On Earthquake Soil Structure Interaction Modeling and Simulation

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UCD Geotech. Seminar, May, 2013

Outline

Outline

The Problem

- Seismic response of Nuclear Power Plants
- 3D, inclined seismic motions consisting of body and surface waves
- Inelastic (elastic, damage, plastic behavior of materials: soil, rock, concrete, steel, rubber, etc.)
- Full coupling of pore fluids (in soil and rock) with soil/rock skeleton
- Buoyant effects (foundations below water table)
- Uncertainty in seismic sources, path, soil/rock response and structural response

Solution

- **Physics based modeling and simulation** of seismic behavior of soil-structure systems (NPP structures, components and systems)
- Development and use of **high fidelity** time domain, nonlinear numerical models, in **deterministic** and **probabilistic** spaces
- Accurate following of the **flow of seismic energy** (input and dissipation) within soil-structure NPP system
- **Directing**, in space and time, with **high (known) confidence**, seismic energy flow in the soil-foundation-structure system

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)

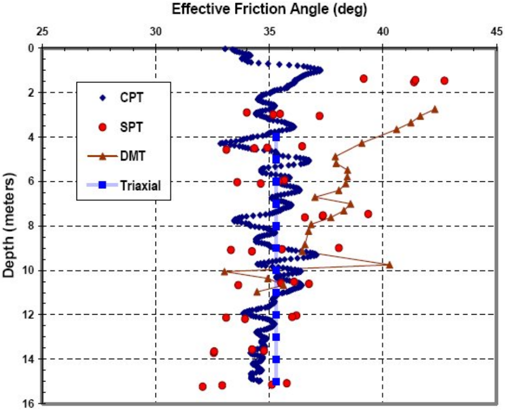
Complexity of and Uncertainty in Ground Motions

- 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))

Outline

Material Behavior Inherently Uncertain

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

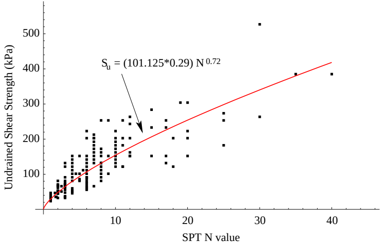


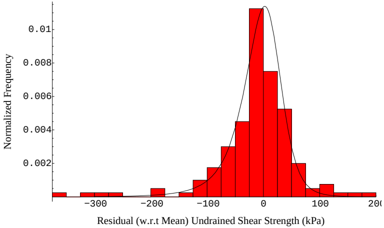
(Mayne et al. (2000)

Soil Uncertainties and Quantification

- Natural variability of soil deposit (Fenton 1999)
  - Function of soil formation process
- Testing error (Stokoe et al. 2004)
  - Imperfection of instruments
  - Error in methods to register quantities
- Transformation error (Phoon and Kulhawy 1999)
  - Correlation by empirical data fitting (e.g. CPT data $\rightarrow$ friction angle etc.)

SPT Based Determination of Shear Strength

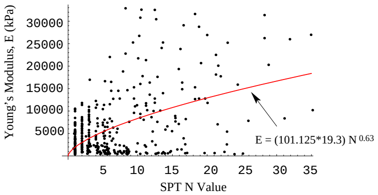


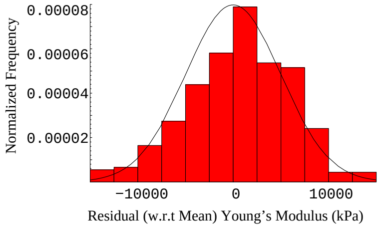


Transformation of SPT N-value → undrained shear strength, s_u (cf. Phoon and Kulhawy (1999B)

Histogram of the residual (w.r.t the deterministic transformation equation) undrained 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

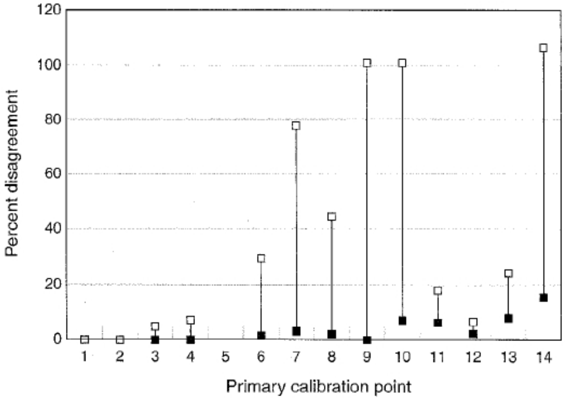
Errors in Scientific Software: The T Experiments

