Proposal:
Prediction model of vibration-induced settlement due to pile driving

PRESENTED BY

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OUTLINE

- Problem statement

- Background
  - Geotechnical aspects of pile driving induced settlement
  - Numerical modeling for dynamic settlement

- Project objectives

- Work plan

- Discussion

PROBLEM STATEMENT

- A survey to geotechnical consultants in FL reported that 75% of the respondents experienced vibration-induced settlement (i.e., dynamic settlement).

- Significant surface settlements in loose to medium dense sands with relative density less than 70% was reported.

- Several ground vibration prediction models have been developed, including (i) wave attenuation method, (ii) scale distance method, (iii) impulse response function method.

- However, there are no existing models and/or methods to predict dynamic settlement due to pile driving and/or construction-induced vibration.

PROJECT OBJECTIVES

Four project objectives:

- To understand the 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).

Main variables:

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

Pile driving can:

i) Cause vibration-induced particle rearrangement, called **settlement!**

ii) Cause excess pore water pressure build-up… and when dissipated generates **settlement!**

iii) Cause soil re-sedimentation (**settlement!**) after localized liquefaction around the pile is generated

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

Geotechnical Aspects of Pile Driving Induced Settlement

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

- Current practice methods are limited to capture many of the key attributes of pile driving-induced settlements. This is the motivation to propose this research.

- Pile driving generates a stress wave and propagates through soil media and wave propagation characteristics along with site condition affects the wave attenuations characteristics.

- Vibrations by pile driving can generate peak particle velocities (PPV) even up to 4 in/s and even if PPV values reach only 0.1 in/s, settlements can still be generated.

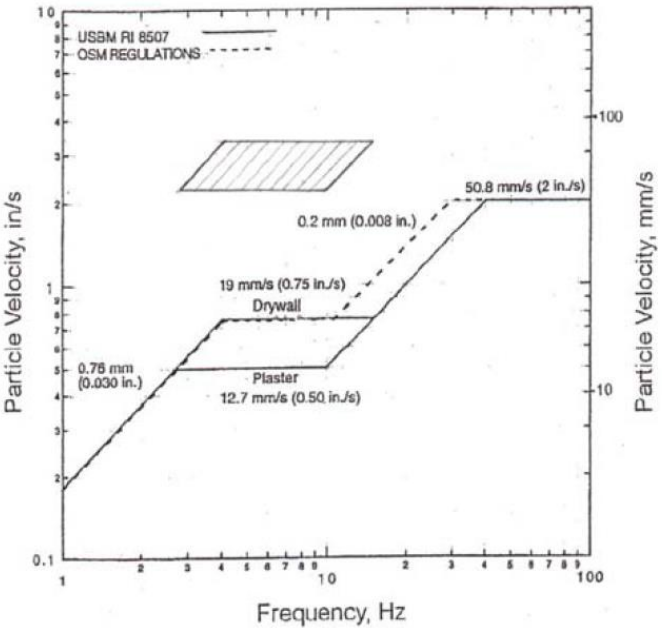
BACKGROUND: Geotechnical Aspects of Pile Driving Induced Settlement

- Accurate calculation of settlements is critical to guarantee integrity of nearby infrastructure.
- Relatively small ground vibrations can cause dynamic settlement in sandy soils.
- Pile driving may cause settlement due to densification and liquefaction of vulnerable soils.
- Relative density changes are easily measured via correlations with CPT tests.

Lacy and Gould (1985)
Bayraktar and Kang (2013)

BACKGROUND: Vibration Limit Examples

- USBM Criteria: (frequency based limits for cosmetic cracking, Siskind et al. 1980)



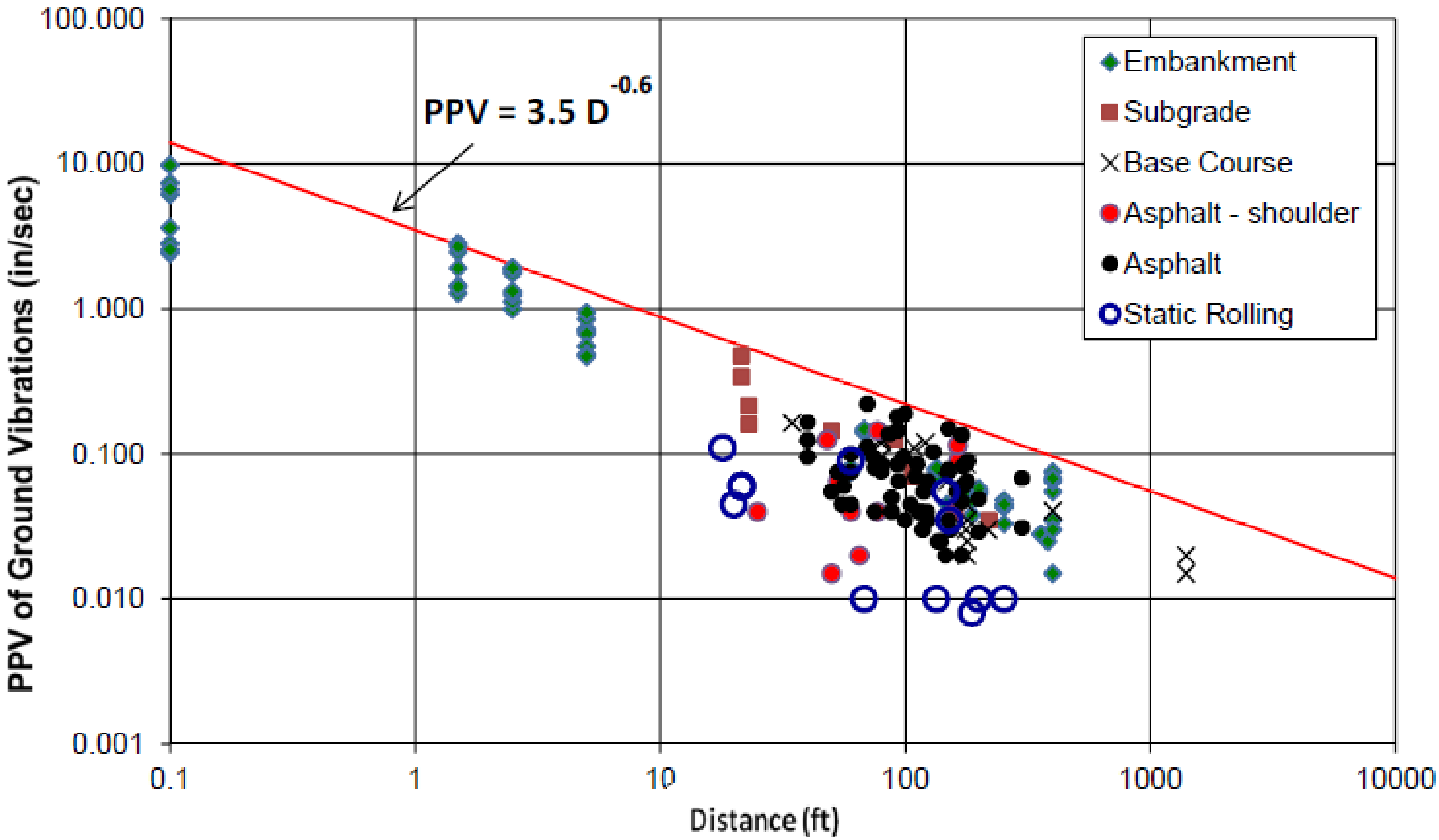
Safe level blasting criteria (USBM RI 8507)
Shaded region represents amplification of 4.5

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

- Major sources of complains in FDOT projects: vibratory rollers, tandem rollers, sheet pile installation

- PPV limit in Florida: 0.5 in/s and 0.2 in/s in some districts. Dowding (1996) and Lacy and Gould (1985) said 0.08 in/s (2 mm/s) is the limit beyond which dynamic settlement may be triggered

