Pile Foundations in Intermediate Geomaterials

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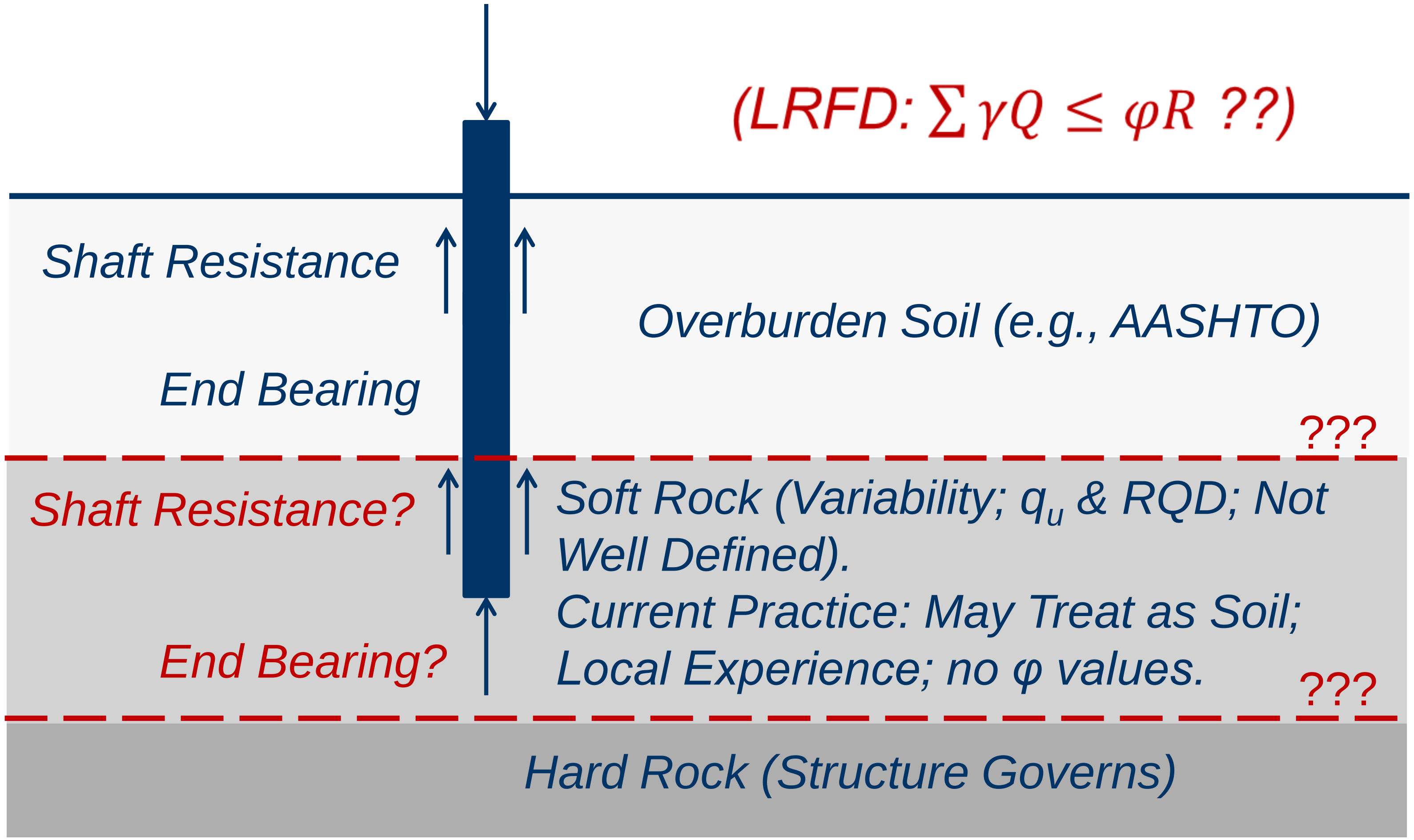
Presentation Outline

- Challenges
- What is IGM or Soft Rock?
- Historical Pile Load Test Data
- Field Pile Load Tests
- Geomaterials Classification for Driven Piles
- Proposed Static Analysis Methods
- Proposed Wave Equation Analysis Procedures
- Calibrated LRFD Resistance Factors
- Implementation

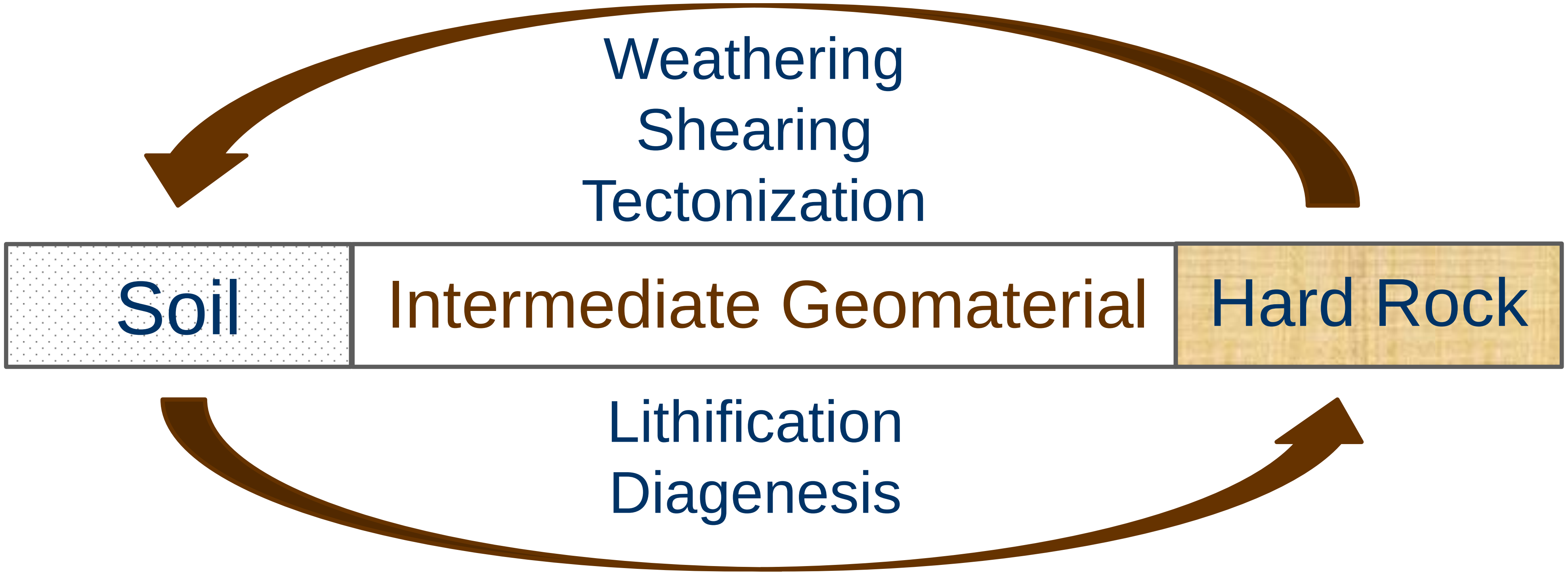
Challenges

Design Stage: Total Resistance?

Construction Stage: WEAP; PDA/CAPWAP; Restrike



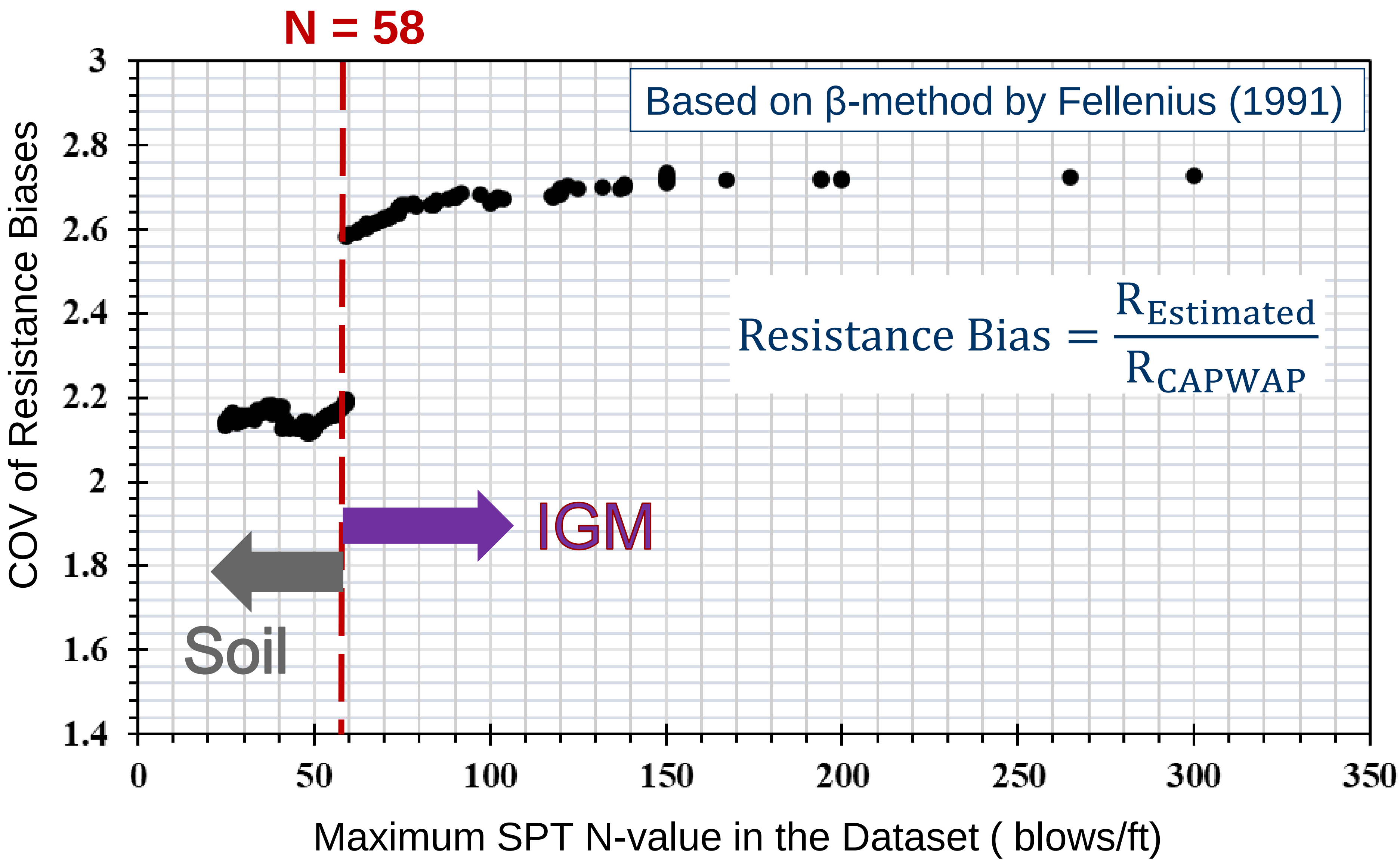
What is Intermediate Geomaterial or Soft Rock?



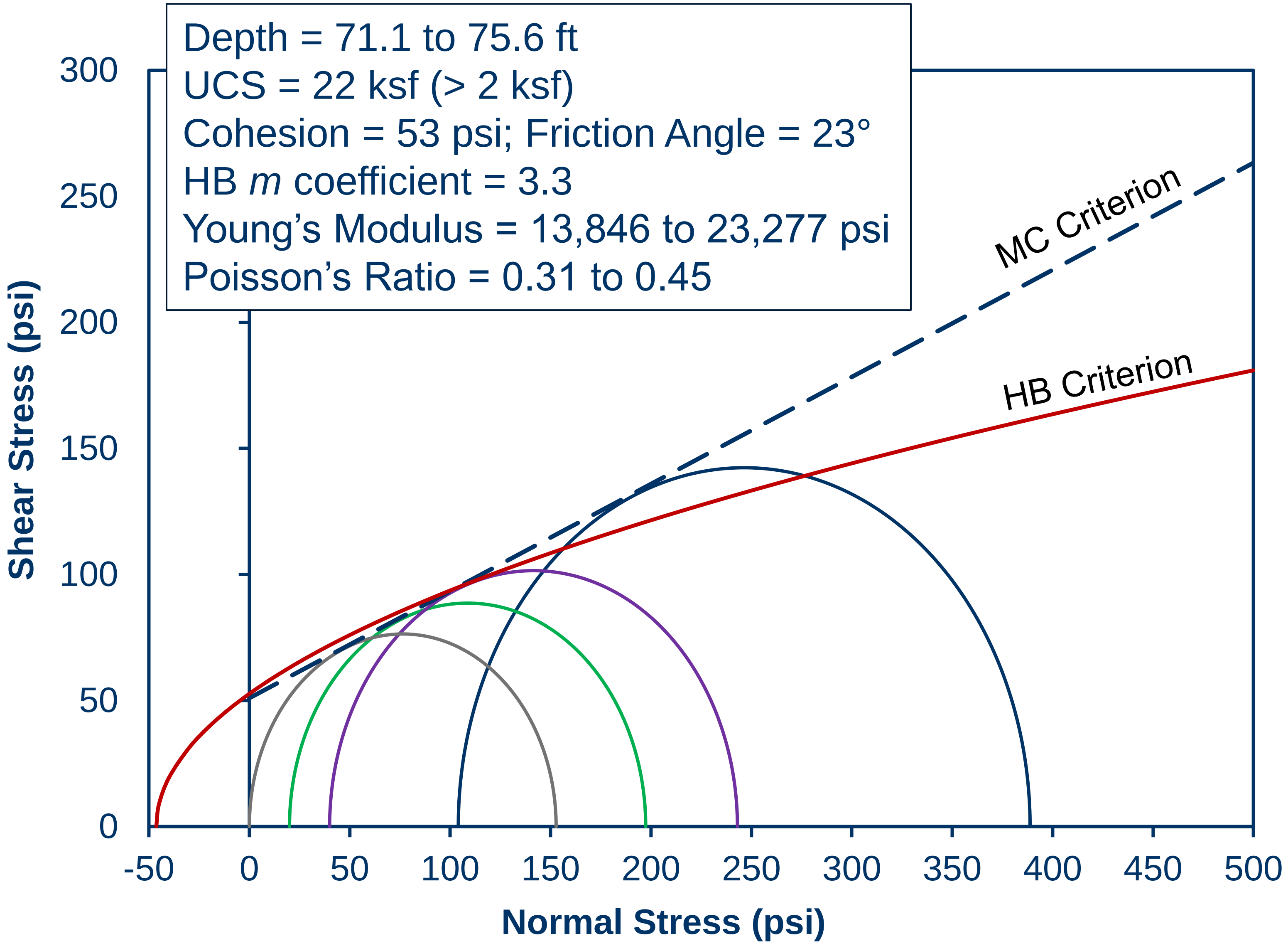
Coarse-grained Soil-based IGM
(SH-28 Lemhi River Bridge Project, Idaho)

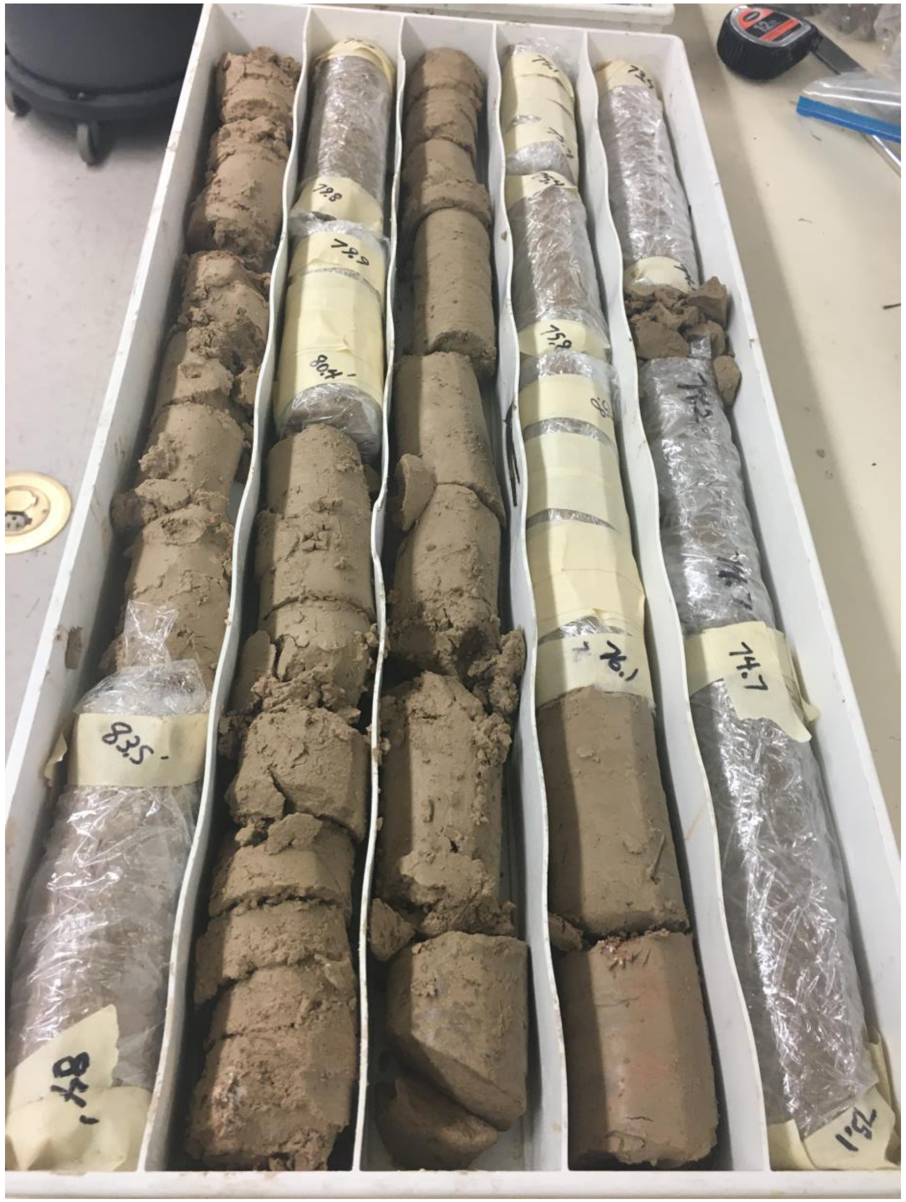
Core samples indicate CG-IGM starting from 12.5 ft and terminated at 50 ft, overlaying the bedrock

Classification of Coarse-grained Soil IGM

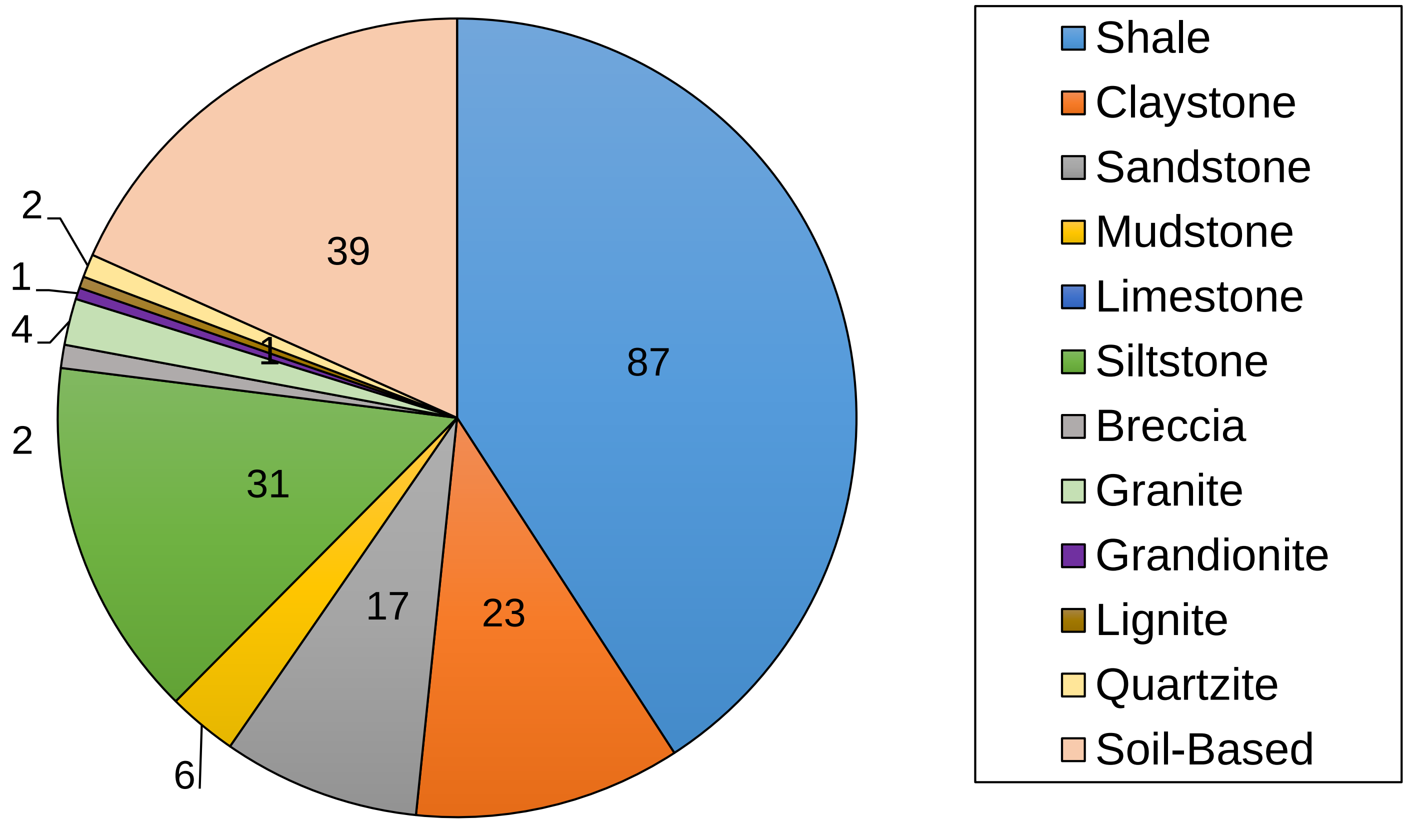


Soft Siltstone (Lodgepole Creek Bridge Project, WY)

