A Brief Overview of the NEESgrid Simulation Platform OpenSees: Application to the Soil–Foundation–Structure Interaction Problems

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Third UJNR Workshop on Soil-Structure Interaction
March 29-30, 2004, Vallombrosa Center, Menlo Park, California

Supported in part by the NSF, PEER, Caltrans, and Cal–EPA.

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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

- The NEES MiniGrand Challenge Project
  - Validation experiments
  - Simulation challenge

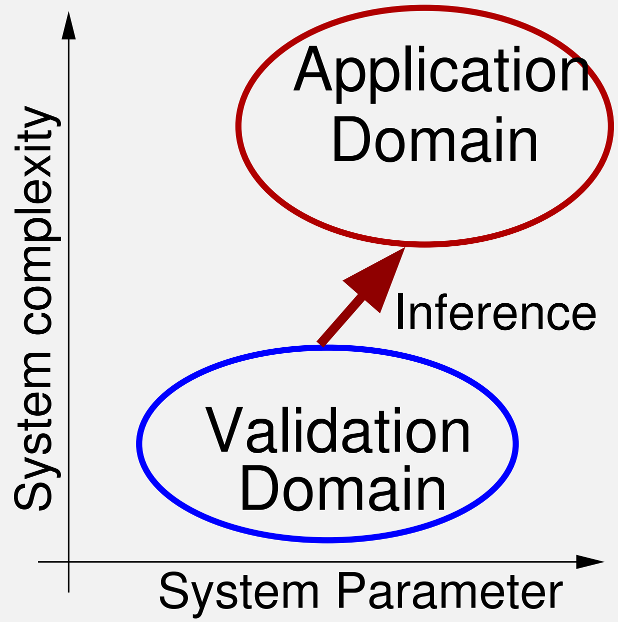
- OpenSees NEESgrid simulation platform
  - Template Elasto–Plasticity
  - Full Coupling of Solid and Fluid
  - Seismic Motions (FEM input)
  - Distributed Memory Parallel Computing
  - General Large Deformations

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

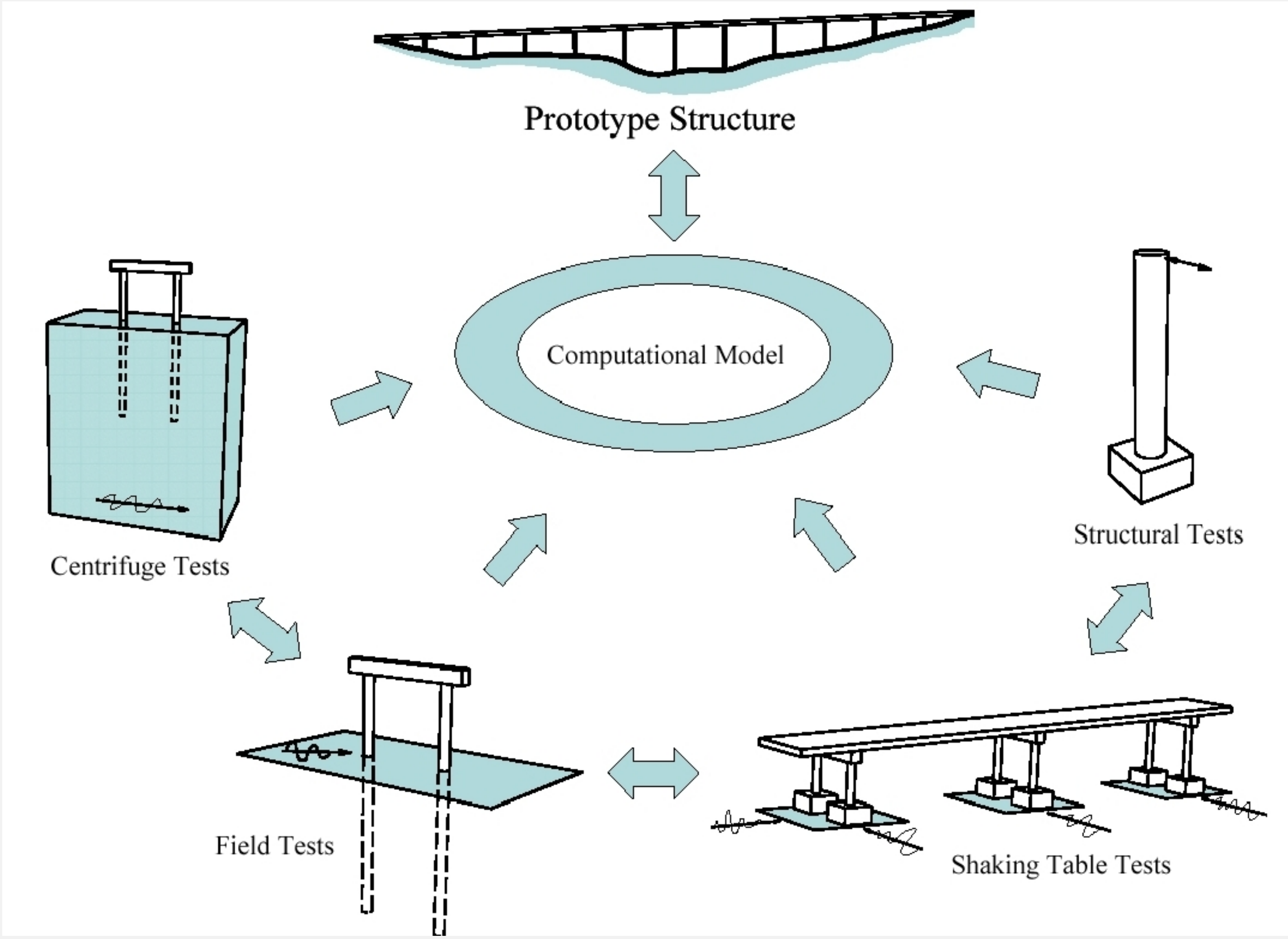
- A validation Experiment should be designed to capture the relevant physics
  - Measure all important modeling data in the experiment
  - Characteristics and imperfections of the experimental facility should be included in the model

Application Domain



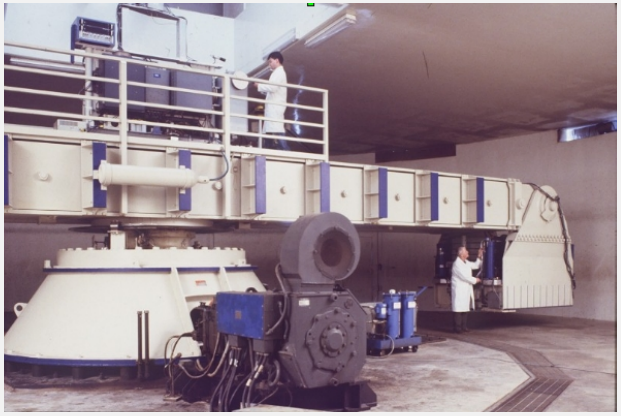
- Inference $\Rightarrow$ Based on **physics** or **statistics**
- Validation domain $\longrightarrow$ non–convex aggregation of physical tests
- Physical experiments (NEES) provide for non–overlapping validation domain

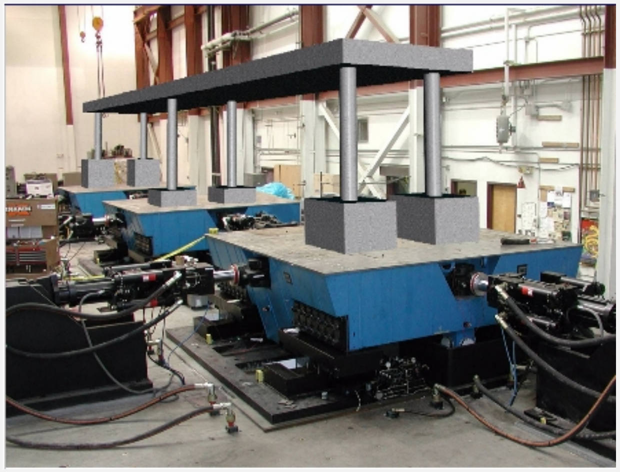
NEES SFSI Project



Participants: Wood (UT), Anagnos (SHSU), Arduino (UW), Eberhard (UW), Fenves (UCB), Finholt (UM), Futrelle (NCSA), Grant (UK), Jeremić (UCD), Kramer (UW), Kutter (UCD), Matamoros (UK), McMullin (SHSU), Ramirez (PU), Rathje (UT), Saidi (UNR), Sanders (UNR), Stokoe (UT), Wilson (UCD).

