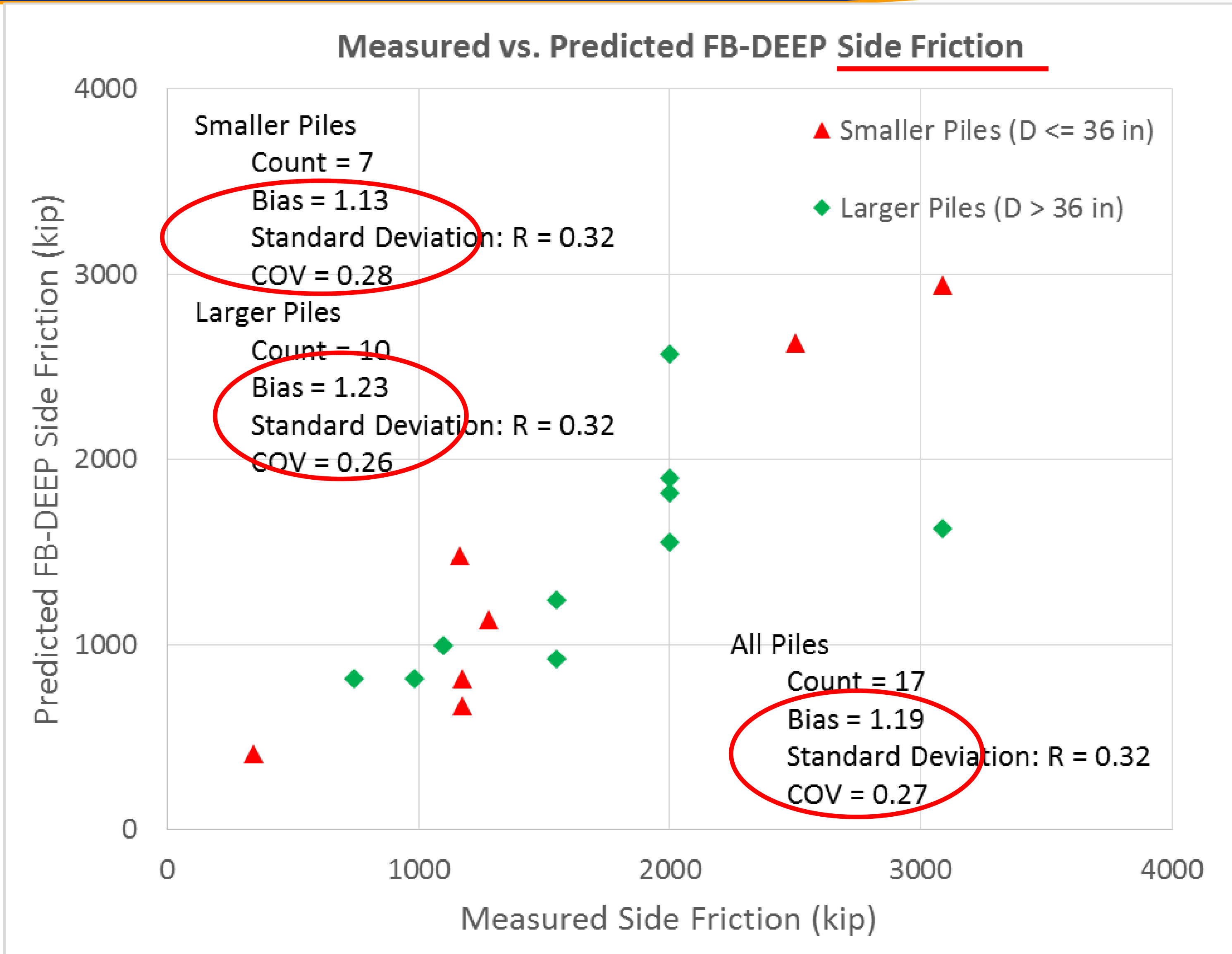
Current FB-DEEP Predictions



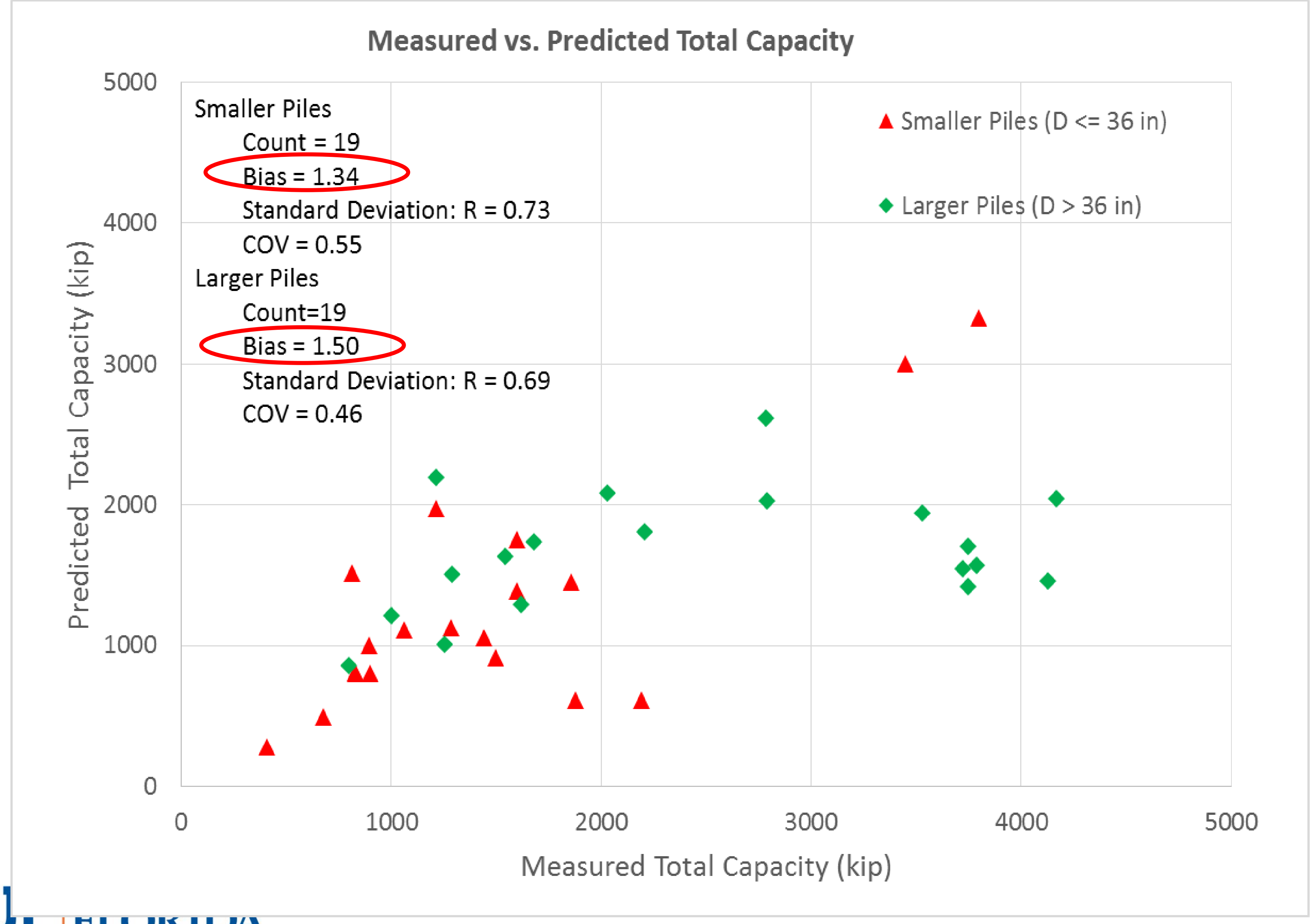
