GRIP MEETING 2021, Progress Report

Project: Prediction model of vibration-induced settlement due to pile driving (BDV24 977-33)

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PRESENTED BY

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FDOT

Outline

- Brief project overview
  - Benefits
  - Objectives
  - Scope of work
- Review of variables involved and methods
- Field testing and data collection
- Numerical analyses
- Timeline

Review of benefits and objectives

Qualitative:

- Better estimation of infrastructure damage as a result of excessive pile-driving induced deformations.
- Understanding pile driving induced settlement mechanisms can improve design practices in Florida.
- Avoid unnecessary countermeasures in FDOT projects. Infrastructure damage will be minimized as a result of pile driving.

Quantitative:

- Produce pile driving induced settlement chart (or correlation or equation) relating PPV, D_r, distance from source, and input energy to be used in FDOT projects.

Objectives:

- To understand mechanisms of near-field and far-field deformations and determine influence zones.
- To measure field vibration-induced soil deformations in predetermined locations in Florida.
- To develop numerical models of dynamic settlements due to pile driving.
- To develop pile driving induced deformations prediction model(s) (e.g., closed formula or chart).

Scope of work

Task 1: Technical review of case studies (completed)

Task 2: Survey to practitioners (completed)

Task 3a-b: Field testing in pile installation sites (completed)

Task 4: Numerical modeling of pile driving induced settlement (In progress)

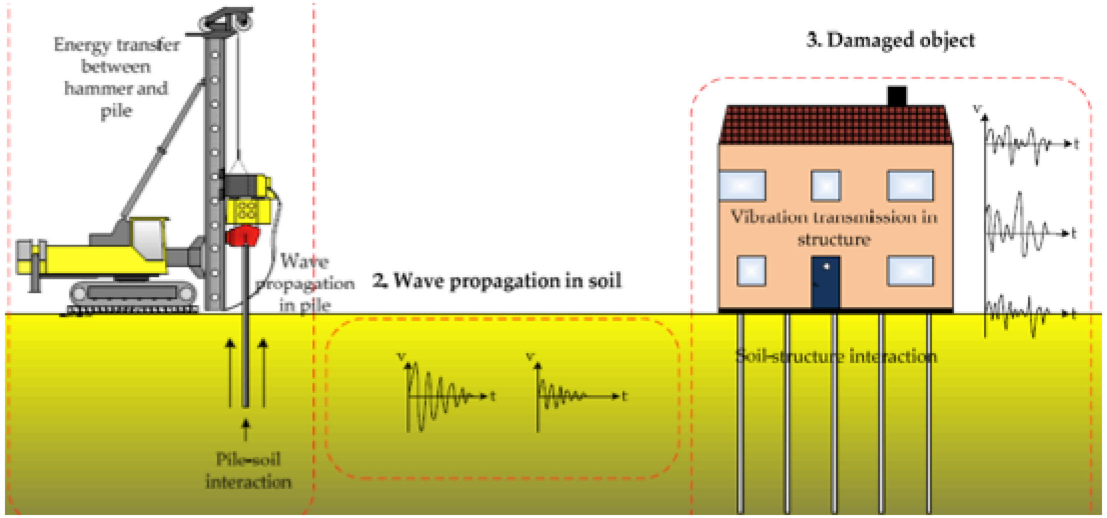
Task 5: Empirical prediction formula or chart for dynamic settlement (In progress)

Task 6: Guidelines and recommendations (In progress)

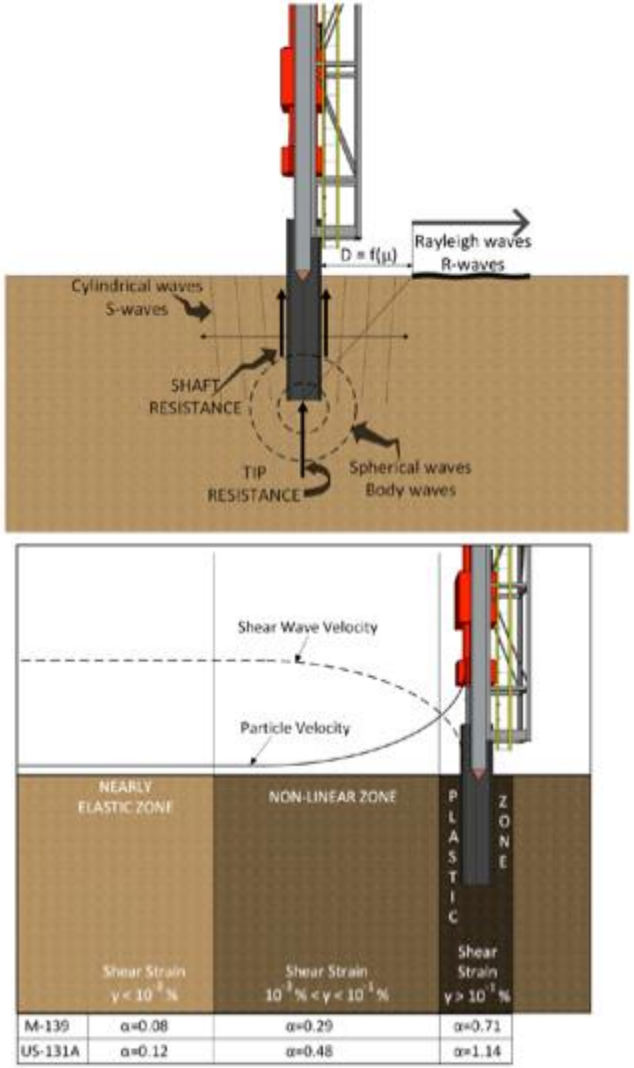
Variables involved in the problem

76 case histories and 55 papers revised to study variables involved:

- Vibration characteristics and input energy: vibration type, amplitude, frequency, and duration of the source
- Soil characteristics: soil gradation and type, relative density, and moisture content
- Attenuation characteristics: geometric and material damping



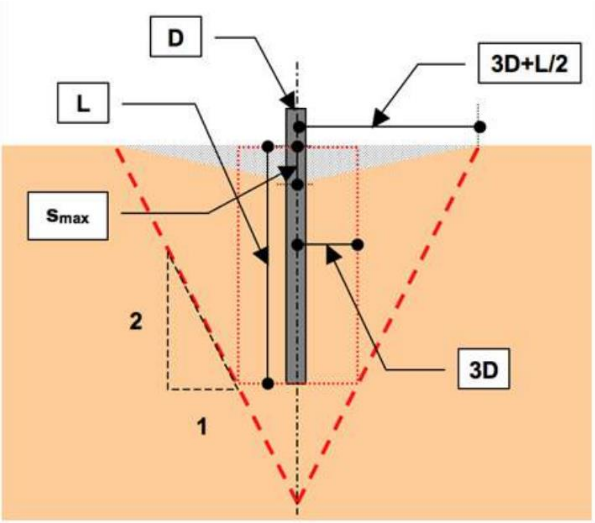
Pile-driving induced vibrations in urban environments (Hintze et al. 1997 and Deckner 2013)



Energy transfer from pile to soil (top)
Hypothetical soil behavior zones in terms of shear strains and attenuation coefficients (bottom)

Review of settlement estimation methods

Massarsch (2004)



$$S_{max} = \alpha(L + 6D)$$

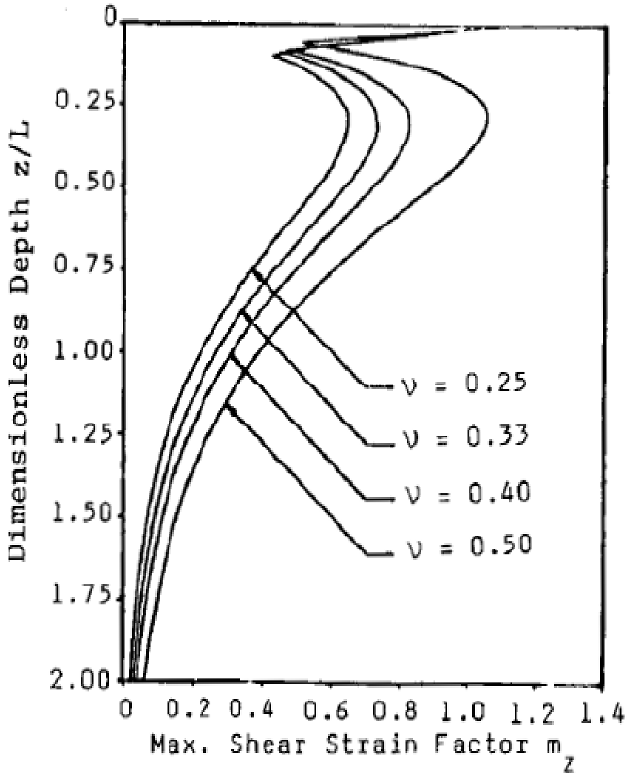
$$S_{avg} = \alpha\frac{(L + 3D)}{3}$$

Drabkin et. al (1996)

Factor	Factor Code	Tested Ranges	Coding of Factors
Peak Particle Velocity (PPV)	x_1	0.1-0.7 in/sec	$x_1 = -1 + \frac{PPV - 0.1}{0.3}$
Deviatoric Stress (s)	x_2	2-15 psi	$x_2 = -1 + \frac{s - 2}{6.5}$
Confining Pressure (p)	x_3	10-30 psi	$x_3 = -1 + \frac{p - 10}{10}$
Sand Mixture	x_4	Coarse, Medium or Fine	x_4 ranges from -1 for coarse sand to 1 for fine sand
Number of vibration cycles (N)	x_5	60-500,000 cycles	$x_5 = -1 + \frac{N - 60}{26{,}997}$
Moisture content	x_6	Dry, Saturated	x_6 ranges from -1 for dry sand to 2 for saturated sand
Initial relative density	x_7	Loose, Medium Dense	x_7 ranges from -1 for loose sand to 2 for medium dense sand

$$\ln Y = 2.27 + 1.19x_1 - 0.71{x_1}^2 + 0.49x_2 - 0.68{x_2}^2 - 0.80x_3 + 1.09{x_3}^2 - 0.46x_4 + 0.06{x_4}^2 + 0.45x_5 - 0.38{x_5}^2 - 0.19x_6 - 0.10x_7$$

Mohamad and Dobry (1987)



$$PPV_t = \frac{\gamma_t V_s \left(\frac{G}{G_{max}}\right)_t^{1/2}}{m_z}$$

$$\gamma_t = 0.01\%$$

Field testing: instrumentation plan

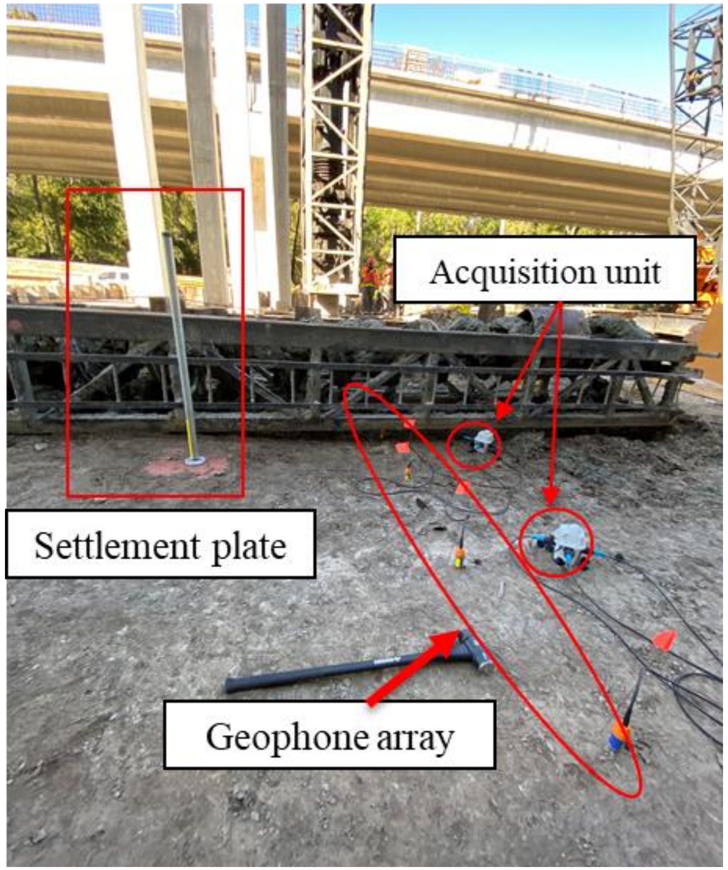
Procedure: Site selection → Instrumentation → Data collection → Analysis

Field testing EDPs:

Measure PPV

Measure Ground Deformations

- Nine 5 Hz geophones (Sercel)
- Acquisition units (Sercel Unite)
- Survey equipment and survey nails
- Settlement plate



Field testing: site locations

Site	Location	Measurements: PDA /EDC	Measurements: PPV	Measurements: Ground deformations
A1	SR 44 over St. John's River (Pier 3)	X	X	X
A2	SR 44 over St. John's River (Pier 2)	X	X	X
B	Wekiva Pkwy Sec.6 (Wekiva River)		X	X
C	Wekiva Pkwy Sec.6 (Wildlife Crossing)	X	X	X
D	Connection Ramp Turnpike with I-4	X		
Z.1	Turnpike over Shingle Creek		X	
Z.2	Sand Lake Rd. over Turnpike		X	
Z.3	SR 528 over Turnpike		X	
Z.4	Turnpike over US 441		X	
Z.5	Kissimmee Park Road		X	

Visited by the research team (A1, A2, B, C)

Provided by FDOT (D)

From Bayraktar et al. (2013) (Z.1–Z.5)

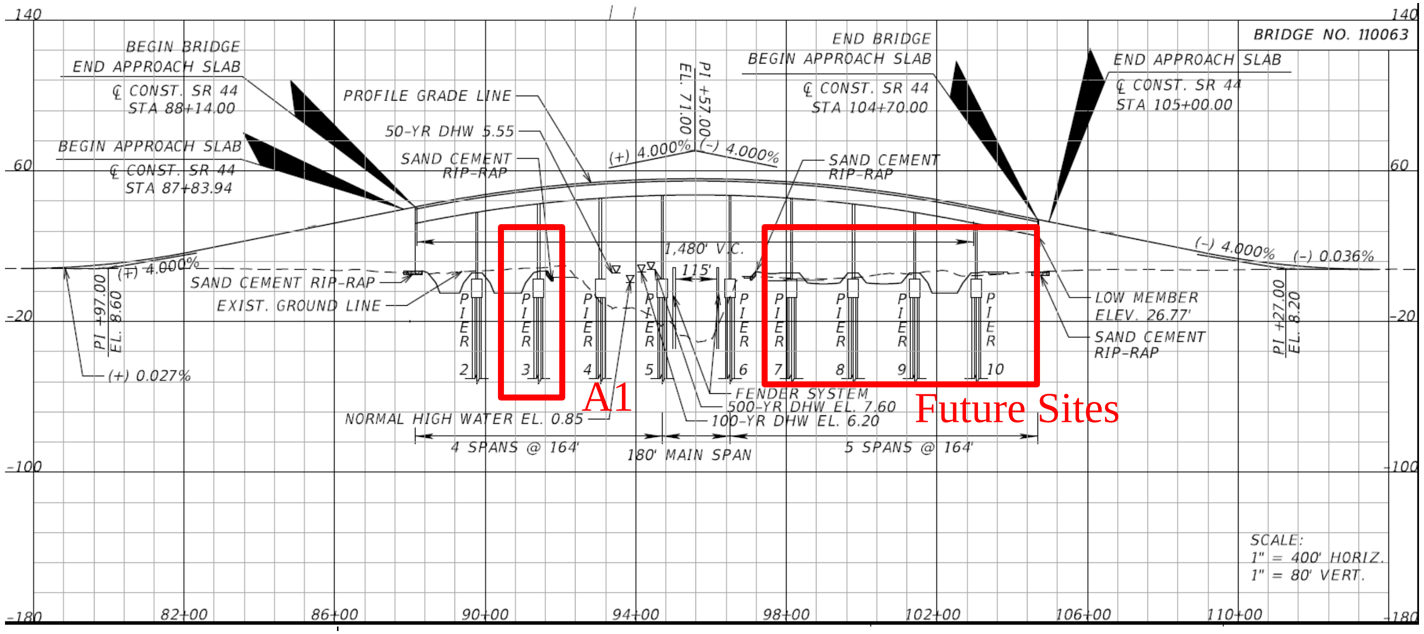
Field testing: site locations

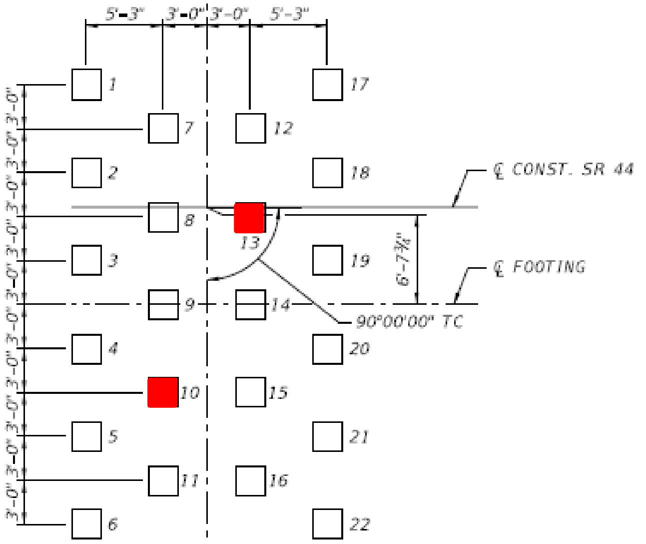
In coordination with FDOT, District 5 and Consulting Engineers:

- Michael Byerly (District 5)
- Larry Jones (FDOT)
- Tharwat Hannadawod (District 5)
- Chris Briggs and Jose Medina at Jacobs (Site A)
- Arnaldo Larrazabal at RS&H (Site B and C)
- Roger Gobin at WSP (Site D)

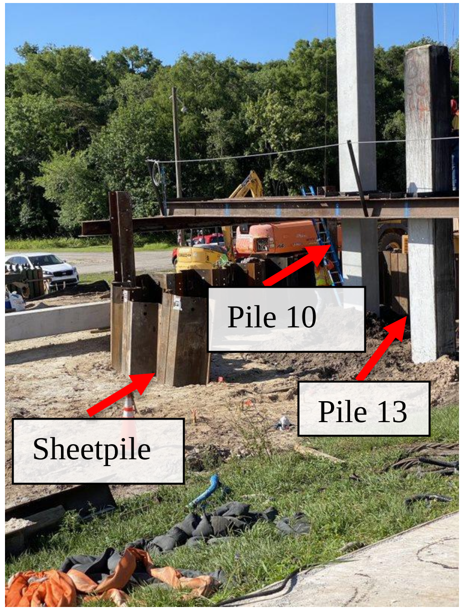
Site description (Site A1)