- Les Hatton, Kingston University (formerly of Oakwood Comp. Assoc.)
- "Extensive tests showed that many software codes widely used in science and engineering are not as accurate as we would like to think."
- "Better software engineering practices would help solve this problem,"
- "Realizing that the problem exists is an important first step."
- Large experiment over 4 years measuring faults (T1) and failures (T2) of scientific and engineering codes

The T2 Experiments

- Specific application area: seismic data processing (inverse analysis)
- Echo sounding of underground and reconstructing "images" of subsurface geological structure
- Nine mature packages, using **same algorithms**, on a **same data set**!
- 14 primary calibration points for results check
- Results "fascinating and disturbing"

T2: Disagreement at Calibration Points



Outline

ESSI Simulator System

- **The 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 NPPs on ESSI-Computer.
- **The ESSI-Computer** is a distributed memory parallel computer, a cluster of clusters with multiple performance processors and multiple performance networks.
- **The ESSI-Notes** represent a hypertext documentation system detailing modeling and simulation of NPP ESSI problems.

ESSI Simulator Program

- Based on a Collection of Useful Libraries (modular, portable)
- Library centric software design
- Various public domain licenses (GPL, LGPL, BSD, CC)
- Verification (extensive) and Validation (not much)
- Program documentation (part of ESSI Notes)
- Target users: US-NRC staff, CNSC staff, IAEA, LBNL, INL, DOE, professional practice collaborators, expert users

Collection of Useful Libraries (Modeling Part)

- Template3D-EP libraries for elastic and elastic-plastic computations (UCD, CC)
- FEMTools finite element libraries provide finite elements (solids, beams, shells, contacts/isolators, seismic input) (UCD, UCB, CU, CC)
- Loading, staged, self weight, service loads, seismic loads (the Domain Reduction Method, analytic input (incoming/outgoing) of 3D, inclined, un-correlated seismic motions) (UCD, CC)
- Domain Specific Language for input (UCD, CC)

Collection of Useful Libraries (Simulation Part)

- Plastic Domain Decomposition (PDD) for parallel computing (UCD, CC)
- PETSc (ANL, GPL-like) and UMFPACK (UF, GPL) solvers
- Modified OpenSees Services (MOSS) for managing the finite element domain (UCD, CC; UCB, GPL?)
- nDarray (UCD, CC), LTensor (CIMEC, GPL), BLAS (UTK, GPL) for lower level computational tasks,
- Message Passing Interface (MPI, openMPI, new BSD license)

ESSI Simulator Computer

A distributed memory parallel (DMP) computer designed for high performance, parallel finite element simulations

- Multiple performance CPUs and Networks
- Most cost-performance effective
- Source compatibility with any DMP supercomputers
- Current systems: 208CPUs, and 48CPUs (+64) and 96CPUs (8x5+2x16+24)...

ESSI Computer Version April 2012

Operating System: Ubuntu

Kernel: 3.2

Controller: 1 node + **Compute:** 8 Nodes

- CPU: 2 x 12 cores Opteron 6234 = 24 cores
- RAM: 32GB (8 x 4GB)
- NICs:
  - GigaBit: Intel 82576 (Controller)
  - InfiniBand: ConnectX-2 QDR IB 40Gb/s (Controller+Compute)
- Disk: 8 $\times$ 2TB Toshiba MK2002TSKB (Controller)
- Disk: 1TB Toshiba MK1002TSKB (Compute)

Network (dual):

- GigaBit: HP ProCurve Switch 1810-48G 48 Port
- InfiniBand:: Mellanox MIS5030Q-1SFCA 36-port QDR

ESSI Simulator Notes

- A hypertext documentation system describing in detail modeling and simulations of NPP ESSI problems
  - Theoretical and Computational Formulations (FEM, EL-PL, Static and Dynamic solution, Parallel Computing)
  - Software and Hardware Platform Design (OO Design, Library centric design, API, DSL, Software Build Process, Hardware Platform)
  - Verification and Validation (code V, Components V, Static and Dynamic V, Wave Propagation V)
  - Application to Practical Nuclear Power Plant Earthquake Soil/Rock Structure Interaction Problems (ESSI with 3D, inclined, uncorrelated seismic waves, ESSI with foundation slip, Isolators)

