Earthquake Soil Structure Interaction (ESSI) Modeling and Simulation

Boris Jeremić

Consulting Engineer, Jeremic Engineering Consultants
Professor, University of California, Davis
Faculty Scientist, Lawrence Berkeley National Laboratory, Berkeley

INL Steering Committee Meeting
December 2013

Outline

Outline

Motivation

- Improving seismic design for Nuclear Power Plants (NPPs)
- Use of high fidelity numerical models for analyzing seismic behavior of NPP soil structure interaction (SSI) system
- Accurately follow, and direct (!), in space and time, flow of seismic energy through the NPP SSI system

Hypothesis

- Interplay of an Earthquake with Soil/Rock and Structure, in time domain, plays a major role in seismic response 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), NPP soil structure systems can be optimized 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: physics based predictive capabilities with **low Kolmogorov Complexity**
- High Fidelity, **hierarchical**, predictive capabilities, aim for higher modeling sophistication then needed

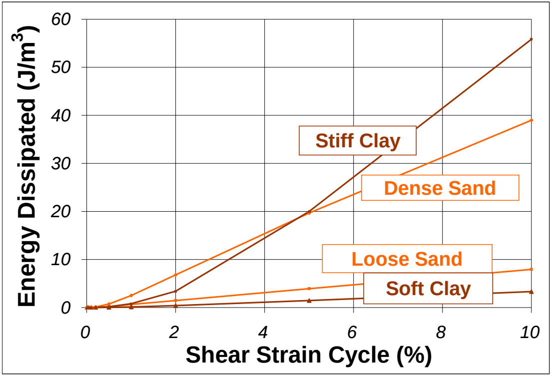
Outline

Seismic Energy Input and Dissipation

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

Energy Dissipation by Soil Plasticity

Energy dissipation (plastic work) capacity for different soils



Outline

Modeling Uncertainty

- Simplified (or inadequate/wrong) modeling: important features are missed (seismic ground motions, etc.)
- Introduction of uncertainty and (unknown) lack of accuracy in results due to use of un-verified simulation tools (software quality, etc.)
- Introduction of uncertainty and (unknown) lack of accuracy in results due to use of un-validated models (due to lack of quality validation experiments)

Complexity of and Uncertainty in Ground Motions

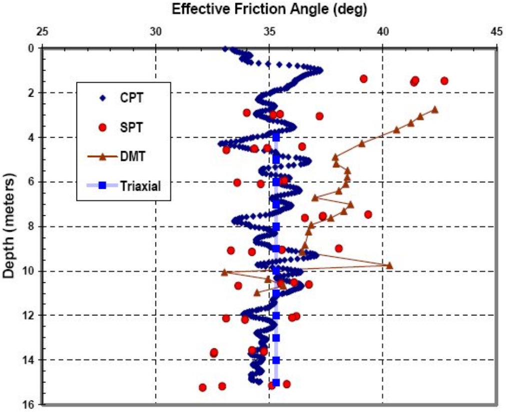
- 6D (3 translations, 3 rotations)
- Vertical motions usually neglected
- Rotational components usually not measured and neglected
- Lack of models for such 6D motions (from measured data))
- Sources of uncertainties in ground motions (Source, Path (rock), soil (rock))

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

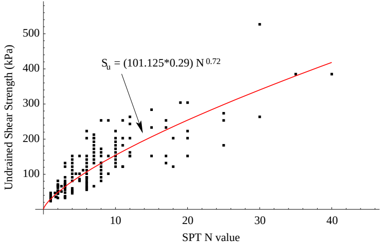
Material Behavior Inherently Uncertain

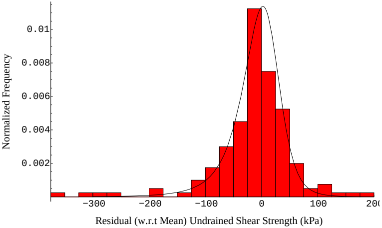
- Spatial variability
- Point-wise uncertainty, testing error, transformation error



(Mayne et al. (2000)

