Computational Modeling and Simulation of Earthquake Soil Structure Interaction Behavior of Nuclear Installations

Boris Jeremić

University of California, Davis, CA
and
Lawrence Berkeley National Laboratory, Berkeley, CA

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Outline

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Motivation

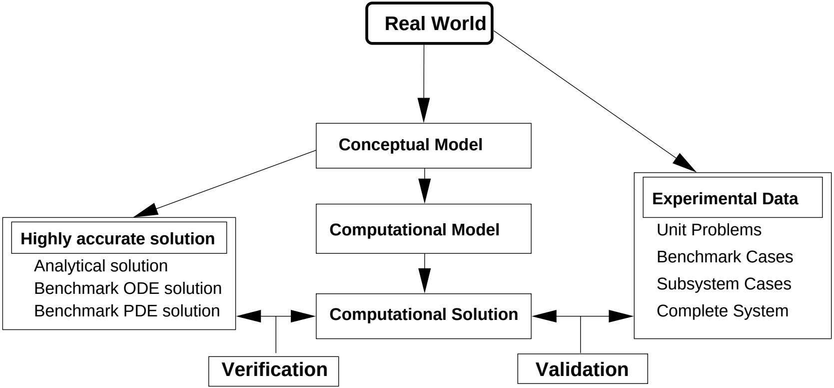
- Improve modeling and simulation for seismic behavior of Nuclear Installations
- Reduce modeling uncertainty
- Follow the flow, input and dissipation, of seismic energy,
- Practical system for modeling and simulation of Earthquakes, Soils, Structures and their Interaction (ESSI):

http://real-essi.info/

Predictive Capabilities

- Prediction under Uncertainty
- Verification: evidence that the model is solved correctly.
- Validation: evidence that the correct model is solved.
- Modeling and parametric uncertainties are always present
- Goal: Predict and Inform rather than (force) Fit
- Risk informed is not enough $\rightarrow$ full risk calculations for ESSI, analytical/numerical, accurate

Verification and Validation Details



Verification

The process of determining that a model implementation accurately represents the developer's conceptual description and specification.

- Identify and remove errors in computer coding
  - Numerical algorithm verification
  - Software quality assurance practice
- Quantification of the numerical errors in computed solution

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.

- Tactical goal: Identification and minimization of uncertainties and errors in the computational model
- Strategic goal: Increase confidence in the quantitative predictive capability of the computational model

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, Real-ESSI, computational model, computational solution, is the customer

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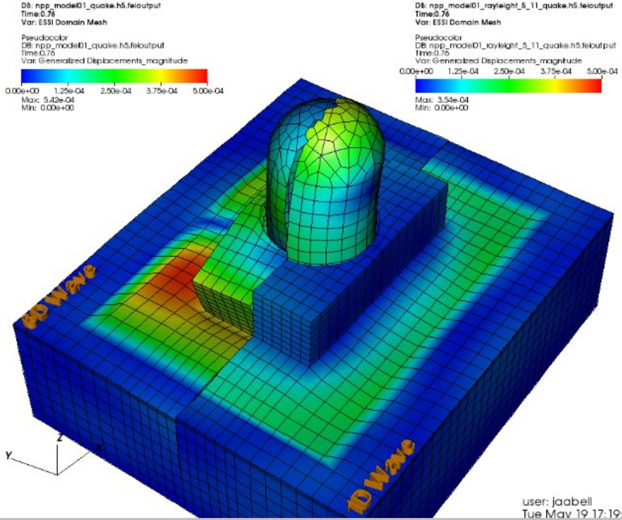
Uncertainties

- Modeling Uncertainty, from simplifying assumptions
  - Low, medium, high sophistication modeling and simulation
  - Sophistication level for confidence in analysis results
- Parametric Uncertainty, $M\ddot{u}_i + C\dot{u}_i + K^{ep}u_i = F(t)$
  - Propagation of uncertainty in M, C and K^{ep}
  - Propagation of uncertainty in loads, $F(t)$
  - Results are PDFs and CDFs for σ_{ij}, ϵ_{ij}, u_i, $\dot{u}_i$, $\ddot{u}_i$

Modeling Uncertainty

- Simplified modeling: Features (important ?) are neglected (3C, 6C ground motions, inelasticity)
- Modeling Uncertainty: unrealistic and unnecessary modeling simplifications
- Modeling simplifications are justifiable if one or two level higher sophistication model shows that features being simplified out are not important

