Seismic Risk Analysis: Time Domain, Intrusive, Stochastic Elastic Plastic Finite Element Method

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CompDyn
Crete, June 2019

Outline

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Motivation

- Improve modeling and simulation for infrastructure objects
- Use of numerical modeling for design and assessment
- Analysis uncertainties
  - Modeling uncertainty
  - Parametric uncertainty

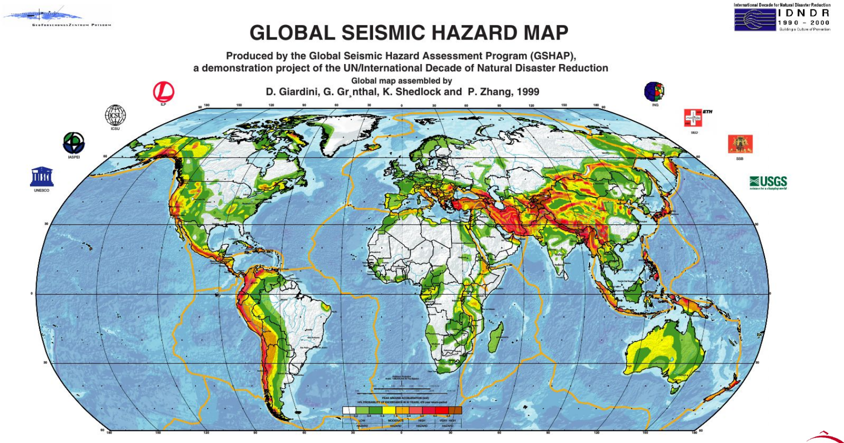
Personal Risk

Personal exposure to natural and man made hazard

Decision making under uncertainty

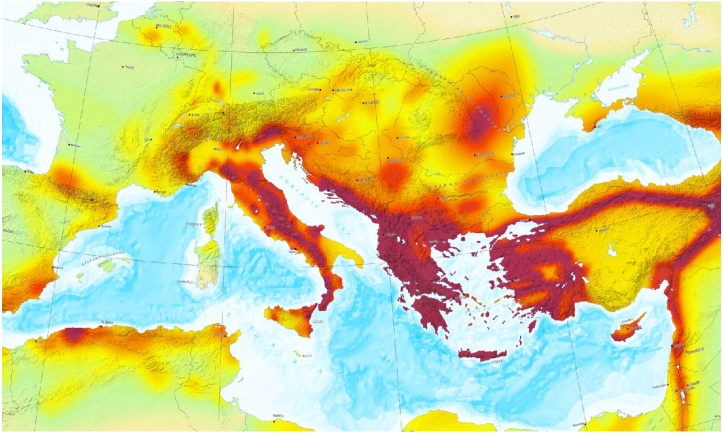
Importance of education: engineering with uncertainty

Motivation: Seismic Hazard



Mediterranean Seismic Hazard

10% probability of exceedance in 50 years (Giardini et al.)



Crete Seismic Hazard

10% probability of exceedance in 50 years (Giardini et al.)

Outline

Predictive Capabilities

Prediction under Uncertainty: use of computational model to predict the state of SSI system under conditions for which the computational model has not been validated.

Verification: provides evidence that the model is solved correctly. Mathematics issue.

Validation: provides evidence that the correct model is solved. Physics issue.

Prediction under Uncertainty

Modeling Uncertainty, simplifying assumptions

- Low, medium, high sophistication modeling and simulation
- Choice of sophistication level for confidence in results

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

- Uncertain LHS: M, C and K^{ep}
- Uncertain RHS $F(t)$
- Results are PDFs and CDFs for σ_{ij}, ϵ_{ij}, u_i, $\dot{u}_i$, $\ddot{u}_i$