BACKGROUND: Results from Previous FDOT Project



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

PROPOSED WORK PLAN

Task 1 – Review settlement case studies throughout state and nation

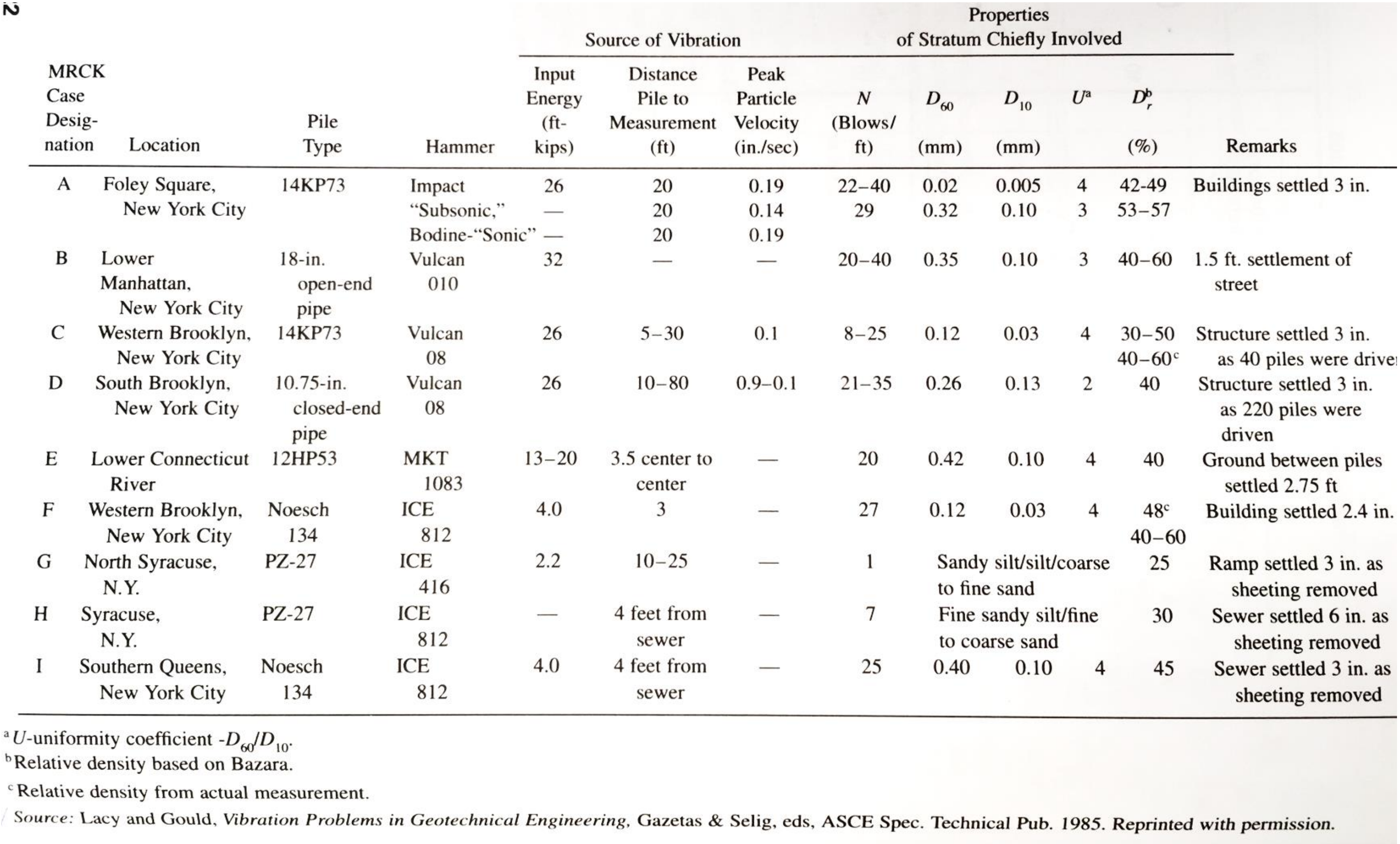
Task 2 – Field testing in pile installation sites

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

Task 1: Review of settlement case studies



				Source of Vibration			Properties of Stratum Chiefly Involved					
MRCK Case Designation	Location	Pile Type	Hammer	Input Energy (ft-kips)	Distance Pile to Measurement (ft)	Peak Particle Velocity (in./sec)	N (Blows/ft)	D_{60} (mm)	D_{10} (mm)	U^a	D_r^b (%)	Remarks
A	Foley Square, New York City	14KP73	Impact "Subsonic," Bodine-"Sonic"	26 — —	20 20 20	0.19 0.14 0.19	22–40 29	0.02 0.32	0.005 0.10	4 3	42-49 53–57	Buildings settled 3 in.
B	Lower Manhattan, New York City	18-in. open-end pipe	Vulcan 010	32	—	—	20–40	0.35	0.10	3	40–60	1.5 ft. settlement of street
C	Western Brooklyn, New York City	14KP73	Vulcan 08	26	5–30	0.1	8–25	0.12	0.03	4	30–50 40–60^c	Structure settled 3 in. as 40 piles were drive
D	South Brooklyn, New York City	10.75-in. closed-end pipe	Vulcan 08	26	10–80	0.9–0.1	21–35	0.26	0.13	2	40	Structure settled 3 in. as 220 piles were driven
E	Lower Connecticut River	12HP53	MKT 1083	13–20	3.5 center to center	—	20	0.42	0.10	4	40	Ground between piles settled 2.75 ft
F	Western Brooklyn, New York City	Noesch 134	ICE 812	4.0	3	—	27	0.12	0.03	4	48^c 40–60	Building settled 2.4 in.
G	North Syracuse, N.Y.	PZ-27	ICE 416	2.2	10–25	—	1	Sandy silt/silt/coarse to fine sand			25	Ramp settled 3 in. as sheeting removed
H	Syracuse, N.Y.	PZ-27	ICE 812	—	4 feet from sewer	—	7	Fine sandy silt/fine to coarse sand			30	Sewer settled 6 in. as sheeting removed
I	Southern Queens, New York City	Noesch 134	ICE 812	4.0	4 feet from sewer	—	25	0.40	0.10	4	45	Sewer settled 3 in. as sheeting removed

[a] U-uniformity coefficient -D_{60}/D_{10}.

[b] Relative density based on Bazara.

[c] Relative density from actual measurement.

Source: Lacy and Gould, *Vibration Problems in Geotechnical Engineering*, Gazetas & Selig, eds, ASCE Spec. Technical Pub. 1985. Reprinted with permission.

(from Dowding 1996)

Task 2: Field testing in pile installation sites

Purpose:

Collect field data of vibration induced settlement

Study concept:

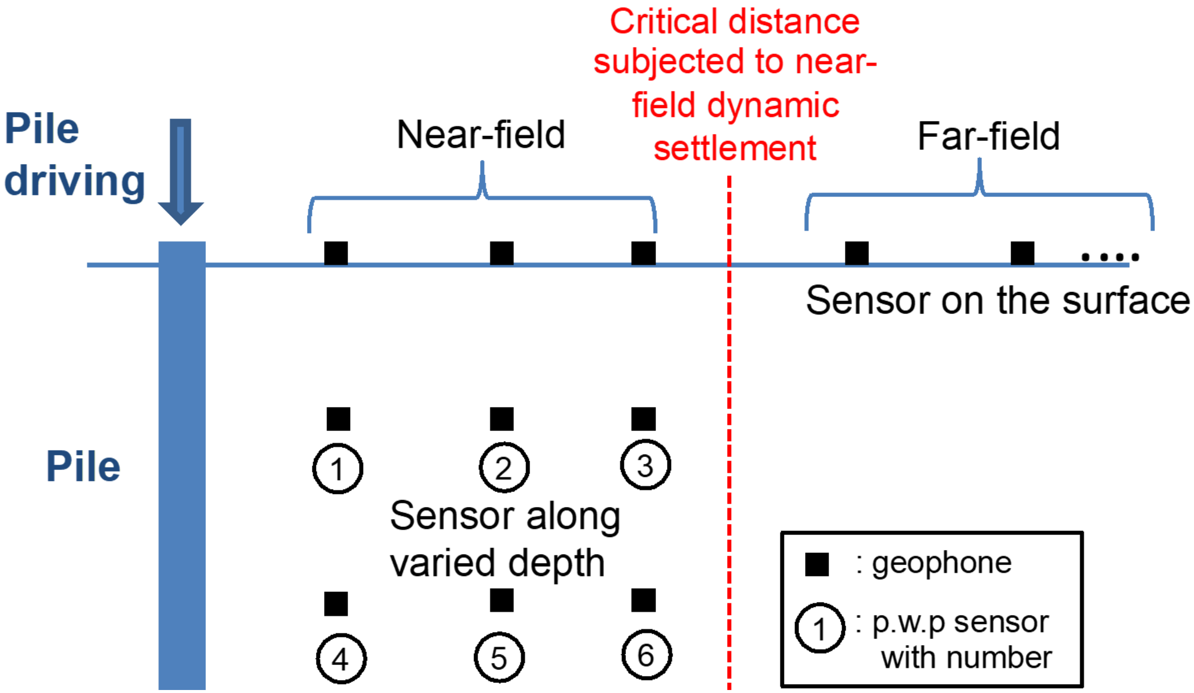
- Near-field settlement: liquefaction mechanism => excess pore water pressure and soil densification
- Far-field settlement: soil densification due to propagated stress waves
- Critical distance (transition) from near-field to far-field

Task 2: (Continuation)

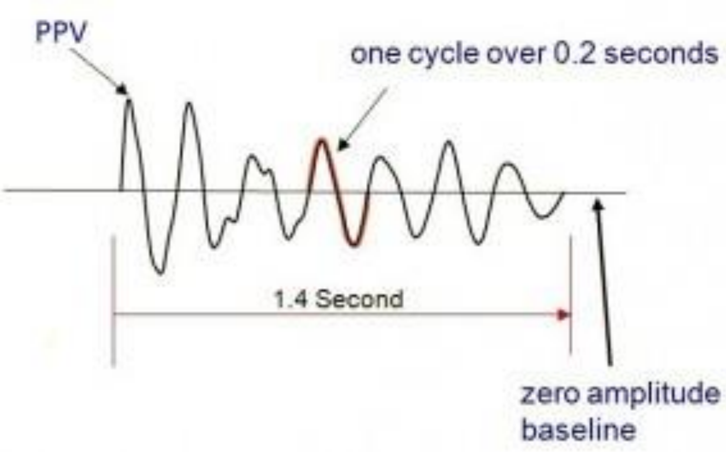
Procedure: Site selection => data collection => instrumentation => field testing

