Time Domain Nonlinear Earthquake Soil/Rock Structure Interaction Modeling and Simulation

Boris Jeremić

Professor, University of California, Davis, CA
Faculty Scientist, Lawrence Berkeley National Laboratory, Berkeley, CA

ASCE-4 Meeting
April 2013

Outline

Outline

The Problem

- Earthquake Soil/Rock Structure Interaction (ESSI) response of Nuclear Power Plants
- 3D, inclined, body and surface seismic waves
- Nonlinear behavior (elastic, damage, plastic behavior of materials: soil, rock, concrete, steel, rubber, etc.)
- Full coupling of pore fluids with soil/rock skeleton
- Contact and buoyancy effects
- Uncertainty in seismic sources, path, soil/rock response and structural response

Solution (?)

- **Physics based modeling and simulation** of seismic behavior of NPP soil/rock – structure 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, Material and Loading Uncertainty

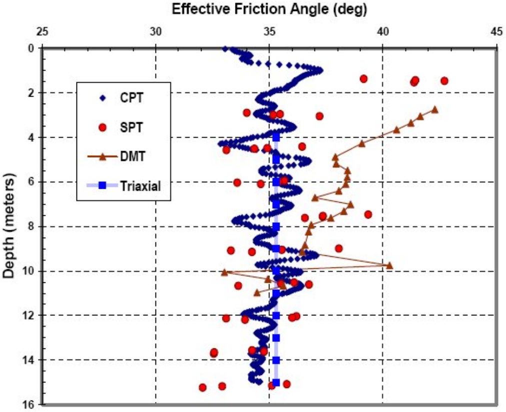
- Simplified (or inadequate/wrong) modeling: important features are missed (seismic ground motions, etc.)
- Introduction of uncertainty and (unknown) lack of accuracy in results due to use of un-verified simulation tools (software quality, etc.)
- Introduction of uncertainty and (unknown) lack of accuracy in results due to use of un-validated models (due to lack of quality validation experiments)
- Material (left hand side) and load (right hand side) uncertainties affect (probabilities of) overall response

Complexity of and Uncertainty in Ground Motions

- 6D (3 translations, 3 rotations)
- Vertical motions usually neglected
- Rotational components usually not measured and neglected
- Sources of uncertainties in ground motions (Source, Path (rock), SSI (soil,rock))

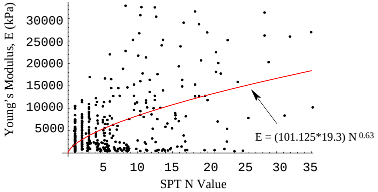
Material Behavior Inherently Uncertain

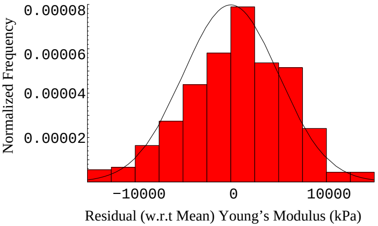
- Spatial variability
- Point-wise uncertainty, testing error, transformation error



(Mayne et al. (2000)

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

Introduction

The Problem

Uncertainties

Verification and Validation

Modeling and Simulation Issues

High Fidelity Modeling

Verification and Validation

Elastic-Plastic Material Modeling

Current Work

NRC ESSI Simulator System

Features in Development

Uncertainty Propagation

Summary

Verification & Validation (V&V) Definition

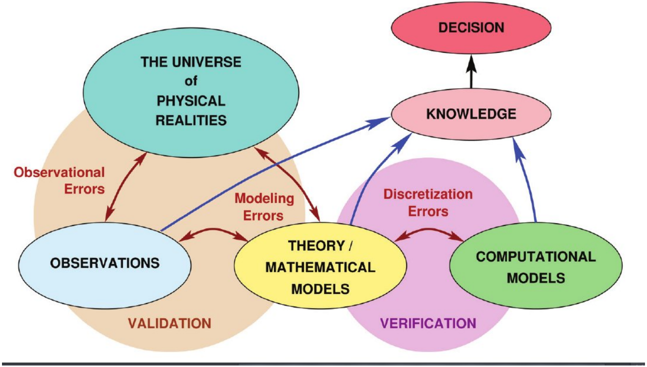
- **Verification**: The process of determining that a model implementation accurately represents the developer's conceptual description and specification. Mathematics issue. *Verification provides evidence that the model is solved correctly.*

- **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.*

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

Role of Verification and Validation



Oden et al.