Outline

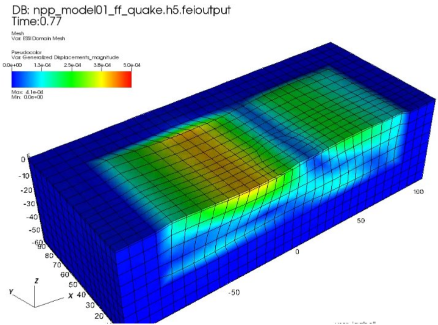
Modeling Uncertainty

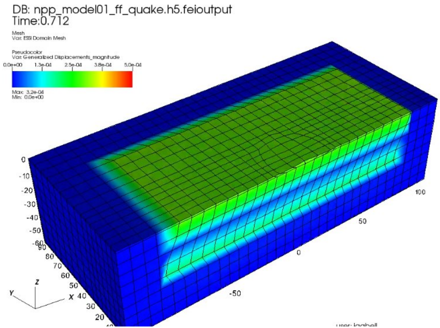
- Important (?!) features are simplified
  - Seismic motions, 1C vs 3C,
  - Inelastic response

- Modeling simplifications are justifiable if one or two level higher sophistication model demonstrates that features being simplified out are not important

Modeling Uncertainty: Free Field Motions

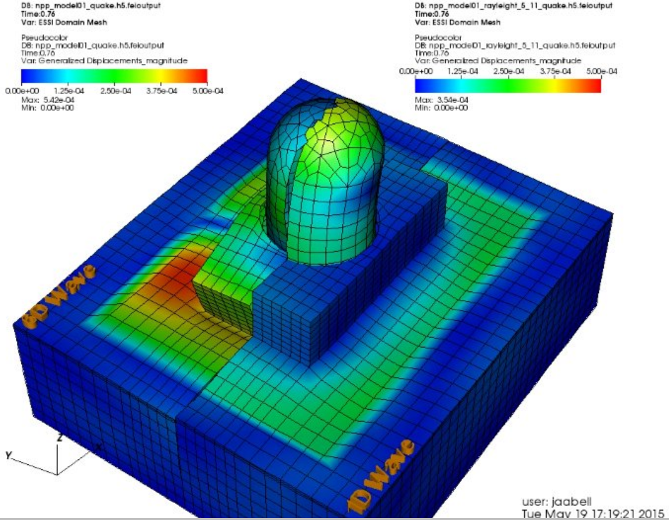
- One component of motions, 1C, from 3C
- Excellent fit





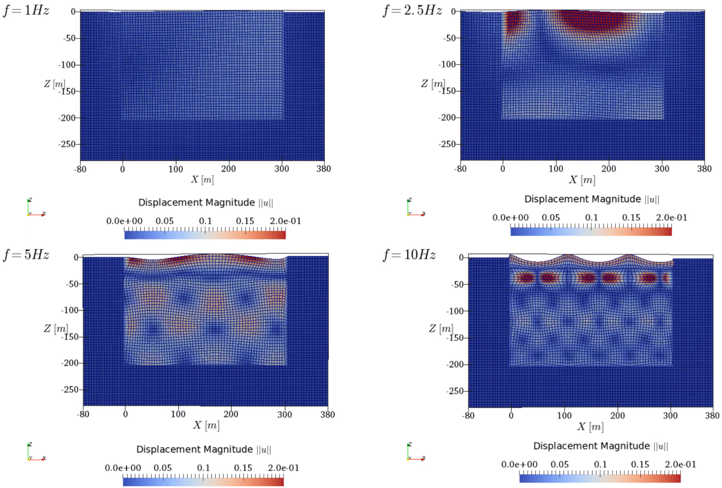
(MP4) (MP4)