Field testing: to measure PPV, excess pore water pressures, and settlements

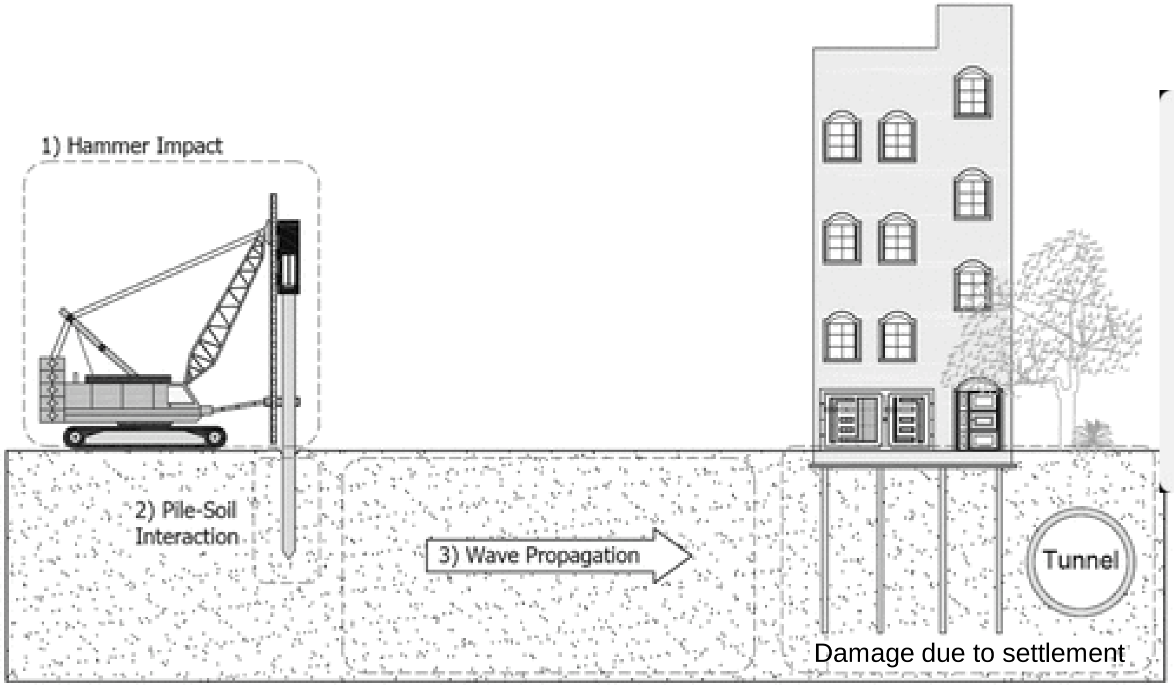
Schematic Diagram



Task 2: (Continuation)



Ground vibration measured at multiple locations



Goal of numerical study:

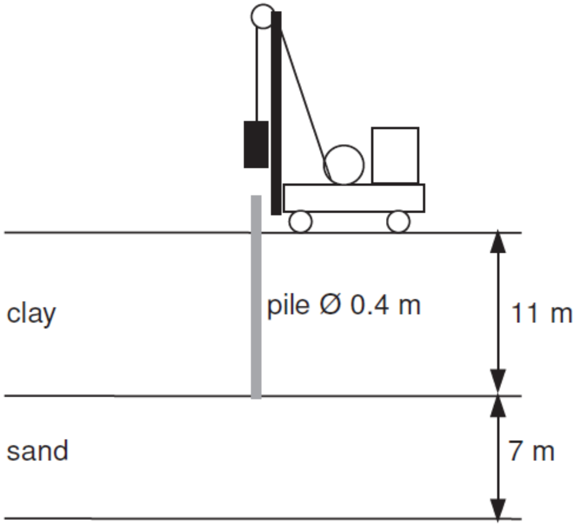
- To solve the question about ground settlements and associated changes in relative density when a pile is driven in Florida soils.

- Use a continuum finite element (FE) numerical model (including soil-pile interaction) to produce a reliable chart (or formula) for pile driving induced settlement.

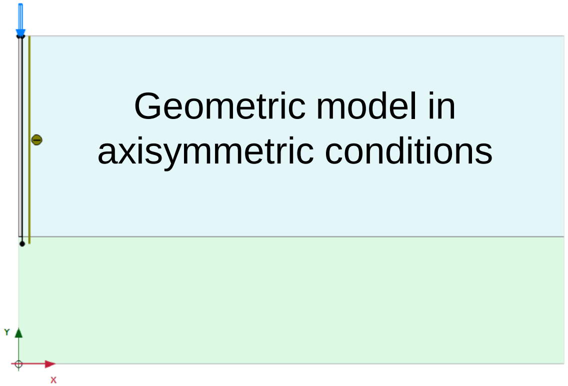
Notes:

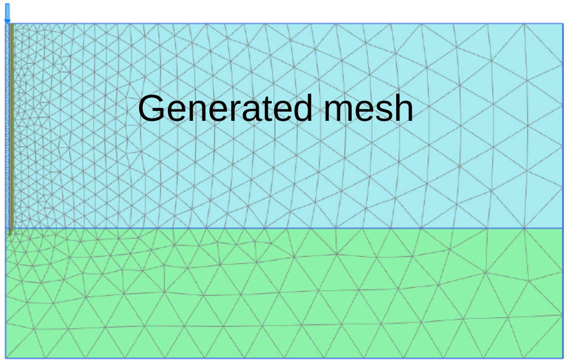
- Research team has used those models in the past (liquefaction analyses and earthquake induced settlements under free-field conditions and when structures are present in earthquake-prone areas, Caltrans Project)

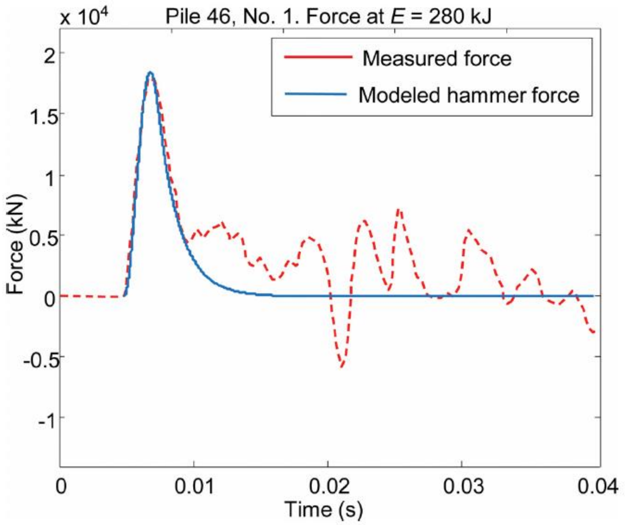
Task 3: Numerical Modeling



Schematic of Pile Driving Installation

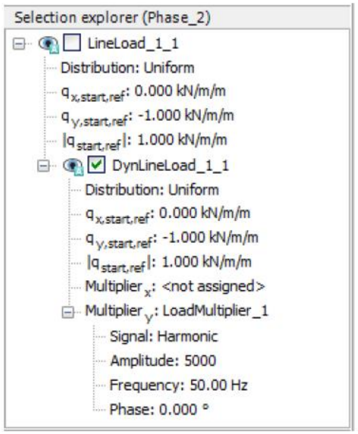






(Typical PDA signal)

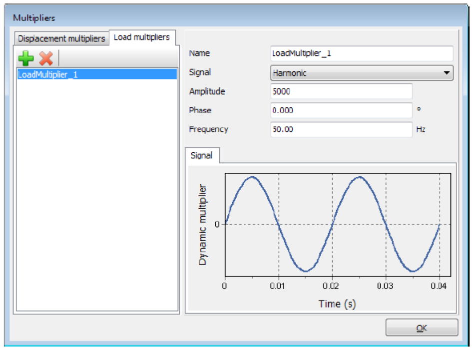
Dynamic loading input



Selection explorer (Phase_2)

- ☐ LineLoad_1_1
  - Distribution: Uniform
  - $q_{x,start,ref}$: 0.000 kN/m/m
  - $q_{y,start,ref}$: -1.000 kN/m/m
  - $|q_{start,ref}|$: 1.000 kN/m/m
  - ☑ DynLineLoad_1_1
    - Distribution: Uniform
    - $q_{x,start,ref}$: 0.000 kN/m/m
    - $q_{y,start,ref}$: -1.000 kN/m/m
    - $|q_{start,ref}|$: 1.000 kN/m/m
    - Multiplier_x: <not assigned>
    - Multiplier_y: LoadMultiplier_1
      - Signal: Harmonic
      - Amplitude: 5000
      - Frequency: 50.00 Hz
      - Phase: 0.000 °

