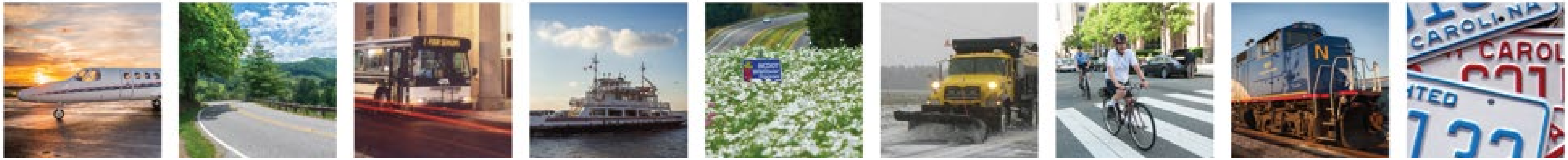
NORTH CAROLINA
Department of Transportation



PILE DRIVING IN COASTAL PLAIN

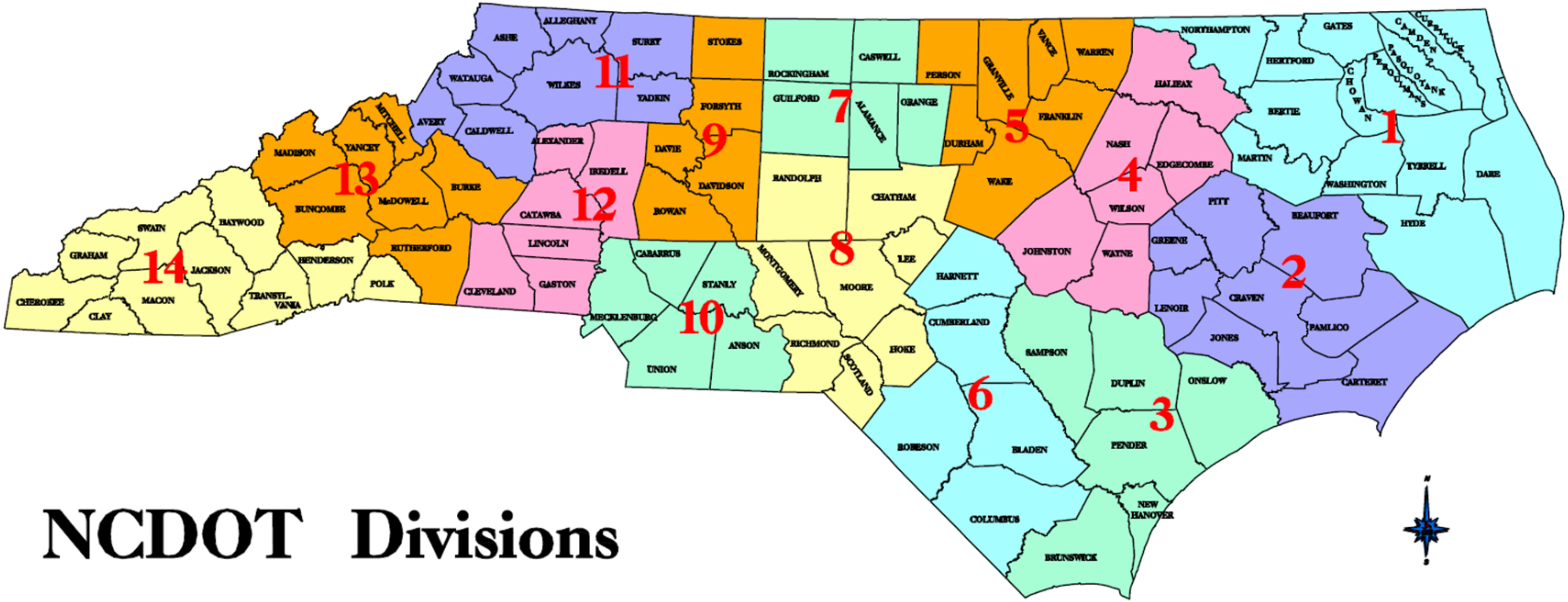
Andrew Drda

NCDOT Geotechnical Unit

10/31/23


WEST VIRGINIA
VIRGINIA
TENNESSEE
GEORGIA
SOUTH CAROLINA
ALLEGHANY
ASHE
SURRY
STOKES
ROCKINGHAM
CASWELL
PERSON
GRANVILLE
VANCE
WARREN
NORTHAMPTON
GATES
CURRITUCK
CAMDEN
PASQUOTANK
PERQUIMANS
HERTFORD
CHOWAN
WATAUGA
WILKES
YADKIN
FORSYTH
GUILFORD
ALAMANCE
ORANGE
DURHAM
FRANKLIN
HALIFAX
BERTIE
AVERY
MITCHELL
CALDWELL
ALEXANDER
DAVIE
MADISON
YANCEY
NASH
EDGECOMBE
MARTIN
TYRRELL
WASHINGTON
DARE
IREDELL
DAVIDSON
RANDOLPH
CHATHAM
WAKE
BURKE
CATAWBA
ROWAN
BUNCOMBE
McDOWELL
HAYWOOD
SWAIN
WILSON
PITT
BEAUFORT
HYDE
JOHNSTON
LEE
GREENE
LINCOLN
CABARRUS
STANLY
MONTGOMERY
MOORE
HARNETT
WAYNE
GRAHAM
HENDERSON
RUTHERFORD
JACKSON
POLK
GASTON
CLEVELAND
CHEROKEE
MACON
TRANSYL-VANIA
CLAY
MECKLENBURG
LENOIR
CRAVEN
PAMLICO
CUMBERLAND
UNION
ANSON
RICHMOND
HOKE
SAMPSON
DUPLIN
JONES
SCOTLAND
ONSLOW
CARTERET
ROBESON
BLADEN
PENDER
COLUMBUS
NEW HANOVER
BRUNSWICK
NORTH CAROLINA
COUNTY OUTLINE MAP
0 10 20 40 60 80 100
Miles
N
W
E
S

NCDOT Divisions



The Piedmont
Mountains
Coastal Plains
Alleghany
Ashe
Wilkes
Watauga
Avery
Mitchell
Yancey
Caldwell
Madison
Burke
Buncombe
McDowell
Haywood
Swain
Graham
Rutherford
Jackson
Polk
Cherokee
Macon
Clay
Henderson
Transylvania
Surry
Stokes
Rockingham
Caswell
Person
Granville
Vance
Warren
Yadkin
Forsyth
Guilford
Alamance
Orange
Durham
Franklin
Alex-
ander
Iredell
Davie
Davidson
Catawba
Rowan
Randolph
Chatham
Wake
Lincoln
Cleveland
Gaston
Cabarrus
Stanly
Mont-
gomery
Moore
Lee
Meckle-
burg
Union
Anson
Rich-
mond
Scot-
land
Hoke
Harnett
Cumber-
land
Robeson
Bladen
Columbus
Brunswick
New Hanover
Pender
Sampson
Duplin
Johnston
Wayne
Wilson
Nash
Halifax
North-
ampton
Hertford
Gates
Bertie
Edge-
combe
Martin
Pitt
Greene
Lenoir
Jones
Onslow
Craven
Carteret
Pamlico
Beaufort
Wash-
ington
Tyrrell
Dare
Hyde
Currituck
Camden
Pasquotank
Perquimans
Chowan

NCDOT LRFD Policy

3.1 Static Analysis

Use AASHTO LRFD Resistance Factors for all piles except Steel H piles in the Coastal Plain.

3.1.1 Exception

Use NCDOT Resistance Factor of 0.7 for Steel H piles in the Coastal Plain.

LRFD Driven Pile Foundation Design Policy
Updated May 10, 2012

Section 3 Resistance Factors

POLICY	COMMENTARY
3.0 Resistance Factors	
3.1 Static Analysis Use AASHTO LRFD Resistance Factors for all piles except steel H piles in the Coastal Plain.	C3.1 See AASHTO LRFD Table 10.5.5.2.3-1 for details.
3.1.1 Exception Use NCDOT Resistance Factor of 0.7 for steel H piles in the Coastal Plain.	C3.1.1 NCDOT Resistance Factors are based on NCSU localized resistance factors calibration research. This factor applies to all soils and all static analysis methods for H piles in the Coastal Plain. This is an exception to AASHTO LRFD Specifications. See FHWA/NC (2002) for details. See Subarticle 1018-2(B), (1) of the Standard Specifications for determining soils in the Coastal Plain. If in doubt, consult project geologic engineer.
3.2 Dynamic Monitoring Use the same resistance factor for both drivability analysis and pile driving criteria.	C3.2 This is an exception to the AASHTO LRFD Specifications. These resistance factors are higher than the AASHTO LRFD Resistance Factors and were established based on NCDOT's pile driving experience.
3.2.1 WEAP without PDA Use a resistance factor of 0.60 for hammer approval.	
3.2.2 PDA and WEAP – Option 1 Use a resistance factor of 0.60 for hammer approval with limited quantity of PDAs.	C3.2.2 PDA may be used without meeting AASHTO LRFD requirements in order to monitor stresses and resistance during pile driving.
3.2.3 PDA and WEAP – Option 2 Use a resistance factor of 0.75 for hammer approval with required quantity of PDAs.	C3.2.3 Minimum number of PDA tests required is two piles per site condition, but no less than 2% of the production piles. See AASHTO LRFD Section 10.5.5.2.3 for the definition of "site".

AASHTO LRFD

Side Resistance and End Bearing: Clay and Mixed Soils

α-method: 0.35
β-method: 0.25
λ-method : 0.40

Side Resistance and End Bearing: Sand

Nordlund/Thurman Method: 0.45
SPT-method (Meyerhof): 0.30
CPT-method (Schmertmann): 0.50
End bearing in rock: 0.45