Modeling Uncertainty: 6C vs 1C



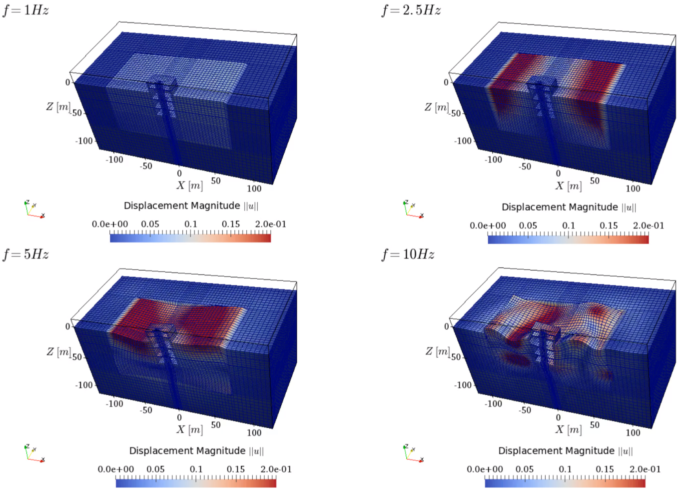
(MP4)

Modeling Uncertainty: Input Frequency



(MP4)

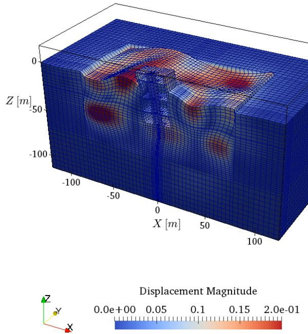
Modeling Uncertainty: SMR ESSI



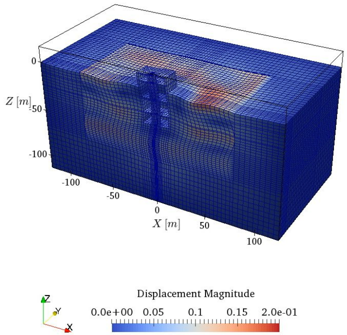
(MP4)

Modeling Uncertainty: 3C vs 3×1C

$3C$



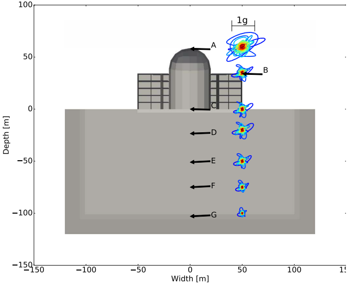
$3 \times 1C$



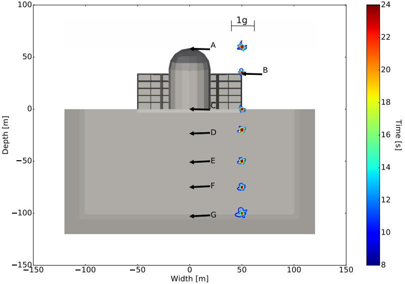
(OGV)