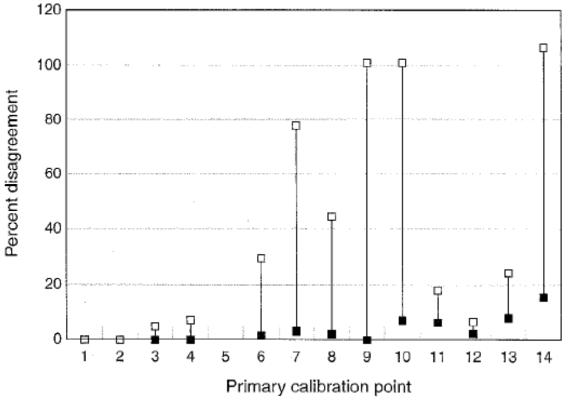
Errors in Scientific Software: The T Experiments

- 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



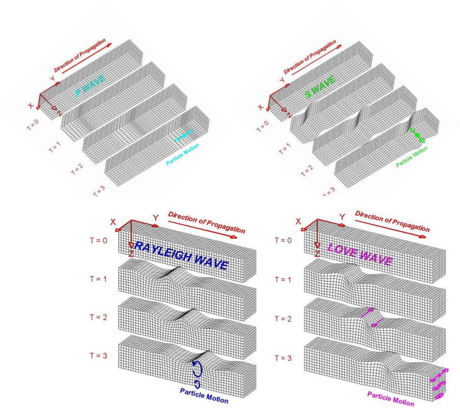
Outline

High Fidelity Modeling

- Energy influx:
  - Seismic 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 sub-domain
  - 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

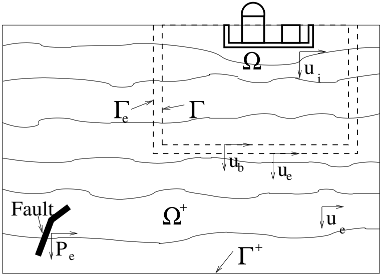
Earthquake Ground Motions

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



Seismic Input: The Domain Reduction Method

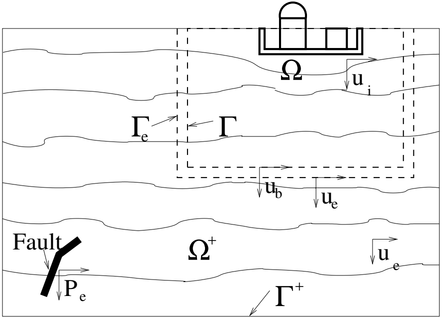
The DRM (Bielak et al.):
The effective force P^{eff}
is a dynamically consistent
replacement the dynamic
source forces P_e



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

DRM

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



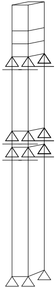
Outline

V & V for ESSI Modeling and Simulations

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

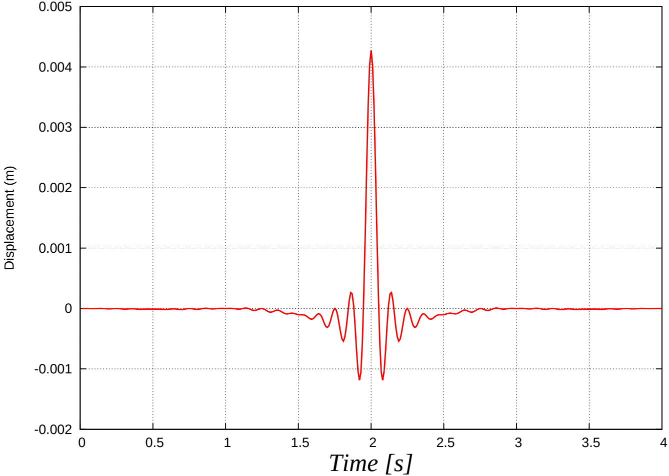
Mesh Size Effects on Seismic Wave Propagation Modeling

- 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

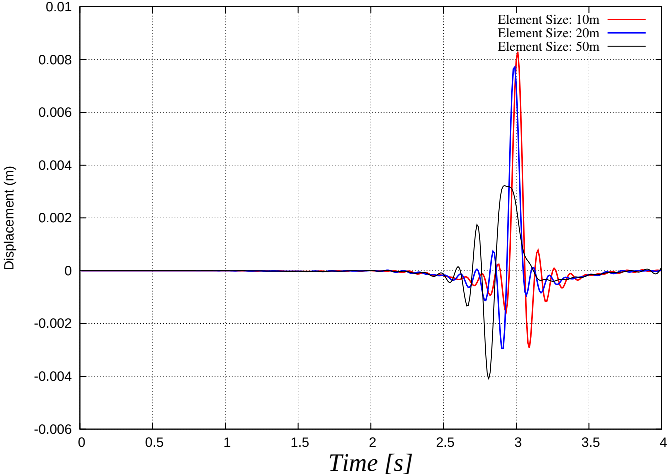


case	model height [m]	V_s [m/s]	El.size [m]	f_{max} (10el) [Hz]
3	1000	1000	10	10
4	1000	1000	20	5
6	1000	1000	50	2

