Earthquake Soil Structure Interaction for Nuclear Power Plants, Modeling and Computational Issues

B. Jeremić
N. Tafazzoli, P. Tasiopoulou, J.A. Abell Mena, B. Kamrani,
C.-G. Jeong, F. Pisanò, M. Martinelli, K. Sett, M. Taiebat

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

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Outline

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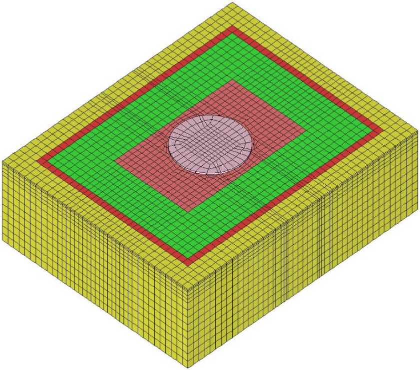
The Problem

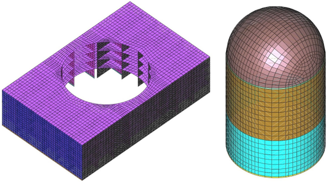
- Seismic response of Nuclear Power Plants ($f \leq$ 50Hz! (20Hz))
- 3D, inclined seismic motions: body and surface waves
- Inelasticity (elastic, damage, plastic behavior of materials: soil, rock, concrete, steel, rubber, contact, etc.)
- Full coupling of pore fluids with soil, rock and concrete skeleton, including buoyancy effects
- Uncertainty in seismic sources, path, soil/rock 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, for licensing and professional practice (every day use)
- 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

NPP Model(s)





Outline

Modeling Uncertainty

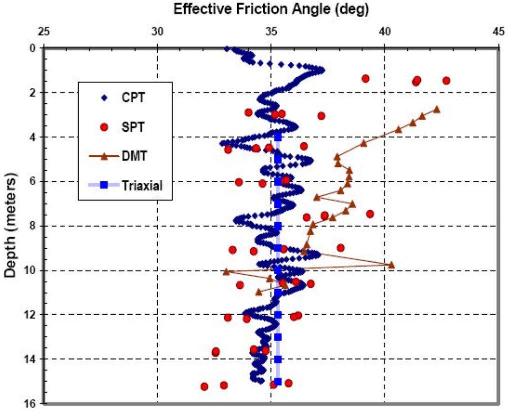
- Simplified (or inadequate/wrong) modeling: important features are missed (seismic ground motions, etc.)
- Introduction of uncertainty and (unknown) lack of accuracy in results due to use of un-verified simulation tools (software quality, etc.)
- Introduction of uncertainty and (unknown) lack of accuracy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

Material Behavior Inherently Uncertain

- (a) Spatial variability
- Point-wise uncertainty, (b) testing error, (c) transformation error



(Mayne et al. (2000))

Outline

Desirable Modeling and Simulation Capabilities

- Body (SH, SV, P) and Surface (Rayleigh, Love, etc) seismic motions modeling and their input into finite element models
- Elastic-plastic modeling of dry and saturated soil/rock behavior beneath foundations
- Elastic-plastic modeling of soil/rock (limited data)
- Soil/rock - foundation contact zone modeling (for dry and saturated conditions)
- Verification and Validation suite
- High performance, parallel simulation using dynamic domain decomposition (Plastic Domain Decomposition) for elastic-plastic simulations
- Probabilistic elasto-plasticity and stochastic elastic-plastic finite element methods

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
- Solids (dry, saturated), beams, shells, contacts, elastic or elastic-plastic
- 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

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 supercomputer
- Current systems: 208CPUs, and 40CPUs (8+32) and 160CPUs (8x5+2x16+24+64)

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)

ESSI: 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

ESSI: High Performance, Parallel Computing

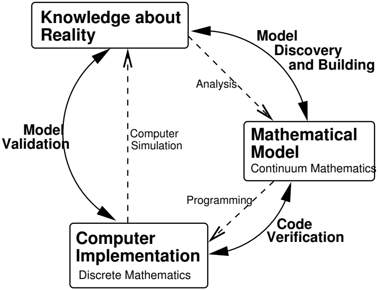
- The ESSI Program can be used in both sequential and parallel modes
- For high fidelity models, parallel is really the only option
- High performance, parallel computing using Plastic Domain Decomposition Method, for elastic-plastic computations (dynamic computational load balancing)
- Developed for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

Outline

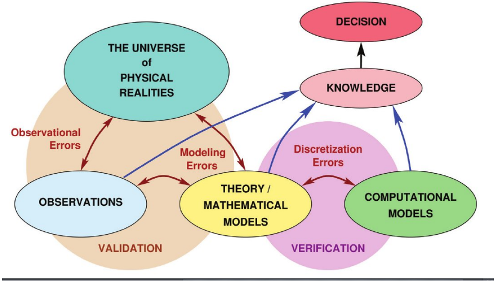
Verification, Validation (V&V) and Prediction

- 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.