Modeling Uncertainty: Elastic vs Inelastic

Accelerations



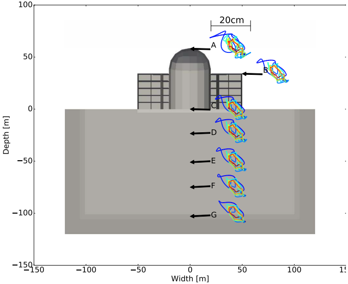
Elastic



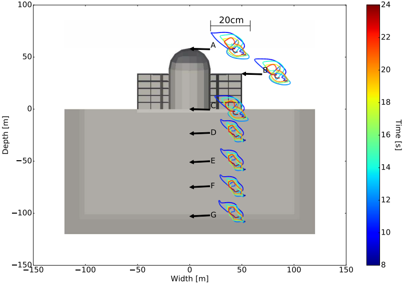
Inelastic

Modeling Uncertainty: Elastic vs Inelastic

Displacements

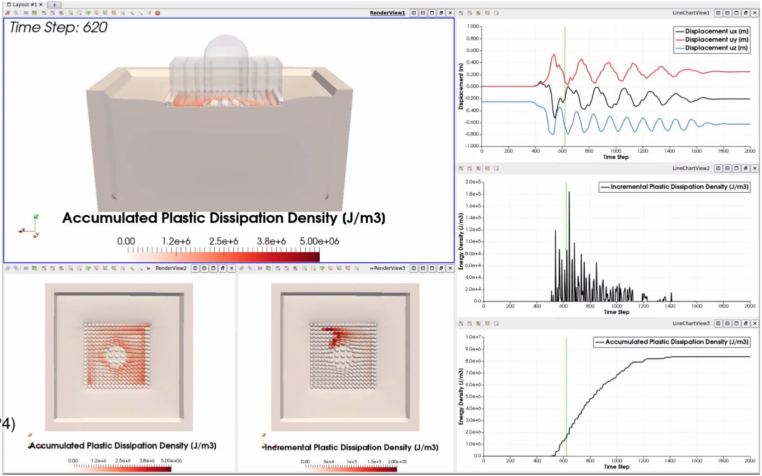


Elastic



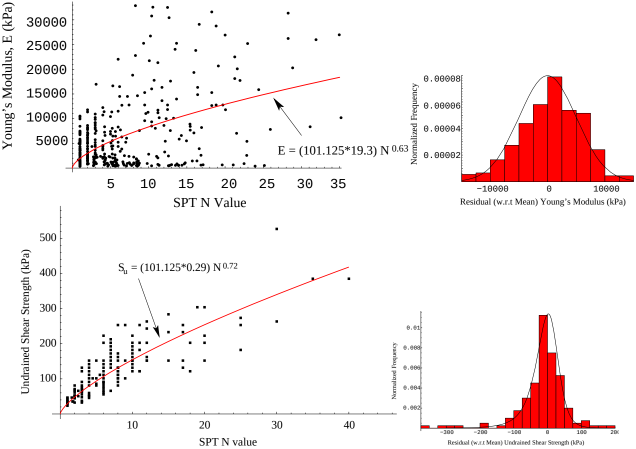
Inelastic

Modeling Uncertainty: Energy Dissipation



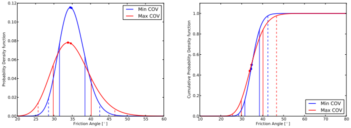
(MP4)

Parametric Uncertainty: Soil Stiffness and Strength

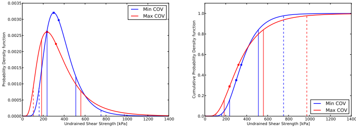


(cf. Phoon and Kulhawy (1999B

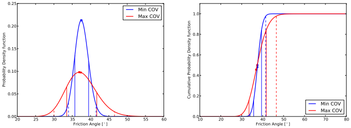
Parametric Uncertainty: Material Properties



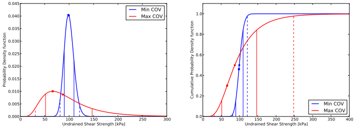
Field ϕ



Field c_u



Lab ϕ



Lab c_u

Uncertain Results: Energy Dissipation

Outline

Current State of Art Seismic Risk Analysis (SRA)

- Intensity measure (IM) selected as a proxy for ground motions, usually Spectral acceleration $Sa(T_0)$
- Ground Motion Prediction Equations (GMPEs) need development, ergodic or site specific
- Probabilistic seismic hazard analysis (PSHA)
- Fragility analysis $P(EDP > x|IM = z)$, deterministic time domain FEM, Monte Carlo (MC)

Seismic Risk Analysis Challenges

- Miscommunication between seismologists and structural engineers, $Sa(T_0)$ not compatible with nonlinear FEM
- IMs difficult to choose, Spectral Acc, PGA, PGV...
- Single IM does not contain all/most uncertainty
- Monte Carlo, not accurate enough for tails
- Monte Carlo, computationally expensive, CyberShake for LA, 20,000 cases, 100y runtime, (Maechling et al. 2007)

Time Domain Intrusive SRA Framework

- Stochastic Elastic-Plastic Finite Element Method, SEPFEM, $M\ddot{u}_i + C\dot{u}_i + K^{ep}u_i = F(t)$,
- Uncertain seismic loads, from uncertain seismic motions, using Domain Reduction Method
- Uncertain elastic-plastic material, stress and stiffness solution using Forward Kolmogorov, Fokker-Planck equation
- Results, probability distribution functions for σ_{ij}, ϵ_{ij}, u_i...