Current FB-DEEP Predictions



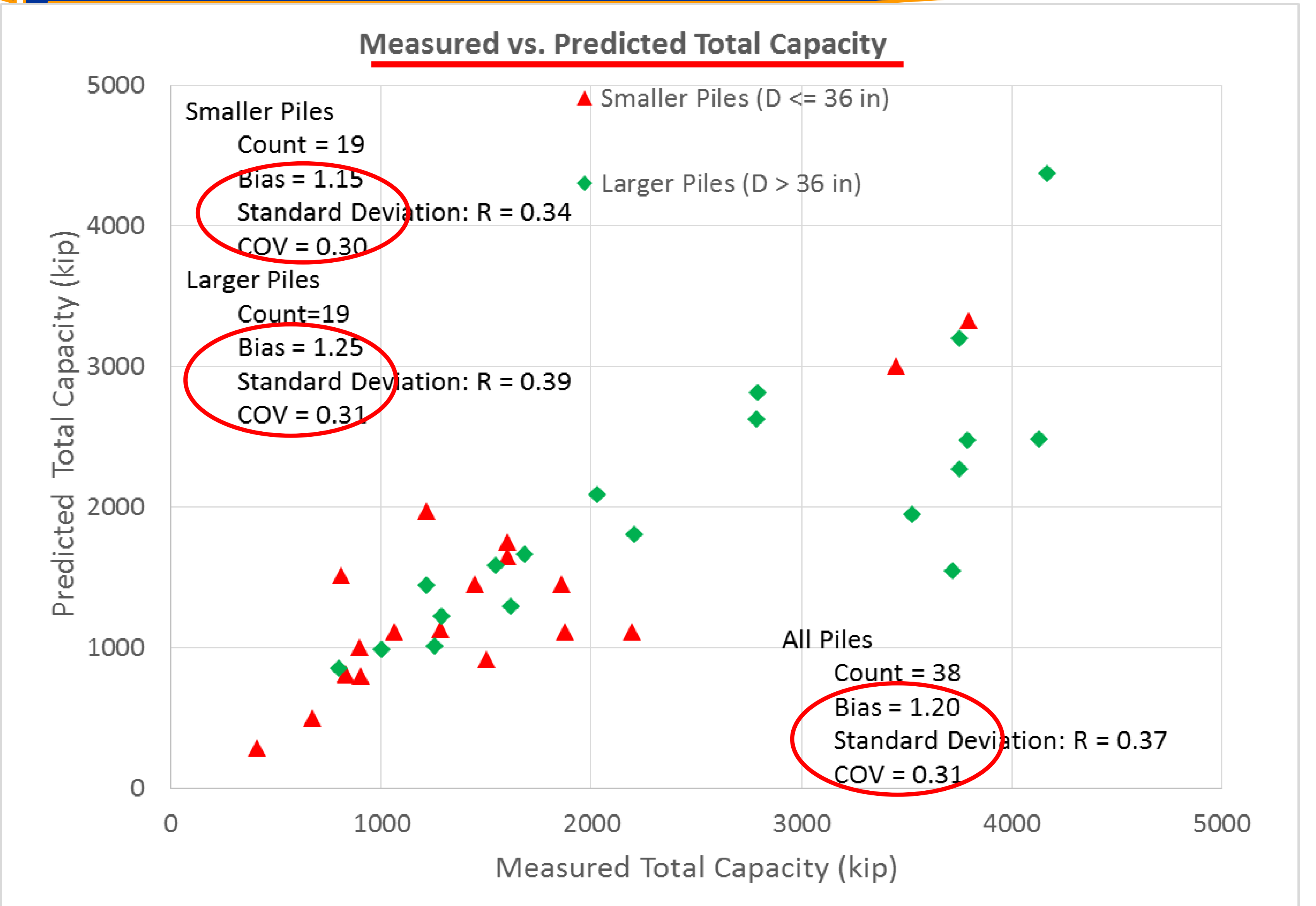
Modify FB-DEEP D>36” End Bearing to Same as D≤36”

