Nonlinear Time Domain Modeling and Simulation of Surface and Embedded NPPS

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Outline

Introduction
  Motivation
  Modeling Uncertainty

ESSI Modeling
  Modeling Issues
  3D, Inclined, Body and Surface Seismic Waves
  Nonlinear Material Behavior

Summary
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Summary
Motivation

- Improving seismic design (safety and economy) for Nuclear Facilities (NFs)
- Earthquake Soil Structure Interaction (ESSI) in time and space, plays a major role in successes and failures
- Accurate following and directing (!) the flow of seismic energy in ESSI system to optimize ESSI system for
  - Safety and
  - Economy
- Development of high fidelity numerical modeling and simulation tools to analyze realistic ESSI behavior, Real ESSI Simulator
Predictive Capabilities

- **Verification** provides evidence that the model is solved correctly. Mathematics issue.

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

- **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.

- **Real ESSI Simulator**: a software, hardware and documentation system for high fidelity, high performance, time domain, nonlinear, 3D, finite element modeling and simulation of earthquake-soil/rock-structure interaction of Nuclear Facilities (NFs)
Seismic Energy Input and Dissipation for NFs

- Seismic waves input (flux) into SSI system
- Mechanical dissipation outside of SSI domain:
  - reflected (surface, NF) wave radiation
  - SSI (NF) system oscillation radiation
- Mechanical dissipation/conversion inside SSI domain:
  - plasticity of soil and rock
  - nonlinear contact zone (foundation – soil/rock)
  - plasticity/damage of structure, foundation
  - viscous coupling of porous solid with pore fluid (soil)
  - viscous coupling of structure/foundation with fluids
- Numerical energy dissipation/production
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Modeling Uncertainty

- Real ESSI goal: reduction of modeling uncertainty
- Simplified modeling: important features are neglected (structure complexity, 6D ground motions, non-linearities)
- Modeling Uncertainty: unnecessary and unrealistic modeling simplifications
- Modeling simplifications are justifiable if one or two level higher sophistication model shows that features being simplified out are not important
Complexity and Uncertainty in Motions and Material

- 6D (3 translations (horizontal and vertical), 3 rotations)
- Sources of uncertainties in ground motions (Source, Path (rock), soil (rock))
- Most engineering materials and components experience inelastic deformations for service and hazard loads
- Pressure sensitive materials (soil, rock, concrete, &c.) have complex constitutive response, tying together nonlinear stress-strain with volume response
- In addition, man-made and natural materials are spatially variable and their material modeling parameters are uncertain
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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ESSI Modeling and Simulation
Important Issues for ESSI Modeling and Simulation

- Verification and Validation
- 6D, inclined, body and surface seismic waves
- Uncorrelated (incoherent) motions
- Nonlinear material (soil, rock, concrete, steel, &c.)
- Nonlinear foundation-soil/rock contact (dry and saturated), slip – gap
- Saturated dense vs loose soil with buoyant forces
- Isolators, dissipators
ESSI Models

Detailed high fidelity models taking into account all of the issues
In Detail: Main ESSI Issues for SMRs
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Real Earthquake Ground Motions

- Body waves: P and S waves
- Inclined waves
- Surface waves: Rayleigh, Love waves, &c.
- 6D waves (3 translations, 3 rotations)
- Surface waves carry most seismic energy
- Lack of correlation (incoherence)
3D, Body and Surface Seismic Waves

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Body and Surface Wave Animations

- Homogeneous soil/rock, 45\textdegree\ off vertical
- Homogeneous soil/rock, 45\textdegree\ off vertical, motion vectors
- Homogeneous soil/rock, 45\textdegree\ off vertical, motion vectors, NPP location
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Nonlinear Material Behavior

Validation: Lotung, LSST07, $G/G_{\text{max}}$ and Damping

- Nonlinear, 3D elastic-plastic, Pisanò material model for Lotung (validation)
- 1D wave propagation, only LSST07 is close to 1D!
- No volume change data (a serious issue!)
Validation: Lotung, LSST07, Downhole Motions

Time History of Surface

Time History of 6m depth

Time History of 11m depth

Time History of 17m depth
Validation: Lotung, LSST07, Fourier Spectra

Fourier Spectrum of Surface

Fourier Spectrum of 6m depth

Fourier Spectrum of 11m depth

Fourier Spectrum of 17m depth

Recorded Motion
Simulated Motion
NPP with Base Slip and Gap

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

Acc. Response for a Full 3D (at 45°) Ricker Wavelet

Slip Behavior
No-slip Behavior

bottom X

bottom Z

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Slipping Response and Energy Dissipated (45° Ricker)

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Gaping Response (45° Ricker Wavelet)
Summary

▶ Earthquake Soil Structure Interaction, in time domain, nonlinear, uncertain, plays a decisive role in seismic performance of Nuclear Facilities

▶ Improve design and retrofits (safety and economy) through high fidelity, physics based modeling and simulation

▶ Real ESSI Simulator System, verified (extensive) and validated (not so extensive), for modeling and simulations used for design, retrofits and regulatory decision making

▶ Education and training of users (designers, regulators, owners) proves essential
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