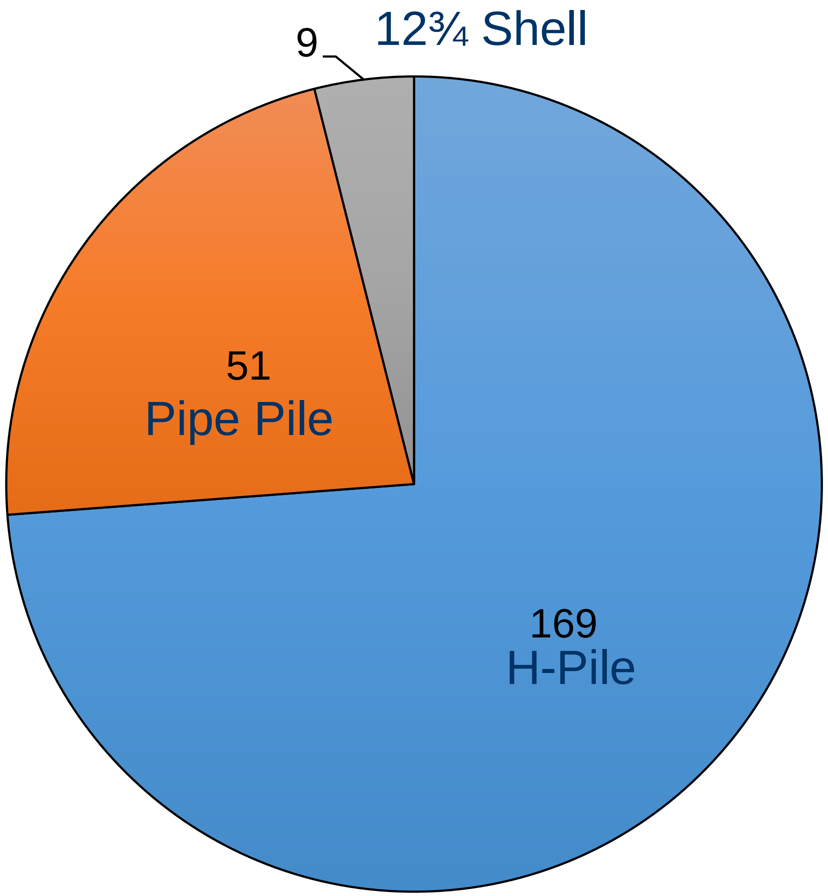




Summary of Pile Load Test Data

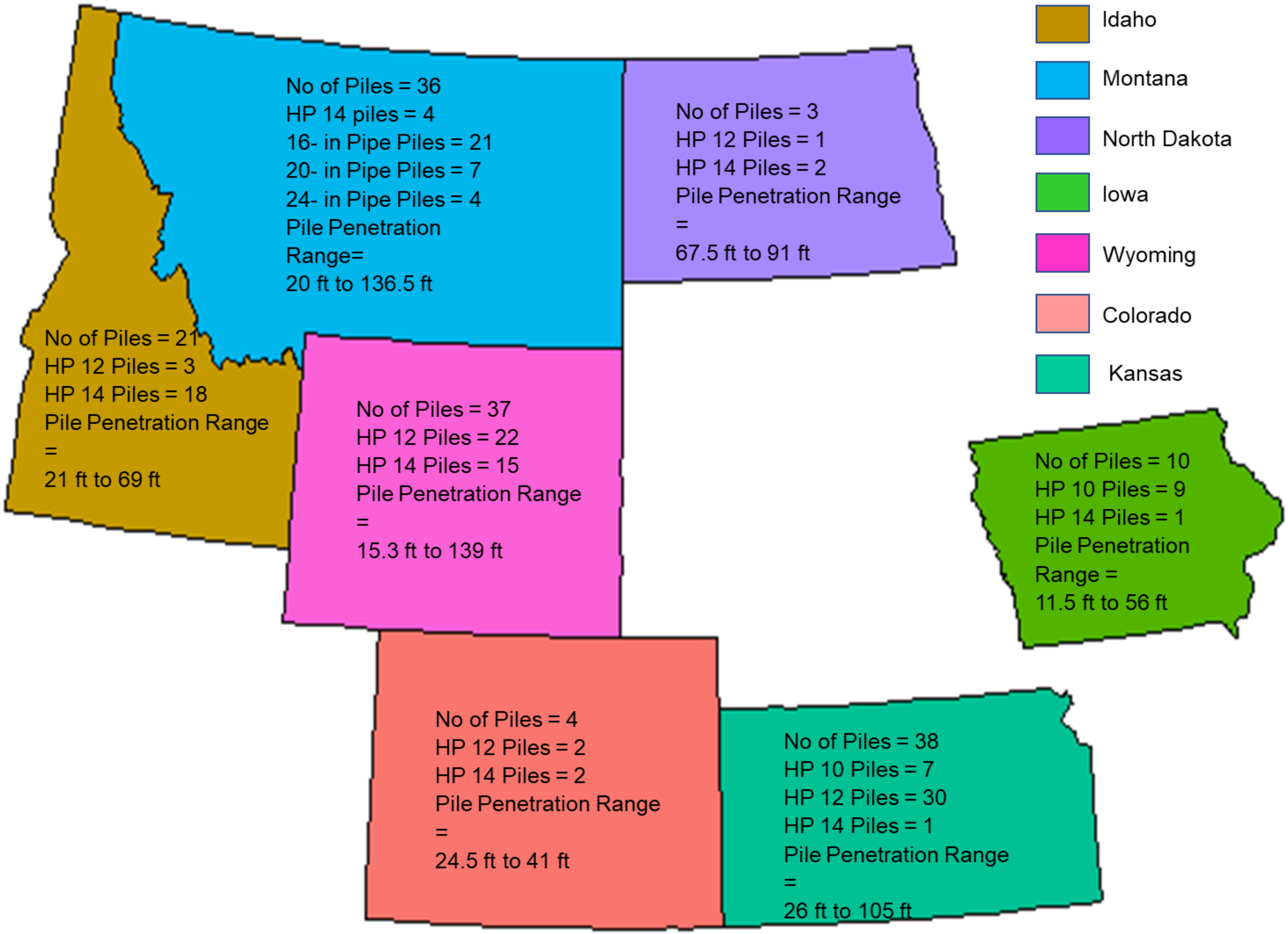


213 Usable Test Piles into Known IGMs

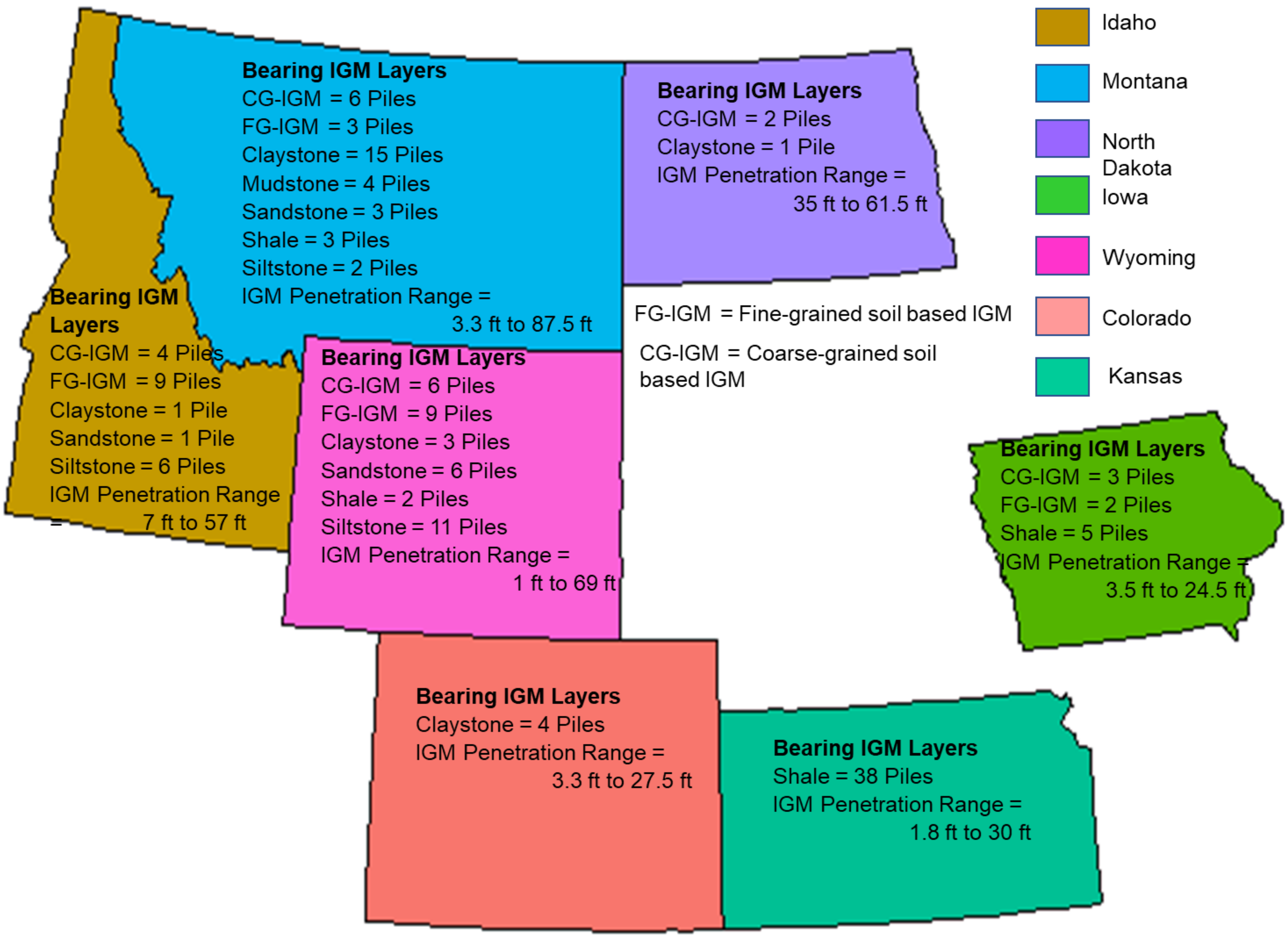


229 Usable Test Pile Types

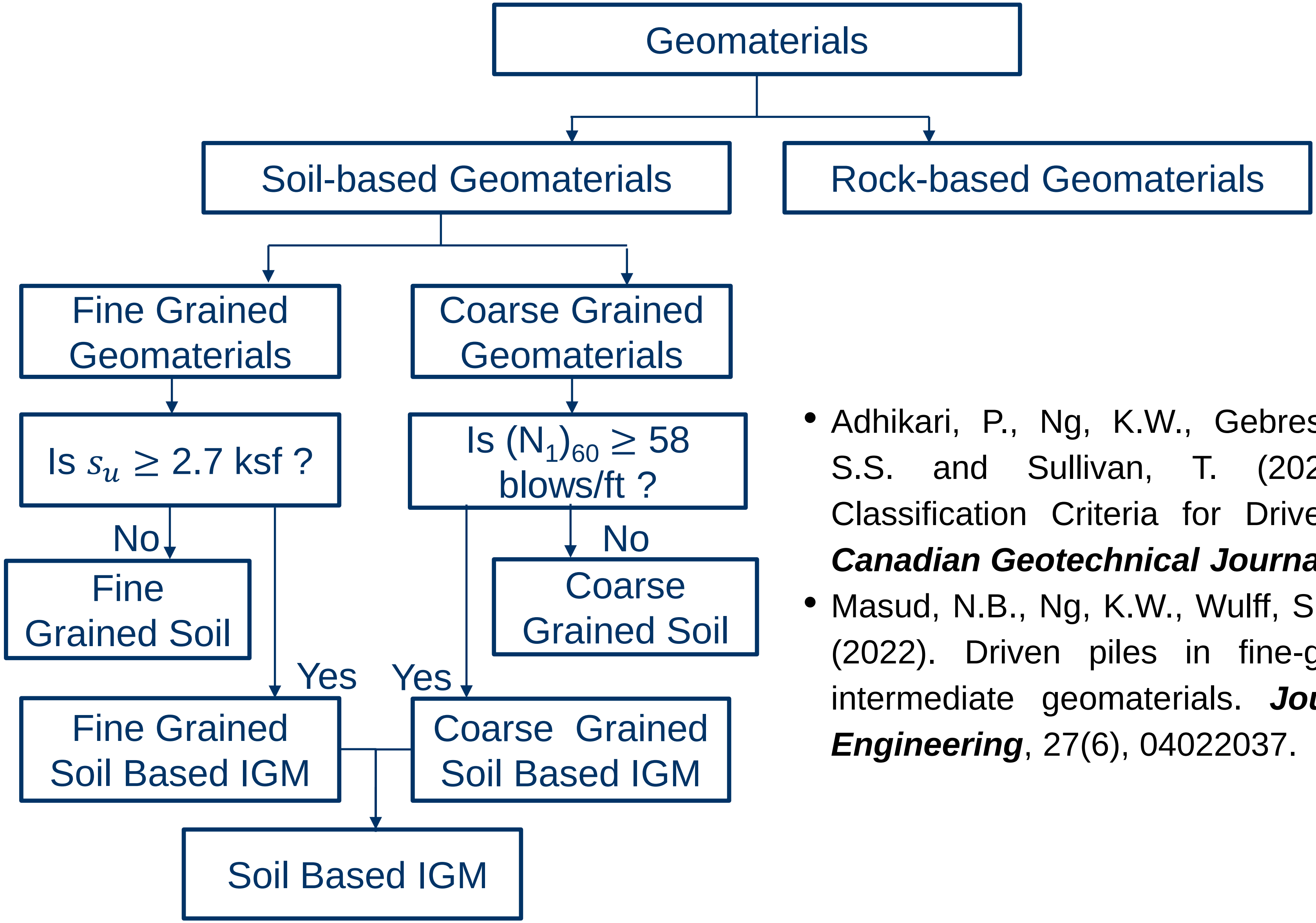
Pile Load Test Data (Pile)



Pile Load Test Data (IGMs)

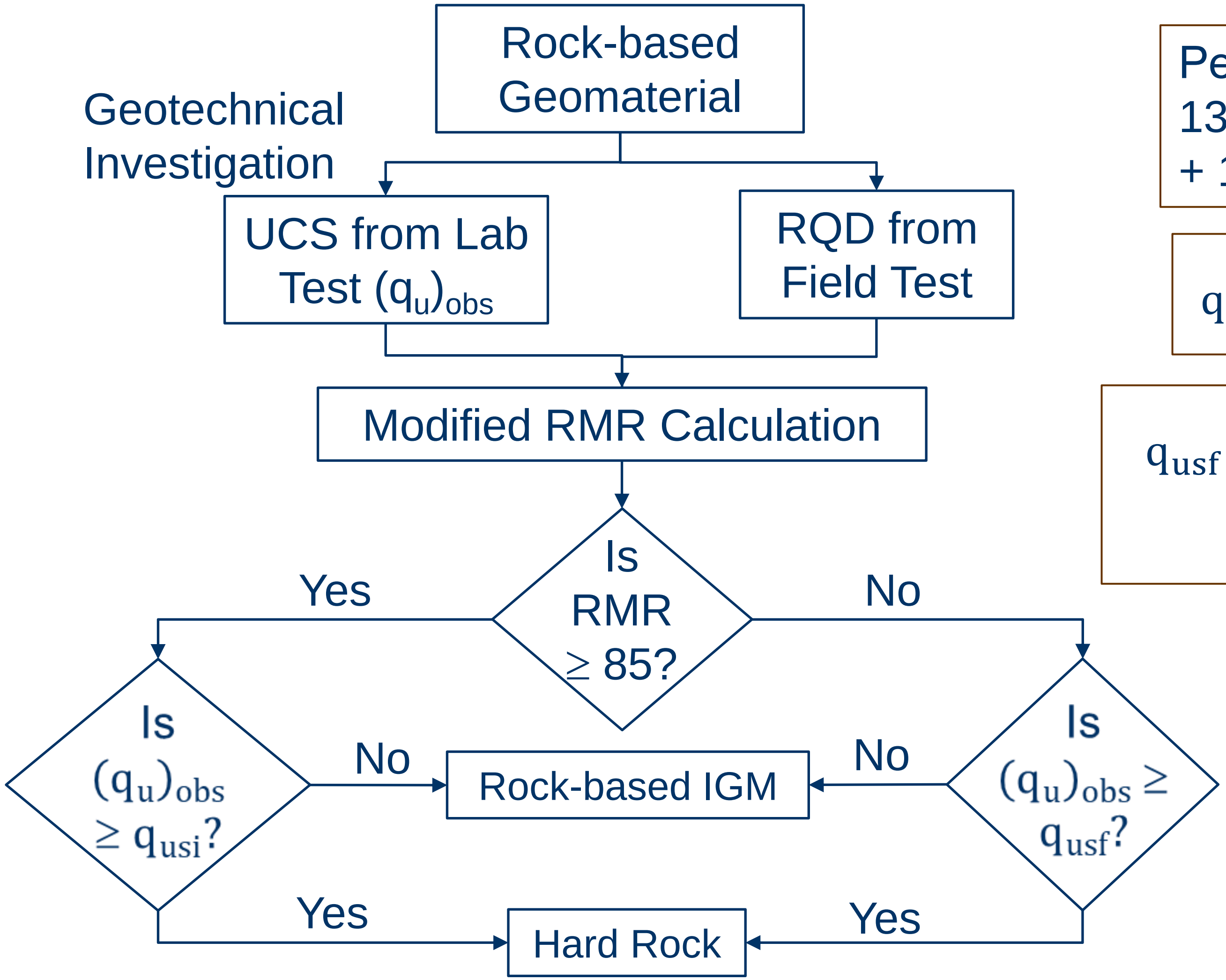


Classification Chart for Soil-based Geomaterials



- Adhikari, P., Ng, K.W., Gebreslasie, Z.Y., Wulff, S.S. and Sullivan, T. (2020). "Geomaterial Classification Criteria for Driven Piles in IGM." ***Canadian Geotechnical Journal***, 57(4), 616-621.
- Masud, N.B., Ng, K.W., Wulff, S.S., & Johnson, T., (2022). Driven piles in fine-grained soil-based intermediate geomaterials. ***Journal for Bridge Engineering***, 27(6), 04022037.

Classification Chart for Rock-based Geomaterials



Percent Toe Resistance ≈ 13.61–0.004(Embedded Pile Length)^2 + 12.8 ln[$(N_1)'_{60}$]

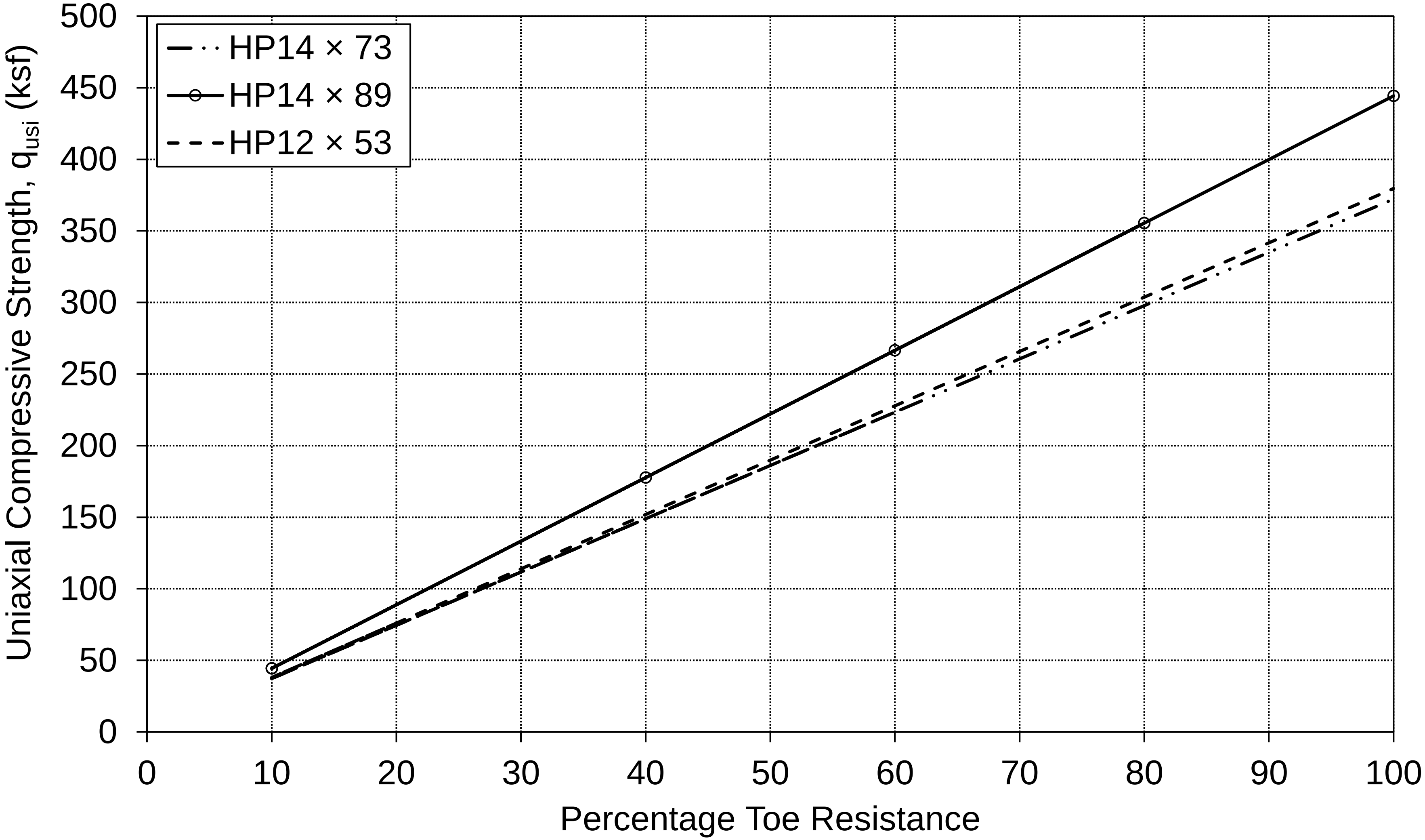
$$q_{usi} = \frac{\text{Percent Toe Resistance} \times 0.6P_n}{2.5 \times 0.5 \times \text{Box Toe Area}}$$

$$q_{usf} = \frac{\text{Percent Toe Resistance} \times 0.6P_n}{\left[\sqrt{s} + \sqrt{(m\sqrt{s} + s)}\right] \times 0.5 \times \text{Box Toe Area}}$$

$(N_1)'_{60}$ = Weighted Average $(N_1)_{60}$ of Overburden Soil

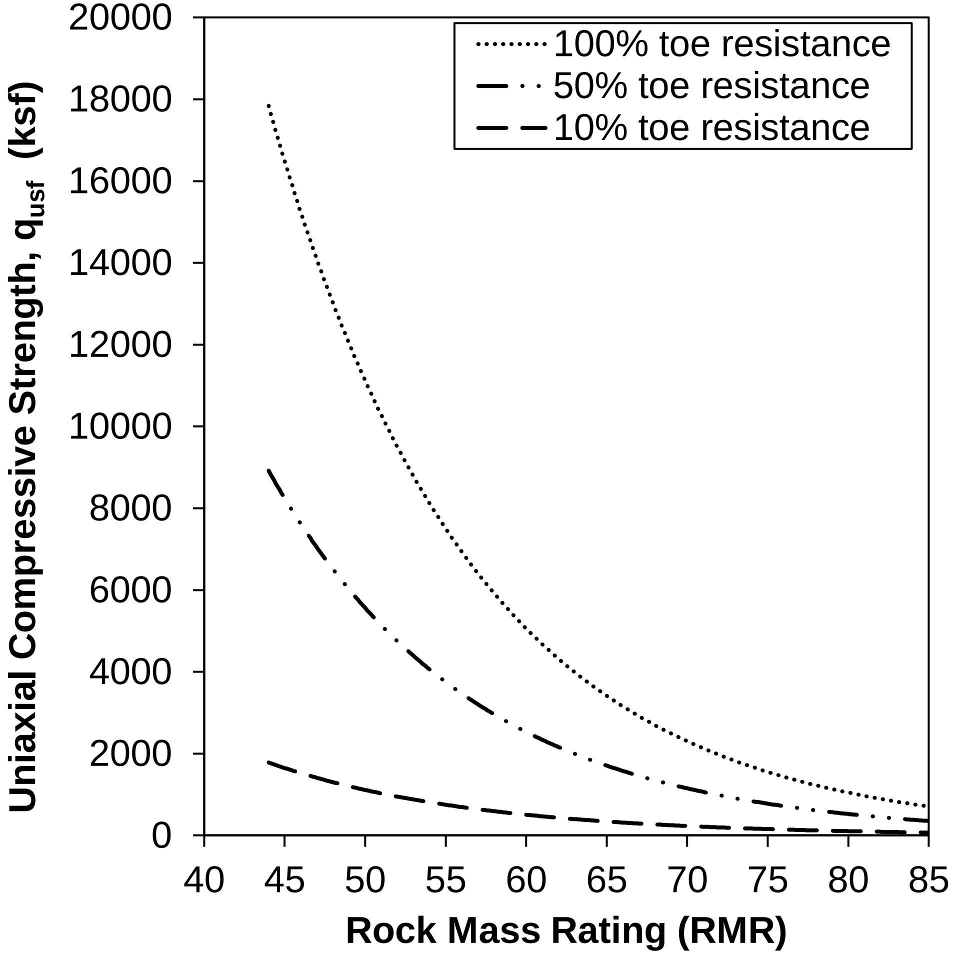
Adhikari, P., Ng, K.W., Gebreslasie, Z.Y., Wulff, S.S. and Sullivan, T. (2020). “Geomaterial Classification Criteria for Driven Piles in IGM.” ***Canadian Geotechnical Journal***, 57(4), 616-621.

