On Seismic Soil Structure Interaction Simulations for Nuclear Power Plants

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Outline

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The ESSI Hypothesis

- NPPSSS response is a function of a tightly coupled (in space and time) triad of dynamic characteristic of
  - Earthquake Ground Motions
  - Underlying Soil/Rock
  - NPP Structure, Systems and Components (NPPSSC)
- Energy balance: input (seismic) and dissipated (inelasticity, radiation, coupling) will control fate of the NPPSSS
- Better understanding of the timing and spatial location of energy dissipation in Earthquake-Soil-Structure Interaction (ESSI) system can add significant benefit to the safety and economy of NPPSSSs
- High Fidelity Numerical Simulations of ESSI for NPPSSS

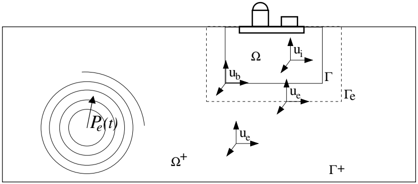
Outline

Seismic Energy Input Into the NPPSSS

- Seismic energy propagates to the NPPSSS
- Kinetic energy flux through closed surface Γ includes both incoming and outgoing waves (using DRM)

$$E_{flux} = \left[0; -M_{be}^{\Omega+}\ddot{u}_e^0 - K_{be}^{\Omega+}u_e^0; M_{eb}^{\Omega+}\ddot{u}_b^0 + K_{eb}^{\Omega+}u_b^0\right]_i \times u_i$$

- 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 within NPPSSS

- Mechanical dissipation outside of NPPSSS domain:
  - reflected wave radiation
  - NPP system oscillation radiation
- Mechanical dissipation/conversion inside NPPSSS:
  - plasticity of the soil/rock subdomain
  - viscous coupling of porous solid with pore fluid (air, water)
  - plasticity/damage of parts of the structure/foundation
  - viscous coupling of structure/foundation with fluids
- Numerical energy dissipation/production

Outline

ESSI Modeling Approaches

- Analytical (closed form) solutions
  - Limited application for realistic NPPSSCs
  - Excellent for verification studies
  - Good for initial insight
  - Potentially large modeling uncertainty!
- Numerical solutions
  - Integral Equations (Boundary Element Method, CLASSI)
  - Finite Element Methods
    - Frequency domain (SASSI, etc.), widely used, linear elastic, etc.
    - Time domain (LS-DYNA, NRC ESSI Simulator, etc.), gaining popularity, full non-linear, etc.
  - Educated developers/modelers/analysts are a must

NRC ESSI Simulator Program: Library Centric Design

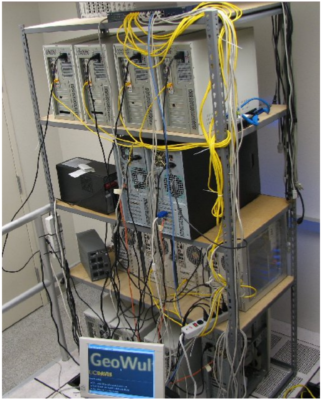
- A full 3D, non-linear Earthquake-Soil-Structure Interaction program, computer and documentation system
- MOSS library (UCD Modified OpenSees Services: trimmed, debugged, verified, documented),
- Plastic Domain Decomposition for Parallel Computing
- Finite element and material libraries (FEMtools, Template3DEP)
- Numerical utility libraries (BLAS, lapack, nDarray, matrix...)
- Solver libraries (UMFPACK, PETSc, SuperLU...)
- Graph libraries (ParMETIS)
- Domain Specific Language (DSL) library
- Verification, Validation, Educational, and Real NPPSSS Examples library

