Effect of Proximity of Sheet Pile Walls on the Apparent Capacity of Driven Displacement Piles (BDV31 977-26)

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Gainesville, Florida

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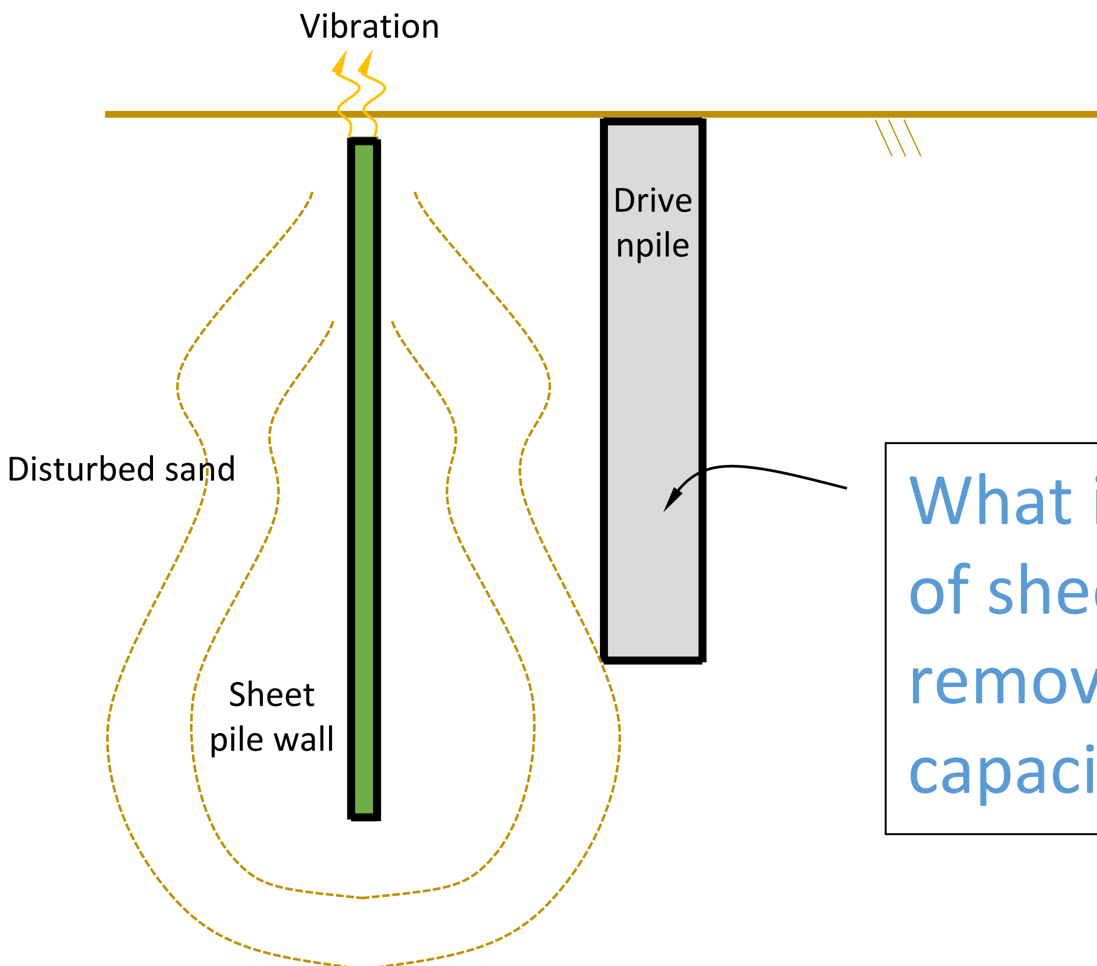
Presentation Outline

- Introduction
- Project Background
- Project Objectives
- Task Outline
- Summary of Research Findings
- Recommendation
- Future Research

Introduction

- For scenarios where driving-induced soil compaction occurs, piles driven in the vicinity of Sheetpile Walls (SPW) or adjacent piles can develop greater load capacities relative to those piles driven in virgin ground.
- The phenomenon that individual pile stress states are dependent upon the proximity of other pre-driven structural members is further complicated for those scenarios where pile driving into granular soil causes grain motions and rearrangement. Subsequent to installation of driven piles, removal (pull-out) of any nearby SPW may well further alter the pile-soil stress states, due to soil disturbances that occur during extraction of the SPW. Such disturbances can lead to reductions in frictional and bearing resistance at piles-soil interfaces, and thus, overestimation of pile design capacities.



What is the effect of sheet pile wall removal on pile capacity?

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Project Subject Background

- In recent years technological advances have been made in relation to piled foundations, and as a result, it is now recognized that the process of pile construction or installation in the ground can cause major changes in the stress state and density conditions of granular soil in the vicinity of the pile.
- Such recognition signifies the value of basic research, which has enabled geotechnical engineers to depart from the relatively more historical approach of employing empirical constants to modify theoretical predictions, where corresponding design predictions were not capable of allowing engineers to reliably account for residual stresses induced during sheet pile wall construction or removal of pre-installed SPW.

Project Objectives

- Evaluate the influence that pertinent parameters have on driven pile resistance under service loadings, e.g., sheet pile proximity, sheet pile depth, and characteristics of dynamic soil-structure interaction;
- Evaluate temporary increases in driven pile resistance associated with nearby SPW;
- Quantify the effect of sheet pile extraction in pile load capacities; and,
- Cultivate design-oriented practical recommendations for calculation of SPW-associated pile capacities.

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Task Descriptions

- **Phase I**
- Task 1. Literature Review
- Task 2. Numerical Modeling Schemes for Granular Soil (medium dense)

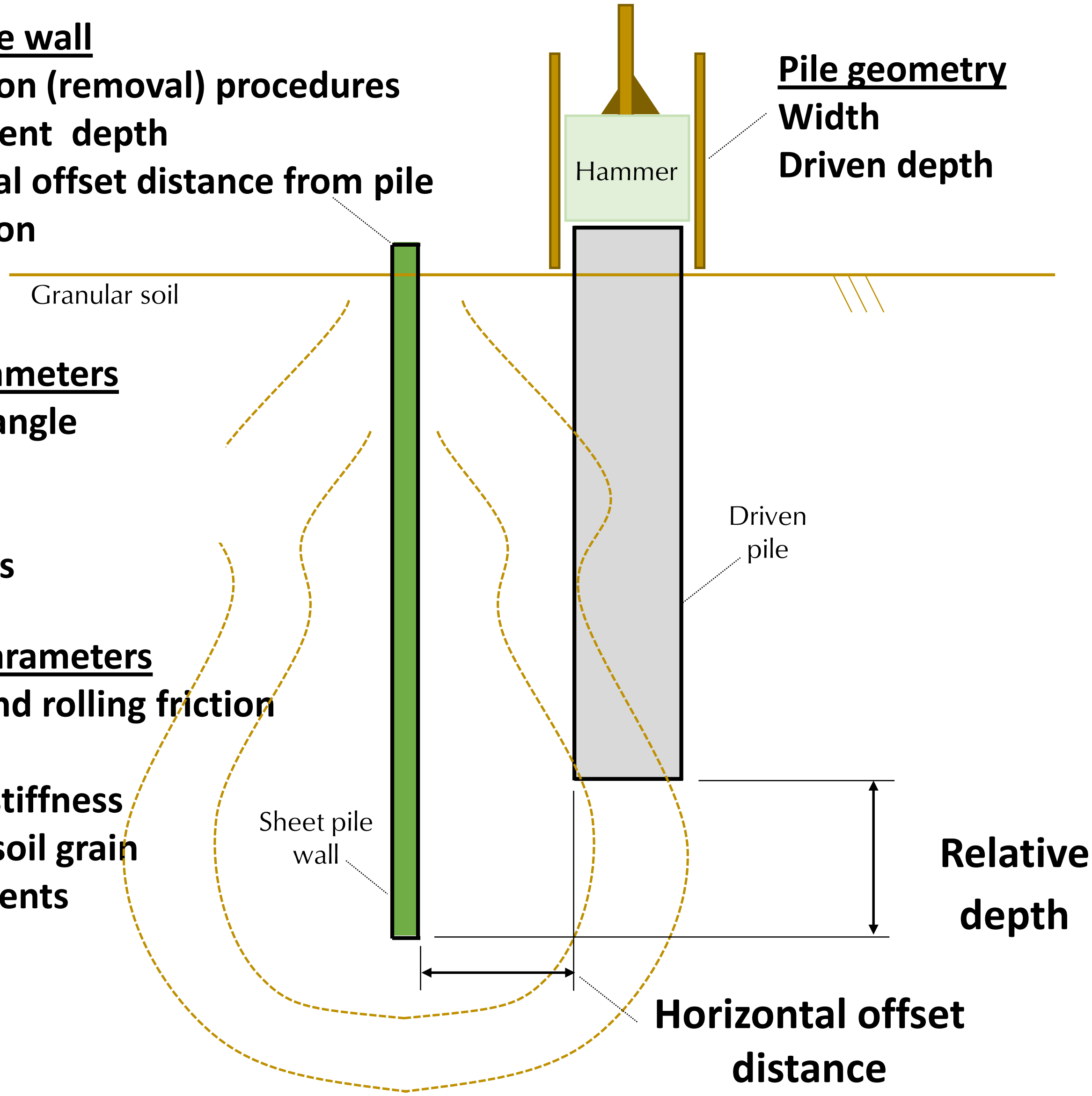
- **Phase II**
- Task 3. Numerical Modeling of Driven foundation in Granular Soils
- Task 4. Physical Laboratory/Centrifuge Experimentation
- Task 5. Reporting of Findings and Design-Oriented Recommendations
- Task 6. Draft Final Report

Task 1. Literature Review: Identification of Key Parameters

Dynamic load rate
Penetration time history measured in centrifuge testing

Sheet pile wall
Installation (removal) procedures
Embedment depth
Horizontal offset distance from pile installation

Pile geometry
Width
Driven depth



Soil physical parameters
Internal friction angle
Relative density
Loading history
Geostatic stresses

Soil numerical parameters
Particle sliding and rolling friction angles
Particle contact stiffness
Mass density of soil grain
Damping coefficients

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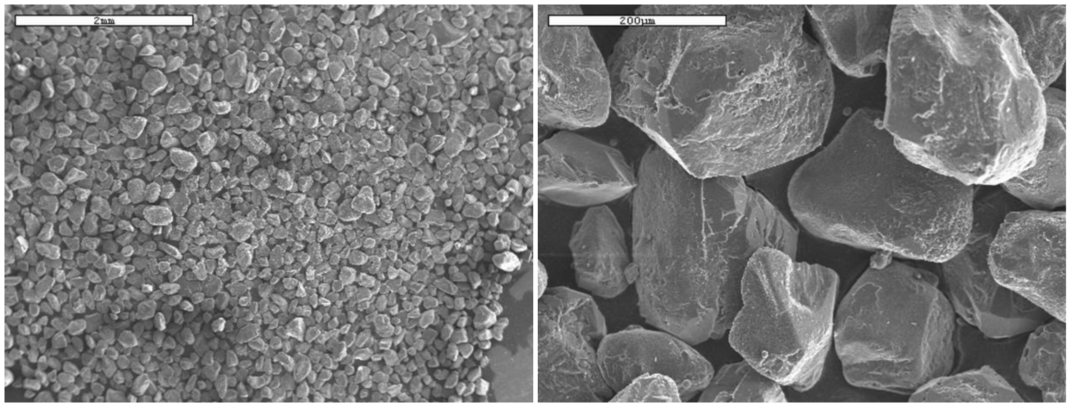
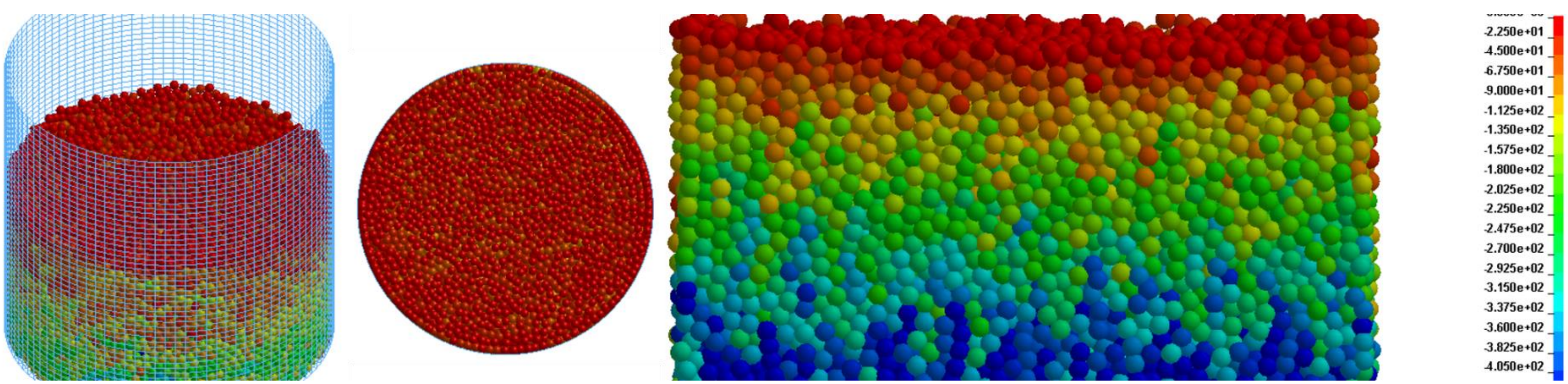
Task 2 Numerical Modeling Schemes for Granular Soil

- A granular medium is composed of distinct soil particles which displace independently one another, and interact only at contact points. The discrete character of the medium results in a complex behavior under loading conditions.



- Combined Discrete Element and Finite element Method.
  - Allow for modeling of dynamic soil (particulate)-structure interaction
  - Meso-scale characterization of soil states
- Challenges
  - Calibration of particle parameters for Florida regional soil
  - Simulation efficiency



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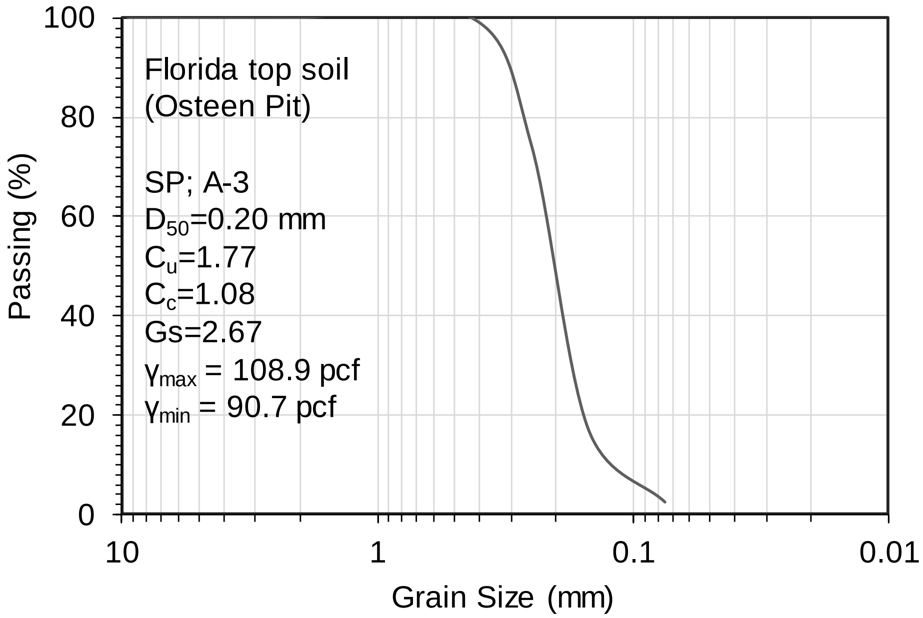
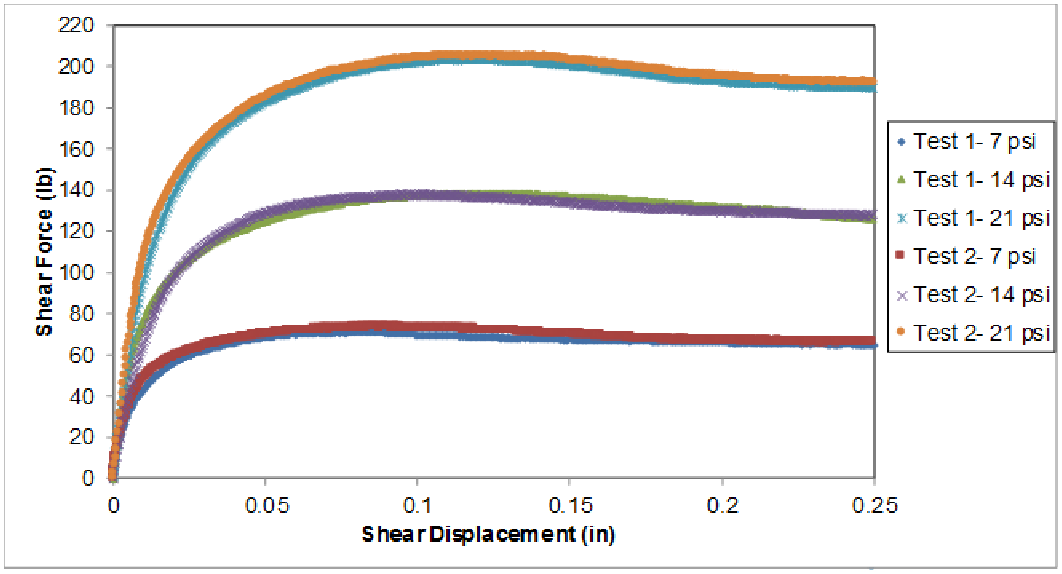
Task 2. Numerical Modeling of Florida Sand

- Florida natural sand with relative density of 60-65%.
- Laboratory tests were performed by the FDOT: States Material Office (SMO) to characterize this soil. Sieve analyses revealed that the USCS name of the soil is "SP" with coefficients of uniformity and curvature of 1.77, and 1.08, respectively.
- Direct Shear Test data was provided by SMO at a relative density of 63% for 3 different applied normal stresses of 7 psi, 14 psi, and 21 psi. Based on the test data, the peak internal friction angle is 31.7 degrees.





