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Southeastern Transportation Geotechnical Engineering Conference
Charlotte 2023

Geotechnical Design and Construction NCDOT Rodanthe Bridge Design-Build Project

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NCDOT – N.C. 12 Rodanthe ‘Jug Handle’ Bridge

A 2.4-mile bridge over Pamlico Sound between the southern end of the Pea Island National Wildlife Refuge and the village of Rodanthe, bypassing a section of N.C. 12 that is vulnerable to ocean overwash; which was damaged in 2011 by Hurricane Irene and in 2012 by Hurricane Sandy.

https://www.ncdot.gov/news/press-releases/Pages/2022/2022-07-28-rodanthe-bridge-opens.aspx

NCDOT – Alligator River Bridge Design-Bid/CMGC (Ongoing 2023)

- Geotechnical: WSP
- Structural: Modjeski and Masters, Inc.
- Contractor: Skanska

NCDOT – N.C. 12 Rodanthe 'Jug Handle' Bridge

Project Information

- ***Construction Began in July 2015***
- ***Open to Traffic on July 28, 2022***
- ***Construction Cost: $155 M***

- ***Contractor: Flatiron Construction Company***
- ***Structural/Civil Engineer: RK&K***
- ***Geotechnical Engineer: WSP USA (Formally Wood)***
- ***PDA (Pile Dynamic Testing): Atlantic Coast Engineering***

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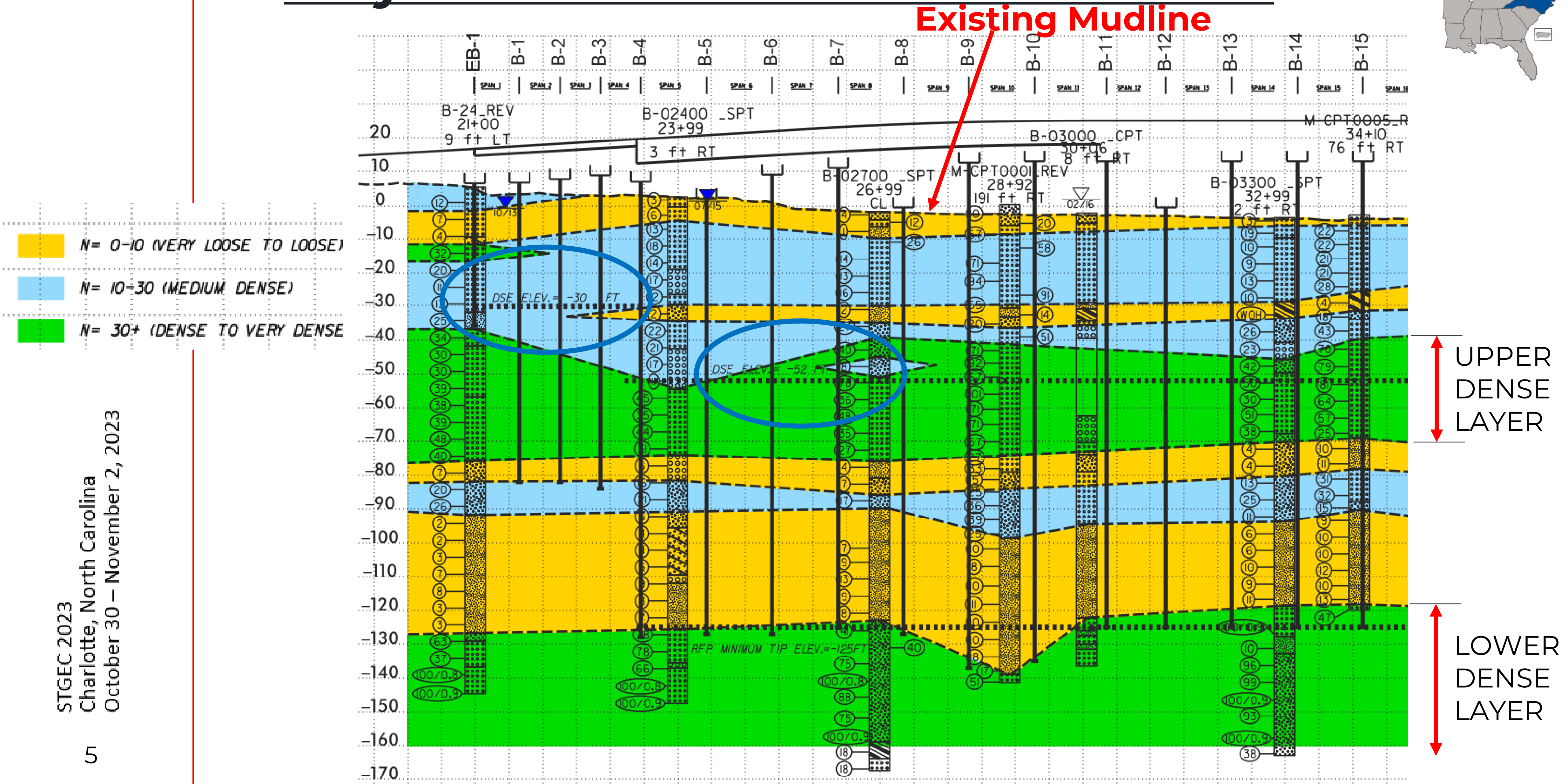
Project Site Subsurface Conditions



Pile Design Scour Elevations

- ***Design Scour Elevations***
  - ***Transition Spans: -30 ft-NAVD***
  - ***Main Bridge Spans: -52 ft-NAVD (…. Approx. near the Top of Upper Dense Sand Layer)***

Pile Design Scour Elevations

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  - ***Transition Spans: -30 ft-NAVD***
  - ***Main Bridge Spans: -52 ft-NAVD (.... Approx. near the Top of Upper Dense Sand Layer)***

QUESTION:

w/ Mudline @ EL. 0 ft; Waterline @ +2 ft; Why Design Scour Elevation was established so deep @ -52 ft?

- ***A critical design requirement for pile foundation Later Stability***

Pile Axial Resistance

- ❖ ***Design Soil Shear Strength Parameters***
  - ➢ ***Based on SPT-N Correlations***
- ❖ ***Calculations of Axial Nominal Bearing Resistance***
  - ➢ ***Run Ensoft APILE; using API Method***

APILE SOIL PROPERTIES - BENTS 4 - 10 (AXIAL)
JETTING TO 10 FT ABOVE MIN. TIP ELEVATION

Jetting Zone (Layers 1 – 7A)

Depth							Elevation 0'
	*N=	11 -> 4					
Layer 1	*(N1)60=	20 -> 4	Φ=	28		End Limit (ksf)=	60
	γ (pcf)=	115	Nq=	12		Side Limit (ksf)=	1.4
(0')	(General Scour)						-39'
	*N=	16 -> 4					
Layer 2	*(N1)60=	20 -> 4	Φ=	28 (0 DSE)		End Limit (ksf)=	60
	γ (pcf)=	120	Nq=	12 (1 DSE)		Side Limit (ksf)=	1.4
(13')	(DSE)						-52'
	N=	34 -> 4					
Layer 3	(N1)60=	38 -> 4	Φ=	28		End Limit (ksf)=	60
	γ (pcf)=	120	Nq=	12		Side Limit (ksf)=	1.4
(36')							-75'
	N=	6 -> 4					
Layer 4	(N1)60=	6 -> 4	Φ=	28		End Limit (ksf)=	60
	γ (pcf)=	105	Nq=	12		Side Limit (ksf)=	1.4
(46')							-85'
	N=	17 -> 4					
Layer 5	(N1)60=	17 -> 4	Φ=	28		End Limit (ksf)=	60
	γ (pcf)=	115	Nq=	12		Side Limit (ksf)=	1.4
(51')							-90'
	N=	5 -> 4					
Layer 6	(N1)60=	4 -> 4	Φ=	28		End Limit (ksf)=	60
	γ (pcf)=	105	Nq=	12		Side Limit (ksf)=	1.4
(69')							-108'
	N=	8 -> 4					
Layer 7A	(N1)60=	7 -> 4	Φ=	28		End Limit (ksf)=	60
	γ (pcf)=	110	Nq=	12		Side Limit (ksf)=	1.4
(76')							-115'
	N=	8					
Layer 7B	(N1)60=	7	Φ=	30		End Limit (ksf)=	100
	γ (pcf)=	110	Nq=	20		Side Limit (ksf)=	1.7
(86')							-125'
	N=	51					
Layer ~~9~~ 8	(N1)60=	50	Φ=	36		End Limit (ksf)=	200
	γ (pcf)=	125	Nq=	40		Side Limit (ksf)=	2
(121')							-160'

Pile Axial Resistance

- ❖ *Design Soil Shear Strength Parameters*
  - ➢ *Based on SPT-N Correlations*
- ❖ *Calculations of Axial Nominal Bearing Resistance*
  - ➢ *Run Ensoft APILE; using API Method*

Question:

Shear Strength Parameters of Jetted Soils?

