

NRC ESSI Simulator

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Earthquake Soil Structure Interaction Modeling: Benefits and Detriments

- ▶ Improved accuracy of Earthquake Soil Structure Interaction (ESSI) modeling and simulation benefits understanding of seismic behavior of Nuclear Power Plants (NPPs)
- ▶ Reduction of modeling uncertainty! In other words, we will know with much more fidelity what is the actual seismic response of an NPP
- ▶ Benefit: reduction of seismic energy input due to energy dissipation of nonlinear material
- ▶ Benefit and Detriment: seismic motion frequency content change

Introduction to the NRC ESSI Simulator

A collaborative project between University of California, Davis (**UCD**), Lawrence Berkeley National Laboratory (**LBNL**), and United States Nuclear Regulatory Commission (**U.S. NRC**) to develop a High Fidelity Modeling and Simulation System for Time Domain, Nonlinear Finite Element Analysis of Earthquake Soil/Rock Structure Interaction (ESSI) response of NPPs.

NRC ESSI Simulator System Components

- ▶ **The NRC ESSI Program:** a 3D, nonlinear, time domain, parallel finite element program specifically developed for High Fidelity modeling and simulation of Earthquake Soil/Rock Structure Interaction (ESSI) problems for NPPs on NRC-ESSI-Computer.
- ▶ **The NRC ESSI Computer:** a distributed memory parallel computer, a cluster of clusters with multiple performance processors and multiple performance networks.
- ▶ **The NRC ESSI Notes:** a hypertext documentation system detailing modeling and simulation of NPP ESSI problems.

NRC ESSI Program

- ▶ Library Centric design and management approach (libraries: CompGeoMech UCD libs, MOSS, PETSc, UMFPACK, LAPACK, BLAS, Ltensor)
- ▶ Application Programming Interface (API) documented in detail
- ▶ Finite elements: Solids (single phase (u), fully coupled, porous solid – pore fluid, (u-p-U, u-p)), structural (truss, beams, shells), special elements (gap, contact, gap-contact, seismic isolators: frictional, rubber, lead-rubber)
- ▶ Material models: linear and nonlinear elastic, isotropic and anisotropic, elastic-plastic (von Mises, Drucker-Prager, Mohr-Coulomb, SANIsand, Dafalias-Manzari, Pisanò-EP (calibrated from G/G_{max} curves), all can be perfectly plastic, isotropic hardening or softening and/or translational and/or rotational kinematic hardening (A-F type);
- ▶ Staged loading (self weight, service loads, hazard loads, seismic loads, aftershocks, etc.)
- ▶ Seismic Input, analytic, using Domain Reduction Method, incorporates seismic body (S, P) and surface (Rayleigh, Love) waves
- ▶ Buoyancy effects (fluid pressure on embedded foundation) modeled analytically (with full coupling with pore fluid pressures changes in foundation soil/rock)
- ▶ Parallel computations using Plastic Domain Decomposition method, for efficient run time computational load balancing (for inelastic computations)
- ▶ Domain Specific Language for model input

Verification and Validation

- The NRC ESSI Program has an extensive (and ever growing) verification and validation suite. This ensures the highest possible quality of numerical prediction results.
- ▶ Verification: a Mathematics issue, provides evidence that the model is solved correctly.
 - ▶ Validation: a Physics issue, 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.

NRC ESSI Computer

- ▶ NRC ESSI Computer is a distributed memory parallel (DMP) computer designed for high performance, parallel finite element simulations using NRC ESSI Program
- ▶ Multiple performance CPUs and Networks (on-board, InfiniBand, GigaBit) can be effectively used
- ▶ Most cost-performance effective design (BeoWulf)
- ▶ NRC ESSI Program runs most efficiently on the NRC ESSI Computer, however, it is also source compatible with any DMP supercomputers (any large national supercomputer or any other cluster parallel computer)
- ▶ Industry standard Message Passing Interface (MPI) for communication between compute nodes
- ▶ Current setup: 208 CPU cores, 288 GB RAM, 24TB disk space, triple network (on-board, Gigabit and InfiniBand)
- ▶ By Spring 2013: 592 CPU cores, 800 GB RAM, 40TB disk space, triple network
- ▶ By Fall 2013: 784 CPU cores, 1056 GB RAM, 48TB disk space, triple network