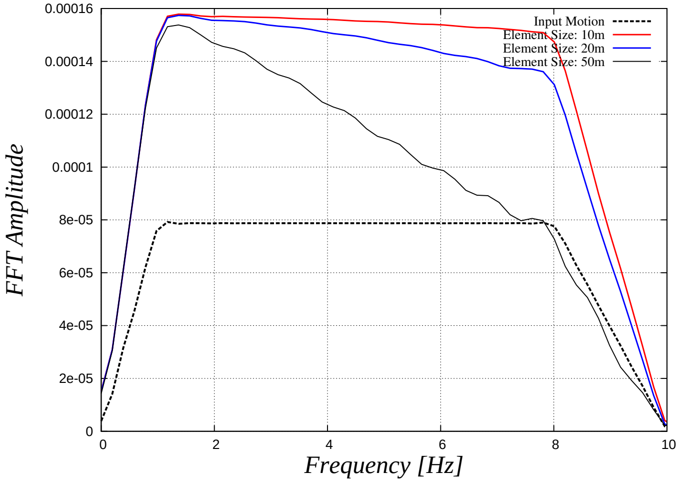
Cases 3, 4, and 6, Ormsby Wavelet Input Motions



Cases 3, 4, and 6, Surface Motions

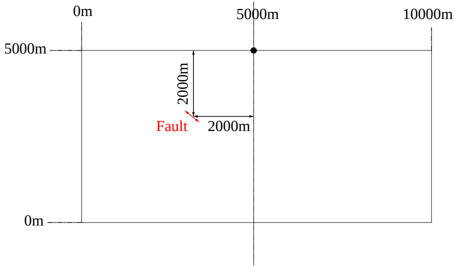


Cases 3, 4, and 6, Input and Surface Motions, FFT



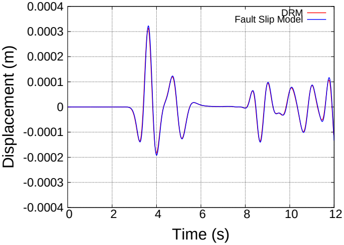
Free Field, Inclined, 3D Body and Surface Waves

- 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

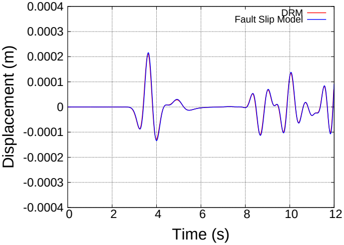


Verification: Displacements, Top Middle Point

(X)

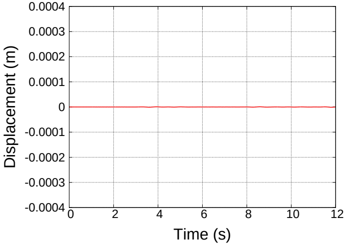


(Z)

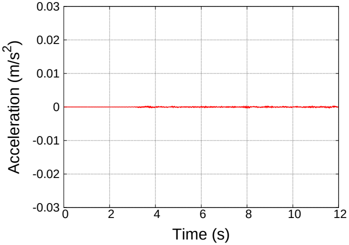


Verification: Disp. and Acc., Out of DRM

Displacement



Acceleration



Outline

Modulus Reduction (G/G_{max}) and Damping Curves

- Idriss and Seed 1970
- Much work gone into development of curves for different types of soils
- However, it is still a linear elastic (secant) approach with some energy dissipation taken into account
- Not good for any case where soil volume change makes a difference or where 2D or 3D behavior is important

G/G_{max} and Damping Curves

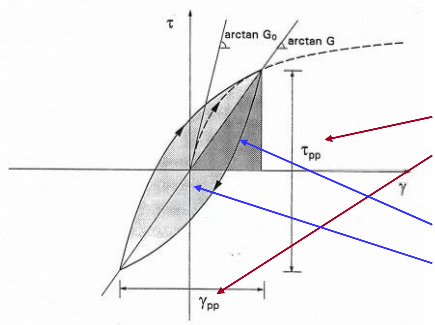
G = shear modulus

(G_0 = initial shear modulus)

$$G = \frac{\tau_{pp}}{\gamma_{pp}}$$

D = damping ratio

$$D = \frac{W_D}{4\pi W_S}$$



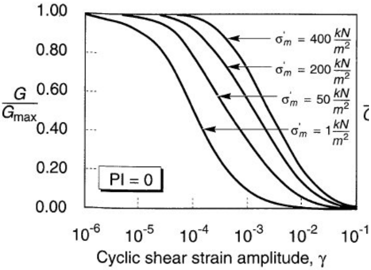
τ_{pp} = peak-to-peak stress

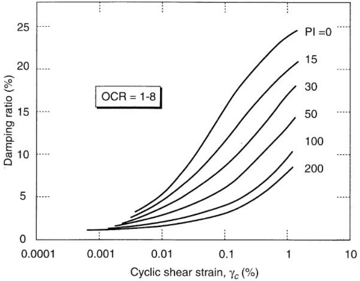
γ_{pp} = peak-to-peak strain

W_S = equivalent elastic energy

W_D = energy damped in one cycle

Commonly used G/G_{max} and Damping Curves: Vučetić and Dobry (1991)

