Progress Report, GRIP MEETING 2019

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

PRESENTED BY

Luis G. Arboleda-Monsalve (PI) and
Boo Hyun Nam (co-PI)

Dept. of Civil, Environmental, and Construction Engineering, Univ. of Central Florida,
Orlando, FL.

UCF

UNIVERSITY OF
CENTRAL FLORIDA

Outline

- Project Overview
- Technical Background

  - Geotechnical aspects of pile driving induced settlement and case histories

  - Numerical modeling strategies for pile driving induced settlement

- Summary and Future Work

Expected project benefits and implementation

Qualitative:

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

Quantitative:

- Produce a pile driving induced settlement chart (or correlation or equation) relating PPV, Dr, distance from source, and input energy to be used across any Florida DOT project involving pile driving.

Project objectives

- To understand mechanisms of near-field and far-field settlement and determine critical distance (influence zone).
- To measure field vibration-induced settlements in predetermined locations in the state of Florida.
- To develop numerical models of settlement prediction that can simulate various site conditions in Florida.
- To develop Florida-specific pile driving induced settlement prediction model(s) (e.g., closed formulas or charts).

Scope of work

Task 1 – Review settlement case studies throughout state and nation

Task 2 – Field testing in pile installation sites

Task 3 – Develop numerical modeling of pile driving induced settlement

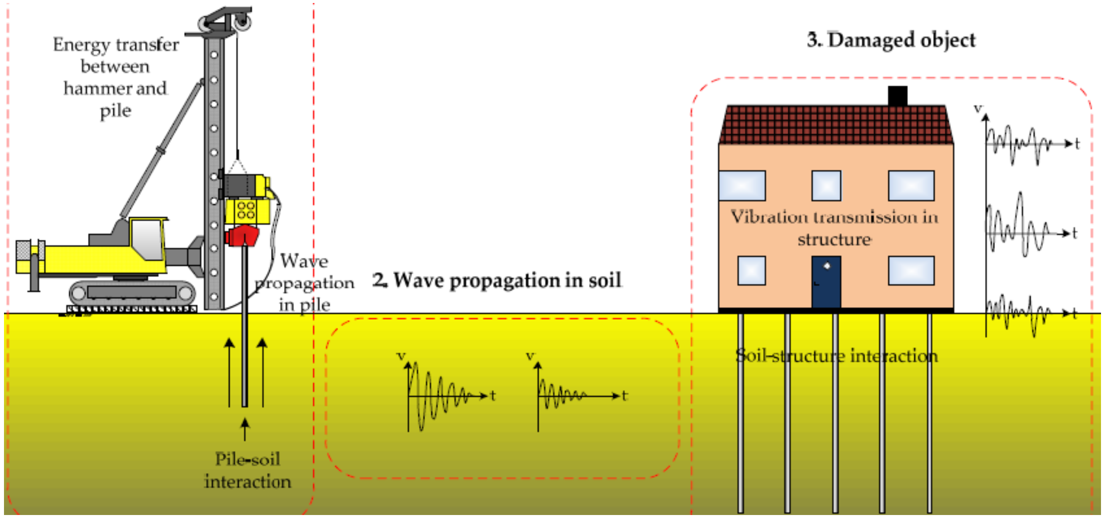
Task 4 – Develop empirical prediction formula or chart for dynamic settlement

Task 5 – Guidelines and recommendations

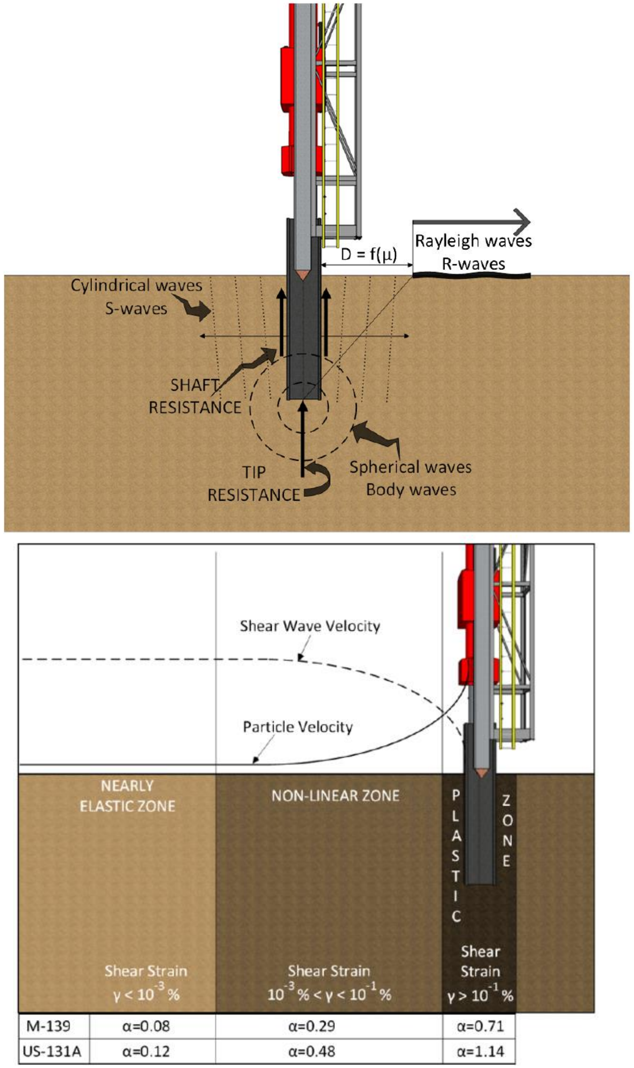
Technical Background: main variables involved in the problem

A total of 14 case histories were revised. Main 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 vibration in urban environments (Hintze et al. 1997 and Deckner 2013)



M-139	α=0.08	α=0.29	α=0.71
US-131A	α=0.12	α=0.48	α=1.14

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

Technical Background: main variables involved in the problem

Pile driving effects:

i) Vibration-induced particle rearrangement: **settlement!**

ii) Excess pore water pressure build-up, that when dissipated: **settlement!**

iii) Soil re-sedimentation after localized liquefaction around pile: **settlement!**
(Pile driving may cause settlement due to densification and liquefaction of vulnerable soils)

iv) Damage nearby infrastructure as a product of **settlement!**

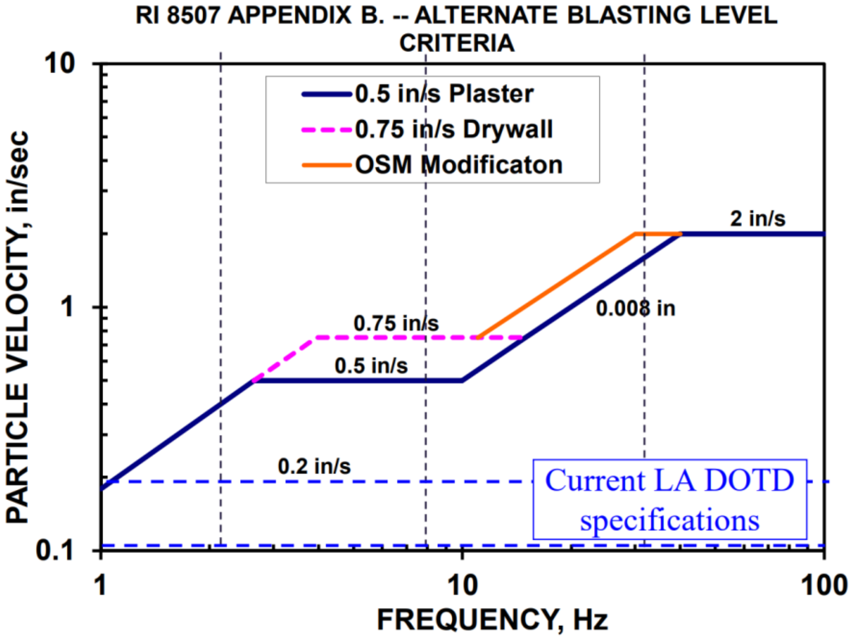
- Dynamic settlements are caused by ground vibrations. Important for contractive loose sands that densify when piles are driven.

- Current methods are limited to capture key attributes of pile driving induced settlements.

- Vibrations by pile driving can generate PPV up to *4 in/s.* Even PPV of only *0.1 in/s*, settlements in sandy soils can still occur.

Technical Background: vibration limits

- USBM Criteria: (frequency-based limits for cosmetic cracking)

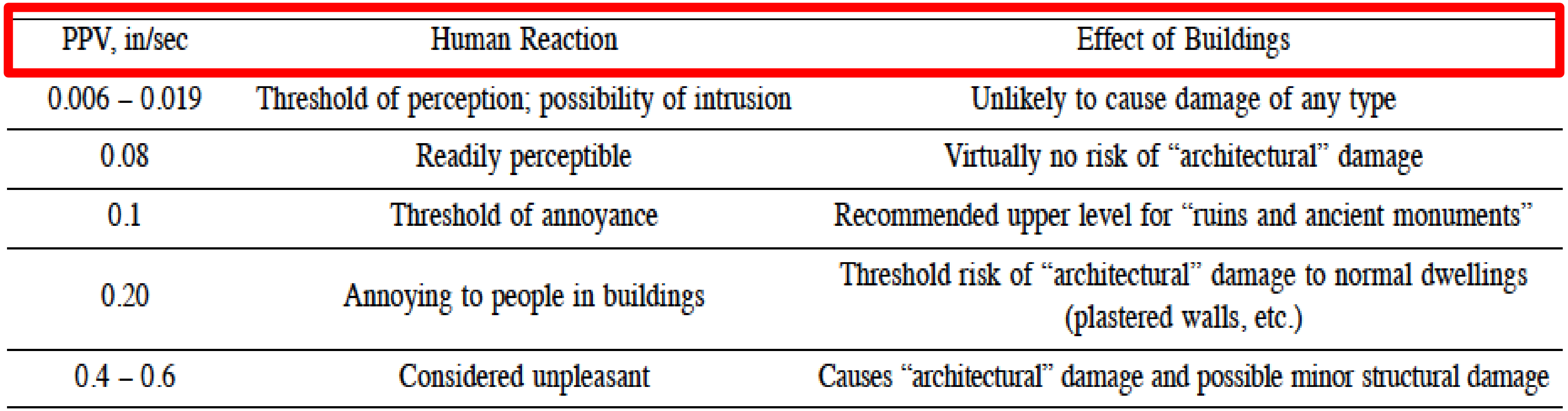


Safe level blasting criteria (USBM RI 8507)
Connecticut, Nevada, Wisconsin: *0.5 in/s*
LADOTD:
Historic and sensitive structures *0.1 in/s*
Residential structures *0.5 in/s*
Industrial structures *2 in/s*
Bridges *2 in/s*
[Similar to Woods (1996): Max. PPV independent of frequency]

- PPV limit in Florida: *0.5 in/s*. Dowding (1996) and Lacy & Gould (1985): *0.08 in/s* is the limit beyond which dynamic settlement may occur.

- Critical vibration limits are not strictly correlated to vibration settlement. Bayraktar and Kang (2013) reported a case of *0.2 in/s* that caused settlement and cracks of a brick chimney, destroyed house driveway, and architectural damage of a 2nd floor due to 26 Hz vibrations.

