Determining Bearing Resistance of Cantilever Sheet Piles
BDV31-977-90

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Date
08/05/2021

Background

- The current FDOT practice requires discrete deep foundation (piles or drilled shafts) for bearing purposes.
- Sheet piles to support both vertical bridge loads and lateral earth loads. However, the concept has not survived final design due to the inability to confirm the capacity of these elements in the field and accept them as bearing piles.
- For end bents of small bridges, there is a potential for realizing savings if we can verify the axial resistance of the sheet piling.
- This would also relieve the complications that arise in construction when driving piles and sheet piles in close proximity.

Objectives

I. Quantify the bearing capacity of permanent steel sheet pile walls
II. Evaluate both the friction and bearing components
III. Develop practical recommendations for designers to estimate the bearing capacity of steel sheet pile walls
IV. Develop practical methods to determine and verify the bearing capacity in the field

Research Tasks

Task 1 - Literature Review and Information Collection

Task 2b - Numerical Modeling

Task 3b - Centrifuge Testing Protocol

Task 2c - Numerical Modeling of Sand Layering

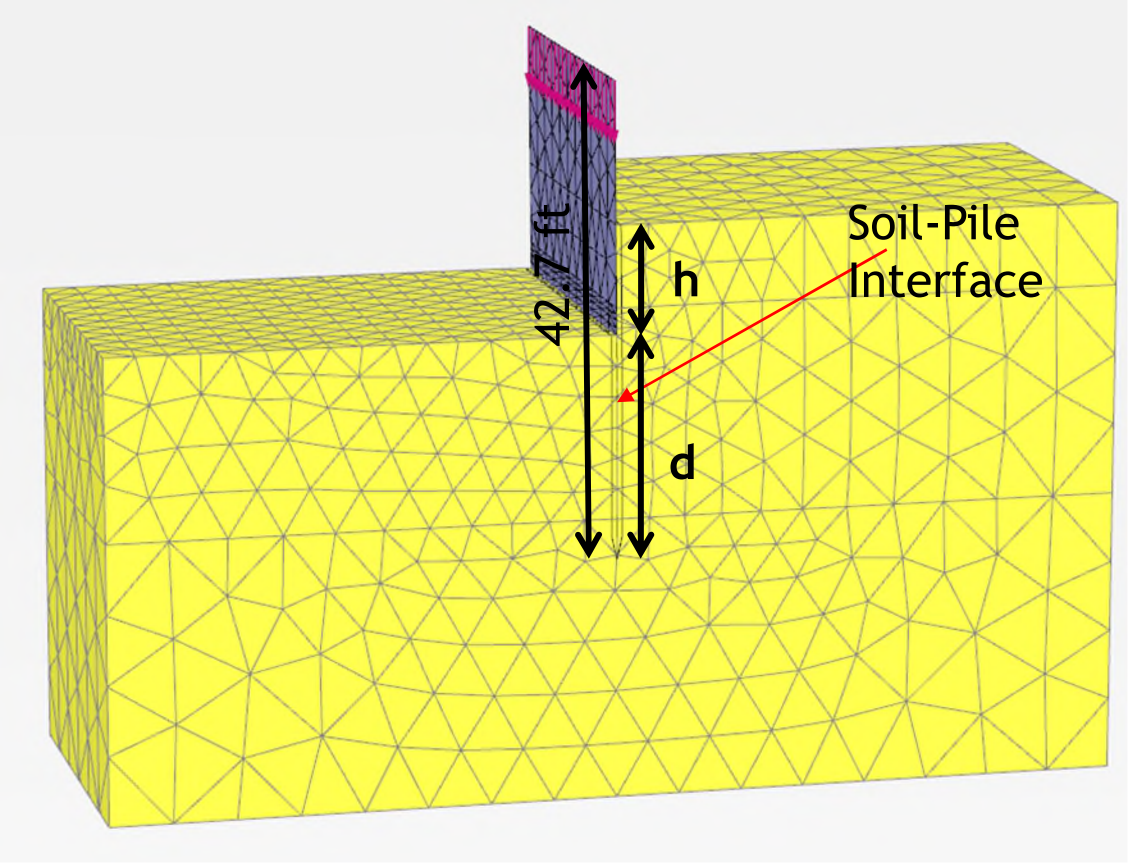
Task 3c – Centrifuge Pile Testing

Task 3c - Numerical Validation & Design Equations

Task 4 - Field testing protocol

Important Variables

- The depth of pile embedded in the soil **d**
- The height of soil retained **h**
- Embedment ratio $r = d/(d+h)$
- Soil relative density D_r
- Soil friction angle ϕ
- The ultimate bearing capacity Q_{ult}



Numerical Validation

Problem Setup

- Figure shows a general solid model for numerical analysis.
- Soil modeled as hardening material using.
- Pile modeled as linear elastic structural plate elements.
- Dimensions of model are at prototype scale of the corresponding centrifuge test.

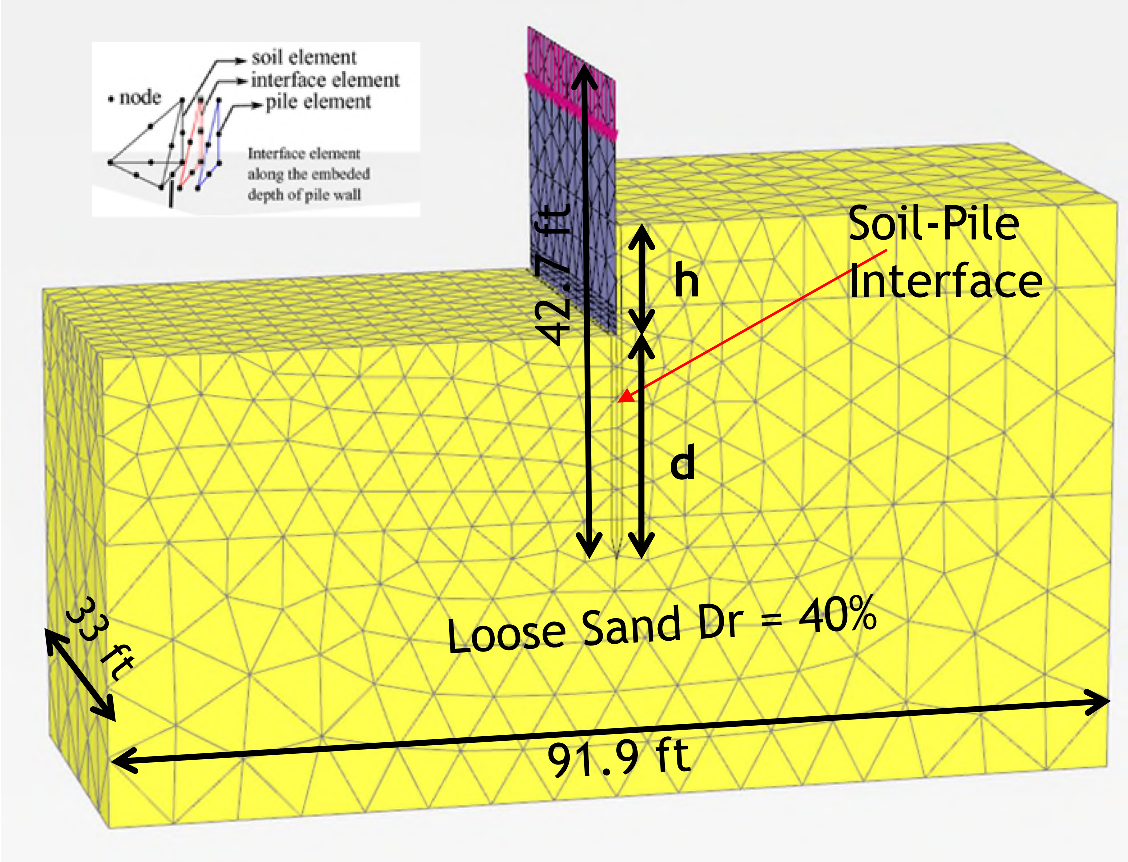


Figure: An example of the problem geometry for an embedded sheet pile wall.

Soil Material Model

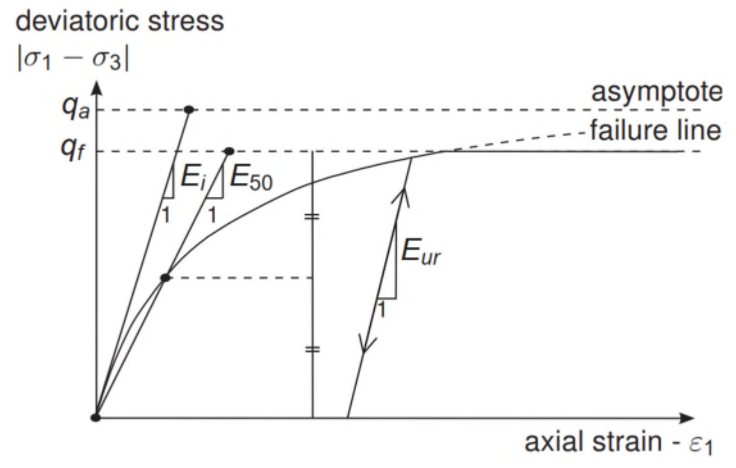
Parameter	Sheet pile	Very dense sand	Dense sand	Interface elements
Material model	Elastic	Hardening Soil	Hardening Soil	Mohr-Coulomb
E_{50}	4385941.2 ksf	1065.0 ksf	789 ksf	500 ksf
E_{oed}	-	1065 ksf	789 ksf	0
E_{ur}	-	3190 ksf	268 ksf	
m		0.44	0.503	
Poisson ratio	0.25	0.2	0.2	-
Friction angle	-	35	32	0.8*Friction Angle
Density	0.486 kip/ft^3	0.1 kip/ft^3	0.105 kip/ft^3	-

