Site Specific Dynamics of Structures: From Seismic Source to the Safety of Occupants and Content

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Outline

Motivation

Improve seismic modeling and simulation for infrastructure objects

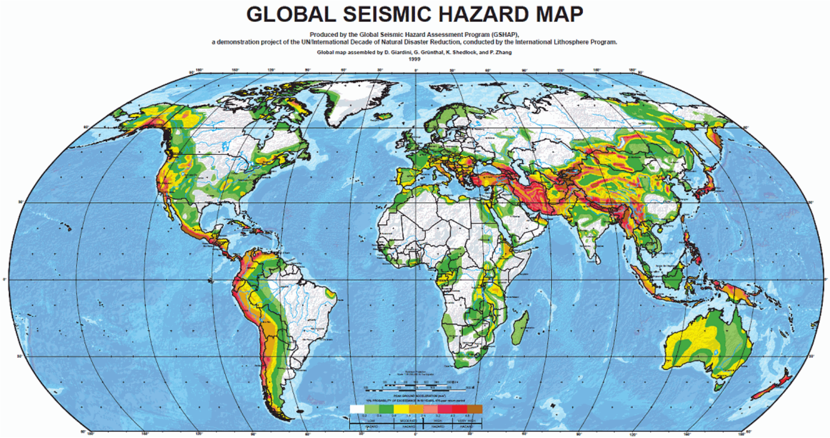
Use of high fidelity numerical models to analyze seismic behavior of soil structure systems

Reduction of modeling uncertainty, ability to perform high(er) level of sophistication modeling and simulation

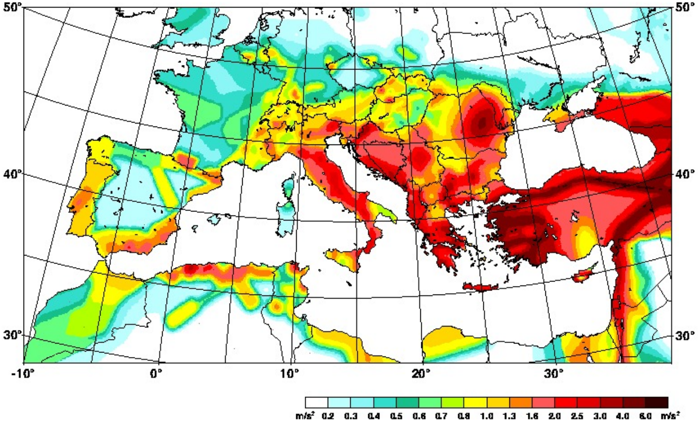
Accurately follow the flow of seismic energy in a soil structure system