Project Name	Pile Name	Diameter (in)	Boring Name	Side Friction (kips)		Tip Resistance (kips)		Total Capacity (kips)		
				Outer Skin	Inner Skin	Ring Tip	Full Tip	Outer Skin + Inner Skin + Ring	Outer Skin + Full Tip	Measured
Louisiana Highway 1 Improvements Phase 1B, LA, USA	T-3-1	30	BR-002	1482.00	1420.25	22.03	270.00	2924.28	1752.00	1597.00
I-880 Port of Oakland Connector Viaduct (Caltrans Bridge No. 33-	TP-9	42	Generalized Boring	754.00	731.56	15.00	255.81	1500.56	1009.81	1253.00
			UTB-23MR	1234.52	1197.78	18.62	317.54	2450.92	1552.06	963.40
Woodrow Wilson Bridge over Potomac River, VA & MD, USA	PL-1	54	ID_63 UNK	1900.00	1829.63	52.00	715.25	3781.63	2615.25	2783.00
			ID_64 UNK	2572.00	2476.74	50.50	694.61	5099.24	3266.61	2783.00
	PL-2	42	ID_64 UNK	1555.00	1480.95	44.20	475.42	3080.15	2030.42	2788.00
			ID_65 UNK	1816.00	1729.52	17.16	184.57	3562.68	2000.57	2788.00
	PL-3	36	ID_64 UNK	811.16	766.10	43.91	406.50	1621.17	1217.66	1597.00
			ID_65 UNK	976.40	922.16	44.33	410.40	1942.89	1386.80	1597.00
Berenda Slough Bridge (Clatrans Bridge No. 41-0009R),CA, USA	TP-1	42	B-1(Generalized Boring)	1022.84	992.40	15.74	268.43	2030.98	1291.27	1618.00
Gulf Intracoastal Waterway West Closure Complex Test Site 3, LA, USA	TP-9	24	ALGSGS-08-2U	1354.66	1298.22	12.93	158.44	2665.80	1513.10	811.20
