Challenges and Tools for Non-Linear SSI Analysis

Boris Jeremić

University of California, Davis
Lawrence Berkeley National Laboratory, Berkeley

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Presentation Goals

- Briefly overview of most important current challenges for SSI modeling and simulation (personal view)
- Briefly overview select current work that aims to address some of those challenges
- Hope for a discussion/information about validation experiments (we are done with the verification for the most part)

Outline

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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))

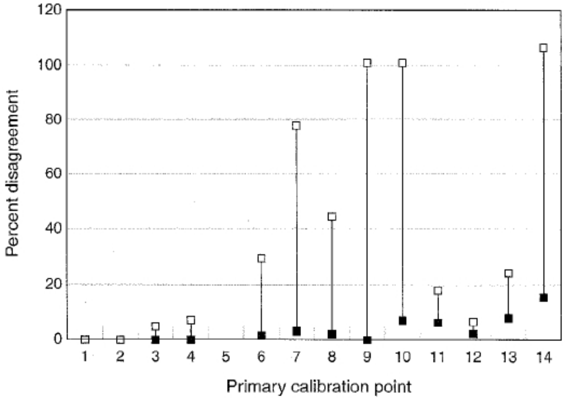
Errors in Scientific Software: The T Experiments

- 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"

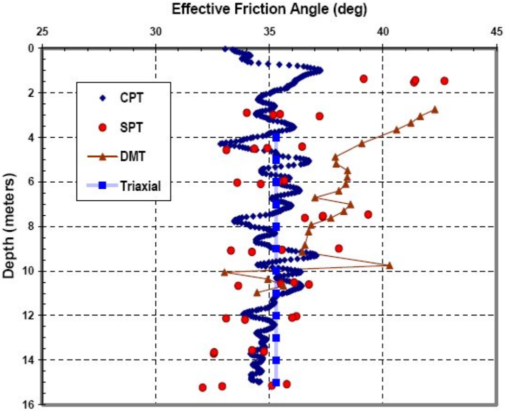
T2: Disagreement at Calibration Points



Outline

Material Behavior Inherently Uncertain

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

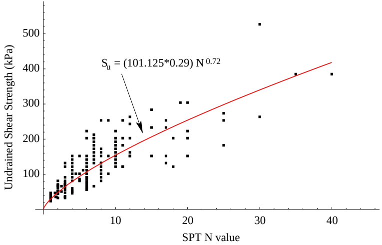


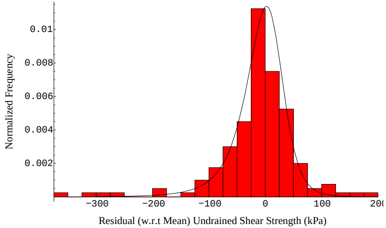
(Mayne et al. (2000)

Soil Uncertainties and Quantification

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

SPT Based Determination of Shear Strength

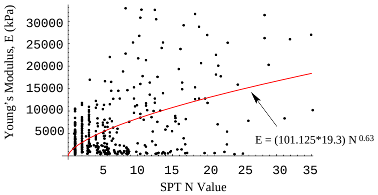


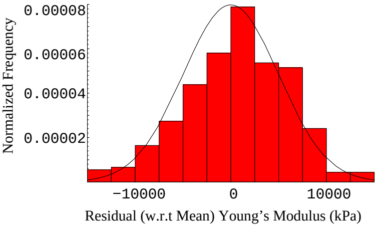


Transformation of SPT N-value $\rightarrow$ undrained shear strength, s_u (cf. Phoon and Kulhawy (1999B)

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

Outline

Verification & Validation (V&V) Definition

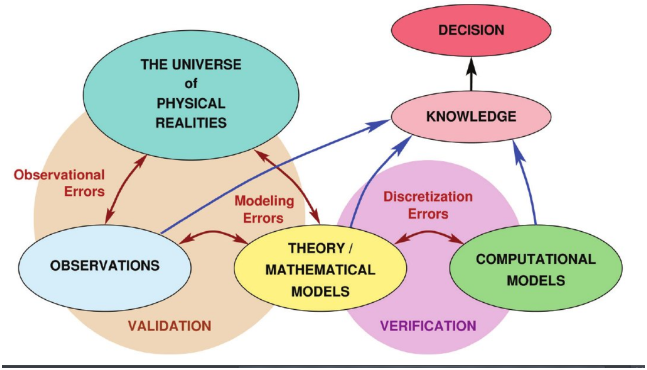
- **Verification**: The process of determining that a model implementation accurately represents the developer's conceptual description and specification. Mathematics issue. *Verification provides evidence that the model is solved correctly.*