Personalization of the seismic problem

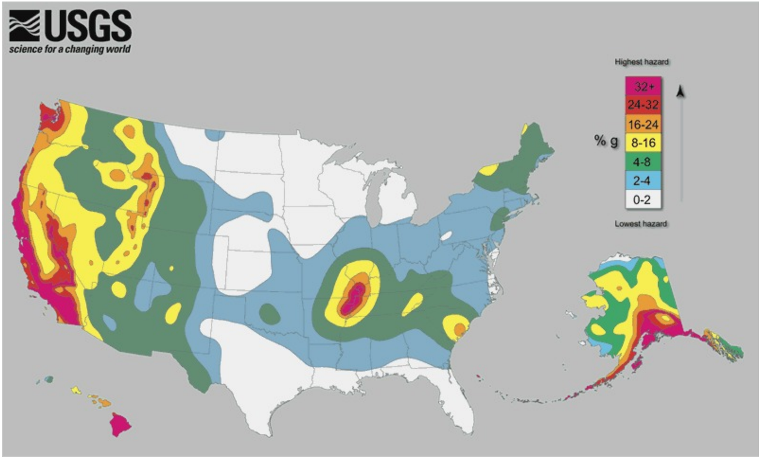
Seismic Hazard, World



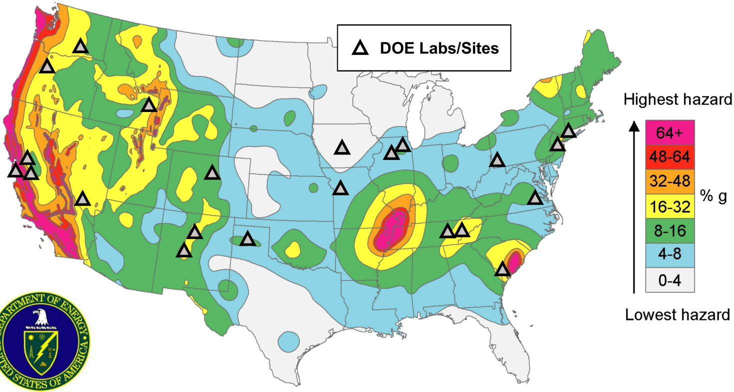
Seismic Hazard, Rhodes



Seismic Hazard, USA



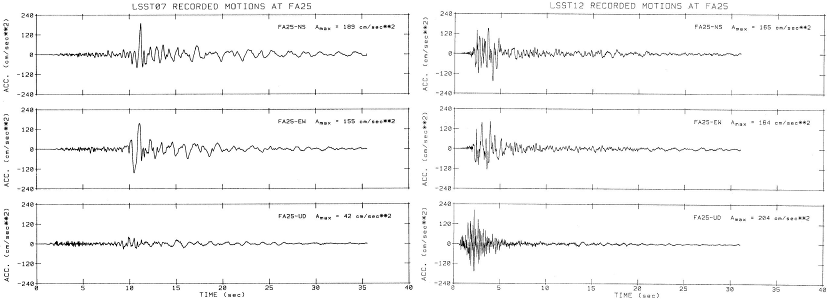
Seismic Hazard, DOE Facilities



Outline

3D (6D) Seismic Motions

- All (most) measured motions are full 3D (6D)
- One example of an almost 2D motion (LSST07, LSST12)

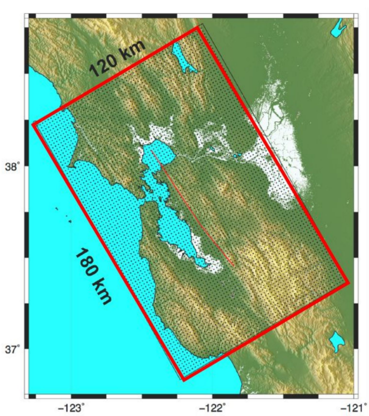


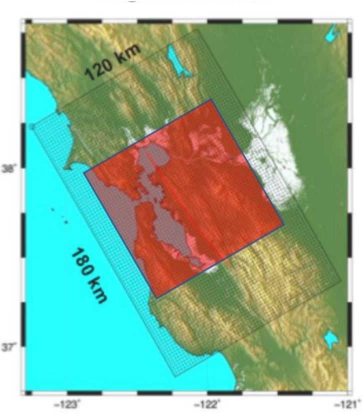
- 1D (?): M 6.9 San Pablo, Guatemala EQ, 14Jun2017

Regional Geophysical Models

- High fidelity free field seismic motions on regional scale
- Knowledge of geology (deep and shallow) needed
- High Performance Computing using SW4 on CORI (LBNL)
- Collaboration with LLNL: Dr. Rodgers, Dr. Pitarka and Dr. Petersson

