NEES Grand Challenge Project
OpenSees User Workshop
Geotechnical tools

Boris Jeremić

Department of Civil and Environmental Engineering
University of California, Davis

Motivation

- 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.

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

Presentation Overview

- Validating computational models
- Enabling Technologies
  - Template Elasto–Plasticity
  - Full Coupling of Solid and Fluid
  - Domain Reduction Method
  - Distributed Memory Parallel Computing
  - General Large Deformations
- Geomechanics Applications
  - Constitutive behavior of test specimens
  - Behavior of piles in layered soils
  - Interactions of piles in pile groups
  - Wave propagation in saturated soils
  - Seismic behavior of soils and soil-structure interactions

Goals of Validation

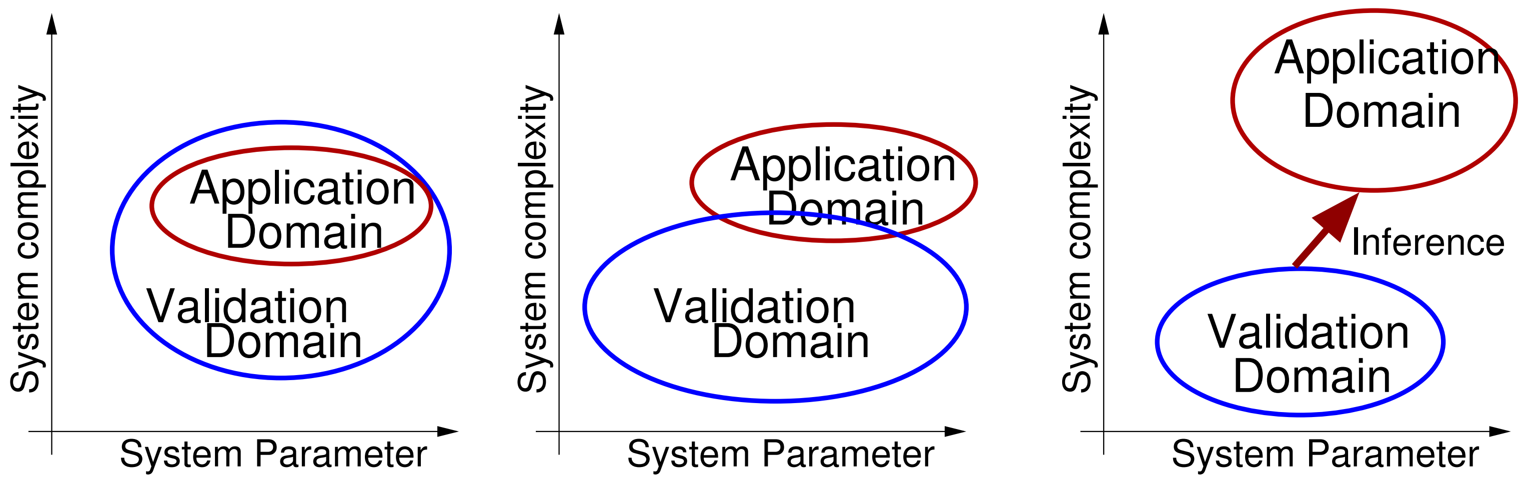
Quantification of uncertainties and errors in the computational model and the experimental measurements

- 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 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



Complete Overlap **Partial Overlap** **No Overlap**

- 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.

Enabling Technologies

- Basic formulation to establish application domain (will skip theory this time)

- Follow on–line notes for my course: Computational Geomechanics

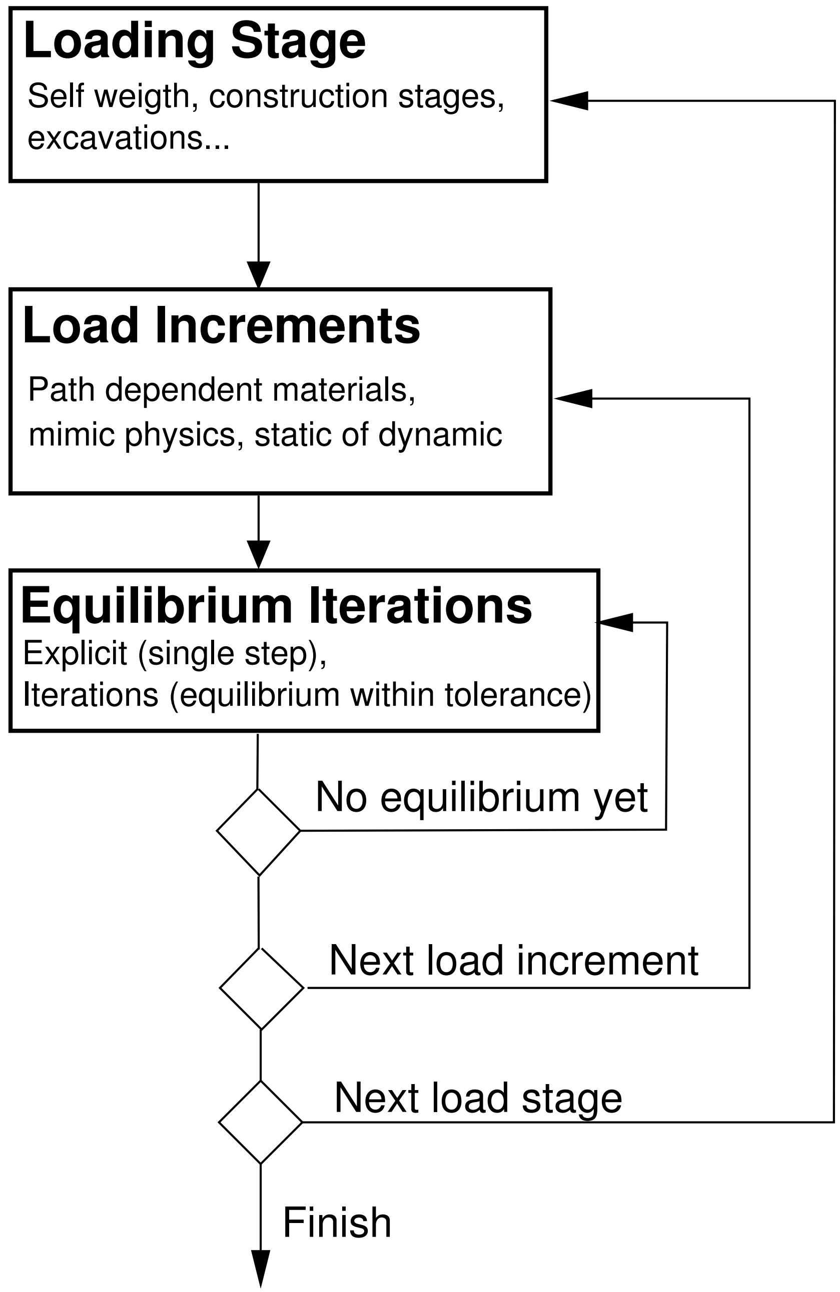
- Papers and reports available on–line as well

- Simple examples of unit element numerical tests

The Simulations Tool
Geotechnical Part

- Fairly strictly based on Thermodynamics (Geomechanics)
- Small deformation, single phase, linear and nonlinear elasticity and incremental elasto–plasticity (including 1D PY springs, 2D and 3D solids)
- General, large deformation huperelasticity and hyperelasto–plasticity
- Full coupling of solid and fluid ($u - p - U$), (small deformations only at the moment
- Seismic input through the Plastic Bowl Method (aka Domain Reduction Method), allows spatial variation in motions...)
- Visualization tools (post–processing)

Analysis Phases



Equilibrium Iterations

- Local, constitutive level iterations
- Global, finite element level iterations
- Convergence criteria
- Convergence tolerance
- Newton family of methods

Template Elasto–Plasticity

Yield function (or lack of YF), potential function (and/or flow directions), hardening/softening laws (scalar, rotational/translational kinematic, distortional...)

- Independent definitions of:

  1. Yield function (and it's derivatives)
  2. Plastic flow direction (first and second derivatives of potential function)
  3. Evolutions laws for the above two

- This is used to create Template Elastic–Plastic Models

Template Commands

```
#Elastic-plastic Drucker-Prager model with von Mises Plastic Potential
# Yield surface
set YS "-DP"
# Potential surface
set PS "-VM"
# Scalar evolution law: linear hardening coef = 1.0
set ES1  "-Leq  1.0"
# Tensorial evolution law: linear hardening coef. = 0.0
set ET1  "-Linear  0.0"
# initial stress
set stressp "0.10 0 0  0 0.10 0  0 0 0.10"
#__________E________Eo____v___rho______________alpha___k
set EPS "70000.0 70000.0 0.2 1.8 -NOD 1 -NOS 2  0.2    0.0 -stressp $stressp"
# where alpha=2*sin(phi)/(3^0.5)/(3-sin(phi)), phi->friction angle, k->cohesion

# Put together all the components in a working elastic-plastic material model
nDMaterial Template3Dep 1 -YS $YS -PS $PS -EPS $EPS -ELS1 $ES1 -ELT1 $ET1
#brick element tag     8 nodes     matID  bforce1 bforce2 bforce3  rho
element brick  1  5 6 7 8 1 2 3 4   1      0.0     0.0    -9.81  1.8
```

Template Elastic–Plastic Models

- Yield surfaces: von Mises `VM`, Drucker–Prager `DP`, Rounded Mohr–Coulomb `RMC`, Cam–Clay `CC`, Parabolic Leon `PL` (still in testing),

- Plastic flow directions (potential surfaces): von Mises `VM`, Drucker–Prager `DP`, Rounded Mohr–Coulomb `RMC`, Cam–Clay `CC`, Manzari–Dafalias (bounding surface plasticity) `MD`, Parabolic Leon `PL` (still in testing),

Template Elastic–Plastic Models (contd)

- Isotropic or kinematic hardening/softening
  - linear and/or nonlinear isotropic hardening/softening of up to 4 scalar internal variables
  - linear or nonlinear kinematic hardening/softening of up to 4 tensorial internal variables
    - Armstrong–Fredericks nonlinear kinematic hardening/softening of up to 4 tensorial internal variables
    - Bounding surface nonlinear (Dafalias–Popov) kinematic hardening/softening of up to 4 tensorial internal variables
- Hierarchical database of models (by materials)

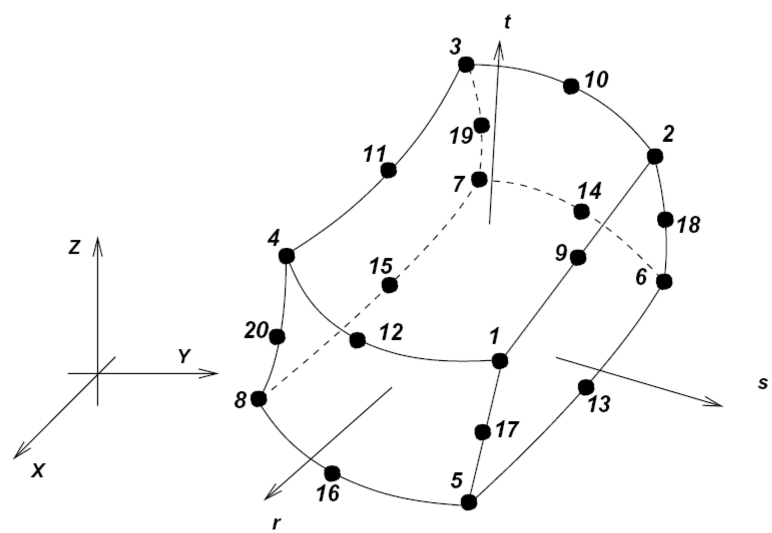
3D Solid Elements

Three types of brick elements:

- 8 node brick element `Brick8N`

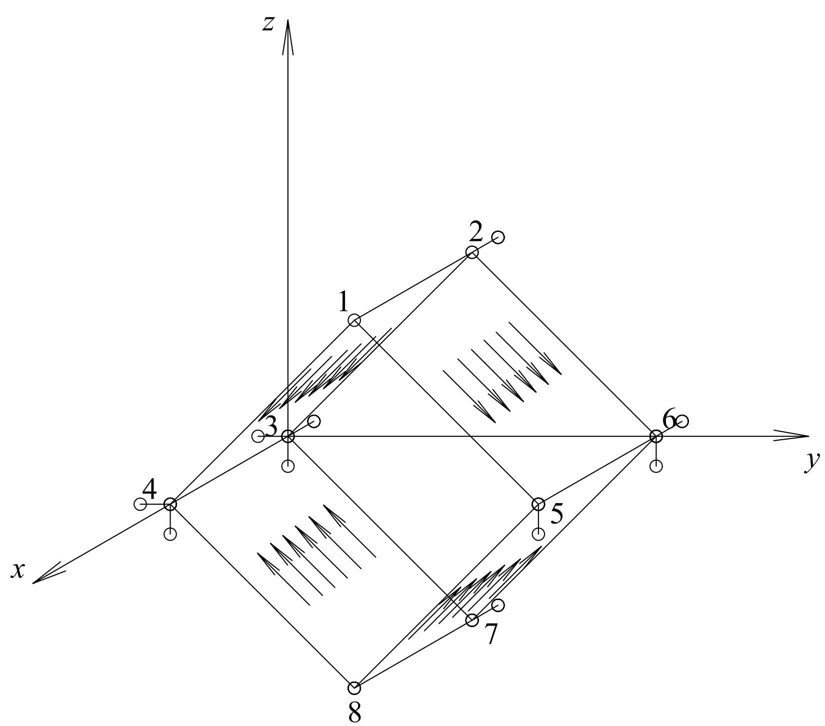
```
#_______________tag_____8 nodes_____matID__bforce1_bforce2_bforce3_rho
element Brick8N  1  1 2 3 4 5 6 7 8  1      0.0     0.0    $g    $rho
```

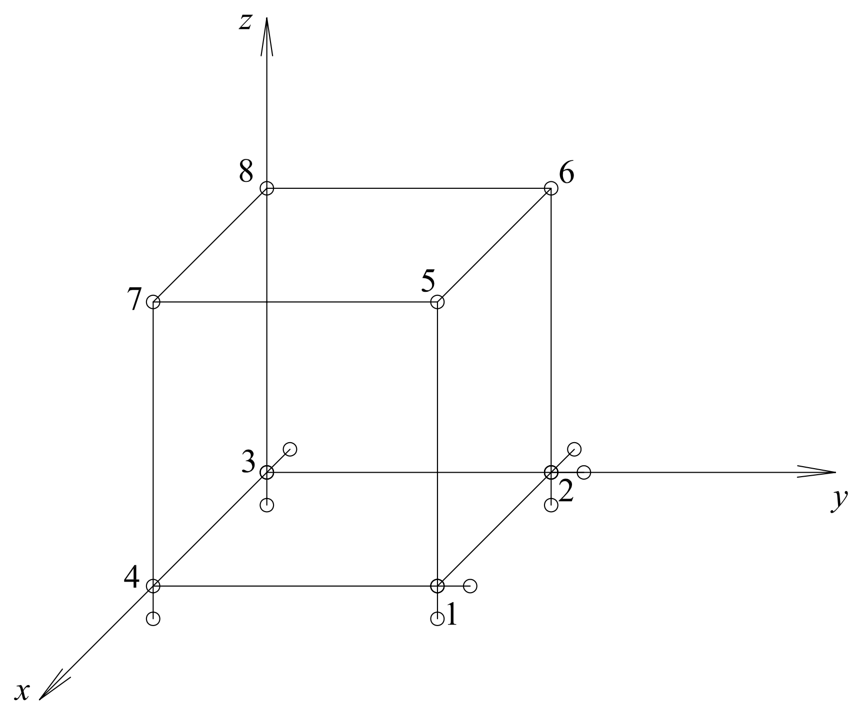
- 20 node brick element `Brick20N`
- 27 node brick element `Brick27N`



