Geomechanics Elements and Models in OpenSees

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Outline

1. Material Models
   - Elastic
   - Elastic–Plastic Continuum Models
   - Small Deformation Elastic–Plastic Multiaxial and Uniaxial
2. Finite Elements
   - Single Phase
   - Multi Phase Finite Elements, Coupled
3. Computational Procedures
   - Solution Control
   - Seismic Loading Application
   - High Performance Computing
4. Selected Examples

Elastic Material Models

- Small deformation elasticity
  - linear isotropic
  - nonlinear isotropic
  - cross anisotropic

- Large deformation hyperelasticity
  - Neo–Hookean
  - Ogden
  - Logarithmic
  - Mooney–Rivlin
  - Simo–Pister

Elastic–Plastic Continuum Models: Small Deformations

- Yield surfaces:
  - von Mises
  - Drucker–Prager
  - Cam–Clay
  - Rounded Mohr–Coulomb
  - Parabolic Leon
- Plastic flow directions (plastic potential functions):
  - von Mises
  - Drucker–Prager
  - Cam–Clay
  - Rounded Mohr–Coulomb
  - Parabolic Leon
  - Dafalias Manzari

Elastic–Plastic Continuum Models: Small Deformations (continued)

- Evolution Laws (hardening and/or softening laws):
  - linear scalar,
  - nonlinear scalar (Cam–Clay type),
  - linear tensorial (kinematic hardening/softening: translational and/or rotational)
  - nonlinear tensorial (kinematic hardening/softening: translational and/or rotational)
    - Armstrong–Frederick hardening
    - bounding surface hardening/softening

Hyperelastic–Plastic Continuum Models: Large Deformations

- Yield surfaces
  - von Mises,
  - Drucker–Prager...
- Plastic flow directions (plastic potential functions):
  - Drucker–Prager,
  - von Mises,
- Evolution Laws:
  - linear and nonlinear scalar,
  - nonlinear scalar
  - linear and nonlinear (AF) tensorial (kinematic hardening/softening: translational and/or rotational)

Elastic–Plastic Multiaxial and Uniaxial Models

- Generalized foundation rocking material (M, N, T) model
- 2D frictional contact material model
- P–Y spring response material model

Single Phase Formulations

- Small deformation solid elements, bricks (8, 20, 21, 27, 8-20 variable node bricks)
- Large deformation (total Lagrangian) solid elements, bricks (20 node brick)

Multi Phase Formulations

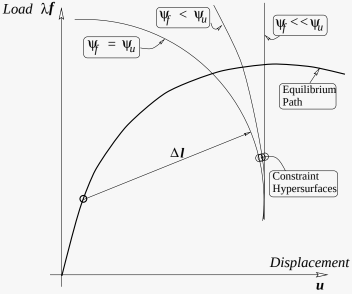
- Fully coupled, u–p–U elements (3D) for small deformations
- Fully coupled, u–p (3D) elements for small deformations
- Fully coupled u–p (3D) elements for large deformations

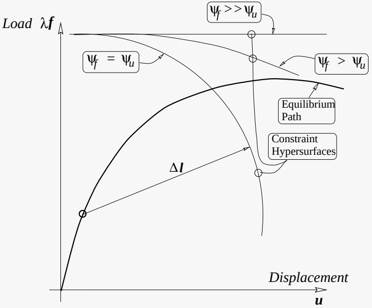
Degrees of freedom (DOFs) are:

- $u \rightarrow$ solid displacements,
- $p \rightarrow$ pore fluid pressures,
- $U \rightarrow$ pore fluid displacements

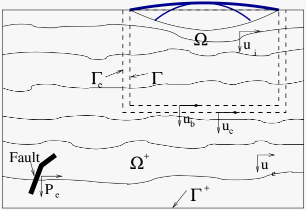
Hyperspherical Arc–length Solution Control

$$\begin{bmatrix} \mathbf{K}_t & -\mathbf{f}_{ext} \\ 2\frac{\psi_u^2}{u_{ref}^2}\Delta\mathbf{u}^T\mathbf{S} & 2\Delta\lambda\,\psi_f^2 \end{bmatrix} \begin{bmatrix} \delta\mathbf{u} \\ \delta\lambda \end{bmatrix} = -\begin{bmatrix} \mathbf{r}^{old} \\ a^{old} \end{bmatrix}$$





Domain Reducation Method (Bielak et al.)