Determination of q_{usi}

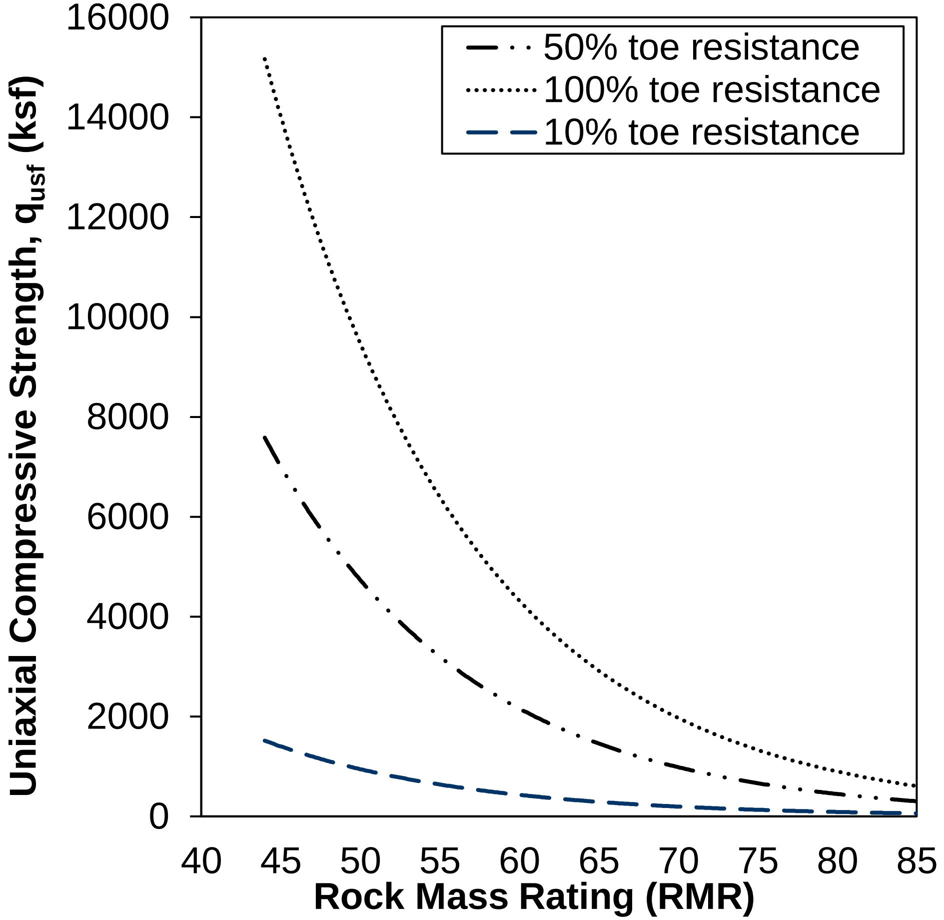


Ng, K.W., Adhikari, P., and Gebreslasie, Z.Y. (2019). Development of Load and Resistance Factor Design Procedures for Driven Piles on Soft Rocks in Wyoming. ***Final Report WY1902F***, Wyoming Department of Transportation, Cheyenne, WY.

Determination of q_{usf} (G50 HP14 x 73 Steel Pile)



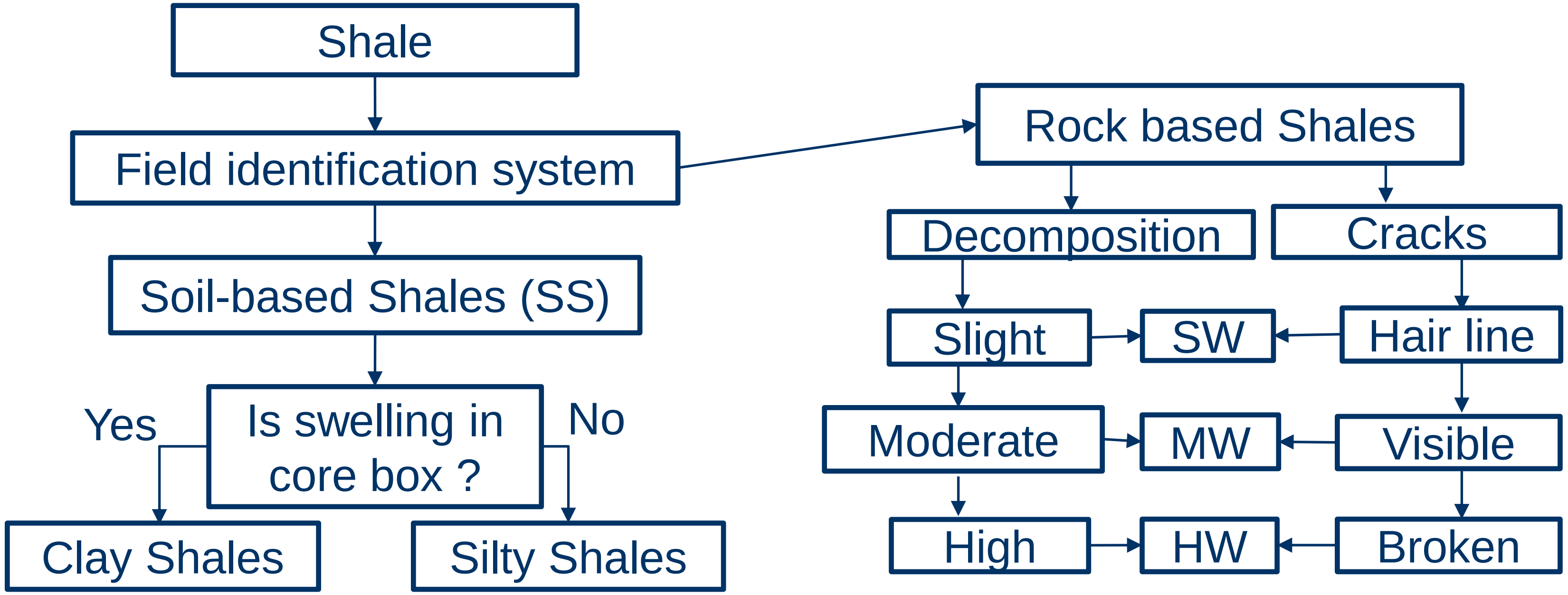
Argillaceous Rocks



Arenaceous Rocks

Ng, K.W., Adhikari, P., and Gebreslasie, Z.Y. (2019). Development of Load and Resistance Factor Design Procedures for Driven Piles on Soft Rocks in Wyoming. ***Final Report WY1902F***, Wyoming Department of Transportation, Cheyenne, WY.

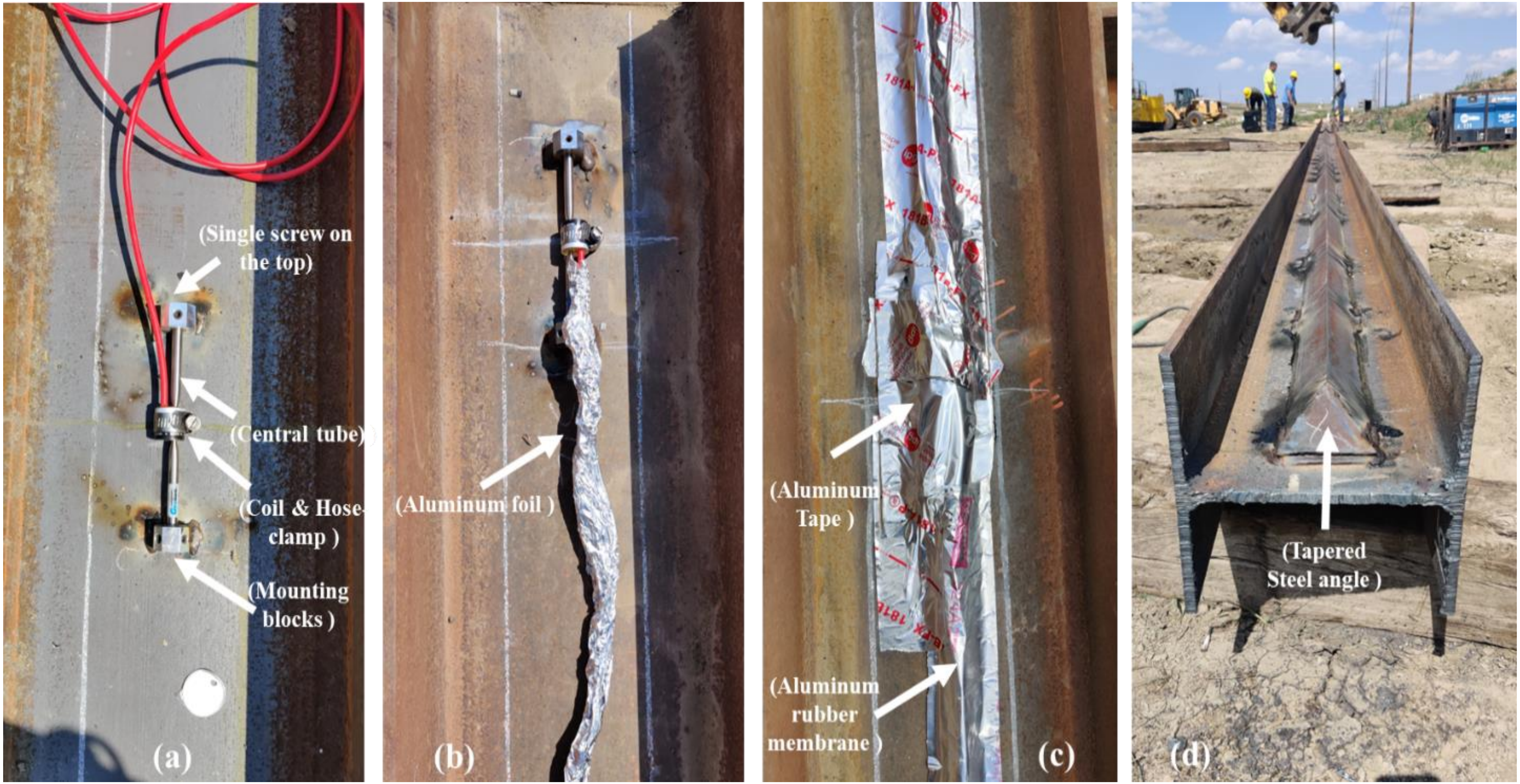
Classification Chart for Shales



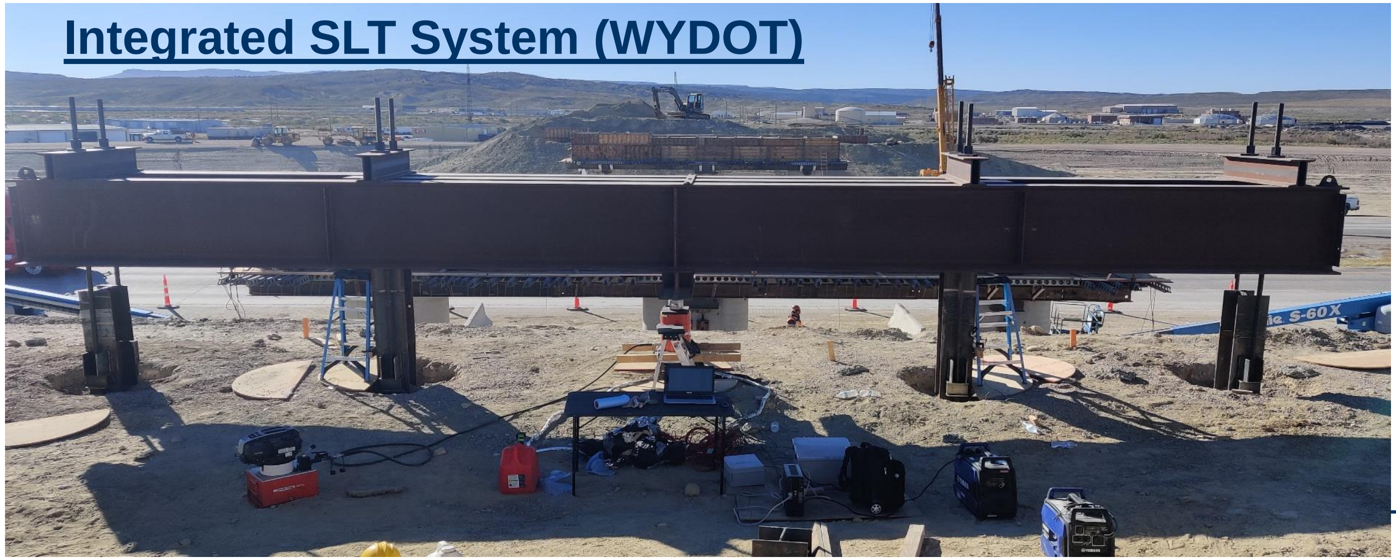
Shale type	Qualitative description	n	q_u (MPa)	E (MPa)	γ (kN/m³)	RQD (%)	q_s (MPa)
Soil-Based Shale (SS)	Clayey shale, silty shale, soft to hard	80	0.61±0.58	42±66	17.4±1.6	77±22	0.079±0.031
Highly Weathered Shale (HW)	Soft, highly weathered	42	0.44±0.37	24±30	16.2±1.3	70±21	0.028±0.013
Moderately Hard & Weathered Shale (MW)	Moderately hard, weathered, and moderately weathered	43	1.18±1.77	84±135	17.3±2.1	81±8	0.077±0.016
Hard & Slightly Weathered Shale (SW)	Hard, slightly weathered, and fresh	56	3.52±3.16	287±340	19.3±1.9	86±11	0.14±0.019

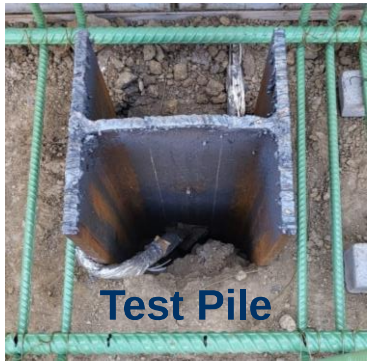
Islam, M.S., Ng, K.W., and Wulff, S.S. (2022). “Prediction of driven piles in shales considering weathering and time effects.” ***Canadian Geotechnical Journal***, 59(11), 1851-1871.

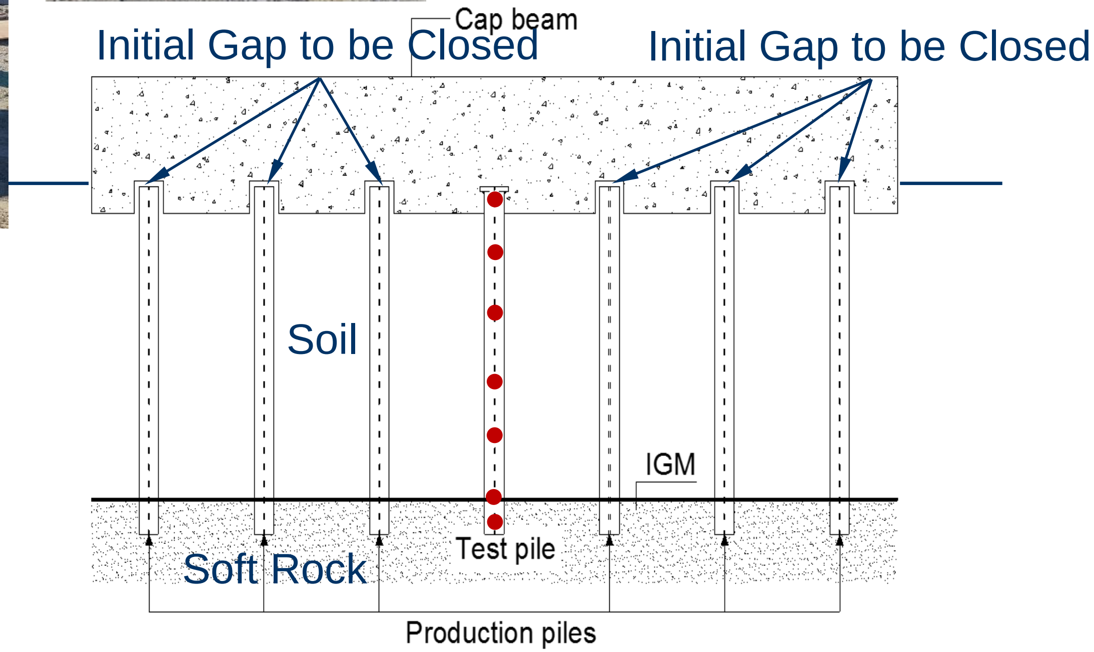
Test Pile Instrumentation and Protection



Static and Dynamic Pile Load Tests





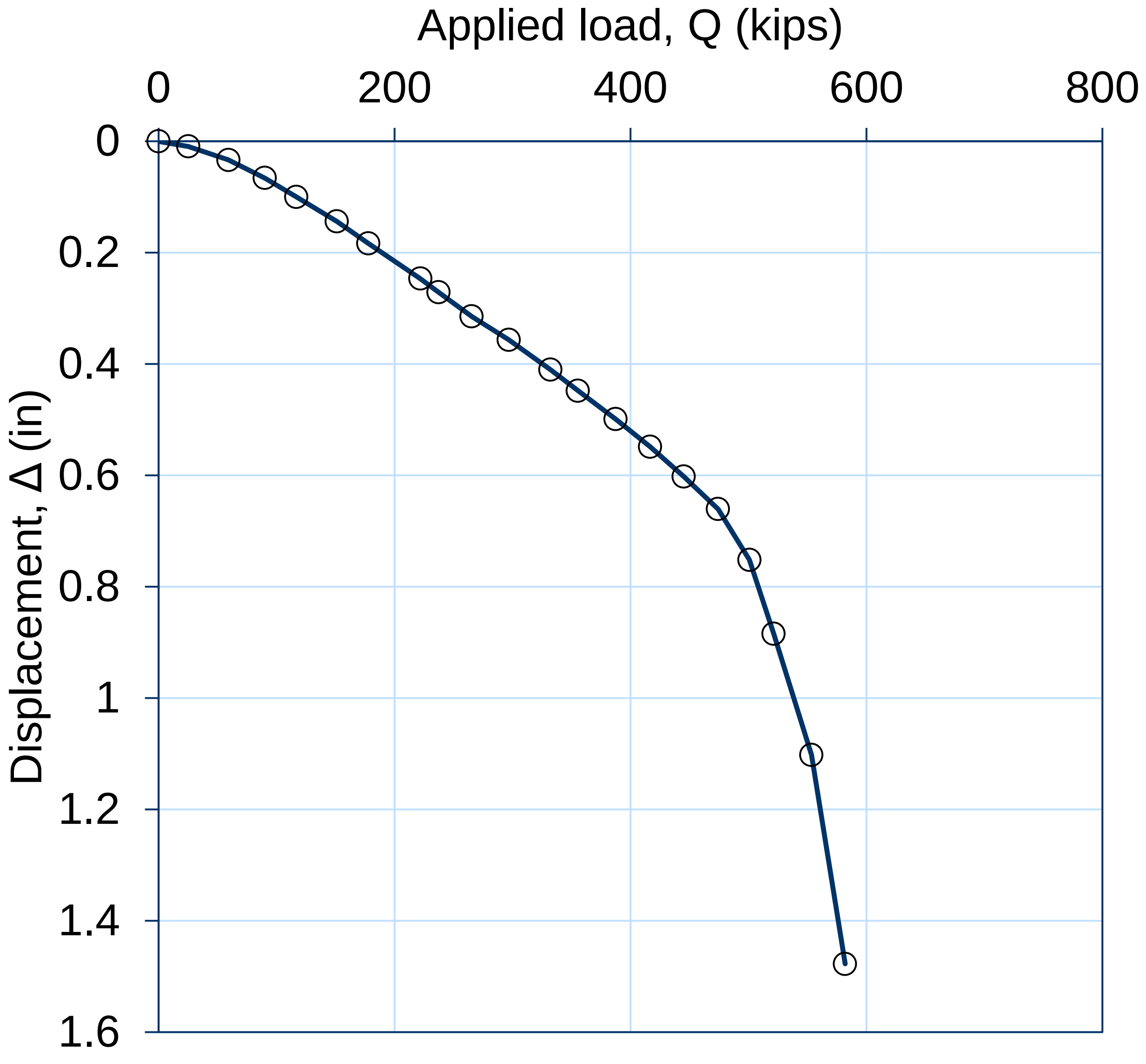


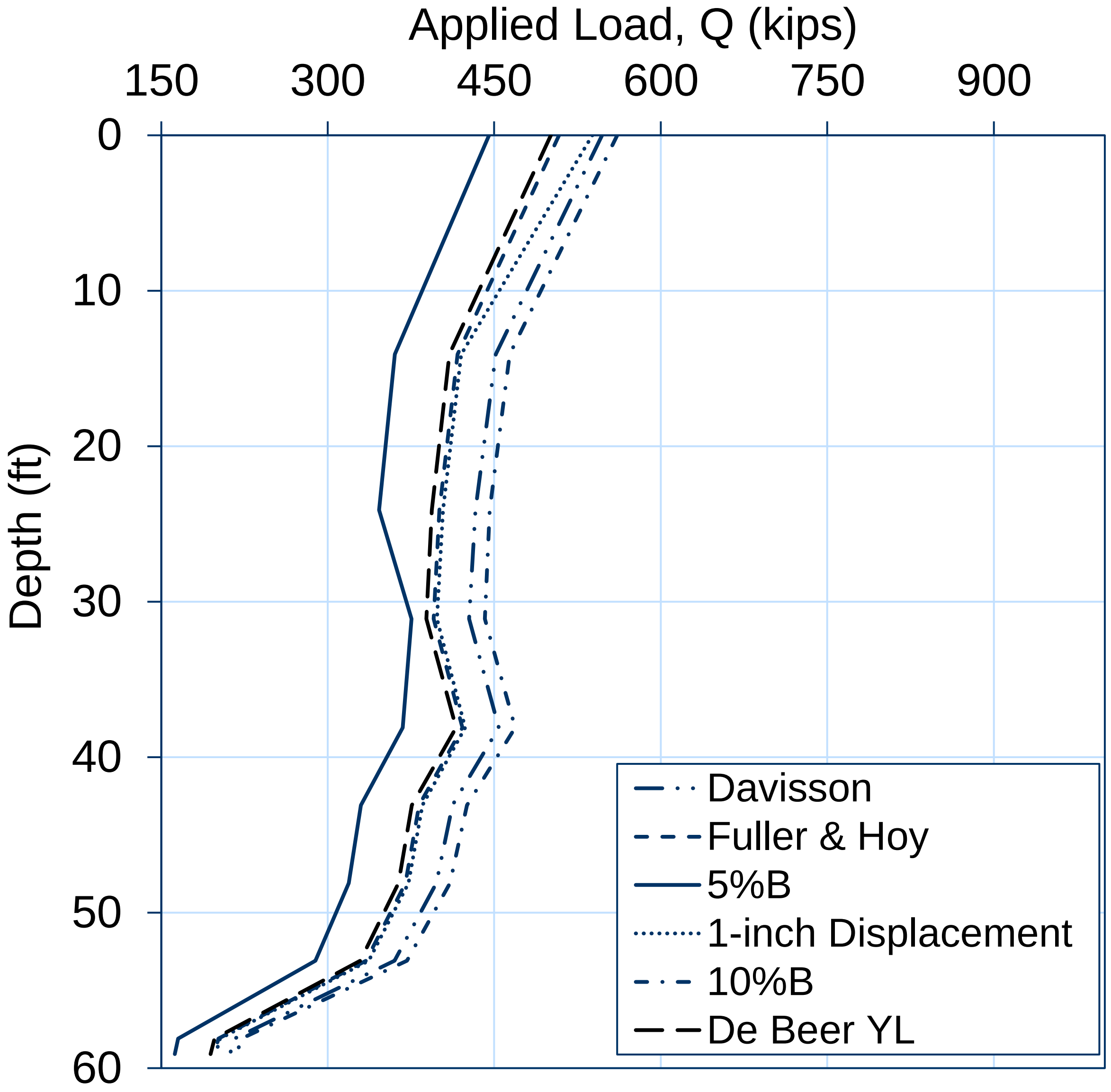
Innovative SLT System (CDOT)

Masud, N., Ng, K.W., Oluwatuyi, O., Islam, S., Kalauni, H.K., and Wulff, S.S. (2023). "Evaluation of Static Load Test Systems for Driven Piles in Intermediate GeoMaterials." ***Transportation Research Record,*** 2677(10), 741-756.