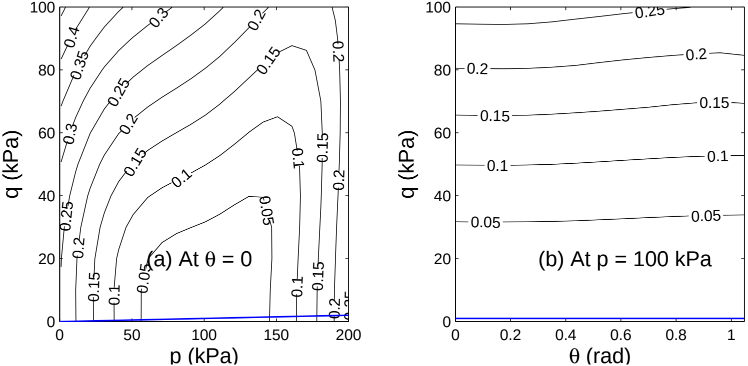
V&V for ESSI Modeling and Simulations

- Code Verification
- 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

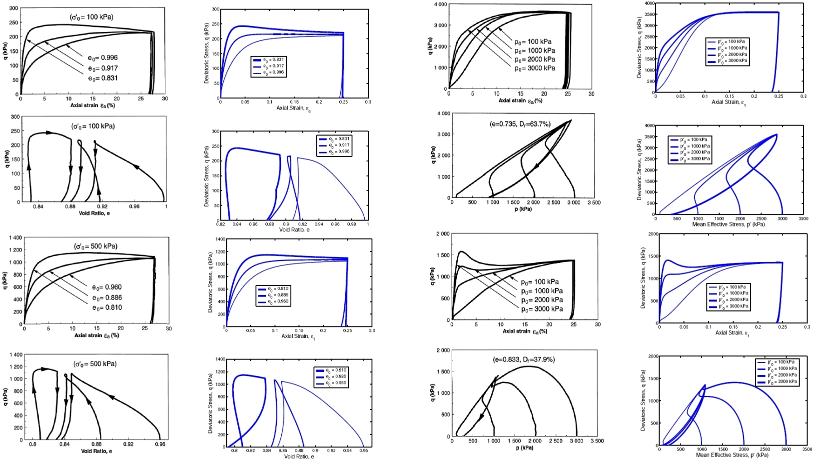
Constitutive Integration Error Maps

Normalized error: $\delta^r = \sqrt{(\sigma_{ij} - \sigma^*_{ij})(\sigma_{ij} - \sigma^*_{ij})} / \sqrt{\sigma^0_{pq}\sigma^0_{pq}}$

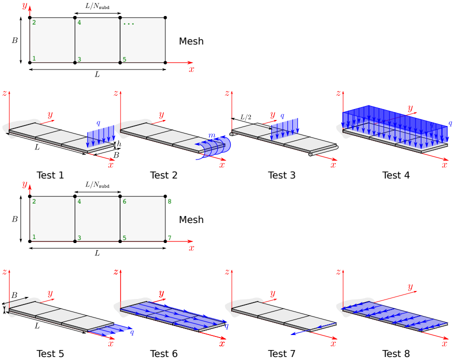
SaniSand2004, rot. kinematic hardening, bounding surface:



Material Model Validation (SanSand2004)

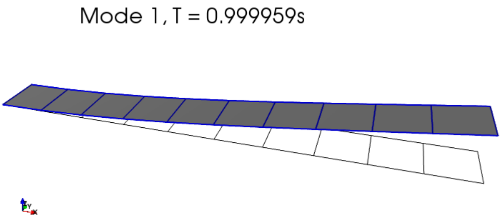


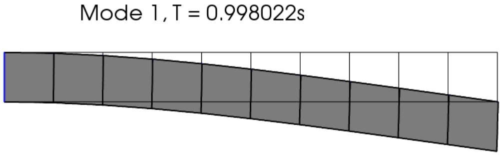
Verification ANDES Shell: Static



Material parameters chosen such that the exact solution is
$u_z = 100.000$ $T = 1.0\,\mathrm{s}$.
Nz = 2, $u_z = 96.212$; Nz = 7, $u_z = 100.096$