Technical Background: vibration limits

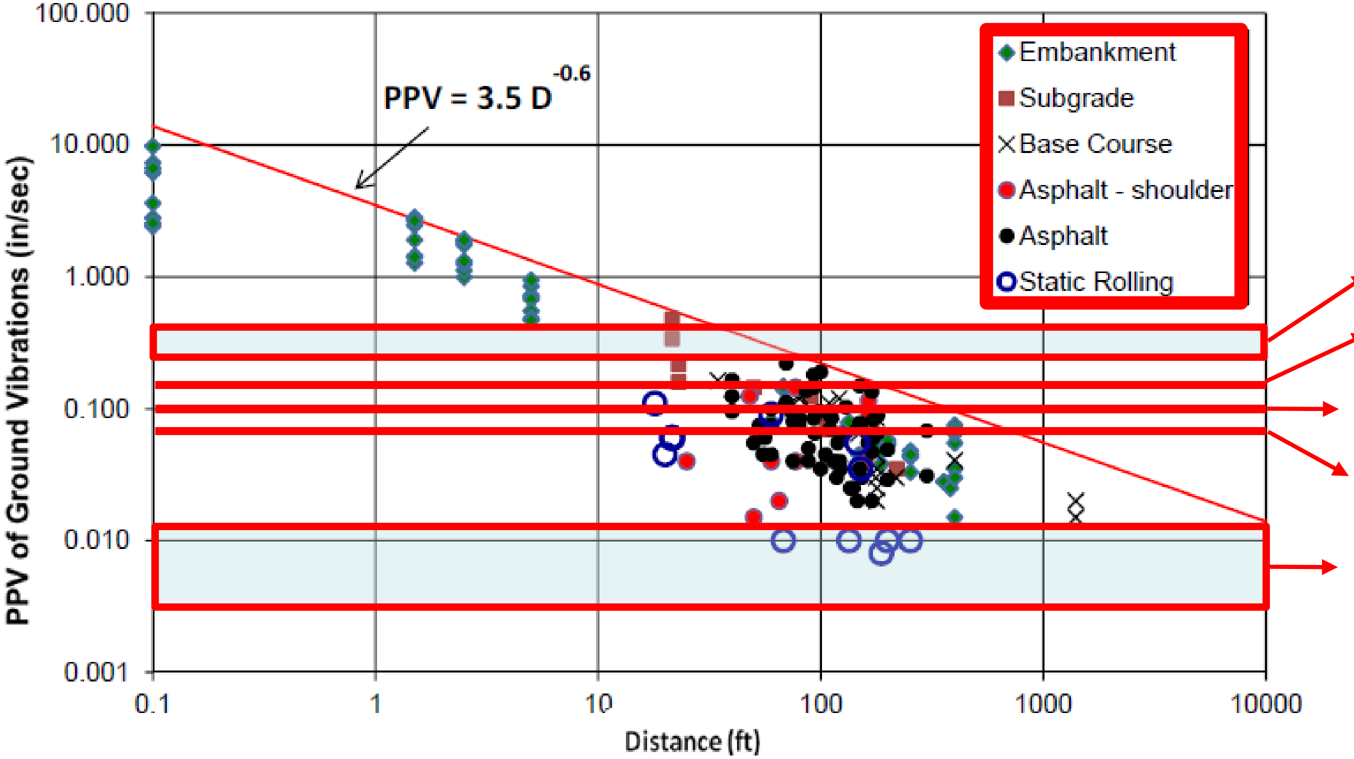


PPV, in/sec	Human Reaction	Effect of Buildings
0.006 – 0.019	Threshold of perception; possibility of intrusion	Unlikely to cause damage of any type
0.08	Readily perceptible	Virtually no risk of “architectural” damage
0.1	Threshold of annoyance	Recommended upper level for “ruins and ancient monuments”
0.20	Annoying to people in buildings	Threshold risk of “architectural” damage to normal dwellings (plastered walls, etc.)
0.4 – 0.6	Considered unpleasant	Causes “architectural” damage and possible minor structural damage

Human reaction and associated damage to buildings from ground vibrations (Whiffen and Leonard 1971)

Best sensor to detect pile driving-induced vibrations… human being!

Technical Background: vibration limits



Considered unpleasant

Annoying in buildings

Threshold of annoyance

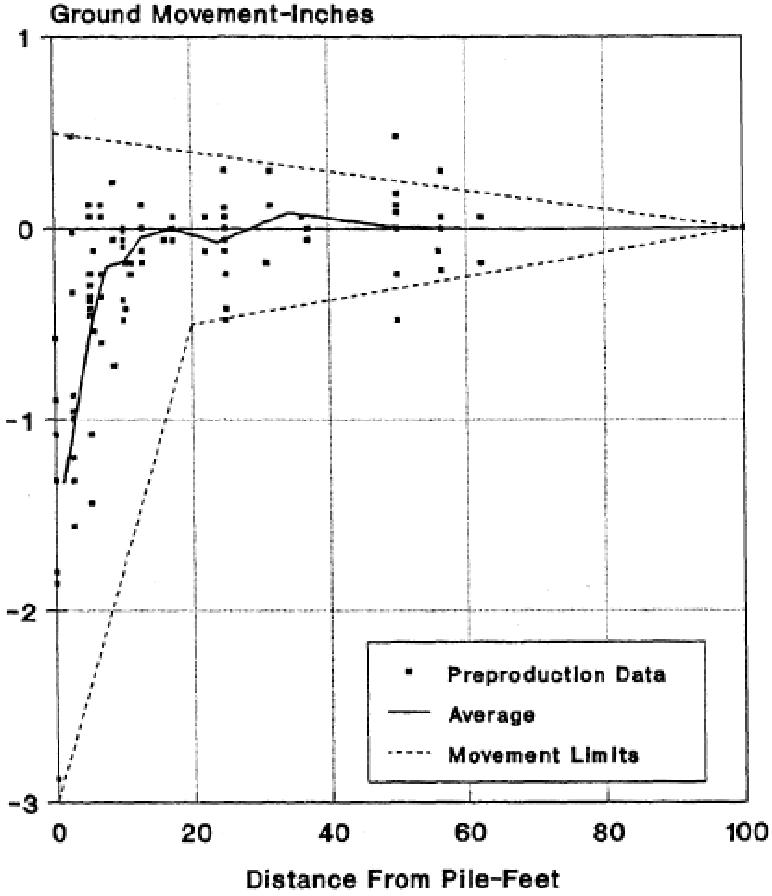
Readily perceptible

Threshold of perception

Bayraktar and Kang (2013), FDOT Project: PPV ground vibrations as a function of horizontal distance and compaction materials (Turnpike projects, 40 different monitoring reports)

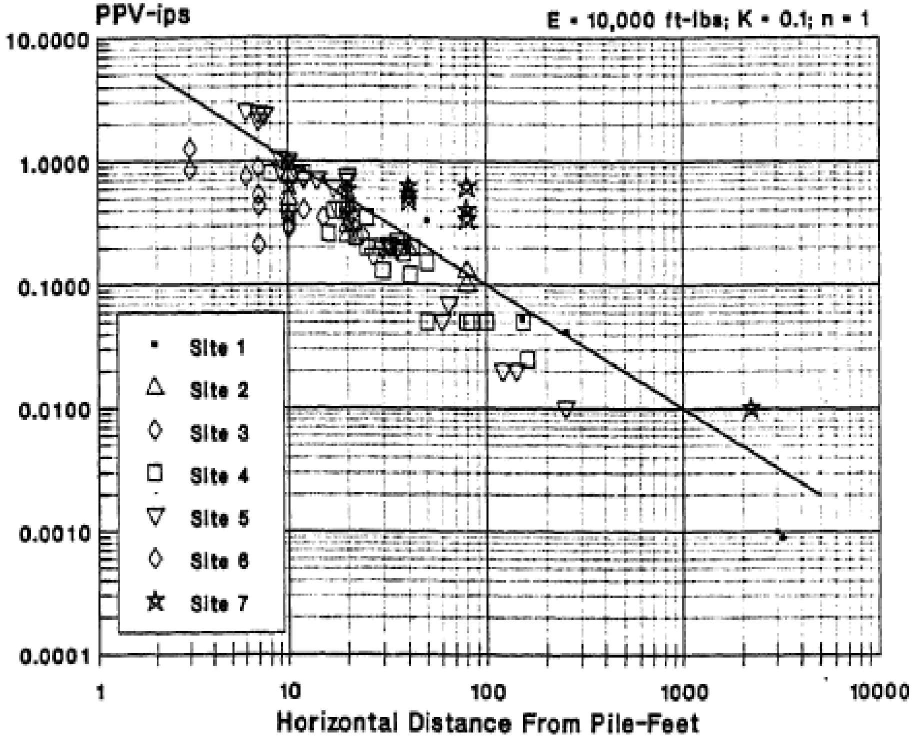
Technical Background: typical variables studied

- Peak particle velocity
- Attenuation parameters
- Pile driving-induced settlements



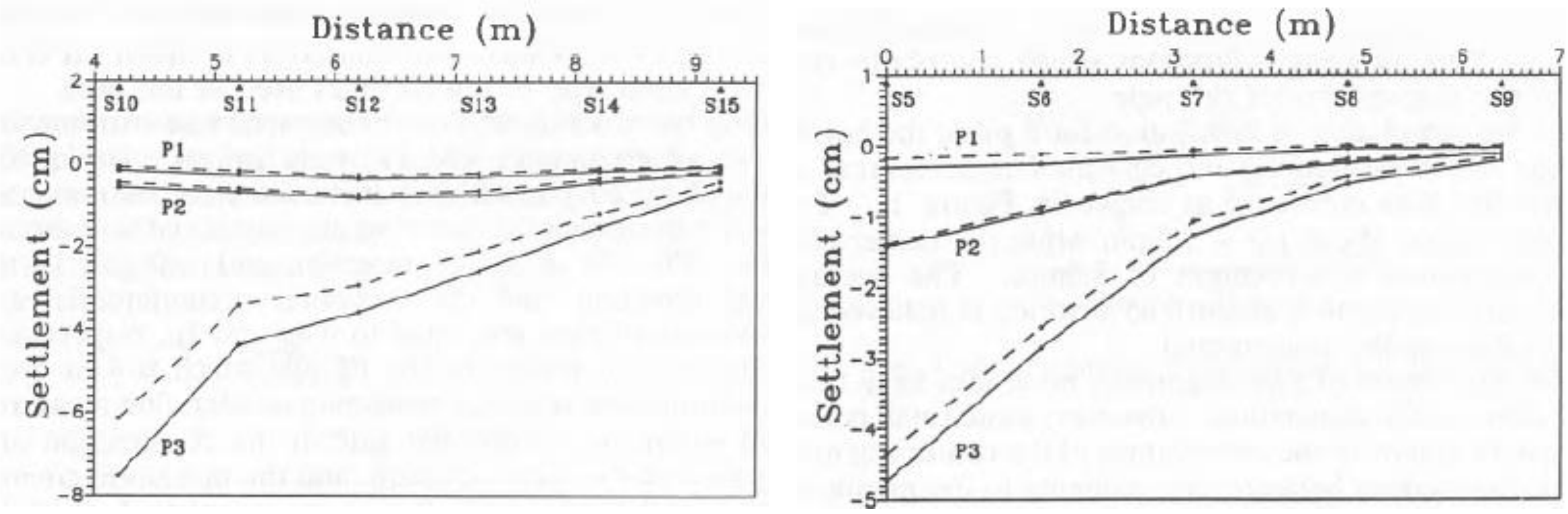
Ground displacement versus distance from the pile (Lewis & Davie, 1993)

- Pile type
  - Single, group, sheet piles
  - Pile material (concrete or steel)
- Pile length
- Hammer characteristics
- Soil conditions



Peak particle velocity vs distance (Lewis & Davie, 1993)

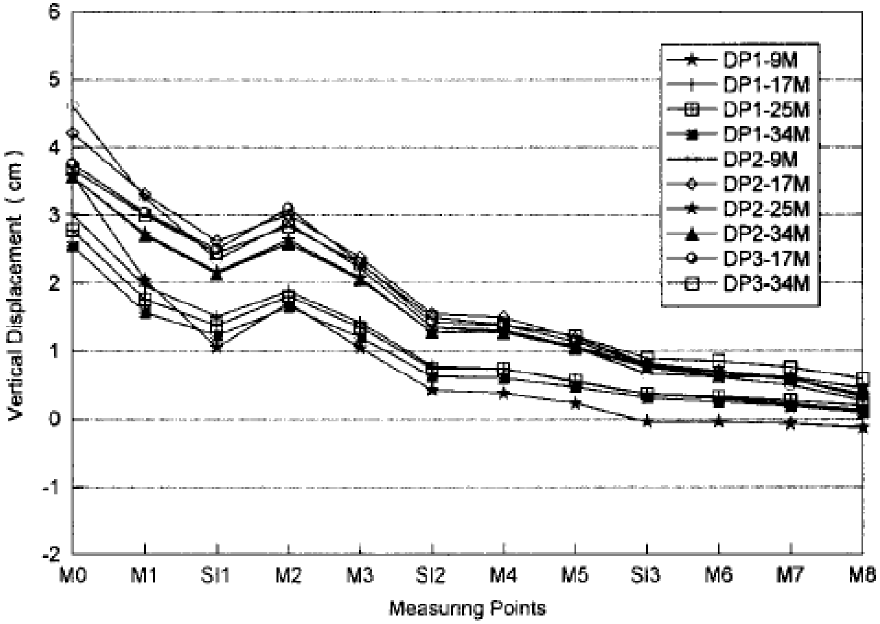
Technical Background: measured settlement



a)