SPT Based Determination of Shear Strength

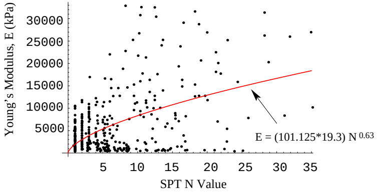


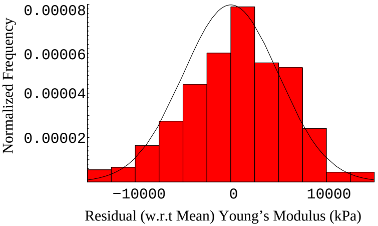


Transformation of SPT N-value $\rightarrow$ un-drained shear strength, s_u (cf. Phoon and Kulhawy (1999B)

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

Outline

ESSI Simulator System

- **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 of NPPs on ESSI-Computer.
- **ESSI-Computer** is a distributed memory parallel computer, a cluster of clusters with multiple performance processors and multiple performance networks.
- **ESSI-Notes** are a hypertext documentation system (Theory and Formulation, Software and Hardware, Verification and Validation, and Case Studies and Practical Examples) detailing modeling and simulation of ESSI problems.

ESSI Program: Finite Elements

- Dry/single phase solids (8, 20, 27 8-27 node bricks)
- Saturated/two phase solids (8 and 27 node bricks, liquefaction modeling, buoyant forces)
- Quad (ANDES) Shell (6DOFs per node)
- Beams (6DOFs and variable DOFs per node)
- Truss
- Contacts (dry or saturated soil/rock - concrete, gap opening-closing, frictional slip)
- Base isolators (elastomeric, frictional pendulum)

ESSI Program: Material Models

- Linear and nonlinear, isotropic and anisotropic elastic
- Elastic-Plastic (von Mises, Drucker Prager, Rounded Mohr-Coulomb, Parabolic Leon, Cam-Clay, SaniSand (Dafalias-Manzari), SaniClay, Pisanò...)
- All elastic-plastic models can be used as perfectly plastic, isotropic hardening/softening and kinematic hardening models

ESSI Program: Seismic Input

- Analytic input of seismic motions
  - Body waves (P, SH, SV)
  - Surface waves (Rayleigh, Love, etc.)
  - Analytic radiation damping
- Domain Reduction Method (Bielak et al.)
- Synthetic and realistic seismic motions (Hisada, fk, FEM, etc.)

ESSI Program: Verification and Validation

- Detailed Verification (math issue)
  - Finite elements
  - Material model
  - Solution algorithms
  - Analysis procedure
  - Code documented in detail in ESSI Notes.
- (Not so) Detailed Validation (physics issue) (lack of high quality experimental data)
- Detailed V&V documentation in ESSI Notes

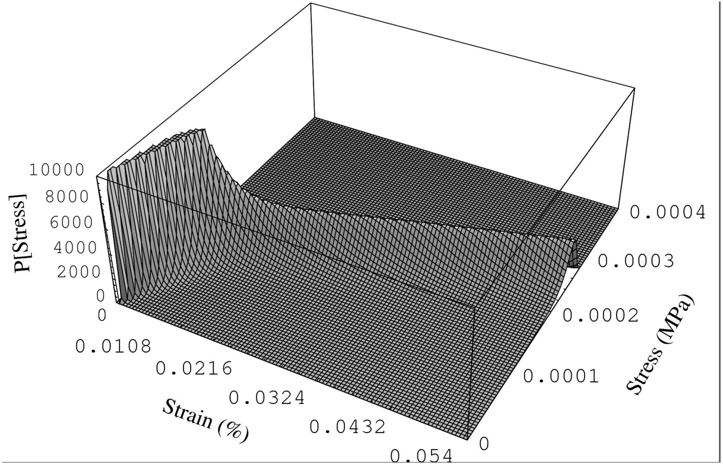
ESSI Program: High Performance Computing, Parallel

- Sequential computing: available for all models, however
- High Performance Parallel Computing: for high fidelity modeling, parallel is really the only option. Parallel ESSI Program available on
  - Single, multi-core/multi-CPU PCs,
  - Clusters of (multi-core/multi-CPU) PCs,
  - Distributed memory parallel (DMP) supercomputers (all top national supercomputers).
- Template metaprograms for local, element and material model level high performance computing

