Modeling and Simulation of Earthquake Soil Structure Interaction for Risk Informed Decision Making

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Outline

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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

Potential 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

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

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 Notes

- A hypertext documentation system describing in detail modeling and simulations of NPP ESSI problems
- Theoretical and Computational Formulations
- Software and Hardware Platform Design
- Verification and Validation
- Application Example

High Fidelity Modeling

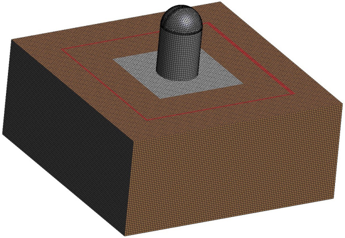
- Energy influx, body and surface waves, 3D, inclined
- Mechanical dissipation outside of SFS domain:
  - Radiation of reflected waves
  - Radiation of oscillating SFS system
- Mechanical dissipation inside SFS domain:
  - Plasticity of soil/rock subdomain
  - Plasticity of foundation – soil/rock interface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

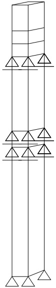
Verification, Validation and Prediction

- 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

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!

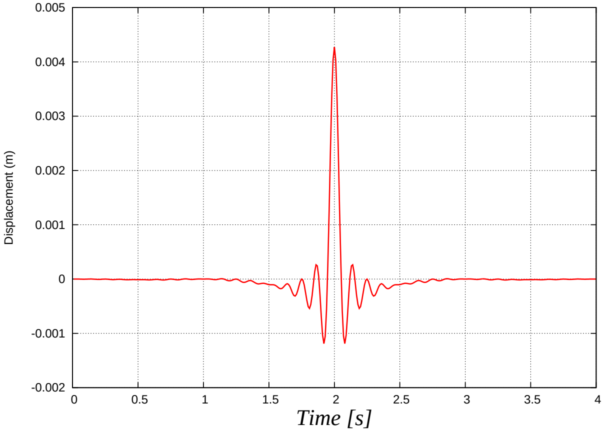
Mesh Size Effects on Seismic Wave Propagation Modeling



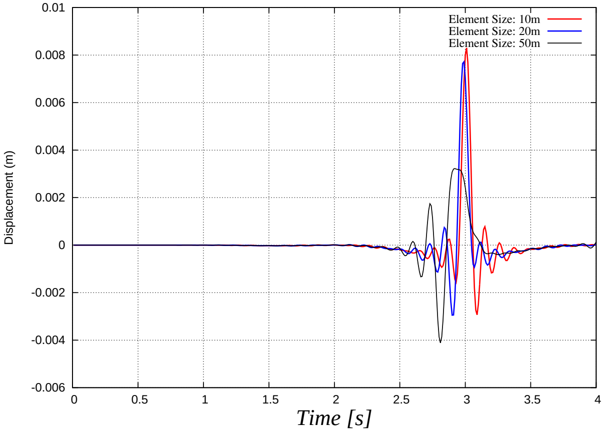
- Finite element mesh "filters out" high frequencies
- Usual rule of thumb: 10-12 elements needed per wave length
- 1D wave propagation model
- 3D finite elements (same in 3D)
- Motions applied as displacements at the bottom

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

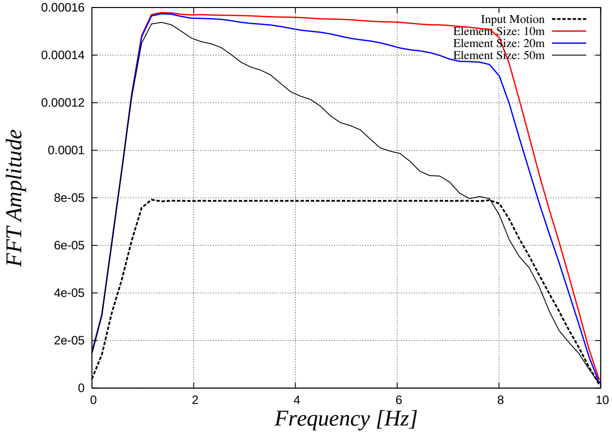
Cases 3, 4, and 6, Ormsby Wavelet Input Motions



