

Soil–Foundation–Structure Interaction Simulations: Static and Dynamic Issues

Boris Jeremić

Department of Civil and Environmental Engineering
University of California, Davis

Leitmotiv

- Create high fidelity models of constructed facilities (bridges, buildings, port structures, dams...).
- Models will live concurrently with the physical system they represent.
- Models to provide owners and operators with the capabilities to assess operations and future performance.
- Use observed performance to update and validate models through simulations.

Presentation Overview

- Role of numerical simulations
- Static (kinematic) behavior
 - Layered soils
 - Pile groups
- Dynamic behavior
 - Application of seismic loads (motions)
 - Site response analysis
 - From large scale geophysical simulations to large scale soil–structure simulations
 - Application to long bridges

Goal

- **Develop** and **use** computational models in order to
 - Design physical tests
 - Use observed behavior to **validate** and **improve** models
 - Use validated models to **predict** behavior of realistic bridge systems
- Educate users about new, exciting simulation tools that are now available

Goals of Validation

Quantification of uncertainties and errors in the computational model and the experimental measurements

- Goals on validation
 - Tactical goal: Identification and minimization of uncertainties and errors in the computational model
 - Strategic goal: Increase confidence in the quantitative predictive capability of the computational model
- Strategy is to reduce as much as possible the following:
 - Computational model uncertainties and errors
 - Random (precision) errors and bias (systematic) errors in the experiments
 - Incomplete physical characterization of the experiment

Validation Procedure Uncertainty

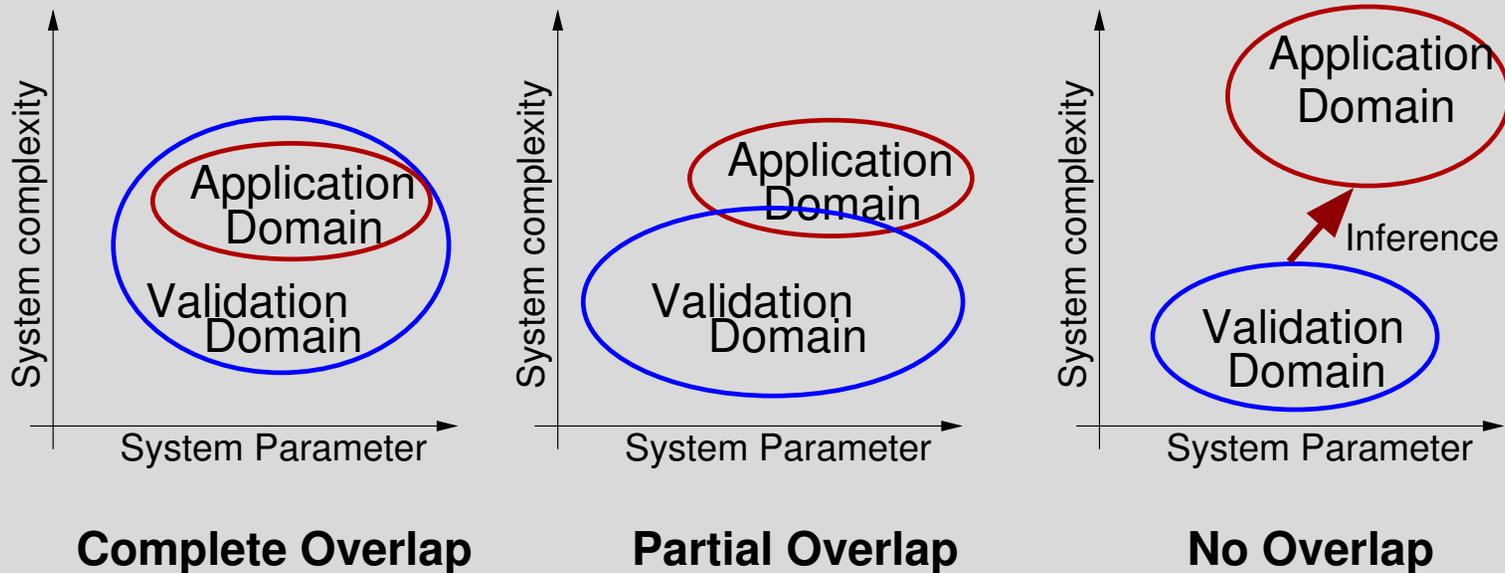
- Aleatory uncertainty → inherent variation associated with the physical system of the environment (variation in external excitation, material properties...). Also known as irreducible uncertainty, variability and stochastic uncertainty.
- Epistemic uncertainty → potential deficiency in any phase of the modeling process that is due to lack of knowledge (poor understanding of mechanics...). Also known as reducible uncertainty, model form uncertainty and subjective uncertainty



Validation Experiments

- A validation experiment should be jointly designed and executed by experimentalist and computationalist
 - Need for close working relationship from inception to documentation
 - Elimination of typical competition between each
 - Complete honesty concerning strengths and weaknesses of both experimental and computational simulations
- A validation Experiment should be designed to capture the relevant physics
 - Measure all important modeling data in the experiment
 - Characteristics and imperfections of the experimental facility should be included in the model

Application Domain



- Inference \Rightarrow Based on **physics** or **statistics**
- Validation domain is actually an aggregation of tests (points) and might not be convex (bifurcation of behavior)
- NEES research provides for validation domain (experimental facilities) that are mostly (if not exclusively) **non-overlapping** with the application domain.

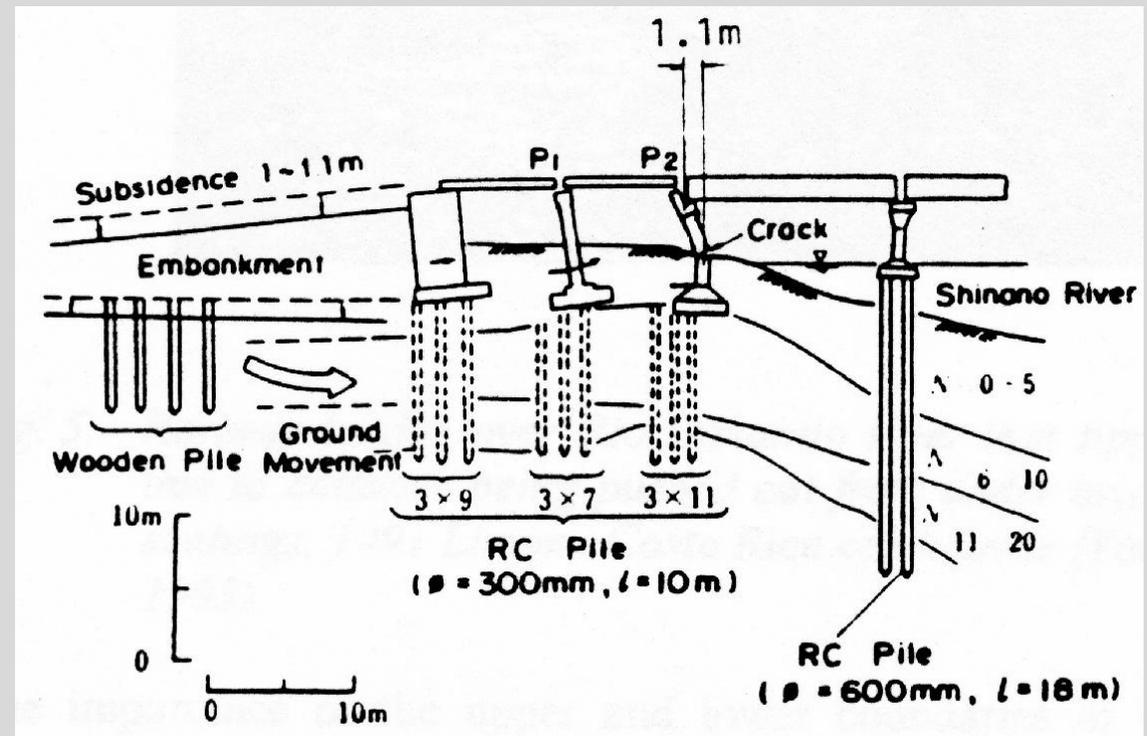
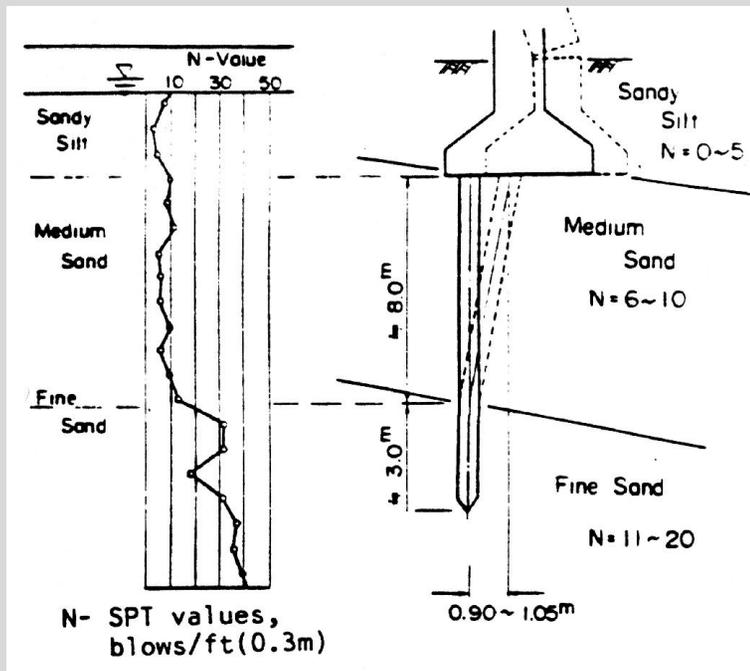
Computability

Physical Problem Computability : (von Neumann computability)
how well a mathematical model can predict the response of a mechanical system (related to validation)

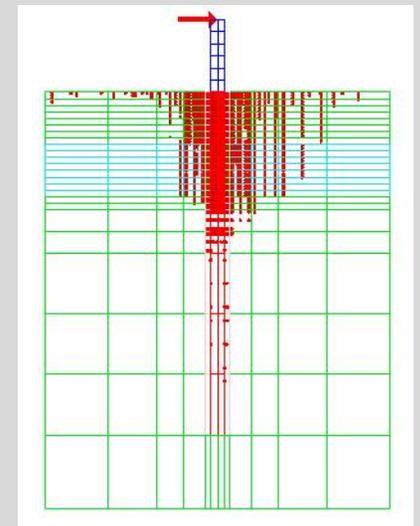
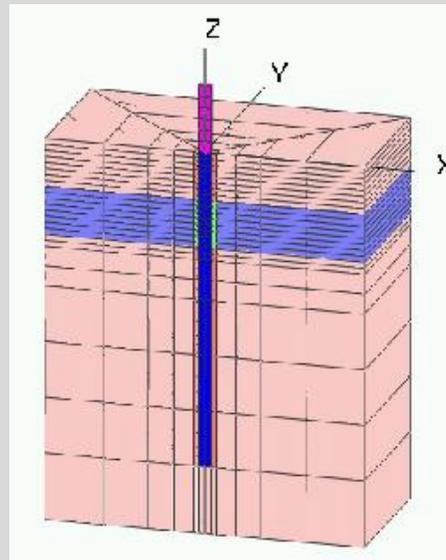
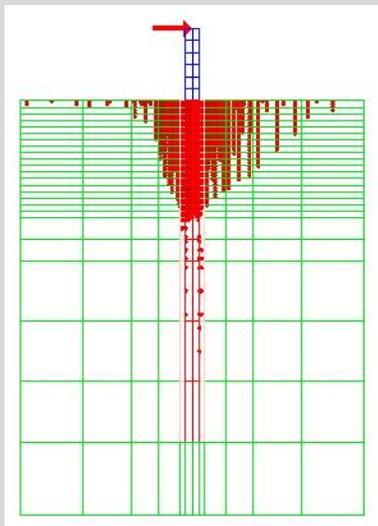
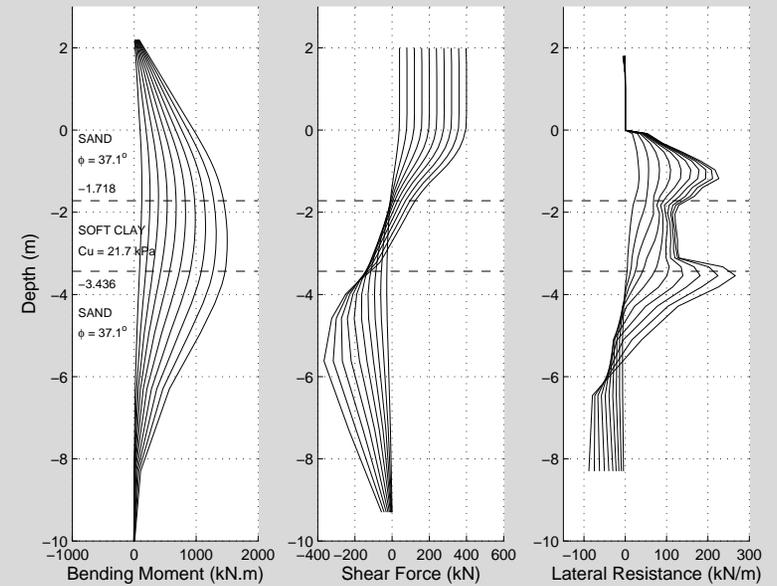
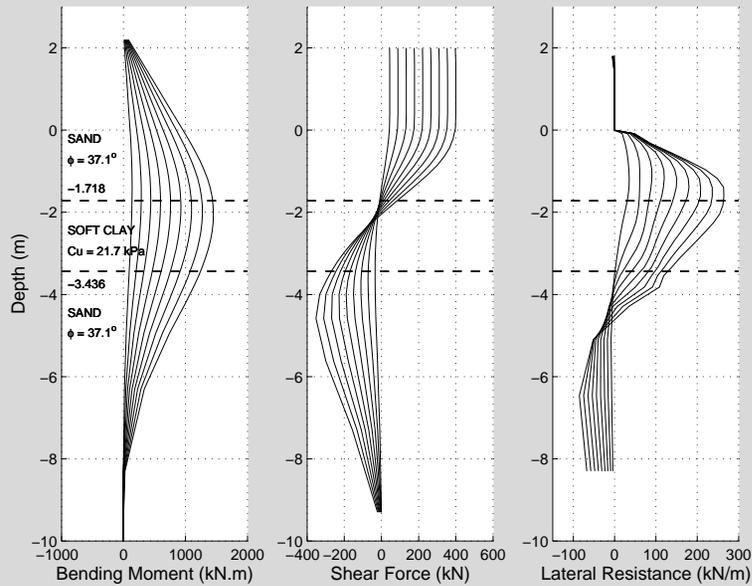
Computational computability : (Turing computability) discretized problem is computable if there exists an algorithm that can solve the problem in a finite number of steps (related to verification)

