Real Earthquake Soil Structure Interaction (Real ESSI) Modeling and Simulation

Boris Jeremić et al.

UCD, LBNL

PRENOLIN
December 2014

Outline

Motivation

- Improving seismic design for infrastructure objects, focus on Nuclear Facilities
- Use of high fidelity numerical models in analyzing seismic behavior of soil structure interaction (SSI) systems
- Accurate following of the flow of seismic energy in the soil/rock-foundation-structure system
- Directing, in space and time, seismic energy flow in the soil/rock-foundation-structure system

Hypothesis

- Interplay of the Earthquake with the Soil/Rock, Foundation and Structure in time domain, plays a major role in successes and failures
- Timing and spatial location of energy dissipation determines location and amount of damage
- If timing and spatial location of energy dissipation can be controlled (directed, designed), we could optimize soil structure system for
  - Safety and
  - Economy

Predictive Capabilities

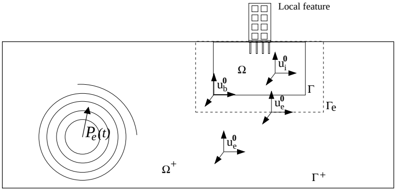
- **Verification** provides evidence that the model is solved correctly. Mathematics issue.
- **Validation** provides evidence that the correct model is solved. Physics issue.
- **Prediction**: use of computational model to foretell the state of a physical system under consideration under conditions for which the computational model has not been validated.
- Goal: predictive capabilities with **low Kolmogorov Complexity**

Seismic Energy Input for the SSI System

- Kinetic energy flux through closed surface Γ includes both incoming and outgoing waves (using Domain Reduction Method by Bielak et al.)

$$E_{flux} = \left[0; -M^{\Omega+}_{be}\ddot{u}^{0}_{e} - K^{\Omega+}_{be}u^{0}_{e}; M^{\Omega+}_{eb}\ddot{u}^{0}_{b} + K^{\Omega+}_{eb}u^{0}_{b}\right]_{i} \times u_i$$

- Alternatively, $E_{flux} = \rho A c \int_0^t \dot{u}_i^2 dt$
- Outgoing kinetic energy is obtained from outgoing wave field (w_i, in DRM)
- Incoming kinetic energy is then the difference.



Seismic Energy Dissipation for the SSI System

- Mechanical dissipation outside of SSI domain:
  - reflected wave radiation
  - SSI system oscillation radiation
- Mechanical dissipation/conversion inside SSI domain:
  - plasticity of soil subdomains
  - plasticity/damage of foundation
  - plasticity/damage of structure
  - viscous coupling of structure/foundation with fluids
  - viscous coupling of porous solid with pore fluid (air, water)
  - potential $\leftrightarrow$ kinetic energy
- Numerical energy dissipation/production

Modeling Uncertainty

- Goal: reduction of modeling uncertainty
- Simplified (or inadequate/wrong) modeling: important features are missed (3D seismic ground motions, nonlinearities, etc.)
- Modeling Uncertainty: introduced with unnecessary and unrealistic modeling simplification
- Avoid use of results obtained using models with (high) modeling uncertainty

Complexity of and Uncertainty in Ground Motions

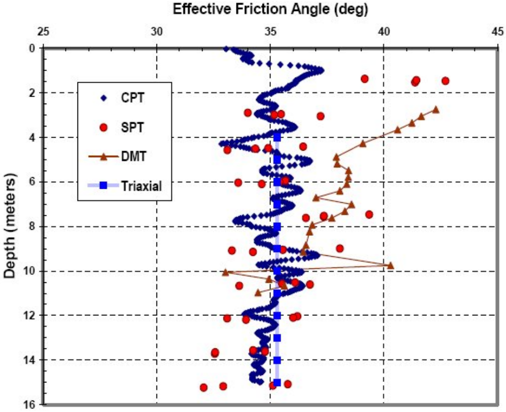
- 6D (3 translations, 3 rotations)
- Vertical motions usually neglected
- Rotational components usually not measured and neglected
- Lack of models for such 6D motions (from measured data))
- Sources of uncertainties in ground motions (Source, Path (rock), soil (rock))