Stochastic Elastic-Plastic Finite Element Method (SEPFEM)

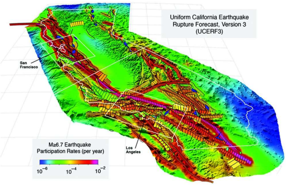
Stochastic system of equations

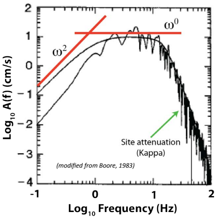
$$
\begin{bmatrix}
\sum_{k=0}^{P_d} < \Phi_k \Psi_0 \Psi_0 > K^{(k)} & \dots & \sum_{k=0}^{P_d} < \Phi_k \Psi_P \Psi_0 > K^{(k)} \\
\sum_{k=0}^{P_d} < \Phi_k \Psi_0 \Psi_1 > K^{(k)} & \dots & \sum_{k=0}^{P_d} < \Phi_k \Psi_P \Psi_1 > K^{(k)} \\
\vdots & \vdots & \vdots & \vdots \\
\sum_{k=0}^{P_d} <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

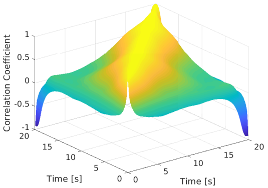
# KL terms material	# KL terms load	PC order displacement	Total # terms per DoF
4	4	10	43758
4	4	20	3 108 105
4	4	30	48 903 492
6	6	10	646 646
6	6	20	225 792 840
6	6	30	$1.1058\ 10^{10}$

Stochastic Seismic Motion Development

- UCERF3 (Field et al. 2014)
- Stochastic motions (Boore 2003)
- Polynomial Chaos Karhunen-Loève expansion
- Domain Reduction Method for P_{eff} (Bielak et al. 2003)





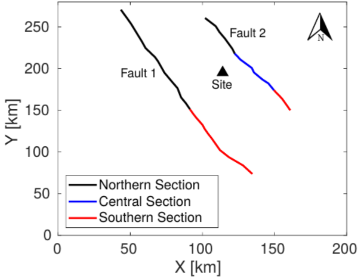


Stochastic Ground Motion Modeling

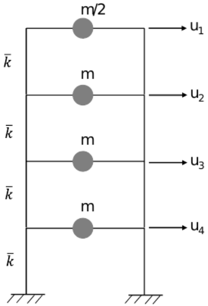
- Modeling fundamental characteristics of uncertain ground motions, Stochastic Fourier amplitude spectra (FAS). and Stochastic Fourier phase spectra (FPS) and not specific IM
- Mean behavior of stochastic FAS, w^2 source radiation spectrum by Brune(1970), and Boore(1983, 2003, 2015).
- Variability models for stochastic FAS, FAS GMPEs by Bora et al. (2015, 2018), Bayless & Abrahamson (2019), Stafford(2017) and Bayless & Abrahamson (2018).
- Stochastic FPS by phase derivative (Boore,2005), Logistic phase derivative model by Baglio & Abrahamson (2017)