Table 10.5.5.2.3-1—Resistance Factors for Driven Piles

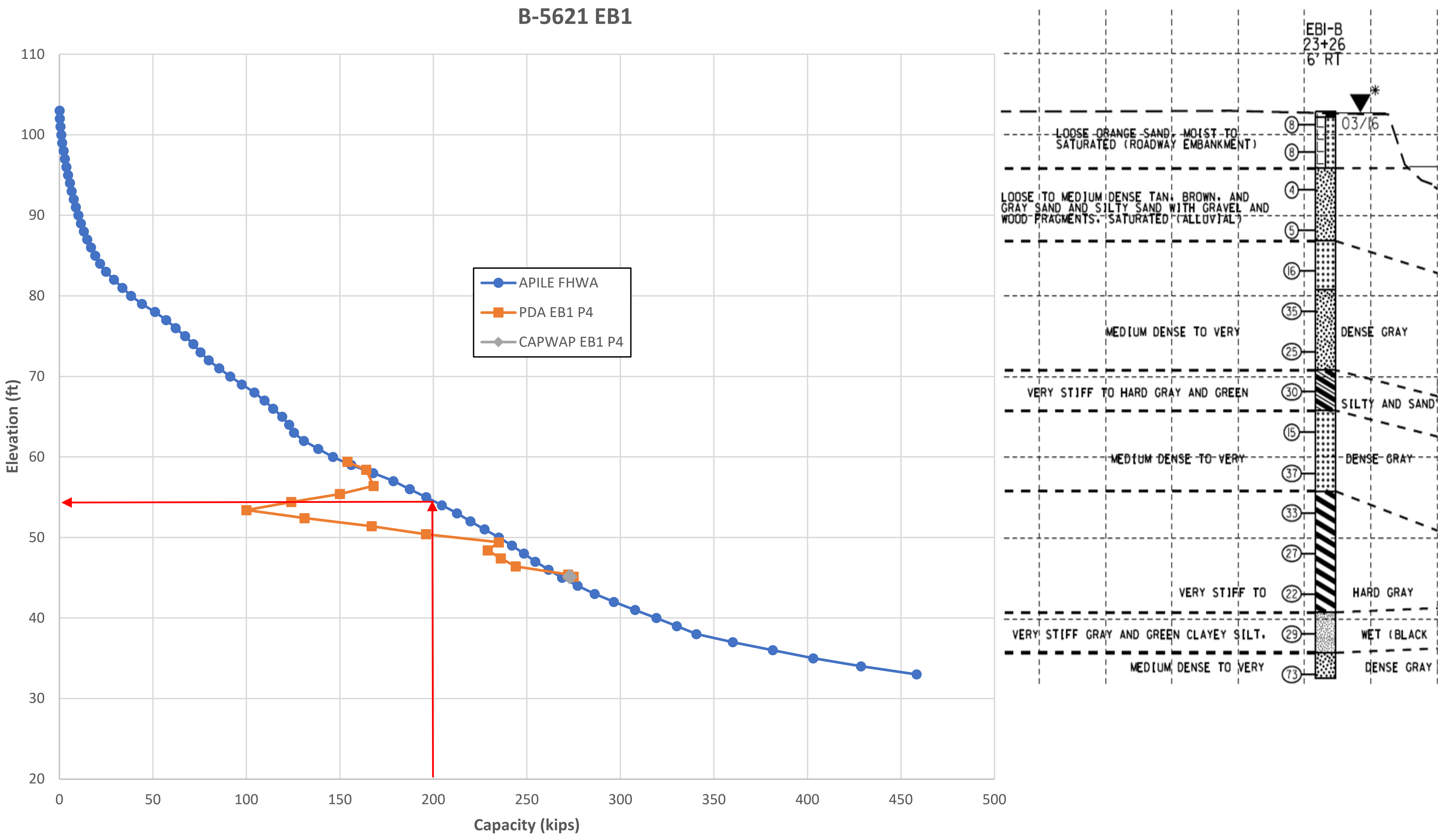
Condition/Resistance Determination Method		Resistance Factor
Nominal Bearing Resistance of Single Pile—Dynamic Analysis and Static Load Test Methods, φ_{dyn}	Driving criteria established by successful static load test of at least one pile per site condition and dynamic testing* of at least two piles per site condition, but no less than 2% of the production piles	0.80
	Driving criteria established by successful static load test of at least one pile per site condition without dynamic testing	0.75
	Driving criteria established by dynamic testing* conducted on 100% of production piles	0.75
	Driving criteria established by dynamic testing*, quality control by dynamic testing* of at least two piles per site condition, but no less than 2% of the production piles	0.65
	Wave equation analysis, without pile dynamic measurements or load test but with field confirmation of hammer performance	0.50
	FHWA-modified Gates dynamic pile formula (End of Drive condition only)	0.40
	Engineering News (as defined in Article 10.7.3.8.5) dynamic pile formula (End of Drive condition only)	0.10
Nominal Bearing Resistance of Single Pile—Static Analysis Methods, φ_{stat}	Side Resistance and End Bearing: Clay and Mixed Soils	
	α-method (Tomlinson, 1987; Skempton, 1951)	0.35
	β-method (Esrig & Kirby, 1979; Skempton, 1951)	0.25
	λ-method (Vijayvergiya & Focht, 1972; Skempton, 1951)	0.40
	Side Resistance and End Bearing: Sand	
	Nordlund/Thurman Method (Hannigan et al., 2005)	0.45
	SPT-method (Meyerhof)	0.30
	CPT-method (Schmertmann)	0.50
	End bearing in rock (Canadian Geotech. Society, 1985)	0.45
Block Failure, φ_{b1}	Clay	0.60
Uplift Resistance of Single Piles, φ_{up}	Nordlund Method	0.35
	α-method	0.25
	β-method	0.20
	λ-method	0.30
	SPT-method	0.25
	CPT-method	0.40
	Static load test	0.60
	Dynamic test with signal matching	0.50
Group Uplift Resistance, φ_{ug}	All soils	0.50
Lateral Geotechnical Resistance of Single Pile or Pile Group	All soils and rock	1.0
Structural Limit State	Steel piles	See the provisions of Article 6.5.4.2
	Concrete piles	See the provisions of Article 5.5.4.2
	Timber piles	See the provisions of Articles 8.5.2.2 and 8.5.2.3
Pile Drivability Analysis, φ_{da}	Steel piles	See the provisions of Article 6.5.4.2
	Concrete piles	See the provisions of Article 5.5.4.2
	Timber piles	See the provisions of Article 8.5.2.2
	In all three Articles identified above, use φ identified as "resistance during pile driving"	

*Dynamic testing requires signal matching, and best estimates of nominal resistance are made from a restrike. Dynamic tests are calibrated to the static load test, when available.

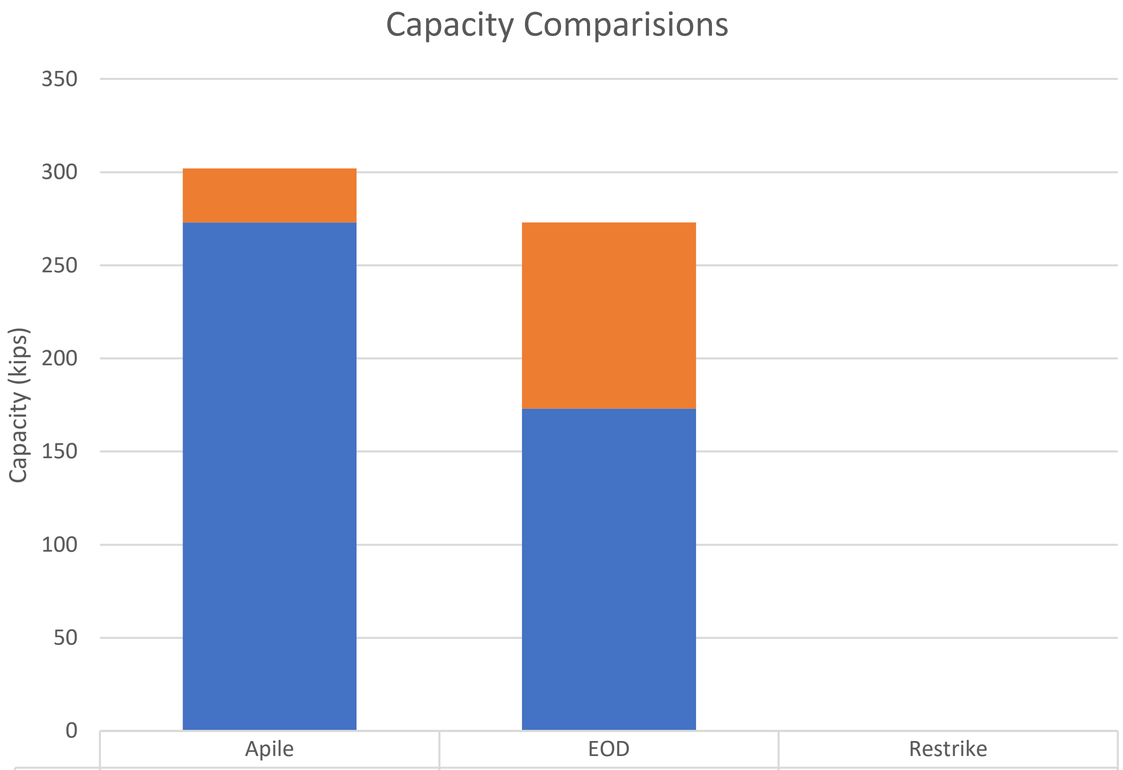
Common Pile Driving Issues

- Overpredicting H pile capacity
  - Design factor (0.7) compared to PDA testing factor (0.6)
  - Overruns
- Underpredicting pipe pile capacity
  - Design factor (0.35) compared to PDA testing factor (0.6)
  - Underruns
  - Difficulty predicting pipe pile plugging
- Uncertainties in PDA testing

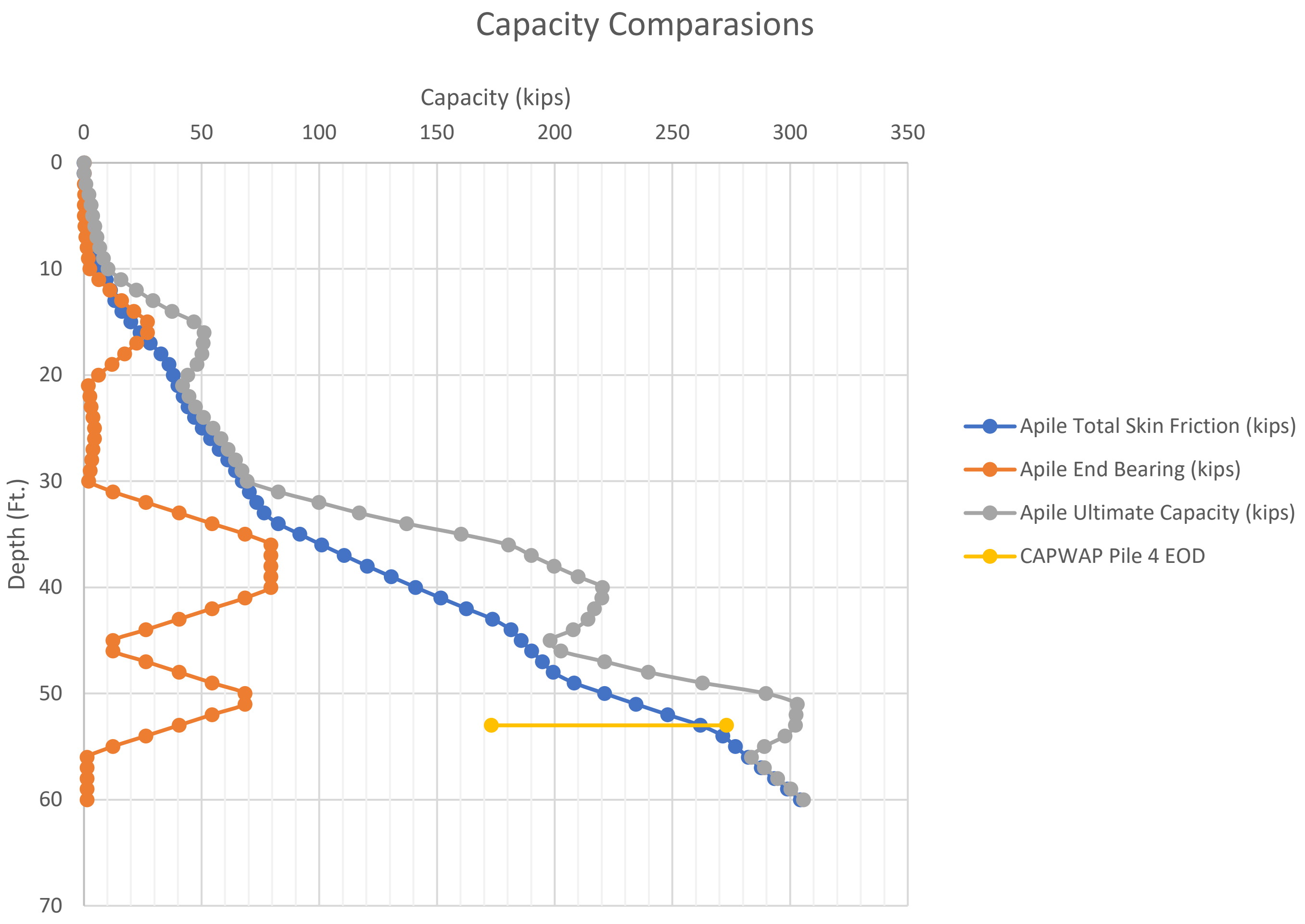
Successful Coastal Plain H Pile Projects