Complexity of and Uncertainty in Material Modeling

- All engineering materials experience inelastic deformations for working loads
- This is even more so for hazard loads (earthquakes)
- Pressure sensitive materials (soil, rock , concrete, etc) can have very complex constitutive response, tying together nonlinear stress-strain with volume response
- Simplistic material modeling (elastic, G/G_{max}, etc.) introduce (significant) uncertainties in response results
- In addition, man-made and natural materials are spatially variable and their material modeling parameters are uncertain

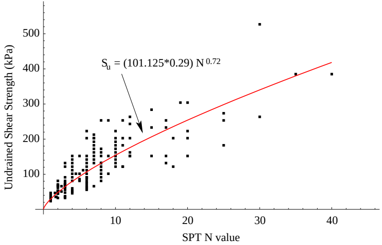
Material Behavior Inherently Uncertain

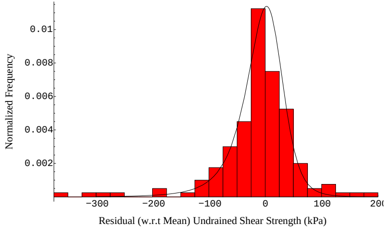
- Spatial variability
- Point-wise uncertainty, testing error, transformation error



(Mayne et al. (2000)

SPT Based Determination of Shear Strength

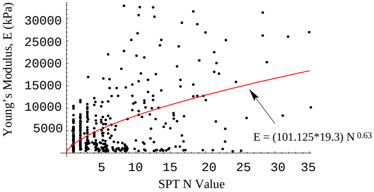


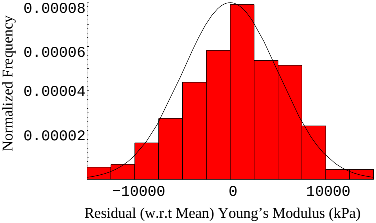


Transformation of SPT N-value $\rightarrow$ un-drained shear strength, s_u (cf. Phoon and Kulhawy (1999B)

Histogram of the residual (w.r.t the deterministic transformation equation) un-drained strength, along with fitted probability density function (Pearson IV)

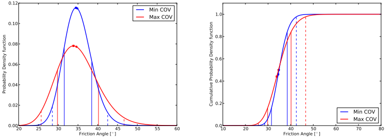
SPT Based Determination of Young's Modulus



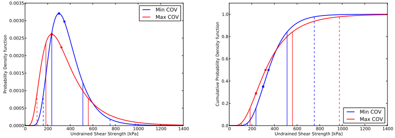


- Transformation of SPT *N*-value → 1-D Young's modulus, *E* (cf. Phoon and Kulhawy (1999B))
- Histogram of the residual (w.r.t the deterministic transformation equation) Young's modulus, along with fitted probability density function

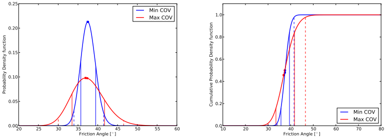
Transformation Error/Uncertainty



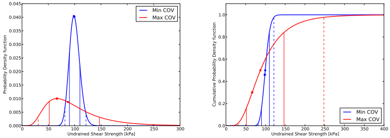
Field ϕ



Field c_u



Lab ϕ



Lab c_u

Real ESSI Simulator System

- **The Real 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 Nuclear Facilities (NPPs and other infrastructure objects) on ESSI-Computers.
- **The Real ESSI-Computer** is a distributed memory parallel computer.
- **The Real ESSI-Notes** are a hypertext documentation system.
- Real ESSI aka, Très Facile, Muy Fácil, Врло Просто, Molto Facile, Πραγματικά Εύκολο, 本当に簡単