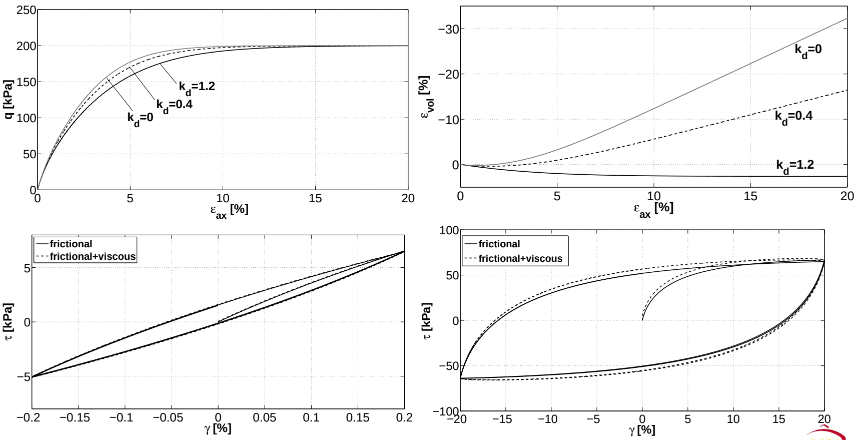




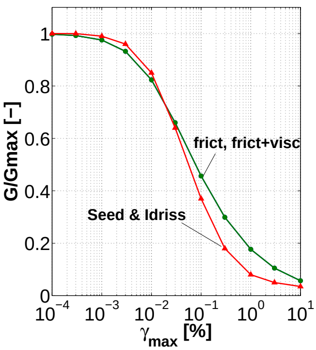
Pisanò 3D Elastic Plastic Material Model

- Split stress into frictional and viscous components
  $\sigma_{ij} = \sigma^f_{ij} + \sigma^v_{ij}$
- Elasticity: classic, linear (can be nonlinear)
- Yield surface, Drucker-Prager cone, collapsed (limit analysis, vanishing elastic regions) to cylinder (von Mises), with conical bounding surface
- Plastic flow and rotational kinematic hardening, borrowed from Manzari-Dafalias model (1997)
- Yield (loading-unloading) condition established using stress projection
- Special (unique) developments of a stiffness tensor (used for FEM)

Pisanò Model: Triaxial and Pure Shear Response



Pisanò Model: Calibration for G/G_{max} and Damping



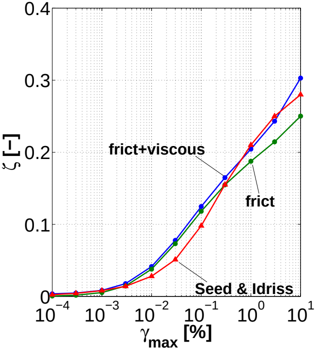


Figure: Comparison between experimental and simulated G/G_{max} and damping curves (p_0=100 kPa, T=2π s, ζ = 0.003, G_{max} = 4 MPa, ν=0.25, M=1.2, k_d=ξ=0, h=$G_{max}/(15p_0)$, m=1)

Pisanò Model: Variation in Confining Pressure

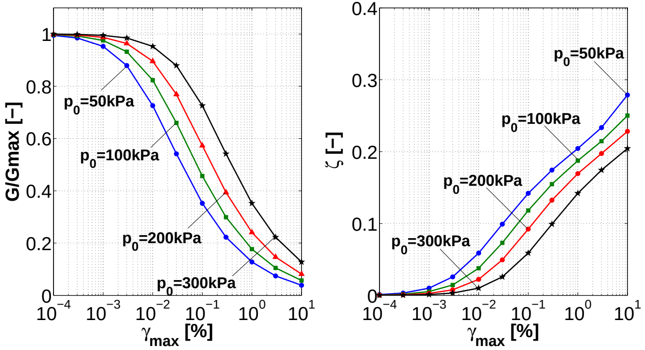
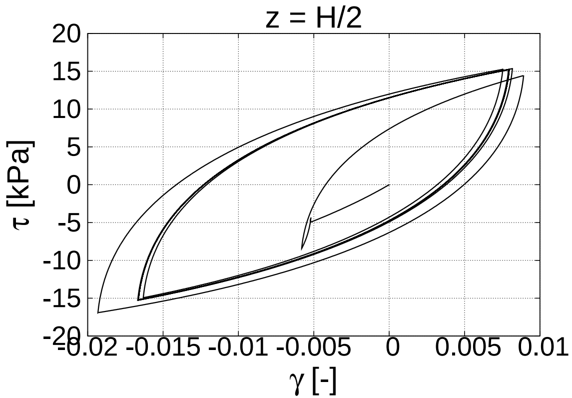


