Computational Modeling and Simulation of Earthquake Soil Structure Interaction Behavior of Nuclear Installations

Boris Jeremić

University of California, Davis, CA
and
Lawrence Berkeley National Laboratory, Berkeley, CA

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Outline

Introduction
  Motivation
  Uncertainties

Modeling and Simulation
  Modeling and Simulation Examples
  Probabilistic Inelastic Modeling

Summary
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Summary
Motivation

- Improve modeling and simulation for seismic behavior of Nuclear Installations
- Reduce modeling uncertainty
- Follow the flow, input and dissipation, of seismic energy,
- Practical system for modeling and simulation of Earthquakes, Soils, Structures and their Interaction (ESSI):
  http://real-essi.info/
Predictive Capabilities

- Prediction under Uncertainty
- Verification: evidence that the model is solved correctly.
- Validation: evidence that the correct model is solved.
- Modeling and parametric uncertainties are always present
- Goal: Predict and Inform rather than (force) Fit
- Risk informed is not enough → full risk calculations for ESSI, analytical/numerical, accurate
Verification and Validation Details

Real World

Conceptual Model

Highly accurate solution
Analytical solution
Benchmark ODE solution
Benchmark PDE solution

Computational Model

Computational Solution

Validation

Experimental Data
Unit Problems
Benchmark Cases
Subsystem Cases
Complete System

Verification
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

The process of determining the degree to which a model is an 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
Types of Physical Experiments

- **Traditional Experiments**
  - Improve the fundamental understanding of physics involved
  - Improve the mathematical models for physical phenomena
  - Assess component performance

- **Validation Experiments**
  - Model validation experiments
  - Designed and executed to quantitatively estimate mathematical model’s ability to simulate well defined physical behavior
  - The simulation tool, Real-ESSI, computational model, computational solution, is the customer
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Uncertainties

- **Modeling Uncertainty**, from simplifying assumptions
  - Low, medium, high sophistication modeling and simulation
  - Sophistication level for confidence in analysis results

- **Parametric Uncertainty**, \( M\ddot{u}_i + C\dot{u}_i + K_{ep}u_i = F(t) \)
  - Propagation of uncertainty in \( M, C \) and \( K_{ep} \)
  - Propagation of uncertainty in loads, \( F(t) \)
  - Results are PDFs and CDFs for \( \sigma_{ij}, \epsilon_{ij}, u_i, \dot{u}_i, \ddot{u}_i \)
Modeling Uncertainty

- Simplified modeling: Features (important ?) are neglected (3C, 6C ground motions, inelasticity)

- Modeling Uncertainty: unrealistic and unnecessary modeling simplifications

- Modeling simplifications are justifiable if one or two level higher sophistication model shows that features being simplified out are not important
Modeling Uncertainty, 6C vs 1C Motions
Parametric Uncertainty: Soil Stiffness

\[ E = (101.125 \times 19.3)^N^{0.63} \]

cf. Phoon and Kulhawy (1999B)
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Energy Input and Dissipation

Energy input, static and dynamic forcing

Energy dissipation outside SSI domain:

- SSI system oscillation radiation
- Reflected wave radiation

Energy dissipation/conversion inside SSI domain:

- Inelasticity of soil, contact zone, structure, foundation, dissipation
- Viscous coupling with internal/pore fluids, and external fluids

Numerical energy dissipation/production
Energy Dissipation in NPP Model

(MP4)
Energy Dissipation for an SMR Model

(MP4)

Accumulated Plastic Dissipation Density (J/m³)

Incremental Plastic Dissipation Density (J/m³)
Seismic Motions

- Variation in inclination, frequency, energy, duration...
- Deterministic andProbabilistic
- Stress test the soil-structure system
Free Field, Variation in Input Frequency, $\theta = 60^\circ$

(MP4)
SMR ESSI, Variation in Input Frequency, $\theta = 60^\circ$
SMR ESSI, 3C vs $3 \times 1C$
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Uncertainty Propagation through Inelastic System

- Incremental el–pl constitutive equation

\[ \Delta \sigma_{ij} = E_{ijkl}^{EP} \Delta \epsilon_{kl} = \left[ E_{ijkl}^{el} - \frac{E_{ijkl}^{el} m_{mn} n_{pq} E_{pqkl}^{el}}{n_{rs} E_{rstu}^{el} m_{tu} - \xi h*} \right] \Delta \epsilon_{kl} \]

- Dynamic Finite Elements

\[ M \ddot{u}_i + C \dot{u}_i + K^{ep} u_i = F(t) \]

- Material and load parameters are uncertain
Probabilistic Elastic-Plastic Response

- Mean
- Mode
- Deterministic Solution
- Std. Deviations

Stress (MPa) vs. Strain (%)

Jeremić et al.
Real-ESSI
Probabilistic Elastic-Plastic Modeling

![Graphs showing cyclic loading of uncertain stress and stiffness with probability density functions for stress and stiffness.](image)
Stochastic Elastic-Plastic Finite Element Method

- Material uncertainty expanded into stochastic shape funcs.
- Loading uncertainty expanded into stochastic shape funcs.
- Displacement expanded into stochastic shape funcs.

\[
\begin{bmatrix}
\sum_{k=0}^{P_d} \varphi_k \psi_0 \psi_0 & K^{(k)} \\
\sum_{k=0}^{P_d} \varphi_k \psi_0 \psi_1 & K^{(k)} \\
\vdots & \vdots \\
\sum_{k=0}^{P_d} \varphi_k \psi_0 \psi_P & K^{(k)} \\
\end{bmatrix}
\begin{bmatrix}
\Delta u_{10} \\
\vdots \\
\Delta u_{N_0} \\
\Delta u_{1P} \\
\vdots \\
\Delta u_{NP_u}
\end{bmatrix}
= 
\begin{bmatrix}
\sum_{i=0}^{P_f} f_i \psi_0 \zeta_i \\
\sum_{i=0}^{P_f} f_i \psi_1 \zeta_i \\
\sum_{i=0}^{P_f} f_i \psi_2 \zeta_i \\
\vdots \\
\sum_{i=0}^{P_f} f_i \psi_{P_u} \zeta_i \\
\end{bmatrix}
\]
SEPFEM: System Size

- SEPFEM offers a complete solution (single step)
- It is NOT based on Monte Carlo approach
- System of equations does grow (!)

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<th># KL terms load</th>
<th>PC order displacement</th>
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SEPFEM: Example in 1D

Stochastic Displacement from SEPFEM

Fragility Curve of Node number 1

Jeremić et al.

Real-ESSI
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- Numerical modeling to predict, rather than fit

- Education and Training is the key!

- Real-ESSI Simulator System: http://real-essi.info/