Outline

Uncertain Model Description



(a) Faults configuration



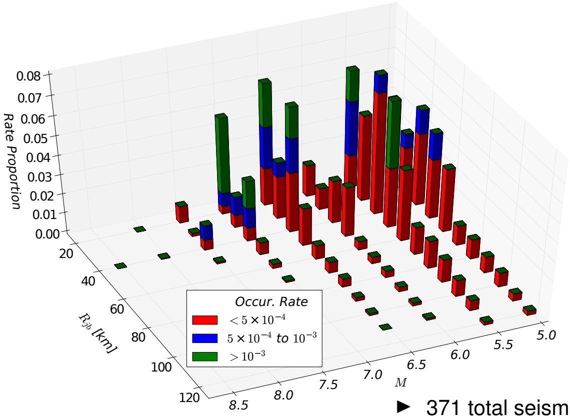
(b) Building structure

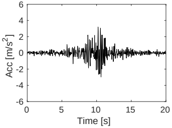
$$Cov_k = \begin{bmatrix} 1.0 & 0.6 & 0.3 & 0.2 \\ 0.6 & 1.0 & 0.5 & 0.2 \\ 0.3 & 0.5 & 1.0 & 0.7 \\ 0.2 & 0.2 & 0.7 & 1.0 \end{bmatrix}$$

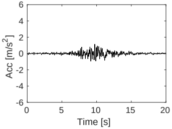
- Fault 1: San Gregorio fault
- Fault 2: Calaveras fault
- Uncertainty: Segmentation, slip rate, rupture geometry, etc.

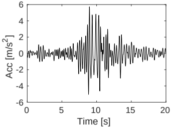
- $Vs_{30} = 620m/s$
- $m = 100kips/g$
- $\bar{k} = 168kip/in$

Seismic Source Characterization



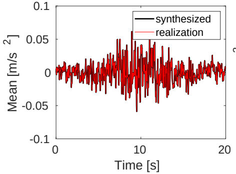




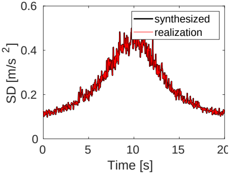


- 371 total seismic scenarios
- M 5 $\sim$ 5.5 and 6.5 $\sim$ 7.0
- R_{jb} $20km \sim 40km$

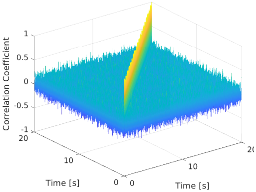
Stochastic Ground Representation



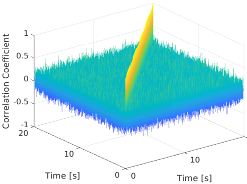
Acc. marginal mean



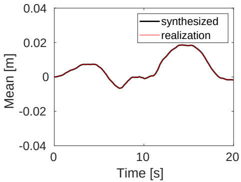
Acc. marginal S.D.



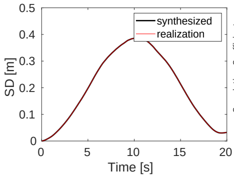
Acc. realization Cov.



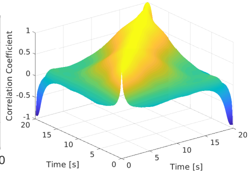
Acc. synthesized Cov.



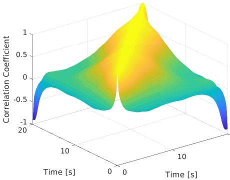
Dis. marginal mean



Dis. marginal S.D.

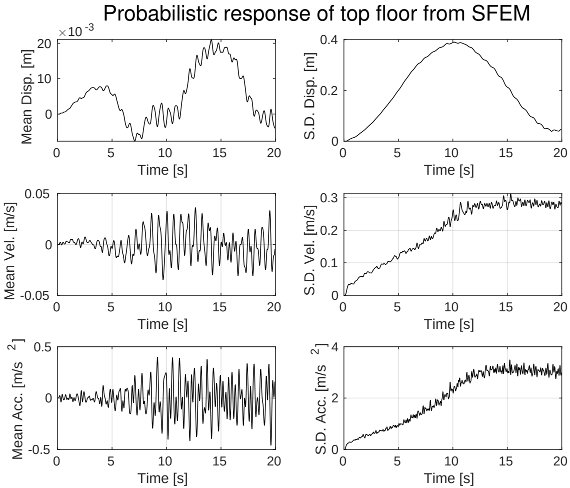


Dis. realization Cov.