Validation SFSI Experiments





- UC Davis centrifuge, single piles, bents, frames, scale 1/50
- UT Austin, pile, pile–column, bent, scale 1/4
- UN Reno, frame (3 bents), scale 1/4
- Purdue U., pier components, scale 1/2 and 1/1

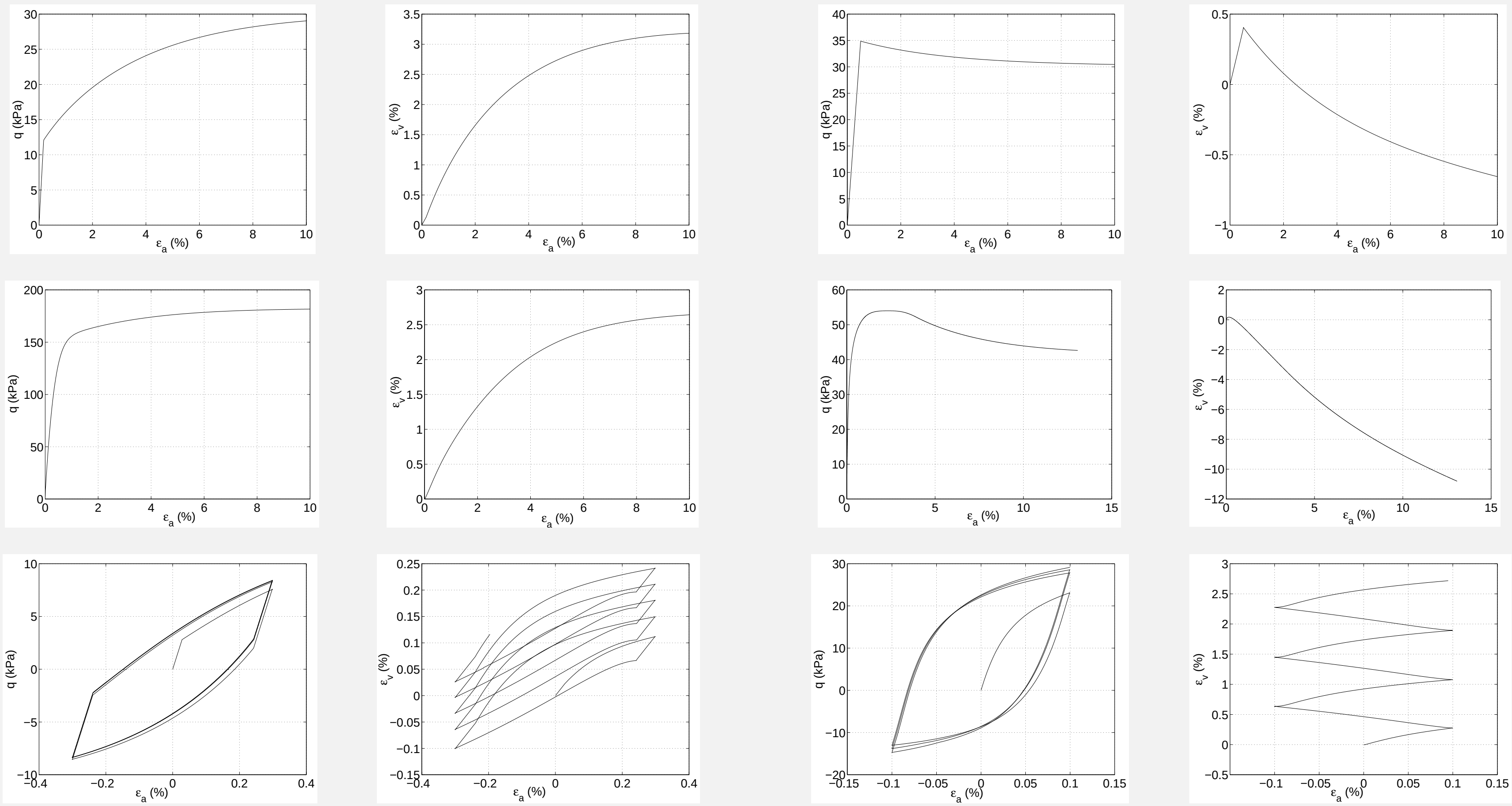
The OpenSees Platform SFSI components

- Small deformation, single phase, linear and nonlinear elasticity and incremental template elasto–plasticity (PY springs, 2D/3D solids)
- General, large deformation huperelasticity and hyperelasto–plasticity for solids
- Full coupling of solid and fluid ($u - p - U$), (small deformations only at the moment)
- Elastic and inelastic beam–column elements, elastic plate and plane stress elements (shells), small and large deformations
- Seismic input through the Domain Reduction Method

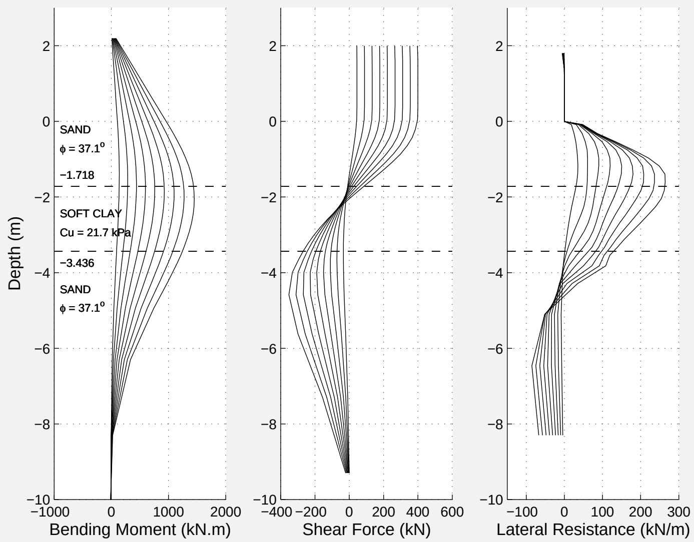
Template Elasto–Plasticity

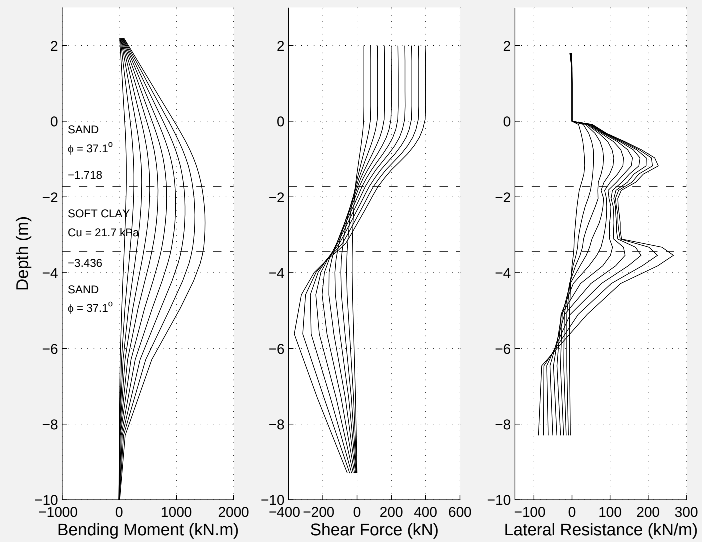
- Yield surfaces: von Mises, Drucker–Prager, Rounded Mohr–Coulomb, Cam–Clay, Parabolic Leon,
- Plastic flow directions (potential surfaces): von Mises, Drucker–Prager, Rounded Mohr–Coulomb, Cam–Clay, Manzari–Dafalias, Parabolic Leon,
- Isotropic or kinematic hardening/softening
  - linear and/or nonlinear isotropic hardening/softening
  - linear or nonlinear kinematic hardening/softening
- Hierarchical database of models (by materials)

