Advanced Geotechnical Simulations with OpenSees Framework

Boris Jeremić

Department of Civil and Environmental Engineering
University of California, Davis

OpenSees Developer Symposium, RFS, August 2006
`http://sokocalo.engr.ucdavis.edu/˜jeremic/`

Outline

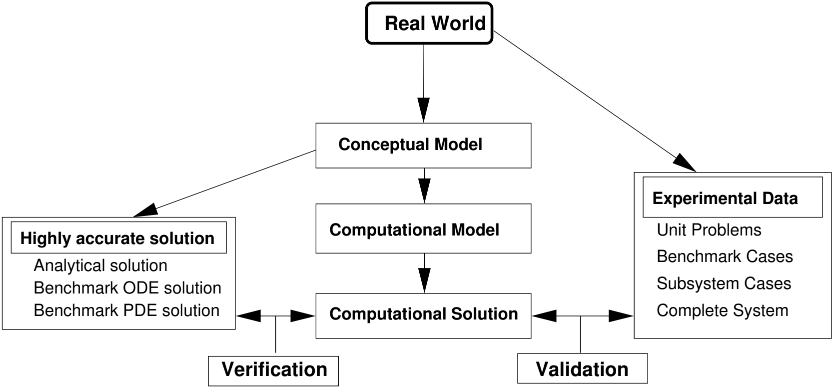
1. Verification and Validation
2. Recent Work at the UCD CompGeomech Group
3. Selected Examples

Symposium

Etymology: Latin, from Greek *symposion*, from *sympinein* to drink together, from *syn-* + *pinein* to drink

- a convivial party (as after a banquet in ancient Greece) with music and conversation
- a social gathering at which there is free interchange of ideas
- a formal meeting at which several specialists deliver short addresses on a topic or on related topics
- a collection of opinions on a subject; especially one published by a periodical

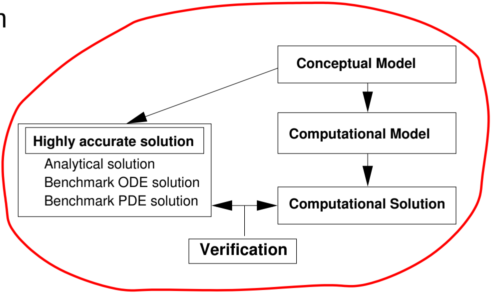
Fundamentals of Verification and Validation



Verification: Model is solved correctly (Mathematics)

Verification: The process of determining that a model implementation accurately represents the developer's conceptual description and specification.

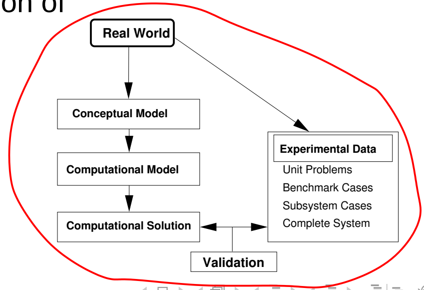
- Identify and remove errors in computer coding
  - Numerical algorithm verification
  - Software quality assurance practice
- Quantification of the numerical errors in computed solution



Validation: Correct model is solved (Physics)

Validation: The process of determining the degree to which a model is accurate representation of the real world from the perspective of the intended uses of the model.

- 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



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)

Single Phase FE 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

Computational Procedures

- Hyperspherical arc–length solution control
- Domain reduction method (Bielak et al.)
- Plastic Domain Decomposition (PDD) parallel simulations

PDD Method: Design Goals

- 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

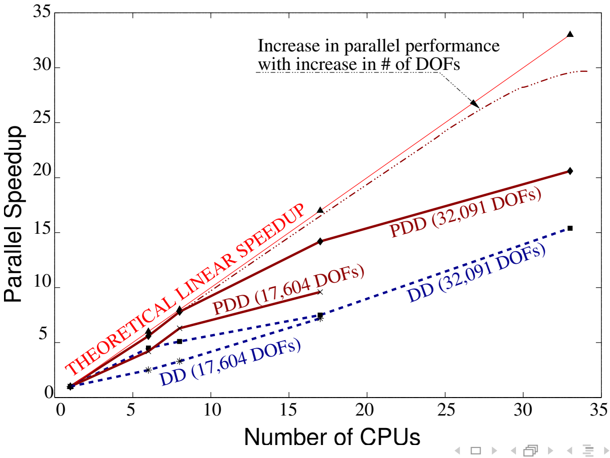
PDD Method: Implementation

- Perform global optimization for both internal state determination and system of equatons solution phases
- Adaptive partitioning done using ParMETIS
- Iterative system of equations solver PETSC
- OpenSees: standard interface and framework
- Works on SMPs, local DMPs, grids of computers

Features

- Initial domain partitioning
- Adaptive domain repartitioning depending on CPU imbalance, LAN and/or WAN performance
- Repartitioning works with loads, constraints..., all necessary movable objects
- Available for all elements (solid, structural) that provide the standard OpenSees interface (sendSelf, RecvSelf, timer or CL weight estimate)
- Scalable to a large number of CPUs
- Performance tuning (local cluster GeoWulf, SDSC, TACC)