NRC ESSI Simulator Program: Management

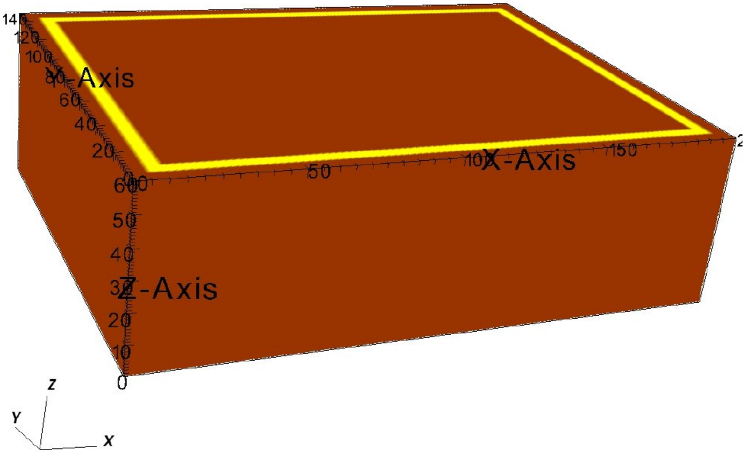
- Application Programming Interface (API): well documented, for all libraries and examples
- Detailed theory background
- Verification examples, extensive
- Validation examples, as available
- Educational examples, extensive
- NRC ESSI Simulation in public domain, an open source license (LPGL)
- Source files management by subversion for a large number of developers and users

NRC ESSI Simulator Computer

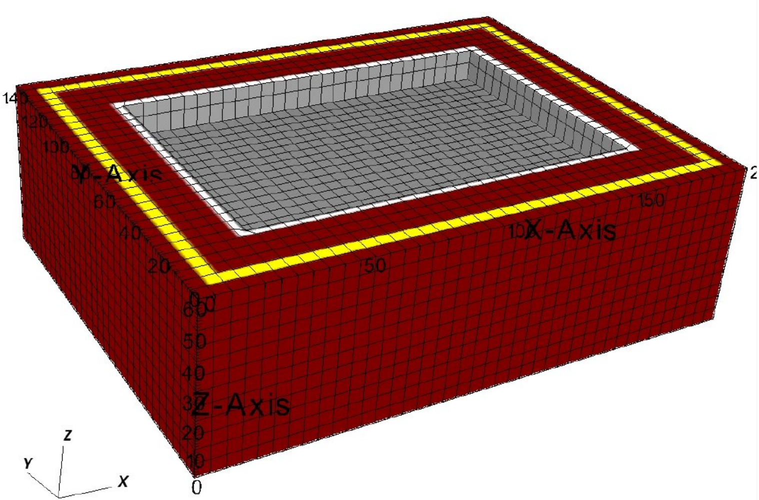
- Distributed memory parallel computer
- Very cost effective, affordable, high availability, design exportable to Companies, Regulatory Agencies, Universities
- Same architecture as large parallel supercomputers (SDSC, TACC, EarthSimulator...)
- Current version at UCD, new version to be acquired soon