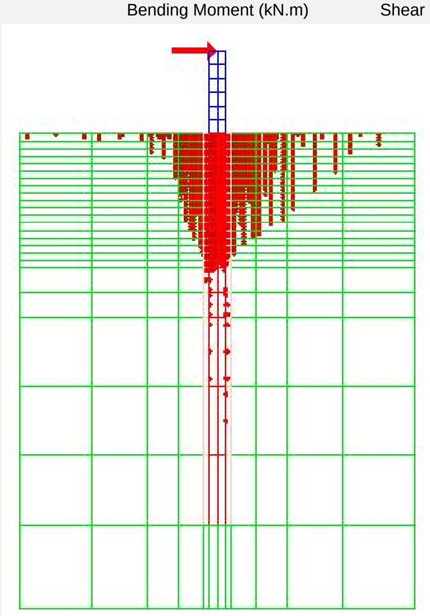
Template Examples

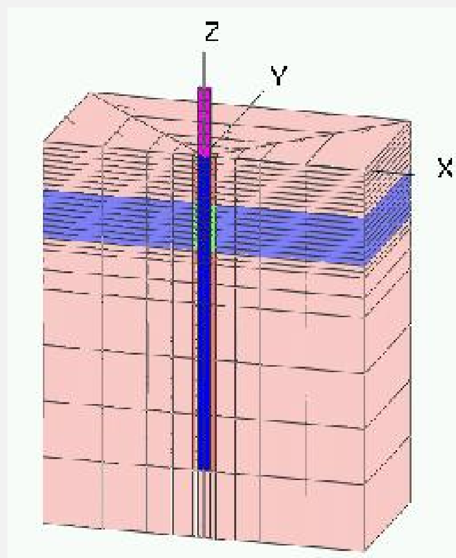


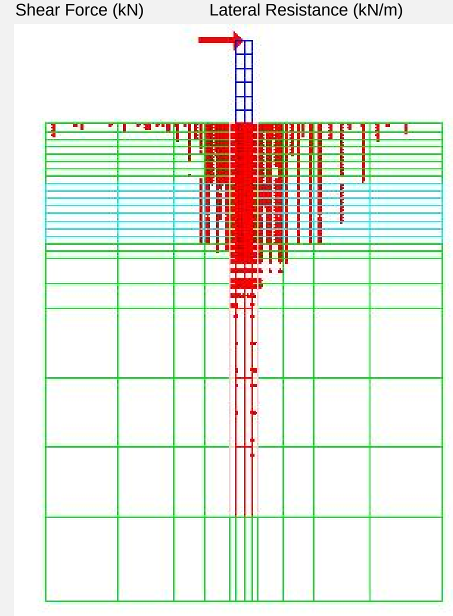
Single Pile in Layered Soils



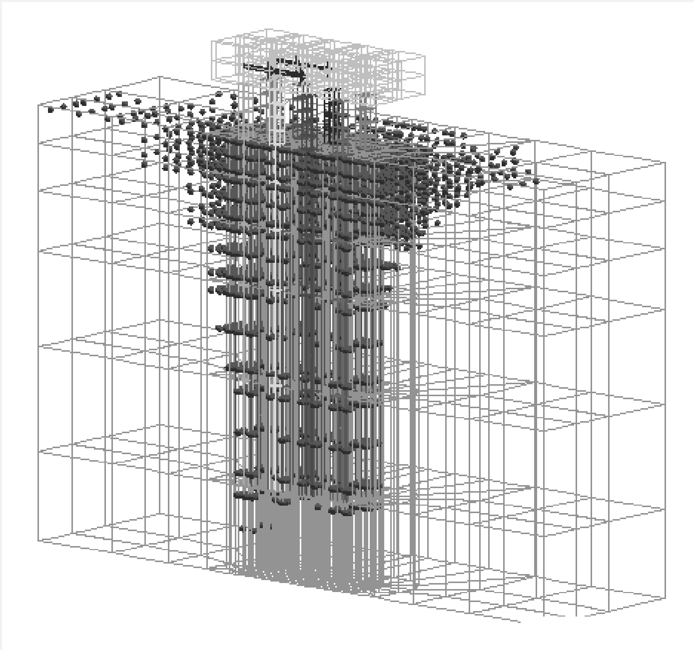


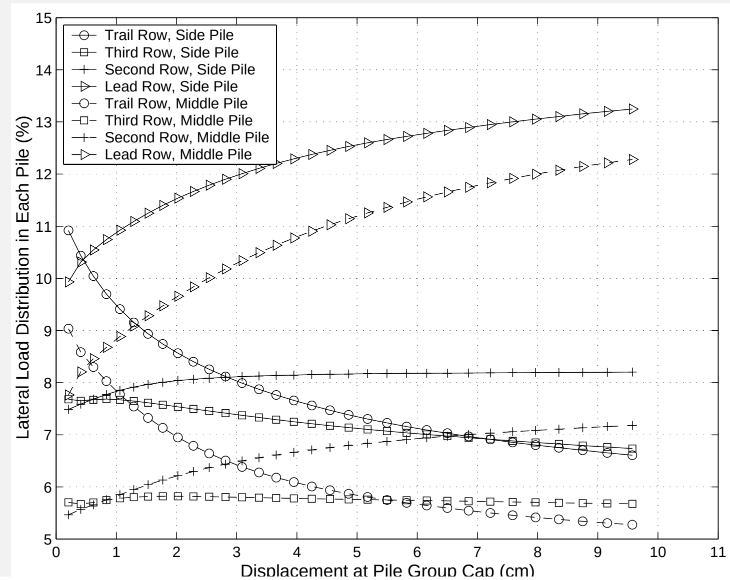




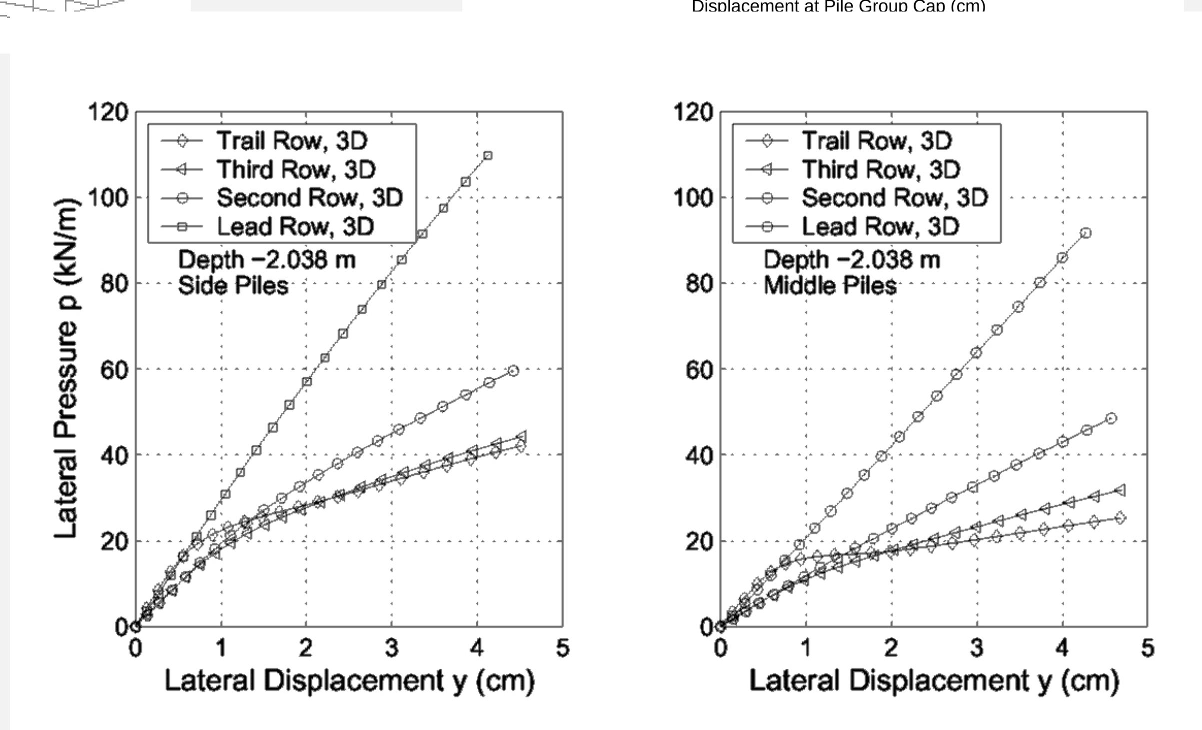


Pile Group Simulations





- Plastic zone
- Load distribution
- Pile interactions (P-Y)