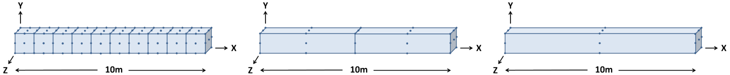
Verification ANDES Shell: Dynamic





Verification for 27 Node Brick

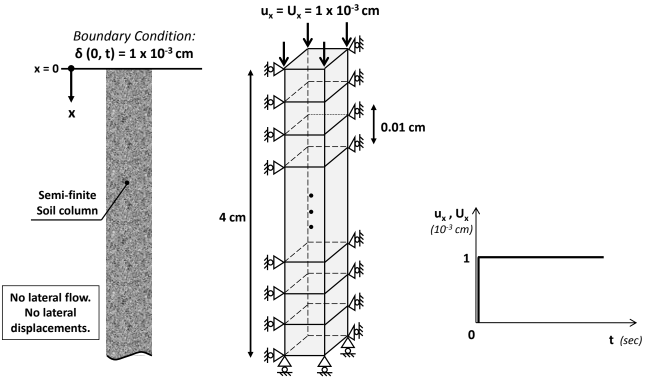
$$d = \frac{PL^3}{3EI} = \frac{9\mathrm{N} \times 1000\mathrm{m}^3}{3 \times 100000\mathrm{Pa} \times \frac{1}{12}\mathrm{m}^4} = 0.36m$$



errors : 0.47% 3.96% 22%

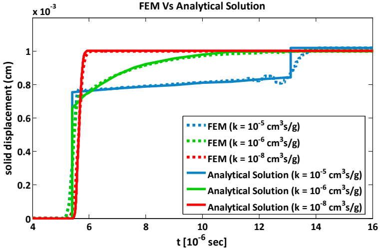
for nodal offset: 40% error: 2%

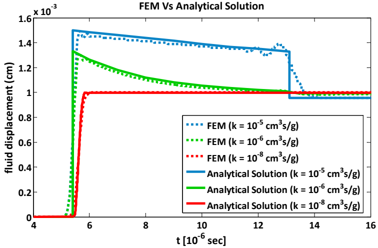
Shock Wave Propagation, Step Displacement



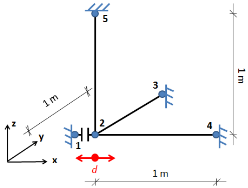
(a) (b) (c)

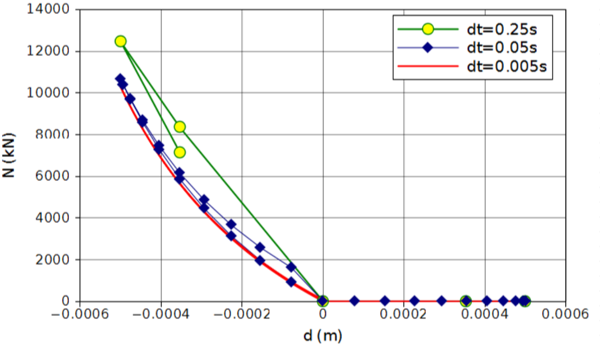
Shock Wave Propagation: Porous Solid, Pore Fluid





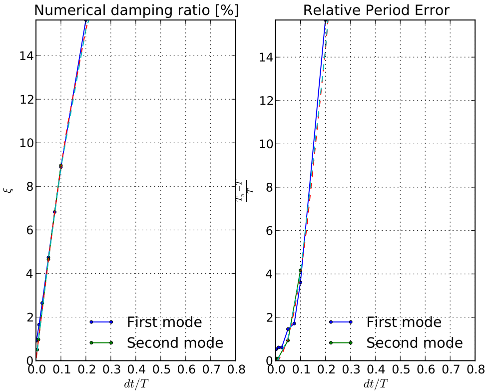
Verification for Dry Contact Element: Truss Model, Normal Displacement





Solution Advancement (Newmark, Hilber-Hughes-Taylor)

