# Probabilistic Seismic Risk Analysis for Inelastic Soil-Structure Systems

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# Outline

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# Motivation

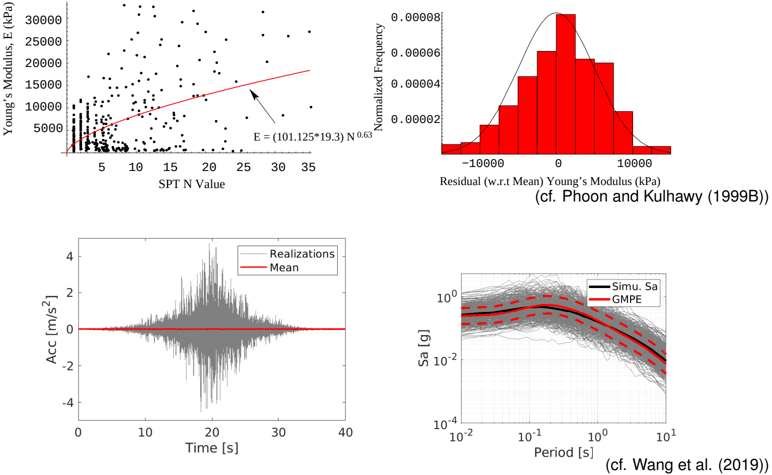
Improve modeling and simulation of infrastructure objects

Modeling, epistemic uncertainty

Parametric, aleatory uncertainty

Goal is to Predict and Inform

# Aleatory Uncertainties, Material, Motions




(cf. Phoon and Kulhawy (1999B))

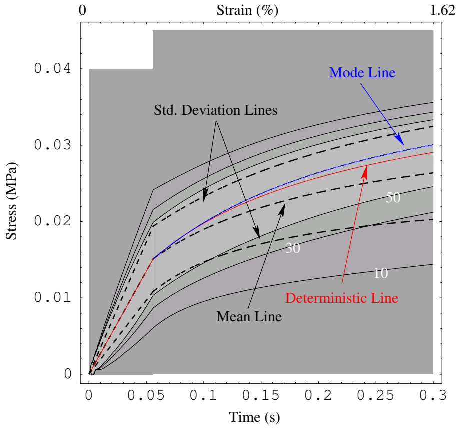
(cf. Wang et al. (2019))

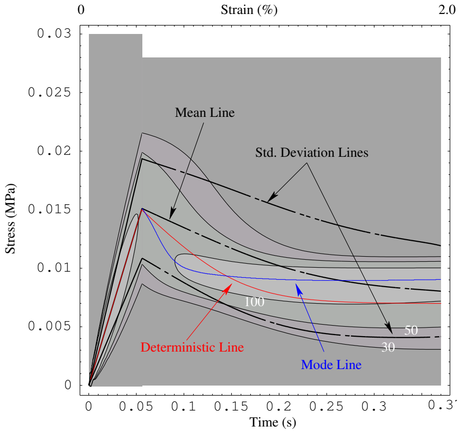
# Outline

# Forward Uncertainty Propagation

- Given uncertain material
- Given uncertain loads
- Determine uncertain response, $u_i, \dot{u}_i, \ddot{u}_i, \epsilon_{ij}, \sigma_{ij}$, PDFs/CDFs
- Direct, intrusive, analytic development
- Circumvent Monte Carlo inefficiencies, inaccuracies

# Cam Clay with Random $G$, $M$ and $p_0$



# Stochastic Elastic-Plastic FEM

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

- Input random field/process(non-Gaussian, heterogeneous/ non-stationary): Multi-dimensional Hermite Polynomial Chaos (PC) with known coefficients
- Output response process: Multi-dimensional Hermite PC with unknown coefficients
- Galerkin projection: minimize the error to compute unknown coefficients of response process

# Probabilistic Seismic Risk Analysis

- Objective, quantitative decision making based on exceedance rate $\lambda(EDP > z)$
- PSRA: convolution of PSHA and fragility

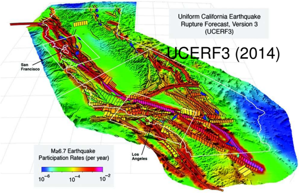
$$\lambda(EDP > z) = \int \underbrace{\left|\frac{d\lambda(IM > x)}{dx}\right|}_{\textbf{PSHA}} \underbrace{G(EDP > z|IM = x)}_{\textbf{fragility analysis}} dx$$

$\lambda(\cdot)$ : rate of exceedance
*EDP*: engineering demand parameter
*PSHA*: probabilistic seismic hazard analysis
*IM*: intensity measure, choice to be made (!)