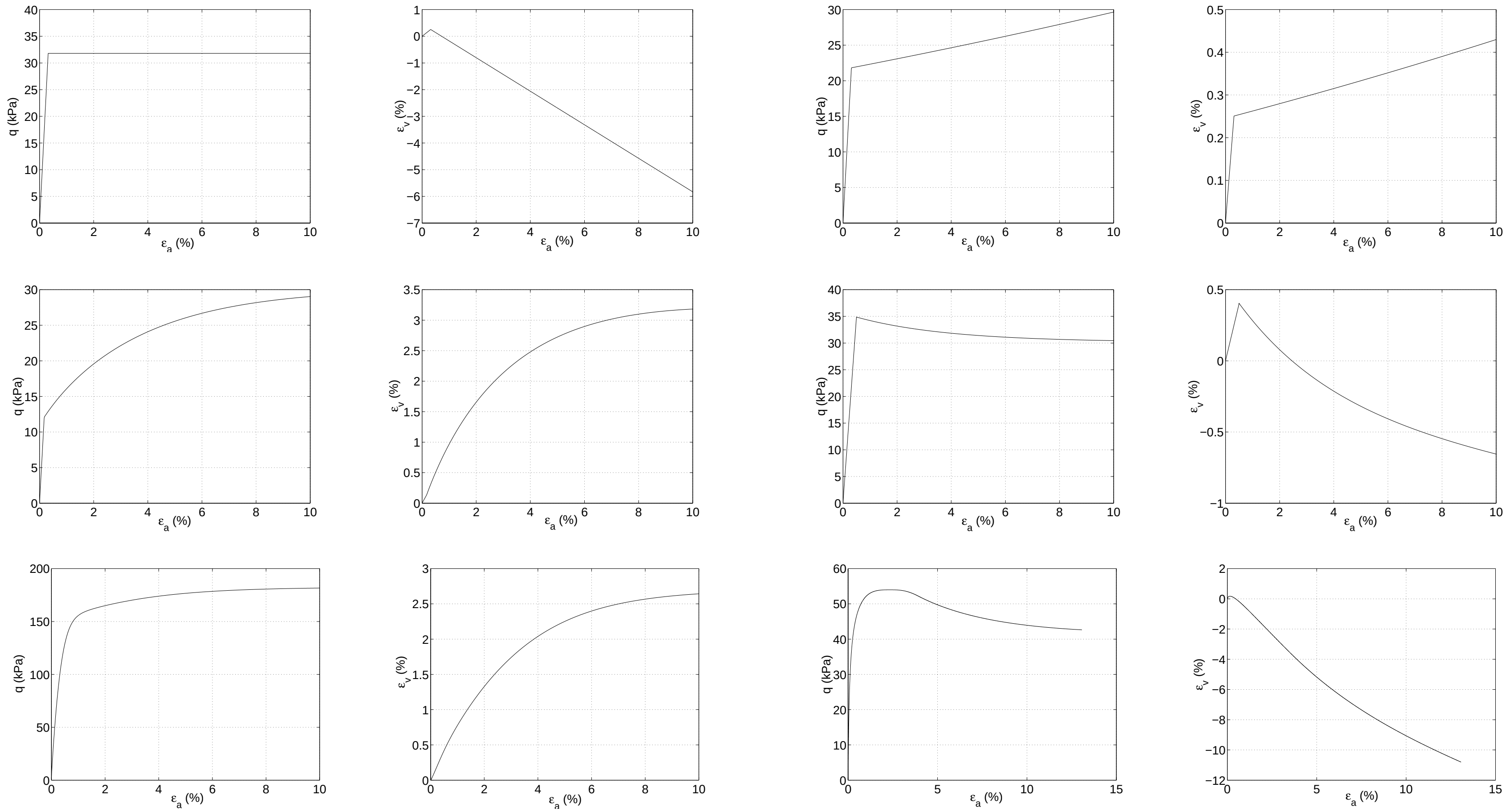
Examples

- `Pure_Shear_Test.ops`
- `Triaxial_Test.ops`
- `Simple_Shear_Test.ops`

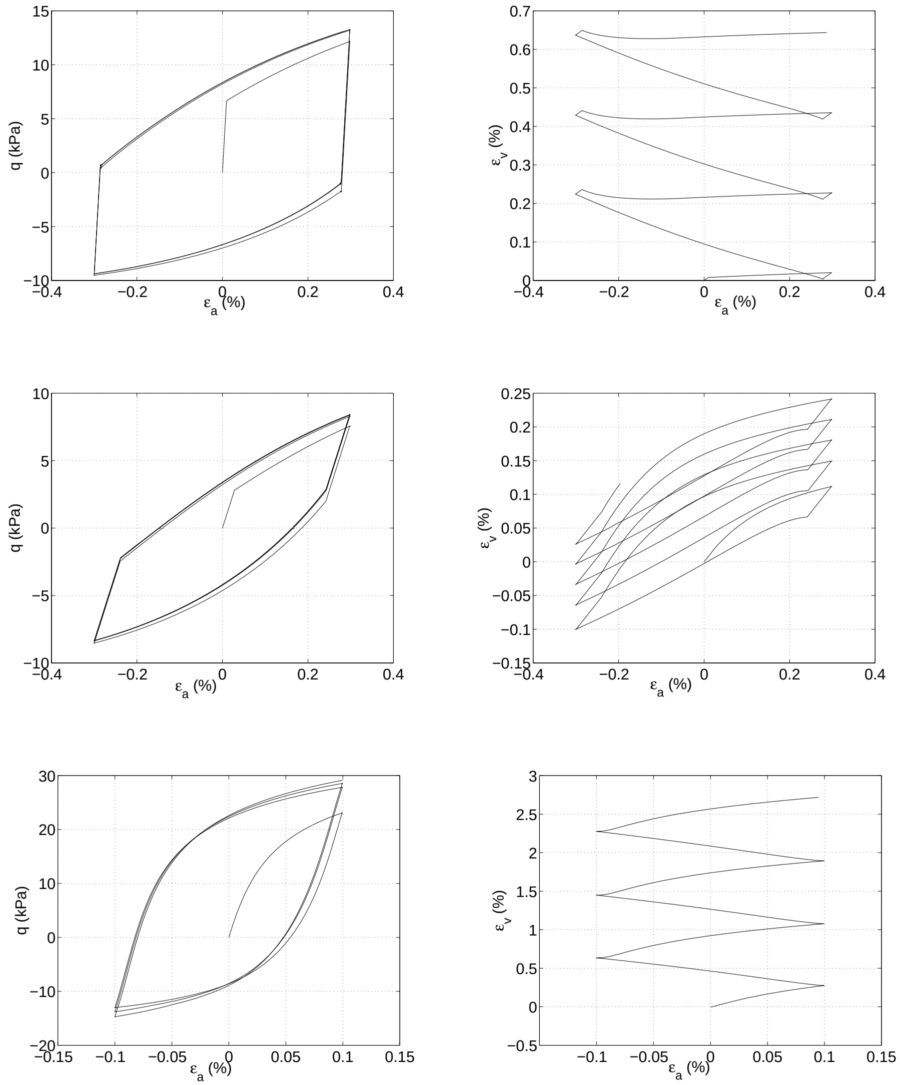




Template Examples



Template Cyclic Examples



Winkler Spings (aka PY springs)

- `uniaxialMaterial PySimple1 matTag? soilType? pult? y50? Cd? <c>`
- `uniaxialMaterial TzSimple1 matTag? tzType? tult? z50? <c>`
- `uniaxialMaterial QzSimple1 matTag? qzType? qult? z50? <suction? c?>`
- `uniaxialMaterial PySimple1 1 1 100 0.01 0.0`
- `element zeroLength 2 2 3 -mat 1 -dir 1`
- Type is usually set to 1 for clay and 2 for sand.
- Note that `p` and `pult p` are distributed loads [force per length of pile] in common design equations, but are both loads for this uniaxialMaterial [i.e., distributed load times the tributary length of the pile].

Full Coupling of Solid and Fluid

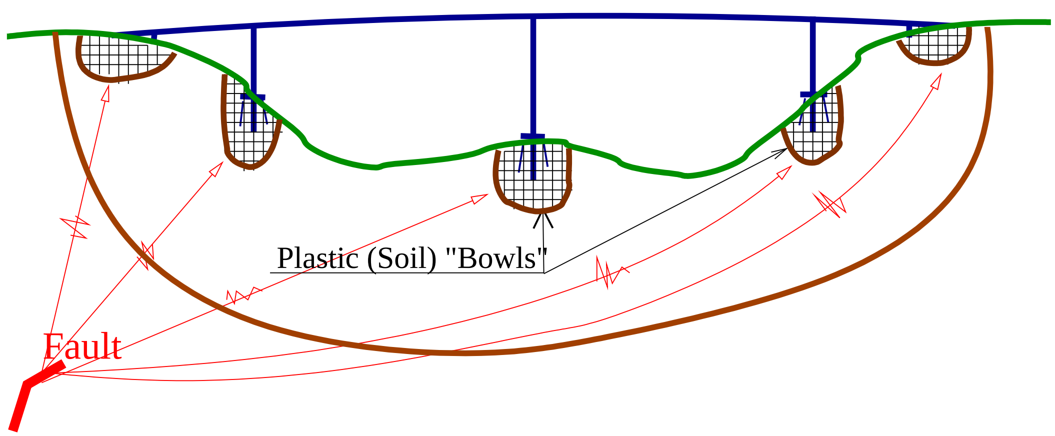
- General form, full coupling, (currently only small deformations)
- DOFs: $\bar{u}_{Lj} \rightarrow$ solid displacement $\bar{p}_L \rightarrow$ fluid pressure $\bar{U}_{Lj} \rightarrow$ fluid displacement
- 8 node brick element `Brick8N_u_p_U`

```
#(28 args)____________tag____8 nodes____matID_bforce1_bforce2_bforce3
                 porosity alpha solid_density fluid_density
                     perm_x perm_y perm_z s_bulk_modu f_bulk_modu pressure
element Brick8N_u_p_U 1  5 6 7 8 1 2 3 4   1     0.0    0.0    -9.81
                    0.8     1.0       1.8            1.0
                      10e-5  10e-5   10e-5    10e5          10e5     0
```

- 20 node brick element `Brick20N_u_p_U`

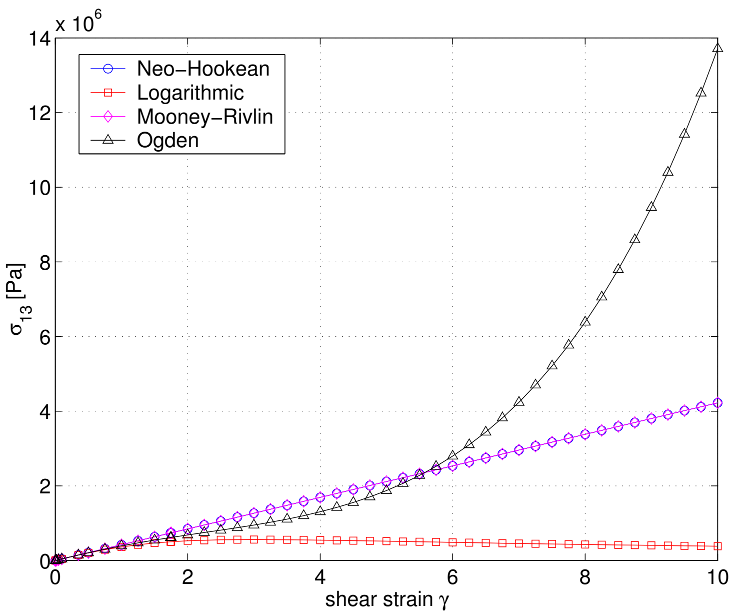
Plastic Bowl Loading (aka Domain Reduction Method)