Modeling Uncertainty, 6C vs 1C Motions



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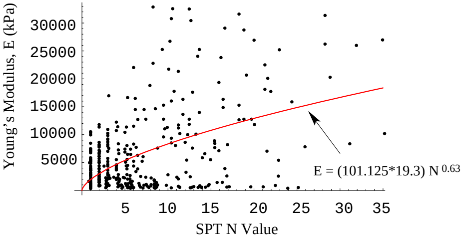
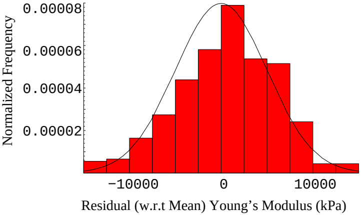
Parametric Uncertainty: Soil Stiffness





cf. Phoon and Kulhawy (1999B)

Outline

Energy Input and Dissipation

Energy input, static and dynamic forcing

Energy dissipation outside SSI domain:

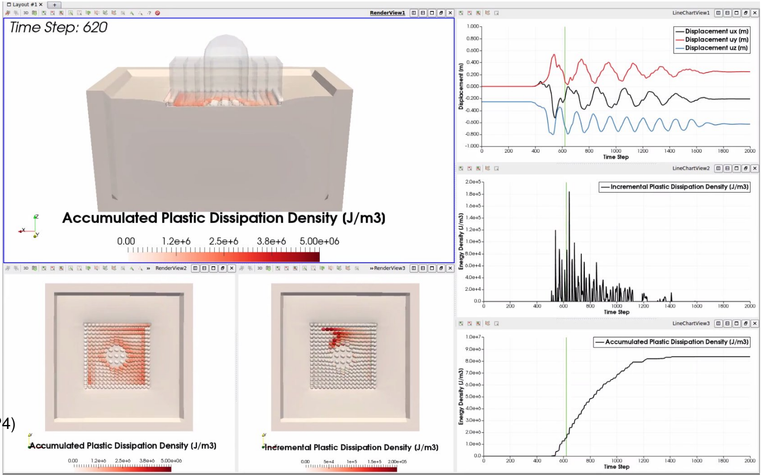
- SSI system oscillation radiation
- Reflected wave radiation

Energy dissipation/conversion inside SSI domain:

- Inelasticity of soil, contact zone, structure, foundation, dissipators
- Viscous coupling with internal/pore fluids, and external fluids

Numerical energy dissipation/production

Energy Dissipation in NPP Model



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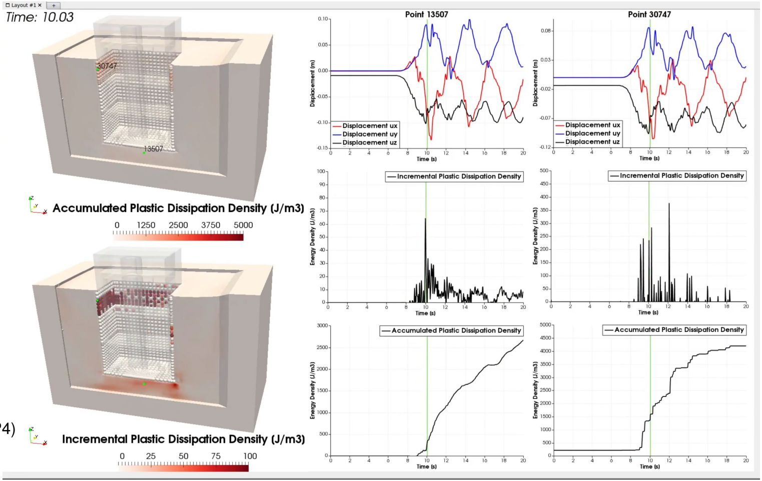
Energy Dissipation for an SMR Model



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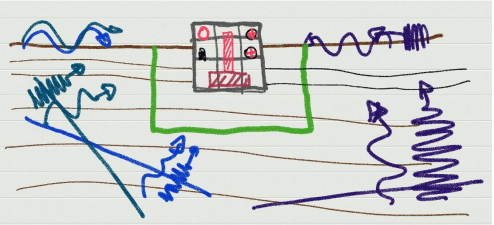
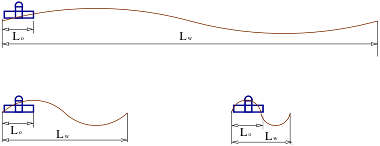
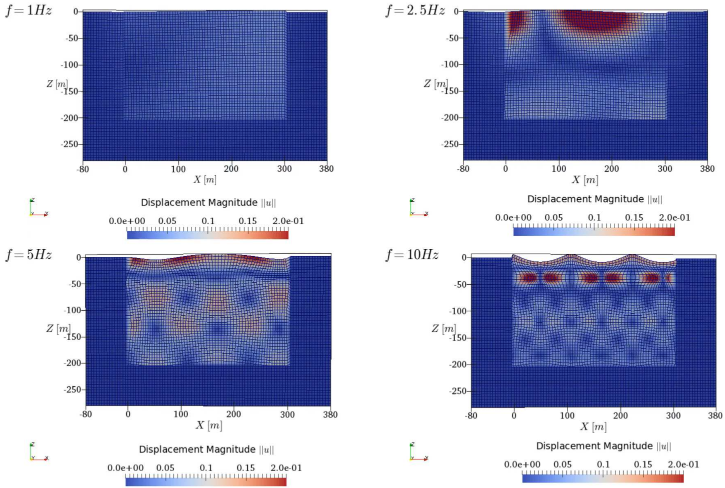
Seismic Motions

