Aspects of Deterministic and Probabilistic Modeling and Simulation in Earthquake Engineering

Boris Jeremić
with Dr. Tafazzoli, Mr. Abell, Mr. Jeong, Dr. Pisanò, Prof. Sett (UA), Prof. Taiebat (UBC), Prof. Yang (UAA), Dr. Cheng (Itasca)

University of California, Davis
Lawrence Berkeley National Laboratory, Berkeley

LBNL Seminar, December 2012

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

NRC ESSI Simulator System

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

NRC 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 and Validation
- Detailed program documentation (part of NRC ESSI Notes)
- Target users: U.S.-NRC staff, UCD students, external 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)

NRC 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 system: 208 CPUs
- Near future: 784 CPUs

NRC ESSI Simulator Version December 2010

- Operating System: Linux Fedora Core 14.
- Kernel: `2.6.35.10-74.fc14.x86_64`
- Compute Nodes (two):
  - CPU: 2 $\times$ Intel Xeon E5620 Westmere 2.4 GHz Quad Core (8 threads)
  - RAM: 6 $\times$ 4GB DDR3 1333 MHz ECC/Registered Memory (24GB Total Memory)
  - Disk: 8 $\times$ 500 GB Seagate Constellation ES 3.5" SATA/300 (Linux Software RAID10)
- Network: single GigaBit

NRC ESSI Simulator 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

NRC 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

Introduction

Deterministic Modeling

Probabilistic Modeling

Summary

High Fidelity Modeling

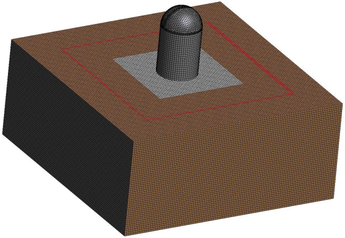
- Energy influx, body and surface waves, 3D, inclined
- Mechanical dissipation outside of SFS domain:
  - Radiation of reflected waves
  - Radiation of oscillating SFS system
- Mechanical dissipation inside SFS domain:
  - Plasticity of soil/rock subdomain
  - Viscous coupling of porous solid with pore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

High Performance, Parallel Computing

- The NRC ESSI Simulator 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)

Representative NPP Example Problem

- Body and surface seismic waves
- Seismic wave frequencies up to 50Hz
- Elastic-plastic soil/rock and structural components,
- Inelastic contact/gap
- Seismic isolator effects



- Buoyant effects for deep foundation embedment
- High Fidelity Model: soil block: $230m \times 230m \times 100m$, foundation $90m \times 90m$ Containment Structure: $40m \times 50m$, 2.1 Million DOFs, 700,000 elements,

Finite Elements

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

Material Models for Solids and Structures

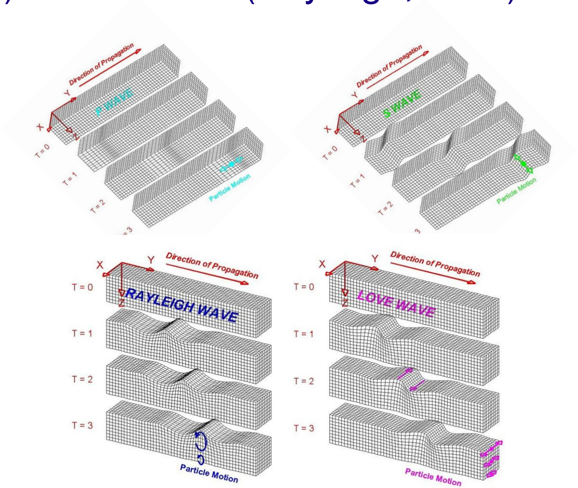
- Elastic: linear, nonlinear isotropic, cross anisotropic
- Elastic-Plastic: von Mises, Drucker–Prager, Cam–Clay, Rounded Mohr–Coulomb, Parabolic Leon, SANIsand (Dafalias–Manzari...), Pisanò-Jeremić.
- Isotropic and kinematic (translational and rotational) kinematic hardening

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

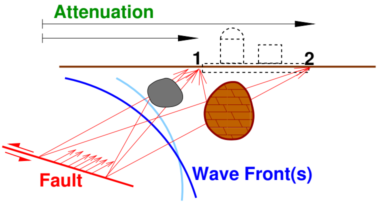


Spatial Variability (Incoherence, Lack of Correlation)