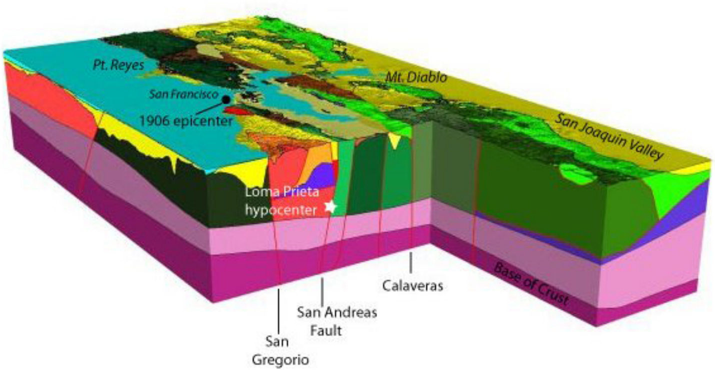
Regional Geophysical Models





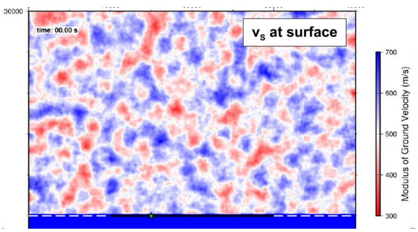
Rodgers and Pitarka

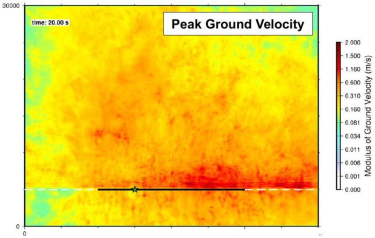
Regional Geophysical Models



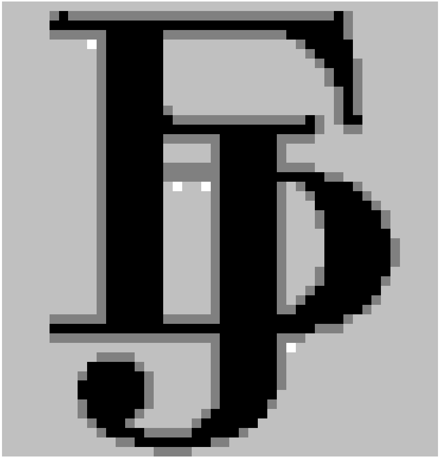
USGS

Example Regional Model

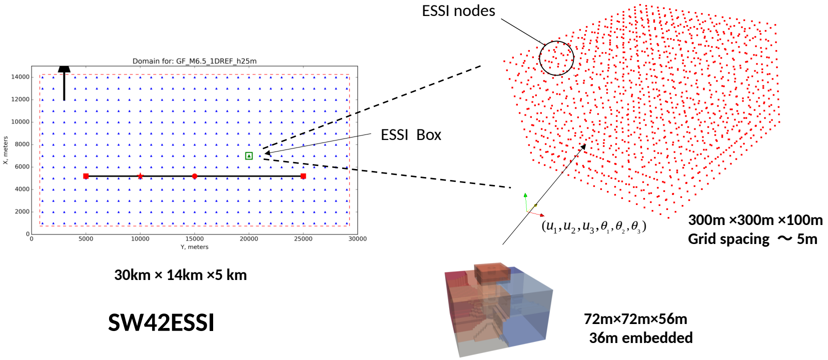




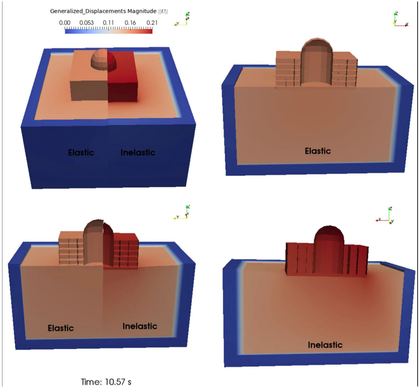
Example Regional Model (Rodgers)



Seismic Motions: SW4 to Real ESSI



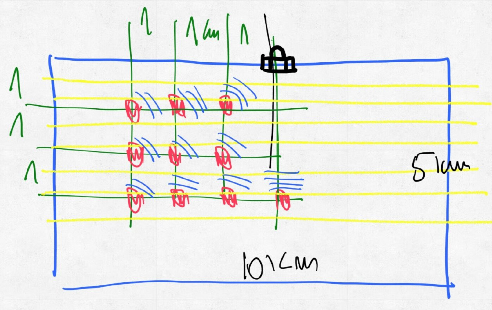
Dynamic Response of an Important Object (NPP)