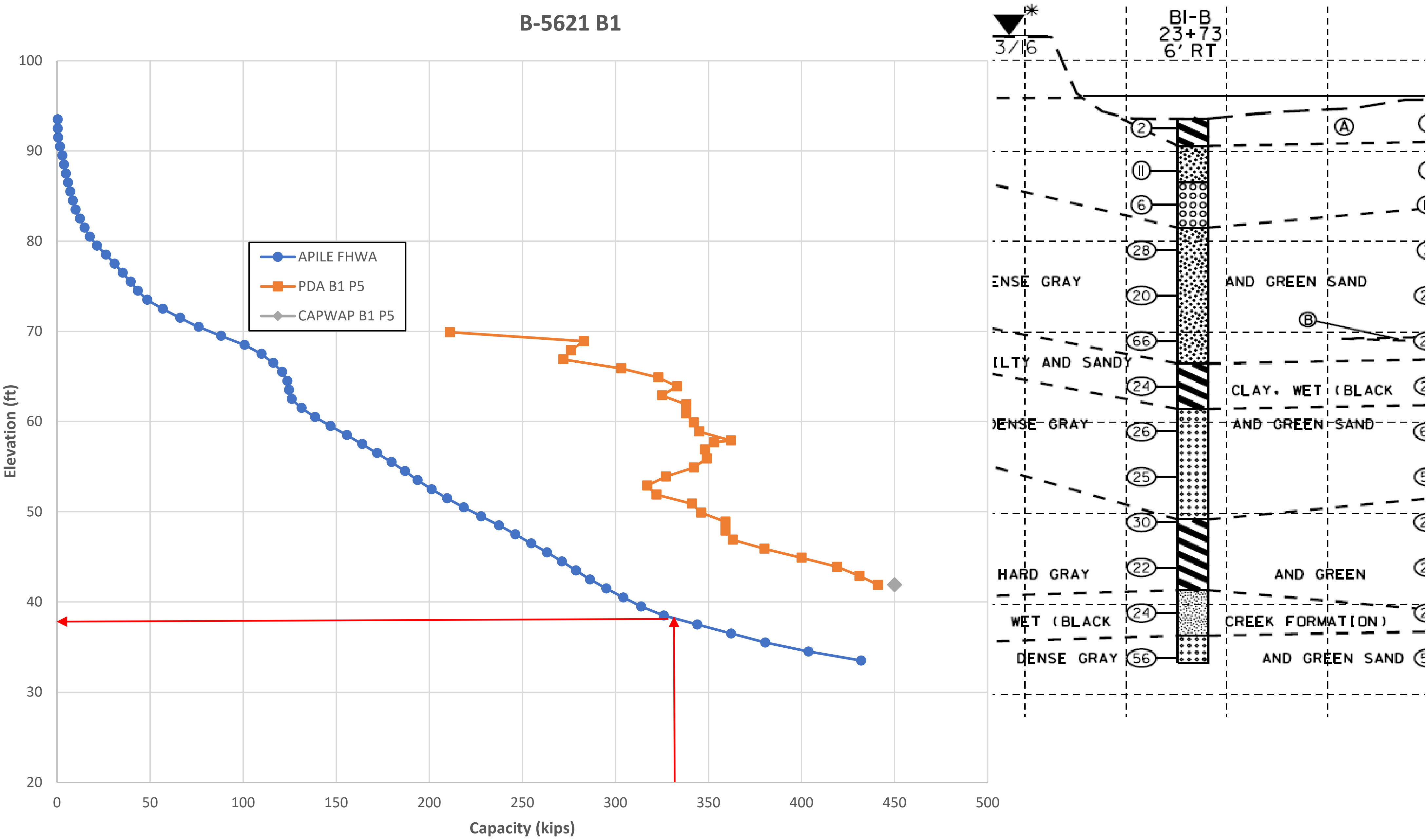

B-5621 EB1
Elevation (ft)
Capacity (kips)
APILE FHWA
PDA EB1 P4
CAPWAP EB1 P4
EBI-B
23+26
6' RT
03/16
LOOSE ORANGE SAND, MOIST TO SATURATED (ROADWAY EMBANKMENT)
LOOSE TO MEDIUM DENSE TAN, BROWN, AND GRAY SAND AND SILTY SAND WITH GRAVEL AND WOOD FRAGMENTS, SATURATED (ALLUVIAL)
MEDIUM DENSE TO VERY
DENSE GRAY
VERY STIFF TO HARD GRAY AND GREEN
SILTY AND SAND
MEDIUM DENSE TO VERY
DENSE GRAY
VERY STIFF TO
HARD GRAY
VERY STIFF GRAY AND GREEN CLAYEY SILT,
WET (BLACK
MEDIUM DENSE TO VERY
DENSE GRAY

B-5621 EB1

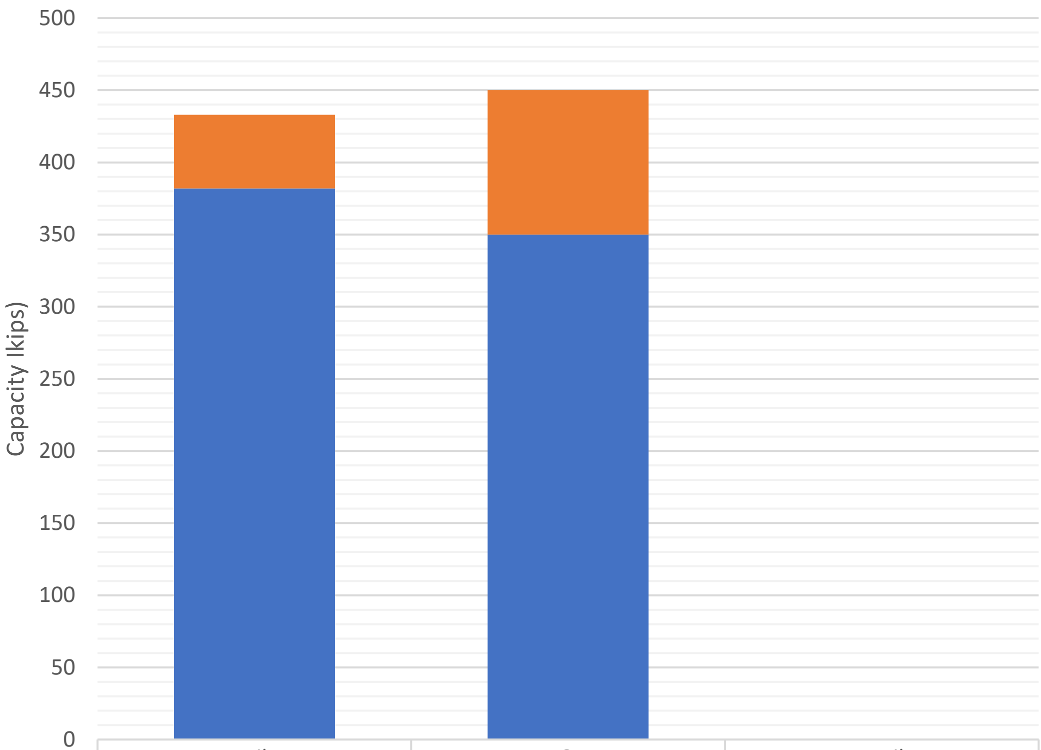


	Apile	EOD	Restrike
Toe	29	100	
Shaft	273	173	

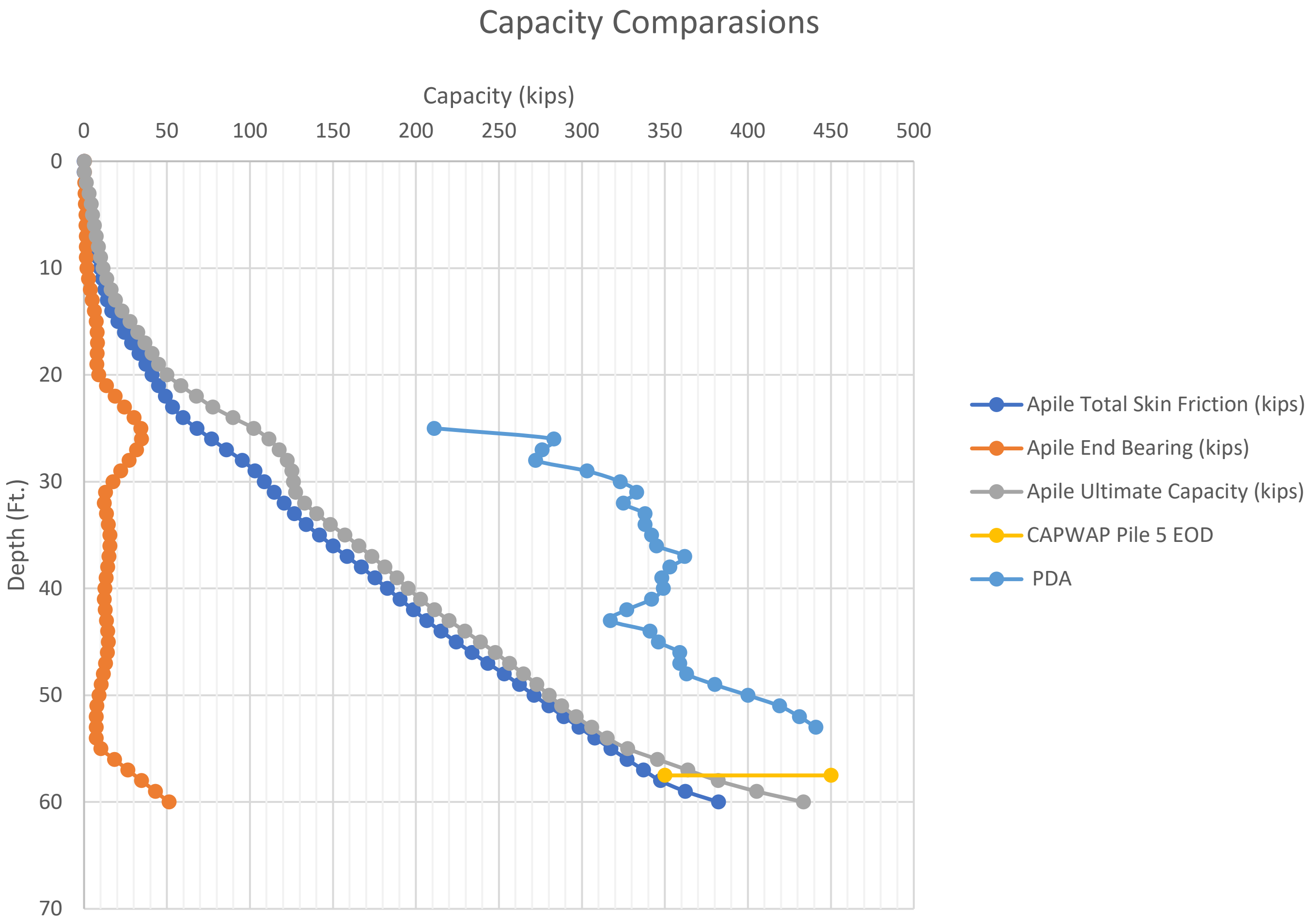



B-5621 B1
Elevation (ft)
Capacity (kips)
APILE FHWA
PDA B1 P5
CAPWAP B1 P5
100
90
80
70
60
50
40
30
20
0
50
100
150
200
250
300
350
400
450
500
BI-B
23+73
6' RT
3/16
ENSE GRAY
AND GREEN SAND
ILTY AND SANDY
CLAY, WET (BLACK
DENSE GRAY
AND GREEN SAND
HARD GRAY
AND GREEN
WET (BLACK
CREEK FORMATION)
DENSE GRAY
AND GREEN SAND

