Modeling and Simulation of Earthquake Soil Structure Interaction for Risk Informed Decision Making

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Outline

Motivation

Deterministic Modeling
  NRC ESSI Simulator System
  Verification and Validation Suite
  Examples

Probabilistic Modeling
  Uncertain Geomaterials
  Probabilistic Elastic–Plastic Response
  Seismic Wave Propagation Through Uncertain Soils

Summary
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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
Potential 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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Summary
The NRC-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 NRC-ESSI-Computer.

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

The NRC-ESSI-Notes represent a hypertext documentation system detailing modeling and simulation of NPP ESSI problems.
NRC 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 and Validation
- Detailed program documentation (part of NRC ESSI Notes)
- Target users: U.S.-NRC staff, UCD students, external users
NRC 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 system: 208 CPUs
- Near future: 784 CPUs
NRC ESSI Simulator Notes

- A hypertext documentation system describing in detail modeling and simulations of NPP ESSI problems
- Theoretical and Computational Formulations
- Software and Hardware Platform Design
- Verification and Validation
- Application Example
High Fidelity Modeling

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

- The NRC ESSI Simulator 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)
**Representative NPP Example Problem**

- Body and surface seismic waves
- Seismic wave frequencies up to 50Hz
- Elastic-plastic soil/rock and structural components,
- Inelastic contact/gap
- Seismic isolator effects
- Buoyant effects for deep foundation embedment
- High Fidelity Model: soil block: $230m \times 230m \times 100m$, foundation $90m \times 90m$ Containment Structure: $40m \times 50m$, 2.1 Million DOFs, 700,000 elements,
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.
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>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1000</td>
<td>1000</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>1000</td>
<td>1000</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>1000</td>
<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

![Graph Showing Displacement vs. Time for Different Element Sizes]
Cases 3, 4, and 6, Input and Surface Motions, FFT
Free Field, Inclined, 3D Body and Surface Waves

- Development of analytic and numerical 3D, inclined, uncorrelated seismic motions for verification
- Large scale models
- Point shear source
- Stress drop:
  - Wavelet (Ricker, Ormsby, etc)
  - Analytic
- Seismic input using DRM
The effective force $P_{\text{eff}}$ is a dynamically consistent replacement for the dynamic source forces $P_e$.

$$
P_{\text{eff}} = \left\{ \begin{array}{c}
P_{\text{eff}}^i \\
P_{\text{eff}}^b \\
P_{\text{eff}}^e \\
\end{array} \right\} = \left\{ \begin{array}{c}
0 \\
-M_{\Omega^b} \ddot{u}_e + K_{\Omega^b} u_e^0 \\
M_{\Omega} \ddot{u}_b + K_{\Omega} u_b^0 \\
\end{array} \right\}
$$
Verification: Displacements, Top Middle Point

(X)

(Z)

Verification and Validation Suite

Displacement (m) vs. Time (s) for (X) and (Z) components.
Verification and Validation Suite

Verification: Disp. and Acc., Out of DRM

![Displacement graph](image1.png)

![Acceleration graph](image2.png)

Motivation

Deterministic Modeling

Probabilistic Modeling

Summary

Jeremić

Modeling and Simulation of Earthquake Soil Structure Interaction for Risk Informed Decision Making
Motivation

Examples

Few Illustrative Examples

- Slip between foundation slab and the soil/rock underneath
- Passive seismic isolation by liquefaction
- Structural response in liquefied soil
Nuclear Power Plant with Base Slip

- Low friction zone between concrete foundation and soil/rock
- Inclined, 3D, body and surface, seismic wave field (wavelets: Ricker, Ormsby; real seismic, etc.)

![Graph showing seismic wave field](image)

**Jeremić**

Modeling and Simulation of Earthquake Soil Structure Interaction for Risk Informed Decision Making
Acc. Response for a Full 3D (at 45°) Ricker Wavelet

Examples

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Modeling and Simulation of Earthquake Soil Structure Interaction for Risk Informed Decision Making
FFT Response for a Full 3D (at 45°) Ricker Wavelet

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Examples

Motivation
Deterministic Modeling
Probabilistic Modeling
Summary

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Modeling and Simulation of Earthquake Soil Structure Interaction for Risk Informed Decision Making
Gaping Response (45° Ricker Wavelet)
Slipping Response and Energy Dissipated (45° Ricker)
Passive Base Isolation in Uniform and Layered Soils