Input driving force versus time (example harmonic)



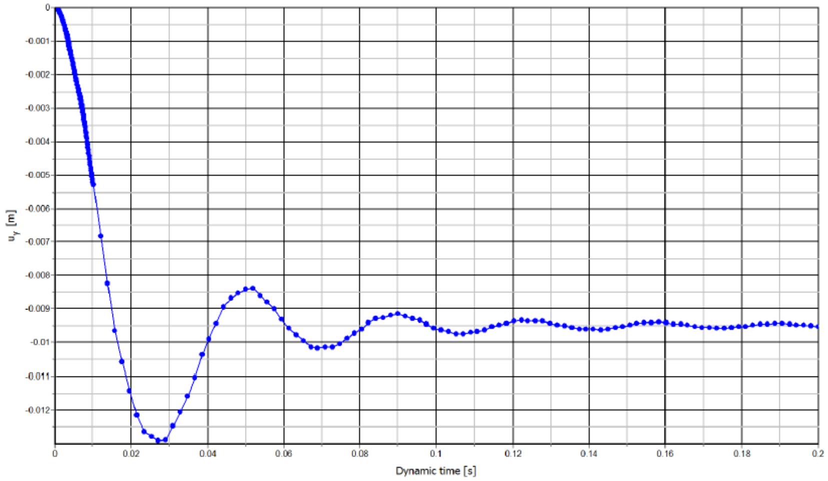
Multipliers

Displacement multipliers | Load multipliers

LoadMultiplier_1

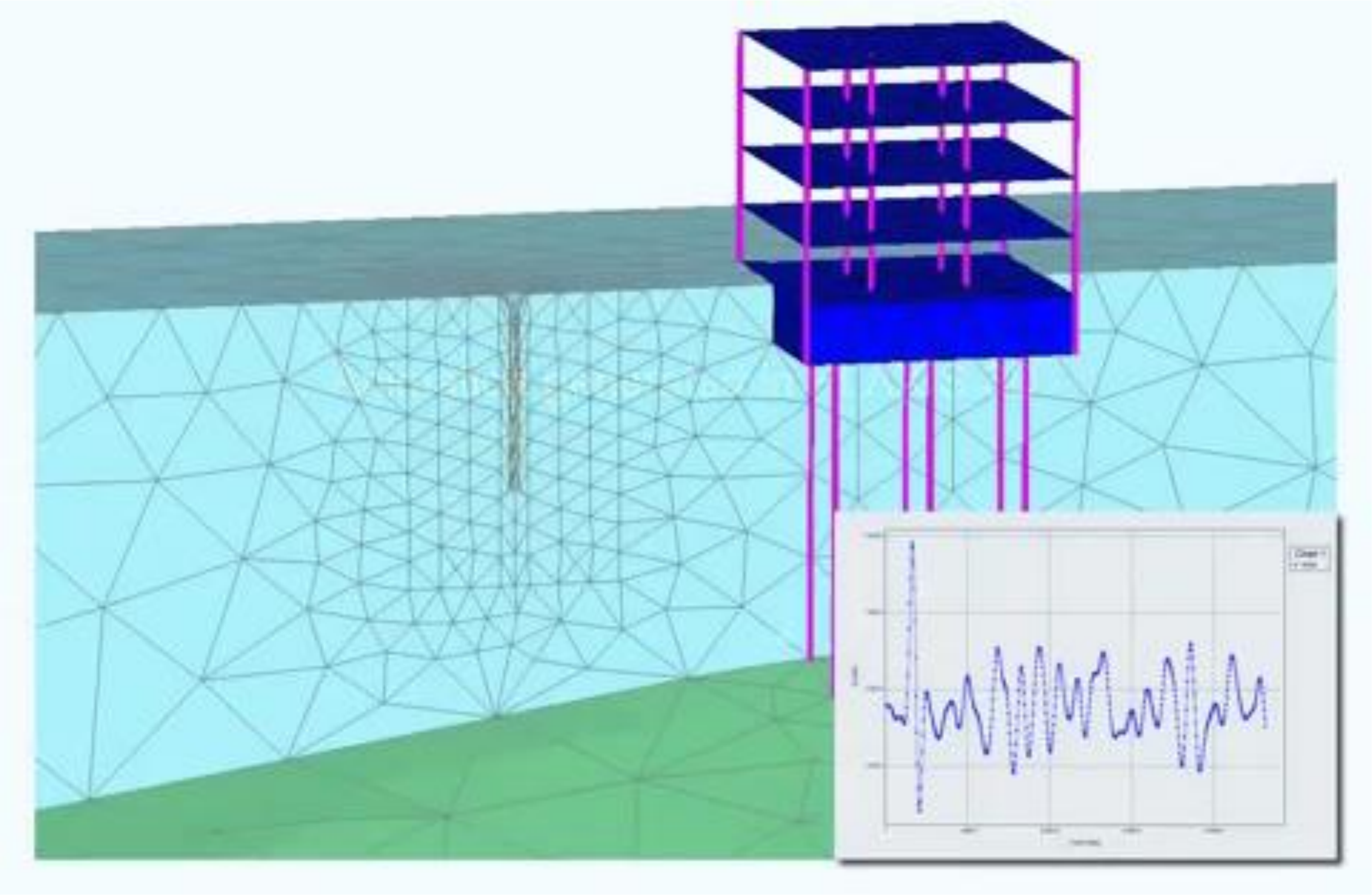
Name: LoadMultiplier_1
Signal: Harmonic
Amplitude: 5000
Phase: 0.000 °
Frequency: 50.00 Hz

Typical output (settlement vs. time) of one hammer blow



Task 3: (Continuation)

Typical output of a forcing function on the pile and structural deformations

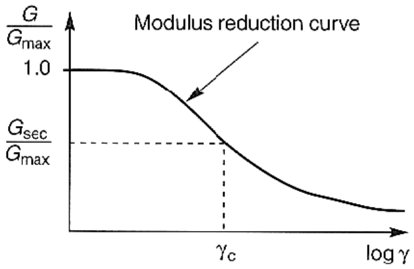


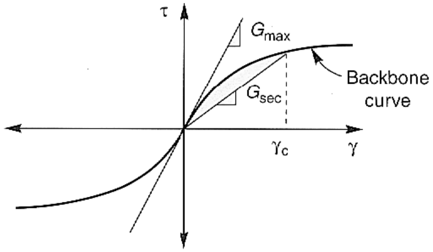
Task 3: (Continuation)

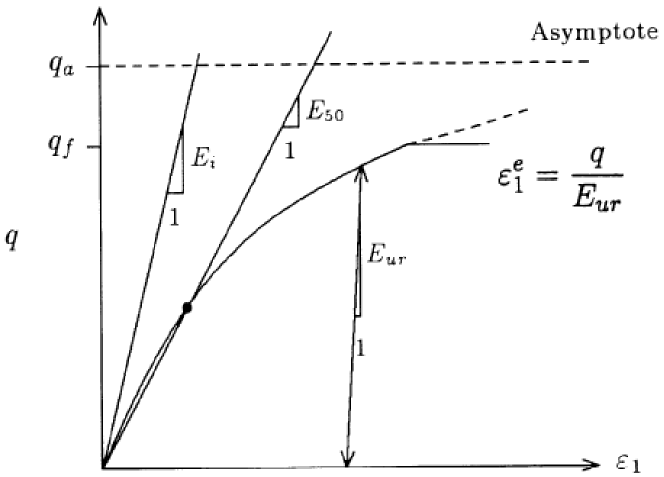
Proposed Model: Hardening Soil Small Model (Plaxis 2D)

Main Characteristics:

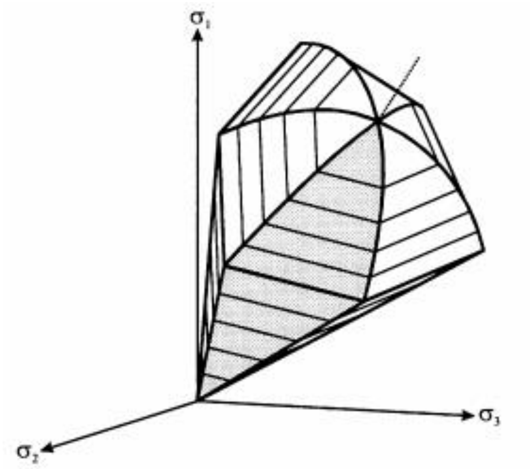
- Elasto-plastic multi-yield surface model
- Hyperbolic stress-strain relation
- Elastic material behavior during unloading and reloading
- Failure based on Mohr-Coulomb criterion
- A yield cap surface controls the volumetric plastic strains
- Small strain behavior included







Hyperbolic stress-strain relation (After Schanz et al. 1999)