Static (Kinematic) SFSI

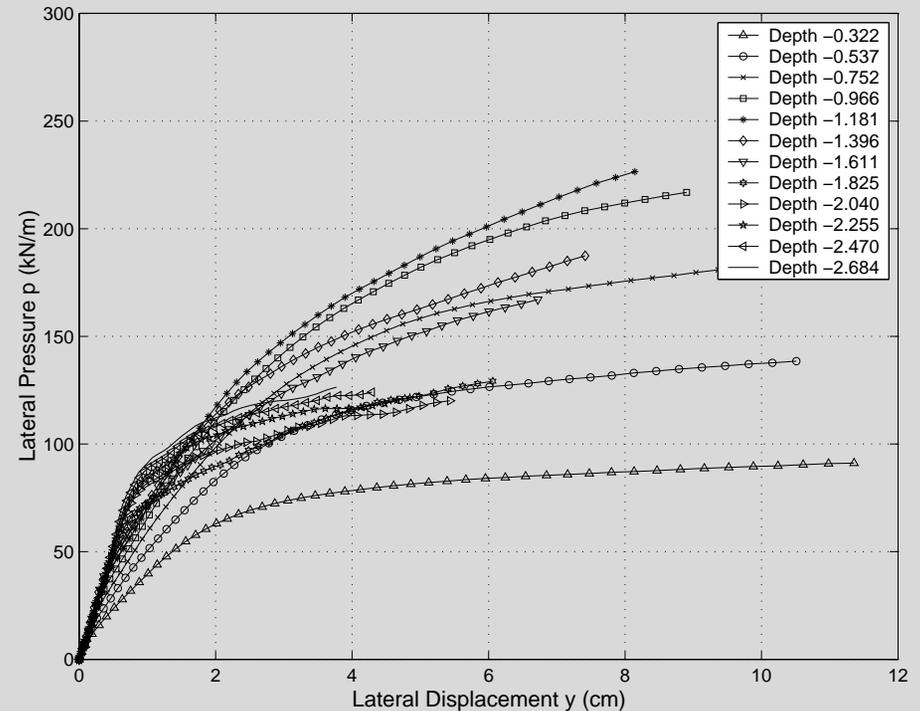
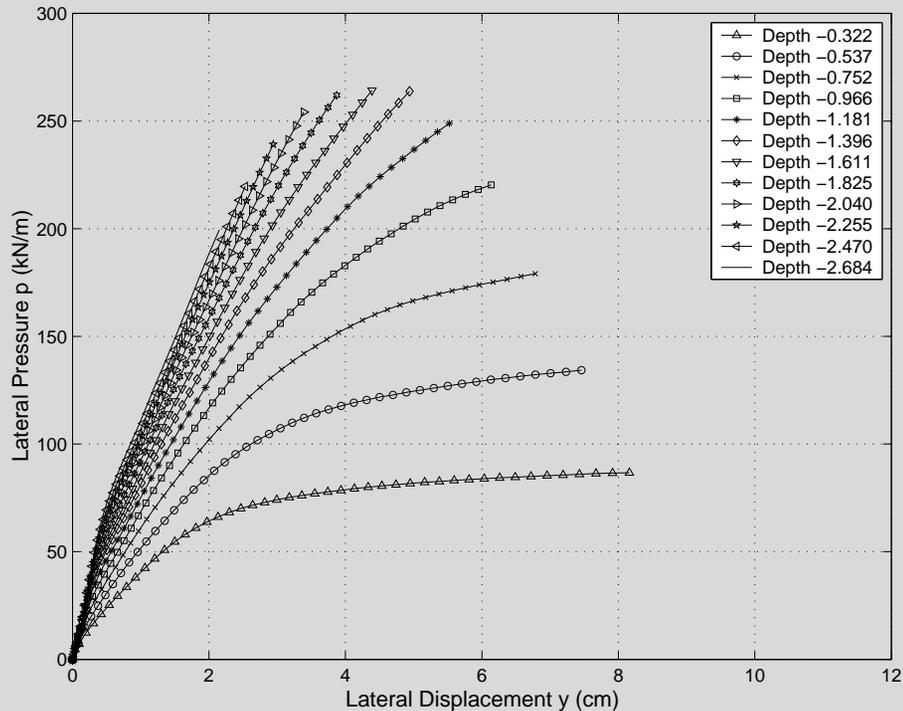
- Computational geomechanics for large scale problems
- Single pile behavior in elastic-plastic soils, effects of layers
- Pile group behavior



Single Pile in Layered Soils

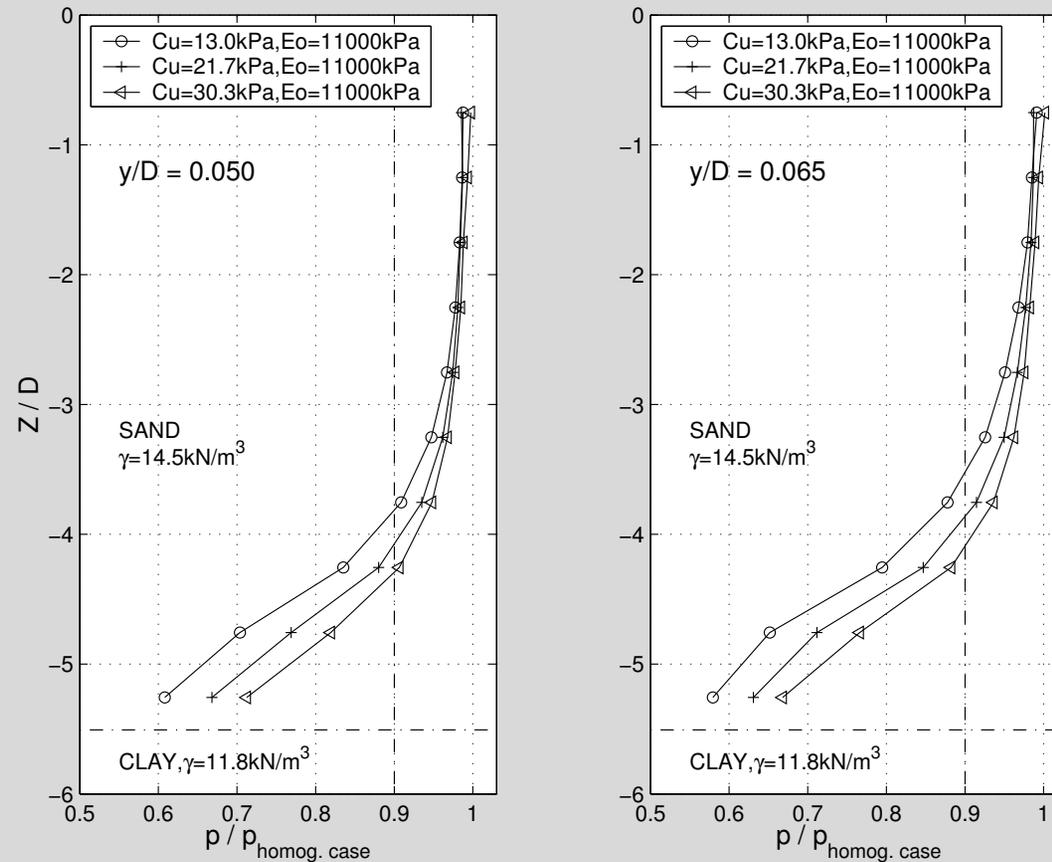


$p - y$ Response for Single Pile in Layered Soils



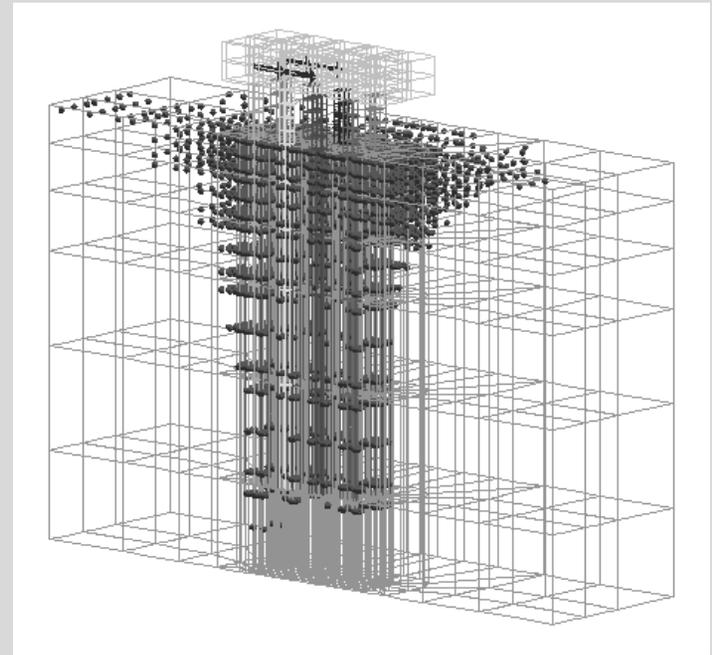
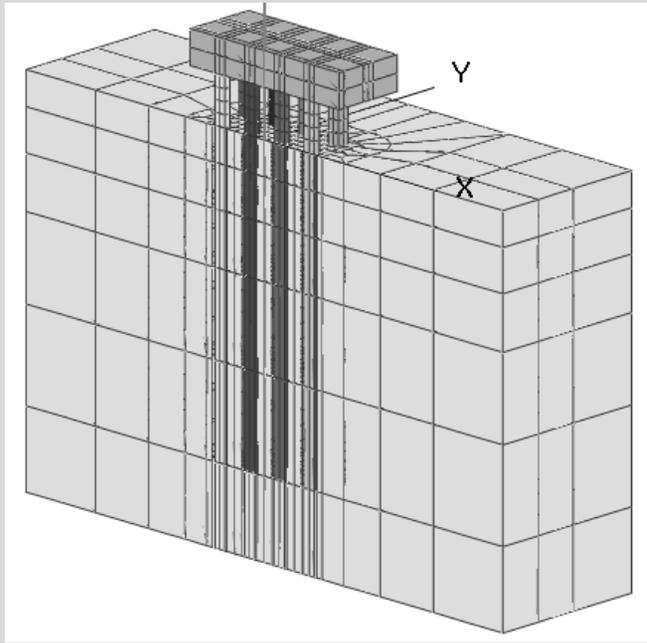
- Influence of soft layers propagates to stiff layers and vice versa
- Can have significant effects in soils with many layers

Lateral Resistance Ratio Distributions



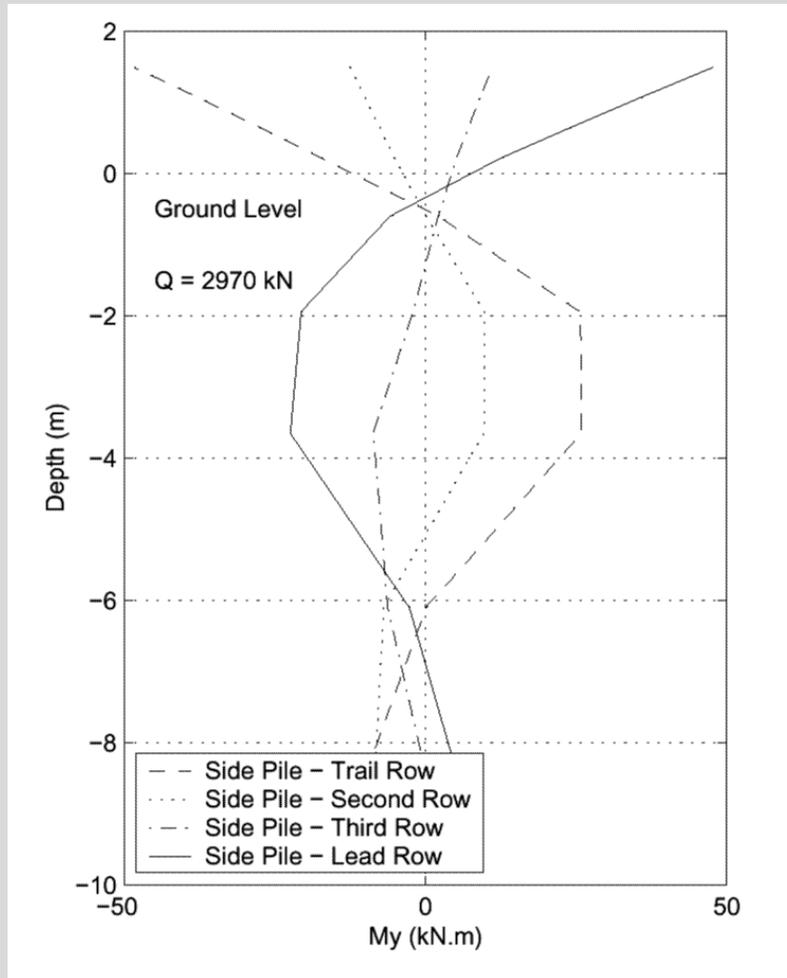
- Influence increases as the shear strength of soft layer decreases (think of cyclic mobility of liquefaction)