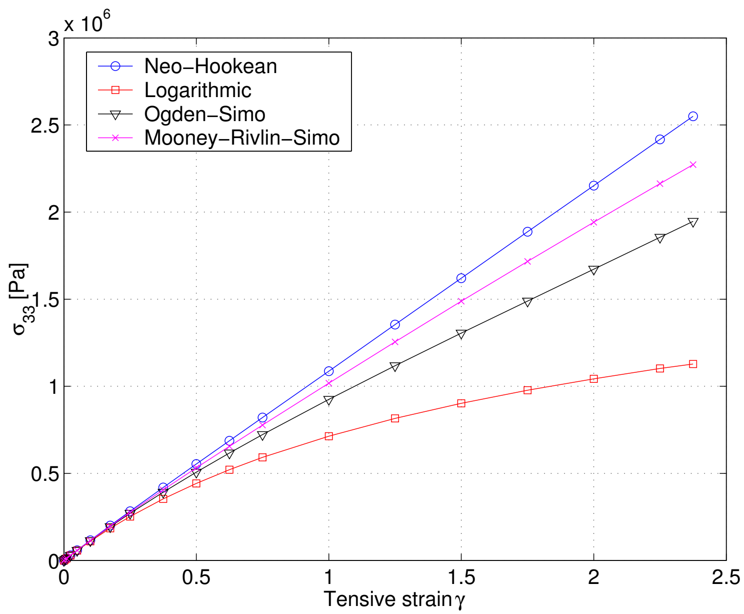
- Based on work by Bielak et al. at CMU.
- Seismic motions and accelerations input at the layer of elements that encompass an elastic–plastic zone (using SHAKE, Green's functions, Quake, SCEC...), non–reflective boundaries
- ```
  pattern PBowlLoading 1 -pbele "$Dir/PBElements.dat"
         -acce "$Dir/Inp_acce.dat" -disp "$Dir/Inp_disp.dat" -dt 0.02
              -factor 1 -xp 6.0 -xm -6.0 -yp 6.0 -ym -6.0 -zp 0.0 -zm -17.5
  ```


  ```

General Large Deformations Hyperelasto–Plasticity

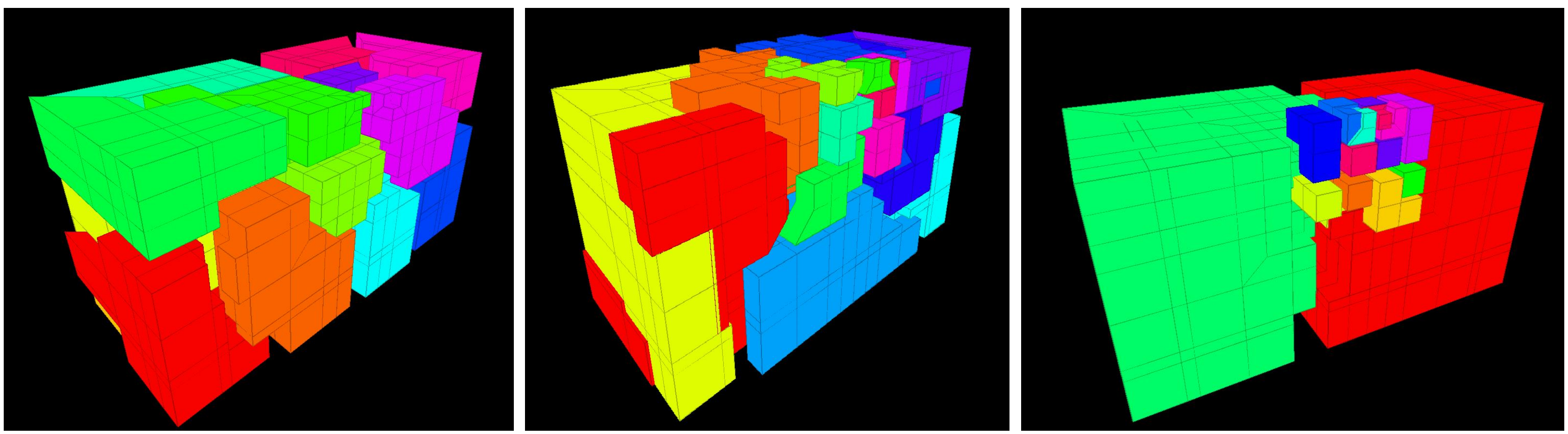
- In implementation phase (issues with material models defined in terms of various stress measures (first and second Piola–Kirchhoff, Mandel, Kirchhoff, Cauchy)





Distributed Memory Parallel Computing

- Distributed memory parallel (DMP) computational model.
- Portable from Beowulf clusters (local networks, bootable CDs) to commercial parallel machines.



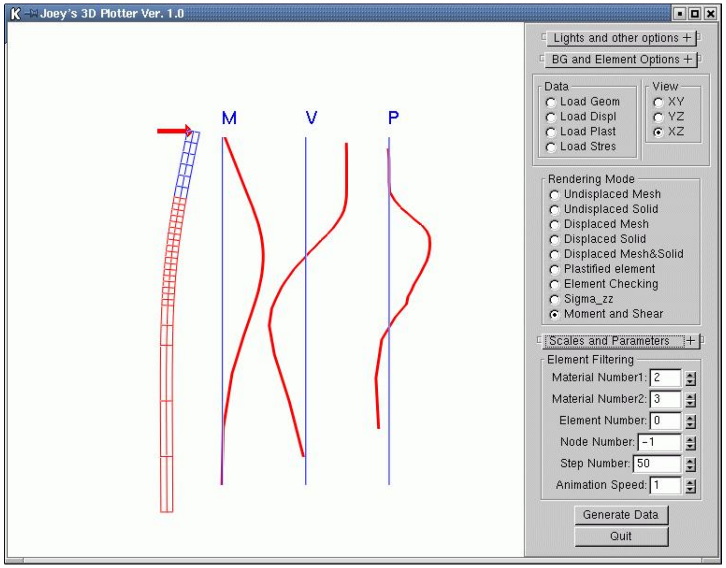
Pre– and Post–Processing