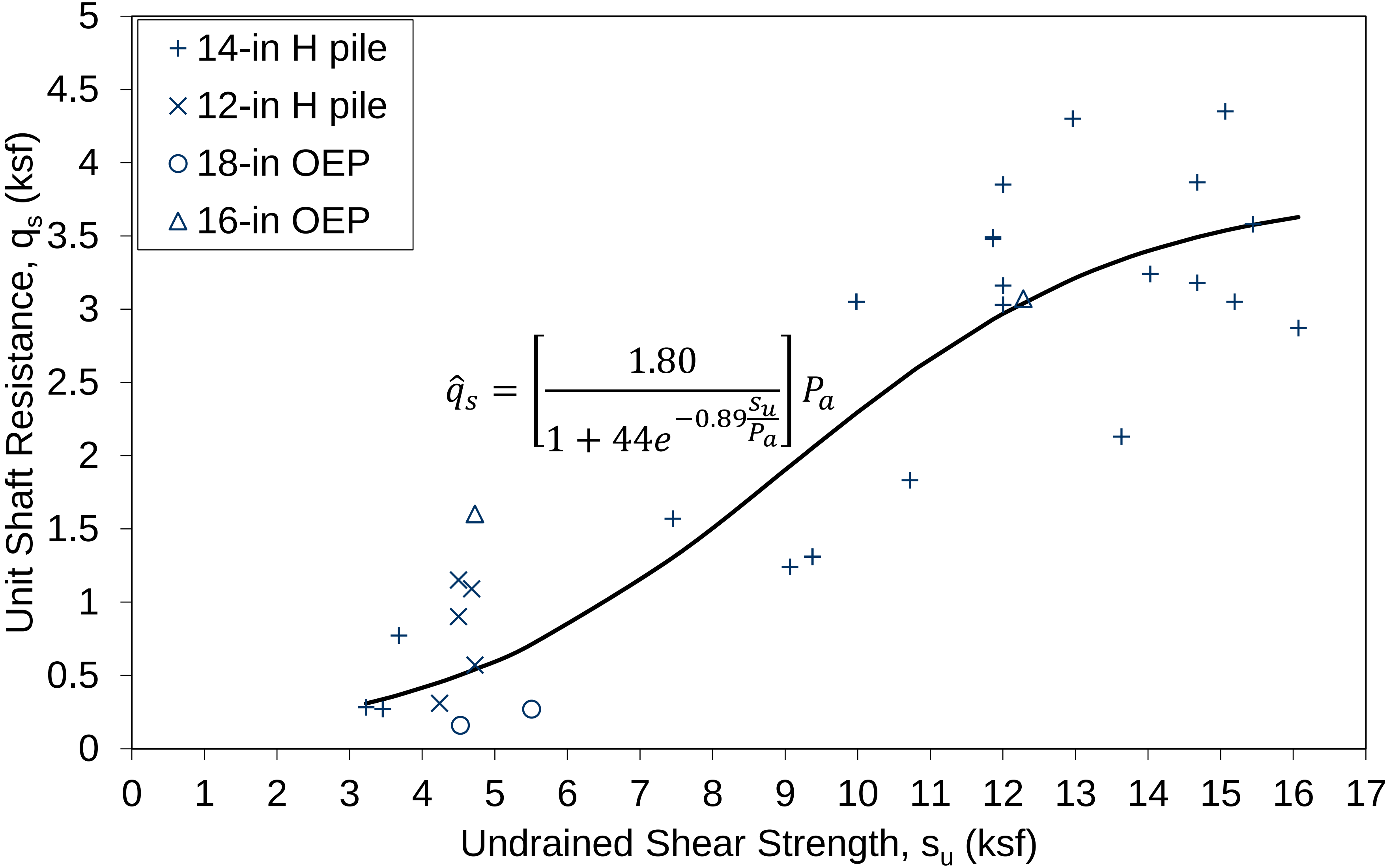
Innovative Static Pile Load System

SLT Results (I-80 Rock Springs, WY)

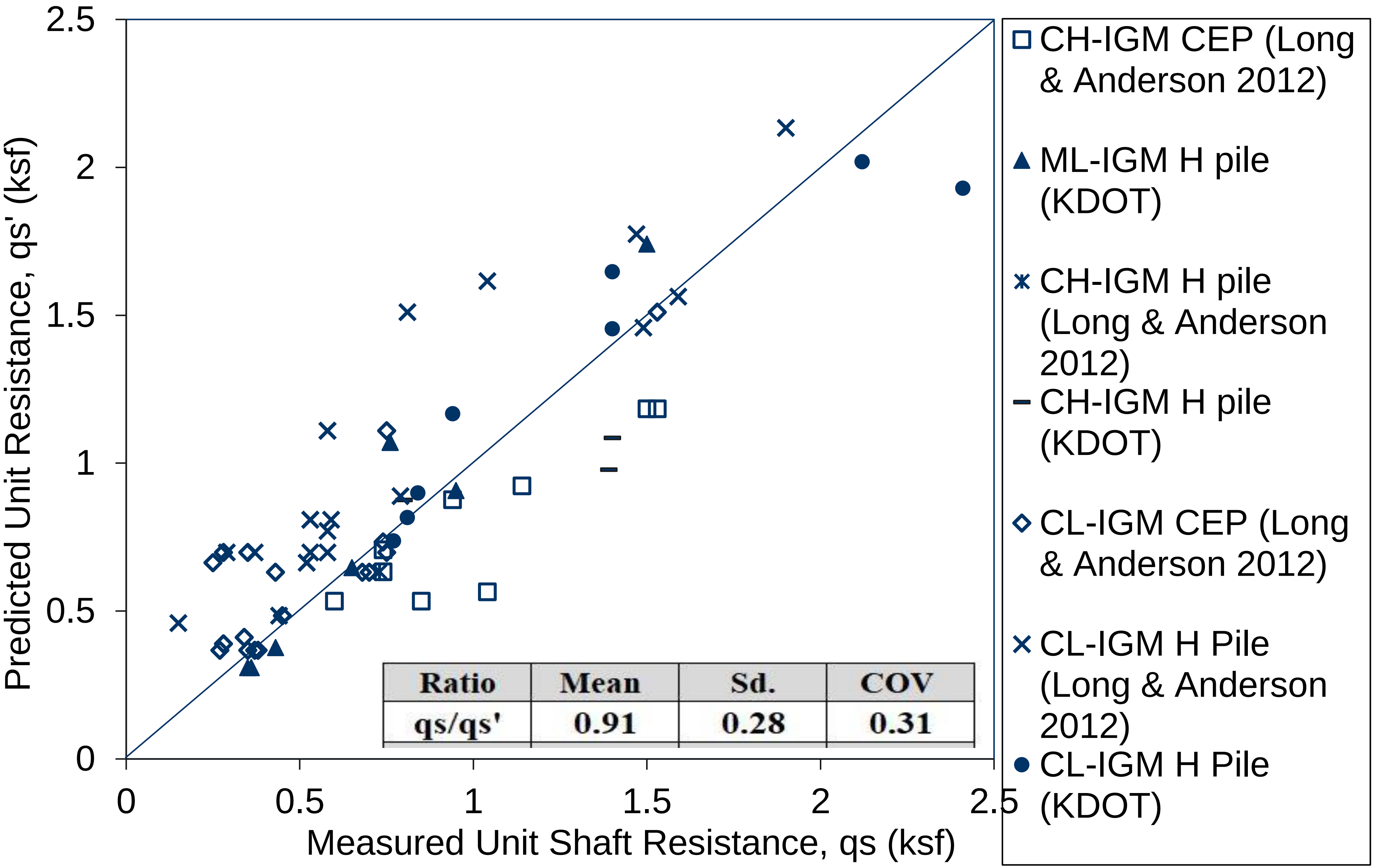




Fine-grained Soil IGM: Low Plasticity Silt (ML-IGM) (Shaft Resistance)

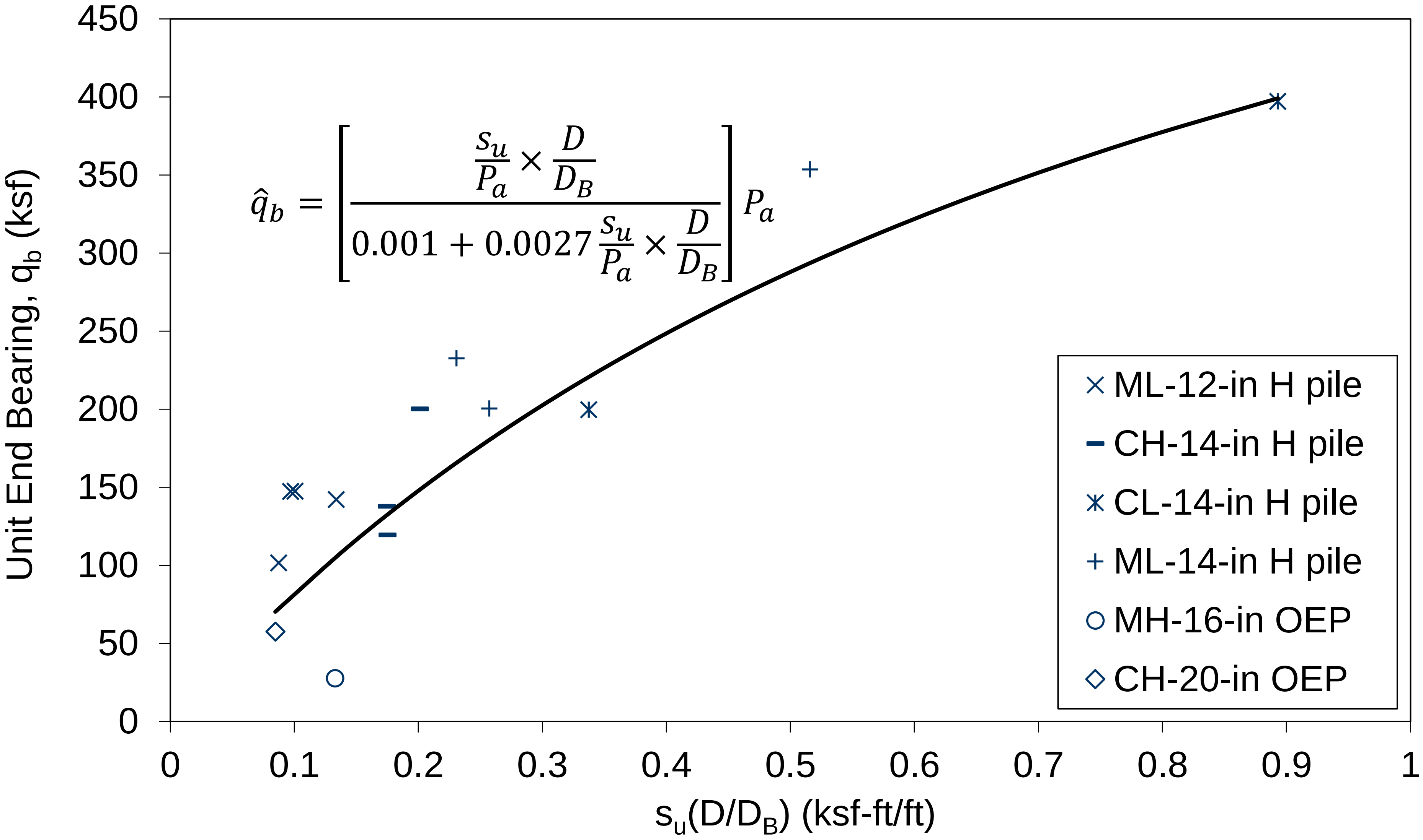


Validation: Piles in Fine-grained Soil IGM

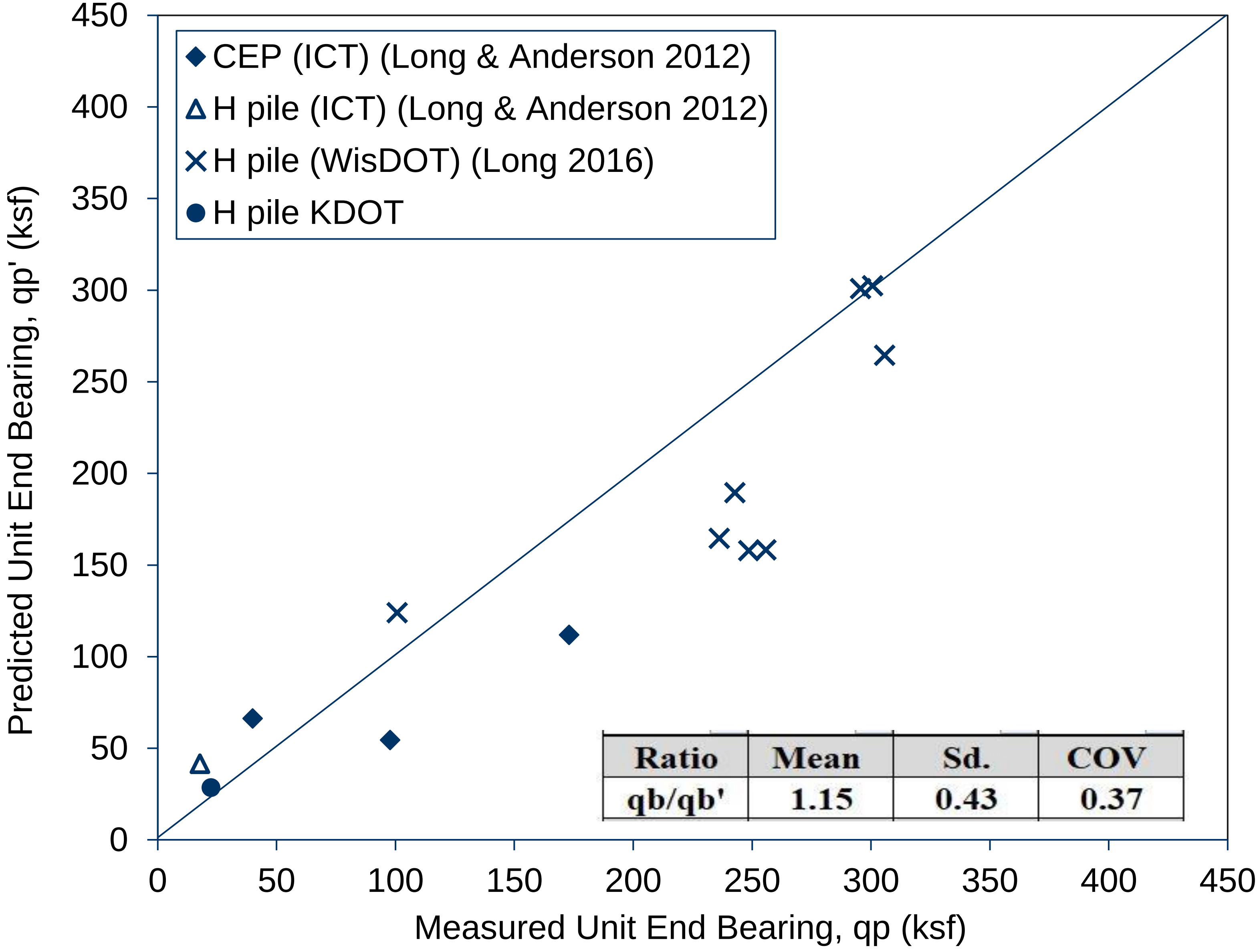


Ratio	Mean	Sd.	COV
qs/qs'	0.91	0.28	0.31

Fine-grained Soil-based IGM (End Bearing)



Validation: Piles in Fine-grained Soil IGM



Ratio	Mean	Sd.	COV
qb/qb'	1.15	0.43	0.37

Static Analysis Equations for FG-IGMs

Unit Resistance	Soil-based IGM	Proposed Static Equation	Applicable Range	Pile
q_s (ksf)	ML-IGM	$\hat{q}_s = \left[\frac{1.80}{1 + 44e^{-0.89\frac{s_u}{P_a}}}\right] P_a$	3.22 ksf≤ s_u ≤16.07 ksf 0.27 ksf≤ q_s ≤4.35 ksf	HP & OEP
q_s (ksf)	CL-IGM	$\hat{q}_s = \left[\frac{1.58}{1 + 47.6e^{-1.34\frac{s_u}{P_a}}}\right] P_a$	3.46 ksf≤s_u ≤15.31 ksf 0.17 ksf≤q_s ≤4.24 ksf	HP & OEP
q_s (ksf)	CH-IGM	$\hat{q}_s = \left[\frac{2}{1 + 50.4e^{-1.4\frac{s_u}{P_a}}}\right] P_a$	2.75 ksf≤s_u ≤15.94 ksf 0.28 ksf≤q_s ≤4.68 ksf	HP & OEP
q_b (ksf)	FG-IGM	$\hat{q}_b = \left[\frac{\frac{s_u}{P_a} \times \frac{D}{D_B}}{0.001 + 0.0027\frac{s_u}{P_a} \times \frac{D}{D_B}}\right] P_a$	0.08 ksf-ft/ft≤ $s_u \frac{D}{D_B} \leq 0.89$ ksf-ft/ft 27.71 ksf≤q_s ≤ 399.16 ksf	HP & OEP

s_u=undrained shear strength (ksf); P_a=atmospheric pressure=2.12 ksf; D=pile dimension or diameter; D_B=total pile penetration; OEP=Open ended steel pipe pile.

Masud, N.B., Ng, K.W., Wulff, S.S., & Johnson, T., (2022). Driven piles in fine-grained soil-based intermediate geomaterials. ***Journal for Bridge Engineering***, 27(6), 04022037.

LRFD Resistance Factors for Piles in FG-IGMs

FG-IGM	Statistical Parameters			Monte Carlo Simulation	
				β_T=2.33	β_T=3.0
	N	Mean	COV	φ	φ
Unit Shaft Resistance					
ML-IGM	41	1.07	0.47	**0.44**	0.31
CL-IGM	92	0.91	0.41	**0.43**	0.31
CH-IGM	43	1.13	0.24	**0.80**	0.66
Unit End Bearing					
FG-IGM	27	1.07	0.36	**0.57**	0.43

N-Sample size; φ–Resistance factor; β_T–Target reliability index; COV–Coefficient of variation.

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Static Analysis Equations for Shales

Shale Type	Proposed Static Equation for $\bar{q}_s$	Applicable Range	Pile
Soil-based (SS) Shale	$\hat{q}_s = \frac{3.523\, q_u}{(8.6 + q_u)^{1.05}}$	2.18 ksf≤ q_u ≤51.5 ksf 0.76 ksf≤q_s ≤2.68 ksf	HP & Shell
Soft & Highly Weathered (HW) Shale	$\hat{q}_s = 0.23 q_u^{0.45}$	2.18 ksf≤ q_u ≤25.6 ksf 0.18 ksf≤q_s ≤1.06 ksf	HP & Shell
Moderately Hard & Weathered (MW) Shale	$\hat{q}_s = \frac{1.196\, q_u}{(0.5 + q_u)^{0.83}}$	2.6 ksf≤ q_u ≤58 ksf 1.12 ksf≤q_s ≤2.29 ksf	HP & Shell
Hard & Slightly Weathered (SW) Shale	$\hat{q}_s = \frac{2.62\, q_u}{(0.467 + q_u)^{0.945}}$	4.54 ksf≤ q_u ≤126 ksf 2.24 ksf≤q_s ≤3.78 ksf	HP & Shell

Shale Type	Proposed Static Equation for $\bar{q}_p$	Applicable Range	Pile
Soil-based Shale and Soft & Highly Weathered (SS-HW) Shale	$\hat{q}_b = 45.72\, q_u{}^{0.35}$	3.61 ksf≤ q_u ≤51.5 ksf 39.7 ksf≤q_b ≤182.7 ksf	HP & Shell
Moderately Hard & Weathered Shale to Hard & Slightly Weathered (MW-SW) Shale	$\hat{q}_b = \frac{190.64\, q_u}{(1 + q_u)^{0.88}}$	5.4 ksf≤ q_b ≤124 ksf 35.1 ksf≤q_b ≤384.5 ksf	HP & Shell

q_u= uniaxial compressive strength in ksf

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LRFD Resistance Factors for Piles in Shales

Shale Type	Statistical Parameters			Monte Carlo Simulation	
				β_T=2.33	β_T=3.0
	N	Mean	COV	φ	φ
Unit Shaft Resistance					
SS	27	1.01	0.33	**0.57**	0.44
HW	23	0.97	0.38	**0.49**	0.37
MW	31	1.02	0.23	**0.74**	0.61
SW	34	1.06	0.32	**0.62**	0.49
Unit End Bearing					
SS-HW	28	0.98	0.32	**0.57**	0.45
MW-SW	36	1.02	0.29	**0.64**	0.51

N-Sample size; φ–Resistance factor; β_T–Target reliability index; COV–Coefficient of variation.