Pile Group Simulations



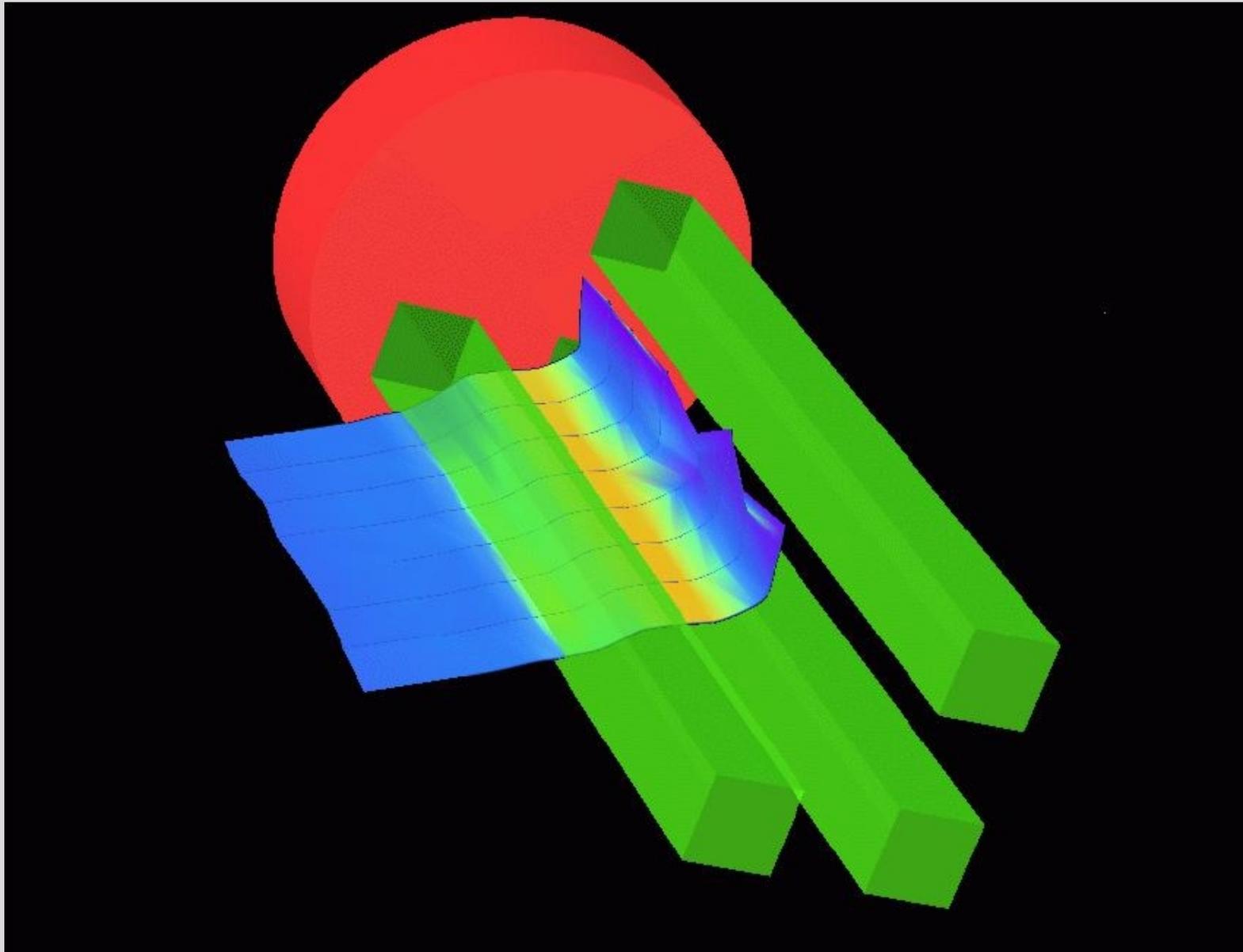
- 4x3 pile group model and plastic zones

Out of Plane Effects

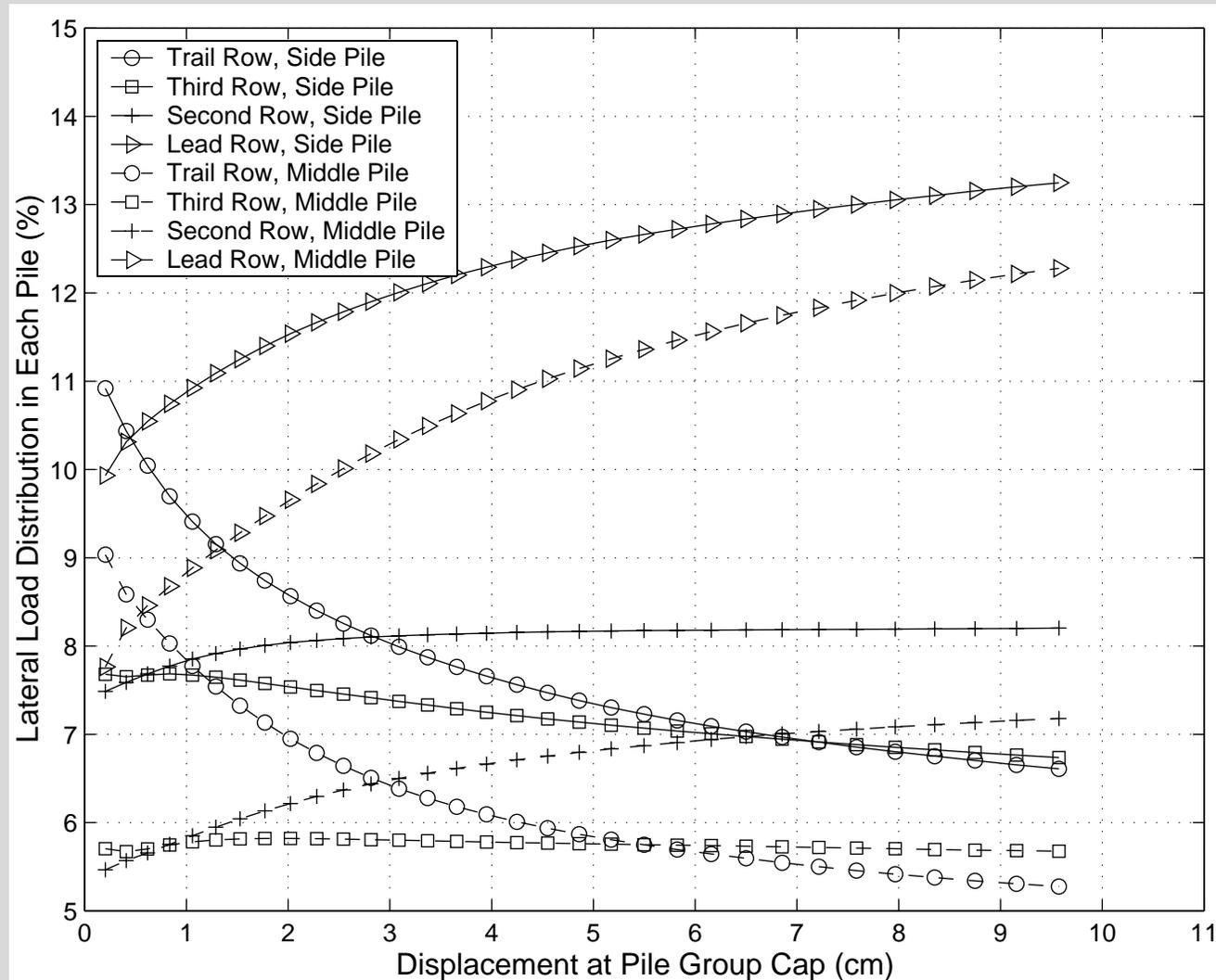


- Out-of-loading-plane bending moment diagram,
- Out-of-loading-plane deformation.