- Variation in inclination, frequency, energy, duration...
- Deterministic and Probabilistic
- Stress test the soil-structure system





Free Field, Variation in Input Frequency, $\theta = 60^o$



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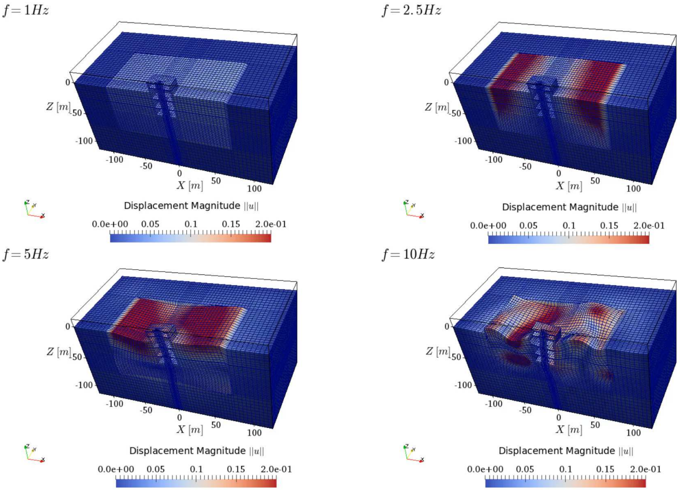
SMR ESSI, Variation in Input Frequency, $\theta = 60^o$



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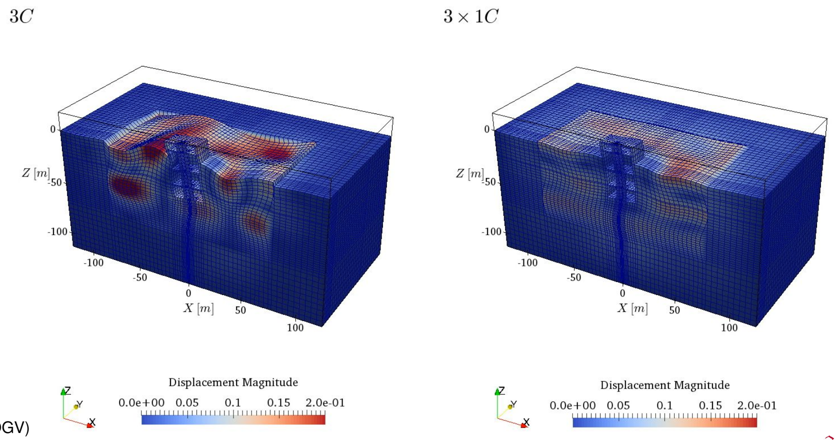
SMR ESSI, 3C vs 3×1C



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Outline

Uncertainty Propagation through Inelastic System

- Incremental el–pl constitutive equation

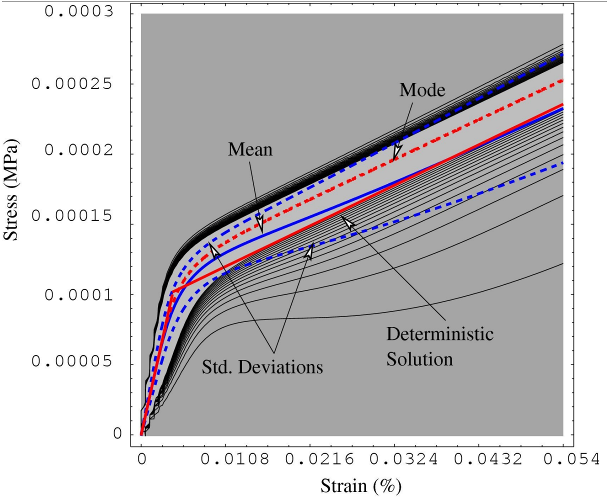
$$\Delta\sigma_{ij} = E^{EP}_{ijkl}\ \Delta\epsilon_{kl} = \left[E^{el}_{ijkl} - \frac{E^{el}_{ijmn} m_{mn} n_{pq} E^{el}_{pqkl}}{n_{rs} E^{el}_{rstu} m_{tu} - \xi_* h_*} \right] \Delta\epsilon_{kl}$$