Figure: Simulated G/G_{max} and damping curves at varying confining pressure (T=2π s, G_{max} = 4 MPa, ν=0.25, M=1.2, k_d=ξ=0, h=G/(15p_0), m=1)

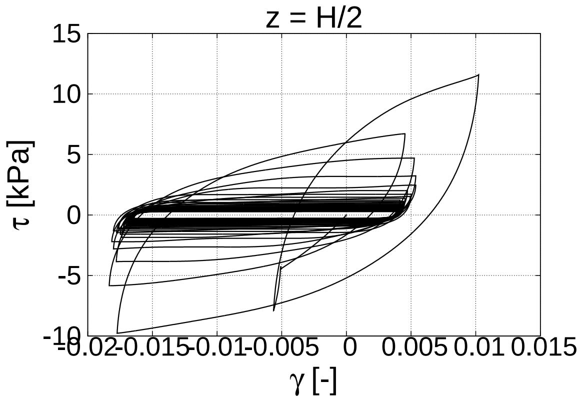
Soil Volume Response

- Soil behavior is very much a function of volumetric response
- Dilative soils: increase volume due to shearing
- Compressive soils: decrease volume due to shearing
- Modulus reduction and damping curves do not provide volumetric data
- Soil volume change will affect response due to volume constraints

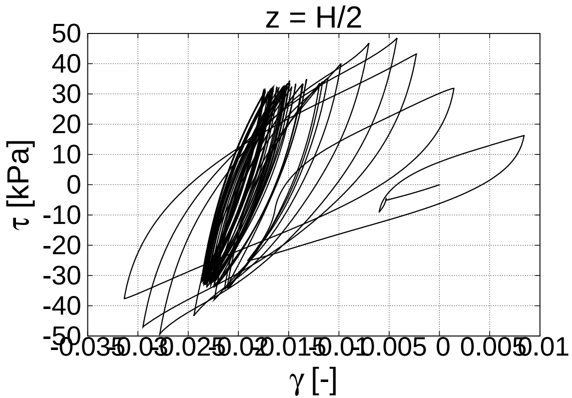
No Volume Change Soil (at Critical State?)



