On Earthquake Soil Structure Interaction Modeling and Simulation

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UCD Geotech. Seminar, May, 2013
Outline

Motivation

Challenges

Uncertainty in Modeling Ground Motions
Uncertainty in Modeling Material
Errors in Scientific Software

ESSI Simulator System

ESSI Simulator System
Modeling and Simulation
Verification and Validation Suite

Probabilistic Modeling

Uncertain (Geo) Materials
Seismic Wave Propagation Through Uncertain Soils

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Summary
The Problem

- Seismic response of Nuclear Power Plants
- 3D, inclined seismic motions consisting of body and surface waves
- Inelastic (elastic, damage, plastic behavior of materials: soil, rock, concrete, steel, rubber, etc.)
- Full coupling of pore fluids (in soil and rock) with soil/rock skeleton
- Buoyant effects (foundations below water table)
- Uncertainty in seismic sources, path, soil/rock response and structural response
Solution

- **Physics based modeling and simulation** of seismic behavior of soil-structure systems (NPP structures, components and systems)

- Development and use of **high fidelity** time domain, nonlinear numerical models, in deterministic and probabilistic spaces

- Accurate following of the **flow of seismic energy** (input and dissipation) within soil-structure NPP system

- **Directing**, in space and time, with **high (known) confidence**, seismic energy flow in the soil-foundation-structure system
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On Earthquake Soil Structure Interaction Modeling and Simulation
Modeling Uncertainty

- Simplified (or inadequate/wrong) modeling: important features are missed (seismic ground motions, etc.)

- Introduction of uncertainty and (unknown) lack of accuracy in results due to use of un-verified simulation tools (software quality, etc.)

- Introduction of uncertainty and (unknown) lack of accuracy in results due to use of un-validated models (due to lack of quality validation experiments)
Complexity of and Uncertainty in Ground Motions

- 6D (3 translations, 3 rotations)
- Vertical motions usually neglected
- Rotational components usually not measured and neglected
- Lack of models for such 6D motions (from measured data)
- Sources of uncertainties in ground motions (Source, Path (rock), soil (rock))
Uncertainty in Modeling Material

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Summary
Material Behavior Inherently Uncertain

- Spatial variability
- Point-wise uncertainty, testing error, transformation error

(Mayne et al. (2000))
Uncertainty in Modeling Material

Soil Uncertainties and Quantification

- Natural variability of soil deposit (Fenton 1999)
  - Function of soil formation process

- Testing error (Stokoe et al. 2004)
  - Imperfection of instruments
  - Error in methods to register quantities

- Transformation error (Phoon and Kulhawy 1999)
  - Correlation by empirical data fitting (e.g. CPT data → friction angle etc.)
SPT Based Determination of Shear Strength

Transformation of SPT $N$-value $\rightarrow$ undrained shear strength, $s_u$ (cf. Phoon and Kulhawy (1999B))

Histogram of the residual (w.r.t the deterministic transformation equation) undrained strength, along with fitted probability density function (Pearson IV)
Uncertainty in Modeling Material

SPT Based Determination of Young’s Modulus

Transformation of SPT $N$-value $\rightarrow$ 1-D Young’s modulus, $E$ (cf. Phoon and Kulhawy (1999B))

Histogram of the residual (w.r.t the deterministic transformation equation) Young’s modulus, along with fitted probability density function
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Summary
Errors in Scientific Software: The T Experiments

- Les Hatton, Kingston University (formerly of Oakwood Comp. Assoc.)

- "Extensive tests showed that many software codes widely used in science and engineering are not as accurate as we would like to think."

- "Better software engineering practices would help solve this problem,"

- "Realizing that the problem exists is an important first step."

- Large experiment over 4 years measuring faults (T1) and failures (T2) of scientific and engineering codes
The T2 Experiments

- Specific application area: seismic data processing (inverse analysis)
- Echo sounding of underground and reconstructing "images" of subsurface geological structure
- Nine mature packages, using **same algorithms**, on a **same data set**!
- 14 primary calibration points for results check
- Results "fascinating and disturbing"
T2: Disagreement at Calibration Points
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Summary
ESSI Simulator System

- **The ESSI-Program** is a 3D, nonlinear, time domain, parallel finite element program specifically developed for Hi-Fi modeling and simulation of Earthquake Soil/Rock Structure Interaction problems for NPPs on ESSI-Computer.

- **The ESSI-Computer** is a distributed memory parallel computer, a cluster of clusters with multiple performance processors and multiple performance networks.