Islam, M.S., Ng, K.W., and Wulff, S.S. (2022). “Prediction of driven piles in shales considering weathering and time effects.” ***Canadian Geotechnical Journal***, 59(11), 1851-1871.

Static Analysis Equations for Rock-based IGMs

Rock-based IGM	Proposed Static Equation for $\bar{q}_s$	Applicable Range	Pile
Siltstone	$\hat{q}_s = 0.45{q_u}^{0.44}$	7.34 ksf≤ q_u ≤67.7 ksf 0.99 ksf≤q_s ≤3.24 ksf	HP & OEP
	$\hat{q}_s = 0.42P_a\left[\frac{(N_1)_{60}}{16}\right]^{0.63}$	16 b/ft≤ $(N_1)_{60}$ ≤151 b/ft 0.89 ksf≤q_s ≤3.90 ksf	HP & OEP
Claystone	$\hat{q}_s = 0.74{q_u}^{0.305}$	1.46 ksf≤ q_u ≤ 163.1 ksf 0.42 ksf≤q_s ≤3.55 ksf	HP & OEP
Mudstone	$\hat{q}_s = 6.19\left[1 - e^{\left(-0.052\frac{N}{19}\times\sigma_v'\right)}\right]$	19 b/ft ≤ N ≤168 b/ft 0.19 ksf ≤ σ_v' ≤ 8.1 ksf 0.19 ksf ≤q_s ≤ 5.2 ksf	HP & OEP
Sandstone	$\hat{q}_s = 0.56{q_u}^{0.37}$	1.25 ksf≤ q_u ≤ 459 ksf 0.42 ksf≤q_s ≤ 5.01 ksf	HP & OEP

Masud, N., Ng, K.W., Kalauni, H., and Wulff, S.S. (2023). “Reliability-based design improvement and prediction of steel driven pile resistances in rock-based intermediate geomaterials.” ***Acta Geotechnica***. https://doi.org/10.1007/s11440-023-01909-1

Static Analysis Equations for Rock-based IGMs

Rock-based IGM	Proposed Static Equation for $\overline{q}_p$	Applicable Range	Pile
Siltstone	$\hat{q}_b = 12.9P_a\left[2.43^{\left(\frac{32.4\,N}{30\,D_B}\right)}\right]$	2.13 b/ft^2 $\leq N/D_B \leq$ 11.13 b/ft^2	HP & OEP
Claystone	$\hat{q}_b = \frac{313.27q_u}{20.96 + q_u}$	3.55 ksf$\leq q_u \leq$ 109.65 ksf 44.7 ksf $\leq q_b \leq$ 264.4 ksf	HP & OEP
Sandstone	$\widehat{N_t} = 0.907\phi^2 - 71.399\phi + 1428.55$ $\hat{q}_b = \widehat{N_t}\sigma'_v$	37 deg.$\leq \phi \leq$45 deg. 6 $\leq \widehat{N_t} \leq$107	HP

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LRFD Resistance Factors for Piles in Rock-based IGMs

Pile Type	Rock-Based IGM	N	Mean	COV	Monte Carlo Simulation	
					β_T=2.33	β_T=3.0
					φ	φ
Unit Shaft Resistance						
H & Pipe Pile	Siltstone: q_u	29	1.02	0.31	**0.61**	0.48
H & Pipe Pile	Siltstone: $(N_1)_{60}$	48	1.04	0.33	**0.60**	0.46
H & Pipe Pile	Claystone	12	1.09	0.45	**0.47**	0.34
H & Pipe Pile	Mudstone	24	0.97	0.44	**0.43**	0.31
H-Pile	Sandstone	17	1.03	0.45	**0.44**	0.31
Unit End Bearing						
H & Pipe Pile	Siltstone	20	1.03	0.47	**0.42**	0.31
H & Pipe Pile	Claystone	9	0.99	0.44	**0.43**	0.31
H-Pile	Sandstone	18	1.17	0.41	**0.55**	0.41

N-Sample size; φ–Resistance factor; β_T–Target reliability index; COV–Coefficient of variation.

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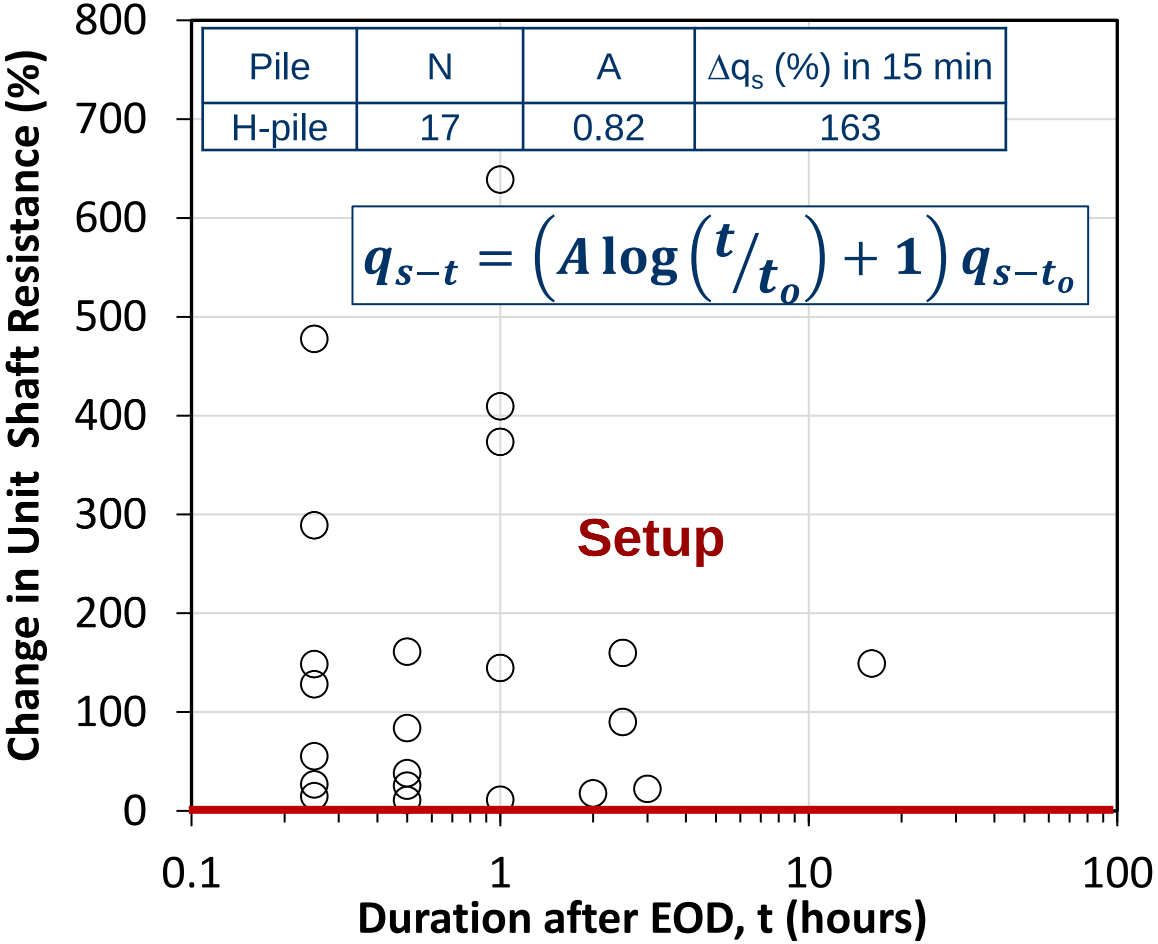
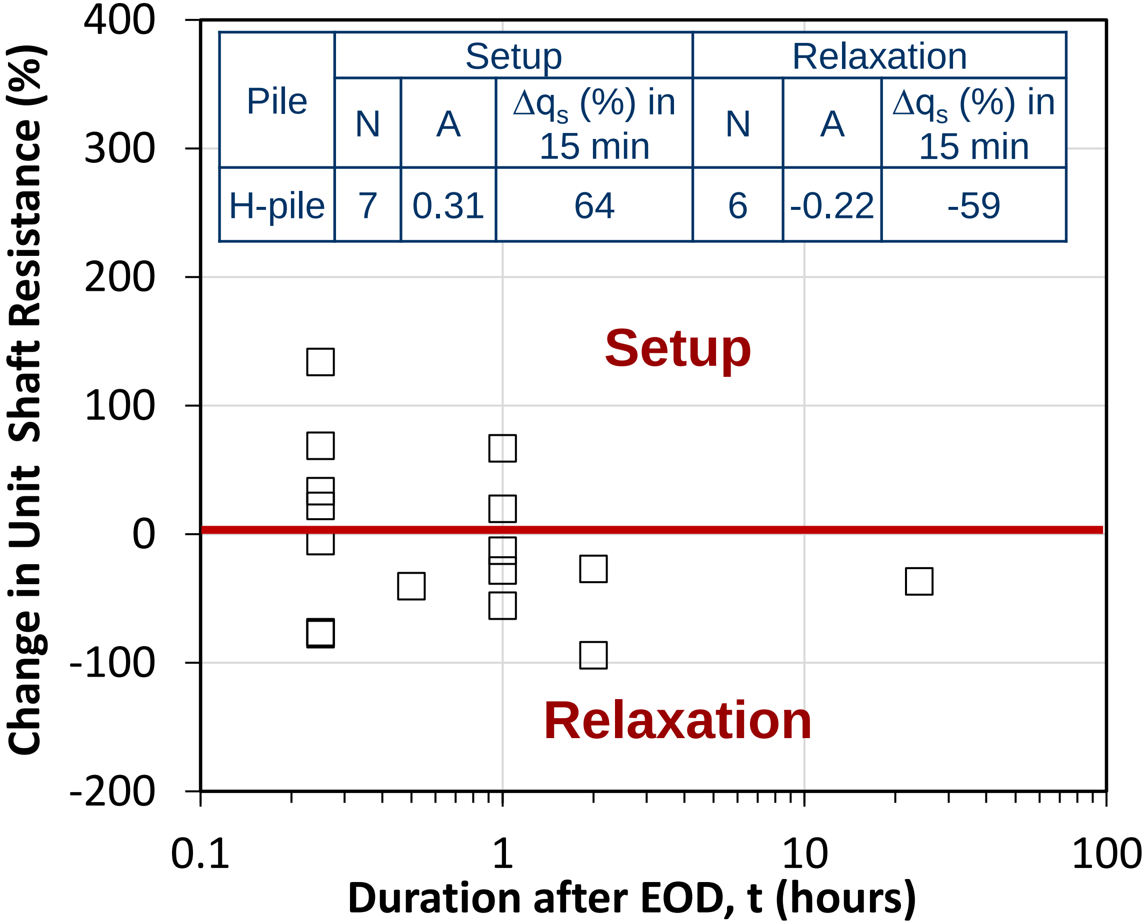
Setup/Relaxation of Unit Shaft Resistance in Shale



Pile	N	A	Δq_s (%) in 15 min
H-pile	17	0.82	163

$$q_{s-t} = \left(A \log\left({}^{t}/_{t_o}\right) + 1\right) q_{s-t_o}$$

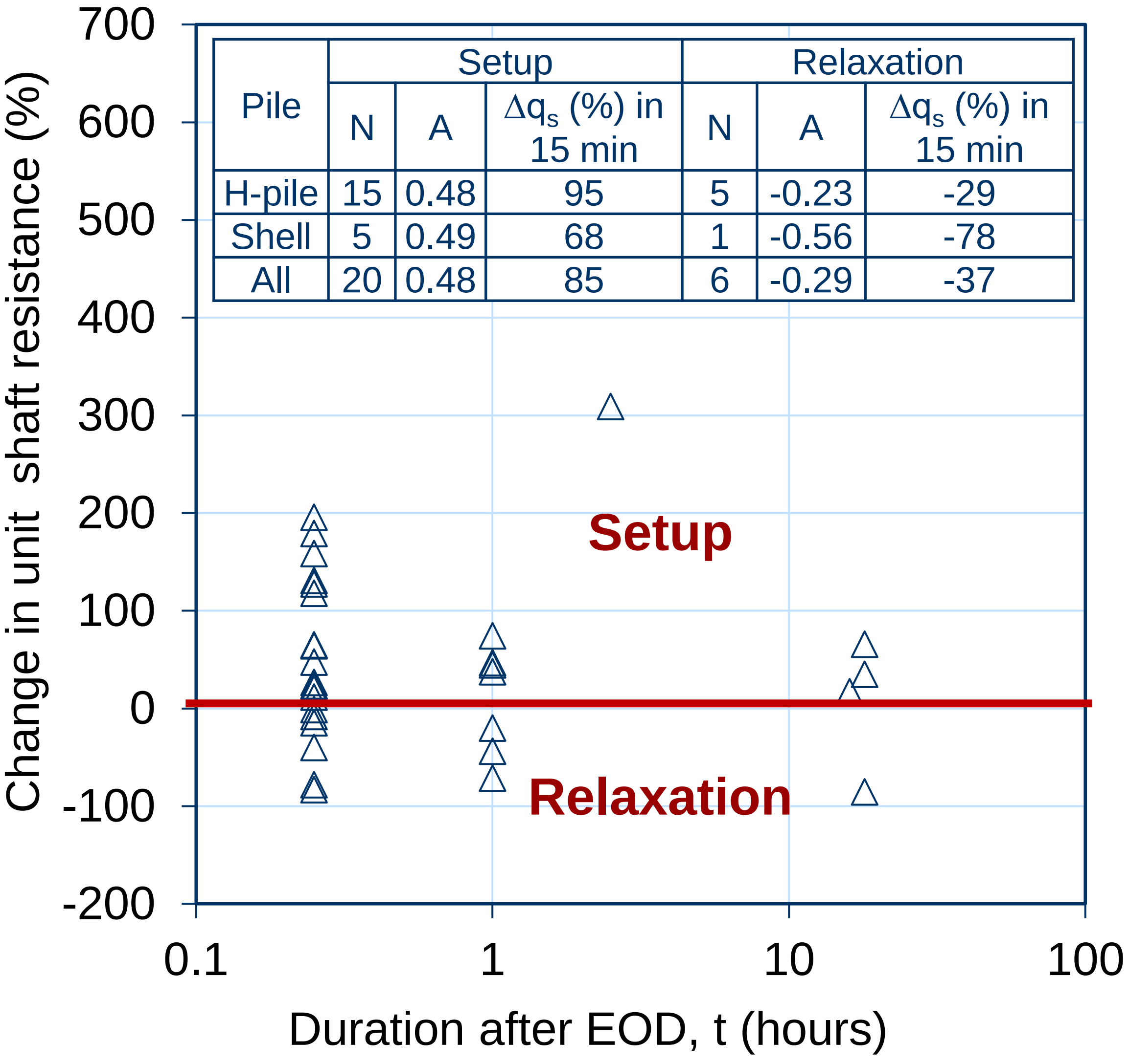
Soil-Based Shale (SS)



Pile	Setup			Relaxation		
	N	A	Δq_s (%) in 15 min	N	A	Δq_s (%) in 15 min
H-pile	7	0.31	64	6	-0.22	-59

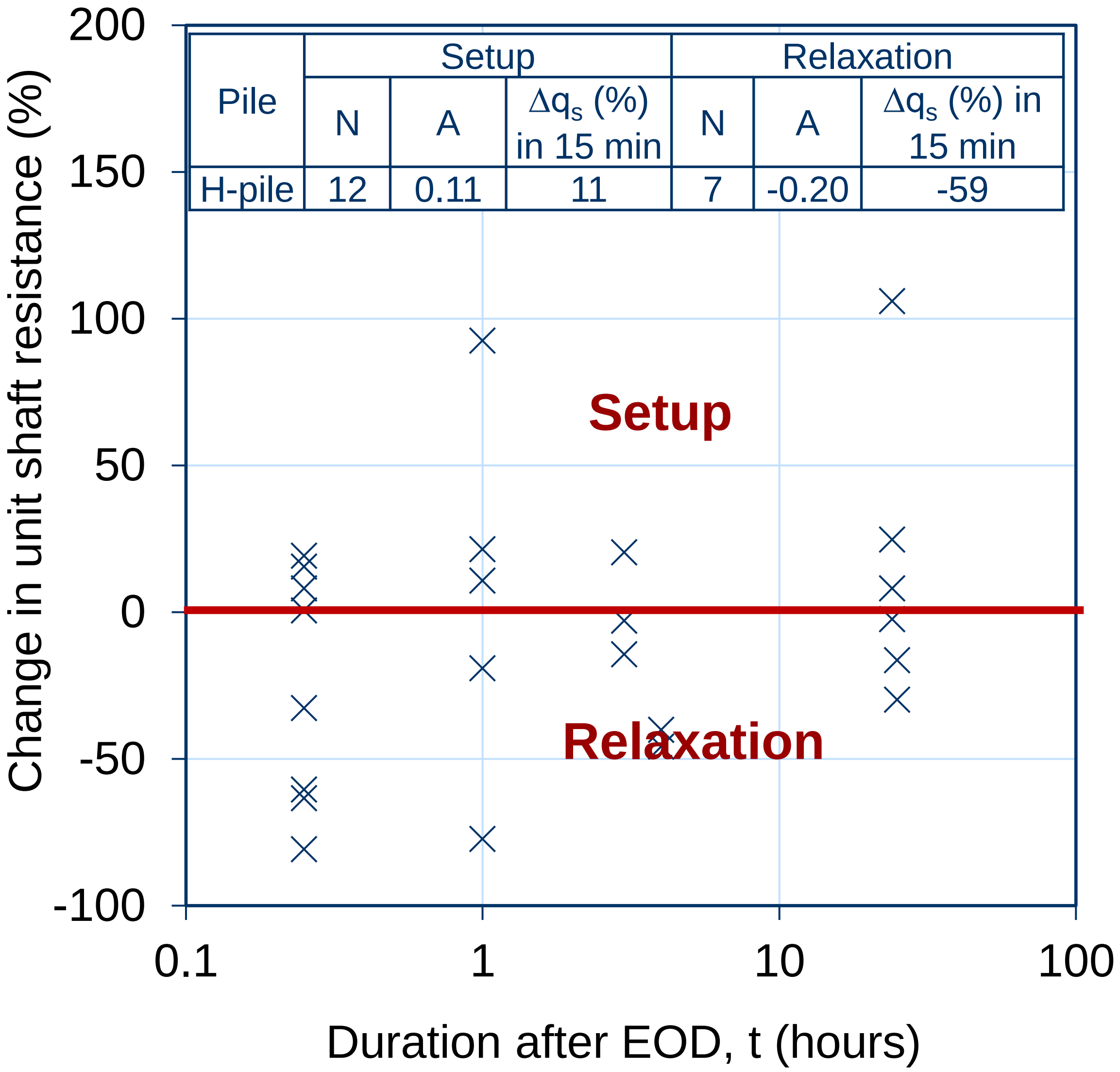
Highly Weathered (HW) Shale

Setup/Relaxation of Unit Shaft Resistance in Shale



Pile	Setup			Relaxation		
	N	A	Δq_s (%) in 15 min	N	A	Δq_s (%) in 15 min
H-pile	15	0.48	95	5	-0.23	-29
Shell	5	0.49	68	1	-0.56	-78
All	20	0.48	85	6	-0.29	-37

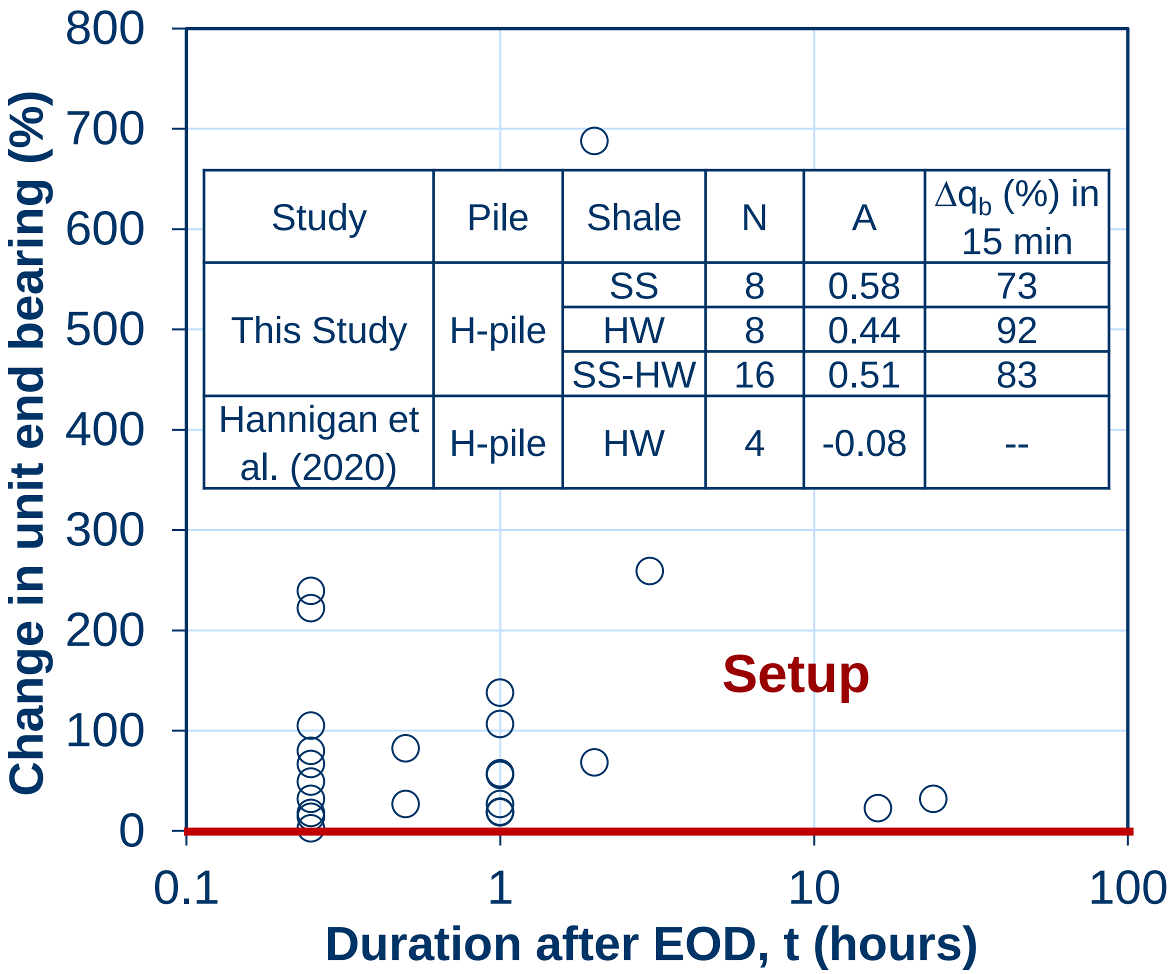
Moderately Weathered (MW) Shale



Pile	Setup			Relaxation		
	N	A	Δq_s (%) in 15 min	N	A	Δq_s (%) in 15 min
H-pile	12	0.11	11	7	-0.20	-59