Real ESSI Simulator Program: Finite Elements

- Dry/single phase solids (8, 20, 27, 8-27 node bricks),
- Saturated/two phase solids (8 and 27 node bricks, $u-p-U$ and $u-p$, liquefaction modeling),
- Truss,
- Beams (six and variable DOFs per node),
- Shell (ANDES) with 6DOF per node,
- Contacts (dry and/or saturated soil/rock - concrete, gap opening-closing, frictional slip),
- Base isolators and dissipators (elastomeric, natural rubber, frictional pendulum)

Real ESSI Simulator Program: Material Models and Seismic Input

- Material Models
  - Linear and nonlinear, isotropic and anisotropic elastic
  - Elastic-Plastic (von Mises, Drucker Prager, Rounded Mohr-Coulomb, Leon Parabolic, Cam-Clay, SaniSand, SaniClay, Pisanò...). All elastic-plastic models can be used as perfectly plastic, isotropic hardening/softening and kinematic hardening models.
- Analytic input of seismic motions (both body (P, S) and surface (Rayleigh, Love, etc., waves), including analytic radiation damping.

Real ESSI Simulator Program: V&V, Parallel

- Verification and Validation: each element, model, algorithm and procedure has been extensively verified (math issue) and (not so extensively) validated (physics issue). Verification and Validation is documented in detail in Real ESSI Notes.

- High Performance Parallel Computing: both parallel and sequential version available. Parallel Real ESSI Simulator (based on the Plastic Domain Decomposition Method, designed for efficient elastic-plastic parallel simulations) runs on clusters of PCs and on large supercomputers (Distributed Memory Parallel machines, all top national supercomputers).

Real ESSI Simulator Program: Probabilistic/Stochastic

- Constitutive: Euler-Lagrange form of Fokker-Planck (forward Kolmogorov) equation for probabilistic elasto-plasticity (PEP)
- Spatial: stochastic elastic plastic finite element method (SEPFEM)

Uncertainties in material and load are analytically taken into account. Resulting displacements, stress and strain are obtained as very accurate (second order accurate for stress) Probability Density Functions. PEP and SEPFEM are not based on a Monte Carlo method, rather they expand uncertain input variables and uncertain degrees of freedom (unknowns) into spectral probabilistic spaces and solve for PDFs of resulting displacement, stress and strain in a single run.

Real ESSI Simulator Program: Design and Users

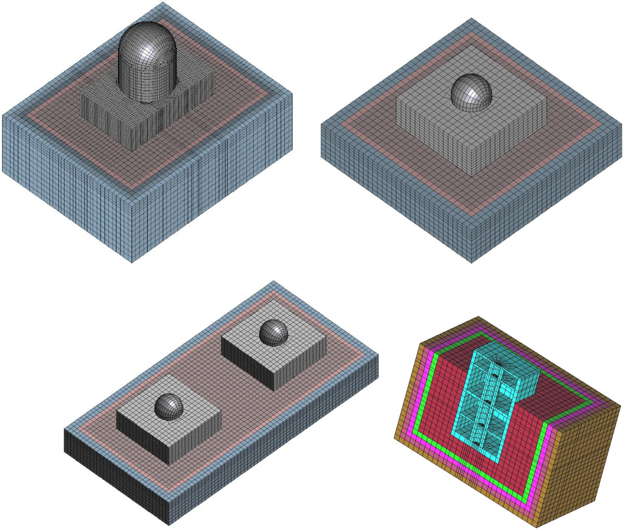
- Library centric software design (portable, modular)
- Sequential (initial use, learning) and Parallel (production modeling and simulation)
- Distributed Memory Parallel (DMP) paradigm, scales well to large supercomputers
- Public domain licenses (CC, GPL, LGPL, BSD, &c.)
- Verification (extensive) and Validation (not much)
- Target users: US-DOE, US-NRC, CNSC, IAEA, AREVA NP GmbH, Shimizu Corp, Rizzo and Assoc., Academic Collaborators, &c.
- Real ESSI is a limited distribution expert modeling and simulation system