- Many small packages around, available for UNIX–like (including Apple) and/or MS Windows systems.

- Work on pre and post processing packages that are problem specific

- Use Matlab, Mathematica, GNUplot, Excell for simple post-processing

Joey3D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Moment and Shear
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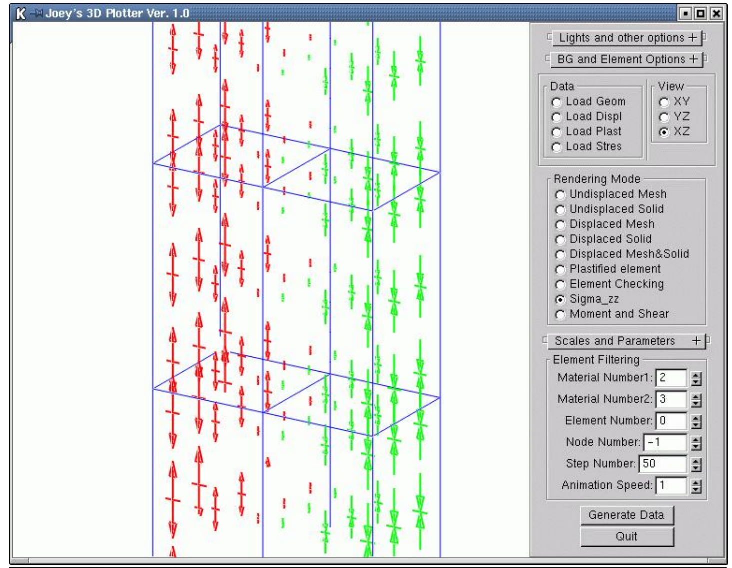
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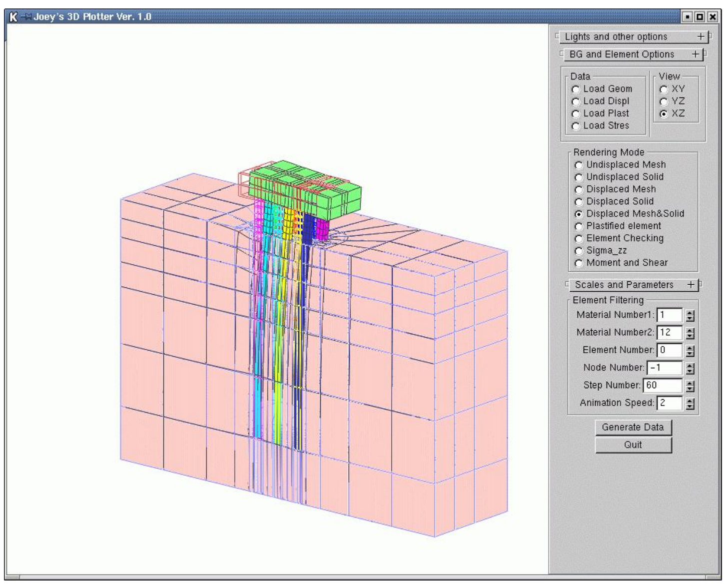
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Animation Speed: 2
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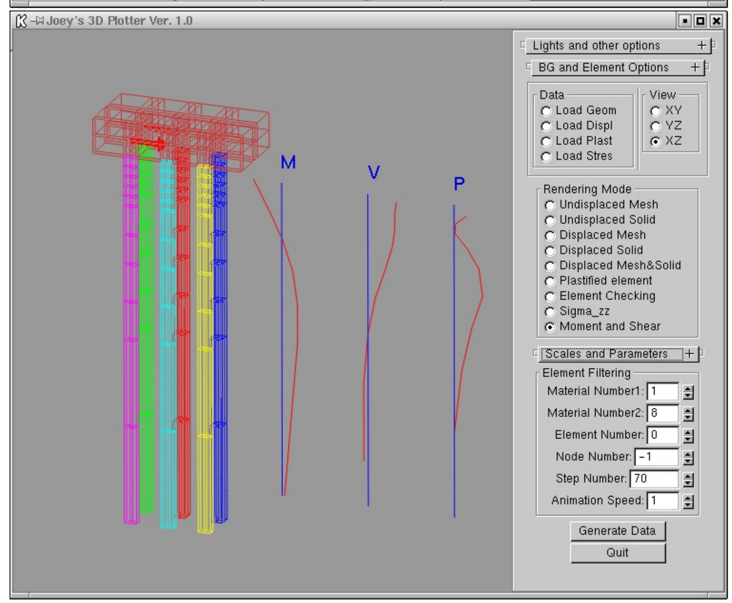
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Element Checking
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Moment and Shear
Scales and Parameters
Element Filtering
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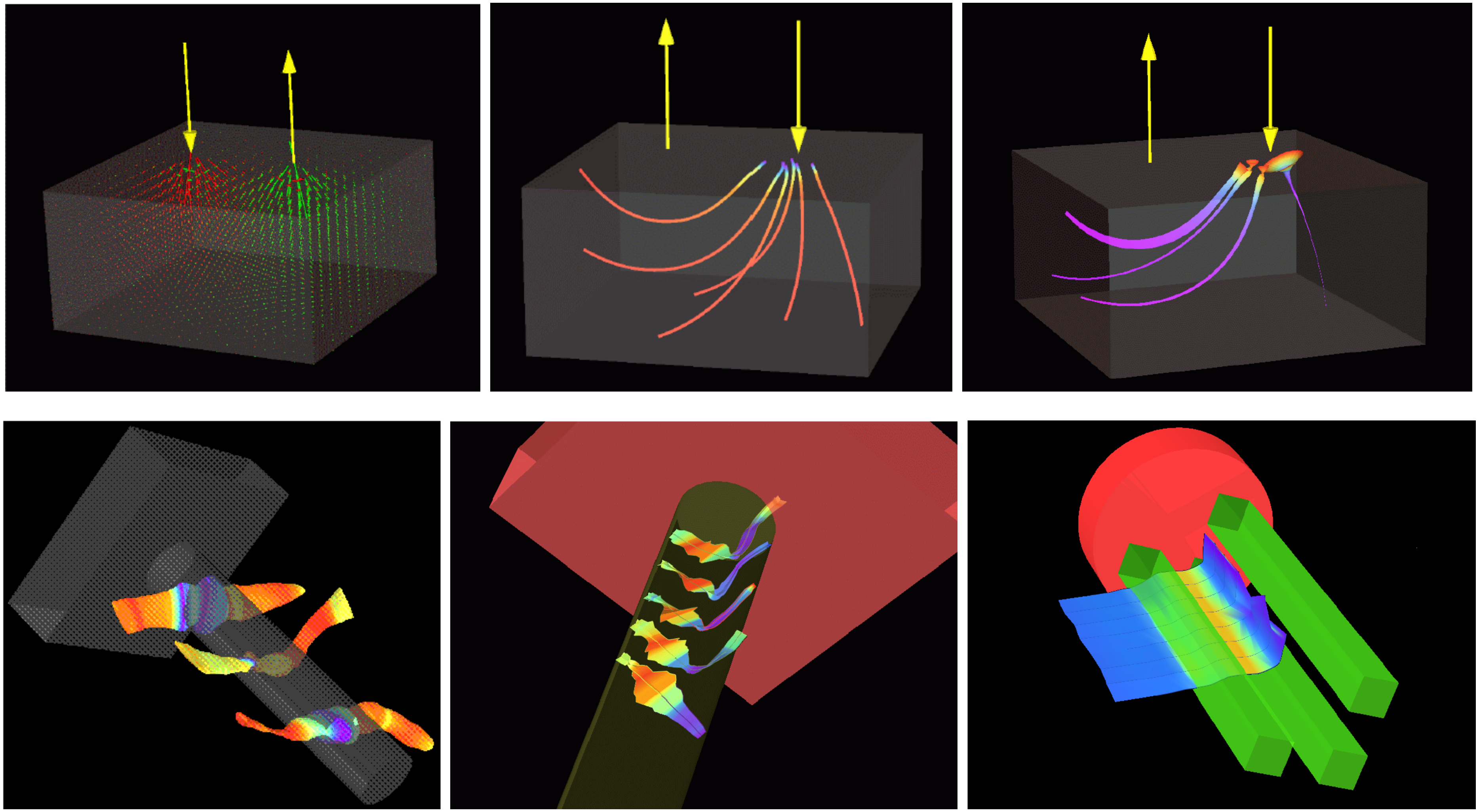
Material Number2: 8
Element Number: 0
Node Number: -1
Step Number: 70
Animation Speed: 1
Generate Data
Quit