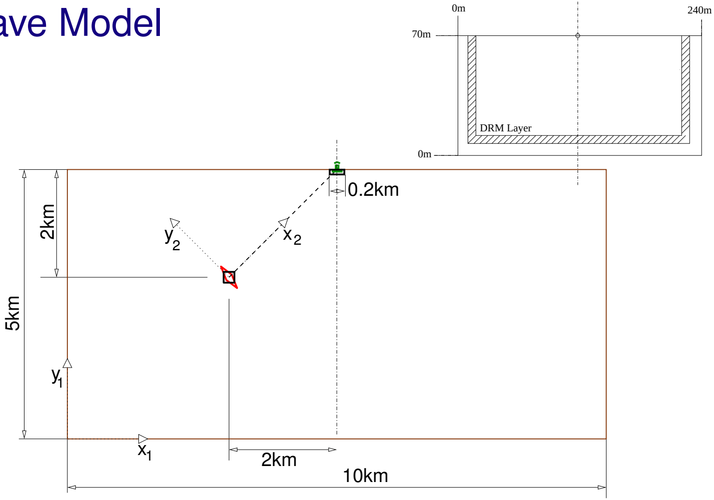
- Variable integration steps sizes, parameters (α, β, γ)
- Compare with theoretical algorithmic damping (spectral radius) and period shift



Seismic Body and Surface Waves

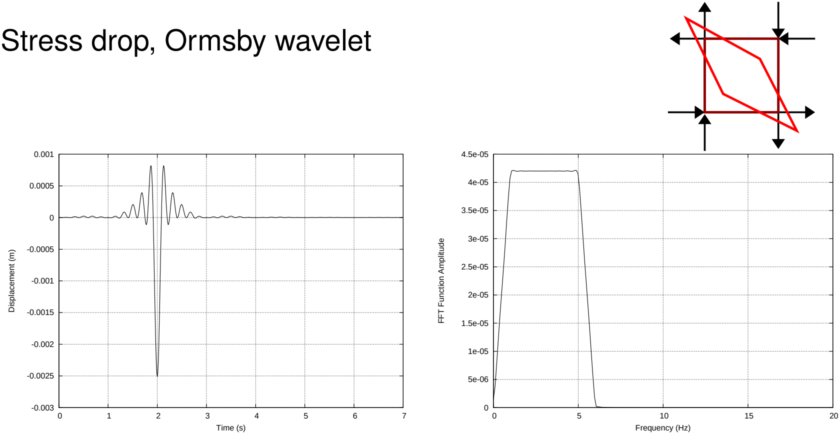
- Both body (P, SV and SH) and surface (Rayleigh, Love, etc.) waves are present
- Surface waves carry most seismic energy
- Analytic (Aki and Richards, Trifunac and Lee, Hisada et al., fk, etc.) and numerically generated, 3D, inclined (plane) body and surface waves are used in tests
- Seismic moment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

Plane Wave Model

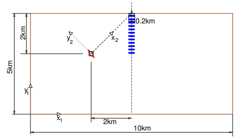


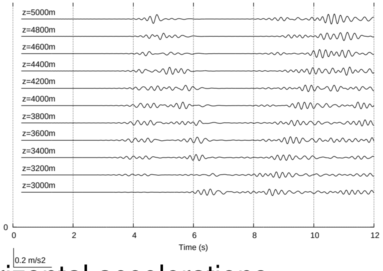
Seismic Source Mechanics

Stress drop, Ormsby wavelet

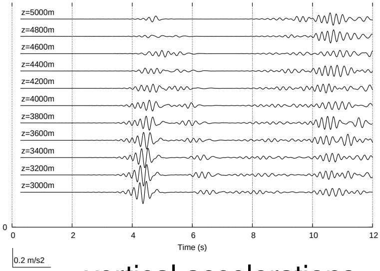


Middle (Structure Location) Plane, Top 2km





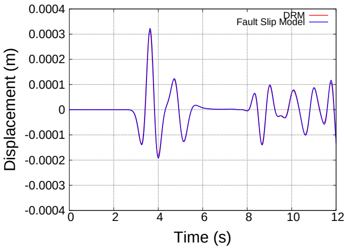
horizontal accelerations



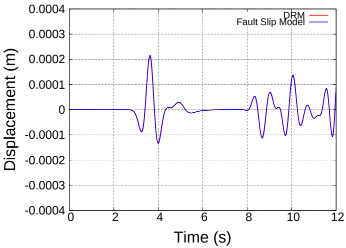
vertical accelerations

Verification: Displacements, Top Middle Point

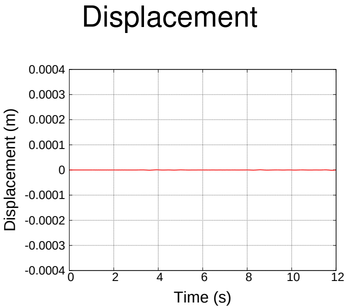
(X)