- **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

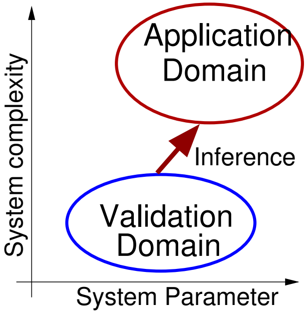


Oden et al.

Types of Physical Experiments

- **Traditional Experiments**
  - Improve the fundamental understanding of physics involved
  - Improve the mathematical models for physical phenomena
  - Assess component performance
- **Validation Experiments**
  - Model validation experiments
  - Designed and executed to quantitatively estimate mathematical model's ability to simulate well defined physical behavior
  - The simulation tool (SimTool) (conceptual model, computational model, computational solution) is the customer
  - Experimental uncertainty analysis!

Validation and Application Domains – No Overlap



- Inference $\Rightarrow$ probabilistic modeling and numerical simulation (deterministic is a special case)

Prediction

- 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
- Validation does not directly make a claim about the accuracy of a prediction
  - Computational models are easily misused (unintentionally or intentionally)
  - How closely related are the conditions of the prediction and specific cases in validation database
  - How well is physics of the problem understood

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

NRC ESSI Simulator Program

- Based on a Collection of Useful Libraries (library centric software design, modular, portable)
- A number of models, elements and algorithms available
- Detailed V&V (actually, good validation experiments are rare!)
- Current users, testers, collaborators: US-NRC, UCD students, National Laboratories, Foreign Nuclear Regulatory Agencies, Nuclear Power Companies

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

Part I: Theoretical and Computational Formulations

Part II: Software and Hardware Platform Design

Part III: Verification and Validation

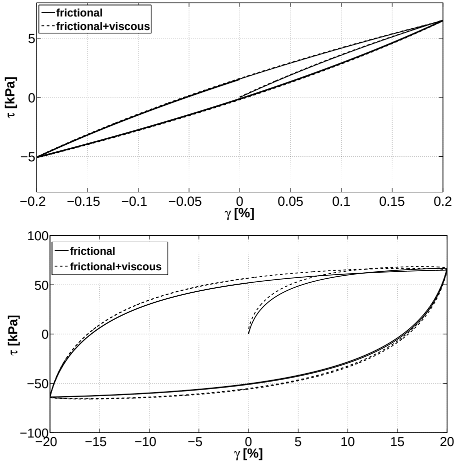
Part IV: Application to Practical Nuclear Power Plant Earthquake Soil/Rock Structure Interaction Problems

Outline

Pisanò Material Model: Brief Description

- Primary modeling objective: calibration of a 3D elastic-plastic model from G/G_{max} and damping curves
- 3D elastic-plastic material model, with vanishing elastic region, rotational kinematic hardening, bounding surface, and stress split into frictional and viscous components
- No volume change data (since it is missing in G/G_{max} and damping curve data), however, volume modeling can be calibrated as well if data is available

Pure Shear Cyclic



Calibration for G/G_{max} and Damping

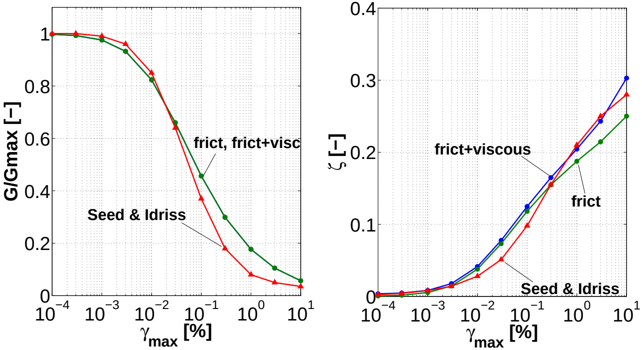


Figure: Comparison between experimental and simulated G/G_{max} and damping curves (p_0=100 kPa, T=2π s, ζ = 0.003, G_{max} = 4 MPa, ν=0.25, M=1.2, k_d=ξ=0, h=$G_{max}/(15p_0)$, m=1)