Outline

High Fidelity Modeling

- Seismic energy influx, body and surface waves, 3D, inclined
- Mechanical dissipation outside of SSI domain:
  - Radiation of reflected waves
  - Radiation of oscillating SSI system
- Mechanical dissipation inside SSI domain:
  - Plasticity of soil/rock subdomain
  - Viscous coupling of porous solid with pore fluid (air, water)
  - Plasticity and viscosity of foundation – soil/rock contact
  - Plasticity/damage of the structure
  - Viscous coupling of structure/foundation with fluids
- Numerical energy dissipation/production

High Performance, Parallel Computing

- The ESSI Program can be used in both sequential and parallel modes
- For high fidelity models, parallel is really the only option
- High performance, parallel computing using Plastic Domain Decomposition Method
- Developed for multiple/variable capability CPUs and networks (DMP and SMPs)

Finite Elements

- Linear and nonlinear truss element
- Linear and nonlinear beam (disp. based), variable BC el.
- Linear shell Triangle and Quad with drilling DOFs
- Single phase solid bricks (8, 20, 27, 8-20, 8-27 nodes)
- Two phase (fully coupled, porous solid, pore fluid) solid bricks (8 and 20 node: $u-p-U$, $u-p$)
- Dry friction slip and gap element
- Saturated gap and slip element
- Seismic isolator (latex rubber, neoprene rubber, rubber with lead core, friction pendulum)

Material Models for Solids and Structures

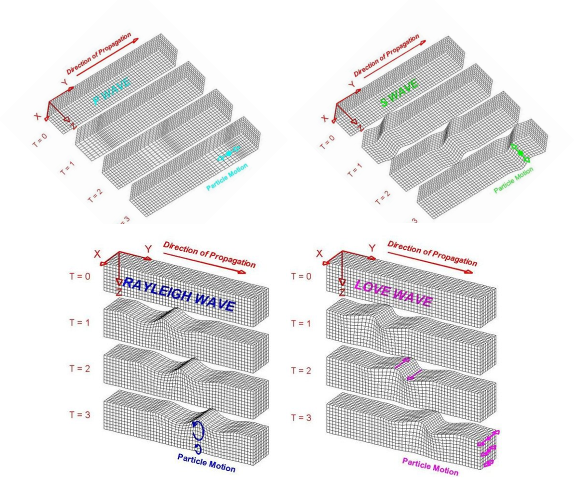
- Small deformation elastic: linear, nonlinear isotropic, cross anisotropic
- Small deformation elastic-Plastic: von Mises, Drucker–Prager, Cam–Clay, Rounded Mohr–Coulomb, Parabolic Leon, SaniSand2004, SaniSand2008, SaniClay, Pisanò; Gens normal contact and Coulomb shear contact model; 1D concrete and steel models
- Large deformation elastic and elastic-plastic: Ogden, neo-Hookean, Mooney-Rivlin, Logarithmic, Simo-Pister, von Mises, Drucker-Prager

Earthquake Ground Motions

Realistic earthquake ground motions

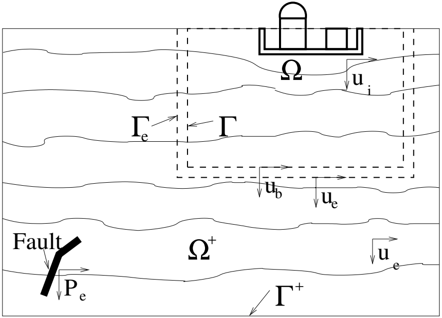
- Body: P and S waves
- Surface: Rayleigh, Love waves, etc.
- Lack of correlation (incoherence)
- Inclined waves
- 3D waves

Body (P, S) and Surface (Rayleigh, Love) Waves



DRM

- Seismic forces P_e replaced by P^{eff}
- P^{eff} applied only to a single layer of elements next to Γ.
- The only outgoing waves are from dynamics of the NPP
- Material inside Ω can be elastic-plastic
- All types of seismic waves (body, surface...) are properly modeled