APILE SOIL PROPERTIES - BENTS 4 - 10 (AXIAL)
JETTING TO 10 FT ABOVE MIN. TIP ELEVATION

Jetting Zone

Layer	Depth	N	(N1)60	γ (pcf)	Φ	Nq	End Limit (ksf)	Side Limit (ksf)	Elevation
									0'
Layer 1	(0') (General Scour)	*N= 11 -> 4	*(N1)60= 20 -> 4	115	28	12	60	1.4	-39'
Layer 2	(13') (DSE)	*N= 16 -> 4	*(N1)60= 20 -> 4	120	28 (0 DSE)	12 (1 DSE)	60	1.4	-52'
Layer 3	(36')	34 -> 4	38 -> 4	120	28	12	60	1.4	-75'
Layer 4	(46')	6 -> 4	6 -> 4	105	28	12	60	1.4	-85'
Layer 5	(51')	17 -> 4	17 -> 4	115	28	12	60	1.4	-90'
Layer 6	(69')	5 -> 4	4 -> 4	105	28	12	60	1.4	-108'
Layer 7A	(76')	8 -> 4	7 -> 4	110	28	12	60	1.4	-115'
Layer 7B	(86')	8	7	110	30	20	100	1.7	-125'
Layer 9 8	(121')	51	50	125	36	40	200	2	-160'

Pile Axial Resistance

FRICTION ANGLE - δ

PILE TYPE	δ
STEEL	20°
CONCRETE	3/4 ϕ
TIMBER	3/4 ϕ

* LIMIT ϕ TO 28° IF JETTING IS USED

** (A) IN CASE A BAILER OR GRAB BUCKET IS USED BELOW GROUNDWATER TABLE, CALCULATE END BEARING BASED ON ϕ NOT EXCEEDING 28°.

(B) FOR PIERS GREATER THAN 24-INCH DIAMETER, SETTLEMENT RATHER THAN BEARING CAPACITY USUALLY CONTROLS THE DESIGN. FOR ESTIMATING SETTLEMENT, TAKE 50% OF THE SETTLEMENT FOR AN EQUIVALENT FOOTING RESTING ON THE SURFACE OF COMPARABLE GRANULAR SOILS. (CHAPTER 5, DM-7.1).

FIGURE 1 (continued)
Load Carrying Capacity of Single Pile in Granular Soils

7.2-194

NAVFAC DM7.2

Pile Lateral Stability Collaboration w/ Structural Engineer

- ***Provided Design Soil Parameters to Structural Engineer for performing FB-Multipier Analyses and determining Point of Fixity & Minimum Pile Tip Elevations.***
- ***Design Soil Subgrade Modulus***
  - ***Adopted Default Values in FB-Multipier***

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QUESTION: What is the Tolerable Foundation Pile Lateral Deflection (... and Settlements)?

Always a Challenging Question to both Geotechnical & Structural Engineers!

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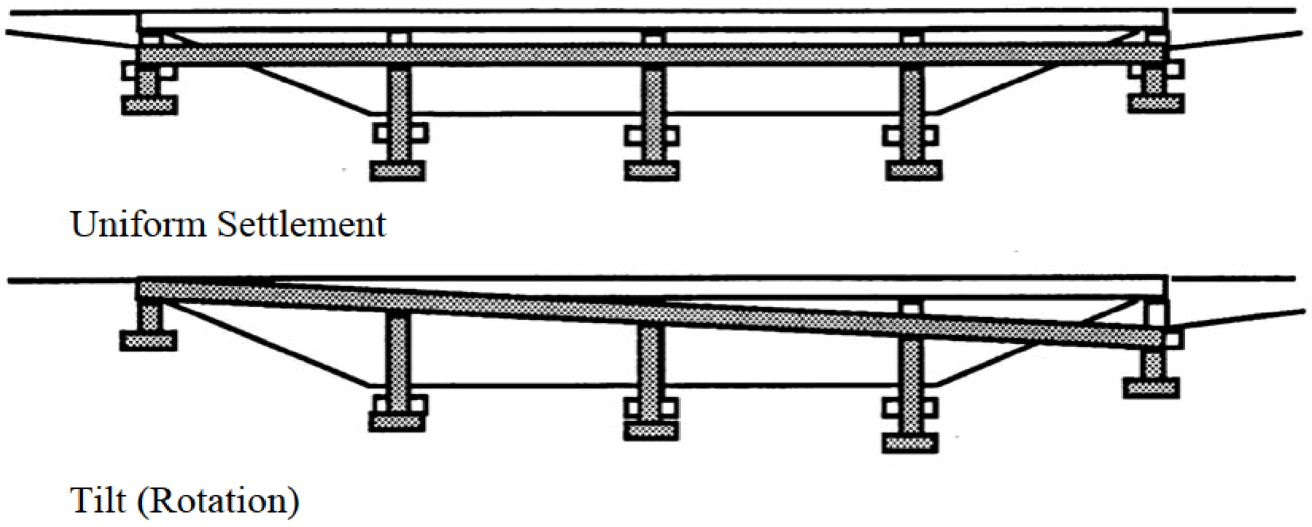
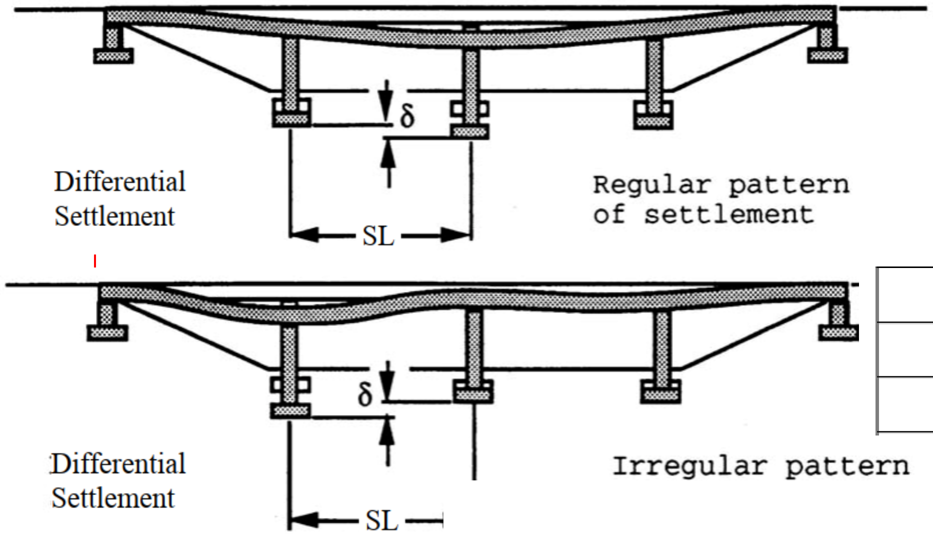
FHWA NHI-06-089
Soils and Foundations – Volume II



- ***Along Bridge Spans – OK!***
- ***At End Bents – Differential to Approach Slab/Embankments (Bumps)***
- ***Practically, Not Possible; Due to Variabilities of Soil Profiles/Properties, Loading, etc.***

FHWA NHI-06-089
Soils and Foundations – Volume II



$$A = \text{Angular Distortion} = \frac{\delta}{SL}$$

Table 8-14
Tolerable movement criteria for bridges (FHWA, 1985; AASHTO 2002, 2004)

Limiting Angular Distortion, δ/SL	Type of Bridge
0.004	Multiple-span (continuous span) bridges
0.005	Single-span bridges

❖ ***Considering Reliability of Estimation of Movements, Duncan and Tan (1991) suggest the following:***

- The settlement of any support element could be as large as the value calculated by using conservative procedures, and
- At the same time, the settlement of the adjacent support element could be zero.

Use of these conservative assumptions would result in an estimated maximum possible differential settlement equal to the largest settlement calculated at either end of any span.

Tolerable Horizontal Bridge Foundation Movement

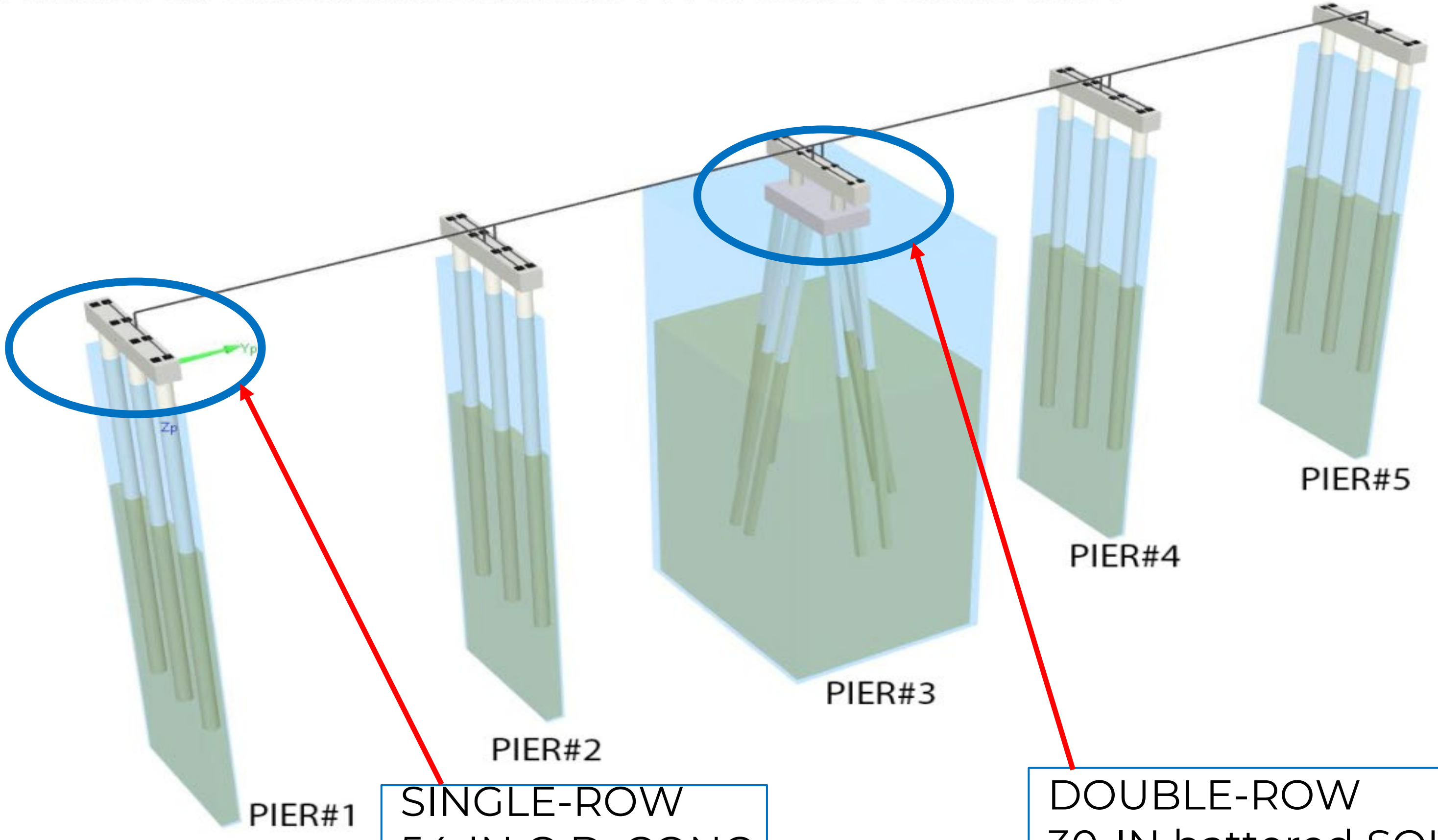
- ***Referring to FHWA (1985) –***
  - ***Conventionally, ≤ 1-inch (Tolerable)***
    > 2 inches (Intolerable)
  - ***Recommendation - 1.5 inches***

