Time Domain, Intrusive Framework for Probabilistic Seismic Risk Analysis of Nonlinear Soil-Structure Systems

H. Wang, H. Yang, F. Wang, J. Bayless,
N. Abrahamson, and B. Jeremić

University of California, Davis, CA

DOE/NRC Natural Phenomena Hazards Meeting
October 2020

Outline

Introduction

Time Domain, Nonlinear, Intrusive, Probabilistic Seismic Risk Analysis (TDNIPSRA)
- Formulation
- Example

Summary

Motivation

- Improve modeling and simulation for infrastructure objects
- Reduction of modeling, epistemic uncertainty
- Propagation of parametric, aleatory uncertainty
- Goal: Predict and Inform rather than force fit
- Engineer needs to know!

Numerical Prediction under Uncertainty

Modeling, epistemic uncertainties, simplifying assumptions

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

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

- Uncertain, spatially variable material
- Uncertain, time varying loads
- Results are PDFs and CDFs for u_i, $\dot{u}_i$, $\ddot{u}_i$, σ_{ij}, ϵ_{ij},

Real-ESSI Simulator System

The Real-ESSI, **Real**istic Modeling and Simulation of **E**arthquakes, **S**oils, **S**tructures and their **I**nteraction.
Time domain, linear and nonlinear, inelastic, deterministic or probabilistic, 3D, modeling and simulation of:

- statics and dynamics of soil,
- statics and dynamics of structures,
- statics of soil-structure systems, and
- dynamics of earthquake-soil-structure system interaction

Used for:

- Design: linear elastic, load combinations, dimensioning
- Assessment: nonlinear/inelastic, risk, safety margins

More information at: **`http://real-essi.us/`**

Outline

Introduction

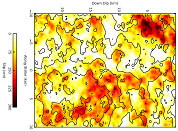
Time Domain, Nonlinear, Intrusive, Probabilistic Seismic Risk Analysis (TDNIPSRA)
Formulation
Example

Summary

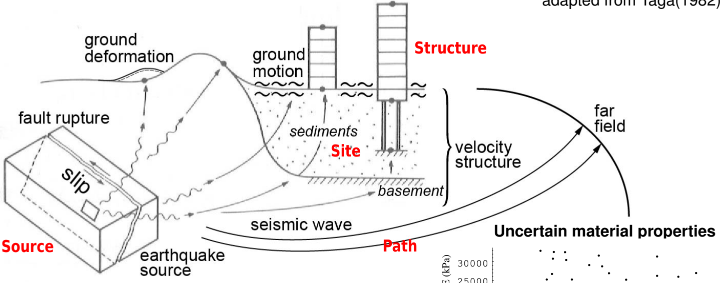
Probabilistic Seismic Risk Analysis (PSRA)

Uncertain source, path, site and structure $\Longrightarrow$ Probabilities of engineering demand parameters (EDP) damage measures (DM), loss, etc

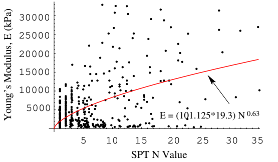
adapted from Taga(1982)



Uncertain source rupture



Uncertain material properties



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

Seismic Risk Analysis Challenges

- IM serves as the proxy of damaging ground motions
- Does a single IM, e.g., $Sa(T_0)$, represent all uncertainty?
- IMs difficult to choose, Spectral Acc, PGA, PGV...
- Fragility analysis: incremental dynamic analysis (IDA)
- Use of Monte Carlo method, accuracy, efficiency...
- Monte Carlo, computationally expensive, CyberShake for LA, 20,000 cases, 100Y runtime, (Maechling et al. 2007)

Time Domain Intrusive PSRA Framework

- Stochastic Elastic-Plastic Finite Element Method, SEPFEM, $M\ddot{u}_i + C\dot{u}_i + K^{ep}u_i = F(t)$, (Sett et al. 2011)

- Uncertain elastic-plastic material

- Uncertain seismic loads/motions

- Results, probability distribution functions for σ_{ij}, ϵ_{ij}, u_i...

Stochastic Elastic-Plastic Finite Element Method

- Material uncertainties: stochastic shape functions: $E^{ep}(x,t,\theta) = \sum_{i=0}^{P_d} E_i(x,t) * \Phi_i[\{\xi_1,...,\xi_m\}]$
- Loading uncertainties: 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: stochastic shape functions: $u(x,t,\theta) = \sum_{i=0}^{P_u} u_i(x,t) * \Psi_i[\{\xi_1,...,\xi_m,\xi_{m+1},...,\xi_f\}]$
- Stochastic system of equations

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

Outline

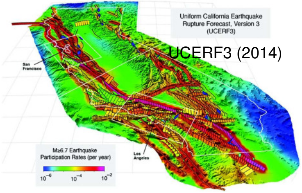
Introduction

Time Domain, Nonlinear, Intrusive, Probabilistic Seismic Risk Analysis (TDNIPSRA)
Formulation
Example