Incoherence $\rightarrow$ frequency domain

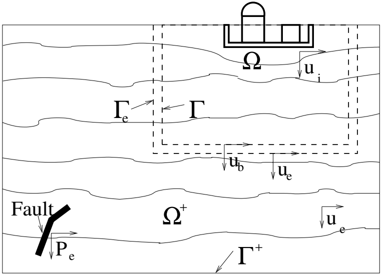
Lack of Correlation $\rightarrow$ time domain

- Attenuation effects
- Wave passage effects
- Extended source effects
- Scattering effects
- Variable seismic energy dissipation



Seismic Input

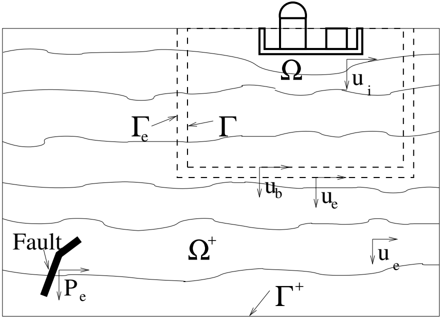
The Domain Reduction Method (Bielak et al.):
The effective force P^{eff}
is a dynamically consistent replacement for the dynamic source forces P_e



$$P^{eff} = \left\{ \begin{array}{c} P_i^{eff} \\ P_b^{eff} \\ P_e^{eff} \end{array} \right\} = \left\{ \begin{array}{c} 0 \\ -M_{be}^{\Omega+} \ddot{u}_e^0 - K_{be}^{\Omega+} u_e^0 \\ M_{eb}^{\Omega+} \ddot{u}_b^0 + K_{eb}^{\Omega+} u_b^0 \end{array} \right\}$$

DRM

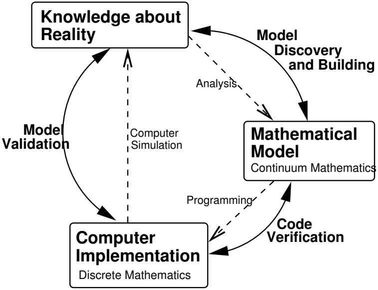
- Seismic forces P_e replaced by P^{eff}
- P^{eff} applied only to a single layer of elements next to Γ.
- The only outgoing waves are from dynamics of the NPP
- Material inside Ω can be elastic-plastic
- All types of seismic waves (body, surface...) are properly modeled

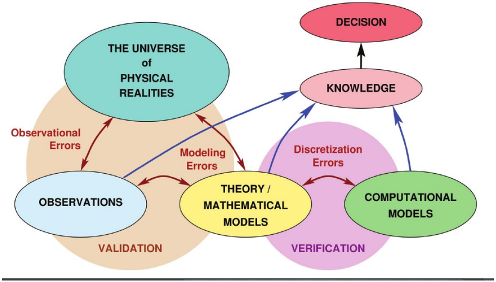


Verification, Validation and Prediction

- 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

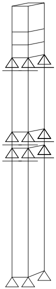
- V & V procedures are the primary means of assessing accuracy in modeling and computational simulations
- V & V procedures are the tools with which we build confidence and credibility in modeling and computational simulations

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

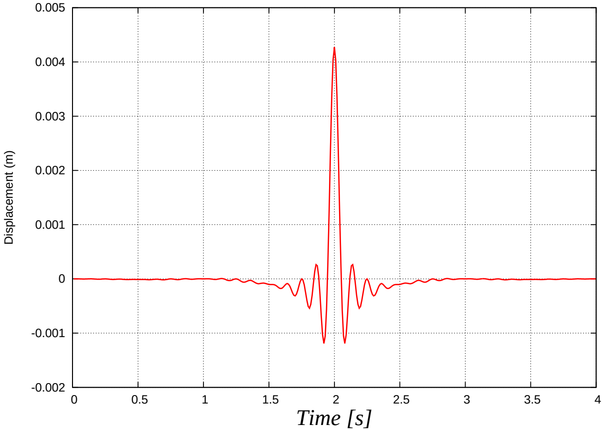
Mesh Size Effects on Seismic Wave Propagation Modeling