Cases 3, 4, and 6, Surface Motions

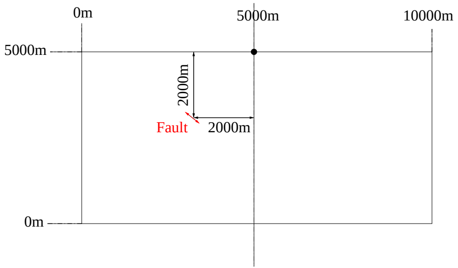


Cases 3, 4, and 6, Input and Surface Motions, FFT



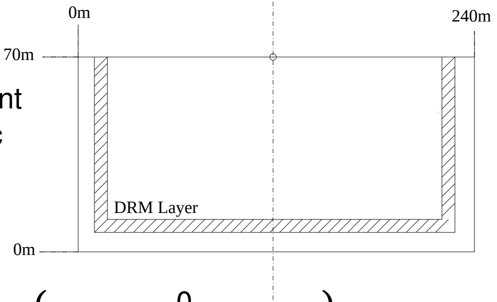
Free Field, Inclined, 3D Body and Surface Waves

- 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



Domain Reduction Method

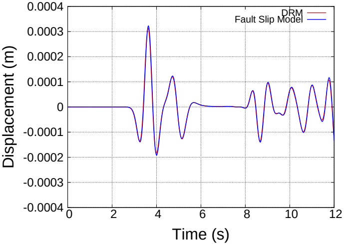
The effective force P^{eff} is a dynamically consistent replacement the dynamic source forces P_e



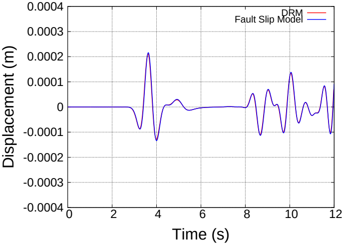
$$P^{eff} = \left\{ \begin{array}{c} P_i^{eff} \\ P_b^{eff} \\ P_e^{eff} \end{array} \right\} = \left\{ \begin{array}{c} 0 \\ -M_{be}^{\Omega+} \ddot{u}_e^0 - K_{be}^{\Omega+} u_e^0 \\ M_{eb}^{\Omega+} \ddot{u}_b^0 + K_{eb}^{\Omega+} u_b^0 \end{array} \right\}$$

Verification: Displacements, Top Middle Point

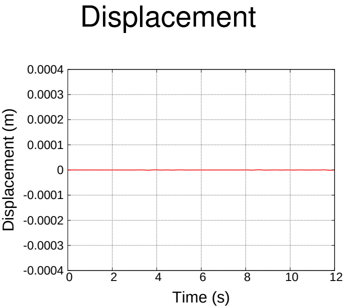
(X)

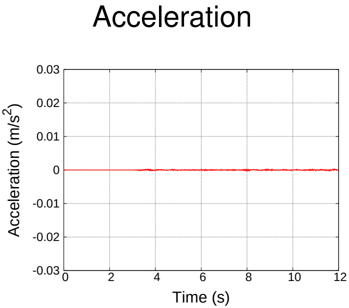


(Z)



Verification: Disp. and Acc., Out of DRM

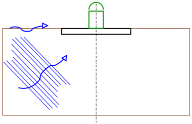




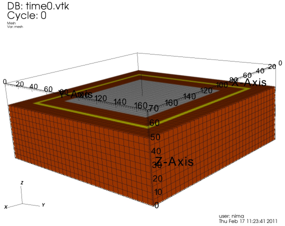
Few Illustrative Examples

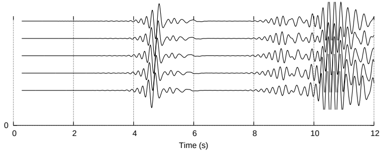
- Slip between foundation slab and the soil/rock underneath
- Passive seismic isolation by liquefaction
- Structural response in liquefied soil

Nuclear Power Plant with Base Slip

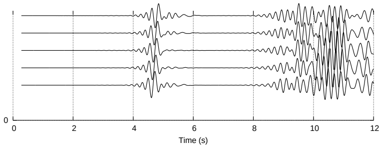


- Low friction zone between concrete foundation and soil/rock
- Inclined, 3D, body and surface, seismic wave field (wavelets: Ricker, Ormsby; real seismic, etc.)