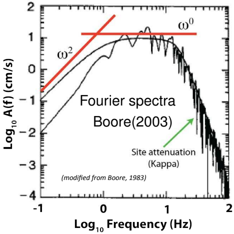
# Outline

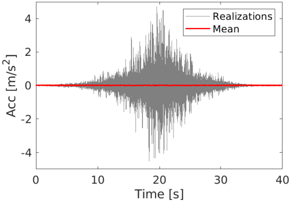
# Application: Seismic Hazard

## Seismic source characterization




## Stochastic ground motion



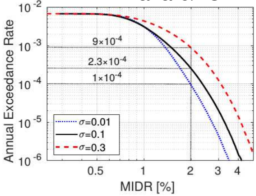



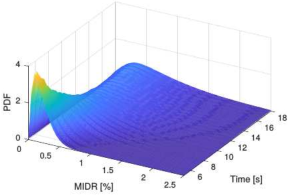

$$\lambda(EDP > z) = \sum N_i(M_i, R_i) P(EDP > z | M_i, R_i)$$

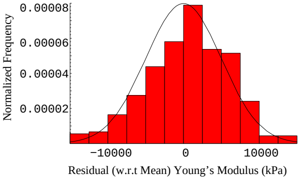
## Uncertainty propagation SEPFEM

## Uncertainty characterization Hermite polynomial chaos

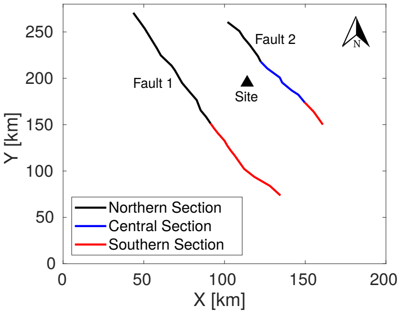
## EDP hazard/risk

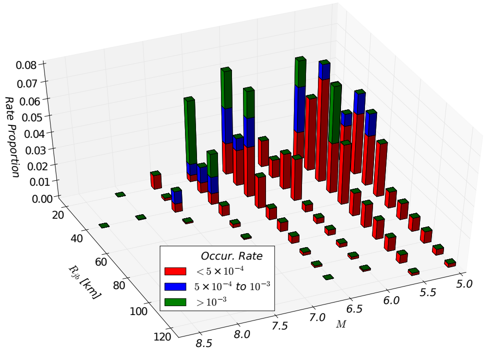


# Example Object



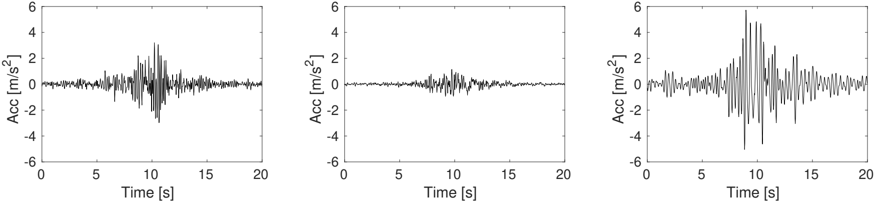




- Fault 1: San Gregorio fault
- Fault 2: Calaveras fault
- Uncertainty: Segmentation, slip rate, rupture geometry, etc.

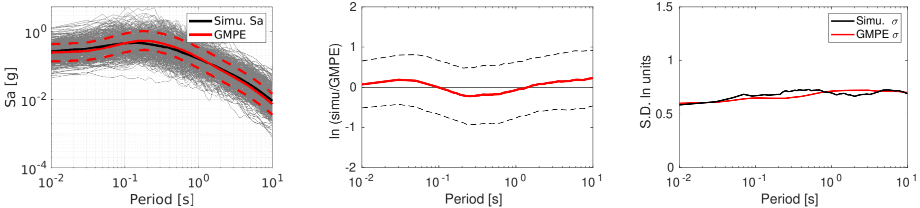
- 371 total seismic scenarios
- $M$ 5 $\sim$ 5.5 and 6.5 $\sim$ 7.0
- $R_{jb}$ 20$km$ $\sim$ 40$km$

# Stochastic Ground Motion Modeling

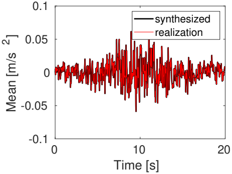
Realizations of simulated uncertain motions for scenario $M = 7$, $R = 15km$:



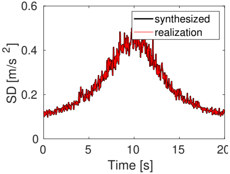

Verification with GMPE:



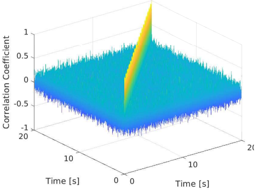
# Stochastic Ground Motion Characterization



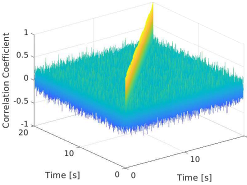
Acc. marginal mean



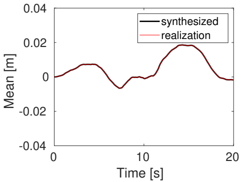
Acc. marginal S.D.



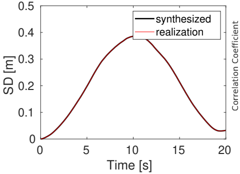
Acc. realization Cov.



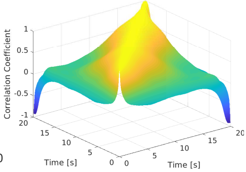
Acc. synthesized Cov.



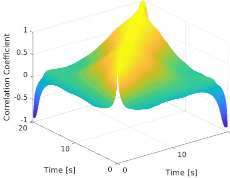
Dis. marginal mean



Dis. marginal S.D.

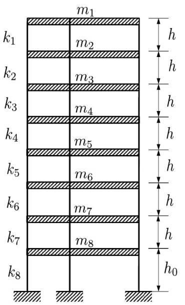


Dis. realization Cov.

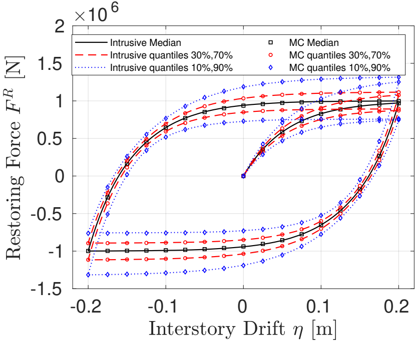


Dis. synthesized Cov.

# Stochastic Soil and Structure Modeling

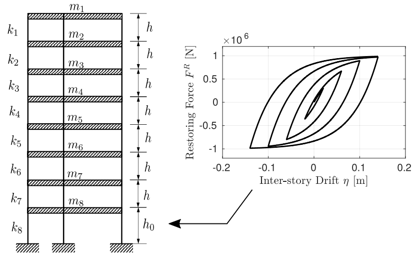



(a) Frame

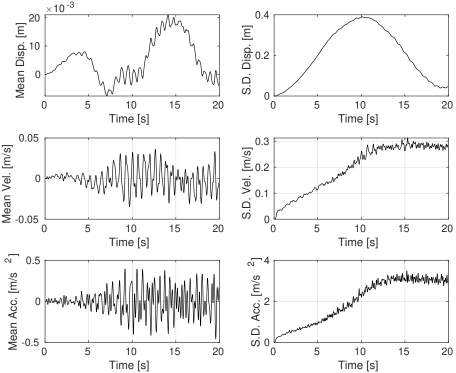



(b) Interstory response

# Probabilistic Dynamic Structural Response




Probabilistic response of top floor from SFEM




- Coefficient of variation 15% for $H_a$ and $C_r$
- Time domain stochastic El-Pl FEM analysis (SEPFEM)

# Seismic Risk, Forward Analysis

- Damage measure defined on single EDP:

| **DM** | MIDR>0.5% | **MIDR>1%** | MIDR>2% | PFA>0.5$\mathrm{m/s^2}$ | **PFA>1$\mathbf{m/s^2}$** | PFA>1.5$\mathrm{m/s^2}$ |
|---|---|---|---|---|---|---|
| **Risk [/yr]** | $6.66\times10^{-3}$ | $\mathbf{3.83\times10^{-3}}$ | $9.97\times10^{-5}$ | $6.65\times10^{-3}$ | $\mathbf{1.92\times10^{-3}}$ | $9.45\times10^{-5}$ |

- Damage measure (DM) defined on multiple EDPs:

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

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

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

# Sensitivity, Backward 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

# Outline

# Summary

- Analysis of uncertainties and sensitivities
- Full, direct, intrusive probabilistic modeling
- No need to define IMs
- `http://real-essi.us/`