Variation in Viscous Damping

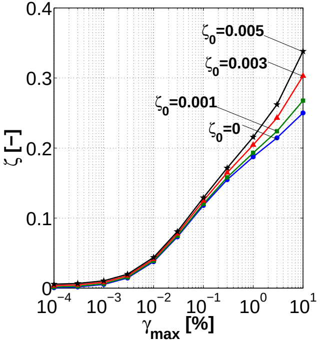
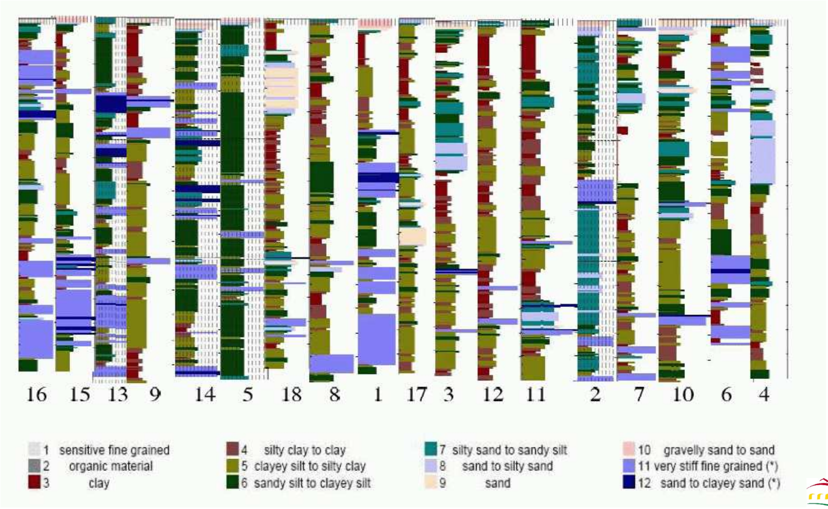


Figure: Damping curves simulated at varying ζ_0 (p_0=100 kPa, $T=2\pi$ s, G_{max} = 4 MPa, ν=0.25, M=1.2, $k_d=\xi=0$, $h=G_{max}/(15p_0)$, m=1)

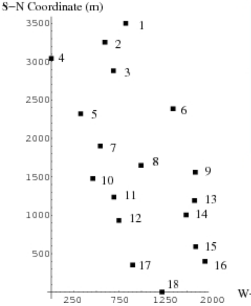
Outline

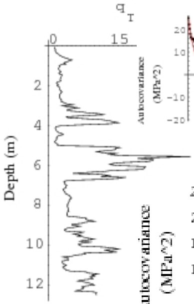
"Uniform" CPT Site Data



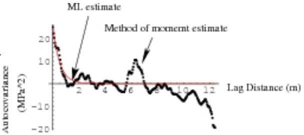
Seismic Wave Propagation through Stochastic Soil