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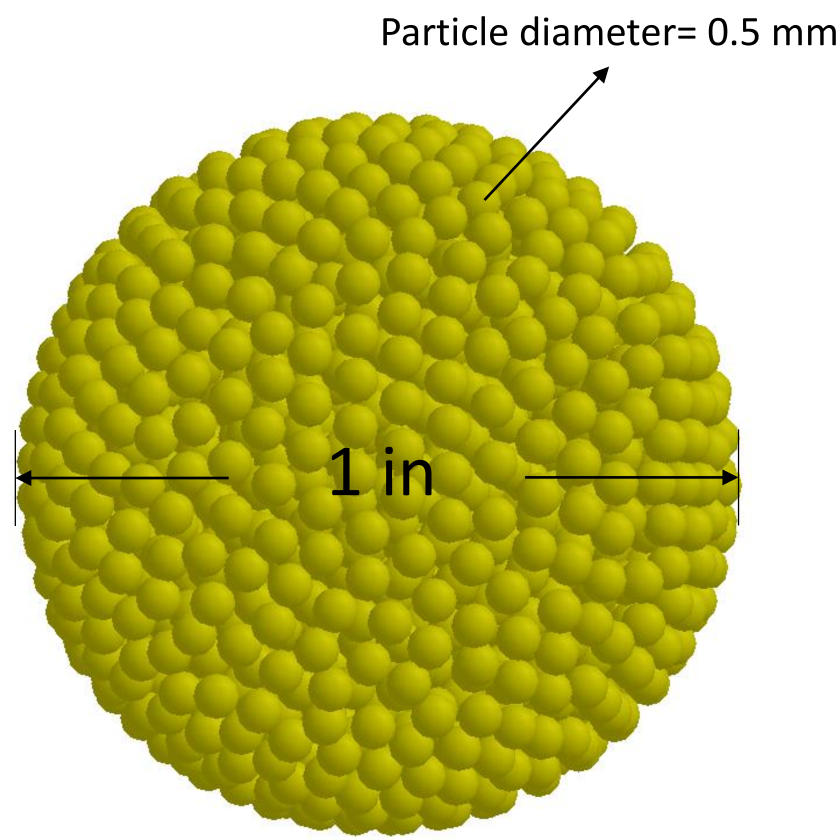
Task 2. Numerical Modeling of Florida Sand

- **Upscaling:**
  - Use of larger discrete elements to represent a pre-defined volume of smaller size particles.
  - Constitutive relationship of the up-scaled representative discrete volume is determined from the material behavior of particles within the representative volume.



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Task 2. Numerical Modeling of Florida Sand

- **Upscaling**

Effective modulus for representative spherical volume

$$E_{eff} = E_o \frac{1-v}{2(2-v)(1-\mu)+\mu^2(1-4v/5)} \rightarrow E_{eff} \equiv fn(E_o, v, \mu)$$

E_0 is the reduced elastic modulus of soil material accounting for surface roughness at grain scale

v is the Poisson's ratio

μ is the inter-particle sliding friction coefficient

$$E_{eff} = 70 \sim 90\, psi \;\; (520 \sim 650 MPa)$$

Task 2. Numerical Modeling of Florida Sand

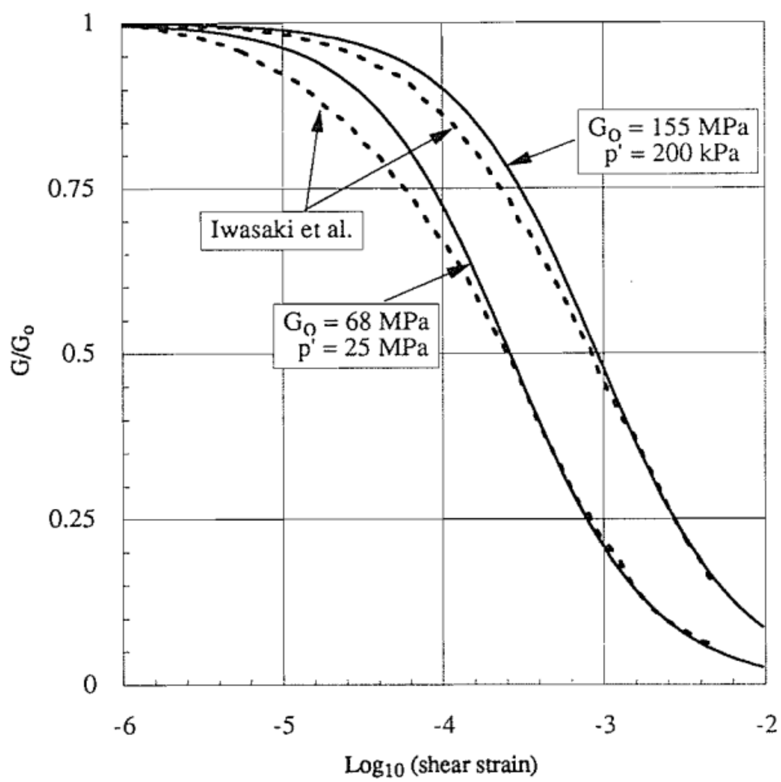
- **Upscaling:** Effective modulus for representative spherical volume

- Effective shear modulus as given by Chang, Misra and Sundaram (1991):

$$G_{eff} = \frac{(5-4v)}{5(2-v)}\left[\frac{\sqrt{3}\cdot cn}{\sqrt{2}\pi(1-v)(1+e)}\right]^{2/3} E_o^{2/3}(\sigma')^{1/3}$$

- Above equation gives an effective shear modulus in the range of 11 ksi to 14 ksi (75 MPa to 95 MPa) for selected range of confining pressures (0.1 MPa to 0.2 MPa)

From Fahey (1992)



Chang, C S., Misra, A., Sundaram, S. S. (1991). "Properties of Granular Packings under low-Amplitude Cyclic Loading," Soil Dynamics and Earthquake Engineering, 10, pp. 201–211.

Fahey, M. (1992). "Shear Modulus of Cohesionless Soil: Variation with Stress and Strain Level," Canadian Geotechnical Journal; 29, pp. 157–161.

Iwasaki, T., Tatsuoka, F.,and Takagi, Y. (1978). "Shear Moduli of Sands under Cyclic Torsional Shear Loading," Soils and Foundation, 18, pp. 39-56.

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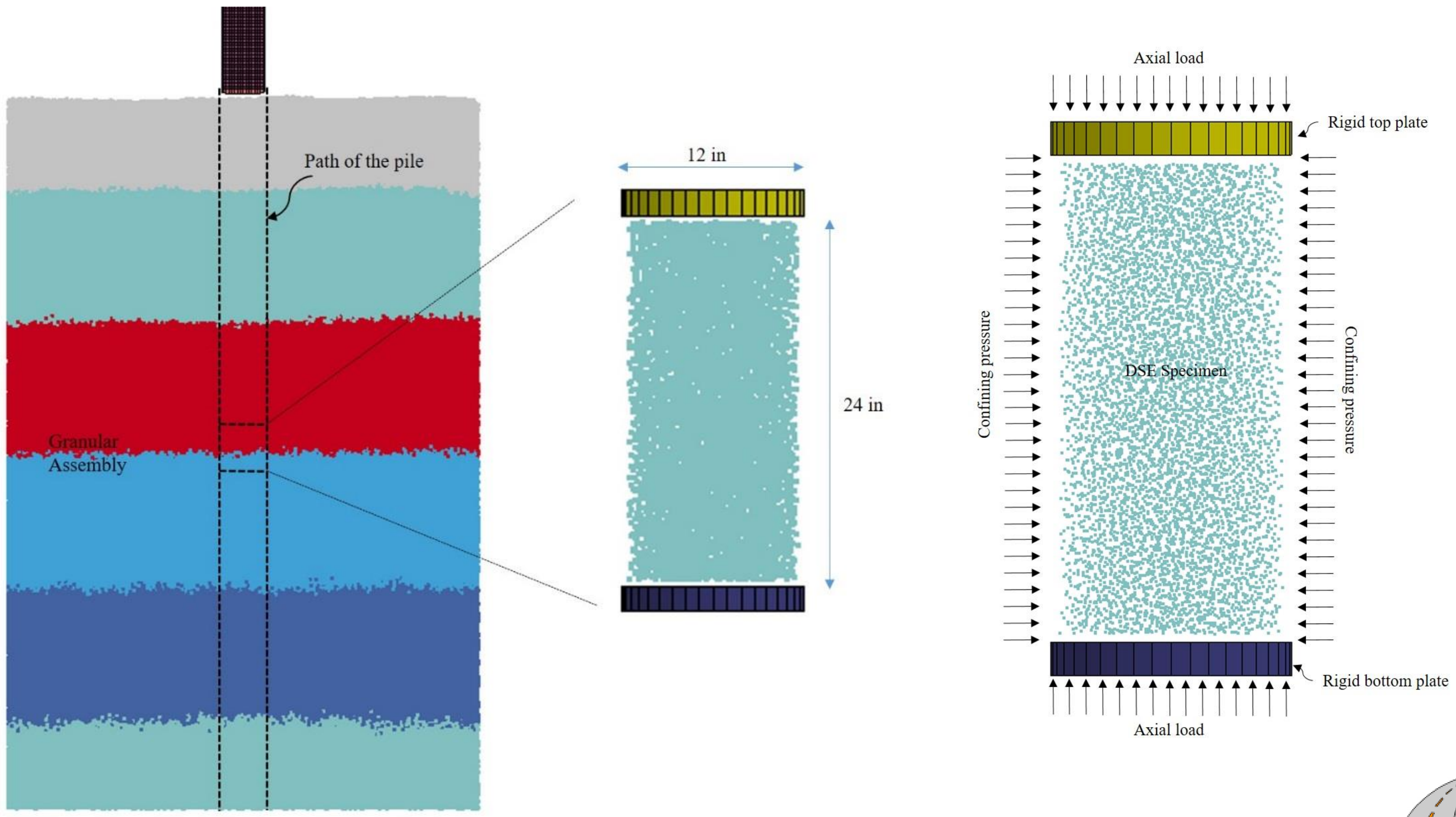
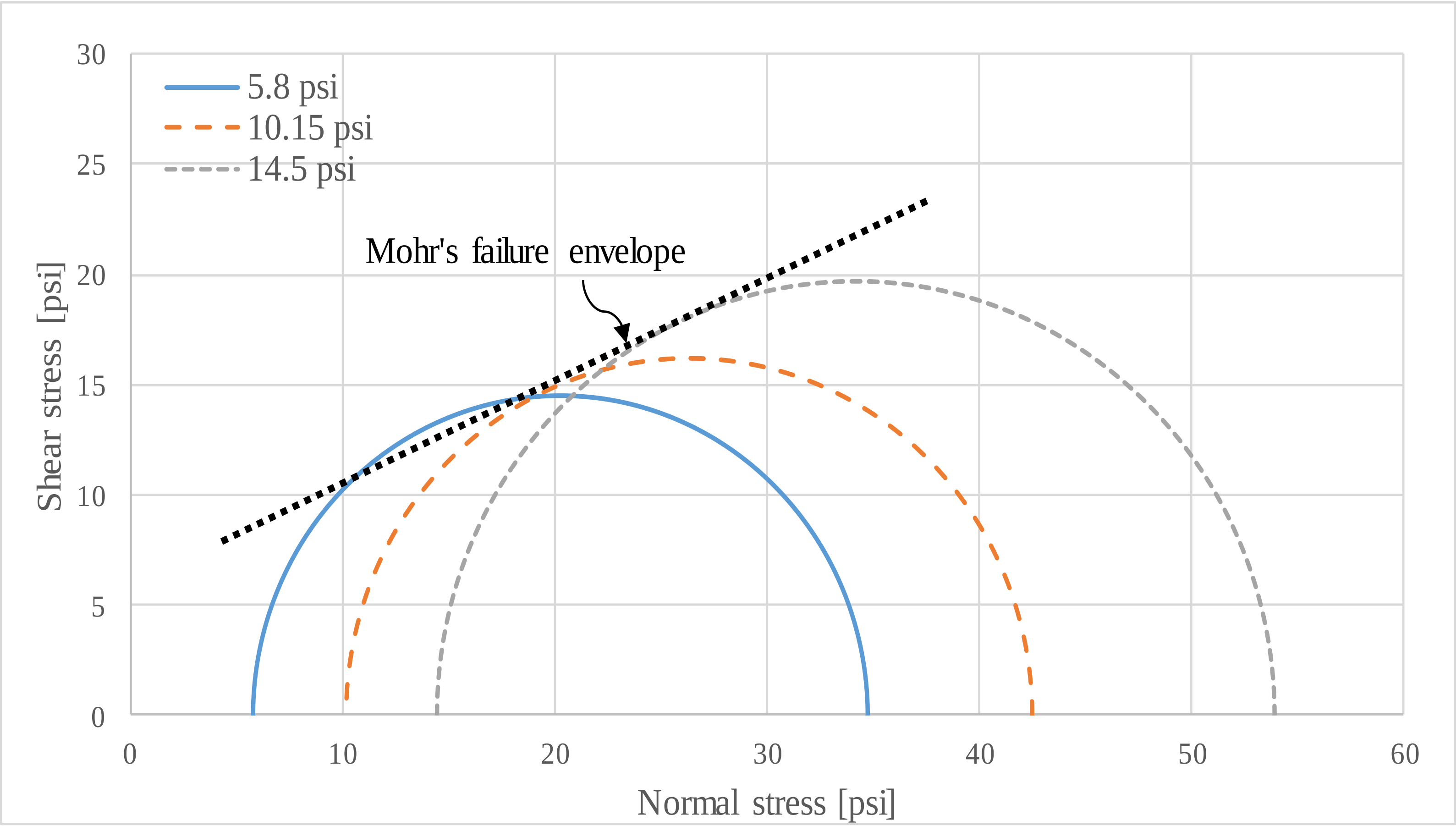
Task 2. Numerical Modeling of Florida Sand

- **Tri-axial Compression Test Simulations**



Task 2. Numerical Modeling of Florida Sand

- **Tri-axial Compression Simulations**



Task 2. Numerical Modeling of Florida Sand

- **Tri-axial Compression Simulations**

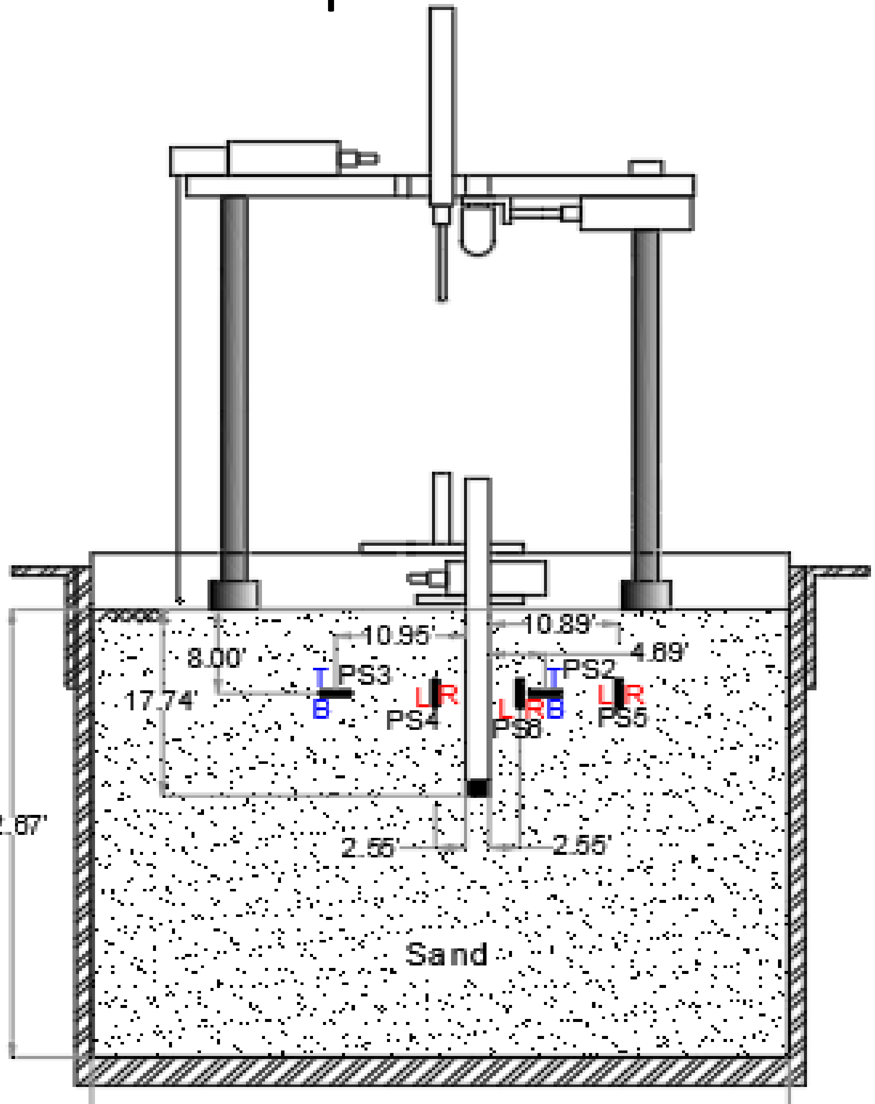
Simulation:	1	2	3	4	5	6	7	8
Elastic properties:								
Mass density (lb/ft^3)	165.5	165.5	165.5	165.5	165.5	165.5	165.5	165.5
Bulk modulus (ksi)	10.52	10.52	15.77	15.77	17.87	17.87	21.02	21.02
Poisson's ratio	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
Rheological model parameters:								
Normal damping	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Tangential damping	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Sliding friction coefficient	0.6	1.0	0.6	1.0	0.6	1.0	0.6	1.0
Rolling friction coefficient	0.06	0.1	0.06	0.1	0.06	0.1	0.06	0.1
Normal stiffness factor	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Tangential stiffness ratio	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Shear behavior under triaxial compression testing:								
At 5.8 psi confinement:								
Peak shear strength (psi)	29	32.625	30.6	33.5	33.2	35.1	36.4	37.56
At 10.15 psi confinement:								
Peak shear strength (psi)	32.33	35.38	34.22	36.98	36.10	40.02	39.88	41.47
At 14.5 psi confinement:								
Peak shear strength (psi)	39.44	43.5	39	44.95	44.52	48	47.27	49.45
Peak internal angle of friction (º)	28.5	30.86	29.8	31.3	31.2	31.94	31.79	32.23

Measured internal friction angle for Florida sand using Direct Shear Test:
Peak friction angle = 31.3º
Ultimate friction angle = 29.5º