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Modeling and Simulation of Earthquake Soil Structure Interaction for Risk Informed Decision Making
Pile in Liquefiable Sloping Ground

t= 2 sec  5 sec  10 sec  15 sec  20 sec  80 sec
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Summary
Material Behavior Inherently Uncertain

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

(Mayne et al. (2000))
Types of Uncertainties

- **Aleatory uncertainty** - inherent variation of physical system
  - Can not be reduced
  - Has highly developed mathematical tools

- **Epistemic uncertainty** - due to lack of knowledge
  - Can be reduced by collecting more data
  - Mathematical tools are not well developed
  - trade-off with aleatory uncertainty

- **Ergodicity** (exchanging ensemble averages for time average) assumed to hold
Recent State-of-the-Art

▲ Governing equation

- Dynamic problems → $M\ddot{u} + C\dot{u} + Ku = F$
- Static problems → $Ku = F$

▲ Existing solution methods

- Random r.h.s (external force random)
  - FPK equation approach
  - Use of fragility curves with deterministic FEM (DFEM)

- Random l.h.s (material properties random)
  - Monte Carlo approach with DFEM → CPU expensive
  - Perturbation method → a linearized expansion! Error increases as a function of COV
  - Spectral method → developed for elastic materials so far

▲ Original development of Probabilistic Elasto–Plasticity
Uncertainty Propagation through Constitutive Eq.

- Incremental el–pl constitutive equation \( \Delta \sigma_{ij} = E_{ijkl} \Delta \epsilon_{kl} \)

\[
E_{ijkl} = \begin{cases} 
  E_{ijkl}^{el} & \text{for elastic} \\
  E_{ijkl}^{el} - \frac{E_{ijmn}^{el} m_{mn} n_{pq} E_{pqkl}^{el}}{n_{rs} E_{rstu}^{el} m_{tu} - \xi_* h_*} & \text{for elastic–plastic}
\end{cases}
\]
Probabilistic Stress Solution: Eulerian–Lagrangian form of FPK Equation

\[
\begin{align*}
\frac{\partial P(\sigma_{ij}(x_t, t), t)}{\partial t} &= \frac{\partial}{\partial \sigma_{mn}} \left[ \left\{ \langle \eta_{mn}(\sigma_{mn}(x_t, t), E_{mnrs}(x_t), \epsilon_{rs}(x_t, t)) \rangle_{P(\sigma_{ij}(x_t, t), t)} \right\} - \int_0^t d\tau \text{Cov}_0 \left[ \frac{\partial \eta_{mn}(\sigma_{mn}(x_t, t), E_{mnrs}(x_t), \epsilon_{rs}(x_t, t))}{\partial \sigma_{ab}} ; \right. \\
&\left. - \langle \eta_{ab}(\sigma_{ab}(x_{t-\tau}, t-\tau), E_{abcd}(x_{t-\tau}), \epsilon_{cd}(x_{t-\tau}, t-\tau)) \rangle_{P(\sigma_{ij}(x_t, t), t)} \right\} \right] \\
&\quad + \frac{\partial^2}{\partial \sigma_{mn} \partial \sigma_{ab}} \left[ \left\{ \int_0^t d\tau \text{Cov}_0 \left[ \eta_{mn}(\sigma_{mn}(x_t, t), E_{mnrs}(x_t), \epsilon_{rs}(x_t, t)) ; \right. \\
&\left. - \langle \eta_{ab}(\sigma_{ab}(x_{t-\tau}, t-\tau), E_{abcd}(x_{t-\tau}), \epsilon_{cd}(x_{t-\tau}, t-\tau)) \rangle_{P(\sigma_{ij}(x_t, t), t)} \right\} \right] \right]
\end{align*}
\]
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
Probabilistic Elastic-Plastic Response
SPT Based Determination of Shear Strength

Transformation of SPT $N$-value → 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)
SPT Based Determination of Young’s Modulus

Transformation of SPT $N$-value → 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
Stochastic Finite Element Formulation

- Governing equations:

\[ A\sigma = \phi(t); \quad Bu = \epsilon; \quad \sigma = E\epsilon \]