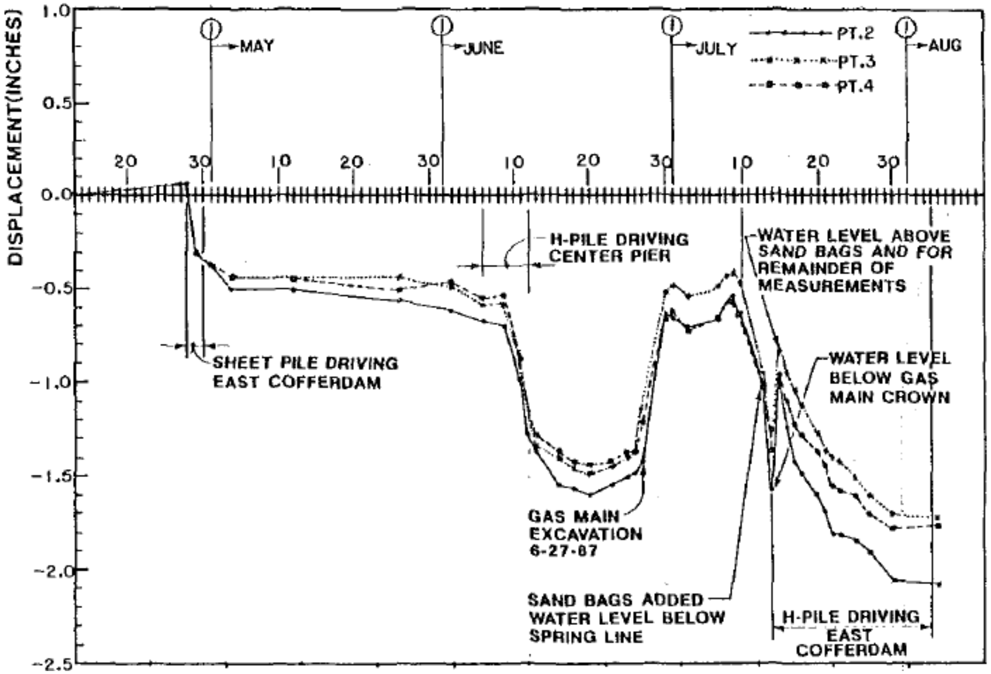
b)

Ground settlements due to P1, P2 and P3 driving along (a) X-axis and (b) Y-axis (Chen, et al., 1997)

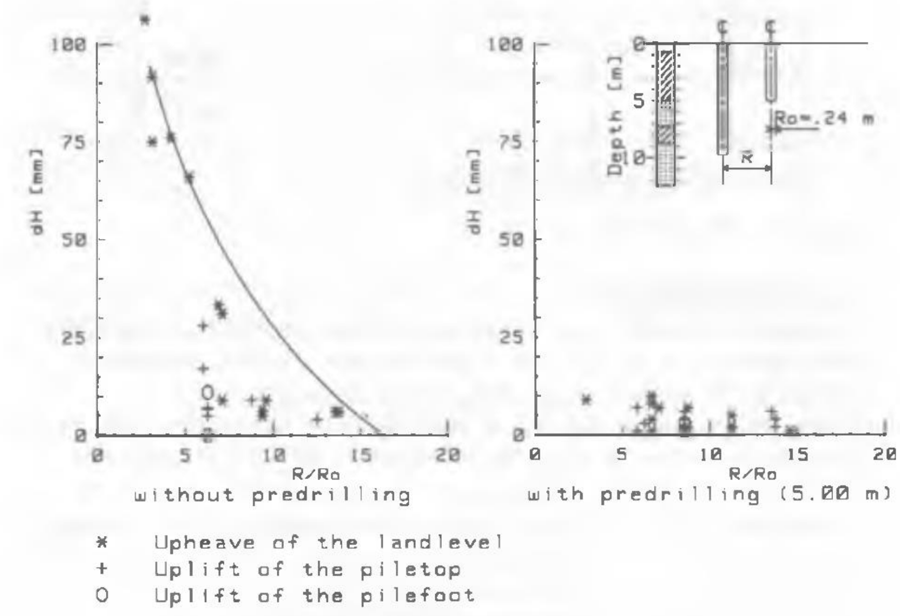


Vertical displacements of settlement points after driving of DP1, DP2 and DP3 piles (Hwang, et al., 2001)

Technical Background: measured settlement



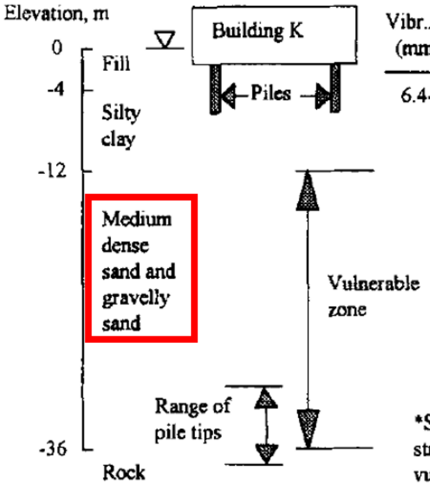
Vertical displacements during construction (Linehan, et al., 1992)



Effects of predrilling on settlements.

Heave of the ground surface and uplift of head and toe of a test pile during driving (Oostveen & Kuppers, 1985)

Case Histories: measured settlement



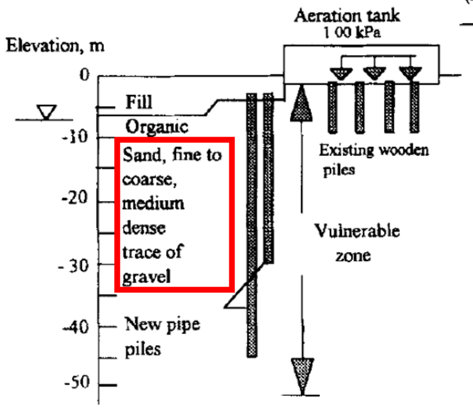
Vibr.Ampl. (mm/sec)	Meas.Sett. (mm)	Calc.Settl (mm)	*Calc.Settl.** (mm)
6.4-15.0	18-54	23-78	28-85

Factor	Natural Value	Coded Value
1	6.4..15.0	-0.5..0.64
2	65 kPa	0.14
3	130 kPa	-0.12
4	Coarse	-1
5	500000 cycles	0.85
6	Moist	2
7	Dense	2

*Settlement was calculated for in-situ stress conditions in the middle of the vulnerable zone

**Settlement was calculated for the vulnerable zone divided into 10 layers

Case history of deformations in sand layers during pile driving at Back Bay Site in Boston



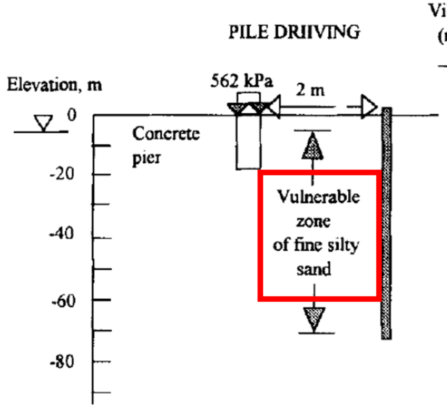
Vibr.Ampl. (mm/sec)	Meas.Sett. (mm)	Calc.Settl.* (mm)	Calc.Settl.** (mm)
17.5	70	49	61

Factor	Natural Value	Coded Value
1	17.5 mm/sec	0.96
2	154 kPa	1
3	306 kPa	1
4	Fine	1
5	500000 cycles	0.85
6	Moist	2
7	Dense	2

*Settlement was calculated for in-situ stress conditions in the middle of the vulnerable zone

**Settlement was calculated for the vulnerable zone divided into 10 layers

Case history of deformations in sand layers during pile driving at South Brooklyn Site, New York



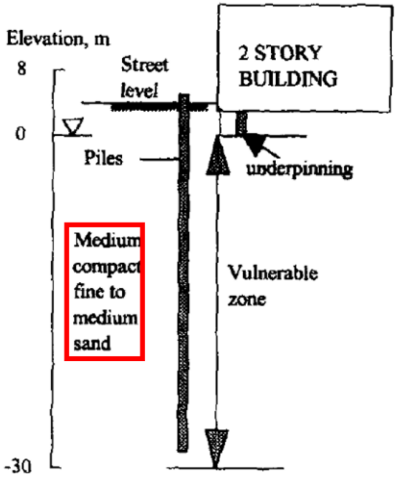
Vibr.Ampl. (mm/sec)	Meas.Sett. (mm)	Calc.Settl.* (mm)	Calc.Settl.** (mm)
17.5	250	80-100	100-120

Factor	Natural Value	Coded Value
1	17.5 mm/sec	0.96
2	188 kPa	1
3	374 kPa	1
4	Fine	1
5	500000 cycles	0.85
6	Moist	2
7	Loose	-1

*Settlement was calculated for in-situ stress conditions in the middle of the vulnerable zone

**Settlement was calculated for the vulnerable zone divided into 10 layers

Case history of pier settlement in Lesaka, Spain



Vibr.Ampl. (mm/sec)	Meas.Sett. (mm)	Calc.Settl.* (mm)	Calc.Settl.** (mm)
5-13	38-69	12-49	18-65

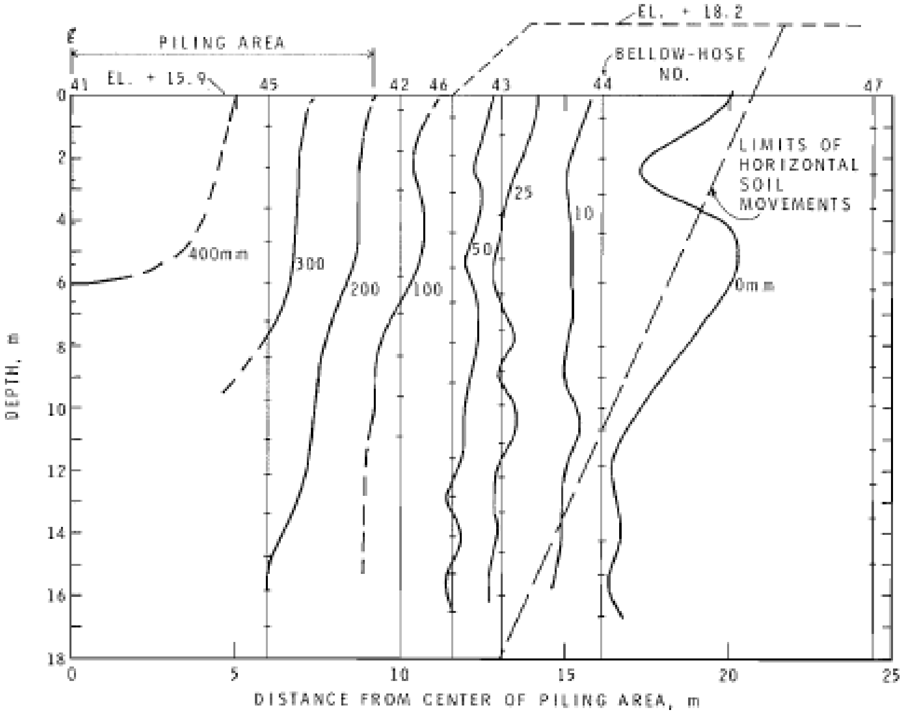
Factor	Natural Value	Coded Value
1	5..13	-0.67..0.37
2	53 kPa	-0.13
3	106 kPa	-0.46
4	Fine	1
5	500000 cycles	0.85
6	Moist	2
7	Dense	2

*Settlement was calculated for in-situ stress conditions in the middle of the vulnerable zone

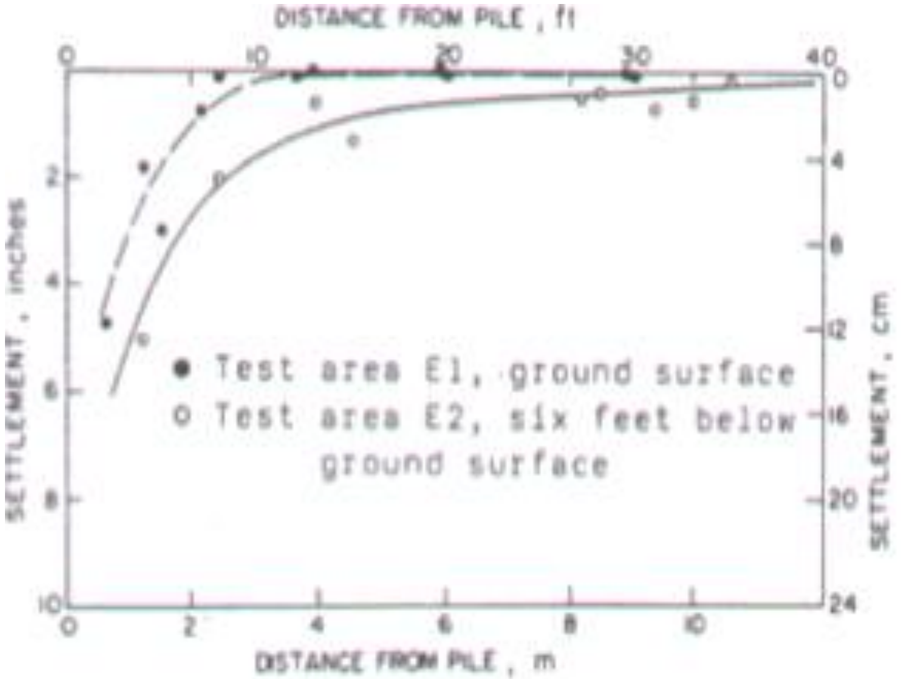
**Settlement was calculated using 10-layers extrapolation scheme