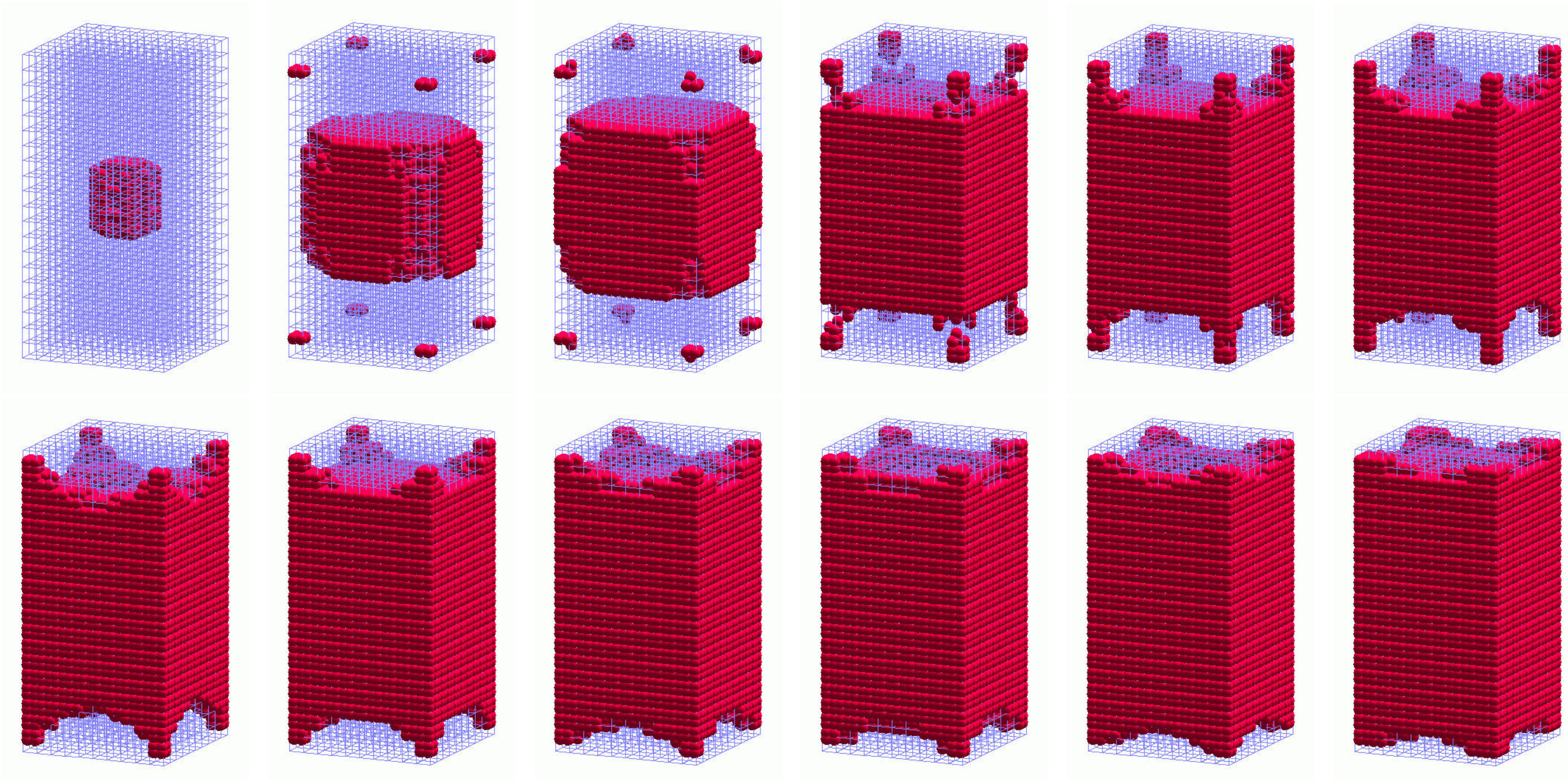
Phantom



Geotechnical Applications

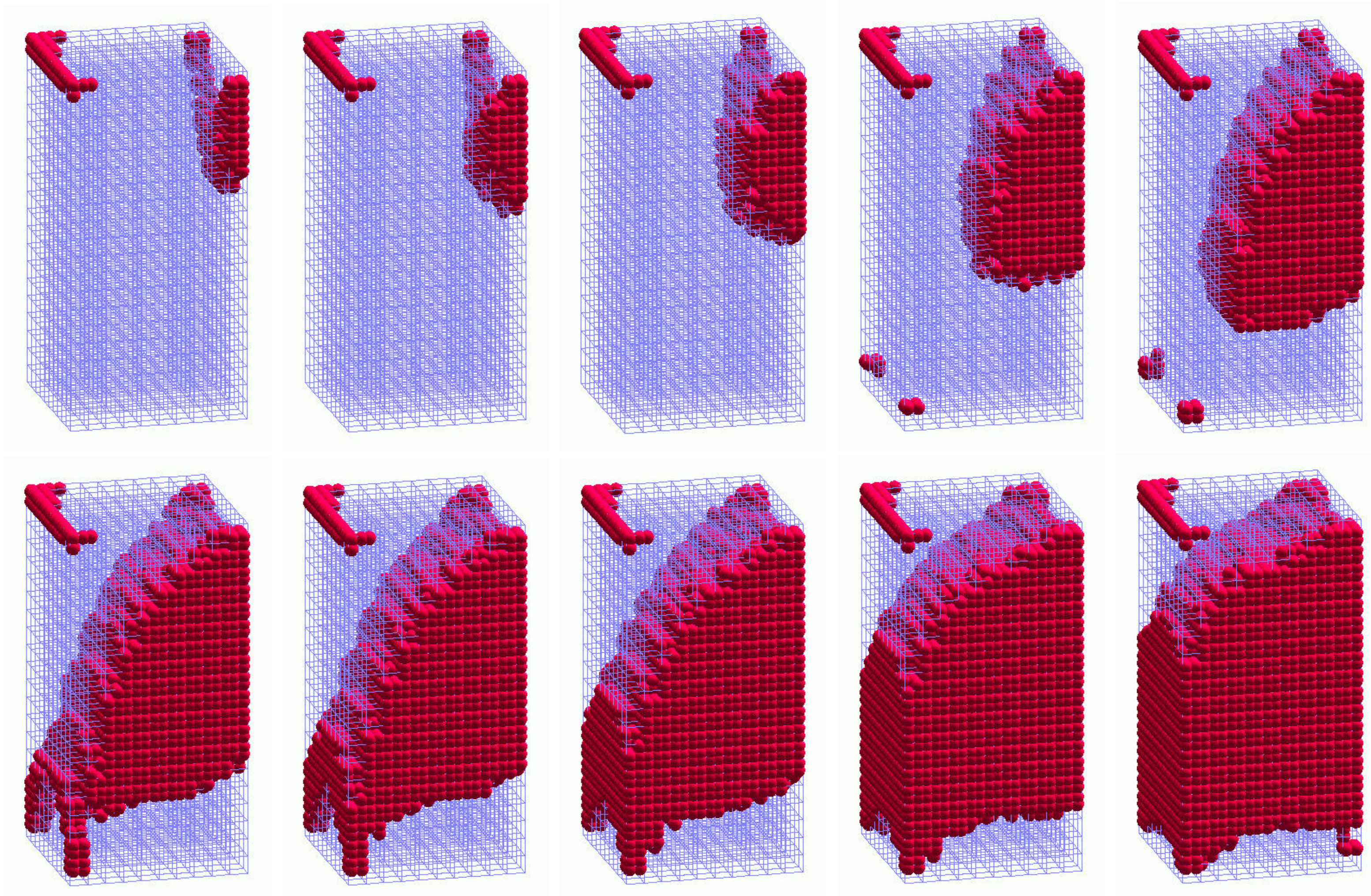
- Constitutive behavior of test specimens
- Behavior of piles in layered soils
- Interactions of piles in pile groups
- Wave propagation in saturated soils
- Seismic behavior of soils and soil-structure interactions

Long Specimen

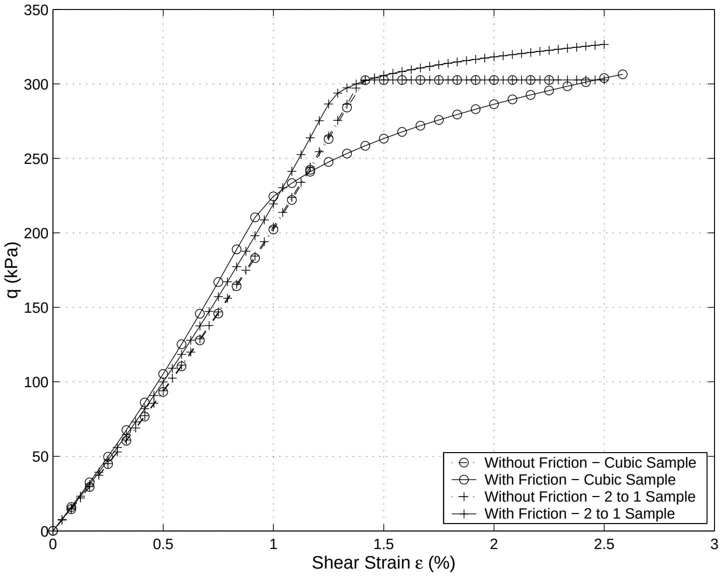


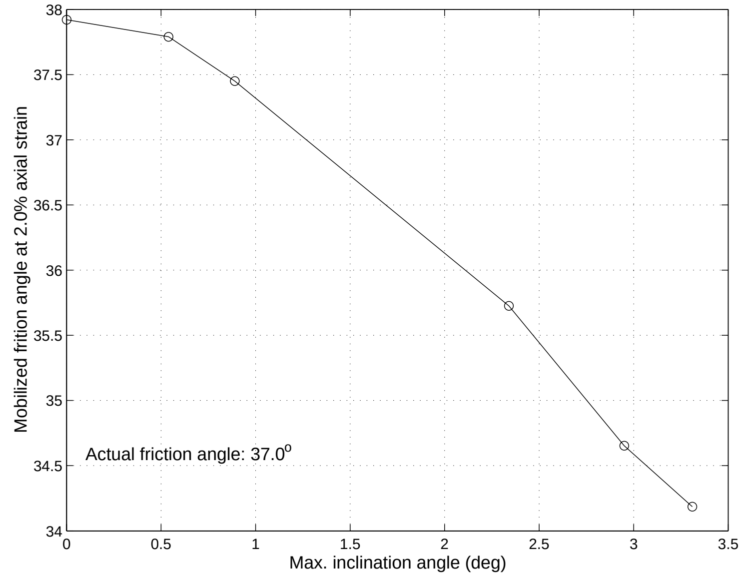
Progression of plastic zone for a long specimen with high friction end platens

Non–Level End Platens

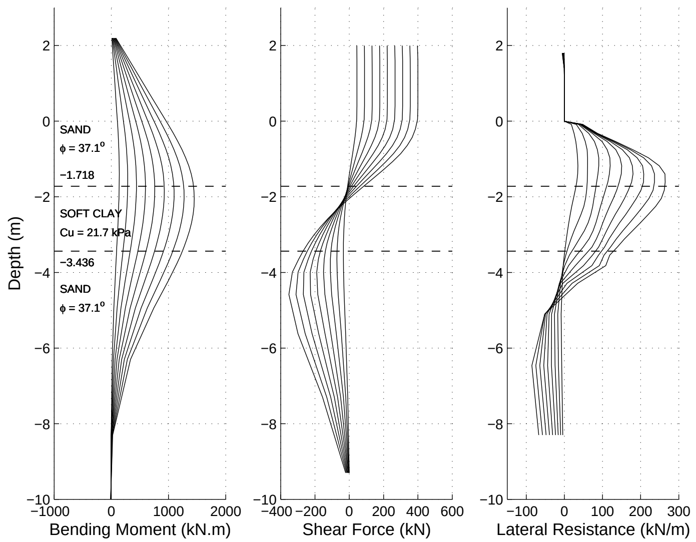


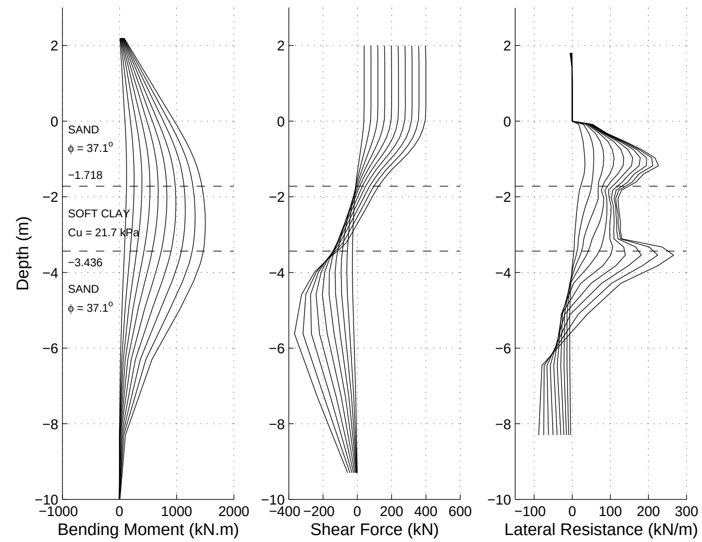
Constitutive Response?

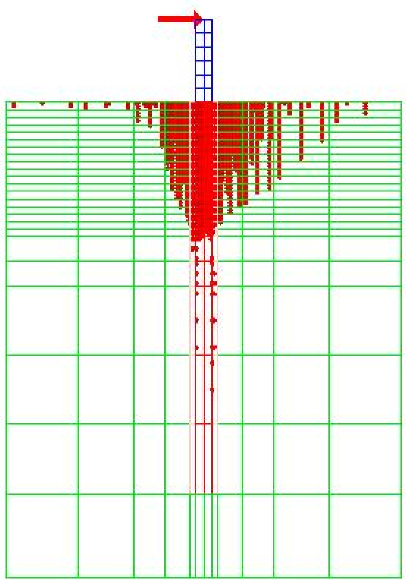


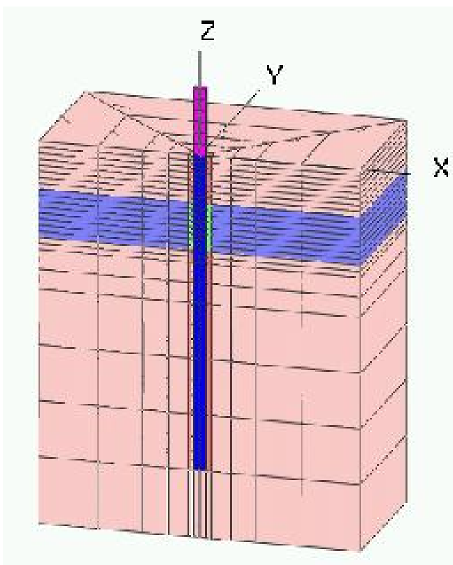


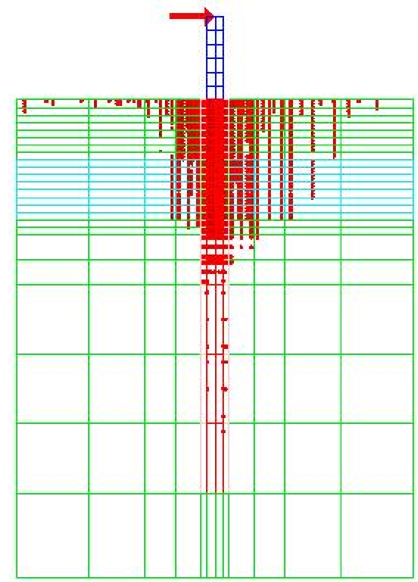
Single Pile in Layered Soils



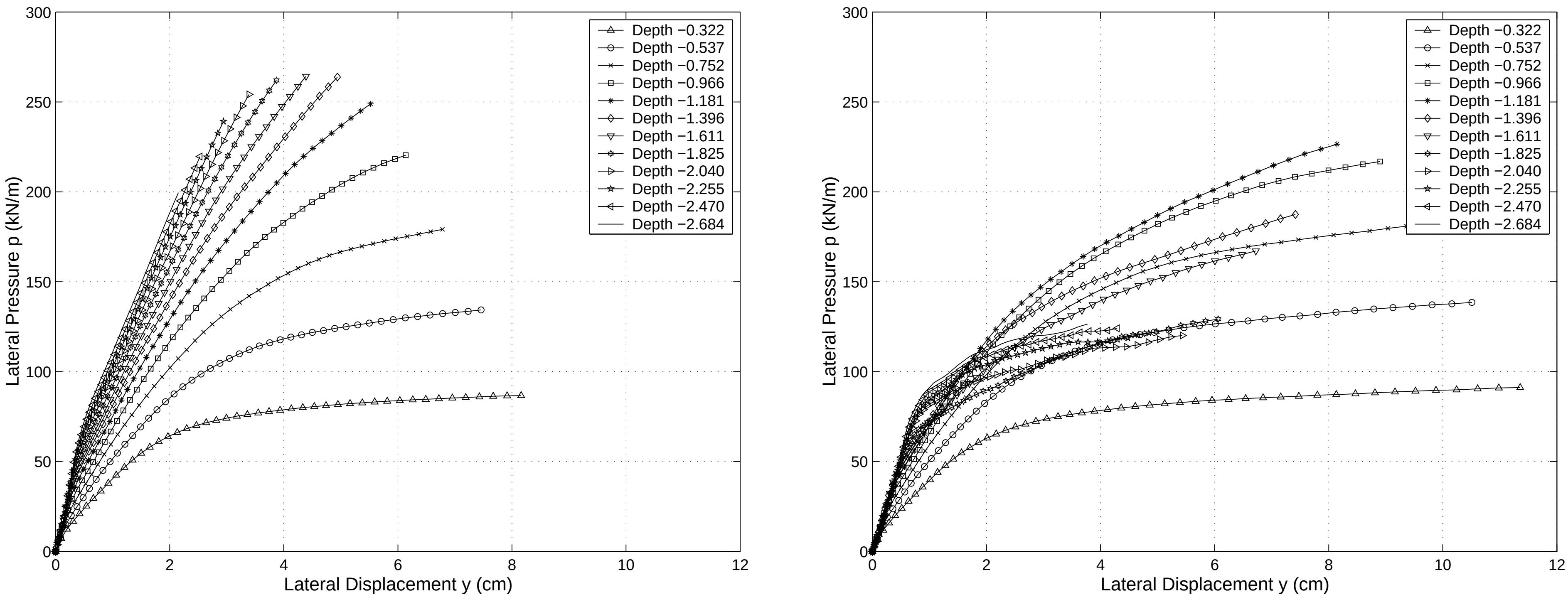








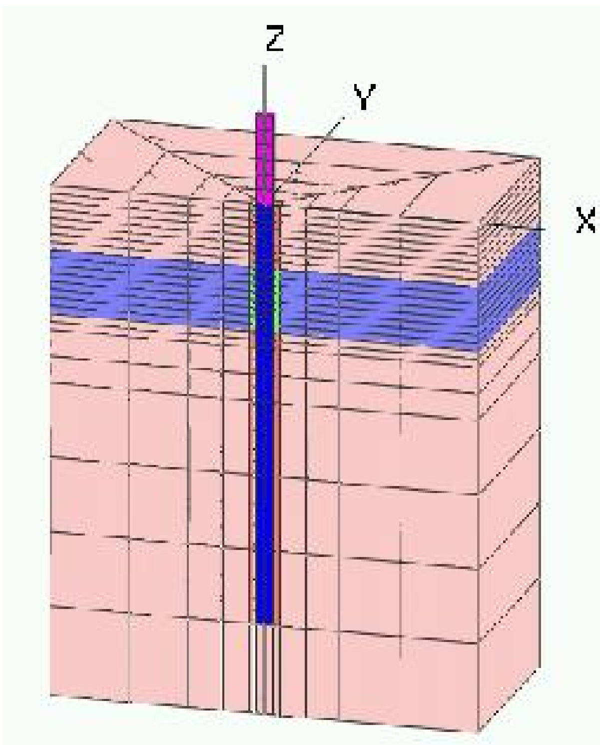
$p - y$ Response for Single Pile in Layered Soils

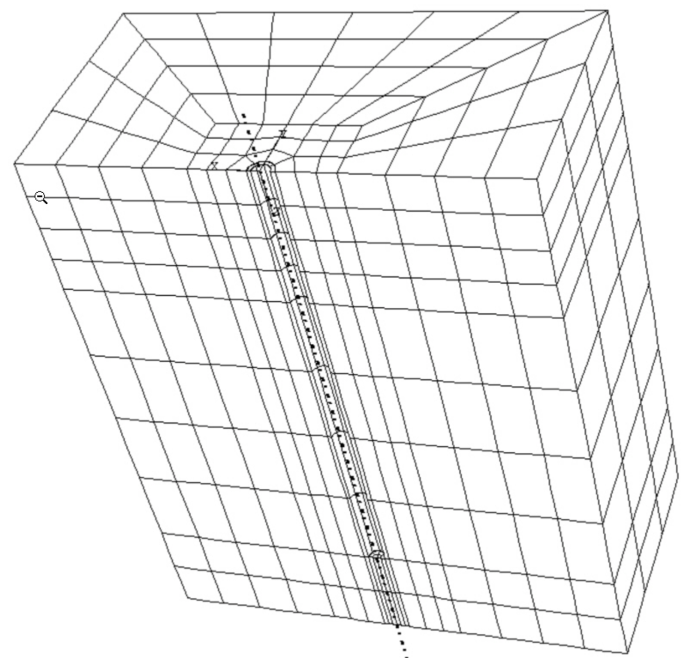


- Influence of soft layers propagates to stiff layers and vice versa