Outline

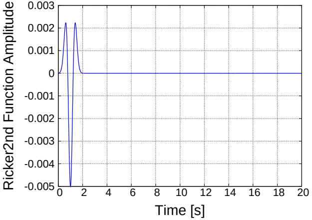
Stress Testing SSI Systems

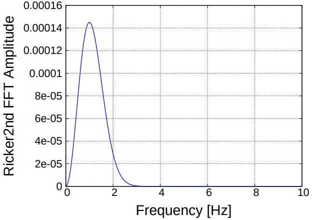
- Excite SSI system with a suite of seismic motions
- Simple sources, variation in strike and dip, P and S waves, surface waves (Rayleigh, Love, etc.)
- Stress test soil-structure system
- Try to "break" the system, shake-out strong and weak links



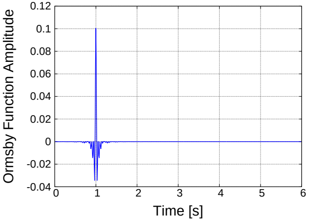
Stress Test Source Signals

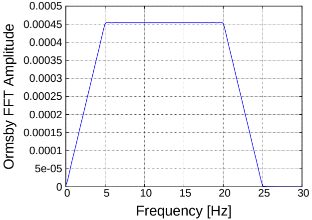
- Ricker





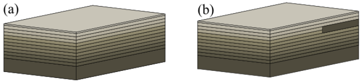
- Ormsby



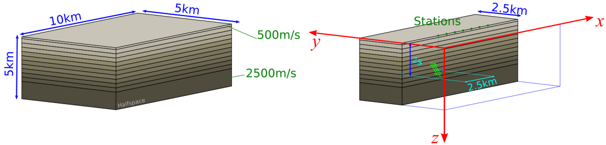


Layered and Dyke/Sill Models

- (a) Horizontal layers
- (b) Dyke/Sill intrusion

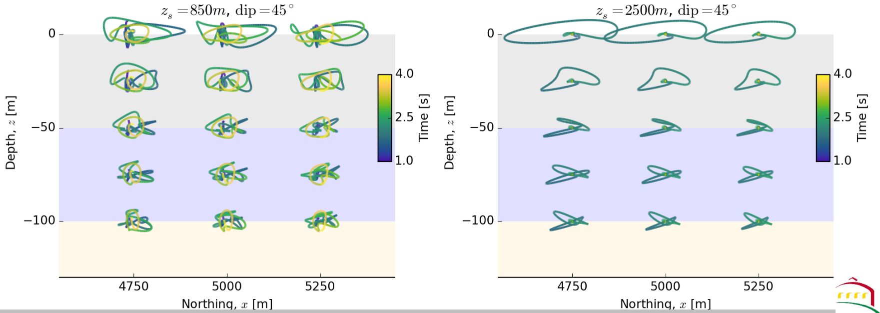


- Source locations matrix (point sources)
- Source strike and dip variation
- Magnitude variations
- Range of frequencies

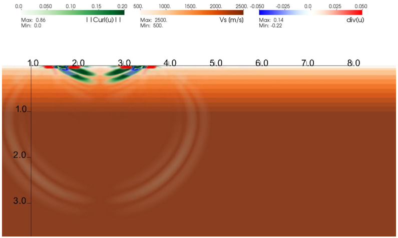


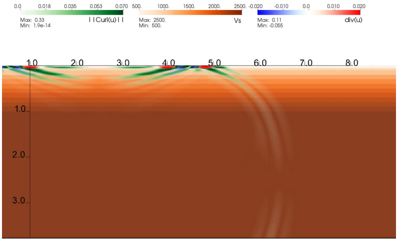
Layered System, Displacement Traces

- Epicenter is 2500m away from the location of interest
- Source depth 850m (left) and 2500m (right)
- Different wave propagation path to the point of interest
- Surface waves quite pronounced
- Layered geology did not filter out surface waves



