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

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Outline

- Background
- Objectives
- Research Tasks
- Deliverables Table (where are we)
- Task 2c: Numerical Modeling of Sand Layering
- Task 3c: Centrifuge Testing and Numerical Validation
- Task 4: Field Load Testing Protocol

Background

- The current FDOT practice requires discrete deep foundation (piles or drilled shafts) for bearing purposes which may or may not be combined with permanent sheet piles for lateral retaining purposes.

- Some designers has previously considered using 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 and eliminate the need for separate deep foundation.

- This would also relieve the complications that arise in construction when driving piles and sheet piles in close proximity.

Background (cont'd): Uncertainties and Issues

- Evaluation of side friction and end bearing resistance by conventional pile design approaches

- Assessment of soil-sheet pile interaction under combined axial and lateral loading

- Evaluation of buckling potential and plastic hinge formation under axial loading

- Determination of the bearing capacity of axially loaded sheet piles through standardized practical field testing protocols

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 2 - Numerical Modeling

Task 3 – Centrifuge Testing and Numerical Validation

Task 4 - Field Load Testing Protocol

Table 6. 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)
Kickoff teleconference	02/2018	
Deliverable #1 / Task 1- Report detailing literature review and information collection on design methods, numerical methods, and field load testing procedures on steel cantilever sheet piles used as axial load bearing elements. The report will present and summarize analysis and design method practices and load testing methods.	6/2018	
Deliverable #2a Task 2 - Report detailing the proposed numerical. The numerical method will include a theoretical and practical justification, a description of the approach, and how the material properties and other factors are considered in the proposed numerical modeling.	12/2018	
Deliverable #3a /Tasks 3- Report detailing the proposed physical modeling. Physical modeling will include the procedures used to construct the soil profile, drive the sheet pile wall, and conduct axial quasi-static and static load testing.	12/2018	
Deliverable #2b /Tasks 2- A written report detailing the results of the 60% of parametric study of the influence of the varying factors affecting the bearing capacity of sheet pile walls.	6/2019	
Deliverable #3b /Task 3 - A written report detailing the progressive findings from the predicted capacities of the evaluated methods and comparisons with the results from the 60% of total number of lab load testing and numerical modeling.	6/2019	
Deliverable #2c /Task 2- A written report detailing the results of the 40% remaining of parametric study of the influence of the varying factors affecting the bearing capacity of sheet pile walls.	12/2019	

Deliverable #3c /Task 3- A written report detailing a summary of the predicted capacities of the evaluated methods and comparisons with the results from all of lab load testing and numerical modeling. Conclusions about the comparisons of predictions and test results and the evaluated design methods. Suggested methodology to estimate load-settlement behavior and bearing capacity. This will include equations, correlations, charts or other design aids that were developed during this task.	12/2019	
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.	6/2020	
Deliverable # 5a /Task 5 Draft final report which will contain findings of the proposed study, including (a) recommended design methodology of 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.	9/01/2020	
Deliverable # 5b /Task 5- PowerPoint Presentation – Closeout Teleconference to review project performance, the deployment plan, and next steps.	11/2020	
Deliverable # 6 / Task 6- Final Report	12/01/2020	

Table 2. Summary of scenarios for numerical analysis

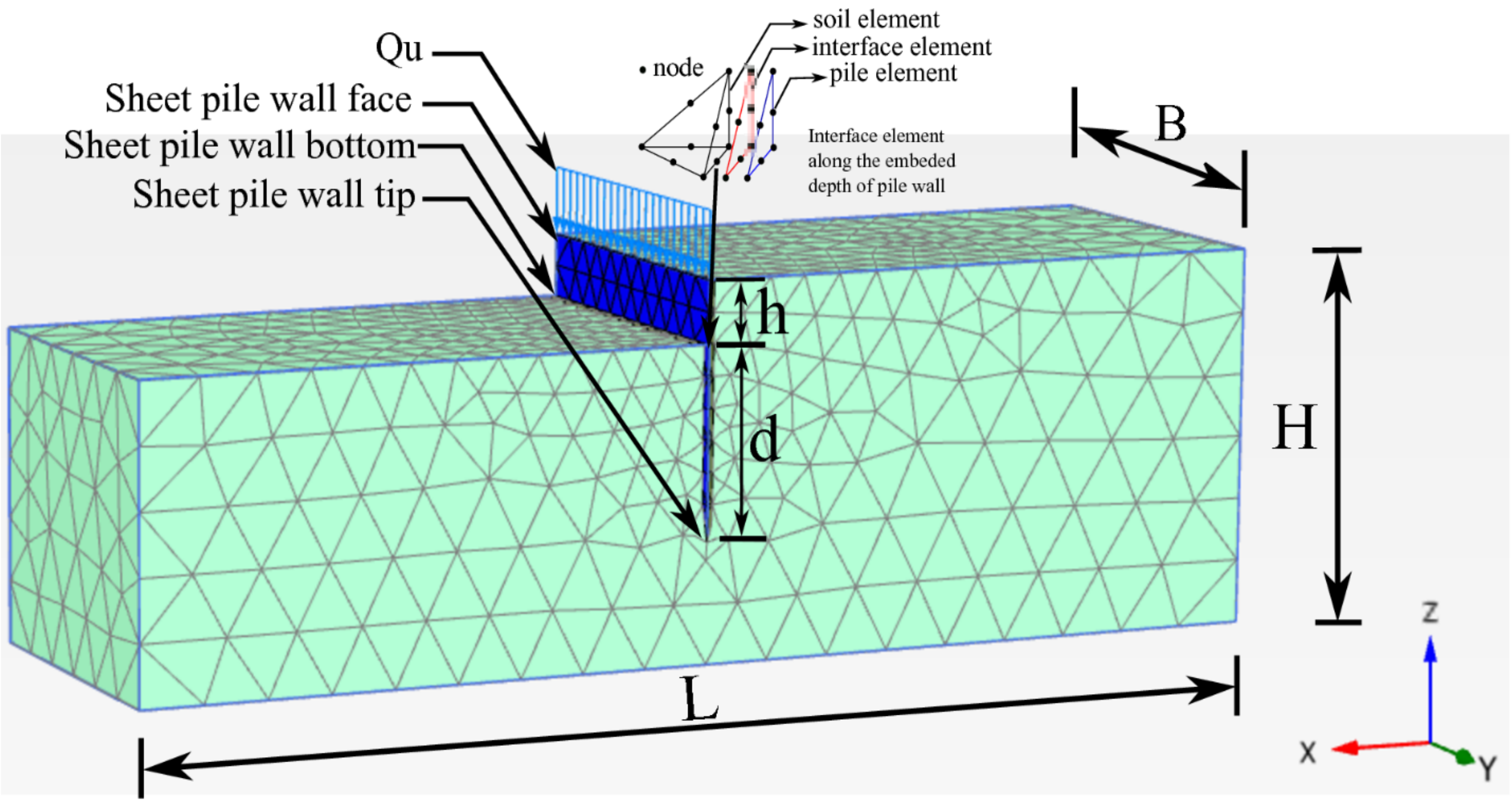
		Pile Embedment	Pile stiffness	Pile head constraints	Surcharge	Total cases
One layer	**Loose**	3	3	2	2	36
	Dense	3	3	2	2	36
	Very Dense	3	3	2	2	36
Two layer	**Loose**	3	3	2	2	36
	Dense	3	3	2	2	36
	Very Dense	3	3	2	2	36
					Sum	216

Table 5. Summary of scenarios for centrifuge testing

	Sheet pile Embedment	Sheet pile stiffness	Sheet pile head constraints	Load Testing	Total cases
Medium-Dense Sand, Dr=60%	2	2	2	2	16
Two layered Profile, (Dr=60% over Dr=90%)	2	2	2	2	16
Repeat Tests					4
Sum					**36**

Task 2c - Numerical Modeling (cont'd)

- *Numerical Modeling via PLAXIS 3D*
- *Soil modeled as elastic perfectly plastic material*
- *Pile modeled as linear elastic material*
- *'d' denotes the embedded depth and 'h' denoted the retained height of the sheet pile*



Task 2c - Numerical Modeling (cont'd)

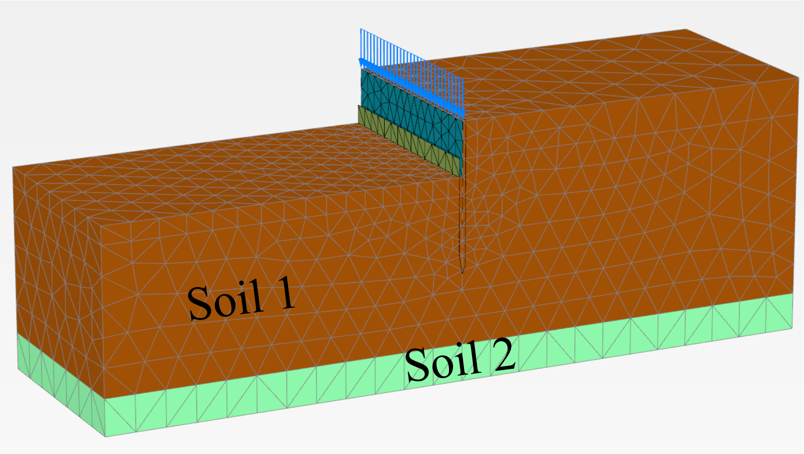
- *Sands: Elastic-plastic Mohr-Coulomb model + continuum elements*
- *Sheet pile wall: an elastic model + a structural element*
- *The interface: Elastic-plastic Mohr-Coulomb model*

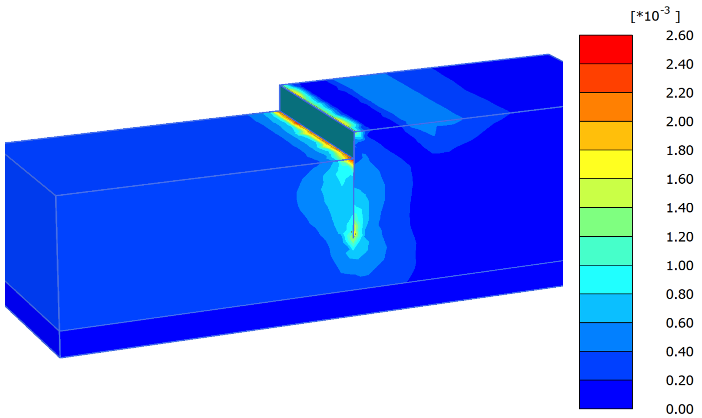
Table 1. Material properties used in the finite element simulations

Parameter	Sheet pile	Very dense sand	Dense sand	Loose sand	Interface elements
Material model	Elastic	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb
Young's modulus	4385941.2 ksf	1670.1 ksf	1043.7 ksf	626.2 ksf	500 ksf
Cohesion	-	0	0	0	0
Poisson ratio	0.25	0.3	0.3	0.3	-
Friction angle	-	35	32	27	-
Density	0.486 kip/ft^3	0.155 kip/ft^3	0.131 kip/ft^3	0.109 kip/ft^3	-

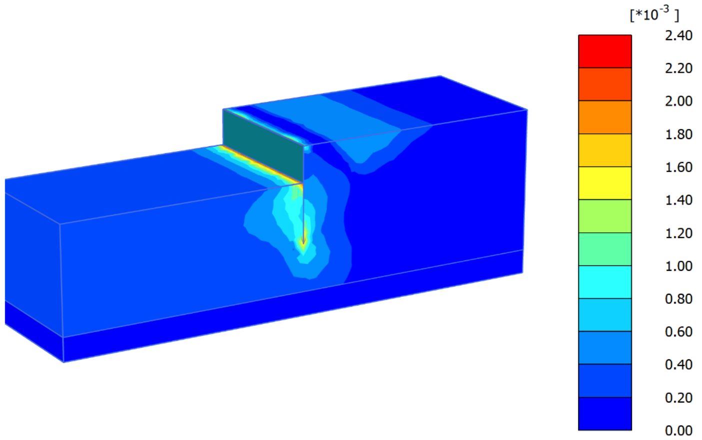
(1) Sand Layering

- *Soil 2 is ALWAYS a very dense sand layer (D_r = 85%).*
- *Soil 1 is varied between dense (D_r = 63%). and loose sand layer (D_r = 42%).*