Case history Tri-Beca site in Manhattan

Case Histories: measured settlement

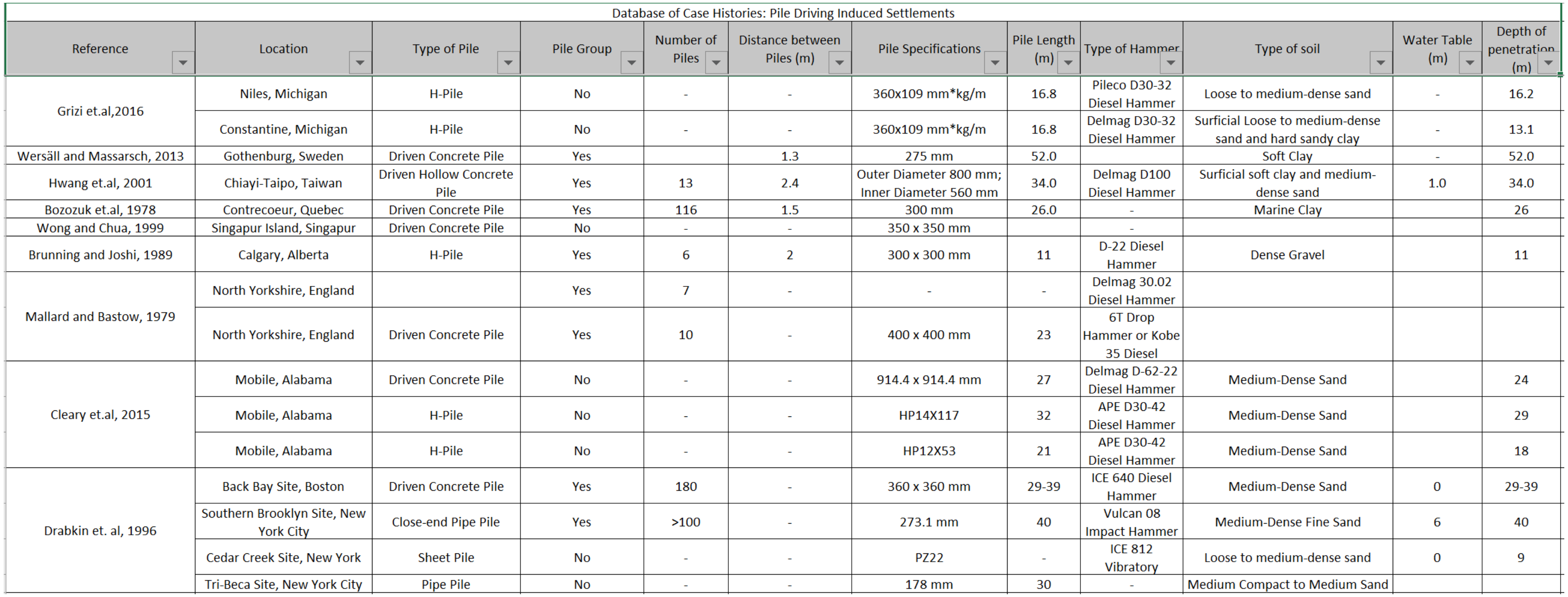


Soil heave contours due to pile driving (Bozozuk, et al., 1978)



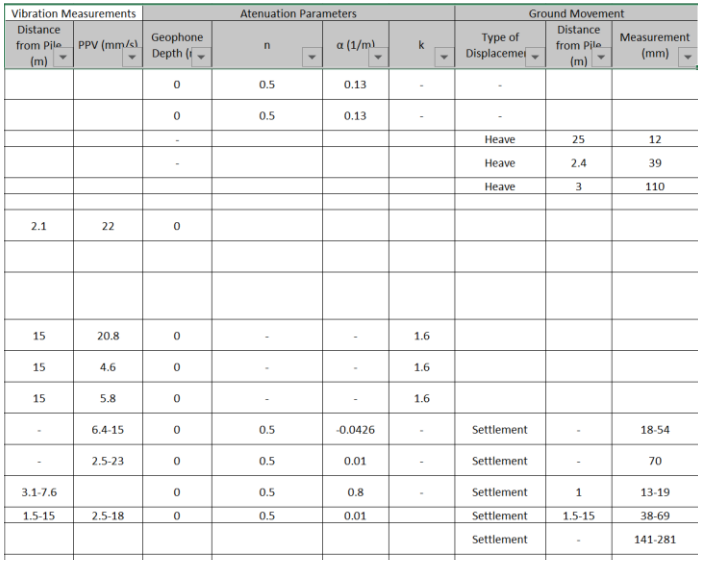
Variation of settlement with distance (Mohamad & Dobry, 1987; Clough & Chameau, 1980)

Case Histories: pile driving database



Database of Case Histories: Pile Driving Induced Settlements

Reference	Location	Type of Pile	Pile Group	Number of Piles	Distance between Piles (m)	Pile Specifications	Pile Length (m)	Type of Hammer	Type of soil	Water Table (m)	Depth of penetration (m)
Grizi et.al,2016	Niles, Michigan	H-Pile	No	-	-	360x109 mm*kg/m	16.8	Pileco D30-32 Diesel Hammer	Loose to medium-dense sand	-	16.2
	Constantine, Michigan	H-Pile	No	-	-	360x109 mm*kg/m	16.8	Delmag D30-32 Diesel Hammer	Surficial Loose to medium-dense sand and hard sandy clay	-	13.1
Wersäll and Massarsch, 2013	Gothenburg, Sweden	Driven Concrete Pile	Yes		1.3	275 mm	52.0		Soft Clay	-	52.0
Hwang et.al, 2001	Chiayi-Taipo, Taiwan	Driven Hollow Concrete Pile	Yes	13	2.4	Outer Diameter 800 mm; Inner Diameter 560 mm	34.0	Delmag D100 Diesel Hammer	Surficial soft clay and medium-dense sand	1.0	34.0
Bozozuk et.al, 1978	Contrecoeur, Quebec	Driven Concrete Pile	Yes	116	1.5	300 mm	26.0	-	Marine Clay		26
Wong and Chua, 1999	Singapur Island, Singapur	Driven Concrete Pile	No	-	-	350 x 350 mm		-			
Brunning and Joshi, 1989	Calgary, Alberta	H-Pile	Yes	6	2	300 x 300 mm	11	D-22 Diesel Hammer	Dense Gravel		11
Mallard and Bastow, 1979	North Yorkshire, England		Yes	7	-	-	-	Delmag 30.02 Diesel Hammer			
	North Yorkshire, England	Driven Concrete Pile	Yes	10	-	400 x 400 mm	23	6T Drop Hammer or Kobe 35 Diesel			
Cleary et.al, 2015	Mobile, Alabama	Driven Concrete Pile	No	-	-	914.4 x 914.4 mm	27	Delmag D-62-22 Diesel Hammer	Medium-Dense Sand		24
	Mobile, Alabama	H-Pile	No	-	-	HP14X117	32	APE D30-42 Diesel Hammer	Medium-Dense Sand		29
	Mobile, Alabama	H-Pile	No	-	-	HP12X53	21	APE D30-42 Diesel Hammer	Medium-Dense Sand		18
Drabkin et. al, 1996	Back Bay Site, Boston	Driven Concrete Pile	Yes	180	-	360 x 360 mm	29-39	ICE 640 Diesel Hammer	Medium-Dense Sand	0	29-39
	Southern Brooklyn Site, New York City	Close-end Pipe Pile	Yes	>100	-	273.1 mm	40	Vulcan 08 Impact Hammer	Medium-Dense Fine Sand	6	40
	Cedar Creek Site, New York	Sheet Pile	No	-	-	PZ22	-	ICE 812 Vibratory	Loose to medium-dense sand	0	9
	Tri-Beca Site, New York City	Pipe Pile	No	-	-	178 mm	30	-	Medium Compact to Medium Sand		



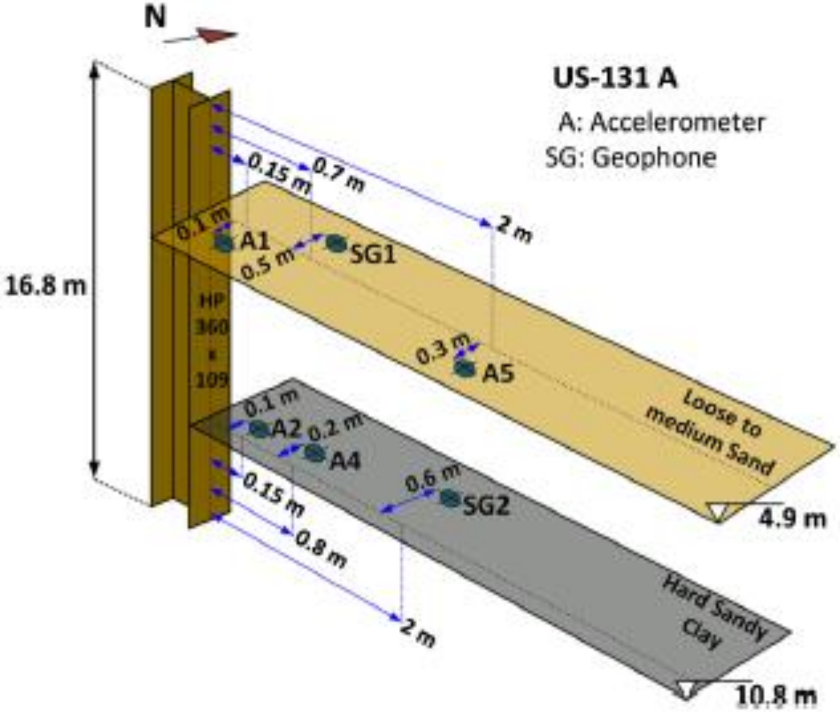
Vibration Measurements		Atenuation Parameters				Ground Movement		
Distance from Pile (m)	PPV (mm/s)	Geophone Depth (m)	n	α (1/m)	k	Type of Displacement	Distance from Pile (m)	Measurement (mm)
		0	0.5	0.13	-	-		
		0	0.5	0.13	-	-		
		-				Heave	25	12
		-				Heave	2.4	39
						Heave	3	110
2.1	22	0						
15	20.8	0	-	-	1.6			
15	4.6	0	-	-	1.6			
15	5.8	0	-	-	1.6			
-	6.4-15	0	0.5	-0.0426	-	Settlement	-	18-54
-	2.5-23	0	0.5	0.01	-	Settlement	-	70
3.1-7.6		0	0.5	0.8	-	Settlement	1	13-19
1.5-15	2.5-18	0	0.5	0.01		Settlement	1.5-15	38-69
						Settlement	-	141-281

Summarized variables in database:

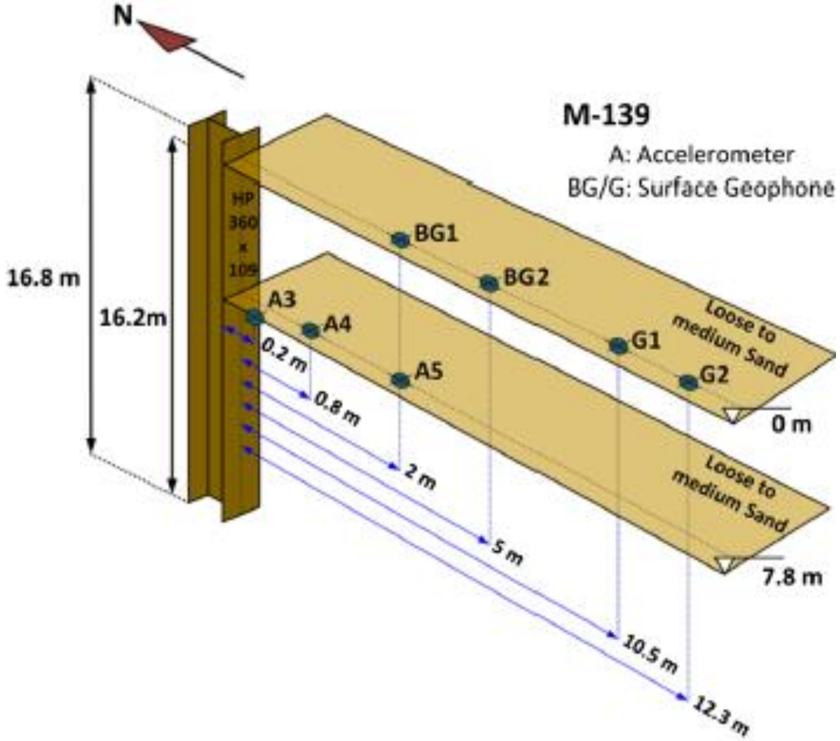
- Reference
- Site location
- Type of pile
- Number of piles
- Distance between piles
- Pile specifications (type, materials and dimensions)
- Pile length
- Type of hammer
- Type of soil
- Water table location
- Depth of penetration
- Distance from pile
- PPV
- Geophone depths
- Attenuation parameters
- Heave? Magnitude
- Settlement? Magnitude