	TP-11	30	ALGSGS-08-2U	1784.00	1709.67	15.20	186.30	3508.87	1970.30	1215.00
Gulf Intracoastal Waterway West Closure Complex, LA, USA	TP-3	30	ALGSGS-08-13U	730.00	699.58	6.58	80.64	1436.16	810.64	830.40
	TP-4	30		1012.00	969.83	8.22	100.70	1990.05	1112.70	1060.00
	TP-5	30		720.00	690.00	6.53	80.00	1416.53	800.00	899.60
	TP-6	30		722.00	691.92	6.55	80.30	1420.47	802.30	830.40
Lagoon Bridge U.S.68/KY80, KY, USA	TPL-2	30	B-3004 UNK	814.00	759.73	31.12	241.42	1604.85	1055.42	1443.00
			B-3051 UNK	672.00	627.20	34.34	266.40	1333.54	938.40	1443.00
US Highway TH61/Mississippi River, MN, USA	TP-10	42	B-09UNK	1539.34	1475.20	25.58	313.49	3040.12	1852.83	4166.00
			B-10UNK	1565.00	1499.79	39.22	480.65	3104.01	2045.65	4166.00
T.H. 36 over the St. Croix River, MN, USA	P-B-1	24	T-205	409.58	392.51	16.70	204.46	818.79	614.04	1875.00
	P-B-2	24		409.58	388.25	20.70	204.00	818.53	613.58	2190.00
	P-B-3	42		815.40	781.23	52.74	642.75	1649.37	1458.15	4128.00
	P-B-4	42		815.40	786.28	52.74	751.78	1654.42	1567.18	3790.00
TH 19 over the Mississippi River, MN, USA	TP-3	42	T12 UNK	997.72	955.91	34.78	423.87	1988.41	1421.59	3750.00
	TP-5	42	T12 UNK	1238.32	1186.43	37.92	462.14	2462.67	1700.46	3750.00
			T19 UNK	924.00	885.28	42.80	521.61	1852.08	1445.85	3750.00

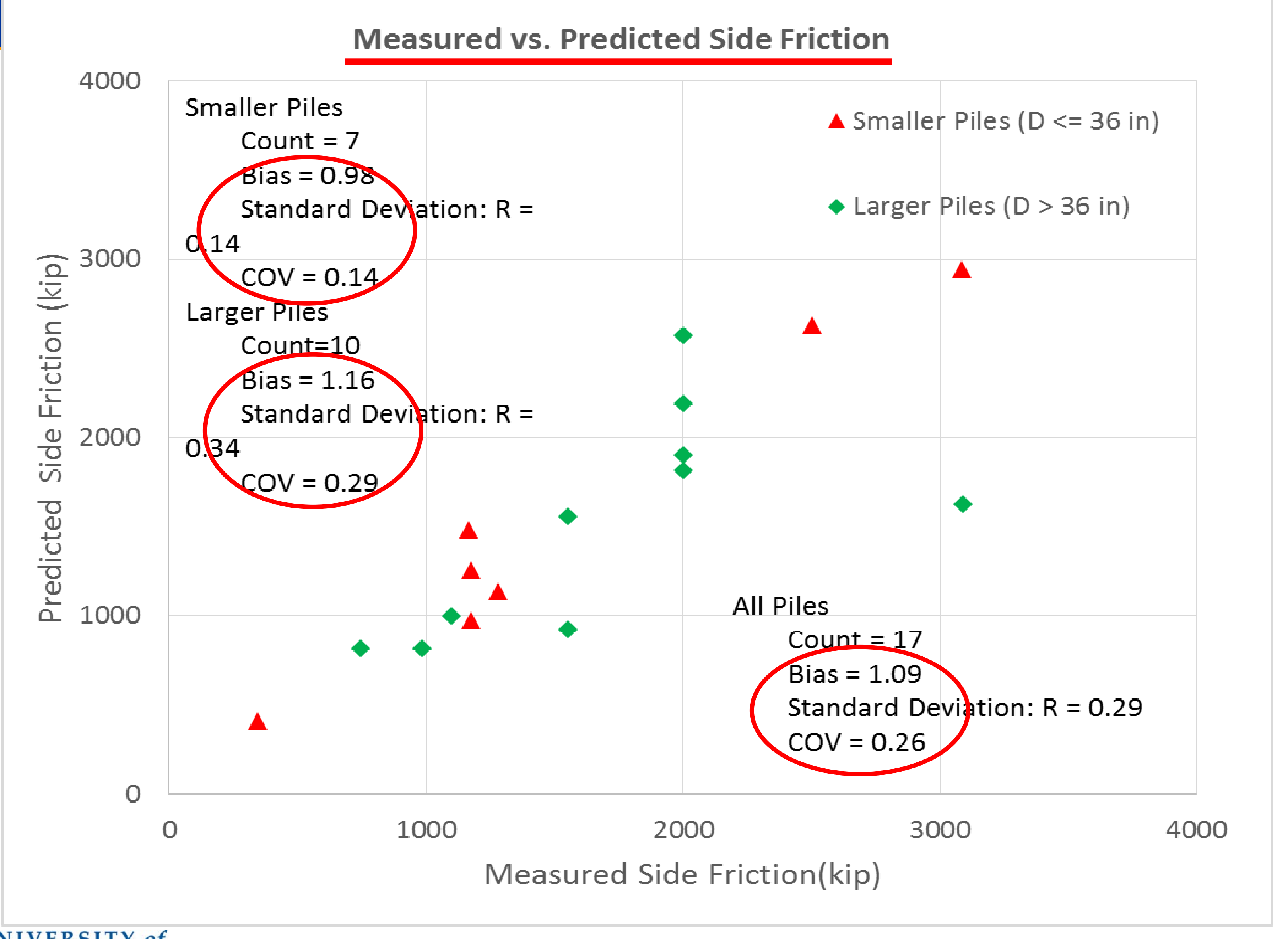
Modify FB-DEEP D>36” End Bearing to Same as D≤36”