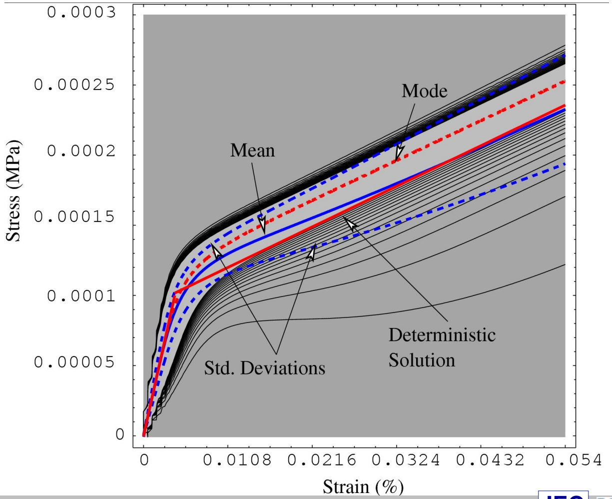
ESSI Program: Probabilistic/Stochastic

- Constitutive: Fokker-Planck-Kolmogorov equation for probabilistic elasto-plasticity (PEP)
- Spatial: stochastic elastic plastic finite element method (SEPFEM)
- Uncertain: material (LHS) and loads (RHS):
  $M_{AacB} \; \ddot{\bar{u}}_{Bc} + C_{AacB} \; \dot{\bar{u}}_{Bc} + K^{EP}_{AacB} \; \bar{u}_{Bc} = F_{Aa}$
- Results $(u_i, \sigma_{ij}, \epsilon ij)$ are very accurate (second order accurate for stress) Probability Density Functions (PDFs)
- PEP and SEPFEM are **not** based on a Monte Carlo method,
- Uncertain input variables and uncertain DOFs are expanded into spectral probabilistic spaces, single run solution

Probabilistic Elastic-Plastic Response



Probabilistic Elastic-Plastic Response



Outline

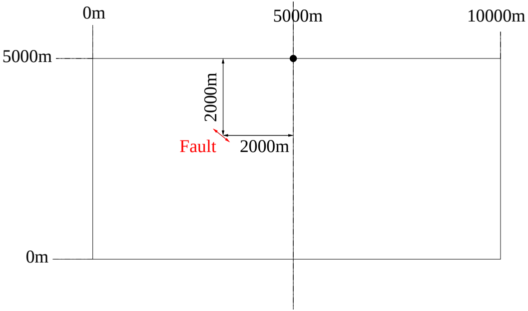
Earthquake Ground Motions

Realistic earthquake ground motions

- Body waves: P and S waves
- Inclined waves
- 3D (6D!) waves
- Surface waves: Rayleigh, Love waves, etc.
- Surface waves carry most seismic energy of interest
- Lack of correlation (incoherence)

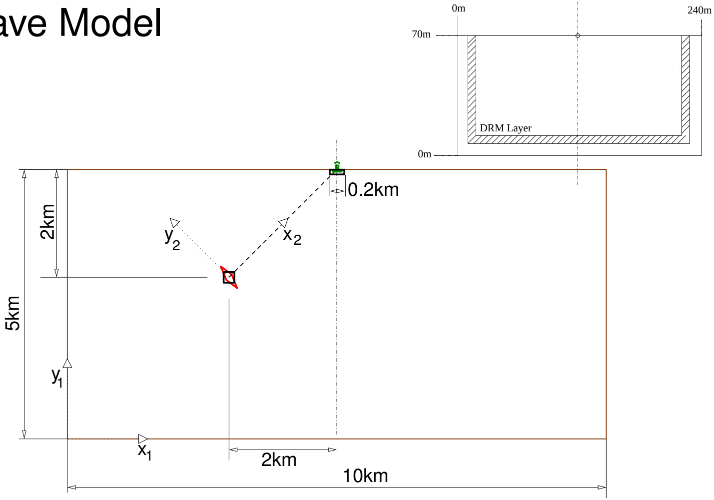
3D Synthetic Seismic Motions

- Development of analytic and numerical 3D, inclined, uncorrelated seismic motions for verification, stress testing of NPPs, etc.
- Large scale model
- Point shear source
- Stress drop:
  - Wavelet (Ricker, Ormsby, etc)
  - Analytic