Technical Background: typical sensor layout

- Geophones
- Piezometers
- Settlement points
- Accelerometers
- Inclinometers



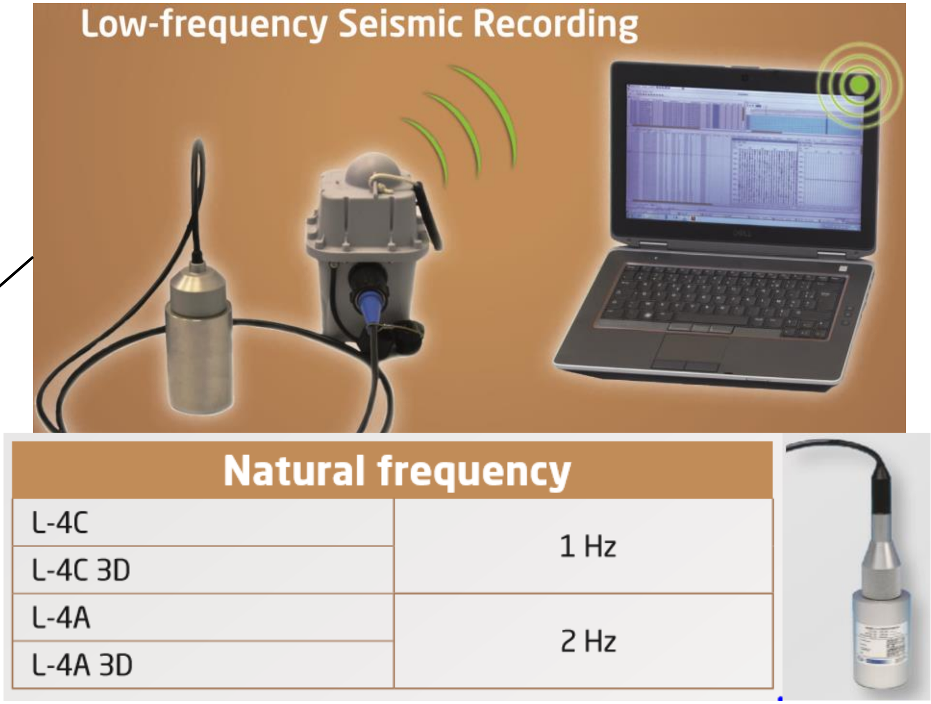
Embedded sensors at US-139A (Grizi, et al., 2016)



Buried and surface sensors at M-139
(Grizi, et al., 2016)

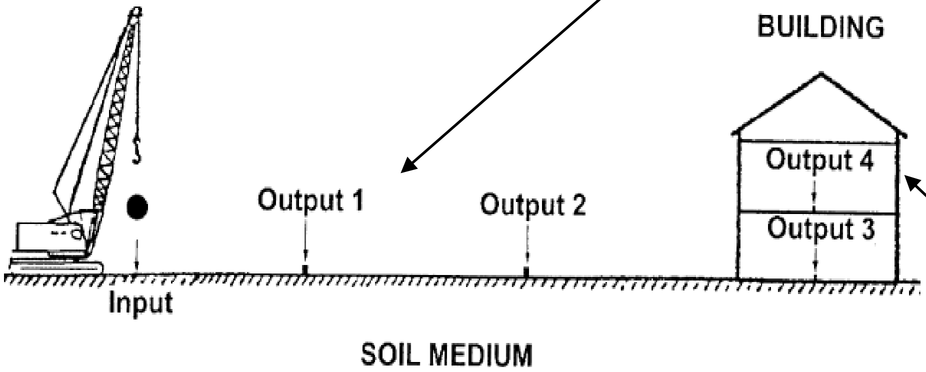
Technical Background: typical sensors used

- Geophones
- Piezometers
- Settlement points
- Accelerometers
- Inclinometers



Natural frequency	
L-4C	1 Hz
L-4C 3D	
L-4A	2 Hz
L-4A 3D	

Data acquisition system and seismometer



Measurement locations (Athanasopoulus & Pelekis, 2000)

Accelerometers

Technical Background: typical sensors used

- Geophones
- Piezometers
- Settlement points
- Accelerometers
- Inclinometers

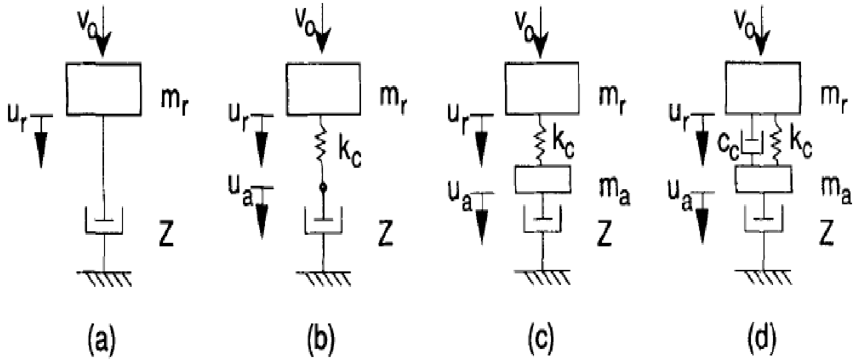
Vibration wire piezometers, readout, and datalogger

Inclinometers.

Topographic equipment

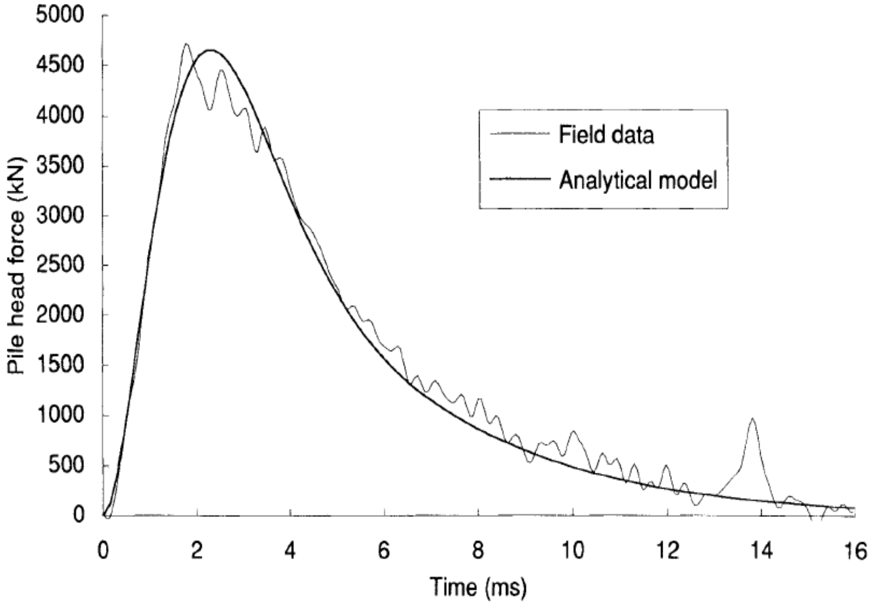
Numerical Analysis: Deeks & Randolph (1993)

Objective: Model force-time signals caused by pile driving.
4 models for drop hammers were presented:



Analytical pile hammer models (Deeks & Randolph, 1993)

m_a anvil mass
m_r ram mass
kc cushion modeled as a spring
Z pile represented as a dashpot
Cc dashpot representing the
cushion non-linearity



Comparison with a BSP 357 hammer (Deeks & Randolph, 1993)

Numerical Analysis: Mabsout et al. (1995)

Objective: Assess effect of a single hammer blow on a clay at different pre-boring depths.

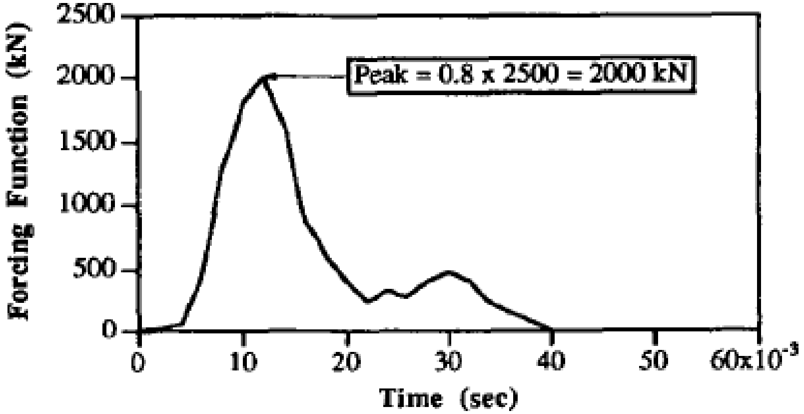
Finite Element Platform:

Open software used with the following characteristics:

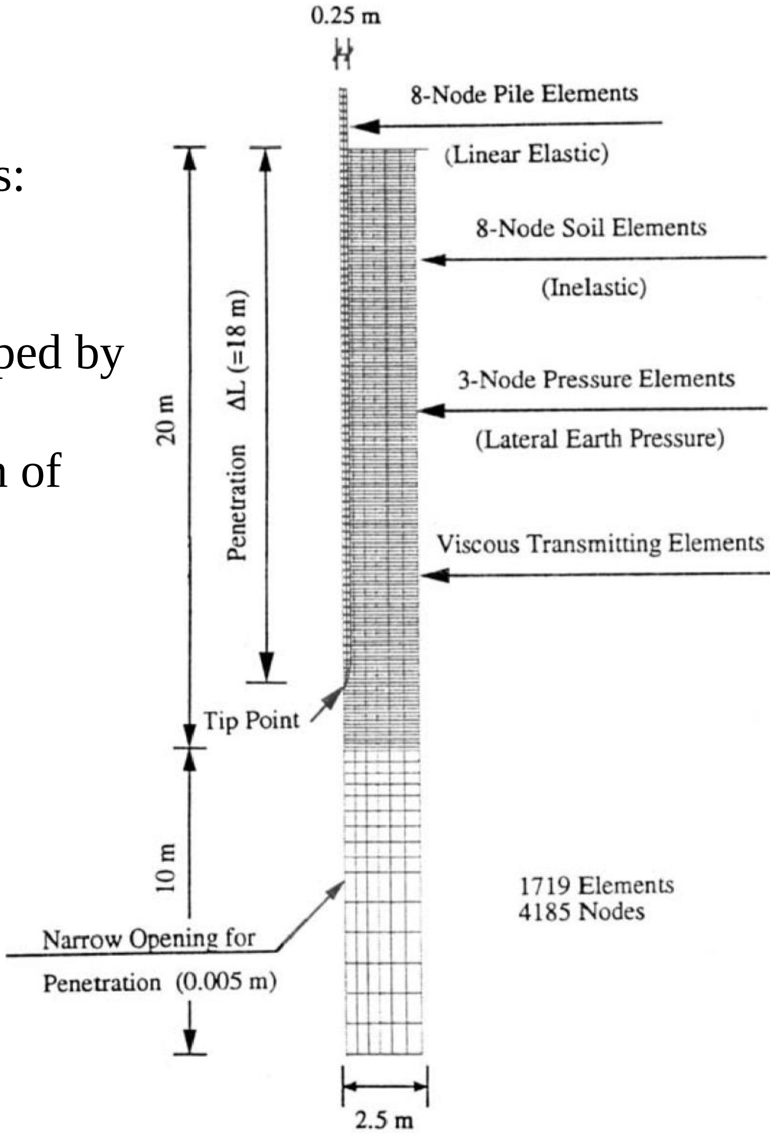
- Axisymmetric formulation.
- 8 and 3 node elements.
- Non-linear analysis based on the approach developed by Nagtegaal (1982).
- Newton-Raphson method used to solve the system of non-linear equations at the end of the step.

Pile driving type:

- An updated Lagrangian formulation.