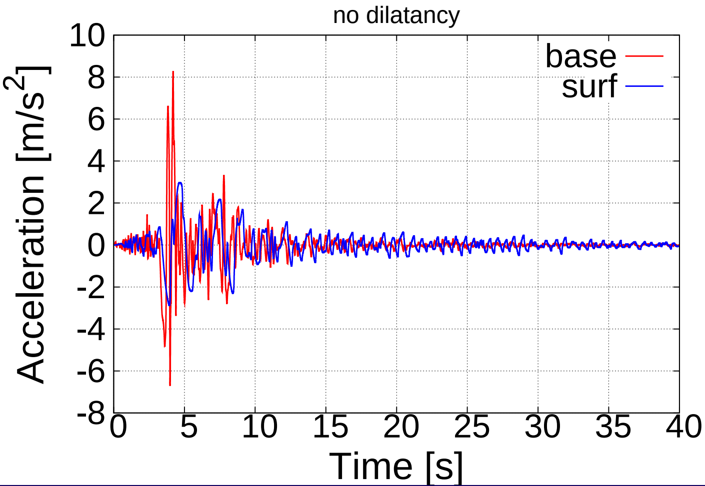
Compressive Soil



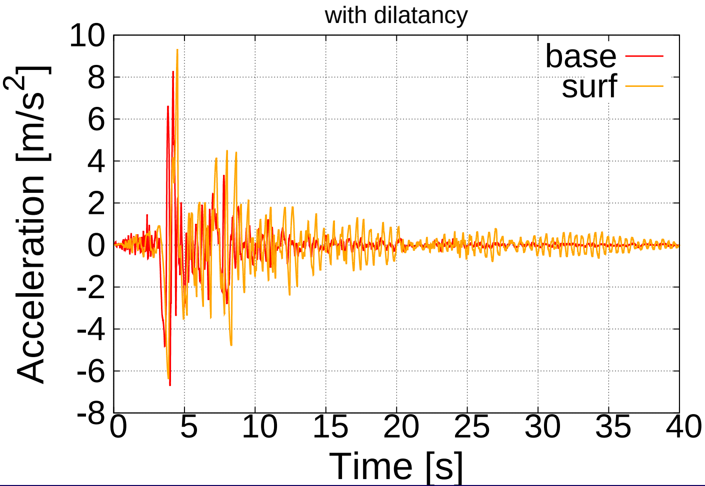
Dilative Soil



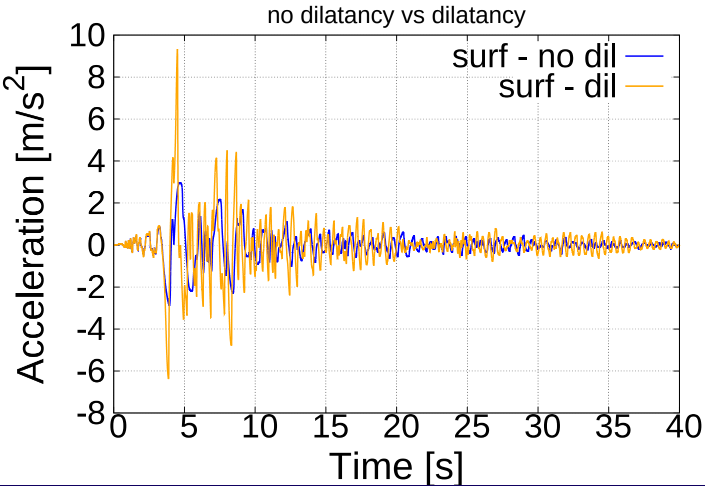
Northridge, No Volume Change Soil



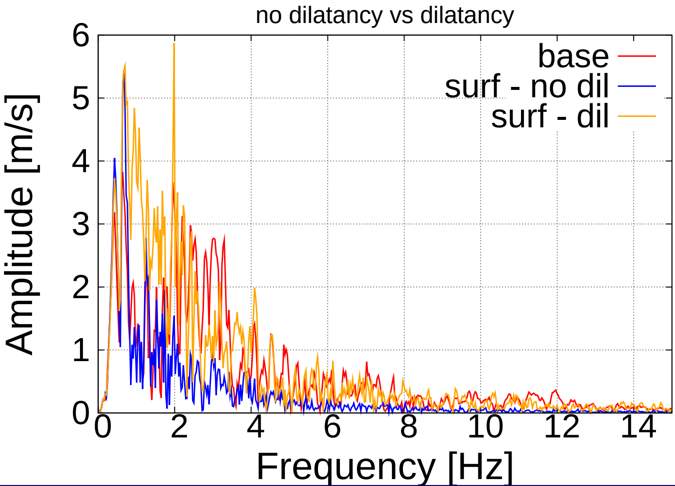
Northridge, Dilatant Soil



Northridge, No Volume Change and Dilative Soils



Northridge, No Volume Change and Dilative Soils



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

- Collection of Useful Libraries (modular, portable)
- Library centric software design
- Various open source licenses (GPL, LGPL, BSD, CC)
- Extensive verification and (not so much) validation
- Detailed program documentation (part of NRC ESSI Notes)
- Target users: U.S.-NRC, other domestic (DOE) and international agencies (CNSC, IAEA), National Labs, Testers, eventually 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

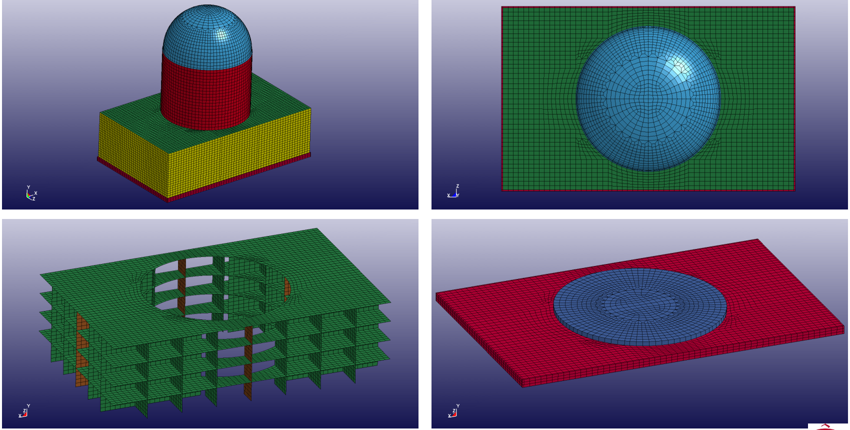
- Theoretical and Computational Formulations
- Software and Hardware Platform Design
- Verification and Validation
- Application Example