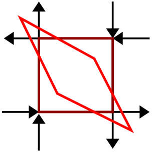
- Seismic input using DRM (Bielak et al (2003))

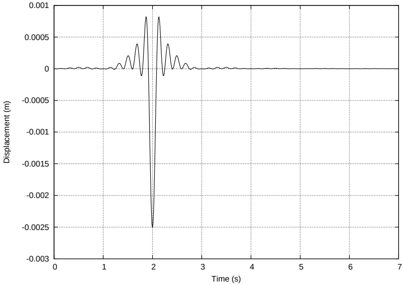
Plane Wave Model

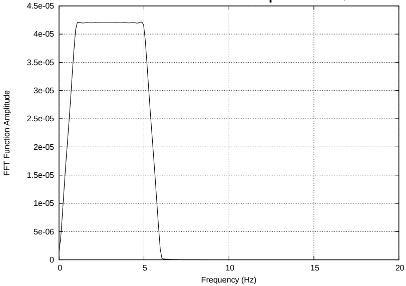


Seismic Source Mechanics

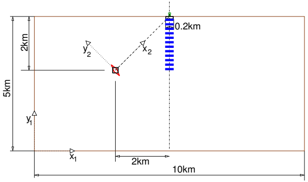
Stress drop, Ormsby wavelet
controlled frequency range

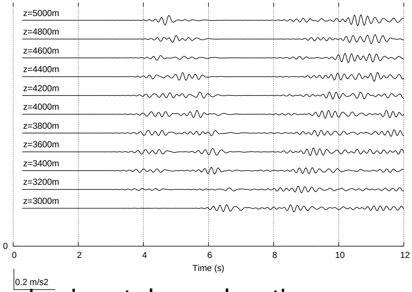




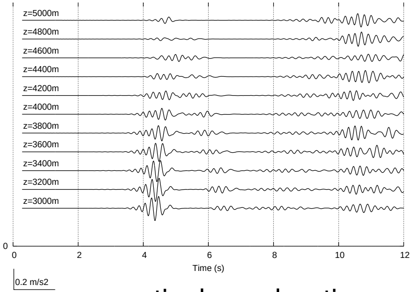


Middle (NPP Location) Plane, Top 2km





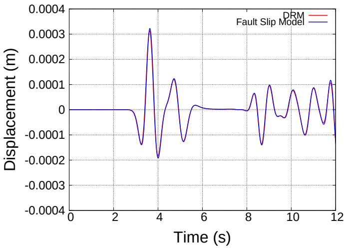
horizontal accelerations



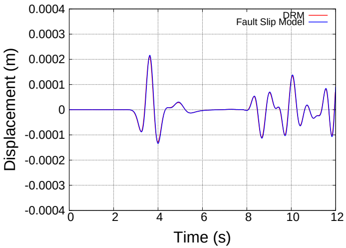
vertical accelerations

Verification: Displacements, Top Middle Point

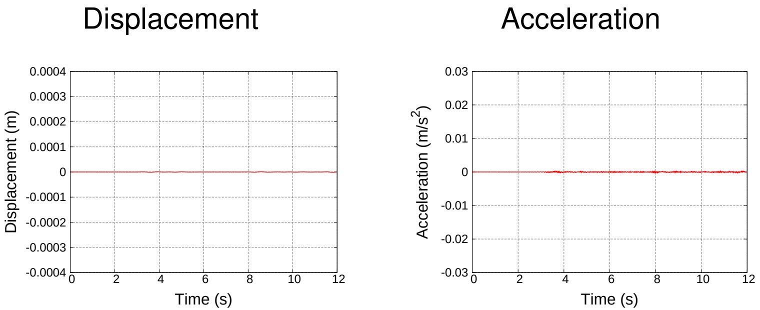
(X)



(Z)