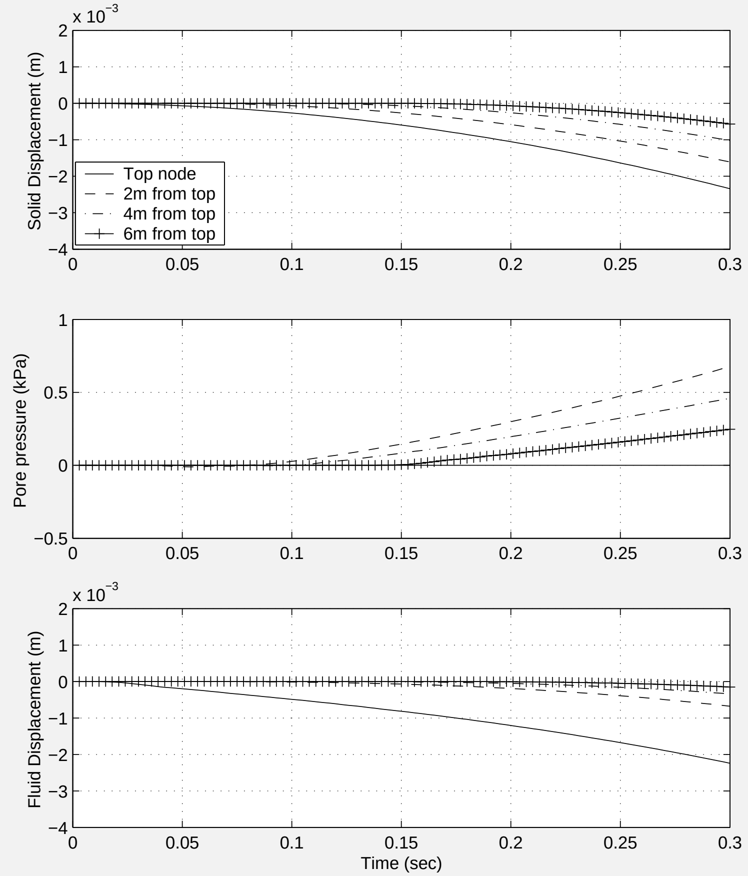
Full Coupling of Solid and Fluid

$$
\begin{bmatrix} (M_s)_{KijL} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & (M_f)_{KijL} \end{bmatrix}
\begin{bmatrix} \ddot{\bar{u}}_{Lj} \\ \ddot{\bar{p}}_{L} \\ \ddot{\bar{U}}_{Lj} \end{bmatrix} +
$$

$$
\begin{bmatrix} (C_1)_{KijL} & 0 & -(C_2)_{KijL} \\ 0 & 0 & 0 \\ -(C_2)_{LjiK} & 0 & (C_3)_{KijL} \end{bmatrix}
\begin{bmatrix} \dot{\bar{u}}_{Lj} \\ \dot{\bar{p}}_{L} \\ \dot{\bar{U}}_{Lj} \end{bmatrix} +
$$

$$
\begin{bmatrix} (K^{EP})_{KijL} & -(G_1)_{KiL} & 0 \\ -(G_1)_{LjK} & -(P)_{KL} & -(G_2)_{LjK} \\ 0 & -(G_2)_{KiL} & 0 \end{bmatrix}
\begin{bmatrix} \bar{u}_{Lj} \\ \bar{p}_{L} \\ \bar{U}_{Lj} \end{bmatrix} =
$$

$$
\begin{bmatrix} (\bar{f}_s)_{Ki} \\ 0 \\ (\bar{f}_f)_{Ki} \end{bmatrix}
$$

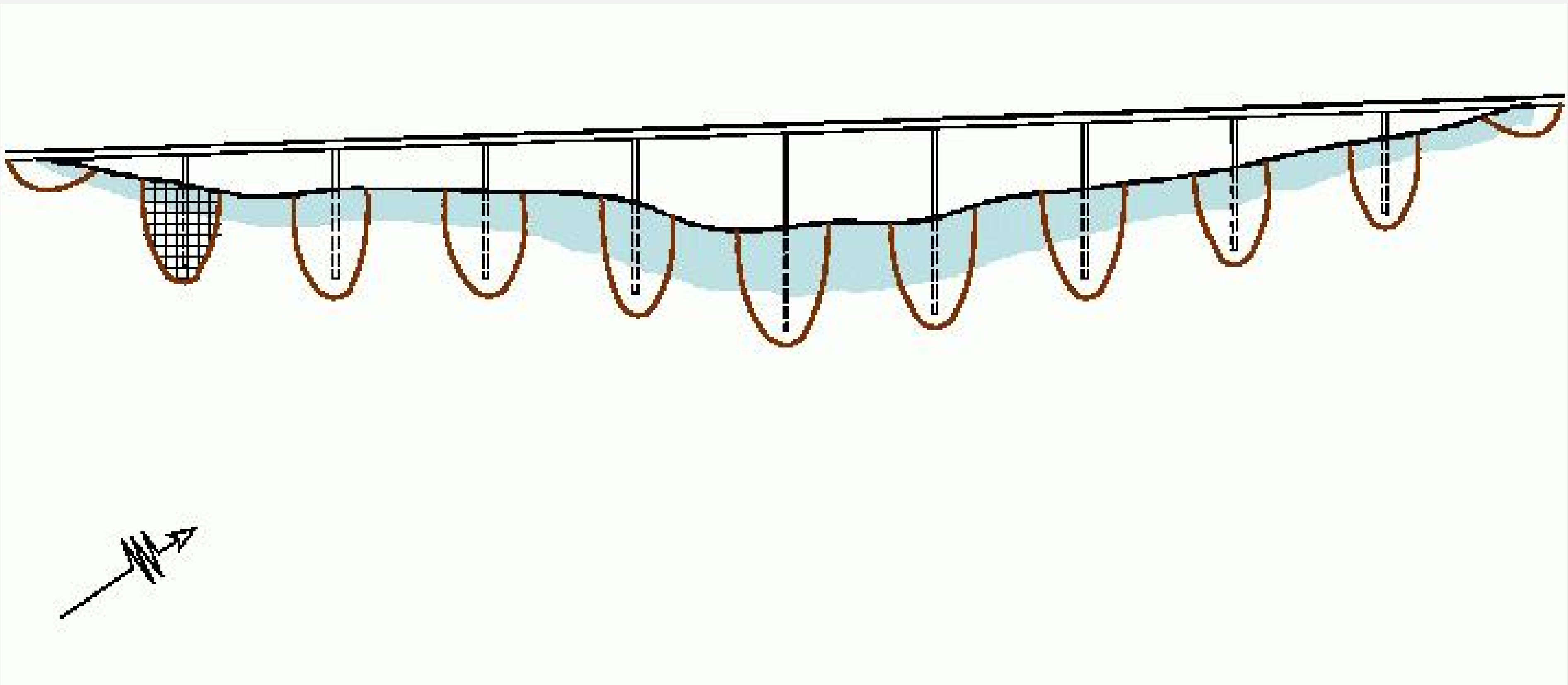


$$
(C_1)_{KijL} = (C_2)_{KijL} = (C_3)_{KijL} =
$$

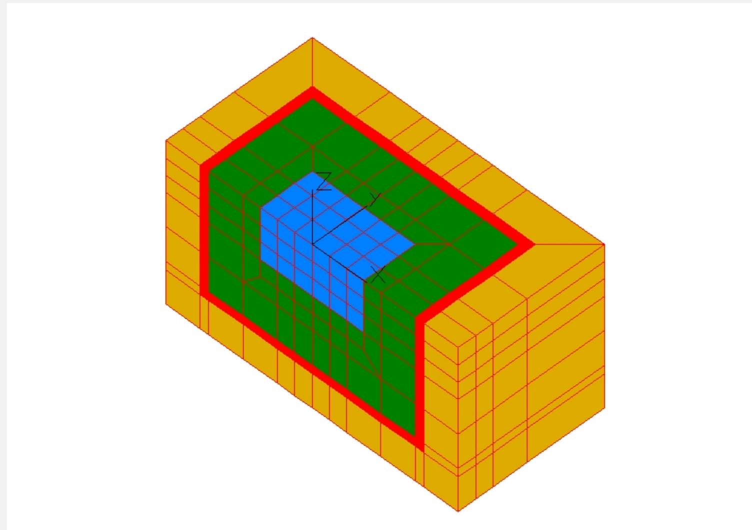
$$
\int_\Omega N_K^{u,U} n^2 k_{ij}^{-1} N_L^{u,U} d\Omega
$$