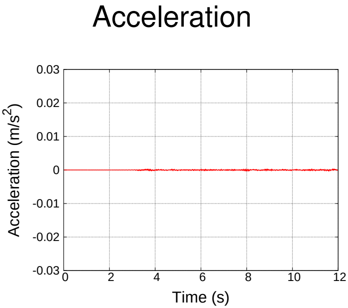


(Z)



Verification: Disp. and Acc., Out of DRM



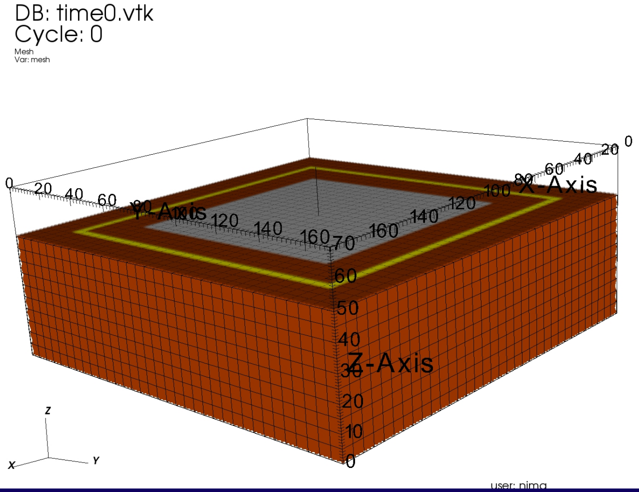


Outline

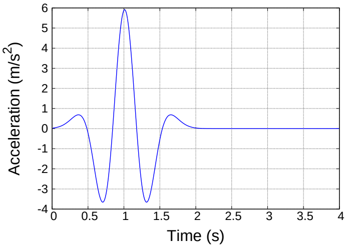
Influence of Inelastic Foundation-Soil/Rock Contact on the NPP Response

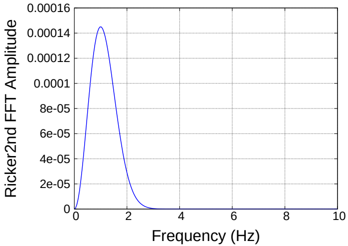
- Soil/rock – foundation interface slip behavior
- Changes in Earthquake Soil/Rock Structure Interaction (reduction or increase in demand)
- Dissipation of seismic energy in the slip plane
- Passive (and active) base isolation

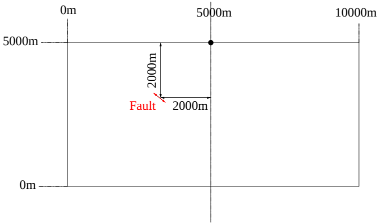
Example Model, ESSI with Slip



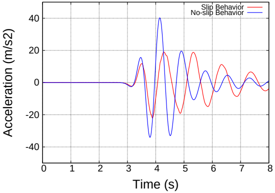
Full 3D (wave at 45^o) Ricker Wavelet



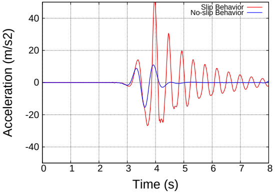




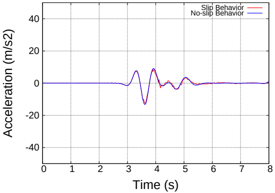
Acc. Response for a Full 3D (at 45°) Ricker Wavelet



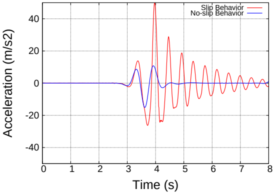
top X



top Z

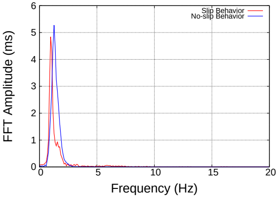


bottom X

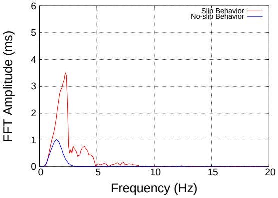


bottom Z

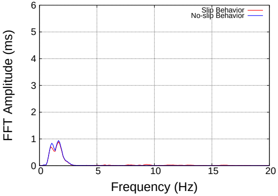
FFT Response for a Full 3D (at 45°) Ricker Wavelet