Outline

Features in Development

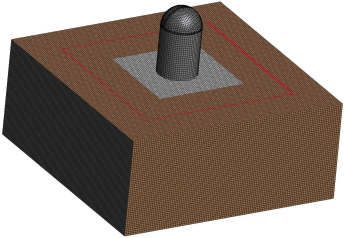
- Buoyancy effects for foundations
- Piles
- Isolators
- Saturated contact (dry is already in)

Models in Development #1



Models in Development #2

- 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,

Outline

Eulerian–Lagrangian FPK Equation and (SEP)FEM

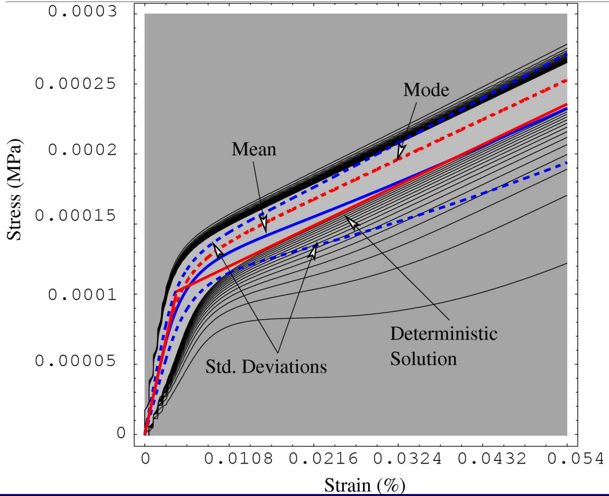
- Advection-diffusion equation

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

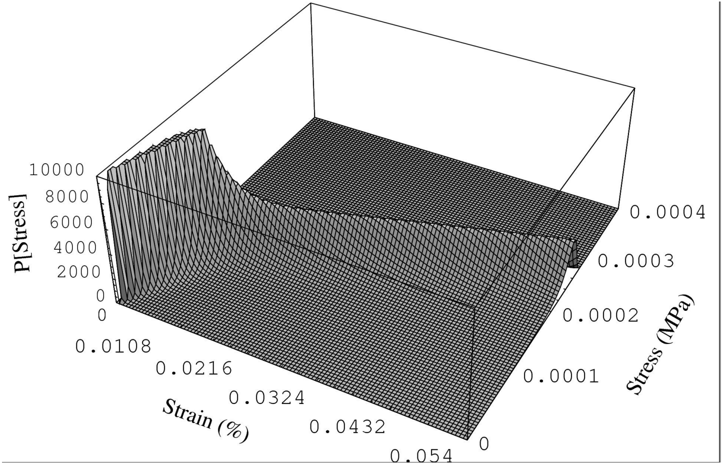
- **Complete** probabilistic description of response
- **Second-order exact** to covariance of time (exact mean and variance)
- Any uncertain FEM problem ($\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{F}$) with
  - uncertain material parameters (stiffness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



Stochastic Finite Element Formulation

- 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

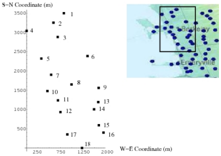
$$\sum_{n=1}^{N} K_{mn}^{ep} d_{ni} + \sum_{n=1}^{N} \sum_{j=0}^{P} d_{nj} \sum_{k=1}^{M} C_{ijk} K_{mnk}^{\prime ep} = \langle F_m \psi_i[\{\xi_r\}] \rangle$$

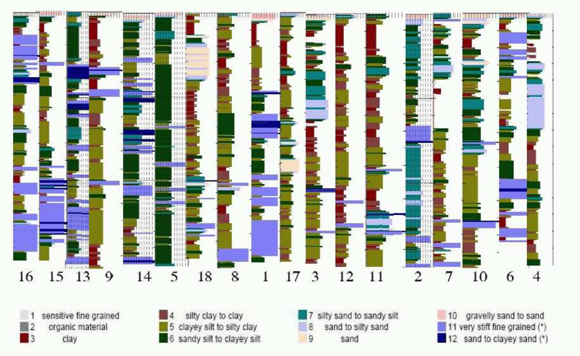
$$K_{mn}^{ep} = \int_D B_n E^{ep} B_m dV \qquad K_{mnk}^{\prime ep} = \int_D B_n \sqrt{\lambda}_k h_k B_m dV$$