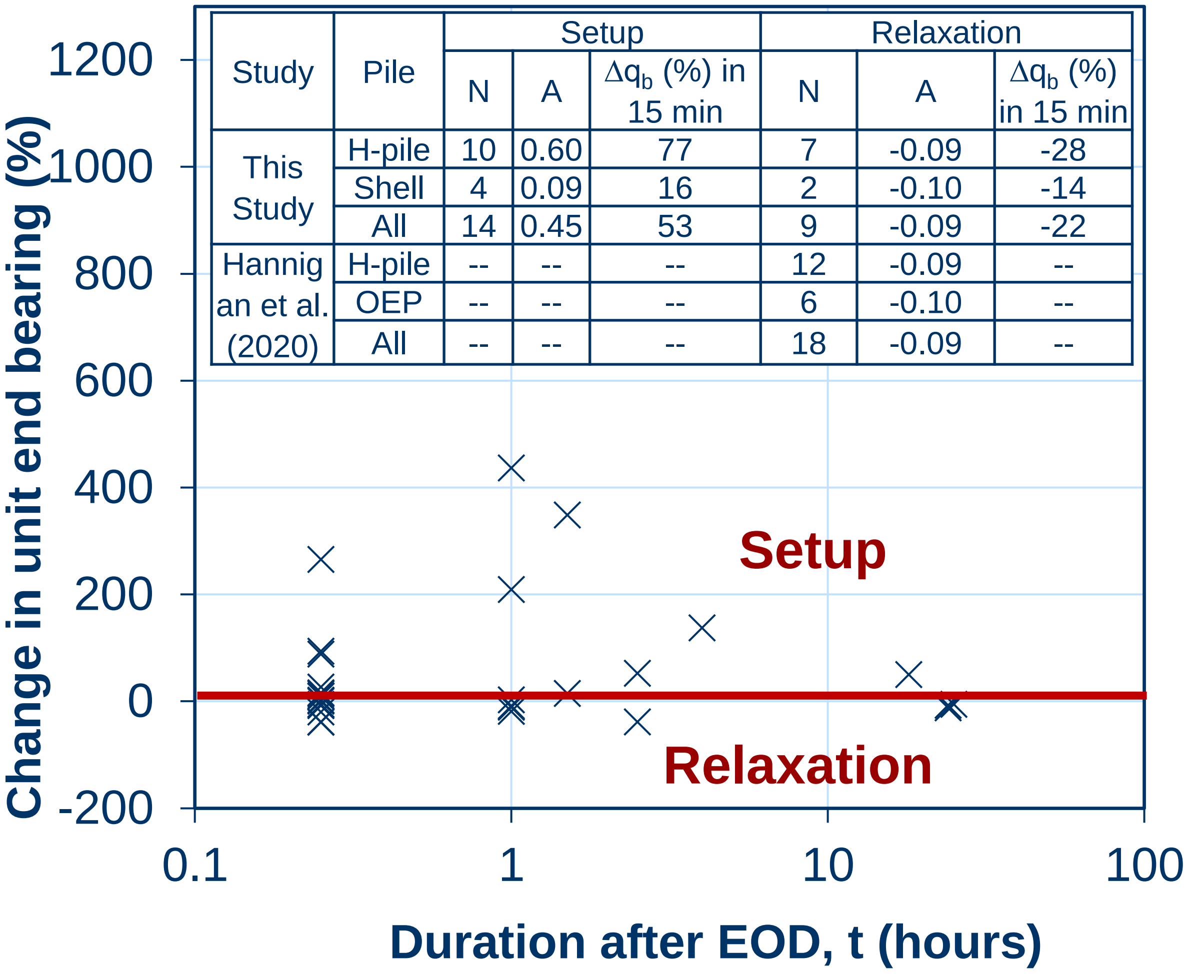
Slightly Weathered (SW) Shale

Setup/Relaxation of Unit End Bearing in Shale



Study	Pile	Shale	N	A	Δq_b (%) in 15 min
This Study	H-pile	SS	8	0.58	73
		HW	8	0.44	92
		SS-HW	16	0.51	83
Hannigan et al. (2020)	H-pile	HW	4	-0.08	--

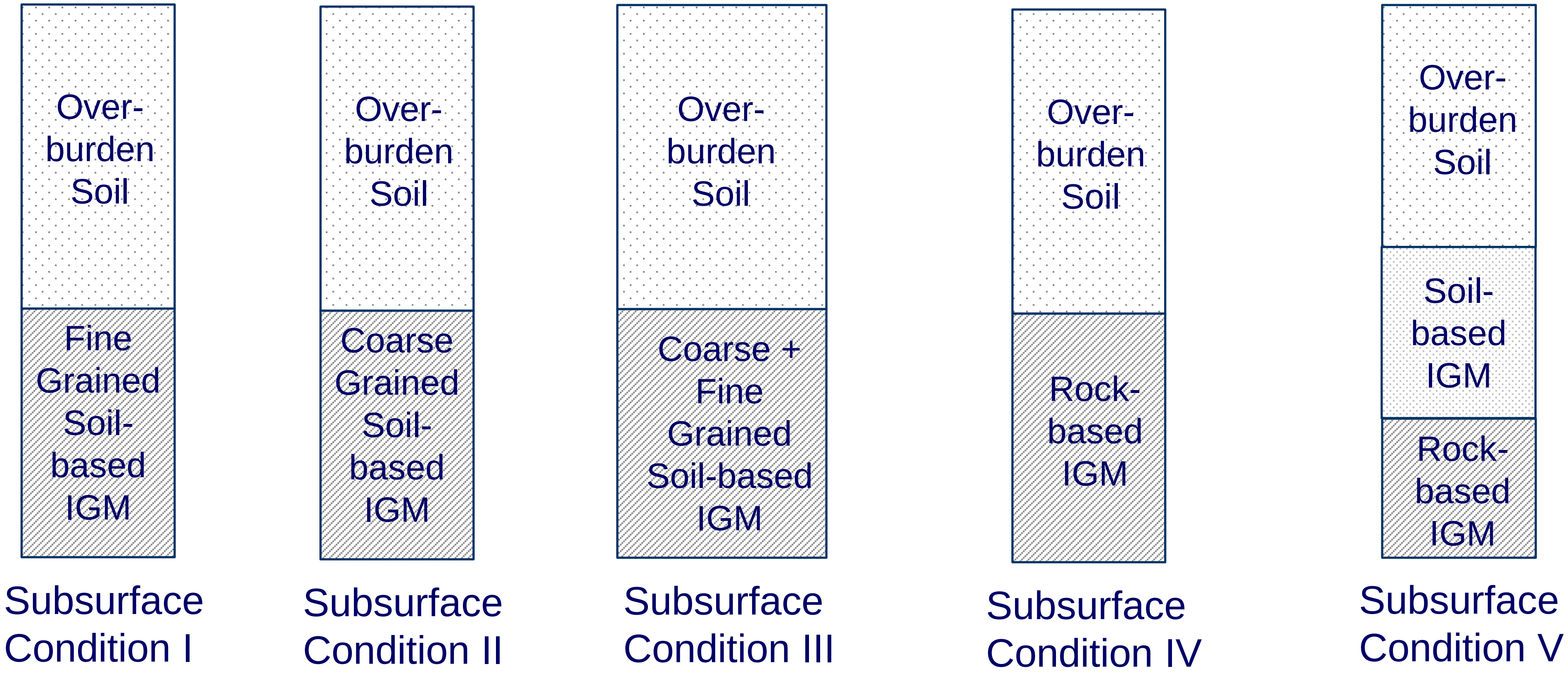
SS-HW Shale



Study	Pile	Setup			Relaxation		
		N	A	Δq_b (%) in 15 min	N	A	Δq_b (%) in 15 min
This Study	H-pile	10	0.60	77	7	-0.09	-28
	Shell	4	0.09	16	2	-0.10	-14
	All	14	0.45	53	9	-0.09	-22
Hannigan et al. (2020)	H-pile	--	--	--	12	-0.09	--
	OEP	--	--	--	6	-0.10	--
	All	--	--	--	18	-0.09	--

MW-SW Shale

Subsurface Conditions I to V for WEAP Procedure



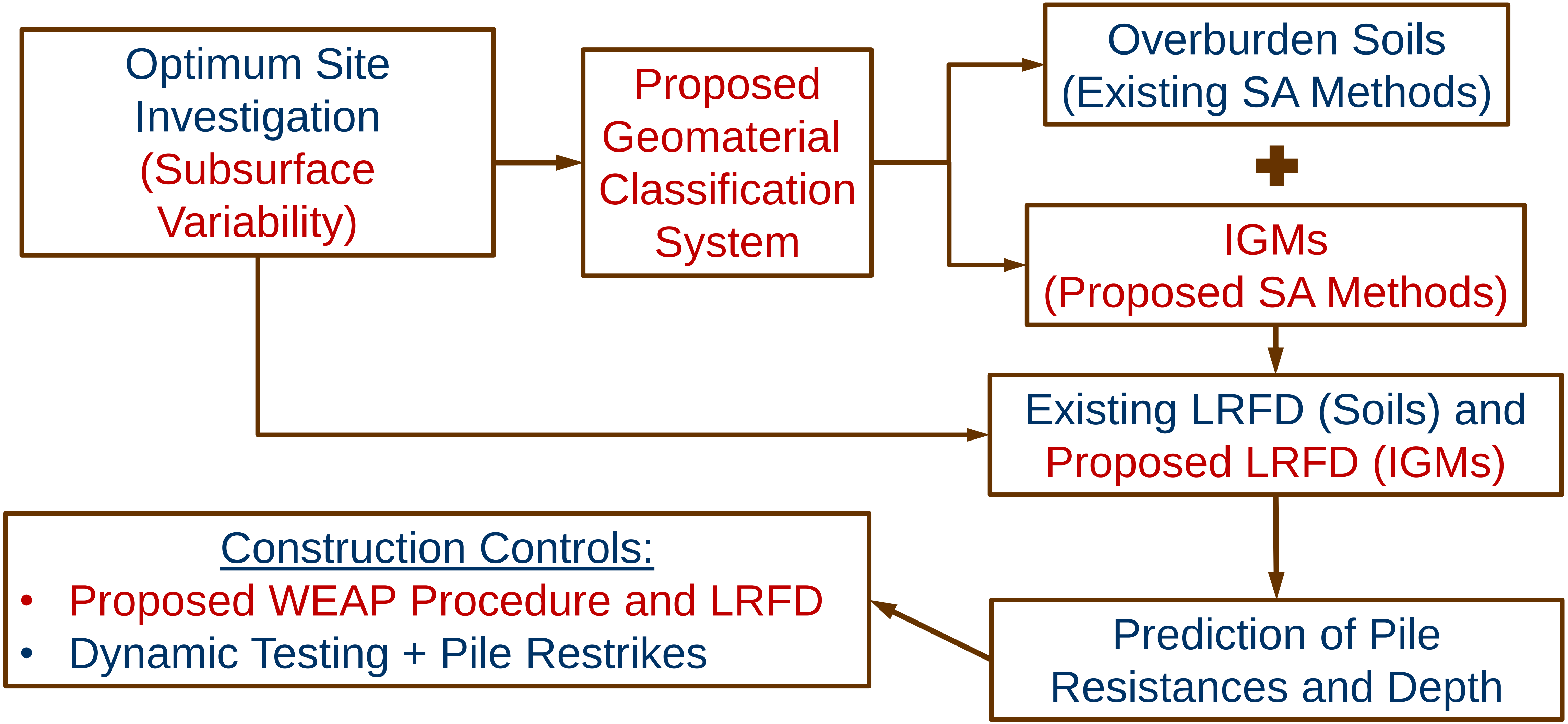
- Islam, M.S., Ng, K.W., and Wulff, S.S. (2022). "Improved Wave Equation Analysis of Steel H-Piles in Shales Considering LRFD and Economic Impact Studies." ***Journal of Bridge Engineering***, 27(6), 04022039.
- Kalauni, H.K. (2021). New static analysis methods and improved wave equation analysis program for driven piles in intermediate geomaterials with load and resistance factor design recommendations. MS thesis, University of Wyoming, Laramie, WY.

LRFD Resistance Factors for WEAP Methods (Rock-based IGMs)

Method	N	Mean	COV	FOSM			
				2.33		3.00	
				φ	φ/x̄	φ	φ/x̄
WEAP-SA-D	119	1.15	0.25	**0.72**	0.62	0.58	0.50
WEAP-UW-D	119	1.16	0.26	**0.73**	0.63	0.6	0.52
WEAP-UW-R	119	1.03	0.20	**0.71**	0.70	0.59	0.58
WEAP-SA-R	119	1.02	0.21	**0.69**	0.70	0.58	0.59

N-Sample size; φ–Resistance factor; β_T–Target reliability index; COV–Coefficient of variation; φ/x̄–Efficiency factor; FOSM–First Order Second Moment; FORM–First Order Reliability Method; MCS–Monte Carlo Simulation.

Recommended Driven Pile Design and Construction Control Process



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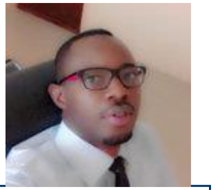

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MS: Carmen Elliott
(Graduated in 2021)

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MS: Becky Holt
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Journal Publications (2019-2023)

1) Masud, N., Ng, K.W., Kalauni, H., and Wulff, S.S. (2023). "Reliability-based design improvement and prediction of driven piles in rock-based intermediate geomaterials." ***Acta Geotechnica***. (In press).
2) Masud, N., Ng, K.W., and Wulff, S.S. (2023). "Resistance responses and design recommendations for driven piles in coarse-grained soil-based Intermediate GeoMaterials." ***Soils and Foundations***, 63(6), 101381.
3) Masud, N., Ng, K.W., Oluwatuyi, O., Islam, Md Shafiqul, Kalauni, H.K. and Wulff, S.S. (2023). "Evaluation of static load test systems for driven piles in intermediate geomaterials." ***Transportation Research Record Journal***, 2677(10), 741-756.
4) Oluwatuyi, O. E., Ng, K.W., Wulff, S.S. (2023). "Improved resistance prediction and reliability for bridge pile foundation in Shales through optimal site investigation plans." ***Reliability Engineering and System Safety***, 239, 109476.
5) Oluwatuyi, O., Ng, K.W., Wulff, S.S., and Rajapakshage, R. (2023). "Optimal site investigation through combined geological and property uncertainties analysis". ***Geotechnical and Geological Engineering***, 41, 2377-2393.
6) Oluwatuyi, O., Ng, K.W., Wulff, S.S. and Masud, N. (2023). "The effect of geological uncertainty on the shaft resistance prediction and reliability of piles driven in multi-layered geomaterials." ***Transportation Research Record Journal***, 2677(6), 687-696.
7) Oluwatuyi, O., Rajapakshage, R., Wulff, S.S., and Ng, K.W. (2023). "Proposed hybrid approach for three-dimensional subsurface simulation to improve boundary determination and design of optimum site investigation plan for pile foundations." ***Soils and Foundations***, 63(1), 101269-1-16.
8) Islam, M.S., Ng, K.W., and Wulff, S.S. (2022). "Prediction of driven piles in shales considering weathering and time effects." ***Canadian Geotechnical Journal***, 59(11), 1851-1871.
9) Adhikari, P., Ng, K.W., Gebreslasie, Z.Y., and Wulff, S.S. (2022). "New static analysis methods and LRFD recommendations for steel H-piles in rock-based intermediate geomaterials." ***Geotechnical and Geological Engineering***, 40, 2553-2567.
10) Oluwatuyi, O., Holt, R., Rajapakshage, R., Wulff, S.S., and Ng, K.W. (2022). "Inherent Variability Assessment from Sparse Property Data of Overburden Soils and Intermediate Geomaterials Using Random Field Approaches". ***GeoRisk: Assessment and Management of Risk for Engineered Systems and Geohazards***, 16(4), 766-781.
11) Islam, M.S., Ng, K.W., and Wulff, S.S. (2022). "Improved Wave Equation Analysis of Steel H-Piles in Shales Considering LRFD and Economic Impact Studies." ***Journal of Bridge Engineering***, 27(6), 04022039-1-13.
12) Masud, N., Ng, K.W., Johnson, T., and Wulff, S.S. (2022). "Driven Piles in fine-grained soil-based Intermediate GeoMaterials." ***Journal of Bridge Engineering***, 27(6), 04022037-1-13.
13) Adhikari, P., Gebreslasie, Z.Y., Ng, K.W., and Wulff, S.S. (2020). "Static and Economic Analyses of Driven H-Piles in IGM using the Wyopile Database." ***Journal of Bridge Engineering***, ASCE, 25(5), 04020016.
14) Adhikari, P., Ng, K.W., Gebreslasie, Z.Y., Wulff, S.S. and Sullivan, T. (2020). "Geomaterial Classification Criteria for Design and Construction of Driven Steel H-Piles." ***Canadian Geotechnical Journal***, 57(4), 616-621.
15) Adhikari, P., Gebreslasie, Z.Y., Ng, K.W. and Wulff, S.S. (2019). "Performance Assessment of Wave Equation Analysis for Driven Steel H-Piles in IGM." ***Deep Foundation Institute Journal***, 13(1), 3-10.

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WYOMING TRANSPORTATION DEPARTMENT

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Example (Replacement of Memorial Bridge, ND)

Subsurface Profile

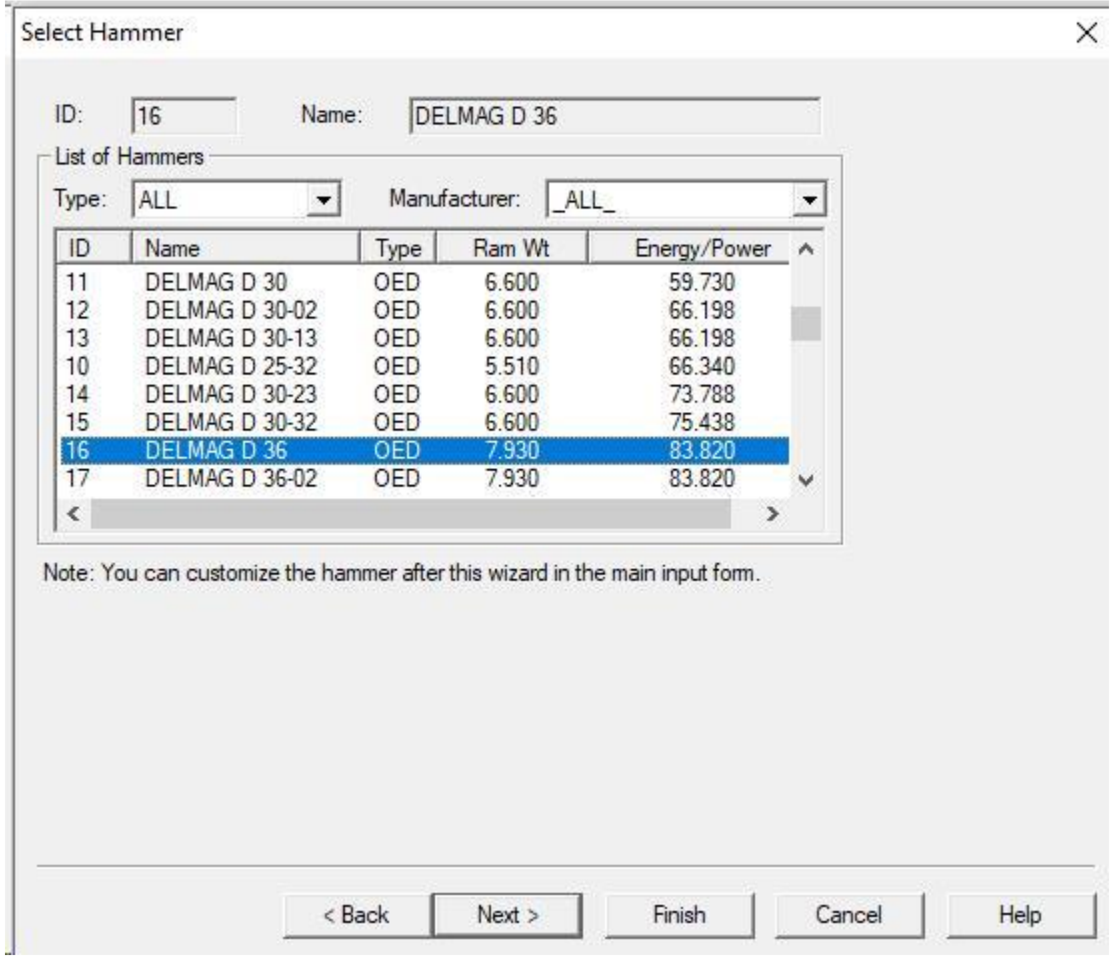
Geo-material	Depth (ft)	N	s_u (ksf)	Description
Sand	35.5	5	--	Soil
Clay	15	23	5.8	Fine-grained soil - based IGM
Clay	15	46	9.6	
Clay	5	34	7.7	
Sand	7	78	--	Coarse-grained soil-based IGM
Sand	19.5	84	--	

Hammer & Pile information

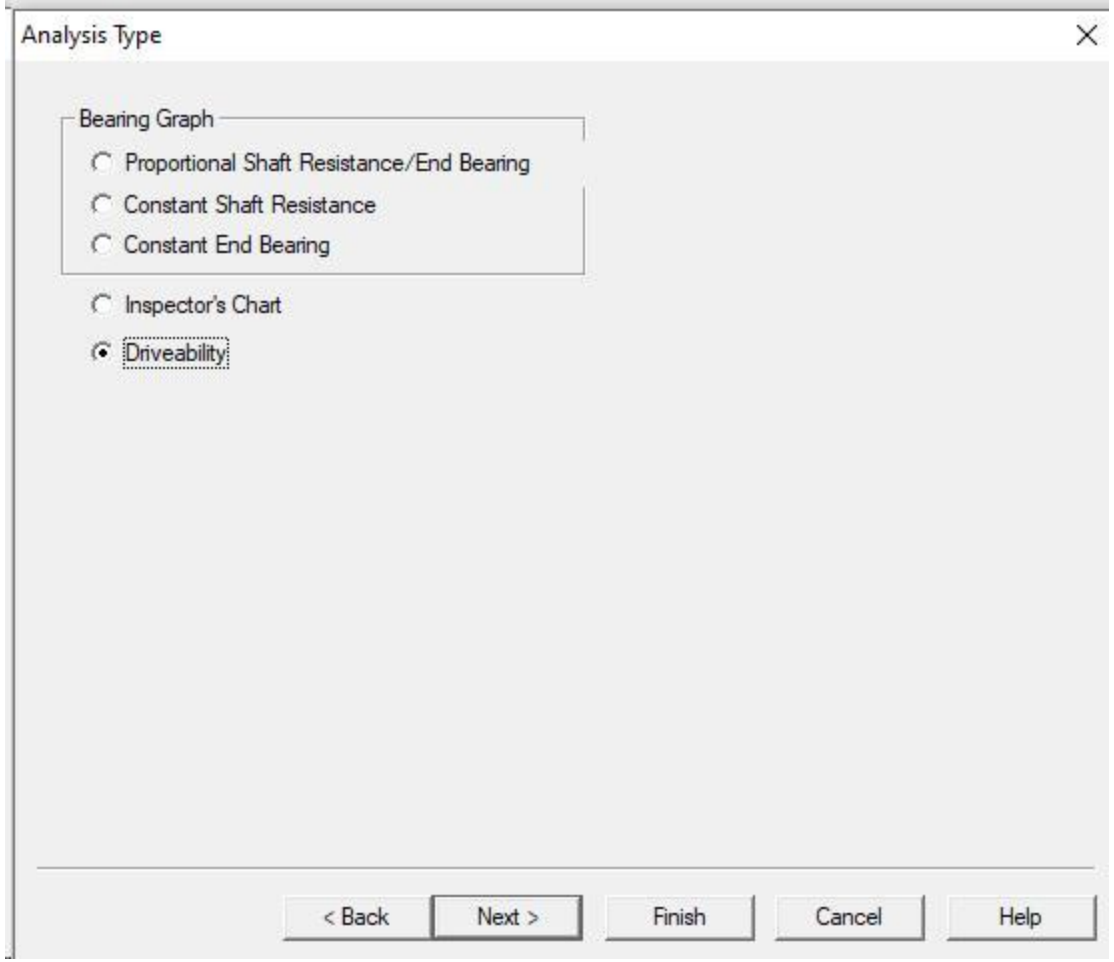
- Hammer: Delmag D 36
- Pile: HP14×102
- Pile Length: 125 ft
- Embedded Length: 97 ft