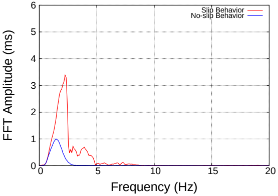
top X



top Z

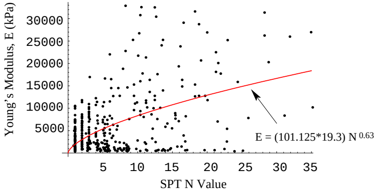


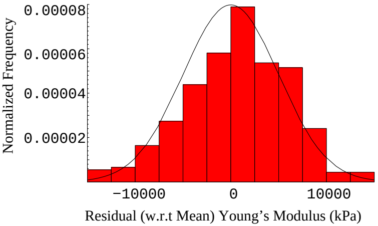
bottom X



bottom Z

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

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

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...

Spectral Stochastic Elastic–Plastic FEM

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

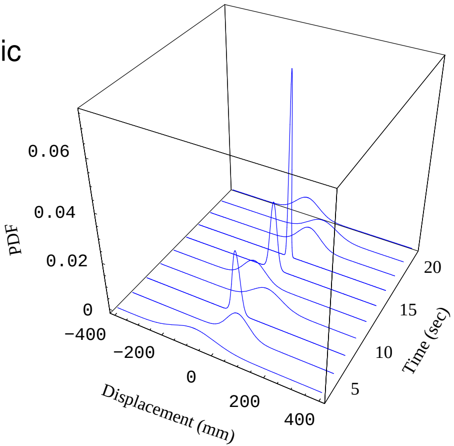
$$\sum_{n=1}^{N} K_{mn}^{ep} d_{ni} + \sum_{n=1}^{N} \sum_{j=0}^{P} d_{nj} \sum_{k=1}^{M} C_{ijk} K_{mnk}^{\prime ep} = \langle F_m \psi_i[\{\xi_r\}] \rangle$$

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

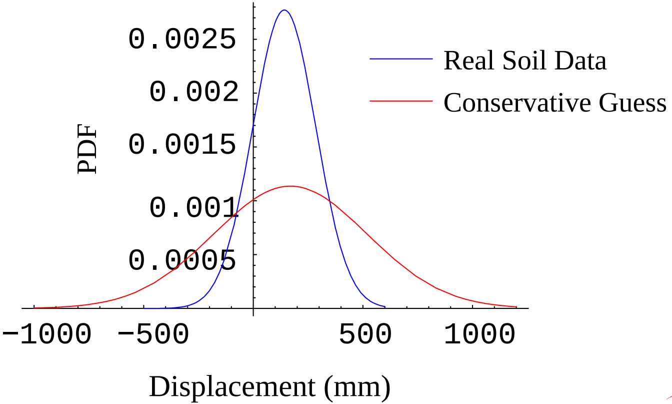
$$C_{ijk} = \left\langle \xi_k(\theta) \psi_i[\{\xi_r\}] \psi_j[\{\xi_r\}] \right\rangle \qquad F_m = \int_D \phi N_m dV$$

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

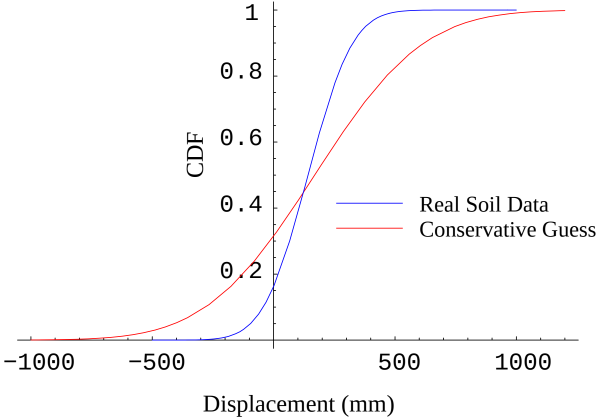
- Stochastic Elastic-Plastic Finite Element Method (SEPFEM)
- Dynamic case
- Full PDF at each time step Δt



PDF at each Δt (say at 6 s)



PDF → CDF (Fragility) at 6 s



Summary

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