SR 44 over St. John's River (Pier 3)





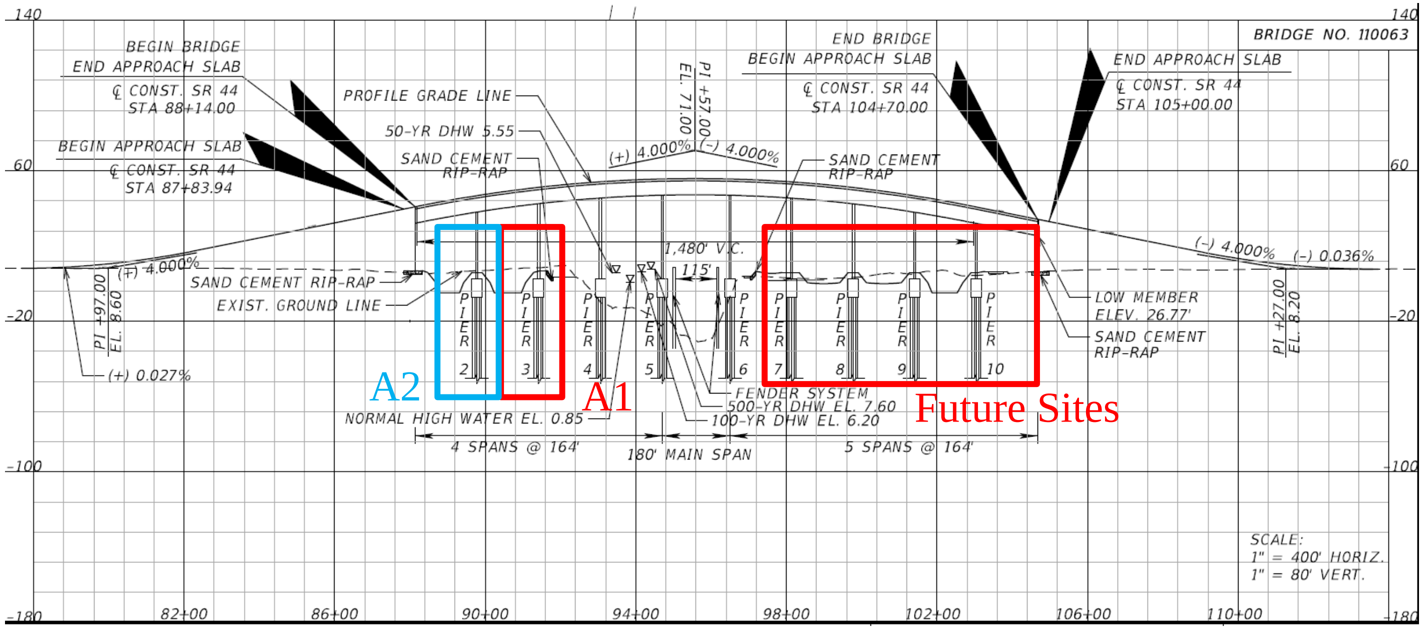
Test pile site A1

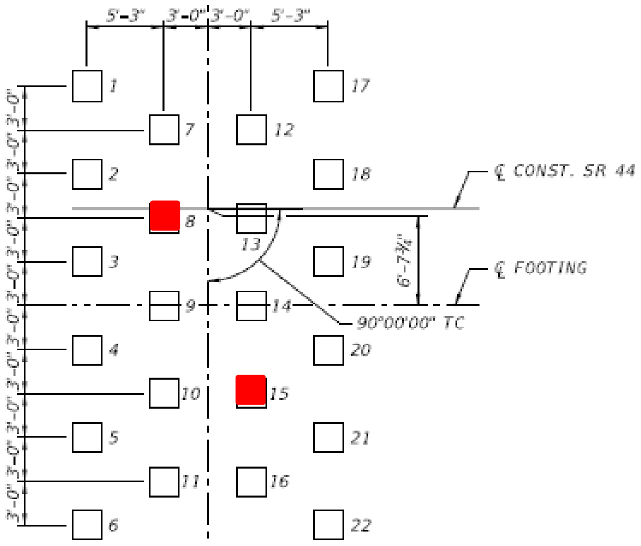


- 1656 ft long bridge with 10 spans and 9 piers. Site A1 corresponds to pier 3 with 22 piles
- Test piles 10 and 13 were 125 ft long, 24 in. wide prestressed concrete piles (PCP)
- Predrilling depth for piles 10 and 13 were 35 and 22 ft, respectively
- Driving sequence: First pile 13 then pile 10
- Embedded Data Collector (EDC) measurements
- Driving Equipment:
  - APE D50-52 hammer
  - 18 in. thick plywood pile cushion
  - 3-1/2 in. thick aluminum + 2-1 in. thick Micarta hammer cushion

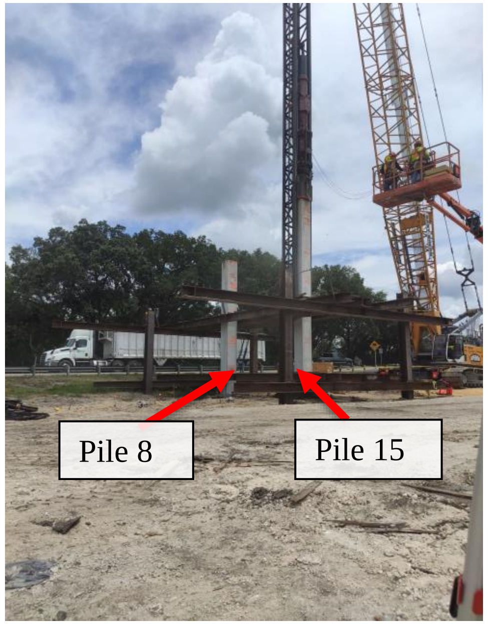
Site description (Site A2)

SR 44 over St. John's River (Pier 2)





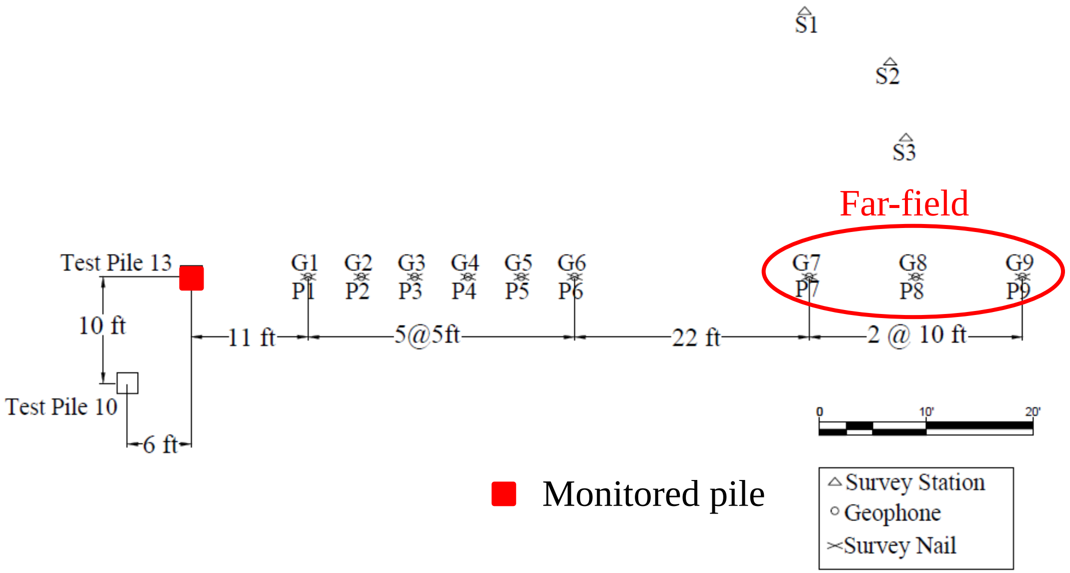
Test pile site A2



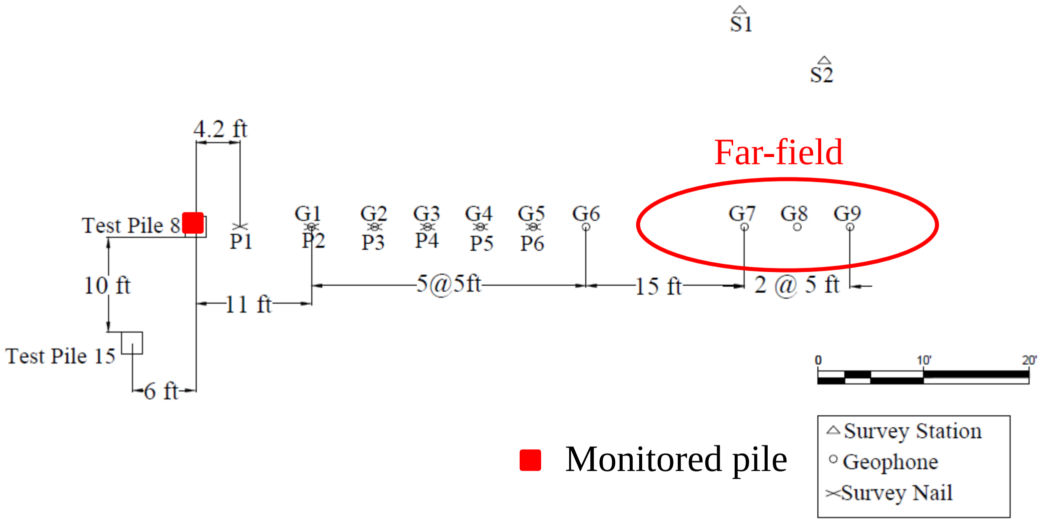
- 1656 ft long bridge with 10 spans and 9 piers. Site A2 corresponds to pier 2 with 22 piles
- **Test piles 8 and 15** were 135 ft long, 24 in. wide presetressed concrete piles (PCP)
- Predrilling depth for **piles 8 and 15** were 28 and 24 ft, respectively.
- Driving sequence: First **pile 8 then pile 15**
- Embedded Data Collecter (EDC) measurements
- Driving Equipment:
  - APE D50-52 hammer
  - 18 in. thick plywood pile cushion
  - 3-1/2 in. thick aluminum + 2-1 in. thick Micarta hammer cushion

Field equipment layout (Site A)

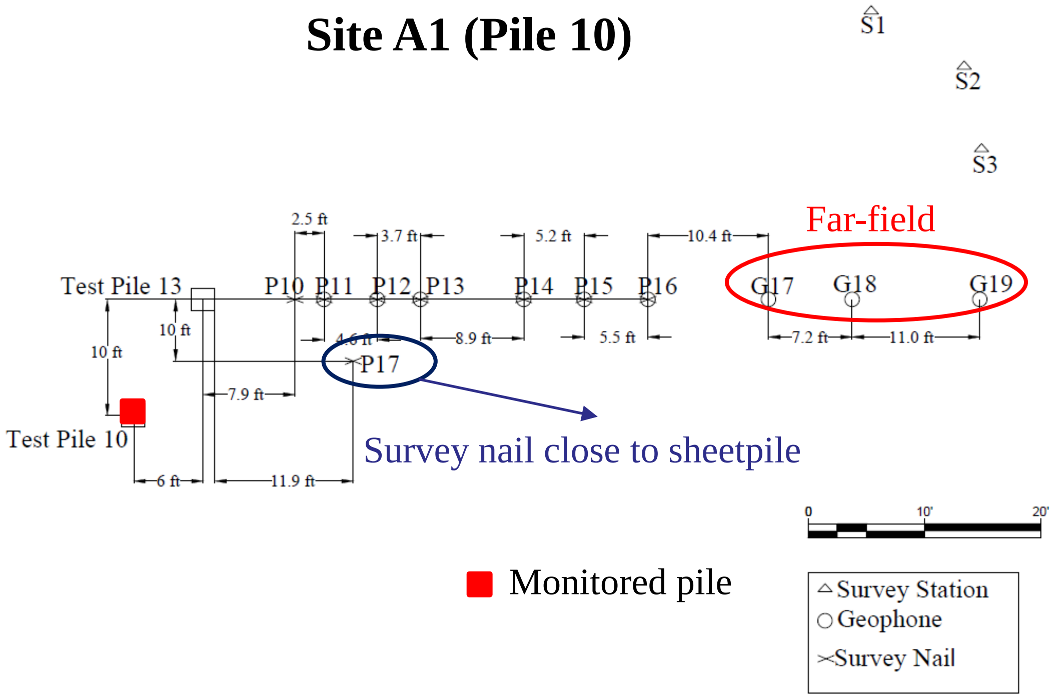
Site A1 (Pile 13)



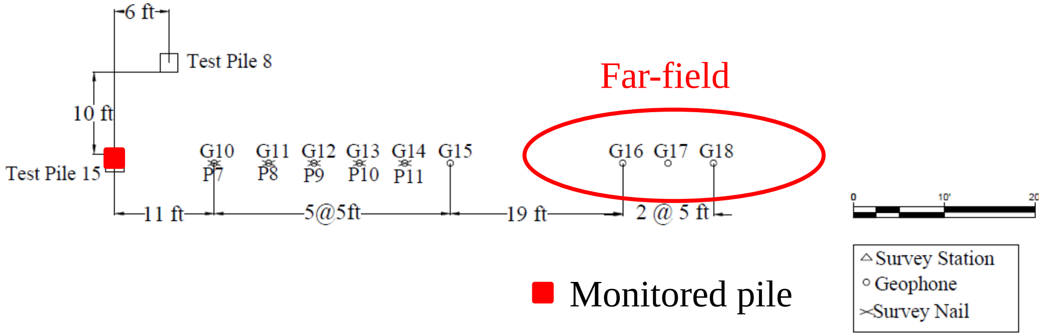
Site A2 (Pile 8)



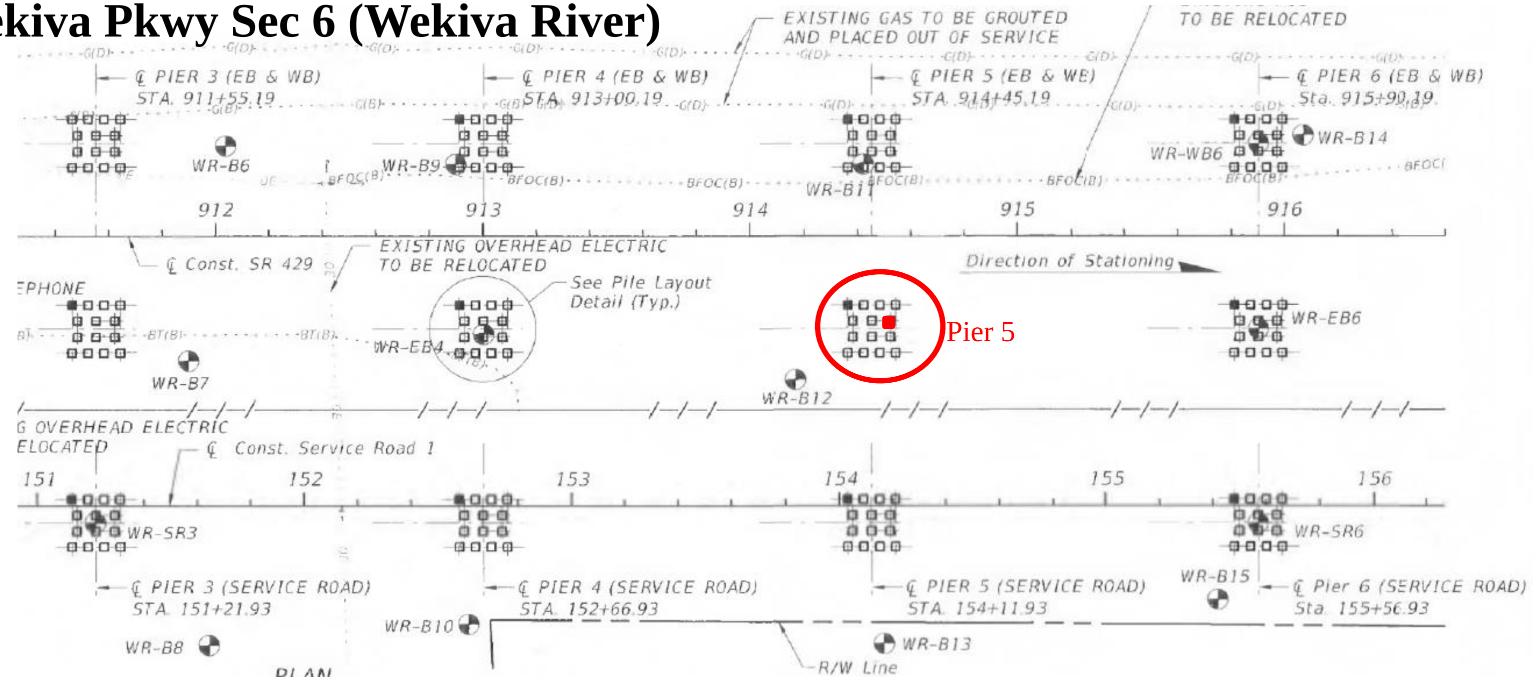
Site A1 (Pile 10)



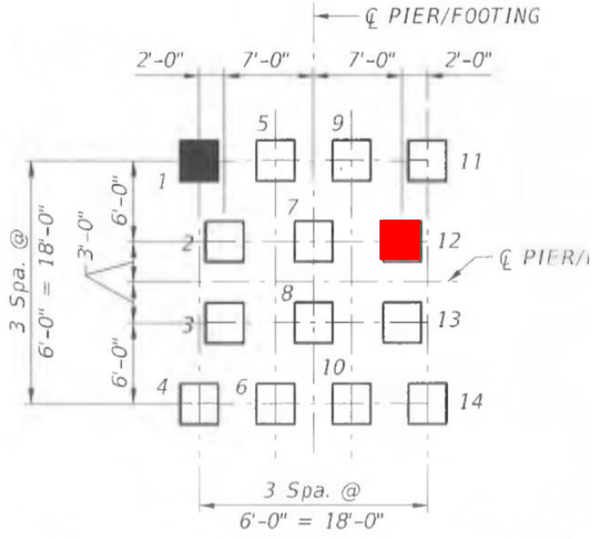
Site A2 (Pile 15)