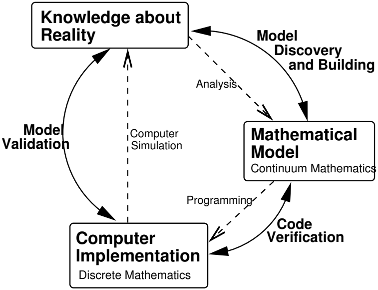


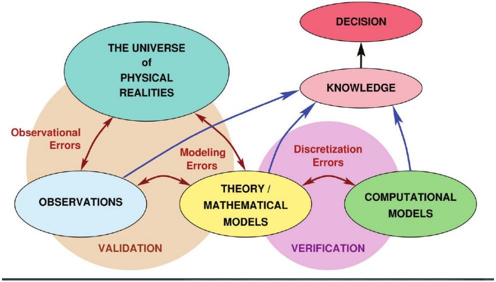
Outline

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 a physical system under consideration under conditions for which the computational model has not been validated

Role of Verification and Validation





Oberkampf et al. Oden et al.

Importance of V&V

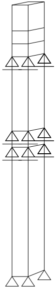
- V & V procedures are the primary means of assessing accuracy in modeling and computational simulations
- V & V procedures are the tools with which we build confidence and credibility in modeling and computational simulations

V & V for ESSI Modeling and Simulations

- Material modeling and simulation (elastic, elastic-plastic...)
- Finite elements (solids, structural, special...)
- Solution advancement algorithms (static, dynamic...)
- Seismic input and radiation
- Finite element model verification

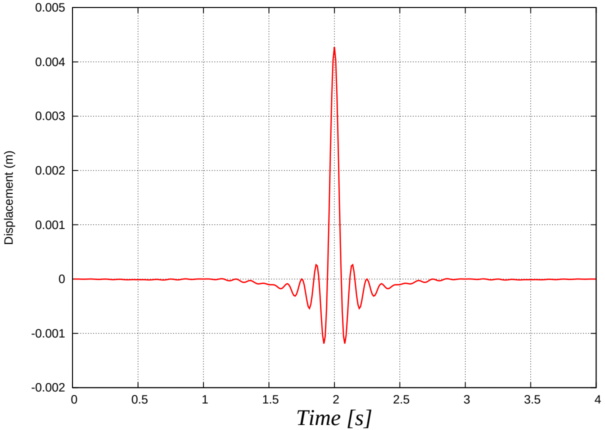
Mesh Size Effects on Seismic Wave Propagation Modeling

- 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

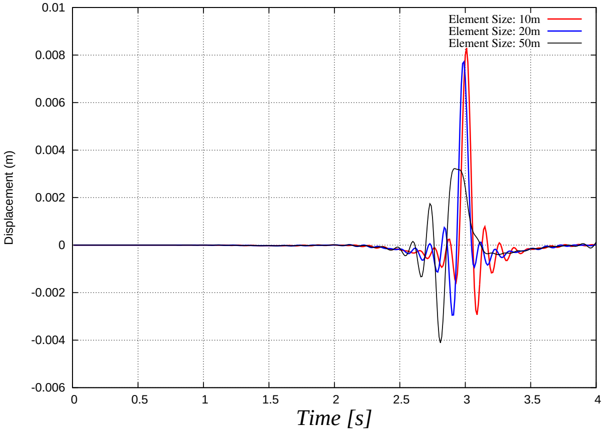


case	model height [m]	V_s [m/s]	El.size [m]	f_{max} (10el) [Hz]
3	1000	1000	10	10
4	1000	1000	20	5
6	1000	1000	50	2

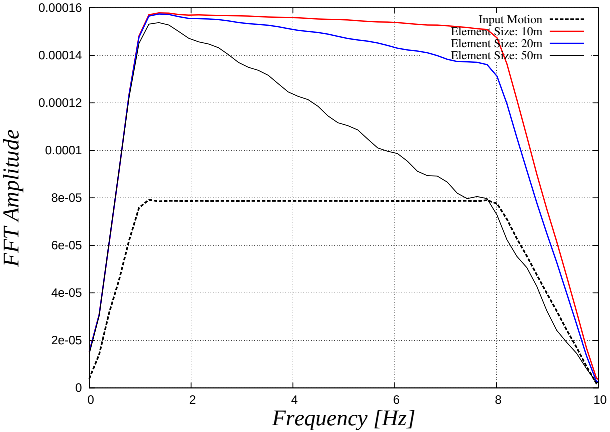
Cases 3, 4, and 6, Ormsby Wavelet Input Motions