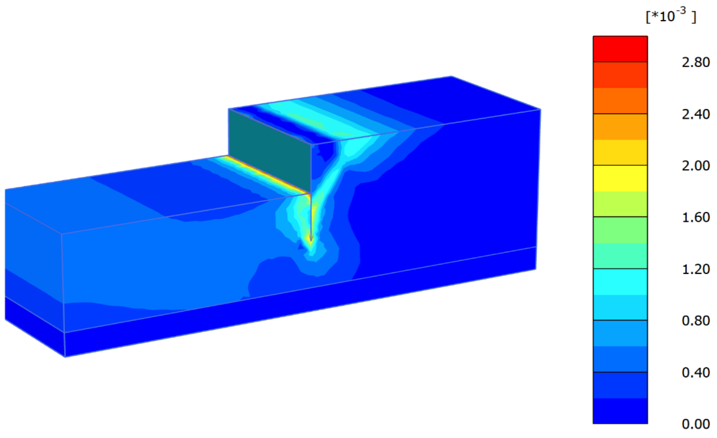




(a) d/h = 3.0



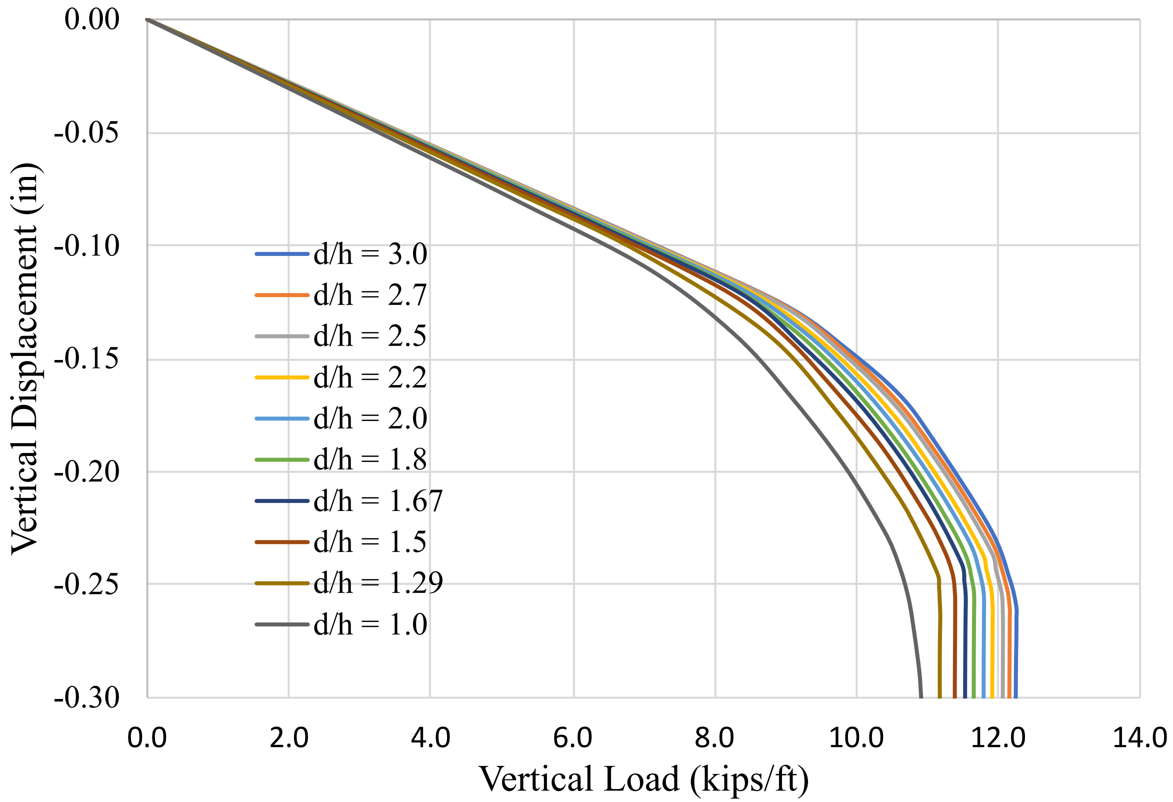
(b) d/h = 1.67



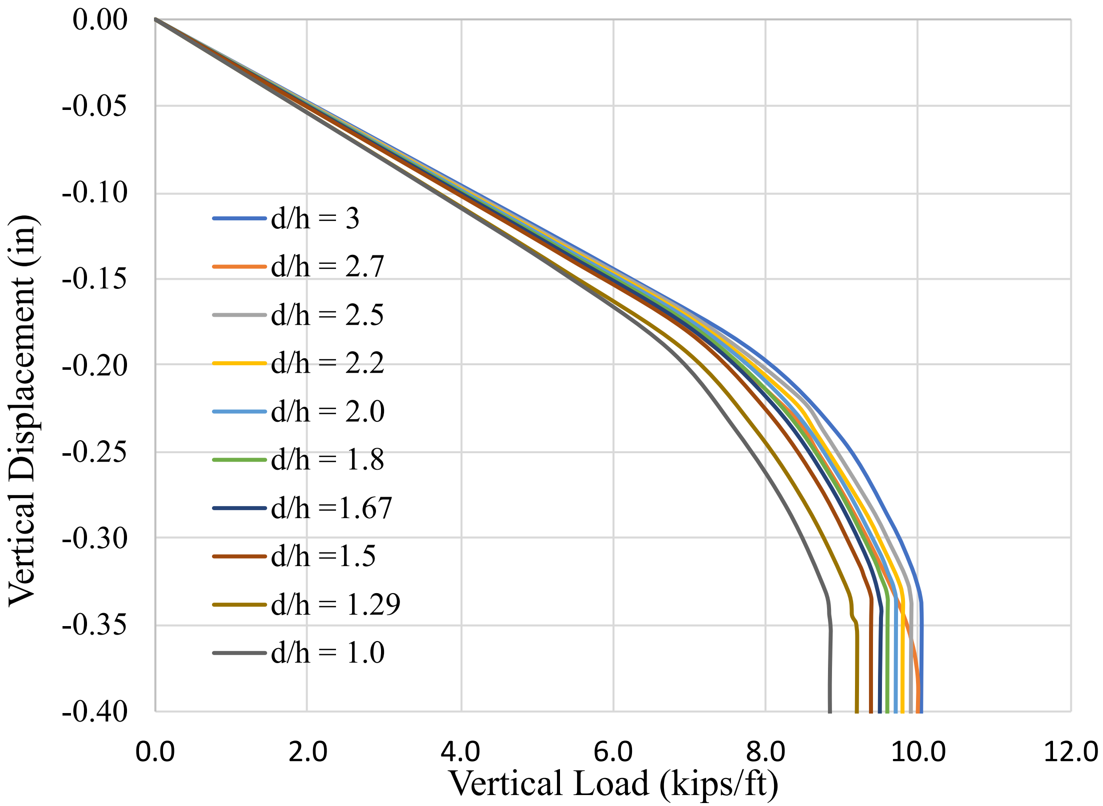
(c) d/h = 1.0.

Contours of total shear strain for a dense sand in the Soil 1 layer at a pile vertical displacement of 0.3 in

(1) Sand Layering (cont'd)



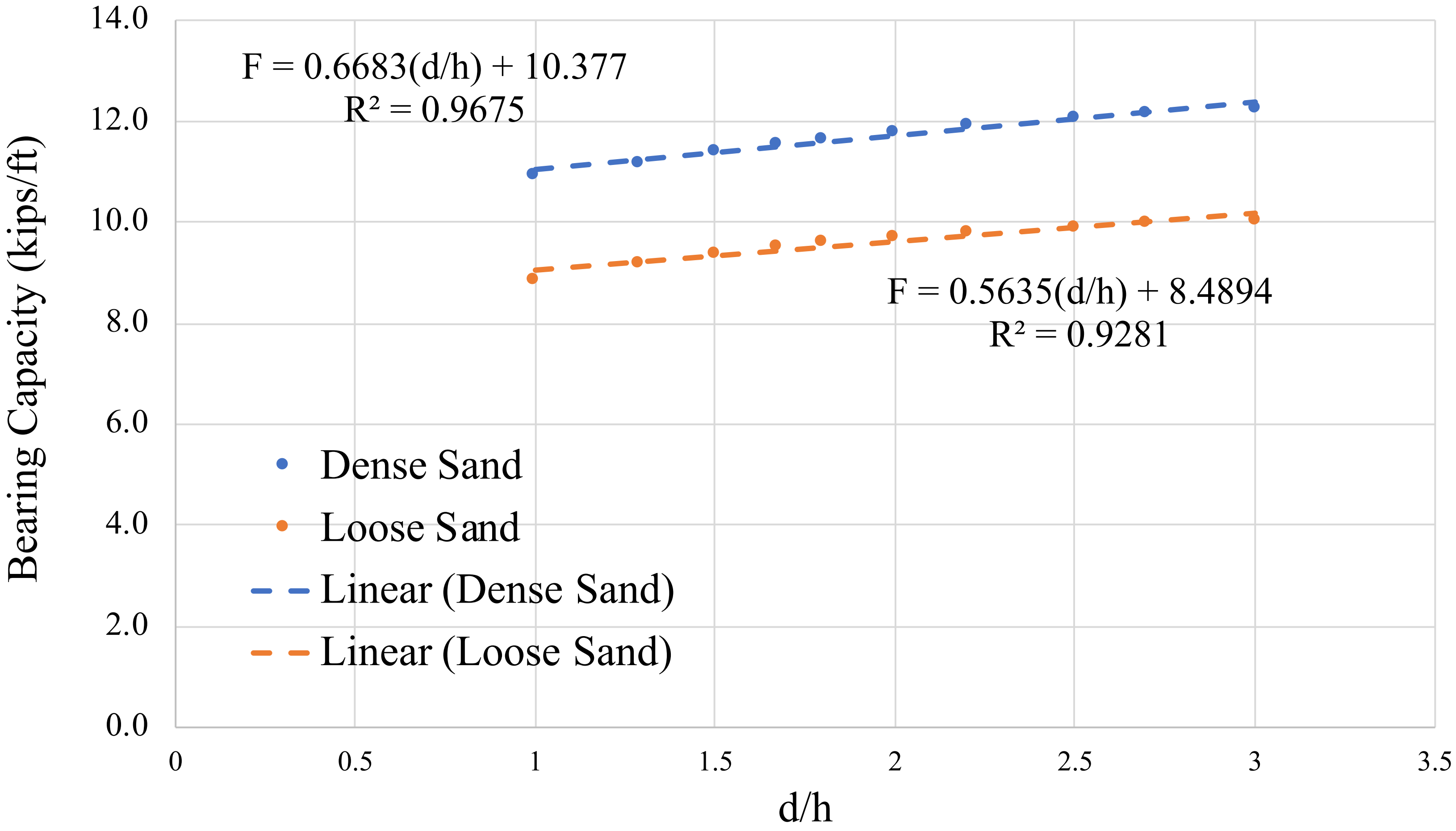
(a) Dense sand in the Soil 1 layer



(b) Loose sand in the Soil 1 layer

Applied Load versus vertical displacement with different d/h ratios (embedded pile depth/retained soil height)

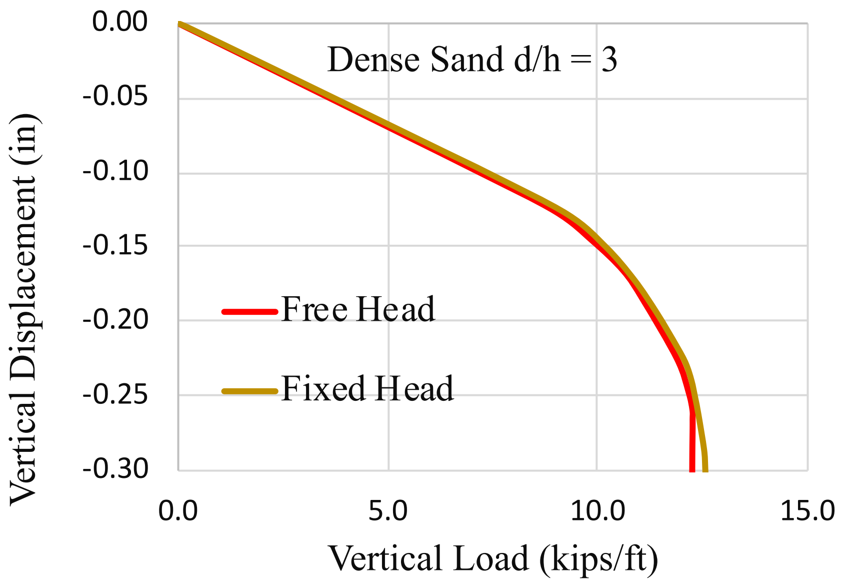
(1) Sand Layering (cont'd)

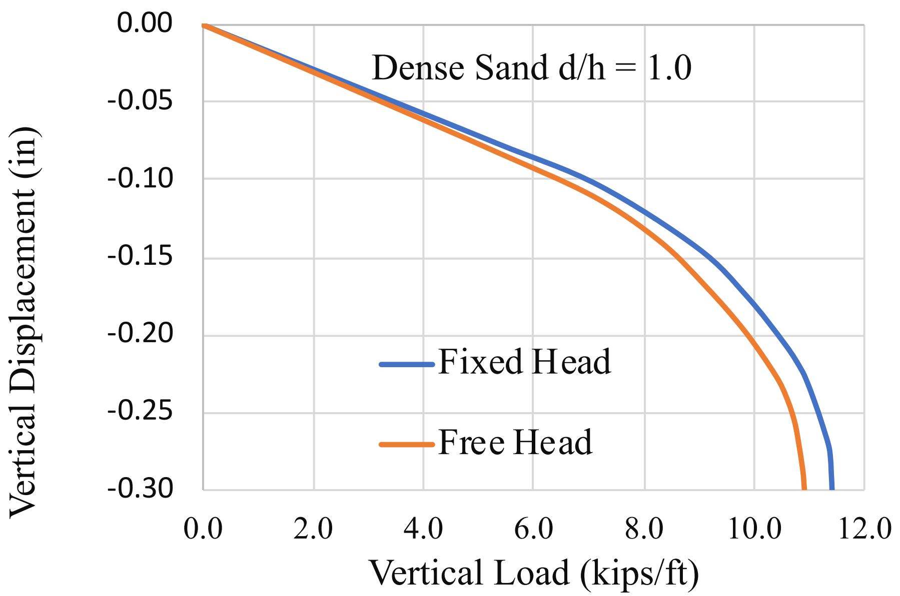


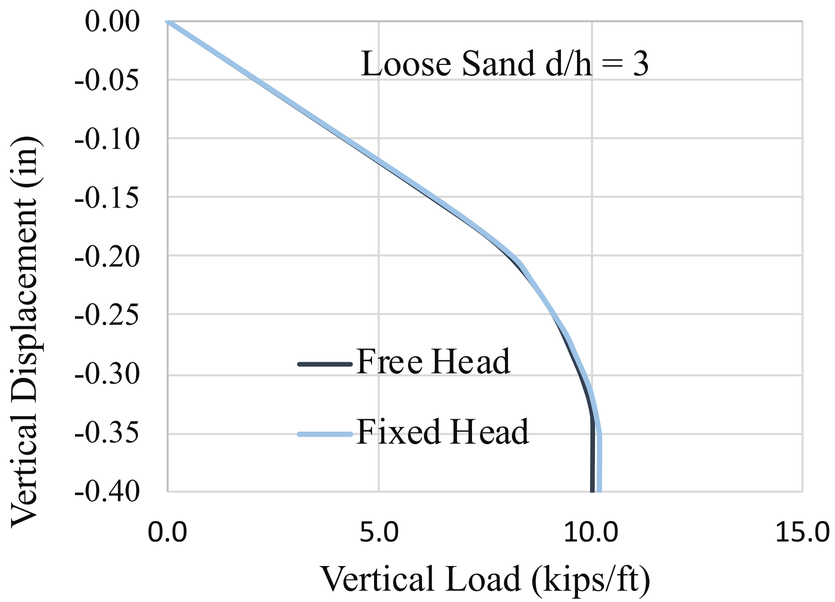
Plot of load bearing capacity of the sheet pile wall against the d/h ratio with linear fits applied to the data.

Note: The R^2 value (the coefficient of determination) is the proportion of the variance in the dependent variable (bearing capacity) that is predictable from the independent variable (d/h) by the linear fit.