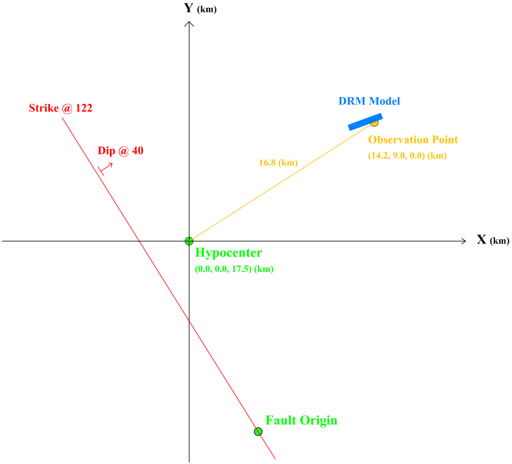
Illustrative Example: Free Field



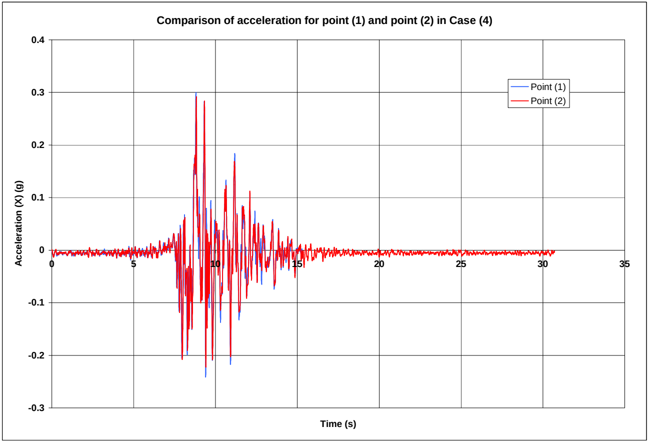
Illustrative Example: ESSI for NPPs



Seismic Input: Green's Function and DRM



Free field Motions: Lack of Correlation



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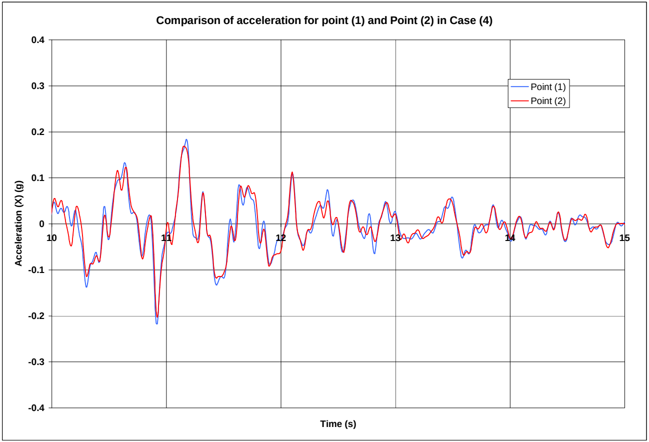
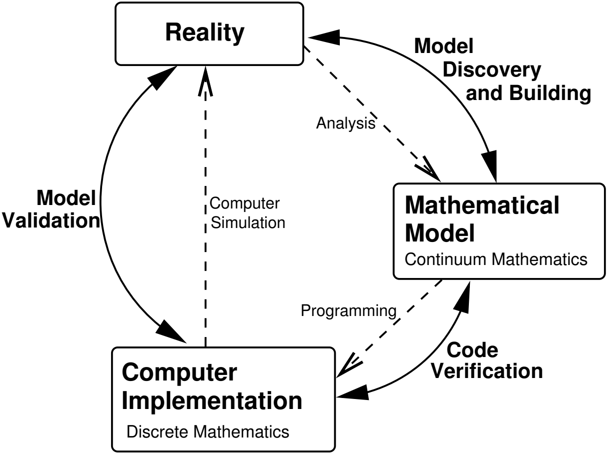


Verification, Validation and Prediction

- Verification: the process of determining that a model implementation accurately represents the developer's conceptual description and specification. Mathematics issue. *Verification provides evidence that the model is solved correctly*
- Validation: the process of determining the degree to which a model is accurate representation of the real world from the perspective of the intended uses of the model. Physics issue. *Validation provides evidence that the correct model is solved*
- Prediction: use of computational model to foretell the state of an NPPSSS under conditions for which the computational model has not been validated

Role of Verification and Validation



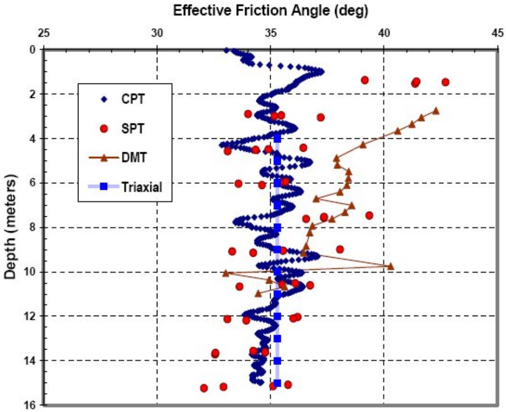
Verification and Validation for Prediction

- How much can (should) we trust model implementations (verification)?
- How much can (should) we trust numerical simulations (validation)?
- How good are our numerical predictions?
- Can a simulation tool (NRC ESSI Simulator) be used for assessing **public safety**?
- V&V procedures are the primary means of assessing accuracy, building confidence and credibility in modeling and computational simulations
- Ever present uncertainties need to be modeled and propagated through the simulation process