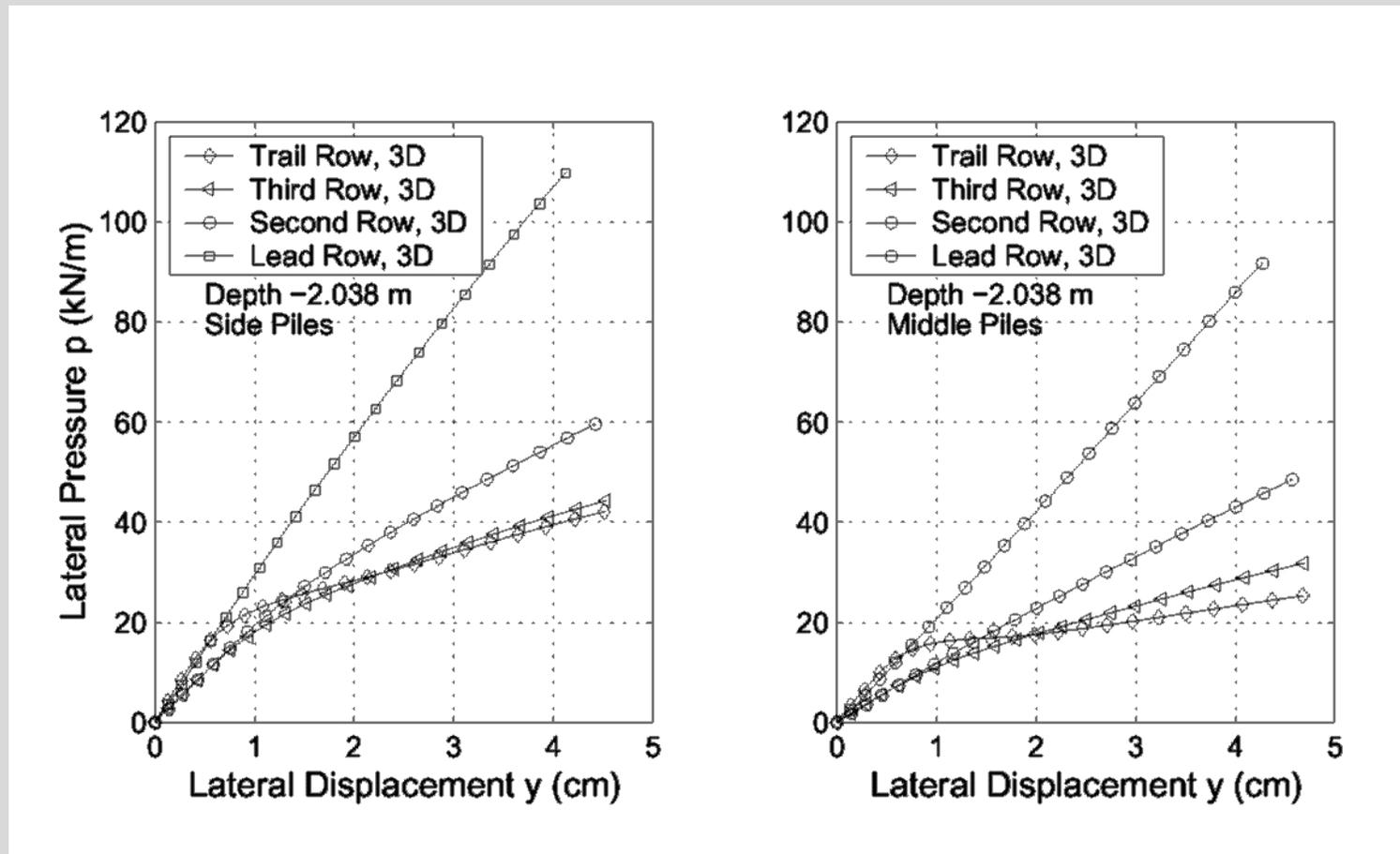
Pile Spreading Stress Path



Load Distribution per Pile

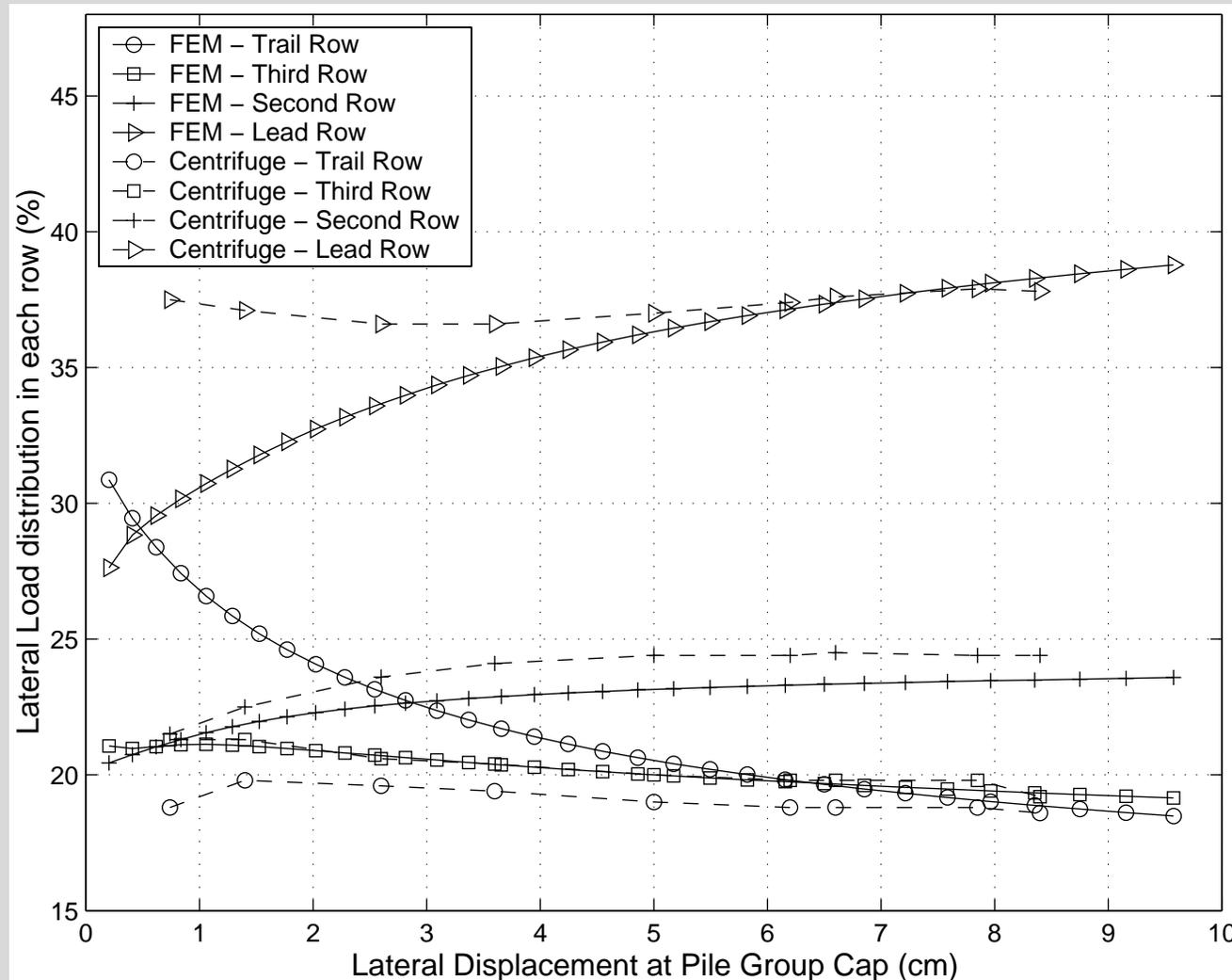


Piles Interaction at -2.0m



- Note the difference in response curves (cannot scale single pile response for multiple piles)

Comparison with Centrifuge Tests



Dynamic SFSI

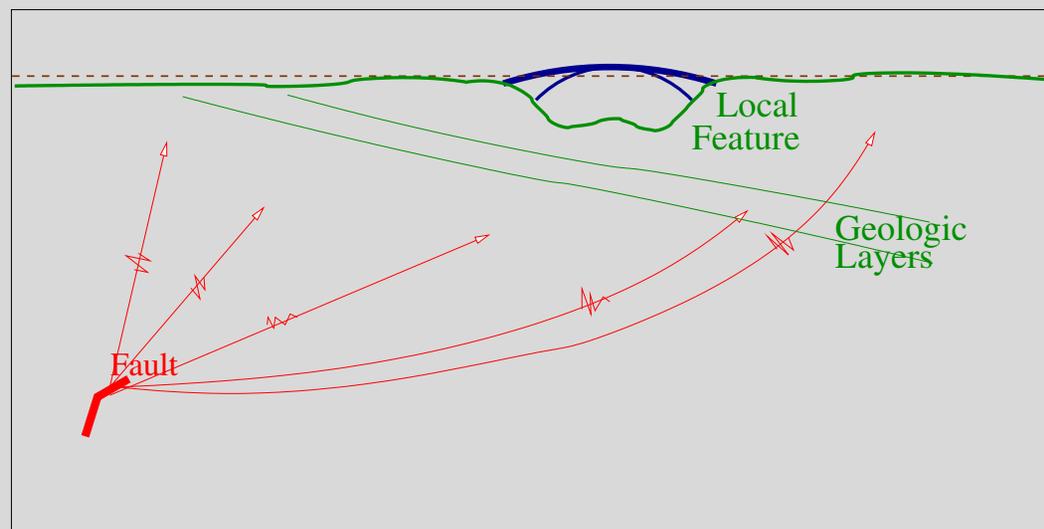
- Application of seismic loads (motions)
- Site response analysis
- From large scale geophysical simulations to large scale soil–structure simulations
- Application to long bridges

Domain Reduction Method (DRM)

- Work by Bielak et al. (2003, Bulletin of the Seismological Society of America) at CMU.
- Modular, two step procedure for large 3D dynamics problems.
- Primary unknowns:
 - Total wave field within the local domain,
 - Scattered wave field in the exterior domain,
- Free field wave field from the background structure only act on a single concave surface.

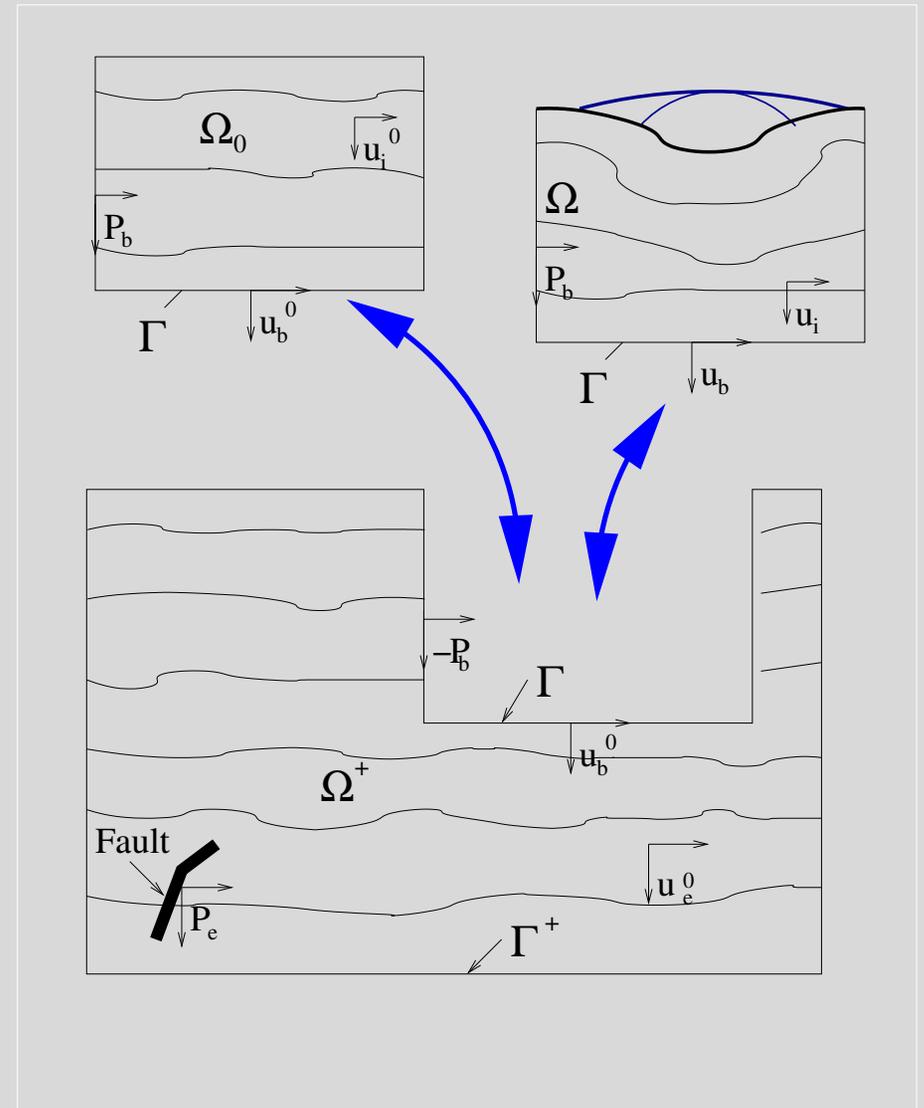
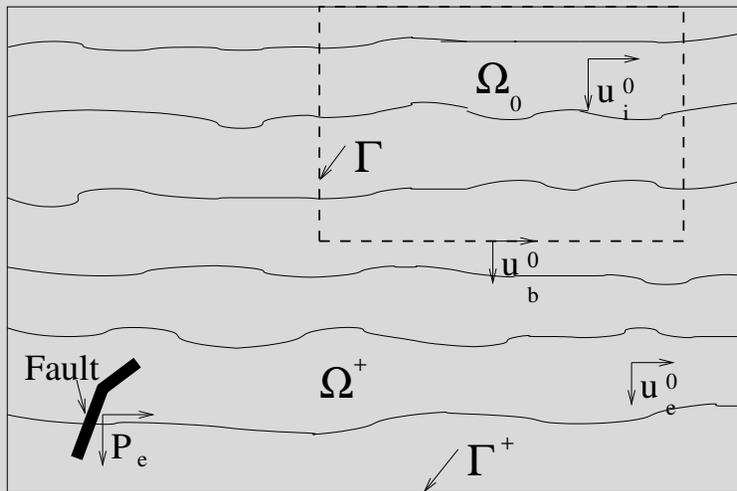
DRM: Background Wave Field

- Determination using any available numerical or measurement technique,
- Need displacement and acceleration field
- Green's functions solutions, Quake system, SCEC database, SHAKE...
- 3D downhole arrays,



DRM: Idea

- Simplified original model
- Local geological feature

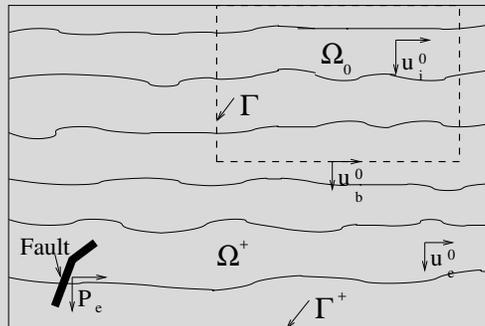


DRM: Dynamics

$$\begin{bmatrix} M_{ii}^{\Omega} & M_{ib}^{\Omega} \\ M_{bi}^{\Omega} & M_{bb}^{\Omega} \end{bmatrix} \begin{Bmatrix} \ddot{u}_i \\ \ddot{u}_b \end{Bmatrix} + \begin{bmatrix} K_{ii}^{\Omega} & K_{ib}^{\Omega} \\ K_{bi}^{\Omega} & K_{bb}^{\Omega} \end{bmatrix} \begin{Bmatrix} u_i \\ u_b \end{Bmatrix} = \begin{Bmatrix} 0 \\ P_b \end{Bmatrix}, \text{ in } \Omega$$

$$\begin{bmatrix} M_{bb}^{\Omega+} & M_{be}^{\Omega+} \\ M_{eb}^{\Omega+} & M_{ee}^{\Omega+} \end{bmatrix} \begin{Bmatrix} \ddot{u}_b \\ \ddot{u}_e \end{Bmatrix} + \begin{bmatrix} K_{bb}^{\Omega+} & K_{be}^{\Omega+} \\ K_{eb}^{\Omega+} & K_{ee}^{\Omega+} \end{bmatrix} \begin{Bmatrix} u_b \\ u_e \end{Bmatrix} = \begin{Bmatrix} -P_b \\ P_e \end{Bmatrix}, \text{ in } \Omega^+$$

$$\begin{bmatrix} M_{ii}^{\Omega} & M_{ib}^{\Omega} & 0 \\ M_{bi}^{\Omega} & M_{bb}^{\Omega} + M_{bb}^{\Omega+} & M_{be}^{\Omega+} \\ 0 & M_{eb}^{\Omega+} & M_{ee}^{\Omega+} \end{bmatrix} \begin{Bmatrix} \ddot{u}_i \\ \ddot{u}_b \\ \ddot{u}_e \end{Bmatrix} + \begin{bmatrix} K_{ii}^{\Omega} & K_{ib}^{\Omega} & 0 \\ K_{bi}^{\Omega} & K_{bb}^{\Omega} + K_{bb}^{\Omega+} & K_{be}^{\Omega+} \\ 0 & K_{eb}^{\Omega+} & K_{ee}^{\Omega+} \end{bmatrix} \begin{Bmatrix} u_i \\ u_b \\ u_e \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ P_e \end{Bmatrix}$$



DRM: Change of Variables

Equations of motion in Ω^+ for changed model

$$\begin{bmatrix} M_{bb}^{\Omega^+} & M_{be}^{\Omega^+} \\ M_{eb}^{\Omega^+} & M_{ee}^{\Omega^+} \end{bmatrix} \begin{Bmatrix} \ddot{u}_b^0 \\ \ddot{u}_e^0 \end{Bmatrix} + \begin{bmatrix} K_{bb}^{\Omega^+} & K_{be}^{\Omega^+} \\ K_{eb}^{\Omega^+} & K_{ee}^{\Omega^+} \end{bmatrix} \begin{Bmatrix} u_b^0 \\ u_e^0 \end{Bmatrix} = \begin{Bmatrix} -P_b^0 \\ P_e \end{Bmatrix} \Rightarrow$$

$$P_e = M_{eb}^{\Omega^+} \ddot{u}_b^0 + M_{ee}^{\Omega^+} \ddot{u}_e^0 + K_{eb}^{\Omega^+} u_b^0 + K_{ee}^{\Omega^+} u_e^0$$