- Can have significant effects in soils with many layers

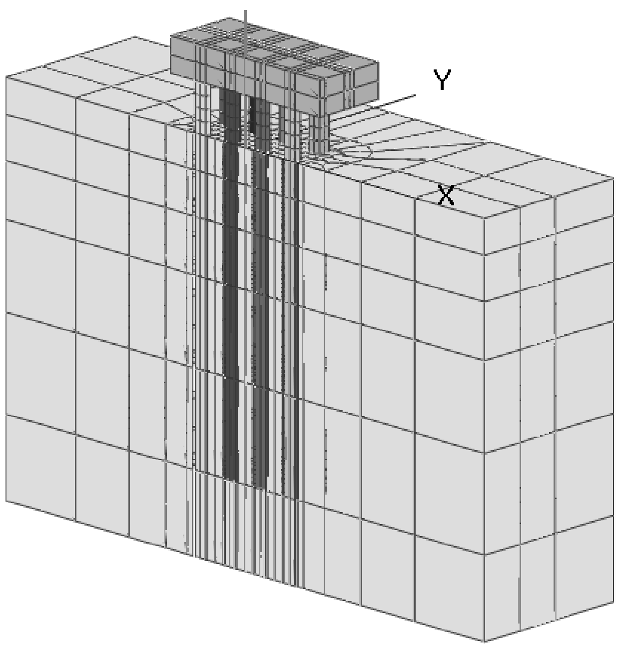
Examples

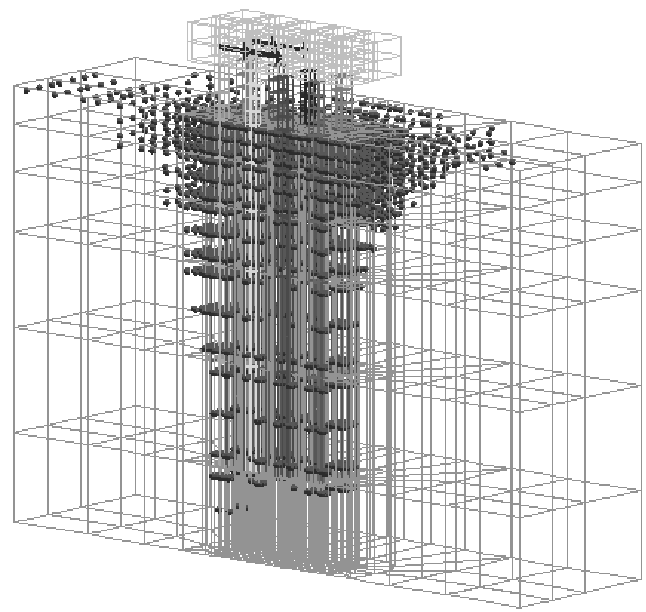
- Series of files in `SPtcl` and `SinglePileModel` directory
- Single pile (elastic, solid beam or beam-column) in soil (solids)
- Stages of loading (self weight of soil only, static pushover)





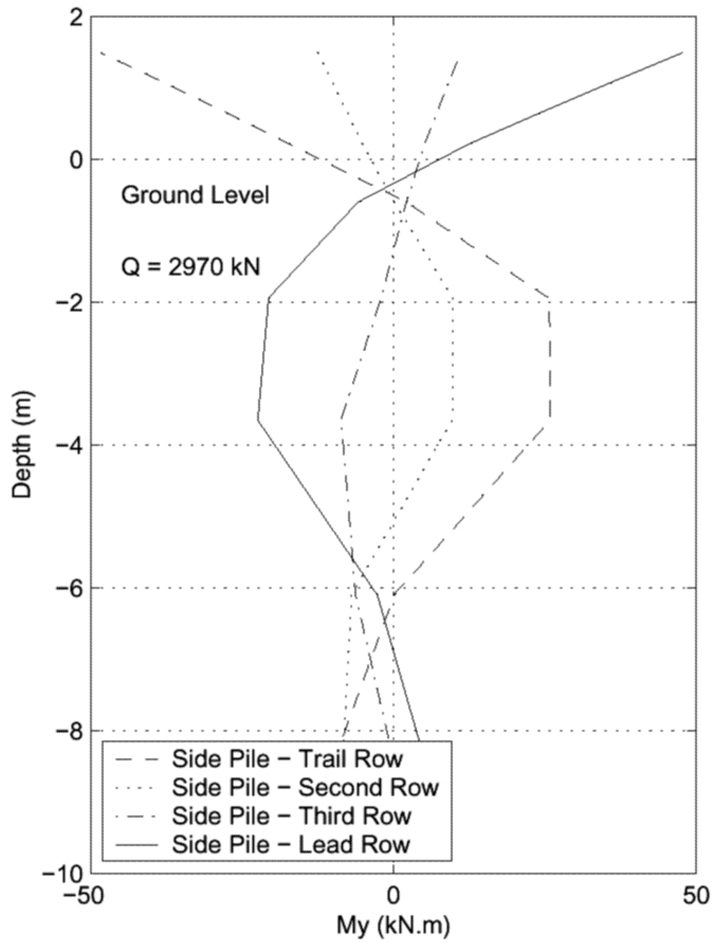
Pile Group Simulations

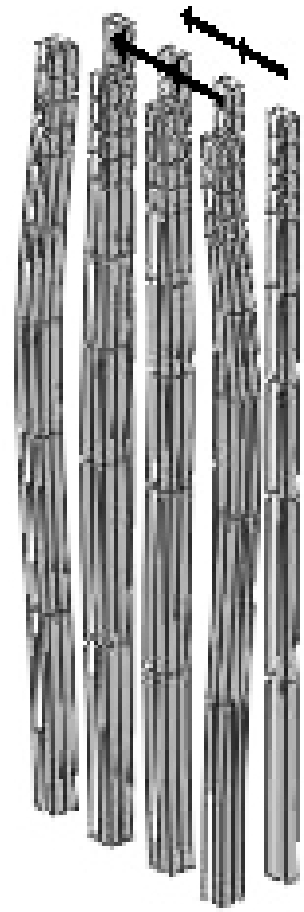




- 4x3 pile group model and plastic zones

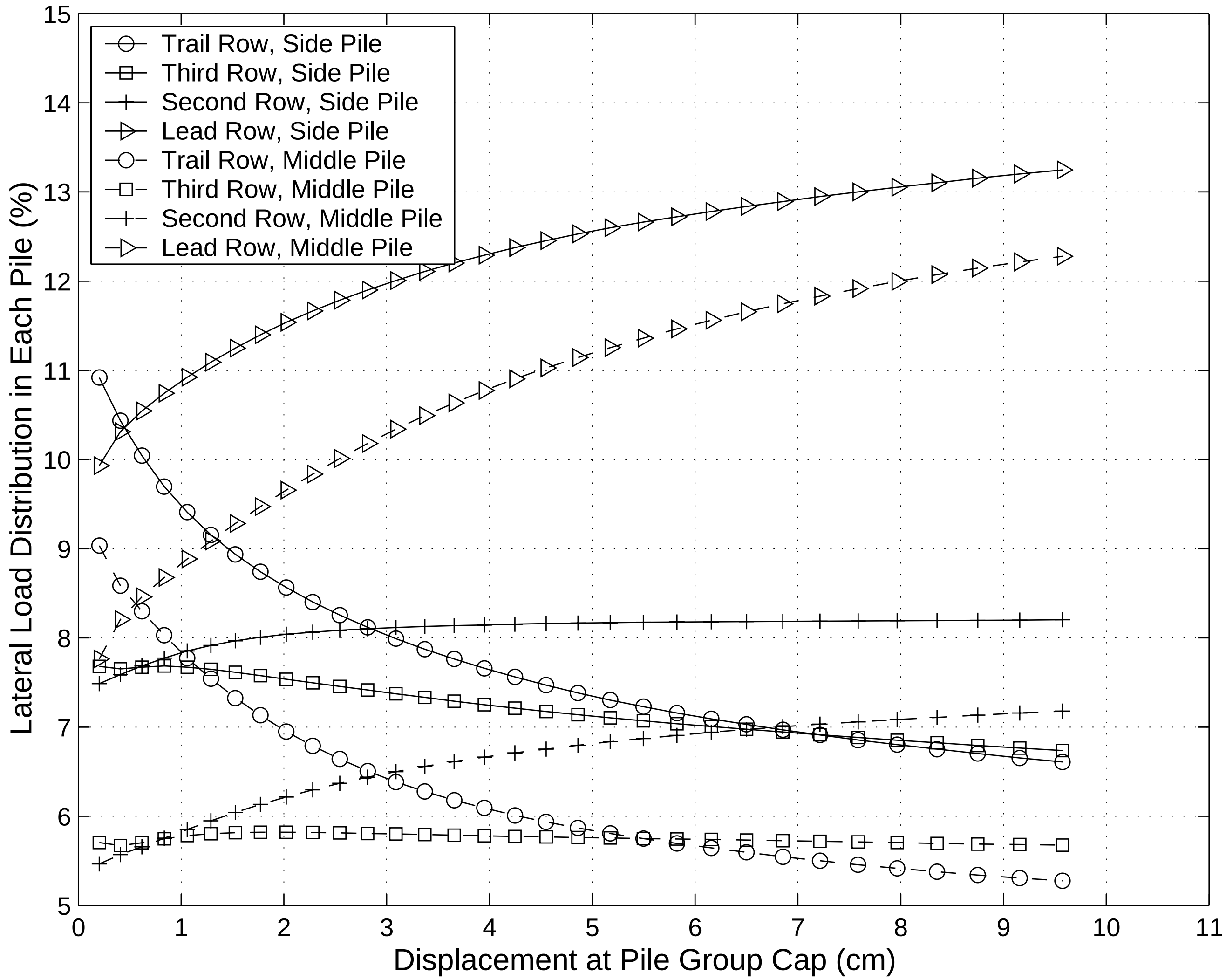
Out of Plane Effects



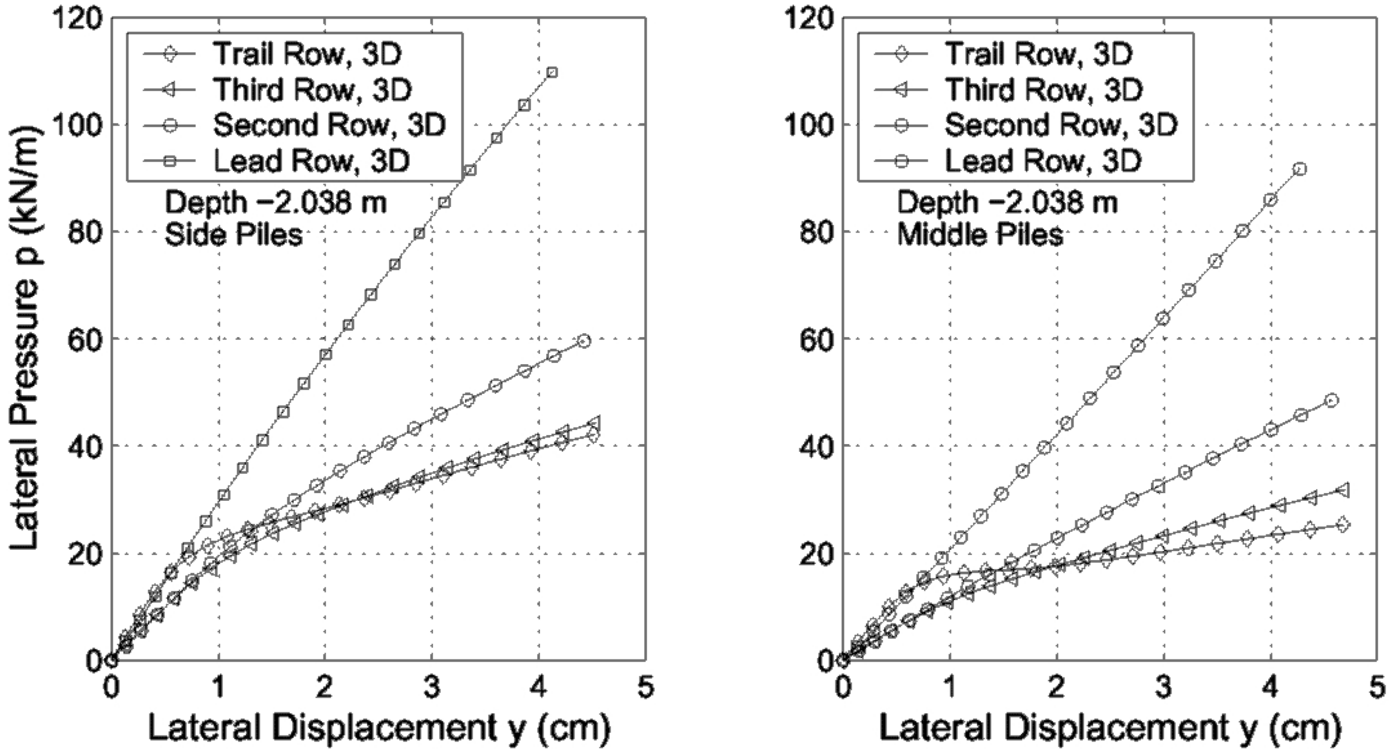


- Out-of-loading-plane bending moment diagram,
- Out-of-loading-plane deformation.

Load Distribution per Pile

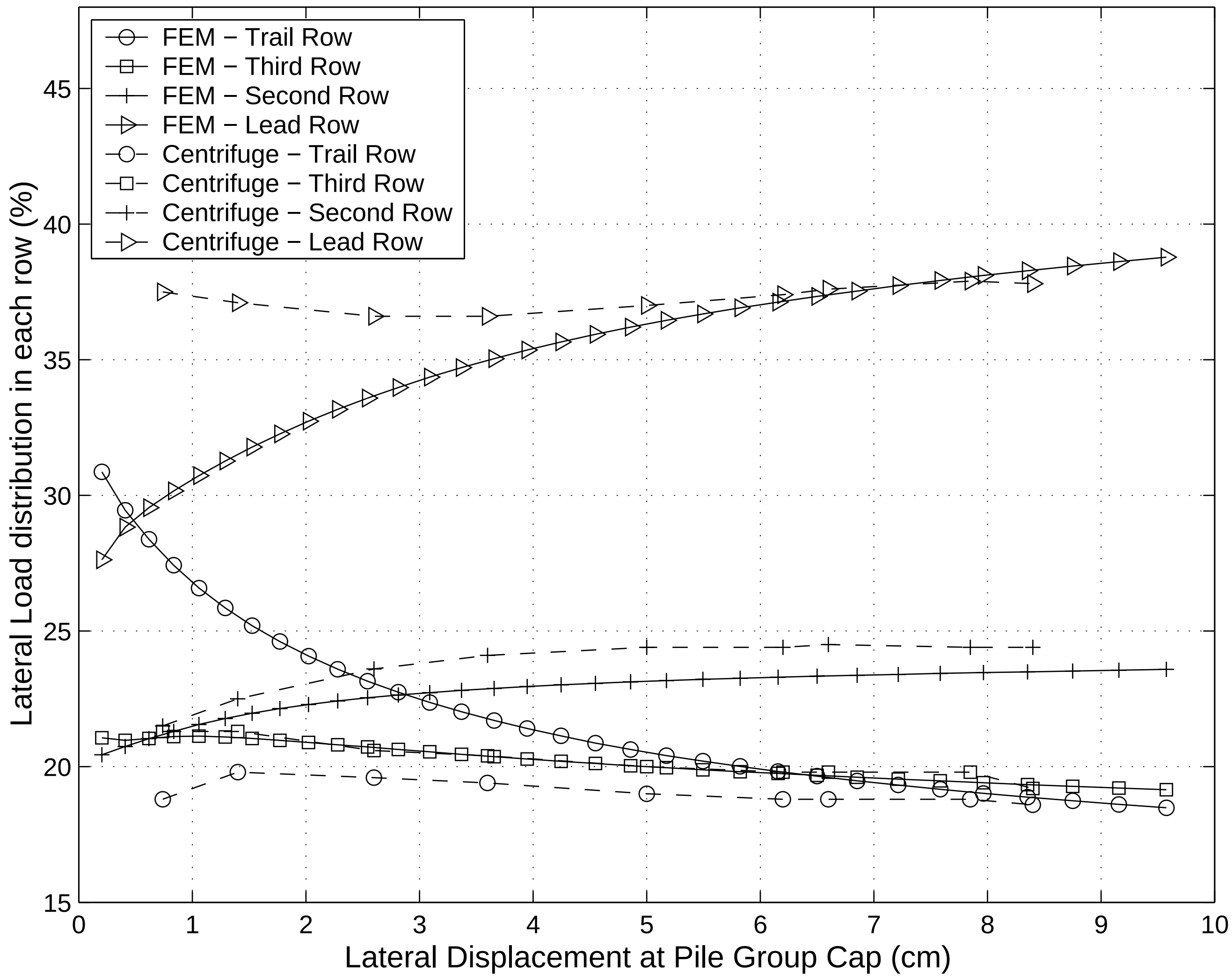


Piles Interaction at -2.0m

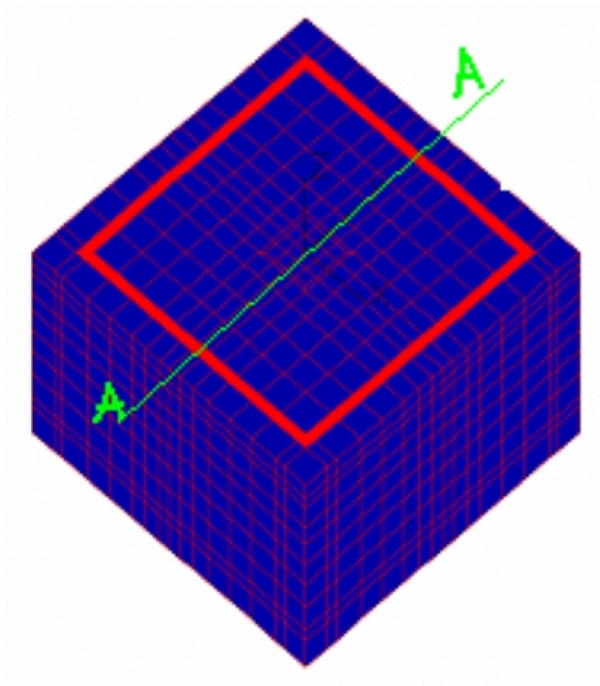


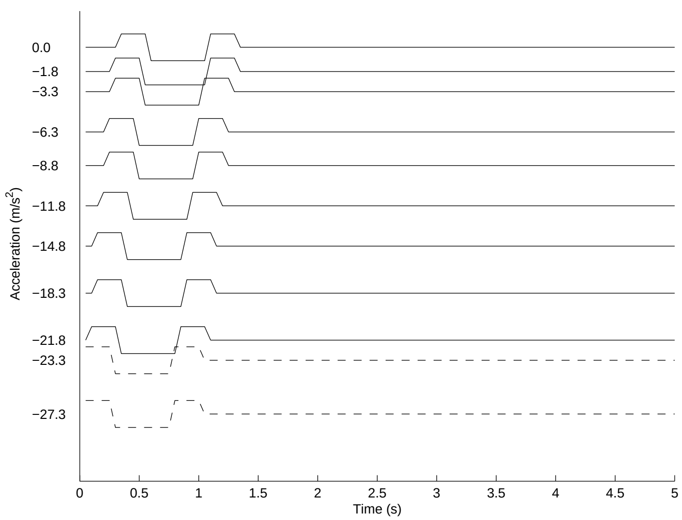
- Note the difference in response curves (cannot scale single pile response for multiple piles)

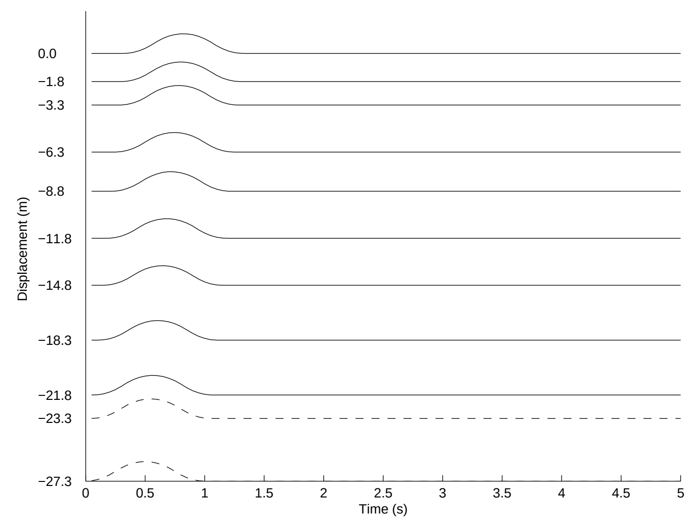