Assumed Forcing Function, modified from (Mabsout, et al., 1995) after (Goble, et al., 1980)

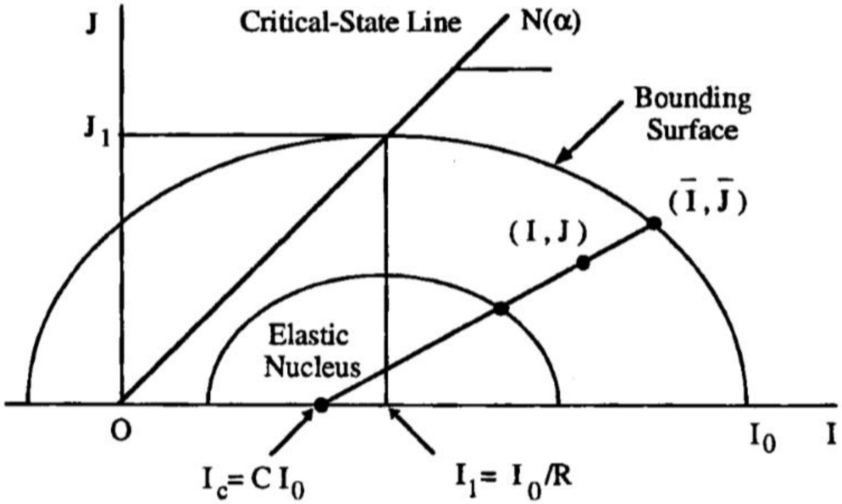


Finite element discretization of the piledriving system (Mabsout and Tassoulas, 1994)

Numerical Analysis: Mabsout et al. (1995)

Soil Constitutive Model:

Bounding-surface plasticity model for isotropic, cohesive soils, developed by (Kaliakin & Dafalias, 1989). It requires the determination of 13 parameters.



Bounding surface in the space of stress invariants (after Kaliakin and Dafaliass) (retrieved from Mabsout and Tassoulas, 1994)

- ➢ 6 parameters (critical-state soil mechanics variables) from lab test.
- ➢ Two parameters (bounding surface geometry)
- ➢ 5 parameters to define the hardening function

Pile constitutive model:

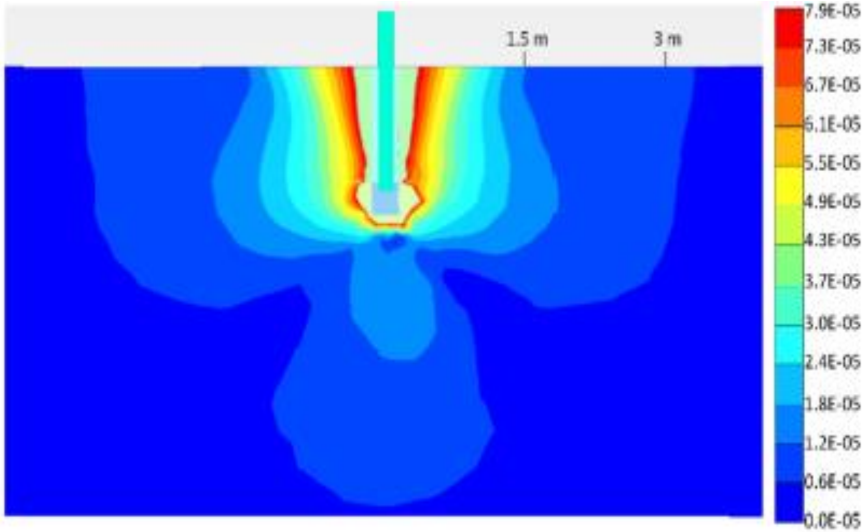
Linear elastic behavior. Failure surface described by Fardis et al. (1983) adopted for concrete piles.

Main findings:

- •Deep pre-boring leads to more resistance to driving due to confinement and leads to larger shaft resistance.
- •Ue increases with hammer blows.

Numerical Analysis: Grizi et al. (2018)

Objective: Validation of a finite element model with a reduced-scaled laboratory test.



Total displacements after 1.0 sec at a pile depth of 1.15 m (Grizi, et al., 2018)

Finite Element Platform:

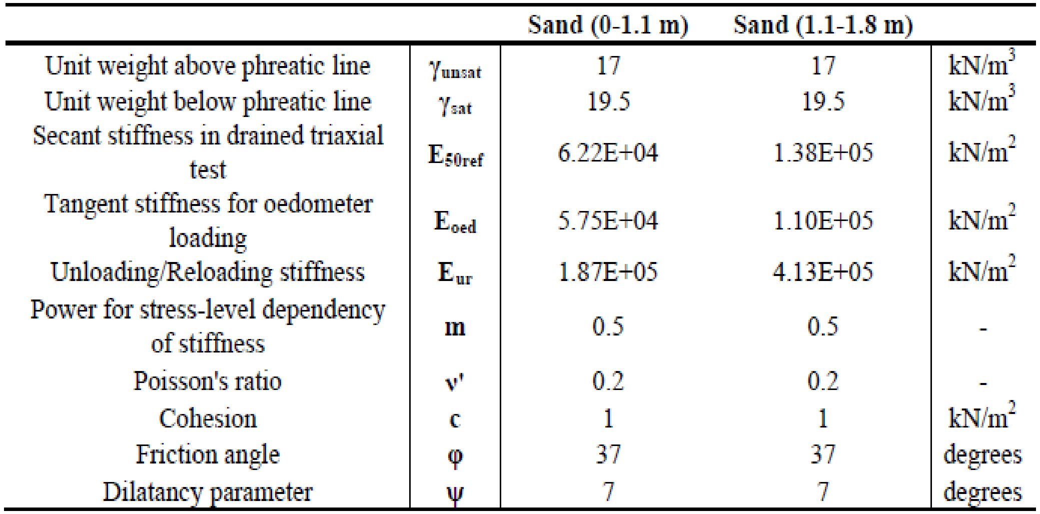
- Plaxis 3D
- Material data set for the pile/soil interface with reduced parameters.
- PDA measured response was used to calculate the input force for the model.
- Hammer force was applied on the pile head during an interval of 0.02 sec.

Pile driving type:

Discontinuous pile driving simulation.

Soil Constitutive Model:

Hardening Soil Model for the silica sand. Clay not modeled.



		Sand (0-1.1 m)	Sand (1.1-1.8 m)	
Unit weight above phreatic line	γ_{unsat}	17	17	kN/m^3
Unit weight below phreatic line	γ_{sat}	19.5	19.5	kN/m^3
Secant stiffness in drained triaxial test	E_{50ref}	6.22E+04	1.38E+05	kN/m^2
Tangent stiffness for oedometer loading	E_{oed}	5.75E+04	1.10E+05	kN/m^2
Unloading/Reloading stiffness	E_{ur}	1.87E+05	4.13E+05	kN/m^2
Power for stress-level dependency of stiffness	m	0.5	0.5	-
Poisson's ratio	ν'	0.2	0.2	-
Cohesion	c	1	1	kN/m^2
Friction angle	φ	37	37	degrees
Dilatancy parameter	ψ	7	7	degrees

Parameters for the Hardening Soil model (Grizi, et al., 2018)

Numerical Analysis: Grizi et al. (2018)

Pile constitutive model:

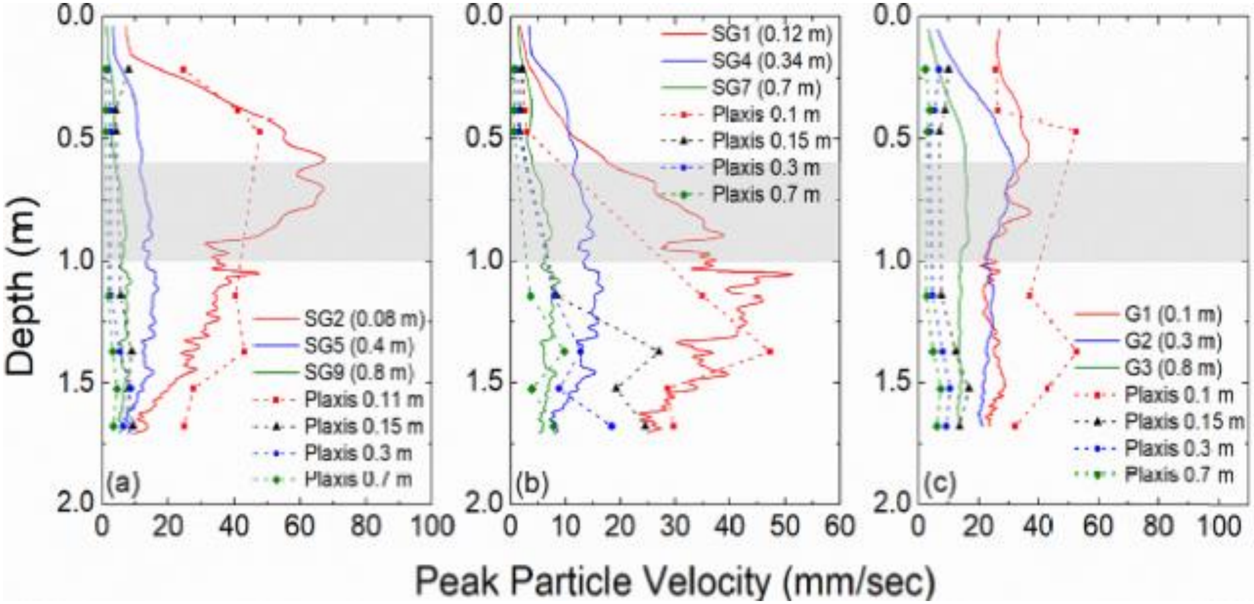
Predetermined material data set (beam elements).

Reduced-scaled laboratory test:

- 6.5 diameter cylindrical pit (h=1.8 m)
- Silica sand undelay by a natural clay deposit
- Type of pile was a S 3x5.7 beam with a length of 2.5 m
- Impact hammer was a steel fence post driver with a weight of 20 kg
- Monitoring by:
  - geophones placed at different distances and depths
  - strain transducers and accelerometers placed near the pile top (PDA)

Numerical Analysis: Grizi et al. (2018)

Results:



Comparison PPV vs. depth: measured data and numerical analysis at depths of (a) 0.6 m; (b) 1.2 m; (c) on the ground surface (Grizi, et al., 2018).

Conclusions:

- A plastic zone with reduced parameters located around the pile can capture very accurately the response in soil-pile interface.
- Different wave fronts appear from the impact. Cylindrical waves form around the shaft and spherical waves at the pile tip.
- When the pile tip is far below the measuring depth, the major factor is the cylindrical front wave that comes from the pile shaft.

Numerical Analysis: Honomayoun Rooz and Hamidi (2017)

Objective: Predict ground vibrations induced by pile driving in sandy clay soil. Parametric study of: Impact hammer force, pile diameter, tip angle, and damping ratio.

Finite Element Platform:

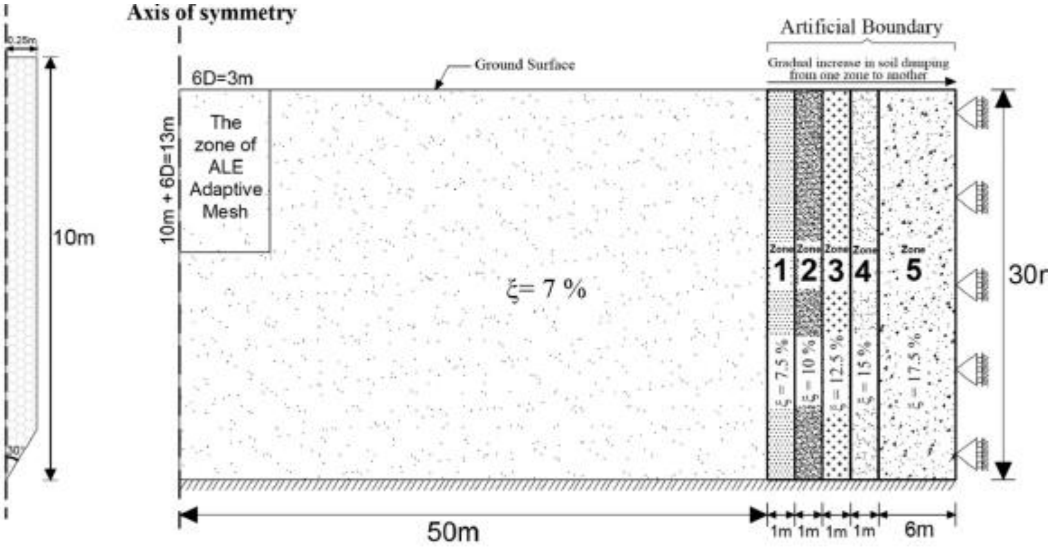
- ABAQUS under axisymmetric conditions

Pile driving type:

- Continuous pile driving simulation (Arbitrary Lagrangian-Eulerian adaptive mesh method) due to significant mesh distortion.
- A surface-to-surface contact discretization was applied in *Abaqus* to represent the contact between pile and soil.