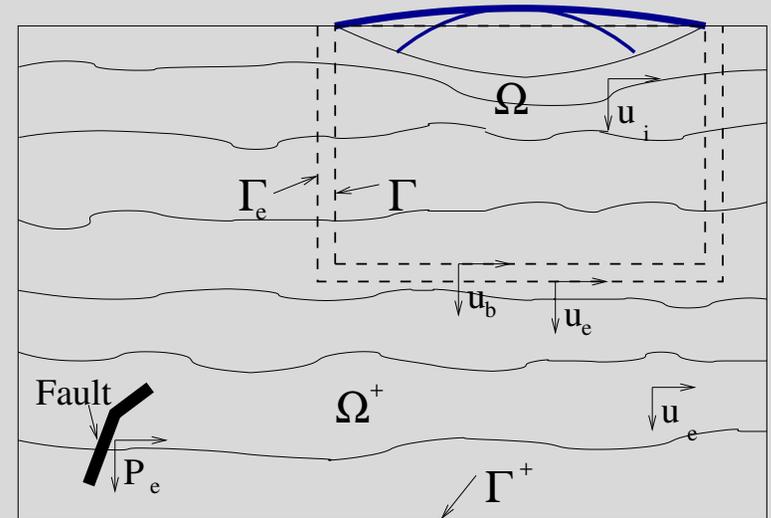
Change of variables: $u_e = u_e^0 + w_e$

- total displacement u_e
- free field, background structure u_e^0
- residual field, relative displacement field with respect to the reference free, background field w_e

$$\begin{bmatrix} M_{ii}^{\Omega} & M_{ib}^{\Omega} & 0 \\ M_{bi}^{\Omega} & M_{bb}^{\Omega} + M_{bb}^{\Omega^+} & M_{be}^{\Omega^+} \\ 0 & M_{eb}^{\Omega^+} & M_{ee}^{\Omega^+} \end{bmatrix} \begin{Bmatrix} \ddot{u}_i \\ \ddot{u}_b \\ \ddot{w}_e \end{Bmatrix} + \begin{bmatrix} K_{ii}^{\Omega} & K_{ib}^{\Omega} & 0 \\ K_{bi}^{\Omega} & K_{bb}^{\Omega} + K_{bb}^{\Omega^+} & K_{be}^{\Omega^+} \\ 0 & K_{eb}^{\Omega^+} & K_{ee}^{\Omega^+} \end{bmatrix} \begin{Bmatrix} u_i \\ u_b \\ w_e \end{Bmatrix} = \begin{Bmatrix} P_i^{eff} \\ P_b^{eff} \\ P_e^{eff} \end{Bmatrix}$$

DRM: Dynamic (Seismic) Forces

$$\begin{Bmatrix} P_i^{eff} \\ P_b^{eff} \\ P_e^{eff} \end{Bmatrix} = \begin{Bmatrix} 0 \\ -M_{be}^{\Omega^+} \ddot{u}_e^0 - K_{be}^{\Omega^+} u_e^0 \\ M_{eb}^{\Omega^+} \ddot{u}_b^0 + K_{eb}^{\Omega^+} u_b^0 \end{Bmatrix}$$



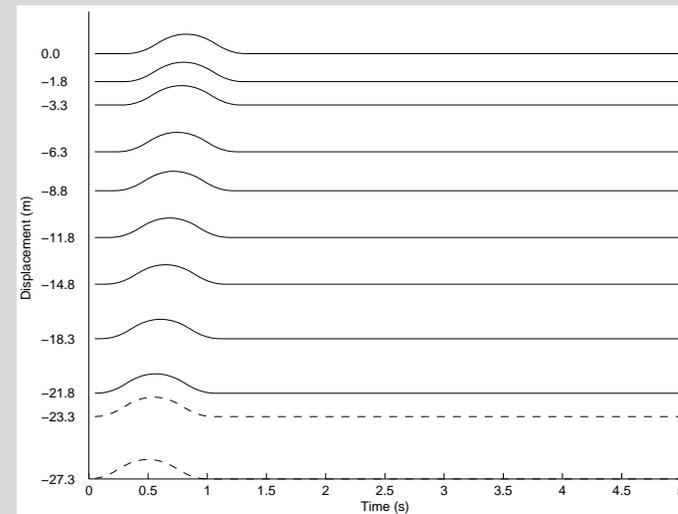
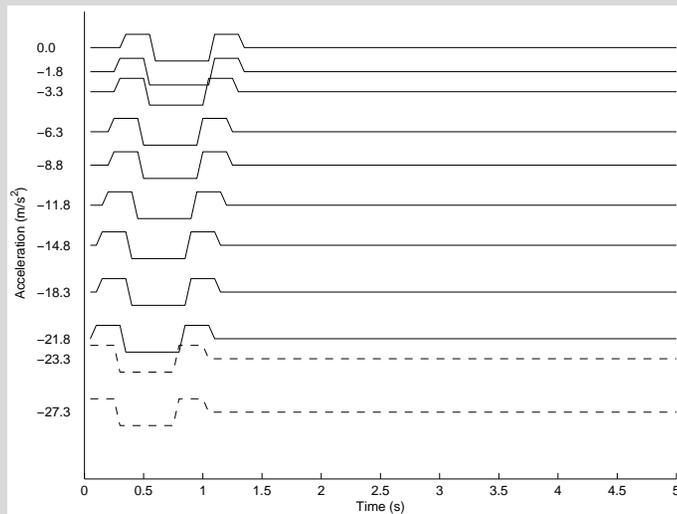
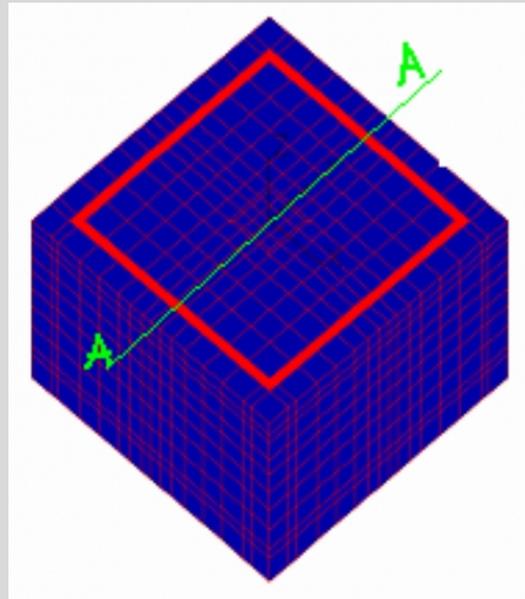
- Seismic forces P_e replaced by the effective nodal forces P^{eff} ,
- P^{eff} involve only submatrices, $M_{be}, K_{be}, M_{eb}, K_{eb}$
- They vanish everywhere except in the single layer of elements in Ω^+ adjacent to Γ .
- The material inside Ω does not have to be linear elastic

Application Examples

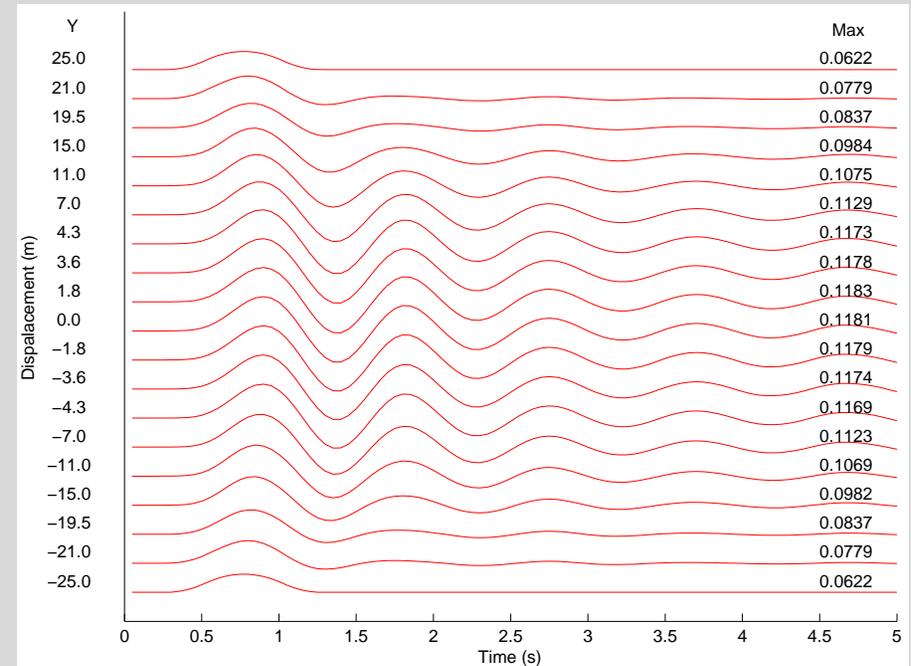
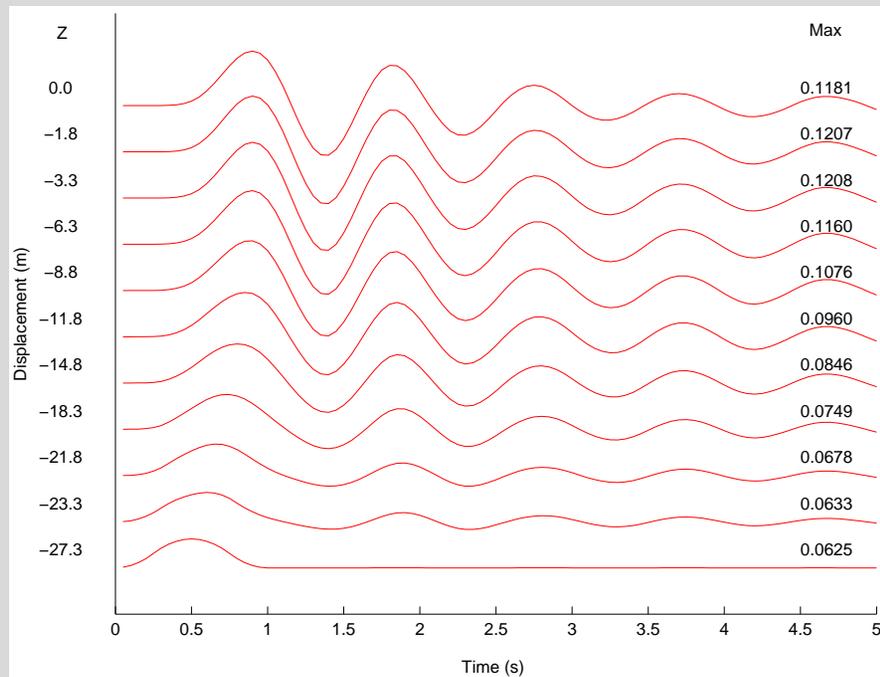
- Seismic wave propagation
 - Effects of elastic plastic soils on free field motions

- Soil–Structure interaction
 - Effects of elastic–plastic soils on dynamic response of pile–column system

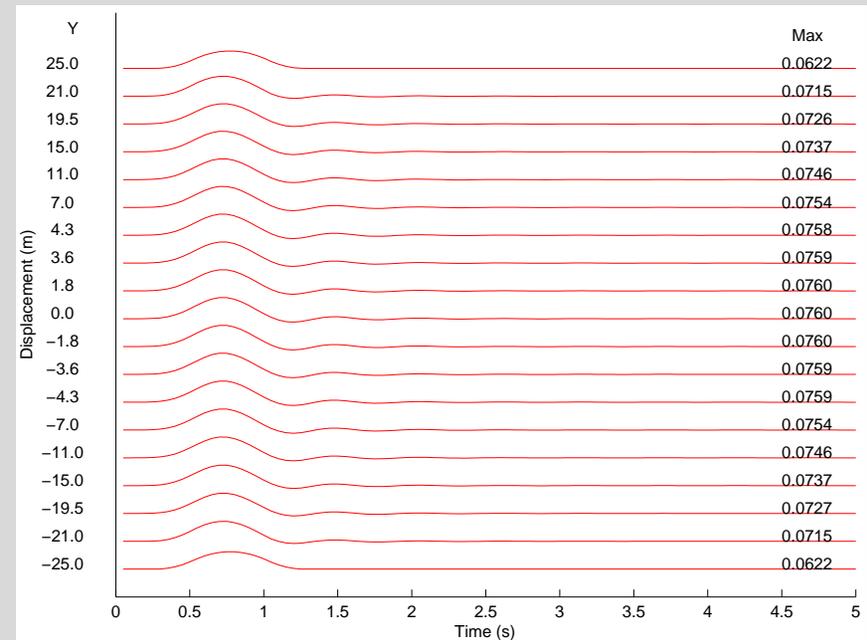
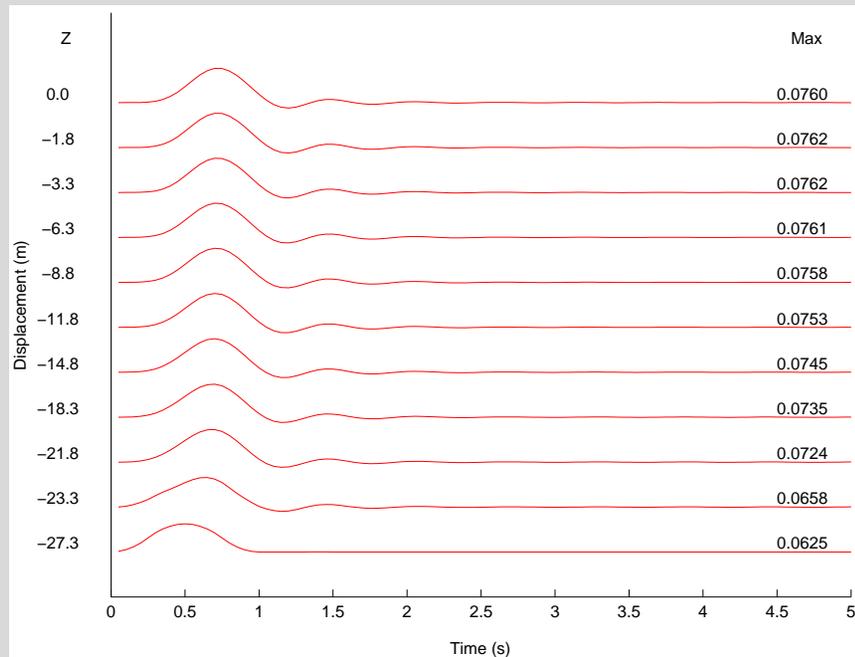
Wave Propagation Model