Speedup Overview

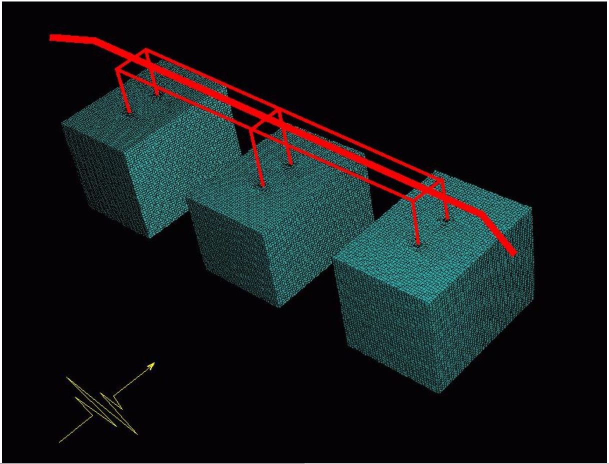


Detailed 3D, FEM model

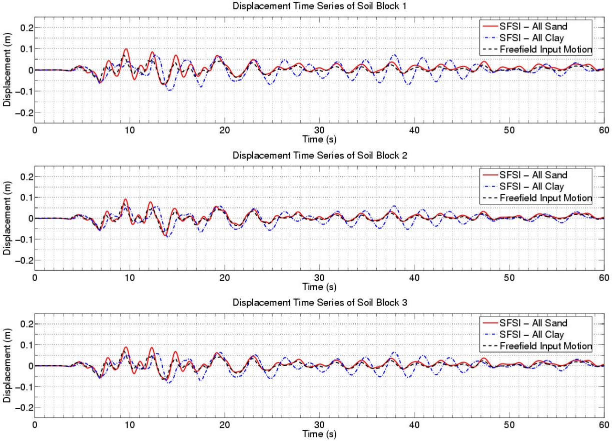
- Construction process
- Two types of soil: stiff soil (UT, UCD), soft soil (Bay Mud)
- Deconvolution of given surface ground motions
- Use of the DRM (Prof. Bielak et al.) for seismic input
- Piles $\rightarrow$ beam-column elements in soil holes
- Structural model developed at UCB (Prof. Fenves et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

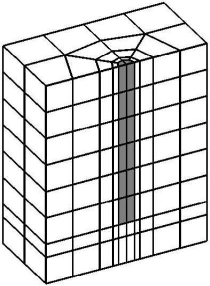


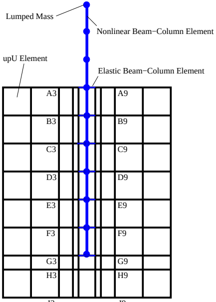
Changes to the Free Field Input Motions: SFSI



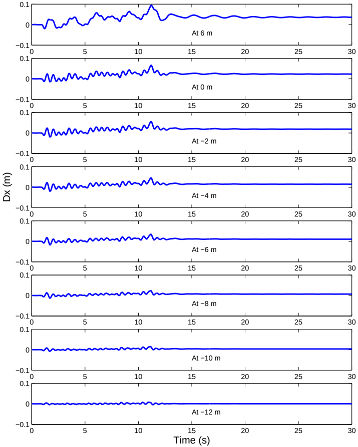
The SFSI Liquefaction Model

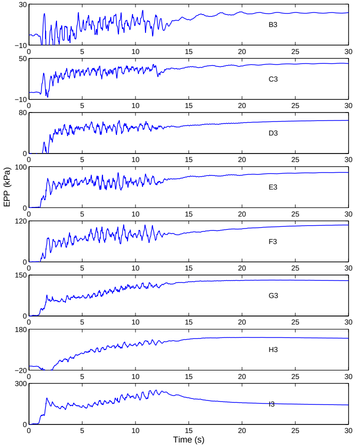
- Construction process
- Piles → beam-column elements in soil holes
- Impermeable pile concrete





Pile Displacements and Pore Pressures





Instead of Summary: Discussion Topics

- Development and use models:
  - Hollywood (subcontracting)
  - Ebay (flea market)
  - Open Source (goal driven, meritocracy)

- Developer's and user's dilemma:
  - *Exploration* of new possibilities
  - *Exploitation* of old certainties

- W. Oberkampf, T. Trucano, and C. Hirsch. Verification, validation and predictive capability in computational engineering and physics. In *Proceedings of the Foundations for Verification and Validation on the 21st Century Workshop*, pages 1–74, Laurel, Maryland, October 22-23 2002. Johns Hopkins University / Applied Physics Laboratory.
- Steven Weber *The Success of Open Source*. Harvard University Press, 2004. ISBN 0-674-01292-5.
- Material (reports, papers, presentations, documentation...) from my web site `http://sokocalo.engr.ucdavis.edu/˜jeremic/`.