- Maximum likelihood estimates

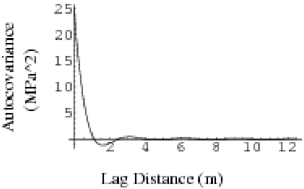




Typical CPT q_T



Finite Scale



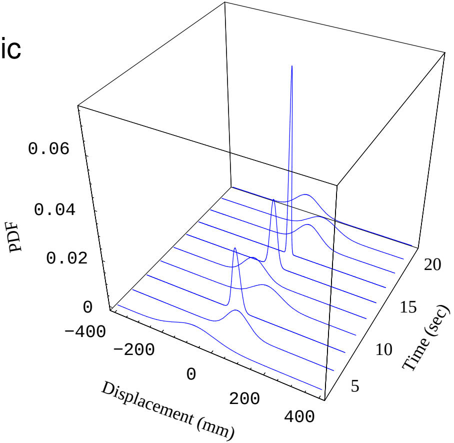
Fractal

Random Field Parameters from Site Data

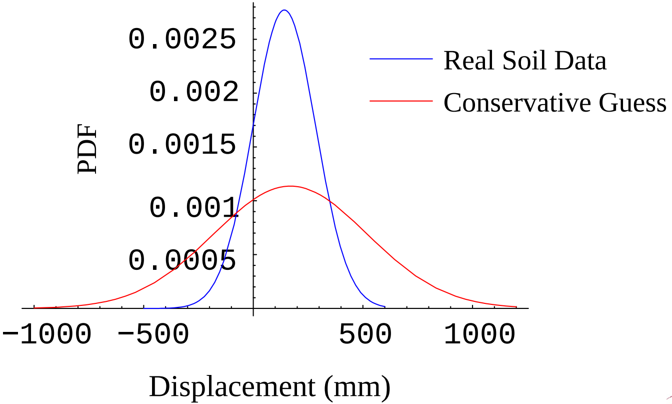
- Soil as 12.5 m deep 1–D soil column (von Mises Material)
  - Properties (including testing uncertainty) obtained through random field modeling of CPT q_T
    $\langle q_T \rangle = 4.99\ MPa$; $Var[q_T] = 25.67\ MPa^2$;
    Cor. Length $[q_T] = 0.61\ m$; Testing Error $= 2.78\ MPa^2$
- q_T was transformed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

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

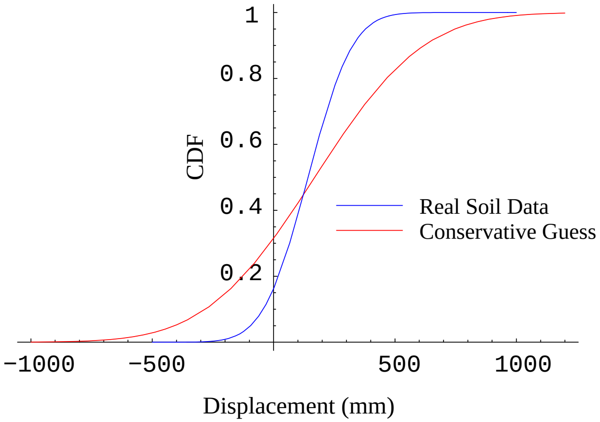
- Stochastic Elastic-Plastic Finite Element Method (SEPFEM)
- Dynamic case
- Full PDF at each time step Δt



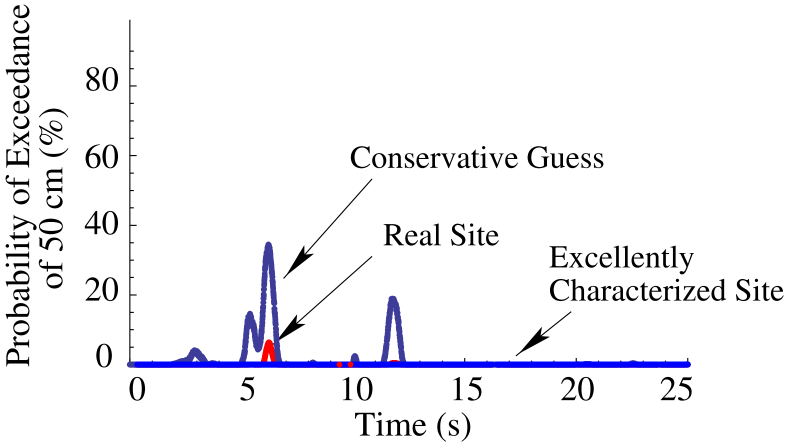
PDF at each Δt (say at 6 s)



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



Probability of Unacceptable Deformation (say 50cm)



Summary and Credits

- **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** are essential!
- Post-Docs and Students: Tafazzoli, Pisanò, Martinelli, Kamrani, Abell, Jeong, Aldridge, Anderson
- Acknowledgement: funding from and collaboration with the US-NRC, CNSC and funding from NSF and DOE is much appreciated