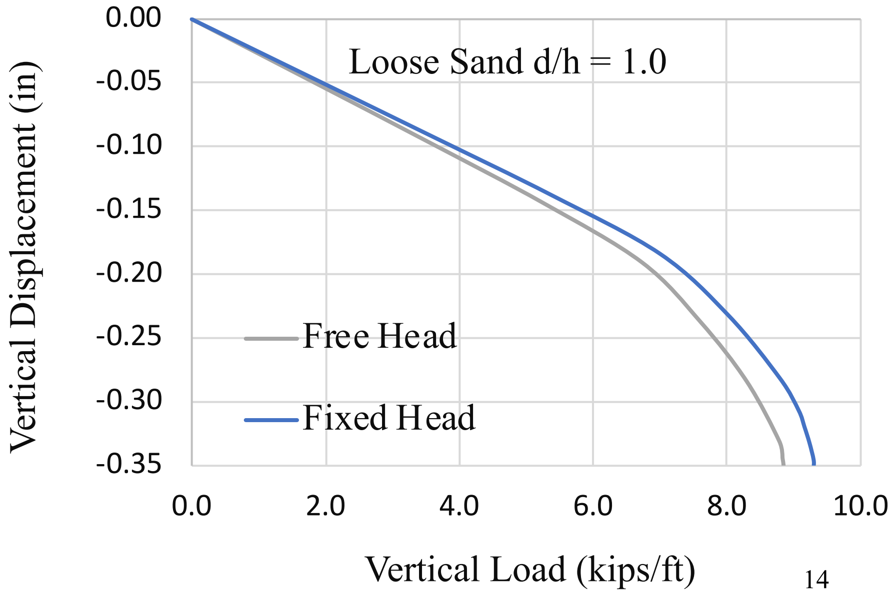
(2) Effects of Pile Head Fixity



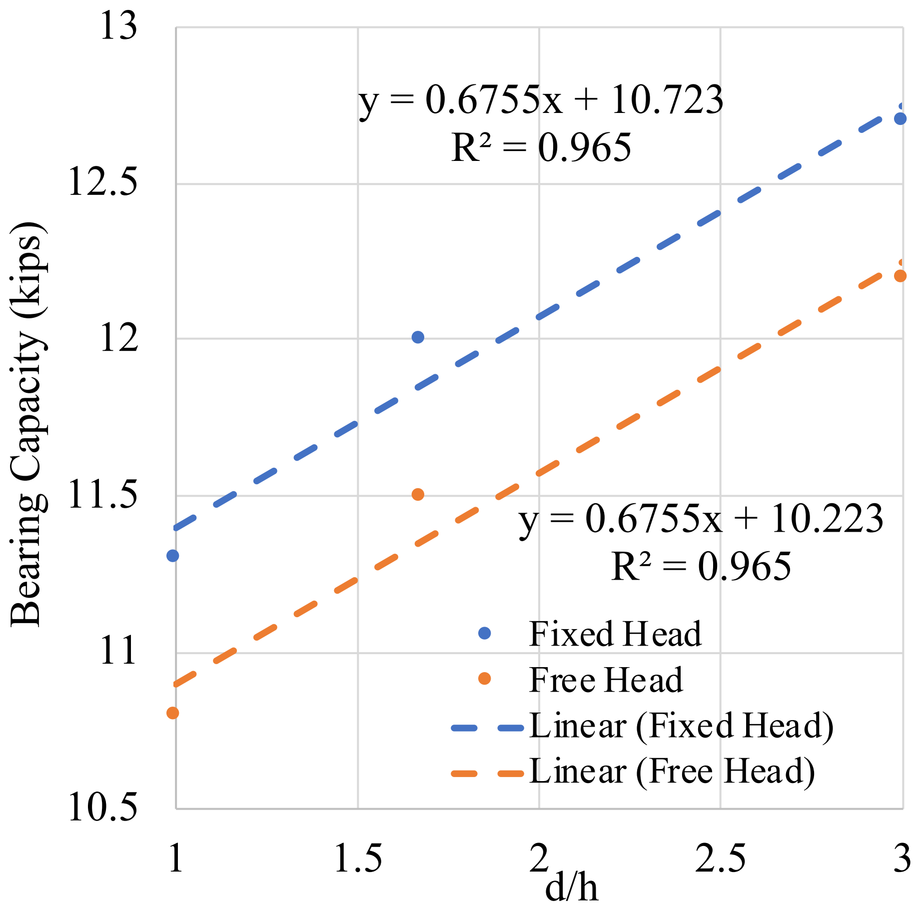




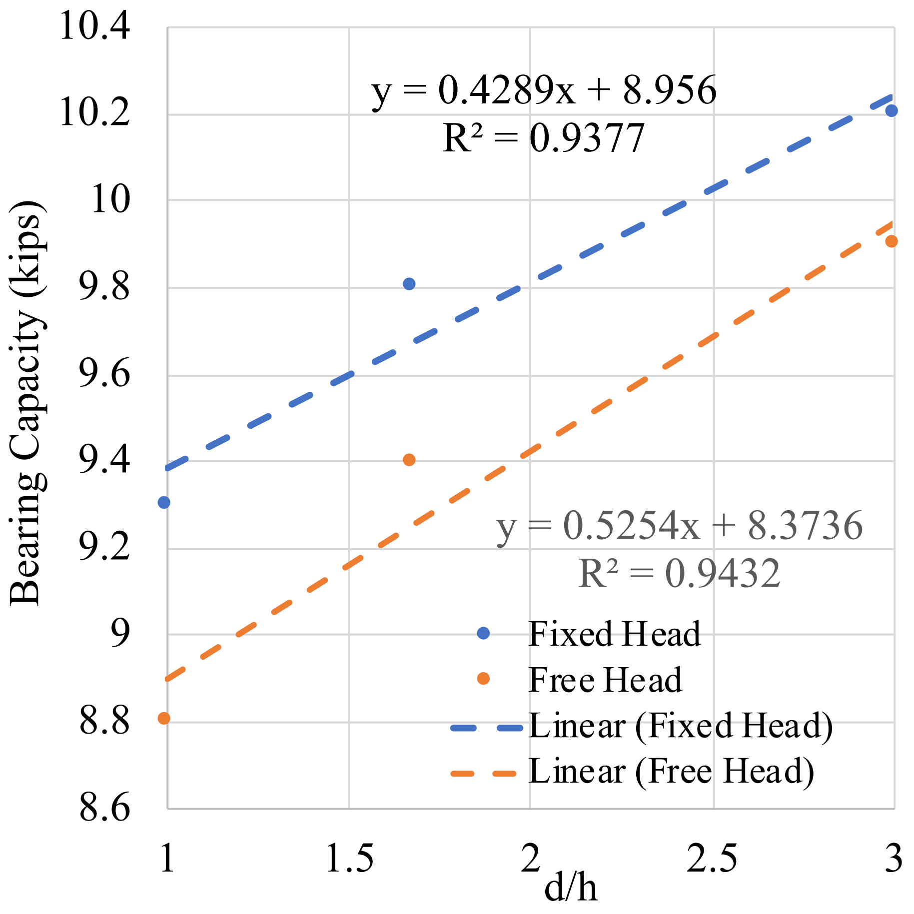
All results shown here are for layered sand profile. The key denotes the sand in Soil 1 layer.



(2) Effects of Pile Head Fixity (cont'd)



(a)



(b)

Increased load capacity of the pile wall with a fixed head compared to a free head for (a) dense sand and (b) loose sand in the Soil 1 layer.

Discussion

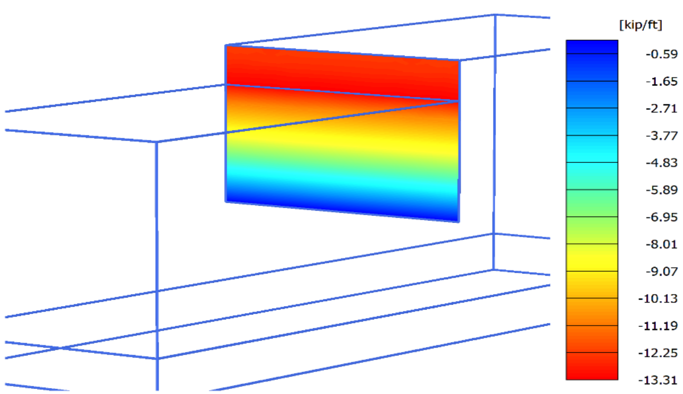
- *Fixing the head of the sheet pile wall reveals no improvement in bearing capacity for d/h=3.0 with either dense or loose sand in Soil 1 layer.*

- *Fixing the head of the sheet pile wall for smaller ratio of d/h showes marked improvement in bearing capacity for both dense and loose sand in Soil 1 layer.*

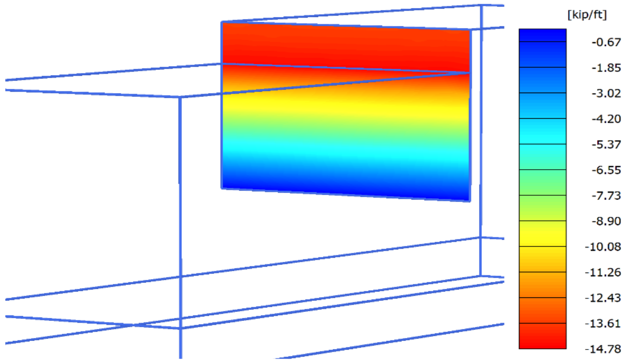
- *The contours of shear strain reveal that fixing the head of the pile reduces lateral deformation in the retained soil but causes intense shearing at the top of the soil-structure interface.*

(3) Effects of Surcharge Loading: Axial Capacity

- *Surcharge loads exert additional lateral pressures on the sheet pile wall system.*
- *Different surcharge intensities were applied to investigate effects on the general behavior*
- *Constant ratio of d/h = 3.0*

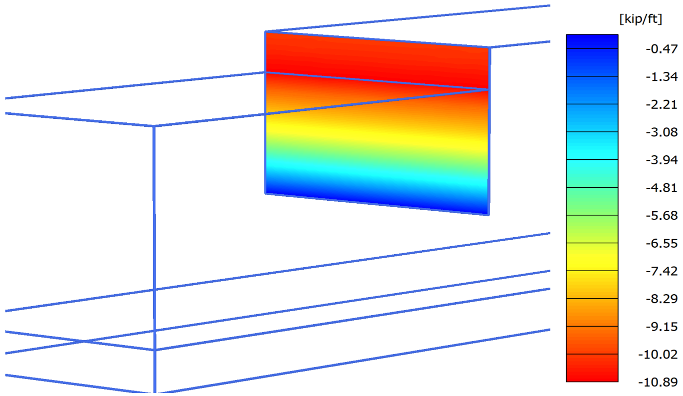


(a)

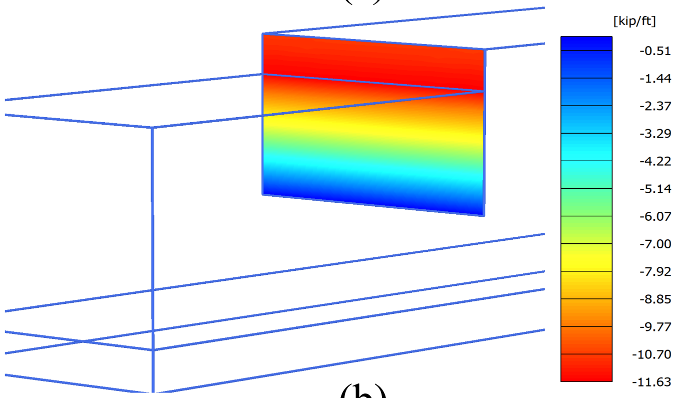


(b)

Axial forces developed in the pile wall for an applied surcharge intensity (a) 0.21 ksf (b) 0.41 ksf with dense sand in the Soil 1 layer.



(a)

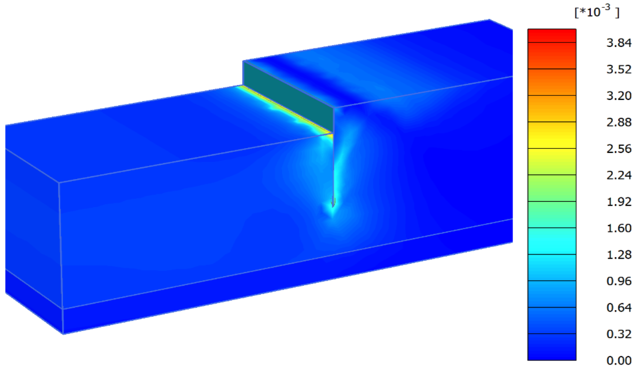


(b)

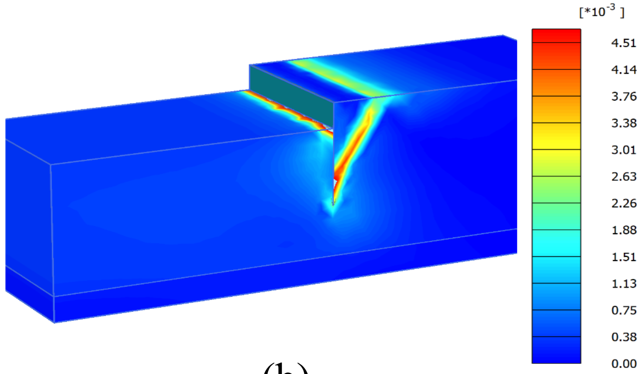
Axial forces developed in the pile wall for an applied surcharge intensity (a) 0.21 ksf (b) 0.41 ksf with loose sand in the Soil 1 layer.

(3) Effects of Surcharge Loading: Shear Strain

- *Surcharge loads exert additional lateral pressures on the sheet pile wall system.*
- *Different surcharge intensities were applied to investigate effects on the general behavior*
- *Constant ratio of d/h = 3.0*

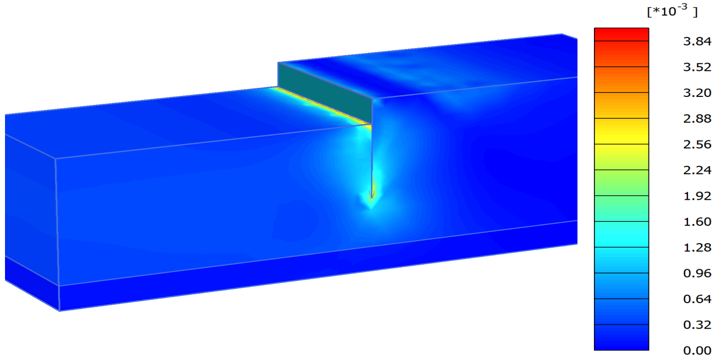


(a)

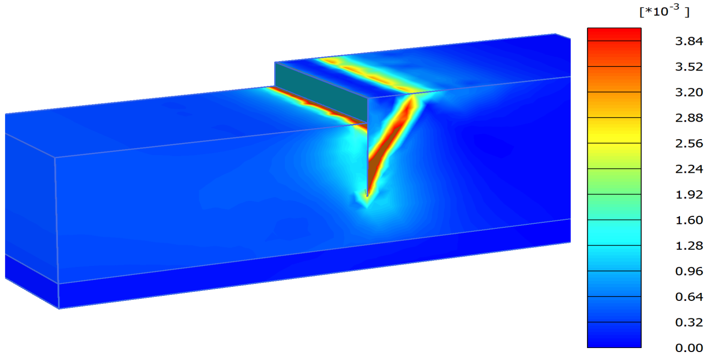


(b)

Total shear strain with dense sand in the Soil 1 layer for an applied surcharge intensity (a) 0.21 ksf (b) 0.41 ksf



(a)



(b)

Total shear strain with loose sand in the Soil 1 layer for an applied surcharge intensity (a) 0.21 ksf (b) 0.41 ksf

Discussion

- *With an increase in the surcharge load, the axial load experienced by the piles increases.*
- *Surcharge loads cause the development of a distinct shear band.*
- *The intensity of localized deformation is greater in the loose sand and greater for larger surcharge.*

Summary of Numerical Modeling

- *Influence of the sand layering is studied using numerical analysis.*
- *Results imply that a direct linear relationship may exist between relative density and ultimate bearing capacity.*
- *For a given Soil 1 layer, maximum displacement of the pile (at peak load on the pile wall) appears to be independent of the retained height.*
- *Fixing the head of pile wall only appears to improve load bearing capacity for smaller d/h ratios.*

Task 3c: Centrifuge Testing

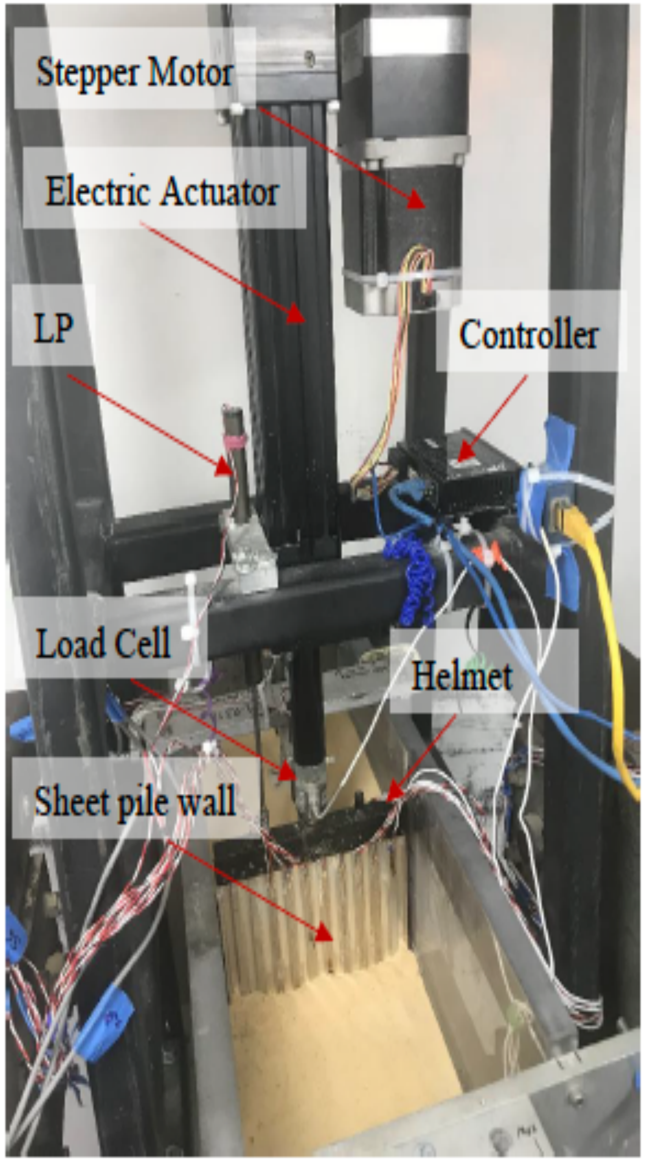


Table 1. Centrifuge Testing Matrix

Test No.	Sheet Pile Wall	Head Boundary Condition	Soil Profile	CRP Rate* (in/s)
1	PZS2	Fixed	PR1	7.87×10^{-4}
2	PZS2	Fixed	PR1	7.87×10^{-4}
3	PZS2	Fixed	PR1	7.87×10^{-5}
4	PZS2	Fixed	PR3	7.87×10^{-4}
5	PZS2	Fixed	PR3	7.87×10^{-5}
6	PZS2	Fixed	PR4	7.87×10^{-5}
7	PZS2	Fixed	PR2	7.87×10^{-5}
8	PZS2	Fixed	PR2	7.87×10^{-4}
9	PZS2	Fixed	PR4	7.87×10^{-4}
10	PZS1	Fixed	PR1	7.87×10^{-5}
11	PZS1	Fixed	PR1	7.87×10^{-4}
12	PZS1	Fixed	PR3	7.87×10^{-4}
13	PZS1	Fixed	PR3	7.87×10^{-5}
14	PZS1	Fixed	PR4	7.87×10^{-5}
15	PZS1	Fixed	PR4	7.87×10^{-4}
16	PZS1	Fixed	PR2	7.87×10^{-4}
17	PZS1	Fixed	PR2	7.87×10^{-5}
18	PZS2	Free	PR1	7.87×10^{-4}
19	PZS2	Free	PR1	7.87×10^{-5}
20	PZS2	Free	PR2	7.87×10^{-5}
21	PZS2	Free	PR2	7.87×10^{-4}
22	PZS2	Free	PR3	7.87×10^{-5}
23	PZS2	Free	PR3	7.87×10^{-4}
24	PZS2	Free	PR4	7.87×10^{-4}
25	PZS2	Free	PR4	7.87×10^{-5}
26	PZS1	Free	PR3	7.87×10^{-4}
27	PZS1	Free	PR3	7.87×10^{-5}
28	PZS1	Free	PR4	7.87×10^{-5}
29	PZS1	Free	PR4	7.87×10^{-4}
30	PZS1	Free	PR1	7.87×10^{-4}
31	PZS1	Free	PR1	7.87×10^{-5}
32	PZS1	Free	PR2	7.87×10^{-4}
33	PZS1	Free	PR2	7.87×10^{-5}
34	PZS1	Free	PR1	11.81×10^{-3}
35	PZS1	Free	PR1	7.87×10^{-4}
36	PZS1	Free	PR1	7.87×10^{-5}

