Time Domain Seismic Risk Analysis Framework for Nuclear Installations

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Outline

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Motivation

Improve modeling and simulation for infrastructure objects

Control and reduction of modeling uncertainty

Propagation of parametric uncertainty

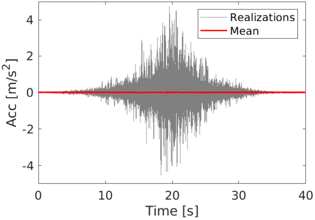
- uncertain seismic motions
- uncertain material in soil and structure

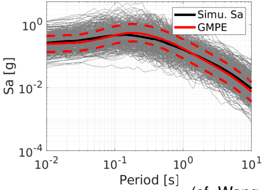
Full risk calculations for earthquake, soil structure system

System for **Real**istic modeling and simulation of **E**arthquakes, **S**oils, **S**tructures and their **I**nteraction:

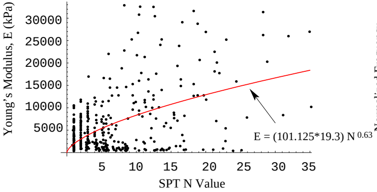
Real-ESSI Simulator `http://real-essi.info/`

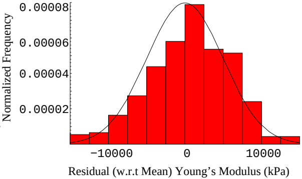
Uncertain Motions and Uncertain Material





(cf. Wang et al. (2019))





(cf. Phoon and Kulhawy (1999B))

Outline

Performance Based Earthquake Engineering

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

- $\lambda(EDP > z) \rightarrow$ annual rate of occurrence of engineering demand parameter (EDP) exceeding specified value z
- EDP hazard $\leftarrow$ convolution of probabilistic seismic hazard analysis (PSHA) and structural fragility for intensity measure (IM) of ground shaking
- PSHA $\leftarrow$ exceedance rate of intensity measure $\lambda(IM > x)$ considering faults and scenarios near site
- Structural fragility $G(EDP > z|IM = x)$ is the probability of exceeding of EDP for ground motion with IM level x

Choice of Intensity Measure

- With defined damage measure (DM) as a function of EDP(s), seismic risk of damage state is calculated
- The choice of IM is important
- IM is a proxy of damaging ground motions
- All the uncertainty in ground motions is represented by the variability of IM

—- However!

- Single IM or multiple IMs cannot represent all uncertainty in ground motions
- Vector, multiple IMs require a large number of simulations
- No guaranty that all uncertainties in motions are addressed

Risk Analysis for Uncertain Nonlinear ESSI Systems

- Time domain, intrusive stochastic, inelastic seismic risk analysis
- Time histories of uncertain motions $\rightarrow$ a random proceess, developed from stochastic Fourier spectra and stochastic Fourier phase spectra
- The random process motions characterized by Polynomial Chaos Karhunen-Loève expansion
- Propagation through uncertain soil-structural system using Stochastic Elastic Plastic Finite Element Method (SEPFEM)
- Time-evolving probabilistic structural response is used for calculating full-spectrum seismic risk

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

Time Domain Stochastic Galerkin Method

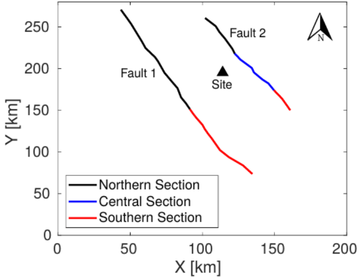
- Input random field/process(non-Gaussian, heterogeneous/ non-stationary)
  Multi-dimensional Hermite Polynomial Chaos (PC) with known coefficients
- Output response process
  Multi-dimensional Hermite PC with unknown coefficients
- Galerkin projection: minimize the error to compute unknown coefficients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

Stochastic Elastic-Plastic Finite Element Method

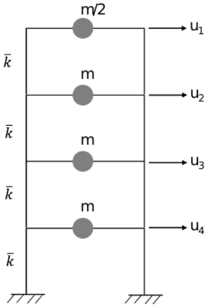
- Material uncertainty expanded into stochastic shape funcs.
- Loading uncertainty expanded into stochastic shape funcs.
- Displacement expanded into stochastic shape funcs.