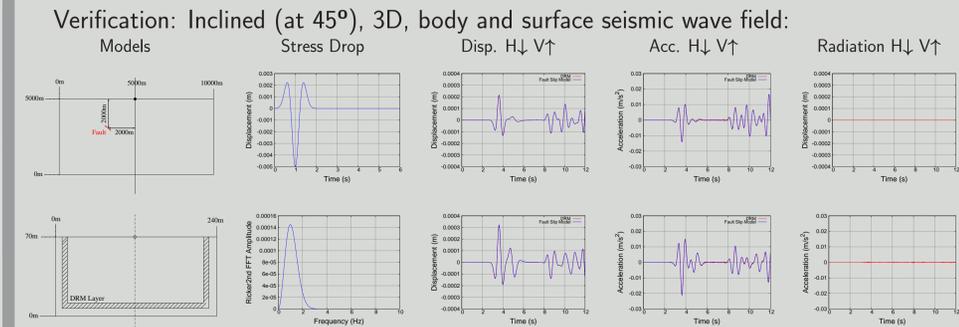
NRC ESSI Notes

- A hypertext documentation system describing in detail modeling and simulations of NPP ESSI problems:
- ▶ Theoretical and Computational Formulations: Finite Element Methods, Elasto-Plasticity, Static and Dynamic Solutions, Parallel Computing
 - ▶ Software and Hardware Platform: Object Oriented Design, Library Centric Design, Application Programming Interface (API for the source code), Domain Specific Language (DSL, C and English language bindings), Software Build Process, Hardware Platform
 - ▶ Verification and Validation (V&V): Verification: code, components (elements, algorithms), static and dynamic solution advancement, wave propagation, Earthquake Soil Structure Interaction; Validation: material modeling, wave propagation, Earthquake Soil Structure Interaction
 - ▶ Application to Practical Nuclear Power Plant Earthquake Soil/Rock Structure Interaction Problems (case studies):
 - ▷ ESSI with 3D, inclined, uncorrelated seismic waves,
 - ▷ ESSI with nonlinear soil/rock and foundation slip,
 - ▷ ESSI with seismic base isolators, horizontal and vertical isolation benefits and detriments,
 - ▷ ESSI with nonlinear soil/rock, base isolators and nonlinear structural response,
 - ▷ ESSI analysis for high frequency response,
 - ▷ ESSI for design basis earthquakes, full nonlinear response (from the list above), safety margins determination,
 - ▷ ESSI for large, beyond design basis earthquakes, full nonlinear response (from the list above), safety margins determination
 - ▶ Draft of the NRC ESSI Notes is available at: <http://nrc-essi-simulator.info/>

Stochastic Modeling

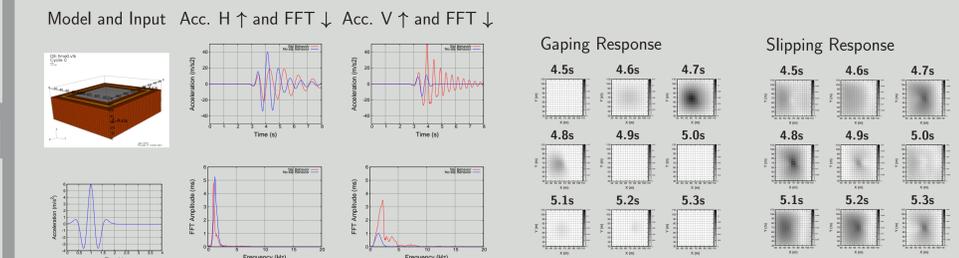
In addition to deterministic modeling and simulations, recently developed Probabilistic Elasto-Plasticity (PEP) and Stochastic Elastic-Plastic Finite Element Methods (SEPFEM) (Jeremić et al.), are currently being integrated into the NRC ESSI Simulator. This will allow for very accurate (analytic, using solution to Fokker – Planck – Kolmogorov equation for PEP) development of full Probability Density Functions (PDFs) for generalized displacements, stress, strain, etc. From developed PDFs one can easily develop full Cumulative Density Functions (CDFs) aka fragility curves for any part/components of the NPP soil/rock-structure system.

Verification Example (select)



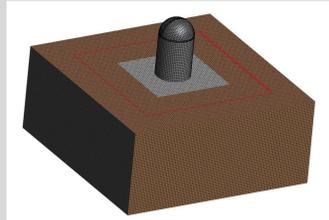
Nonlinear Example (select)

Gapping–Slipping at the foundation–soil/rock contact, for full 3D (at 45°, horizontal and vertical, body and surface) seismic wave:



Current Example Problem

- Representative NPP, emphasis on very accurate modeling and simulation of:
- ▶ Body and surface seismic wave effects,
 - ▶ Elastic-plastic soil/rock and structures,
 - ▶ Inelastic contact/gap (foundation-soil)
 - ▶ Seismic isolator effects
 - ▶ Buoyant effects for embedded foundations
 - ▶ Seismic wave frequencies ≤ 50 Hz
 - ▶ High Fidelity model: soil/rock block: 230m \times 230m \times 100m, foundation slab 90m \times 90m, Containment Structure: 40m \times 50m, 2.1 Million DOFs, 700,000 elements,



NRC ESSI Simulator License

A version of **Attribution-NonCommercial-ShareAlike 3.0 Unported (CC BY-NC-SA 3.0) license**, for components and the system.

Education is the Key!

Available are: short courses, lectures, advising and consultancy, etc.

Current and Former Student Collaborators and Developers

- ▶ Drs: Guanzhou Jie, Matthias Preisig, Zhao Cheng, Nima Tafazzoli, Federico Pisanò;
- ▶ Professors: Zhaohui Yang, Kallol Sett, Mahdi Taiebat;
- ▶ Students: Panagiota Tasiopoulou, Babak Kamranimoghadam, Chang-Gyun Jeong, José Abell Mena, Benjamin Aldridge, Justin Anderson;

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