Modify FB-DEEP D>36” End Bearing to Same as D≤36” and Limit N=100

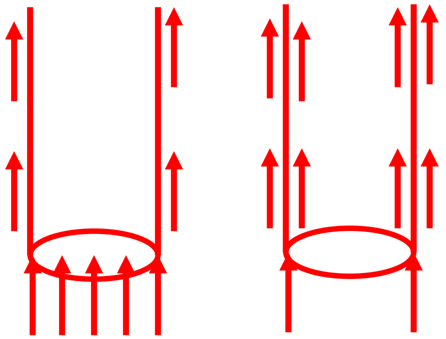


Modify FB-DEEP D>36” End Bearing to Same as D≤36” and Limit N=100



Summary of Suggested Changes to FB-DEEP's Open Pipe Pile Analysis

1. **End Bearing:**
   - **Change Analysis for D>36"**
   - **Consider Smaller of unit tip resistance times full cross-sectional area or unit skin friction x inner surface area plus unit tip resistance x ring area**



2. **SPT N Value Limit:**
   - **Raise Limit on N from 60 to 100**

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Other Analysis of Open End Pipe Piles – API (2011)

α Method: (API, 2011)	fs = α · Su α is defined as: $\alpha = 0.5 \cdot \Psi^{-0.5}$ for $\Psi \leq 1.0$ $\alpha = 0.5 \cdot \Psi^{-0.25}$ for $\Psi > 1.0$ where $\Psi = s_u / (\sigma'_v)$ and $\alpha \leq 1.0$	α = adhesion factor Su = undrained shear strength σ'_v = vertical effective stress
β Method: (API, 2011)	$fs = \beta \cdot \sigma'_v$ where β = f (density, soil) (see Table 6)	β = friction coefficient σ'_v = vertical effective stress
End Bearing: (API, 2011)	$q_p = Nc \cdot Su$ $q_p = N\text{q} \cdot \sigma'_v$	Su = undrained shear strength Nc = cohesion bearing capacity factor Nq= cohesionless bearing capacity factor

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Other Analysis of Open End Pipe Piles – API (2011)

Soil Description	Side Friction Coefficient β (-)	Limiting Unit Side Resistance Values kPa (ksf)	Base Resistance Factor N_q (-)	Limiting Unit Base Resistance Values MPa (ksf)
Very loose sand Loose sand Loose sand-silt Medium dense silt Dense silt	Not applicable	Not applicable	Not applicable	Not applicable
Medium dense sand-silt	0.29	67 (1.4)	12	3 (60)
Medium dense sand Dense sand-silt	0.37	81 (1.7)	20	5 (100)
Dense sand Very dense sand-silt	0.46	96 (2.0)	40	10 (200)
Very dense sand	0.56	115 (2.4)	50	12 (250)
NOTE: The parameters listed in this table are intended as guidelines only. Where detailed information, such as CPT records, strength tests on high quality samples, model tests, or pile driving performance, is available, other values may be justified.				