$E_{50} = 6E4\ D_r$ kN/m2

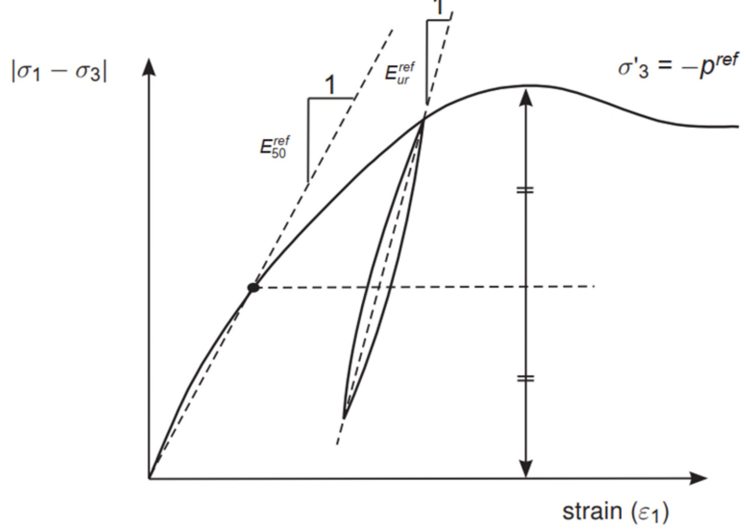
$E_{oed} = 6E4\ D_r$ kN/m2

$E_{ur} = 1.8E5\ D_r$ kN/m2

Equations reproduced from Brinkgreve et al 2010

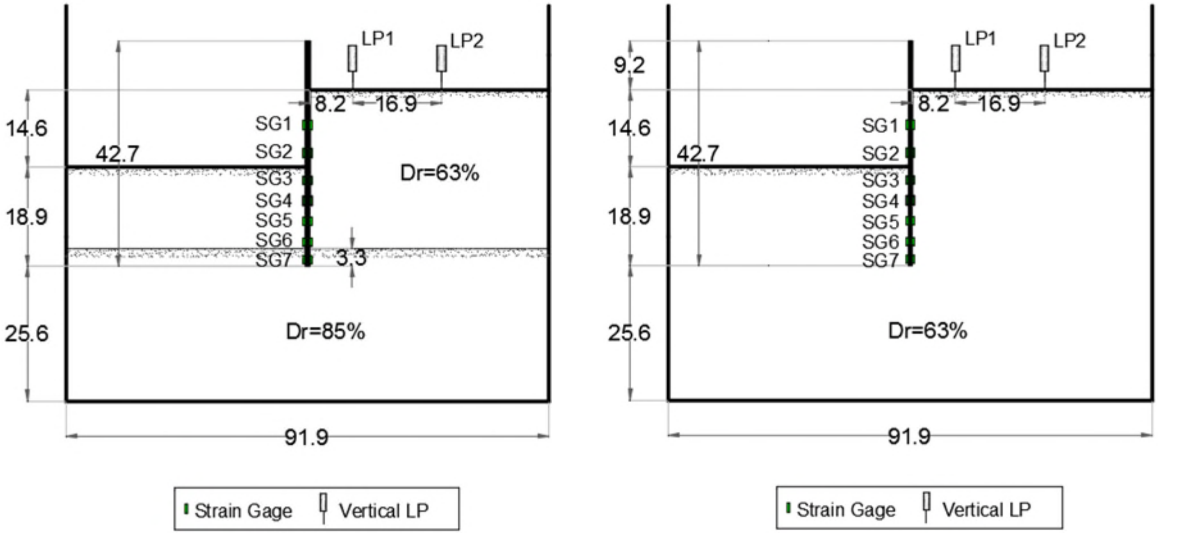


Hyperbolic stress-strain relationship for standard drained triaxial test



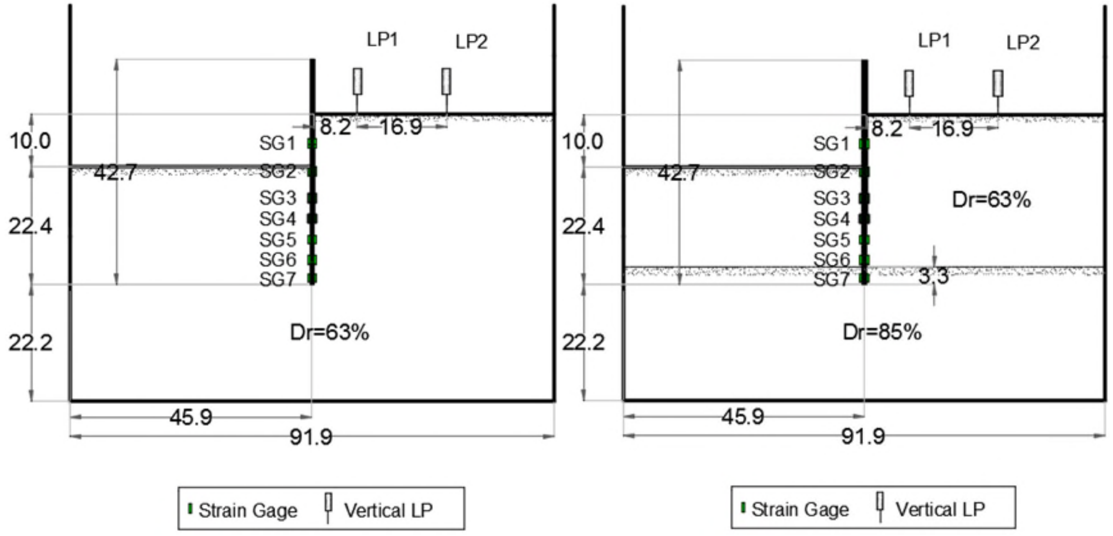
Definition of E_{50} and E_{ur}

Test Setup and Model Scenarios



(a) (b)

Figure: Cross-section of the centrifuge model for tests with r = **d**/**d**+**h**=0.57: (a) two layers of sand (PR2) and (b) homogenous sand (PR1). The dimensions are provided in prototype-scale in feet.



(a) (b)

Figure: Cross-section of the centrifuge model for tests with r = **d**/**d**+**h**= 0.69: (a) homogenous sand (PR3); and (b) two layers of sand (PR4). The dimensions are provided in prototype-scale in feet.

Example Test Results

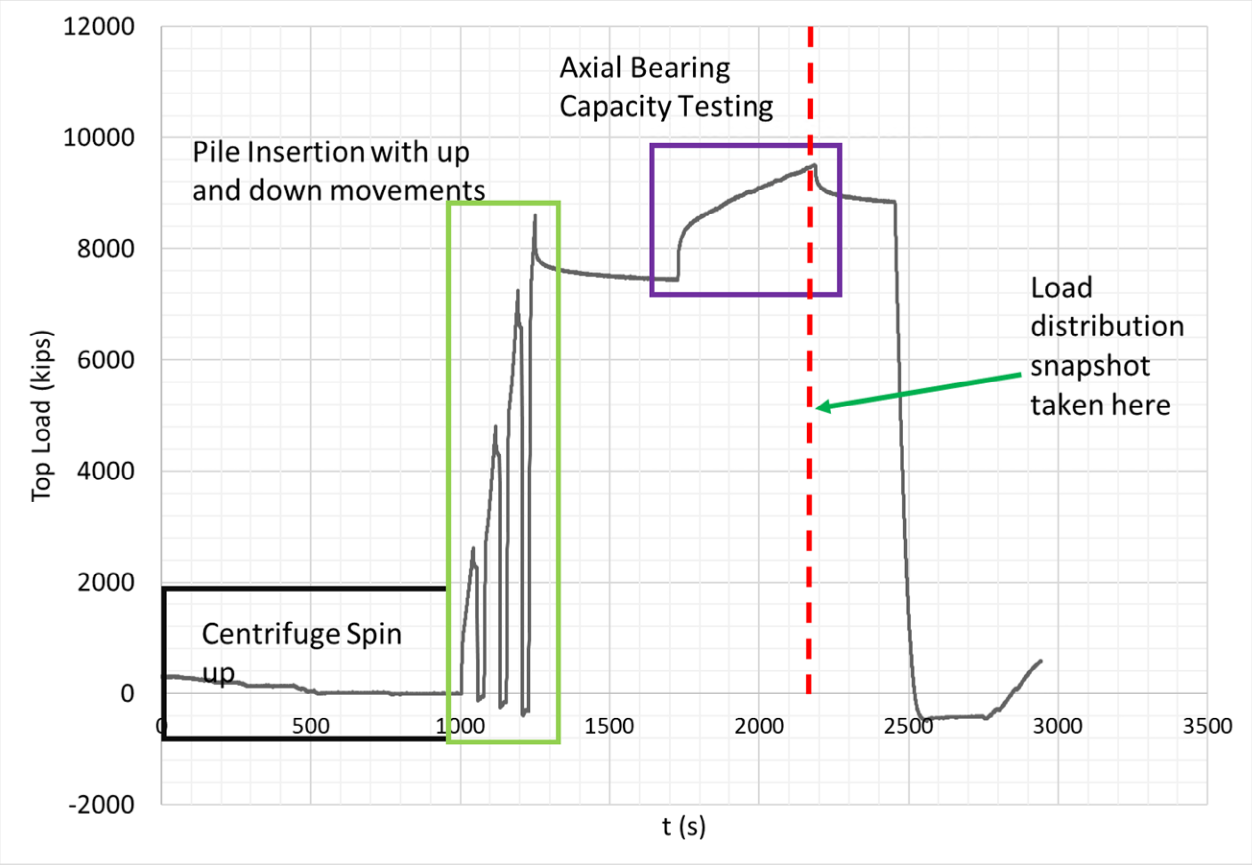
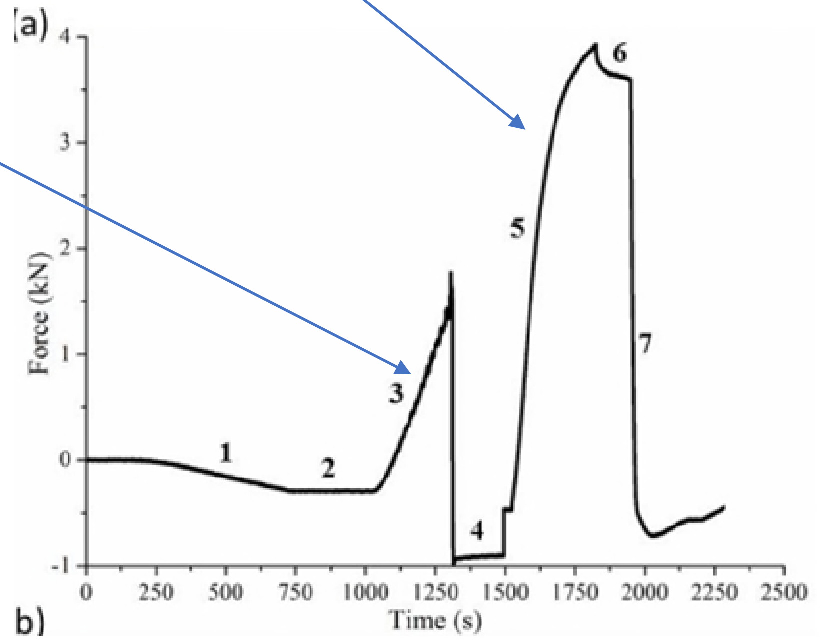


Figure: Time history of the top load (from LC) over the duration of the test

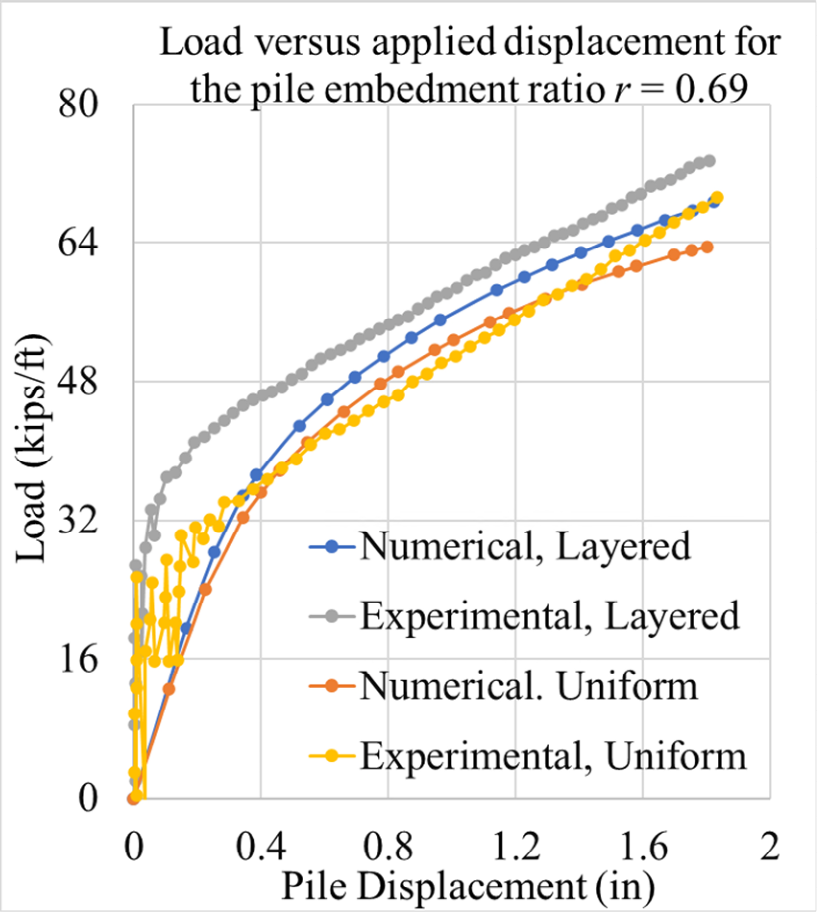
Load test

Insertion



Al-Baghdadi, T. A., Michael J. Brown, and Jonathan A. Knappett. "Development of an inflight centrifuge screw pile installation and loading system." *3rd European Conference on Physical Modelling in Geotechnics*. IFSTTAR, 2016.