Task 4. Prototype-scale Centrifuge Tests on FL Sand

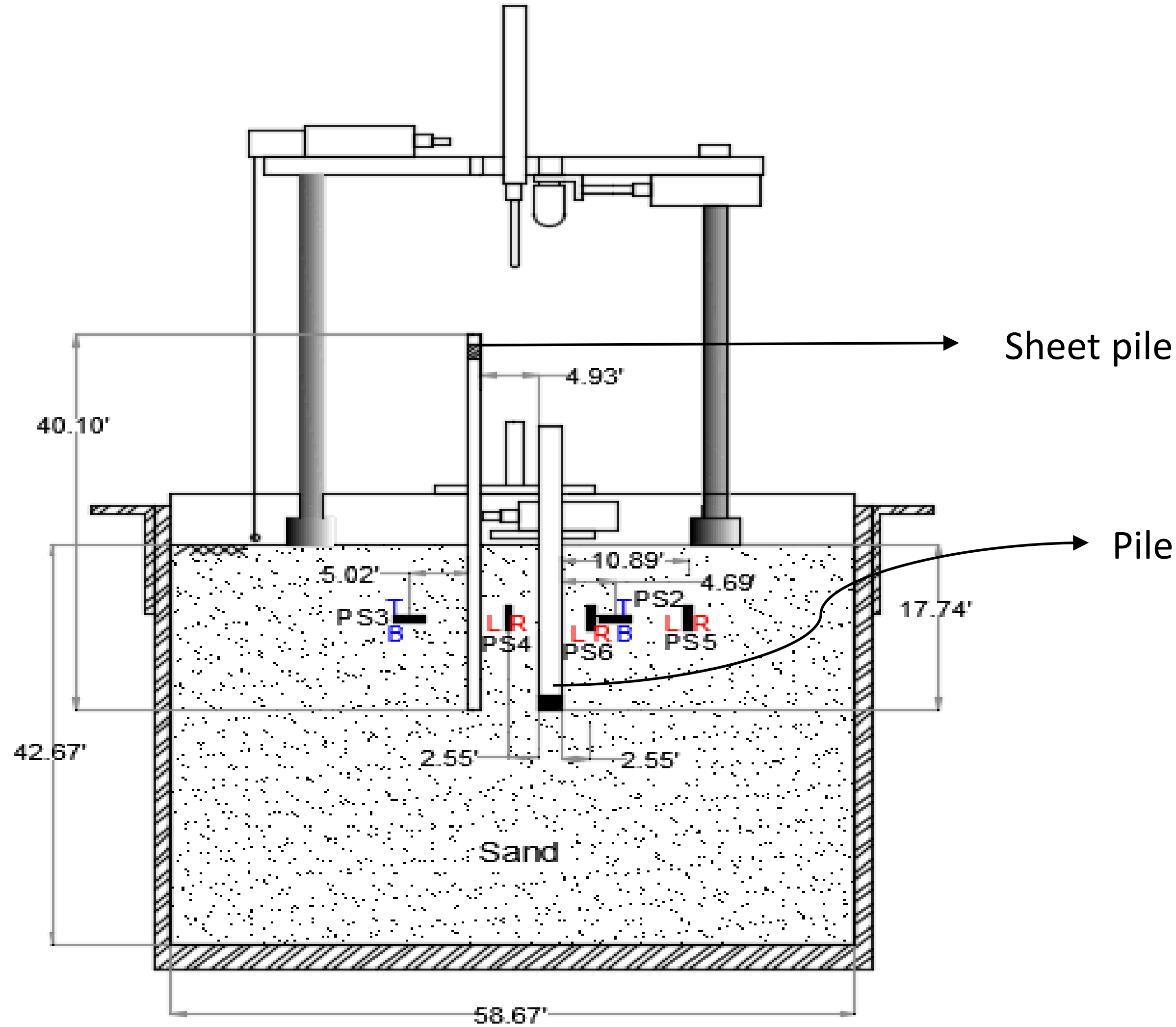
Three loading scenarios are considered for centrifuge tests:

- Scenario 1: A pile is driven into the soil and is subjected to incremental quasi-static top down loads.



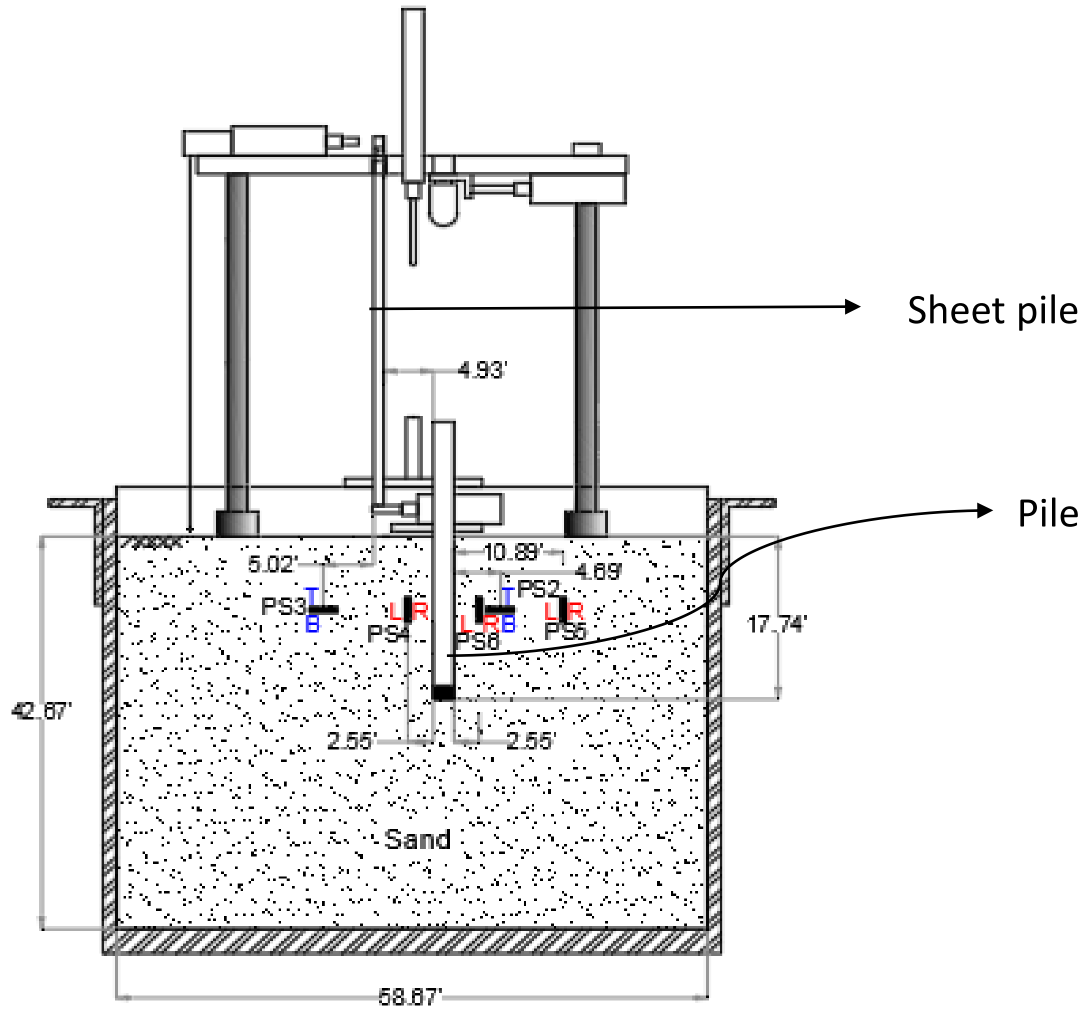
Task 4. Prototype-scale Centrifuge Tests on FL Sand

- Scenario 2: A sheet pile is pushed into the soil, followed by a pile driven in the vicinity of the sheet pile (2.5 times width; 2.5B), and is subjected to incremental quasi-static top down loads.

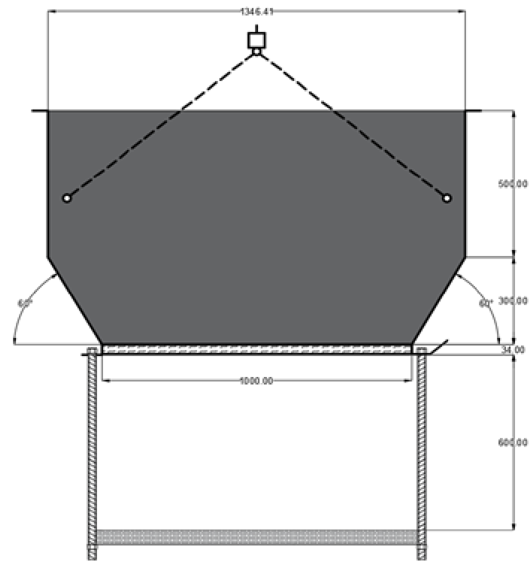


Task 4. Prototype-scale Centrifuge Tests on FL Sand

- <u>Scenario 3:</u> A sheet pile is driven into the soil followed by the pile. Prior to application of quasi-static axial loads on the pile, the sheet pile is vertically extracted (with no vibration) from the soil.



Task 4 Prototype-scale Centrifuge Tests on FL Sand



Pluviator: Side View

Mass flow rate determined by a maximum size of the DEM model.

Drop height = 380 mm (±12.5 mm)

The unscaled mass flow rate values for 0.5 mm and 0.85 mm diameter sphere generation are taken as averaged values from maximum DEM injection rate: 5.78E+4 mm^3/s and 4.26E+4 mm^3/s, respectively.

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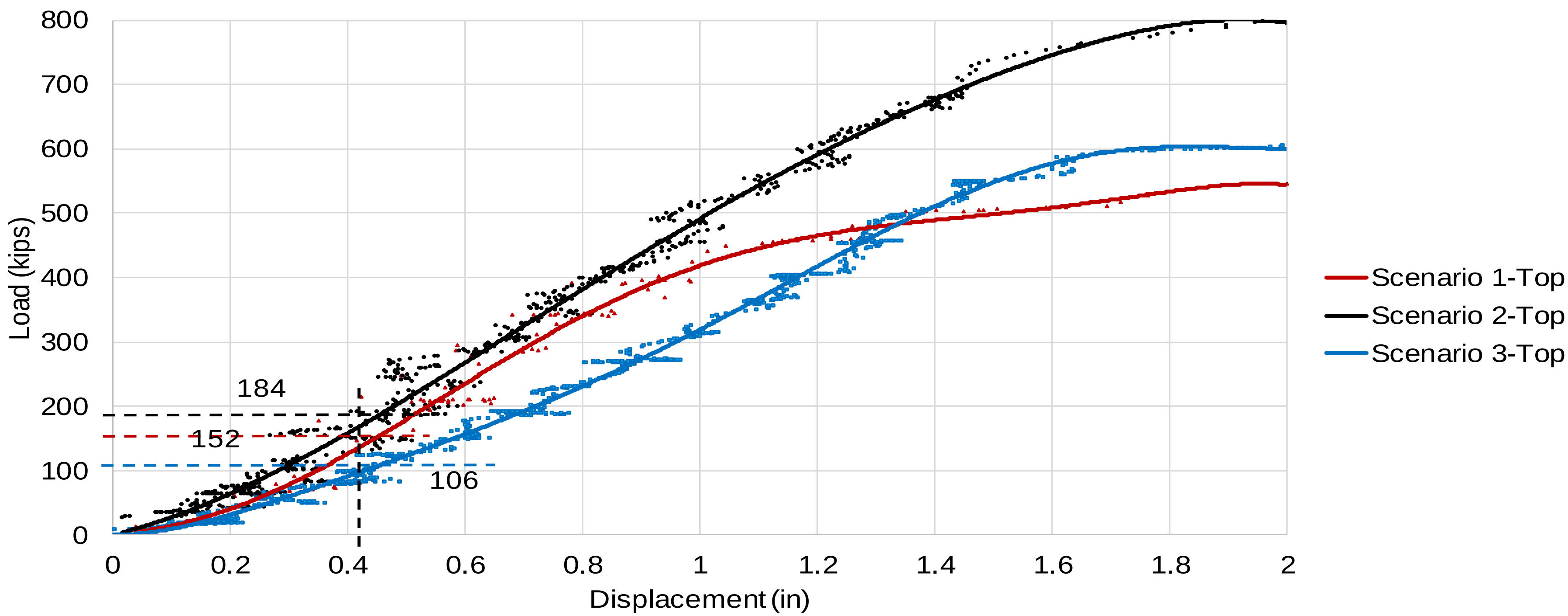
Task 4. Prototype-scale Centrifuge Tests on FL Sand

Quasi-static Top Down Load-Settlement Test Result:

SPW is pre-installed at the full-embedment length (18 ft) of the pile (i.e., 9B)



Load Test Scenario	Relative Density (%)	Ultimate Capacity (kips)	Davisson Capacity (kips)
Scenario 1	65	547	152
Scenario 2	65	807	184
Scenario 3	65	606	106

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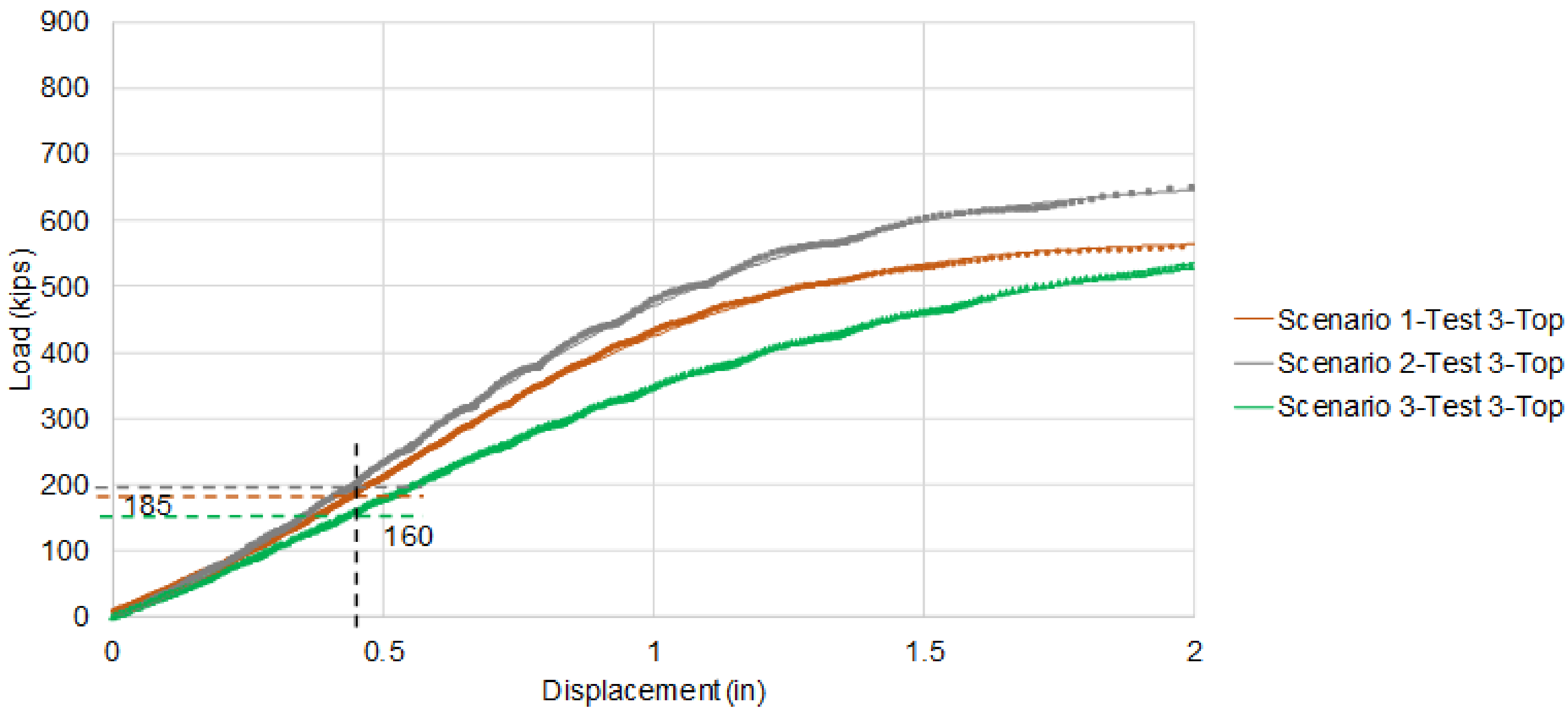
Task 4. Prototype-scale Centrifuge Tests on FL Sand

Quasi-static Top Down Load-Settlement Test Result:

SPW is pre-installed at the half-embedment length (9 ft) of the pile (i.e., 4.5B)