Cases 3, 4, and 6, Surface Motions



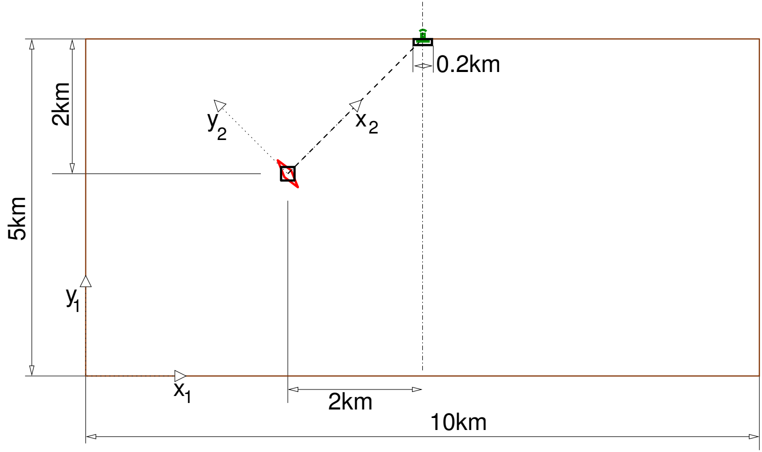
Cases 3, 4, and 6, Input and Surface Motions, FFT



Seismic Body and Surface Waves

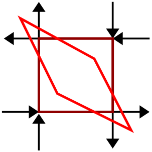
- Both body (P, SV and SH) and surface (Rayleigh, Love, etc.) waves are present
- Surface waves carry most seismic energy
- Analytic (Aki and Richards, Trifunac and Lee, Hisada et al., fk, etc.) and numerically generated, 3D, inclined (plane) body and surface waves are used in tests
- Seismic moment from a point source at 2km depth used
- Stress drop at the source: Ricker and/or Ormsby wavelets