B-5621 B1

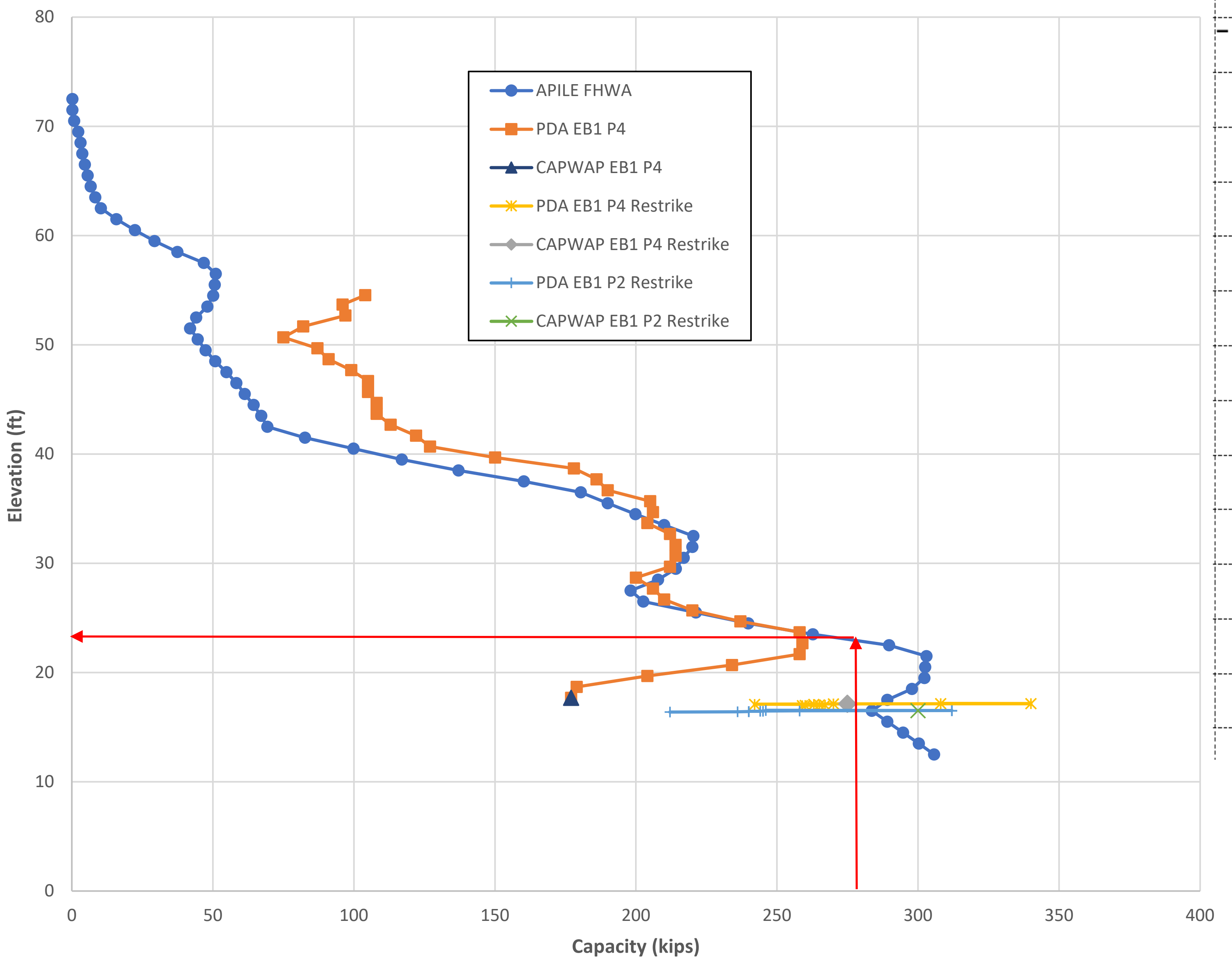


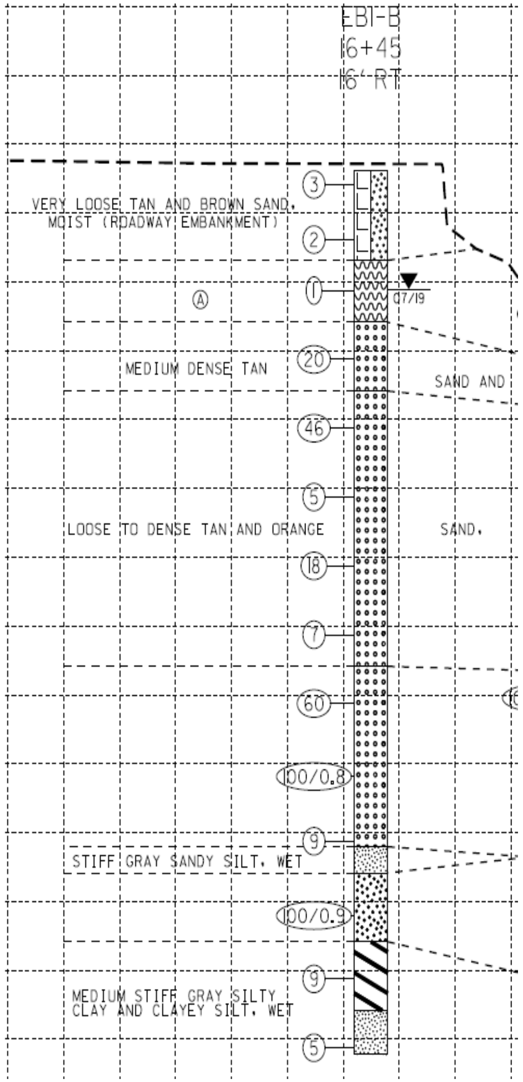
	Apile	EOD	Restrike
Toe	51	100	
Shaft	382	350	



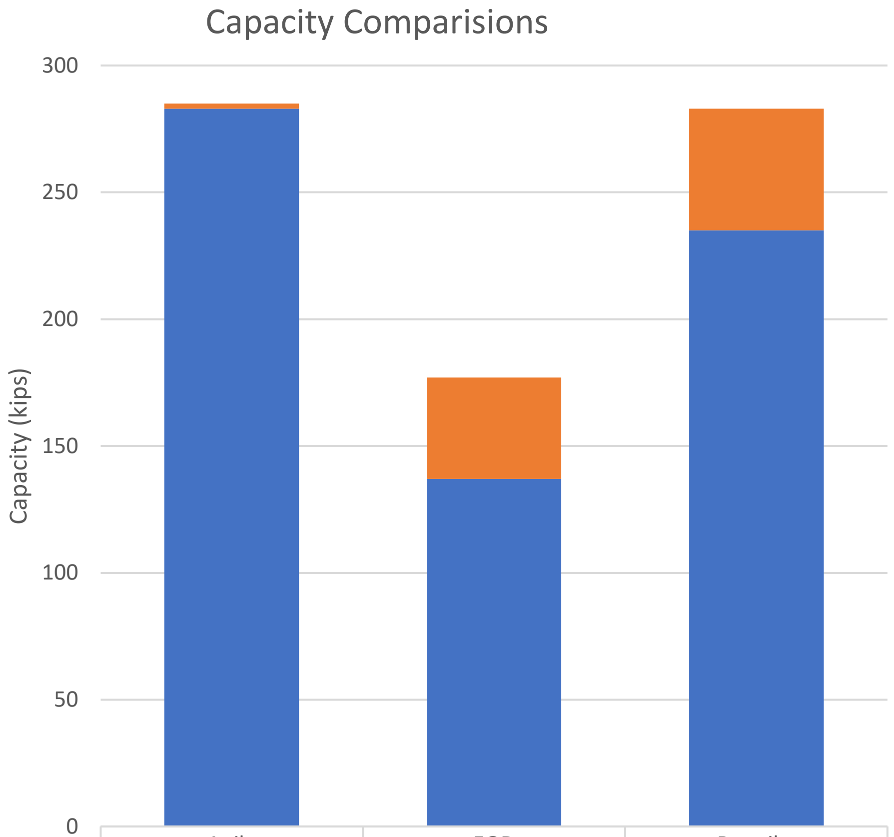
Overrun/Reduced Required Driving Resistance (RDR) Coastal Plain H Pile Projects