Important Issues for ESSI Modeling and Simulation

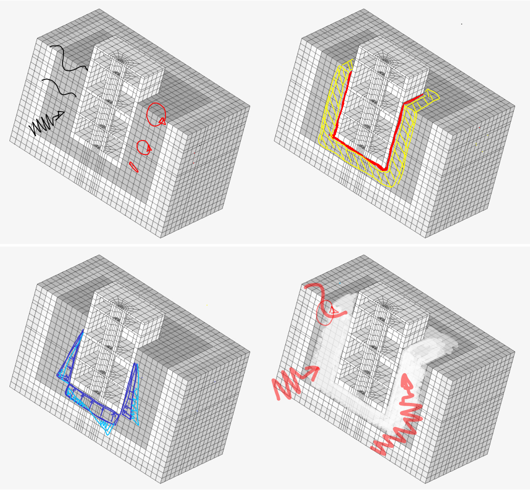
- Verification and Validation
- 6D, inclined, body and surface seismic waves
- Uncorrelated (incoherent) motions
- Nonlinear material (soil, rock, concrete, steel, &c.)
- Nonlinear foundation-soil/rock contact (dry and saturated), slip – gap
- Seismic Isolators and Dissipators
- Saturated dense vs loose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

ESSI Models

Detailed high fidelity models taking into account all of the issues

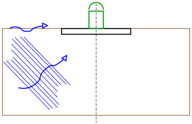


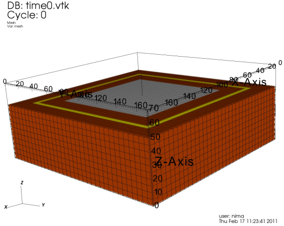
In Detail: Main ESSI Issues for SMRs

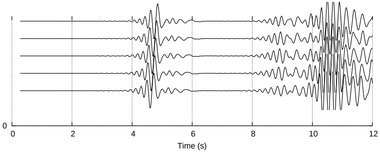


NPP with Base Slip and Gap

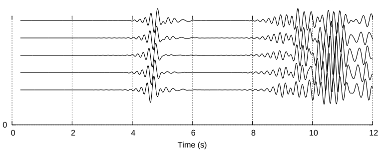
- Low friction zone between concrete foundation and soil/rock
- Inclined, 3D, body and surface, seismic wave field (wavelets: Ricker, Ormsby; real seismic, &c.)





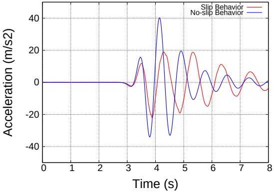


horizontal

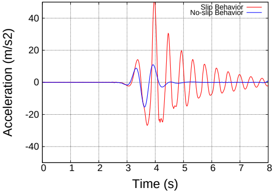


vertical

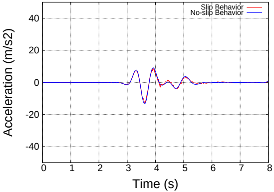
Acc. Response for a Full 3D (at 45°) Ricker Wavelet



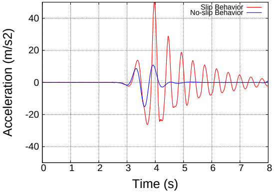
top X



top Z

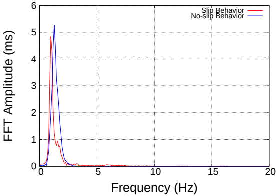


bottom X

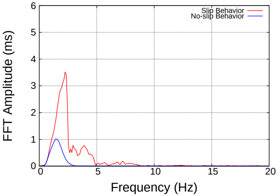


bottom Z

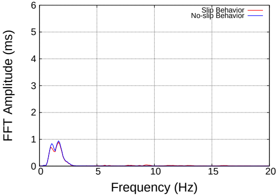
FFT Response for a Full 3D (at 45°) Ricker Wavelet