Yield Contour (After Schanz et al. 1999)

$$f_{12} = \frac{q_a}{E_{50}} \frac{(\sigma_1 - \sigma_2)}{q_a - (\sigma_1 - \sigma_2)} - \frac{2(\sigma_1 - \sigma_2)}{E_{ur}} - \gamma^p$$

$$f_{13} = \frac{q_a}{E_{50}} \frac{(\sigma_1 - \sigma_3)}{q_a - (\sigma_1 - \sigma_3)} - \frac{2(\sigma_1 - \sigma_3)}{E_{ur}} - \gamma^p$$

$$\gamma^p := \varepsilon_1^p - \varepsilon_2^p - \varepsilon_3^p = 2\varepsilon_1^p - \varepsilon_v^p \approx 2\varepsilon_1^p$$

On the cap yield surface

$$f_c = \frac{\tilde{q}^2}{M^2} + (p + a)^2 - p_c + a)^2$$

Task 3: (Continuation)

Proposed Model: Hardening Soil Small Model

Constitutive Parameters (Schanz et al. 1999, Plaxis 2016):

Parameter	Description	Method
E_{50}^{ref}	Reference modulus for primary loading in drained triaxial test	Drained triaxial test
E_{oed}^{ref}	Reference modulus for primary loading in oedometer test	Oedometer test
E_{ur}^{ref}	Reference modulus for unloading/reloading in drained triaxial test	Drained triaxial test
G_0^{ref}	Reference shear modulus at very small strains	Cyclic shear test
$\gamma_{0.7}$	Threshold shear strain at which $G_s=0.722G_0$	Cyclic shear test
m	Modulus exponent for stress dependency	Curve Fit
υ_{ur}	Poisson´s ratio for loading/unloading	
c'	Effective cohesion intercept at failure	Triaxial or Direct Shear tests
Φ'	Effective friction angle at failure	Triaxial or Direct Shear tests
ψ	Dilatancy angle at failure	Triaxial or Direct Shear tests
σ_p	Initial preconsolidation stress	Oedometer test
ko	Earth pressure coefficient at rest	

Proposed correlations:

$$E_{50} = E_{50}^{ref}\left(\frac{\sigma_3 + c\cot\varphi_p}{\sigma^{ref} + c\cot\varphi_p}\right)^m$$

$$E_{oed} = E_{oed}^{ref}\left(\frac{\sigma_1 + c\cot\varphi_p}{\sigma^{ref} + c\cot\varphi_p}\right)^m$$

$$E_{ur} = E_{ur}^{ref}\left(\frac{\sigma_3 + c\cot\varphi_p}{\sigma^{ref} + c\cot\varphi_p}\right)^m$$

$$E_{ur,oed} \approx 3E_{oed}$$

$$E_{ur}^{ref} \approx 3E_{oed}^{ref}/\sqrt{K_0} \approx 4E_{oed}^{ref}$$

$$G_0 = G_0^{ref}\left(\frac{c\cos\varphi - \sigma'_3\sin\varphi}{c\cos\varphi + p^{ref}\sin\varphi}\right)^m$$

$$\gamma_{0.7} \approx \frac{1}{9G_0}[2c'(1+\cos(2\varphi')) - \sigma'_1(1+K_0)\sin(2\varphi')]$$

After Schanz et al. (1999) and Plaxis (2016)

12 Constitutive Parameters

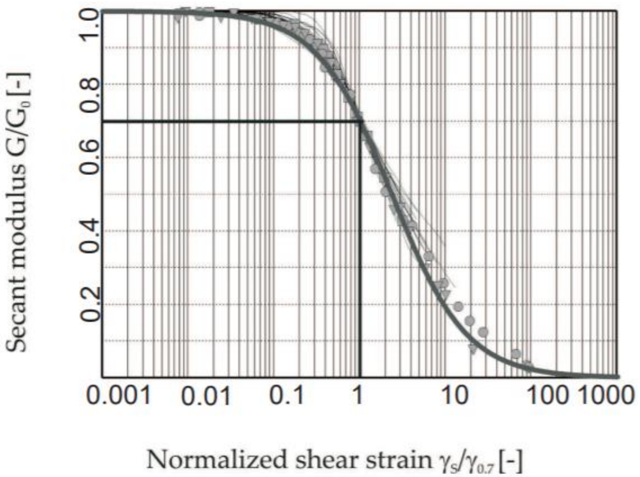
Task 3: (Continuation)

Proposed Model: Hardening Soil Small Model

More features:

- Elastoplastic type of hyperbolic model based on HS model
- Incorporates strain-dependent stiffness moduli to simulate soil behavior at small strains from the very small (i.e., strains lower than 0.001%) to large until failure (i.e., strains above 0.1%)

Results from Hardin-Drnevich relationship compared to Santos and Correia (2001)



Hyperbolic law, Hardin and Drnevich (1972)

$$\frac{G_s}{G_0} = \frac{1}{1 + \left|\frac{\gamma}{\gamma_r}\right|}$$

Where threshold shear strain is: $\gamma_r = \frac{\tau_{max}}{G_0}$

Example, Santos and Correia (2001): $\gamma_r = \gamma_{0.7}$ at which the secant shear modulus Gs is reduced to 70% of its initial value

$$\frac{G_s}{G_0} = \frac{1}{1 + a\left|\frac{\gamma}{\gamma_{0.7}}\right|}$$

where $a = 0.385$

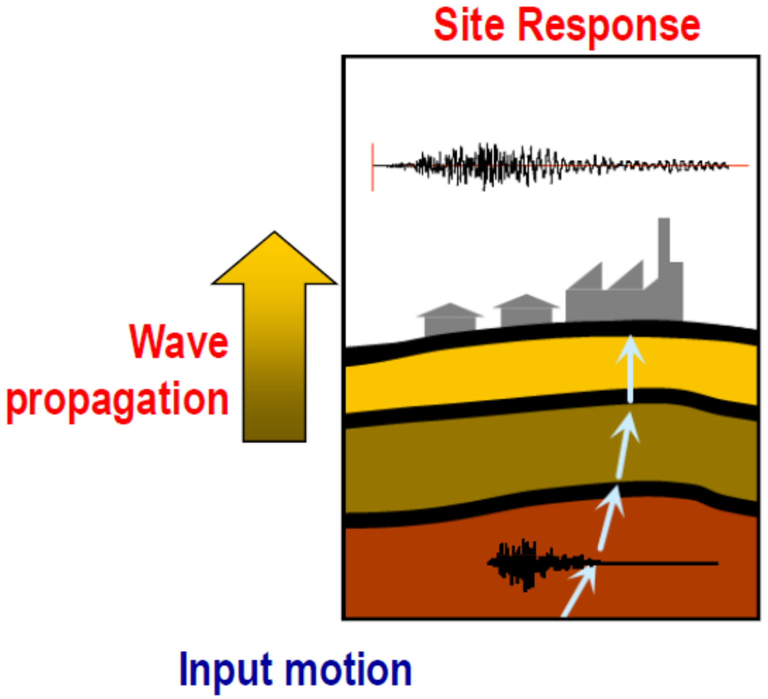
(Taken from Plaxis Material Model Manual, 2016)

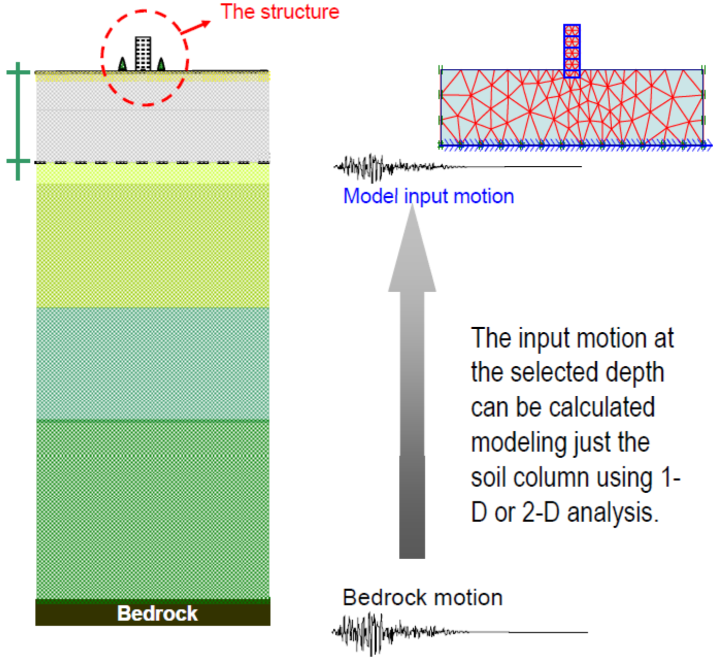
Task 3: (Continuation)

Analogous Problem: Numerical simulation of liquefaction and seismic response of tall buildings

- Site response effects are evaluated by a simulation of the propagation of the seismic waves.

- Wave propagation can be described by the solution of the dynamic equation of motion PLUS with a stress-strain model (i.e., constitutive soil model) of the material in which the waves propagate





The input motion at the selected depth can be calculated modeling just the soil column using 1-D or 2-D analysis.