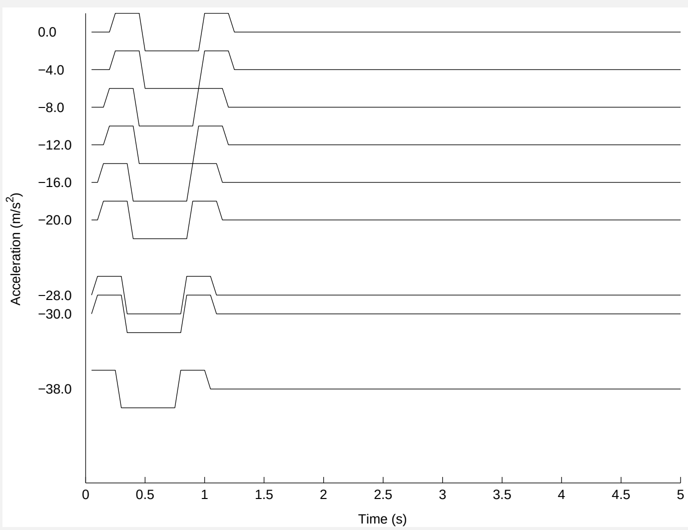
Seismic Input

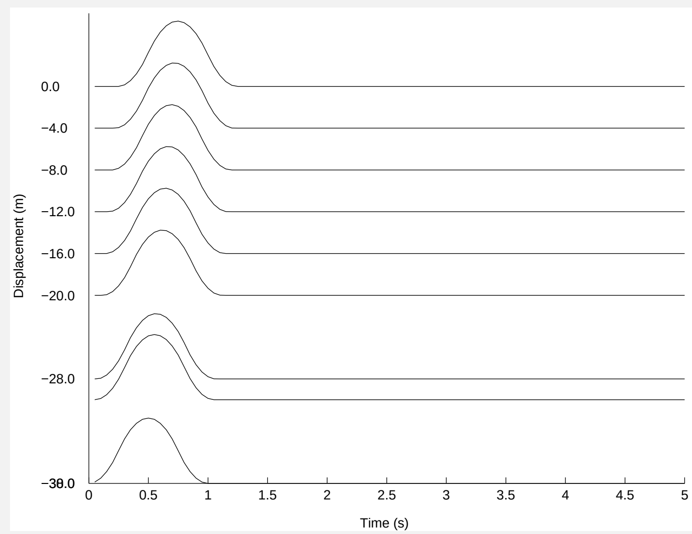
- Domain Reduction Method, (Bielak et al. at CMU)
- Seismic motions and accelerations input at the layer of elements that encompass an elastic–plastic zone (using SHAKE, Green's functions, Quake, SCEC...), non–reflective boundaries