- Dynamic Finite Elements

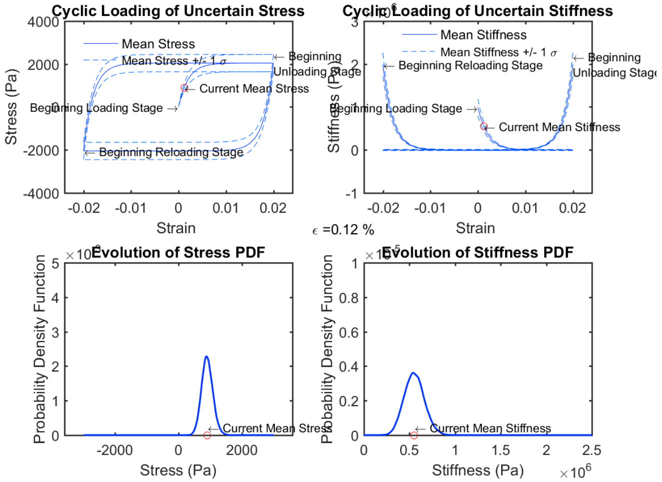
$$M\ddot{u}_i + C\dot{u}_i + K^{ep} u_i = F(t)$$

- Material and load parameters are uncertain

Probabilistic Elastic-Plastic Response



Probabilistic Elastic-Plastic Modeling



Stochastic Elastic-Plastic Finite Element Method

- Material uncertainty expanded into stochastic shape funcs.
- Loading uncertainty expanded into stochastic shape funcs.
- Displacement expanded into stochastic shape funcs.

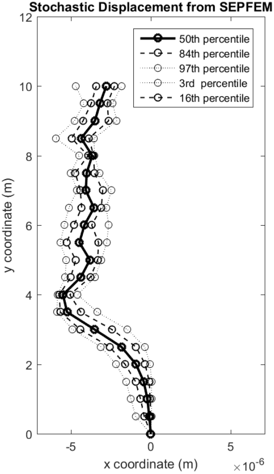
$$
\begin{bmatrix}
\sum_{k=0}^{P_d} < \Phi_k \Psi_0 \Psi_0 > K^{(k)} & \dots & \sum_{k=0}^{P_d} < \Phi_k \Psi_P \Psi_0 > K^{(k)} \\
\sum_{k=0}^{P_d} < \Phi_k \Psi_0 \Psi_1 > K^{(k)} & \dots & \sum_{k=0}^{P_d} < \Phi_k \Psi_P \Psi_1 > K^{(k)} \\
\vdots & \vdots & \vdots & \vdots \\
\sum_{k=0}^{P_d} < \Phi_k \Psi_0 \Psi_P > K^{(k)} & \dots & \sum_{k=0}^{M} < \Phi_k \Psi_P \Psi_P > K^{(k)}
\end{bmatrix}
\begin{bmatrix}
\Delta u_{10} \\ \vdots \\ \Delta u_{N0} \\ \vdots \\ \Delta u_{1P_u} \\ \vdots \\ \Delta u_{NP_u}
\end{bmatrix}
=
\begin{bmatrix}
\sum_{i=0}^{P_f} f_i < \Psi_0 \zeta_i > \\
\sum_{i=0}^{P_f} f_i < \Psi_1 \zeta_i > \\
\sum_{i=0}^{P_f} f_i < \Psi_2 \zeta_i > \\
\vdots \\
\sum_{i=0}^{P_f} f_i < \Psi_{P_u} \zeta_i >
\end{bmatrix}
$$

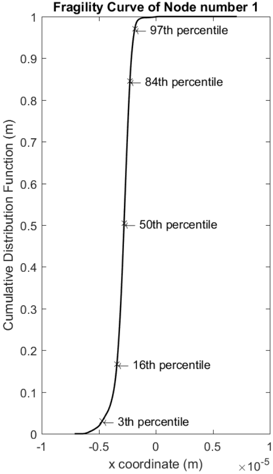
SEPFEM: System Size

- SEPFEM offers a complete solution (single step)
- It is NOT based on Monte Carlo approach
- System of equations does grow (!)

# KL terms material	# KL terms load	PC order displacement	Total # terms per DoF
4	4	10	43758
4	4	20	3 108 105
4	4	30	48 903 492
6	6	10	646 646
6	6	20	225 792 840
6	6	30	$1.1058\ 10^{10}$
8	8	10	5 311 735
8	8	20	$7.3079\ 10^{9}$
8	8	30	$9.9149\ 10^{11}$
...	...	...	...

SEPFEM: Example in 1D





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Summary

- Numerical modeling to predict, rather than fit
- Education and Training is the key!
- Real-ESSI Simulator System:
  `http://real-essi.info/`