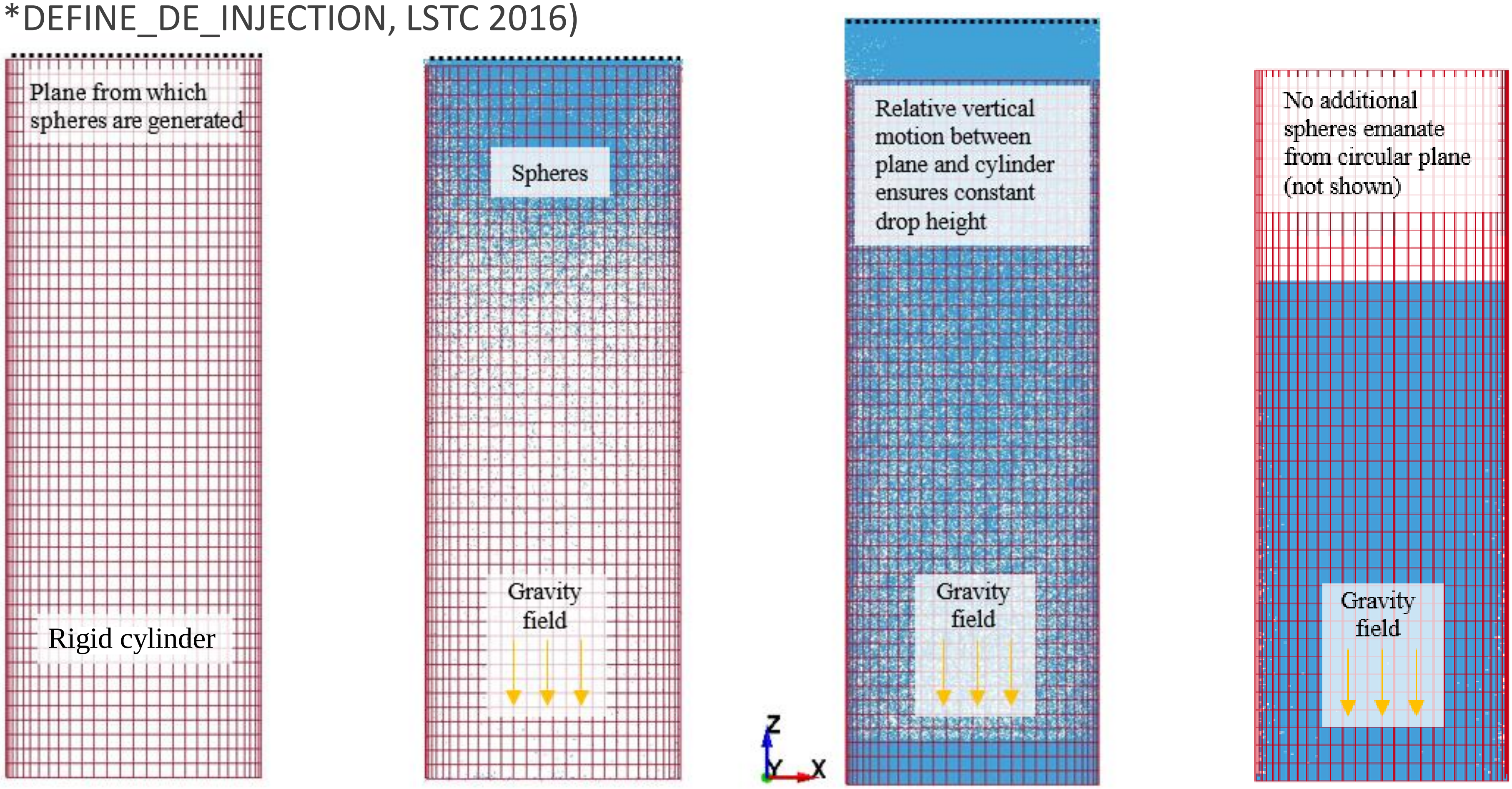
Load Test Scenario	Ultimate Capacity (kips)	Davisson Capacity (kips)
Scenario 1	561	185
Scenario 2	649	197
Scenario 3	534	160

Task 3 Numerical Modeling of Driven foundation in Granular Soils

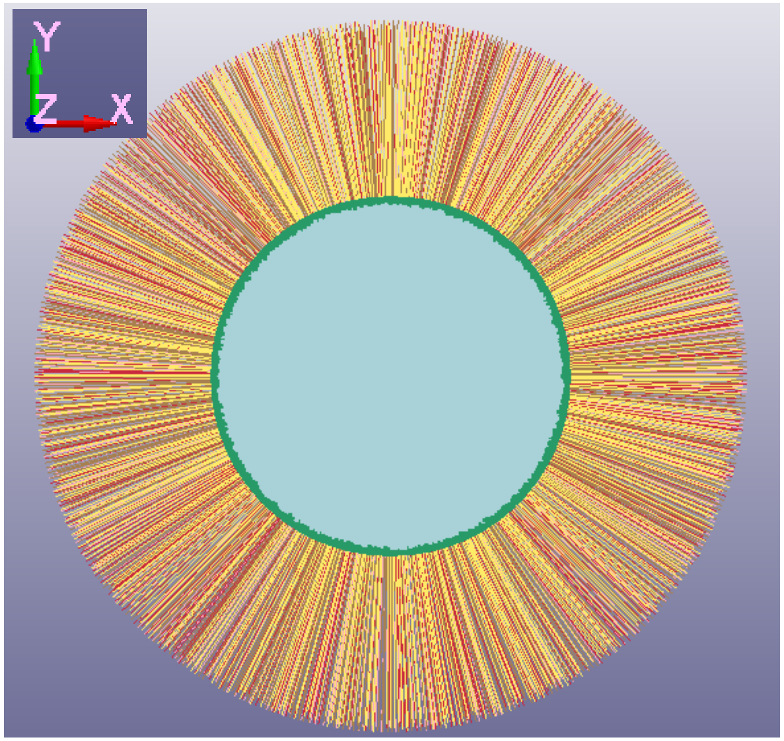
The scaled mass flow rate values for 0.85 mm diameter sphere generation are taken as averaged values from maximum DEM injection rate: 4.26E+4 mm^3/s.

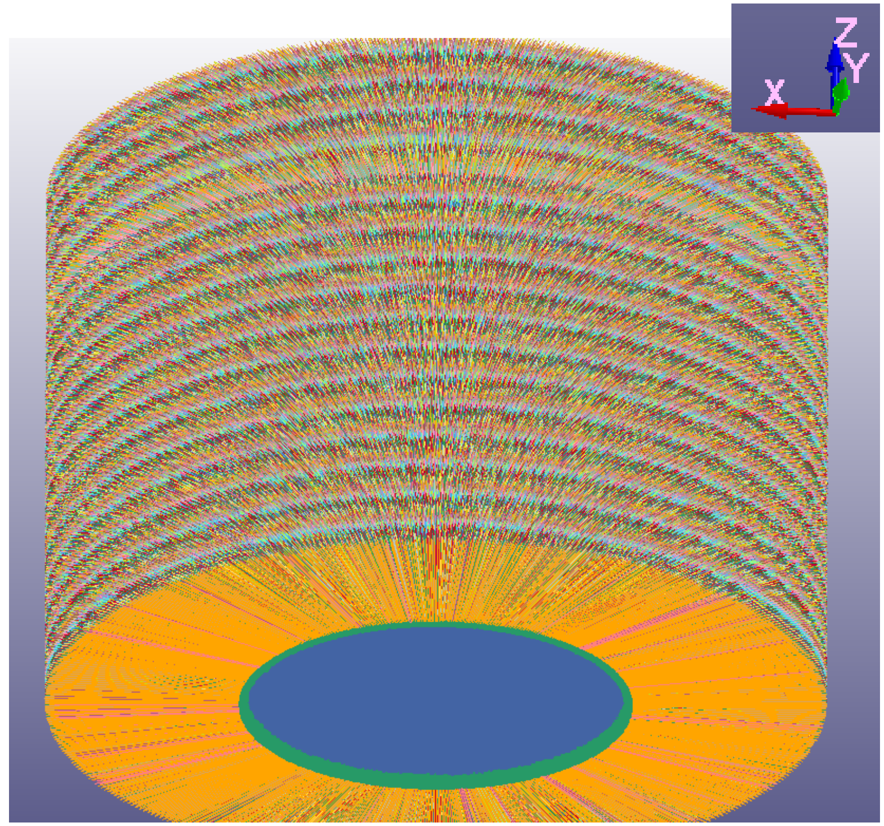
With a planar injection method, the diameter of the domain is 3000 mm, which limits a number of DSE to be generated in plane. Thus, centrifuge pluviation rate is calibrated as per the numerical maximum mass flow rate.

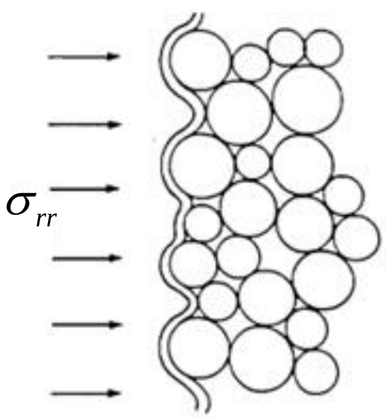
(*DEFINE_DE_INJECTION, LSTC 2016)



Task 3 Numerical Modeling of Driven foundation in Granular Soils







Boundary Spring Constant

σ_{rr}

$$\sigma_{rr} = K_o \sigma_{zz} = K_o \gamma z(h) \leq K_p \gamma z(h)$$

$$E_{eff} \propto \sqrt{\frac{\sigma'_{zz} + 2\sigma'_{rr}}{3}}$$

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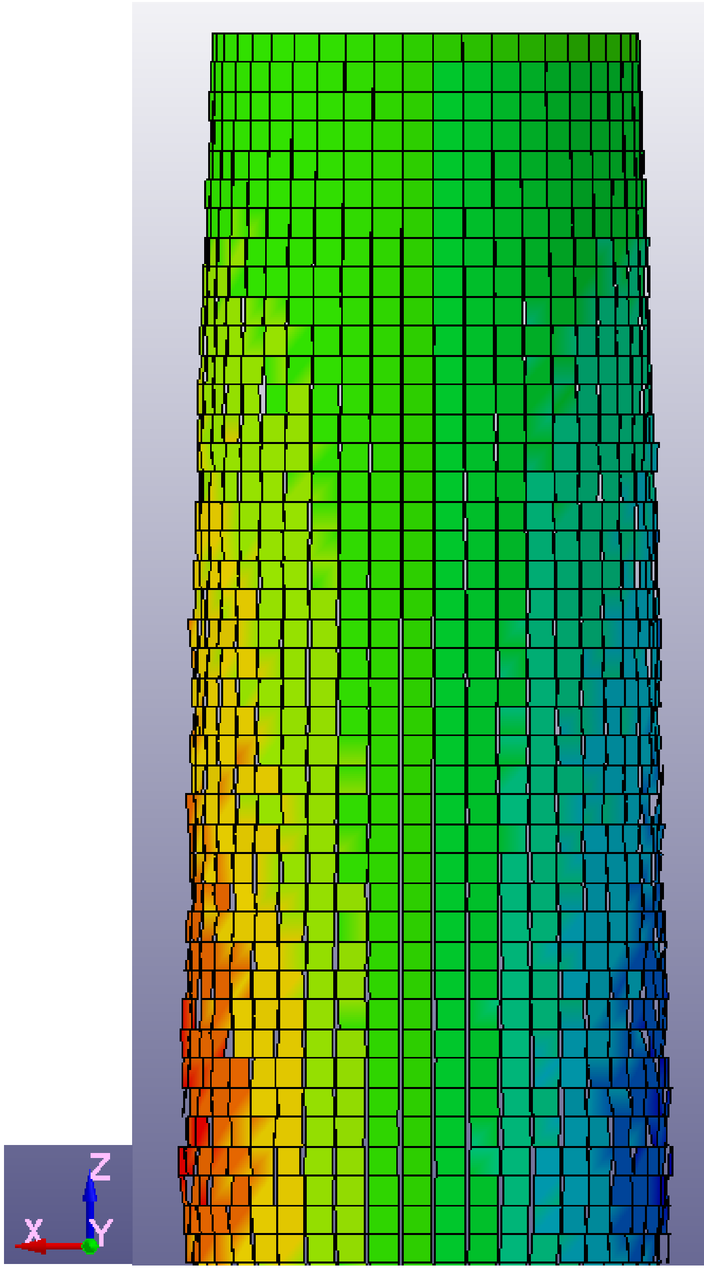
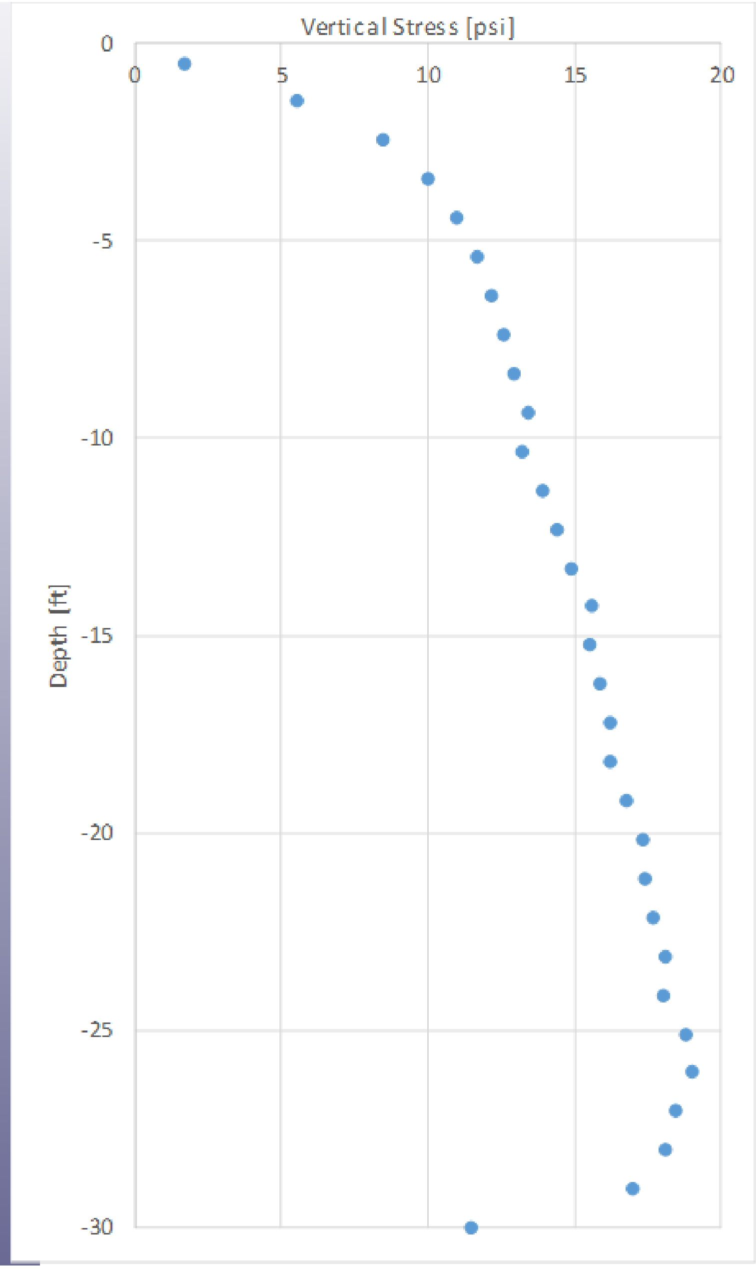
Simulated Geostatic Stress Conditions





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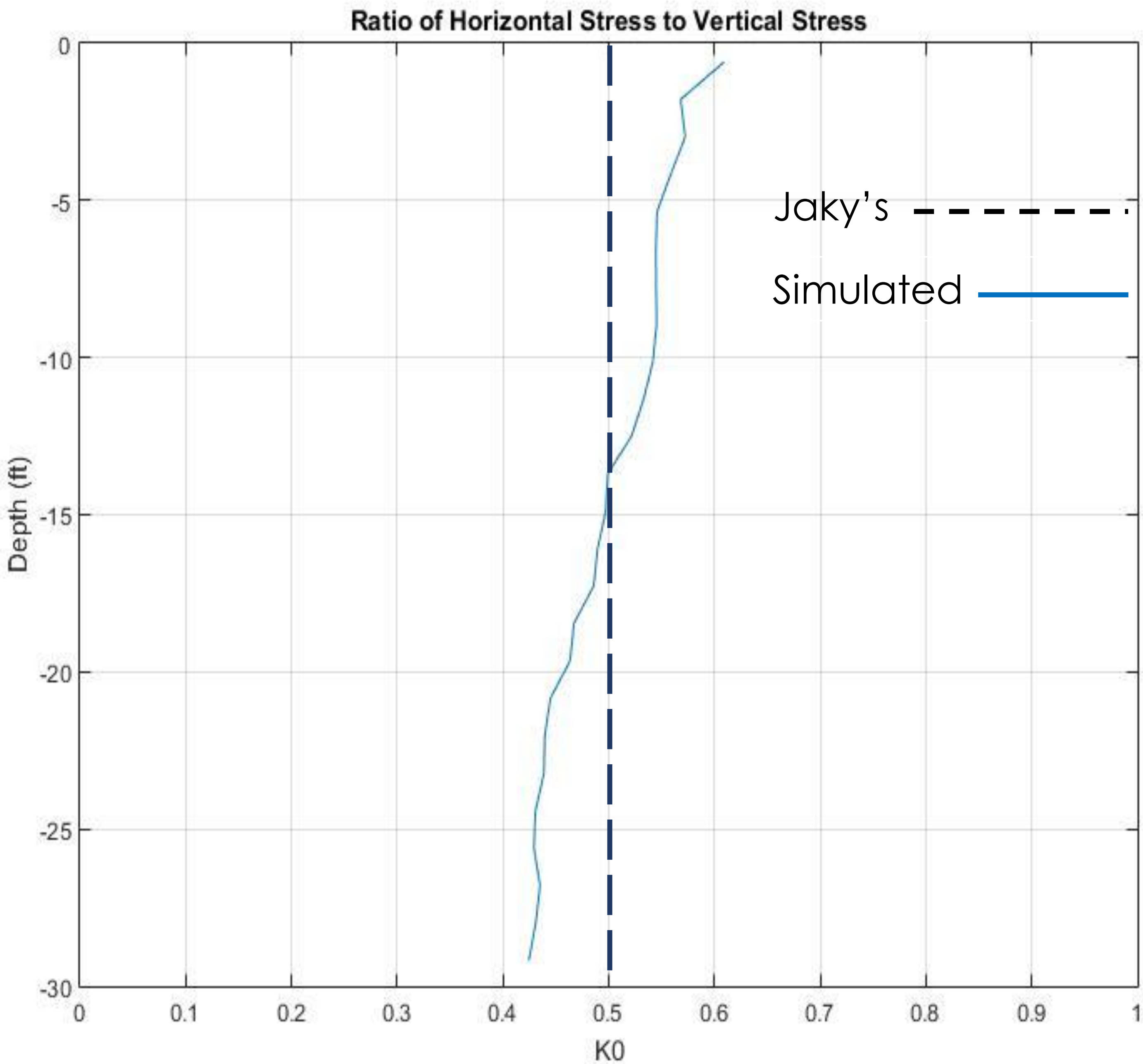
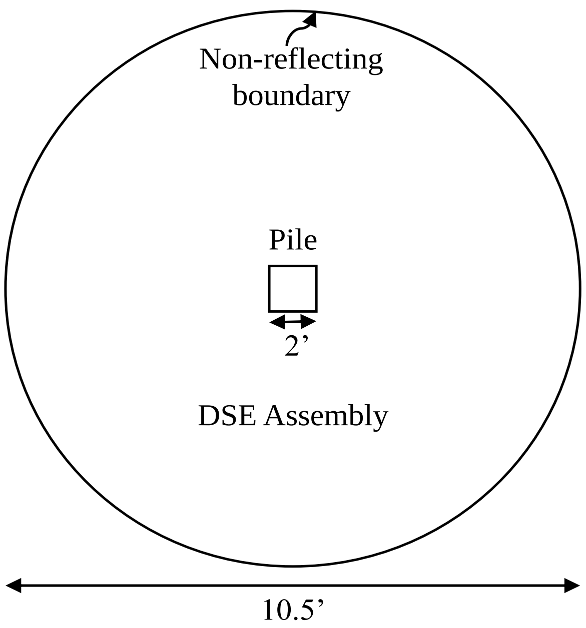
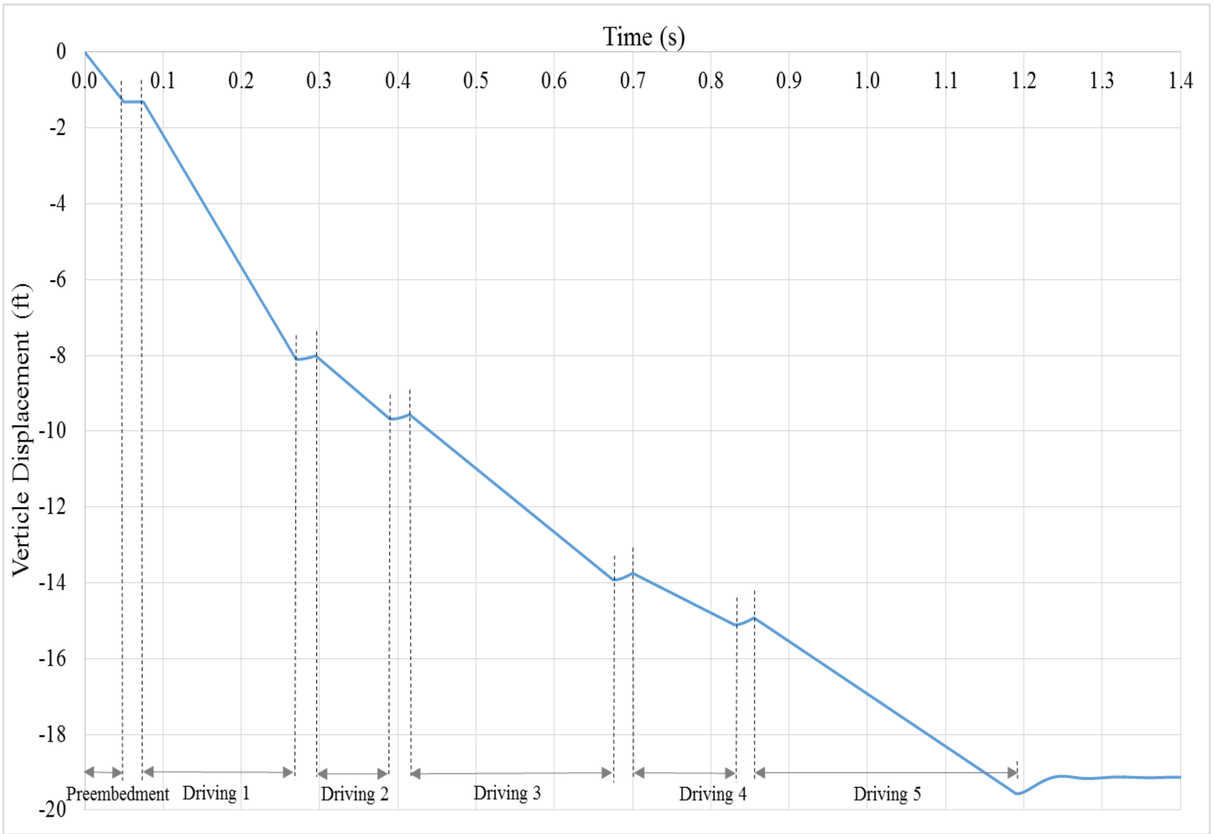
Simulated Geostatic Stress Conditions