Numerical & Experimental Load Curves



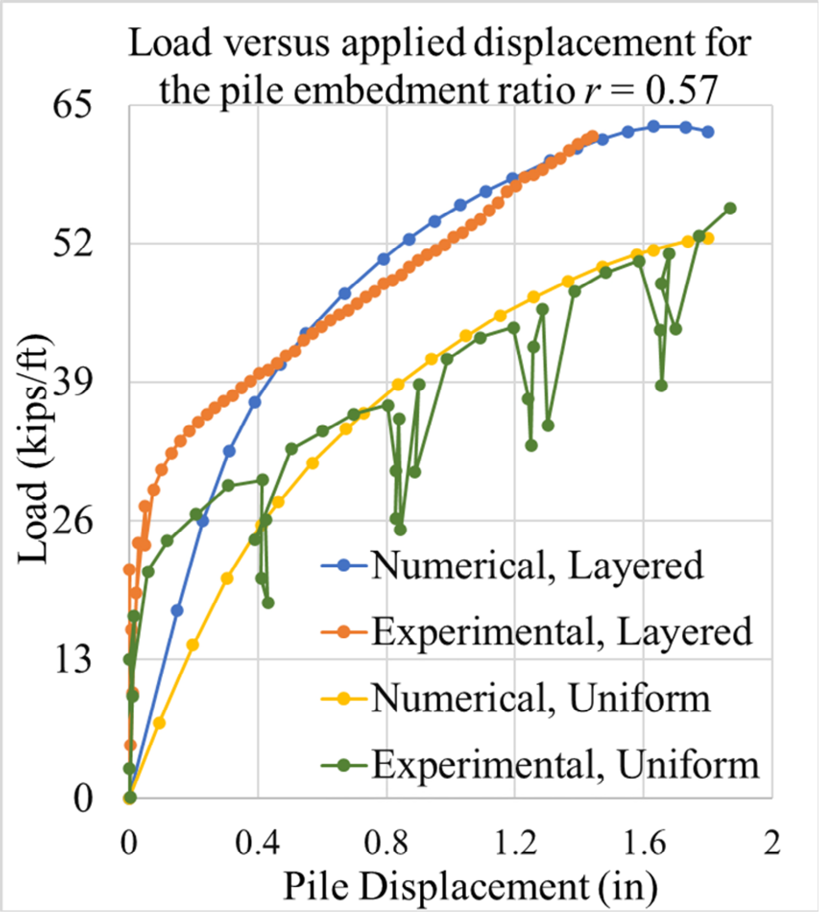


Figure: Plot of load versus vertical displacement from numerical model and centrifuge test for (left) embedment ratio r = 0.69 (right) embedment ratio r = 0.57

Summary - 1

- Though not identical, the numerical model captured the hardening response observed in the centrifuge pile test.

- The mismatch during the early stages of the simulation may be due to effects like soil densification and plugging in the experiment.

Design Equations for Sheet Pile Walls

Parametric Analysis

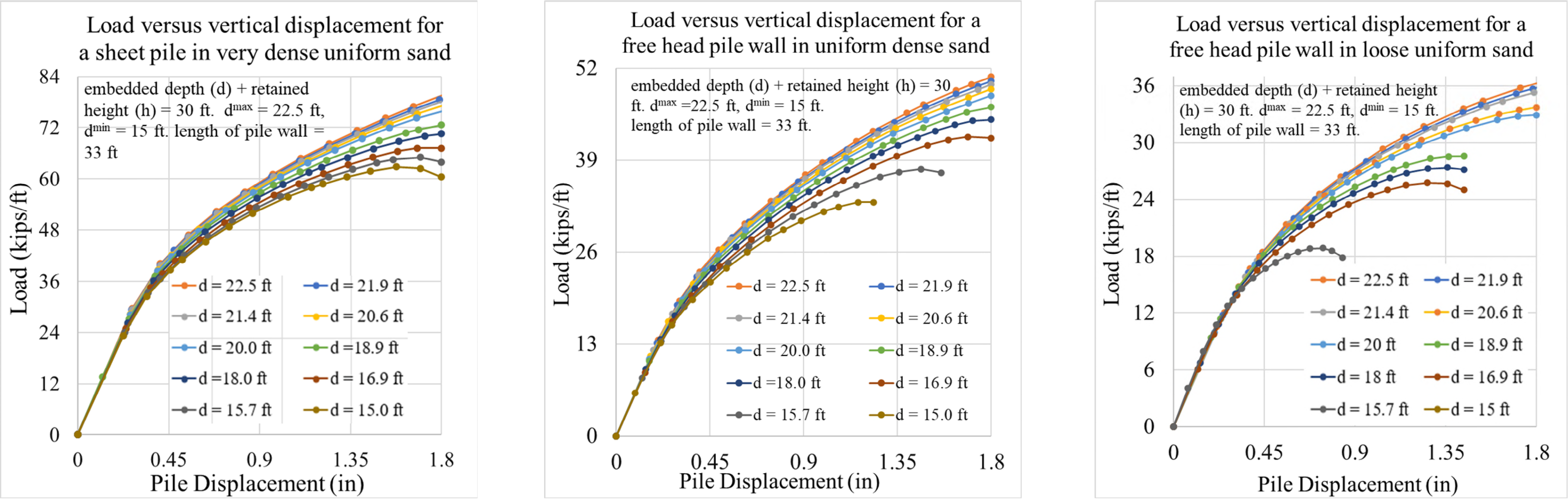
Parameter	No. of Cases	No. of Pile Depths Considered	Total No. of Simulations
Density	3	10 (15 – 22.5 ft)	30
Tip Resistance	2	10 (15 – 22.5 ft)	20
Head Boundary	2	10 (15 – 22.5 ft)	20

- The base simulations are conducted using uniform sand profile for 10 embedment ratios in 3 different sands (density and friction angle)

- The effect of tip resistance is modeled using soil layering: the tip of the pile wall is embedded in very dense sand which is overlaid by different sand layer

- The influence of the head boundary conditions is studied by comparing a fixed and free head condition in identical pile-soil systems (both layered and uniform).

Relative density & Bearing Capacity



Plots of applied load versus displacement (left) D_r =85 % (ϕ = 35°), (center) D_r = 63 % (ϕ = 32°), and (right) D_r = 40 % (ϕ = 27°)

Relative density– Power Law Fit

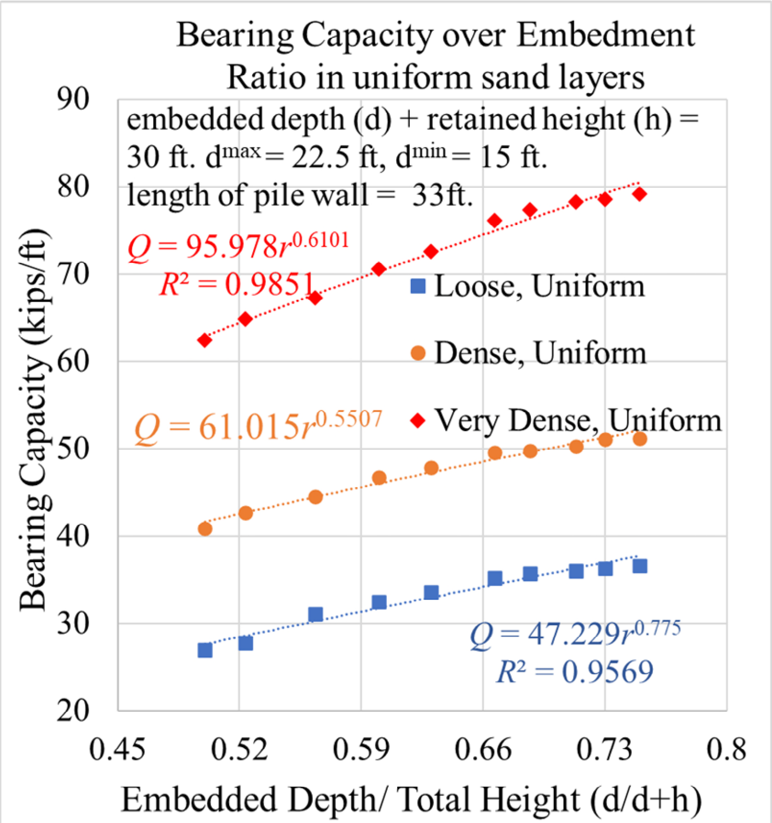


Figure: Plot comparing the bearing capacity over the embedment for different soil densities

Given $r = \frac{d}{d+h}$ and the internal friction angle, ϕ^*

$$Q_{ult} = (100 \times \phi) r^{0.6101} \text{ kips/ft}, \quad \text{(loose)}$$

$$Q_{ult} = (109 \times \phi) r^{0.5507} \text{ kips/ft}, \quad \text{(medium dense)}$$

$$Q_{ult} = (157.5 \times \phi) r^{0.775} \text{ kips/ft}, \quad \text{(very dense)}$$

Note: these equations are valid for the 33 ft long sheet pile in the model.

*For these equations, the internal friction angle was taken as 0.47, 0.56 and 0.61 radians for loose, dense and very dense sand, respectively.

Summary - 2

- As expected, bearing capacity increases with density/friction angle.
- A nonlinear relationship (power law) is proposed relating the ultimate capacity to the embedment ratio and friction angle.
- The specific relationship used is determined by the range of soil-density.