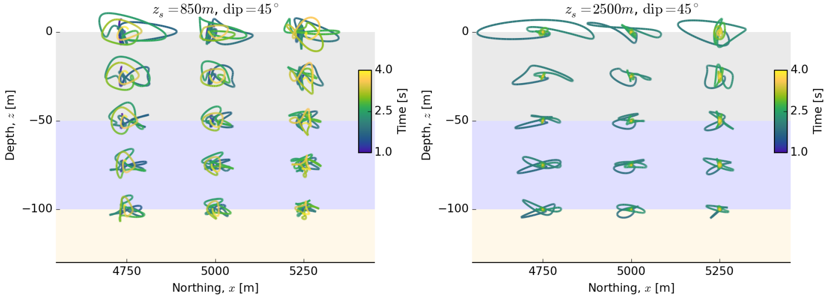
Layered System, Variable Source Depth



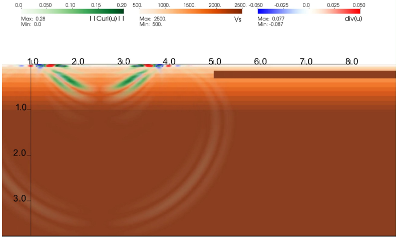


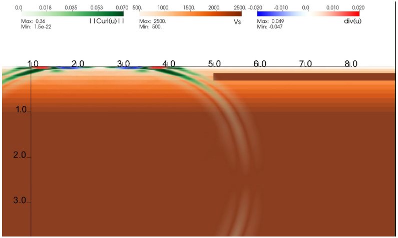
Dyke/Sill Intrusion, Variable Source Depth

- Lower amplitudes than with layered only model!
- Difference in body and surface wave arrivals
- Surface waves present, more complicated wave field



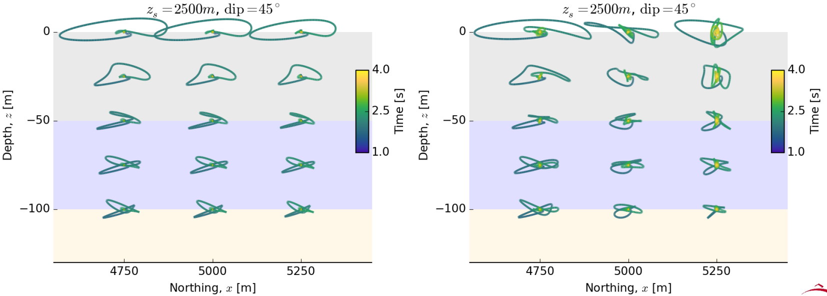
Dyke/Sill Intrusion, Variable Source Depth





Dyke/Sill as Seismic Energy Sink

- Dyke/Sill (right Fig), made of stiff rock, is an energy sink, as well as energy reflector
- Variable wave lengths behave differently, depending on dyke/sill geometry and location



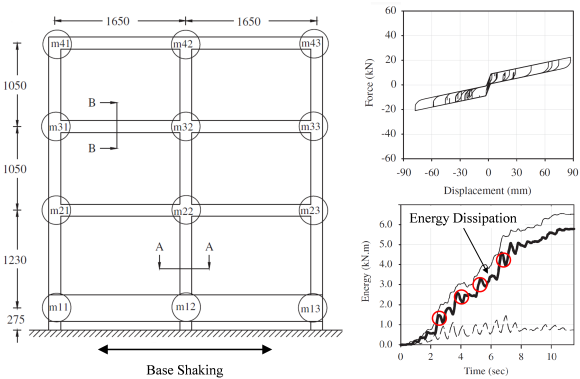
Outline

Seismic Energy Input and Dissipation

- Seismic energy input, through a closed boundary (DRM)
- Mechanical dissipation outside SSI domain:
  - Reflected wave radiation
  - SSI system oscillation radiation
- Mechanical dissipation/conversion inside SSI domain:
  - Inelasticity of soil and contact zone
  - Inelasticity/damage of structure and foundation
  - Viscous coupling of fluids and soils and structure
- Numerical energy dissipation/production