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

Plastic Domain Decomposition

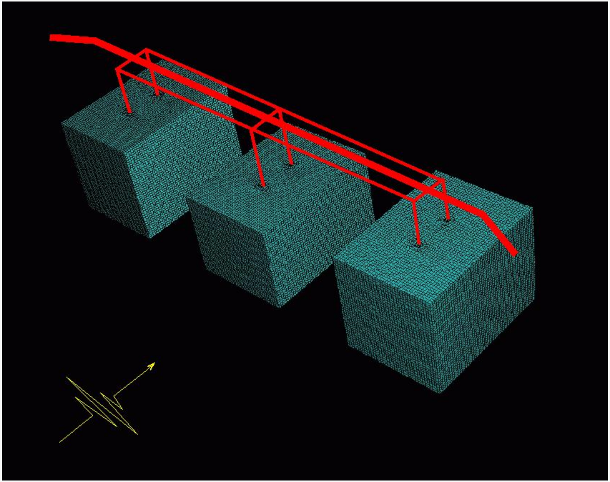
- Graph partitioning → balance multiple phases simultaneously, while also minimizing the inter-processor communications costs
- It is a multi-objective optimization problem (minimize both the inter-processor communications, the data redistribution costs and create balanced partitions)
- Take into the account (deterministic or probabilistic):
  - heterogeneous element loads that change in each iteration
  - heterogeneous processor performance (multiple generations nodes)
  - inter-processor communications (LAN or WAN)
  - data redistribution costs

Detailed 3D, FEM model

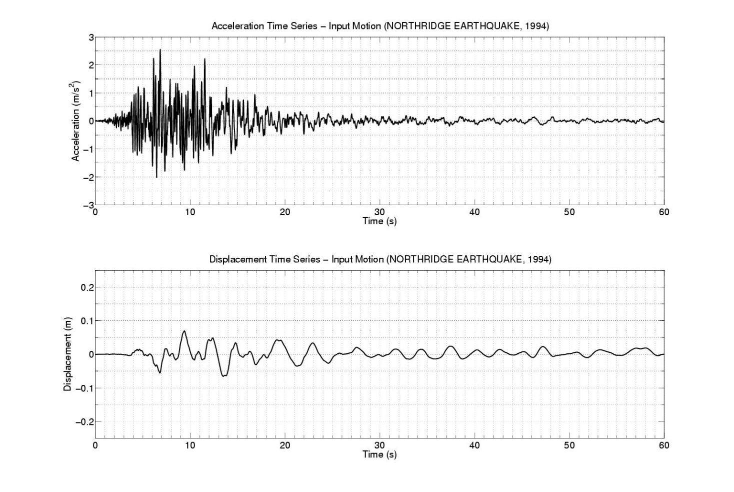
- Construction process
- Two types of soil: stiff soil (UT, UCD), soft soil (Bay Mud)
- Deconvolution of given surface ground motions
- Use of the DRM (Prof. Bielak et al.) for seismic input
- Piles $\rightarrow$ beam-column elements in soil holes
- Structural model developed at UCB (Prof. Fenves et al.)
- Element size issues (filtering of frequencies)

model size	el. size	f_{cutoff}	min. $G/Gmax$	γ
12K	1.0 m	10 Hz	1.0	<0.5 %
15K	0.9 m	>3 Hz	0.08	1.0 %
150K	0.3 m	10 Hz	0.08	1.0 %
500K	0.15 m	10 Hz	0.02	5.0 %