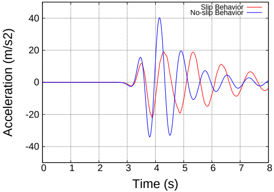


horizontal

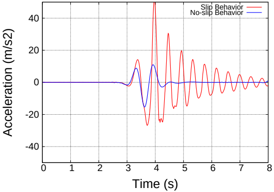


vertical

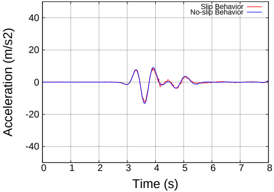
Acc. Response for a Full 3D (at 45°) Ricker Wavelet



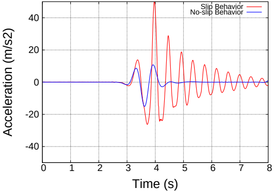
top X



top Z

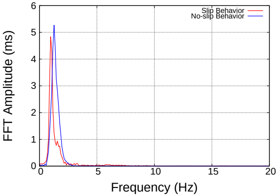


bottom X

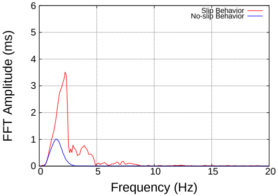


bottom Z

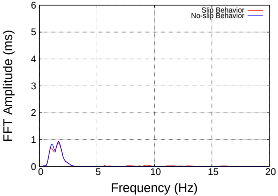
FFT Response for a Full 3D (at 45°) Ricker Wavelet



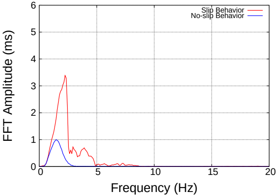
top X



top Z

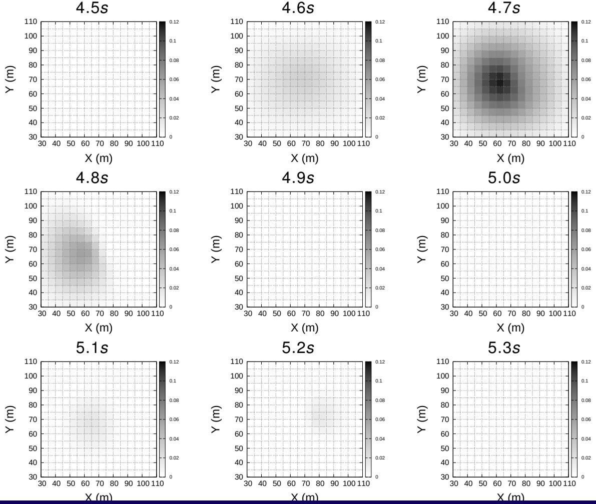


bottom X

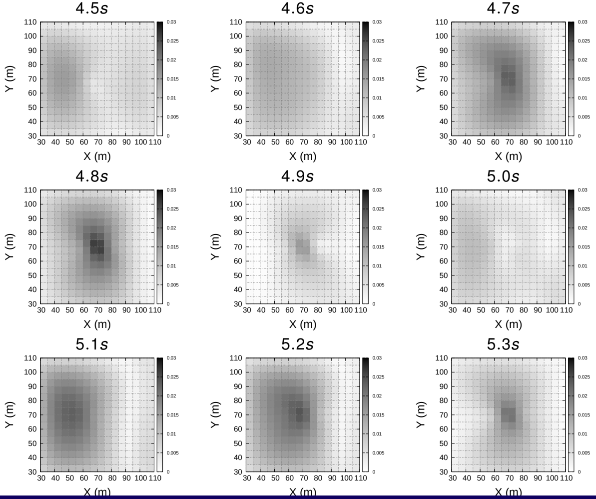


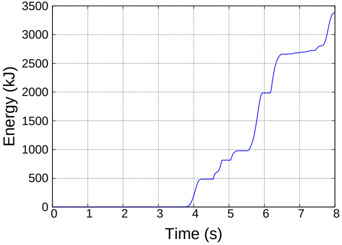
bottom Z

Gaping Response (45° Ricker Wavelet)