Incremental Plastic Work: $dW_p = \sigma_{ij} \, d\epsilon_{ij}^{pl}$

- Negative incremental energy dissipation
- Plastic work is NOT plastic dissipation



From a paper on *Soil Dynamics and Earthquake Engineering* (2011)

Negative Incremental Energy Dissipation!

Direct violation of the second law of thermodynamics

600 papers since 1990 (!?!) repeat this error

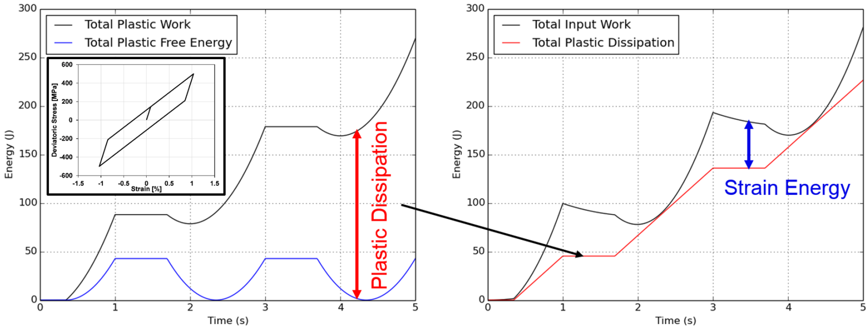
Important form of energy missing: Plastic Free Energy

First described by Taylor and Quinney in 1934!

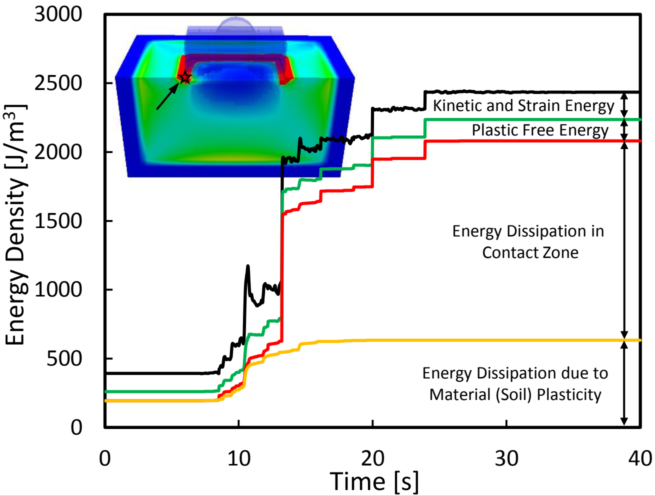
Plastic Work vs. Plastic Energy Dissipation

Energy Dissipation on Material Level

- Single elastic-plastic element under cyclic shear loading
  - Difference between plastic work and dissipation
  - Plastic work can decrease, dissipation always increases

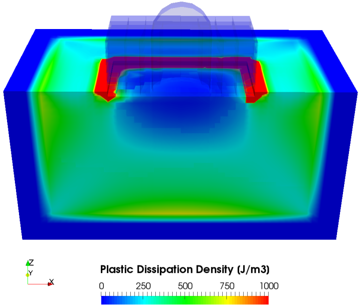


Energy Dissipation in a Large-Scale Model (NPP)