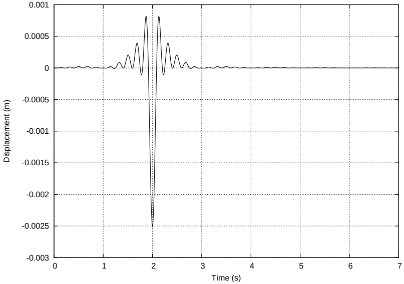
Plane Wave Model

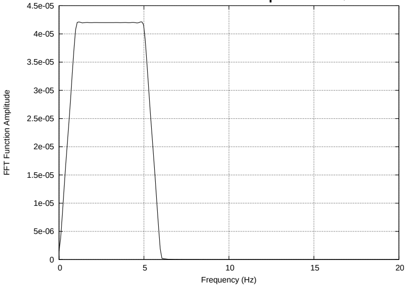


Seismic Source Mechanics

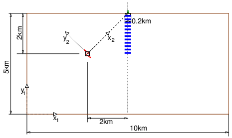
Stress drop, Ormsby wavelet

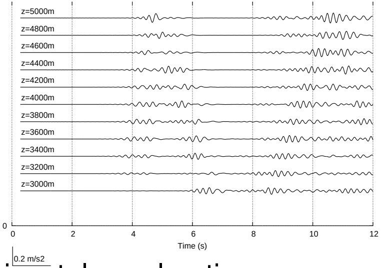




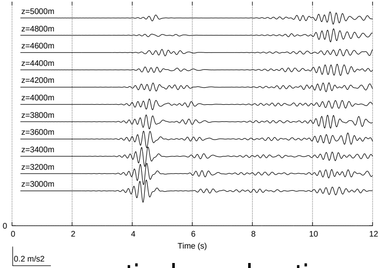


Middle (Structure Location) Plane, Top 2km



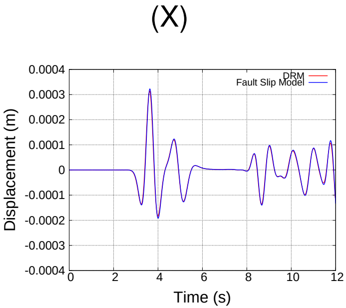


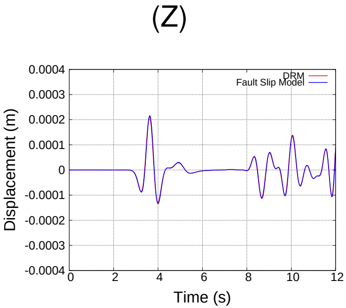
horizontal accelerations



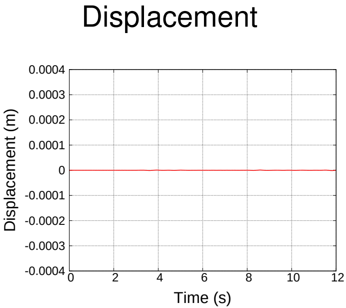
vertical accelerations

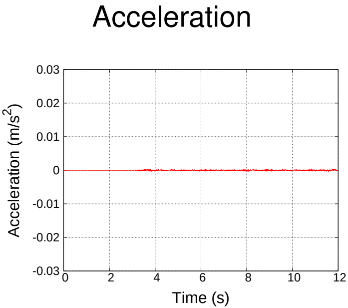
Verification: Displacements, Top Middle Point





Verification: Disp. and Acc., Out of DRM





Outline

Uncertainty Propagation through Constitutive Eq.

- Incremental el–pl constitutive equation $\Delta\sigma_{ij} = D_{ijkl}\Delta\epsilon_{kl}$

$$D_{ijkl} = \begin{cases} D^{el}_{ijkl} & \text{for elastic} \\ D^{el}_{ijkl} - \dfrac{D^{el}_{ijmn} m_{mn} n_{pq} D^{el}_{pqkl}}{n_{rs} D^{el}_{rstu} m_{tu} - \xi_* r_*} & \text{for elastic–plastic} \end{cases}$$

- What if all (any) material parameters are uncertain
- PEP and SEPFEM methods for spatially variable and point uncertain material

Probabilistic Stress Solution: Eulerian–Lagrangian form of FPK Equation

$$
\begin{aligned}
\frac{\partial P(\sigma_{ij}(x_t,t),t)}{\partial t} = \frac{\partial}{\partial \sigma_{mn}} \Bigg[\Bigg\{ \Big\langle \eta_{mn}(\sigma_{mn}(x_t,t), E_{mnrs}(x_t), \epsilon_{rs}(x_t,t)) \Big\rangle \\
+ \quad \int_0^t d\tau Cov_0 \left[\frac{\partial \eta_{mn}(\sigma_{mn}(x_t,t), E_{mnrs}(x_t), \epsilon_{rs}(x_t,t))}{\partial \sigma_{ab}} ; \right. \\
\left. \eta_{ab}(\sigma_{ab}(x_{t-\tau}, t-\tau), E_{abcd}(x_{t-\tau}), \epsilon_{cd}(x_{t-\tau}, t-\tau) \right] \Bigg\} P(\sigma_{ij}(x_t,t),t) \Bigg] \\
+ \quad \frac{\partial^2}{\partial \sigma_{mn} \partial \sigma_{ab}} \Bigg[\Bigg\{ \int_0^t d\tau Cov_0 \Big[\eta_{mn}(\sigma_{mn}(x_t,t), E_{mnrs}(x_t), \epsilon_{rs}(x_t,t)); \\
\eta_{ab}(\sigma_{ab}(x_{t-\tau}, t-\tau), E_{abcd}(x_{t-\tau}), \epsilon_{cd}(x_{t-\tau}, t-\tau)) \Big] \Bigg\} P(\sigma_{ij}(x_t,t),t) \Bigg]
\end{aligned}
$$

Eulerian–Lagrangian FPK Equation and (SEP)FEM

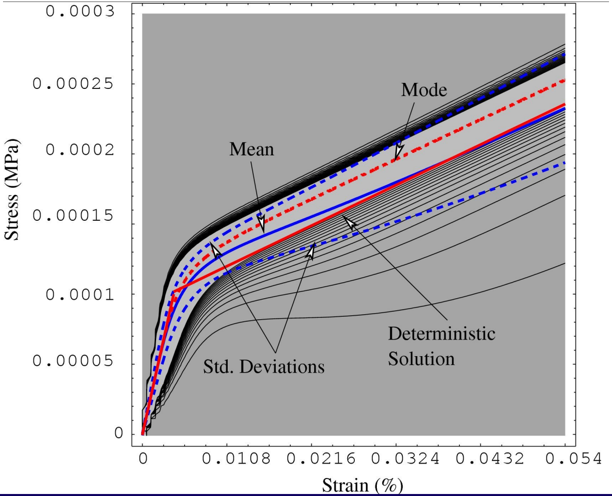
- Advection-diffusion equation

$$\frac{\partial P(\sigma_{ij},t)}{\partial t} = -\frac{\partial}{\partial \sigma_{ab}} \left[N_{ab}^{(1)} P(\sigma_{ij},t) - \frac{\partial}{\partial \sigma_{cd}} \left\{ N_{abcd}^{(2)} P(\sigma_{ij},t) \right\} \right]$$