17BP.2.R.90 EB1

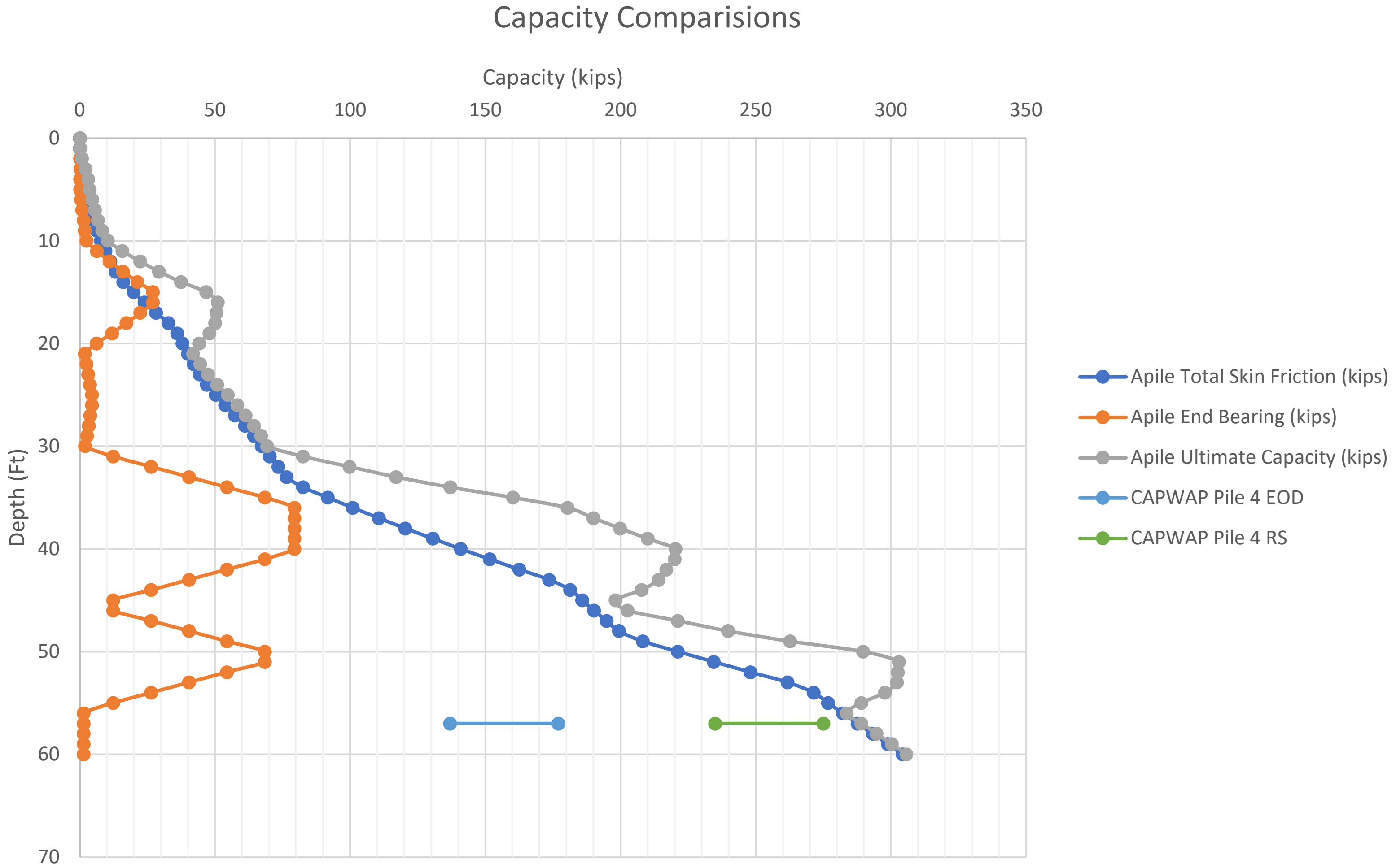


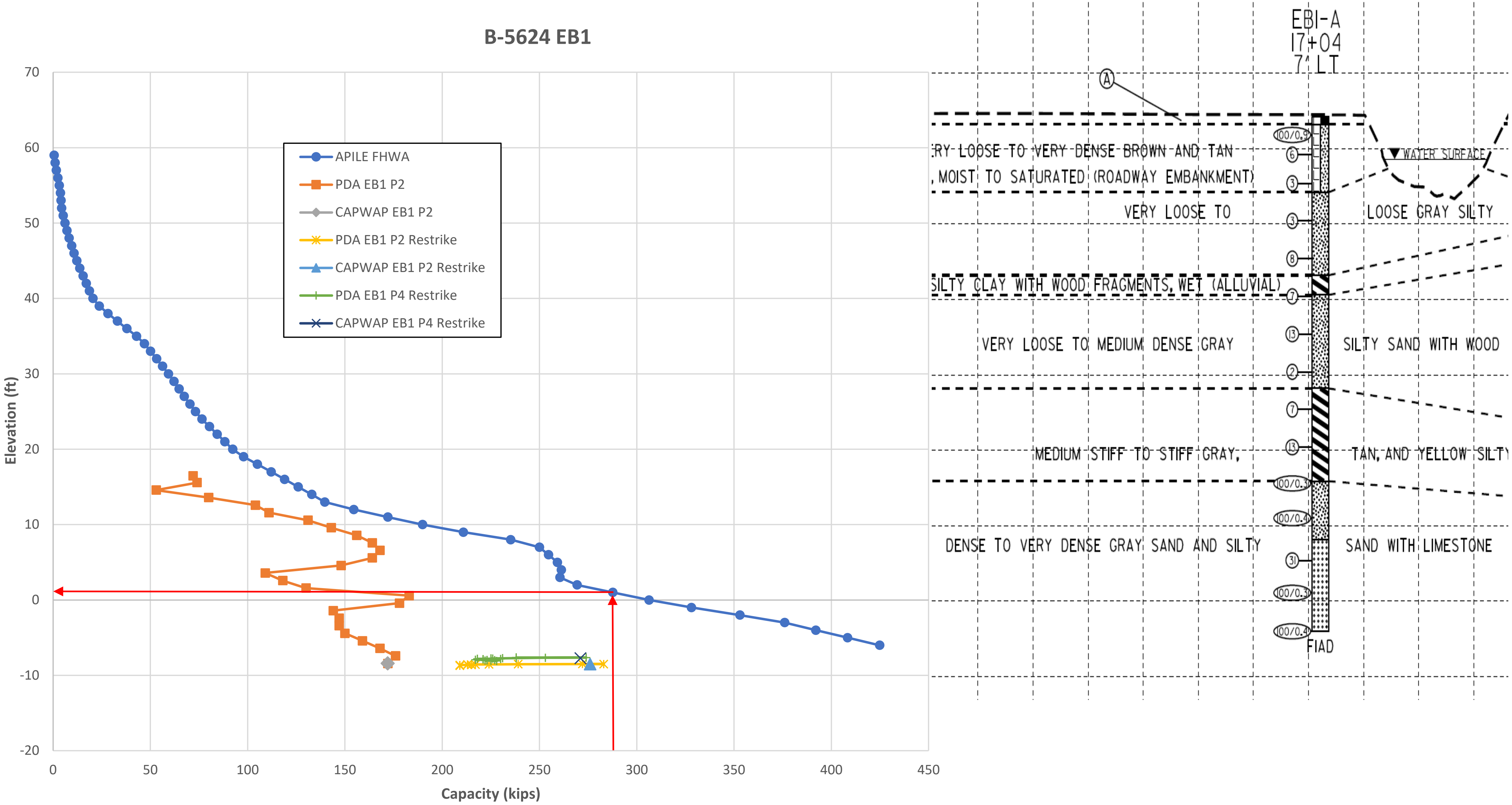


17BP.2.R.90 EB1



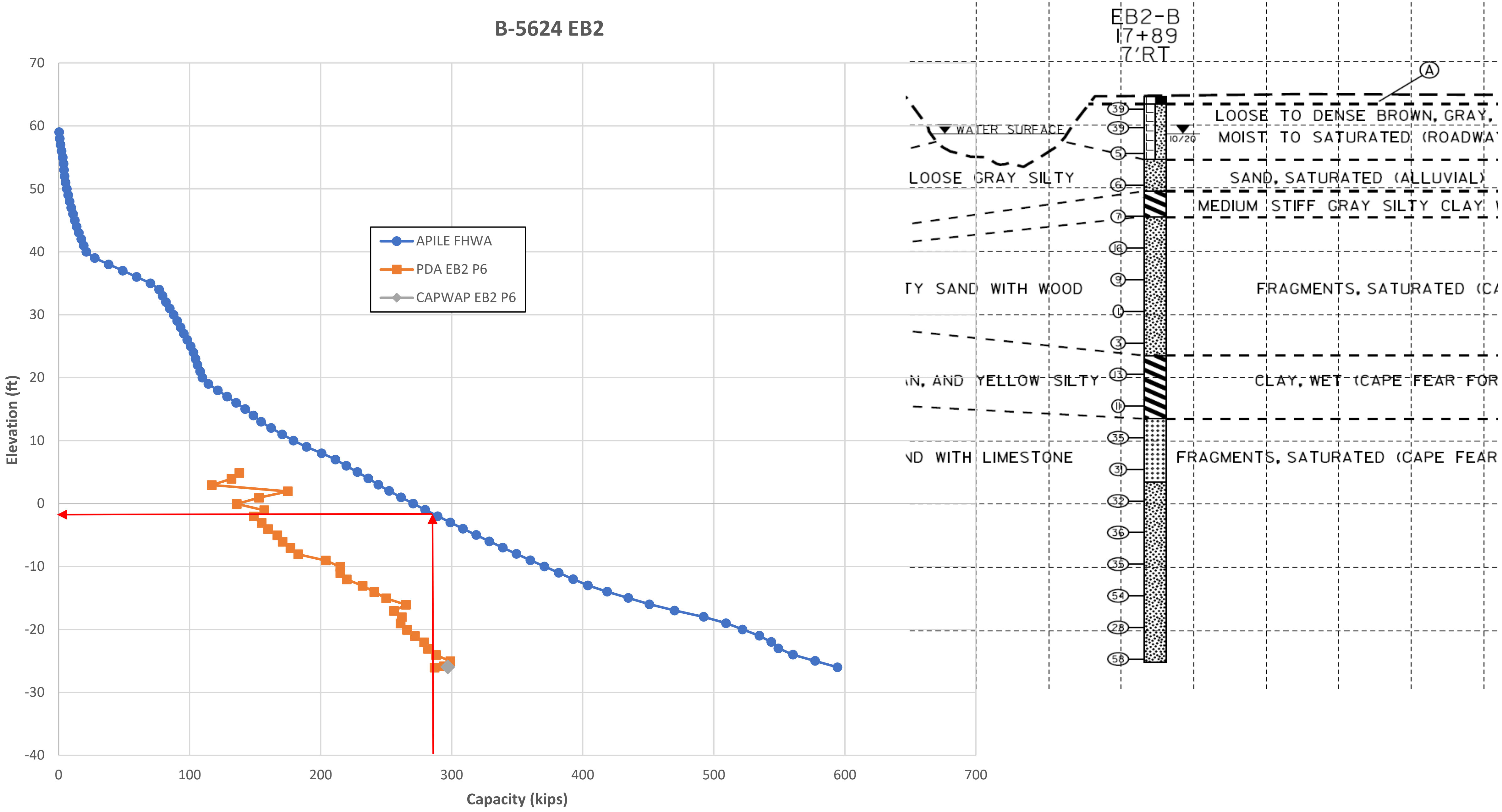
	Apile	EOD	Restrike
Toe	2	40	48
Shaft	283	137	235





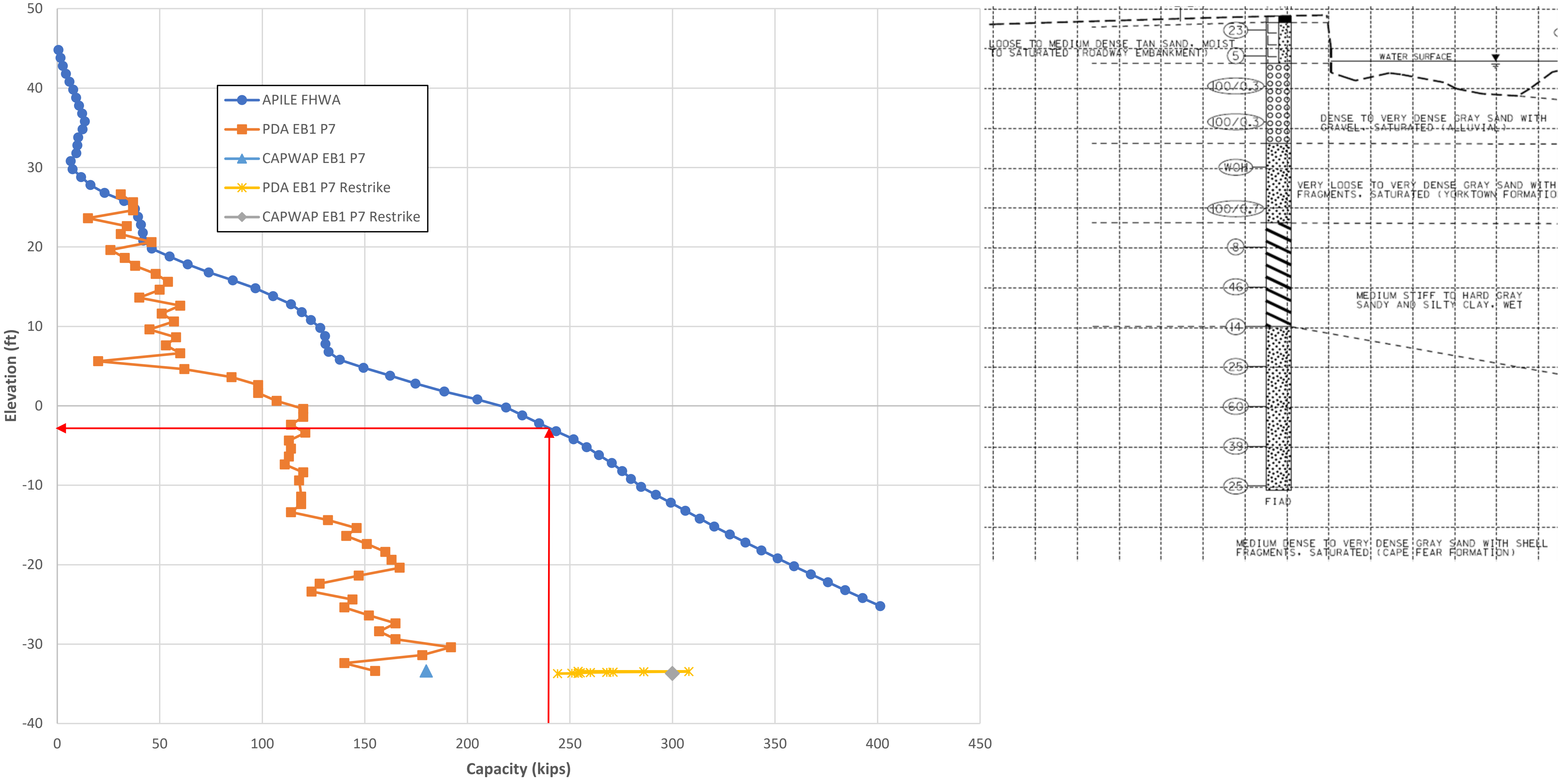
B-5624 EB1
Elevation (ft)
Capacity (kips)
APILE FHWA
PDA EB1 P2
CAPWAP EB1 P2
PDA EB1 P2 Restrike
CAPWAP EB1 P2 Restrike
PDA EB1 P4 Restrike
CAPWAP EB1 P4 Restrike
EB1-A
17+04
7' LT
WATER SURFACE
RY LOOSE TO VERY DENSE BROWN AND TAN
, MOIST TO SATURATED (ROADWAY EMBANKMENT)
VERY LOOSE TO
LOOSE GRAY SILTY
SILTY CLAY WITH WOOD FRAGMENTS, WET (ALLUVIAL)
VERY LOOSE TO MEDIUM DENSE GRAY
SILTY SAND WITH WOOD
MEDIUM STIFF TO STIFF GRAY,
TAN, AND YELLOW SILTY
DENSE TO VERY DENSE GRAY SAND AND SILTY
SAND WITH LIMESTONE
FIAD

B-5624 EB2



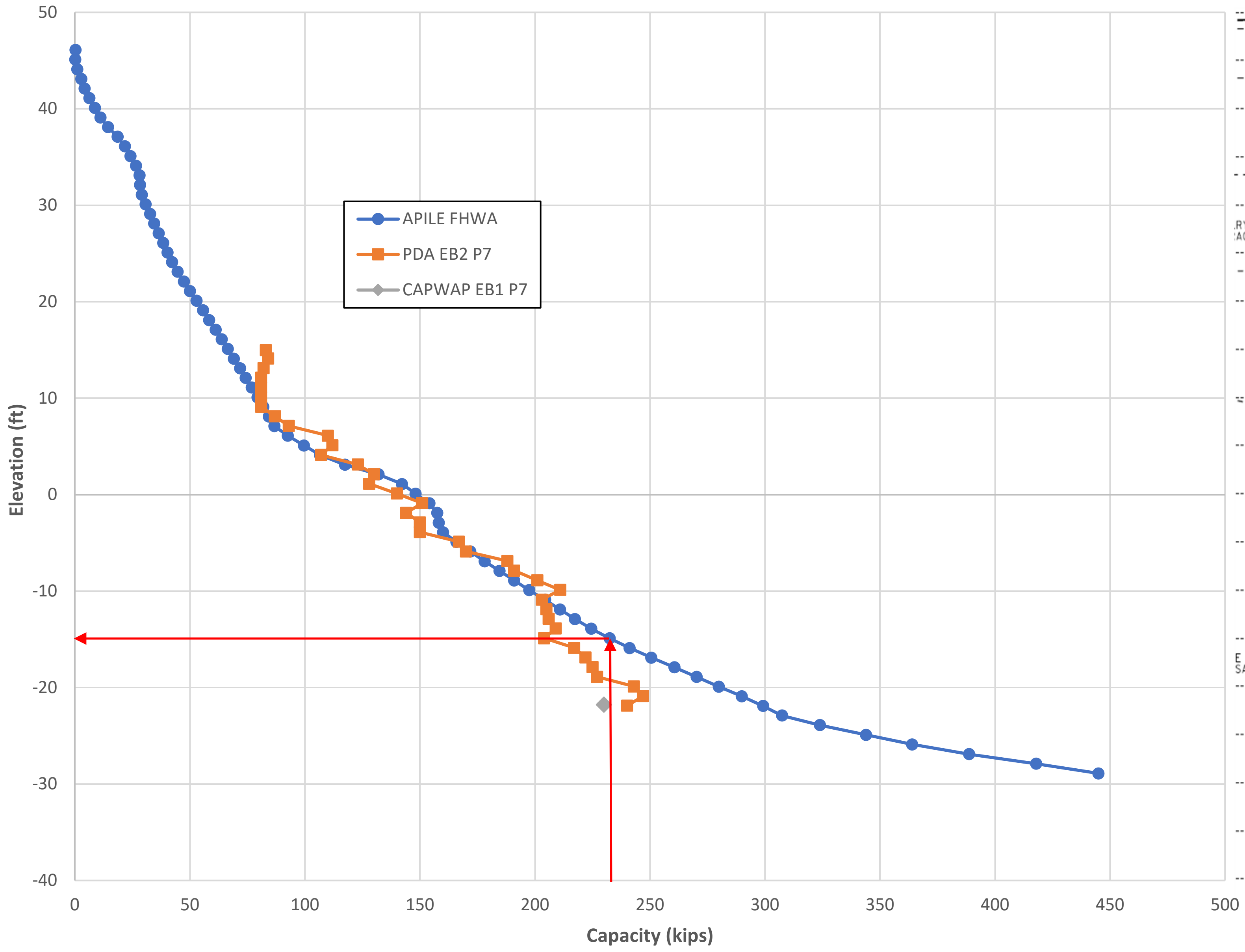
70
60
50
40
30
20
10
0
-10
-20
-30
-40
Elevation (ft)
0
100
200
300
400
500
600
700
Capacity (kips)
APILE FHWA
PDA EB2 P6
CAPWAP EB2 P6
EB2-B
17+89
7'RT
A
WATER SURFACE
10/20
LOOSE TO DENSE BROWN, GRAY,
MOIST TO SATURATED (ROADWA
LOOSE GRAY SILTY
SAND, SATURATED (ALLUVIAL)
MEDIUM STIFF GRAY SILTY CLAY
TY SAND WITH WOOD
FRAGMENTS, SATURATED (CA
N, AND YELLOW SILTY
CLAY, WET (CAPE FEAR FOR
ND WITH LIMESTONE
FRAGMENTS, SATURATED (CAPE FEAR