Task 3. Numerical Modeling of Loading Scenarios

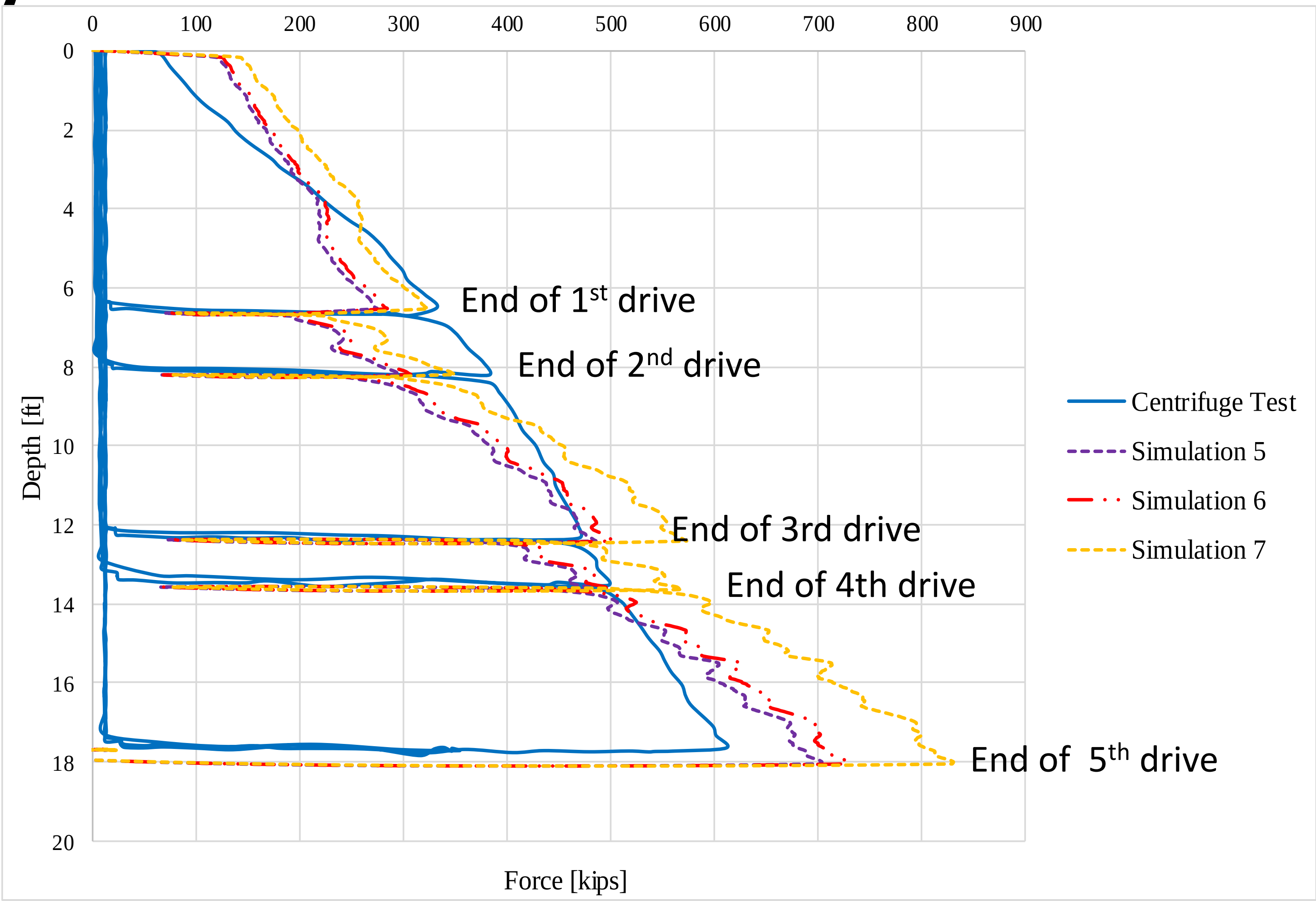
- **Scenario 1 : Penetration-Depth Time History**





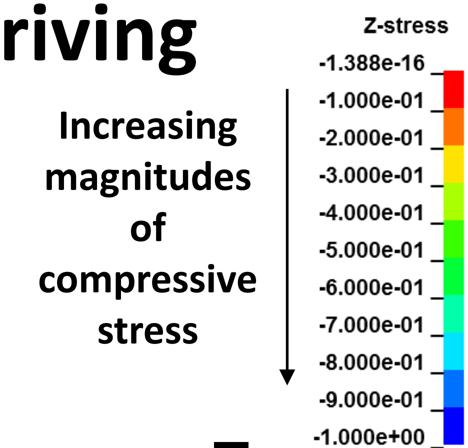
Task 3. Numerical Modeling of Loading Scenarios

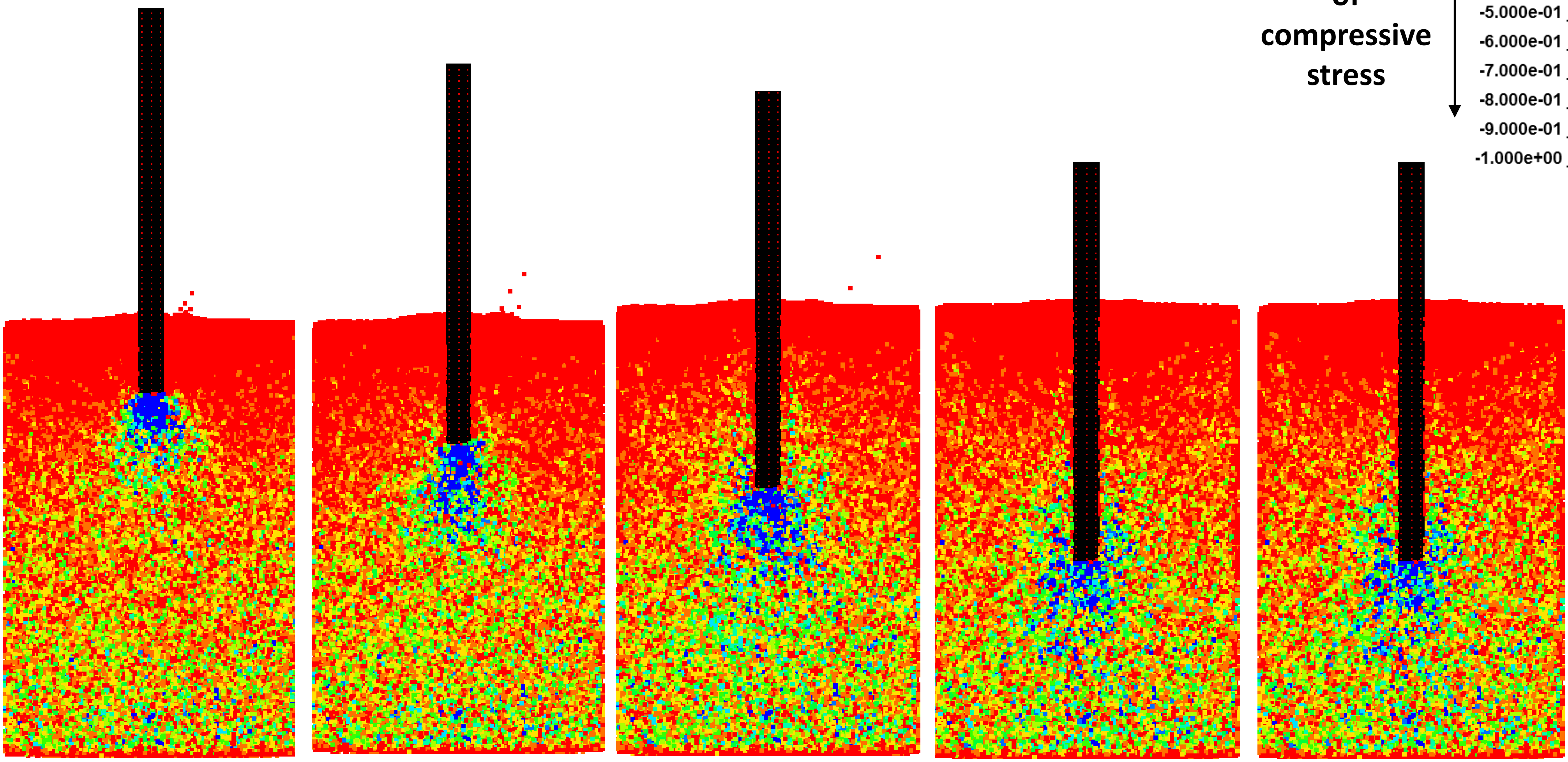
- **Scenario 1: Simulations of Pile Driving Force Time History**



Task 3. Numerical Modeling of Loading Scenarios

- **Scenario 1: Vertical stresses during pile driving (units of MPa)**

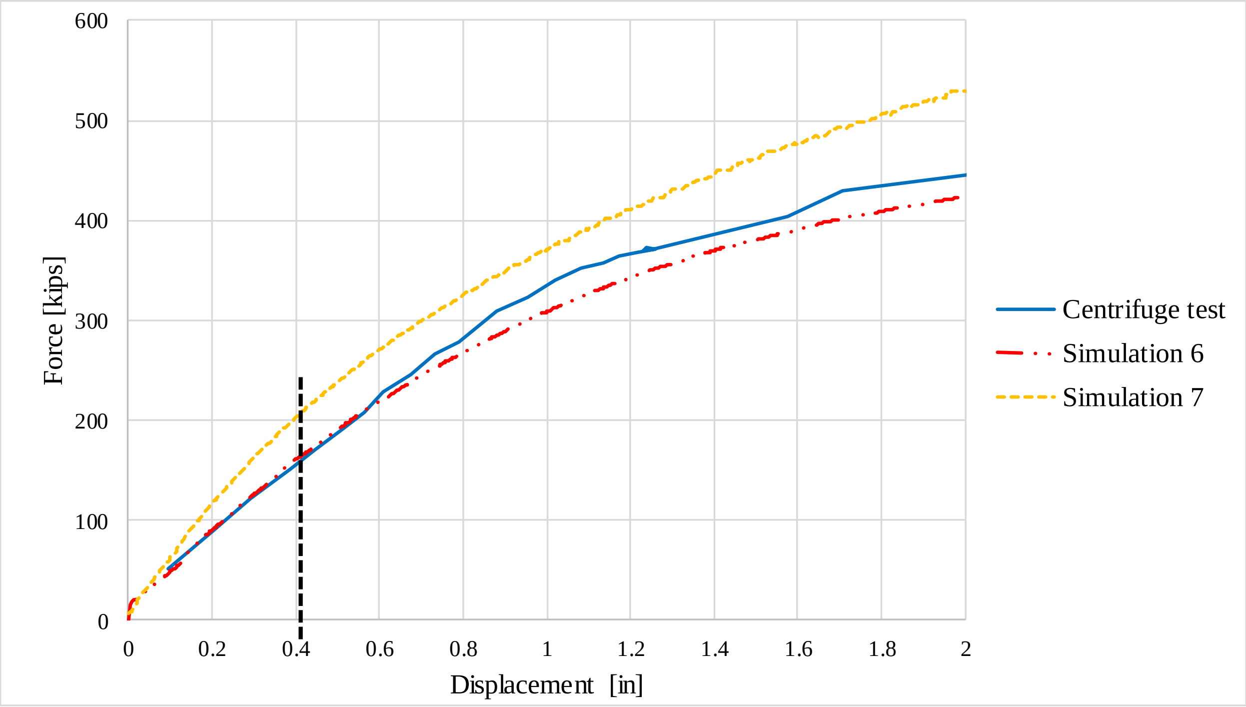




At the end of 1st blow | At the end of 2nd blow | At the end of 3rd blow | At the end of 4th blow | At the end of 5th blow

Task 3. Numerical Modeling of Loading Scenarios

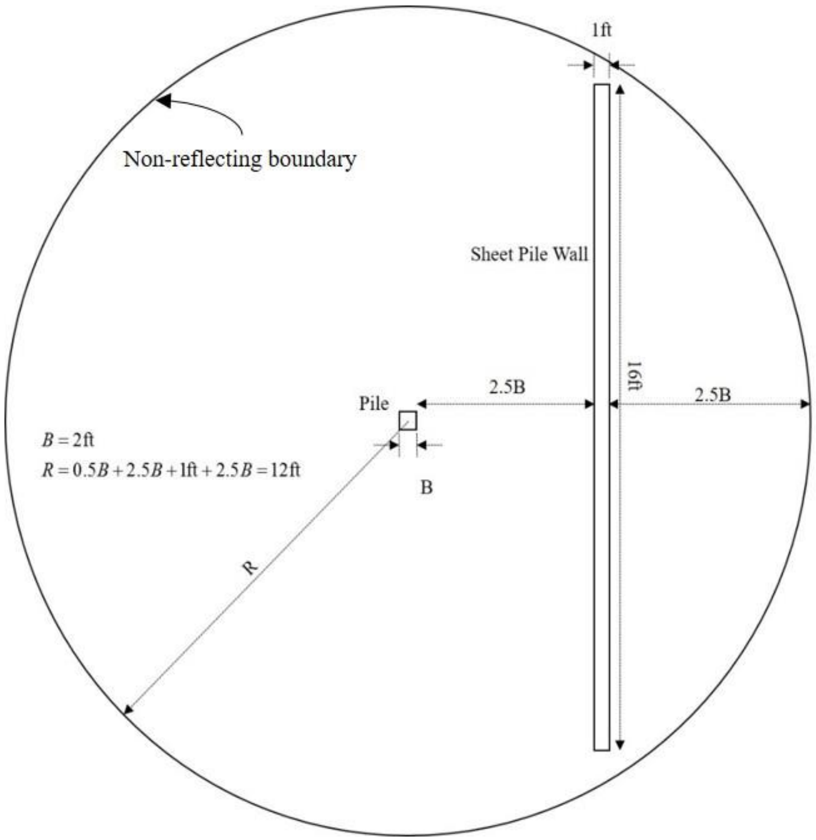
- **Scenario 1: Prediction of quasi-static axial load-settlement behaviors**



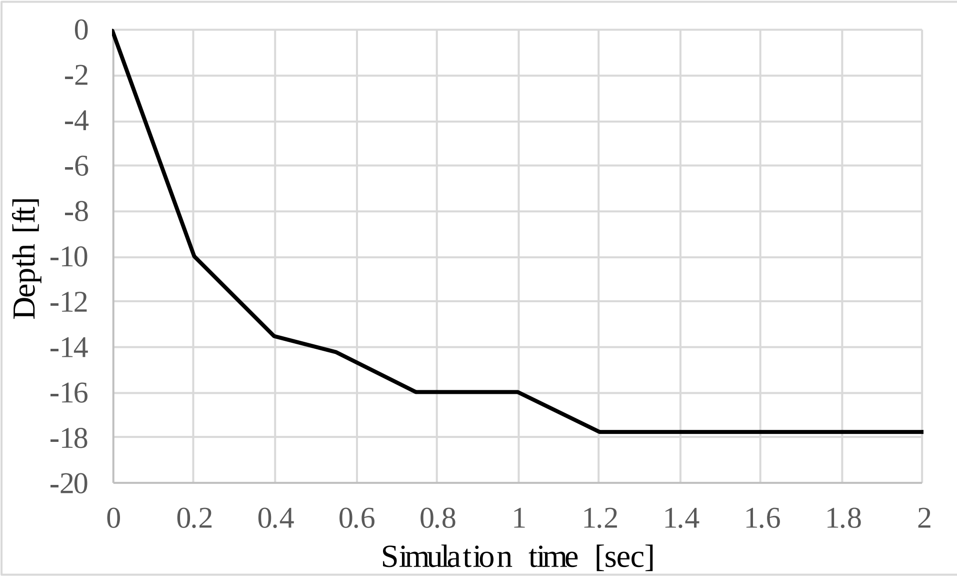
Load Test Scenario	Ultimate Capacity (UC) (kips)	Davisson Capacity (DC) (kips)
Centrifuge test	468	150
Simulation 6(S1)	425	152
Simulation 7(S1)	532	200

