

# Time Domain, Intrusive Probabilistic Seismic Risk Analysis of Nonlinear Earthquake Soil Structure Interaction Systems

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# Outline

Introduction

Uncertain Inelastic Dynamics

Summary

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# Motivation

Improve modeling and simulation of infrastructure objects

Modeling, epistemic uncertainty

Parametric, aleatory uncertainty

Goal is to Predict and Inform

Engineer needs to know!

# Dedication

Robert P. Kennedy, 1939-2018



"Response of a soil structure system is nonlinear, and I would really like to know what that response is!"

Nebojša Orbović, 1962-2021



"As an engineer, I have to know what are response sensitivities to modeling choices and model parameters."

# Numerical Prediction under Uncertainty

- Modeling, Epistemic Uncertainty

  - Modeling Simplifications

  - Modeling sophistication for confidence in results

  - Verification and Validation

- Parametric, Aleatory Uncertainty

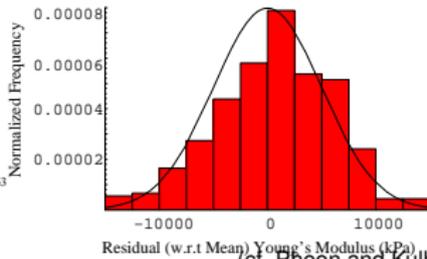
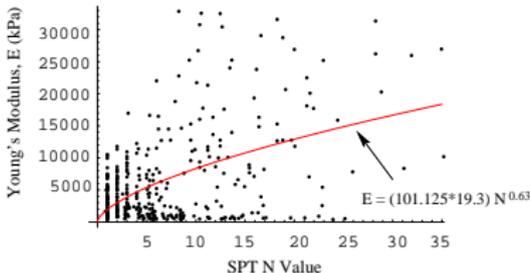
- $M\ddot{u}_i + C\dot{u}_i + K^{ep}u_i = F(t),$

  - Uncertain: mass  $M$ , viscous damping  $C$  and stiffness  $K^{ep}$

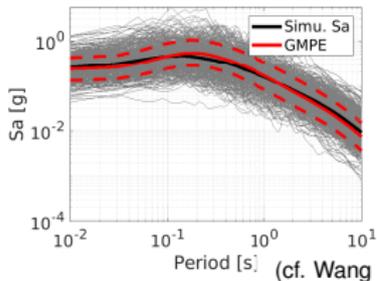
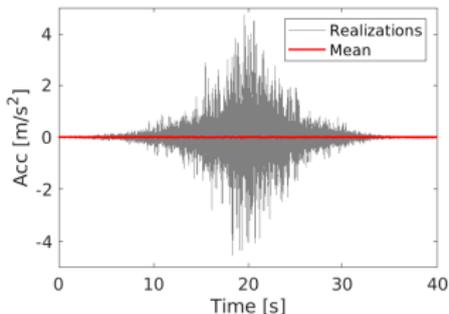
  - Uncertain loads,  $F(t)$

  - Results are PDFs and CDFs for  $\sigma_{ij}, \epsilon_{ij}, u_i, \dot{u}_i, \ddot{u}_i$

# Parametric, Aleatory Uncertainty



(cf. Phoon and Kulhawy (1999B))



(cf. Wang et al. (2019))

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**Uncertain Inelastic Dynamics**

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# Forward Uncertainty Propagation

- Given uncertain material and uncertain loads
- Determine uncertain response,  $u_i, \dot{u}_i, \ddot{u}_i, \epsilon_{ij}, \sigma_{ij}$ , PDFs/CDFs
- Intrusive, analytic development, to circumvent Monte Carlo inefficiencies

# Forward Uncertain Inelasticity

- Incremental el-pl constitutive equation

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

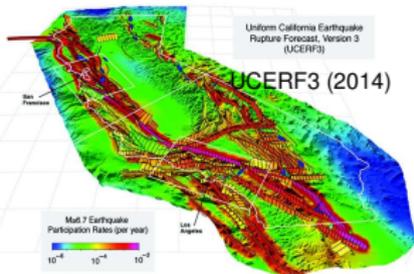
- Dynamic Finite Elements

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

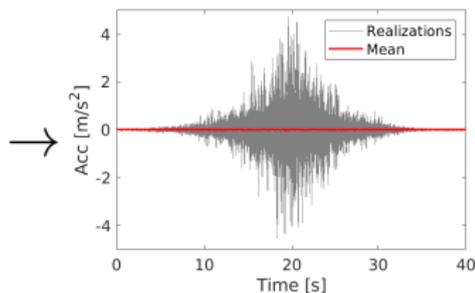
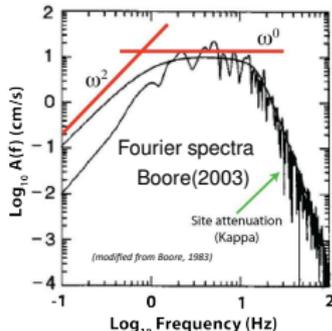
- Material and loads are uncertain