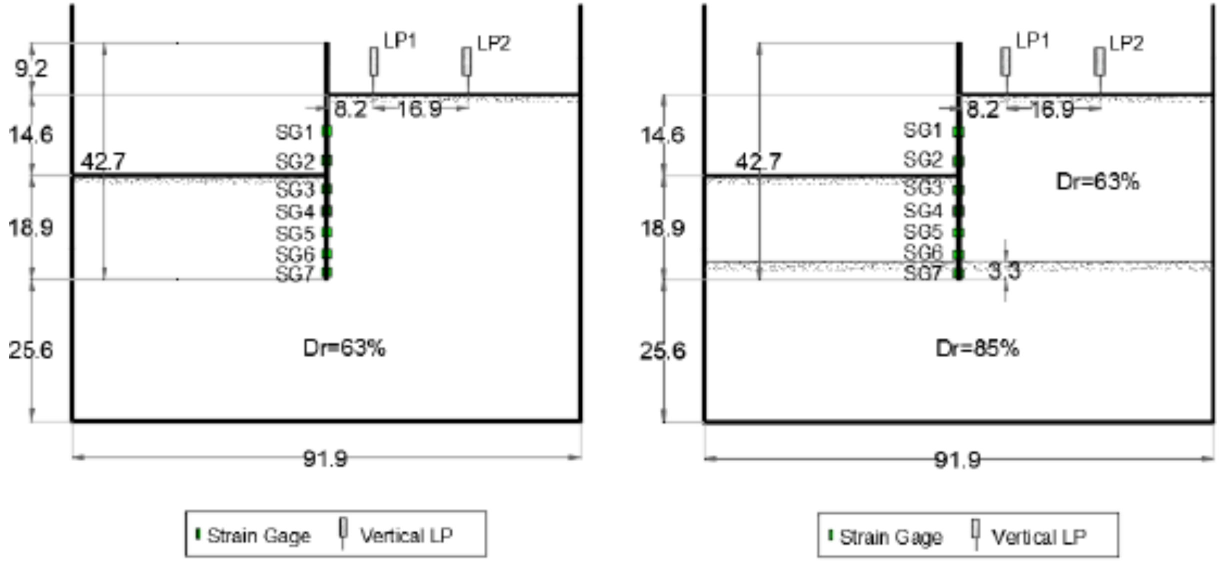
* Constant Rate of Penetration (CRP)

Table 5. Summary of scenarios for centrifuge testing

	Sheet pile Embedment	Sheet pile stiffness	Sheet pile head constraints	Load Testing	Total cases
Medium-Dense Sand, Dr=60%	2	2	2	2	16
Two layered Profile, (Dr=60% over Dr=90%)	2	2	2	2	16
Repeat Tests					4
Sum					**36**

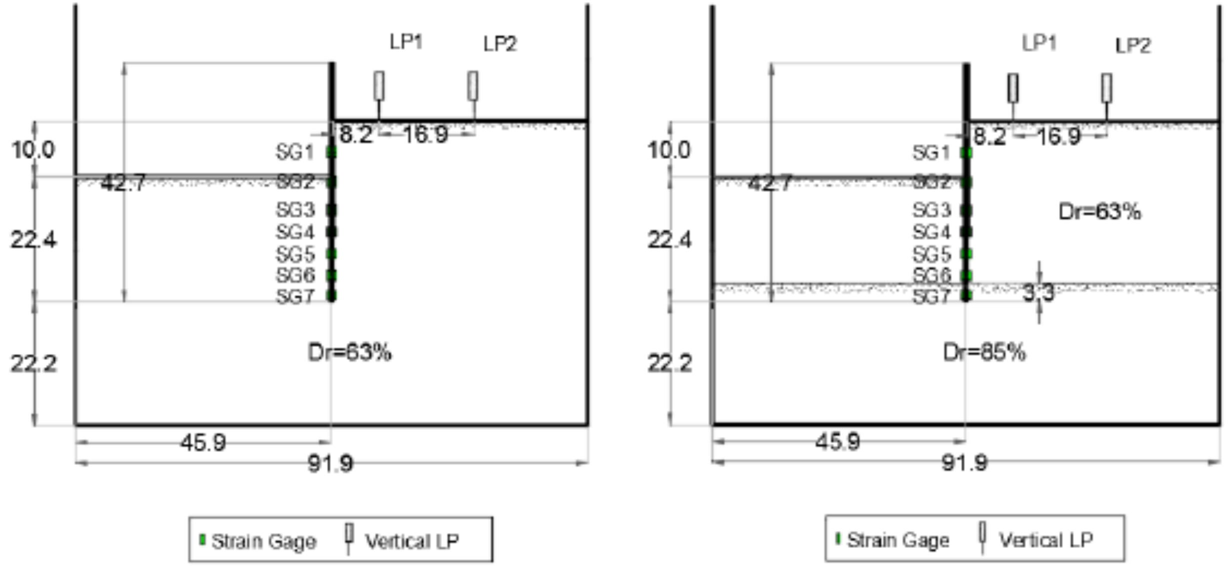
Task 3c: Centrifuge Testing

Cross section of centrifuge models



(b) (c)

D/H=1.3

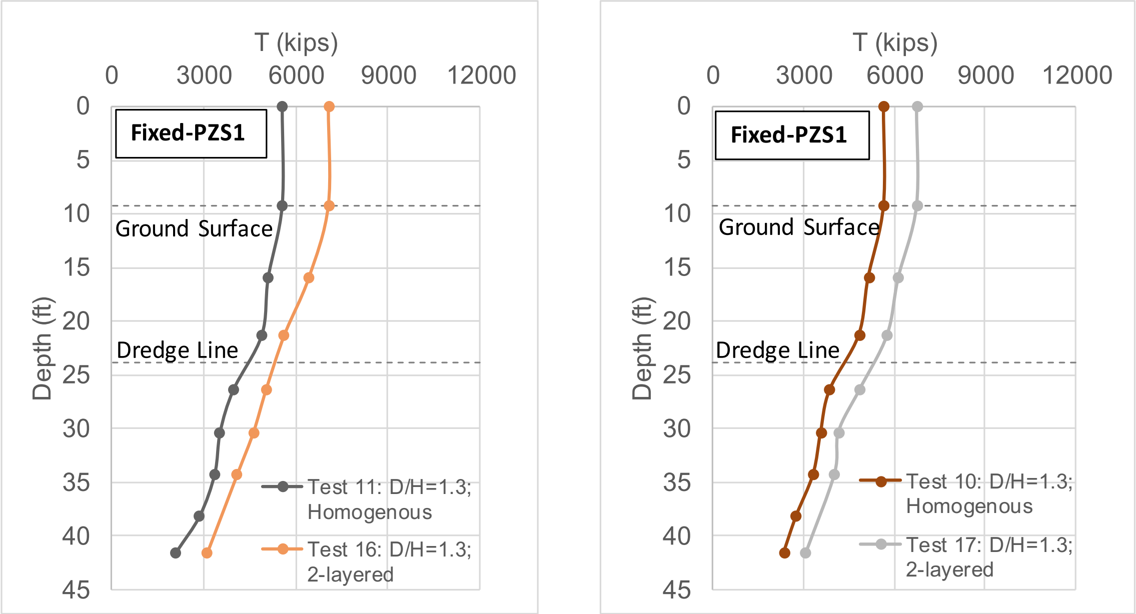


(b) (c)

D/H=2.24

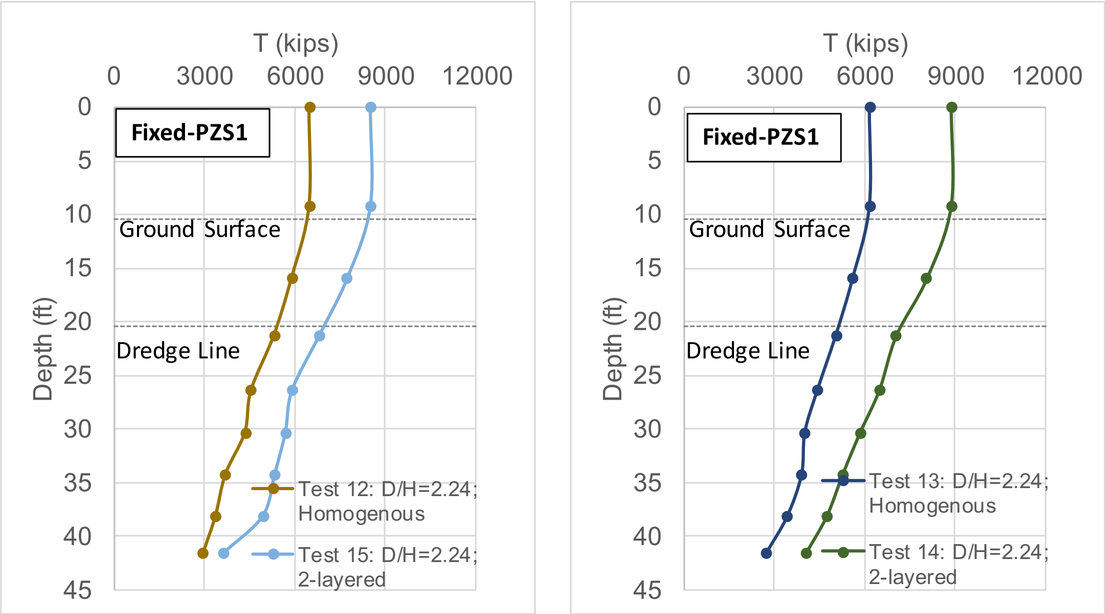
- *For uniform layer: pile wall is in medium dense sand with relative density D_r = 63% (PR1/PR3). (Side friction only?)*
- *For layered sand : pile tip is embedded in very dense sand (D_r = 85%) underlaying a medium dense sand (PR2/PR4). (Side friction + Tip bearing ?)*

(1) Effect of sand layering



(a) (b)

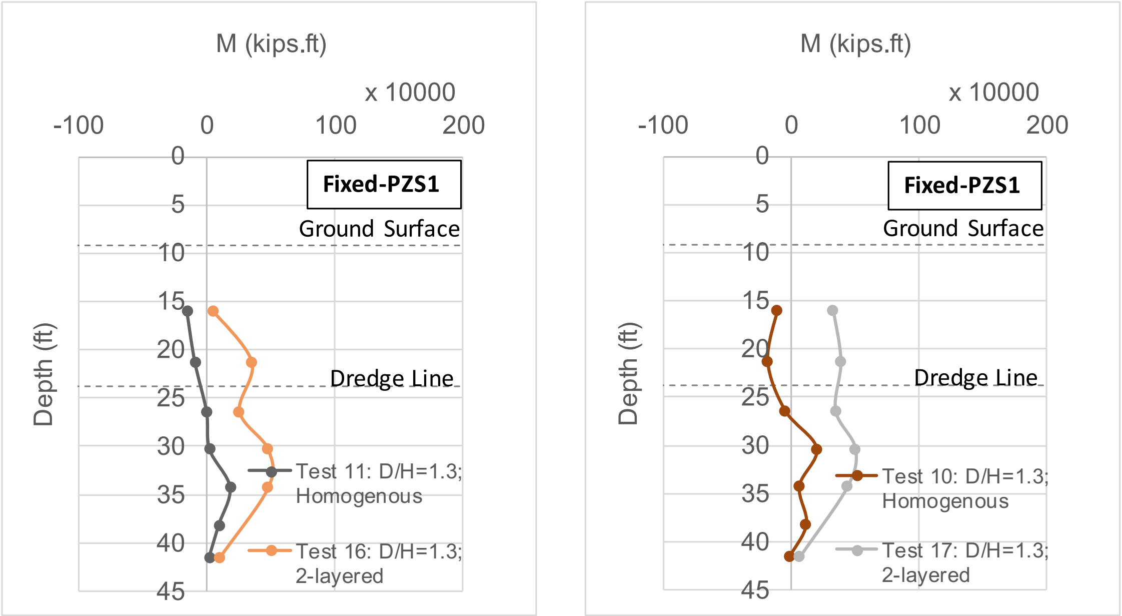
Increased axial resistance of the sheet pile wall PZS1 in the profile PR2 (tests 16 and 17) compared to that in the profile PR1 (tests 11 and 10) with CRP: (a) CPR=7.87×10^{-4} in/s; and (b) CPR=7.87×10^{-5} in/s for d/h = 1.3



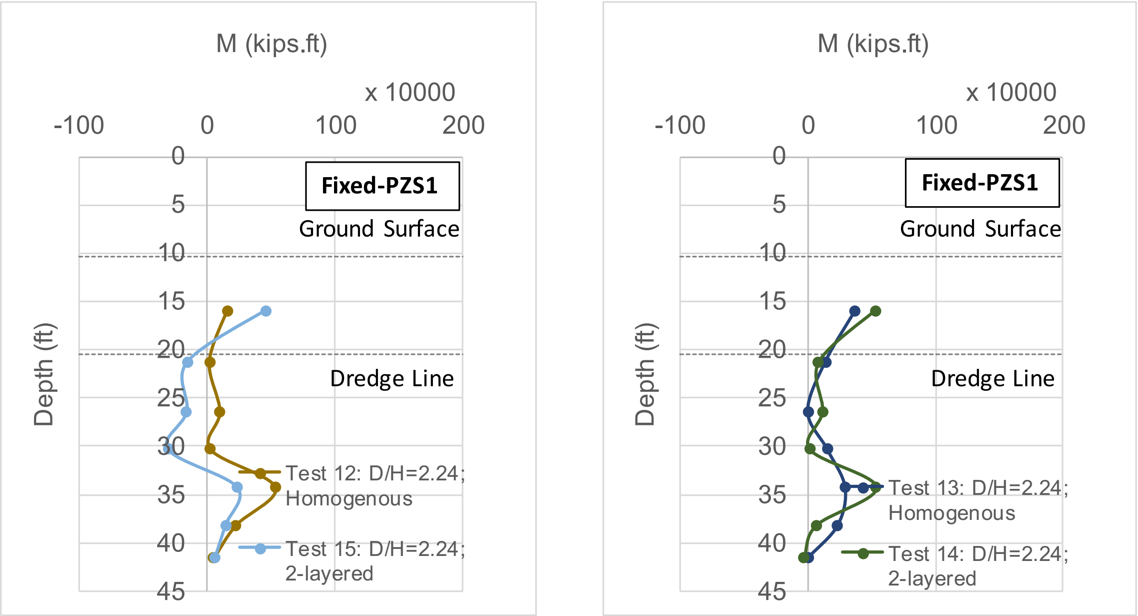
(a) (b)