Outline

Material Behavior Inherently Uncertain

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



Mayne et al. (2000)

Probabilistic Elasto-Plasticity (PEP) and Stochastic Elastic-Plastic Finite Element Method (SEPFEM)

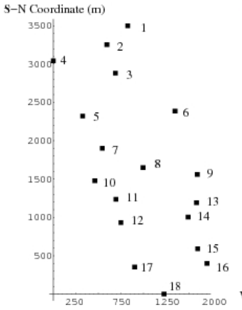
- PEP: Eulerian–Lagrangian form of the Fokker-Planck-Kolmogorov (FPK) equation
  - Input, probability distribution of material properties
  - Output: Complete probabilistic description of response, solution is a Probability Density Function (PDF) of stress
  - Solution PDF is second-order **exact** to covariance of time (exact mean and variance)
- PEP $+$ Spectral Stochastic Finite Element Method
  - Input: PDF for material properties (LHS), probabilistic seismic loading (RHS)
  - Output: accurate, full PDF of displacements (and $\dot{u}_i$, $\ddot{u}_i$), stress, strain, etc.

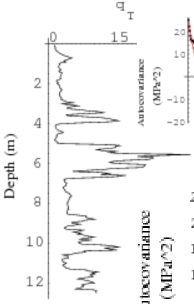
Decision About Site (Material) Characterization

- Do an inadequate site characterization (rely on experience): conservative **guess** for soil data, $COV = 225\%$, large correlation length (length of a model).
- Do a good site characterization: $COV = 103\%$, correlation length calculated ($= 0.61$m)
- Do an excellent (much improved) site characterization if probabilities of exceedance are unacceptable!