Soil Constitutive Model:

Mohr-Coulomb



Model Geometry (Homayoun Rooz & Hamidi, 2017)

Pile Constitutive Model:

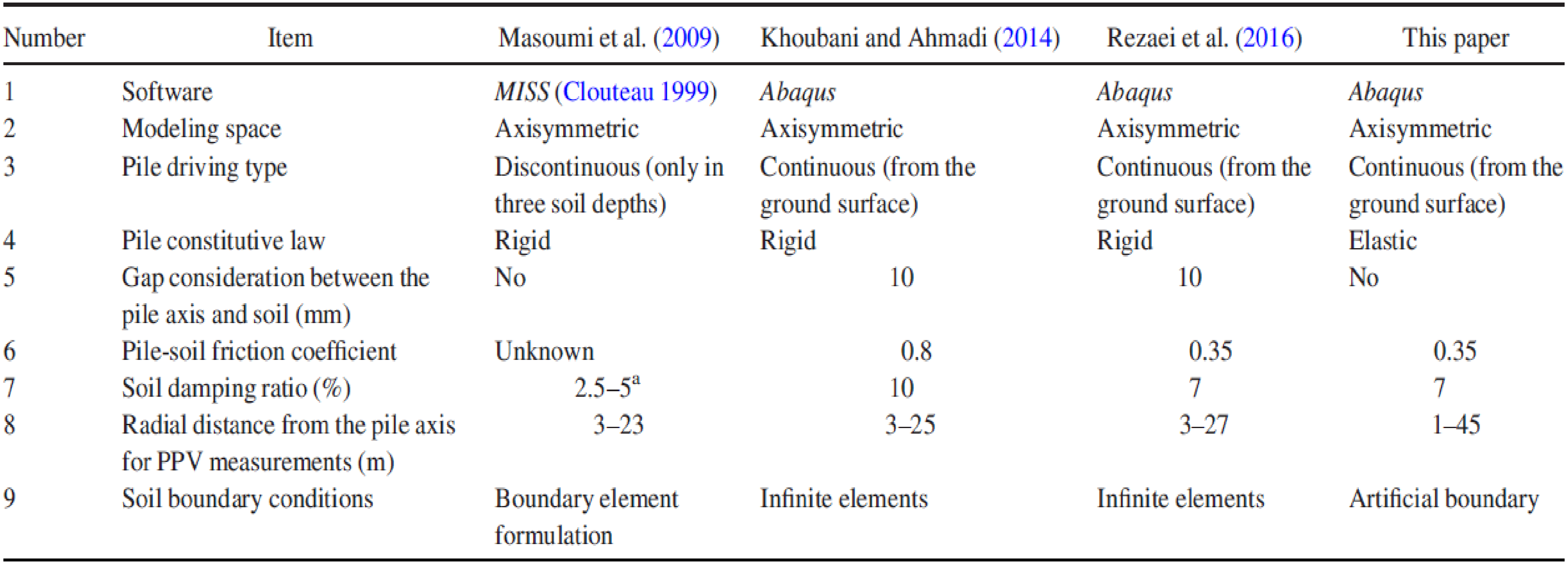
Elastic parameters

Property	Concrete pile	Sandy Clay
Diameter (m)	0.5	-
Length (m)	10	-
Poisson's Ratio	0.25	0.4
Elastic modulus (MPa)	40000	80
Density (kg/m^3)	2500	2000
Cohesion (kPa)	-	15
Friction Angle (degrees	-	25

Pile and Soil Properties modified after (Homayoun Rooz & Hamidi, 2017)

Numerical Analysis: Honomayoun Rooz and Hamidi (2017)

Summary of other studies (Homayoun Rooz & Hamidi, 2017)



Number	Item	Masoumi et al. (2009)	Khoubani and Ahmadi (2014)	Rezaei et al. (2016)	This paper
1	Software	*MISS* (Clouteau 1999)	*Abaqus*	*Abaqus*	*Abaqus*
2	Modeling space	Axisymmetric	Axisymmetric	Axisymmetric	Axisymmetric
3	Pile driving type	Discontinuous (only in three soil depths)	Continuous (from the ground surface)	Continuous (from the ground surface)	Continuous (from the ground surface)
4	Pile constitutive law	Rigid	Rigid	Rigid	Elastic
5	Gap consideration between the pile axis and soil (mm)	No	10	10	No
6	Pile-soil friction coefficient	Unknown	0.8	0.35	0.35
7	Soil damping ratio (%)	2.5–5[a]	10	7	7
8	Radial distance from the pile axis for PPV measurements (m)	3–23	3–25	3–27	1–45
9	Soil boundary conditions	Boundary element formulation	Infinite elements	Infinite elements	Artificial boundary

Typical problem simulation procedure:

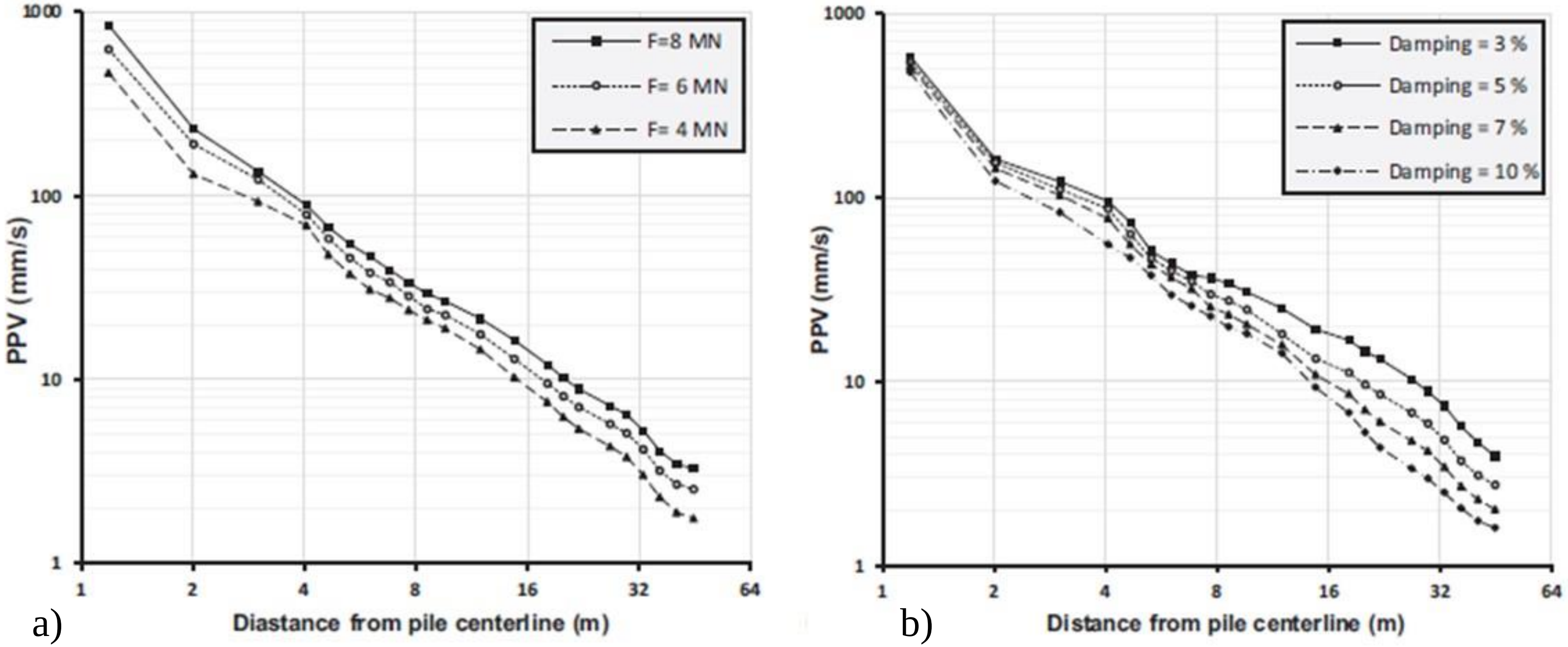
a) Pile embedment on the ground surface.

b) Initial stress field generated through application of the gravity load.

c) Static penetration of the pile due to its own weight with an interval of 0.25 seconds.

d) Application of successive hammer impacts up to a final depth of 10.0 m.

Numerical Analysis: Honomayoun Rooz and Hamidi (2017)



a) b)

Parametric study of the PPV at different distances from the pile varying: (a) Impact Hammer Force; and (d) Damping ratio of the soil. (Homayoun Rooz & Hamidi, 2017)

Conclusions:

- ➢ The maximum PPV occurs at a particular depth of penetration known as the critical depth of vibration.
- ➢ Maximum PPVs that depend on the distance from the pile vary with depth.
- ➢ Significant factors that affect the response of soils due to pile driving: impact hammer force, pile diameter, soil friction angle and damping ratio.

Numerical Analysis: Khoubani & Ahmadi (2014)

Objective: Simulate a continuous pile penetration to a desired depth from the ground surface

Finite Element Platform:

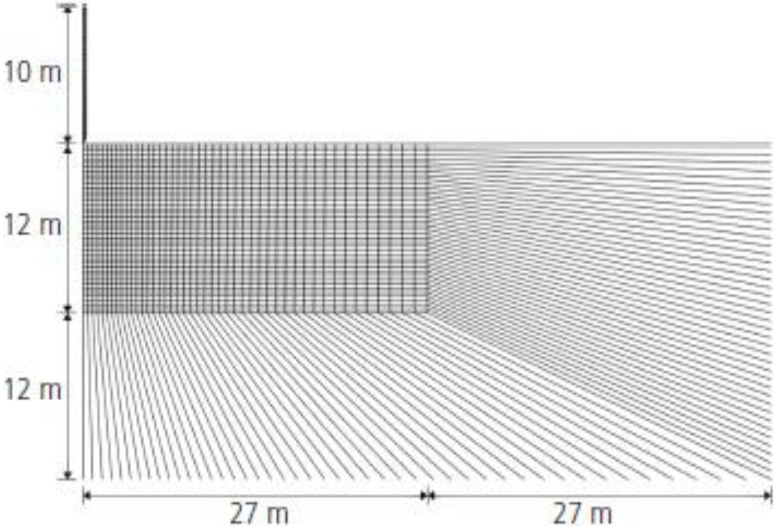
- ABAQUS under axisymmetric conditions
- Four-node quadrilateral finite elements.

Pile Driving Type:

- Continuous pile driving simulation using Arbitrary Lagrangian-Eulerian adaptive mesh method.

Soil Constitutive Model:

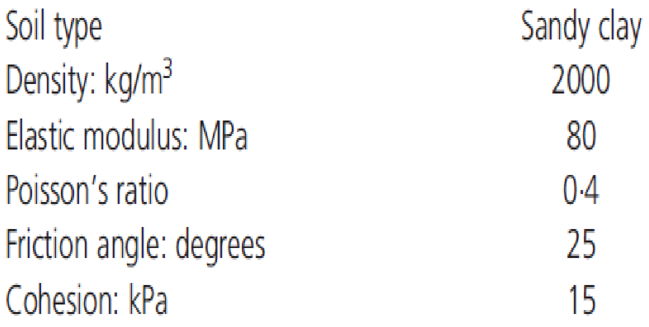
Mohr-Coulomb Model for the sand clay.



Axisymmetric finite-element model and infinite-element mesh (Khoubani & Ahmadi, 2014)

Pile type element:

Rigid body.