Increased axial resistance of the sheet pile wall PZS1 in the profile PR2 compared to that in the profile PR1 with CRP : (a) CPR=7.87×10^{-4} in/s; and (b) CPR=7.87×10^{-5} in/s for d/h = 2.24

(1) Effect of sand layering (cont’d)



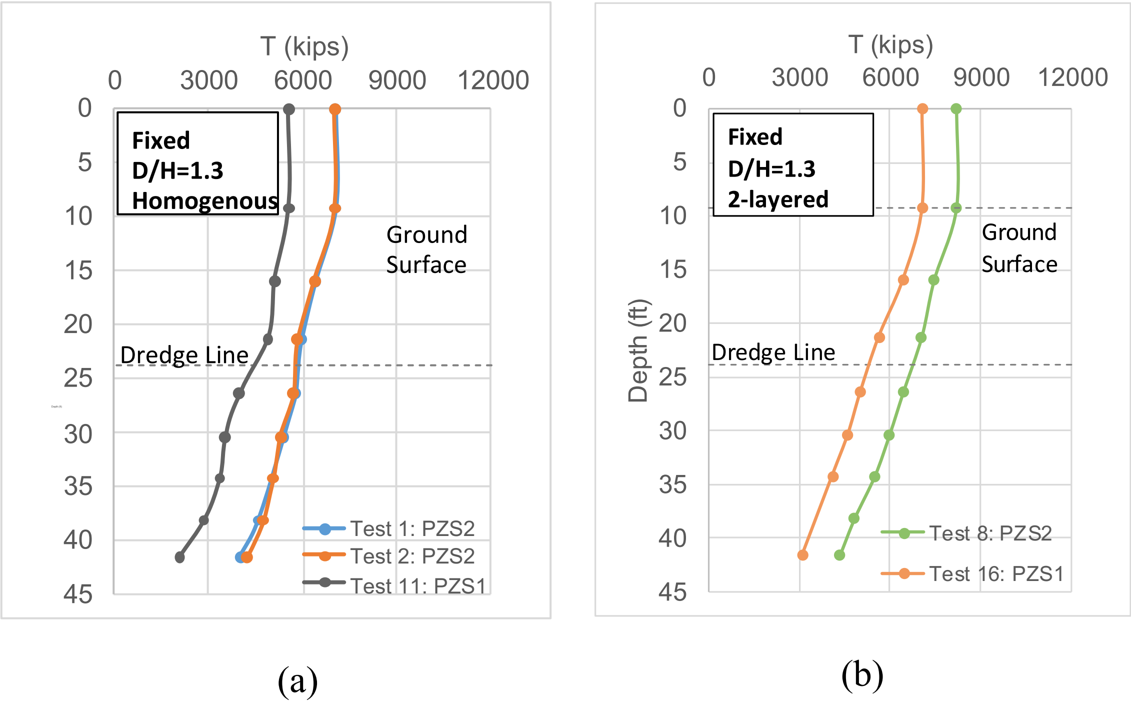
Bending moment profiles of the sheet pile wall PZS1 in the profile PR2 compared to that in the profile PR1 (a) CPR=7.87×10^{-4} in/s; and (b) CPR=7.87×10^{-5} in/s



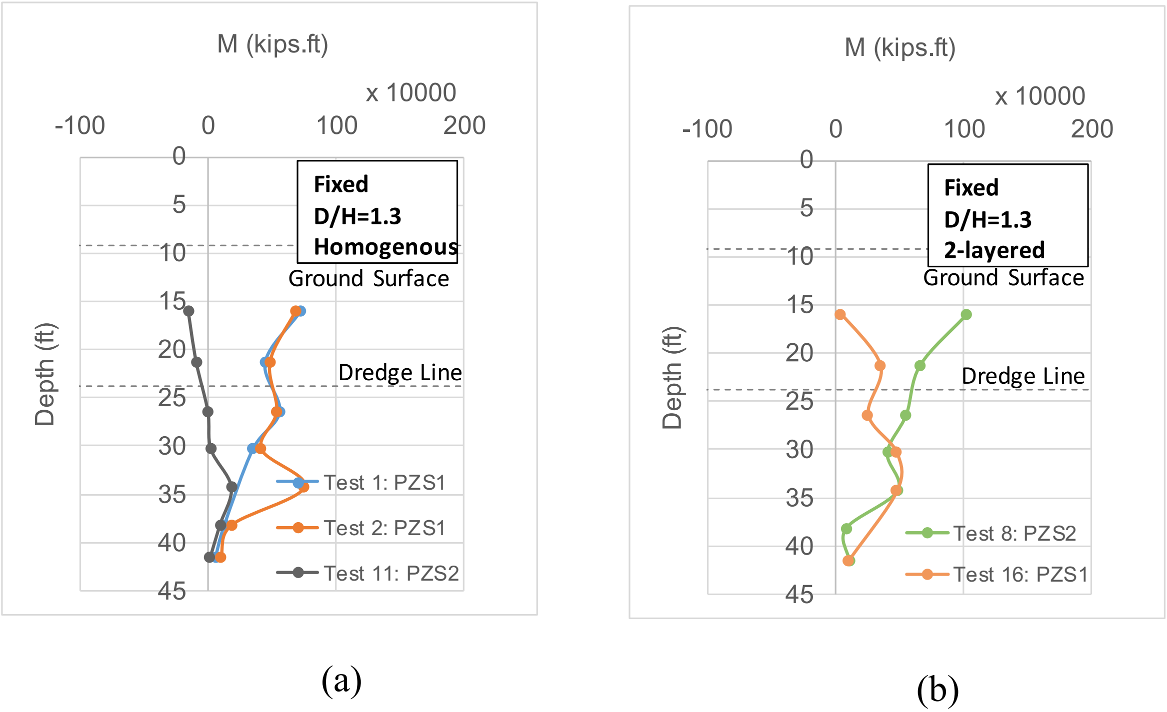
Bending moment profiles of the sheet pile wall PZS1 in the profile PR4 compared to that in the profile PR3: (a) CPR=7.87×10^{-4} in/s; and (b) CPR=7.87×10^{-5} in/s

- *Axial resistance of the pile wall consistently increased due to its penetration in the dense sand layer in the PR2 profile.*
- *However, the gain in axial resistance in for d/h = 2.24 has been more than that for d/h = 1.3, when comparing to the corresponding homogenous profiles. Greater penetration means greater driving resulting in more compaction of sand around the sheet pile.*
- *Maximum bending moment occurs at 34.25 ft depth, which is generally consistent across all centrifuge load tests.*
- *Greater bending moments are obtained in the two-layered profiles than those in homogeneous layers, related to increased axial resistance in the former.*

(2) Effect of Pile Stiffness



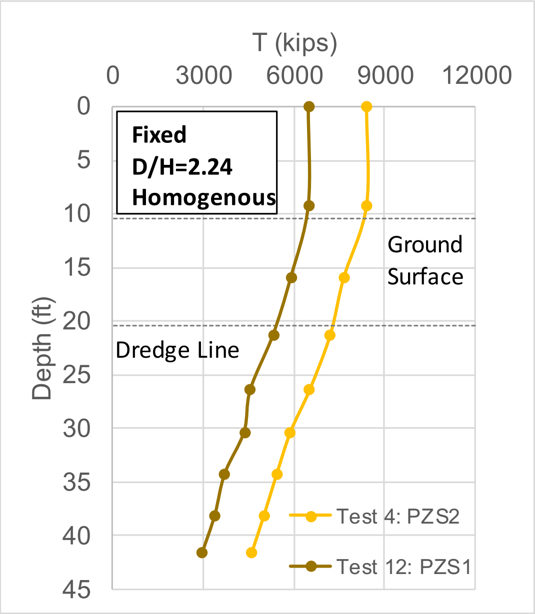
Influence of pile stiffness (denoted by differing sections PZS1 and PZS2) on axial resistance of the sheet pile wall in (a) homogeneous and (b) layered soil profiles with d/h = 1.3



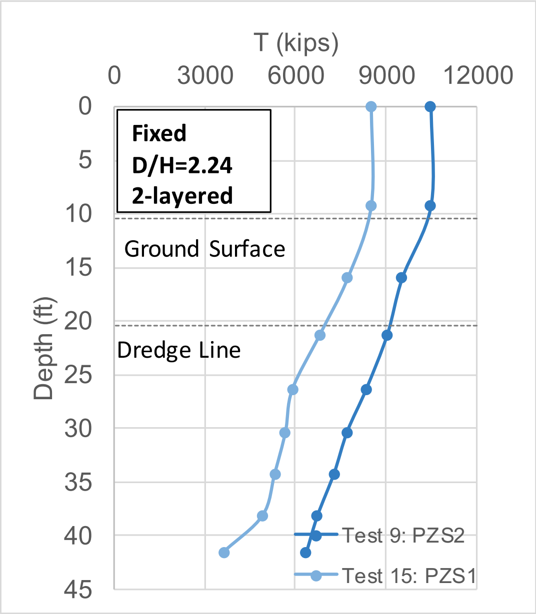
Influence of pile stiffness (denoted by differing sections PZS1 and PZS2) on bending moment profiles of the sheet pile wall in (a) homogeneous and (b) layered soil profiles with d/h = 1.3.

- *Influence of pile stiffness on the axial resistance and bending moment profiles acting on the sheet pile wall.*
- *Pile stiffness is studied by using two different cross-section profiles (PZS1 and PZS2).*

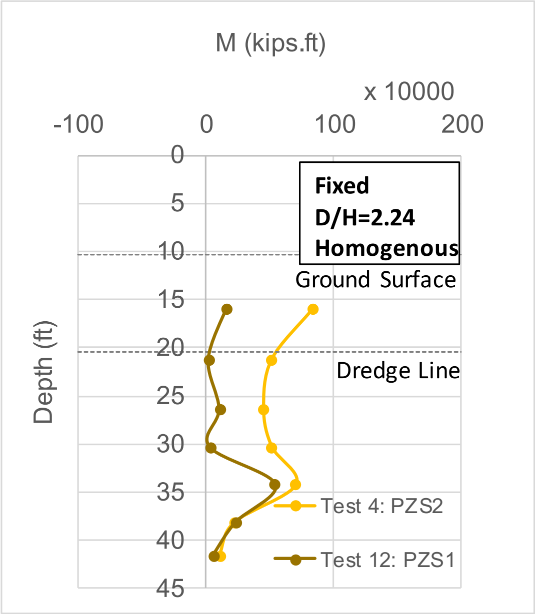
(2) Effect of Pile Stiffness (cont'd)



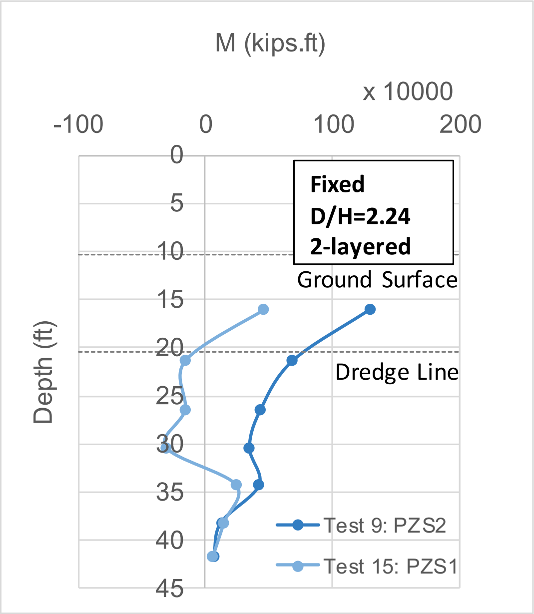
(a)



(b)



(a)



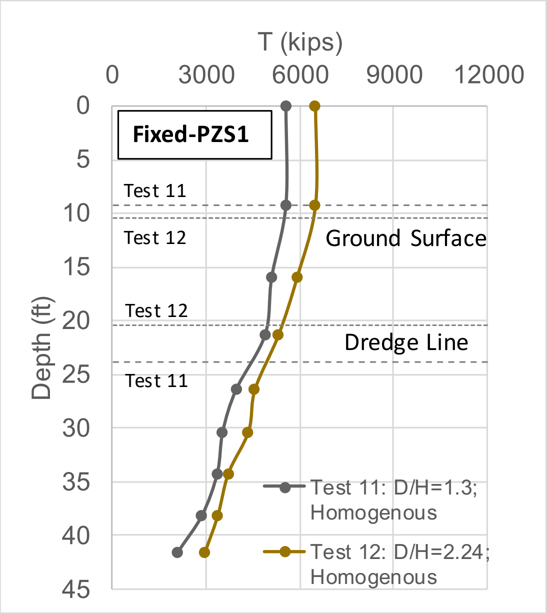
(b)

Influence of pile stiffness (denoted by differing sections PZS1 and PZS2) on axial resistance of the sheet pile wall in (a) homogeneous and (b) layered soil profiles with d/h = 2.24

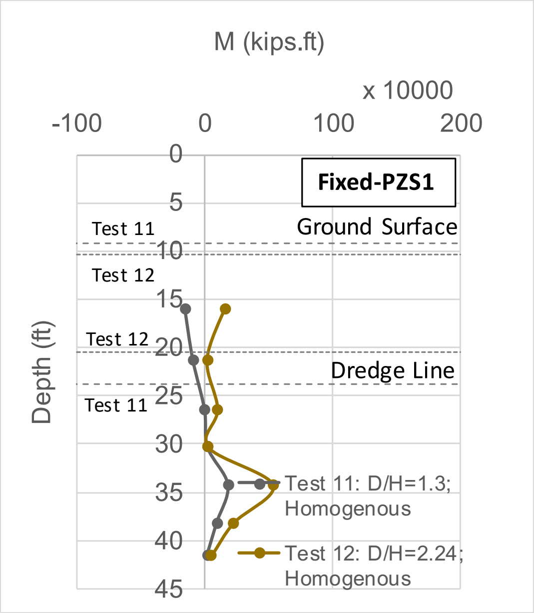
Influence of pile stiffness (denoted by differing sections PZS1 and PZS2) on bending moment profiles of the sheet pile wall in (a) homogeneous and (b) layered soil profiles with d/h = 2.24.