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

Seismic Wave Propagation through Stochastic Soil

Uniform CPT site data





Random Field Parameters from Site Data

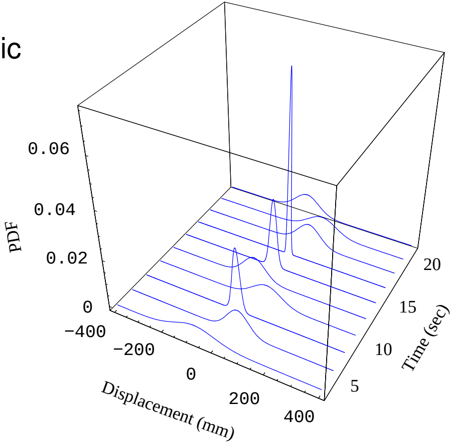
- Soil as 12.5 m deep 1–D soil column (von Mises Material)
  - Properties (including testing uncertainty) obtained through random field modeling of CPT q_T
    $\langle q_T \rangle = 4.99\ MPa$; $Var[q_T] = 25.67\ MPa^2$;
    Cor. Length $[q_T] = 0.61\ m$; Testing Error $= 2.78\ MPa^2$
- q_T was transformed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

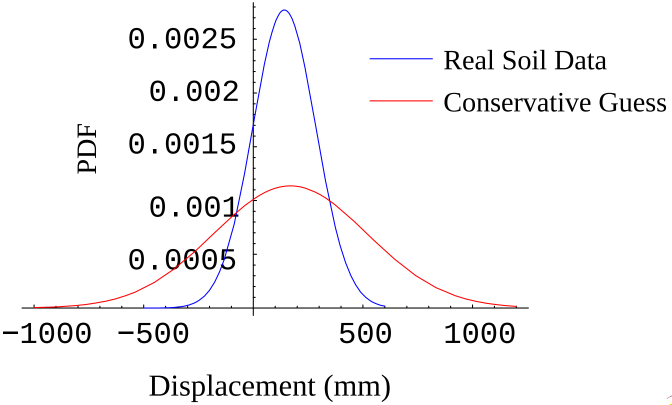
- Do nothing about site characterization (rely on experience): conservative **guess** of soil data, $COV = 225\%$, correlation length $= 12$m.
- Do better than standard site characterization: $COV = 103\%$, correlation length $= 0.61$m)
- Improve site (material) characterization if probabilities of exceedance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

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

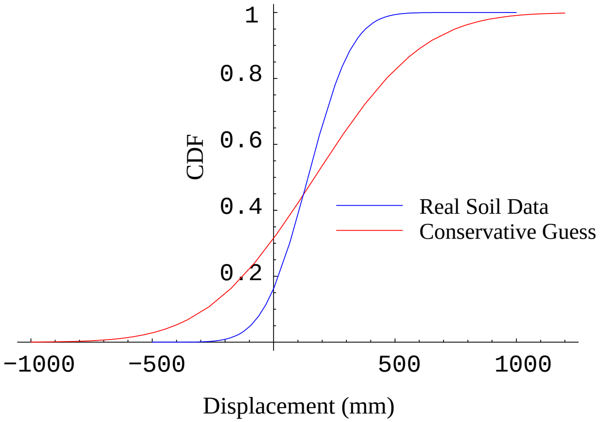
- Stochastic Elastic-Plastic Finite Element Method (SEPFEM)
- Dynamic case
- Full PDF at each time step Δt



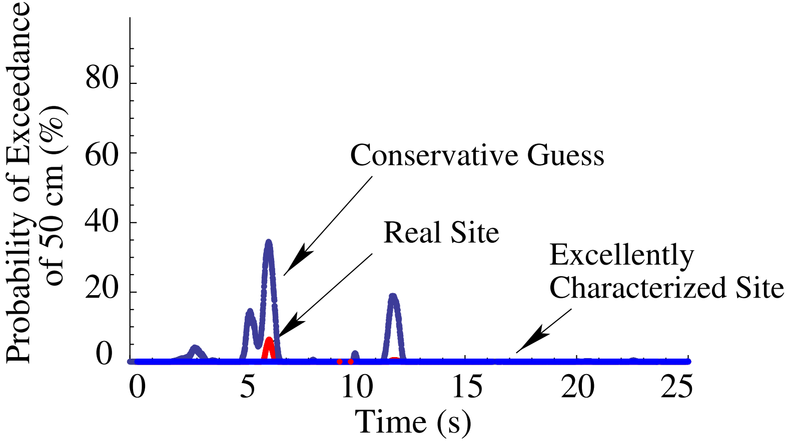
PDF at each Δt (say at 6 s)



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



Probability of Unacceptable Deformation (50cm)



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 (Verified and Validated) Time Domain. **Deterministic** and **Stochastic** Elastic-Plastic Finite Element modeling and simulation
- **Acknowledgement:** funding and collaboration with the US-NRC, CNSC, NSF, DOE, AREVA, Shimizu. Drs. and students: Nima Tafazzoli, Federico Pisanò, Mario Martinelli, José Abell Mena, Kohei Watanabe, Babak Kamrani, Chang-Gyun Jeong...