- ***Actual Design Analysis – Consult with Structural Engineer, which could be greater than 2 inches.***

Pile Lateral Stability Collaboration w/ Structural Engineer

PRELIMINARY DESIGN – OPTION #1

FB-MultiPier GLOBAL MODEL OF A TYPICAL 4-SPAN UNIT



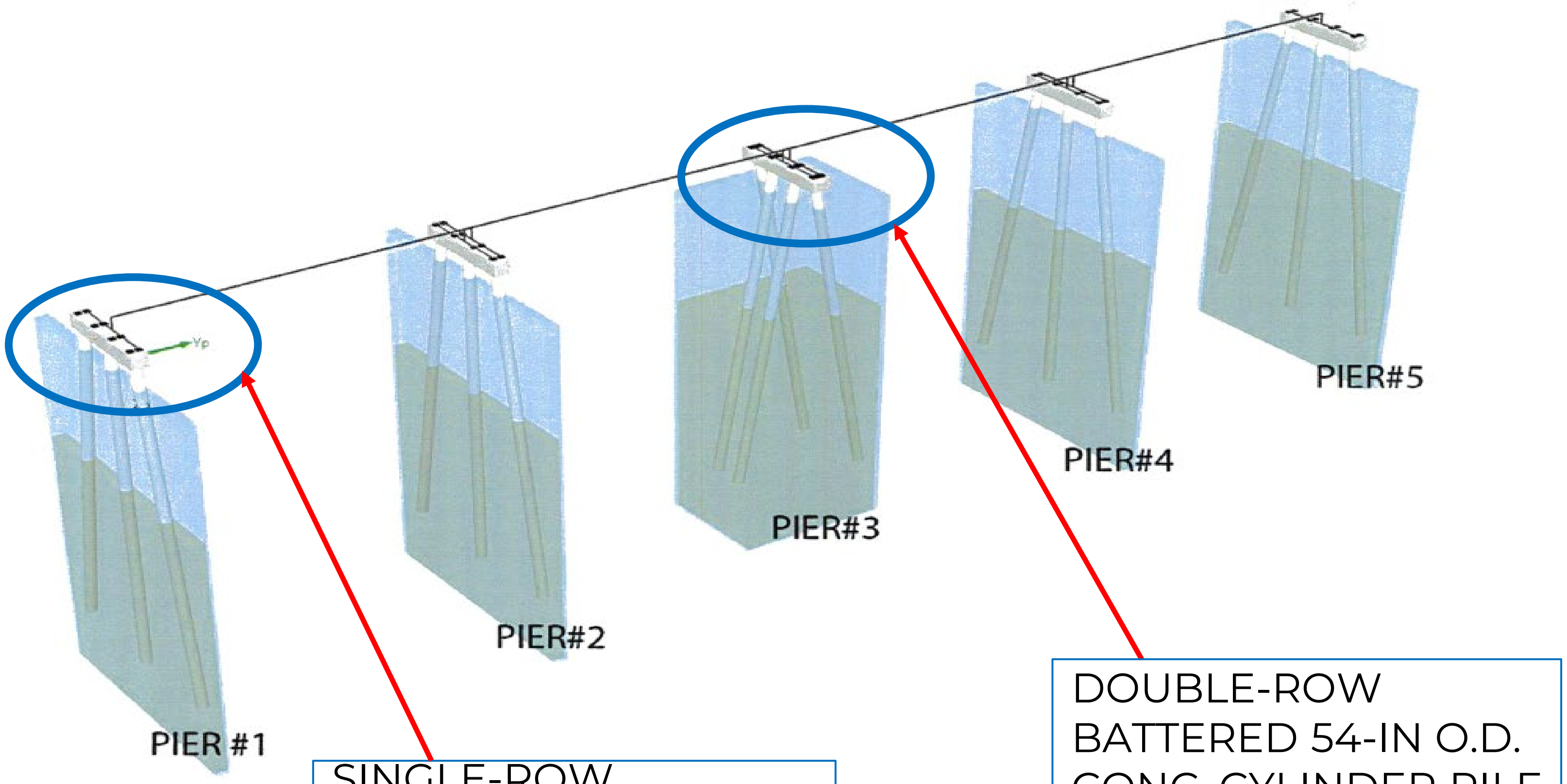
SINGLE-ROW
54-IN O.D. CONC.
CYLINDER PILE

DOUBLE-ROW
30-IN battered SQUARE
PILE FOOTING

Pile Lateral Stability Collaboration w/ Structural Engineer

PRELIMINARY DESIGN – OPTION #2

FB-Multipier Global Model of a Typical 4-span Unit



SINGLE-ROW
w/ BATTERED 54-IN O.D.
CONC. CYLINDER PILE

DOUBLE-ROW
BATTERED 54-IN O.D.
CONC. CYLINDER PILE

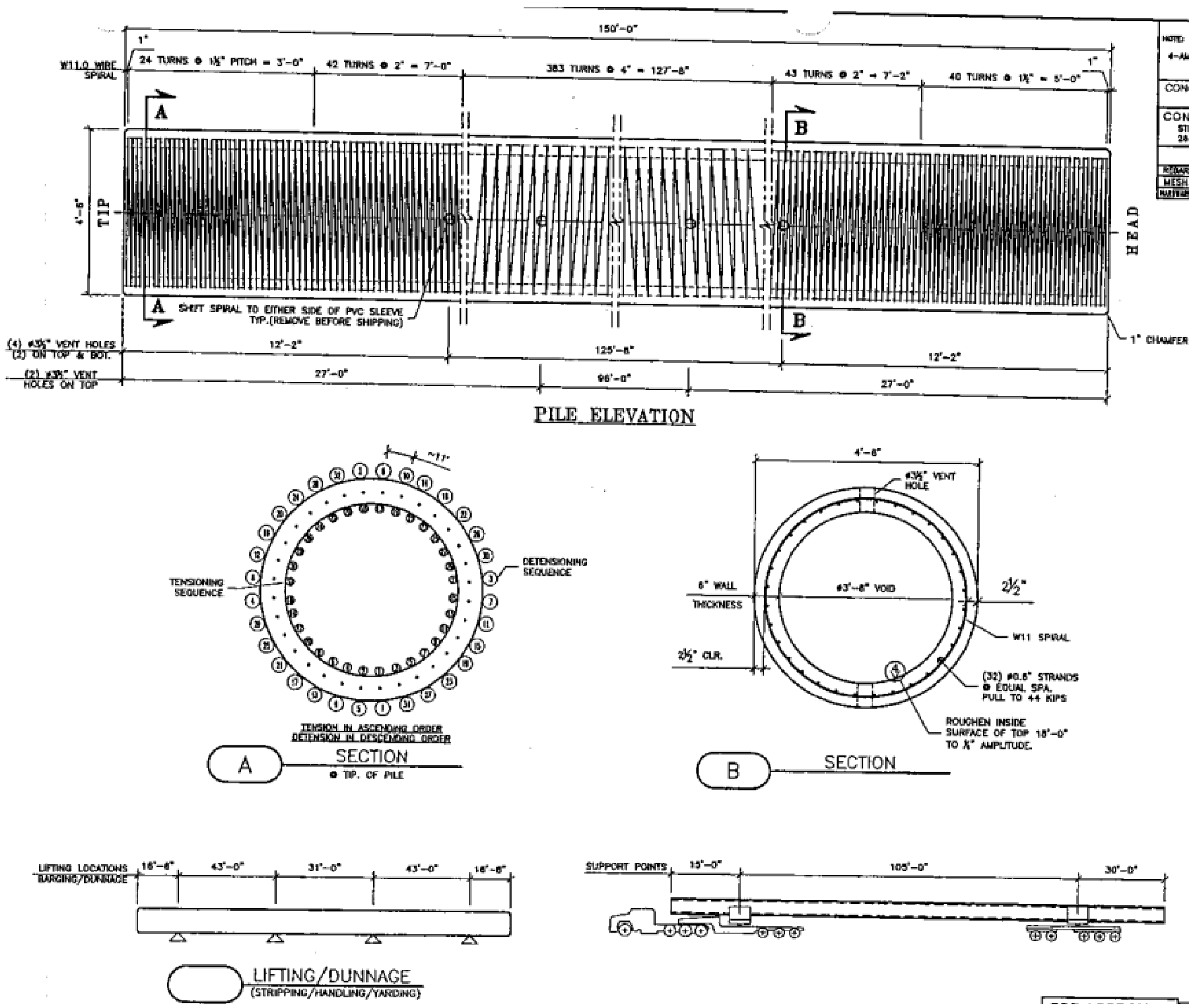
Pile Lateral Stability
Collaboration w/ Structural Engineer