Soil Layering Profiles

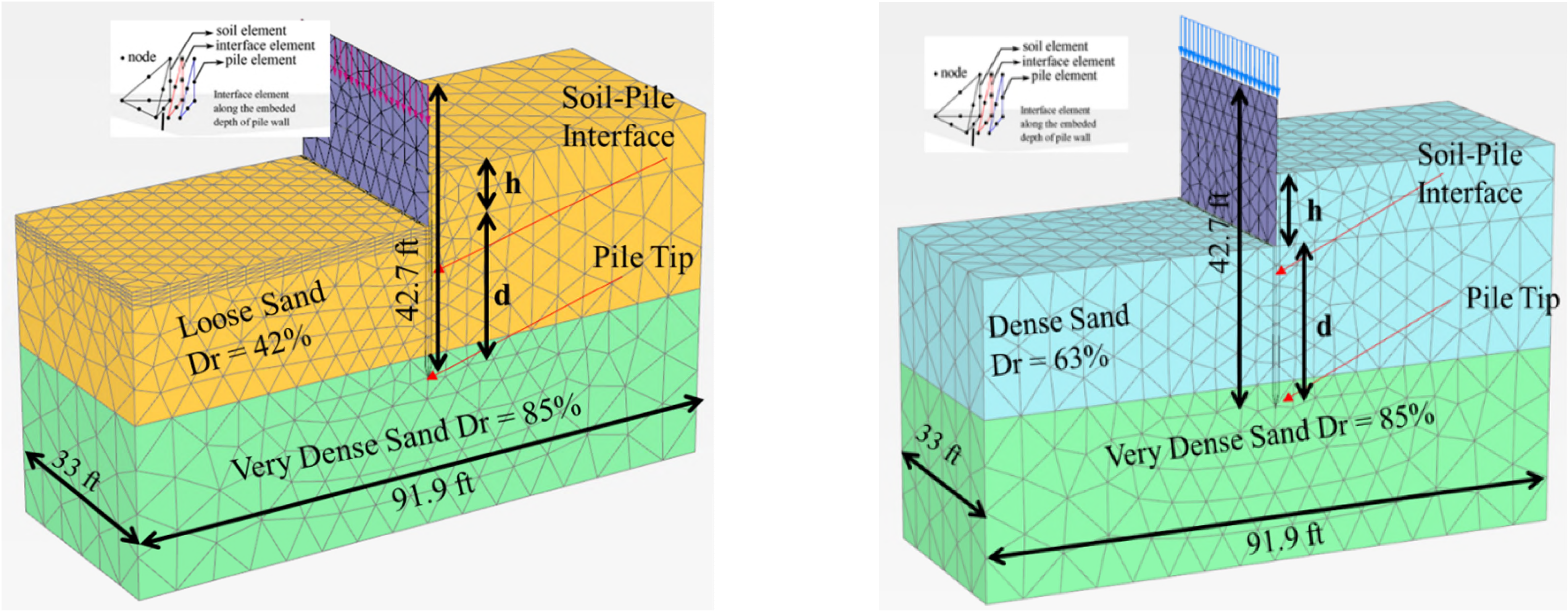


Figure: An illustration of the (left) layered soil profile A (loose sand over very dense sand) and (right) layered soil profile B (dense sand over very dense sand).

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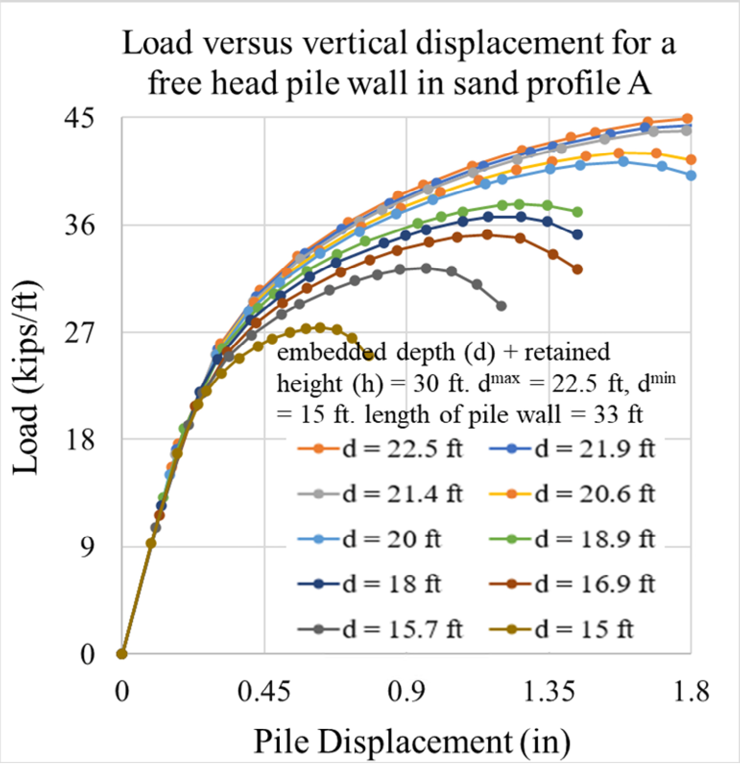
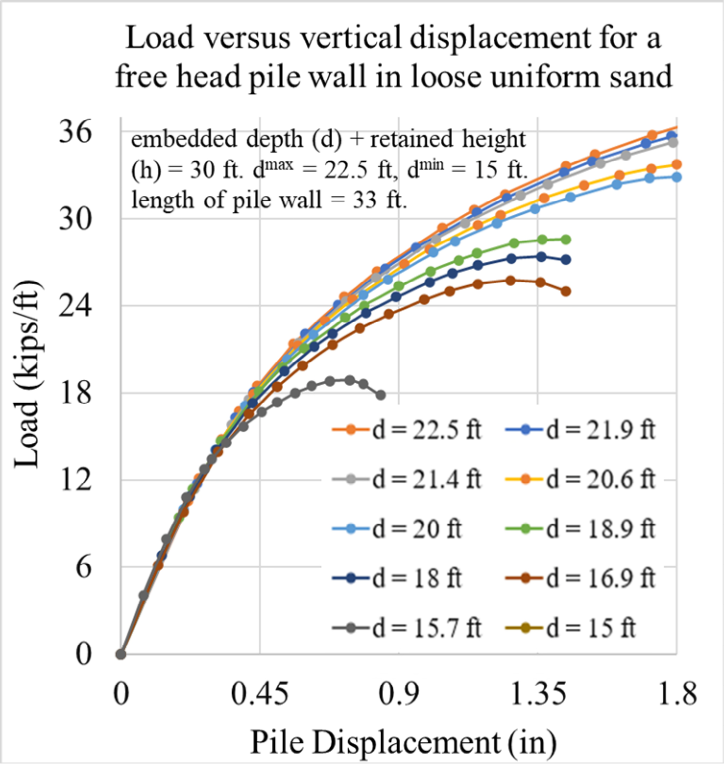
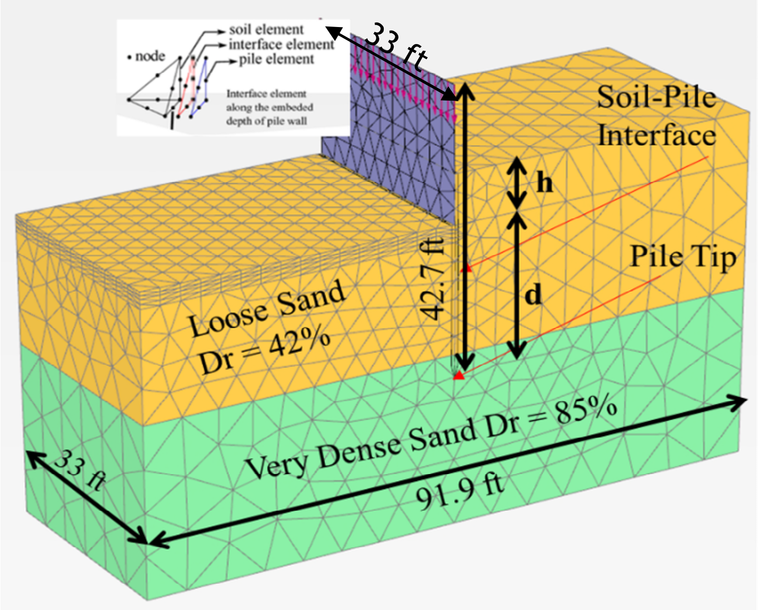
Soil Layering & Bearing Capacity I