Task 4: Develop empirical prediction formula or chart

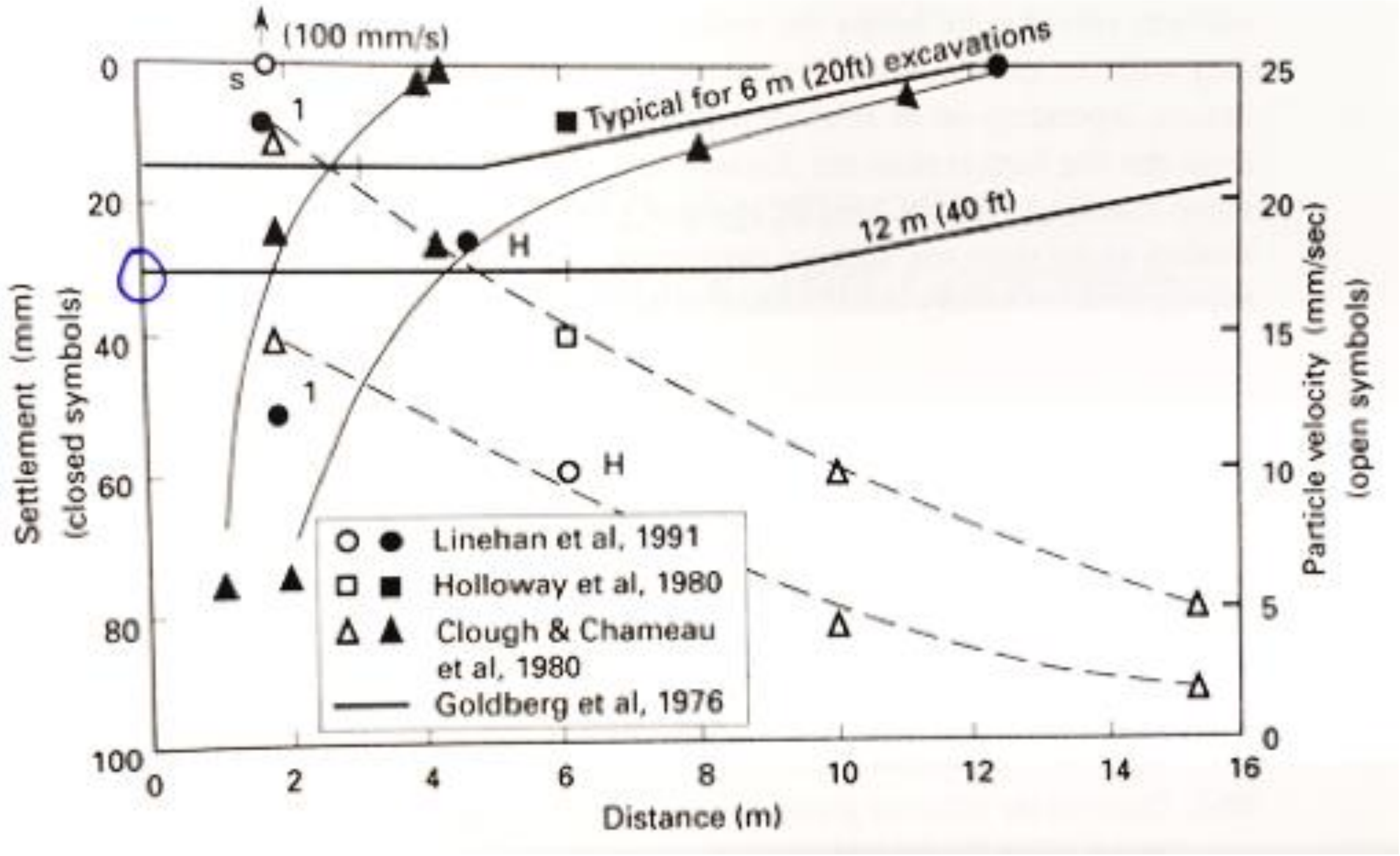
- Scope:
  To develop a dynamic settlement prediction formula and/or chart

- Correlations
  PPV vs. distance; Settlement vs. variables (e.g. PPV, distance, Dr, excess pwp)

- Dynamic settlement prediction model
  Dyn. Settlement = f(PPV, distance, soil condition)

Task 4: (Continuation)

Example of settlement vs. distance (from Dowding 1996)



Task 5: Guidelines and Recommendations

1) Guideline of field instrumentation procedures for measurement and monitoring dynamic settlements (e.g., sensor type, sensor number, location, and spacing)

2) Recommendations and key considerations for near-field and far-field dynamic settlement analysis

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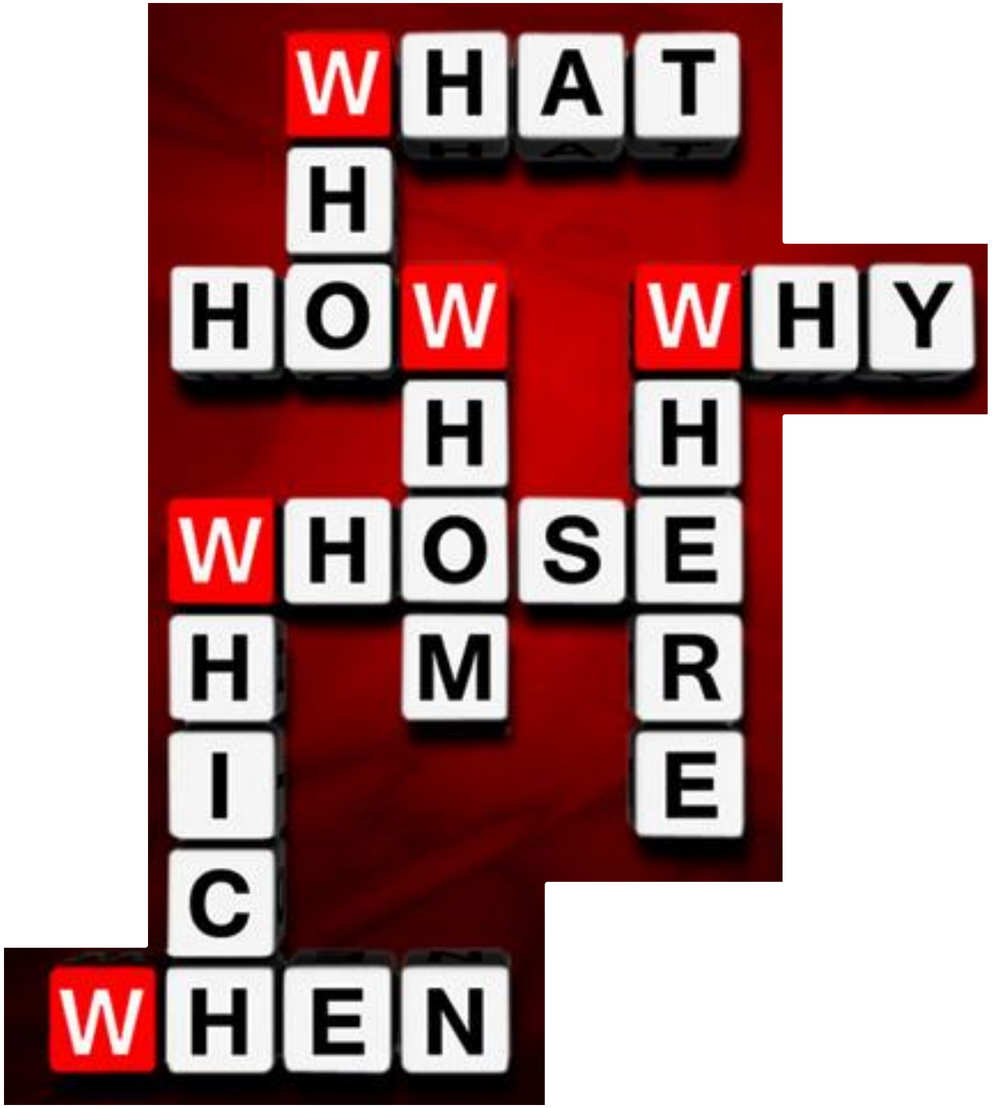
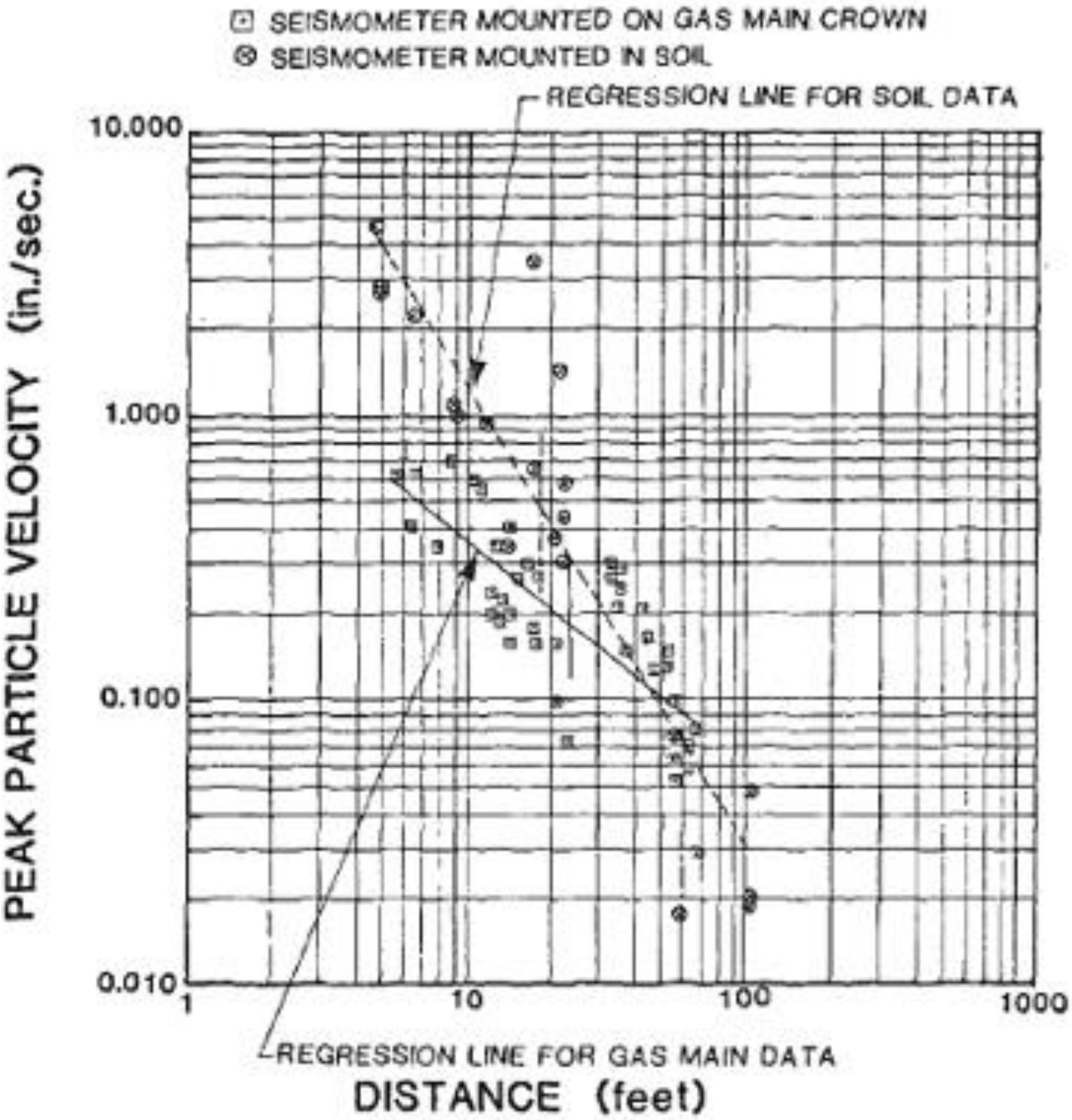


