High Performance, High Fidelity Modeling and Simulation of Earthquake-Soil-Structure Interaction for Nuclear Power Industry

Boris Jeremić

Professor, University of California, Davis
Faculty Scientist, Lawrence Berkeley National Laboratory, Berkeley

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Outline

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The Problem: ESSI Modeling

- Seismic waves: 6D (3 translations, 3 rotations), Inclined, Body (P and S) and Surface (Love and Rayleigh) waves, Uncorrelated (incoherent), frequency range (0.1Hz – 50Hz)
- Material behavior (soil, rock, concrete, metal, seismic isolation elements, foundation interface zones...): elastic, elastic-plastic, elastic-damage-plastic
- Geometries: solids, structures, components and interfaces

ESSI Modeling and Simulation Requirements

- High fidelity modeling and high performance simulation
- Reduction of modeling uncertainty
- High performance (parallel) computing
- Nonlinear, time domain finite element modeling and simulation of Earthquake – Soil/Rock – Structure Interaction (ESSI) of Nuclear Power Plants (NPPs)
- Quality Assurance (QA): Verification and Validation
- Education: seminars, lecture notes, advising
- Documentation: theory, formulation, implementation, Application Programming Interface (API), verification and validation examples, case studies

ESSI Modeling and Simulation Goals

- Develop modeling and simulation system for high fidelity modeling and high performance simulation of ESSI for NPPs
  - Software (GPL, LPGL)
  - Hardware (off the shelf, customized architecture)
  - Education (most important)
  - Documentation (extensive, CC license)
- The NRC ESSI Simulator
- The NRC ESSI Simulator is developed for US-NRC, however, it is in public domain

Outline

NRC ESSI Simulator Program

- Based on a Collection of Useful Libraries
- Public Domain License (GPL, LGPL)
- Verification: code, methods and models
- Validation, uncertainties
- Documentation: theory, formulation, verification, validation, examples, Application Programming Interface (API), Creative Commons (CC)
- Education, ensures continuation

NRC ESSI Simulator Program: Library Centric Design

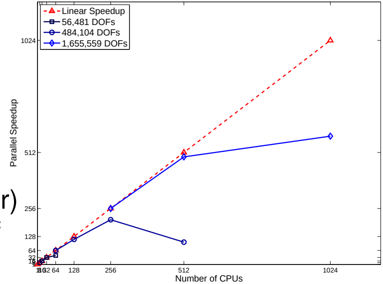
- Finite element libraries: solids (8, 20, 27, variable # of nodes), beams (displacement based), shell, contact/interface, seismic isolator, single phase (dry), two/three phase (fully/partially saturated, fully coupled)
- Material model libraries: elastic (isotropic, anisotropic, linear, nonlinear), elastic-plastic (various for soil/rock/concrete/metal)
- Plastic Domain Decomposition (PDD) for Parallel Computing
- MOSS library: Modified OpenSees Services (MOSS): changed (for PDD), trimmed, reorganized, API-ed

NRC ESSI Simulator Program: Library Centric Design

- Numerical utility libraries (BLAS, lapack, nDarray, L-Tensor...)
- Solver libraries (UMFPACK, PETSc,...)
- Graph libraries (ParMETIS, ZOLTAN)
- Template meta-programming
- Domain Specific Language (DSL) library
- Management: API, V&V, regression testing, documentation, (L)GPL, subversion for code management (number of developers and users)

Plastic Domain Decomposition Method

- Dynamic computational load (re-)balancing based on
  - Computer node(s) performance
  - Network(s) performance
- Optimally efficient on variable capability computer nodes and multiple interconnect networks:
  - Tightly connected HPC parallel machines (DMP)
  - Multiple CPUs / multiple core HPC machines (SMP)
  - Tightly connected cluster (DMP) of clusters (SMP) (NRC ESSI Simulator Computer)
  - Loosely connected collection of virtual machines (cloud)



NRC ESSI Simulator Computer

- Dual network (MPI and PFS) cluster of compute nodes (Distributed Memory Parallel, DMP)
- Each compute node consists of multiple CPUs/cores (Shared Memory Parallel, SMP, but used as DMP)
- Use of General Purpose Graphical Processor Units (GPGPU)
- High availability (I'm root)
- Secure (US-NRC...)
- Locally designed and maintained (exportable)
- Documentation (hardware, system software, system libraries) (internal UCD, US-NRC and external use)

Development Process Management

- Program libraries peer reviewed,
- Documentation (extensive), verification and validation examples required
- Application Program Interface (API)
- Focus on US-NRC and UCD contributions and needs
- Public domain libraries source code, documents (GPL, LGPL and CC)

Development Process: Verification

Verification provides evidence that the model is solved correctly.