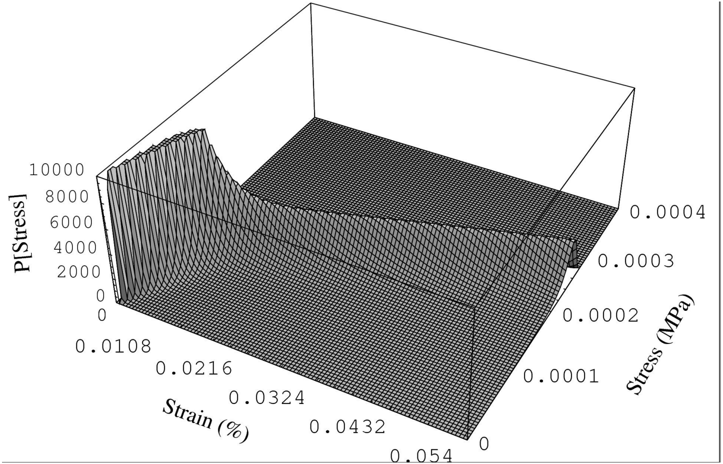
- **Complete** probabilistic description of response
- **Second-order exact** to covariance of time (exact mean and variance)
- Any uncertain FEM problem ($\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{F}$) with
  - uncertain material parameters (stiffness matrix **K**),
  - uncertain loading (load vector **F**)

  can be analyzed using PEP and SEPFEM to obtain PDFs of DOFs, stress, strain...

Probabilistic Elastic-Plastic Response



Probabilistic Elastic-Plastic Response



Spectral Stochastic Elastic–Plastic FEM

- Minimizing norm of error of finite representation using Galerkin technique (Ghanem and Spanos 2003):

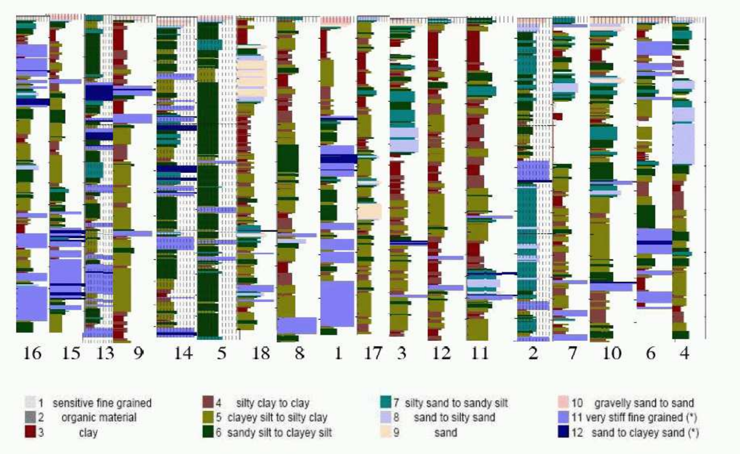
$$\sum_{n=1}^{N} K_{mn}^{ep} d_{ni} + \sum_{n=1}^{N} \sum_{j=0}^{P} d_{nj} \sum_{k=1}^{M} C_{ijk} K_{mnk}^{\prime ep} = \langle F_m \psi_i[\{\xi_r\}] \rangle$$

$$K_{mn}^{ep} = \int_D B_n E^{ep} B_m dV \qquad K_{mnk}^{\prime ep} = \int_D B_n \sqrt{\lambda}_k h_k B_m dV$$

$$C_{ijk} = \langle \xi_k(\theta) \psi_i[\{\xi_r\}] \psi_j[\{\xi_r\}] \rangle \qquad F_m = \int_D \phi N_m dV$$