FINAL DESIGN

SINGLE-ROW
w/ BATTERED 54-IN O.D.
CONC. CYLINDER PILE

FOUR-SPAN MODEL (Image courtesy of RK&K)

Final Design: 54-inch OD Open-Ended Concrete Cylinder Pile



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Final Design

- *Main Bridge Spans: Bents B-4 thru B-101*
- *Transition Spans: Bents B-1 thru B-4 & B-101 thru B-106*
- *End Bents: EB-1 & EB-2*
- *Bents B-4 thru B-101: 54" OD Open-Ended Conc. Cylinder Pile*
  - *Pile Length 140 to 165 feet; penetrating approx. 1 to 2 ft into Lower Dense Sand Layer)*
  - *Design Axial Factored Load = 815 Tons/pile*
- *Transition Bents: 30" Sq. Concrete Piles*

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What's NEXT?


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KENWORTH

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Challenge in Constructability
Driving Piles through Upper Dense Sand Layer

❖ ***Pre-Excavation/Pre-Drilling … Feasible, but Not Considered***

Challenge in Constructability
Driving Piles through Upper Dense Sand Layer

- ***Pre-Excavation/Pre-Drilling … Feasible, but Not Considered***
- ***Jetting***

Jetting During Pile Installatrion

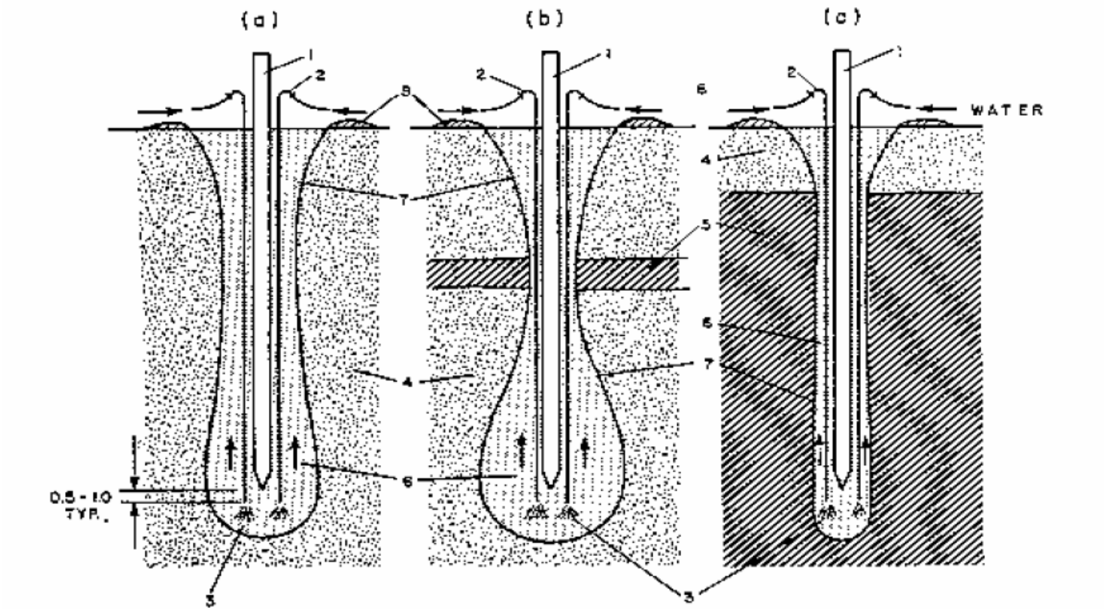

Figure 2-1 Variation in Annulus Dimensions for Various Foundation Soil (Matlin, 1983).

(a) Uniform Sand; (b) Sand with Clay Stratum; (c) Sand with Underlain Clay: 1 – Pile; 2 – Jet Pipe; 3 – Water Jet; 4 – Sand; 5 – Clay; 6 – Loose Sand; 7 – Return Annulus; 8 – Particle Deposition

References

1. Gunaratne, M., R.A. Hameed, C. Kuo, S. Putcha, and D.V. Reddy (1999) Investigation of the Effects of Pile Jetting and Preforming, Research Report No. 772, Florida Department of Transportation, in cooperation with Federal Highway Administration.
2. Characterization of Jetting-Induced Disturbance Zone and Associated Ecological Impacts (2004), by M. A. Gabr, et al., Publication FHWA/NC/2006-09.

Consideration of Jetting During Pile Installation

3.0 CONSTRUCTION METHODS

Do not jet below a depth of 10 feet above the "Pile Tip No Higher Than Elev." shown on the plans unless approved by the Engineer. Do not jet piles supporting the temporary rail system.

Use jet pumps, supply lines, jet pipes, and jet nozzles that provide pressure and volume of water or water and air mixture to erode the soil. Minimize jetting effort when installing concrete piles.

Obtain water for jetting in accordance with the all project B-2500B environmental commitments from locations as shown in the permit drawings unless otherwise approved by the Engineer.

Use a minimum of two external jet pipes. Do not extend the jet nozzles below the tip of the concrete piles without approval of the Engineer. When jetting and advancing concrete piles simultaneously, position the jet nozzles a minimum of 3 feet above the advancing pile tip or as approved by the Engineer.

Challenge in Constructability
Driving Piles through Upper Dense Sand Layer

- ***Pre-Excavation/Pre-Drilling … Feasible, but Not Considered***
- ***Jetting … Field Trial; Did Not Work due to difficulties in managing spoils***