- Elements (tests: patch, aspect ratio, ...)
- Constitutive simulations (integration error, bounds test, localization condition, ...)
- Finite element level static and dynamic solution advancement (integration) algorithms (analytic solution tests, ...)
- System of equations solvers (error, ...)
- Wave propagation (seismic motion input and radiation, energy dissipation, flat frequency modification, ...)

Development Process: Validation

Validation provides evidence that the correct model is solved.

- Component validation (material modeling, vibration analysis, soil pressures, ...)
  - Constitutive (material) behavior
  - Component dynamics
  - Contact/interface behavior
  - Energy dissipation characteristics

- Complete system validation
  - Lotung LSST tests
  - Kashiwazaki-Kariwa NPP data (IAEA KARISMA project)
  - Fukushima-Daiichi NPP data
  - NEES data (?)

Education and Documentation

- Lecture Notes
  - Theory and formulation
  - Implementation (literate programming, API)
  - Application Programming Interface
  - Verification examples
  - Validation examples
  - Practical examples
- Seminars (US-NRC, IAEA, Nuclear Industry...)

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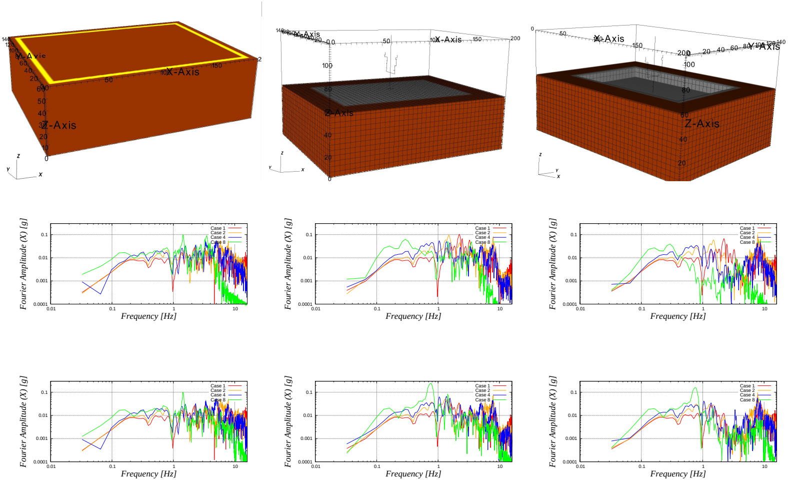
Real(istic) Seismic Waves and NPP Response

- Surface (Love and Rayleigh) and body waves (P and S) (six dimensional, 6D, 3 translations, 3 rotations)
- Lack of correlation modeling (incoherence)
- Inclined wave field(s)
- Influence of soil/rock variability and uncertainty on seismic motions

Inelastic Foundation-Soil/Rock Interface

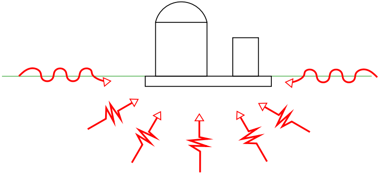
- Soil/rock – foundation interface slip behavior
- Changes in ESSI: reduction/increase in demand
- Dissipation of seismic energy in a slip zone
- Passive (and active) base isolation

Early Examples

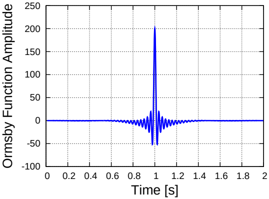


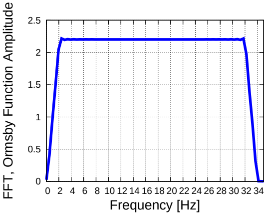
Shake Out: Stress Test NPP Soil-Structure System

- Synthetic ground motions: emphasize soil-structure system weakness



- Variations in input angle, input orientation, input energy...





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Summary and Conclusions

- Importance of reducing modeling uncertainty
- High fidelity modeling and high performance simulations
- Education and Documentation crucial (UCD, US-NRC, IAEA, Nuclear Industry,...
- Significant number of very interesting technical issues with NPPs for research. licensing and professional practice

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