Task 3. Numerical Modeling of Loading Scenarios

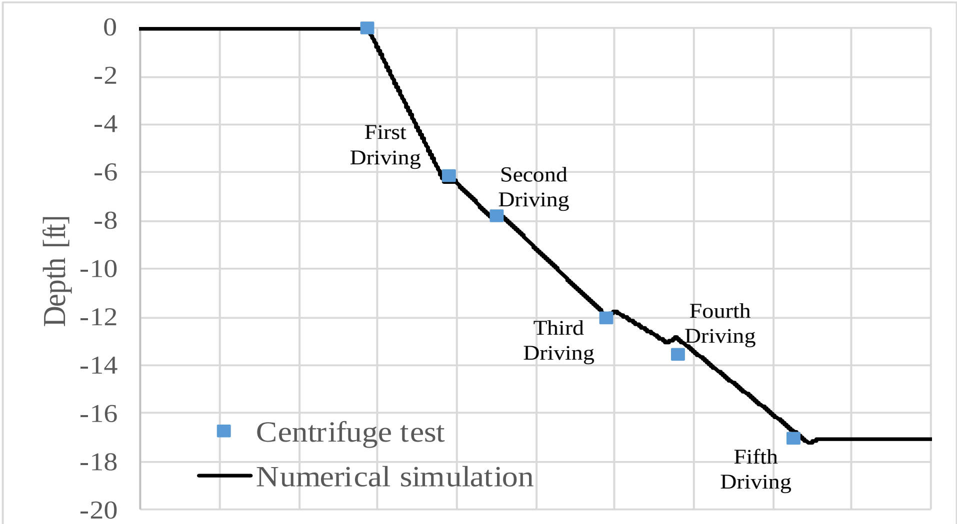
- **Scenario 2**



SPW displacement time history



Pile driving time history



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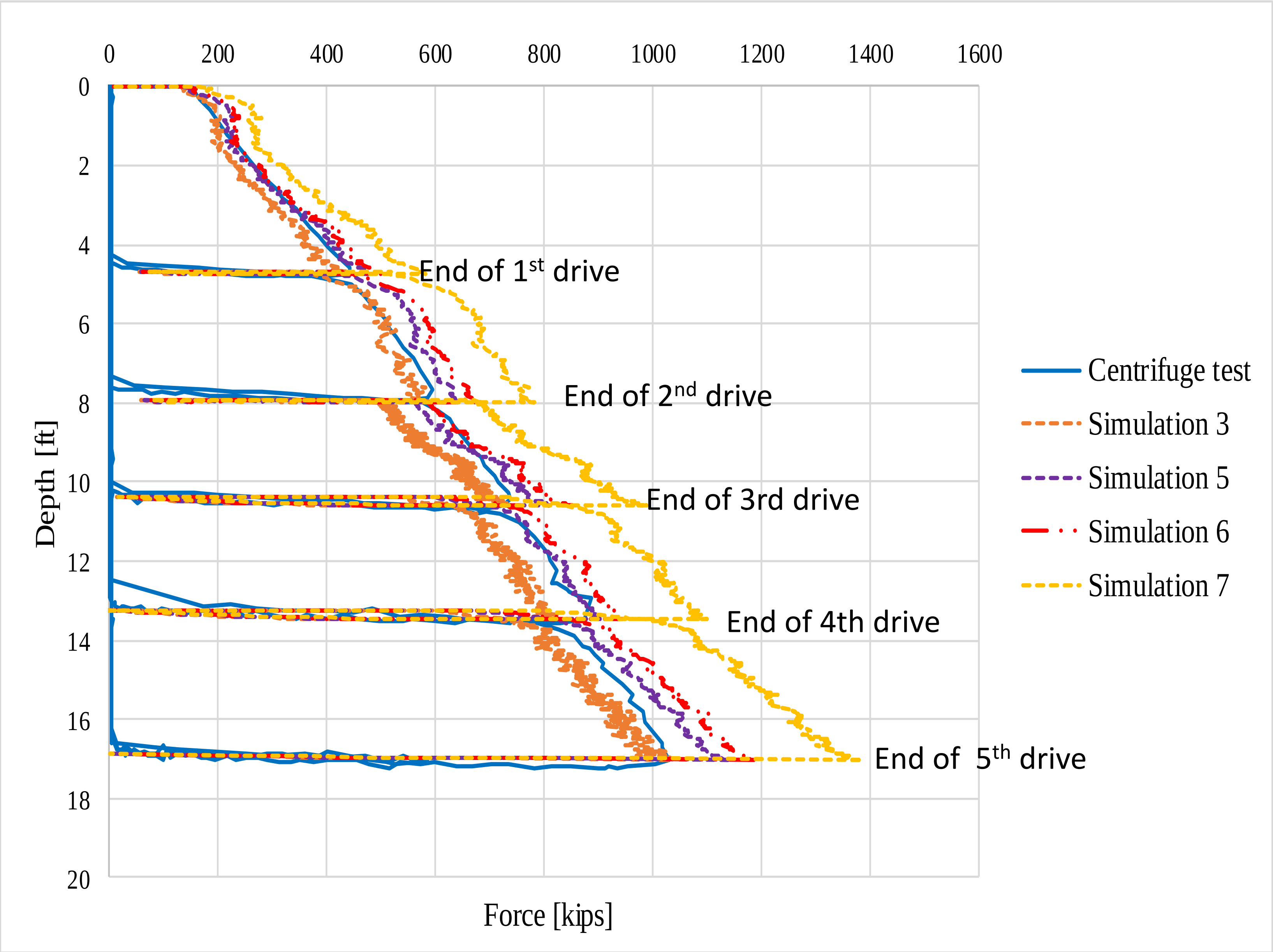
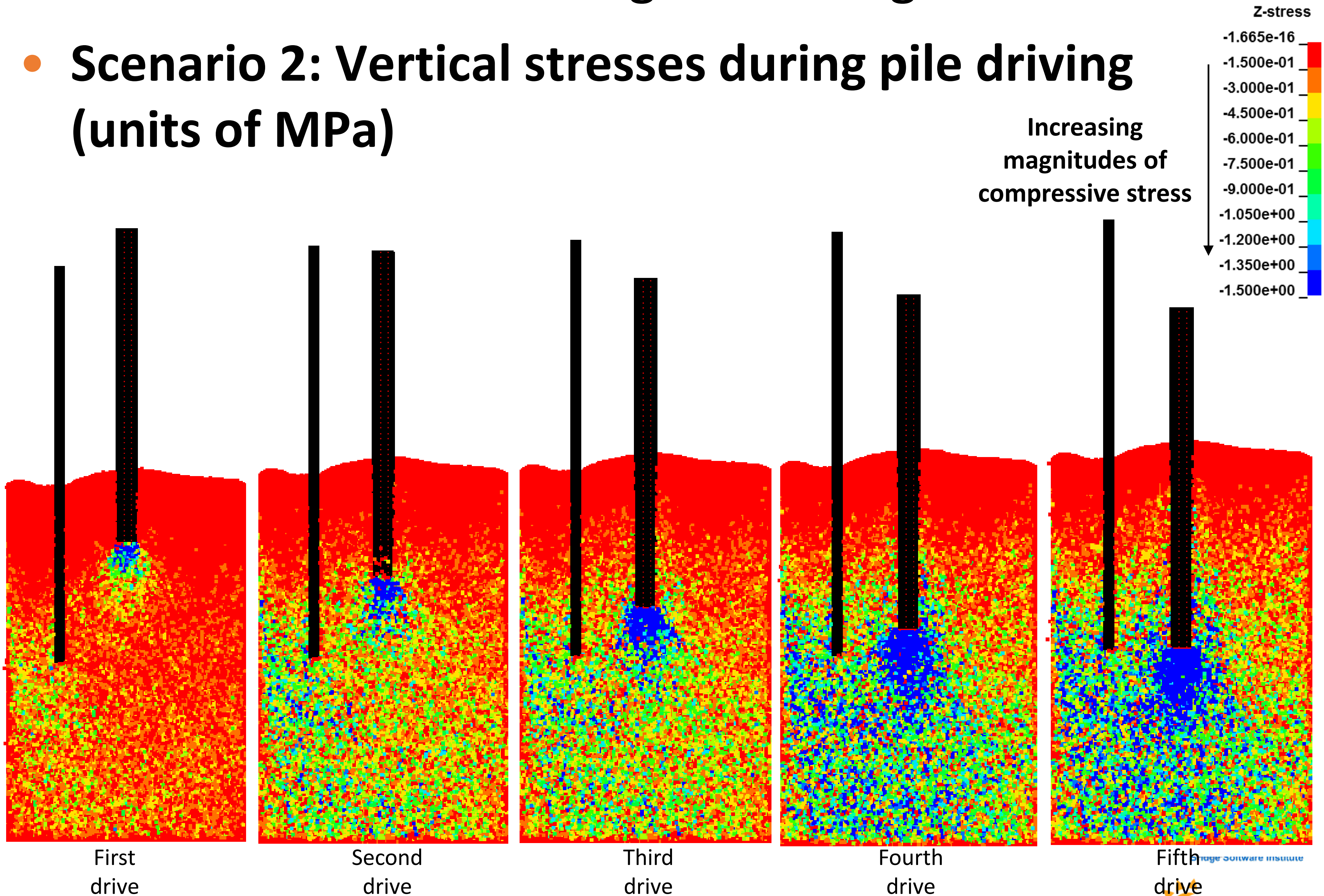
Task 3. Numerical Modeling of Loading Scenarios

- **Scenario 2: Simulation of pile driving force history**



Task 3. Numerical Modeling of Loading Scenarios

- **Scenario 2: Vertical stresses during pile driving (units of MPa)**



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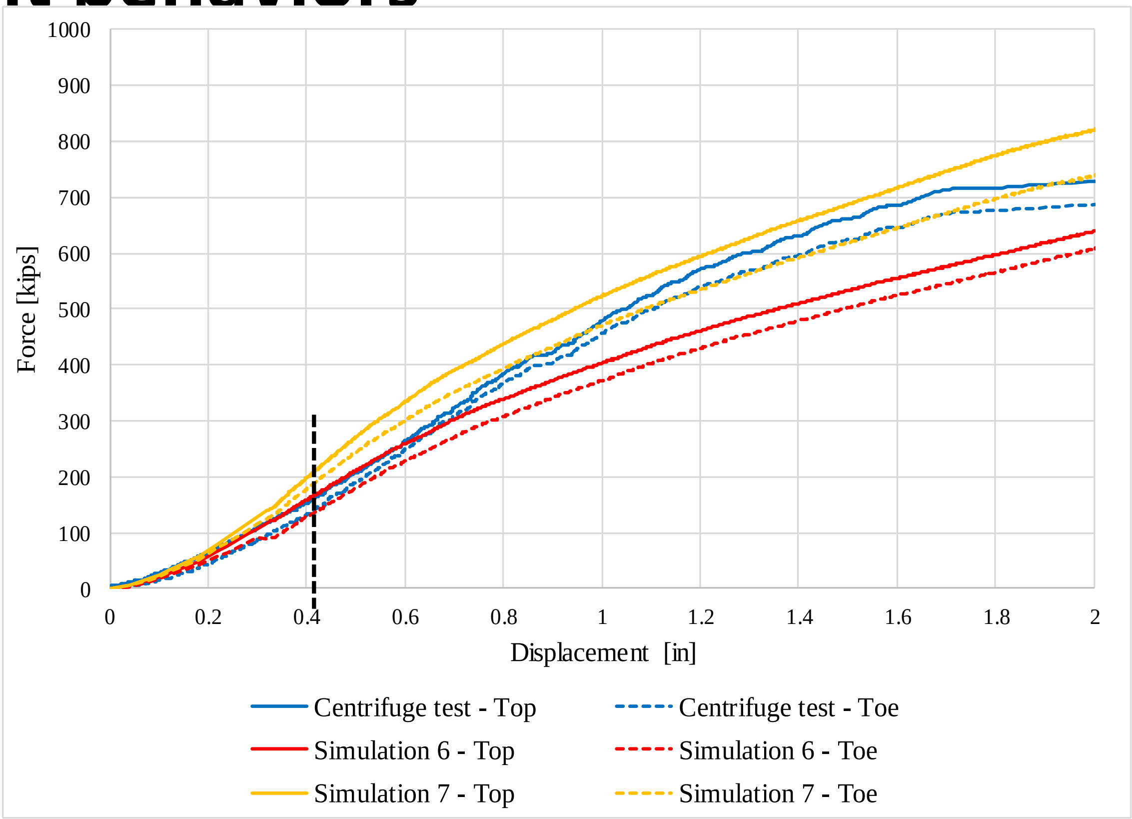
Task 3. Numerical Modeling of Loading Scenarios

- **Scenario 2: Prediction of quasi-static top down load settlement behaviors**

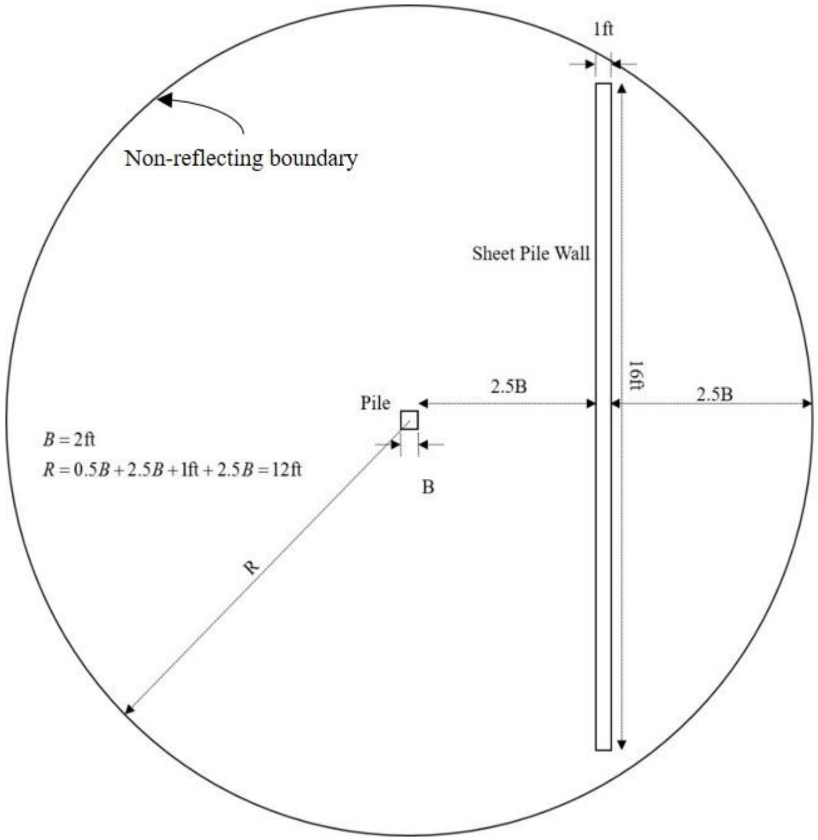


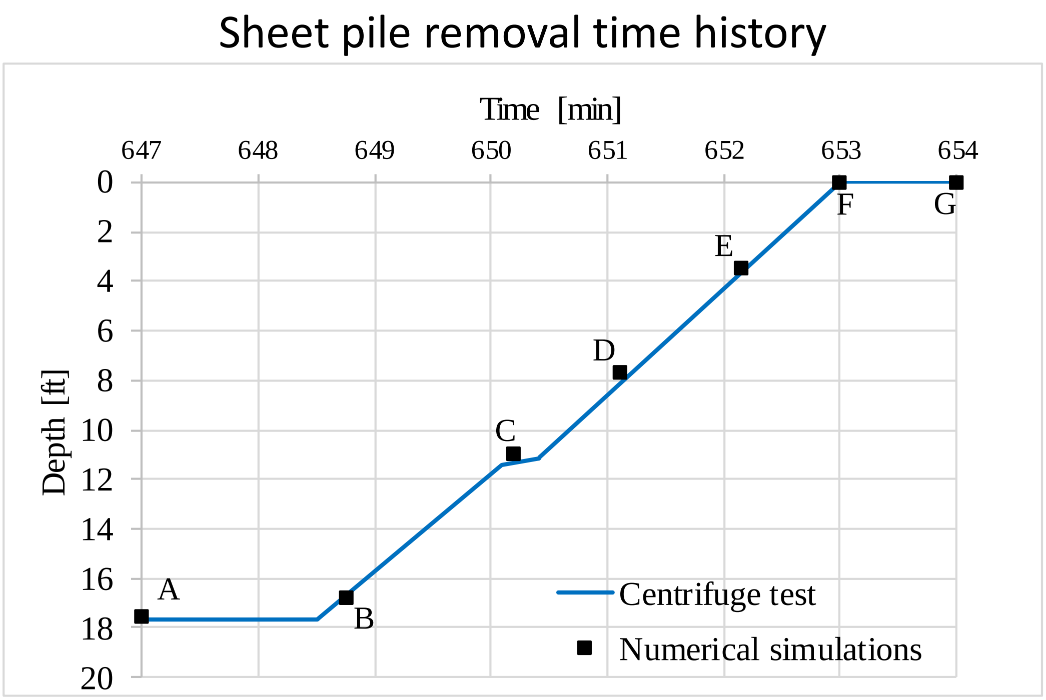
Load Test Scenario	Ultimate Capacity (UC) (kips)	Davisson Capacity (DC) (kips)
Centrifuge test	728	182
Simulation 6(S2)	698	183
Simulation 7(S2)	820	233

Task 3. Numerical Modeling of Loading Scenarios

- **Scenario 3**

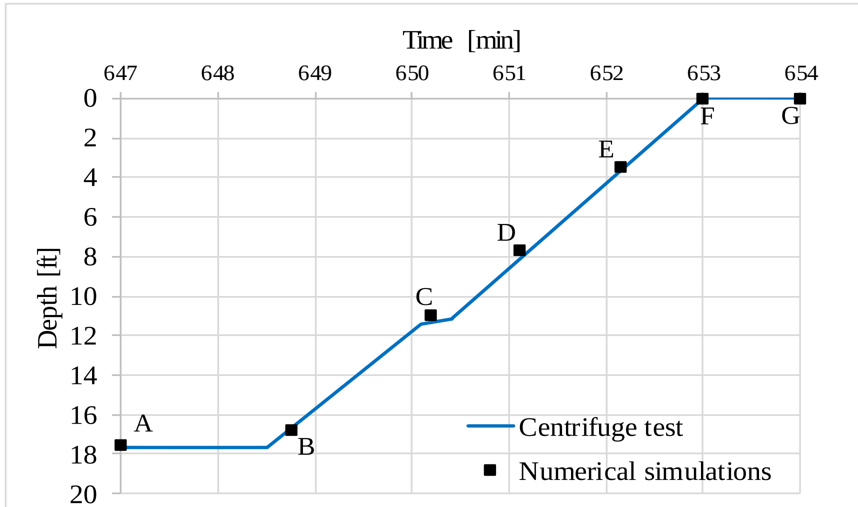
- The Scenario 2 installation sequence is repeated, but SPW is vertically pulled out prior to application of vertical loads at the top of the pile.