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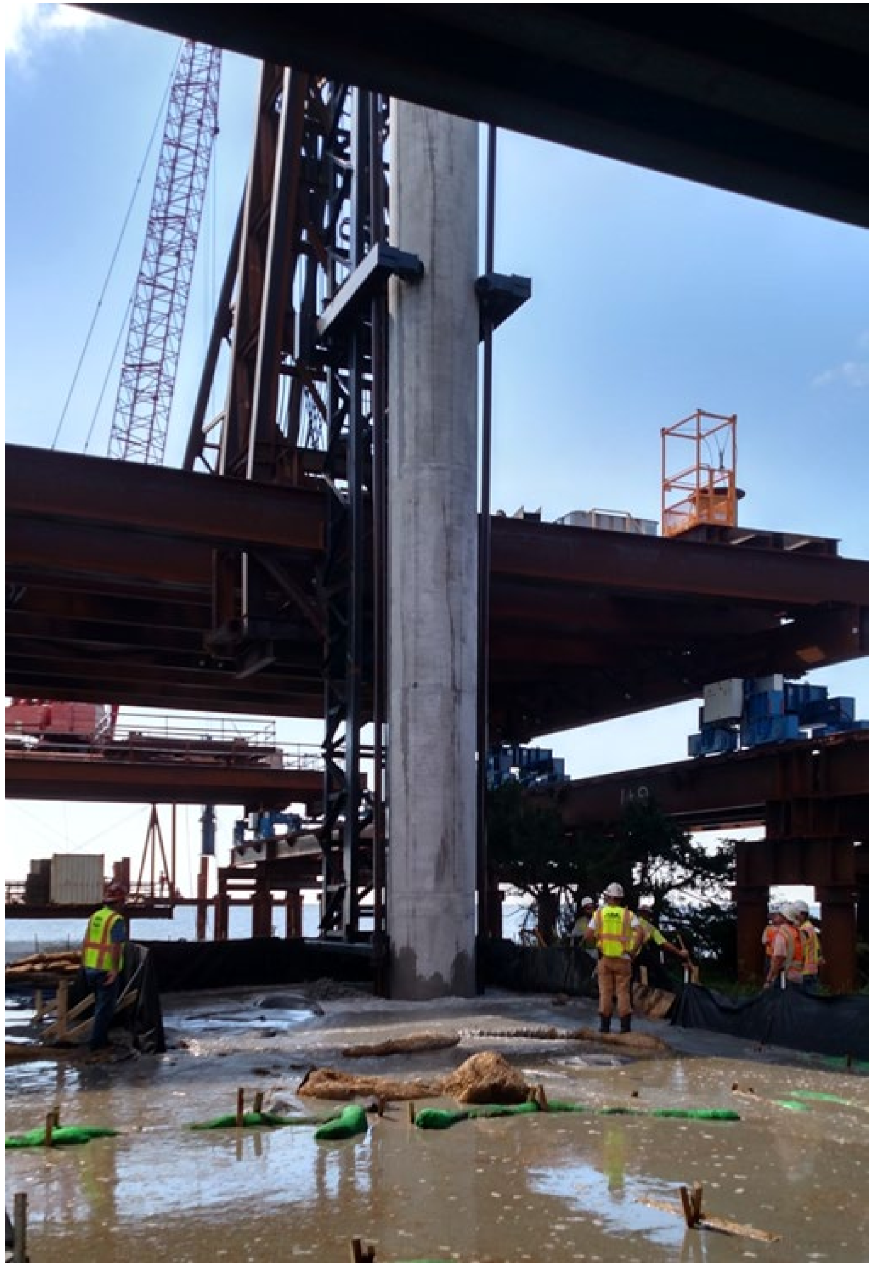
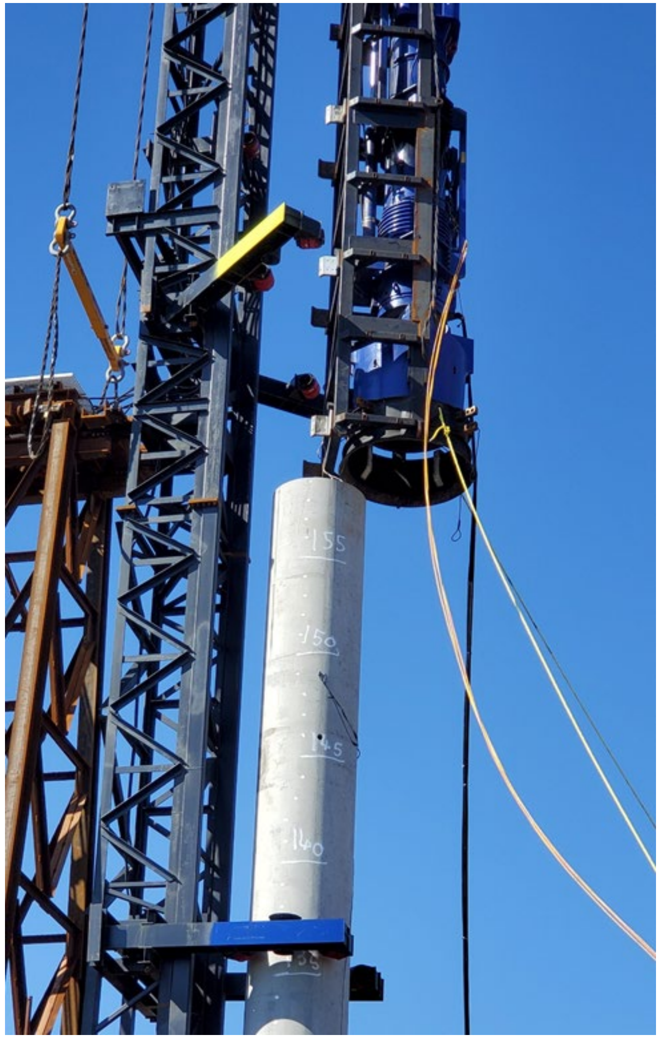
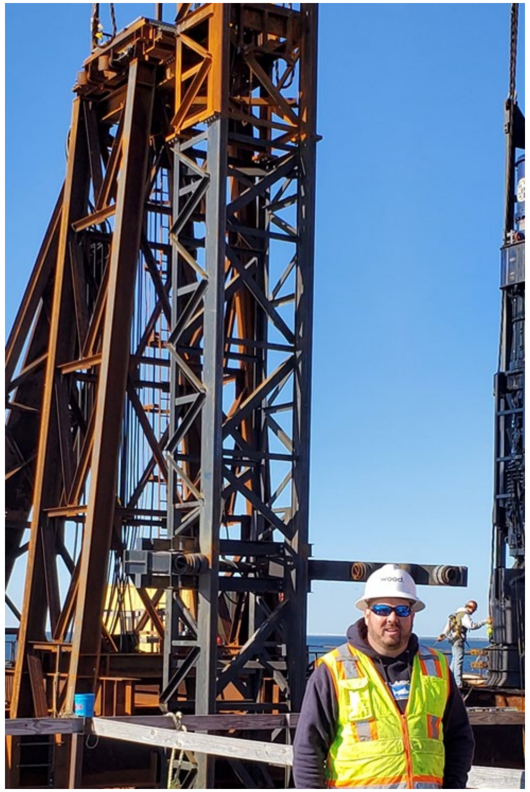


Challenge in Constructability
Driving Piles through Upper Dense Sand Layer

- *Pre-Excavation/Pre-Drilling ... Feasible, but Not Considered*
- *Jetting ... Field Trial; Did Not Work due to difficulties in managing spoils*
- *Eventually, driving thorough directly by using a heavy-duty hammer*





Pileco D180-32 Diesel Hammer;
Max. Rated Energy 443.5 kip-ft

Construction from Both Ends Simultaneously towards the Center

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Advancing Rail System

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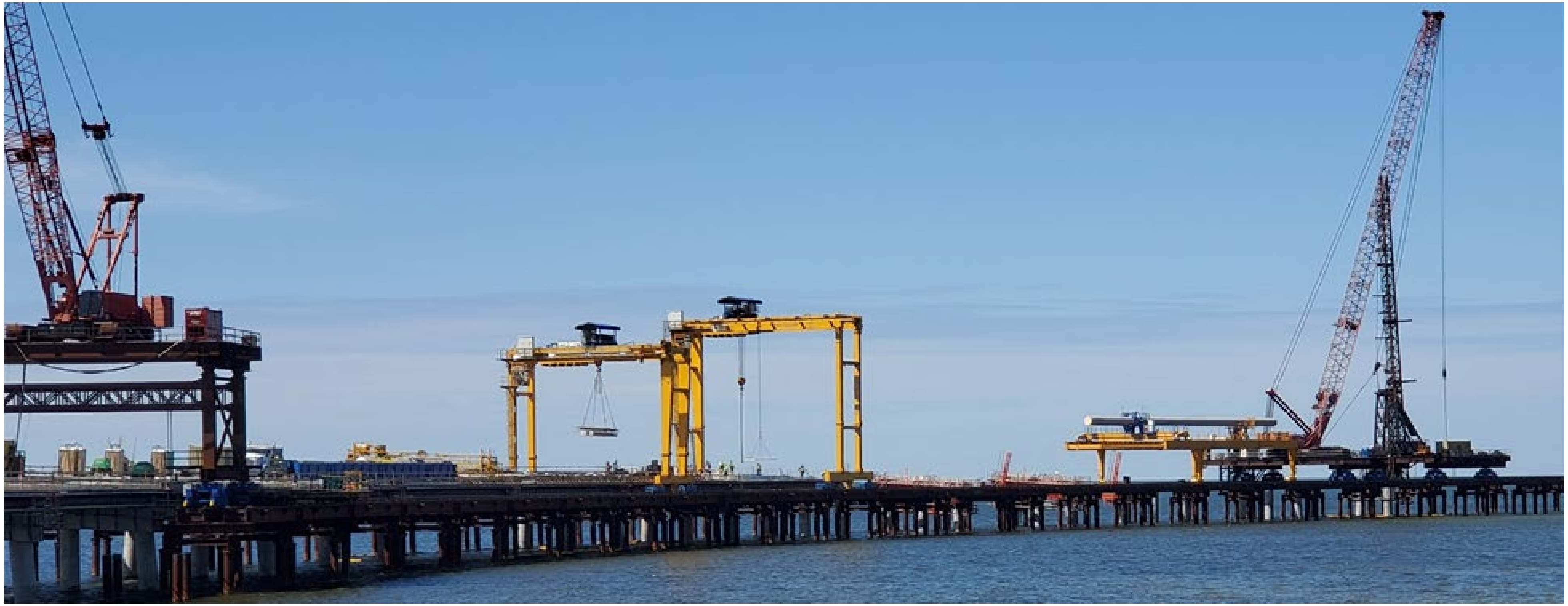

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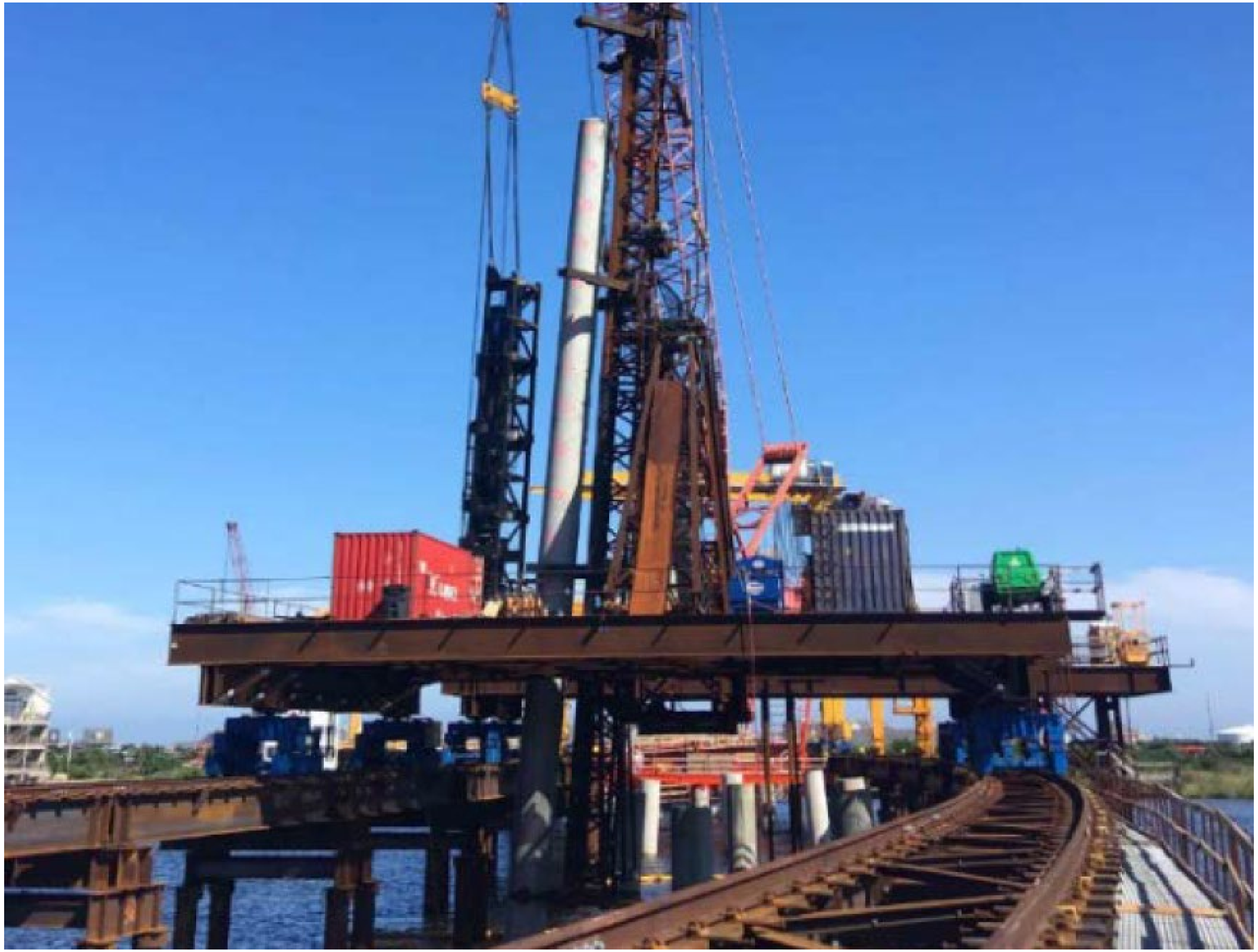