BP1.R004 EB1

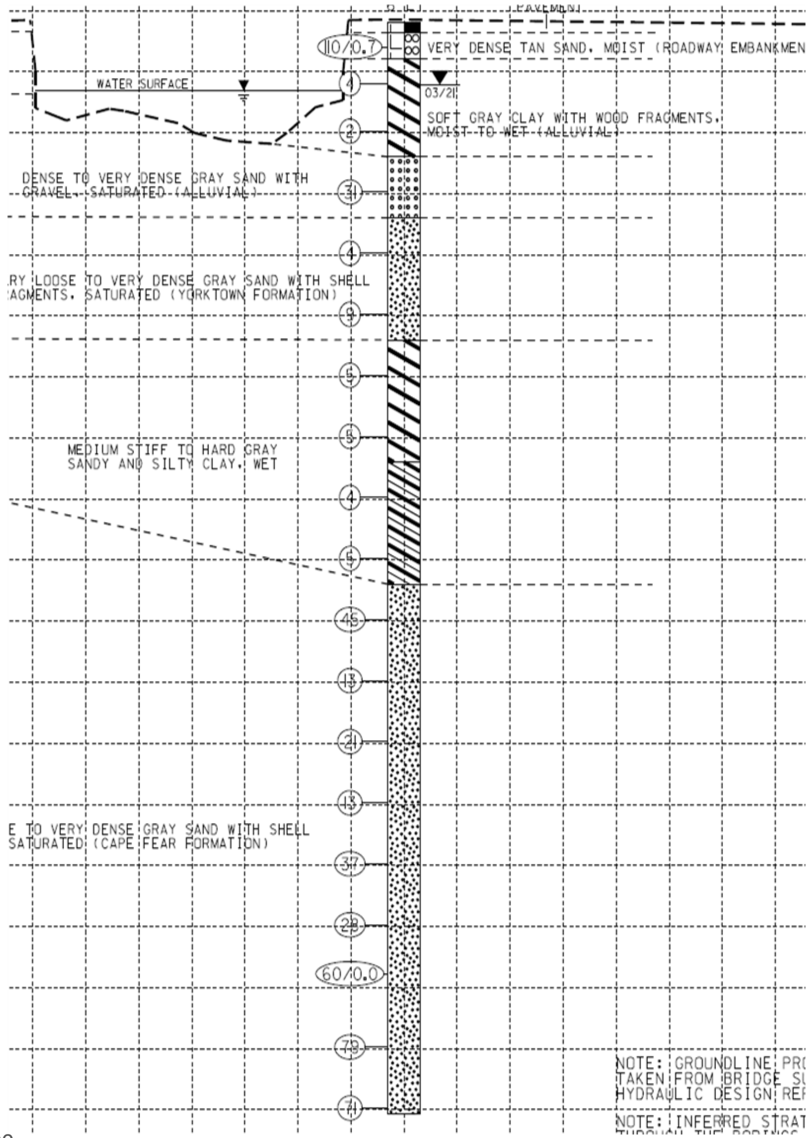


Elevation (ft)
Capacity (kips)
APILE FHWA
PDA EB1 P7
CAPWAP EB1 P7
PDA EB1 P7 Restrike
CAPWAP EB1 P7 Restrike
50
40
30
20
10
0
-10
-20
-30
-40
0
50
100
150
200
250
300
350
400
450
LOOSE TO MEDIUM DENSE TAN SAND, MOIST TO SATURATED (ROADWAY EMBANKMENT)
WATER SURFACE
DENSE TO VERY DENSE GRAY SAND WITH GRAVEL, SATURATED (ALLUVIAL)
VERY LOOSE TO VERY DENSE GRAY SAND WITH FRAGMENTS, SATURATED (YORKTOWN FORMATIO
MEDIUM STIFF TO HARD GRAY SANDY AND SILTY CLAY, WET
MEDIUM DENSE TO VERY DENSE GRAY SAND WITH SHELL FRAGMENTS, SATURATED (CAPE FEAR FORMATION)
23
5
100/0.3
100/0.3
WOH
100/0.7
8
46
14
25
60
39
25
FIAD

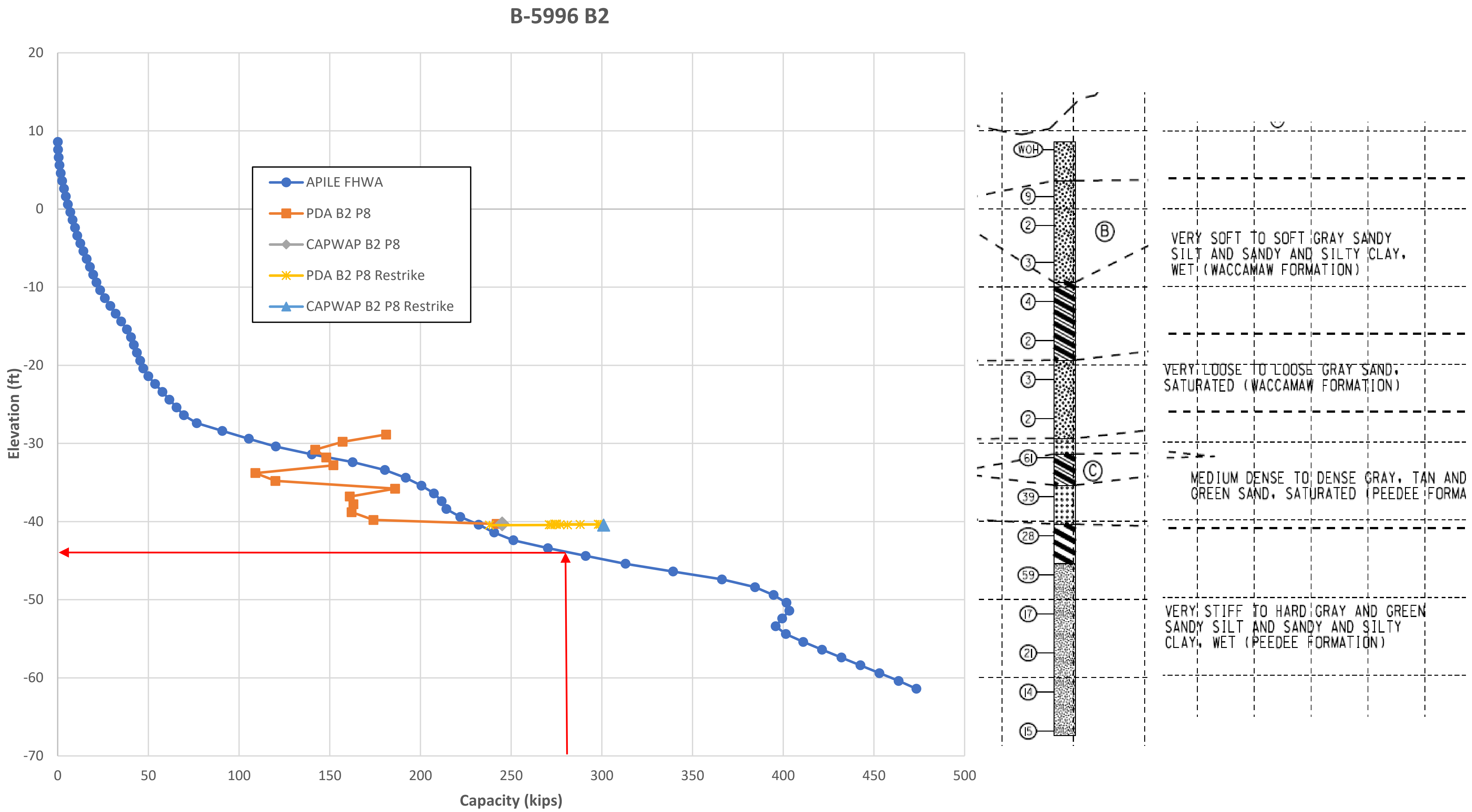
BP1.R004 EB2



Elevation (ft)
Capacity (kips)
APILE FHWA
PDA EB2 P7
CAPWAP EB1 P7
50
40
30
20
10
0
-10
-20
-30
-40
0
50
100
150
200
250
300
350
400
450
500

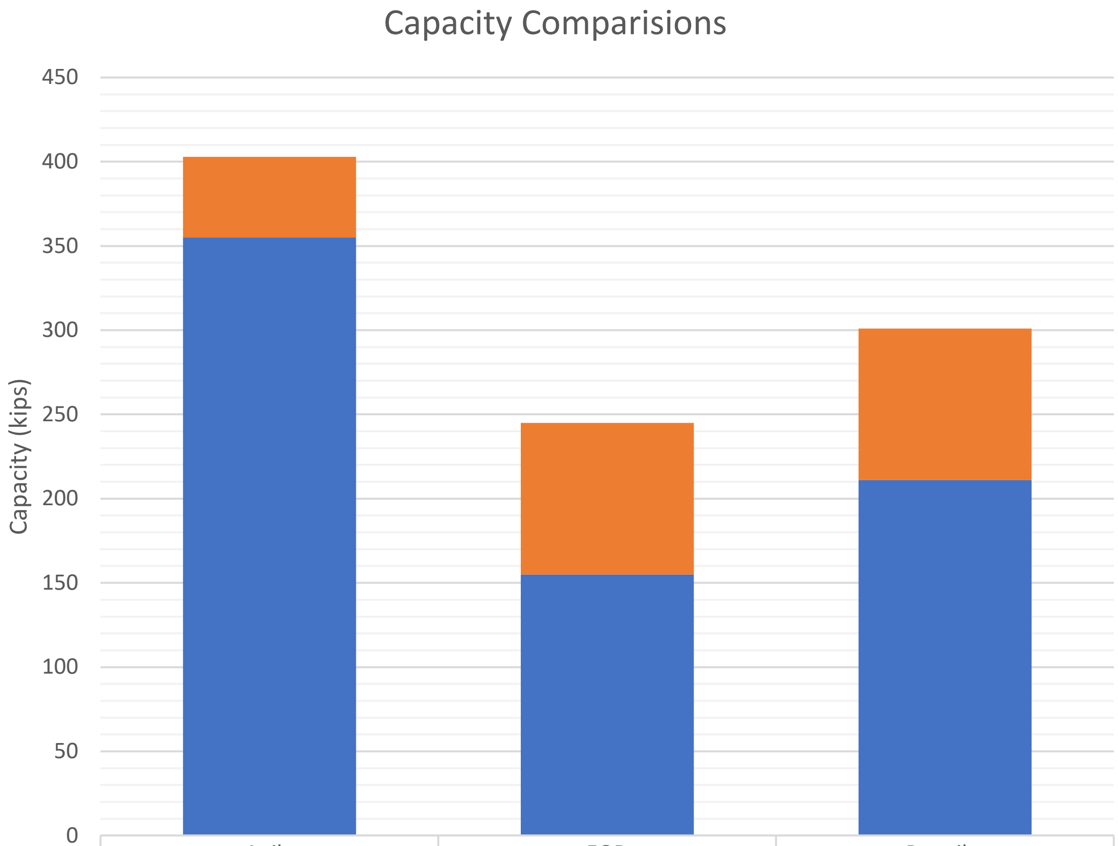


VERY DENSE TAN SAND, MOIST (ROADWAY EMBANKMEN
WATER SURFACE
03/21
SOFT GRAY CLAY WITH WOOD FRAGMENTS,
MOIST TO WET (ALLUVIAL)
DENSE TO VERY DENSE GRAY SAND WITH
GRAVEL, SATURATED (ALLUVIAL)
RY LOOSE TO VERY DENSE GRAY SAND WITH SHELL
AGMENTS, SATURATED (YORKTOWN FORMATION)
MEDIUM STIFF TO HARD GRAY
SANDY AND SILTY CLAY, WET
E TO VERY DENSE GRAY SAND WITH SHELL
SATURATED (CAPE FEAR FORMATION)
NOTE: GROUNDLINE PR
TAKEN FROM BRIDGE S
HYDRAULIC DESIGN RE
NOTE: INFERRED STRAT