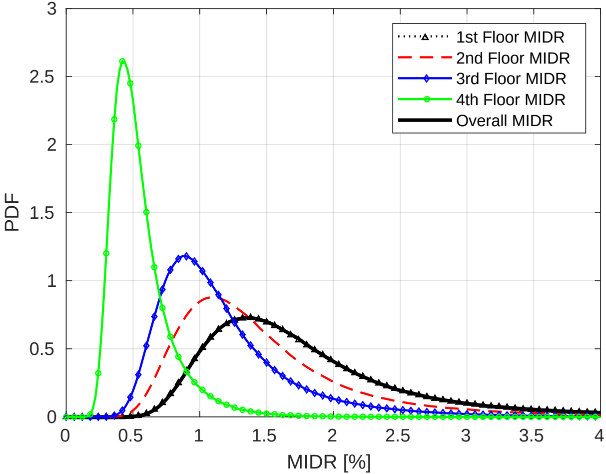


Dis. synthesized Cov.

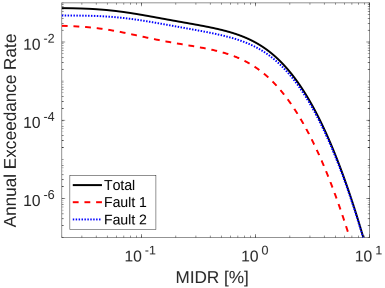
Probabilistic Dynamic Response

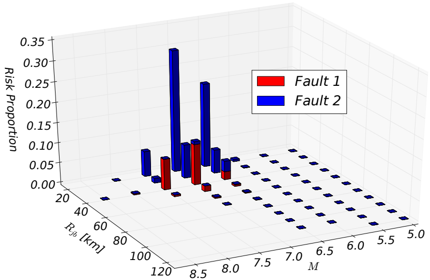


Maximum Inter-story Drift Ratio (MIDR)



Seismic Risk Analysis





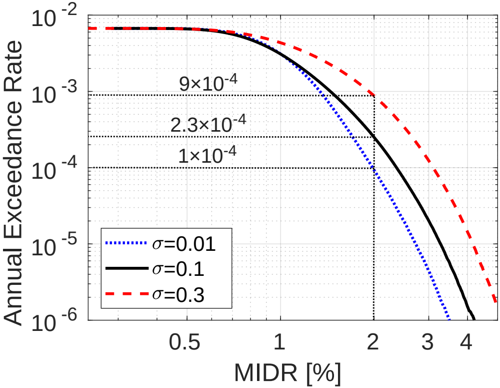
$\lambda(MIDR > 1\%) = 9.7 \times 10^{-3}$

$\lambda(MIDR > 2\%) = 1.7 \times 10^{-3}$

$\lambda(MIDR > 4\%) = 5.9 \times 10^{-5}$

Risk de-aggregation for $\lambda(MIDR > 1\%)$

Seismic Risk, Uncertain Material



Outline

Method Summary

- Full probabilistic modeling and simulation of earthquake soil structure interacting (ESSI) systems
- Intrusive modeling using SEPFEM
- Input: uncertain seismic ground motions
- Input: uncertain material
- Output: accurate probability density functions for σ_{ij}, ϵ_{ij}, u_i, $\dot{u}_i$, $\ddot{u}_i$, and any of their combinations
- Objective risk analysis, removing subjective choices
- Requires data and is computationally intensive, however, less demanding and more accurate than MC approach

Conclusion

- Numerical modeling to predict and inform, rather than fit
- Education and Training is the key!
- Collaborators: Wang, Wang, Feng, Yang, Behbehani, Sinha, Pisanó, Abell, Cheng, Jie, Luo, Tafazzoli, Preisig, Tasiopoulou, Watanabe
- Funding from and collaboration with the US-DOE, US-NRC, US-NSF, CNSC-CCSN, UN-IAEA, Shimizu Corp. and ILEE is greatly appreciated,
- Real-ESSI Simulator System:

`http://real-essi.info/`