140
140

Challenge during the Construction

- Piles subject to potential damage during pile driving
    - Subject to Unsymmetric Hoop Stresses (Alignment Control)

Challenge during the Construction

- ***Piles subject to potential damage during pile driving***
  - ***Subject to Unsymmetric Hoop Stresses (Alignment Control)***
  - ***Into & Through Upper Dense Sand Layer (Driveability)***

Challenge during the Construction

- Piles subject to potential damage during pile driving
  - Subject to Unsymmetric Hoop Stresses (Alignment Control)
  - Into & Through Upper Dense Sand Layer (Driveability)
  - Passing Upper Dense Layer into underlying loose soils (Subject to Tension)

Challenge during the Construction

❖ ***Piles subject to potential damage during pile driving***

- ***Subject to Unsymmetric Hoop Stresses (Alignment Control)***
- ***Into & Through Upper Dense Sand Layer (Driveability)***
- ***Passing Upper Dense Layer into underlying loose soils (Subject to Tension)***
- ***Into Lower Dense Sand Layer to achieve the Required Pile Driving Resistance (Hard Driving Stresses)***

Challenge during the Construction

Complications "ALWAYS" Happened!

Image 4 taken at approximate elevation -18ft to -19ft.

Multiple reinforcing strands and spirals exposed.

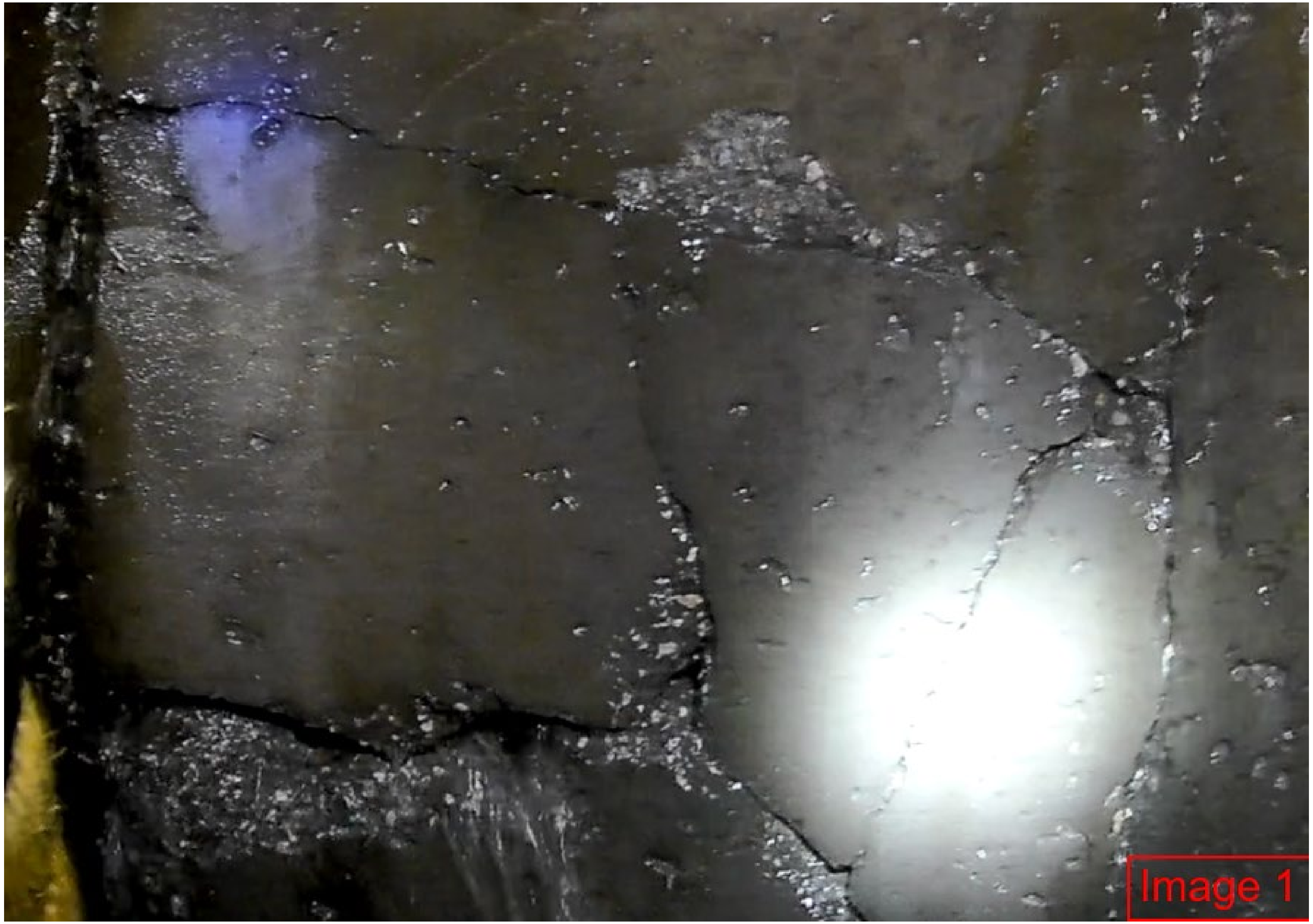
Image 1

What to do if pile is damaged?

❖ ***Evaluated the Axial Resistance and lateral Stability based on the As-Built along with the damage***

What to do if pile is damaged?

- ***Evaluated the Axial Resistance and lateral Stability based on the As-Built along with the damage***
- ***Installed a smaller diameter (48") open-ended pipe pile through inside of the 54" Conc. Cylinder Pile; followed by grouting the annulus.***

How to proactively mitigate potential pile damage due significant driving stresses?

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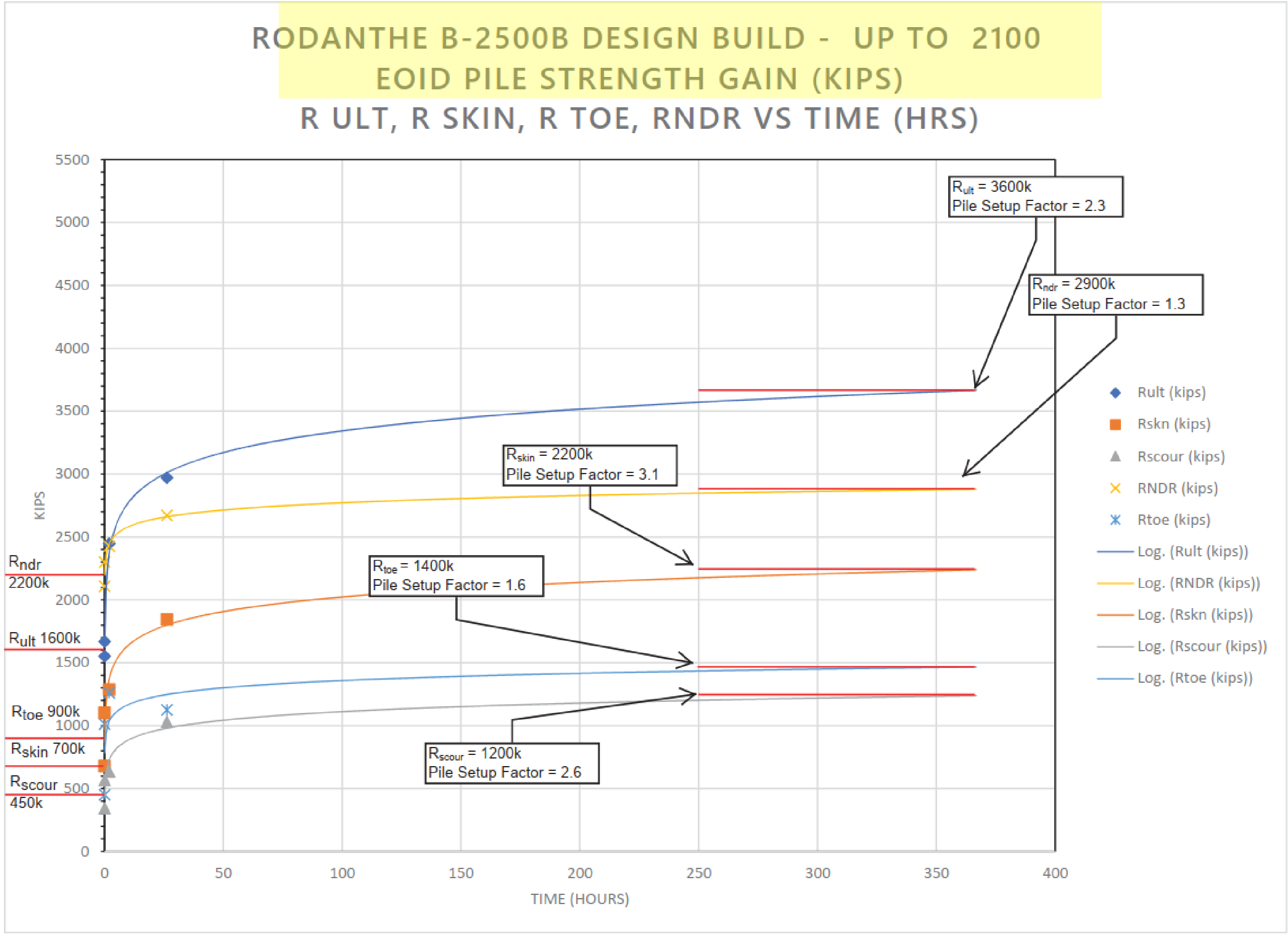
Establishing pile set up factors based on Results of Re-Strikes w/ PDA/CAPWAP