- 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

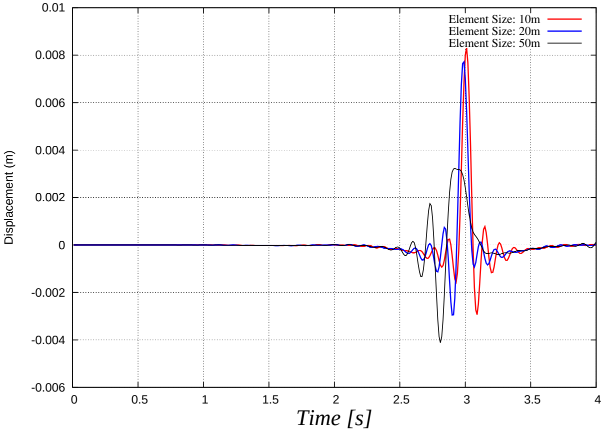


case	model height [m]	V_s [m/s]	El.size [m]	f_{max} (10el) [Hz]
3	1000	1000	10	10
4	1000	1000	20	5
6	1000	1000	50	2

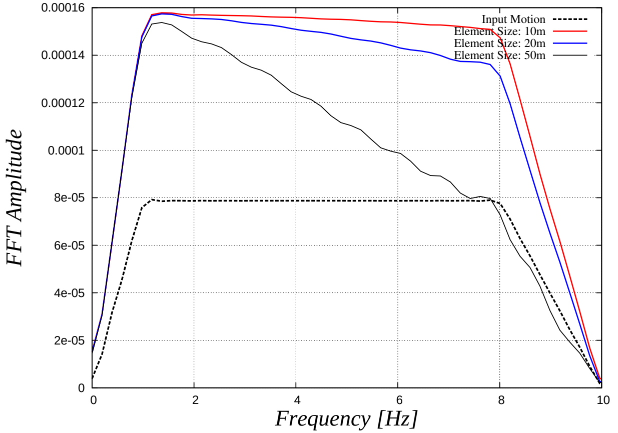
Cases 3, 4, and 6, Ormsby Wavelet Input Motions



Cases 3, 4, and 6, Surface Motions

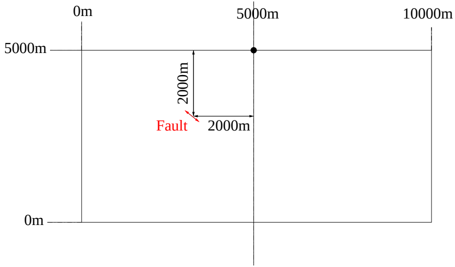


Cases 3, 4, and 6, Input and Surface Motions, FFT



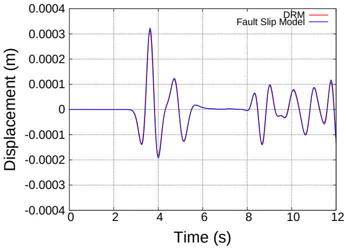
Free Field, Inclined, 3D Body and Surface Waves

- Development of analytic and numerical 3D, inclined, uncorrelated seismic motions for verification
- Large scale models
- Point shear source
- Stress drop:
  - Wavelet (Ricker, Ormsby, etc)
  - Analytic
- Seismic input using DRM

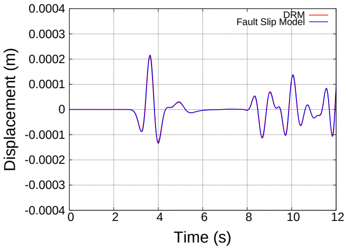


Verification: Displacements, Top Middle Point

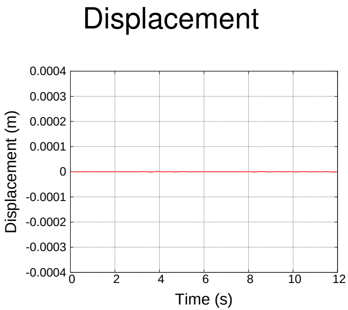
(X)

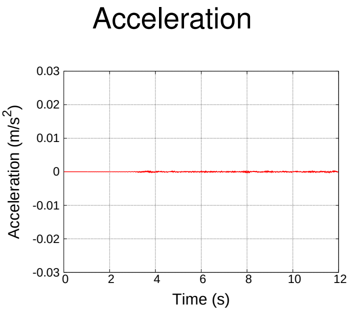


(Z)