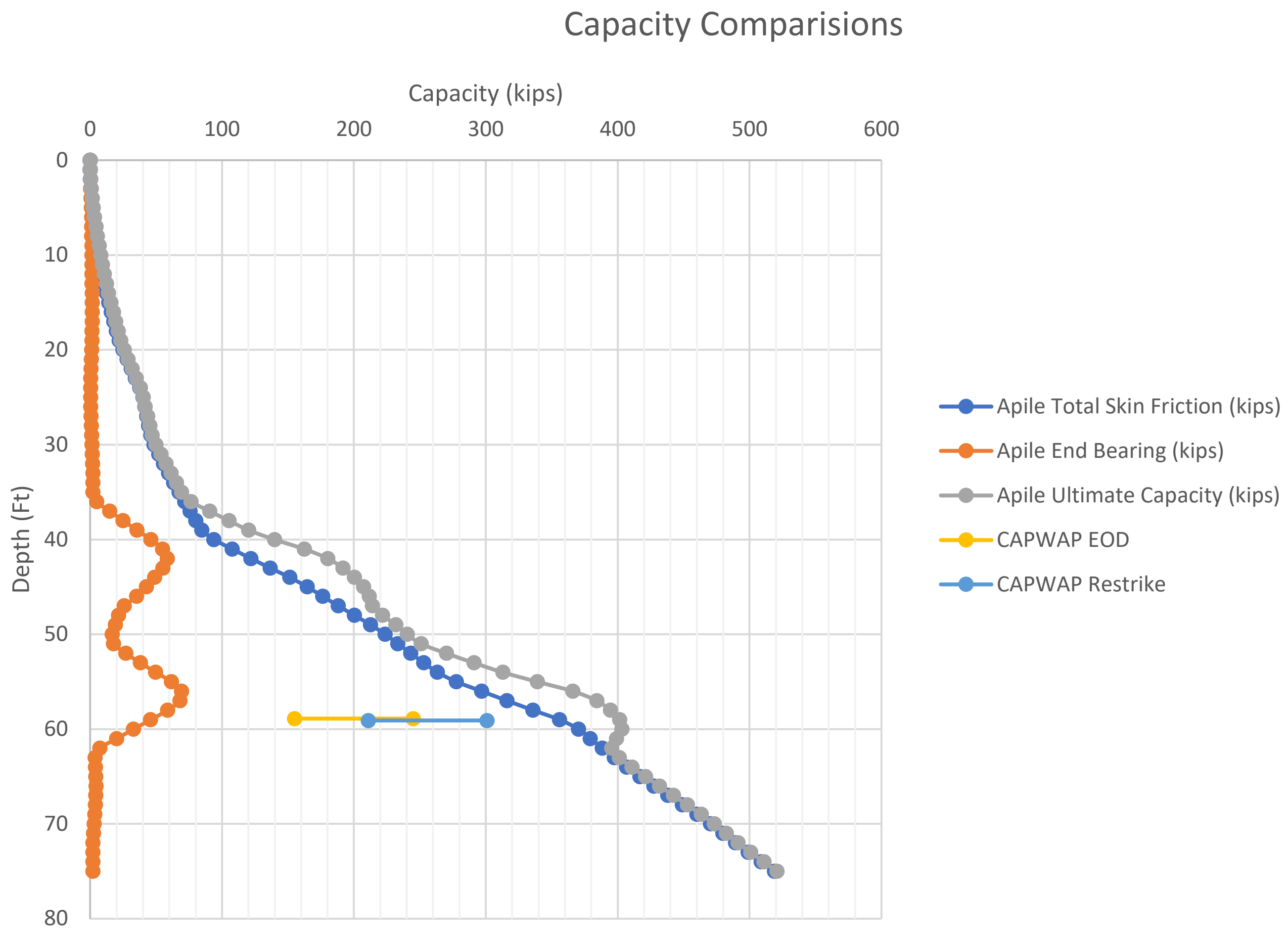


B-5996 B2
Elevation (ft)
Capacity (kips)
APILE FHWA
PDA B2 P8
CAPWAP B2 P8
PDA B2 P8 Restrike
CAPWAP B2 P8 Restrike
20
10
0
-10
-20
-30
-40
-50
-60
-70
0
50
100
150
200
250
300
350
400
450
500
WOH
B
C
VERY SOFT TO SOFT GRAY SANDY SILT AND SANDY AND SILTY CLAY, WET (WACCAMAW FORMATION)
VERY LOOSE TO LOOSE GRAY SAND, SATURATED (WACCAMAW FORMATION)
MEDIUM DENSE TO DENSE GRAY, TAN AND GREEN SAND, SATURATED (PEEDEE FORMA
VERY STIFF TO HARD GRAY AND GREEN SANDY SILT AND SANDY AND SILTY CLAY, WET (PEEDEE FORMATION)

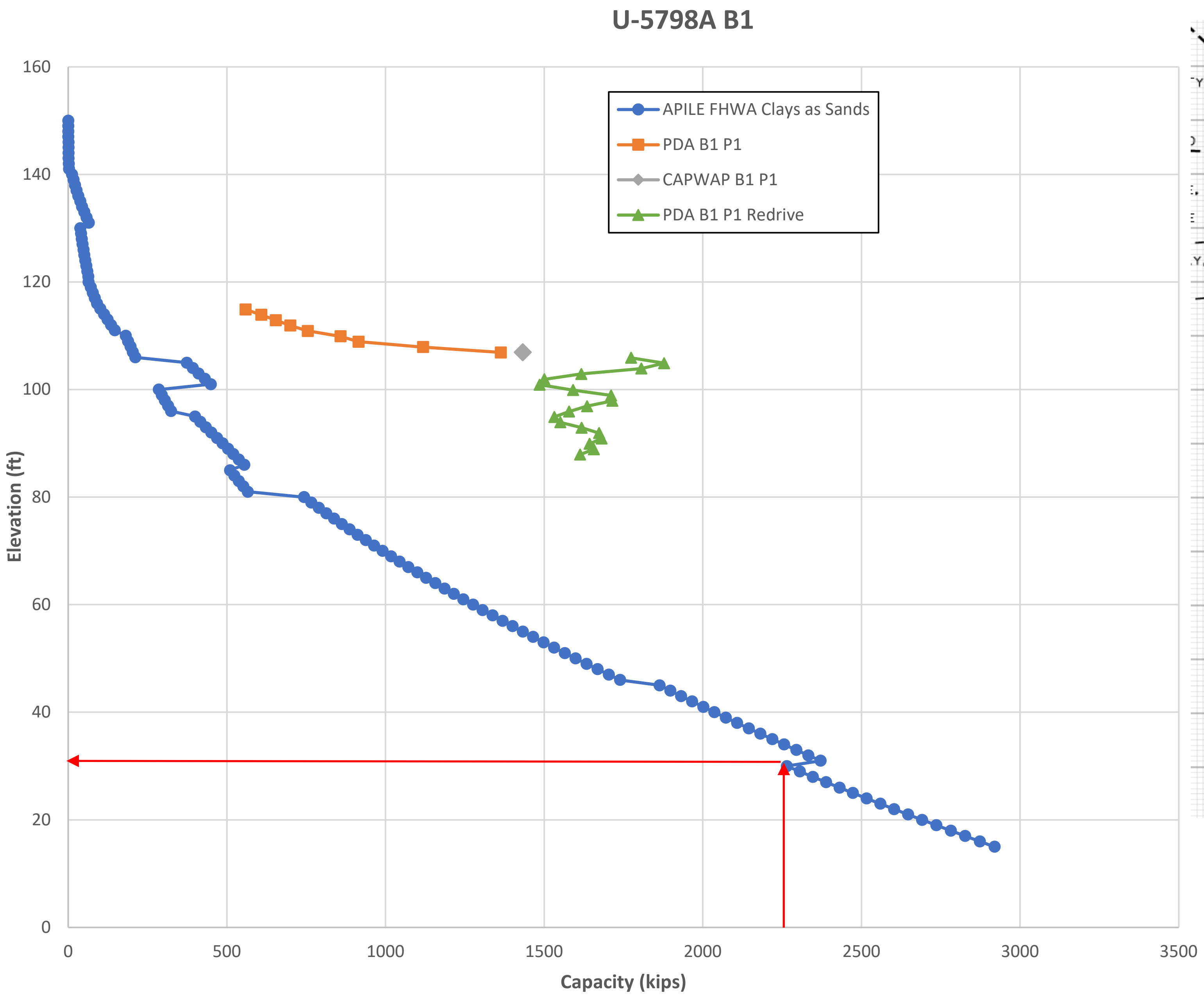
B-5996 B2



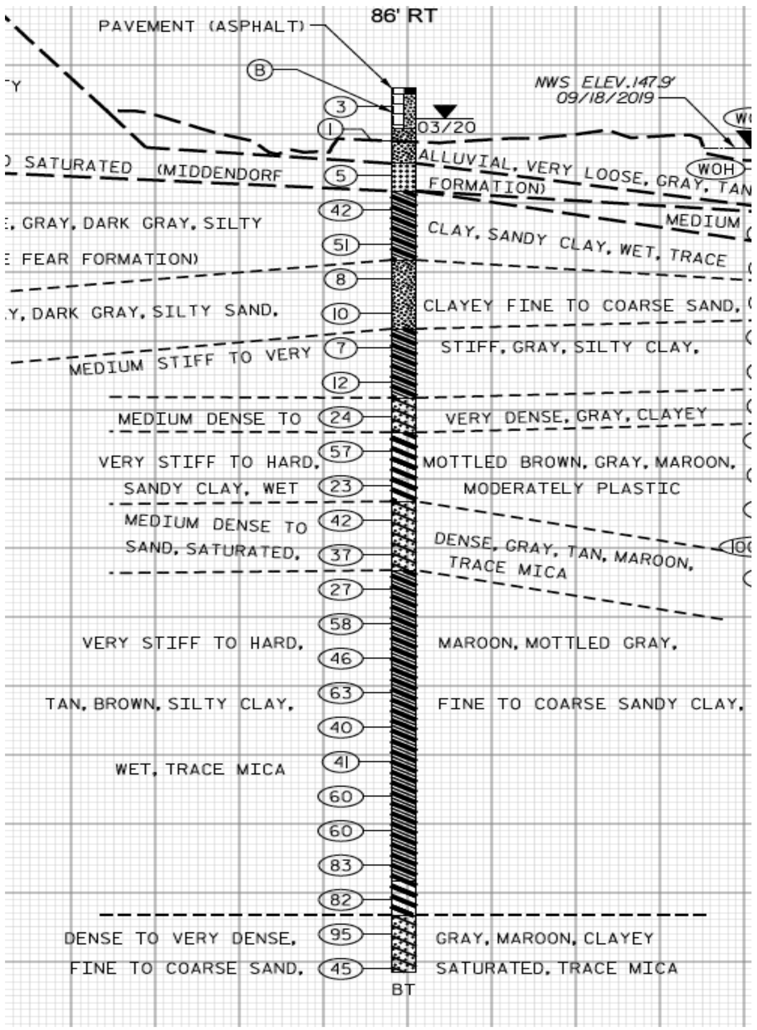
	Apile	EOD	Restrike
Toe	48	90	90
Shaft	355	155	211