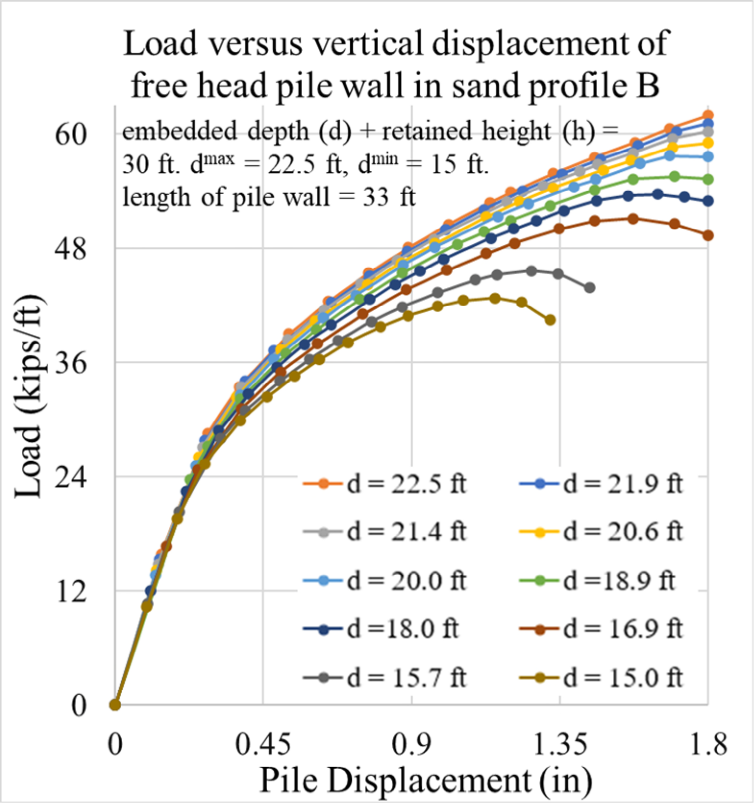


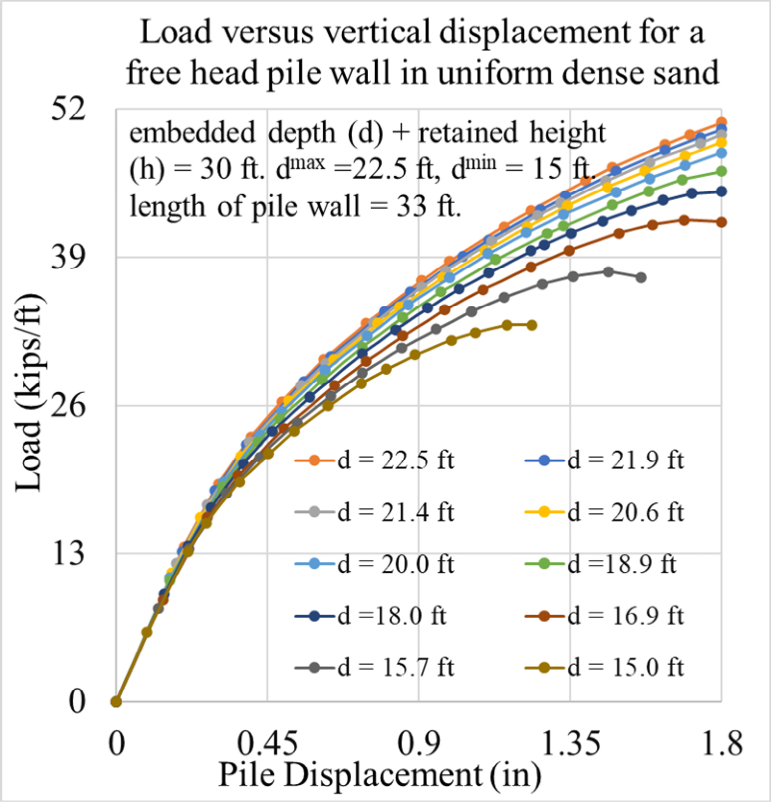


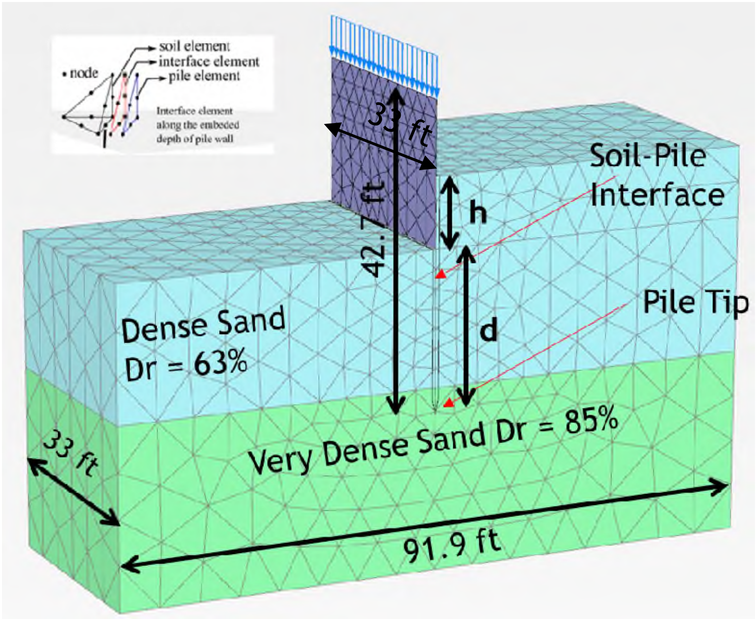


Plot of load versus displacement for a sheet pile embedded in (left) uniform loose soil and (right) layered profile A (loose sand over very dense sand)

Soil Layering & Bearing Capacity II







Plot of load versus displacement for a sheet pile embedded in (left) uniform dense soil and (right) layered profile B (dense sand over very dense sand)

Influence of Soil Layering – Power Law Fit

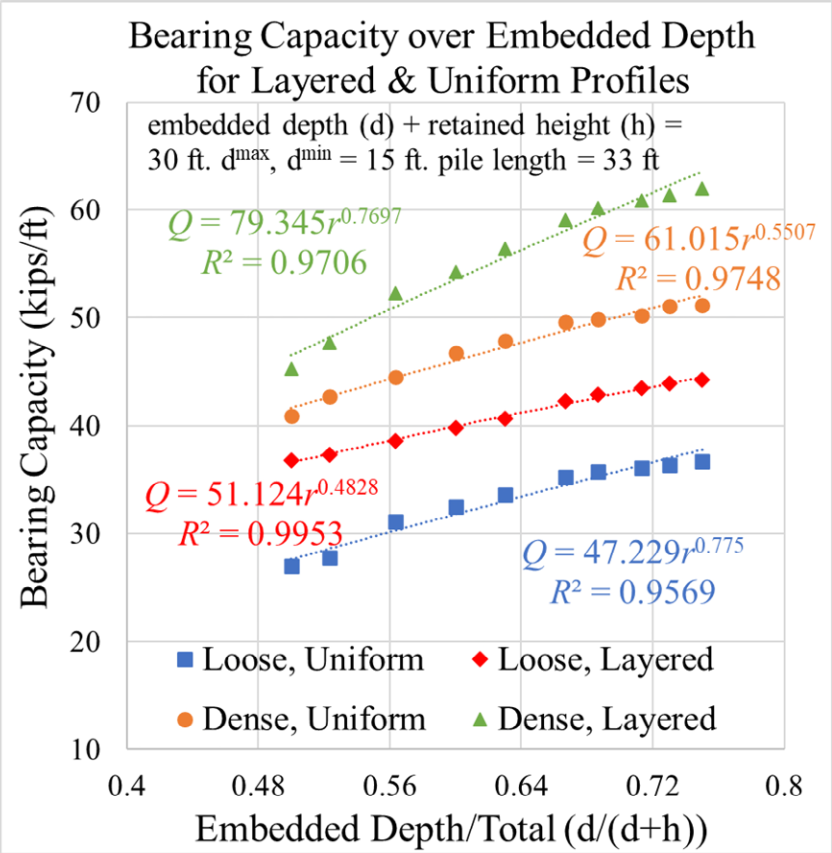


Figure: Plot comparing the bearing capacity over the embedment for layered and uniform soil profiles

Given $r = \frac{d}{d+h}$ and the internal friction angle, ϕ^*

$$Q_{ult} = 1.3(109 \times \phi)r^{0.7697} \text{ kips/ft}, \quad \text{(dense layered)}$$

$$Q_{ult} = (109 \times \phi)r^{0.5507} \text{ kips/ft}, \quad \text{(dense uniform)}$$

$$Q_{ult} = 1.1(100 \times \phi)r^{0.4828} \text{ kips/ft}, \quad \text{(loose layered)}$$

$$Q_{ult} = (100 \times \phi)r^{0.775} \text{ kips/ft}, \quad \text{(loose uniform)}$$

Note: these equations are valid for the 33 ft long sheet pile in the model.

*For these equations, the internal friction angle was taken as 0.47, 0.56 and 0.61 radians for loose, dense and very dense sand, respectively.

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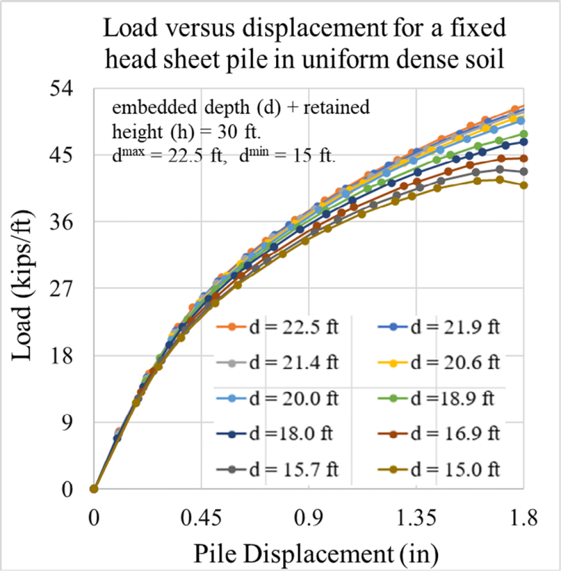
Summary - 3

- Embedding the pile tip in very dense sand increases bearing capacity by increasing pile tip resistance.
- For profile A (loose sand over very dense sand) pile tip resistance is more important for a $r < 0.6$.
- For profile B (dense sand over very dense sand) pile tip resistance does not appear to be significant.
- The power law relationships for the layered sand layer are modified by coefficients for the corresponding uniform profile.

Head Fixity – Uniform Soil



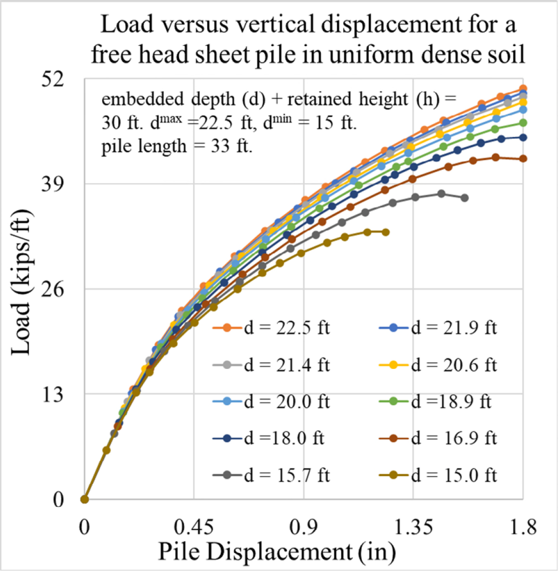
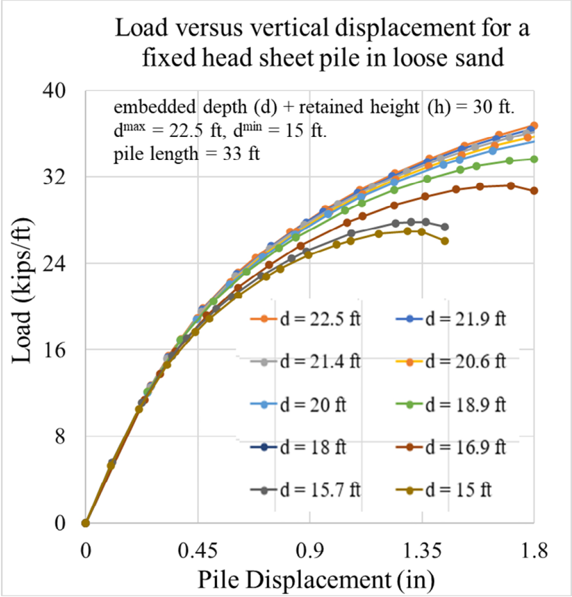


Figure: Plot of the load versus applied displacement for (left) a fixed head pile and (right) free head pile in **uniform dense** sand



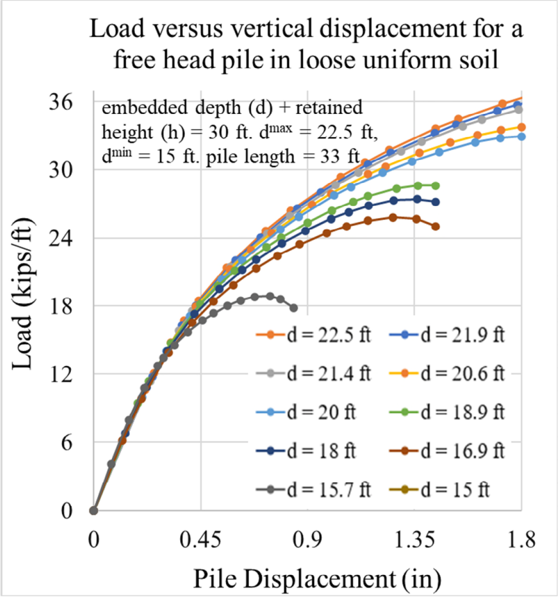


Figure: Plot of the load versus applied displacement for (left) a fixed head pile and (right) free head pile different embedment ratios in **uniform loose** sand