Default WEAP Method – Drivability Analysis

Step 1: Drivability Analysis using the SA input procedure



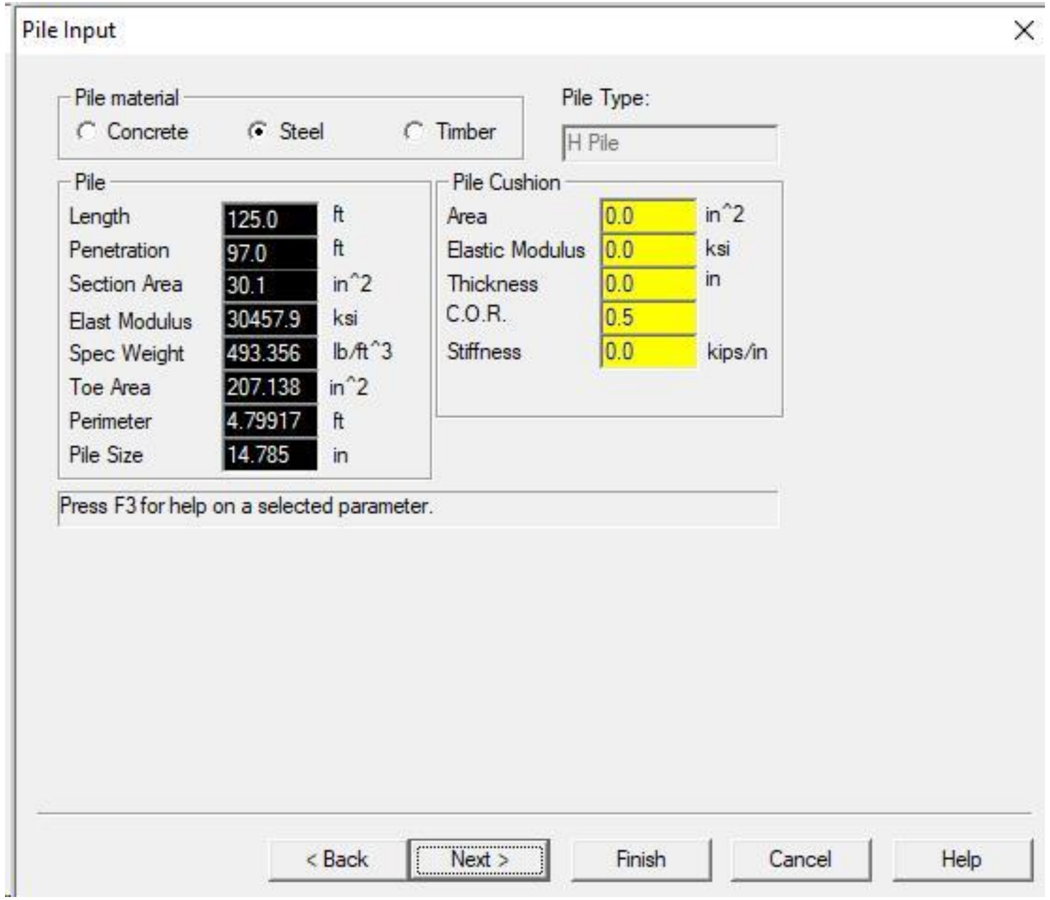
Selection of Hammer



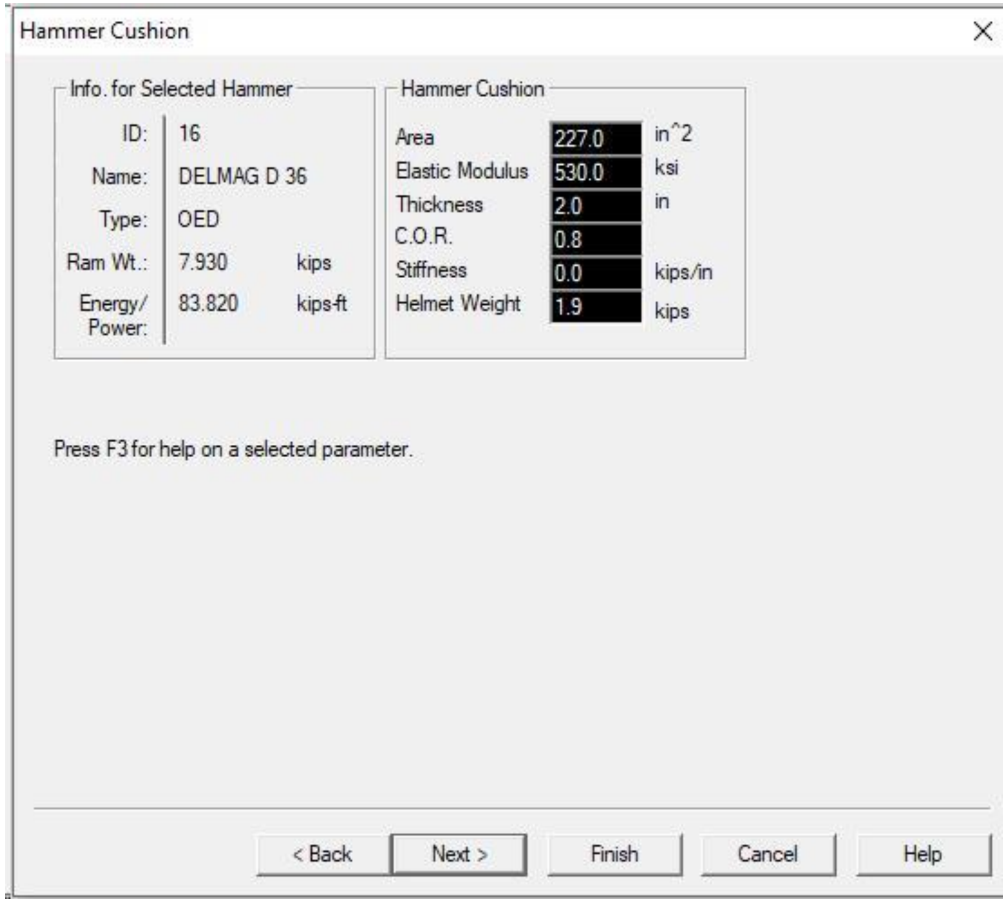
Analysis Selection

Default WEAP Method – Drivability Analysis

Step 1: Drivability Analysis using the SA input procedure



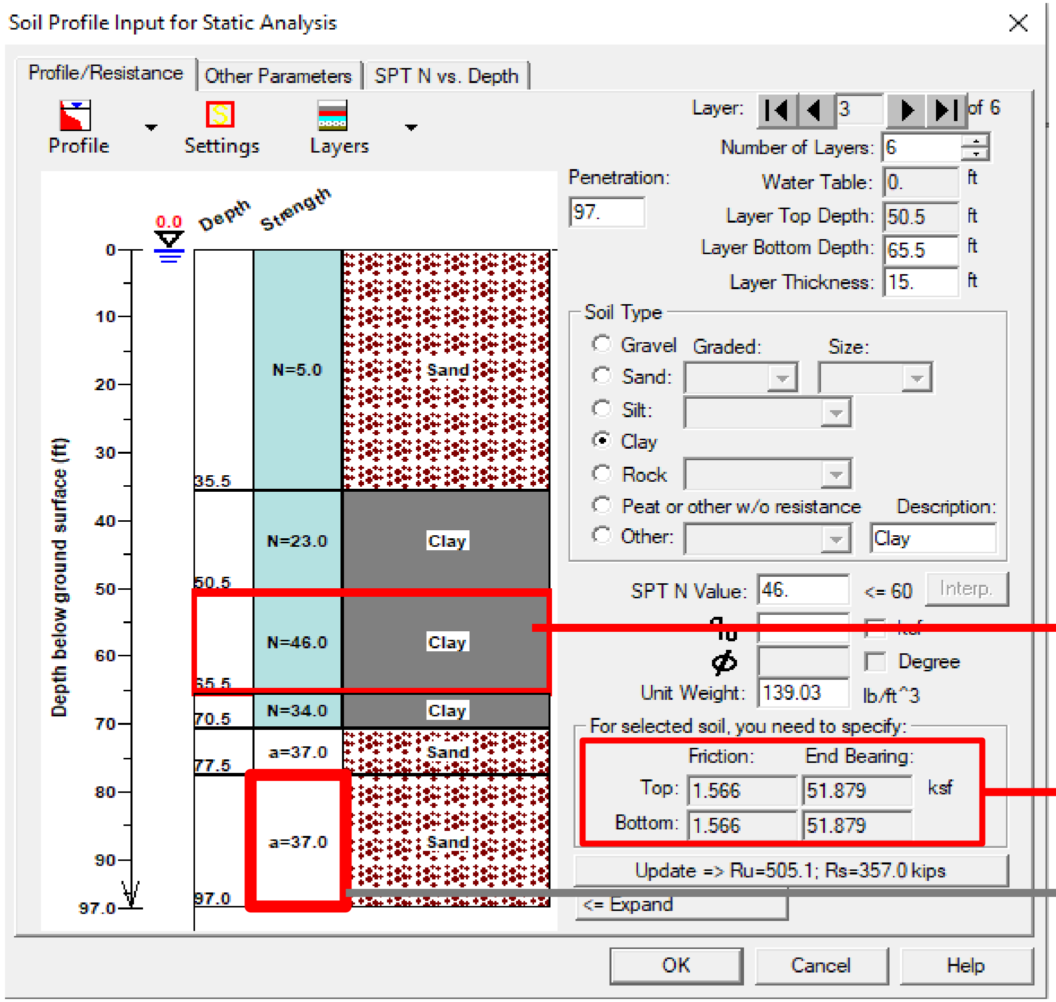
Pile Information Input



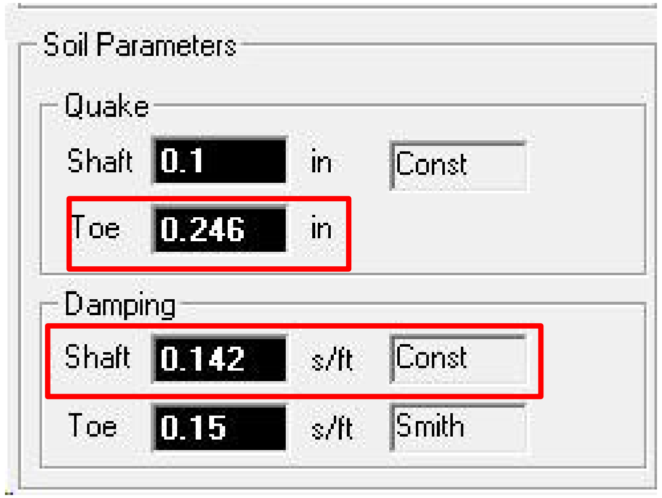
Hammer Cushion Input

Geomaterial Input – Drivability Analysis

Step 1: Drivability Analysis using the SA input procedure



SA Input Form



Smith Parameters for Drivability Analysis

Fine grained soil-based IGM

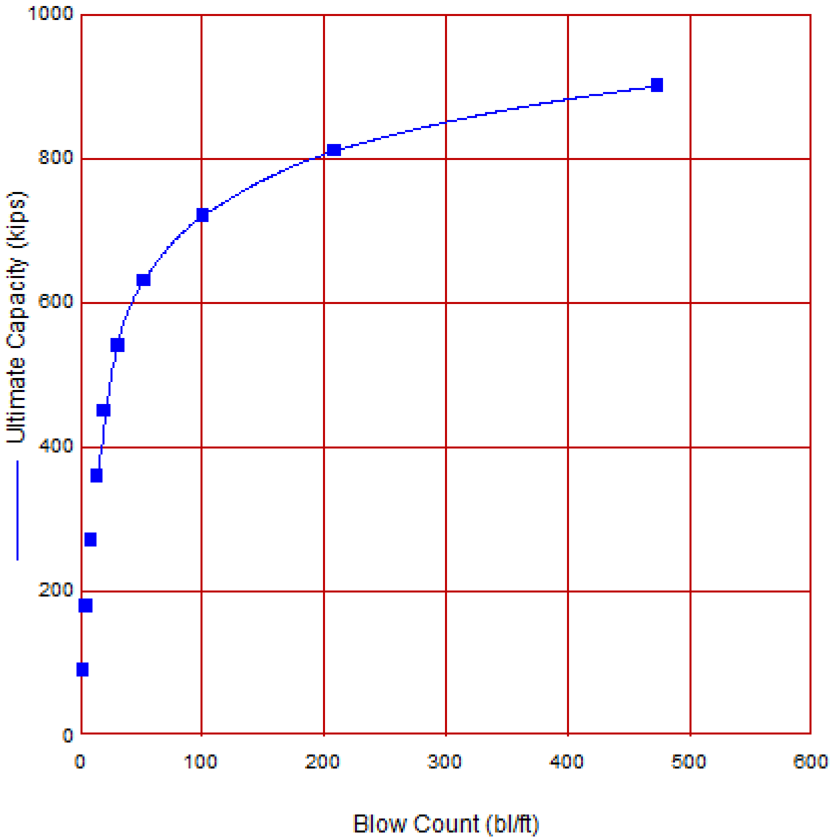
Unit resistances assigned by WEAP

Alternate input for coarse grained IGM N>60

Run Drivability Analysis to Obtain Percent Shaft Resistance

Default WEAP – Bearing Graph Analysis

Step 2: Use the percent shaft resistance to run bearing graph analysis



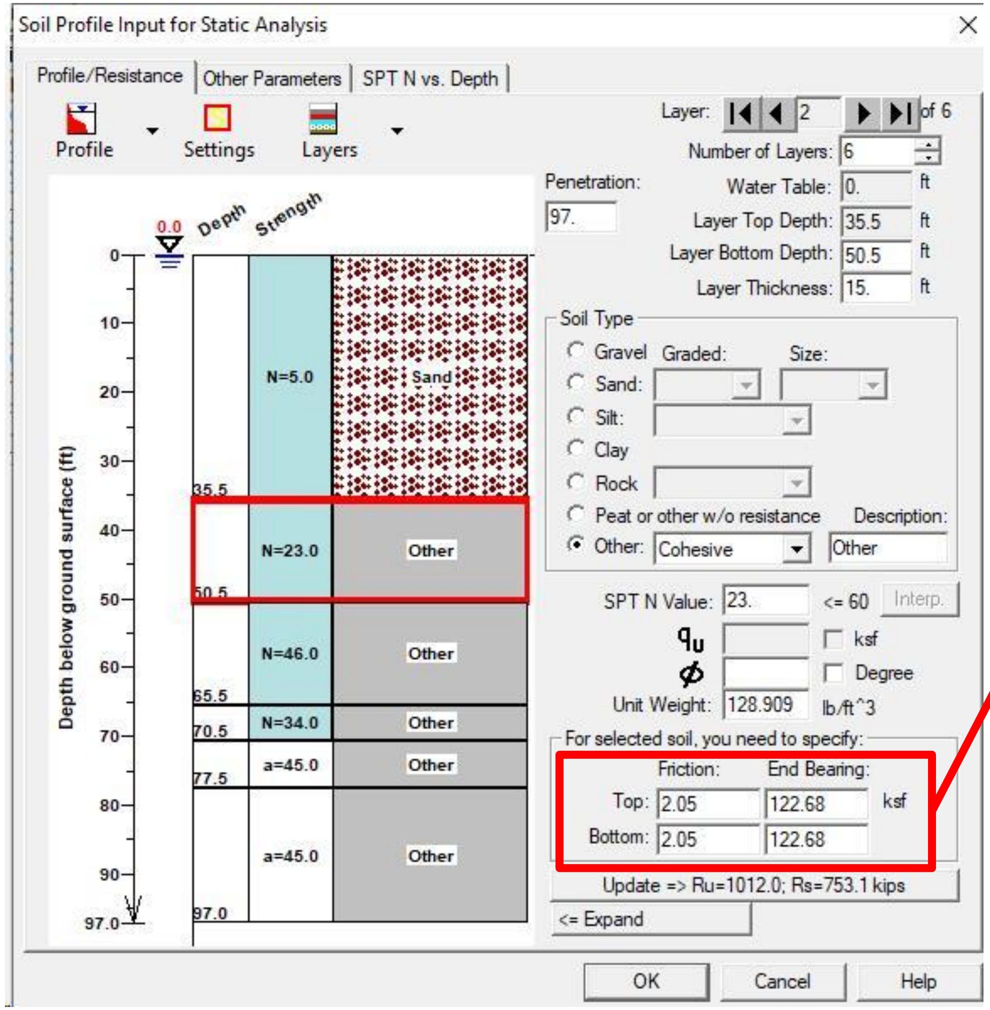
DELMAG D 36		
Stroke	8.50	ft
Ram Weight	7.93	kips
Efficiency	0.800	
Pressure	Variable	
Helmet Weight	1.90	kips
Hammer Cushion	60155	kips/in
COR of H.C.	0.800	
Skin Quake	0.100	in
Toe Quake	0.246	in
Skin Damping	0.142	sec/ft
Toe Damping	0.150	sec/ft
Pile Length	125.00	ft
Pile Penetration	97.00	ft
Pile Top Area	30.10	in2

Smith parameters assigned by the WEAP

Bearing Graph Using Default WEAP Method

Proposed WEAP Method – Geomaterial input

Step 1: Drivability Analysis using the UW proposed static analysis methods



SA input form for geomaterial input

Low plasticity clay based IGM

$$\hat{q}_s = \left[\frac{1.58}{1 + 47.6e^{-1.34\frac{s_u}{P_a}}}\right] P_a$$

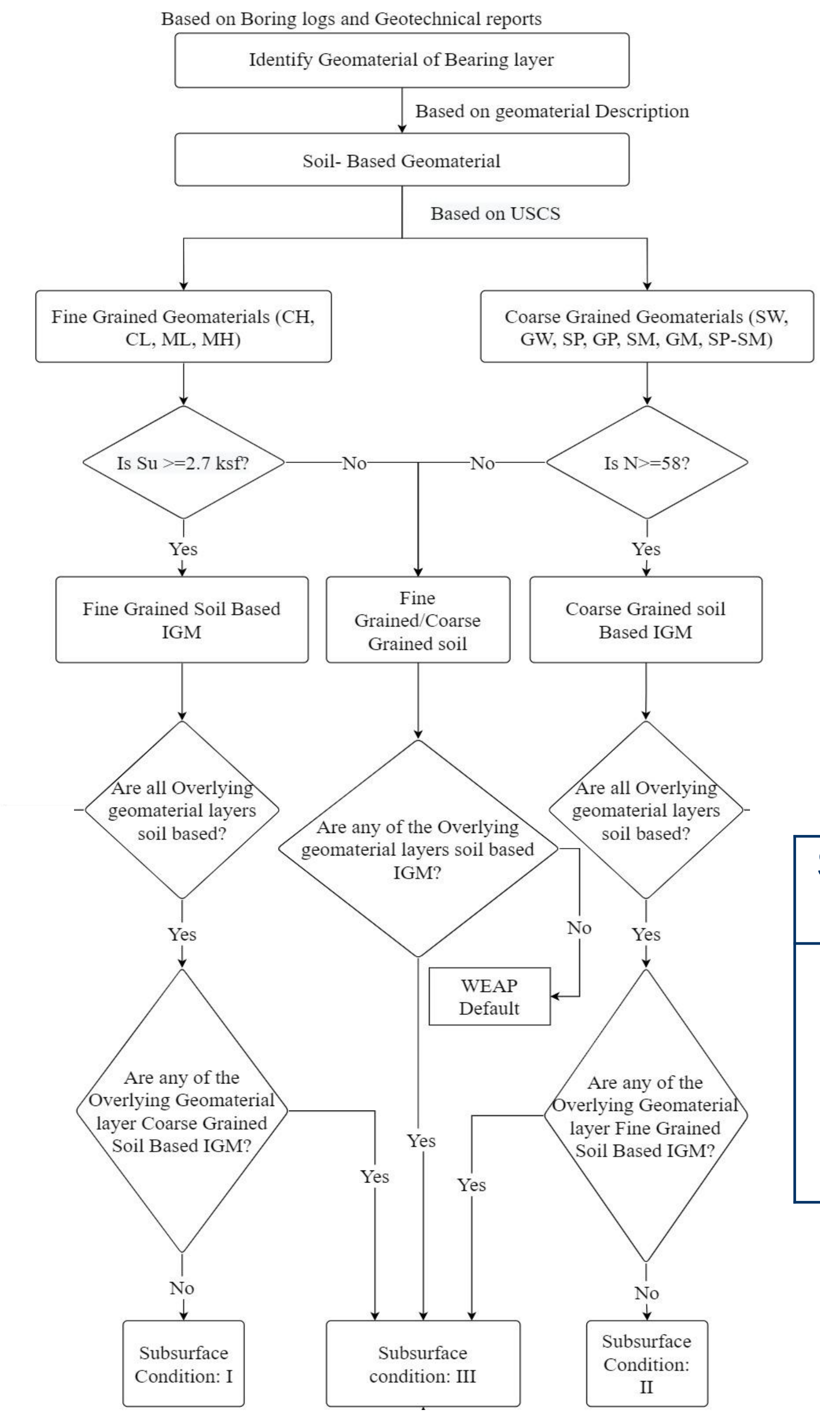
$$\hat{q}_b = \left[\frac{\frac{s_u}{P_a}\frac{D}{D_B}}{0.0011 + 0.0027\frac{s_u}{P_a}\frac{D}{D_B}}\right] P_a$$

Sand based IGM (Steel H-pile)

$$\hat{q}_s = 0.63 P_a \left[\frac{\sigma'_v}{P_a}\frac{58}{N}\right]^{1.1}$$

$$\hat{q}_b = \left[\frac{\frac{P_a}{\sigma'_v} \times \frac{N}{58}}{0.0029 + 0.0071\frac{P_a}{\sigma'_v} \times \frac{N}{58}}\right] P_a$$

Run drivability analysis to obtain new percent shaft resistance



Proposed WEAP – Subsurface Condition

Step 2: Determine subsurface condition

Bearing Layers – Soil Based IGMs:

I – Overburden Soil + Fine Grained Soil based-IGMs

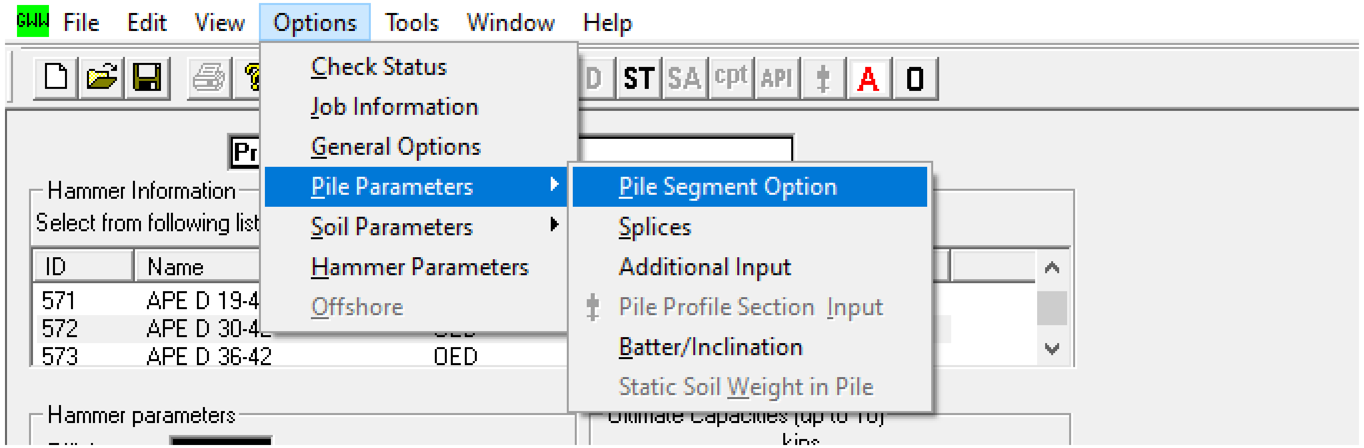
II – Overburden Soil + Coarse Grained Soil based-IGMs

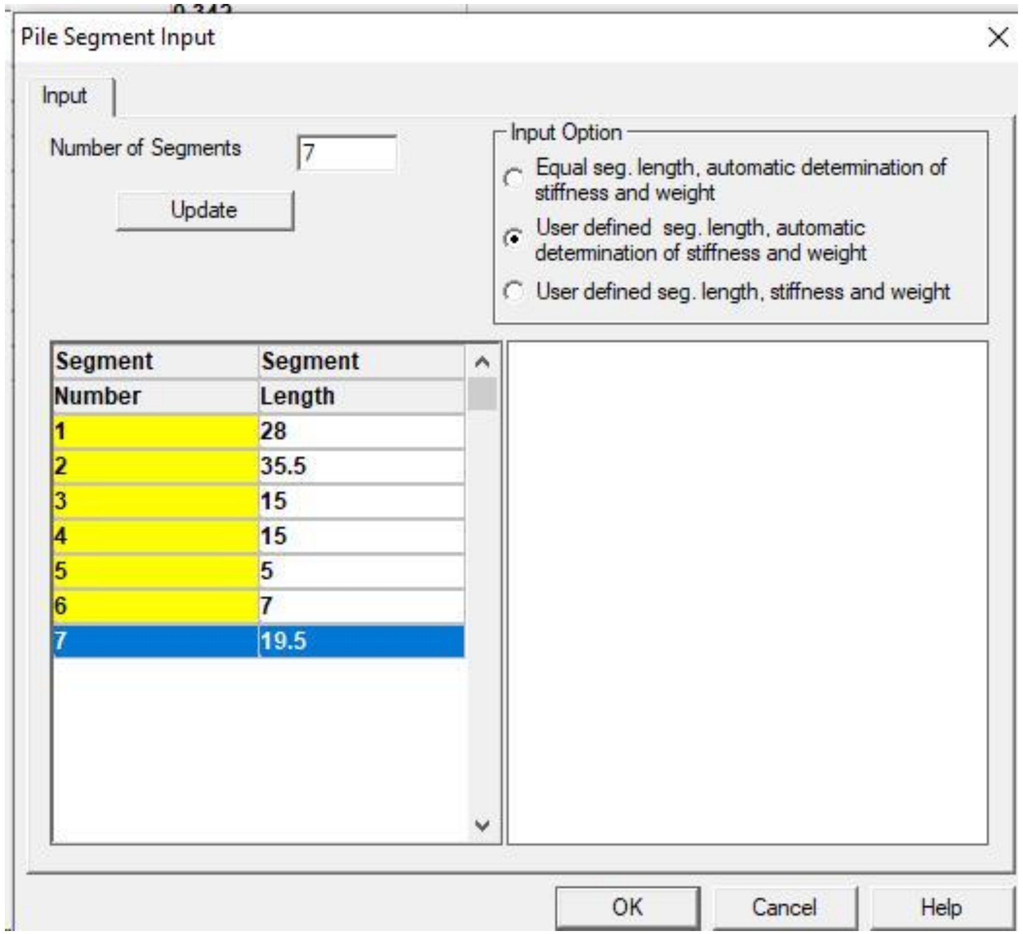
III – Overburden Soil + Coarse Grained Soil based-IGMs + Fine Grained Soil based-IGMs

Subsurface Condition	Geomaterial	Q_s (in)	Q_t (in)	Shaft or Toe Damping (s/ft)
III	Soil	0.1	D/60; Soft soils D/120; Hard soils	0.05 (Coarse); 0.10 (Fine)
	Fine-Grained SB-IGM		D/120	0.18
	Coarse-grained SB-IGM		D/120	0.10

Bearing Graph – Soil/Pile Segment Input

Step 3: Assign new back-calculated quake and damping values





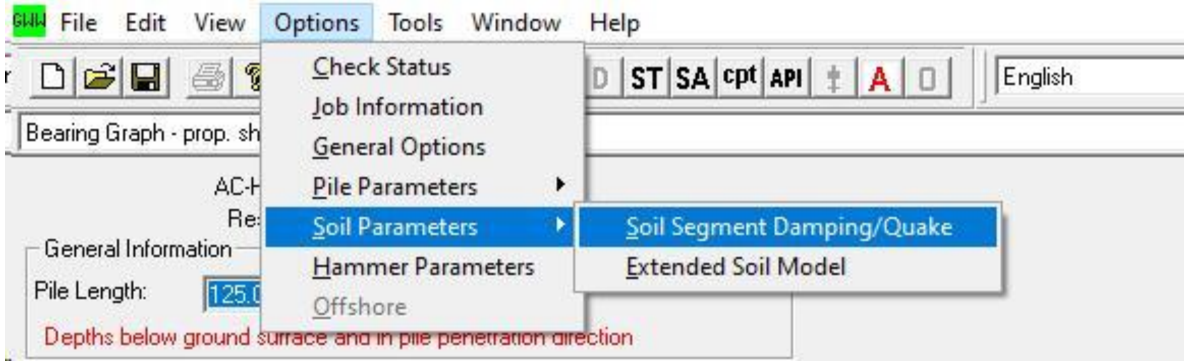
Assign The Soil/Pile Segments

Pile Segment	Geomaterial	Depth (ft)	Description
1	Above Ground	28	None
2	Sand	35.5	Soil
3	Clay	15	Fine-grained soil - based IGM
4	Clay	15	
5	Clay	5	
6	Sand	7	Coarse-grained soil-based IGM
7	Sand	19.5	

Pile Segment Input Form

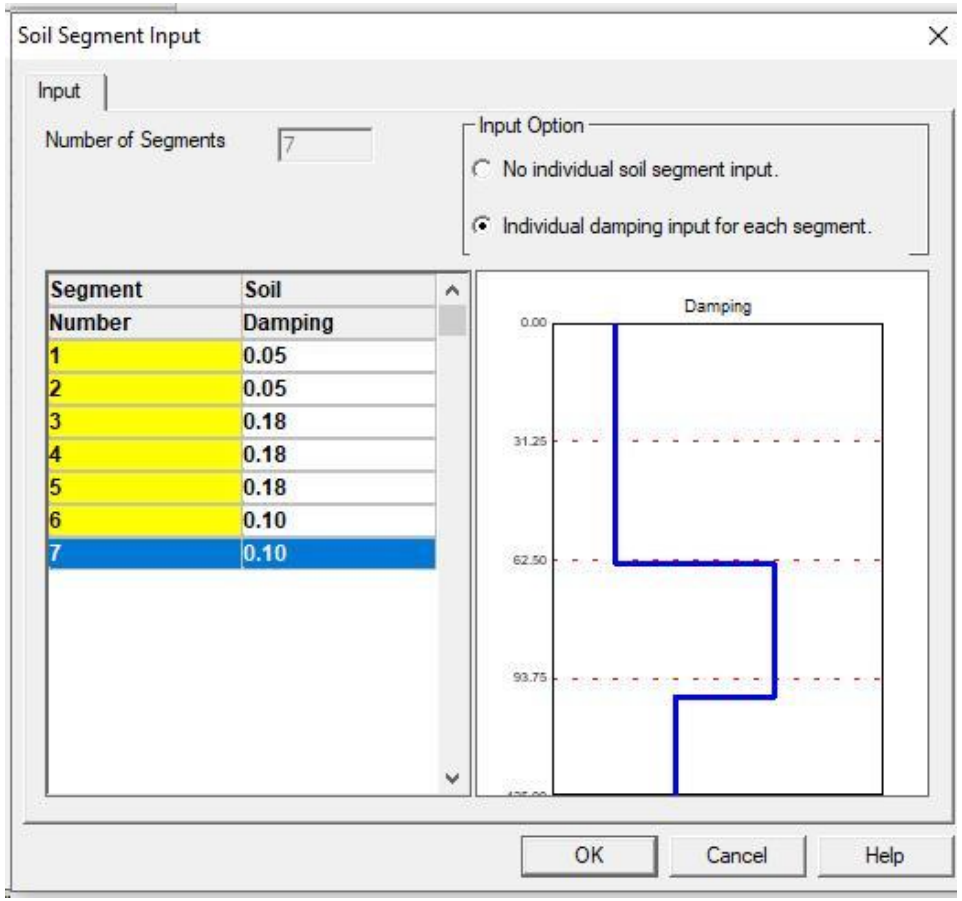
Bearing Graph – Shaft Damping Input

Step 3: Assign new back-calculated quake and damping values



Assign Shaft Damping to Pile Segments

Pile Segment	Geomaterial	Depth (ft)	Description	Damping (s/ft)
1	Above Ground	28	None	Any
2	Sand	35.5	Soil	0.05
3	Clay	15	Fine-grained soil -based IGM	0.18
4	Clay	15		0.18
5	Clay	5		0.18
6	Sand	7	Coarse-grained soil-based IGM	0.10
7	Sand	19.5		0.10

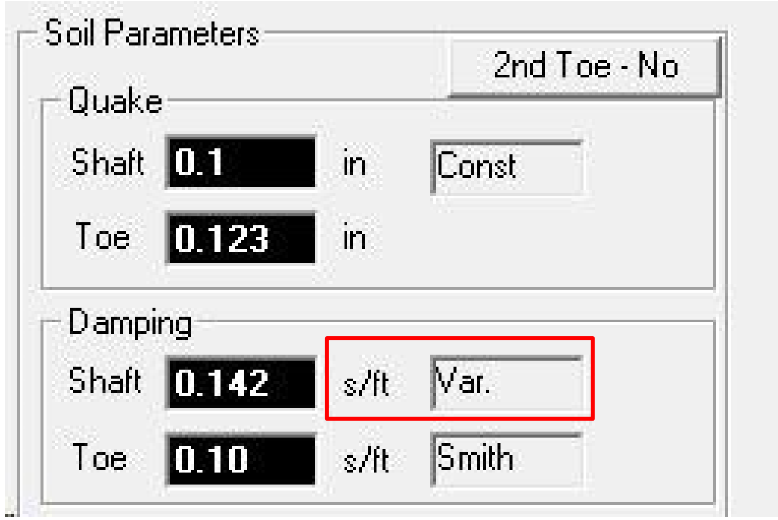


Pile Segment Input Form

Bearing Graph – Quake/Damping Input

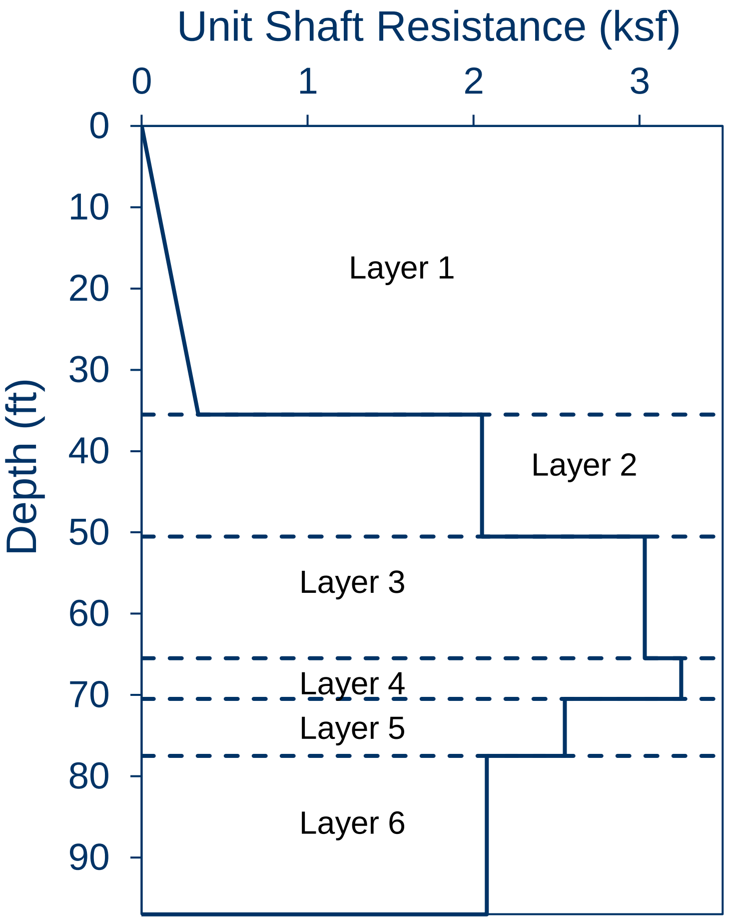
Step 3: Assign new back-calculated quake and damping values

- Toe damping and toe quake are input on the main form



Subsurface Condition	Geomaterial	Q_s (in)	Q_t (in)	Shaft or Toe Damping (s/ft)
III	Soil	0.1	D/60 (Soft soils) D/120 (Hard soils)	0.05 (Coarse); 0.10 (Fine)
	Fine-Grained SB-IGM		D/120	0.18
	Coarse-grained SB-IGM		D/120	0.10

Alternative Method to Input Shaft Damping

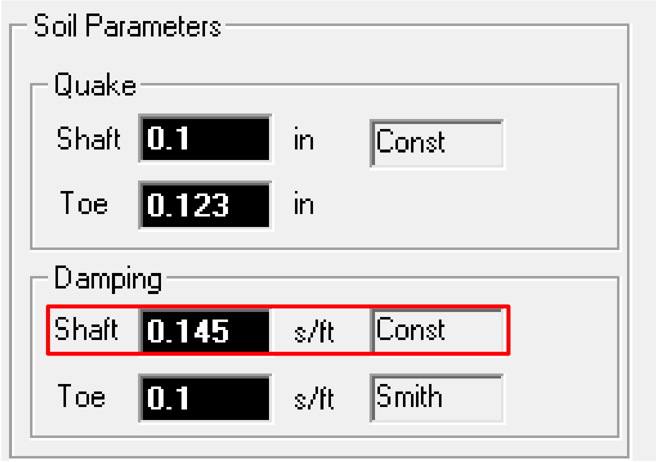


- $J_s = \dfrac{\sum_{i=1}^{n} A_i \times J_i}{\sum_{i=1}^{n} A_i}$

A_i = Area of shaft resistance profile

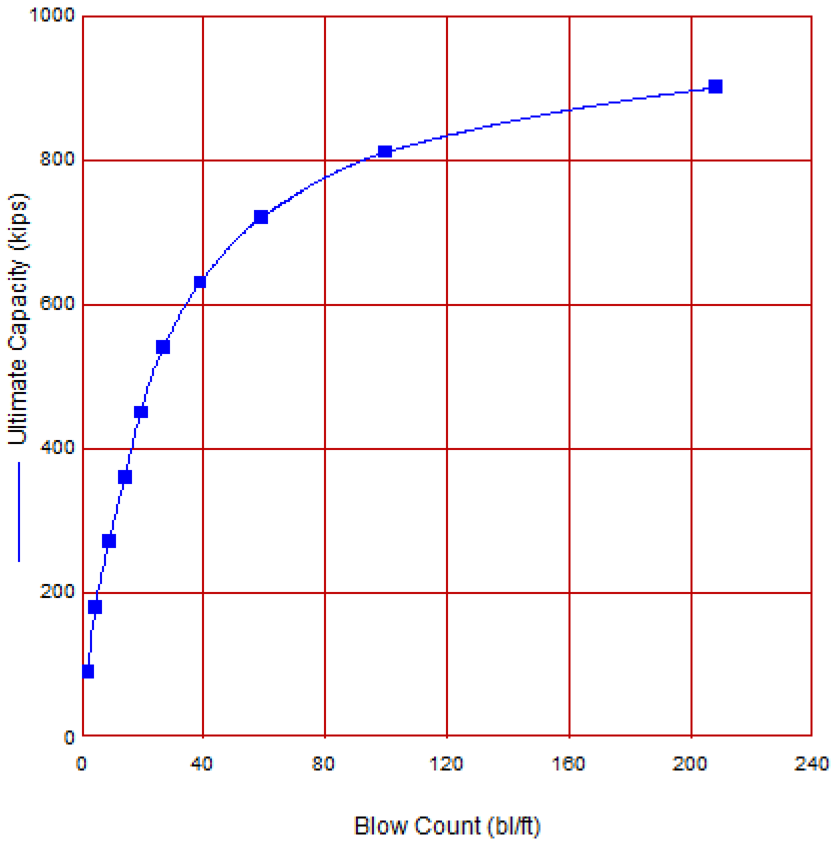
Layer	J_i(s/ft)	A_i	$A_i \times J_i$
1	0.05	6.07	0.30
2	0.18	30.75	5.54
3	0.18	45.45	8.18
4	0.18	16.25	2.93
5	0.1	17.85	1.79
6	0.1	40.56	4.06
	Sum =	156.93	22.79

$$J_s = \frac{22.79}{156.93} = 0.145$$



Proposed WEAP - Bearing Graph Analysis

Step 4: Run bearing graph based on the new percent shaft resistance



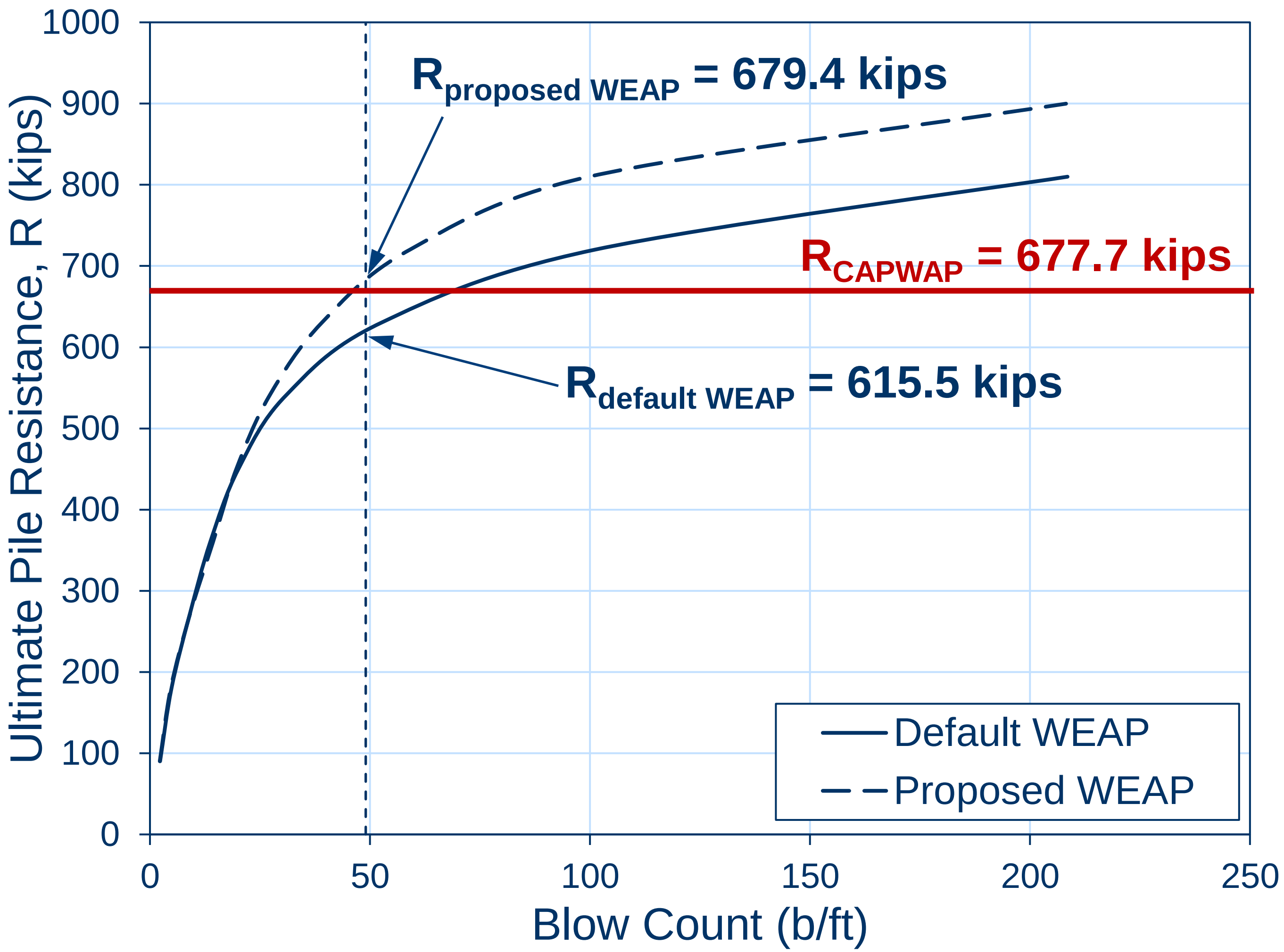
Bearing Graph Using Proposed WEAP

DELMAG D 36

Stroke	8.50 ft
Ram Weight	7.93 kips
Efficiency	0.800
Pressure	Variable
Helmet Weight	1.90 kips
Hammer Cushion	60155 kips/in
COR of H.C.	0.800
Skin Quake	0.100 in
Toe Quake	0.123 in
Skin Damping	Variable
Toe Damping	0.100 sec/ft
Pile Length	125.00 ft
Pile Penetration	97.00 ft
Pile Top Area	30.10 in2

Newly assigned Smith parameters

Default WEAP vs Proposed WEAP



Bearing Graph Comparison for Stoke Height = 8.5 ft and Hammer Blow Count = 49 bl/ft