# Application: Seismic Hazard

Seismic source characterization



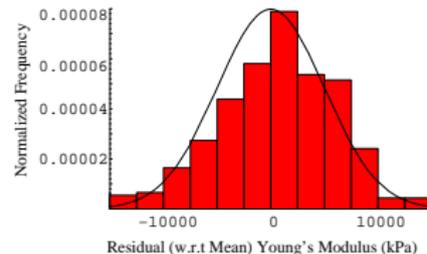
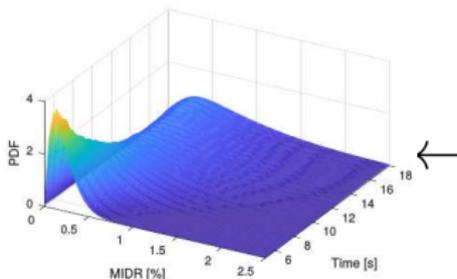
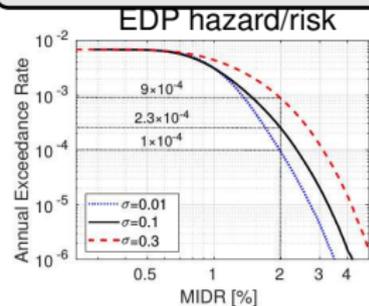
Stochastic ground motion



$$\lambda(EDP > z) = \sum N_i(M_i, R_i)P(EDP > z | M_i, R_i)$$

Uncertainty propagation  
SEPFEM

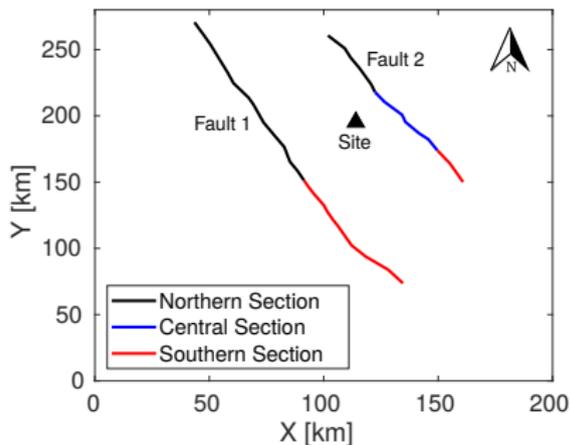
Uncertainty characterization  
Hermite polynomial chaos



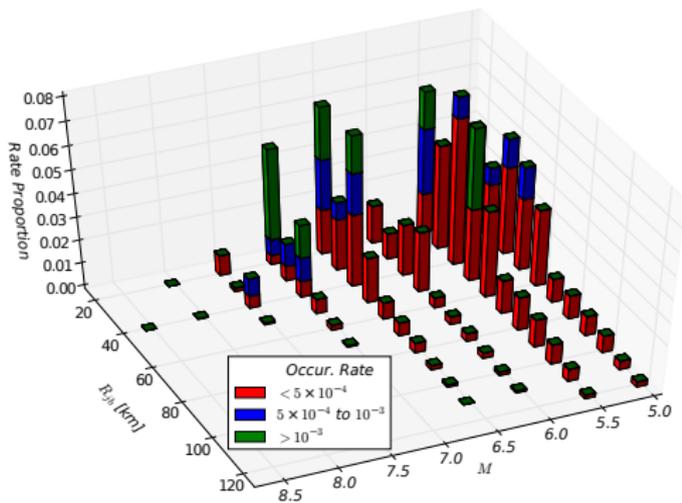
# Stochastic Ground Motion Modeling

- Shift from modeling specific IM to fundamental characteristics of ground motions
  - Uncertain Fourier amplitude spectra (FAS)
  - Uncertain Fourier phase spectra (FPS)
- GMPE studies of FAS, ( *Bora et al. (2018)*, *Bayless & Abrahamson (2018,2019)*, *Stafford(2017)*, )
- Stochastic FPS by phase derivative (Boore,2005) (Logistic phase derivative model by *Baglio & Abrahamson (2017)*)
- Change from  **$Sa(T_0)$**  to **FAS** and **FPS**