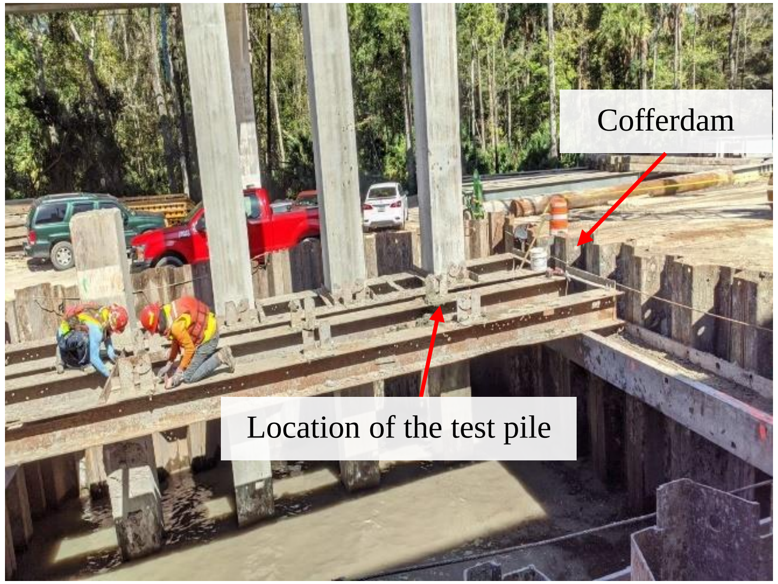
Wekiva Pkwy Sec 6 (Wekiva River)

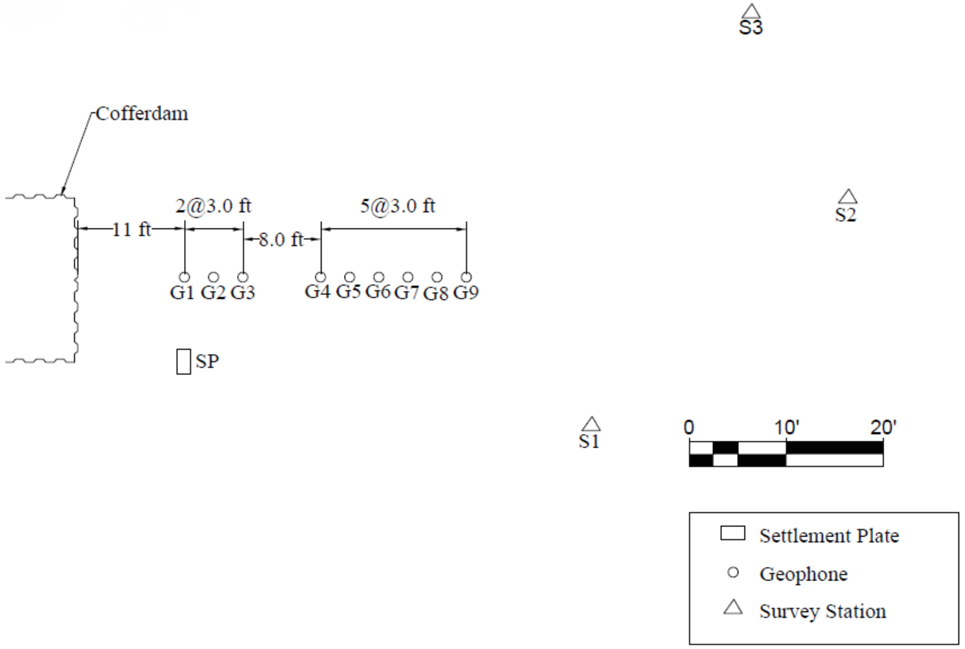


- A total of 3 bridges were projected at this site: bridges 110118, 110119, and 110120
- Pier 5 at bridge 110119 consists of 14 piles
- Test pile 12 was 24 in. wide and 65 ft long
- Pile Driving Analyzer (PDA) test performed at the site
- Pile driving records will be provided by the contractor



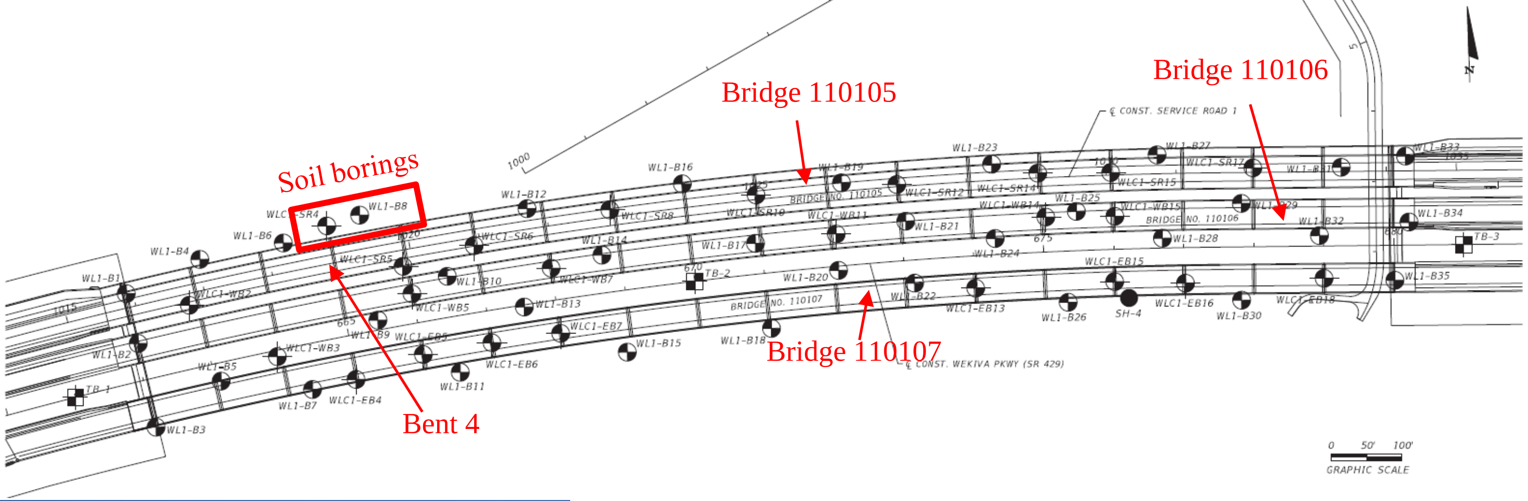
Test pile site A1

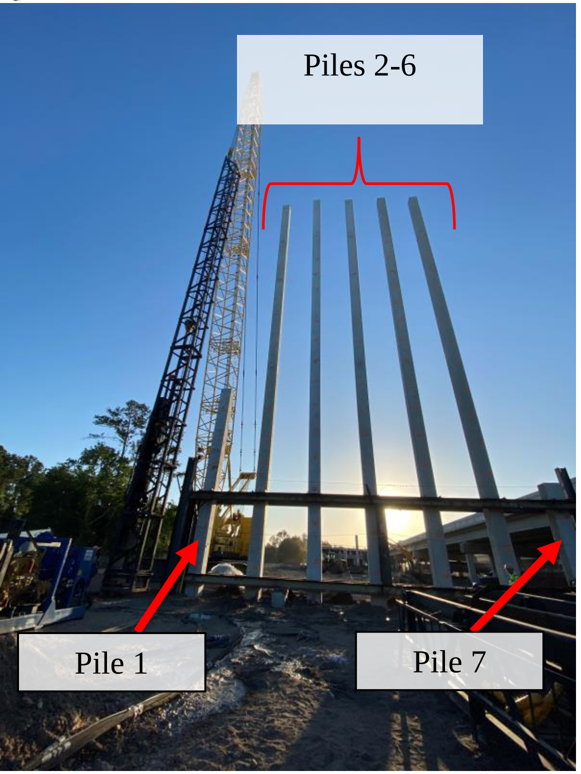


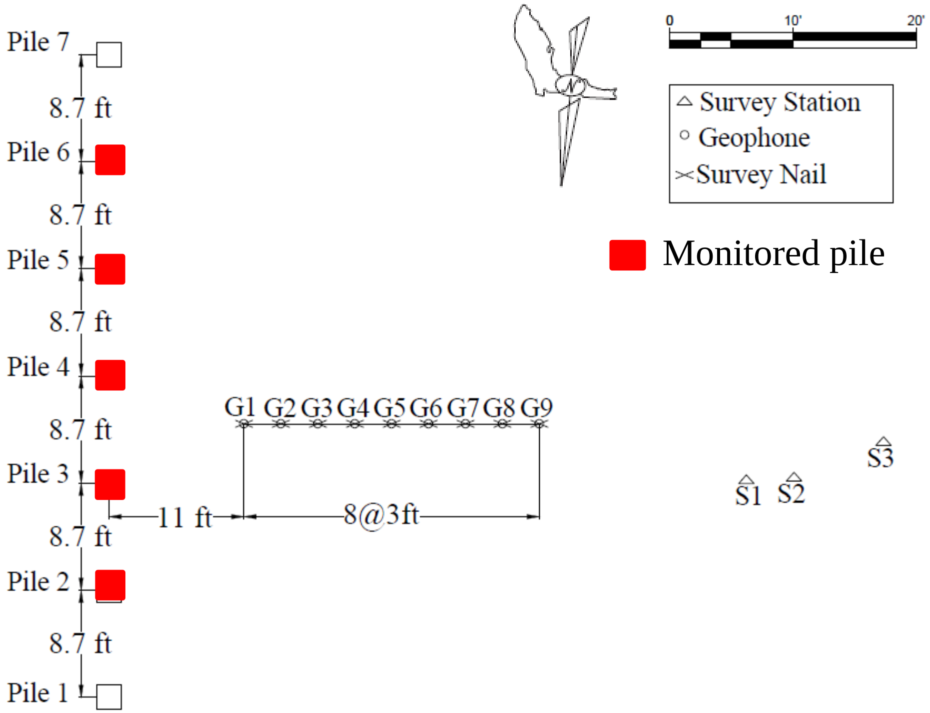


Site description (Site C)

Wekiva Pkwy Sec 6 (Wildlife Crossing)



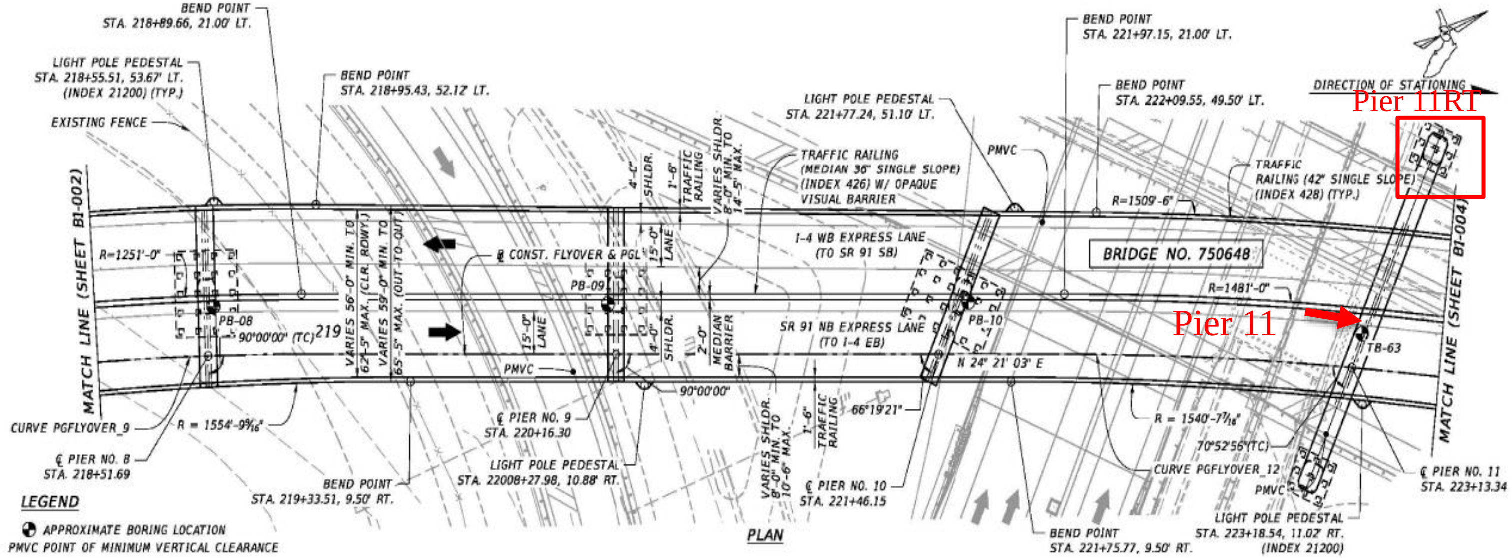




- A total of 3 bridges were projected at this site: bridges 110105, 110106, and 110107
- Bent 4 at bridge 110105 consists of 7 production piles
- Piles 1 through 7 were 24 in. wide with a length of 110 ft
- Piles spaced at 8.7 ft
- Final penetration depth: 90 ft
- Piles 1 and 7 were driven prior to visit
- Driving sequence: Pile 6, 5, 4, 3, and 2
- Driving Equipment:
  - APE D70-52 hammer
- Pile driving records will be provided by the contractor

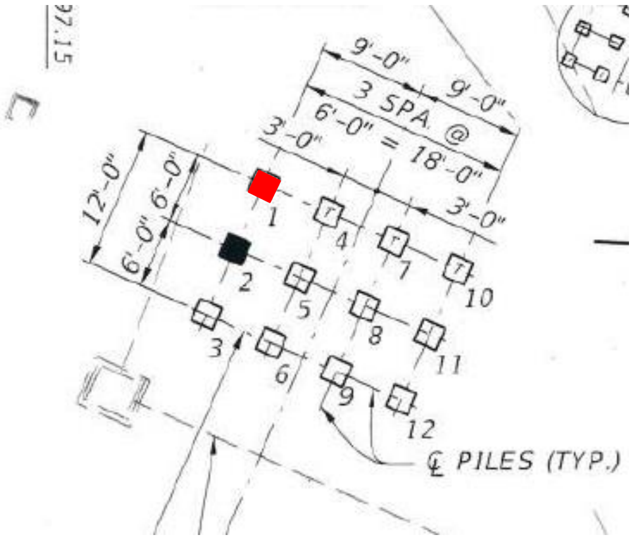
Site description (Site D)

Connection Ramp Turnpike with I-4



- 2100 ft long flyover bridge consisting of 13 spans and 15 piers
- The test pile is a 90 ft long, 24 in. wide prestressed concrete pile
- Driving equipment:
  - APE D 70-52 hammer
  - 1.0 in. thick micarta hammer cushion
  - 18 in. thick plywood pile cushion
- Predrilling depth: 32.0 ft
- Pile Driving Analyzer (PDA) measurements were provided by FDOT