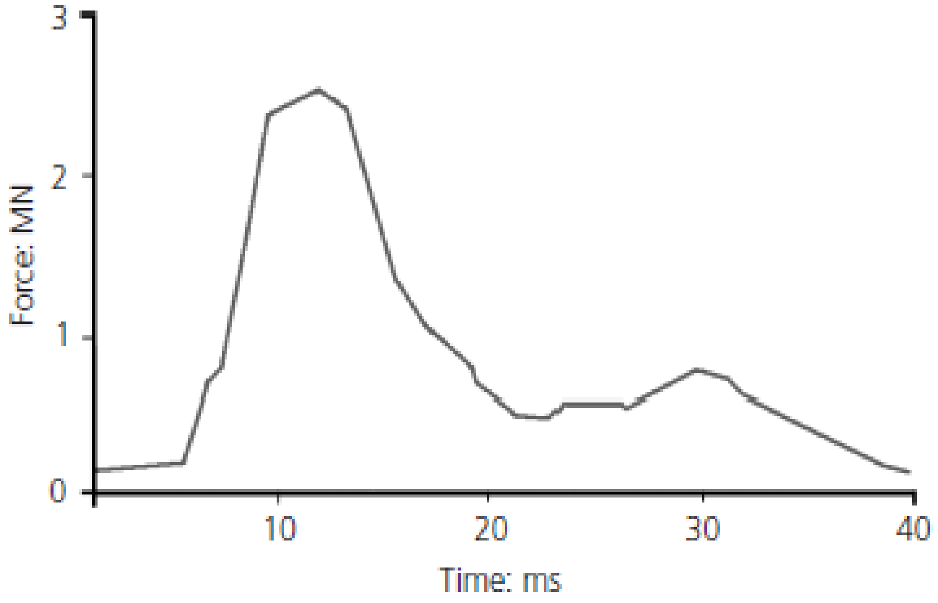
Soil type	Sandy clay
Density: kg/m^3	2000
Elastic modulus: MPa	80
Poisson's ratio	0·4
Friction angle: degrees	25
Cohesion: kPa	15

Soil Properties modified from (Khoubani & Ahmadi, 2014) after (Masoumi, et al., 2009)

Numerical Analysis: Khoubani & Ahmadi (2014)

Problem simulation procedure:

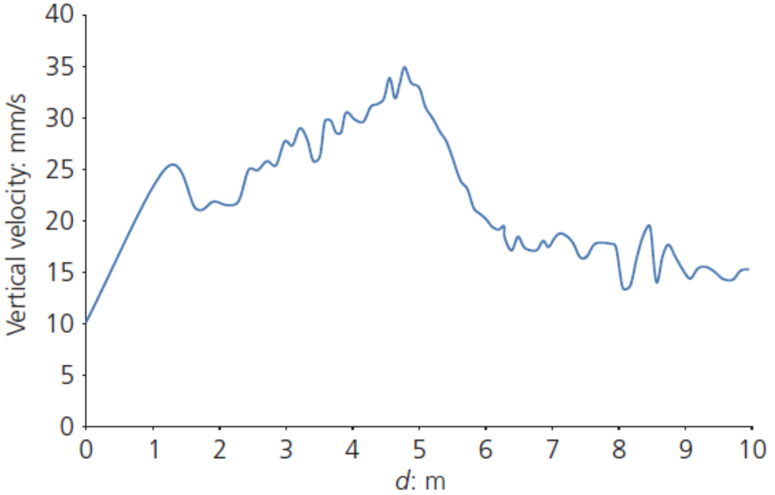
- Gravity load.
- Pile toe located at the ground surface.
- Successive hammer impacts applied to the pile head.



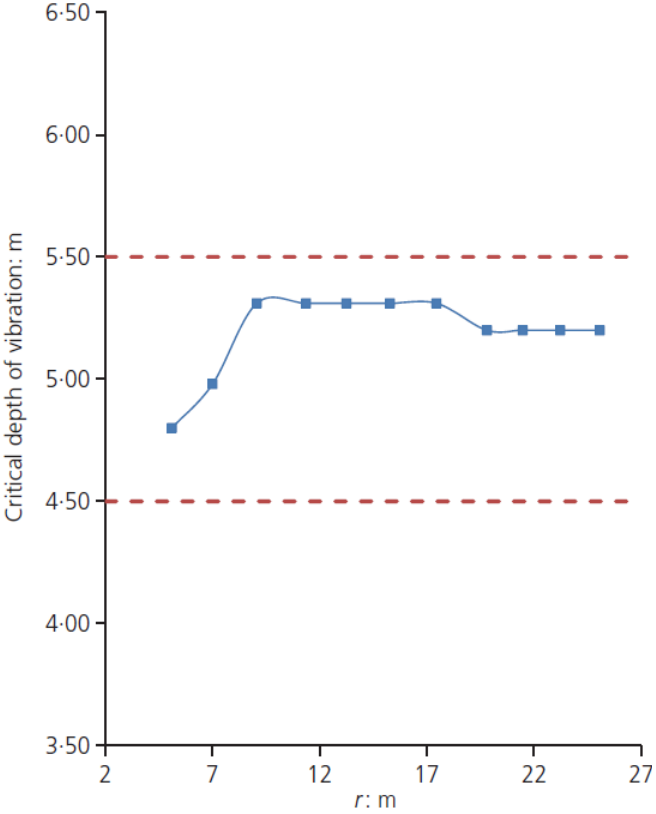
Input hammer impact force-time curve from (Khoubani & Ahmadi, 2014) after (Goble, et al., 1980)

Numerical Analysis: Khoubani & Ahmadi (2014)

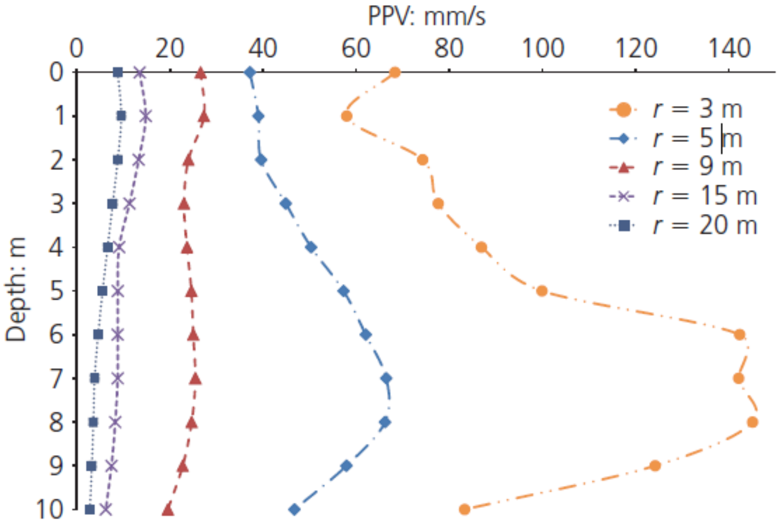
Results:



Vertical velocity of ground surface at a distance of 5 m from the center of pile versus depth of pile penetration, d



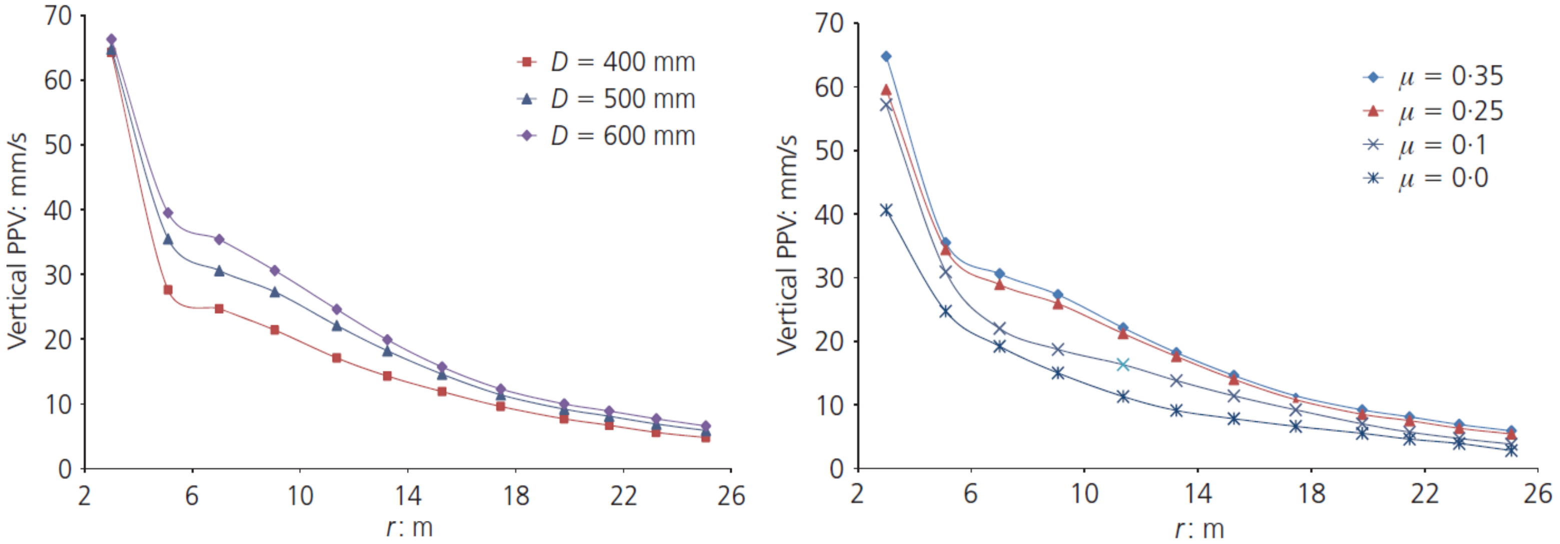
Critical depth of vibration versus distance from the pile (Khoubani & Ahmadi, 2014)



PPV values versus depth for points located at various distances from the pile center (Khoubani & Ahmadi, 2014)

Numerical Analysis: Khoubani & Ahmadi (2014)

Parametric study results example:



Vertical PPV values of ground surface points vs distance from the pile for various pile diameters with an impact force of 3MN, and various values of soil-pile friction (Khoubani & Ahmadi, 2014)

Conclusions:

- Adaptive meshing is preferable.
- A critical penetration depth generated the maximum PPV.
- For locations close to the pile, the maximum PPV was found deeper than for locations away the center of the pile where the maximum PPV was shallower.
- Ground vibrations depend on the impact hammer force, type of pile, type of soil, and the soil-pile interface/interaction.

Summary and Future Work

- **Summary:**
  - Total of 14 case histories were reviewed. Findings/information will be used for Task 2 (field experiment) and Task 3 (numerical modeling).

- **Future Work:**
  - Task 2 – Field testing in pile installation sites
  - Task 3 – Develop numerical modeling of pile driving induced settlement
  - Task 4 – Develop empirical prediction formula or chart for dynamic settlement
  - Task 5 – Guidelines and recommendations

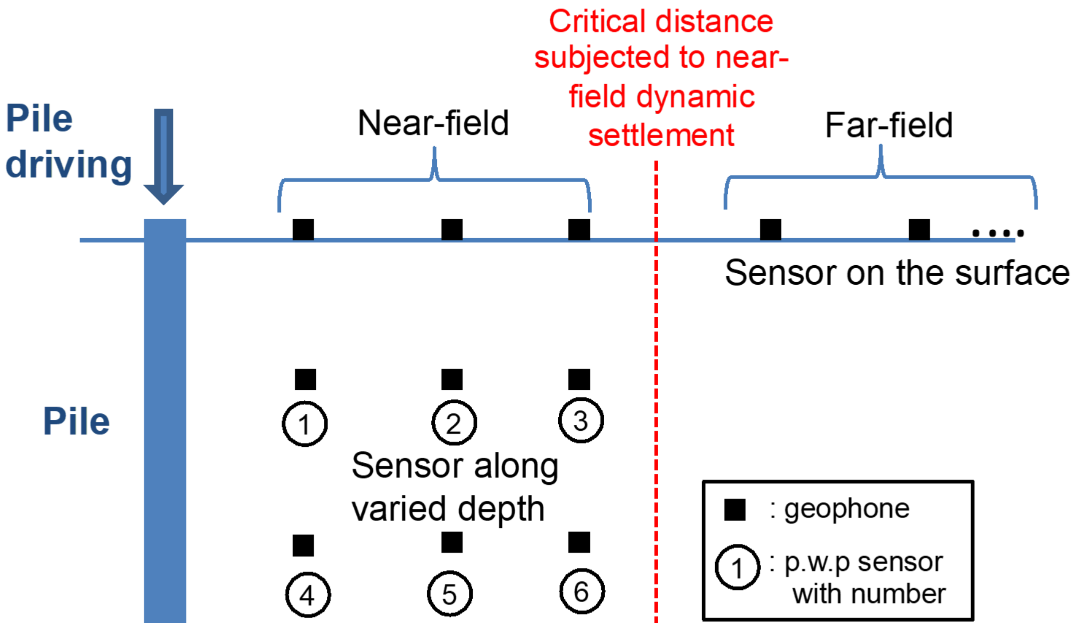
Our plan of attack

Procedure: Site selection → Instrumentation → Data collection → Analysis

Field testing EDPs:

- Measure PPV
- Pore water pressures
- Settlements

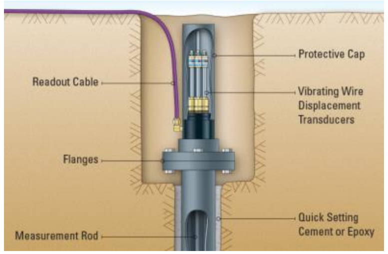
Schematic Diagram



Geophone and reader

piezometers

magnetic extensometers



VW continuous settlement

PRESENTED BY

Luis G. Arboleda-Monsalve and Boo Hyun Nam
Univ. of Central Florida, Orlando, FL.

UCF
UNIVERSITY OF
CENTRAL FLORIDA