- **The ESSI-Notes** represent a hypertext documentation system detailing modeling and simulation of NPP ESSI problems.
ESSI Simulator Program

- Based on a Collection of Useful Libraries (modular, portable)
- Library centric software design
- Various public domain licenses (GPL, LGPL, BSD, CC)
- Verification (extensive) and Validation (not much)
- Program documentation (part of ESSI Notes)
- Target users: US-NRC staff, CNSC staff, IAEA, LBNL, INL, DOE, professional practice collaborators, expert users
Collection of Useful Libraries (Modeling Part)

- Template3D-EP libraries for elastic and elastic-plastic computations (UCD, CC)
- FEMTools finite element libraries provide finite elements (solids, beams, shells, contacts/isolators, seismic input) (UCD, UCB, CU, CC)
- Loading, staged, self weight, service loads, seismic loads (the Domain Reduction Method, analytic input (incoming/outgoing) of 3D, inclined, un-correlated seismic motions) (UCD, CC)
- Domain Specific Language for input (UCD, CC)
Collection of Useful Libraries (Simulation Part)

- Plastic Domain Decomposition (PDD) for parallel computing (UCD, CC)
- PETSc (ANL, GPL-like) and UMFPACK (UF, GPL) solvers
- Modified OpenSees Services (MOSS) for managing the finite element domain (UCD, CC; UCB, GPL?)
- nDarray (UCD, CC), LTensor (CIMEC, GPL), BLAS (UTK, GPL) for lower level computational tasks,
- Message Passing Interface (MPI, openMPI, new BSD license)
ESSI Simulator Computer

A distributed memory parallel (DMP) computer designed for high performance, parallel finite element simulations

▶ Multiple performance CPUs and Networks
▶ Most cost-performance effective
▶ Source compatibility with any DMP supercomputers
▶ Current systems: 208CPUs, and 48CPUs (+64) and 96CPUs (8x5+2x16+24)...
ESSI Computer Version April 2012

Operating System: Ubuntu
Kernel: 3.2

Controller: 1 node + Compute: 8 Nodes
- CPU: 2 x 12 cores Opteron 6234 = 24 cores
- RAM: 32GB (8 x 4GB)
- NICs:
  - GigaBit: Intel 82576 (Controller)
  - InfiniBand: ConnectX-2 QDR IB 40Gb/s (Controller+Compute)
- Disk: 8 × 2TB Toshiba MK2002TSKB (Controller)
- Disk: 1TB Toshiba MK1002TSKB (Compute)

Network (dual):
- GigaBit: HP ProCurve Switch 1810-48G 48 Port
- InfiniBand:: Mellanox MIS5030Q-1SFCA 36-port QDR
A hypertext documentation system describing in detail modeling and simulations of NPP ESSI problems

- Theoretical and Computational Formulations (FEM, EL-PL, Static and Dynamic solution, Parallel Computing)
- Software and Hardware Platform Design (OO Design, Library centric design, API, DSL, Software Build Process, Hardware Platform)
- Verification and Validation (code V, Components V, Static and Dynamic V, Wave Propagation V)
- Application to Practical Nuclear Power Plant Earthquake Soil/Rock Structure Interaction Problems (ESSI with 3D, inclined, uncorrelated seismic waves, ESSI with foundation slip, Isolators)
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ESSI Simulator System

Modeling and Simulation

Verification and Validation Suite

Probabilistic Modeling

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Summary

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On Earthquake Soil Structure Interaction  Modeling and Simulation
High Fidelity Modeling

- Seismic energy influx, body and surface waves, 3D, inclined
- Mechanical dissipation outside of SSI domain:
  - Radiation of reflected waves
  - Radiation of oscillating SSI system
- Mechanical dissipation inside SSI domain:
  - Plasticity of soil/rock subdomain
  - Viscous coupling of porous solid with pore fluid (air, water)
  - Plasticity and viscosity of foundation – soil/rock contact
  - Plasticity/damage of the structure
  - Viscous coupling of structure/foundation with fluids
- Numerical energy dissipation/production
High Performance, Parallel Computing

- The ESSI Program can be used in both sequential and parallel modes
- For high fidelity models, parallel is really the only option
- High performance, parallel computing using Plastic Domain Decomposition Method
- Developed for multiple/variable capability CPUs and networks (DMP and SMPs)
Finite Elements

- Linear and nonlinear truss element
- Linear and nonlinear beam (disp. based), variable BC el.
- Linear shell Triangle and Quad with drilling DOFs
- Single phase solid bricks (8, 20, 27, 8-20, 8-27 nodes)
- Two phase (fully coupled, porous solid, pore fluid) solid bricks (8 and 20 node: \( u - p - U, u - p \))
- Dry friction slip and gap element
- Saturated gap and slip element
- Seismic isolator (latex rubber, neoprene rubber, rubber with lead core, friction pendulum)
Material Models for Solids and Structures

- Small deformation elastic: linear, nonlinear isotropic, cross anisotropic
- Large deformation elastic and elastic-plastic: Ogden, neo-Hookean, Mooney-Rivlin, Logarithmic, Simo-Pister, von Mises, Drucker-Prager
Earthquake Ground Motions