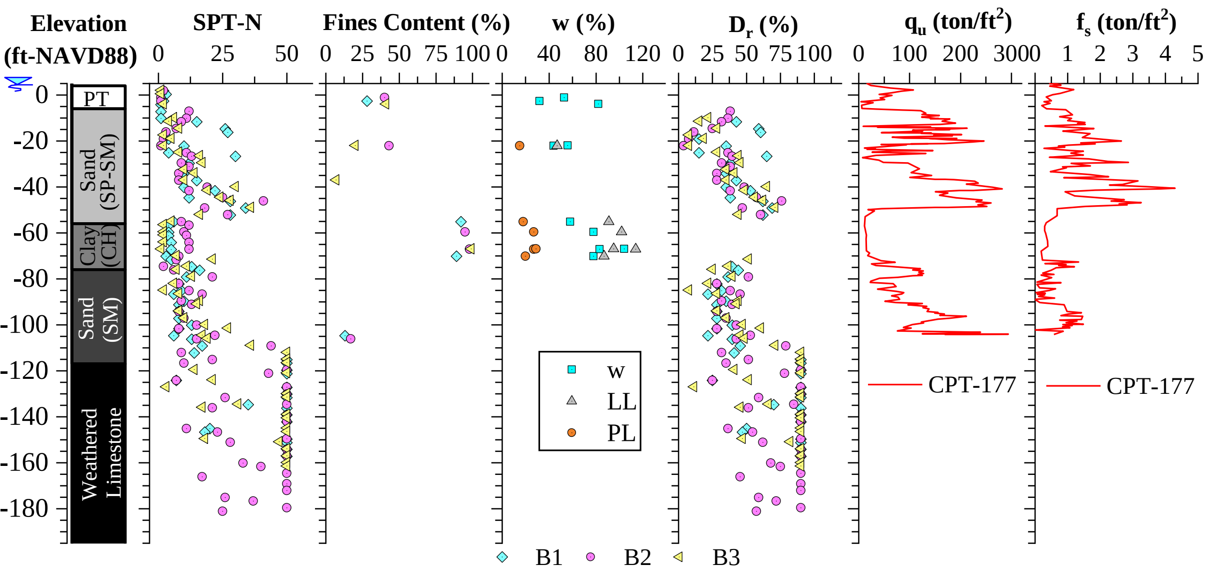
Soil borings



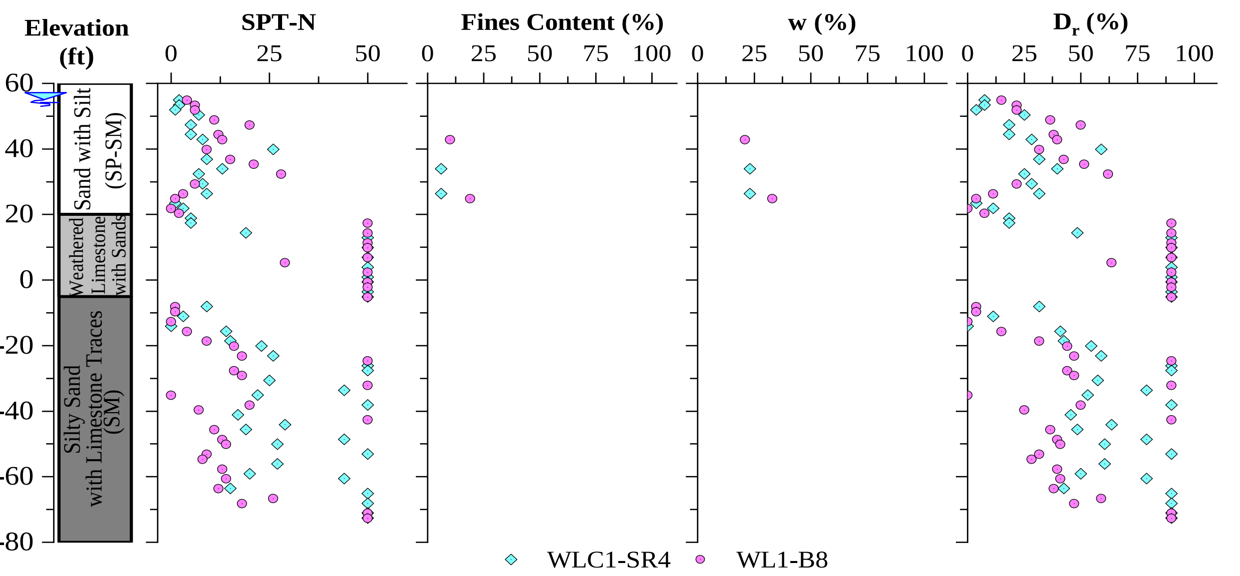
■ Monitored pile

Soil conditions

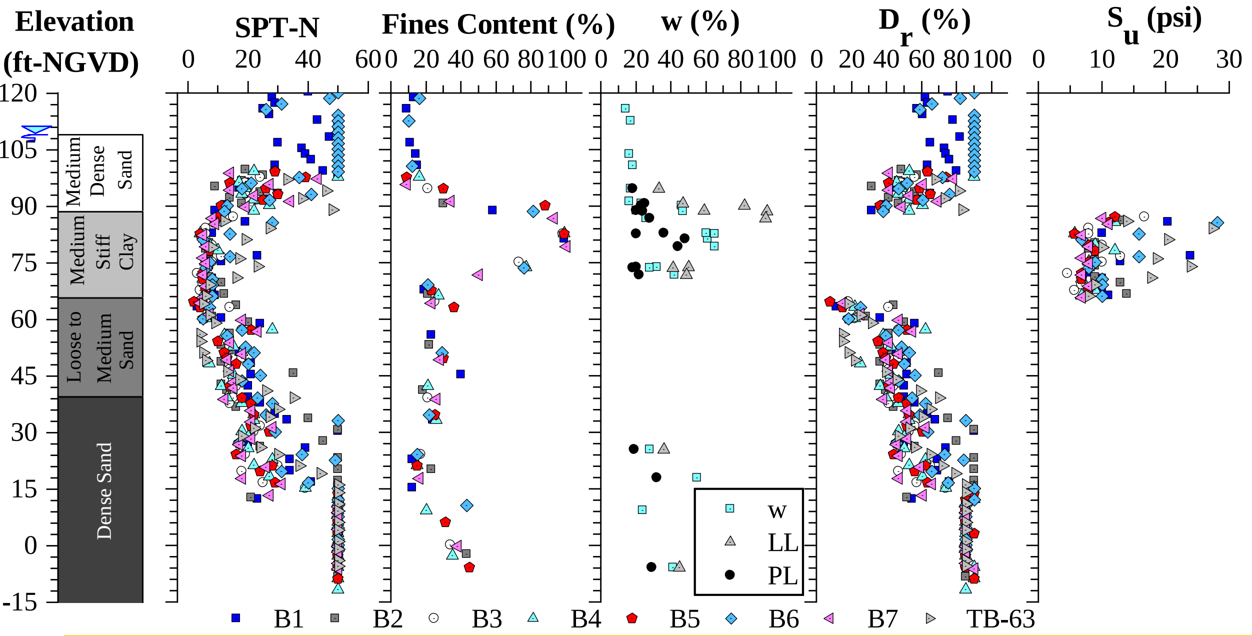
Site A



Site B



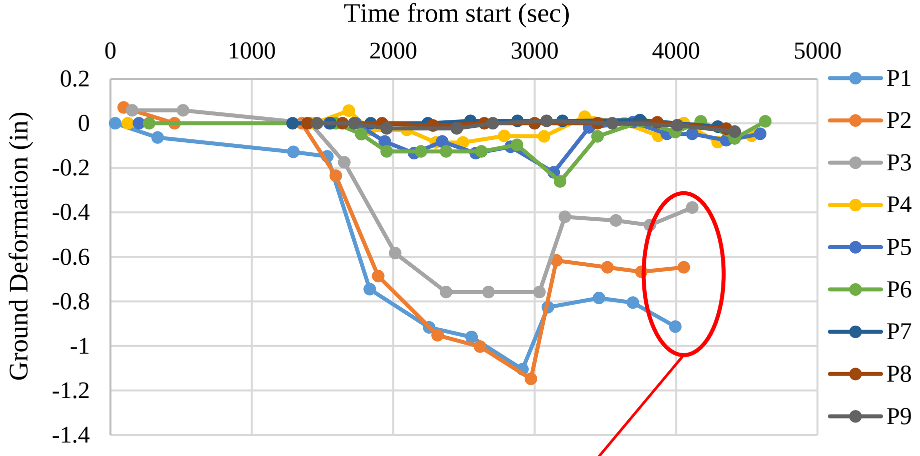
Site D



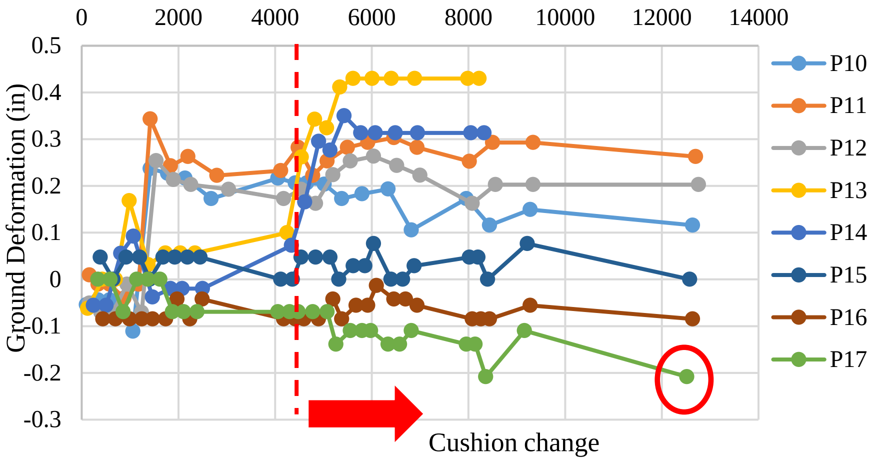
- Soil profiles based on SPTs, CPTs, and index properties
- Relative density (D_r) and undrained shear strength (S_u) defined based on Kulhawy and Mayne (1990)
- Soil conditions: mainly poorly graded sands and silty sands (i.e., SP and SM)!
- Shallow groundwater table
- Relative densities in the loose to medium-dense range!
- Interbedded fat clay layers (CH)

Ground deformations (Site A1)

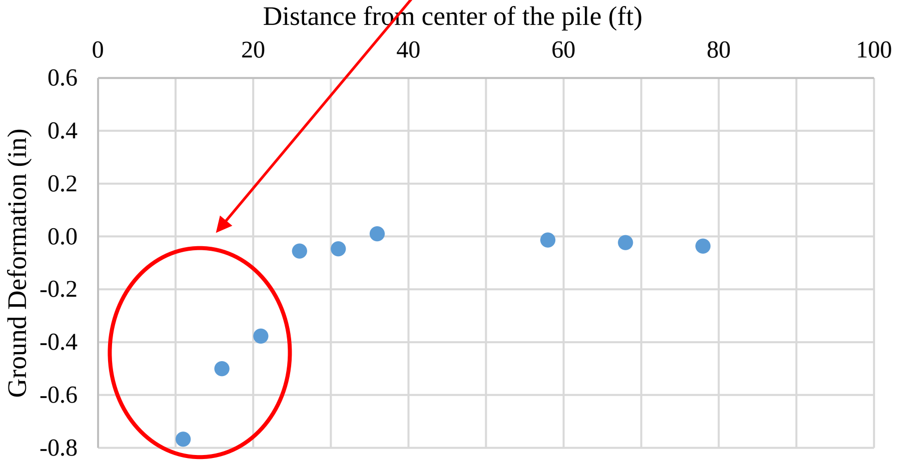
Pile 13

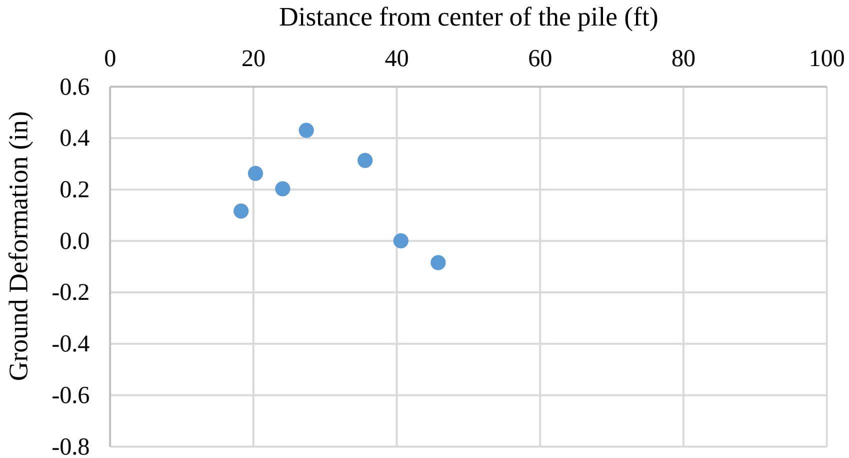


Pile 10



Ground deformation time histories during driving of each pile





Final ground deformations after driving of each pile

<u>Maximum</u> ground deformations:

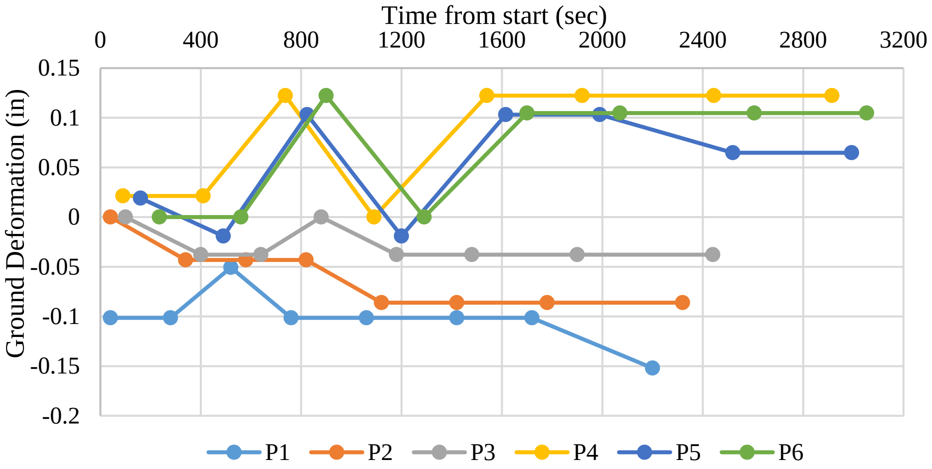
- Pile 13: **<u>-1.2 in.</u>** at 5.5D
- Pile 10: **<u>0.5 in</u>**. at 13.4D
- Most of ground deformation occurred at early stages!
- Sudden increase after cushion change in pile 10 driving
- Different response close to sheet pile

Maximum **<u>final</u>** ground deformations:

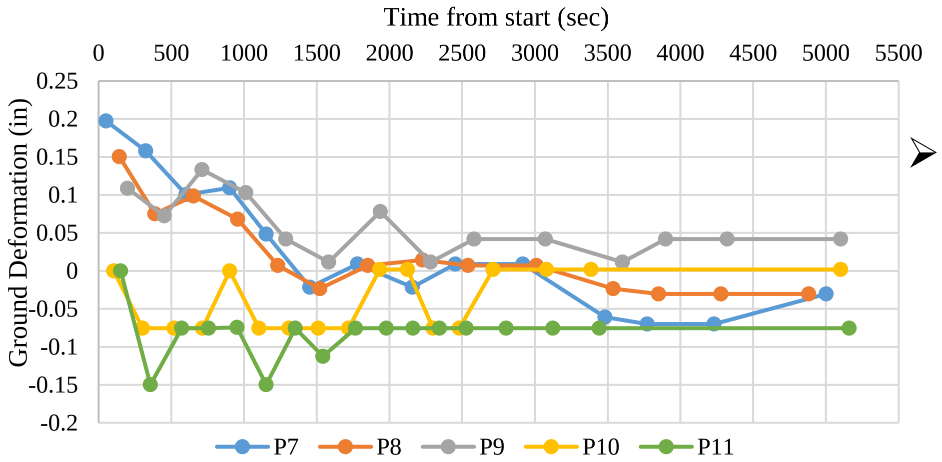
- Pile 13: **<u>-0.8 in</u>**. at 5.5D
- Pile 10: **<u>0.5 in</u>**. at 13.4D
- Significant attenuation
- First settlement then heave. Densification then dilation.

Ground deformations (Site A2)

Pile 8

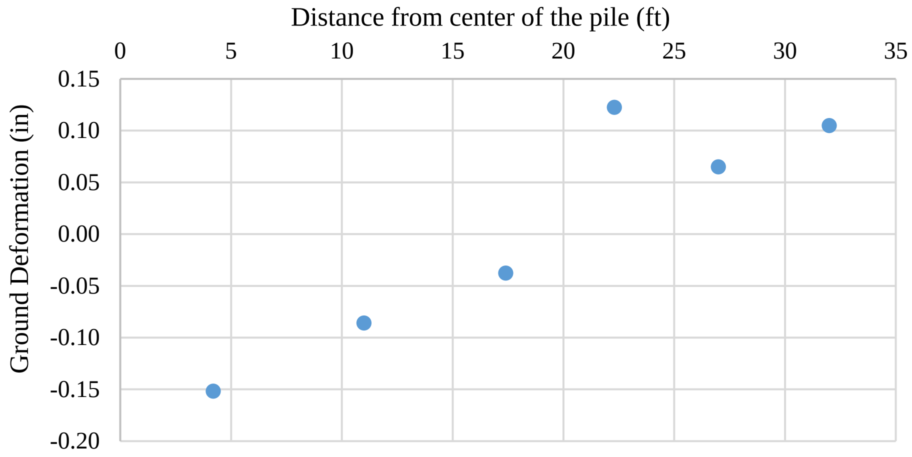


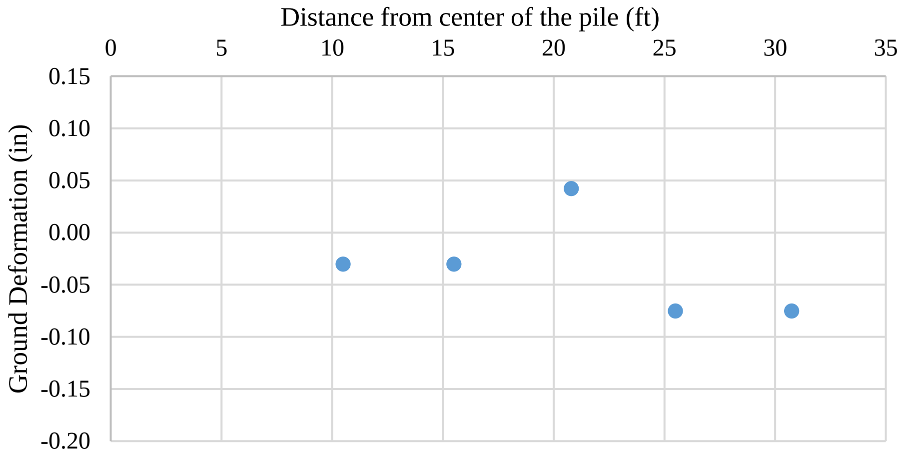
Pile 15



Ground deformation time histories during driving of each pile

- Again, most of ground deformation occurred at early stages!





Final ground deformations after driving of each pile

- Maximum ground deformations between **-0.2** and **0.2** in. after pile 8 driving
- Negligible deformations after driving of pile 15

Ground deformations (Sites B and C)

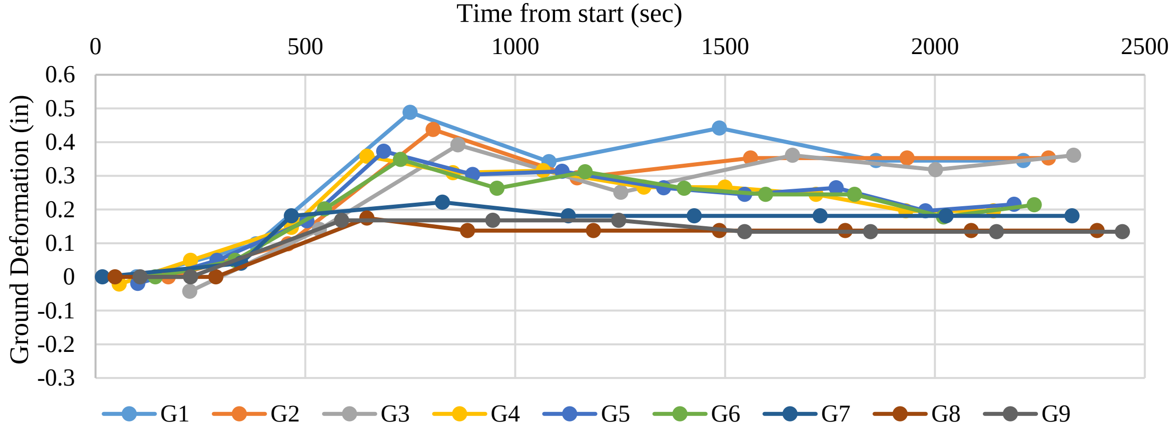
Site B

- Negligible ground surface deformations at site B
- Cofferdam installed prior to driving affected the ground deformations

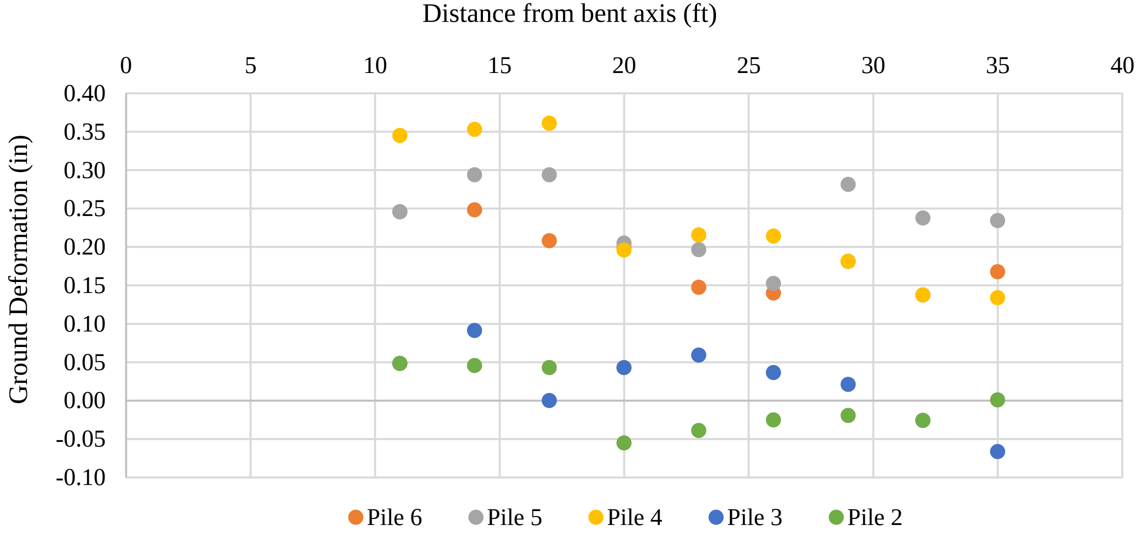
Site C

- Time histories measured during driving of each pile (Pile 2 through 7)
- Most of ground deformation occurred at early stages. Two piles were already driven in place before measurements were collected. Soil densification occurred then heave
- Location of pile tip influences ground surface deformations
- Maximum ground deformation of <u>**0.4 in**</u>. at 8.5D from bent axis after driving of pile 4
- Negligible deformations after driving of piles 3 and 2 (last in driving sequence).