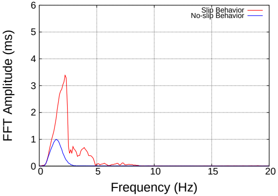
top X



top Z

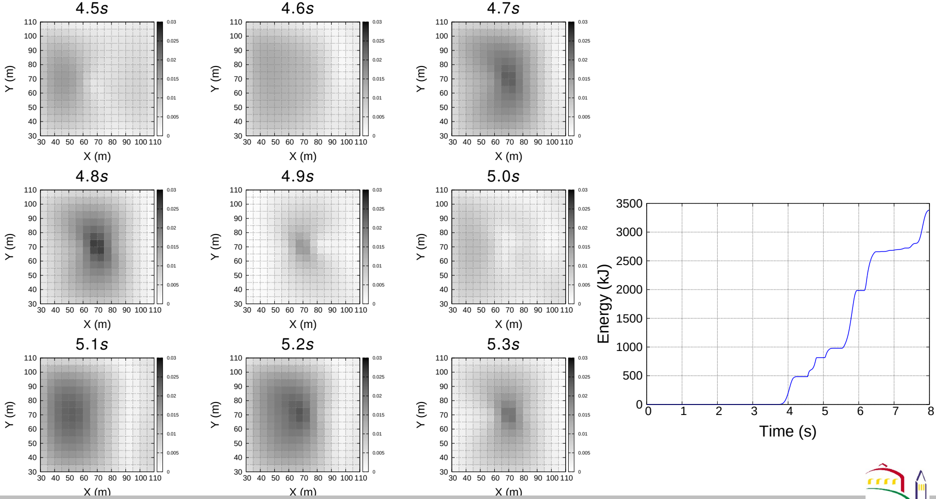


bottom X

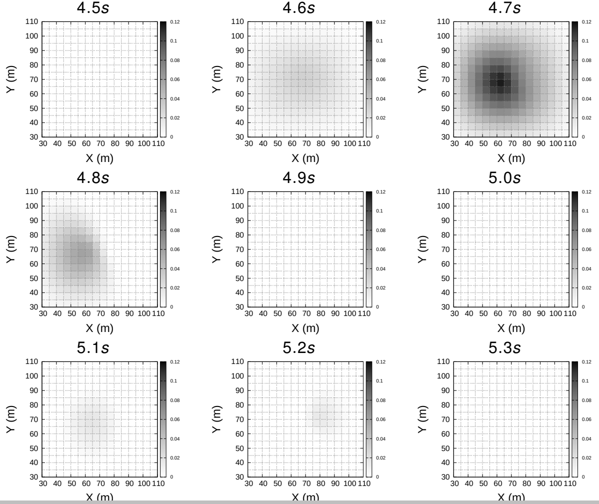


bottom Z

Slipping Response and Energy Dissipated (45° Ricker)



Gaping Response (45° Ricker Wavelet)



Summary

- **Interplay** of **Earthquake**, **Soil**, and **Structure**, in time domain, plays a decisive role in seismic performance of NPPs and other infrastructure objects
- Improve **design** (**safety** and **economy**) through **high fidelity**, modeling and simulation
- **Real ESSI Simulator**, developed with this in mind, is used for modeling, simulations, design and regulatory decision making
- **Education** and **training** of users (designers, regulators, owners) will prove essential

Acknowledgement

- Funding from and collaboration with the US-NRC, US-DOE, CNSC, US-NSF, AREVA NP GmbH, and Shimizu Corp. is greatly appreciated,
- Collaborators, students: Messrs. Abell, Jeong, Aldridge. Kamranimoghadam, Karapiperis, Watanabe, Chao, Drs. Tafazzoli, Cheng, Profs. Pisanò, Sett, Taiebat, Yang