Verification: Disp. and Acc., Out of DRM

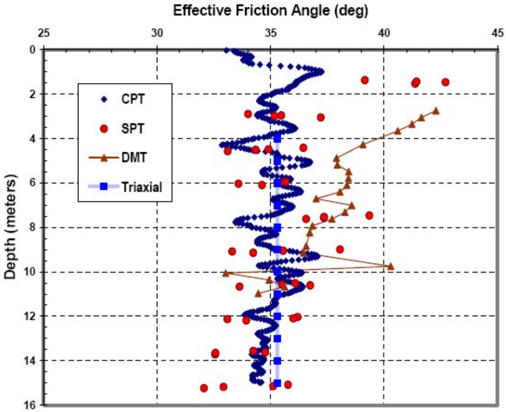




Outline

Material Behavior Inherently Uncertain

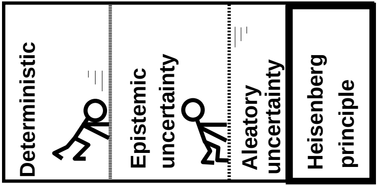
- Spatial variability
- Point-wise uncertainty, testing error, transformation error



(Mayne et al. (2000)

Types of Uncertainties

- Aleatory uncertainty - inherent variation of physical system
  - Can not be reduced
  - Has highly developed mathematical tools
- Epistemic uncertainty - due to lack of knowledge
  - Can be reduced by collecting more data
  - Mathematical tools are not well developed
  - trade-off with aleatory uncertainty



- Ergodicity (exchanging ensemble averages for time average) assumed to hold

Recent State-of-the-Art

- Governing equation
  - Dynamic problems $\rightarrow M\ddot{u} + C\dot{u} + Ku = F$
  - Static problems $\rightarrow Ku = F$
- Existing solution methods
  - **Random r.h.s** (external force random)
    - FPK equation approach
    - Use of fragility curves with deterministic FEM (DFEM)
  - **Random l.h.s** (material properties random)
    - Monte Carlo approach with DFEM $\rightarrow$ CPU expensive
    - Perturbation method $\rightarrow$ a linearized expansion! Error increases as a function of COV
    - Spectral method $\rightarrow$ developed for elastic materials so far
- Original development of **Probabilistic Elasto–Plasticity**

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

Solution to Probabilistic Elastic-Plastic Problem

- Use of stochastic continuity (Liouiville) equation (Kubo 1963)
- With cumulant expansion method (Kavvas and Karakas 1996)
- To obtain ensemble average form of Liouville Equation
- Which, with van Kampen's Lemma (van Kampen 1976): ensemble average of phase density is the probability density
- Yields Eulerian-Lagrangian form of the Forward Kolmogorov (Fokker-Planck-Kolmogorov) equation