Site C



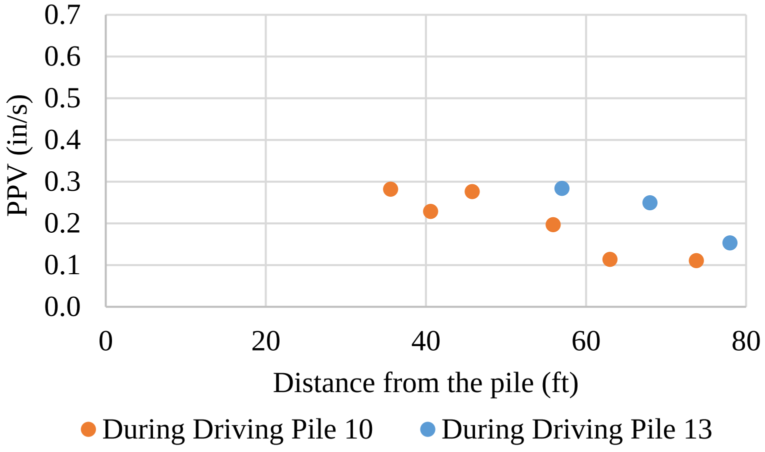
Ground deformation time histories during Pile 4 driving



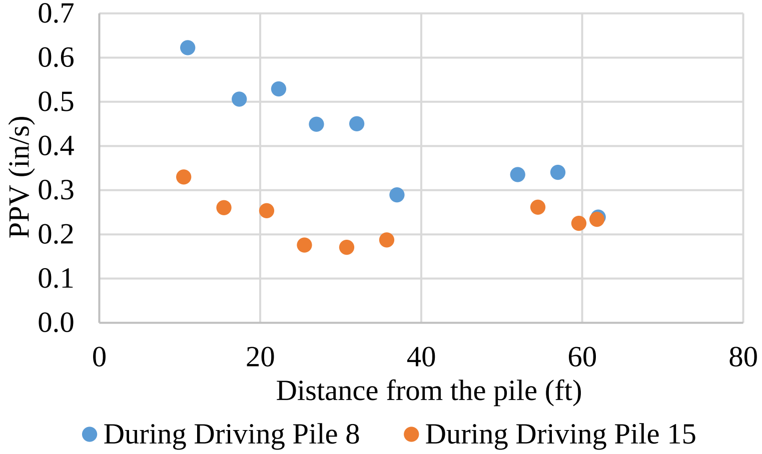
Final ground deformations after driving of piles 2 through 6 at site C.

Ground vibrations (Sites A and B)

Site A1

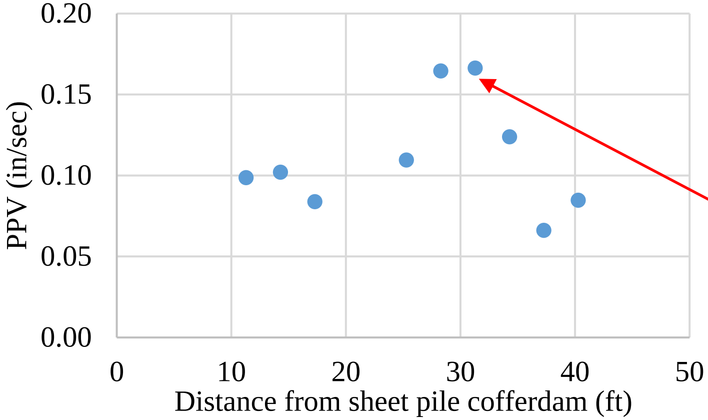


Site A2

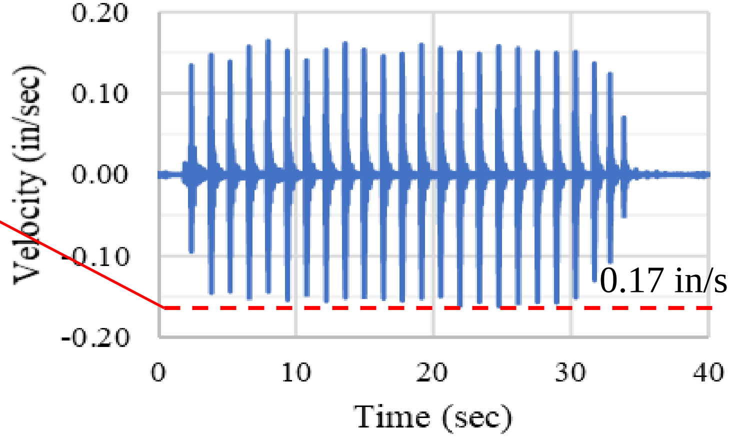


Measured PPV values during driving of test piles at sites A1 and A2

Site B



Measured PPV values during driving of test pile at site B



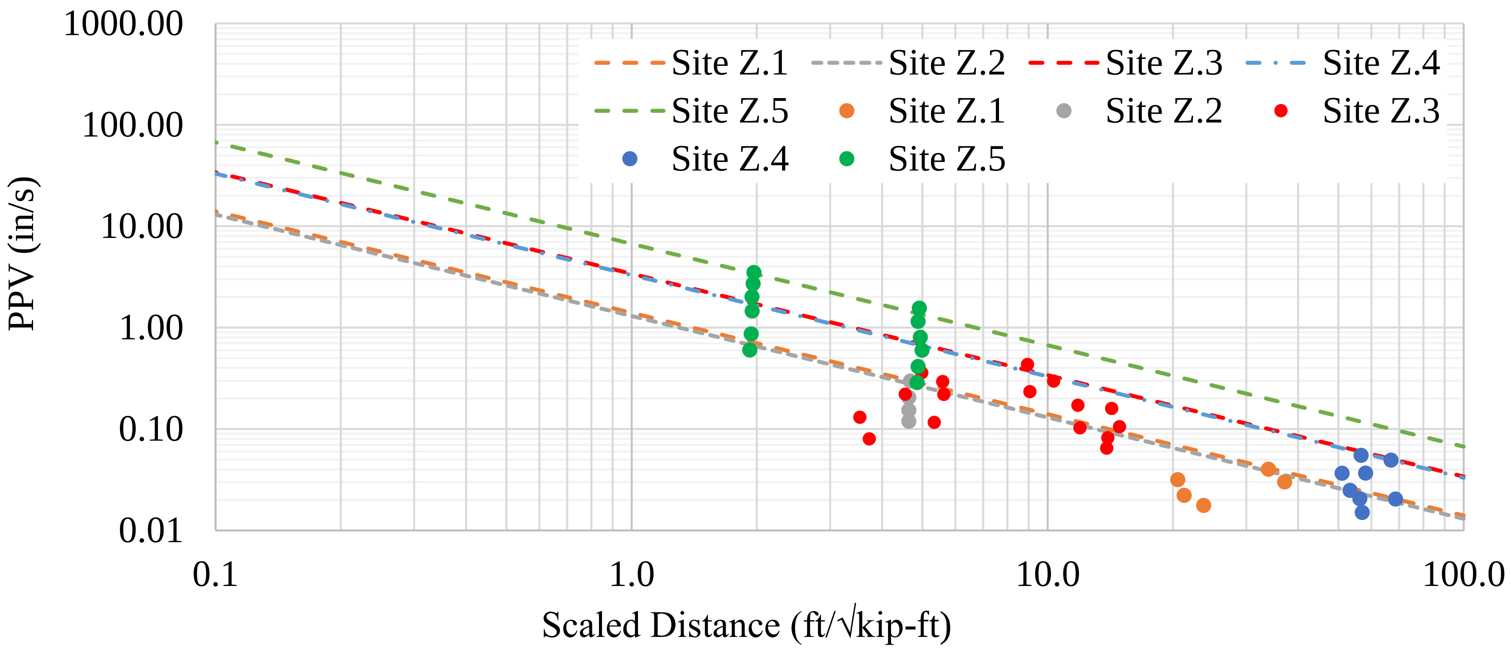
Measured velocity time history during driving of test pile at geophone G6 at site B

- ➢ For sites A1 and A2 higher PPV were recorded during first driven pile. Changes in attenuation characteristics as piles are driven in the group
- ➢ Smaller PPV values recorded at site B due to presence of cofferdam
- ➢ For site C the geophones malfunctioned limiting up to a value of 0.3 in/s. Vibration levels higher than 0.3 in/s occurred at the site.

Ground vibrations (Sites Z.1 through Z.5)

Additional PPV values reported by Bayraktar et al. (2013):

- Sand Lake Rd. over the Turnpike (Site Z.1)
- SR 528 over the Turnpike (Site Z.2)
- Turnpike over Shingle Creek (Site Z.3)
- Turnpike over US 441 (Site Z.4)
- Kissimmee Park Rd. over Turnpike (Site Z.5)



Measured PPV values and upper limit boundaries in nearby projects (Bayraktar et al. 2013)

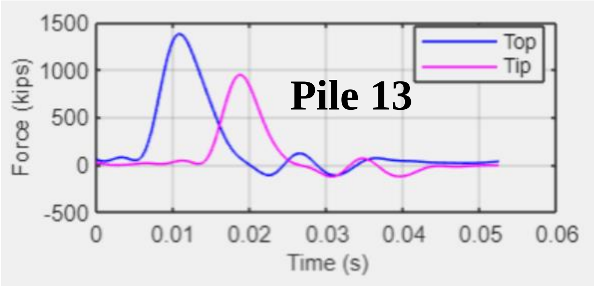
Project locations with respect to site D (Turnpike over I-4)

Numerical Modeling Strategy Flowchart

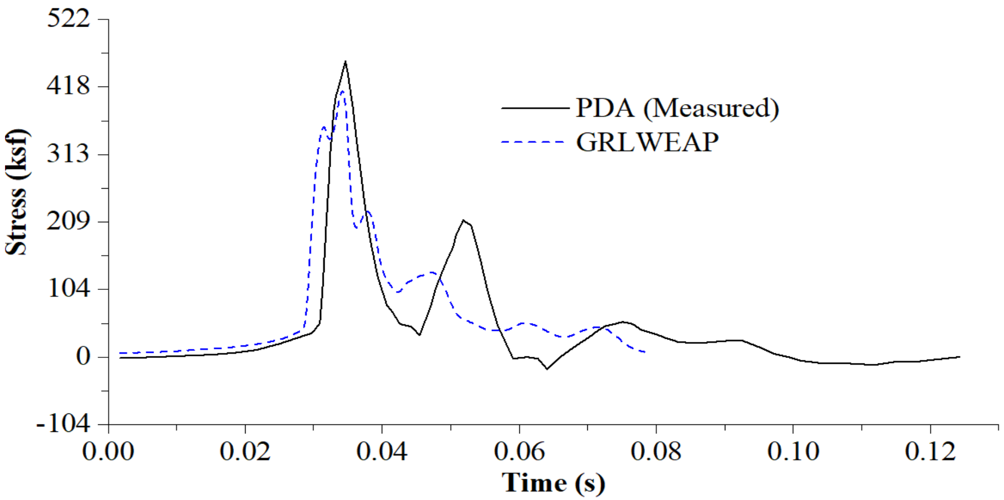
Testing Site Selection → Summarize Soil Profile → Analyze CAPWAP/ PDA / EDC Results → GRLWEAP "Calibration" from PDA Results → PLAXIS

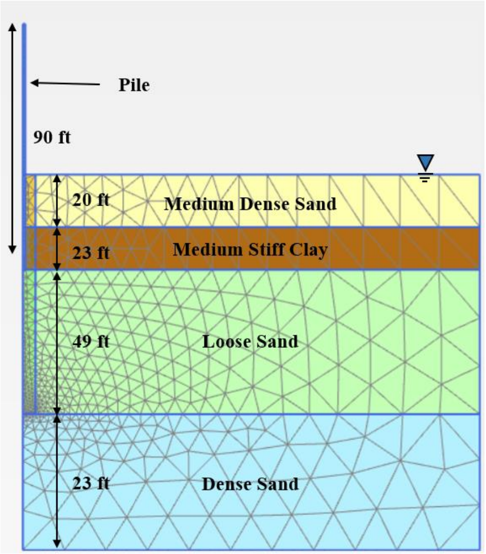
- **Summarize Soil Profile**: From soil borings and FDOT soil boring viewer
- **Analyze CAPWAP/ PDA / EDC Results**: From geotechnical reports
- **GRLWEAP "Calibration" from PDA Results**: To calibrate forcing function and penetration displacement per blow
- **PLAXIS**: Apply forcing function to analyze response in soil continuum

CAPWAP/PDA/EDC measurement → **GRLWEAP "calibration"** → **Numerical simulations**



Site A1 (EDC) (typical signal)

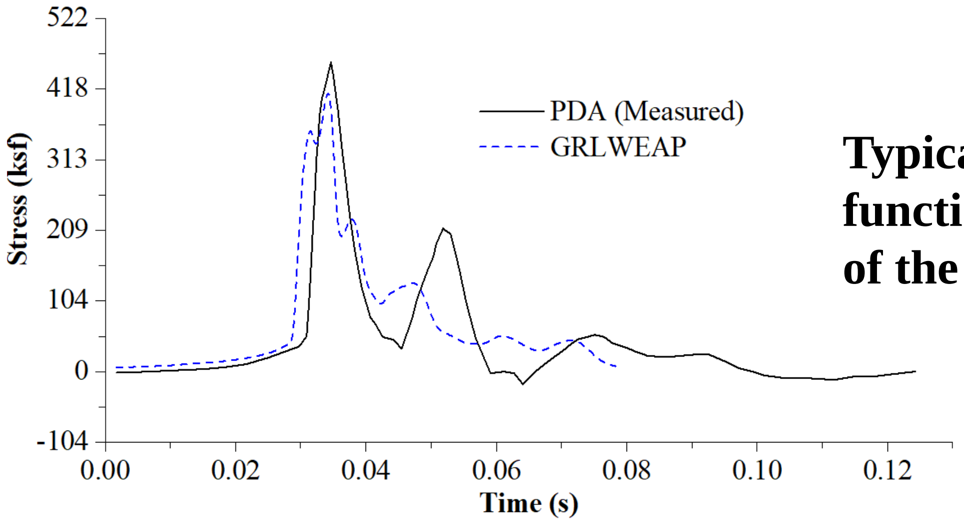




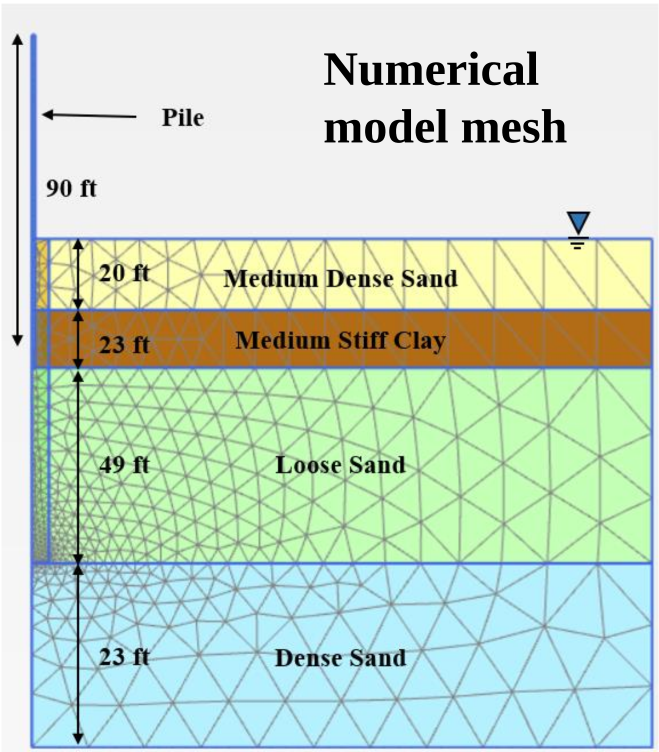
Modeling: main phases in the numerical model

Pile driving numerical model stages:

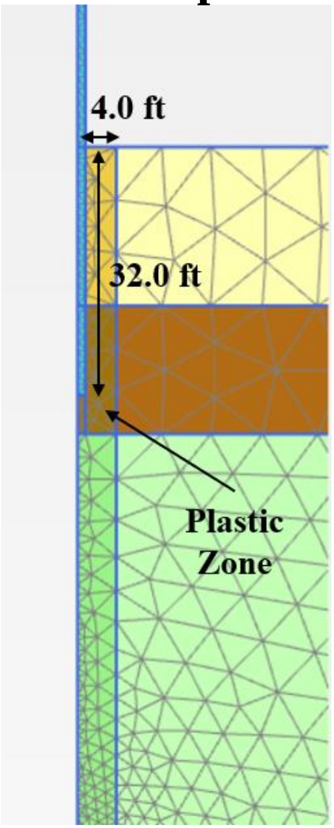
1. Define material properties (HSS and Hypo models) and drainage conditions. Type of analysis: dynamic with consolidation
2. Define model geometry (pile, soil layers and plastic zone clusters)
3. Mesh definition
4. Initialization of soil stress field
5. Activation stage: pile and plastic zone cluster
6. Dynamic analysis: application of 1824 blows separated one second between each other.