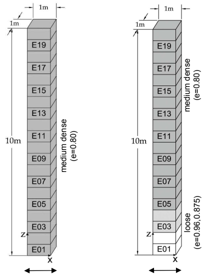


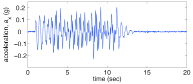
Slipping Response and Energy Dissipated (45° Ricker)

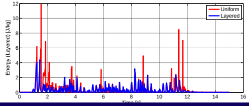


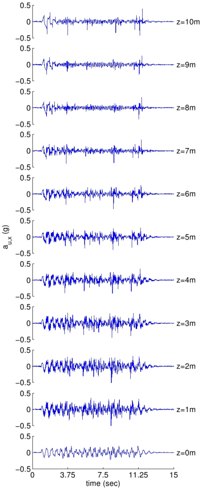


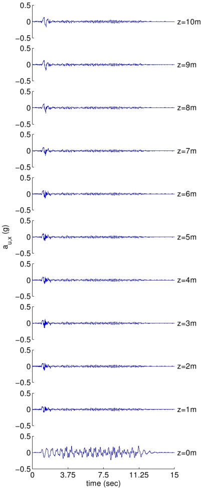
Passive Base Isolation in Uniform and Layered Soils



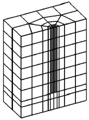


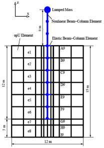


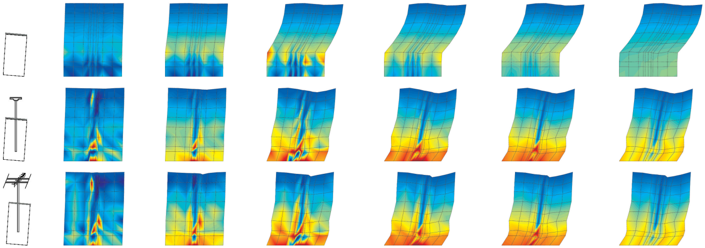




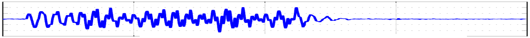
Pile in Liquefiable Sloping Ground







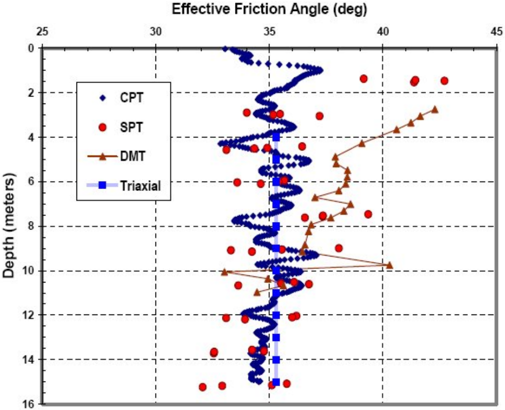
t= 2 sec 5 sec 10 sec 15 sec 20 sec 80 sec



Outline

Material Behavior Inherently Uncertain

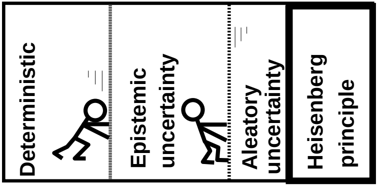
- Spatial variability
- Point-wise uncertainty, testing error, transformation error



(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 $\Delta\sigma_{ij} = E_{ijkl}\Delta\epsilon_{kl}$