Validation with Centrifuge Tests



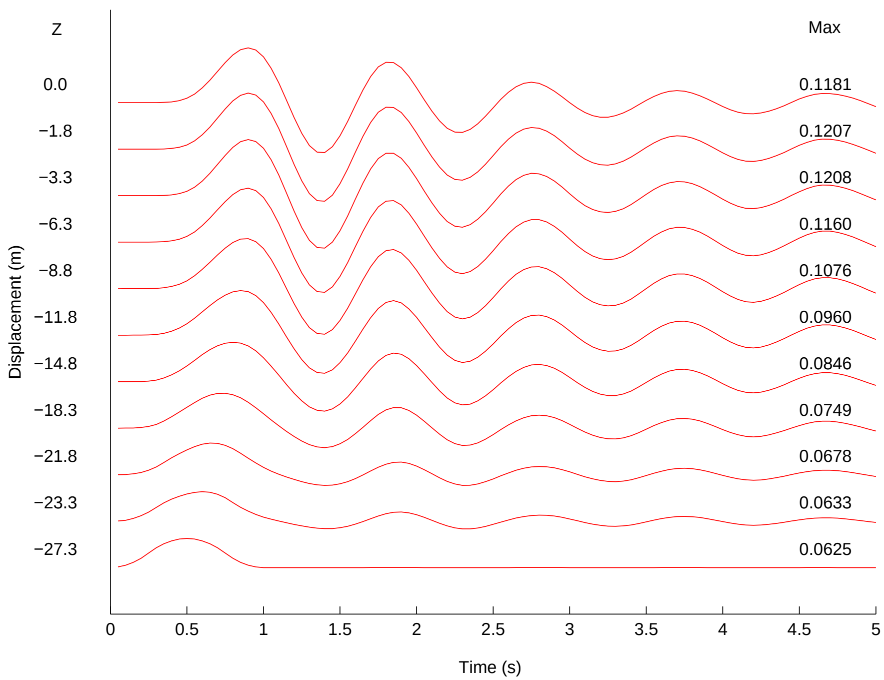
Seismic Wave Propagation Model

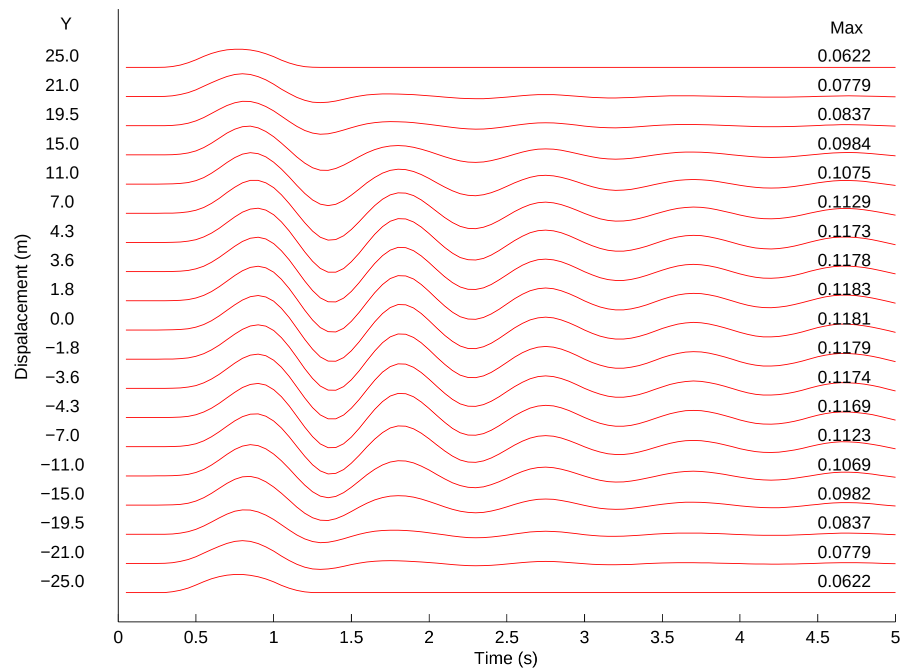




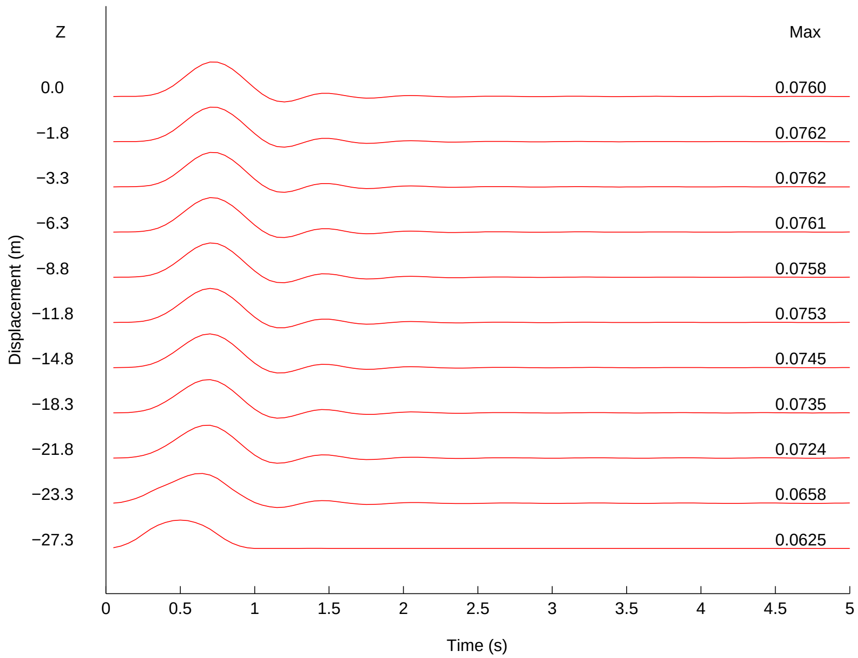


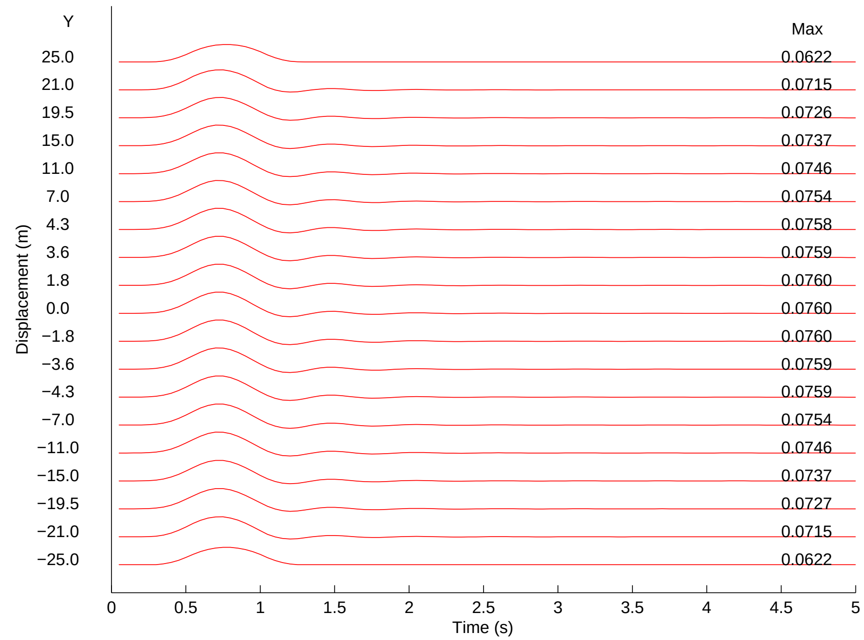
Seismic Wave Propagation
Soft Soil



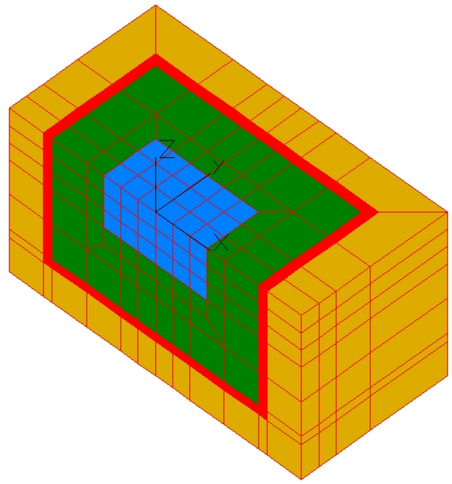


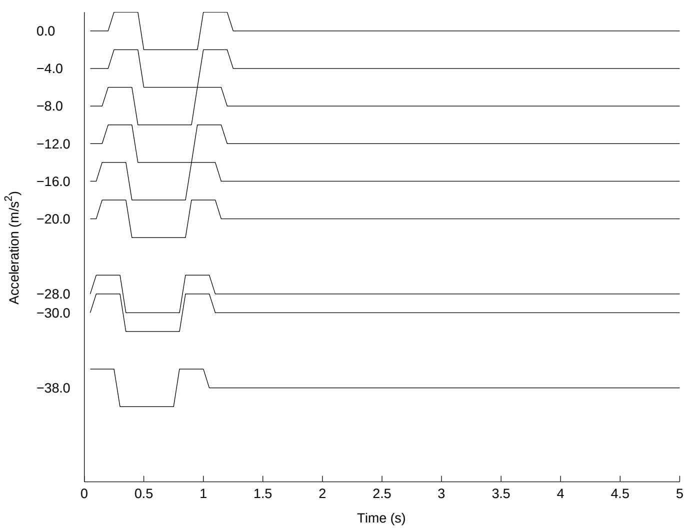
Seismic Wave Propagation
Stiff Soil

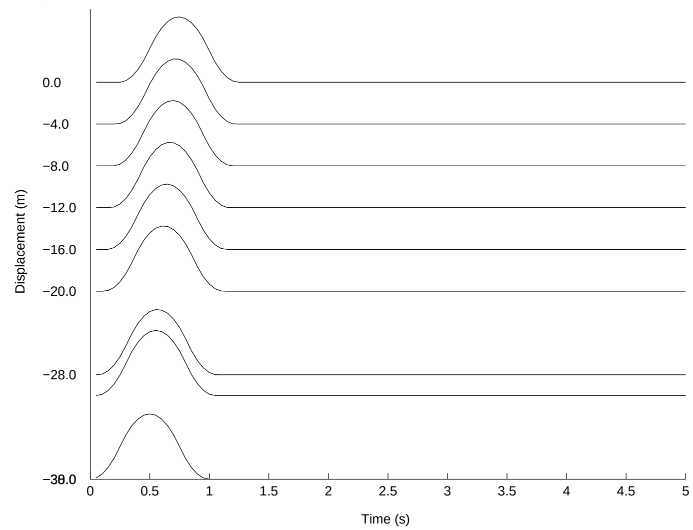




SSI Model

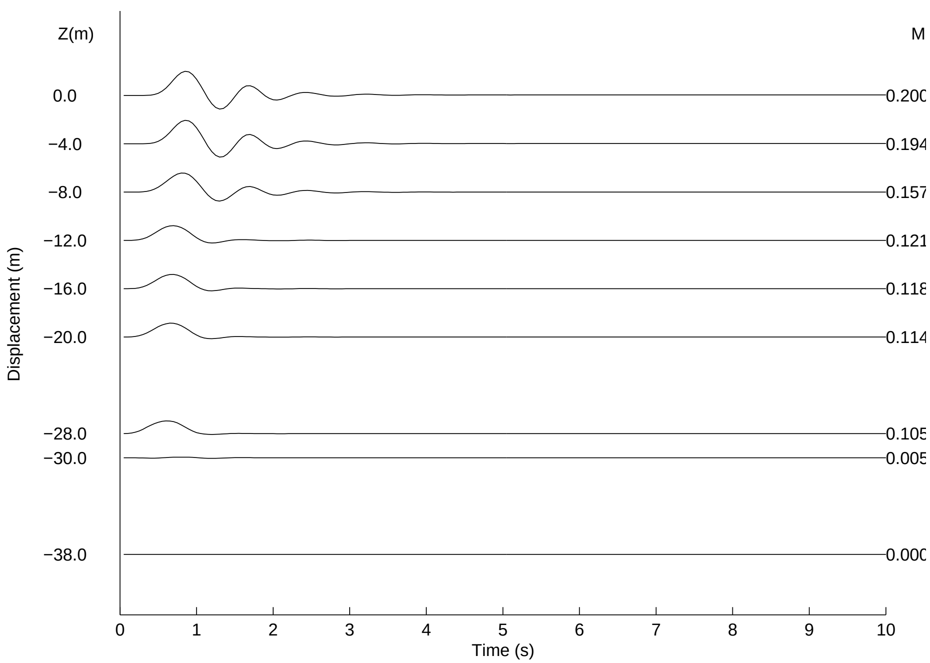


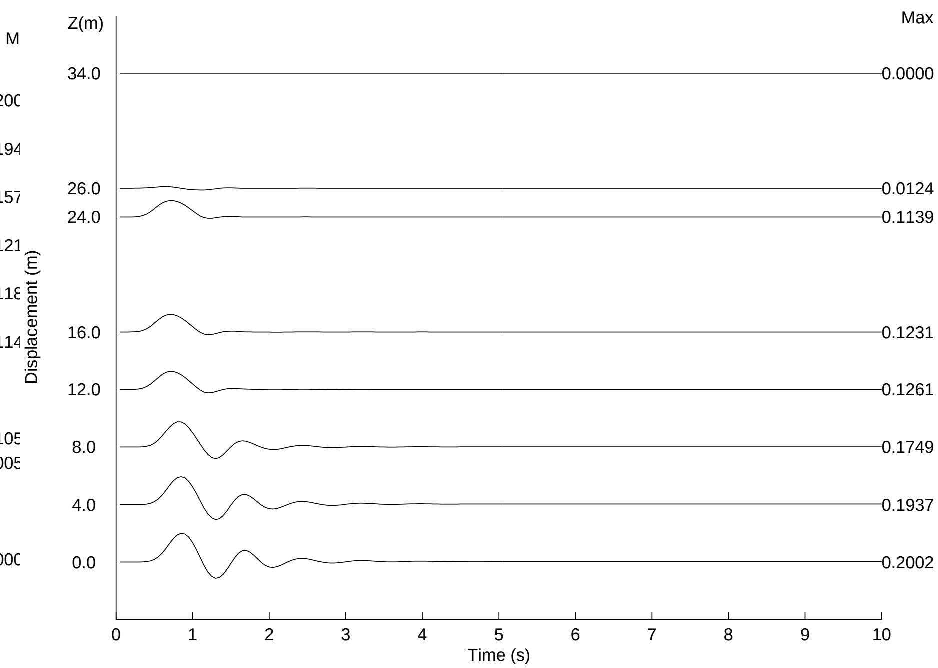




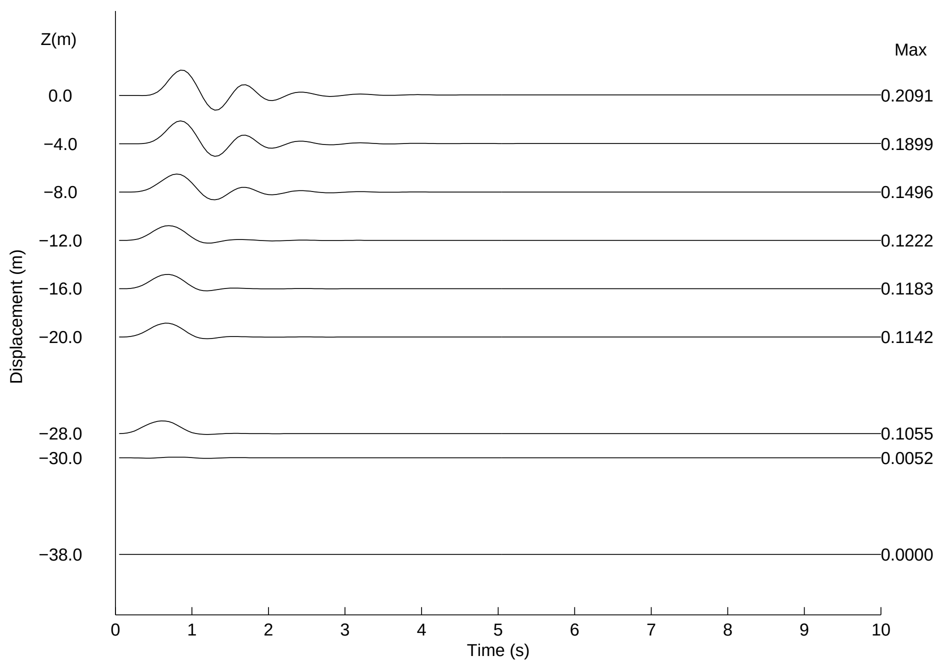
Files in directory `DRMtcl`

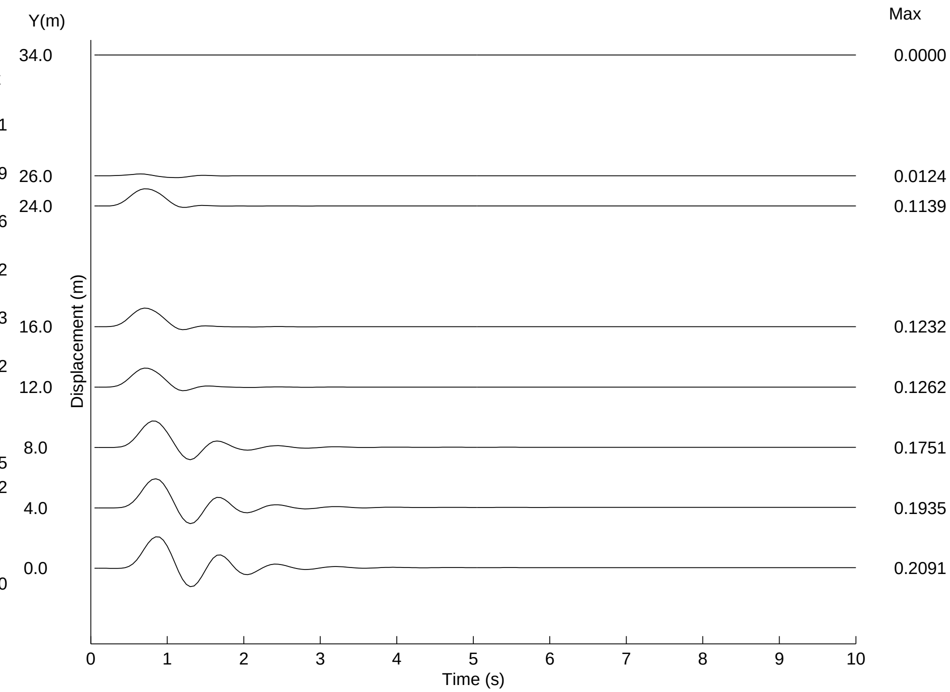
SSI Model Free Field
Stiff Elastic–Plastic Soil



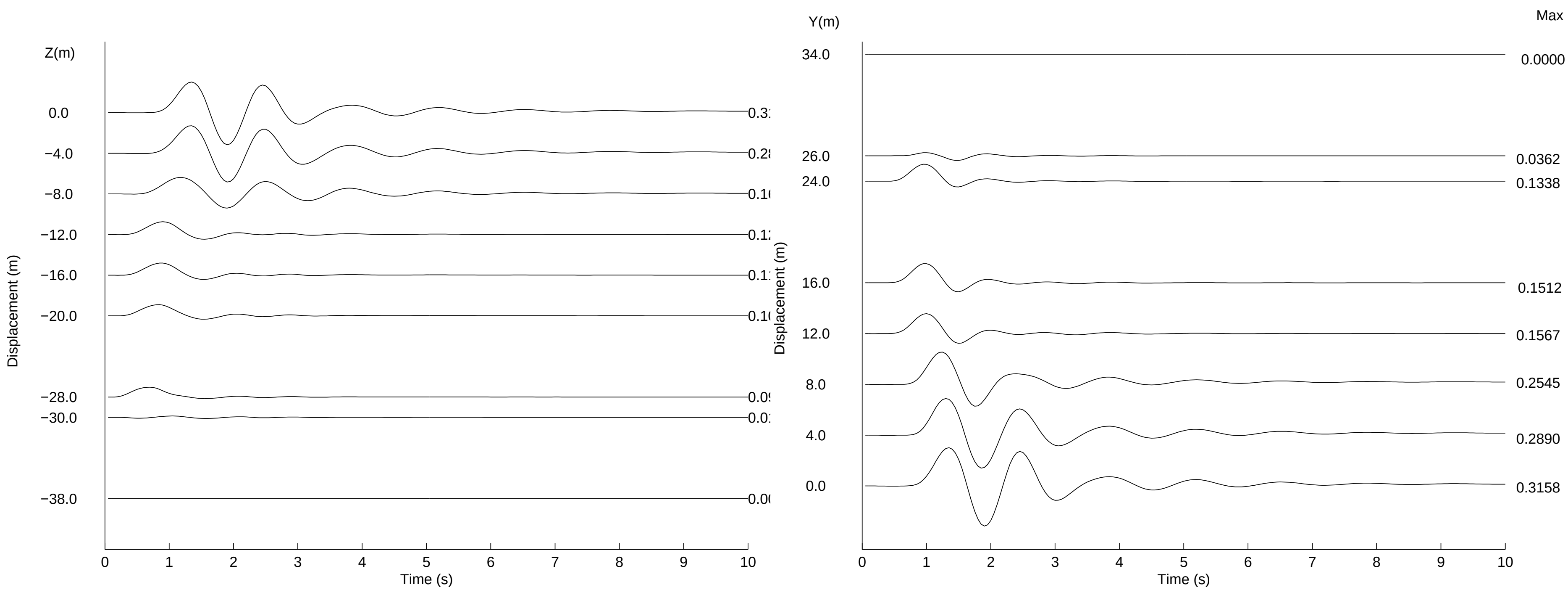


SSI Model Pile–Column Stiff Elastic–Plastic Soil

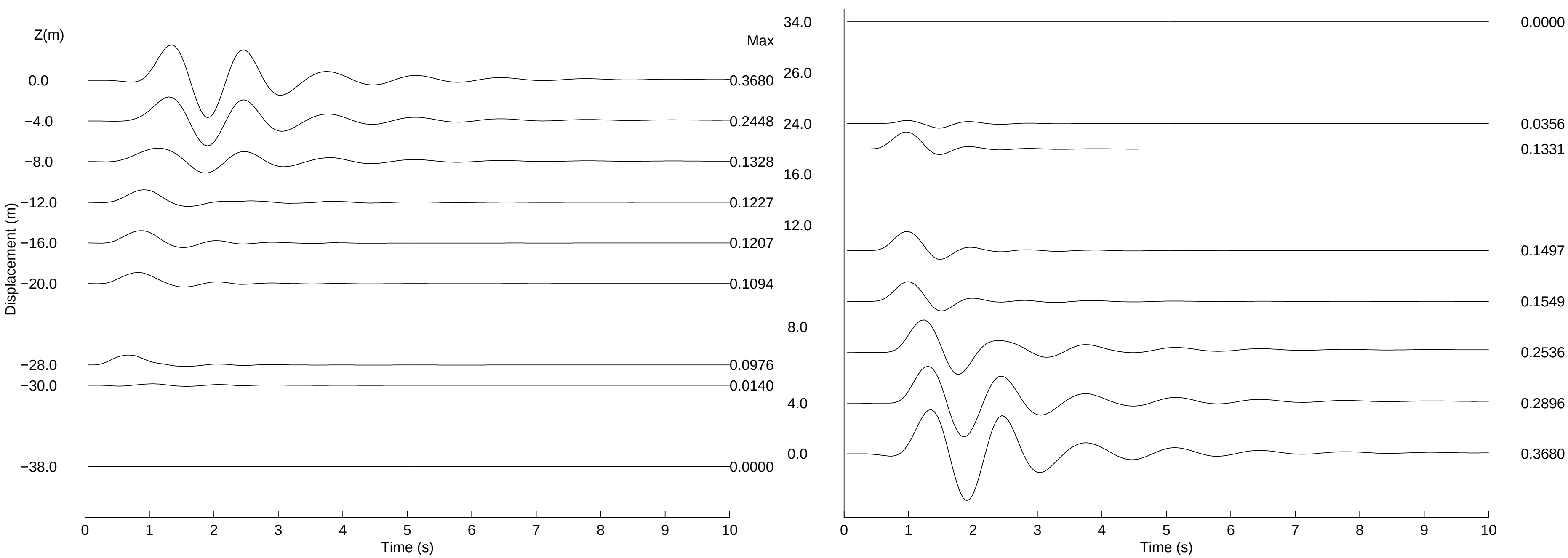




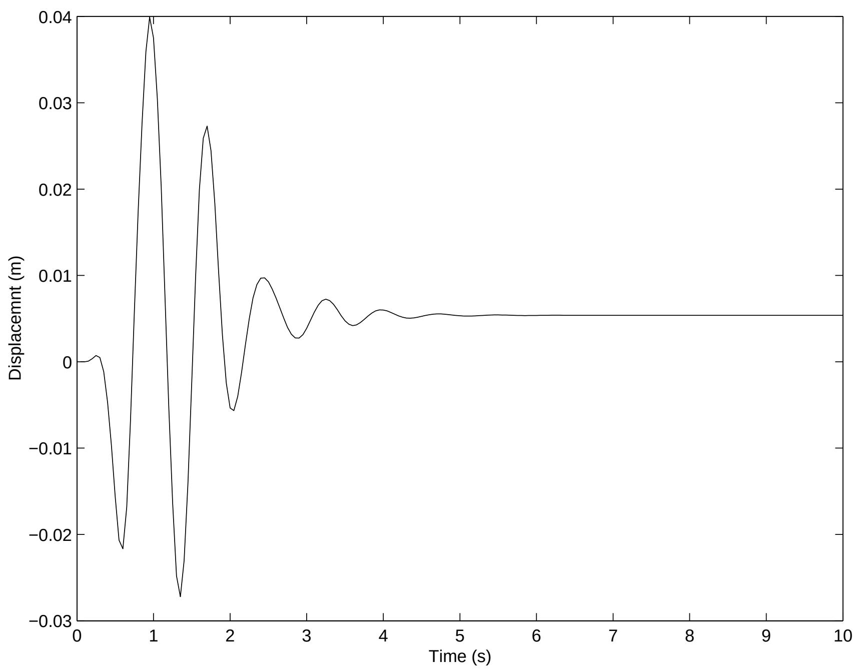
SSI Model Free Field
Soft Elastic–Plastic Soil



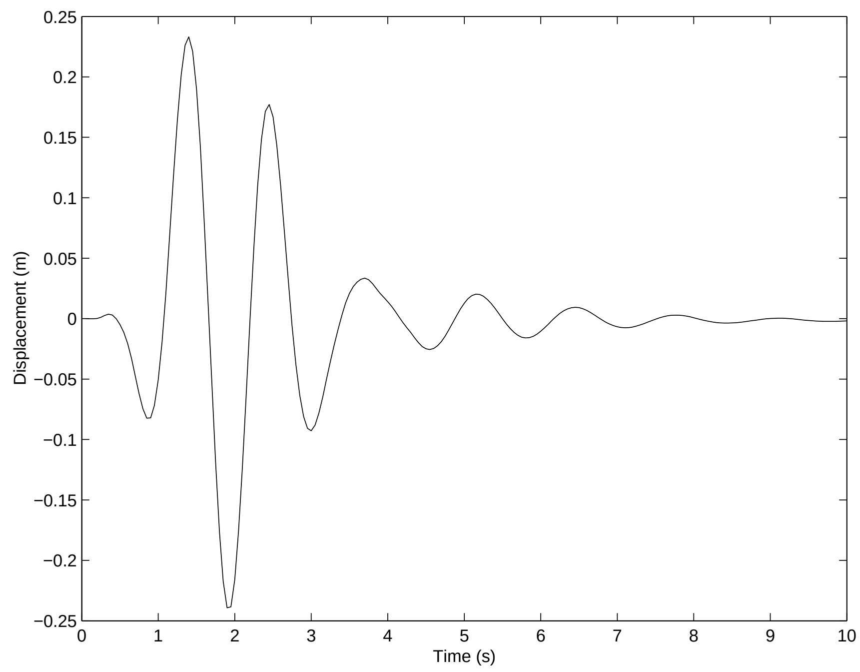
SSI Model Pile–Column
Soft Elastic–Plastic Soil