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

Uncertain Model Description



(a) Faults configuration



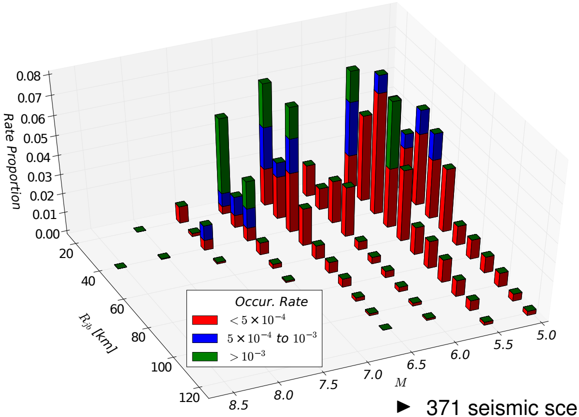
(b) Building structure

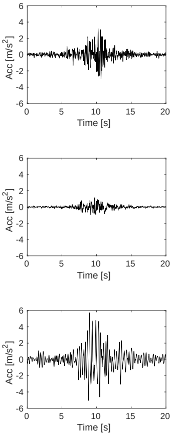
$$Cov_k = \begin{bmatrix} 1.0 & 0.6 & 0.3 & 0.2 \\ 0.6 & 1.0 & 0.5 & 0.2 \\ 0.3 & 0.5 & 1.0 & 0.7 \\ 0.2 & 0.2 & 0.7 & 1.0 \end{bmatrix}$$

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

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

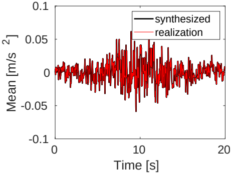
Seismic Source Characterization



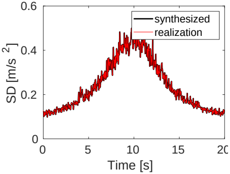


- 371 seismic scenarios
- M 5 $\sim$ 5.5 and 6.5 $\sim$ 7.0
- R_{jb} 20km $\sim$ 40km

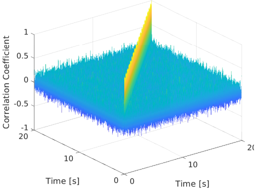
Stochastic Ground Representation



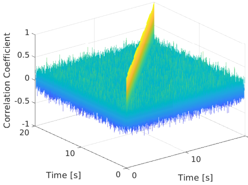
Acc. marginal mean



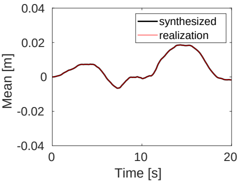
Acc. marginal S.D.



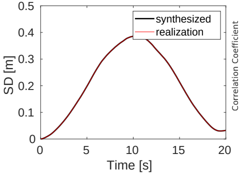
Acc. realization Cov.



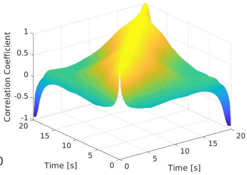
Acc. synthesized Cov.



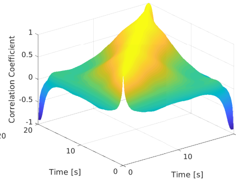
Dis. marginal mean



Dis. marginal S.D.

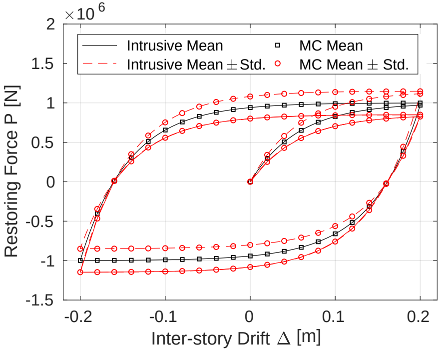


Dis. realization Cov.