- **Spatial** and **stochastic** discretization

  - Deterministic spatial differential operators \((A & B)\) → Regular shape function method with Galerkin scheme
  - Input random field material properties \((E)\) → Karhunen–Loève (KL) expansion, optimal expansion, error minimizing property
  - Unknown solution random field \((u)\) → Polynomial Chaos (PC) expansion
Spectral Stochastic Elastic–Plastic FEM

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

\[
\sum_{n=1}^{N} K_{mn}^{ep} d_{ni} + \sum_{n=1}^{N} \sum_{j=0}^{P} d_{nj} \sum_{k=1}^{M} C_{ijk} K_{mnk} = \langle F_{m} \psi_{i}[\{\xi_{r}\}] \rangle
\]

\[
K_{mn}^{ep} = \int_{D} B_{n} E_{m}^{ep} B_{m} dV
\]

\[
K_{mnk}^{ep} = \int_{D} B_{n} \sqrt{\lambda_{k} h_{k}} B_{m} dV
\]

\[
C_{ijk} = \langle \xi_{k}(\theta) \psi_{i}[\{\xi_{r}\}] \psi_{j}[\{\xi_{r}\}] \rangle
\]

\[
F_{m} = \int_{D} \phi N_{m} dV
\]
Inside SSEPFEM

- Explicit stochastic elastic–plastic finite element computations
- FPK probabilistic constitutive integration at Gauss integration points
- Increase in (stochastic) dimensions (KL and PC) of the problem
- Excellent for parallelization, both at the element and global levels
- Development of the probabilistic elastic–plastic stiffness tensor
Seismic Wave Propagation through Stochastic Soil

- Maximum likelihood estimates

Typical CPT $q_T$

Finite Scale

Fractal

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"Uniform" CPT Site Data

1 sensitive fine grained
2 organic material
3 clay
4 silty clay to silt
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 (*)
Random Field Parameters from Site Data

- Soil as 12.5 m deep 1–D soil column (von Mises Material)
  - Properties (including testing uncertainty) obtained through random field modeling of CPT $q_T$
    \[
    \langle q_T \rangle = 4.99 \text{ MPa}; \quad \text{Var}[q_T] = 25.67 \text{ MPa}^2; \\
    \text{Cor. Length } [q_T] = 0.61 \text{ m}; \quad \text{Testing Error } = 2.78 \text{ MPa}^2
    \]

- $q_T$ was transformed to obtain $G$: $G/(1 - \nu) = 2.9q_T$
  - Assumed transformation uncertainty = 5%
    \[
    \langle G \rangle = 11.57\text{MPa}; \quad \text{Var}[G] = 142.32\text{MPa}^2 \\
    \text{Cor. Length } [G] = 0.61m
    \]

- Input motions: modified 1938 Imperial Valley
Decision About Site (Material) Characterization

- Do nothing about site characterization (rely on experience): conservative \textbf{guess} of soil data, $COV = 225\%$, correlation length $= 12\m$.

- Do better than standard site characterization: $COV = 103\%$, correlation length $= 0.61\m$.

- Improve site (material) characterization if probabilities of exceedance are unacceptable!
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 $\Delta t$
Evolution of Mean ± SD for Guess Case

Displacement (mm) vs. Time (sec)
PDF at each $\Delta t$ (say at 6 s)

[Graph showing PDF distribution for Real Soil Data and Conservative Guess with displacement in mm on the x-axis and PDF on the y-axis]
Motivation

Deterministic Modeling

Probabilistic Modeling

Summary

Seismic Wave Propagation Through Uncertain Soils

PDF $\rightarrow$ CDF (Fragility) at 6 s

![CDF graph]

- Real Soil Data
- Conservative Guess

Displacement (mm)
Probability of Unacceptable Deformation (50cm)

- Conservative Guess
- Real Site
- Excellently Characterized Site
Risk Informed Decision Process

- Conservative
- Guess
- Real Site
- Excellently Characterized Site

Probability of Exceedance (%)

Displacement (cm)
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▶ Interplay of Uncertain Earthquake, Uncertain Soil/Rock, and Uncertain Structure in time domain probably plays a decisive role in seismic performance of NPPs

▶ Improve risk informed decision making through high fidelity Deterministic and Stochastic Elastic-Plastic Finite Element modeling and simulation

▶ Education and training of users will prove essential

▶ Acknowledgement: funding and collaboration with the US-NRC, and funding from NSF, DOE.