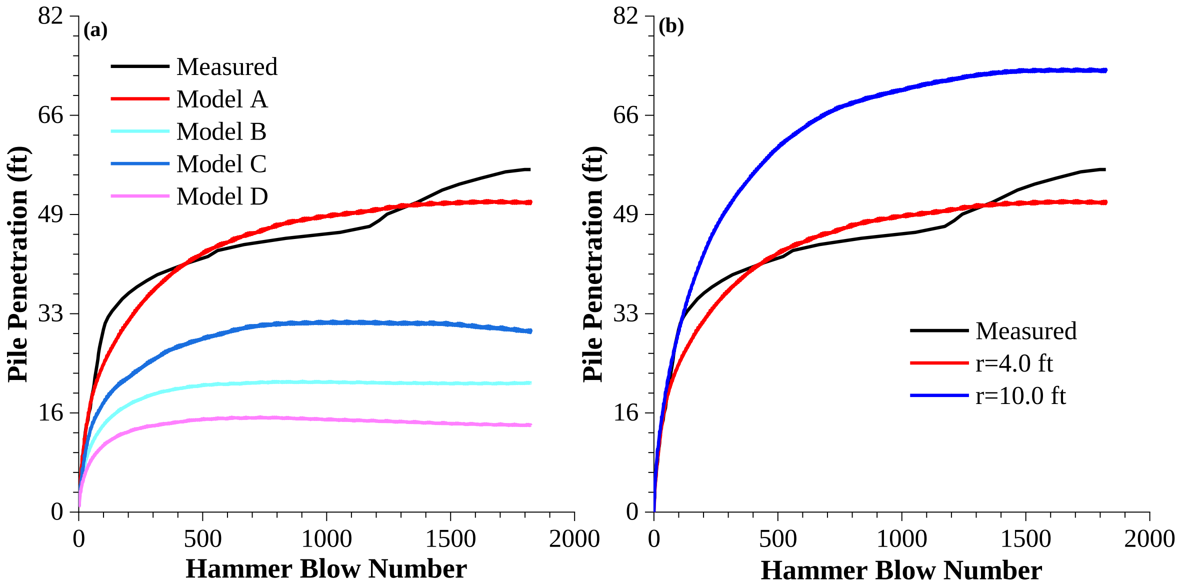
Typical stress function at the top of the pile



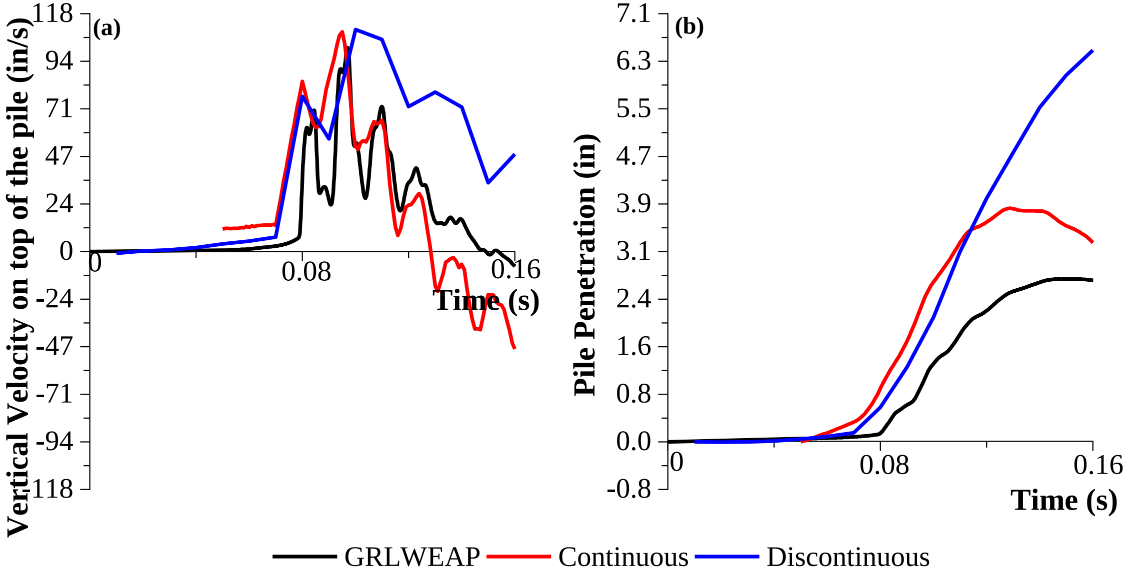
Close up view



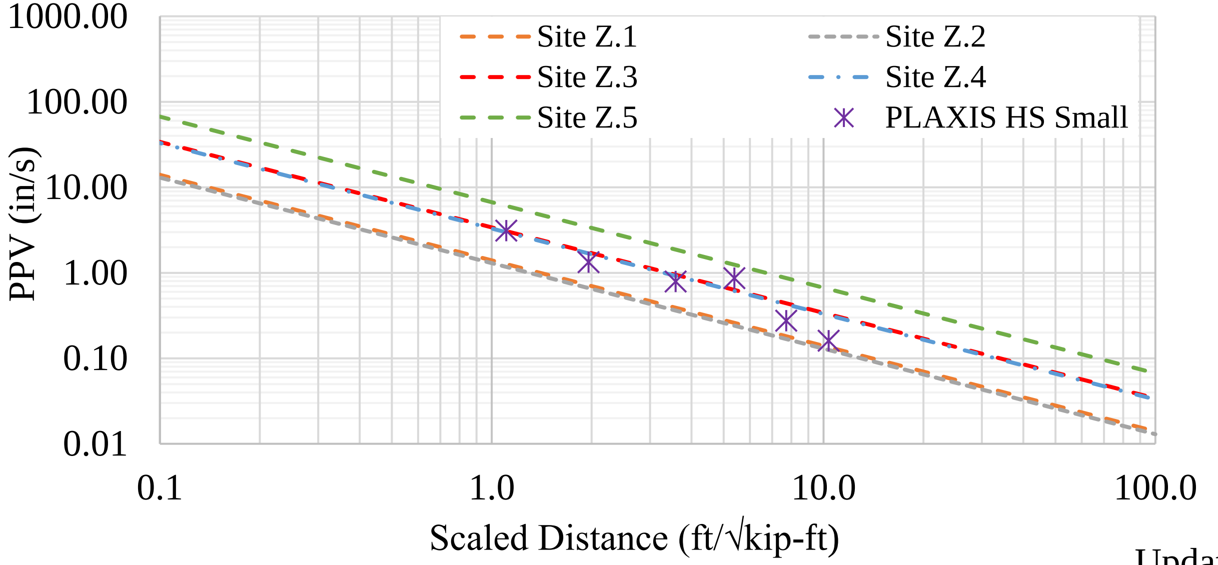
Comparison “continuous” vs. “discontinuous” pile driving modeling



Comparison of different soil parameters and dimensions for the plastic zone.



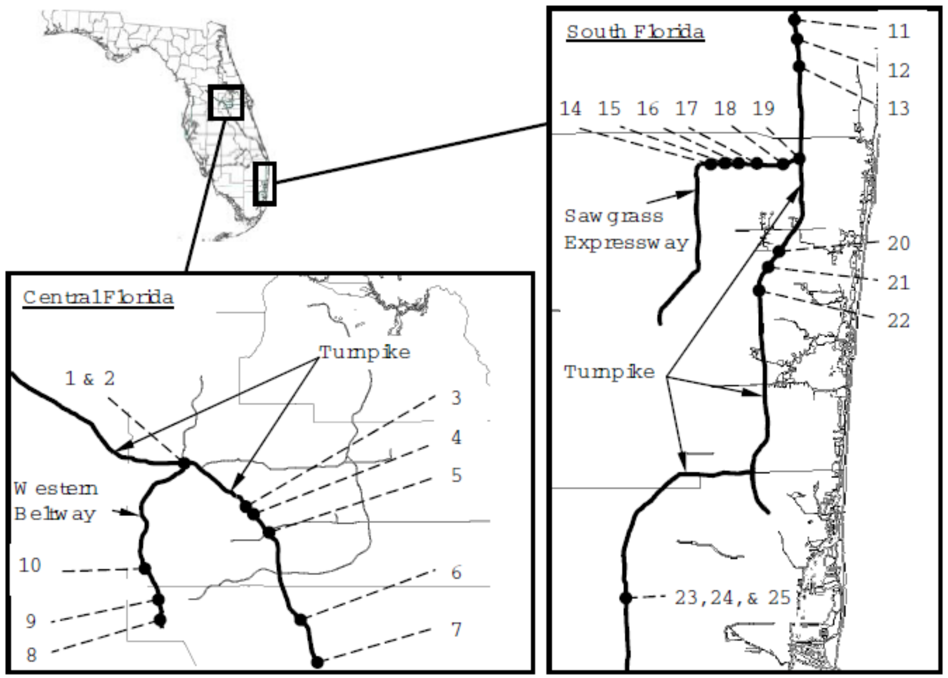
Comparison of discontinuous and continuous modeling approaches with values from GRLWEAP on top of the pile.



Computed with continuous model (<u>updated Lagrangian large deformation formulation</u>) vs. measured values in nearby projects (Bayraktar et al., 2013)

Updated mesh: (Bathe, 1982; Van Langen and Vermeer, 1991)

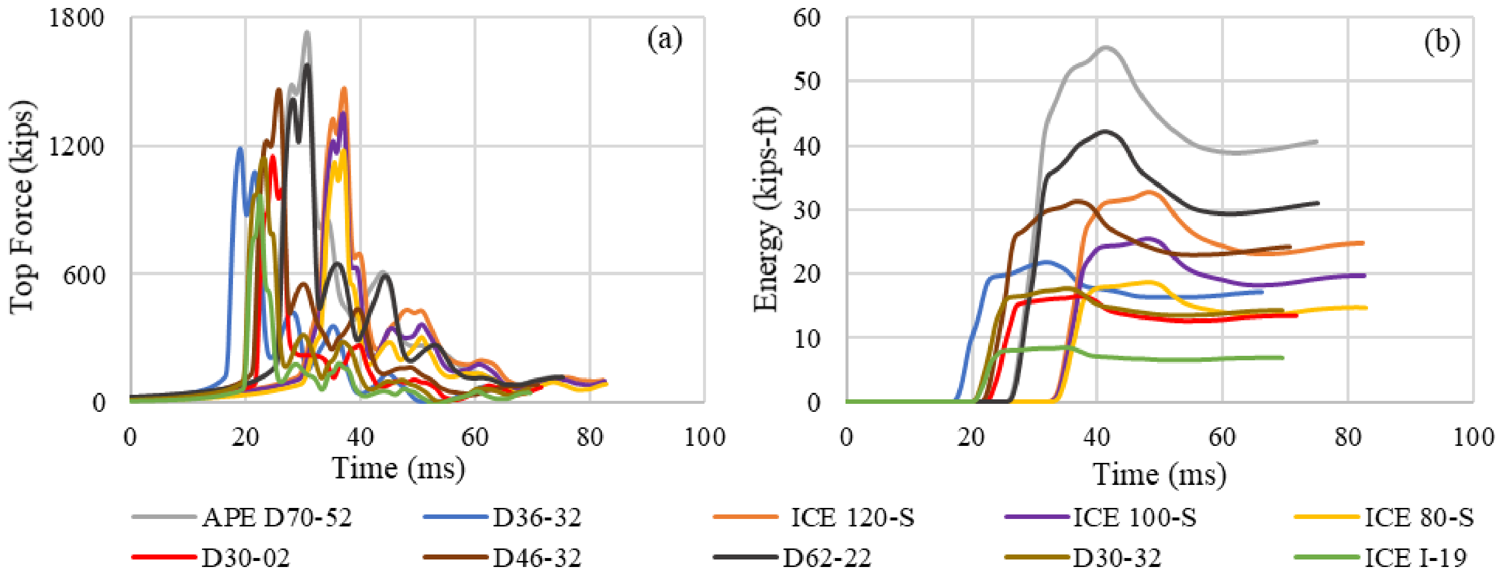
Common hammers in Florida



Hammer Type	Number of Projects	Rated Energy (kips-ft)	Maximum Transfer Energy (kips-ft)	Energy Efficiency (%)
APE D70-52	Site D	173.6	55.2	31.8
D36-32	9	90.6	21.8	24.1
ICE 120-S	4	120.0	32.8	27.3
ICE100-S	3	100.0	20.4	20.4
ICE80-S	3	80.0	15.0	18.8
D30-02	3	66.2	14.5	21.9
D46-32	2	122.2	34.5	28.2
D62-22	1	164.6	47.4	28.8
D30-32	1	75.4	20.4	27.0
ICE I-19	1	43.2	8.6	19.9

- **Heung et al. (2007)** presented a total of 25 pile driving projects along Florida's Turnpike

- Mostly large displacement prestressed concrete piles (PCP) were used

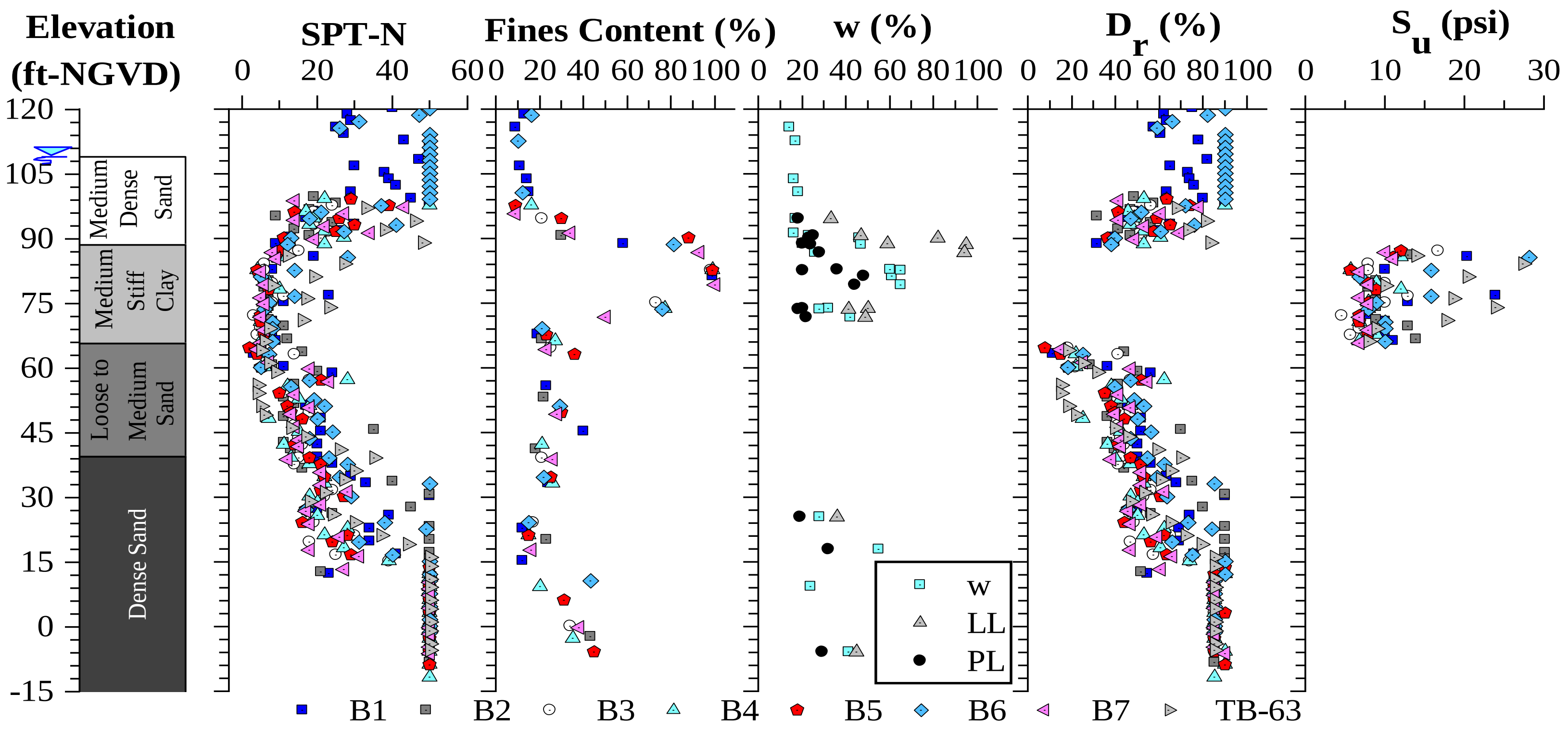


Analysis of variables involved on pile driving induced deformations

Variables involved in this analysis:

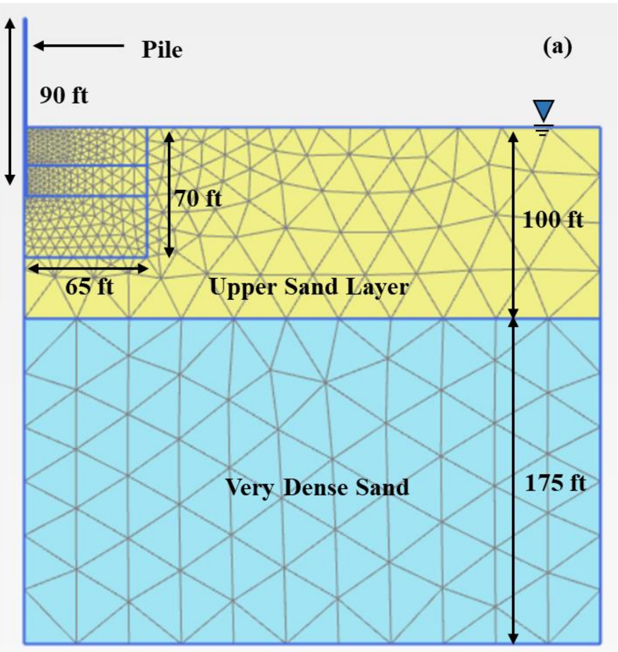
- Relative density of the sandy soils → Dynamic behavior of the soil
- Peak particle velocity → Vibration effects
- Distance from the pile → Attenuation characteristics
- Type of hammer and energy transmitted to the pile → Input energy