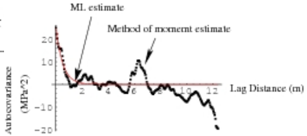
Random Field Parameters from Site Data

- Maximum likelihood estimates

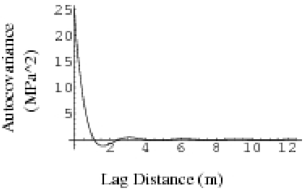




Typical CPT q_T

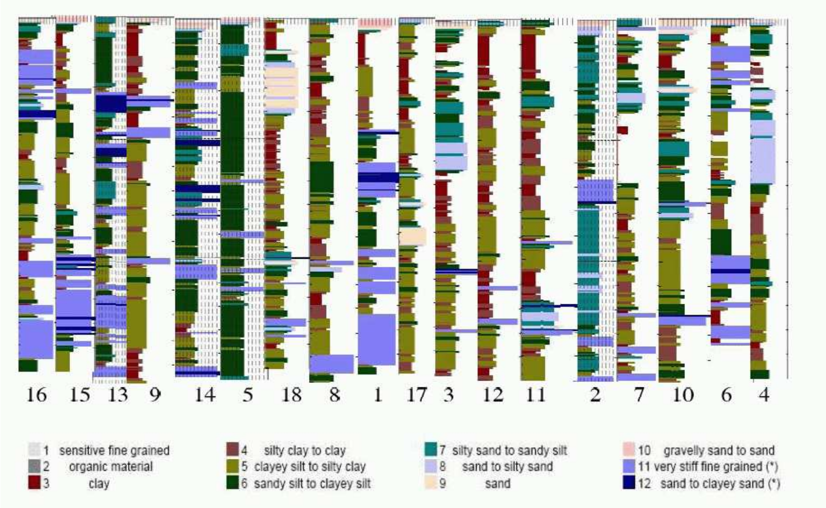


Finite Scale



Fractal

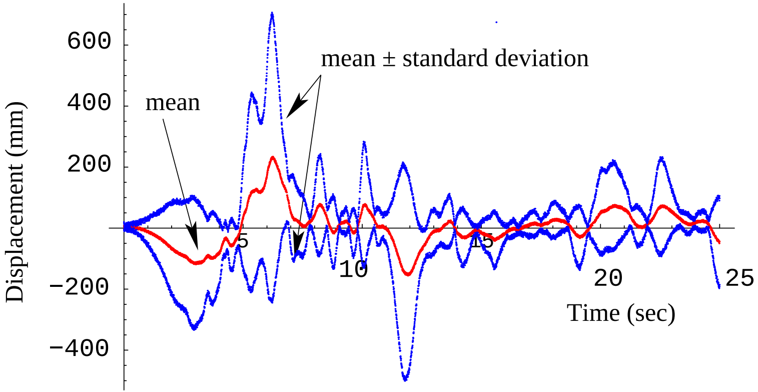
"Uniform" CPT Site Data (Courtesy of USGS)



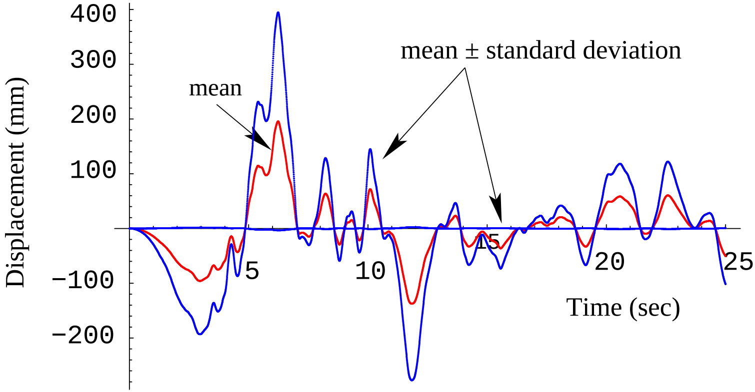
Statistics of Stochastic Soil Profile(s)

- Soil as 12.5m deep 1–D soil column (von Mises material)
  - Properties (including testing uncertainty) obtained through random field modeling of CPT q_T
    $\langle q_T \rangle = 4.99\ MPa$; $Var[q_T] = 25.67\ MPa^2$;
    Cor. Length $[q_T] = 0.61\ m$; Testing Error $= 2.78\ MPa^2$
- q_T was transformed to obtain G: $G/(1-\nu) = 2.9 q_T$
  - Assumed transformation uncertainty = 5%
    $\langle G \rangle = 11.57 MPa$; $Var[G] = 142.32 MPa^2$
    Cor. Length $[G] = 0.61 m$
- Input motions: modified 1938 Imperial Valley

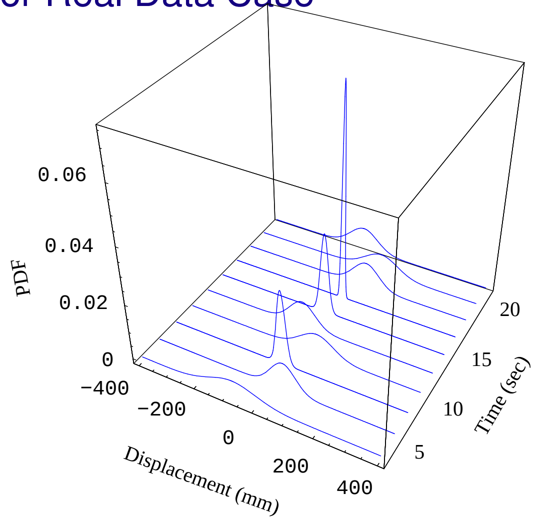
Evolution of Mean ± SD for Guess Case



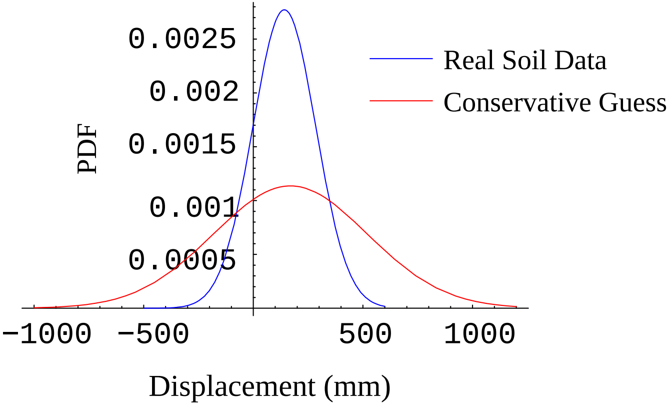
Evolution of Mean ± SD for Real Data Case