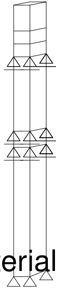
Verification: Disp. and Acc., Out of DRM



Outline

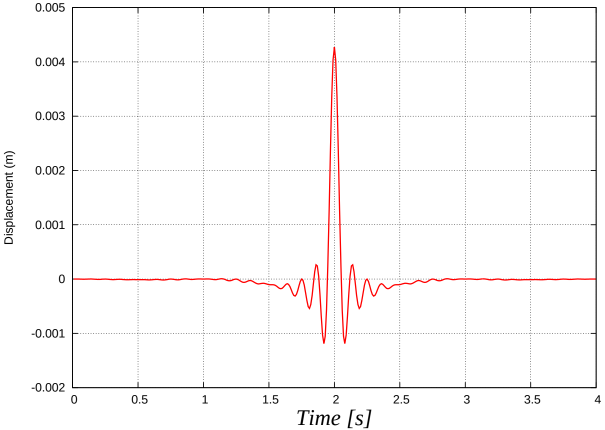
Motion Filtering: Mesh Size Effects

- Finite element mesh "filters out" high frequencies
- Usual rule of thumb: 10-12 elements needed per wave length
- 1D wave propagation model
- 3D finite elements (same in 3D)
- Motions applied as displacements at the bottom
- Linear elastic and elastic – linear hardening plastic material

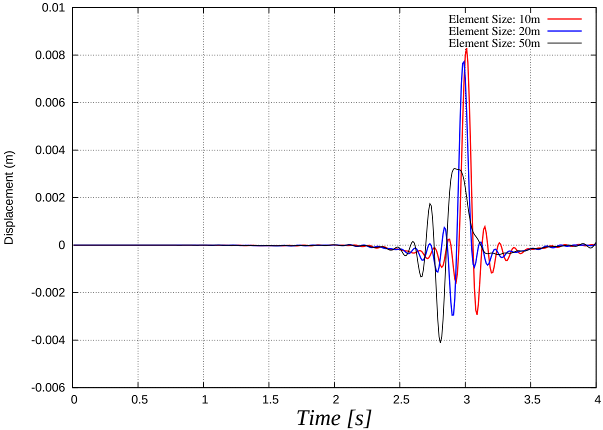


case	model height [m]	V_s [m/s]	El.size [m]	f_{max} (10el) [Hz]
3	1000	1000	10	10
4	1000	1000	20	5
6	1000	1000	50	2

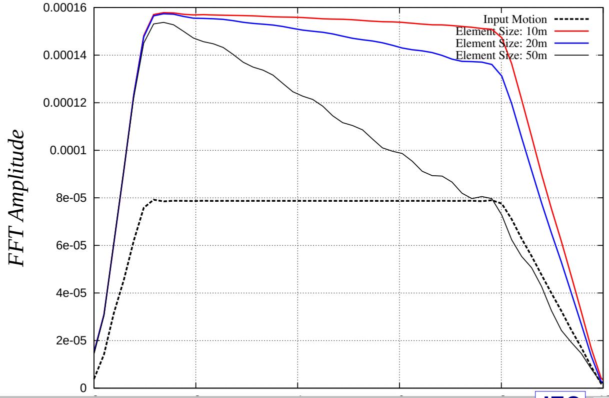
Ormsby Wavelet Input Motions



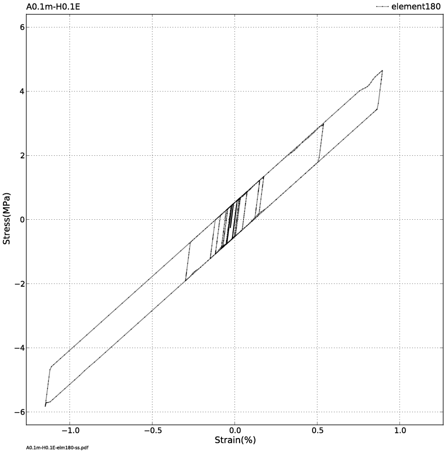
Linear Elastic Material: Surface Motions