Other Analysis of Open End Pipe Piles – API (2011)

Project Name	Pile Name	Diameter (in)	Boring Name	Side Friction (kips)		Tip Resistance		Total Capacity (kips)		
				Outer Skin	Inner Skin	Ring Tip	Full Tip	Outer Skin + Inner Skin + Ring	Outer Skin + Full Tip	Measured
Louisiana Highway 1 Improvements Phase 1B, LA, USA	T-3-1	30	BR-002	834.72	799.94	39.55	484.74	1674.20	1319.46	1597.00
I-880 Port of Oakland Connector Viaduct (Caltrans Bridge No. 33-	TP-9	42	Generalized Boring	1134.11	1100.36	17.75	302.73	1674.20	1319.46	1253.00
			UTB-23MR							963.40
Berenda Slough Bridge (Clatrans Bridge No. 41-0009R),CA, USA	TP-1	42	B-1(Generalized Boring)	1595.15	1547.67	57.49	980.44	3200.31	2575.58	1618.00
Gulf Intracoastal Waterway West Closure Complex Test Site 3, LA,	TP-9	24	ALGSGS-08-2U	842.58	807.47	3.33	40.87	1653.38	883.44	811.20
	TP-11	30	ALGSGS-08-2U	1136.18	1088.84	5.47	67.05	2230.49	1203.23	1215.00
Gulf Intracoastal Waterway West Closure Complex, LA, USA	TP-3	30	ALGSGS-08-13U	836.59	801.73	5.44	66.68	1643.76	903.27	830.40
	TP-4	30		1126.77	1079.82	7.05	86.42	2213.63	1213.18	1060.00
	TP-5	30		823.75	789.42	5.04	61.78	1618.21	885.53	899.60
	TP-6	30		828.27	793.76	5.18	63.46	1627.21	891.73	830.40
Lagoon Bridge U.S.68/KY80, KY, USA	TPL-2	30	B-3004 UNK	1200.40	1120.37	33.03	256.24	2353.80	1456.64	1443.00
			B-3051 UNK	1171.04	1092.97	40.39	313.37	2304.41	1484.42	1443.00
US Highway TH61/Mississippi River, MN, USA	TP-10*	42	B-09UNK	2597.87	2489.63	196.26	2405.28	5283.77	5003.15	4166.00
			B-10UNK	2622.54	2513.27	196.26	2405.28	5332.07	5027.82	4166.00
T.H. 36 over the St. Croix River, MN, USA	P-B-1*	24	T-205	357.90	342.99	62.80	769.69	763.69	1127.59	1875.00
	P-B-2*	24		353.37	334.97	78.12	769.97	766.46	1123.35	2190.00
	P-B-3*	42		950.91	911.06	114.66	1397.35	1976.63	2348.26	4128.00
	P-B-4*	42		950.91	916.95	98.03	1397.35	1965.89	2348.26	3790.00
TH 19 over the Mississippi River, MN, USA	TP-3*	42	T12 UNK	1158.12	1109.59	167.08	2036.19	2434.78	3194.31	3750.00
	TP-5*	42	T12 UNK	1694.70	1623.68	187.05	2279.58	3505.43	3974.28	3750.00
T.H. 43 over the Mississippi River, MN, USA	TP-1	42	T-103	2374.37	2289.57	167.53	2388.10	4831.48	4762.47	3720.60
Port of Oakland Connector Viaduct Maritime On/Off-Ramps (Caltrans Bridge No. 33-612E), CA, USA	TP3-10NCI	42	UTB-161	778.24	750.45	11.41	162.69	1540.10	940.93	800.00
	TP6-17NCI	42	UTB-24A	995.31	959.77	8.50	121.23	1963.58	1116.54	1000.00
	TP9-27NCI	42	UTB-05	1250.00	1212.80	11.61	197.92	2474.40	1447.92	1288.00

Note: * Piles with Su estimated from Sowers (1979)