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

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

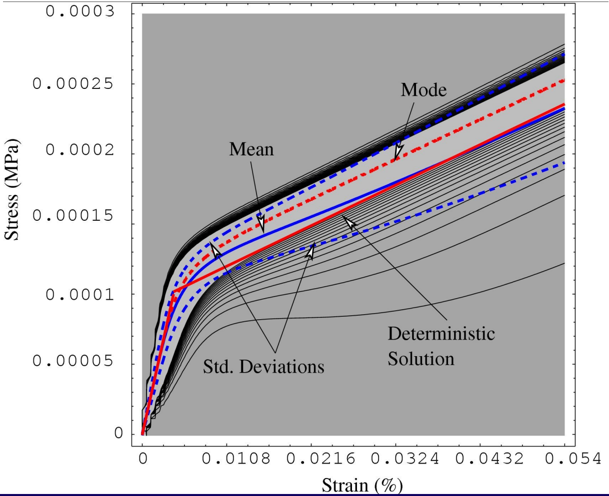
- Advection-diffusion equation

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

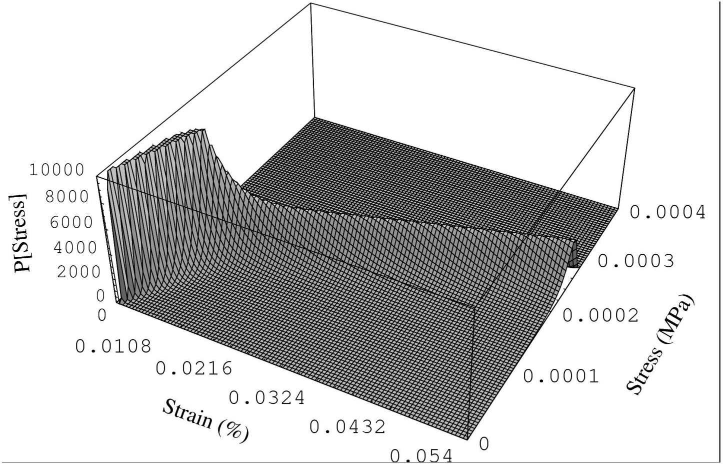
- **Complete** probabilistic description of response
- **Second-order exact** to covariance of time (exact mean and variance)
- Any uncertain FEM problem ($\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{F}$) with
  - uncertain material parameters (stiffness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

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

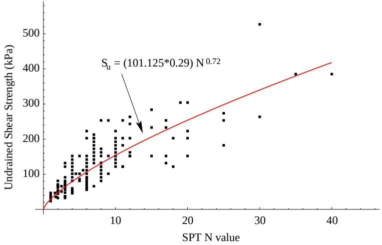
Probabilistic Elastic-Plastic Response

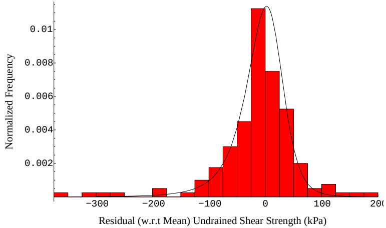


Probabilistic Elastic-Plastic Response



SPT Based Determination of Shear Strength

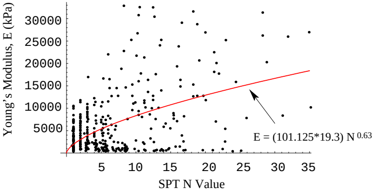


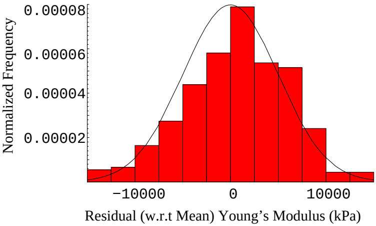


Transformation of SPT N-value $\rightarrow$ undrained shear strength, s_u (cf. Phoon and Kulhawy (1999B)

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):

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

$$K^{ep}_{mn} = \int_D B_n E^{ep} B_m dV \qquad K'^{ep}_{mnk} = \int_D B_n \sqrt{\lambda}_k h_k B_m dV$$

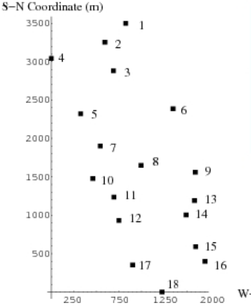
$$C_{ijk} = \left\langle \xi_k(\theta) \psi_i[\{\xi_r\}] \psi_j[\{\xi_r\}] \right\rangle \qquad F_m = \int_D \phi N_m dV$$

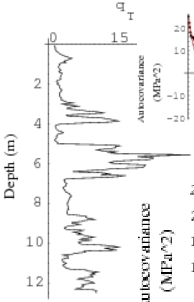
Inside SSEPFEM

- 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

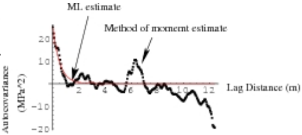
Seismic Wave Propagation through Stochastic Soil