Probabilistic Stress Solution: Eulerian–Lagrangian form of FPK Equation

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

Eulerian–Lagrangian FPK Equation and (SEP)FEM

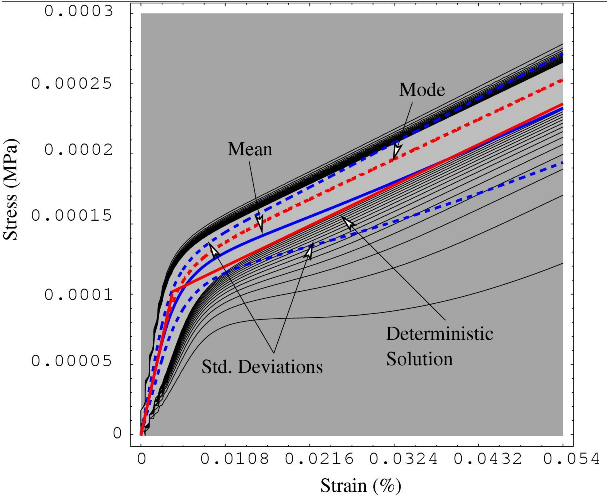
- Advection-diffusion equation

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

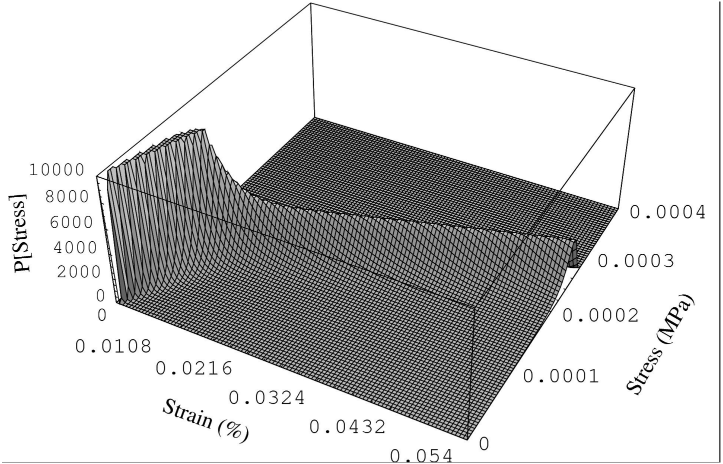
- **Complete** probabilistic description of response
- **Second-order exact** to covariance of time (exact mean and variance)
- Any uncertain FEM problem ($\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{F}$) with
  - uncertain material parameters (stiffness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

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

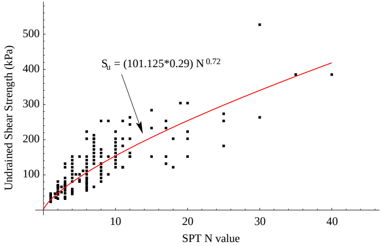
Probabilistic Elastic-Plastic Response

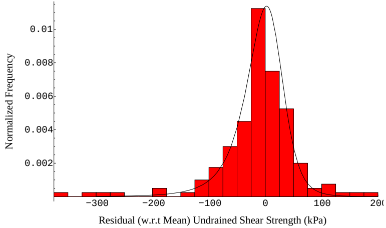


Probabilistic Elastic-Plastic Response



SPT Based Determination of Shear Strength

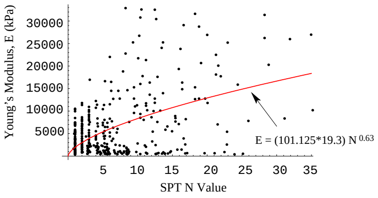


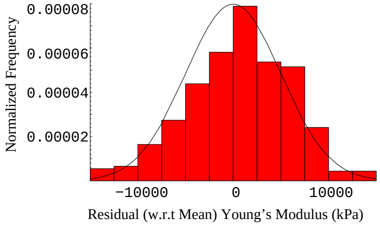


Transformation of SPT *N*-value $\rightarrow$ undrained shear strength, s_u (cf. Phoon and Kulhawy (1999B)

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

Stochastic Finite Element Formulation

- Governing equations:

$$A\sigma = \phi(t); \quad Bu = \epsilon; \quad \sigma = E\epsilon$$

- **Spatial** and **stochastic** discretization
  - Deterministic spatial differential operators (A & B) $\rightarrow$ Regular shape function method with Galerkin scheme
  - Input random field material properties (E) $\rightarrow$ Karhunen–Loève (KL) expansion, optimal expansion, error minimizing property
  - Unknown solution random field (u) $\rightarrow$ Polynomial Chaos (PC) expansion

Spectral Stochastic Elastic–Plastic FEM

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

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

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

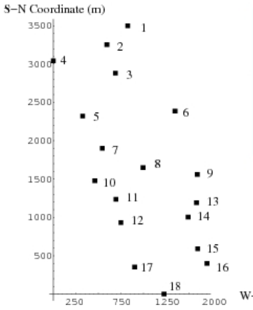
$$C_{ijk} = \left\langle \xi_k(\theta) \psi_i[\{\xi_r\}] \psi_j[\{\xi_r\}] \right\rangle \qquad F_m = \int_D \phi N_m dV$$

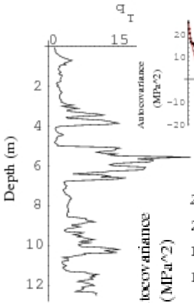
Inside SSEPFEM

- Explicit stochastic elastic–plastic finite element computations
- FPK probabilistic constitutive integration at Gauss integration points
- Increase in (stochastic) dimensions (KL and PC) of the problem
- Excellent for parallelization, both at the element and global levels
- Development of the probabilistic elastic–plastic stiffness tensor

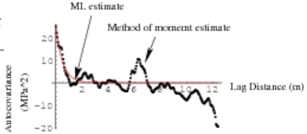
Seismic Wave Propagation through Stochastic Soil