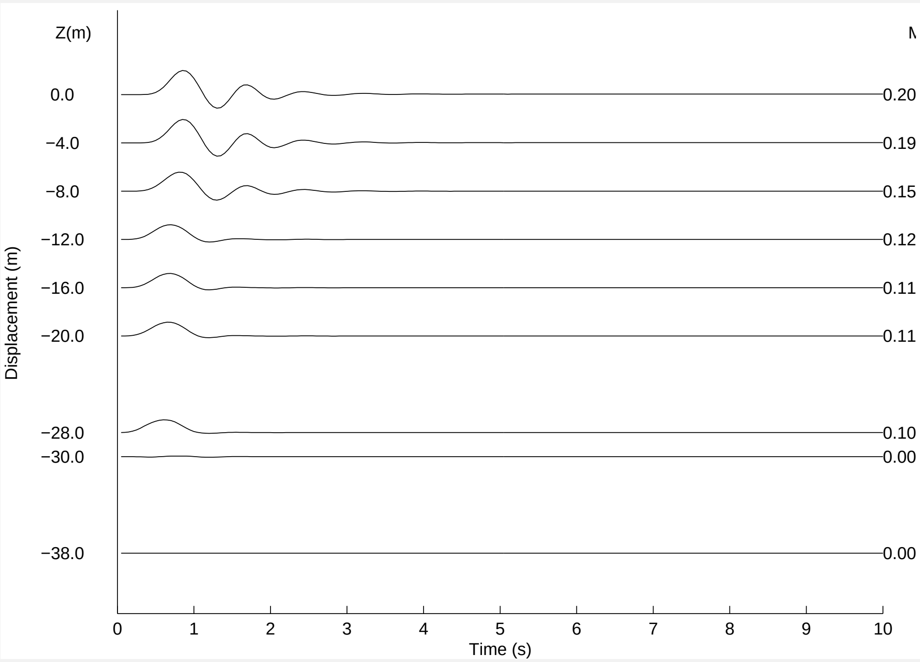
Verification SFSI Model



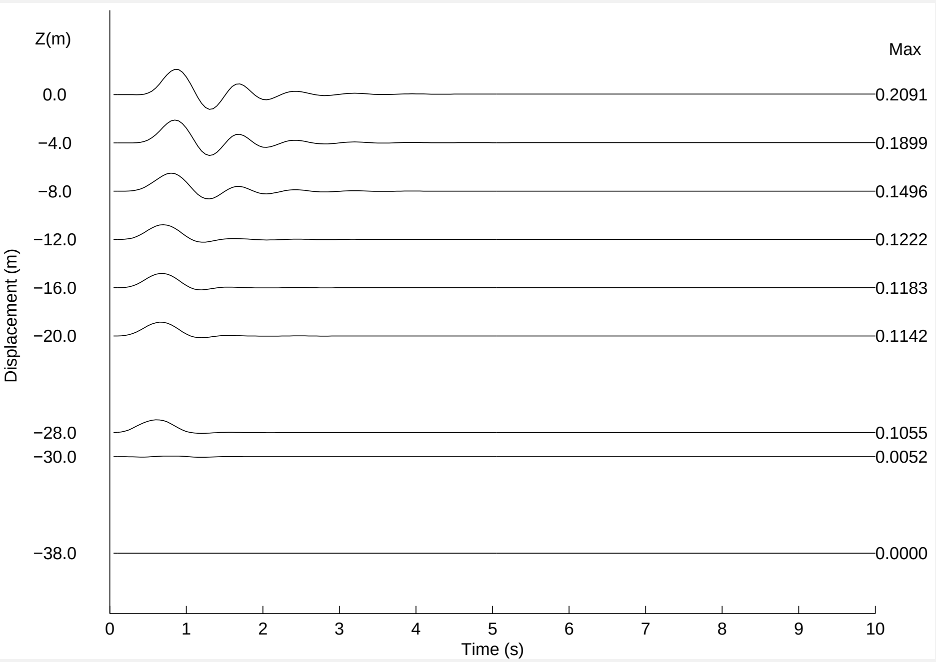




SFSI: Stiff Soil Model

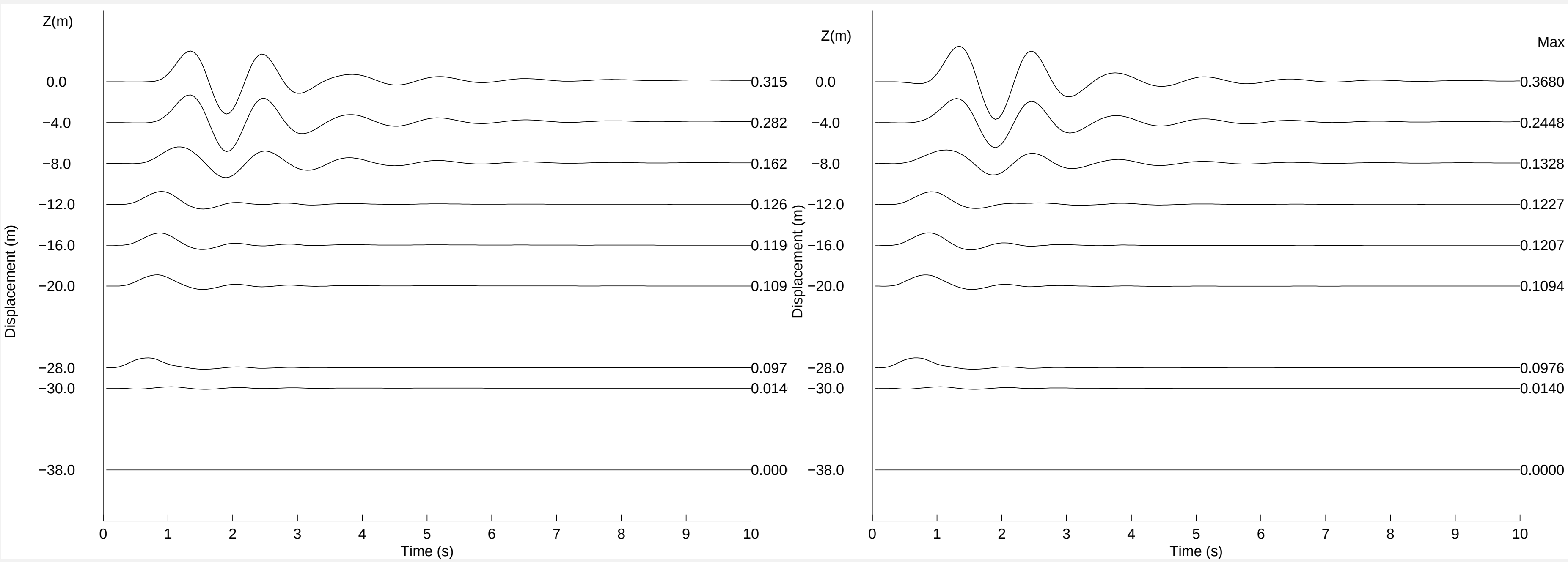


Free Field



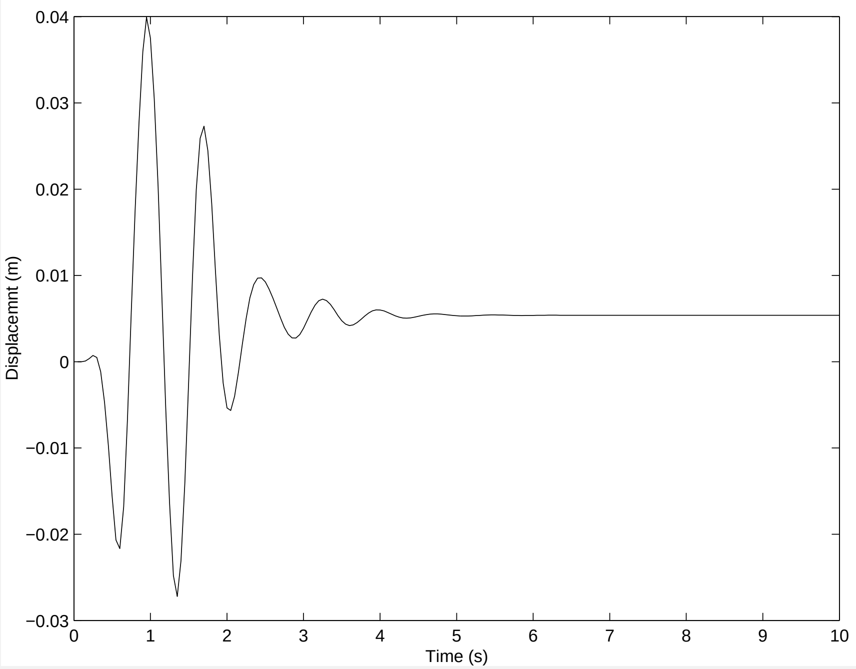
SFSI

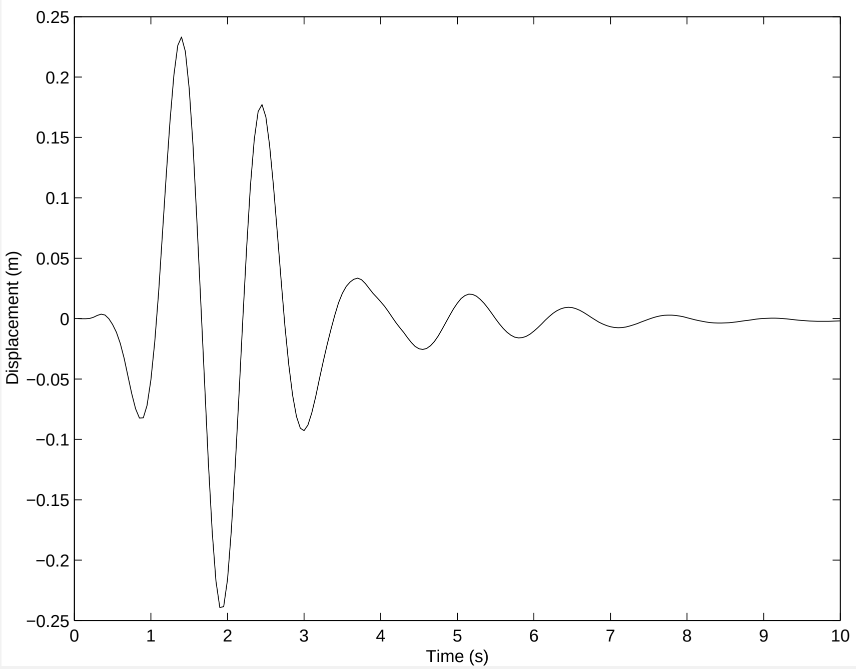
SFSI: Soft Soil Model



Free Field SFSI

SFSI Model: Pile–Column Behavior

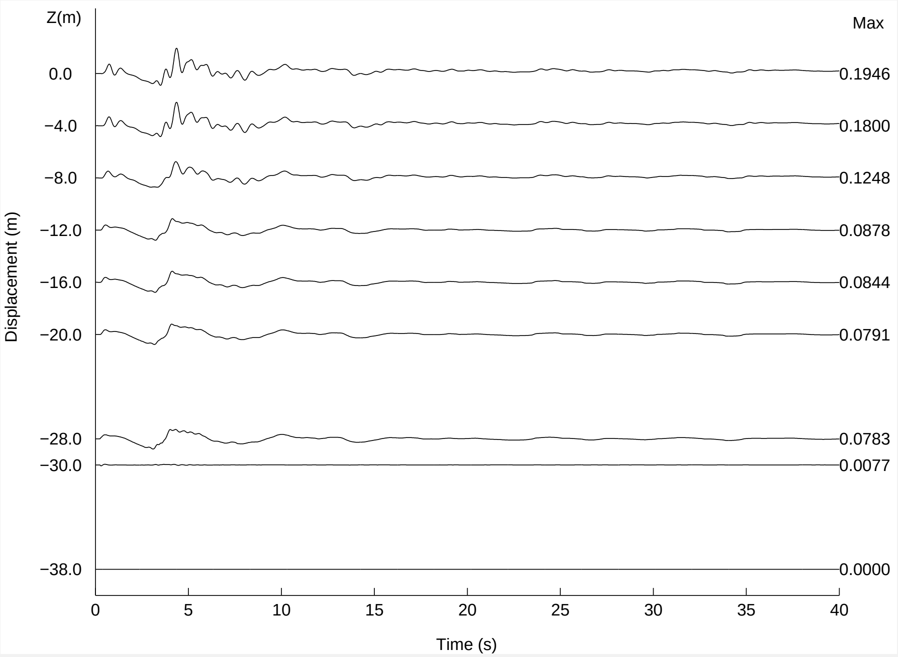


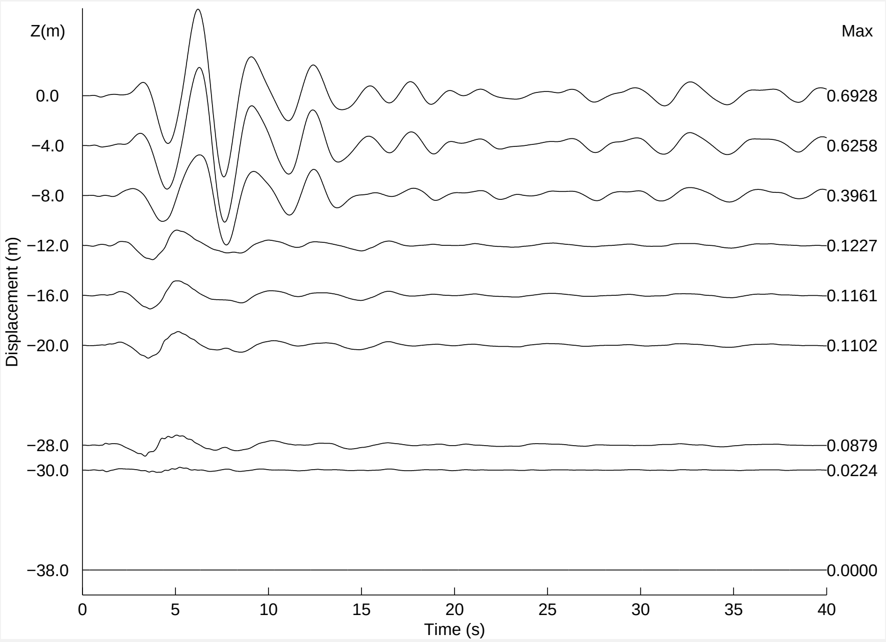