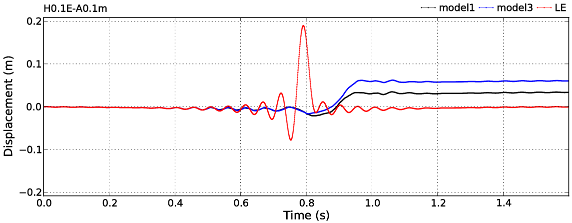
Linear Elastic Material, FFT of Input and Surface Motions



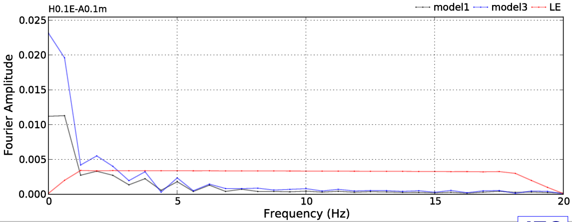
Elastic Plastic Material, Stress-Strain Response



Elastic Plastic Material, Surface Response

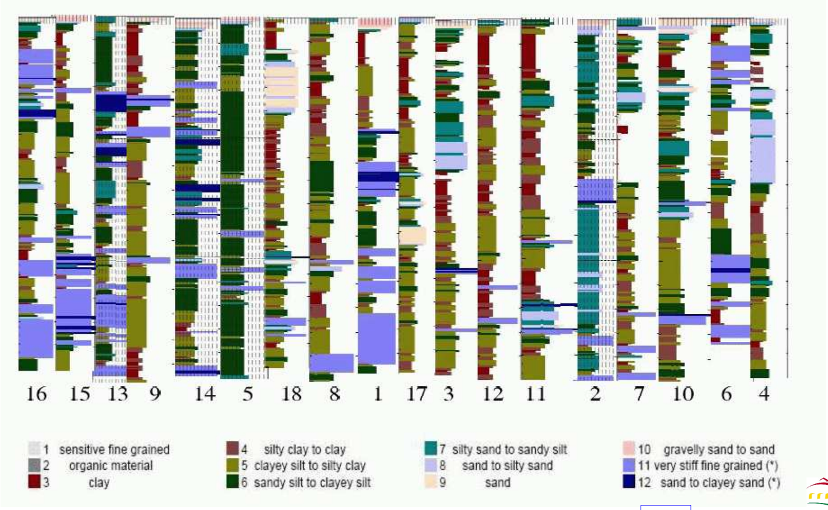


H0.1E-A0.1m-disp.pdf



Outline

"Uniform" CPT Site Data



Random Field Parameters from Site Data

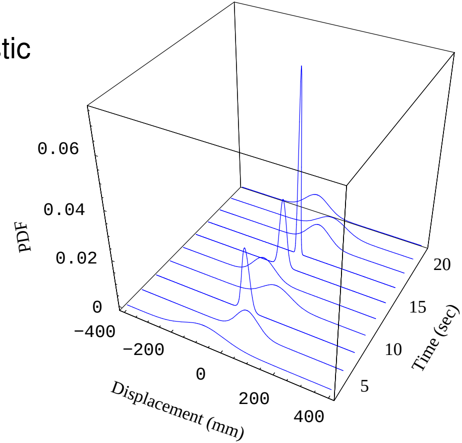
- Soil as 12.5 m deep 1–D soil column (von Mises Material)
  - Properties (including testing uncertainty) obtained through random field modeling of CPT q_T
    $\langle q_T \rangle = 4.99\ MPa$; $Var[q_T] = 25.67\ MPa^2$;
    Cor. Length $[q_T] = 0.61\ m$; Testing Error $= 2.78\ MPa^2$
- q_T was transformed 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