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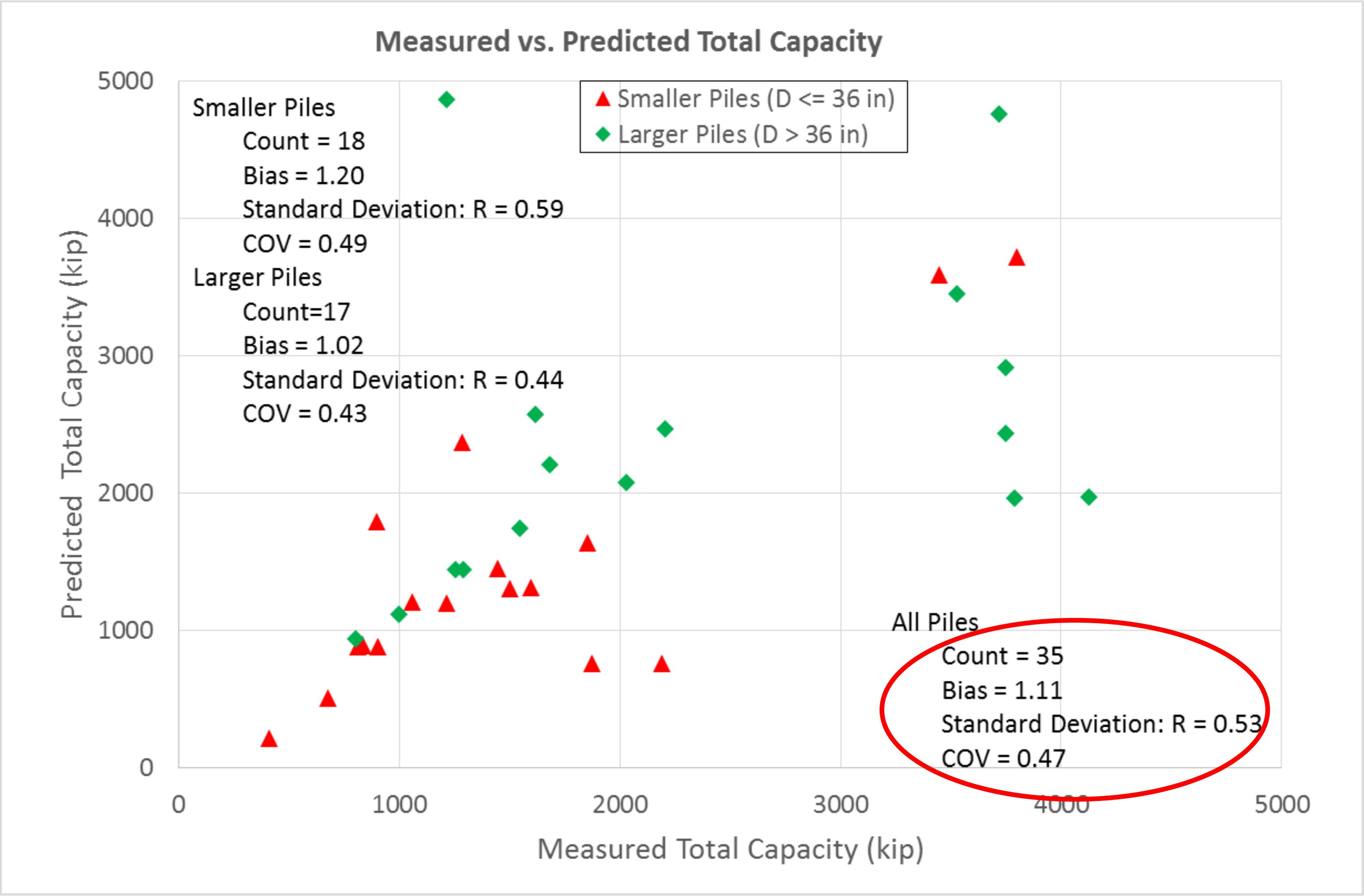
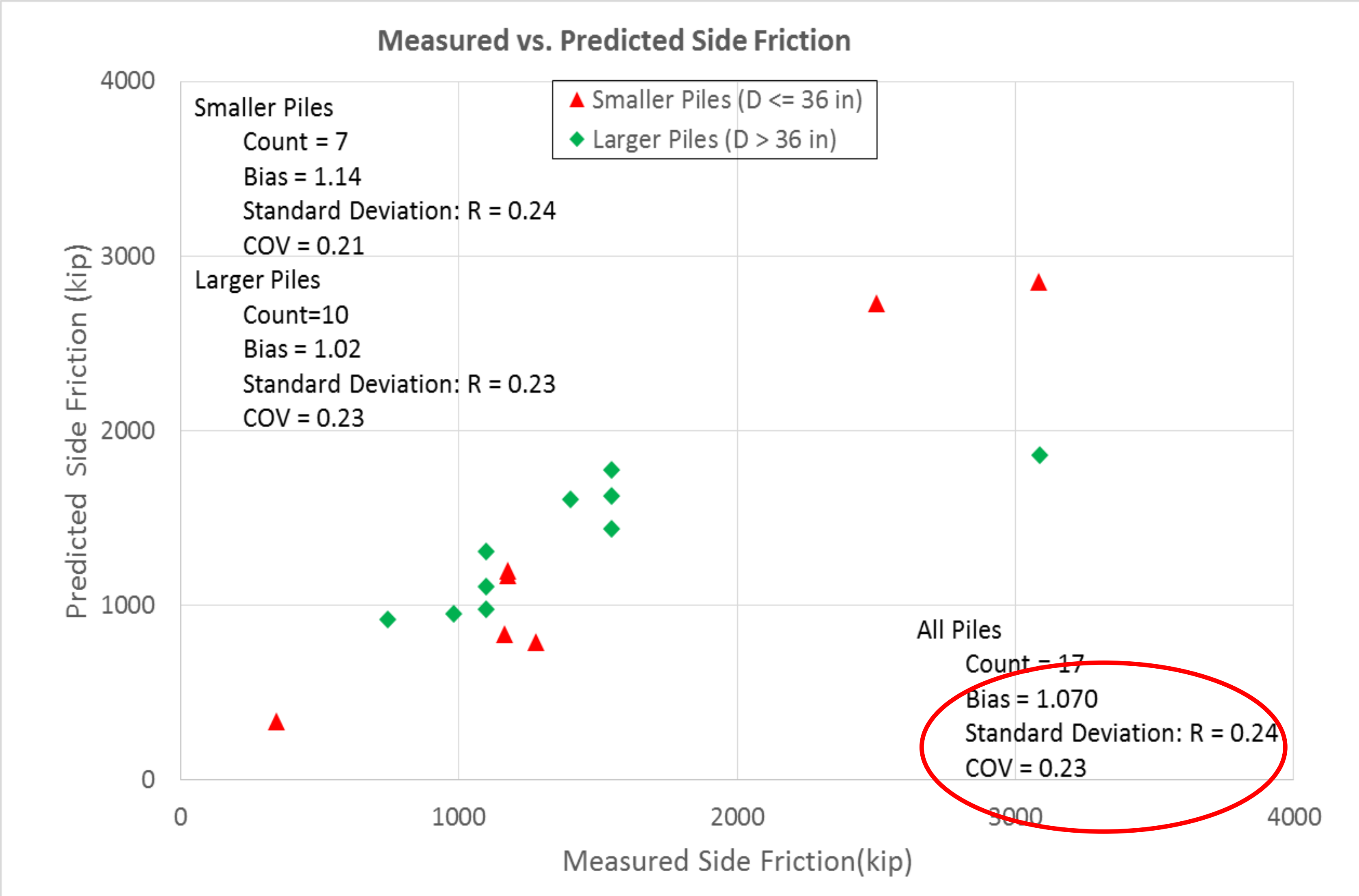
Other Analysis of Open End Pipe Piles – API (2011)