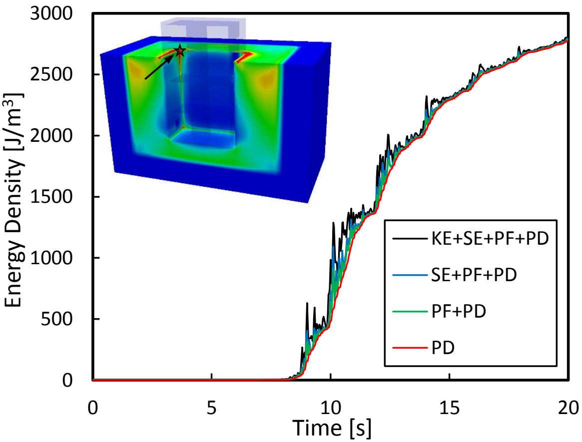


Energy Dissipation in Large-Scale Model (NPP)

Elastoplastic soil with contact elements

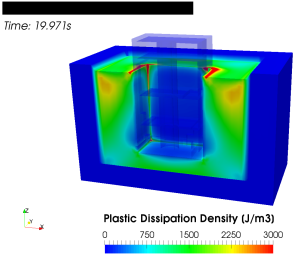


Energy Dissipation in Large-Scale Model (SMR)



Energy Dissipation in Large-Scale Model (SMR)

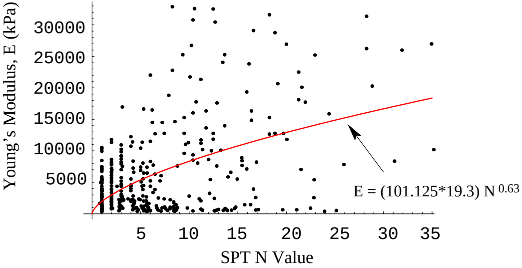
Elastoplastic soil without contact elements

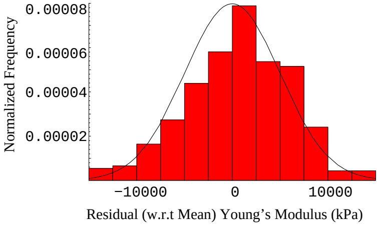


Outline

Parametric Uncertainty: Material and Loads

- Significant uncertainty in material and loads
- Propagate uncertainties in space and time





Transformation of SPT *N*-value: 1-D Young's modulus, *E* (cf. Phoon and Kulhawy (1999B))

Stochastic Elastic-Plastic Finite Element Method (SEPFEM)

Material uncertainty expanded along stochastic shape functions: $D(x,t,\theta) = \sum_{i=0}^{P_d} r_i(x,t) * \Phi_i[\{\xi_1, ..., \xi_m\}]$

Loading uncertainty expanded along stochastic shape functions: $f(x,t,\theta) = \sum_{i=0}^{P_f} f_i(x,t) * \zeta_i[\{\xi_{m+1}, ..., \xi_f]$

Displacement expanded along stochastic shape functions: $u(x,t,\theta) = \sum_{i=0}^{P_u} u_i(x,t) * \Psi_i[\{\xi_1, ..., \xi_m, \xi_{m+1}, ..., \xi_f\}]$