Stiff soil

Soft soil

SFSI Model: Seismic Results

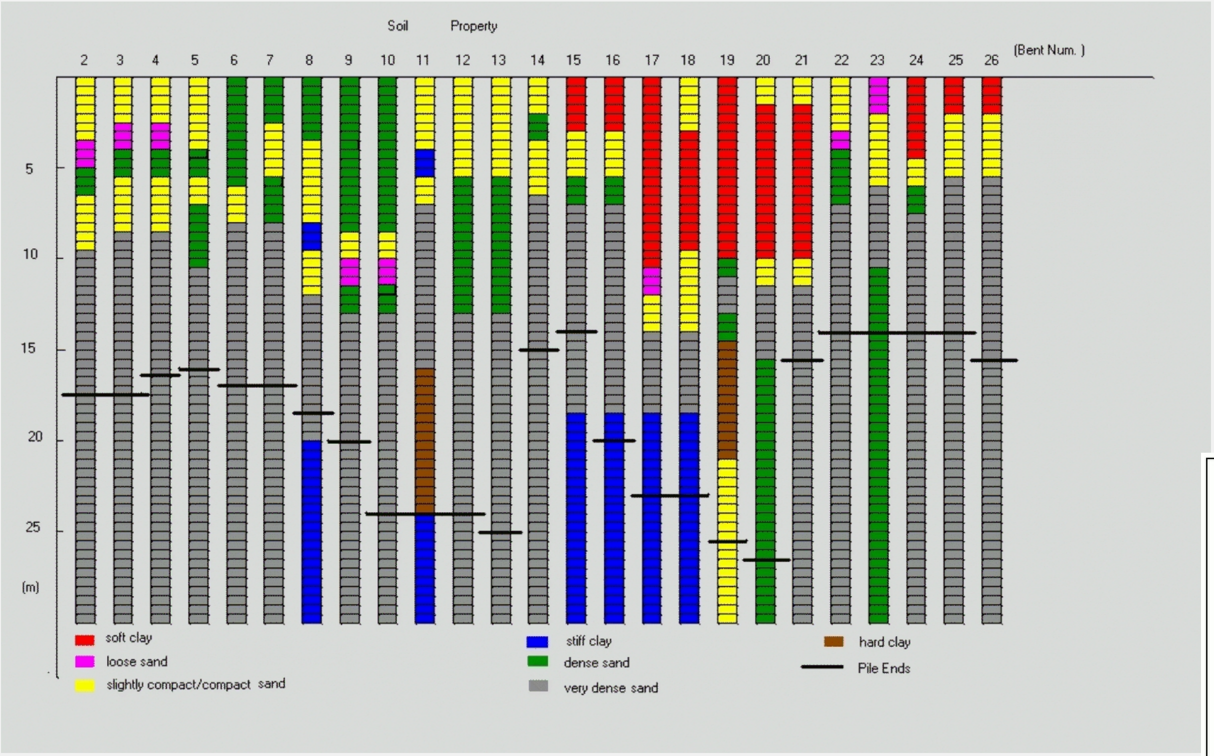


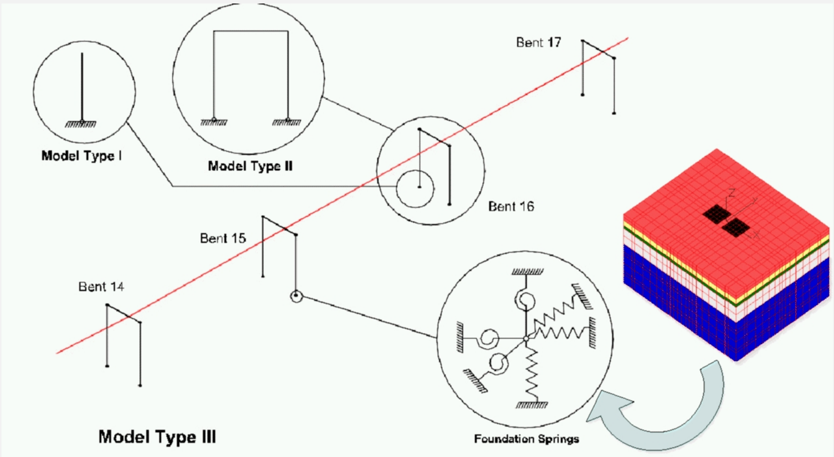


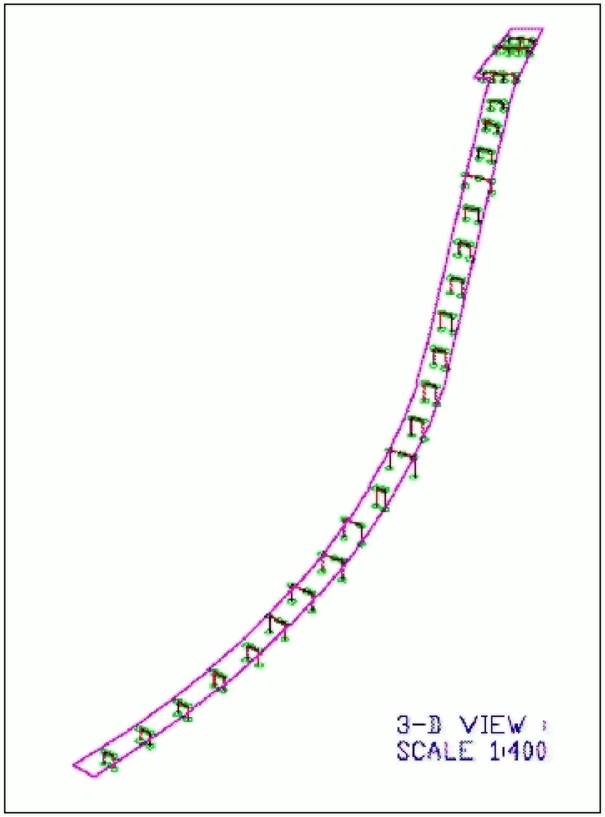
Stiff soil

Soft soil

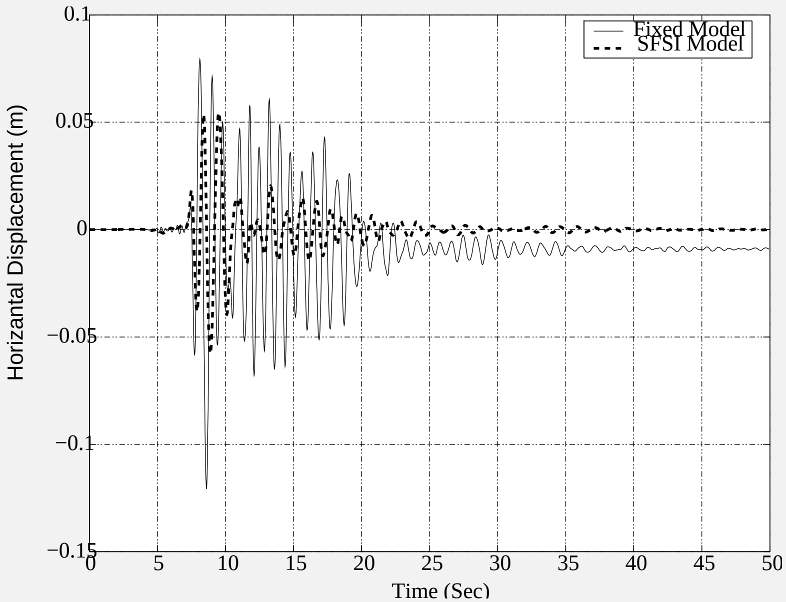
I–880 SFSI Example

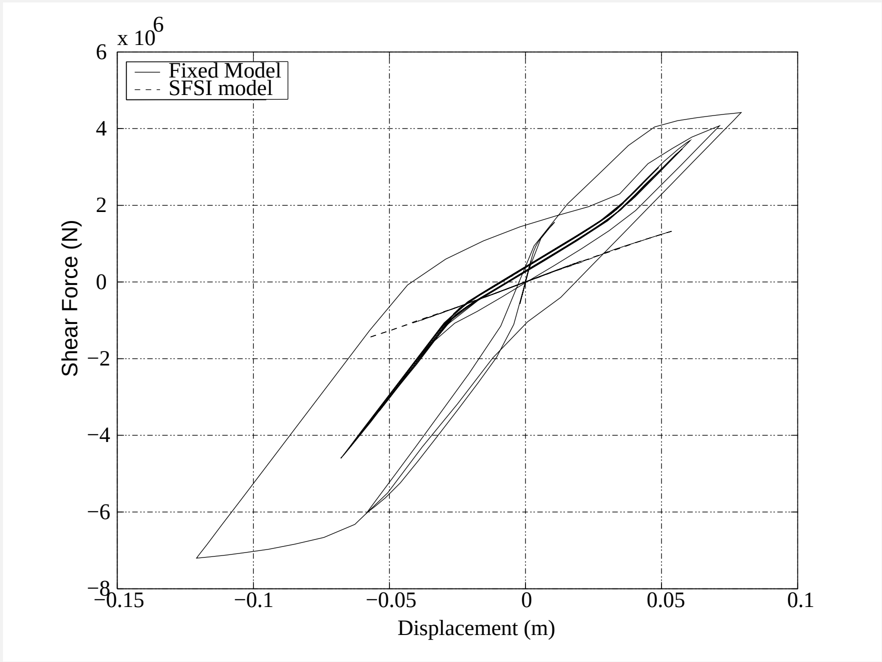






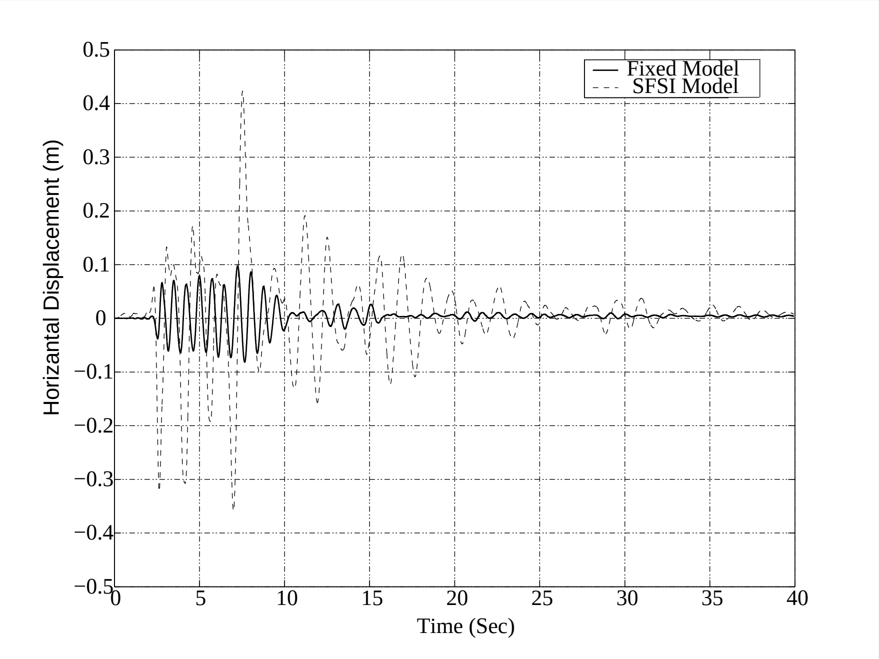
SFSI Advantageous

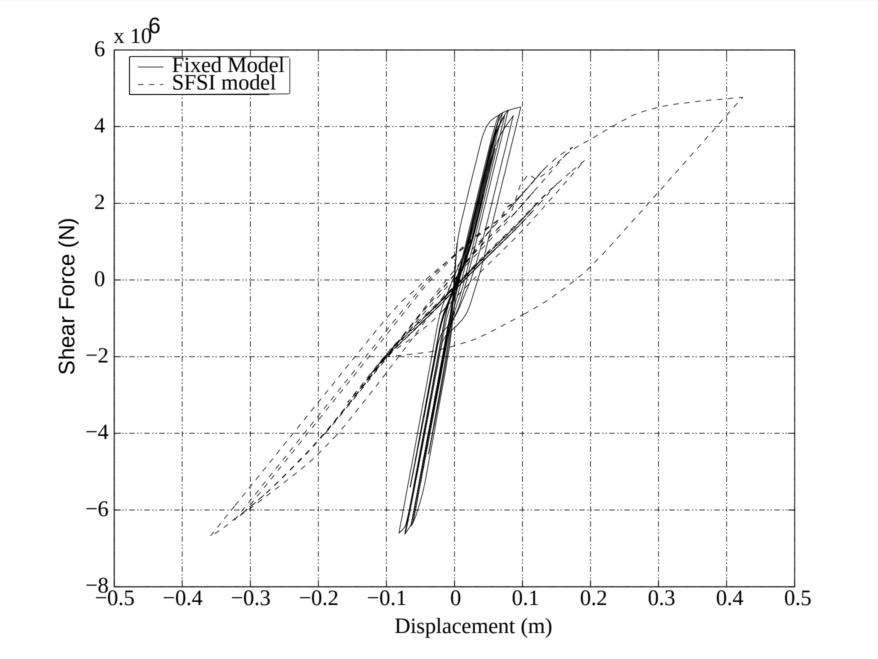




Kobe–JMA

SFSI Disadvantageous





LP–Corralitos

Conclusions

- SFSI problem requires close cooperation of experimentalists, modelers and simulators,
- **Validation domain** and **Application domain** to be bridged using simulation tools,
- One such simulation tool is OpenSees, the NEESgrid simulation platform
- The main OpenSees web site `http://opensees.berkeley.edu/` has links to documentation, examples, source code, executables, message board...