- Maximum likelihood estimates

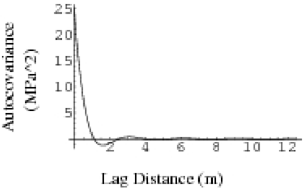




Typical CPT q_T

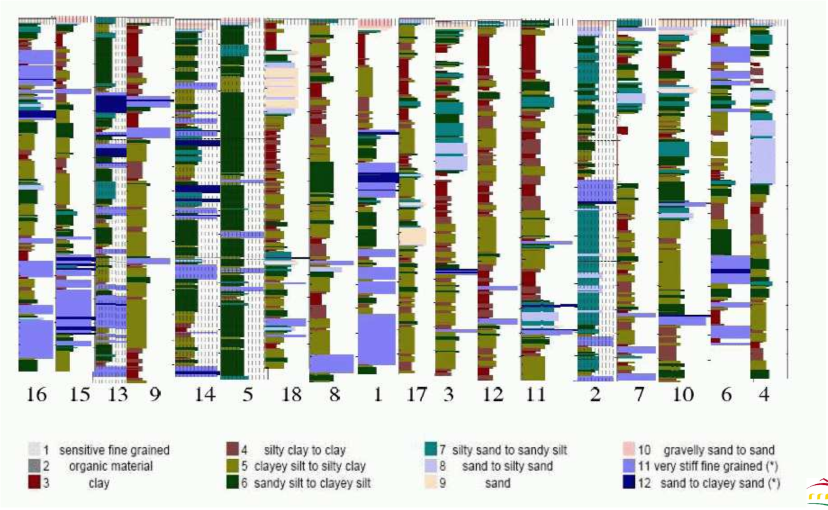


Finite Scale



Fractal

"Uniform" CPT Site Data



Random Field Parameters from Site Data

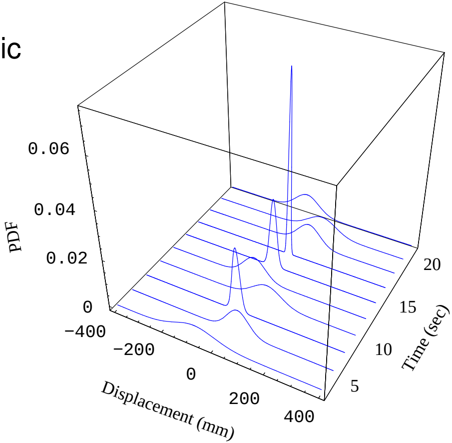
- Soil as 12.5 m deep 1–D soil column (von Mises Material)
  - Properties (including testing uncertainty) obtained through random field modeling of CPT q_T
    $\langle q_T \rangle = 4.99\ MPa$; $Var[q_T] = 25.67\ MPa^2$;
    Cor. Length $[q_T] = 0.61\ m$; Testing Error $= 2.78\ MPa^2$
- q_T was transformed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

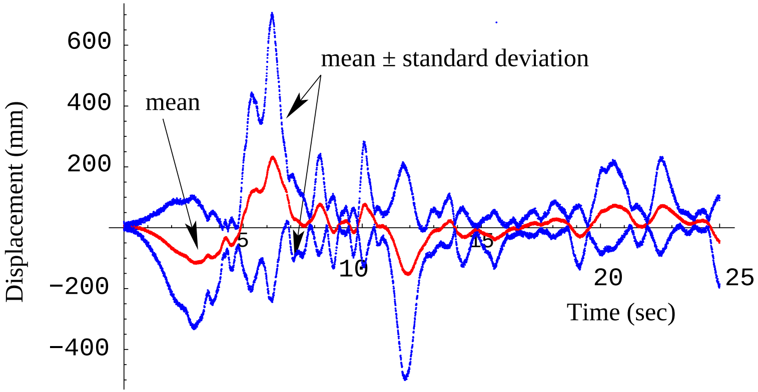
- Do nothing about site characterization (rely on experience): conservative **guess** of soil data, $COV = 225\%$, correlation length $= 12$m.
- Do better than standard site characterization: $COV = 103\%$, correlation length $= 0.61$m)
- Improve site (material) characterization if probabilities of exceedance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