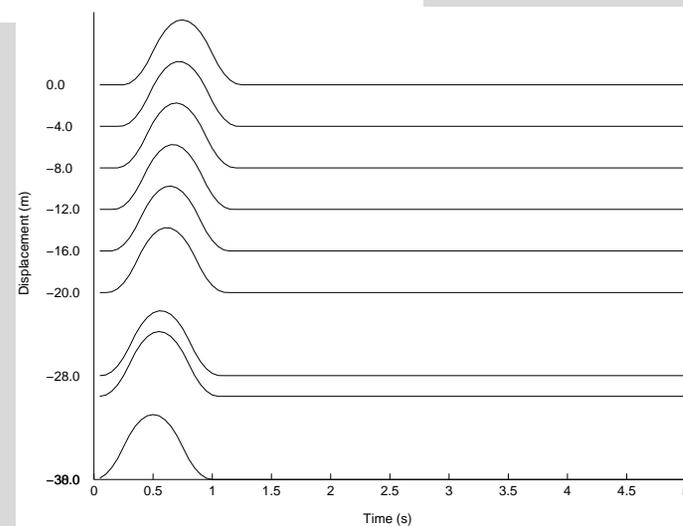
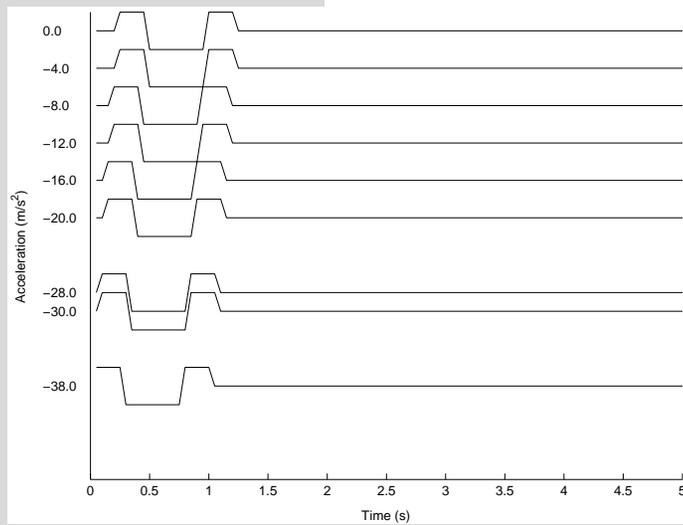
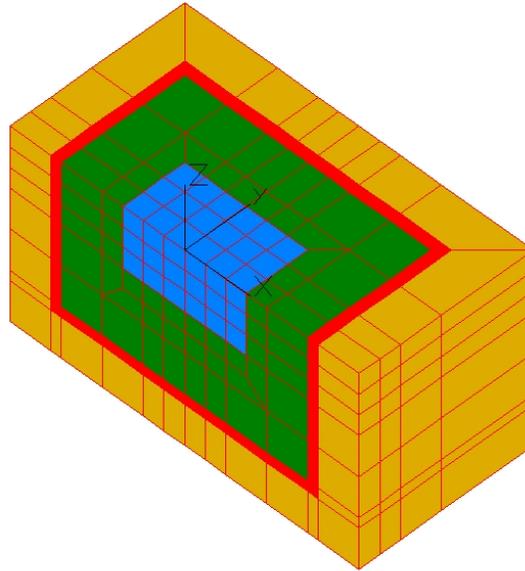
Wave Propagation Soft Soil