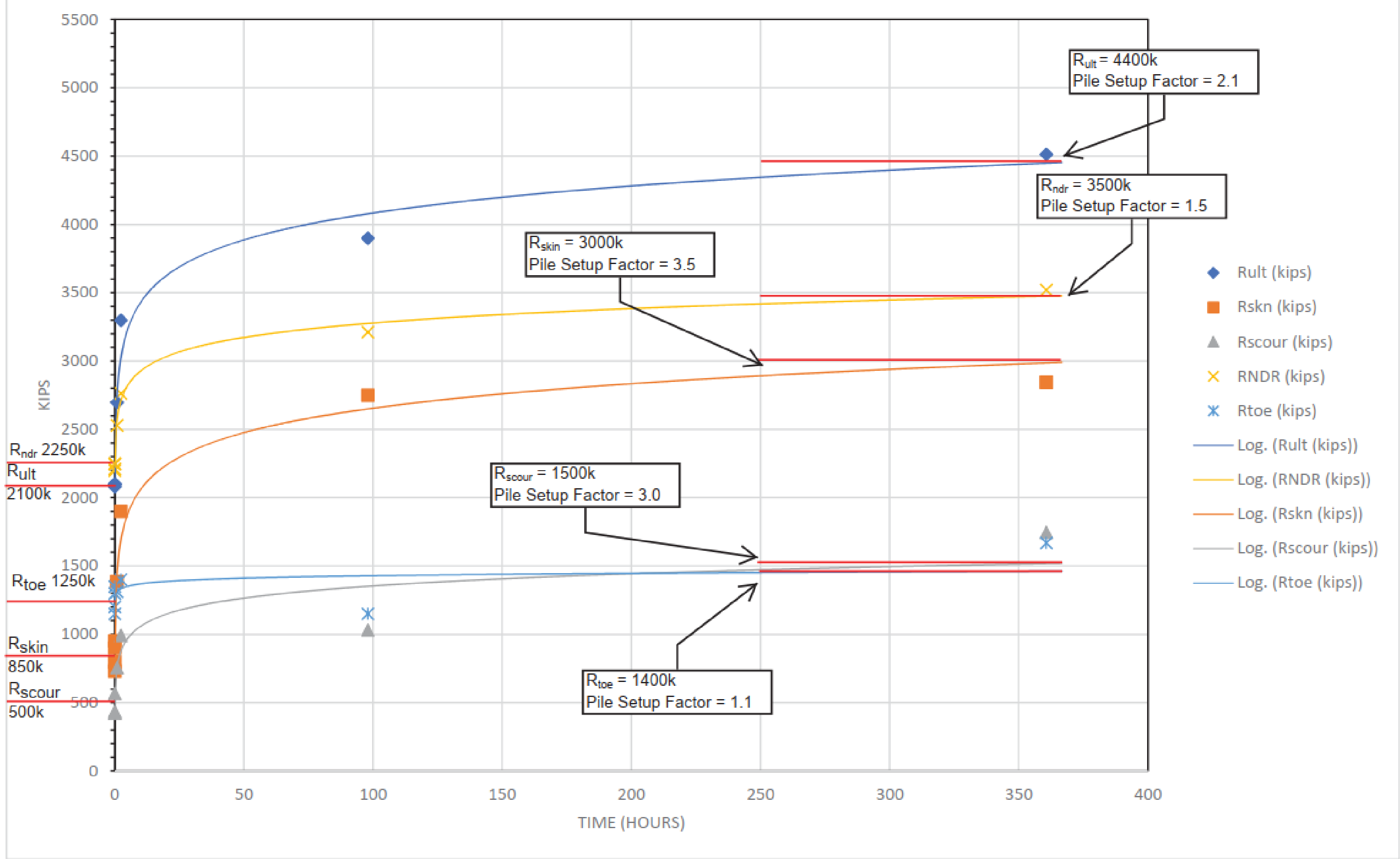
- *Requiring that pile cushion should have at least 500 blows prior to the end of drive to ensure that pile driving energy is efficiently transferred to the pile and the pile cushion not be changed within 10 feet of the anticipated tip elevation.*
- *Pile should be driven to the lower dense sand layer to achieve a substantial amount of tip resistance.*
- *Performed restrikes ranging from 1 hour to 360 hours after initial drive on several production*



RODANTHE B-2500B DESIGN BUILD - UP TO 2100
EOID PILE STRENGTH GAIN (KIPS)
R ULT, R SKIN, R TOE, RNDR VS TIME (HRS)
KIPS
TIME (HOURS)
Rult = 3600k
Pile Setup Factor = 2.3
Rndr = 2900k
Pile Setup Factor = 1.3
Rskin = 2200k
Pile Setup Factor = 3.1
Rtoe = 1400k
Pile Setup Factor = 1.6
Rscour = 1200k
Pile Setup Factor = 2.6
Rndr
2200k
Rult 1600k
Rtoe 900k
Rskin 700k
Rscour
450k
Rult (kips)
Rskn (kips)
Rscour (kips)
RNDR (kips)
Rtoe (kips)
Log. (Rult (kips))
Log. (RNDR (kips))
Log. (Rskn (kips))
Log. (Rscour (kips))
Log. (Rtoe (kips))

RODANTHE B-2500B DESIGN BUILD - 2100 TO 2250 EOID PILE STRENGTH GAIN (KIPS)

R ULT, R SKIN, R TOE, RNDR VS TIME (HRS)



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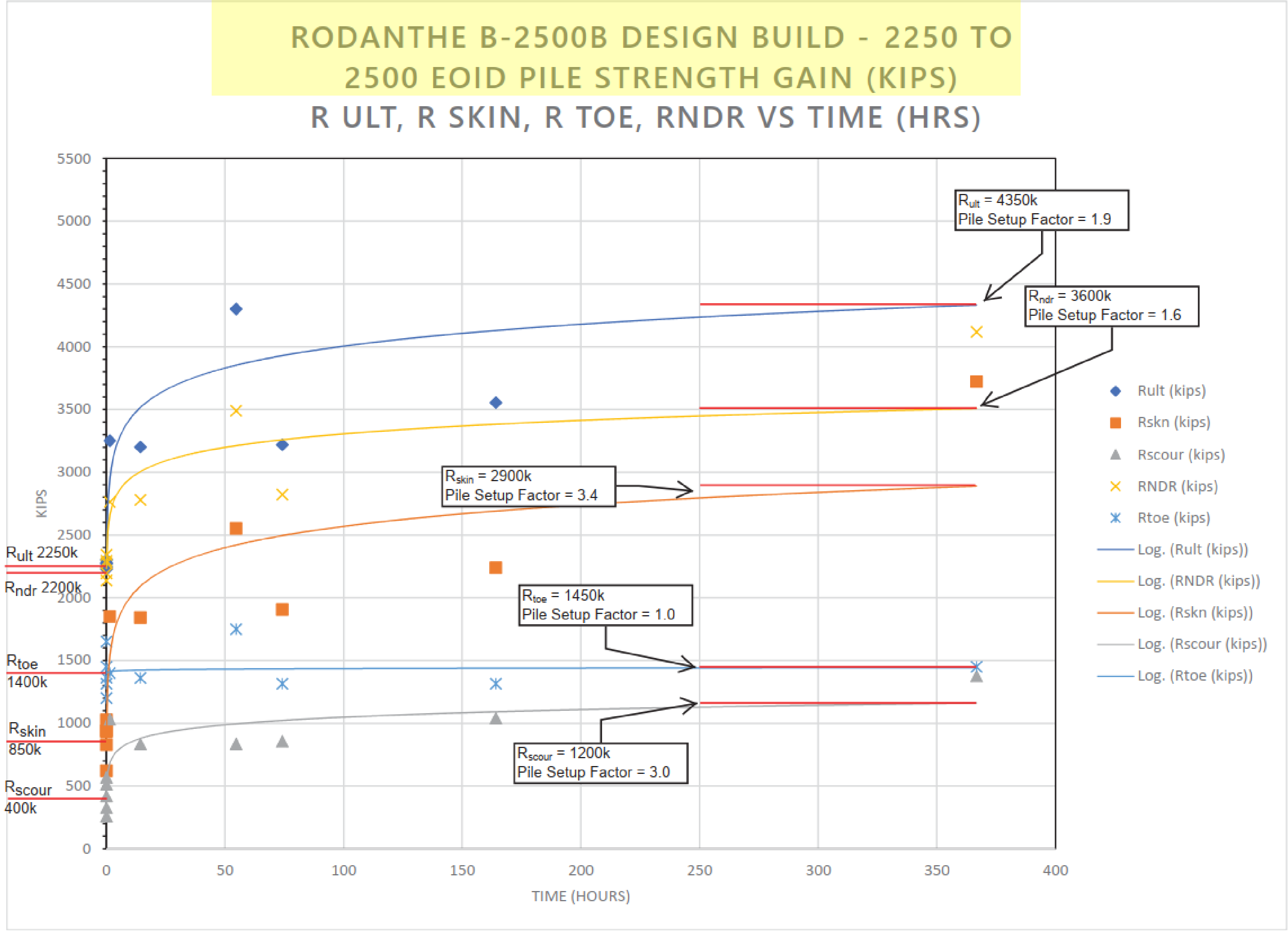