- *The PZS2 sheet pile consistently showed a greater axial resistance than the PZS1.*
- *The main contributing factor for this observation would be the higher cross-sectional area in PZS2 compared to that in PZS1.*
- *Consequently, the greater soil plugging occurs in the PZS2 and has contributed to the enhancement of the axial resistance.*

(3) Effect of D/H

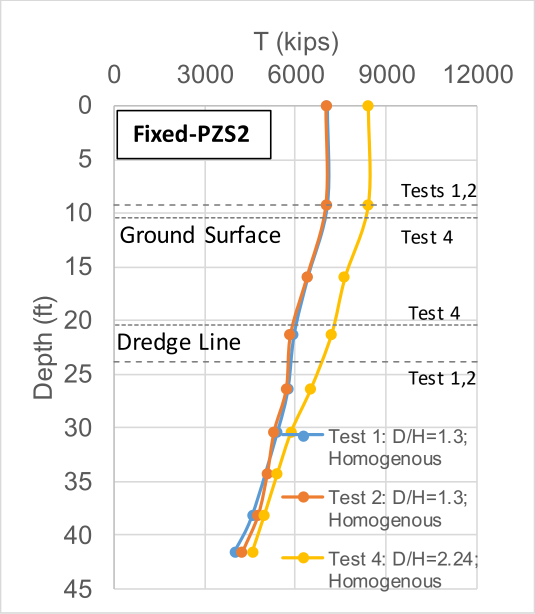


(a)

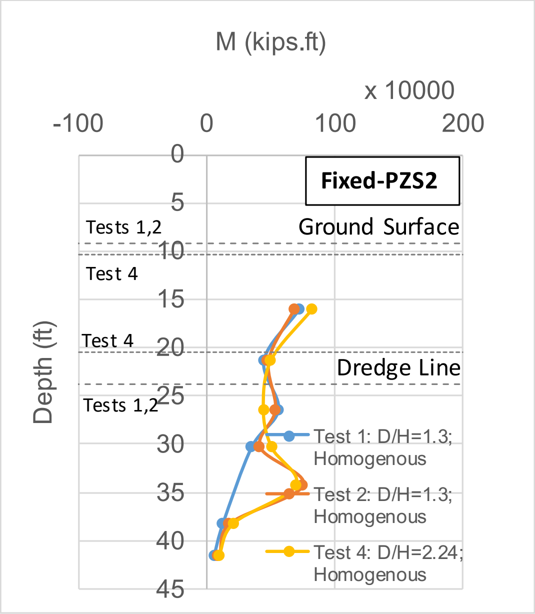


(b)

Influence of relative retained heights of soil on the (a) axial resistance and (b) bending moment profiles in sheet pile wall section PZS1.



(a)

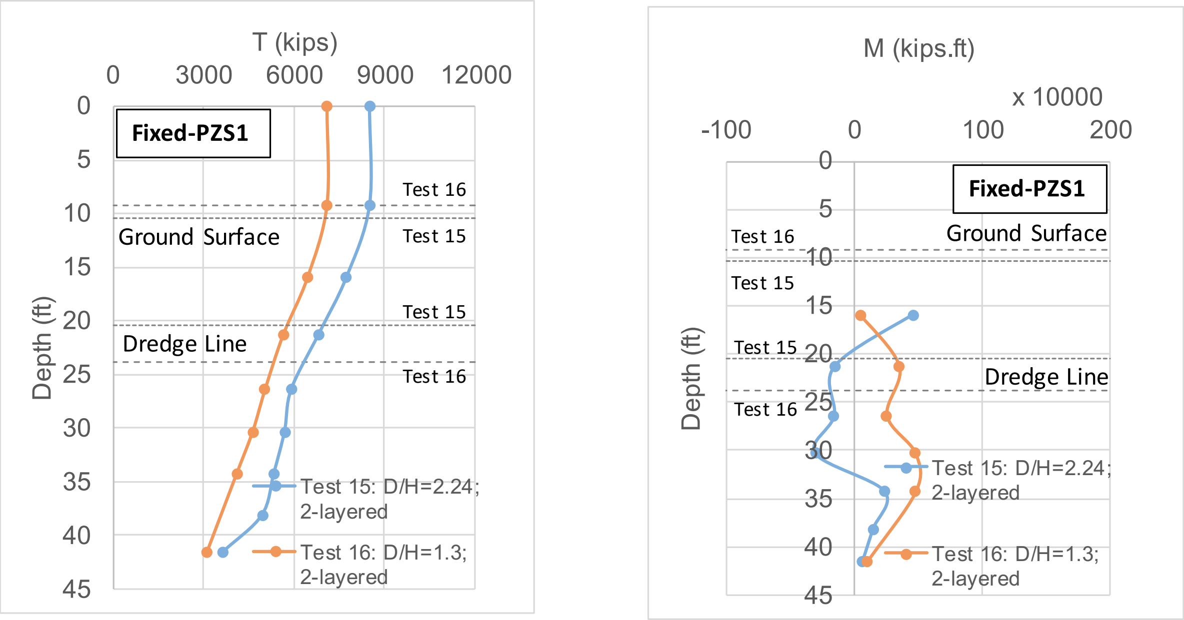


(b)

Influence of relative retained heights of soil on the (a) axial resistance and (b) bending moment profiles in sheet pile wall section PZS2.

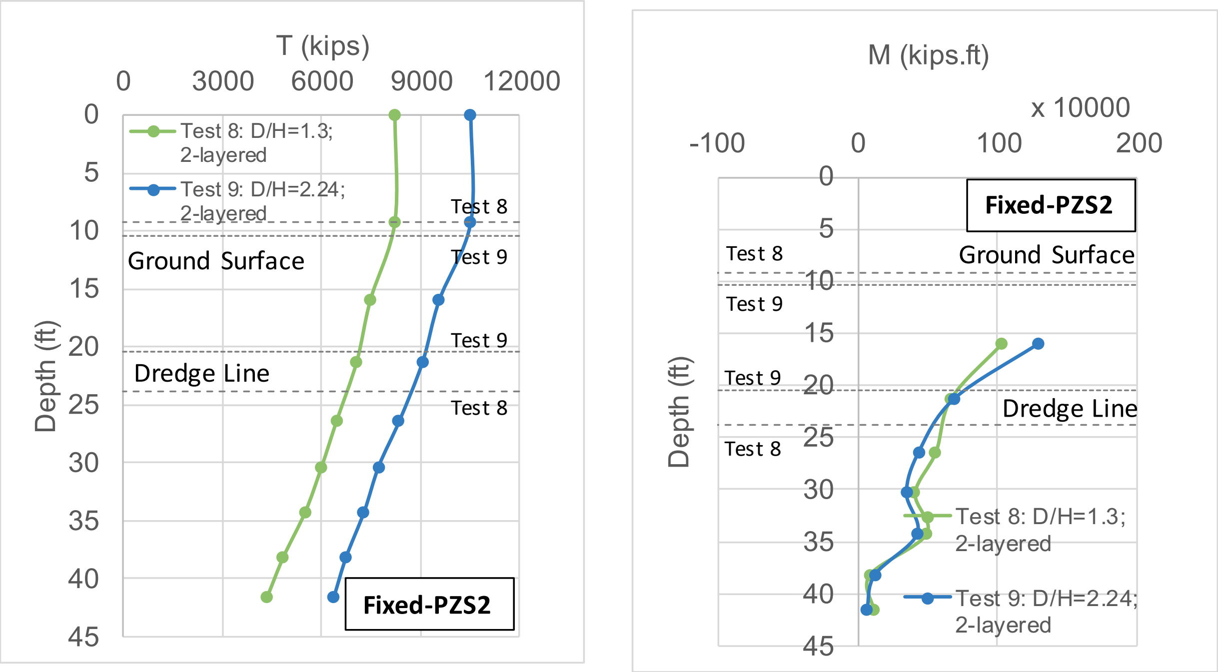
- *Effects of depth of penetration (D) and unsupported length (H) on the axial behavior and bearing resistance of the sheet pile walls*
- *Two different penetration depth to retained soil height ratios (D/H) of 1.3 and 2.24 were considered.*

(3) Effect of D/H (cont'd)



(a) (b)

Comparison of (a) axial resistance and (b) bending moment profiles in sheet pile wall section PZS1 for different relative retained heights of soil or d/h ratios.

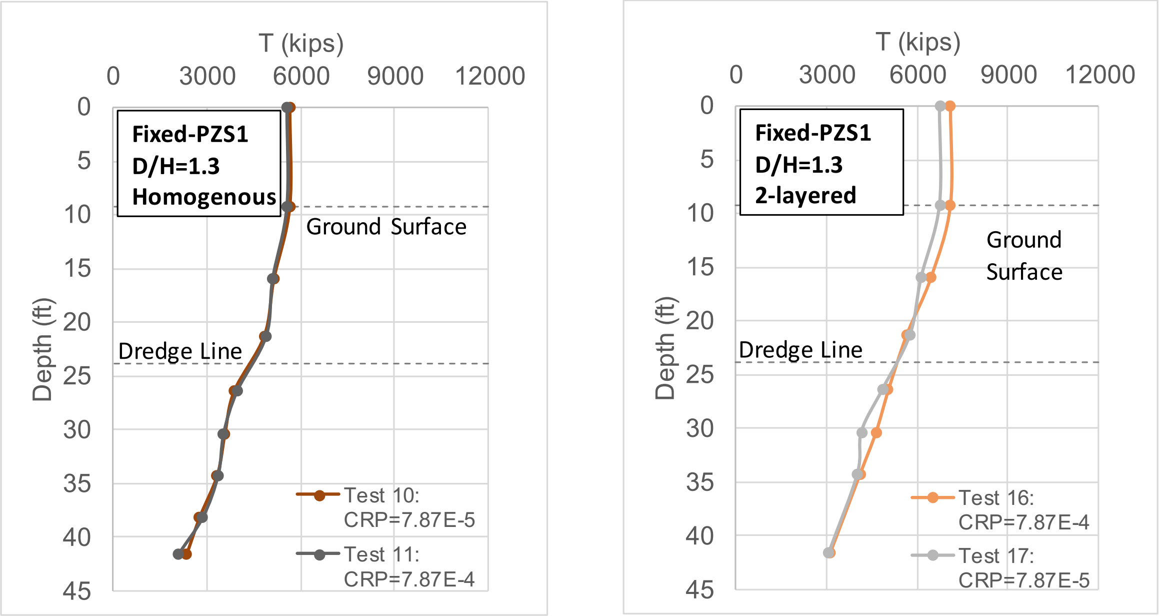


(a) (b)

Comparison of (a) axial resistance and (b) bending moment profiles in sheet pile wall section PZS2 for different relative retained heights of soil or d/h ratios.

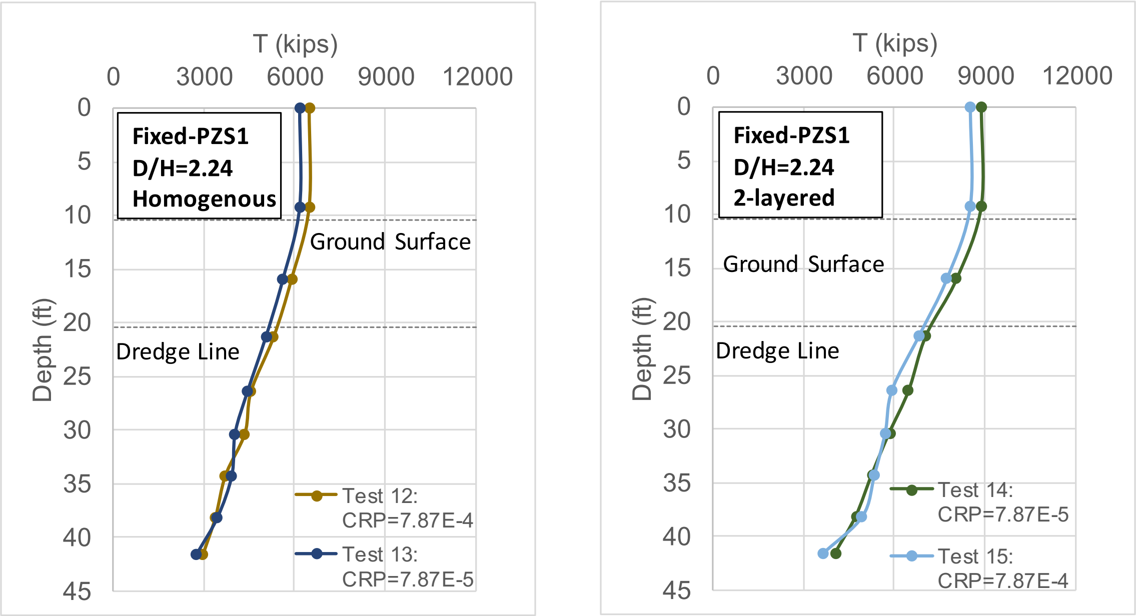
- *Influence of the retained height on bearing capacity in the inhomogeneous or layered soil profile.*
- *Increasing the D/H ratio increased the axial resistance in both homogenous and two-layered profiles.*
- *Increase in axial resistance is higher for the stratified profiles (up to 24%) compared to those in homogenous sand profiles (about 17%).*
- *Accordingly, greater bending moments act on the pile wall in the two-layer profile compared to the homogenous profile.*

(4) Effect of Loading Rates



(a) (b)

Influence of loading rates on axial resistance of the sheet pile wall in (a) homogeneous and (b) layered soil profiles.

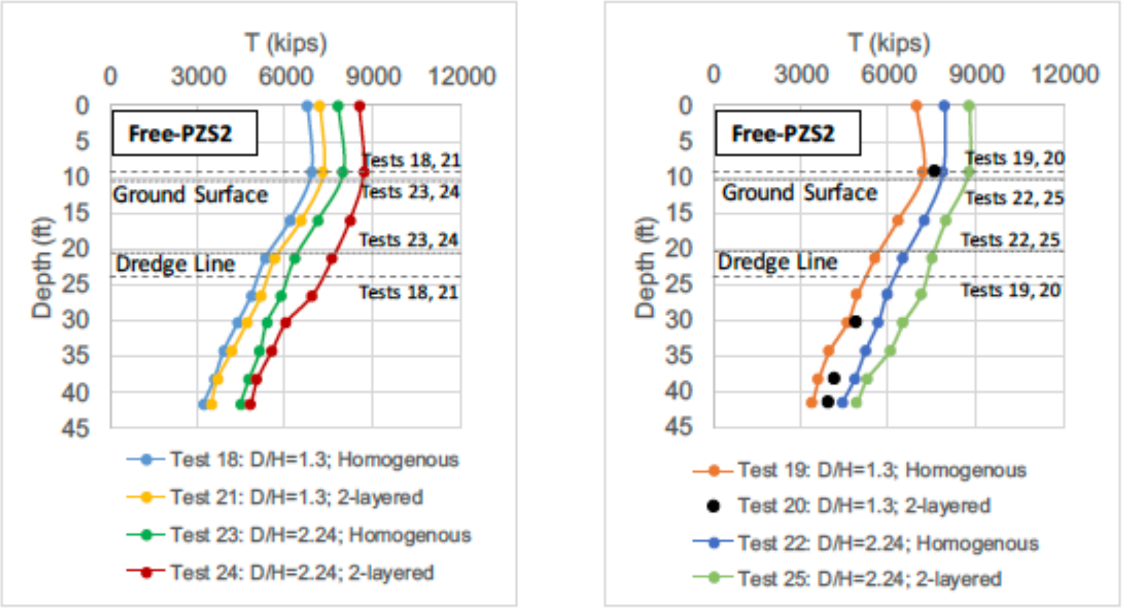


(a) (b)

Influence of loading rates on axial resistance of the sheet pile wall in (a) homogeneous and (b) layered soil profiles.