Recall: soil conditions mainly loose to medium-dense sand and silty sands

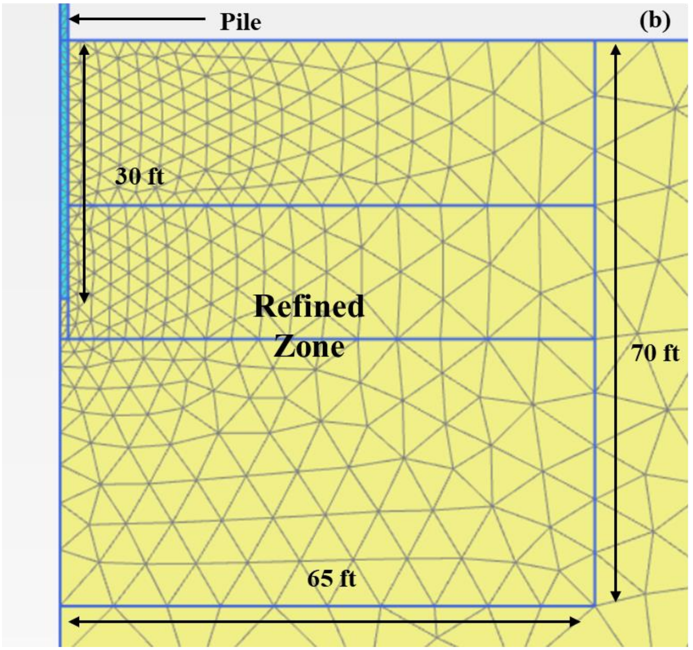


Analysis of variables involved on pile driving induced deformations

Numerical model mesh



Close up view



Upper sand layer:

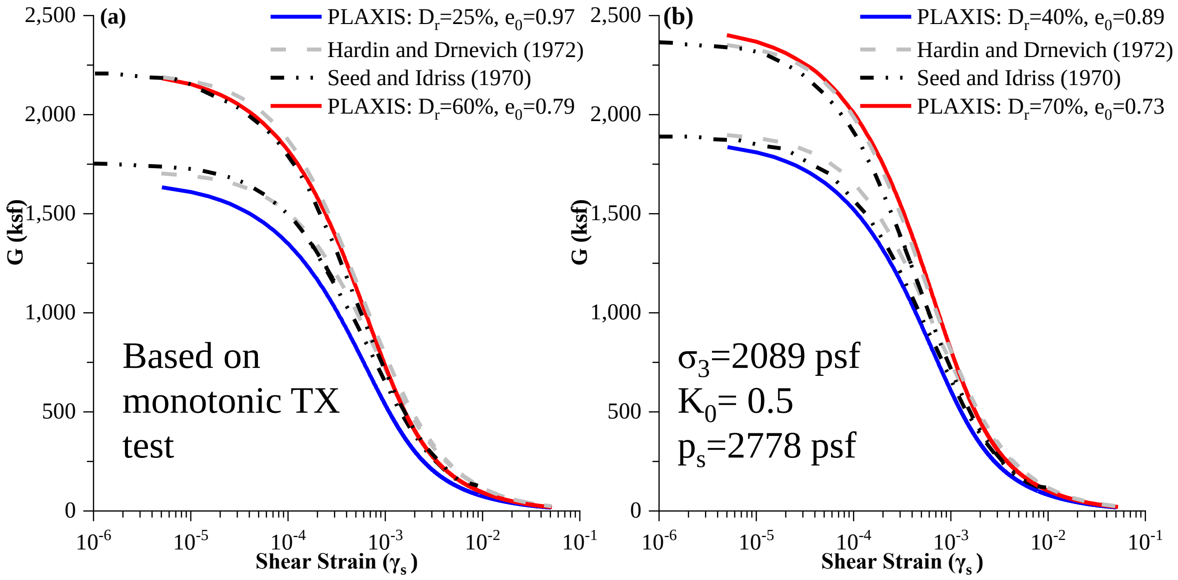
- D_r: 25%, 40%, 55%, 60%, 70%, and 75%
- Hypoplasticity model for sands enhanced with intergranular strain concept

Lower sand layer:

- D_r: 90%
- HS small model

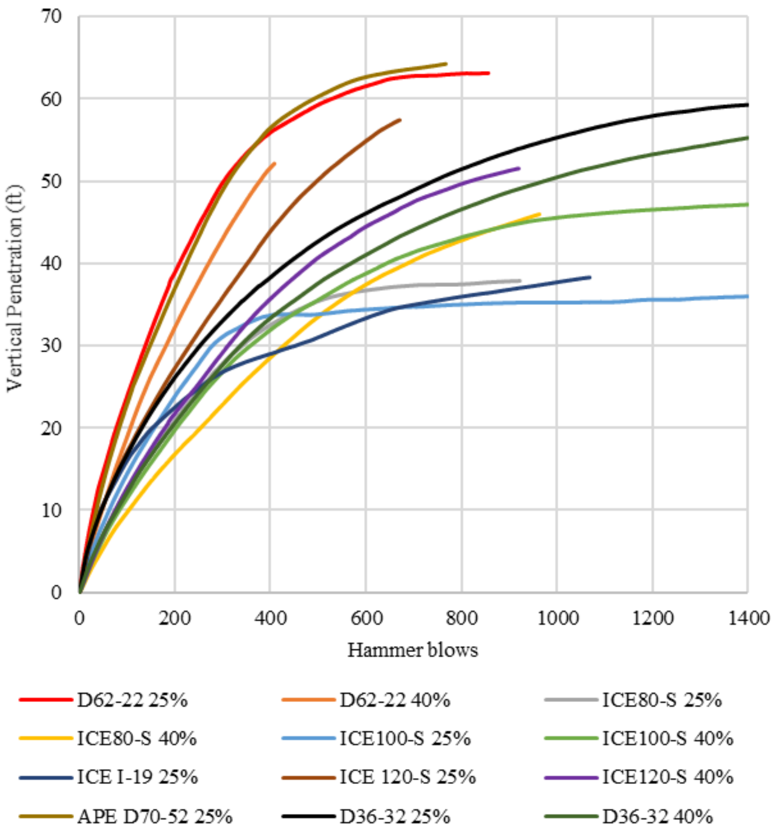
e_{d0}=1.10 Maximum void ratio
e_{c0}=0.58 Minimum void ratio

From Zapata-Medina et al. (2019) and Lade et al. (1998)
Poorly Graded Sands tested in Dorchester, South Carolina and Nevada

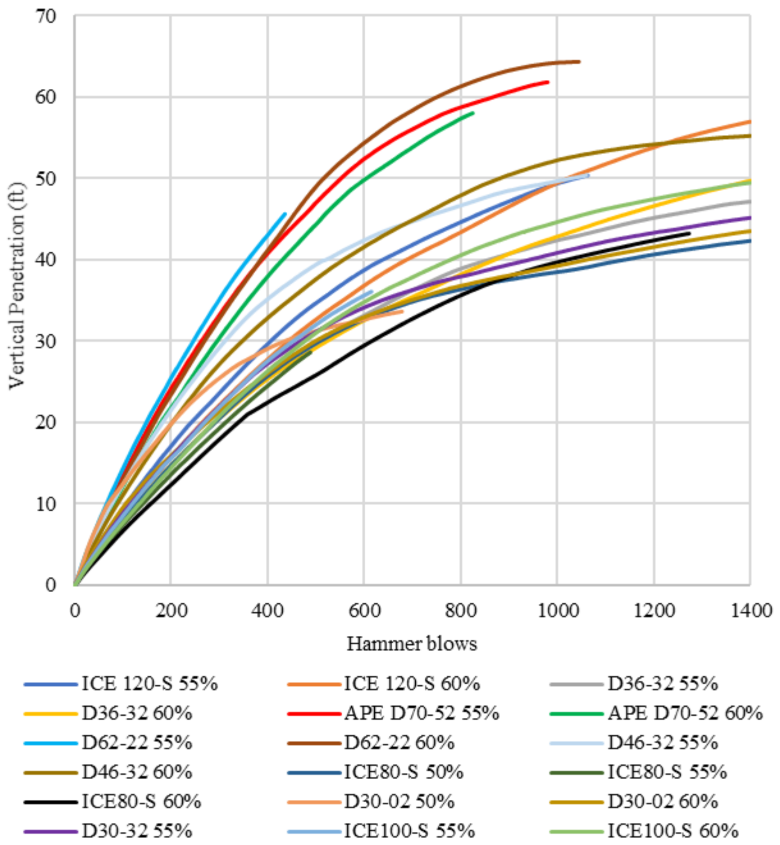


No.	Parameter	Description	Value	Unit
1	ϕ_c	Critical state friction angle	31	°
2	pt	Shift of the mean stress due to cohesion	0	psf
3	h_s	Granular hardness	25062	ksf
4	n	Exponent for pressure sensitive of a grain skeleton	0.37	-
5	e_{d0}	Minimum void ratio at zero pressure (ps = 0)	0.58	-
6	e_{c0}	Critical void ratio at zero pressure (ps = 0)	1.096	-
7	e_{i0}	Maximum void ratio at zero pressure (ps = 0)	1.315	-
8	α	Exponent for transition between peak and critical stresses	0.05	-
9	β	Exponent for stiffness dependency on pressure and density	1.4	-
10	m_R	Stiffness increase for 180° strain reversal	5	-
11	m_T	Stiffness increase for 90° strain reversal	2	-
12	R_{max}	Size of elastic range	5.00×10^{-5}	-
13	β_r	Material constant representing stiffness degradation	0.1	-
14	χ	Material constant for evolution of intergranular strains	1.0	-

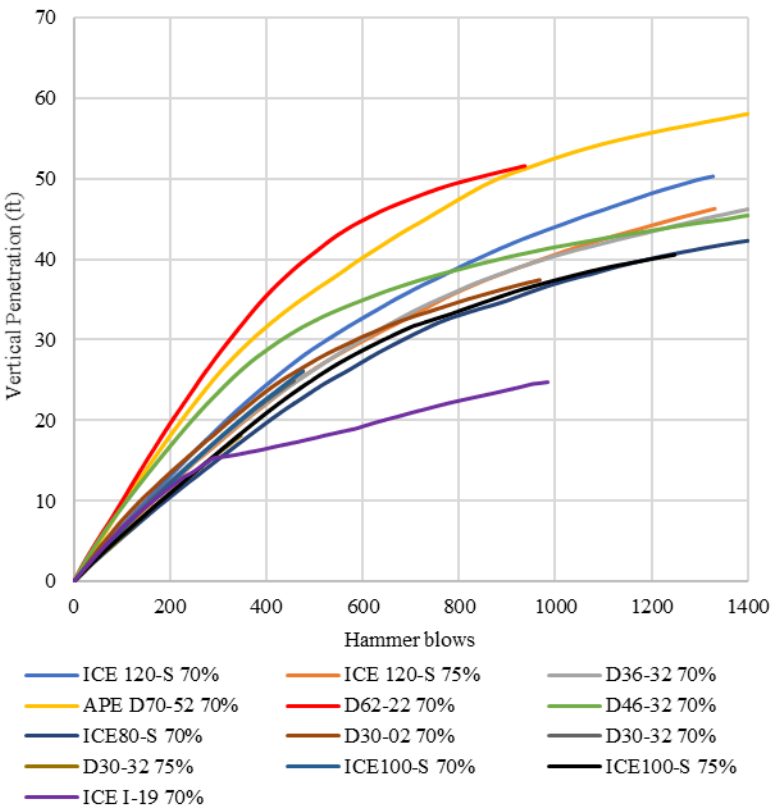
Comparison of vertical penetration for different hammer types



Loose sands
(D_r: 25% and 40%)



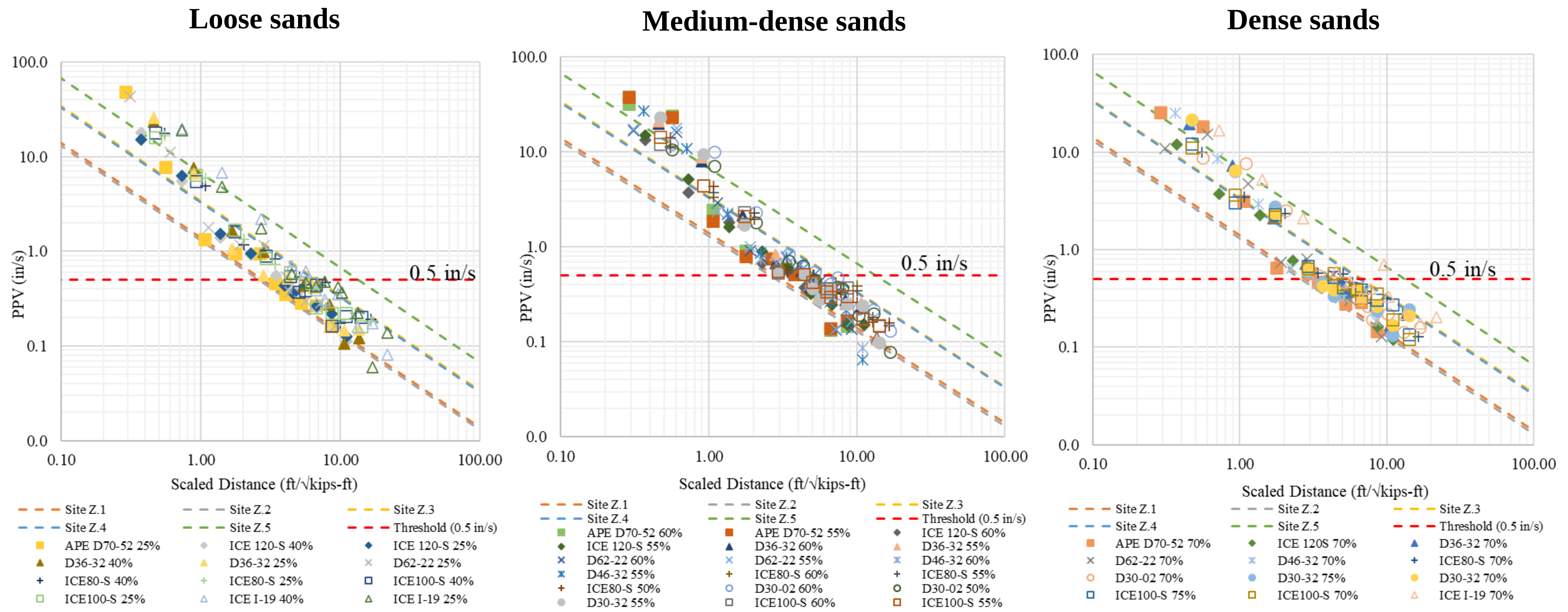
Medium-dense sands
(D_r: 50%, 55%, and 60%)



Dense sands
(D_r: 70% and 75%)

- Less driving effort required to drive piles when hammers with highest input energies were used
- Driving effort vary depending on relative density

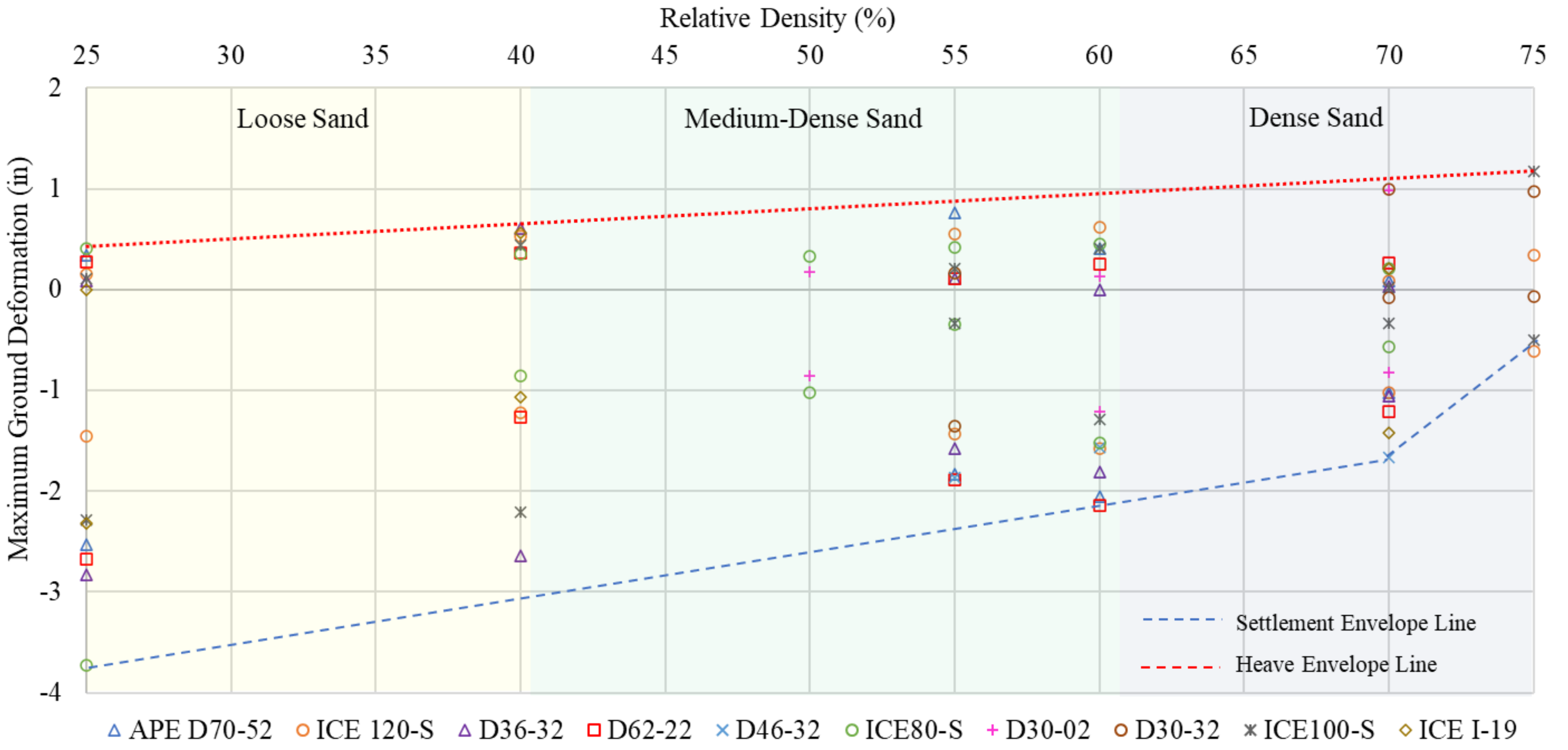
Ground vibrations – PPV



PPV versus scaled distance computed for piles installed in sands in relation to those reported boundaries by Bayraktar et al. (2013)