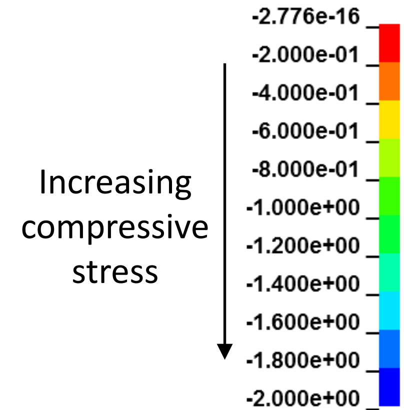


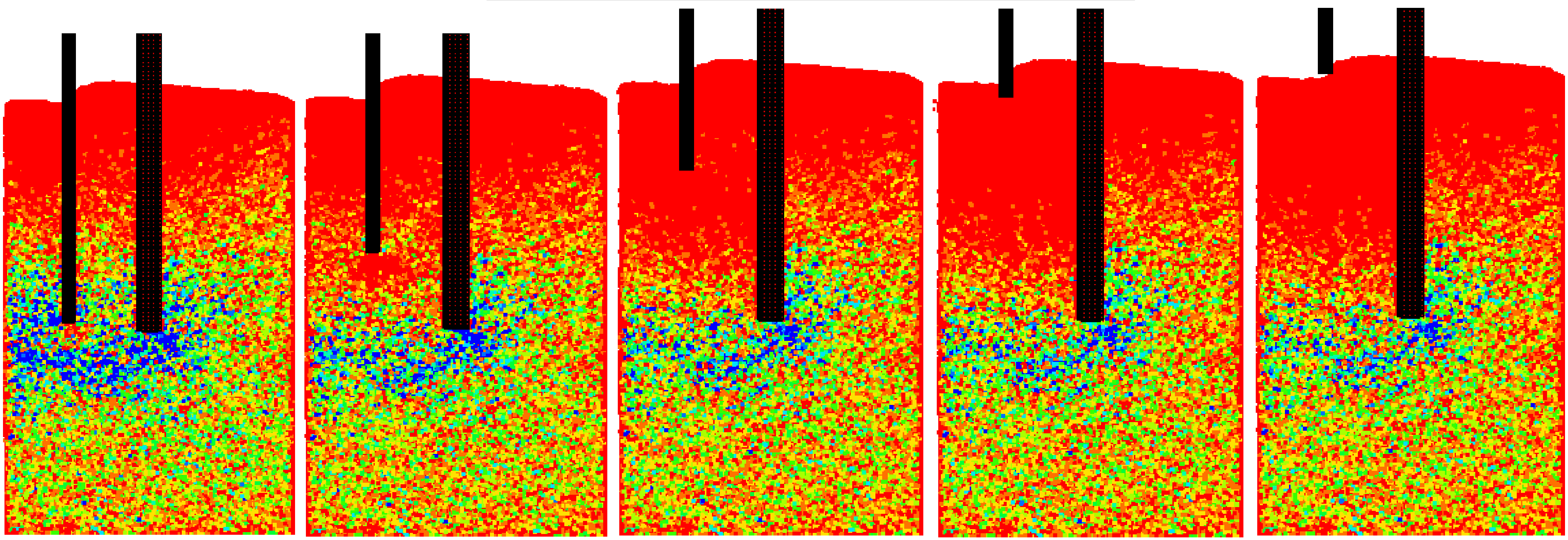


Task 3. Numerical Modeling of Loading Scenarios

- **Scenario 3: Vertical stresses during SPW removal (units of MPa)**







At B | At C | At D | At E | At F

Locations B, C, D, E, and F are marked on sheet pile removal displacement time history

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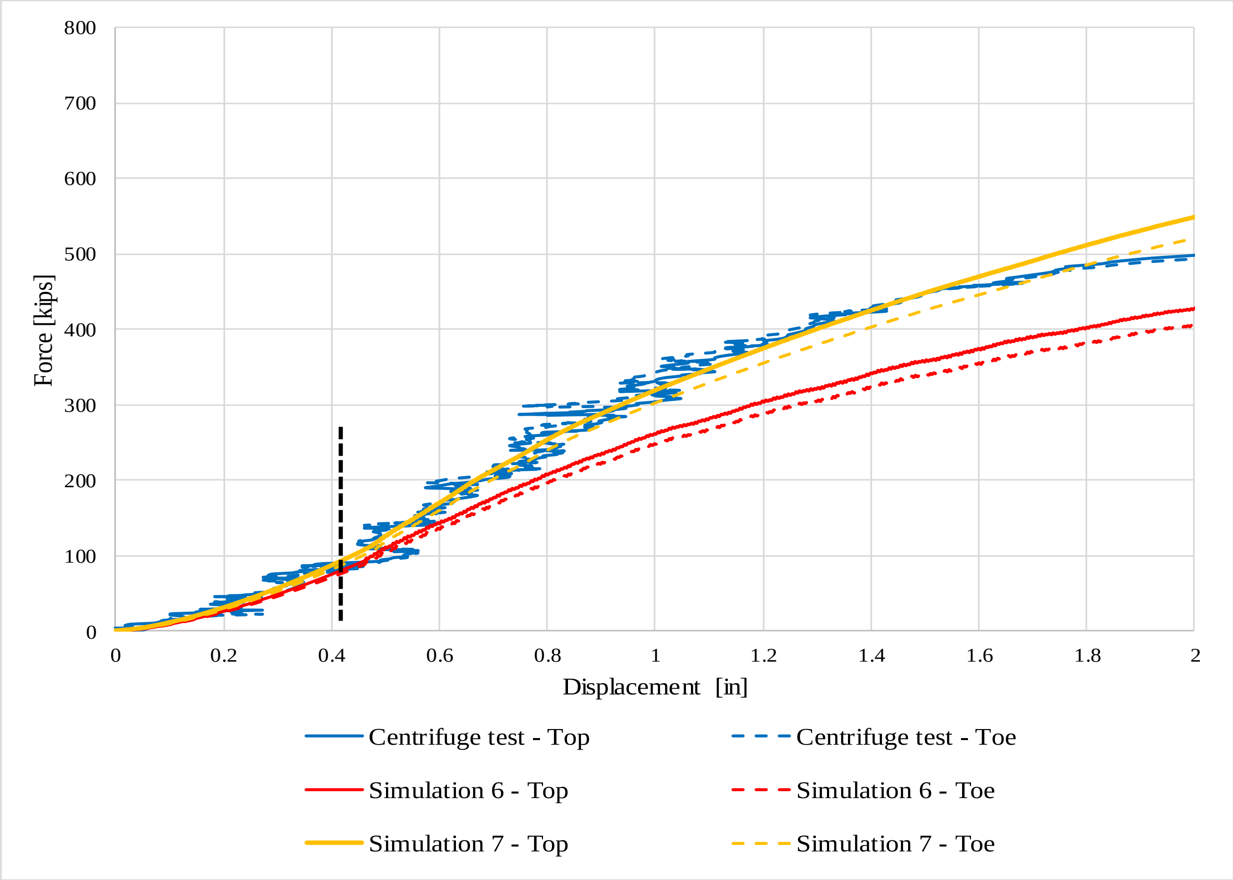
Task 3. Numerical Modeling of Loading Scenarios

- **Scenario 3: Prediction of quasi-static top down load-settlement behaviors**



Load Test Scenario	Ultimate Capacity (UC) (kips)	Davisson Capacity (DC) (kips)
Centrifuge test	499	80
Simulation 6(S3)	428	83
Simulation 7(S3)	549	95

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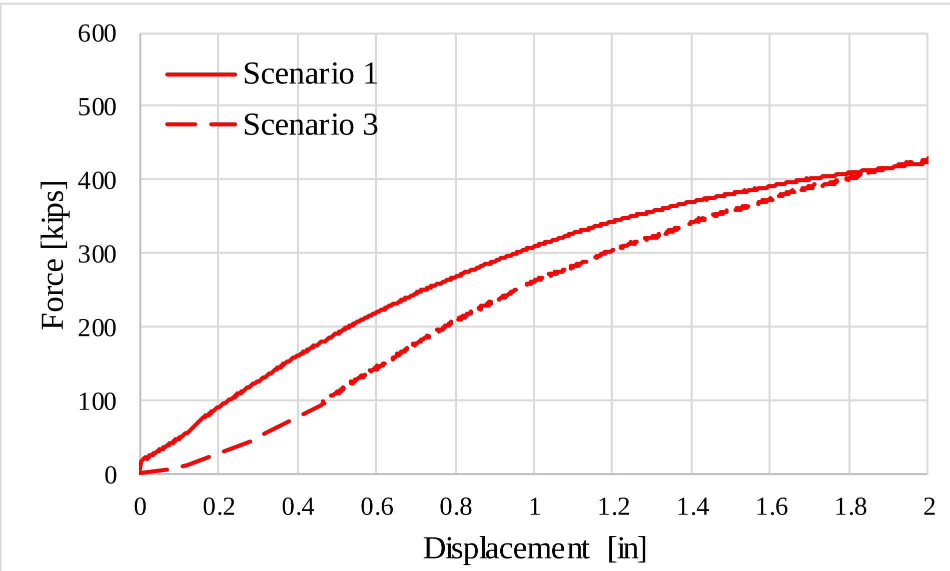
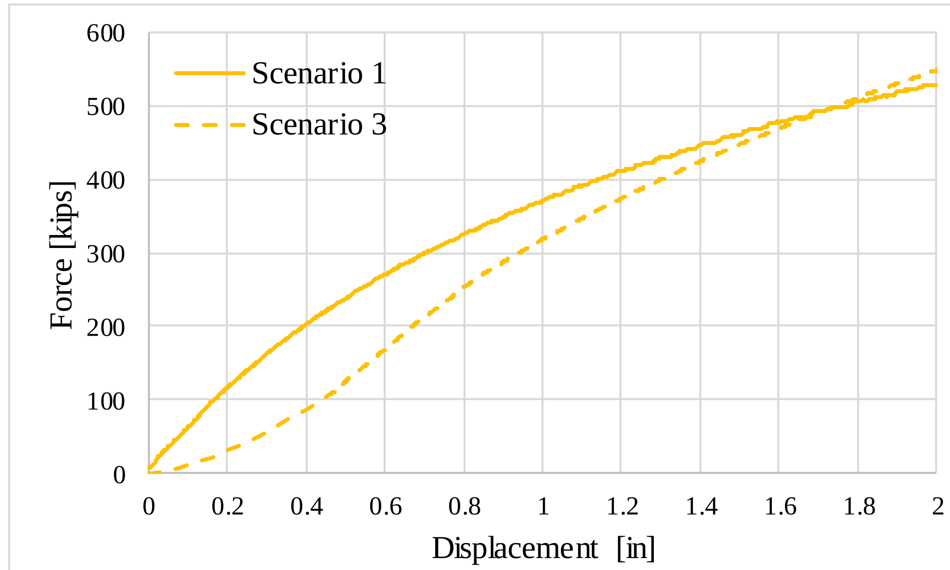
Task 3. Numerical Modeling of Loading Scenarios

- **Summary of Scenario 1 vs. Scenario 3**



Simulation 6



Simulation 7

Pile capacity	Loading scenario	Centrifuge test	Numerical results		
			Simulation 6	Simulation 7	Average
Davisson	1	150 kips	152 kips	200 kips	176 kips
	3	80 kips	83 kips	95 kips	89 kips
	% change	46.6 (-)	45.4 (-)	52.5 (-)	49.4 (-)
Ultimate	1	468 kips	425 kips	532 kips	478.5 kips
	3	499 kips	428 kips	549 kips	488.5 kips
	% change	6.62 (+)	0.71 (+)	3.2 (+)	2.1 (+)

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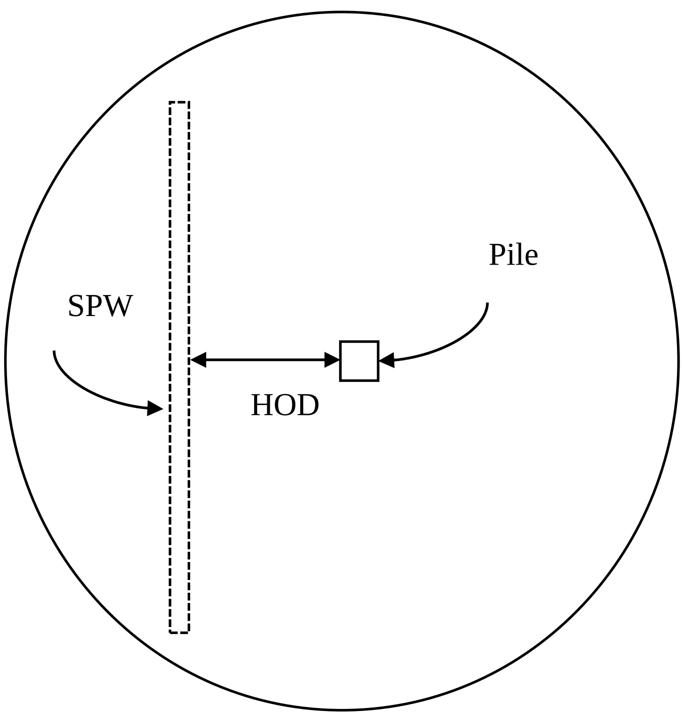
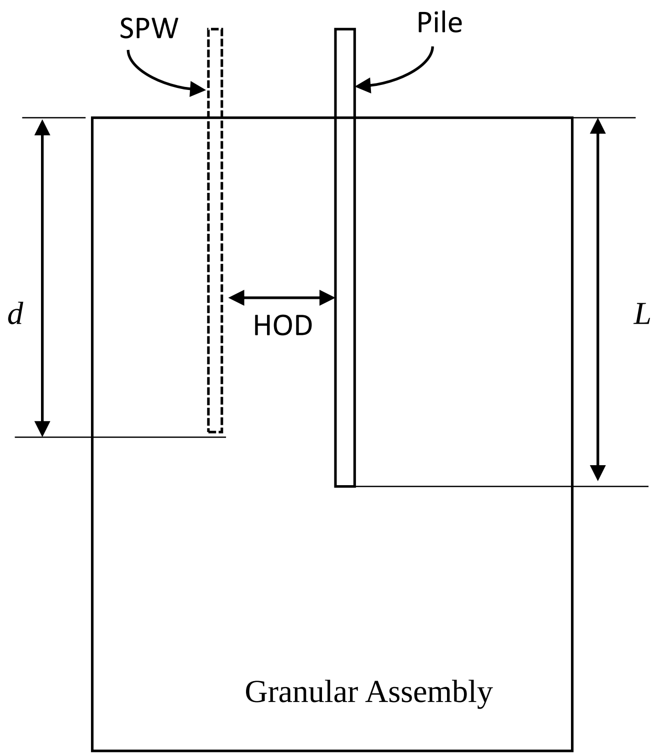
Task 5. Findings and Design-Oriented Recommendations

Geometric Parameters selected for parametric study:

- Horizontal offset distance (HOD) between pile and sheet pile – 4 ft; 5 ft; 6 ft; 8 ft; and 10 ft.
- Ratio of sheet pile embedment depth to pile embedment length – 0.25; 0.5; 0.75; and 1.0





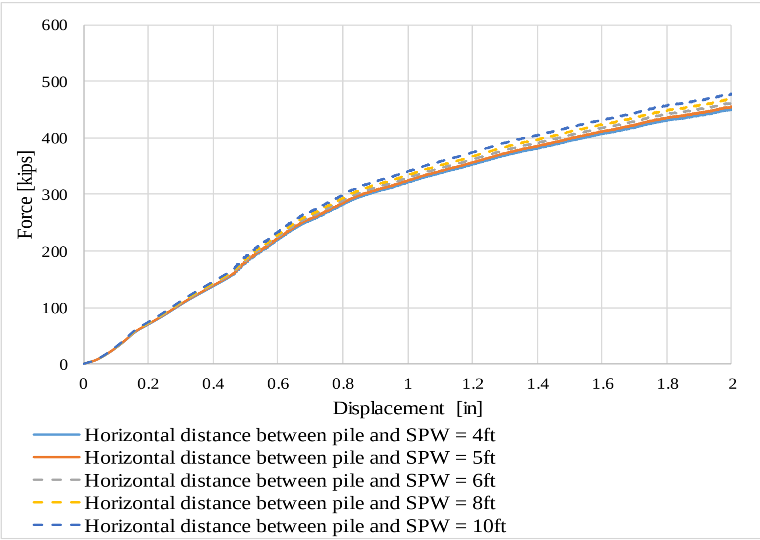
Embedment-depth ratio

$$\frac{d}{L}$$

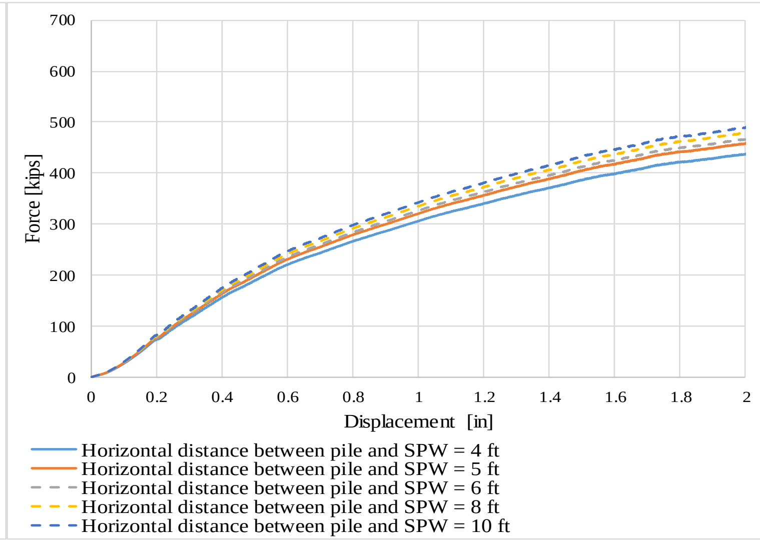
Task 5: Findings and Design-Oriented Recommendations