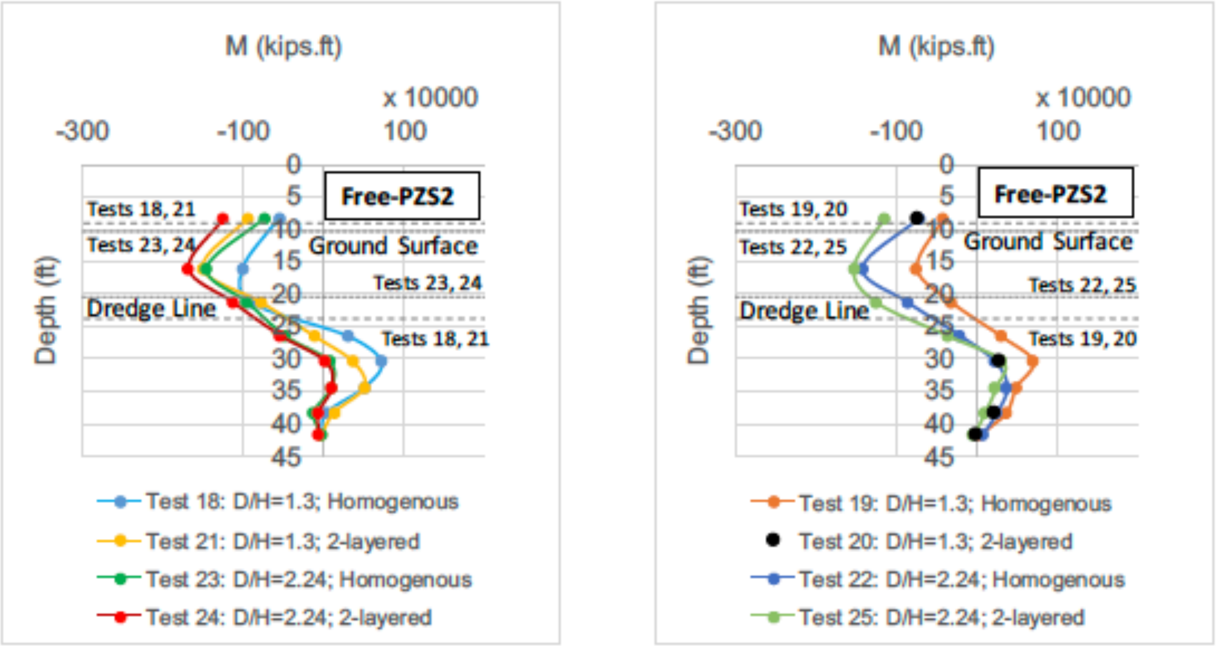
- *CRP/ Load rate does not change the axial resistances in any of the investigated profiles.*
- *It can be attributed to testing in dry condition.*
- *Findings are consistent with literature on pile wall testing.*

(5) Effect of boundary condition (pile head)



(a) (b)

Figure 43. Axial resistance of the sheet pile wall PZS2 in different soil profiles (a) CPR=7.87×10^{-4} in/s; and (b) CPR=7.87×10^{-5} in/s. Tests 18-19; 20-21; 22-23; and 24-25 represent the load test results in PR1; PR2; PR3; and PR4, respectively.



(a) (b)

Figure 44. Bending moment profiles of the sheet pile wall PZS2 in different soil profiles (a) CPR=7.87×10^{-4} in/s; and (b) CPR=7.87×10^{-5} in/s. Tests 18-19; 20-21; 22-23; and 24-25 represent the load test results in PR1; PR2; PR3; and PR4, respectively.

(6) Ground settlement

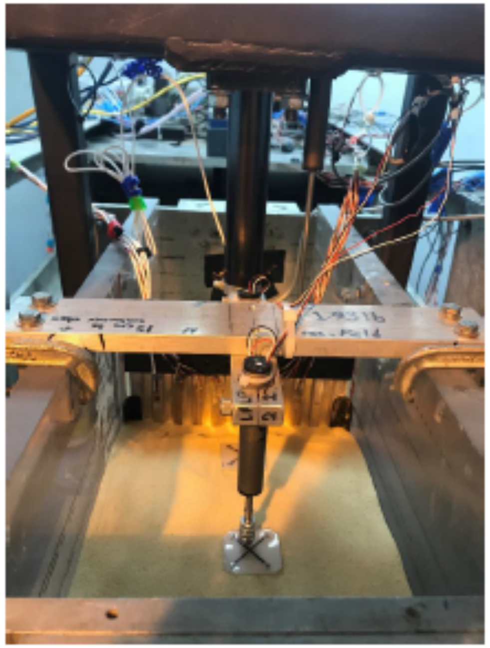


Figure 47. Settlement measurement by two vertical LPs

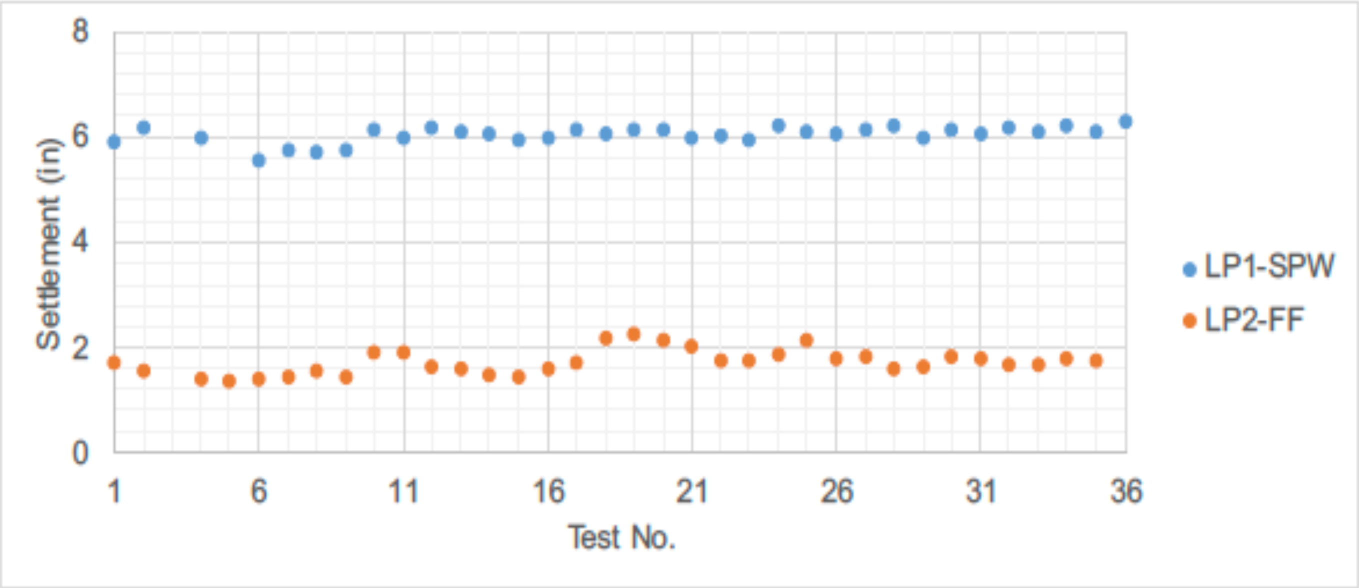
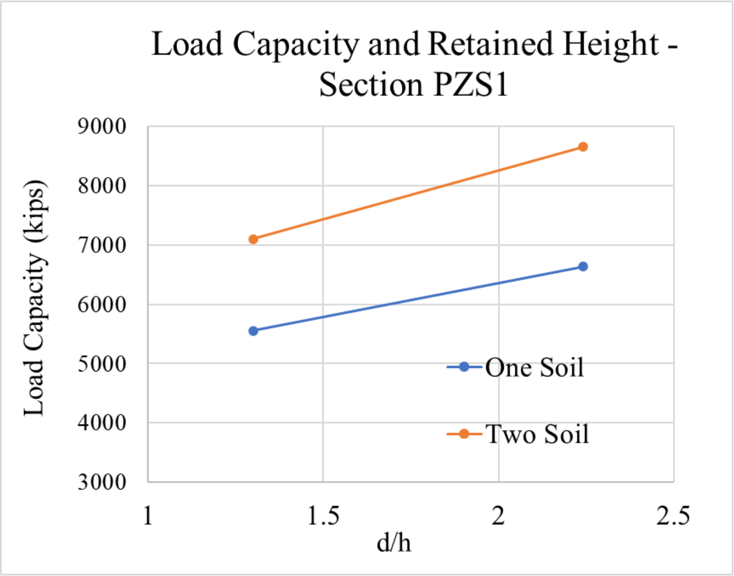
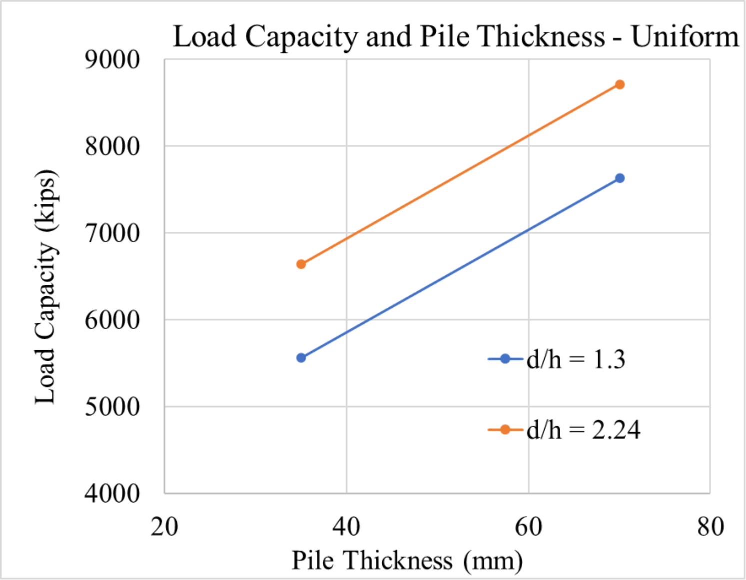
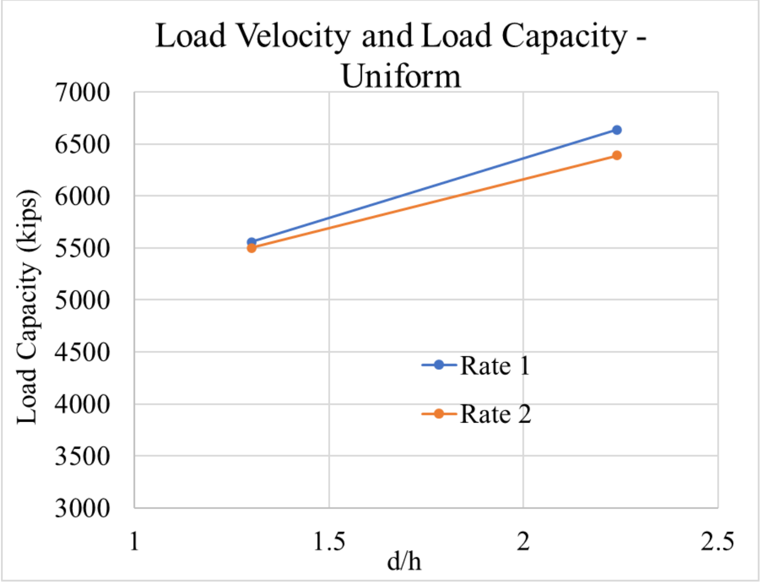


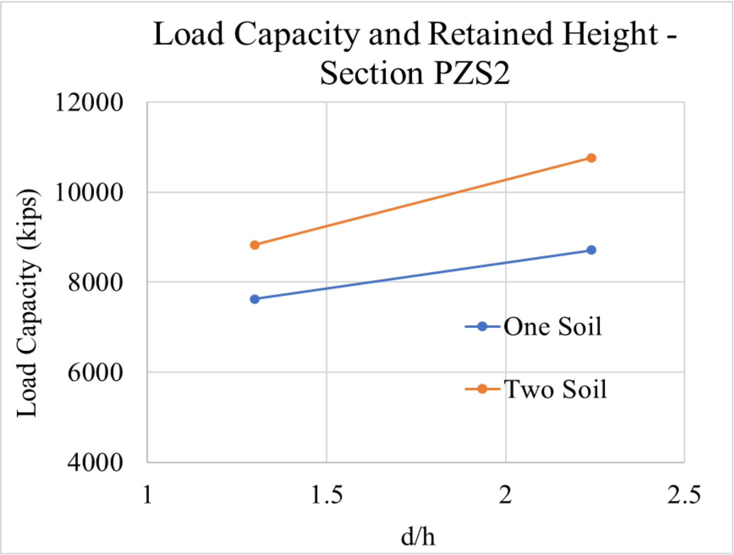
Figure 49. Peak ground settlement during driving and load testing of sheet piles at different presented tests

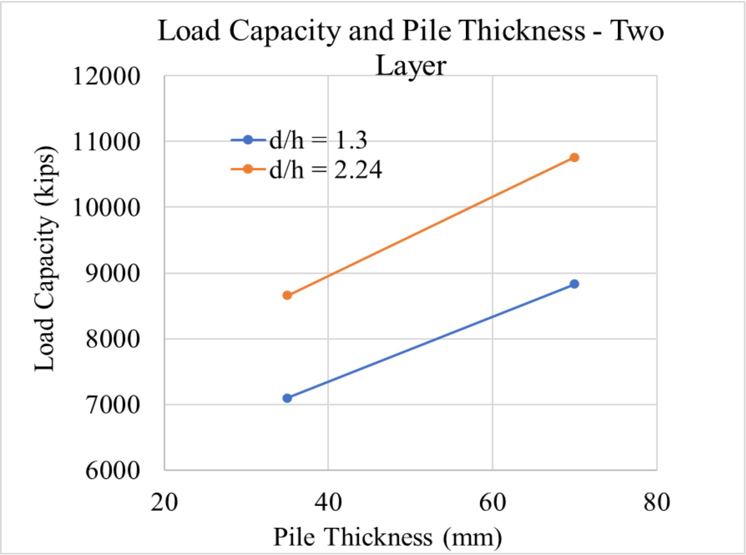
Summary of Centrifuge Testing

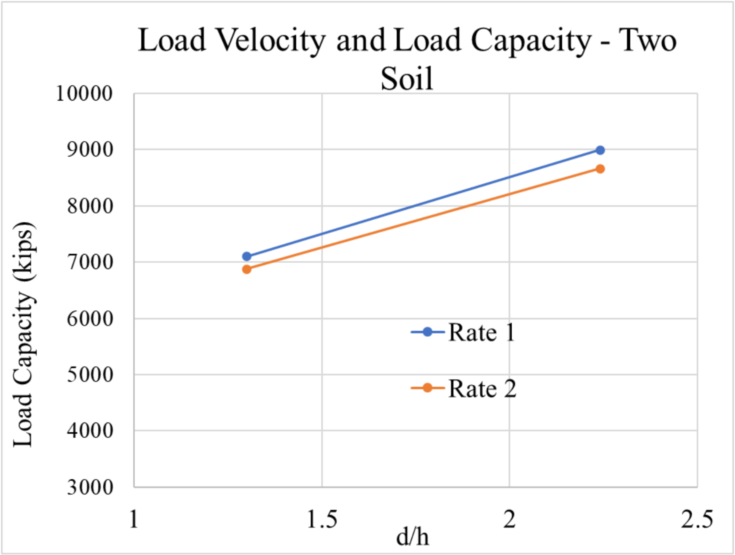










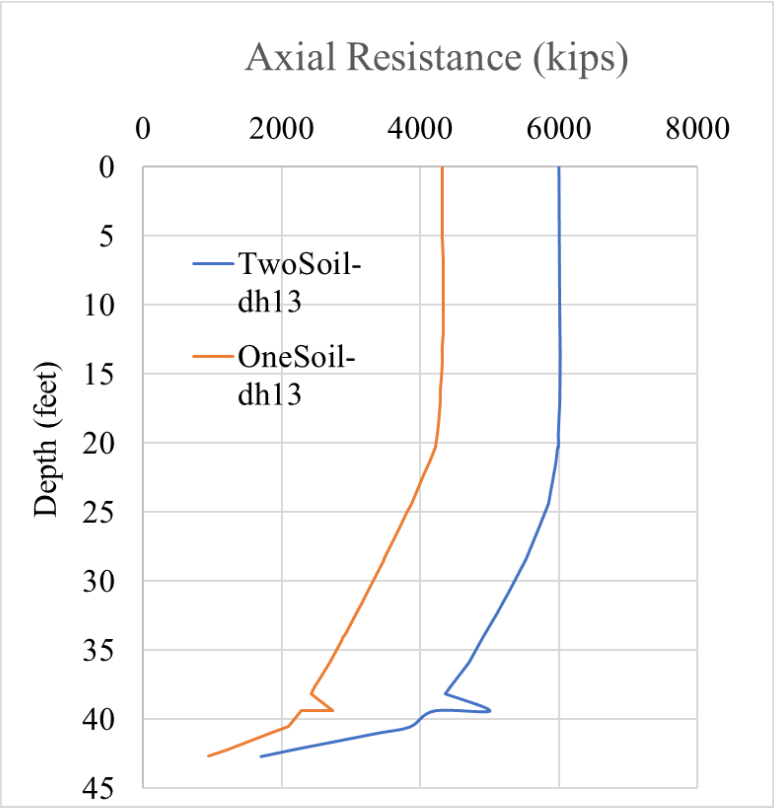


Summary of Centrifuge Testing (cont'd)