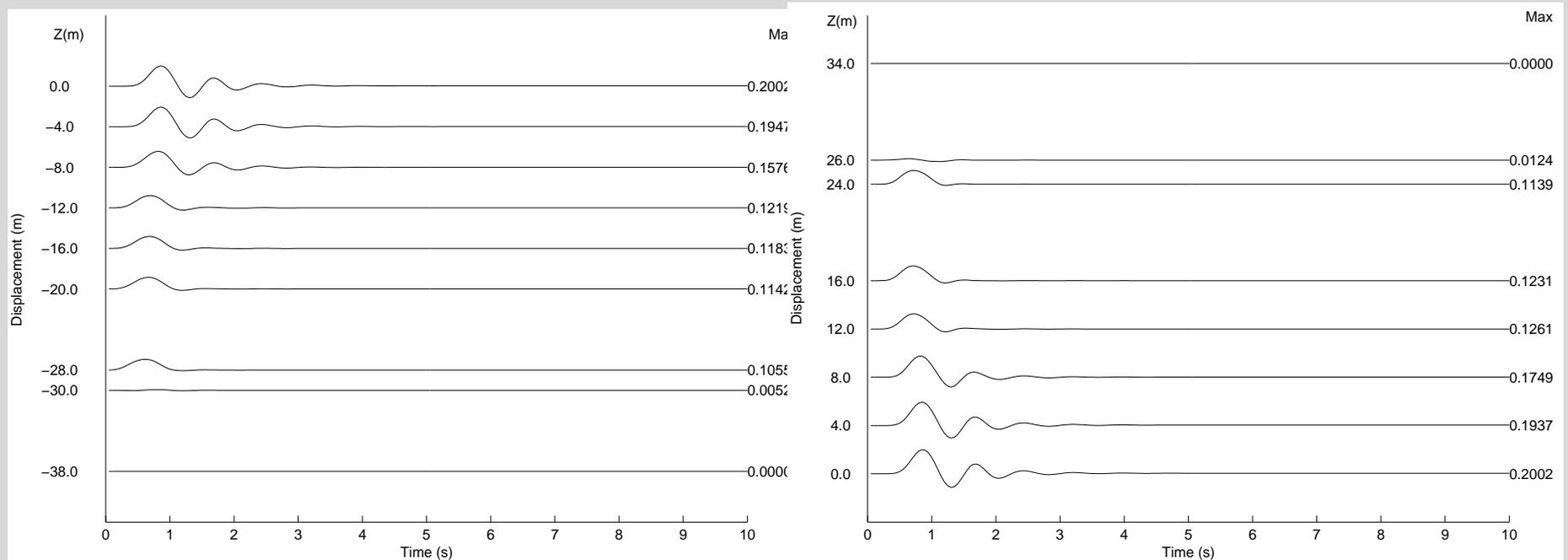
Wave Propagation Stiff Soil



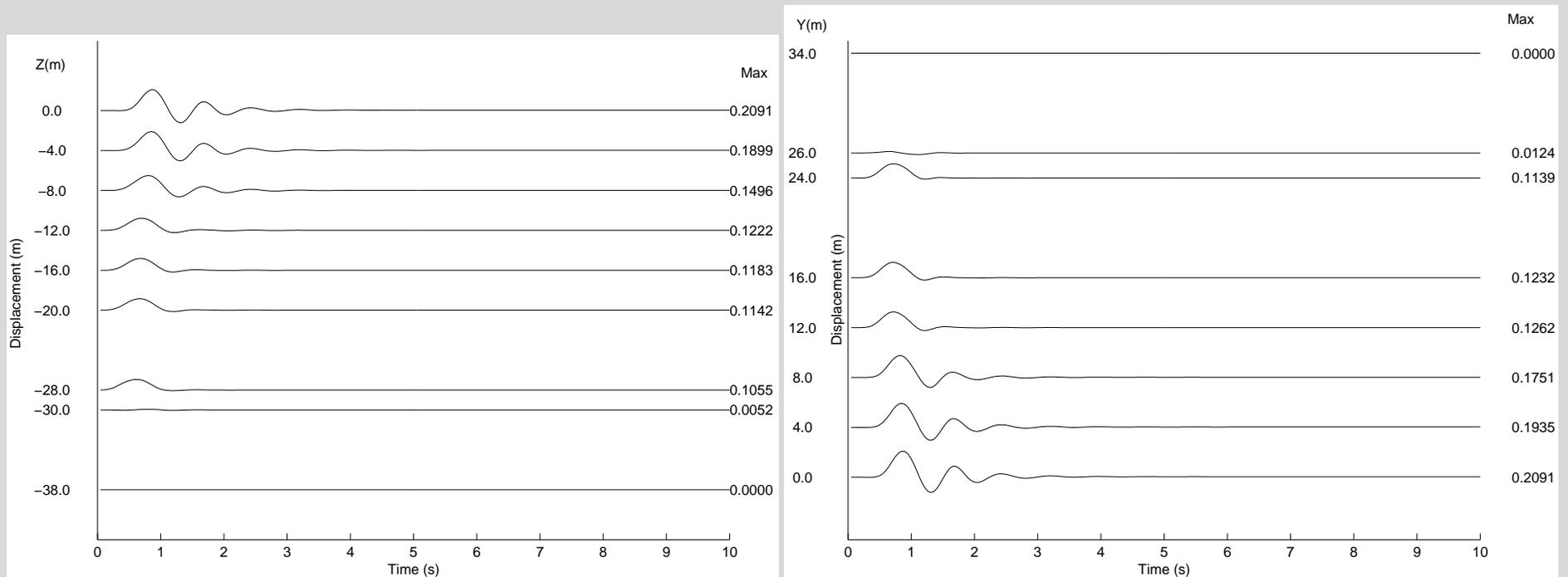
SSI Model



SSI Model Free Field Stiff Elastic-Plastic Soil

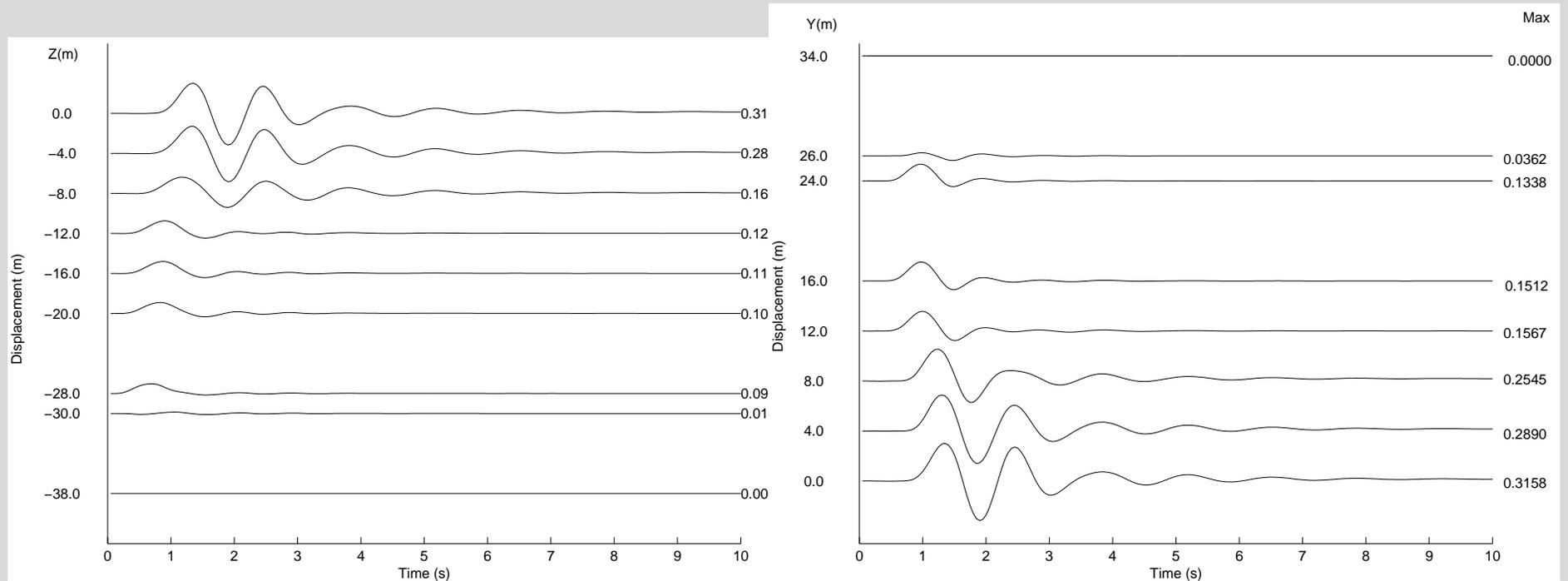


SSI Model: Pile–Column Stiff Elastic–Plastic Soil

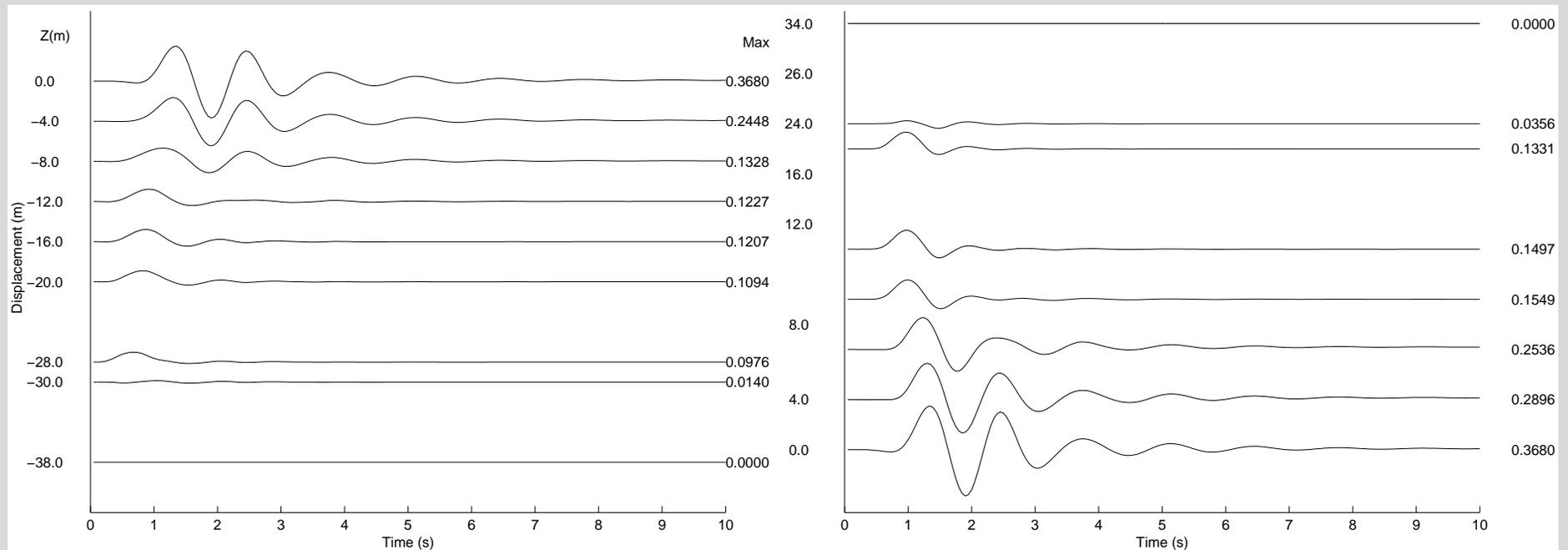


SSI Model Free Field

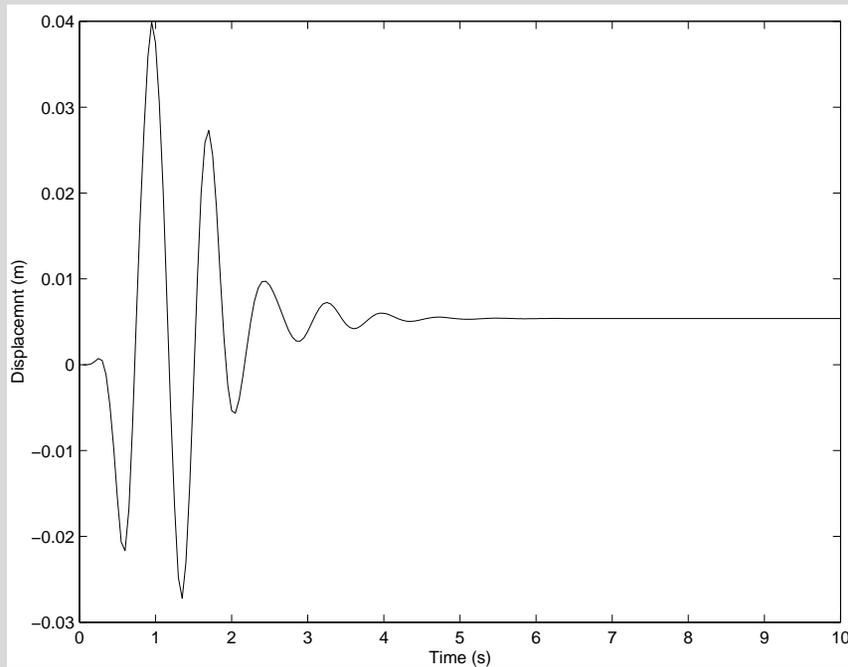
Soft Elastic–Plastic Soil



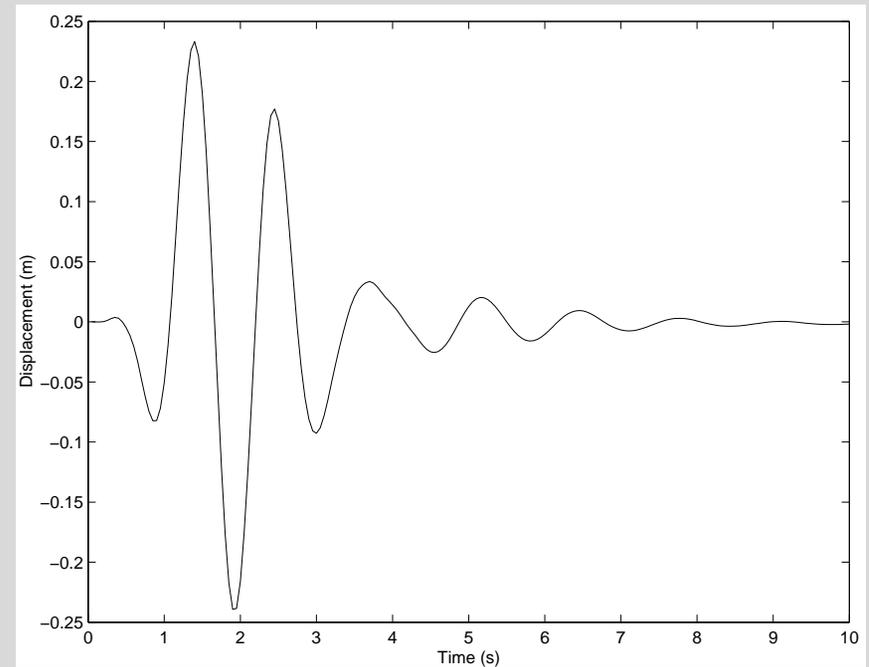
SSI Model: Pile–Column Soft Elastic–Plastic Soil



SSI Model: Pile–Column Behavior



Stiff soil

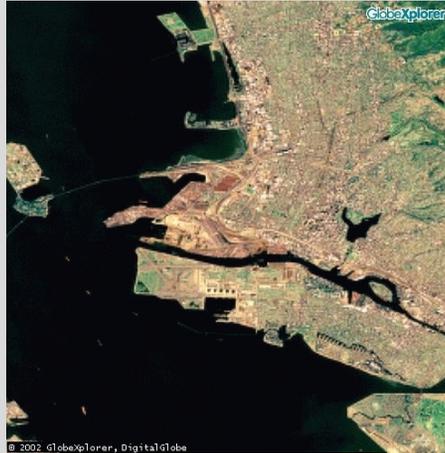


Soft soil

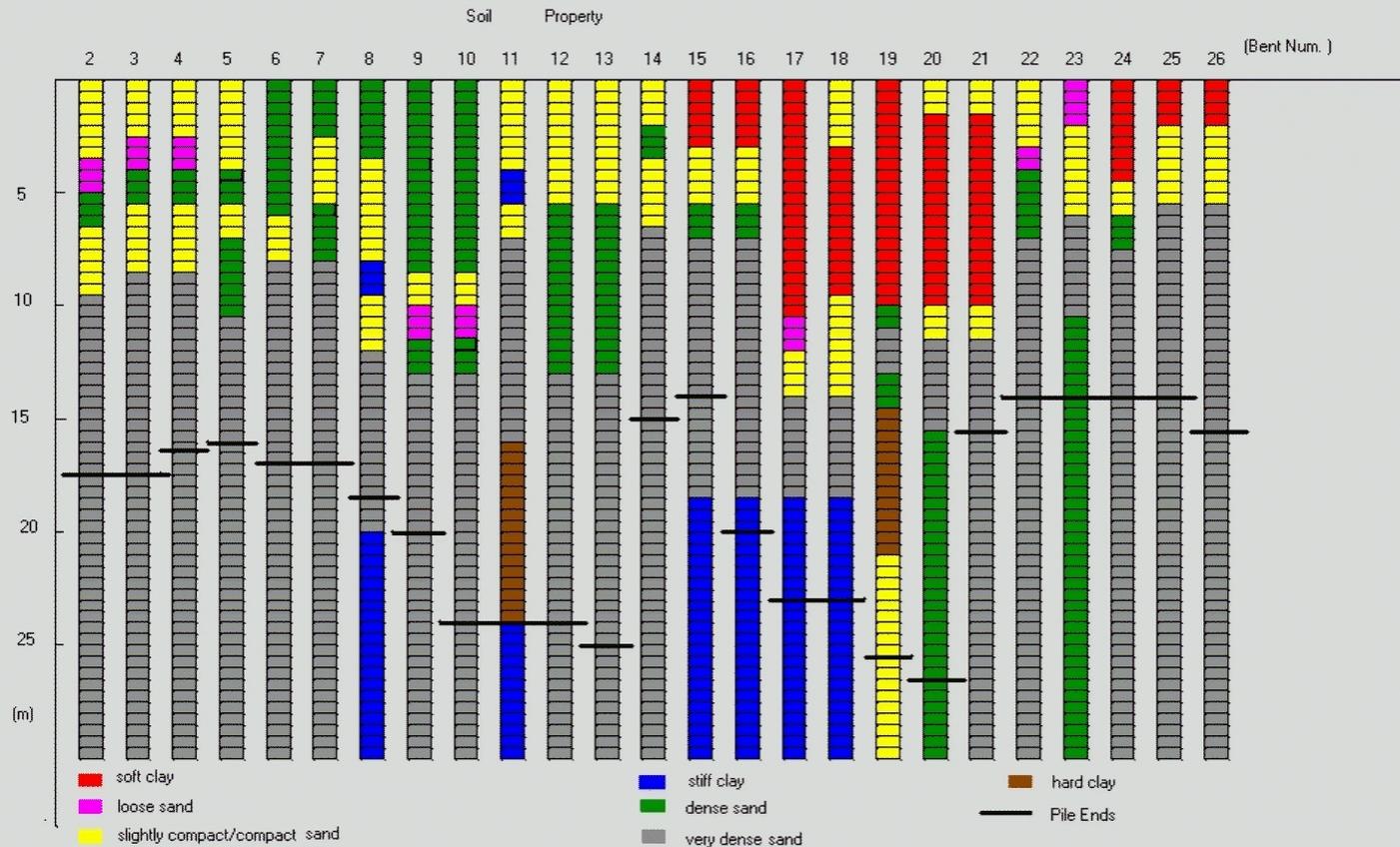
I-880 Bridge SFSI Issues

- Seismic response of I-880 viaduct using performance based engineering
- Hierarchical set of SFSI simulations models developed to represent engineering demand parameters (EDP)
- Local site conditions (inelastic SFSI interaction problem)
- Wave propagation over the bridge length (scale problem)
- Single point (spatial) far field input motions
- Stochastic distribution of materials (properties) over spatial scales

Geologic and Soil Conditions



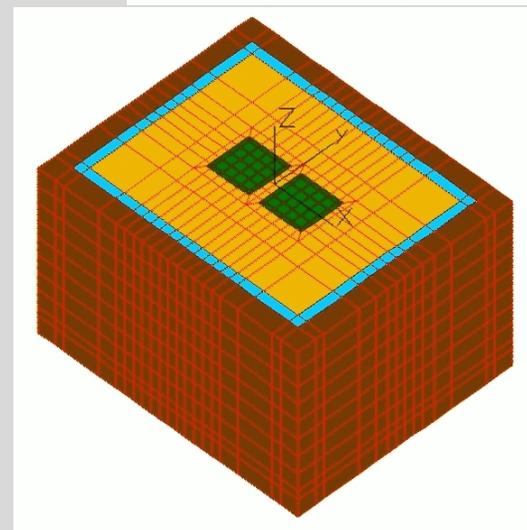
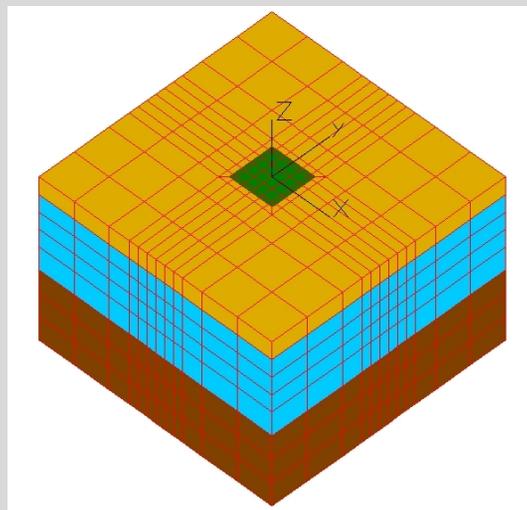
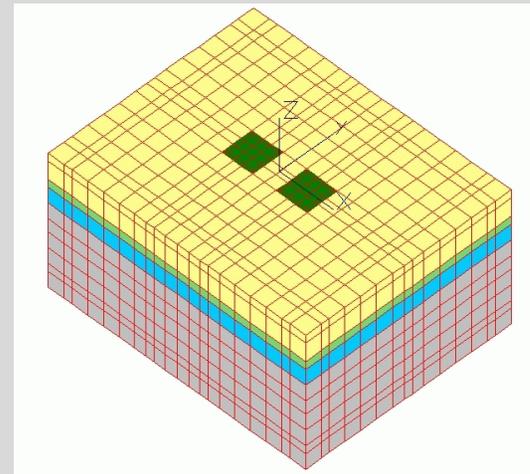
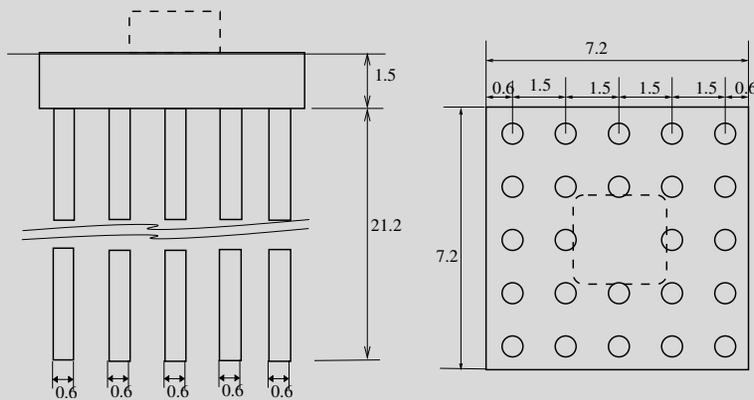
Local Site Conditions