Realistic earthquake ground motions

- Body: P and S waves
- Surface: Rayleigh, Love waves, etc.
- Lack of correlation (incoherence)
- Inclined waves
- 3D waves
Body (P, S) and Surface (Rayleigh, Love) Waves

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DRM

- Seismic forces $P_e$ replaced by $P^{\text{eff}}$
- $P^{\text{eff}}$ applied only to a single layer of elements next to $\Gamma$.
- The only outgoing waves are from dynamics of the NPP
- Material inside $\Omega$ can be elastic-plastic
- All types of seismic waves (body, surface...) are properly modeled
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ESSI Simulator System
- ESSI Simulator System
- Modeling and Simulation

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On Earthquake Soil Structure Interaction Modeling and Simulation
Verification, Validation and Prediction

► Verification: the process of determining that a model implementation accurately represents the developer’s conceptual description and specification. Mathematics issue. *Verification provides evidence that the model is solved correctly.*

► 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. Physics issue. *Validation provides evidence that the correct model is solved.*

► Prediction: use of computational model to foretell the state of a physical system under consideration under conditions for which the computational model has not been validated.
Role of Verification and Validation

Knowledge about Reality

Model Discovery and Building

Mathematical Model
Continuum Mathematics

Computer Implementation
Discrete Mathematics

Code Verification

Analysis

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Oden et al.

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Oberkampf et al.

Oden et al.

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Importance of V&V

- V & V procedures are the primary means of assessing accuracy in modeling and computational simulations

- V & V procedures are the tools with which we build confidence and credibility in modeling and computational simulations
V & V for ESSI Modeling and Simulations

- Material modeling and simulation (elastic, elastic-plastic...)
- Finite elements (solids, structural, special...)
- Solution advancement algorithms (static, dynamic...)
- Seismic input and radiation
- Finite element model verification
Mesh Size Effects on Seismic Wave Propagation Modeling

- Finite element mesh "filters out" high frequencies
- Usual rule of thumb: 10-12 elements needed per wave length
- 1D wave propagation model
- 3D finite elements (same in 3D)
- Motions applied as displacements at the bottom

<table>
<thead>
<tr>
<th>case</th>
<th>model height [m]</th>
<th>$V_s$ [m/s]</th>
<th>El.size [m]</th>
<th>$f_{max}$ (10el) [Hz]</th>
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<tr>
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<td>1000</td>
<td>10</td>
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<tr>
<td>6</td>
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<td>1000</td>
<td>50</td>
<td>2</td>
</tr>
</tbody>
</table>
Cases 3, 4, and 6, Ormsby Wavelet Input Motions
Cases 3, 4, and 6, Surface Motions
Cases 3, 4, and 6, Input and Surface Motions, FFT
Seismic Body and Surface Waves

- Both body (P, SV and SH) and surface (Rayleigh, Love, etc.) waves are present
- Surface waves carry most seismic energy
- Analytic (Aki and Richards, Trifunac and Lee, Hisada et al., fk, etc.) and numerically generated, 3D, inclined (plane) body and surface waves are used in tests
- Seismic moment from a point source at 2km depth used
- Stress drop at the source: Ricker and/or Ormsby wavelets
Plane Wave Model
Seismic Source Mechanics

Stress drop, Ormsby wavelet

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Middle (Structure Location) Plane, Top 2km

horizontal accelerations

vertical accelerations

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Verification and Validation Suite

Verification: Displacements, Top Middle Point

\[(X)\]

\[(Z)\]
Verification and Validation Suite

Verification: Disp. and Acc., Out of DRM

Displacement

Acceleration

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Motivation  Challenges  ESSI Simulator System  Probabilistic Modeling  Summary

Uncertain (Geo) Materials

Uncertainty Propagation through Constitutive Eq.

- Incremental el–pl constitutive equation $\Delta \sigma_{ij} = D_{ijkl} \Delta \epsilon_{kl}$

$$D_{ijkl} = \begin{cases} D^e_{ijkl} \\ D^e_{ijkl} - \frac{D^e_{ijmn} m_{mn} n_{pq} D^e_{pqkl}}{n_{rs} D^e_{rstu} m_{tu} - \xi * r^*} \end{cases}$$