- Maximum likelihood estimates

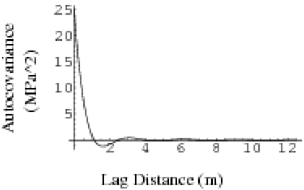




Typical CPT q_T

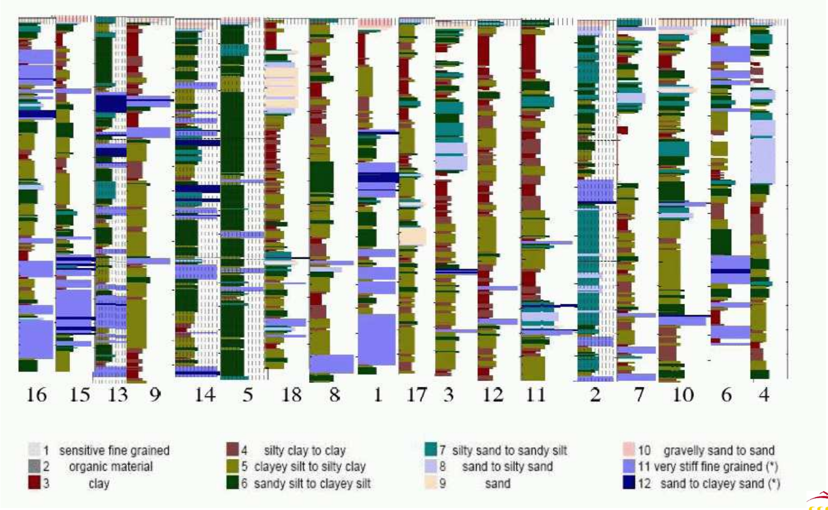


Finite Scale



Fractal

"Uniform" CPT Site Data



Random Field Parameters from Site Data

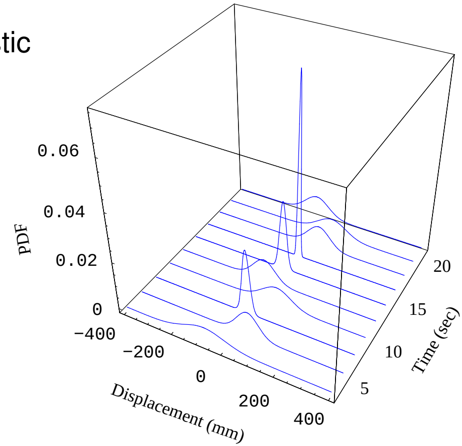
- Soil as 12.5 m deep 1–D soil column (von Mises Material)
  - Properties (including testing uncertainty) obtained through random field modeling of CPT q_T
    $\langle q_T \rangle = 4.99\ MPa$; $Var[q_T] = 25.67\ MPa^2$;
    Cor. Length $[q_T] = 0.61\ m$; Testing Error $= 2.78\ MPa^2$
- q_T was transformed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

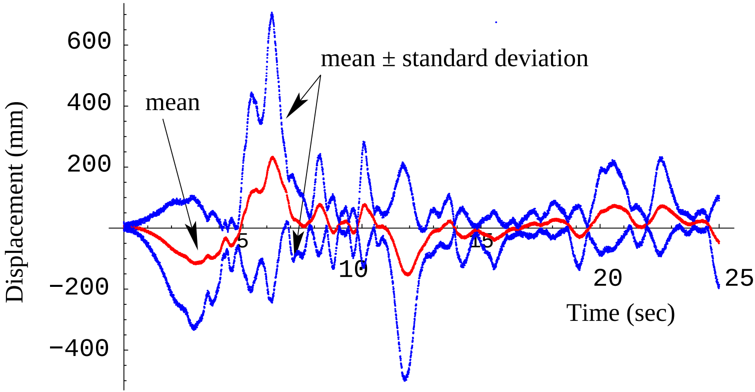
- Do nothing about site characterization (rely on experience): conservative **guess** of soil data, $COV = 225\%$, correlation length $= 12$m.
- Do better than standard site characterization: $COV = 103\%$, correlation length $= 0.61$m)
- Improve site (material) characterization if probabilities of exceedance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