RODANTHE B-2500B DESIGN BUILD - 2250 TO 2500 EOID PILE STRENGTH GAIN (KIPS)
R ULT, R SKIN, R TOE, RNDR VS TIME (HRS)
KIPS
TIME (HOURS)
Rult 2250k
Rndr 2200k
Rtoe 1400k
Rskin 850k
Rscour 400k
Rult = 4350k
Pile Setup Factor = 1.9
Rndr = 3600k
Pile Setup Factor = 1.6
Rskin = 2900k
Pile Setup Factor = 3.4
Rtoe = 1450k
Pile Setup Factor = 1.0
Rscour = 1200k
Pile Setup Factor = 3.0
Rult (kips)
Rskn (kips)
Rscour (kips)
RNDR (kips)
Rtoe (kips)
Log. (Rult (kips))
Log. (RNDR (kips))
Log. (Rskn (kips))
Log. (Rscour (kips))
Log. (Rtoe (kips))

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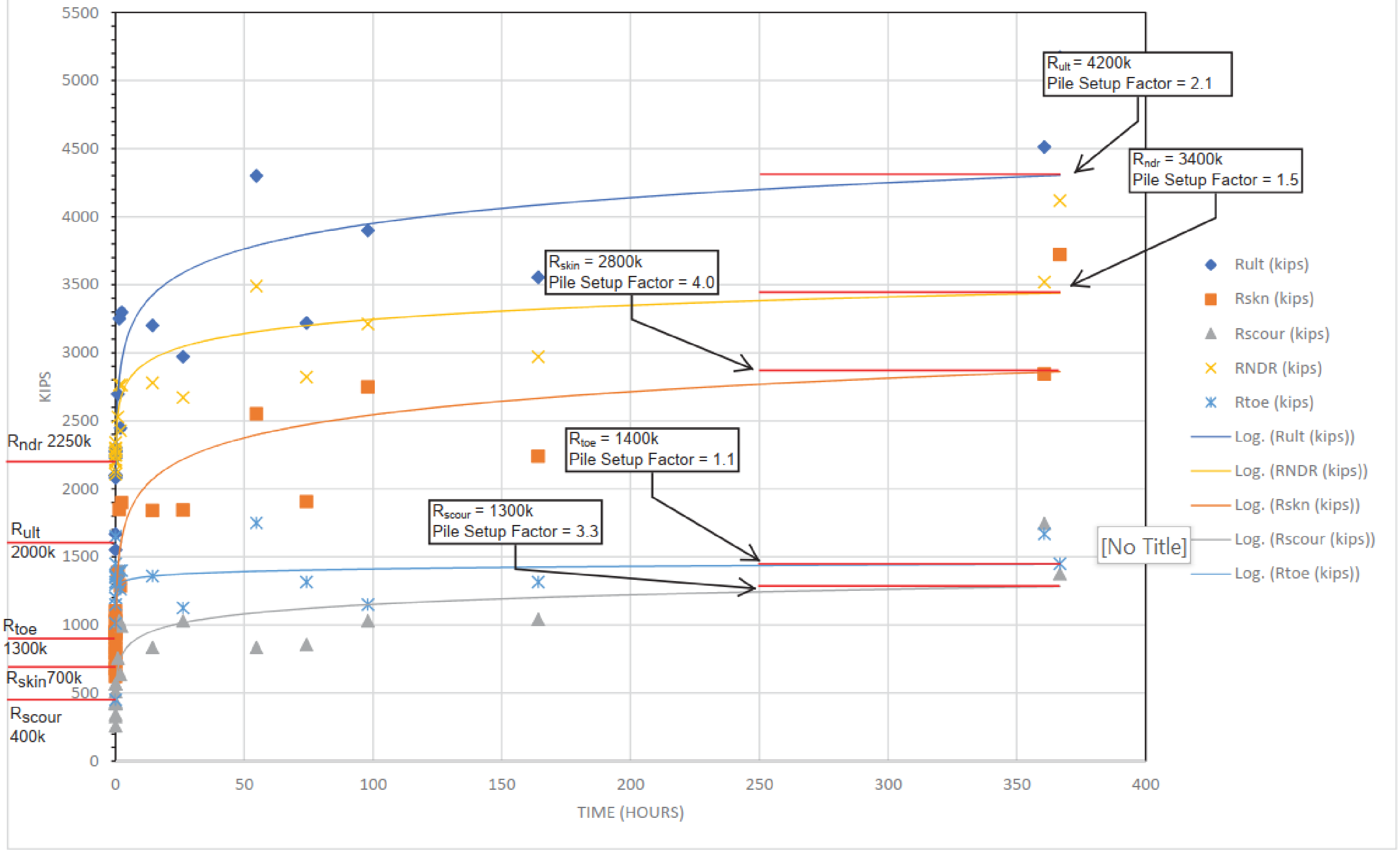
RODANTHE B-2500B DESIGN BUILD - ALL PILES PILE STRENGTH GAIN (KIPS)

R ULT, R SKIN, R TOE, RNDR VS TIME (HRS)



Establishing Pile Set Up Factors
- Recommendations -

- *A setup factor value of 2.2 is applicable to the nominal (ultimate) bearing resistance, if EOID (End of Initial Drive) pile resistance equal or less than 1700 kips.*
- *A setup factor value of 2.0 is applicable to the nominal (ultimate) bearing resistance, if EOID pile resistance is greater than 1700 kips*

Establishing Pile Set Up Factors
- Recommendations -

- ***Required Driving Resistance should consider compensation due to that Setup would occur within sections both above & below the Design Scour Elevation.***

Using a resistance factor of 0.75,

$$R_{ndr} = \frac{Factored\ Axial\ Resistance + Factored\ Pile\ Dead\ Load}{Dynamic\ Resistance\ Factor} + Unfactored\ Scour\ Resistance$$

Establishing Pile Set Up Factors
- Applications/Benefits -

❖ ***Decrease Production Pile EOID Requirement***

Establishing Pile Set Up Factors
- Applications/Benefits -

- ***Decrease Production Pile EOID Requirement***
- ***Mitigate potential of damaging piles due to final hard driving/re-strike into lower dense, end-bearing sand layer***

Establishing Pile Set Up Factors
- Applications/Benefits -

- ***Decrease Production Pile EOID Requirement***
- ***Mitigate potential of damaging piles due to final hard driving/re-strike into lower dense, end-bearing sand layer***
- ***Schedule Saving***

Lessons Learned

- ***DESIGN***
  - ***Engineering Tools (Practically Sufficient; FB-Multipier, LPILE, APILE, ASSHTO LRFD/FHWA GECs, etc.)***
  - ***Sufficient Subsurface Data & Reliable Design Soil Parameters (… We Wish!)***

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Lessons Learned

- ***DESIGN***
  - *Engineering Tools (Practically Sufficient; FB-Multipier, LPILE, APILE, ASSHTO LRFD/FHWA GECs, etc.)*
  - *Sufficient Subsurface Data & Reliable Design Soil Parameters (… We Wish!)*
- ***CONSTRUCTION***
  - *Goal is CLEAR*
  - *Challenge is HOW TO GET THERE (Effectively & Efficiently)*

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Lessons Learned

- ***DESIGN***
  - *Engineering Tools (Practically Sufficient; FB-Multipier, LPILE, APILE, ASSHTO LRFD/FHWA GECs, etc.)*
  - *Sufficient Subsurface Data & Reliable Design Soil Parameters (… We Wish)*
- ***CONSTRUCTION***
  - *Goal is CLEAR*
  - *Challenge is HOW TO GET THERE (Effectively & Efficiently)*
- ***COLLABORATION***
  - *Among Geotechnical, Structural, hydraulic Engineers, Contractors (General & Specialty), PDA Testing, and ….. DOTs*

Lessons "To-Learn"

We Understand Better/Could Handle Better & "Worry/Risk Less" in terms of STRESS/MOMENT than DEFORMATION; because .....

- ***STRESS/MOMENT; Based on Strength Limit Design (Inherent Factor of Safety)***
- ***DEFORMATION (Settlements/Deflections/Movements); Based on Service Limit Analysis (Unfactored)***
- ***Knowledge of fundamental Stress-Strain relationships and soil-structural interactions.***
- .....

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Why do we worry what we could not see less than what we could see?

Thank you

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