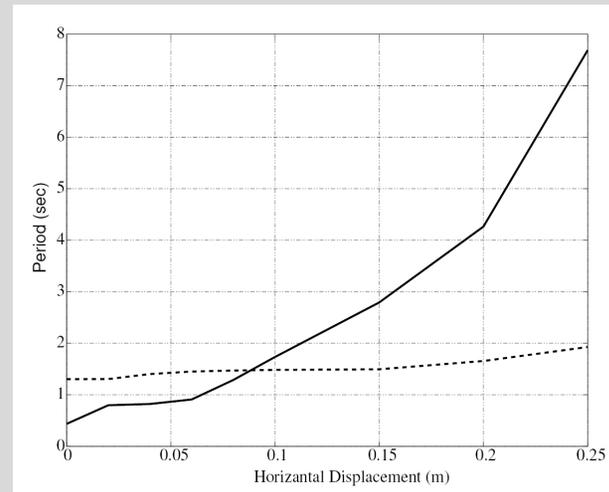
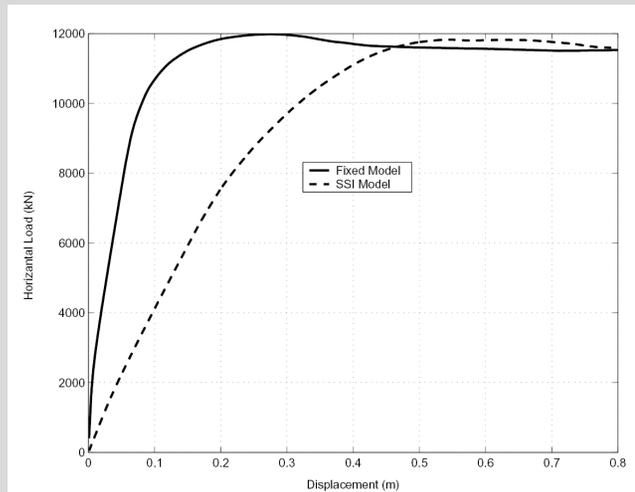
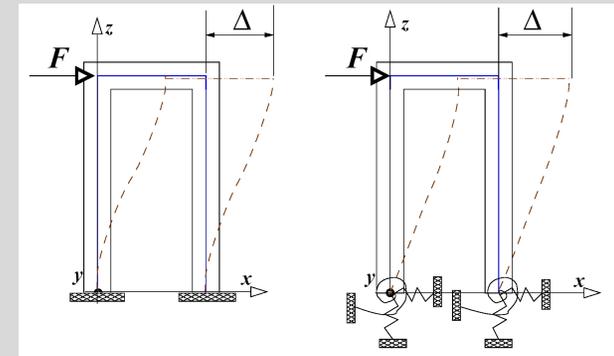
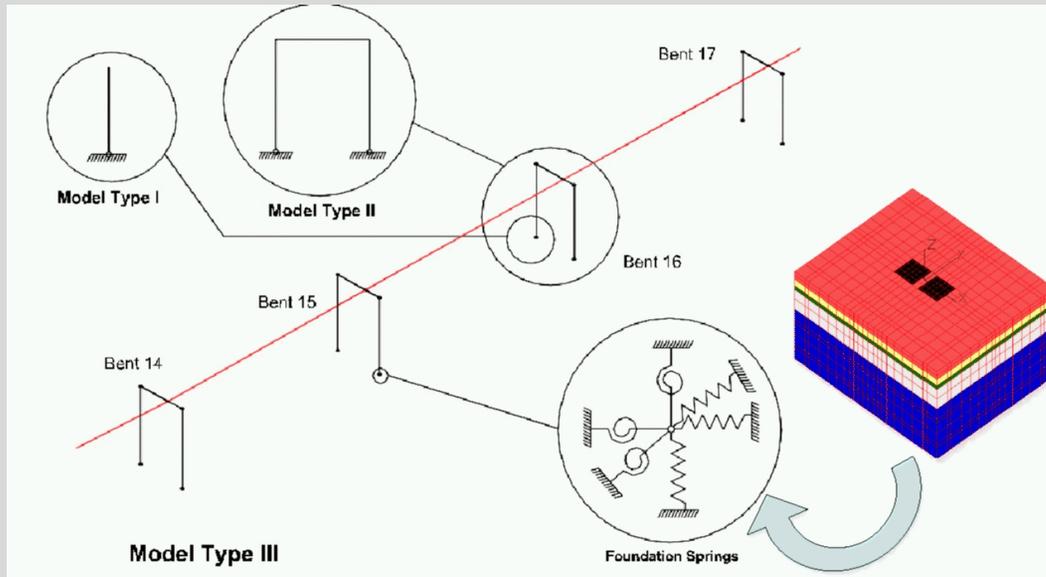
- Adjacency of foundations in soft and stiff soil
- Spatial distribution of soil materials

Soil–Foundation System Models

- Hierarchical set of models used to estimate performance
- Reducing epistemic uncertainty as much as possible

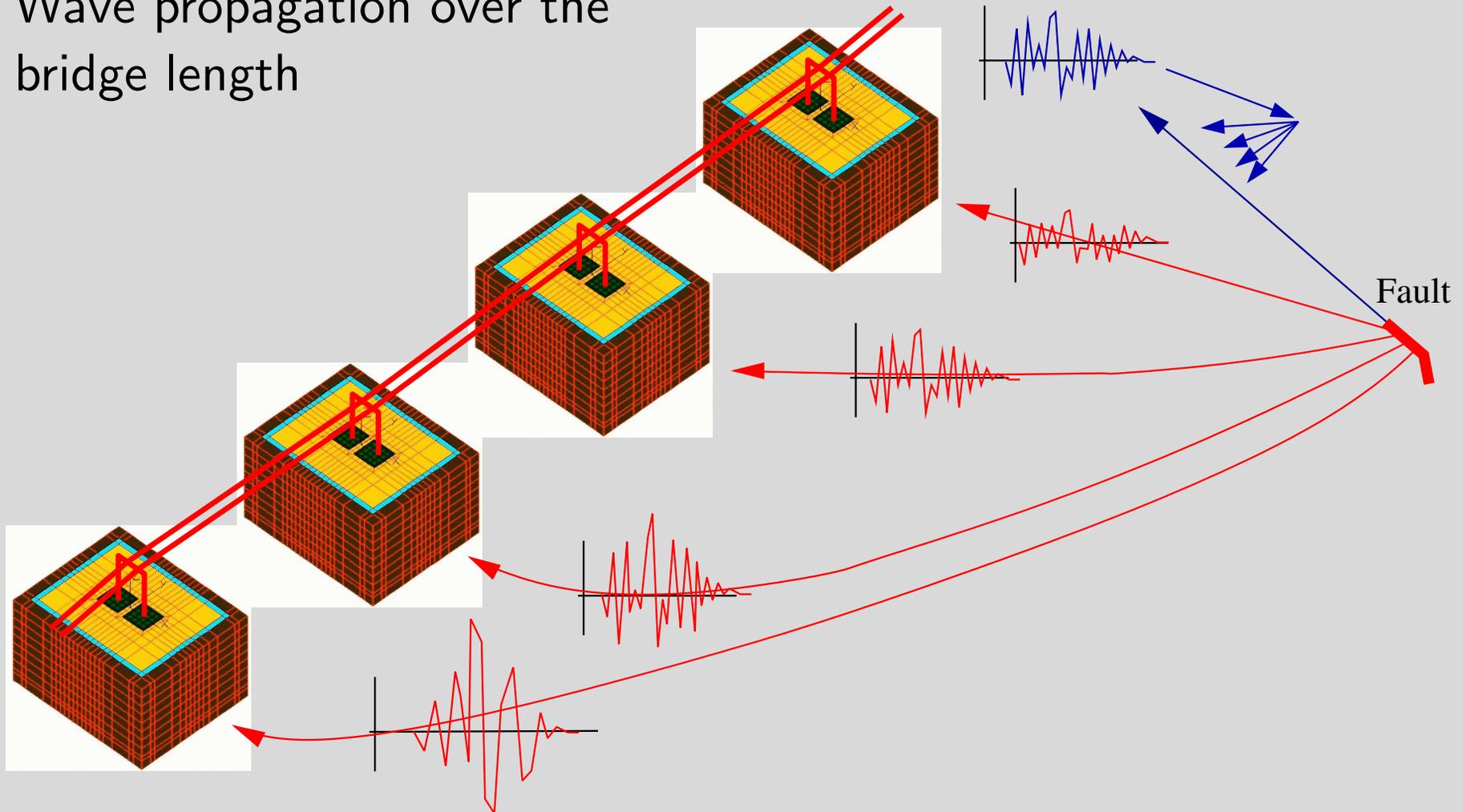


I-880: Hierarchy of Models



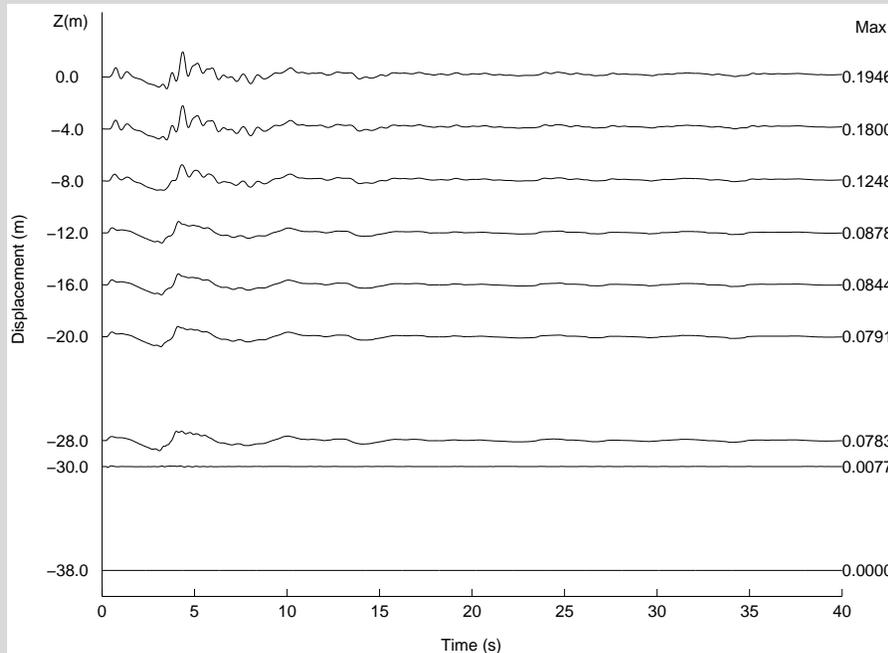
I-880: Seismic Input

- Coupling free field motions to SFSI system (Domain Reduction Method)
- Wave propagation over the bridge length

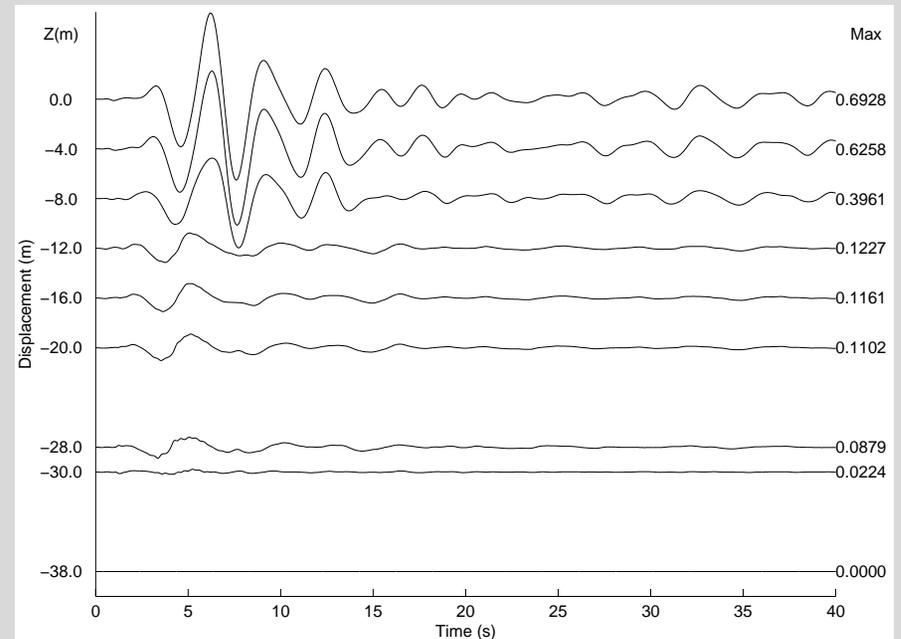


Seismic Amplification

- Adjacent bents
- Foundation will survive but the superstructure or joints might not



Stiff soil



Soft soil

Concluding Remarks

- Static (kinematic) SFSI issues
 - Layered soils
 - Piles in liquefied soils (layers)
- Dynamic (seismic) SFSI issues
 - Free field vs. SFSI motions
 - Very large scale coupling (with geophysical simulations)

Thank you