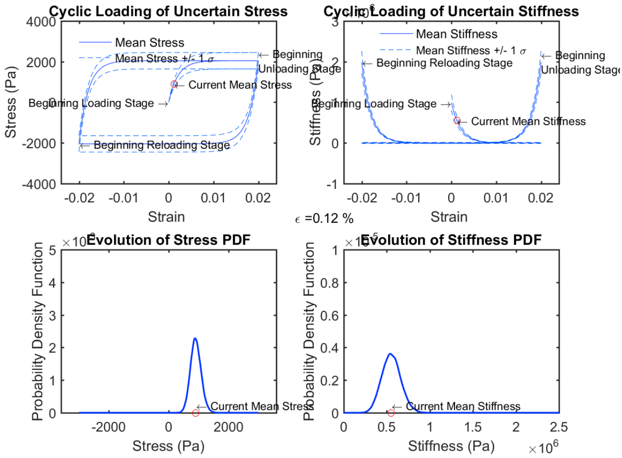
SEPFEM : Formulation

Stochastic system of equation resulting from Galerkin approach

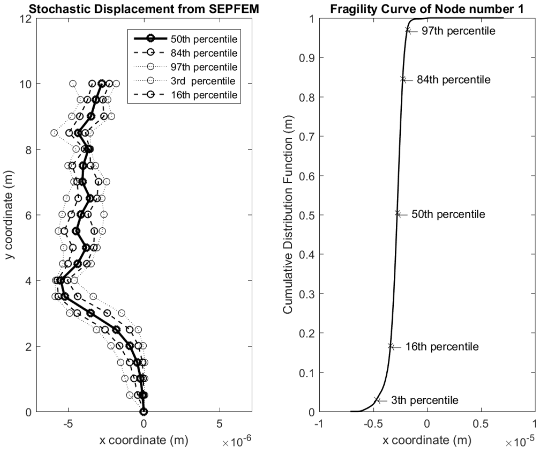
$$
\begin{bmatrix}
\sum_{k=0}^{P_d} < \Phi_k \Psi_0 \Psi_0 > K^{(k)} & \dots & \sum_{k=0}^{P_d} < \Phi_k \Psi_P \Psi_0 > K^{(k)} \\
\sum_{k=0}^{P_d} < \Phi_k \Psi_0 \Psi_1 > K^{(k)} & \dots & \sum_{k=0}^{P_d} < \Phi_k \Psi_P \Psi_1 > K^{(k)} \\
\vdots & \vdots & \vdots \\
\sum_{k=0}^{P_d} < \Phi_k \Psi_0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

# 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	$1.1058\ 10^{10}$
...	...	...	...

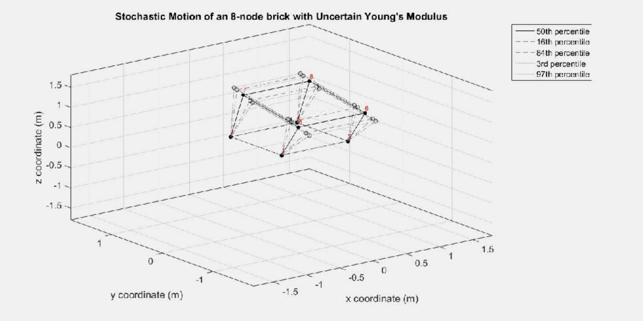
SEPFEM : Probabilistic Elastic-Plastic Modeling



SEPFEM : Example in 1D



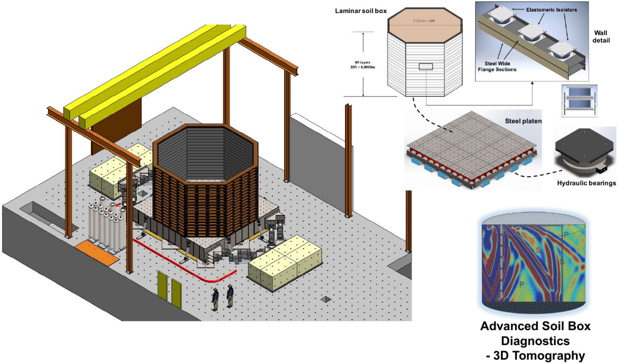
SEPFEM : Example in 3D



Outline

US-DOE Project for ESSI of Nuclear Facilities

- The Real ESSI Simulator (inelastic, deterministic and probabilistic, time domain, 3D FEM)
- Modeling from seismic source to NPP (SW4, Real ESSI)
- Extensive Verification (NQA-1, ISO), and Validation



Summary

Importance of using proper models correctly (verification, validation, level of sophistication)

Personalization of the Earthquake Soil Structure Interaction (ESSI) problem

Development of the Real ESSI Simulator system http://real-essi.us

Collaborators: Feng, Lacour, Han, Behbehani, Sinha, Wang, Pisanó, Abell, McCallen, McKenna, Petrone, Rodgers, Petersson, Pitarka

Funding from and collaboration with the US-DOE, US-NRC, US-NSF, CNSC-CCSN, UN-IAEA, and Shimizu Corp. is greatly appreciated,