Decision About Site (Material) Characterization

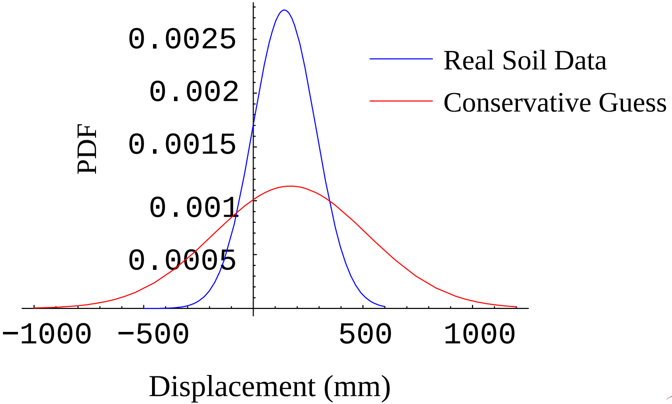
- Do nothing about site characterization (rely on experience): conservative **guess** of soil data, $COV = 225\%$, correlation length $= 12$m.
- Do better than standard site characterization: $COV = 103\%$, correlation length $= 0.61$m)
- Improve site (material) characterization if probabilities of exceedance are unacceptable!

Full PDFs of all DOFs (and σ_{ij}, ϵ_{ij}, etc.)

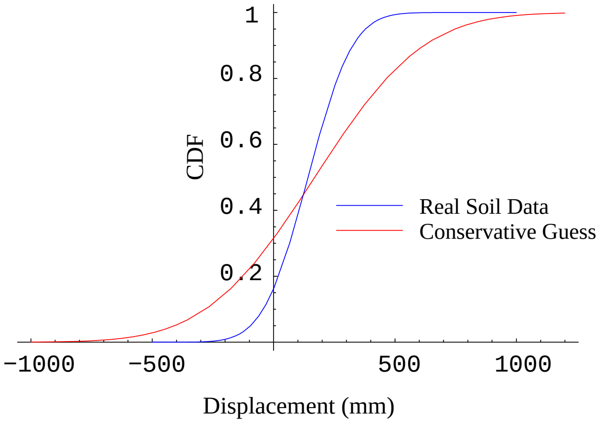
- Stochastic Elastic-Plastic Finite Element Method (SEPFEM)
- Dynamic case
- Full PDF at each time step Δt



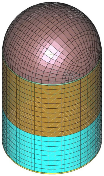
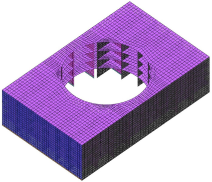
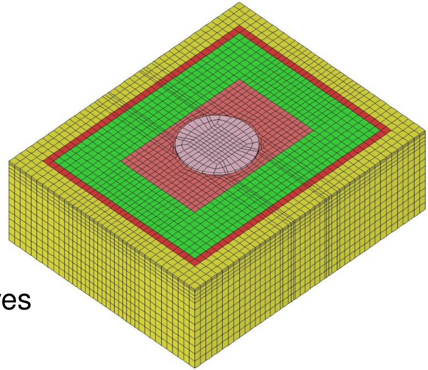
PDF at each Δt (say at 6 s)



PDF → CDF (Fragility) at 6 s



Current NPP Model(s)

- General 3D seismic waves
- Foundation slip – gap
- Isolators, dissipators
- Uncorrelated (incoherent) motions
- Saturated dense vs loose soil with buoyant forces
- Piles and pile groups
- Uncertain material (LHS) and seismic motions (RHS)

Summary

- **Interplay** of **uncertain earthquake**, **uncertain soil**, and **uncertain structure**, in time domain, **probably** plays a decisive role in seismic performance of NPPs

- Improve **risk informed decision making** (**design** $\Rightarrow$ **safety** and **economy**) through **high fidelity**, modeling and simulation (**ESSI Simulator System**)

- **Education** and **training** of users (designers, regulators, owners) will prove essential

Acknowledgement

- Funding from and collaboration with the US-NRC, US-NSF, US-DOE, CNSC, LLNL, INL, AREVA NP GmbH, Shimizu Corp., and EDF is greatly appreciated,
- Collaborators, students: Mr. Abell, Mr. Jeong, Mr. Aldridge. Mr. Kamranimoghadam, Mr. Karapiperis, Mr. Watanabe, Mr. Chao, Dr. Tafazzoli, Dr. Pisanò, Dr. Martinelli, Dr. Preisig, Dr. Chang, Prof. Sett (U. Bufallo), Prof. Taiebat (U. British Columbia), Prof. Yang (U. Alaska)