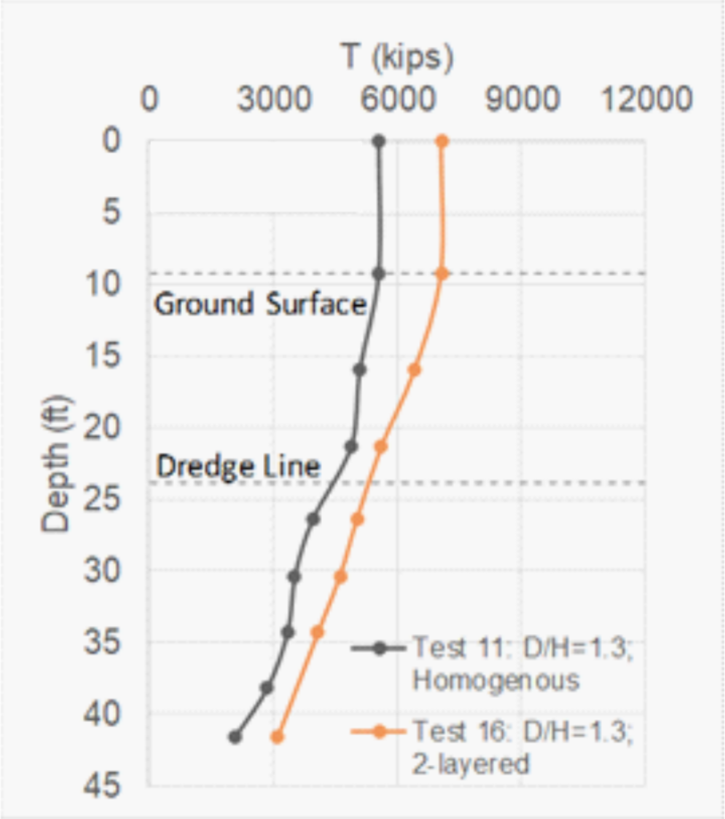
- A strain-hardening type axial load-displacement behavior was observed (can be attributed to soil plugging).
- Emplacement of pile wall tip in denser sand increases axial resistance, more so for d/h = 2.24 than d/h =1.3 (can be attributed to greater compaction due to longer driving time).
- Increasing sheet pile stiffness (cross-section area) generally improves the load bearing capacity.
- Rate effects observed are minimal due to absence of pore pressure and damping forces which is consistent with the existing literature on pile walls in dry sands (any discrepancy could be attributed to instrumentation error).

Validating the Numerical Model
(preliminary results)

Axial Resistance



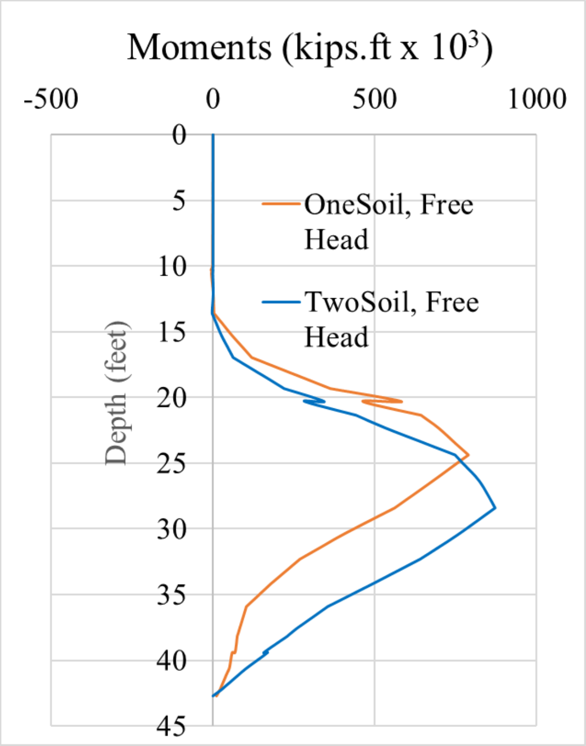
(a)



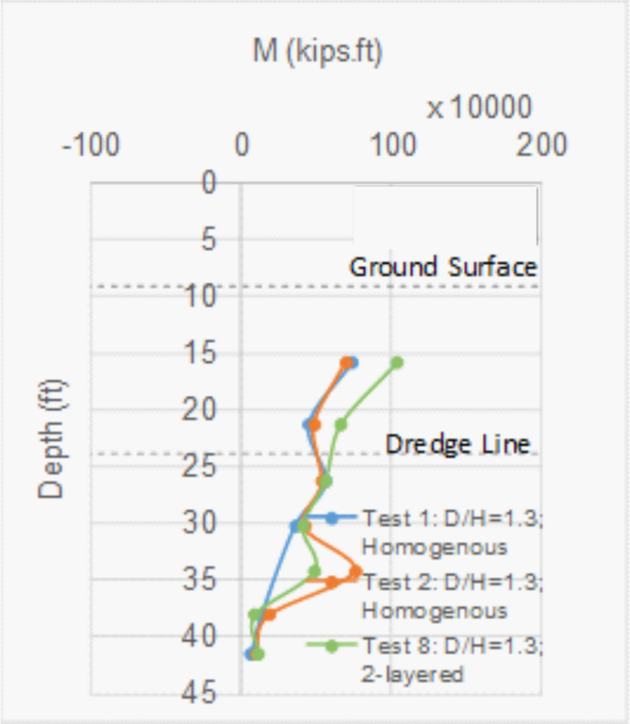
(b)

(a) Predicted axial resistance developed in the pile wall from numerical model, (b)Measured axial resistance developed in the pile wall from the centrifuge test

Bending Moment – Free Head



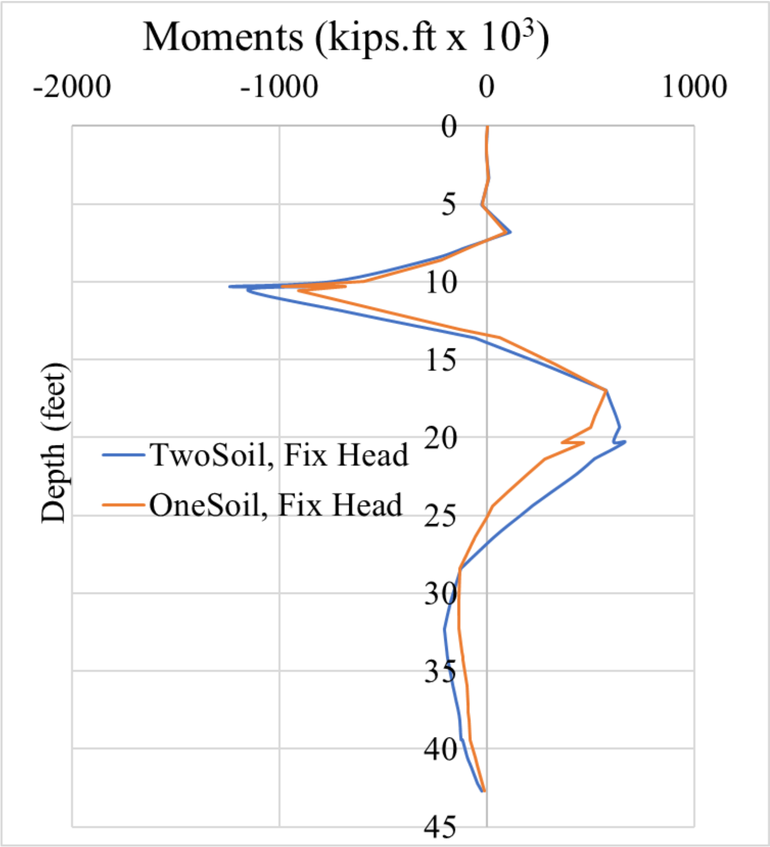
(a)



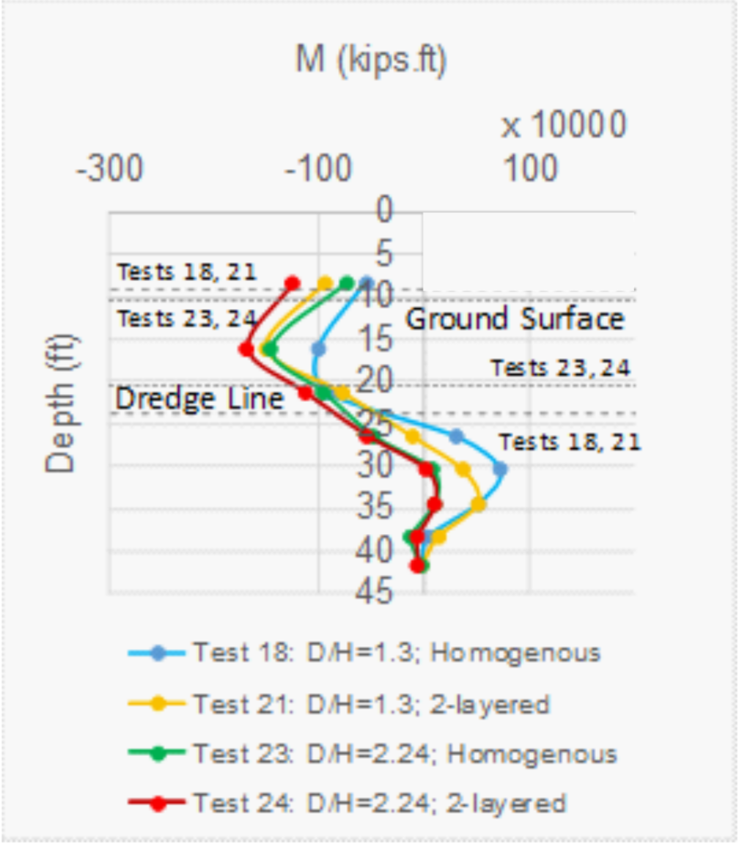
(b)

(a) Predicted bending moments acting on the pile wall from numerical model, (b) Measured bending moments acting on the pile wall from the centrifuge test

Bending Moment – Fixed Head



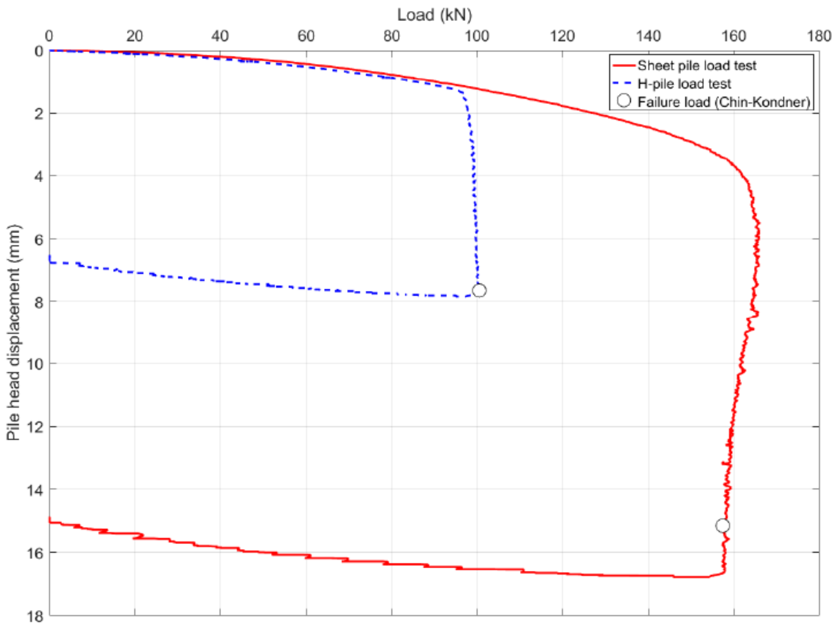
(a)

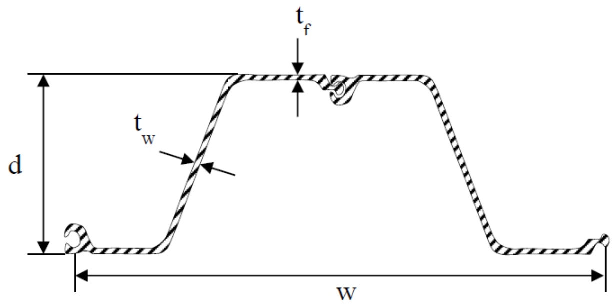


(b)

(a) Predicted bending moments acting on the pile wall from numerical model, (b) Measured bending moments acting on the pile wall from the centrifuge test for a fixed head boundary condition

Task 4: Field Load Test Protocol





- *Axial load test program for steel PZ 27 sheet piles.*
- *The test piles were installed using both a vibratory and impact hammer.*
- *Loads were applied using a hollow plunger cylinder with 533.8 kN capacity.*
- *Displacement was measured at the four corners of the pile head using digital dial gauges with measurement resolution of 0.002 mm.*
- *A load cell with 444.8 kN full-scale range was used to measure the applied axial load at the pile head.*
- *Testing was performed using the constant rate of penetration with 0.13 mm/min.*

Sylvain, M.B., Pando, M.A., Whelan, M.J., Rice, C.D., Ogunro, V.O., Park, Y. and Koch, T., Case History of a Full Scale Axial Load Test of Sheet Piles. In Geotechnical Frontiers 2017 (pp. 355-365).

Task 4: Field Load Test Protocol

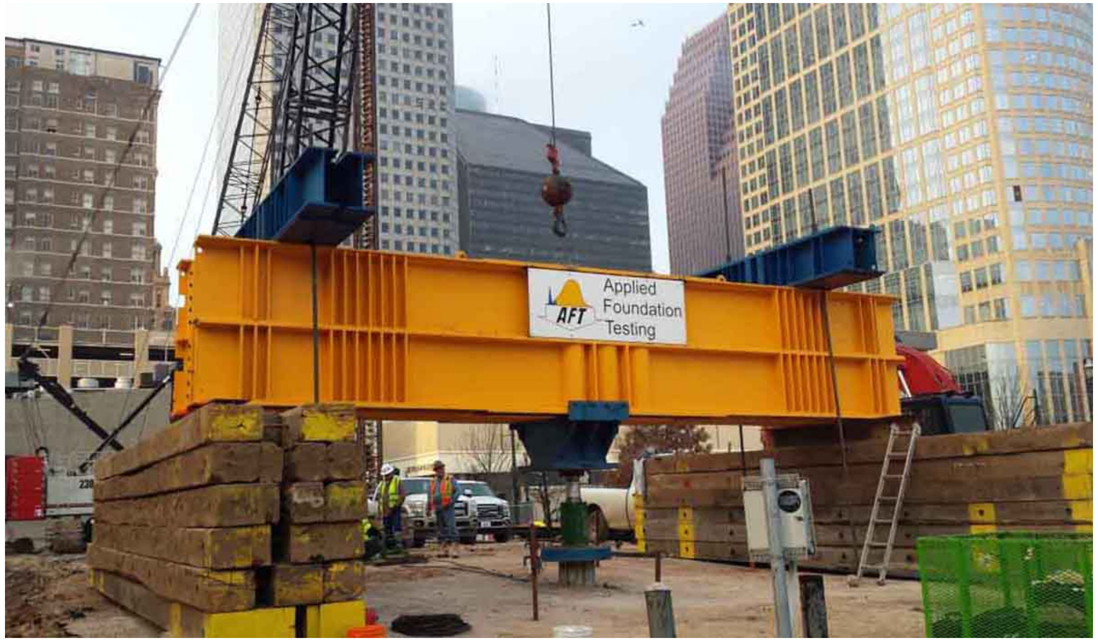


Figure: Static load testing by AFT

Thank you!

Questions?