SSI Model: Pile–Column Behavior

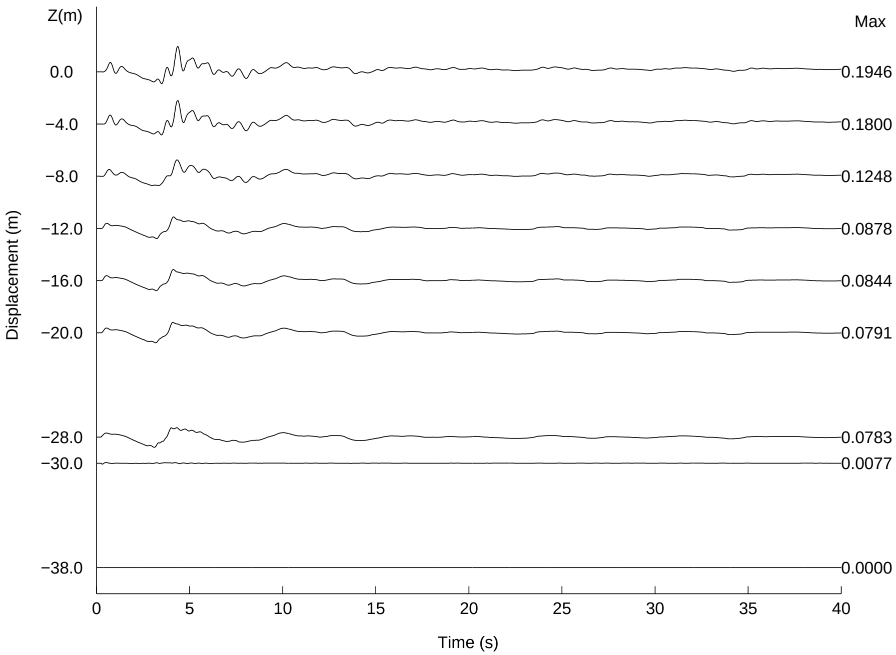


Stiff soil

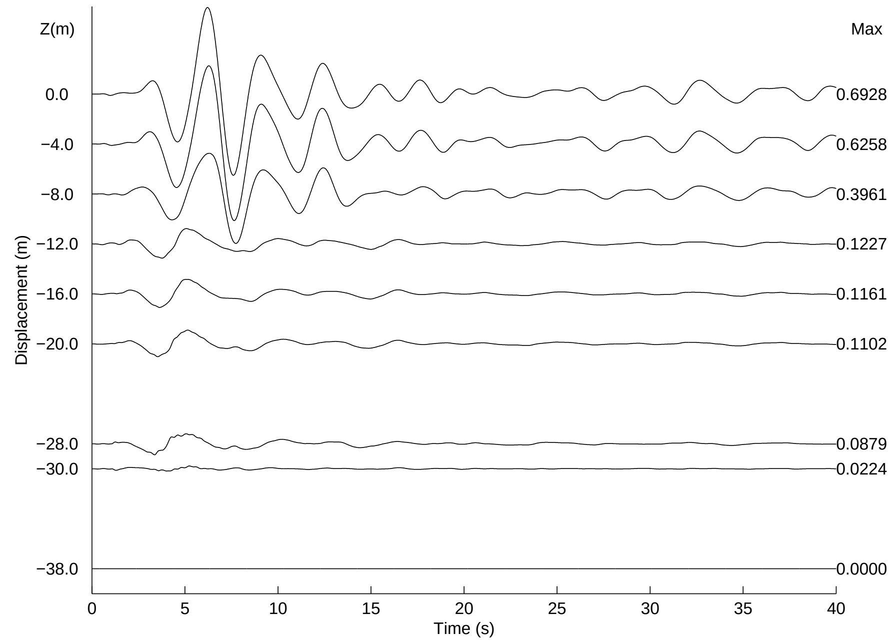


Soft soil

SSI Model: Seismic Results

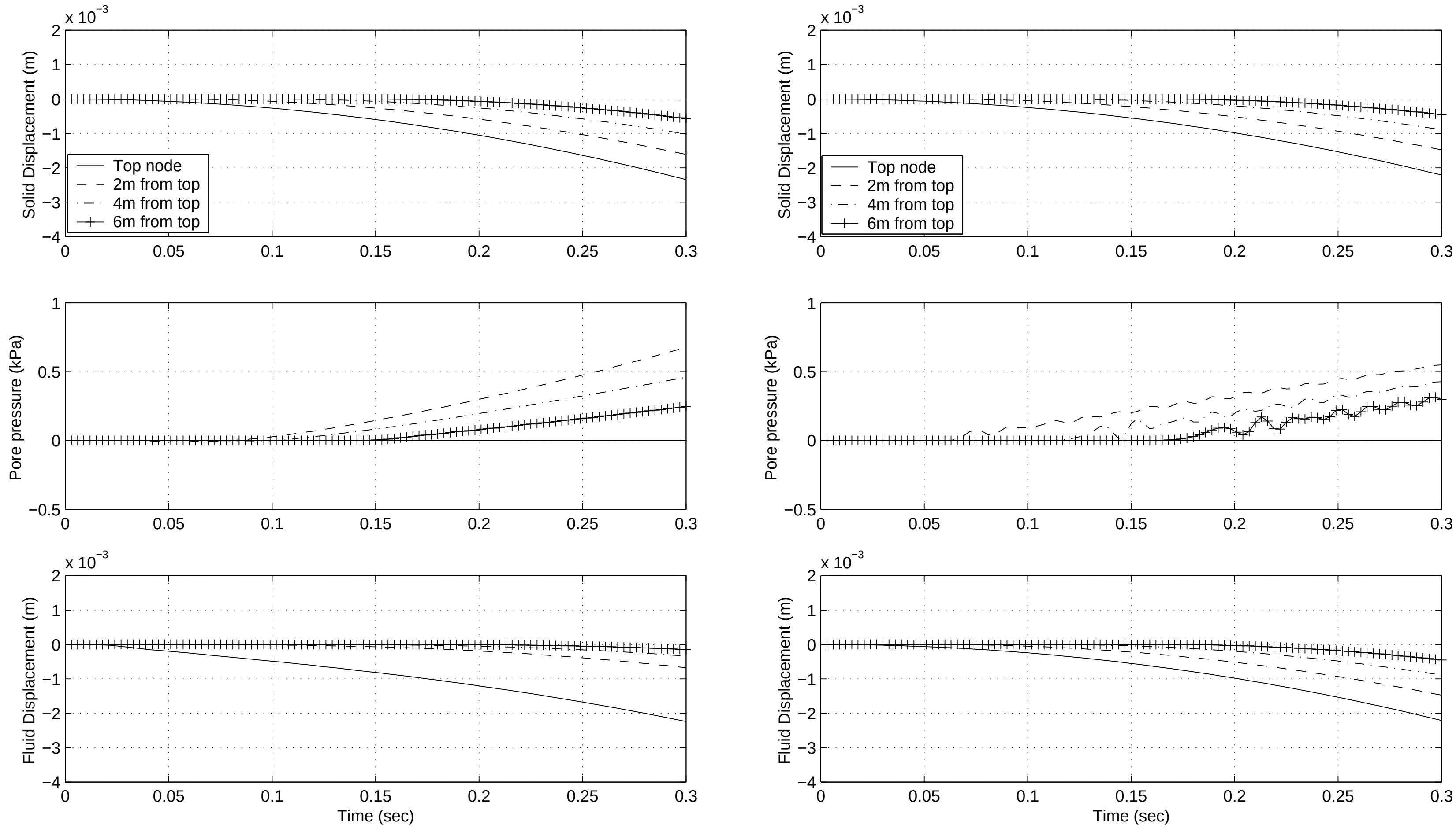


Stiff soil



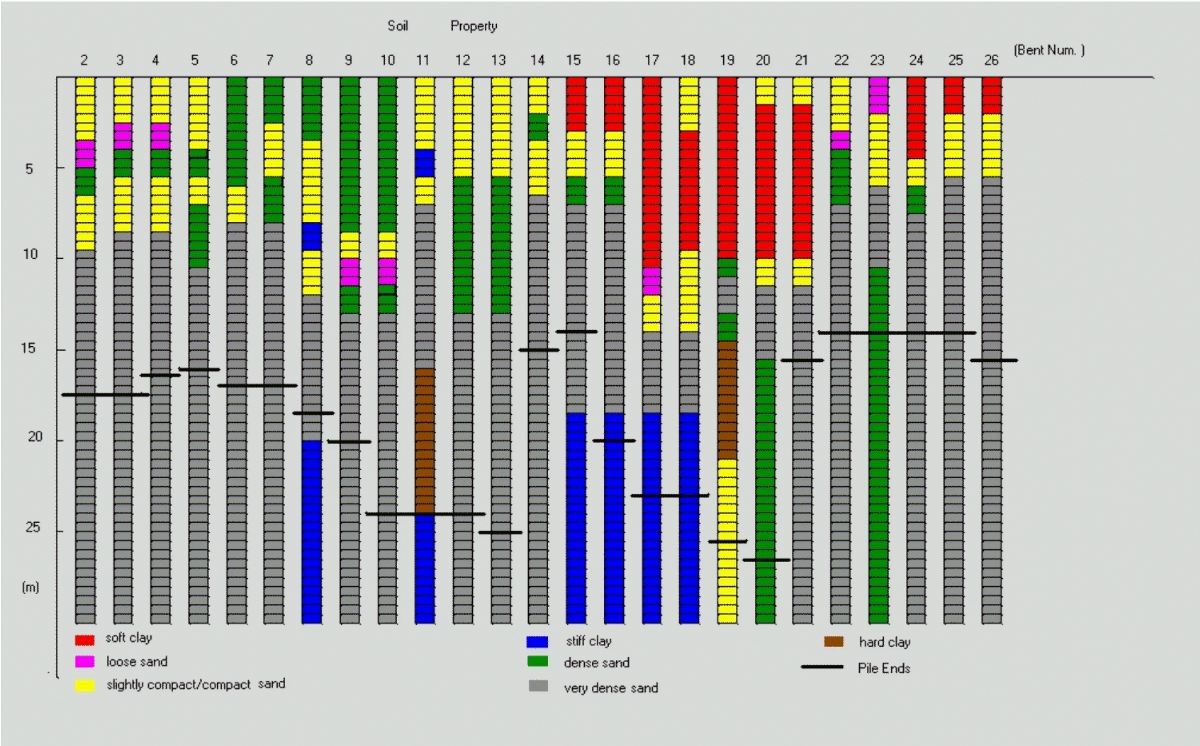
Soft soil

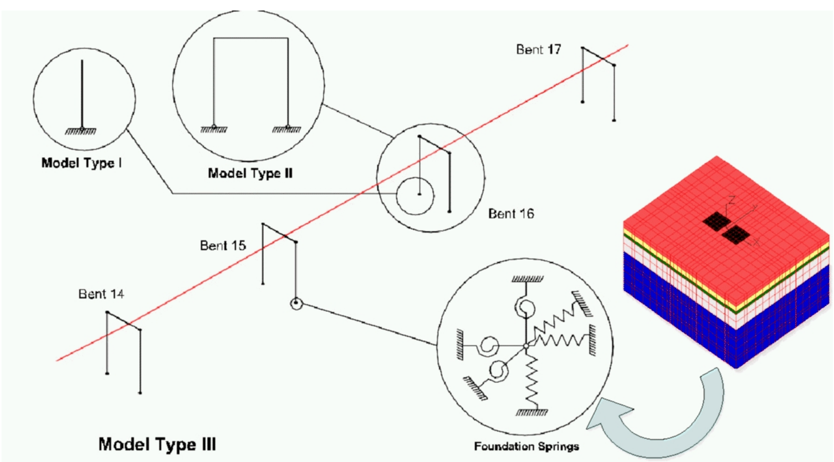
Wave Propagation in Saturated Soils

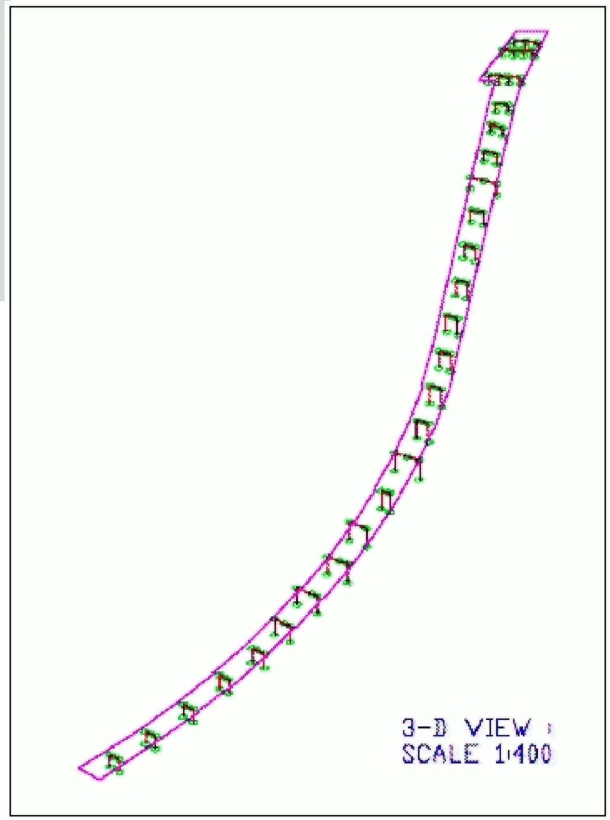


Half space, ramp load $k = 10^{-3,5} m/s$

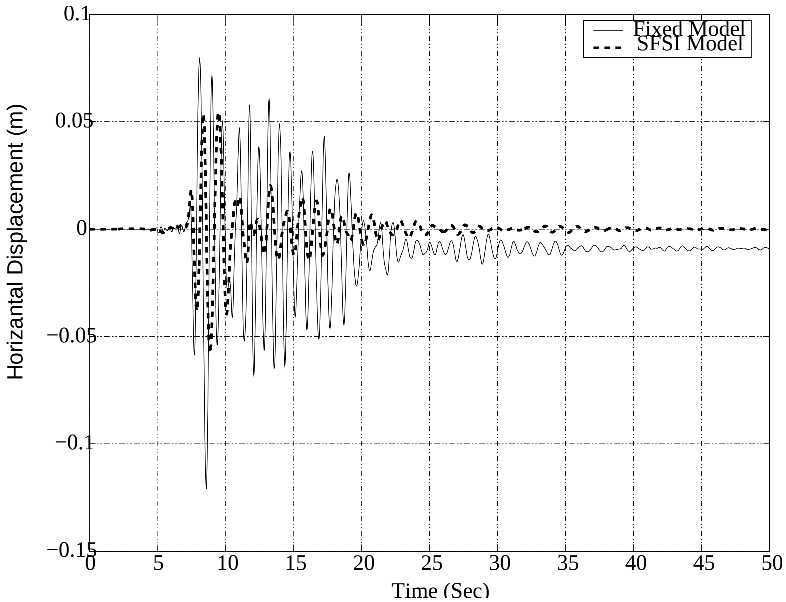
Soil–Structure Interaction

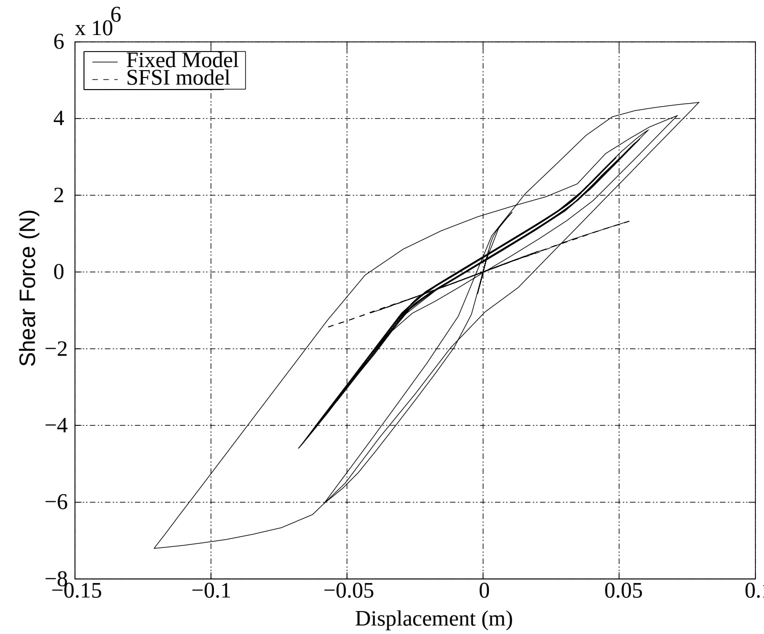






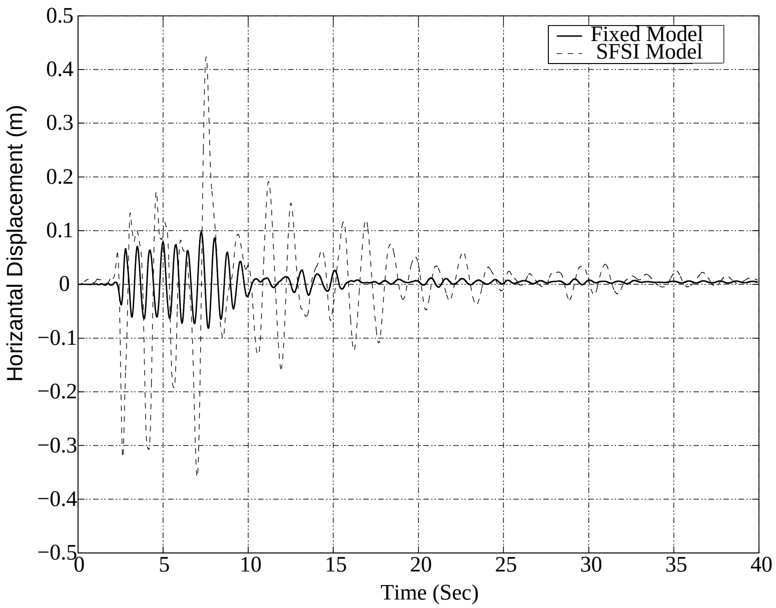
SSI Advantageous

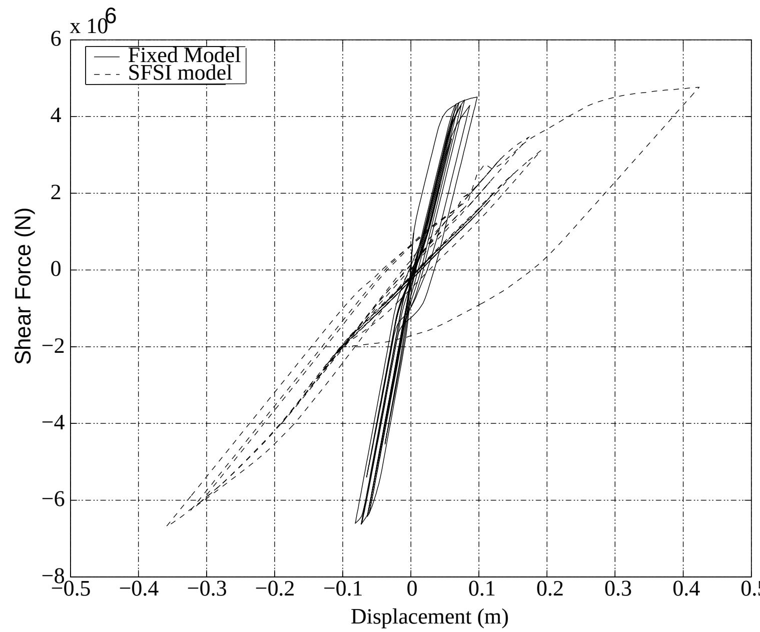




Kobe–JMA

SSI Disadvantageous





LP–Corralitos

Conclusions

- Examples, lecture notes, executables available at:
  `http://sokocalo.engr.ucdavis.edu/~jeremic`
  and at
  `http://opensees.berkeley.edu/`
- Manual is constantly being improved
- Executables available for both UNIX-like (up–to–date, preferable) and MS Windows.
- MS Windows, soon to have up to date executables