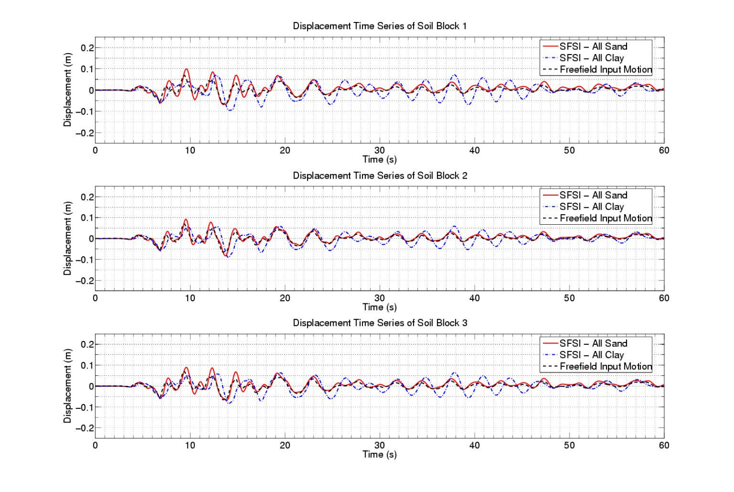
FEM Mesh (one of)



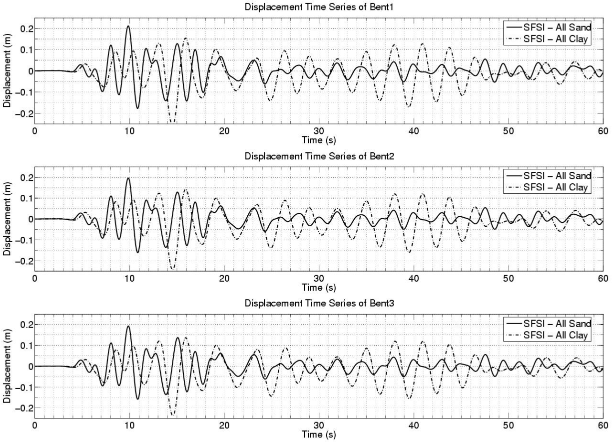
Input Motions, Northridge (one of)



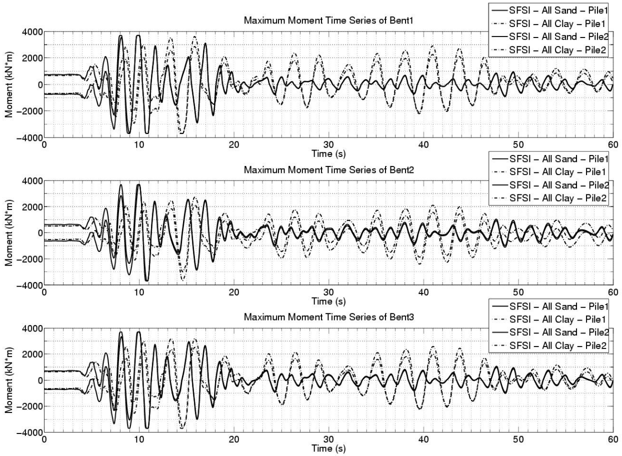
Changes to the Free Field Input Motions: SFSI



Structure Displacements



Moment Redistributions



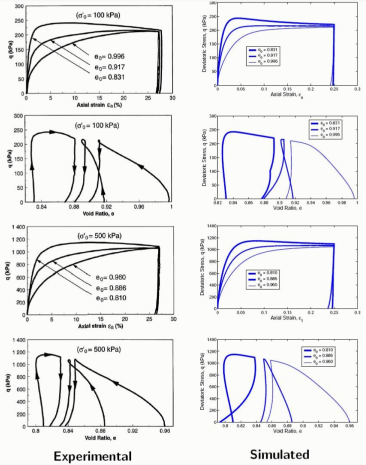
Drained Single Element Tests

Material Level:

Toyoura Sand,
Drained Triaxial Tests:

Experimental Data (left)
(Verdugo and Ishihara 1996)

Numerical Results (right)



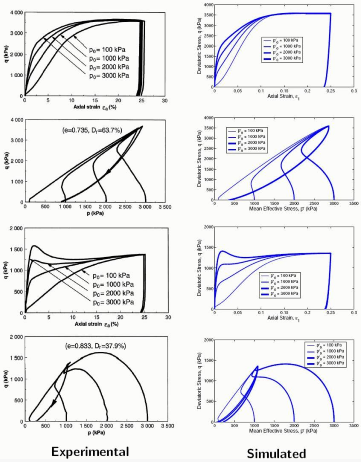
Undrained Single Element Tests

Material Level:

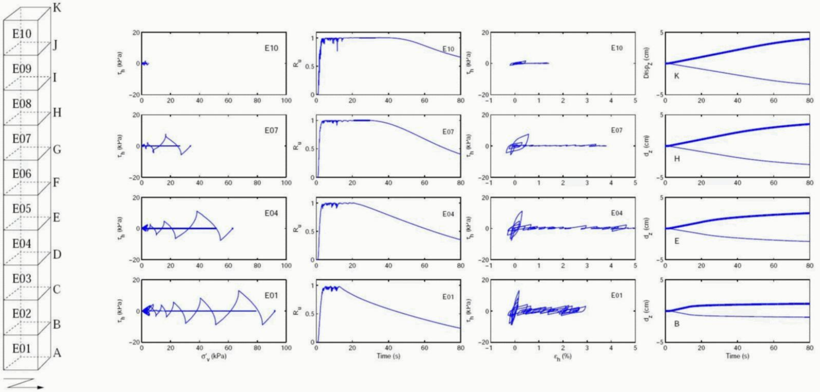
Toyoura Sand,
Undrained Triaxial Tests:

Experimental Data (left)
(Verdugo and Ishihara 1996)

Numerical Results (right)

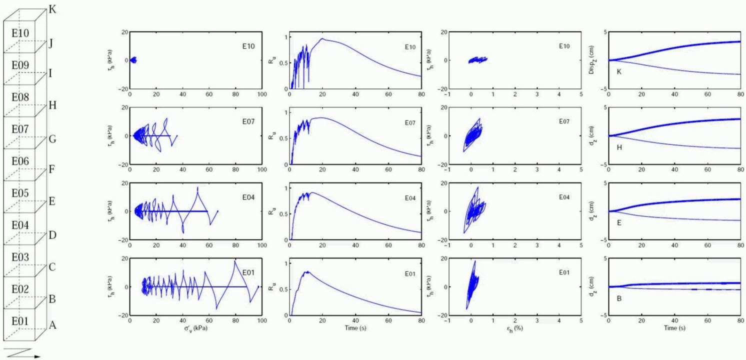


Liquefaction of a Soil Column



$(e_0 = 0.85)$

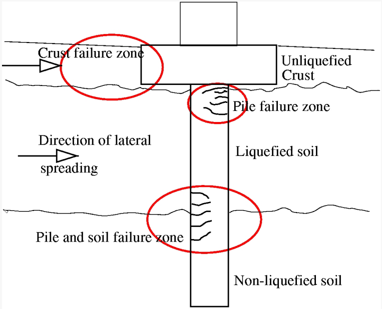
Liquefaction of a Soil Column

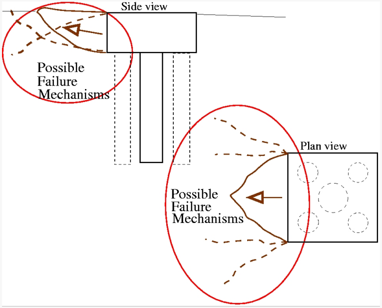


$(e_0 = 0.75)$

Failure Modes for the Dry Crust

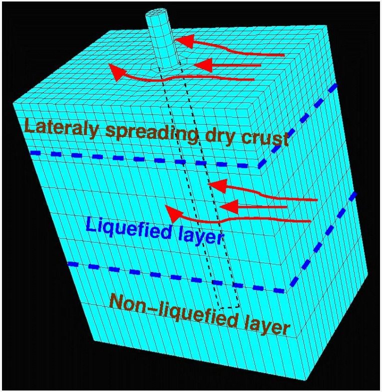
- Influence of crust failure mode on piles
- Can we help the SFS system survive?





Liquefied Soil Flows Around Piles

- Influence of liquefied soil flow on piles
- Need to understand the mechanics
- Can we help the SFS system survive?



Summary

- A number of simplistic and advanced models, elements and procedures are available for use in simulations
- Targeting both
  - advanced geomechanics problems
  - practical geotechanicsl problems
- Theories, formulations, implementation details, as well as verification, validation and application examples are available at:
`http://sokocalo.engr.ucdavis.edu/˜jeremic/`