Task 4: (Continuation)

Example of PPV vs. distance (Linehan et al. 1991)



Proposed Model 2: Pressure dependent multi-yield model (OpenSees)

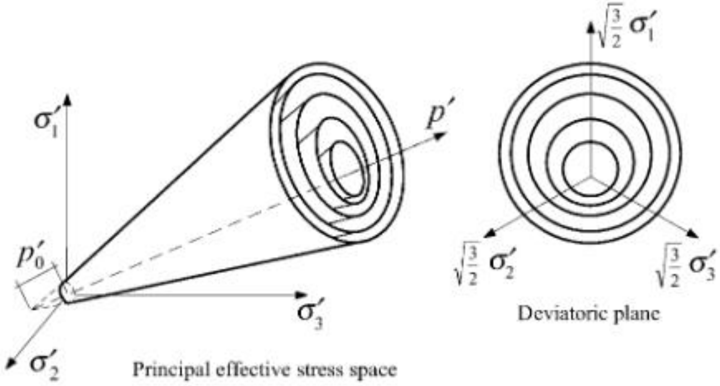
Main Characteristics:

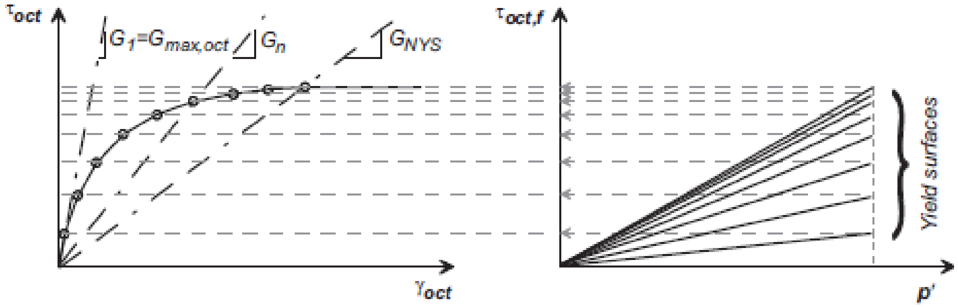
- Post-liquefaction is captured (necessary to estimate settlements)
- Main model and program used for liquefaction purposes in California
- Fully coupled model of water and soil necessary to accurately model settlement from water pressures
- The research team has experience on its use for earthquake loadings (similar but the main difference is the range of frequencies)

Proposed Model 2: Pressure dependent multi-yield model (OpenSees)

Main Characteristics:

- It is an elastoplastic model used to simulate the monotonic and cyclic response depending on the confining pressure.
- It defines the multi-yield criteria by the number of open conical shaped yield surfaces (i.e., Drucker-Prager yield surface) with a common apex at the origin.
- The outermost surface defines the shear strength envelope of the material.
- Uses a nonlinear kinematic hardening and non-associative flow rules to reproduce the dilative or contractive behavior.
- The plastic flow is purely deviatoric, thus no plastic change of volume takes place under a constant stress ratio.





Elgamal et al. 2002; Yang et al. 2003, 2008

BACKGROUND: Numerical modeling for dynamic settlement

Proposed Model 2: Pressure dependent multi-yield model (OpenSees)

Parameter	Dr=32% to 35% CID Tests
Mass Density (kN)	1.9
Reference G (MPa)	60000
Reference B (MPa)	180000
Frinction Angle (°)	34.5
Peak Shear Strain (%)	0.15
Ref. Pression (kPa)	101
Press Depend Coef. (-)	0.5
Phase Transformation Angle (°)	30
Contraction Param. 1 (-)	0.06
Contraction Param. 2 (-)	4
Contraction Param. 3 (-)	0.21
Dilation Param. 1 (-)	0.1
Dilation Param. 2 (-)	3
Dilation Param. 3 (-)	0.2
Liquefaction Param. 1 (-)	1
Liquefaction Param. 2 (-)	0
noYieldSurf (-)	30
Void ratio(-)	0.74
cs1 (-)	0.9
cs2 (-)	0.02
cs3 (-)	0
pa (kPa)	101
c (-)	0.1

Elastic Parameters

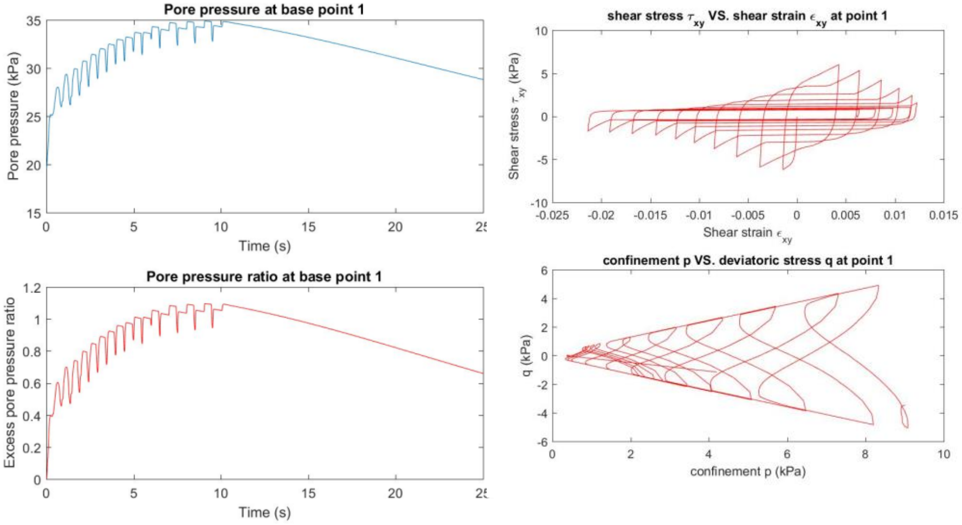
Fitting Parameters

Behavior Parameters

Liquefaction
Limit State

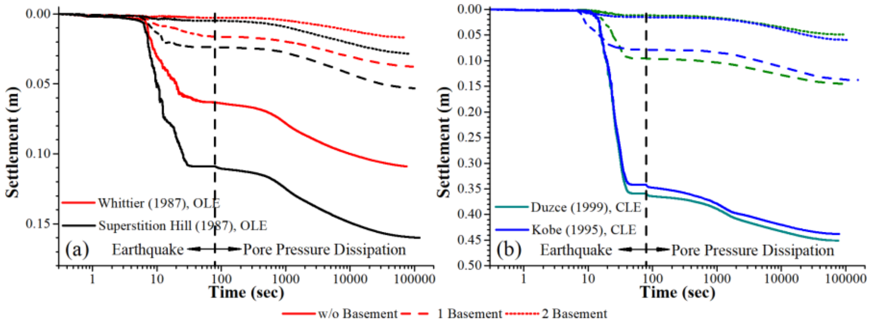
Critical State
Parameters

Numerical Simulations and Cyclic Strength Curve

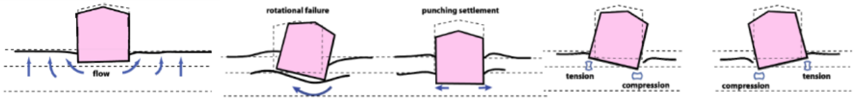


Task 3: (Continuation)