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

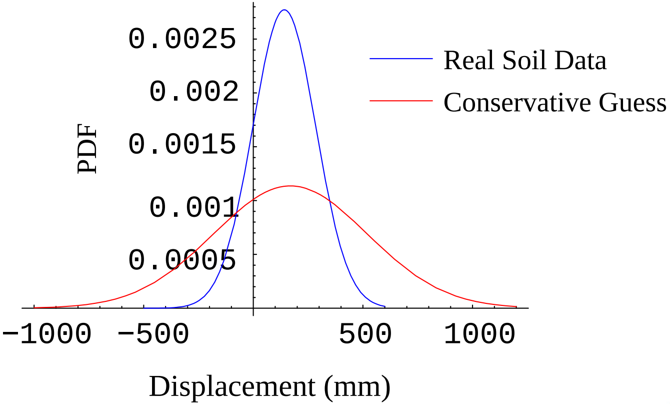
- Stochastic Elastic-Plastic Finite Element Method (SEPFEM)
- Dynamic case
- Full PDF at each time step Δt



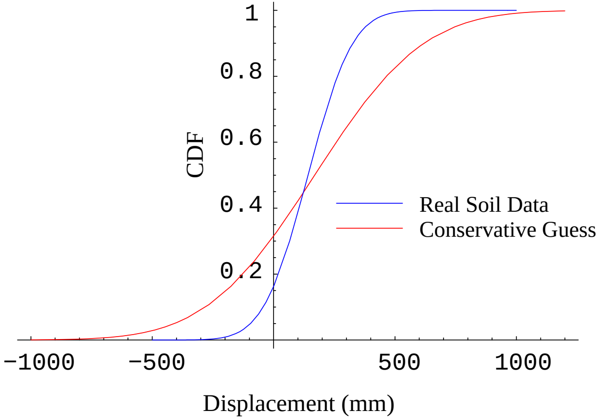
Evolution of Mean ± SD for Guess Case



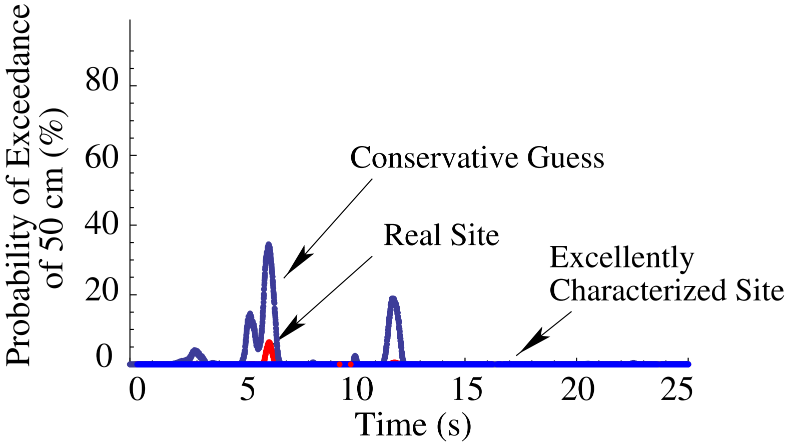
PDF at each Δt (say at 6 s)



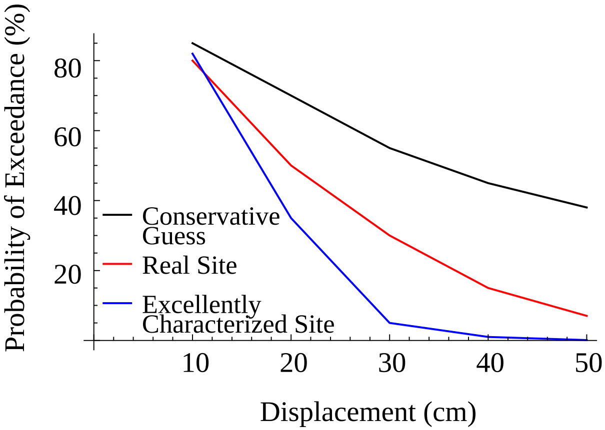
PDF $\rightarrow$ CDF (Fragility) at 6 s



Probability of Unacceptable Deformation (50cm)



Risk Informed Decision Process



Outline

Summary

- **Interplay** of **Uncertain Earthquake**, **Uncertain Soil/Rock**, and **Uncertain Structure** in time domain **probably** plays a decisive role in seismic performance of structures (NPPs, etc.)
- Improve **risk informed decision making** through high fidelity **Deterministic** and **Stochastic Elastic-Plastic Finite Element** modeling and simulation
- **Education and training** of users will prove essential
- **Acknowledgement:** funding and collaboration with the US-NRC, and funding from NSF, DOE, CNSC