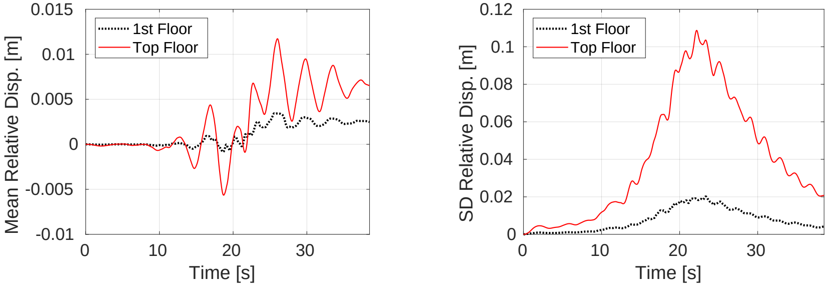


Dis. synthesized Cov.

Cyclic Inelastic Uncertain Response

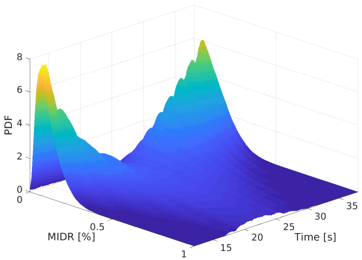


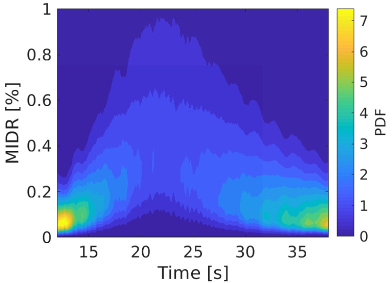
Time History of Inelastic Uncertain Response



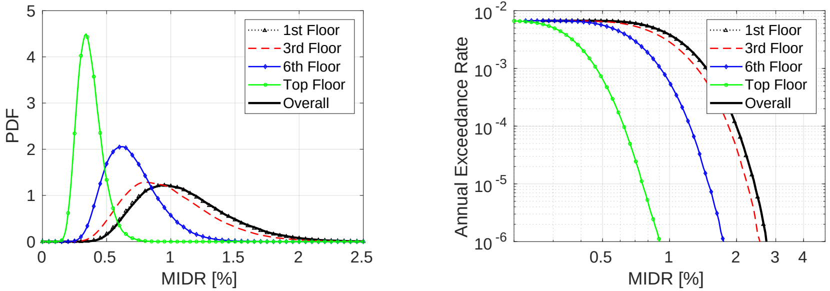
Time History of PDF of MIDR

Maximum Interstory Drift Ratio (MIDR)

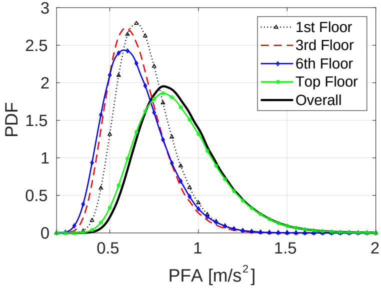


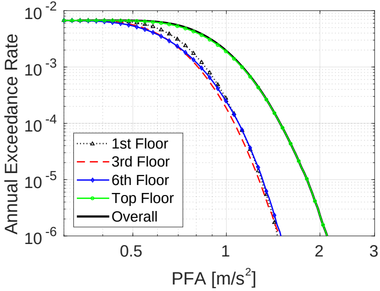


PDF and CDF of MIDR



PDF and CDF of Peak Floor Acceleration





Outline

Summary

- Numerical modeling to predict and inform, rather than fit
- Engineers need to know (probably)
- Importance of modeling and propagating uncertainties
- Full probabilistic modeling and simulation, full risk results
- **`http://real-essi.info/`**