Dynamic settlement due to EQs



Primary liquefaction-induced displacement mechanisms (Dashti and Bray 2013)

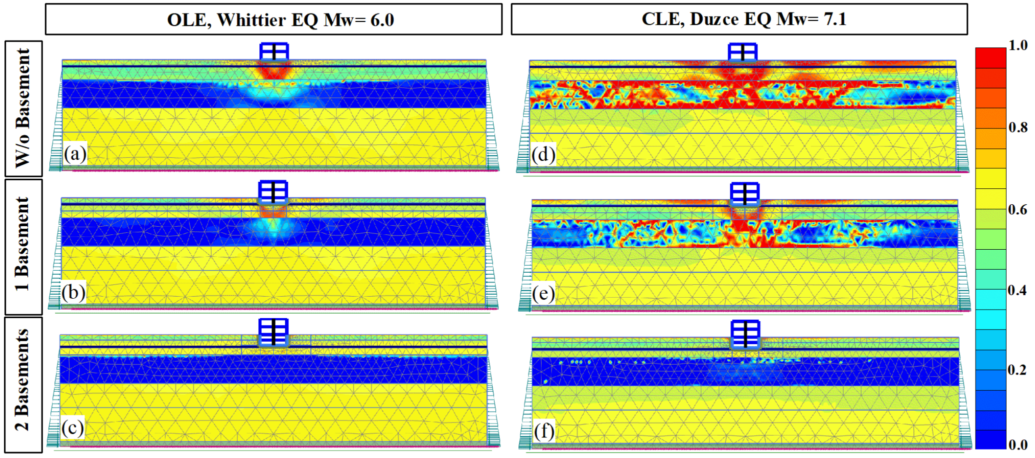


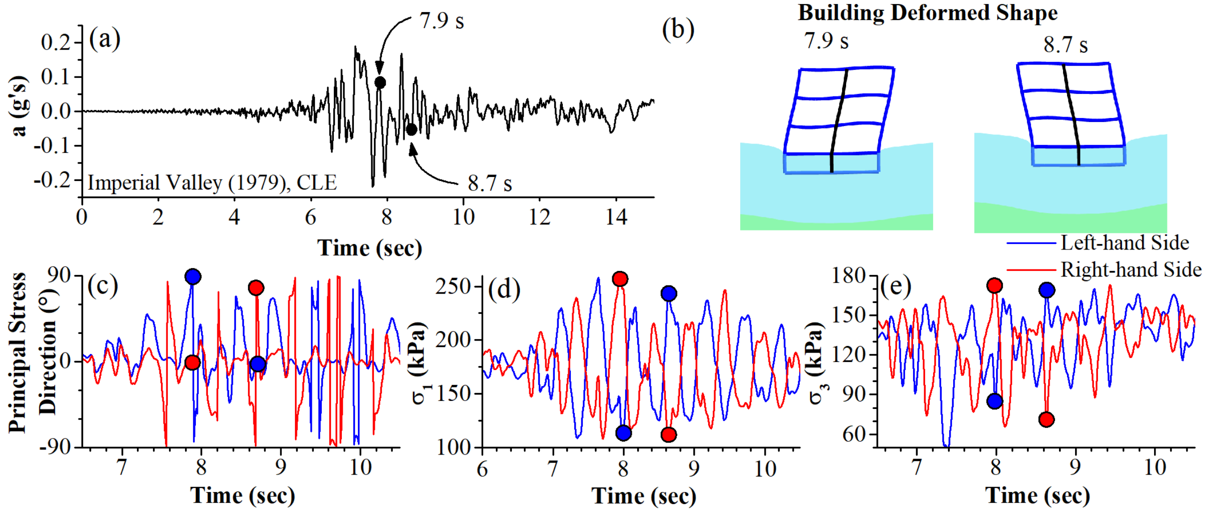
(a) vol. strains by water flow in response to transient gradients;

(b) partial bearing capacity failure as a result of soil softening;

(c) liquefaction-induced building ratcheting during earthquake loading

Relative shear stresses





Task 2: (Continuation)

Option No. 2 (prescribed displacements)

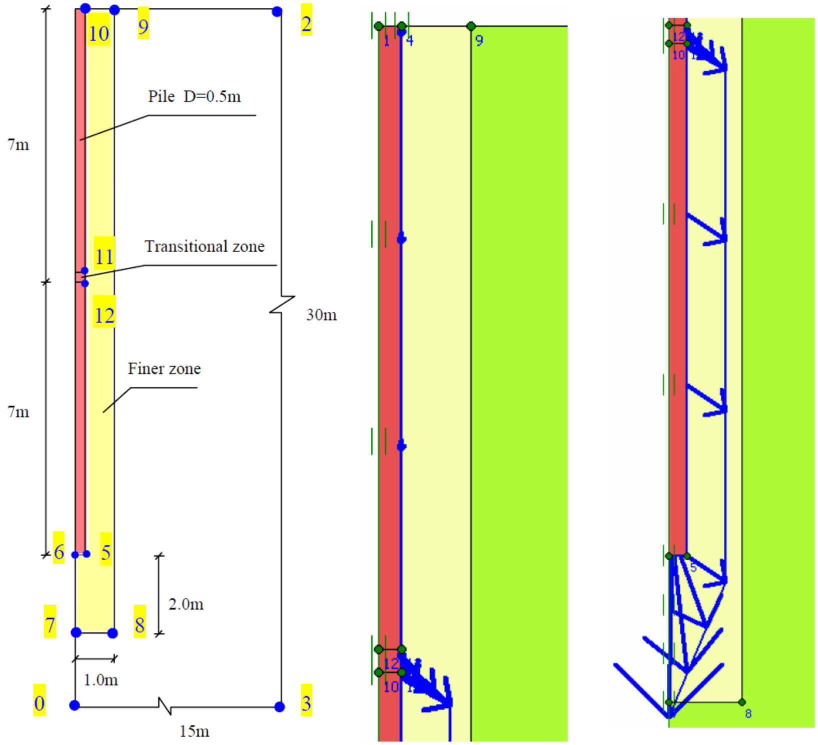
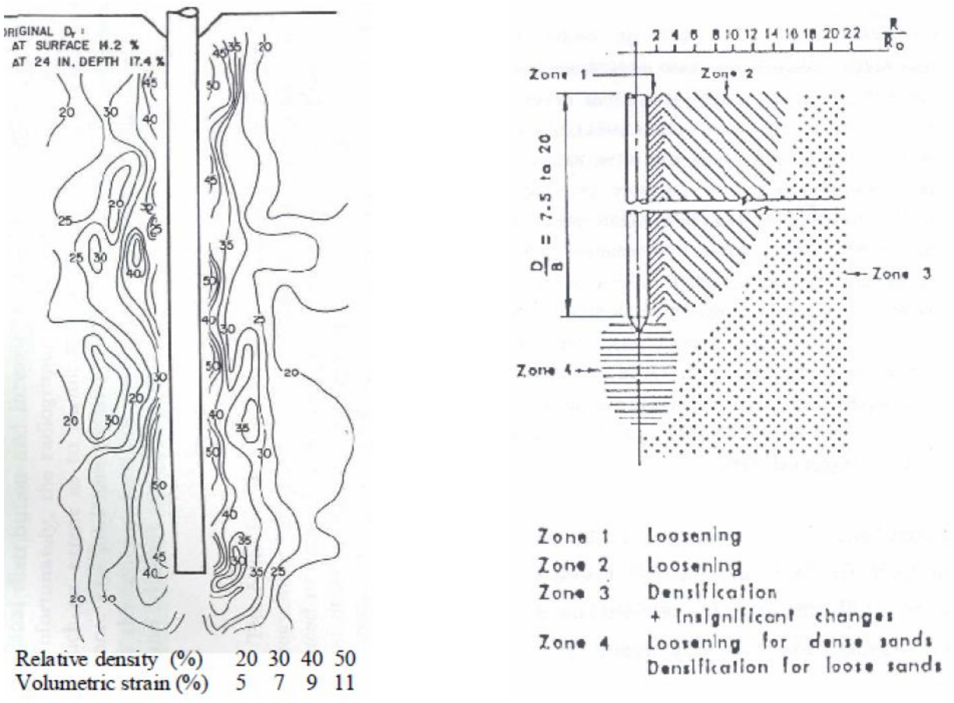


Fig. 5.5: Detailed pile model (left) and prescribed displacements (right)

Simulation of installation effects



Robinsky and Morrison [32]

Chong [8]

Fig. 5.6: Observed changes in density during the installation