- Maximum transfer energy was used for calculation of scaled distance
- PPV values go below 0.5 in/s beyond a scaled distance of approximately 3 $ft/\sqrt{kips - ft}$
- Computations matched very well the reported PPV limits by Bayraktar et al. (2013)

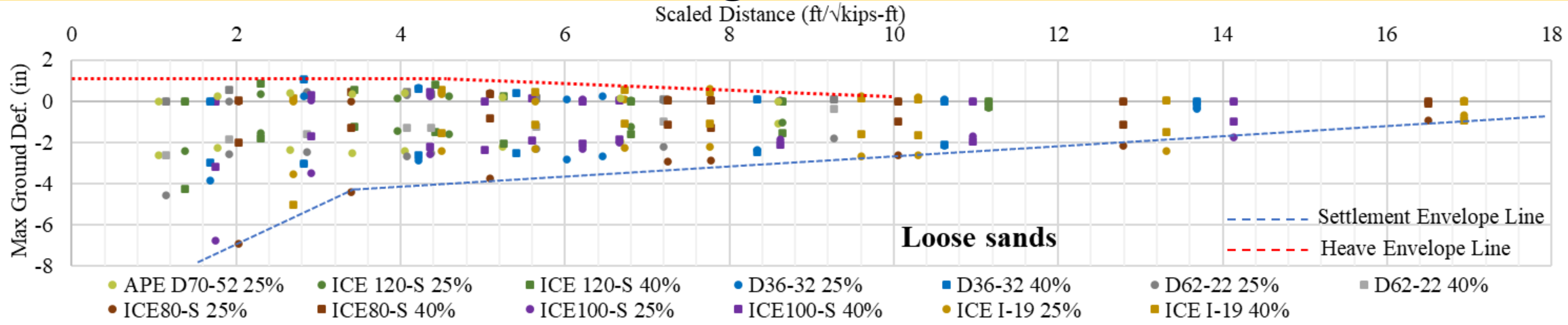
Computed Ground Deformation

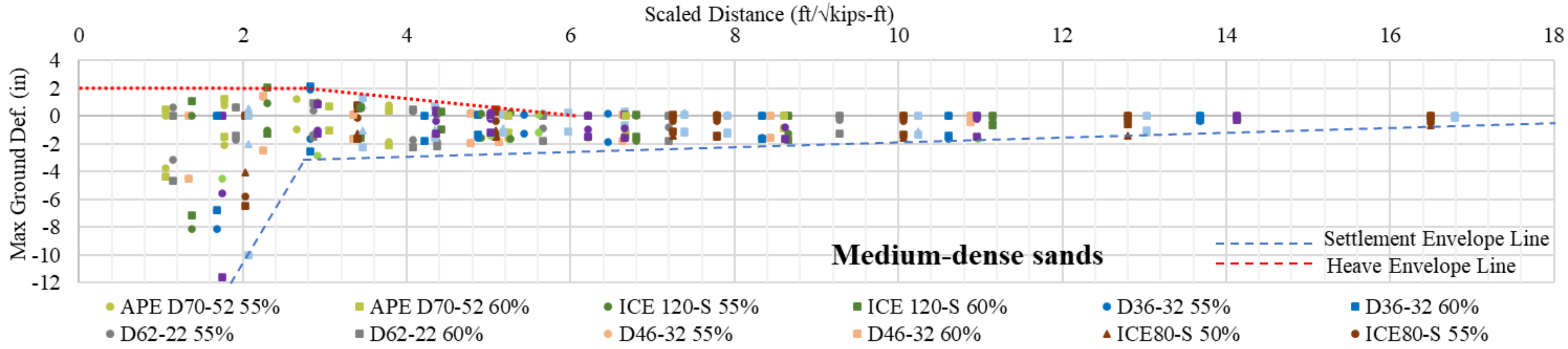


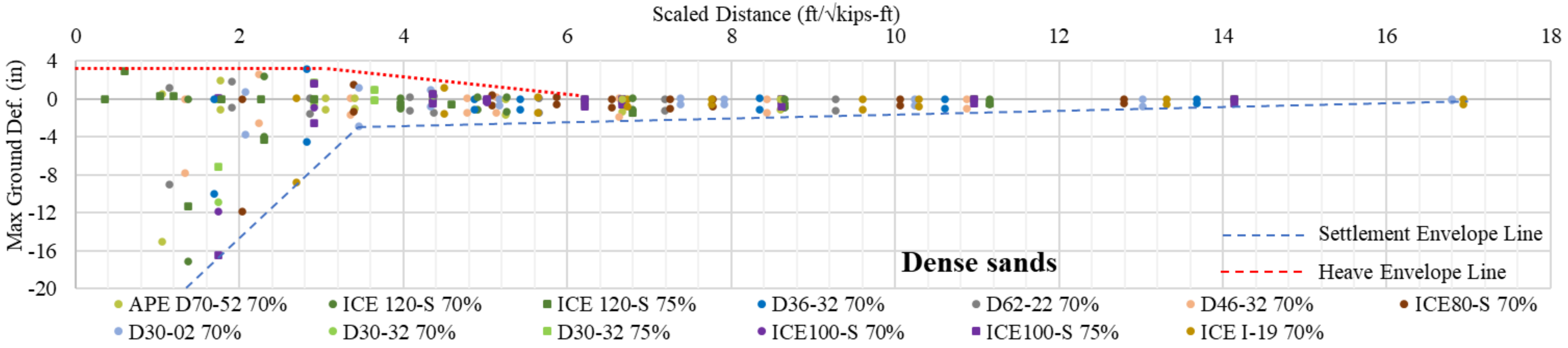
Maximum computed ground deformations (i.e., settlement and heave) even after the condition of max. PPV of 0.5 in/s was satisfied. Plot shows various relative densities and multiple input energies.

- 44 simulations and 358 data points. PPV of 0.5 in/s was met at different distances from the pile, input energies, and relative densities.
- Max. settlement and heave values were defined at the distance of PPV equal to (or less than) 0.5 in/s versus relative densities. Data obtained from the computed deformation time histories with the different input energies typically used for pile driving operations in FL.
- Larger settlement was computed loose sands while larger heave occurred on dense sands (as expected: contractive vs. dilative responses!)

Maximum ground deformations vs. scaled distance

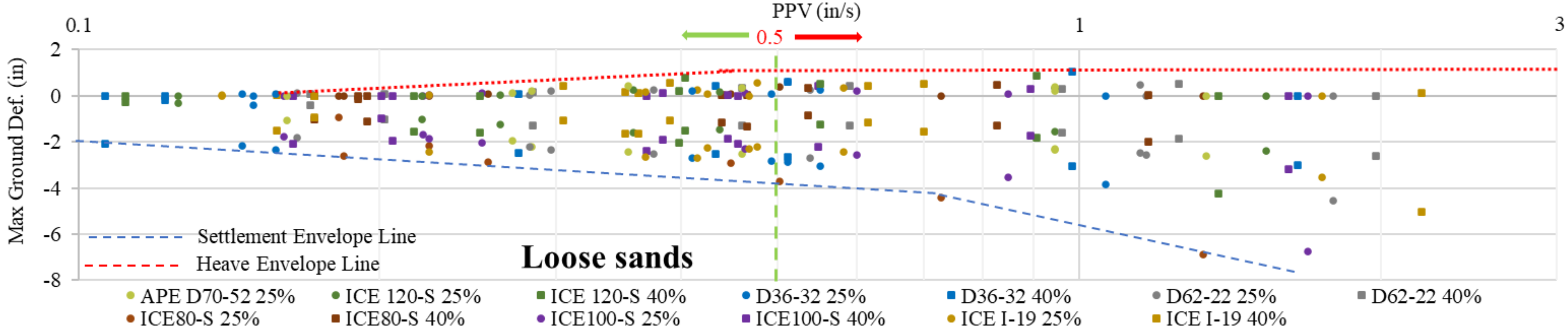


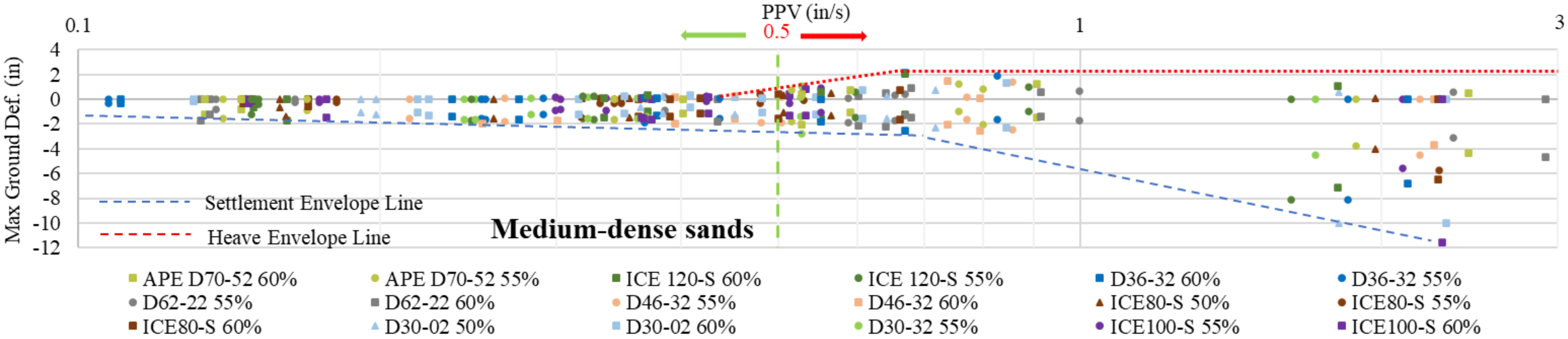


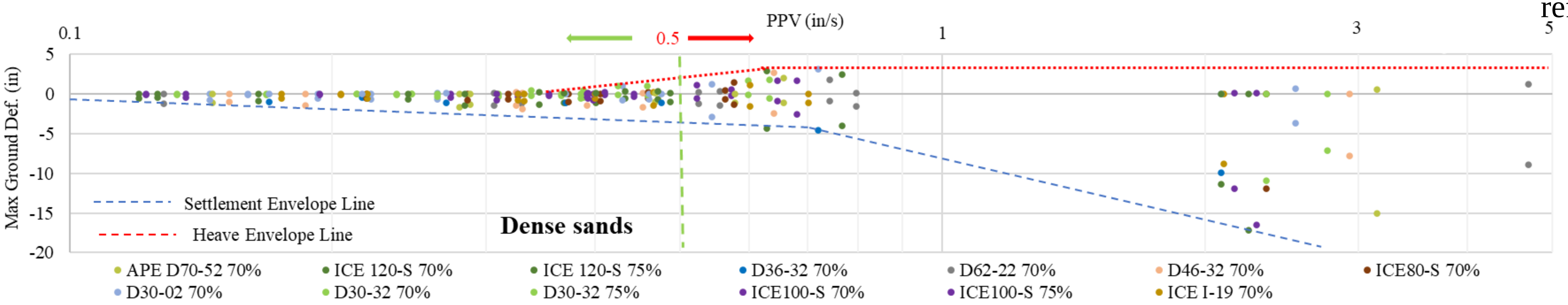


- All data points do not necessarily satisfy the 0.5 in/s
- 2 data points (heave and settlement) are presented for each input energy
- Influence zone for loose sands is larger than dense sands.
- Heave envelope extends to a further distance at loose sands than medium-dense to dense sands but magnitude of heave is larger for dense materials

Maximum computed ground deformations vs. PPV

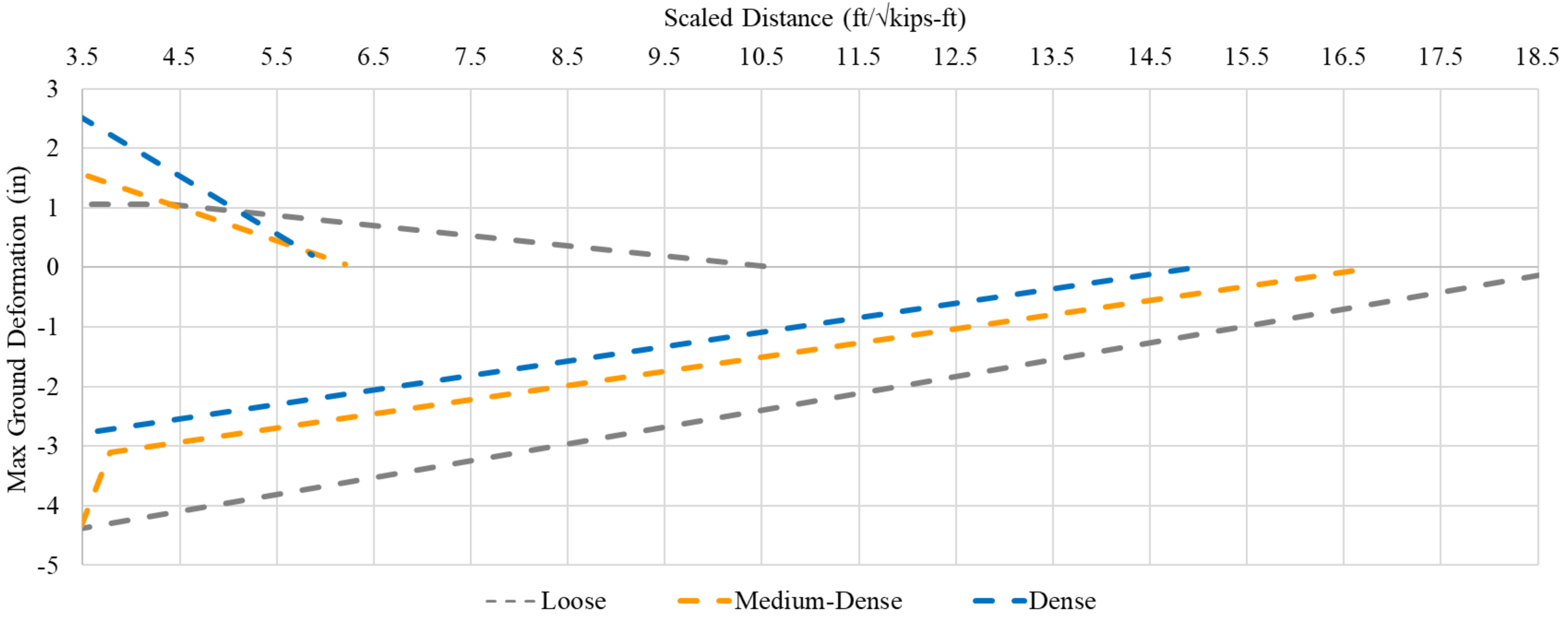






- Maximum settlement, maximum heave, and PPV values occurred at different times
- Distortions (i.e., differential settlements / spacing between supports) should be verified in the field even if PPV values are below 0.5 in/s
- Green arrow means computed maximum deformations occurred below FDOT PPV reference value (0.5 in/s)

Maximum ground deformations vs. scaled distance envelopes



Summary of maximum ground deformation envelopes (settlement and heave) versus scaled distance for loose, medium-dense, and dense relative density groups.

- Computed deformations presented beyond a scaled distance of 3.5 $ft/\sqrt{kips-ft}$
- Maximum settlements are higher in the loose sands than in the dense sands
- Maximum heaves are higher in the dense sands than in the loose sands due to soil dilation
- The magnitude of maximum ground surface deformations decreases with the scaled distance

Conclusions and challenges

1. Numerical analyses computed large ground deformations in cases where PPVs exceeded 0.5 in/s (FDOT threshold).

2. Large ground deformations are expected for loose and medium sandy soils as a result of “impact pile driving”… and for “vibratory pile driving” …?

3. Heave was computed mostly in dense soils, which indicates dilation (i.e., volumetric expansion) triggered by pile driving operations.

4. Field measurements and numerical analyses proved that there is a densification process due to pile driving induced vibrations. Pile group effects…” unknown.

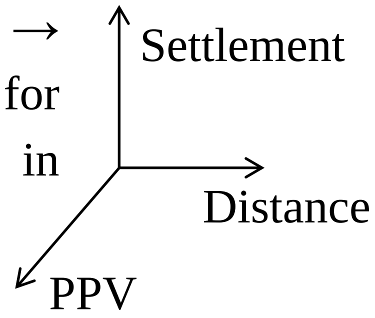
5. Ground deformations are affected by the transmitted energy to the pile rather than the rated energy of the hammer. This will include the effects of driving accessories such as the hammer and pile cushions.

6. Some numerical issues were found: stiffness errors, model divergence, computational time, and characteristics of forcing function and stroke height changes with depth.

7. More numerical analyses including hammers presented in the field data into the analyses to refine the obtained results (In progress).

8. Collect additional field data regarding ground deformations and vibrations to further validate the numerical models (In progress).

9. Finalize relationships among PPV → distance from source → settlement for different input energies and soil types in Florida. (In progress).



Tasks timeline and future plans

Task 1 – Technical review

Task 2 – Survey

Task 3 – Field testing

Task 4 – Numerical modeling

Task 5 – Prediction method

Task 6 – Recommendations

Future Plans

Deliverable # / Description of Deliverable as provided in the scope (included associated task #)	Anticipated Date of Deliverable Submittal (month/year)	Comments
Project kickoff teleconference	03/2019	Completed
Deliverable 1: A technical report presenting the results of the technical background on pile-driving induced settlement and past case studies.	05/2019	Completed
Deliverable 2: A survey instrument and technical report with the analysis of the survey data.	09/2020	Completed
Deliverable 3: A technical report summarizing the results of the first field test, including: (i) details of pile installation, (ii) soil properties at the selected site, (iii) data of excess pore water pressure and ground vibration (PPV) during pile driving, and (iv) measured settlement data during pile installation.	03/2021	Completed
Deliverable 3b: A technical report summarizing the results of the second field test.	06/2021	Completed
Deliverable 4: A technical report summarizing the results of the numerical models and parametric studies developed in this research.	09/2021	Working on it!
Deliverable 5: A technical report summarizing the correlations between settlement, PPV, and distance from source, including a prediction equation or chart for pile-driving induced settlement as a function of PPV, distance, and energy source.	11/2021	
Deliverable 6a: Draft Final Report	12/2021	
Deliverable 6b: Closeout teleconference meeting and PowerPoint presentation	1/2022	
Deliverable 7: Final Report	2/2022	

Acknowledgments

FDOT

Jacobs

RS&H

SUPERIOR CONSTRUCTION

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