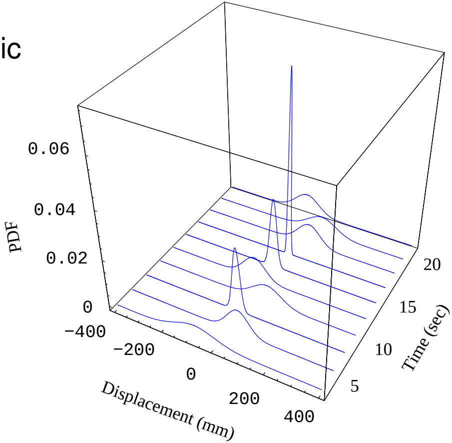
Outline

"Uniform" CPT Site Data

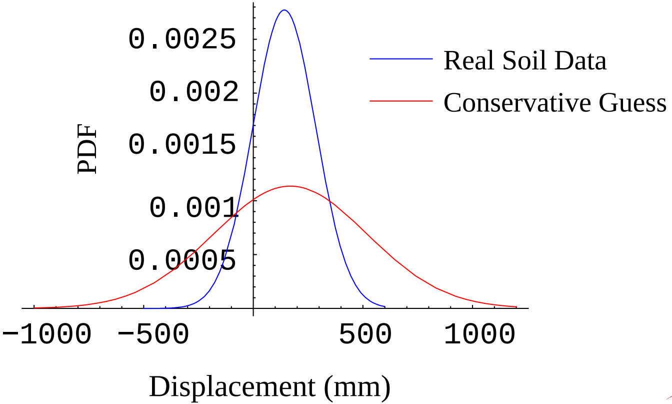


Full PDFs of all DOFs (and σ_{ij}, ϵ_{ij}, etc.)

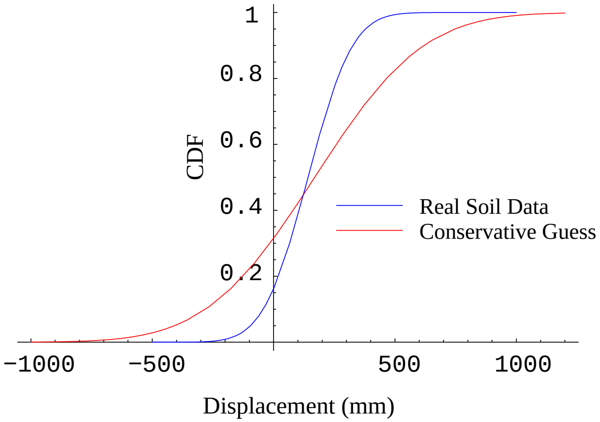
- Stochastic Elastic-Plastic Finite Element Method (SEPFEM)
- Dynamic case
- Full PDF at each time step Δt



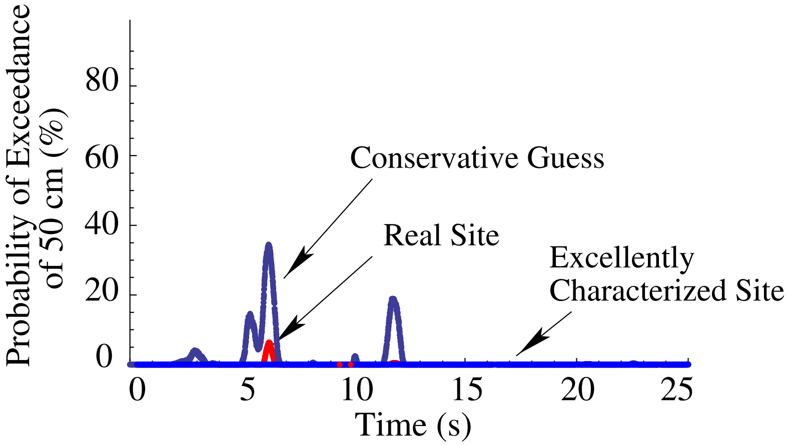
PDF at each Δt (say at 6 s)



PDF $\rightarrow$ CDF (Fragility) at 6 s



Probability of Unacceptable Deformation (50cm)



Summary

- High fidelity, time domain, nonlinear, earthquake soil structure interaction (ESSI) modeling and simulations (deterministic and probabilistic)
- The ESSI Simulator System (Program, Computer, Lecture Notes)
- Educational effort is essential (US-NRC, CNSC, IAEA, UCD, LBNL, INL, companies), seminars, short courses
- Funding from the US-NRC, DOE, NSF, and CNSC is much appreciated