Head Fixity – Uniform Soil Power Law Fit

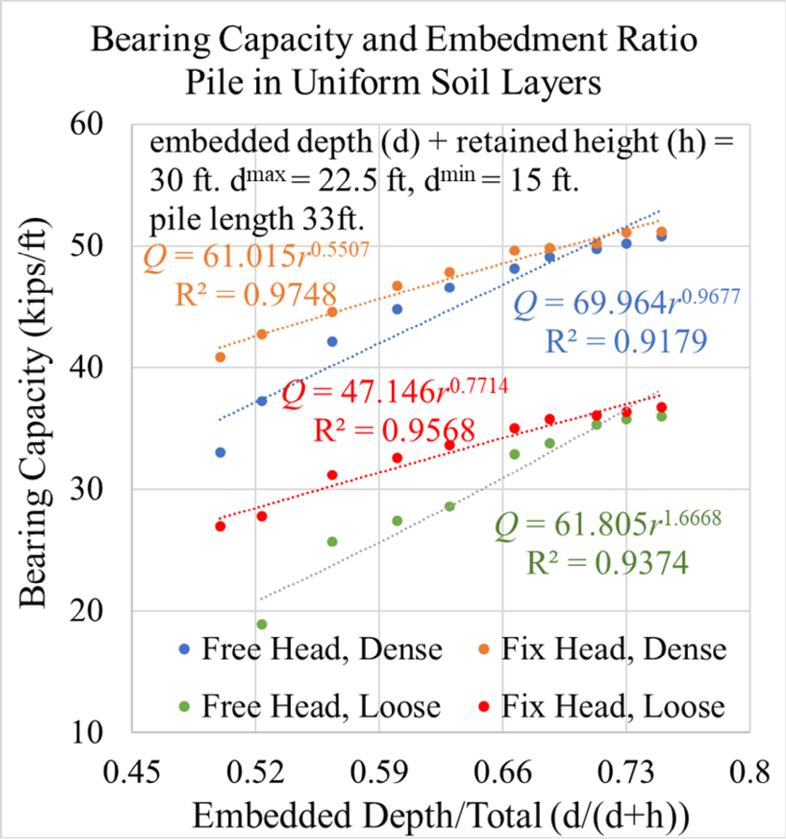


Figure: Plot comparing the bearing capacity over embedment ratio for different head boundary condition in uniform soil profiles

Given $r = \frac{d}{d+h}$ and the internal friction angle, ϕ^*

$$Q_{ult} = (109 \times \phi) r^{0.5507} \text{ kips/ft}, \quad \text{(dense fixed head)}$$

$$Q_{ult} = 1.15(109 \times \phi) r^{0.9677} \text{ kips/ft}, \quad \text{(dense free head)}$$

$$Q_{ult} = (100 \times \phi) r^{0.7714} \text{ kips/ft}, \quad \text{(loose fixed head)}$$

$$Q_{ult} = 1.3(100 \times \phi) r^{1.6668} \text{ kips/ft}, \quad \text{(loose free head)}$$

Note: these equations are valid for the 33 ft long sheet pile in the model.

*For these equations, the internal friction angle was taken as 0.47, 0.56 and 0.61 radians for loose, dense and very dense sand, respectively.

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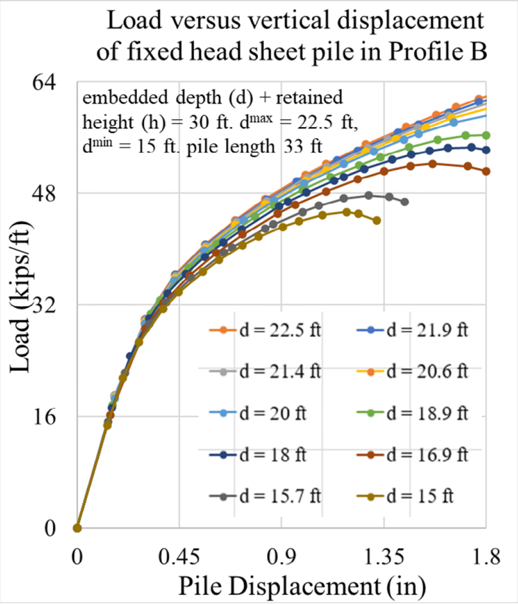
Summary - 4

- Head fixity can increase bearing capacity for low embedment ratios (r < 0.6)

- Head fixity is also more influential with loose sand

- For embedment ratio r>0.66 head fixity condition is not a significant factor irrespective of soil density

Head Fixity – Layered Soil



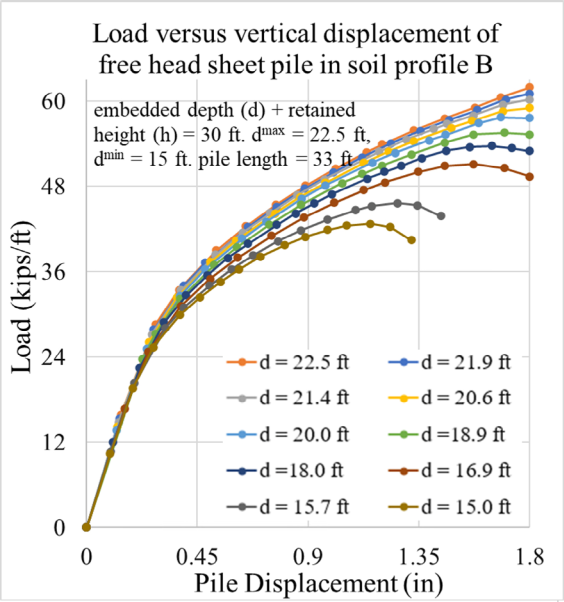
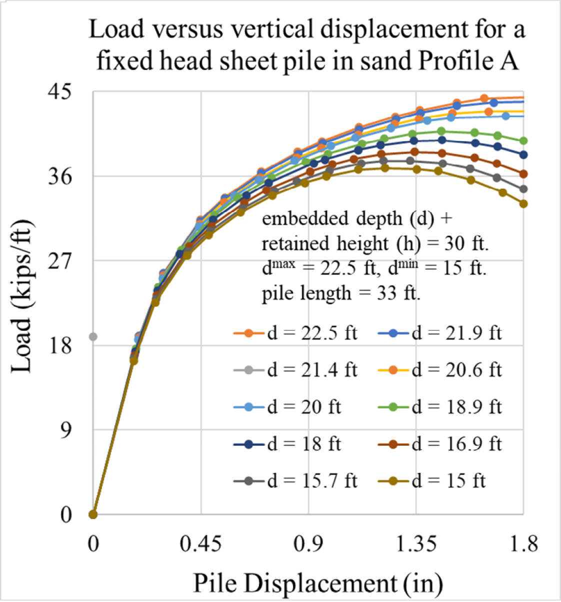


Figure: Plot of the load versus applied displacement for (left) a fixed head pile and (right) free head pile in **layered sand profile B**



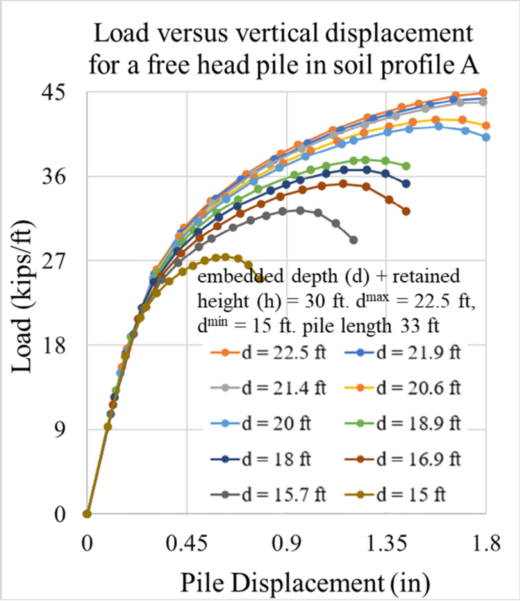


Figure: Plot of the load versus applied displacement for (left) a fixed head pile and (right) free head pile in **layered sand profile A**

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Head Fixity – Layered Soil Power Law Fit

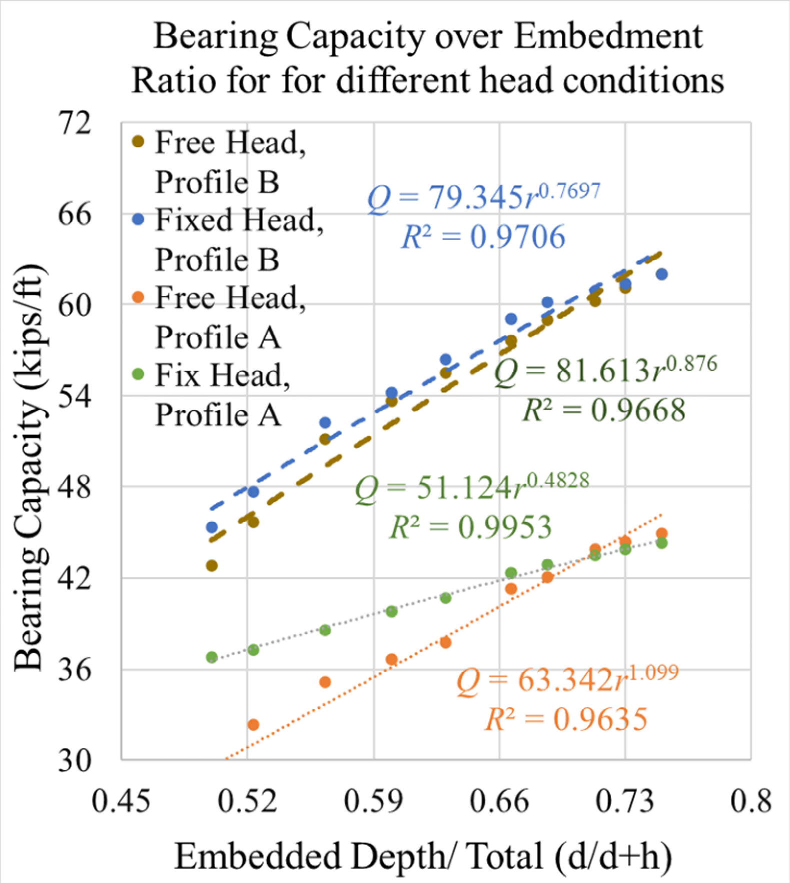

Figure: Plot comparing the bearing capacity over embedment ratio for different head boundary condition

Given $r = \frac{d}{d+h}$ and the internal friction angle, ϕ^*

$$Q_{ult} = 1.3(109 \times \phi)r^{0.7697} \text{ kips/ft}, \qquad \text{(Profile B fixed head)}$$
$$Q_{ult} = 1.3(112.9 \times \phi)r^{0.876} \text{ kips/ft}, \qquad \text{(Profile B free head)}$$
$$Q_{ult} = 1.1(100 \times \phi)r^{0.4828} \text{ kips/ft}, \qquad \text{(Profile A fixed head)}$$
$$Q_{ult} = 1.1(123.2 \times \phi)r^{1.099} \text{ kips/ft}, \qquad \text{(Profile A free head)}$$

Note: these equations are valid for the 33 ft long sheet pile in the model.

*For these equations, the internal friction angle was taken as 0.47, 0.56 and 0.61 radians for loose, dense and very dense sand, respectively.

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Summary - 5

- Head boundary condition has very little influence on bearing capacity for profile B (dense sand over very dense sand).

- Conversely, has a strong influence in profile A (loose sand over very dense sand) when embedment ratio r<0.6 .

- For embedment ratio r>0.66 head condition is not a significant factor for either soil profile.

Design Equations

- Numerical model of vertically loaded sheet pile walls was validated centrifuge load testing
- Validated model was used to generate design equations

Soil Density

$$Q_{ult} = (109 \times \phi) r^{0.5507} \text{ kips/ft}, \quad \text{(dense uniform)}$$

$$Q_{ult} = (100 \times \phi) r^{0.775} \text{ kips/ft}, \quad \text{(loose uniform)}$$

Soil Layering

$$Q_{ult} = 1.3(109 \times \phi) r^{0.7697} \text{ kips/ft}, \quad \text{(dense layered)}$$

$$Q_{ult} = 1.1(100 \times \phi) r^{0.4828} \text{ kips/ft}, \quad \text{(loose layered)}$$

Head Fixity - Uniform

$$Q_{ult} = 1.15(109 \times \phi) r^{0.9677} \text{ kips/ft}, \quad \text{(dense free head)}$$

$$Q_{ult} = 1.3(100 \times \phi) r^{1.6668} \text{ kips/ft}, \quad \text{(loose free head)}$$

Head Fixity - Layered

$$Q_{ult} = 1.3(112.9 \times \phi) r^{0.876} \text{ kips/ft}, \quad \text{(Profile B free head)}$$

$$Q_{ult} = 1.1(123.2 \times \phi) r^{1.099} \text{ kips/ft}, \quad \text{(Profile A free head)}$$

Note: these equations are valid for the 33 ft long sheet pile in the model.