- **Prediction of load capacities for Scenario 3**

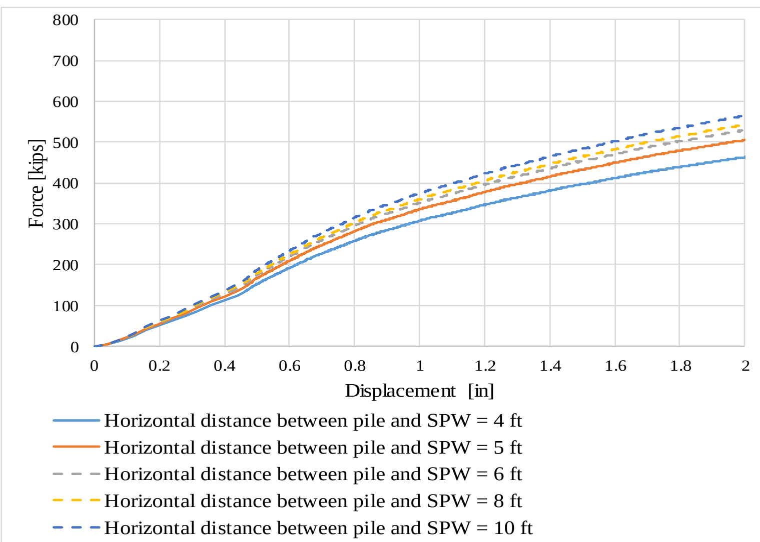
Ratio = 0.25



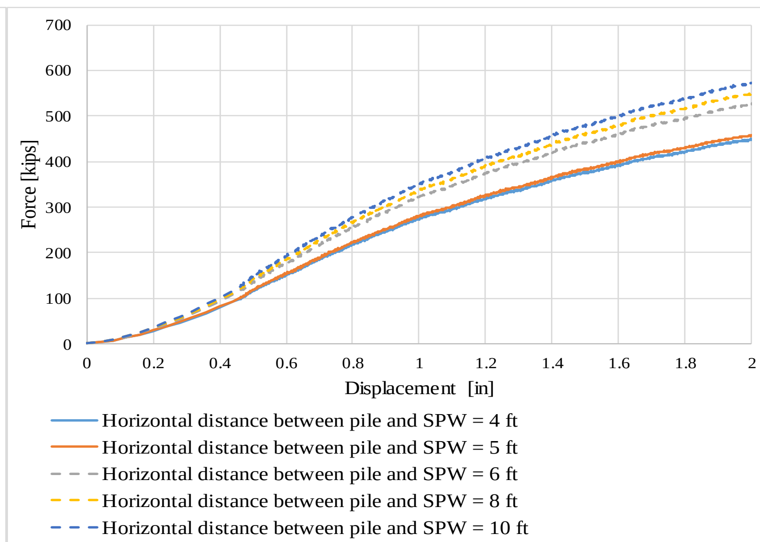
Ratio = 0.5



Ratio = 0.75



Ratio = 1.0



Loading scenario 3: A sheet pile is driven into the soil followed by the pile. Prior to application of quasi-static axial loads on the pile, the sheet pile is vertically extracted (with no vibration) from the soil.

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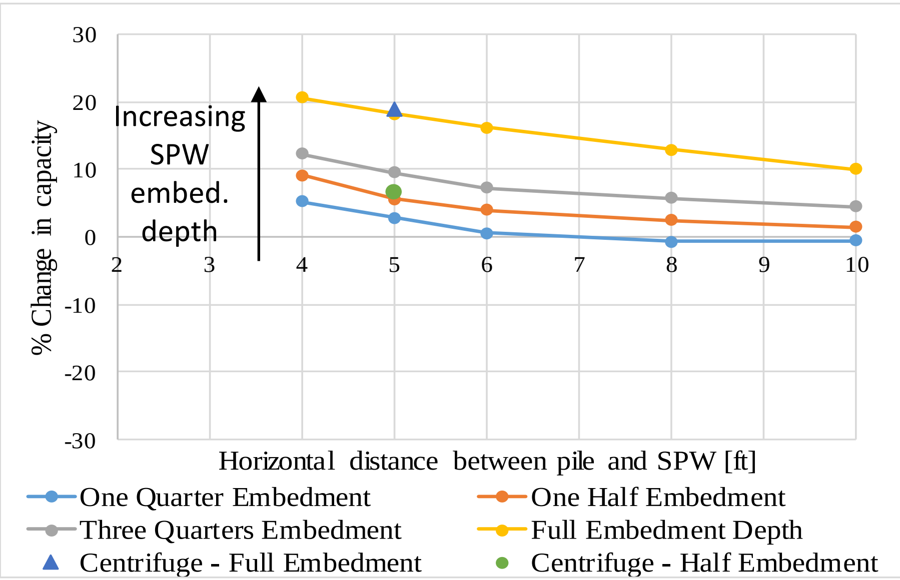
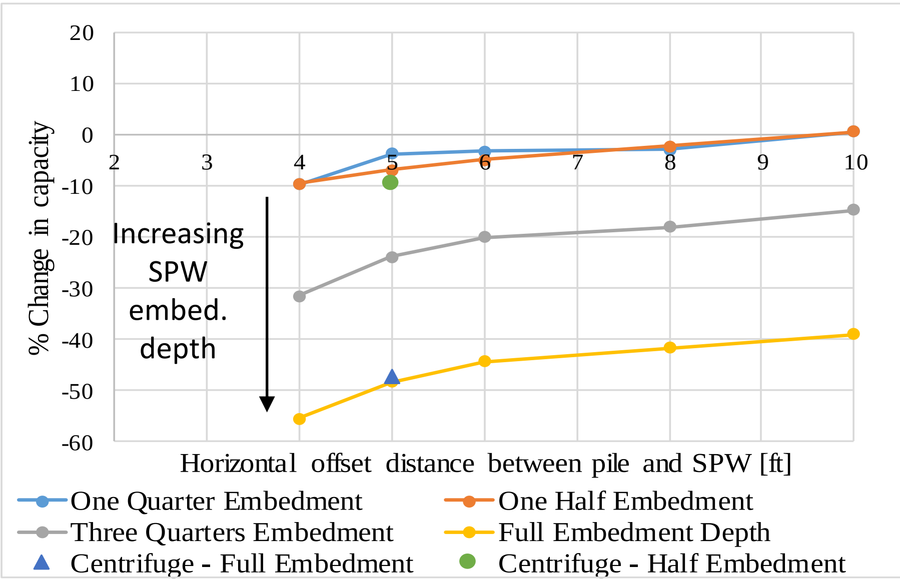
Task 5. Design Recommendations

- **Abscissa values represent horizontal offset distances (Davisson pile capacity).**

Scenario 2



Scenario 3



<u>Loading scenario 2</u>: A sheet pile is pushed into the soil, followed by a pile driven in the vicinity of the sheet pile (2.5 times width; 2.5B), and is subjected to incremental quasi-static top down loads.

<u>Loading scenario 3</u>: A sheet pile is driven into the soil followed by the pile. Prior to application of quasi-static axial loads on the pile, the sheet pile is vertically extracted (with no vibration) from the soil.

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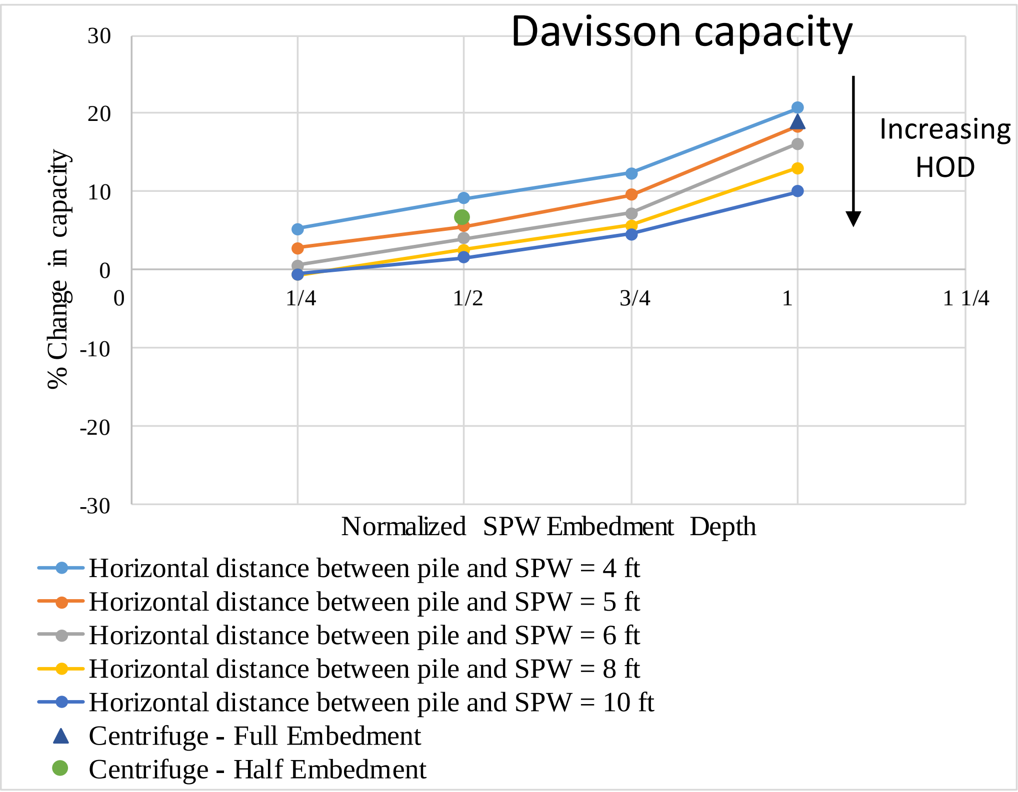
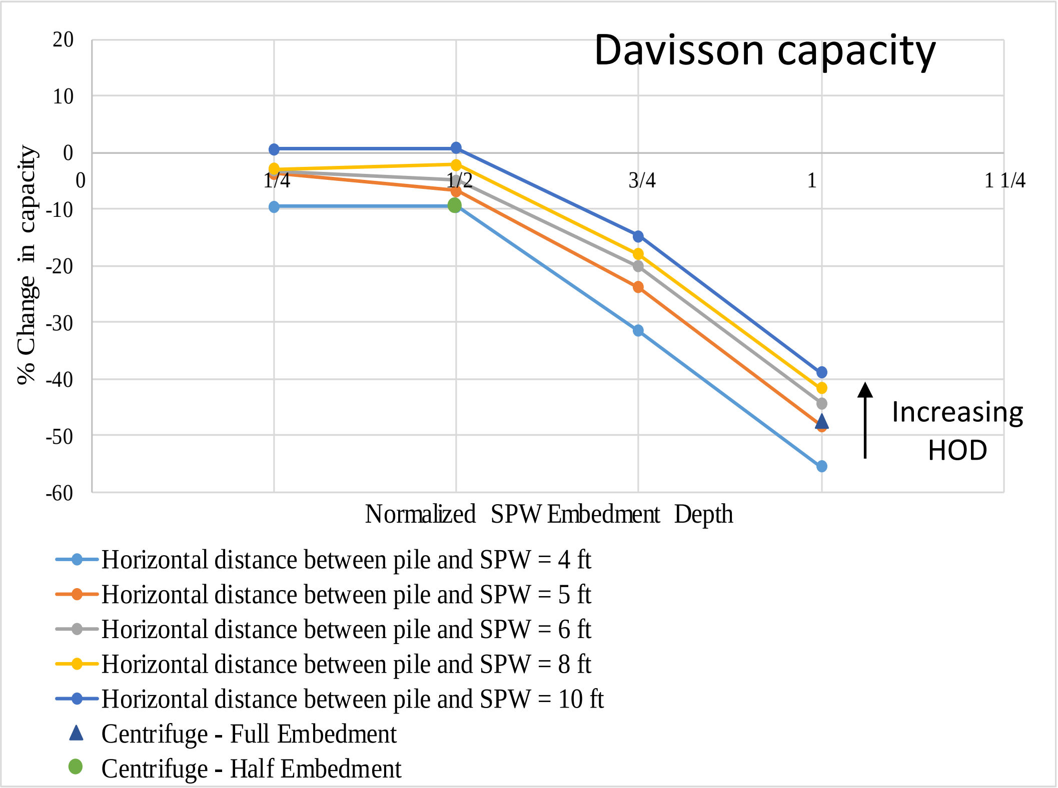
Task 5. Design Recommendations

- **Abscissa values represent ratios of SPW embedment depth to pile embedment length.**

Scenario 2



Scenario 3



Loading scenario 2: A sheet pile is pushed into the soil, followed by a pile driven in the vicinity of the sheet pile (2.5 times width; 2.5B), and is subjected to incremental quasi-static top down loads.

Loading scenario 3: A sheet pile is driven into the soil followed by the pile. Prior to application of quasi-static axial loads on the pile, the sheet pile is vertically extracted (with no vibration) from the soil.

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Recommendations

- **Semi-Empirical Assessment of Reduction Factors**
- **Problem Statement:**

Given a sheet pile wall installation depth = 25 ft

Depth of pile driving = 40 ft.

Horizontal offset distance = 6 ft

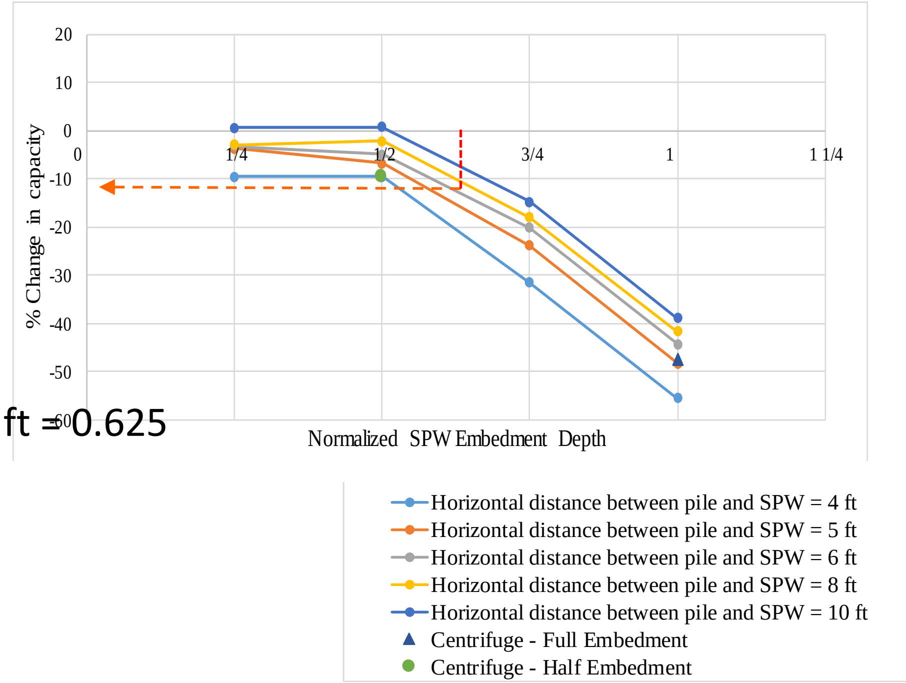
Davisson capacity of pile = 320 kips

Ultimate capacity of pile = 960 kips

Solution:

Ratio of SPW installation to depth of pile = 25ft / 40 ft = 0.625

From figures in previous slides: For HOD = 6 ft:



Reduction in Davisson pile capacity

$$\frac{0.625-0.5}{0.75-0.5}\times(20\%-5\%)+5\%=12.5\%$$

Thus, Davisson capacity on removal of SPW

$$320 \text{ kips } -\frac{12.5}{100}(320 \text{ kips})=320-40=280 \text{ kips}$$

Ultimate capacity remains unchanged after SPW removal.

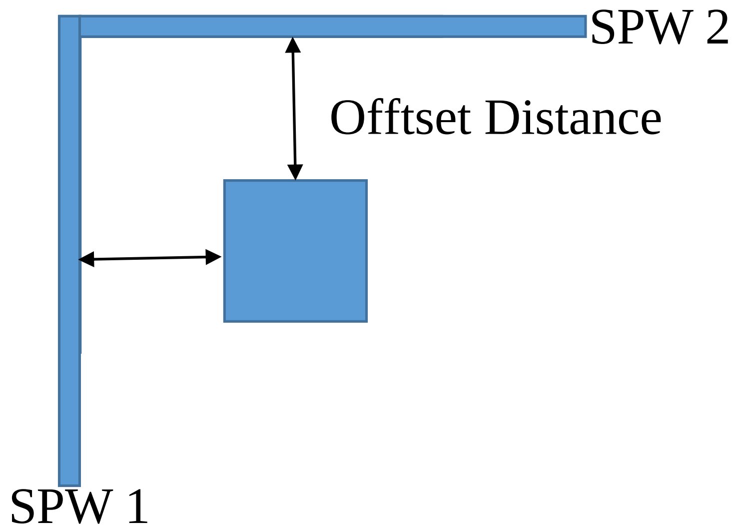
Conclusions

Semi-Empirical Assessment can be made using capacity reduction factors.

- Based on the parametric sensitivity study of Task 5, patterns in the reduction of pile capacities are found.
- Graphical representation of the force trends is presented as guidelines to estimate Scenario 3 pile capacities with respect to geometric configurations of the SPW installation and subsequent removal.

Future Research

- **Reduction Factors for Cofferdam Configuration are to be determined.**



- **Effects of Installation (Driving) and Vibratory Removal Methods in SPW or Pile Load Capacities can be further investigated.**

Thank you.

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