- What if all (any) material parameters are uncertain
- PEP and SEPFEM methods for spatially variable and point uncertain material
Probabilistic Stress Solution: Eulerian–Lagrangian form of FPK Equation

\[
\frac{\partial P(\sigma_{ij}(x_t, t), t)}{\partial t} = \frac{\partial}{\partial \sigma_{mn}} \left\{ \left\langle \eta_{mn}(\sigma_{mn}(x_t, t), E_{mnrs}(x_t), \epsilon_{rs}(x_t, t)) \right\rangle \right.
\]
\[+ \int_0^t d\tau \text{Cov}_0 \left[ \frac{\partial \eta_{mn}(\sigma_{mn}(x_t, t), E_{mnrs}(x_t), \epsilon_{rs}(x_t, t))}{\partial \sigma_{ab}} ; \eta_{ab}(\sigma_{ab}(x_{t-\tau}, t-\tau), E_{abcd}(x_{t-\tau}), \epsilon_{cd}(x_{t-\tau}, t-\tau)) \right\} P(\sigma_{ij}(x_t, t), t) \right. \]
\[+ \frac{\partial^2}{\partial \sigma_{mn} \partial \sigma_{ab}} \left\{ \left\langle \int_0^t d\tau \text{Cov}_0 \left[ \eta_{mn}(\sigma_{mn}(x_t, t), E_{mnrs}(x_t), \epsilon_{rs}(x_t, t)) ; \eta_{ab}(\sigma_{ab}(x_{t-\tau}, t-\tau), E_{abcd}(x_{t-\tau}), \epsilon_{cd}(x_{t-\tau}, t-\tau)) \right] \right\} P(\sigma_{ij}(x_t, t), t) \right. \]
Eulerian–Lagrangian FPK Equation and (SEP)FEM

- **Advection-diffusion equation**

\[
\frac{\partial P(\sigma_{ij}, t)}{\partial t} = - \frac{\partial}{\partial \sigma_{ab}} \left[ N^{(1)}_{ab} P(\sigma_{ij}, t) - \frac{\partial}{\partial \sigma_{cd}} \left\{ N^{(2)}_{abcd} P(\sigma_{ij}, t) \right\} \right]
\]

- **Complete** probabilistic description of response
- **Second-order exact** to covariance of time (exact mean and variance)
- Any uncertain FEM problem \((M\ddot{u} + C\dot{u} + Ku = F)\) with
  - uncertain material parameters (stiffness matrix \(K\)),
  - uncertain loading (load vector \(F\))

can be analyzed using PEP and SEPFEM to obtain PDFs of DOFs, stress, strain...
Probabilistic Elastic-Plastic Response

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Probabilistic Elastic-Plastic Response
Spectral Stochastic Elastic–Plastic FEM

- Minimizing norm of error of finite representation using Galerkin technique (Ghanem and Spanos 2003):

\[
\sum_{n=1}^{N} K_{mn}^e d_{ni} + \sum_{n=1}^{N} \sum_{j=0}^{P} d_{nj} \sum_{k=1}^{M} C_{ijk} K_{mnk} = \langle F_m \psi_i[\{\xi_r\}] \rangle
\]

\[
K_{mn}^e = \int_D B_n E^{ep} B_m dV
\]

\[
C_{ijk} = \langle \xi_k(\theta) \psi_i[\{\xi_r\}] \psi_j[\{\xi_r\}] \rangle
\]

\[
F_m = \int_D \phi N_m dV
\]

\[
K_{mnk} = \int_D B_n \sqrt{\lambda_k h_k} B_m dV
\]

\[
K_{mnk}^e = \int_D B_n E^{ep} B_m dV
\]
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"Uniform" CPT Site Data

1 sensitive fine grained
2 organic material
3 clay
4 silty clay to clay
5 clayey silt to silty clay
6 sandy silt to clayey silt
7 silty sand to sandy silt
8 sand to silty sand
9 sand
10 gravelly sand to sand
11 very stiff fine grained (*)
12 sand to clayey sand (*)
Full PDFs of all DOFs (and $\sigma_{ij}$, $\epsilon_{ij}$, etc.)

- Stochastic Elastic-Plastic Finite Element Method (SEPFEM)
- Dynamic case
- Full PDF at each time step $\Delta t$
PDF at each $\Delta t$ (say at 6 s)

Displacement (mm)

Real Soil Data
Conservative Guess
PDF $\rightarrow$ CDF (Fragility) at 6 s

![Graph showing PDF to CDF for earthquake ground displacement](image)

- **Real Soil Data**
- **Conservative Guess**

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Probability of Unacceptable Deformation (50cm)

On Earthquake Soil Structure Interaction Modeling and Simulation

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Seismic Wave Propagation Through Uncertain Soils

Conservative Guess

Real Site

Excellently Characterized Site
Summary

- High fidelity, time domain, nonlinear, earthquake soil structure interaction (ESSI) modeling and simulations (deterministic and probabilistic)
- The ESSI Simulator System (Program, Computer, Lecture Notes)
- Educational effort is essential (US-NRC, CNSC, IAEA, UCD, LBNL, INL, companies), seminars, short courses
- Funding from the US-NRC, DOE, NSF, and CNSC is much appreciated