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Field testing protocol

Steel sheet pile

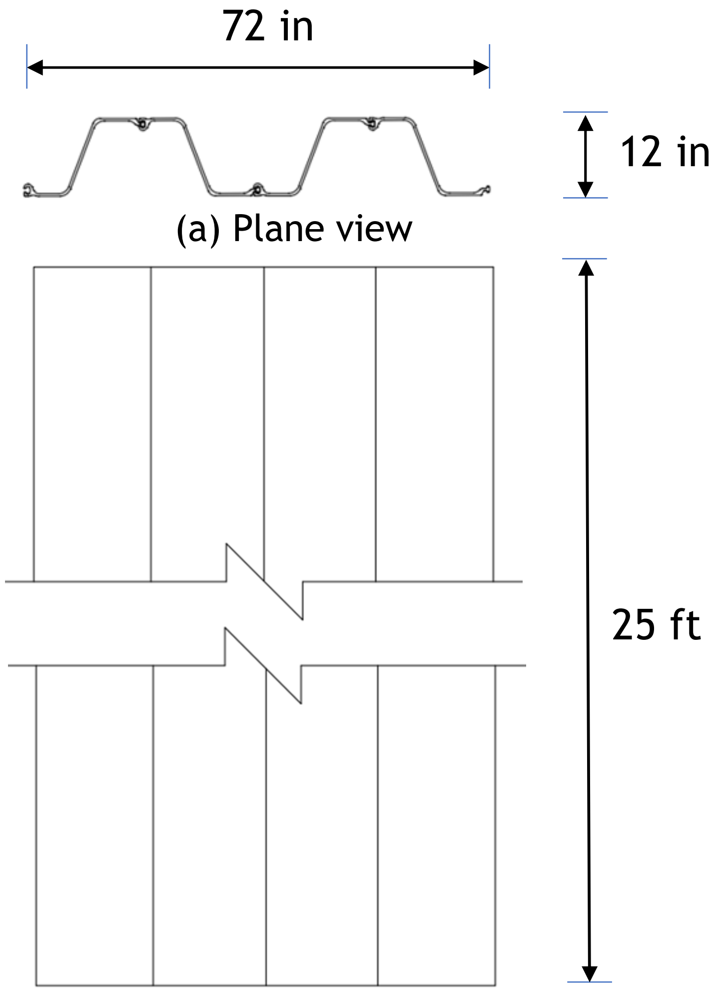


Figure: Grouped sheet piles

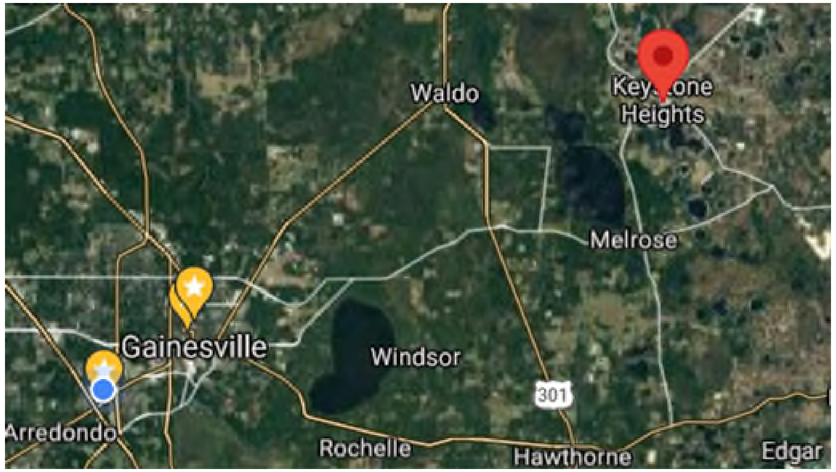
- Four PZ 27 sections, e.g., a sheet pile wall of length 72 in
- Length of each sheet pile: 25 ft

Steel sheet pile — NUCOR SKYLINE **(delivered in 1 or 2 weeks)**

Installation — FARRELL BROS MARINE CONSTRUCTION, INC.

Static load test — AFT APPLIED FOUNDATION TESTING Specialty Geotechnical Services provides reaction beams, tie-down beams, load cells, hydraulic jacks, and strain gages.

Site location - Keystone Heights



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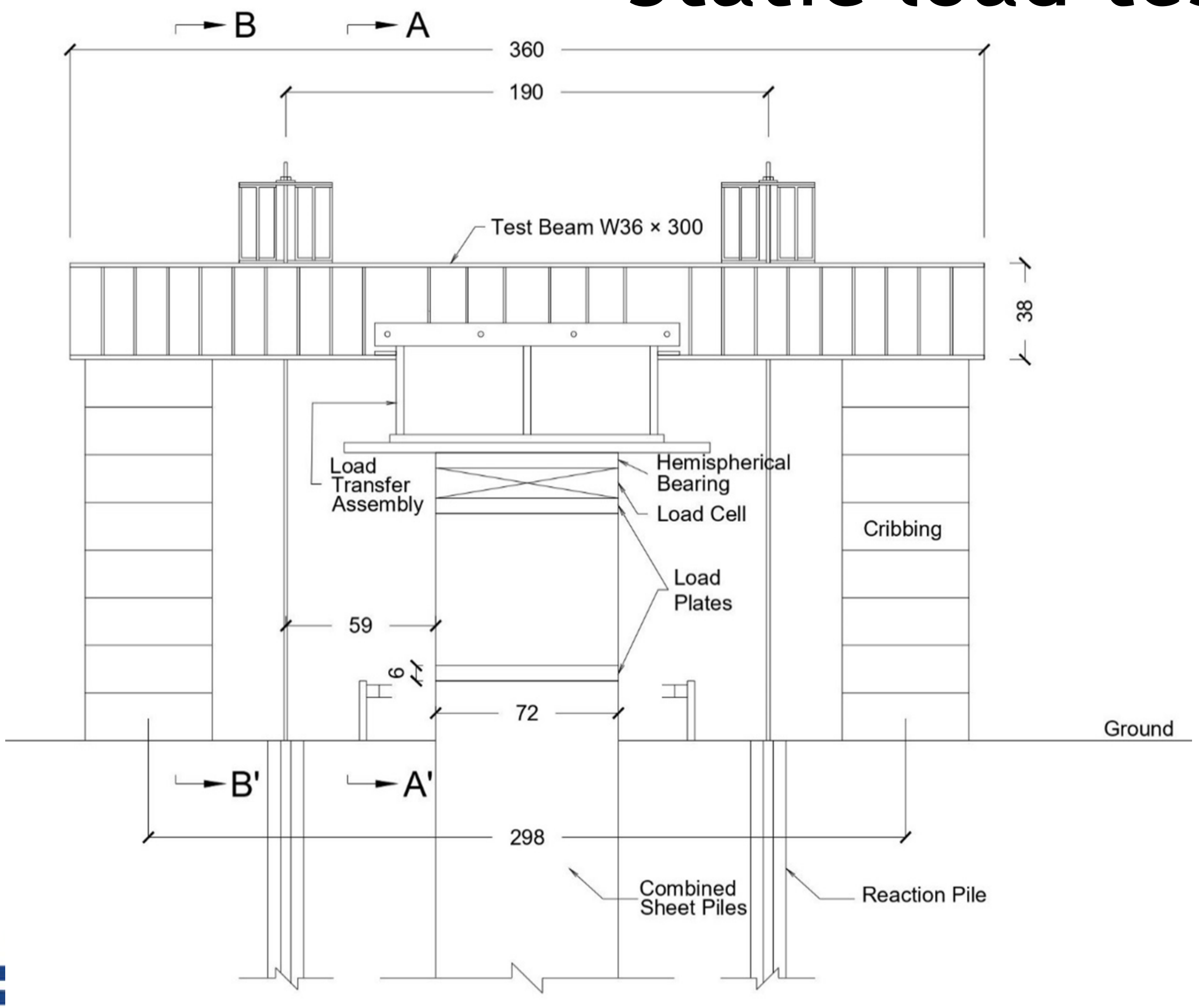
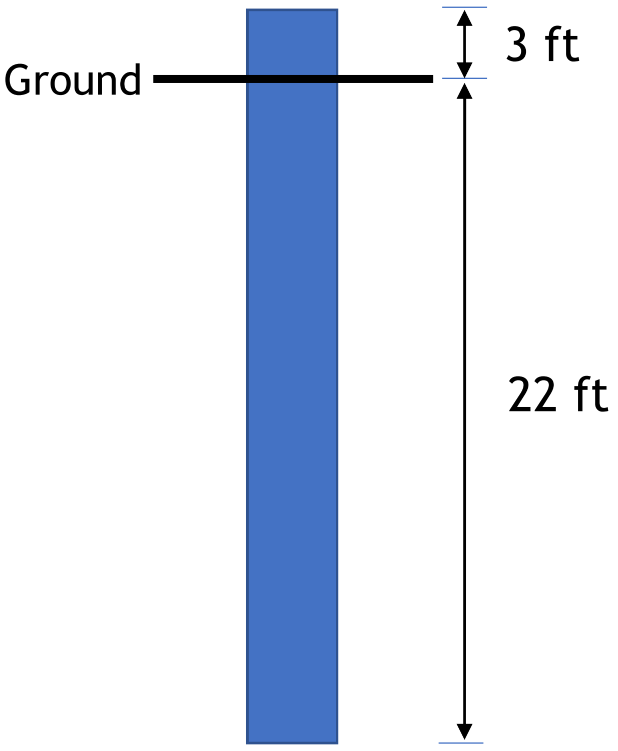
Static load test setup