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

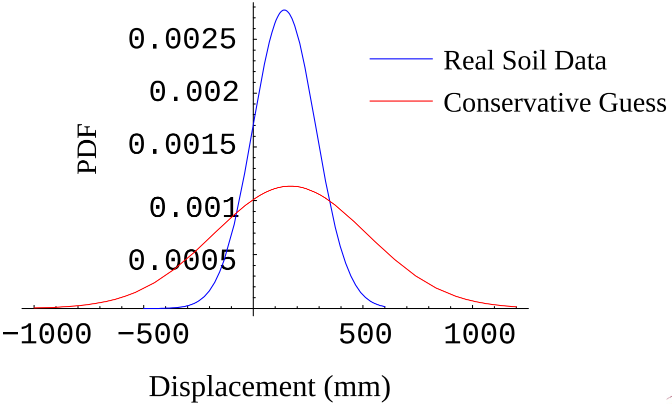
- Stochastic Elastic-Plastic Finite Element Method (SEPFEM)
- Dynamic case
- Full PDF at each time step Δt



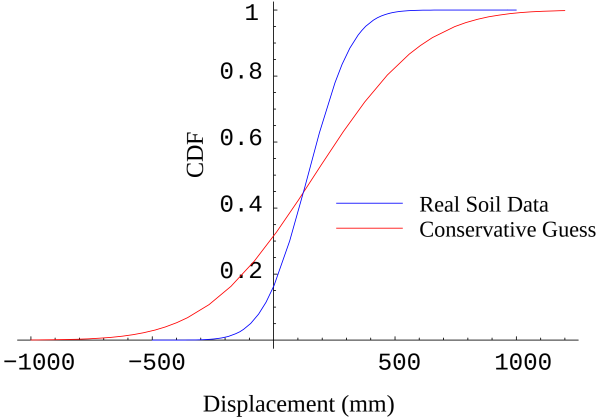
Evolution of Mean ± SD for Guess Case



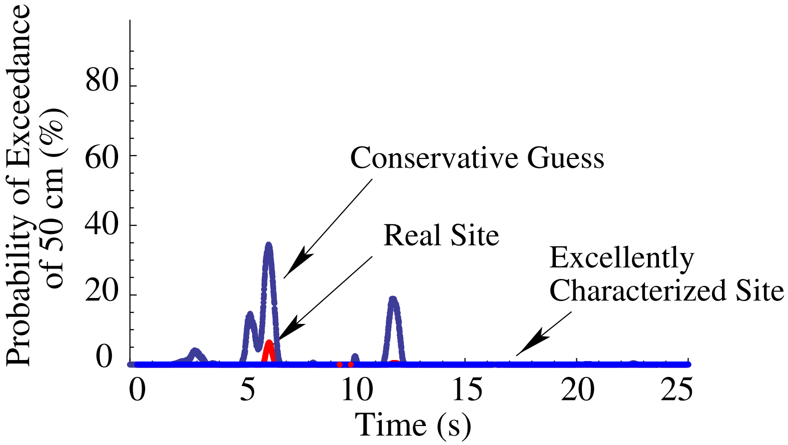
PDF at each Δt (say at 6 s)



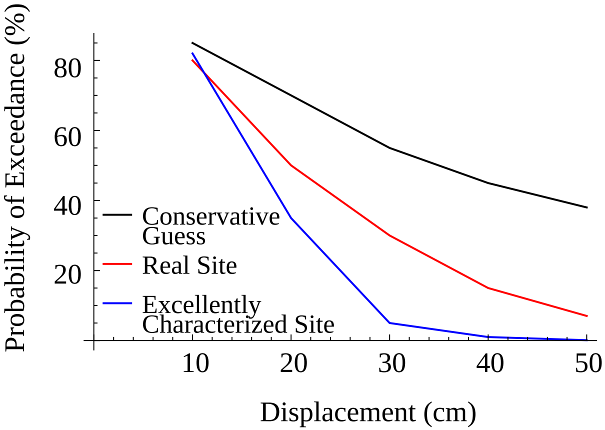
PDF $\rightarrow$ CDF (Fragility) at 6 s



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 NPPs
- 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.

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