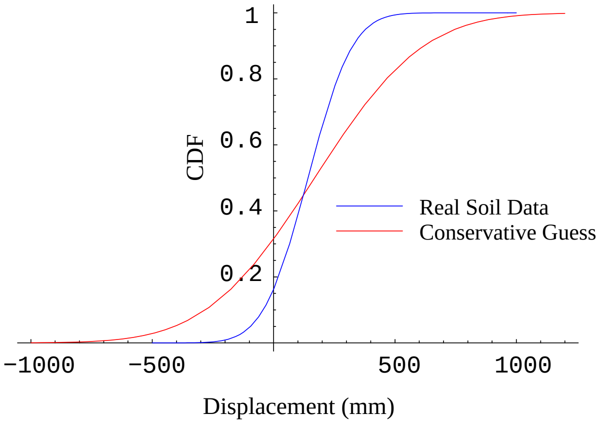
Full PDFs for Real Data Case



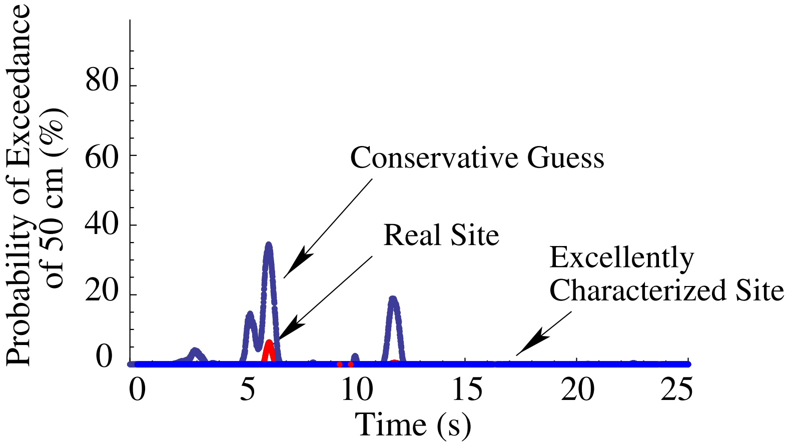
Example: PDF at 6 s



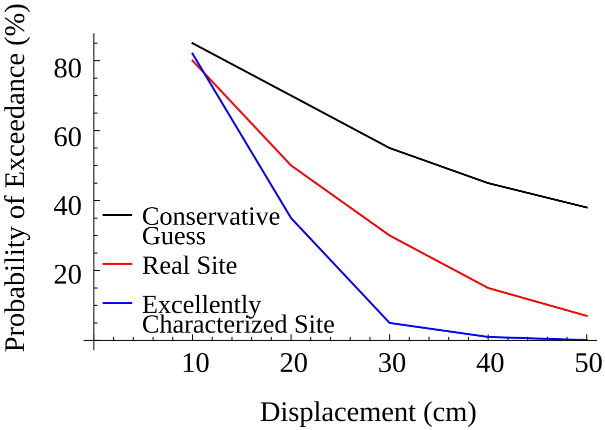
Example: CDF at 6 s



Probability of Unacceptable Deformation (50cm)



Risk Informed Decision Process



Outline

Summary

- There is a need for high fidelity modeling and simulations (verified and validated, deterministic and probabilistic) for NPPSSSs
- Such high fidelity modeling and simulations will improve safety and economy
- Education for Developers, Modelers/Analysts, Researchers, Consultants, Regulators is very important
- Presented research was/is funded in part and performed in collaboration with the Caltrans, NSF, U.S. NRC and CNSC
- CompDyn2011 Corfu, Greece, 26-28 May, Soil-Structure Interaction Mini-Symposium