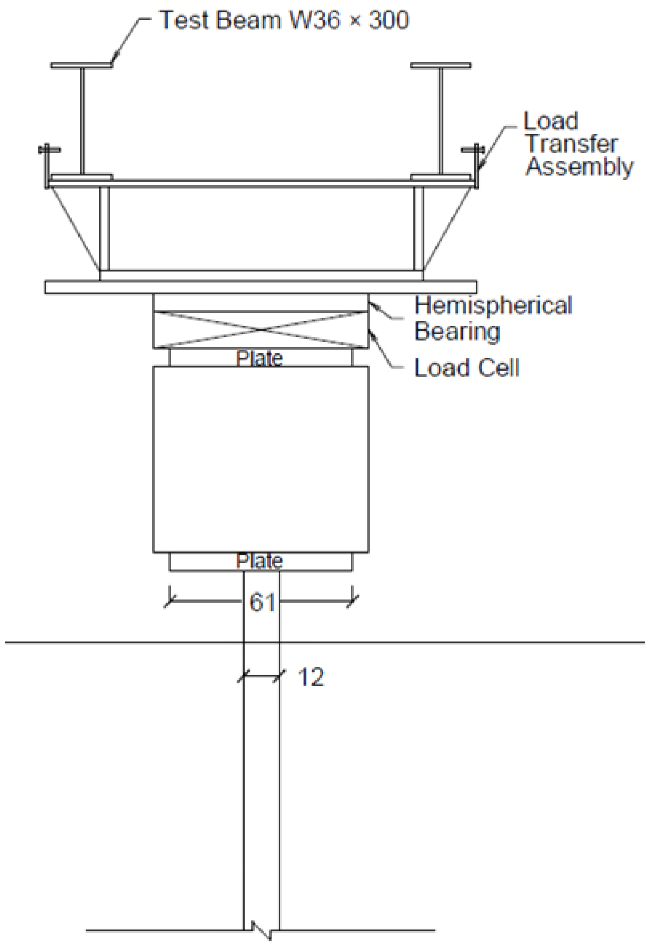


(a) Elevation view

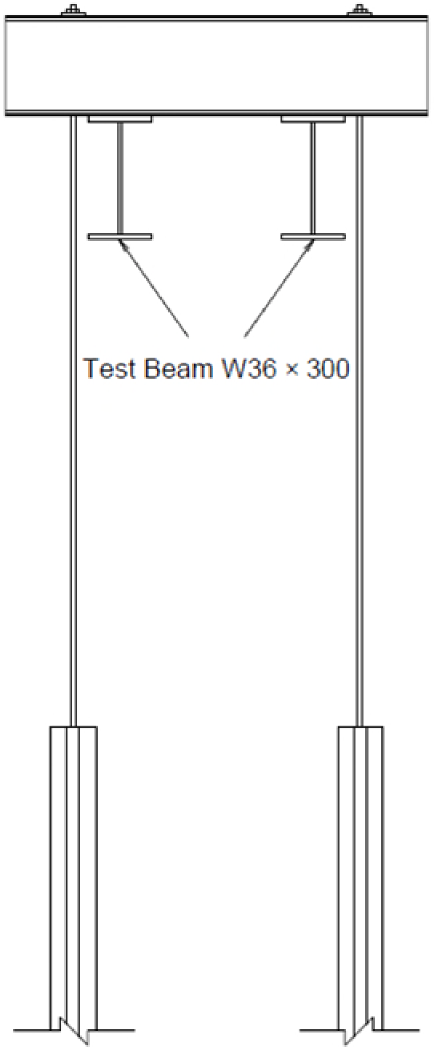


*Note: Dimensions in inches.

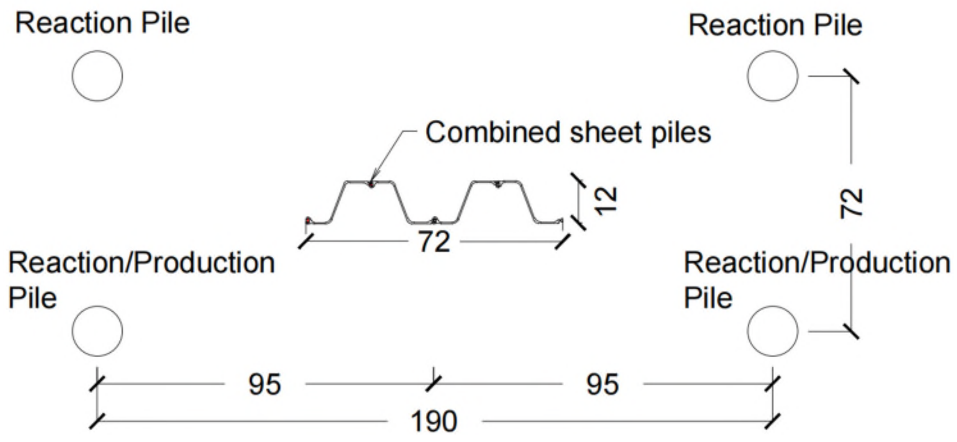
Static load test setup



(b) Section A-A'

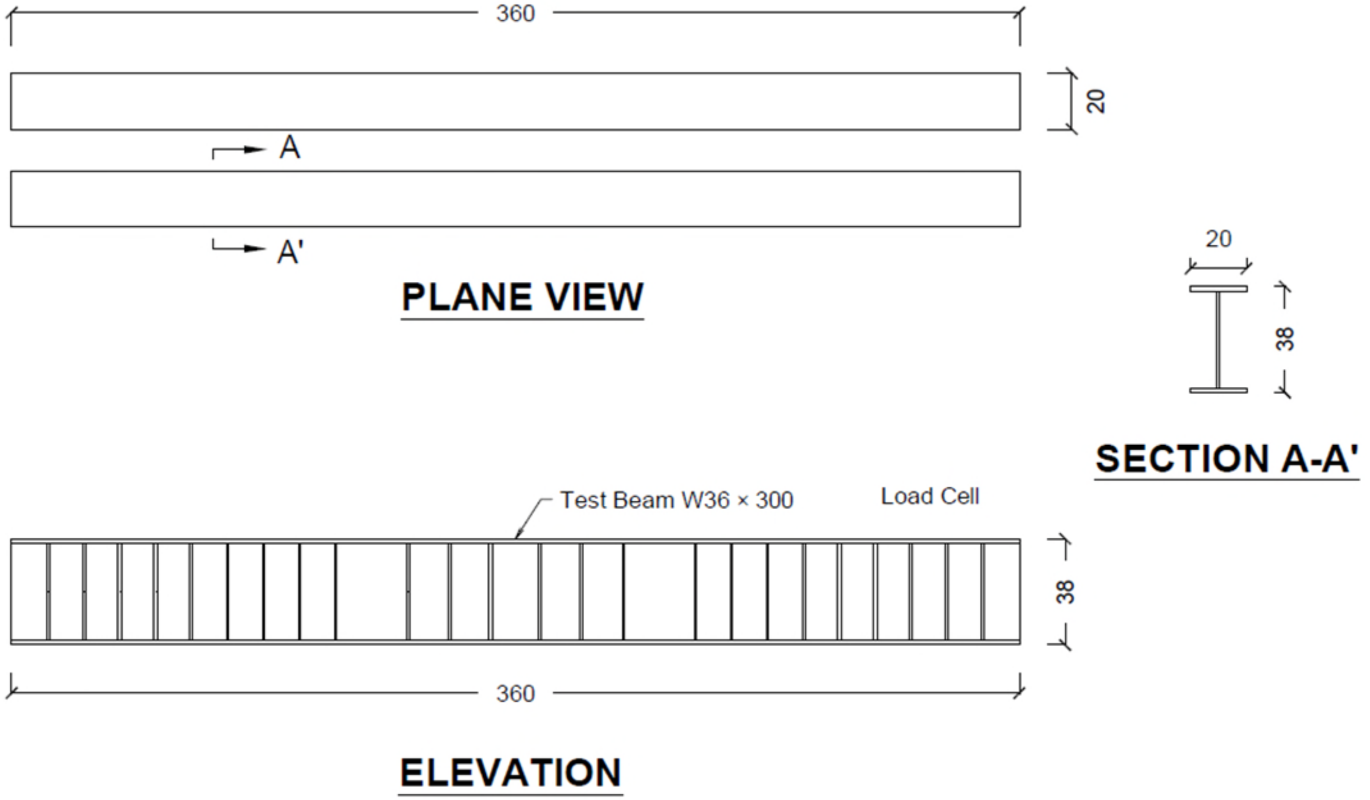


(c) Section B-B'

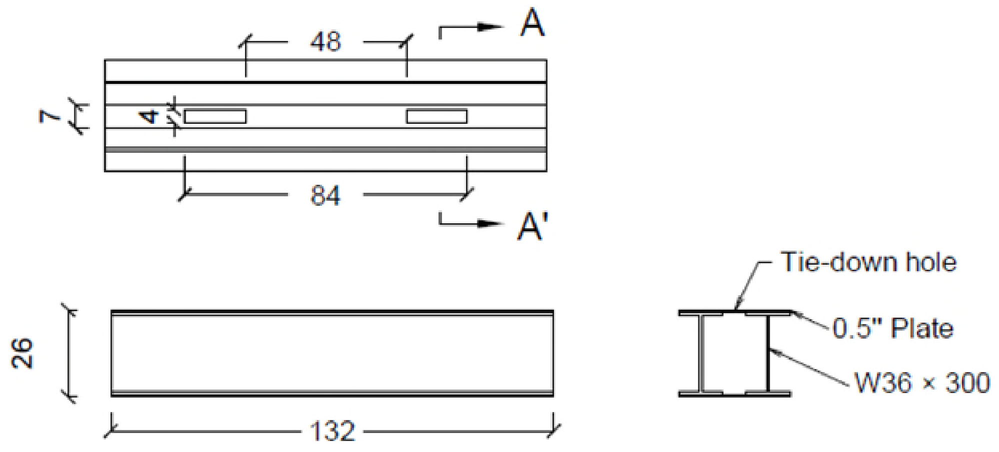


(d) Plane view

Static load test setup



(e) Test beams



(f) Tie-down beams

Figure: Schematic of static load test setup

Loading procedure – Modified quick test

Cell Calibration Factors:		0.1047		
Max Test Load (kips) :		450		
Increment	Target Load (kips)	Estimated Pressure (psi)	Hold Time (minutes)	Total Time (minutes)
Initial	0	0	0	0
1	22.5	215	8	8
2	45	430	8	16
3	67.5	645	8	24
4	90	860	8	32
5	112.5	1074	8	40
6	135	1289	8	48
7	157.5	1504	8	56
8	180	1719	8	64
9	202.5	1934	8	72
10	225	2149	8	80
11	247.5	2364	8	88
12	270	2579	8	96
13	292.5	2794	8	104
14	315	3009	8	112
15	337.5	3223	8	120
16	360	3438	8	128
17	382.5	3653	8	136
18	405	3868	8	144
19	427.5	4083	8	152
20	450	4298	30	182

*__EXPECTED__ loading procedure. Based on an example static load test setup provided by AFT.

Updated Deliverable Schedule

Deliverable #/Description of Deliverable as Provided in the scope (included associated task #)	Anticipated Date of Deliverable Submittal (Month/Year)	TO BE COMPLETED BY RESEARCH CENTER (performance monitoring)
Deliverable #4/Task 4 A written report detailing field testing protocol Including (a) conclusions and recommended methodology for the analysis and design of steel sheet piling as foundations, (b) practical equations, correlations and charts of the recommended procedures, (c) proposed procedures, drawings and sketches to illustrate the required devices and equipment needed for both static load testing and quasi-static load testing, and (d) recommendations for any following phase of implementation of findings.	8/31/2021	
Deliverable # 5a /Task 5 Draft final report which will contain findings of the proposed study, including (a) recommended design methodology for sheet piling as foundations, including equations, design aids and charts/graphs, (b) field testing protocol be used to verify the design estimate, (c) potential benefits of using steel sheet piles as bearing elements, and (d) recommendations for next phase of implementation of findings.	10/31/2021	
Deliverable #5b/Task 5 PowerPoint Presentation – Closeout Teleconference to review project performance, the deployment plan, and next steps.	11/31/2021	
Deliverable # 6 / Task 6 Final Report	12/31/2021	

Ongoing Work

- Drafting and submission of the final task report
- Validating the design equations using full scale field test data

Acknowledgements

- We thank the FDOT for funding this research project
- We are grateful to Juan Castellanos, David Horhota, Rodrigo Herrera and Larry Jones for their support and insightful discussions on this project

Questions ?