# Example Object



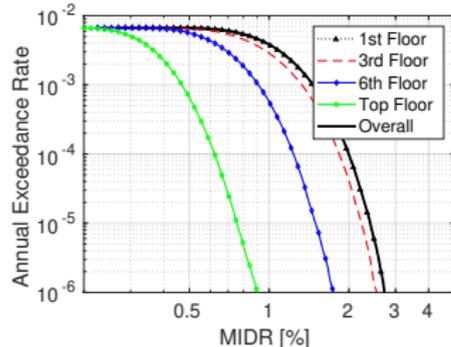
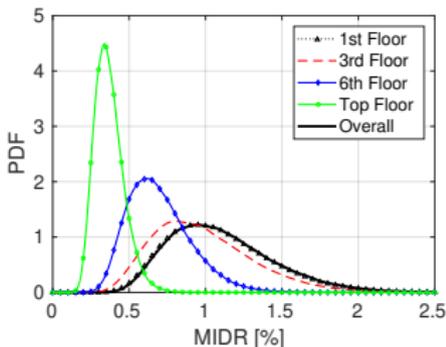
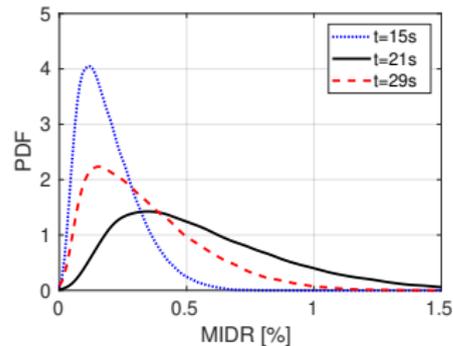
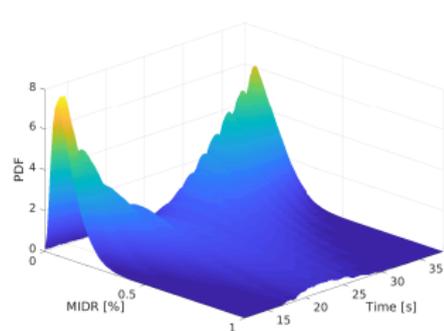
- ▶ Fault 1: San Gregorio fault
- ▶ Fault 2: Calaveras fault
- ▶ Uncertainty: Segmentation, slip rate, rupture geometry, etc.



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

# Seismic Risk Analysis

Engineering demand parameter (EDP): Maximum inter-story drift ratio (MIDR)



# Seismic Risk Analysis

- Damage measure defined on single EDP:

DM	MIDR>0.5%	MIDR>1%	MIDR>2%	PFA>0.5m/s <sup>2</sup>	PFA>1m/s <sup>2</sup>	PFA>1.5m/s <sup>2</sup>
Risk [/yr]	$6.66 \times 10^{-3}$	<b><math>3.83 \times 10^{-3}</math></b>	$9.97 \times 10^{-5}$	$6.65 \times 10^{-3}$	<b><math>1.92 \times 10^{-3}</math></b>	$9.45 \times 10^{-5}$

- Damage measure (DM) defined on multiple EDPs:

$DM : \{MIDR > 1\% \cup PFA > 1m/s^2\}$ , seismic risk is  $4.2 \times 10^{-3}/yr$

$DM : \{MIDR > 1\% \cap PFA > 1m/s^2\}$ , seismic risk is  $1.71 \times 10^{-3}/yr$

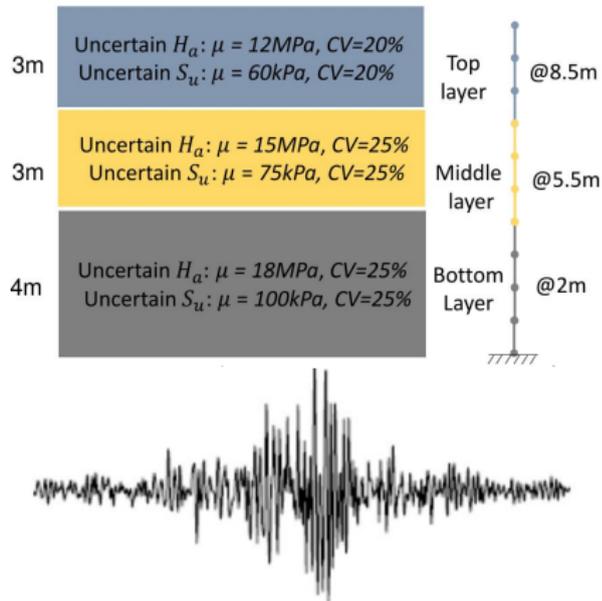
- Seismic risk for DM defined on multiple EDPs can be quite different from that defined on single EDP

# Backward Uncertainty Propagation, Sensitivities

- Given forward uncertain response, PDFs, CDFs...
- Contributions of uncertain input to forward uncertainties
- Sensitivity of forward uncertain response to input uncertainties
- Sobol sensitivity indices, using ANOVA representation and Polynomial Chaos (Sobol 2001, Sudret 2008)

# Application: Stochastic Site Response

- Uncertain material:  
uncertain random field,  
marginally lognormal  
distribution,  
exponential correlation  
length 10m
- Uncertain seismic  
rock motions:  
seismic scenario  
M=7, R=50km



# Sensitivity Analysis

Total variance in PGA, in this particular case (!), dominated by uncertain ground motions

49% from uncertain rock motions at depth

2% from uncertain soil

49% from interaction of uncertain rock motions and uncertain soil

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- Analytic analysis of uncertainties
- Analytic analysis of sensitivities
- Predict and Inform
- Real-ESSI Simulator Systems
- `http://real-essi.us`