Other Analysis of Open End Pipe Piles – API (2011)



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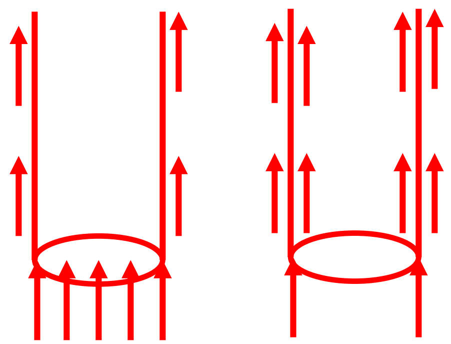
Summary of Open Pipe Pile Analysis

1. **Current FBDEEP:**
   - **Side Resistance Bias =1.19 and COV =0.27**
   - **Total Resistance Bias=1.75 and COV = 0.55**
2. **Suggested Changes to FBDEEP:**
   - **Adopting End Bearing D>36" as →**
   - **Increase N limit from 60 to 100**
     - **Total Resistance Bias = 1.20 and COV = 0.31**
     - **Side Resistance Bias = 1.09 and COV = 0.26**
3. **Other Method: API (2011):**
   - **Side Resistance Bias =1.07 and COV =0.23**
   - **Total Resistance Bias=1.11 and COV = 0.47**



Thank You