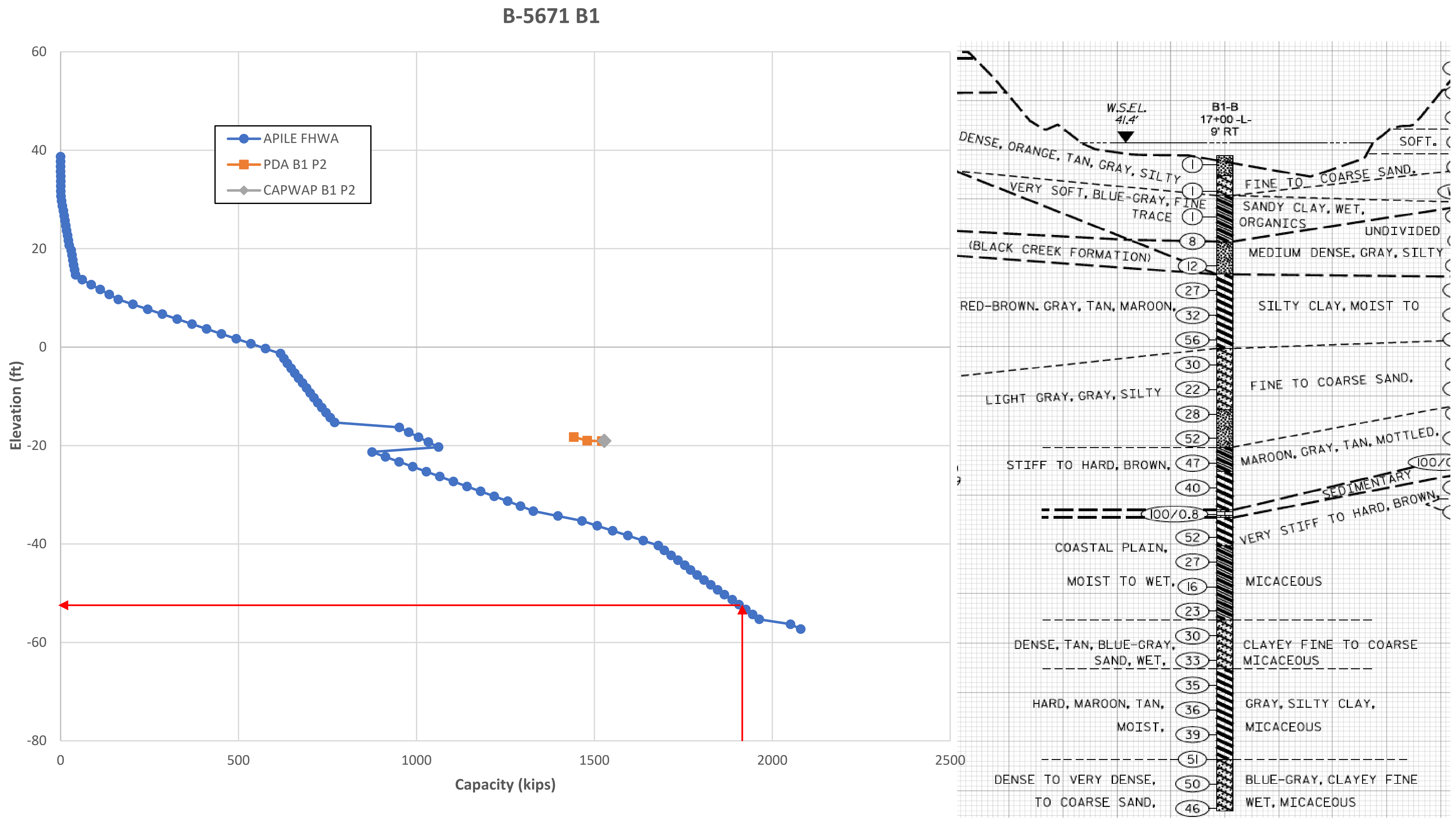
Underrun Pipe Pile Projects



U-5798A B1
APILE FHWA Clays as Sands
PDA B1 P1
CAPWAP B1 P1
PDA B1 P1 Redrive
Elevation (ft)
Capacity (kips)
0
20
40
60
80
100
120
140
160
0
500
1000
1500
2000
2500
3000
3500



86' RT
PAVEMENT (ASPHALT)
NWS ELEV.147.9'
09/18/2019
03/20
WOH
SATURATED (MIDDENDORF FORMATION)
ALLUVIAL, VERY LOOSE, GRAY, TAN
GRAY, DARK GRAY, SILTY
MEDIUM
CLAY, SANDY CLAY, WET, TRACE
FEAR FORMATION)
DARK GRAY, SILTY SAND,
CLAYEY FINE TO COARSE SAND,
MEDIUM STIFF TO VERY
STIFF, GRAY, SILTY CLAY,
MEDIUM DENSE TO
VERY DENSE, GRAY, CLAYEY
VERY STIFF TO HARD,
MOTTLED BROWN, GRAY, MAROON,
SANDY CLAY, WET
MODERATELY PLASTIC
MEDIUM DENSE TO
DENSE, GRAY, TAN, MAROON,
SAND, SATURATED,
TRACE MICA
VERY STIFF TO HARD,
MAROON, MOTTLED GRAY,
TAN, BROWN, SILTY CLAY,
FINE TO COARSE SANDY CLAY,
WET, TRACE MICA
DENSE TO VERY DENSE,
GRAY, MAROON, CLAYEY
FINE TO COARSE SAND,
SATURATED, TRACE MICA
BT
3
1
5
42
51
8
10
7
12
24
57
23
42
37
27
58
46
63
40
41
60
60
83
82
95
45



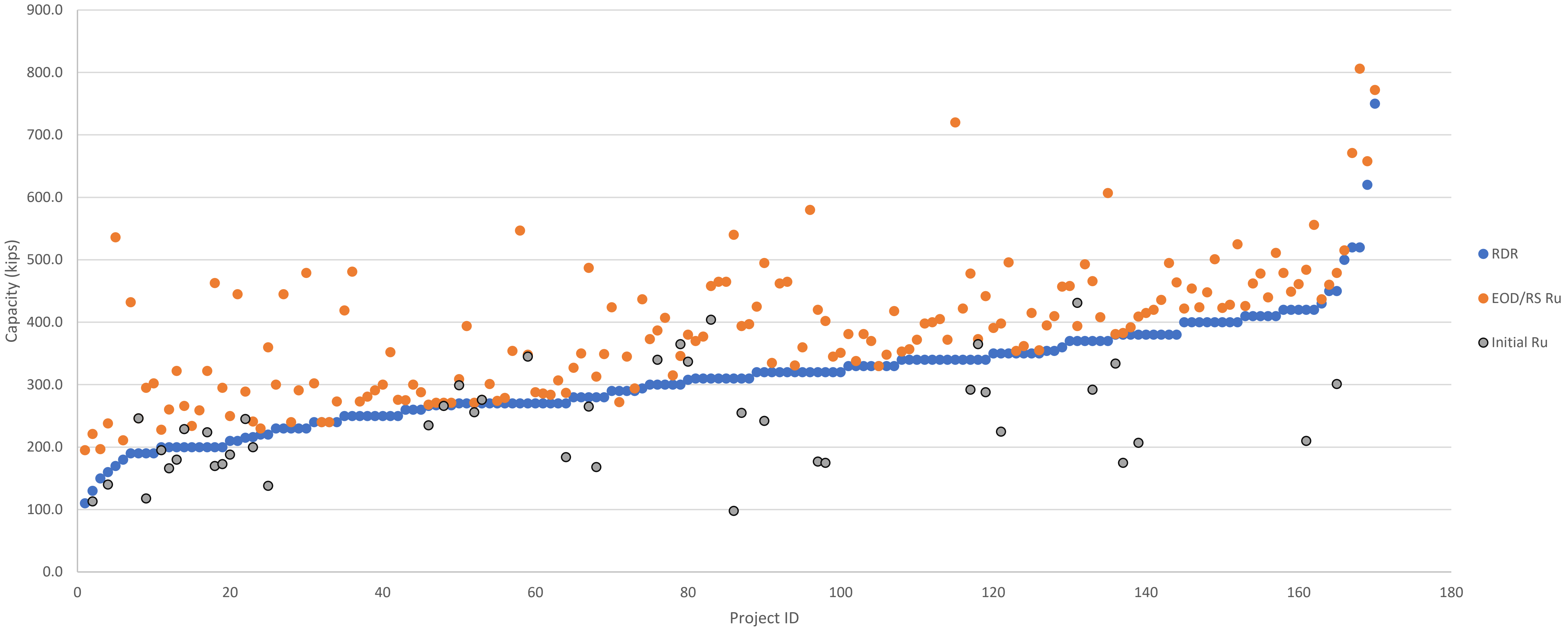
B-5671 B1
APILE FHWA
PDA B1 P2
CAPWAP B1 P2
Elevation (ft)
Capacity (kips)
60
40
20
0
-20
-40
-60
-80
0
500
1000
1500
2000
2500
W.S.EL. 41.4'
B1-B
17+00 -L-
9' RT
DENSE, ORANGE, TAN, GRAY, SILTY
FINE TO COARSE SAND,
SOFT,
VERY SOFT, BLUE-GRAY, FINE
SANDY CLAY, WET,
TRACE
ORGANICS
UNDIVIDED
(BLACK CREEK FORMATION)
MEDIUM DENSE, GRAY, SILTY
RED-BROWN, GRAY, TAN, MAROON,
SILTY CLAY, MOIST TO
LIGHT GRAY, GRAY, SILTY
FINE TO COARSE SAND,
MAROON, GRAY, TAN, MOTTLED,
STIFF TO HARD, BROWN,
SEDIMENTARY
VERY STIFF TO HARD, BROWN,
COASTAL PLAIN,
MOIST TO WET,
MICACEOUS
DENSE, TAN, BLUE-GRAY,
CLAYEY FINE TO COARSE
SAND, WET,
MICACEOUS
HARD, MAROON, TAN,
GRAY, SILTY CLAY,
MOIST,
MICACEOUS
DENSE TO VERY DENSE,
BLUE-GRAY, CLAYEY FINE
TO COARSE SAND,
WET, MICACEOUS
1
1
1
8
12
27
32
56
30
22
28
52
47
40
100/0.8
52
27
16
23
30
33
35
36
39
51
50
46

PDA Database

Summary of Quake and Damping Soil Parameters

Only for HP 12X53 & HP 14X73 in Coastal Plain			Min.	Avg.	Max.
Design/Analysis	Damping (s/ft)	Skin	0.05-0.20		
		Toe	0.15		
	Quake (in)	Skin	0.1		
		Toe	0.1 -0.20		
EOID (Database)	Damping (s/ft)	Skin	0.02	0.112	0.29
		Toe	0.02	0.092	0.4
	Quake (in)	Skin	0.04	0.084	0.4
		Toe	0.04	0.173	0.51
Restrike (Database)	Damping (s/ft)	Skin	0.05	0.115	0.22
		Toe	0.02	0.082	0.32
	Quake (in)	Skin	0.04	0.079	0.21
		Toe	0.04	0.179	0.50

RDR vs PDA Data



Two Different CAPWAP Results for a PDA test

★ Total CAPWAP Capacity: 555.2 kips

Along Shaft: 205.2 kips

At Toe: 350 kips

- Qs = 0.05 in
- Qt = 0.08in
- Ss = 0.06 sec/ft
- St = 0.05 sec/ft

➢ Match Quality = 2.39

Total CAPWAP Capacity: 461.7 kips

Along Shaft: 121.1 kips

At Toe: 340.6 kips

- Qs = 0.13 in
- Qt = 0.20 in
- Ss = 0.26 sec/ft
- St = 0.18 sec/ft

➢ Match Quality = 2.18

Things to Consider

- Ignore isolated inflated N values
- Reduce inflated N values from cementation
- Static analysis resistance factors, should we limit to 0.6 for H piles in coastal plain?
- Revise coastal plain H pile policy (Clays as sands, Hammer efficiency corrections)
- Choose resistance factor based on testing
- Method of predicting scour resistance has impacts

Questions?

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