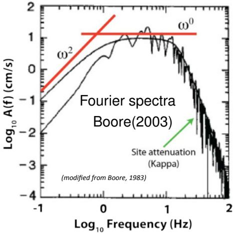
Summary

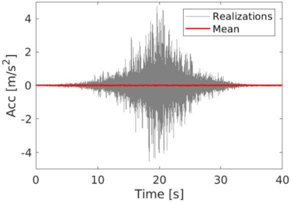
TDNIPSRA Framework

Seismic source characterization



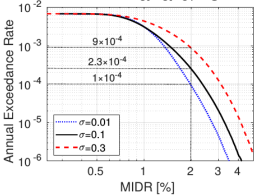
Stochastic ground motion



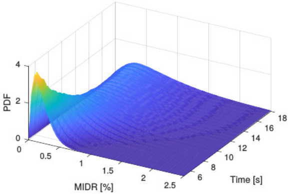


$$\lambda(EDP > z) = \sum N_i(M_i, R_i) P(EDP > z | M_i, R_i)$$

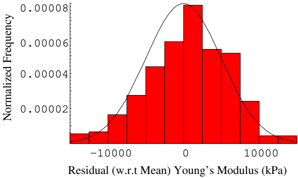
EDP hazard/risk



Uncertainty propagation SEPFEM



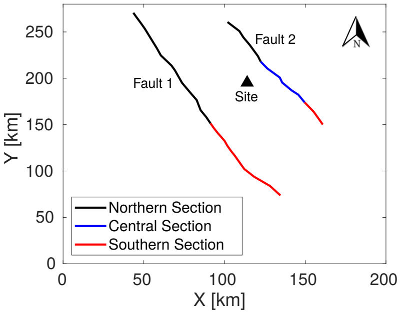
Uncertainty characterization Hermite polynomial chaos

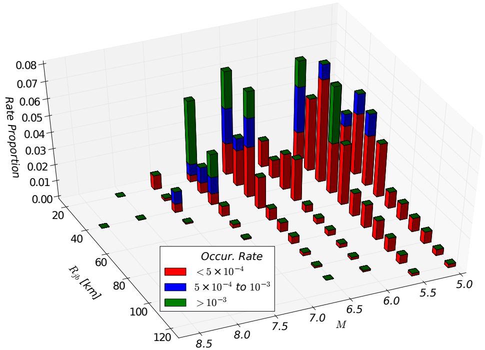


Stochastic Ground Motion Modeling

- 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)*)
- Near future change from $\boldsymbol{Sa(T_0)}$ to **FAS**

TDNIPSRA Example Object



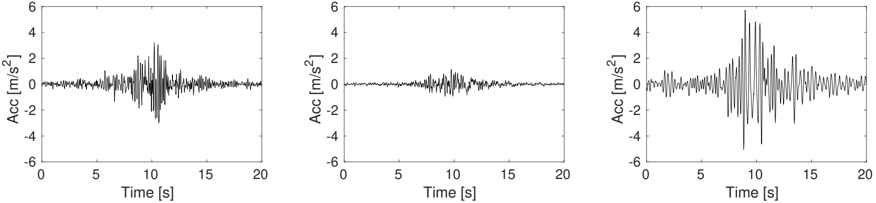


- Fault 1: San Gregorio fault
- Fault 2: Calaveras fault
- Uncertainty: Segmentation, slip rate, rupture geometry, etc.

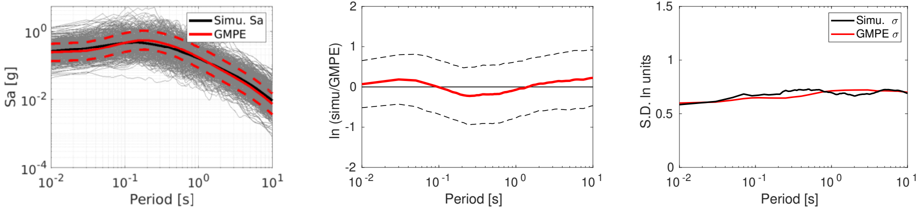
- 371 total seismic scenarios
- M 5 $\sim$ 5.5 and 6.5 $\sim$ 7.0
- R_{jb} 20km $\sim$ 40km

Stochastic Ground Motion Modeling

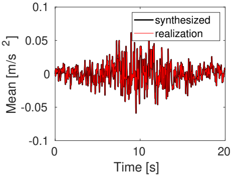
Realizations of simulated uncertain motions for scenario $M = 7$, $R = 15km$:



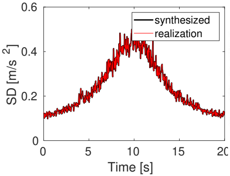
Verification with GMPE:



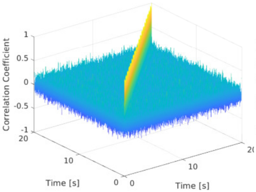
Stochastic Ground Motion Characterization



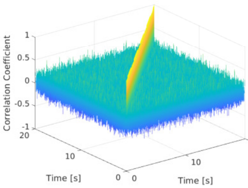
Acc. marginal mean



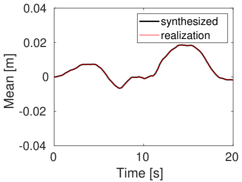
Acc. marginal S.D.



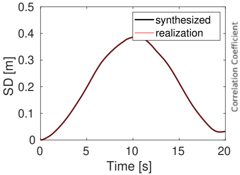
Acc. realization Cov.



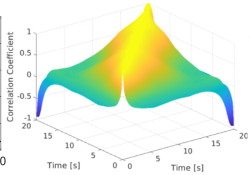
Acc. synthesized Cov.



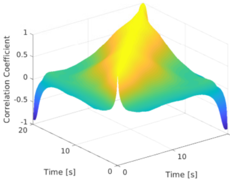
Dis. marginal mean



Dis. marginal S.D.

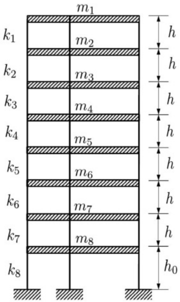


Dis. realization Cov.

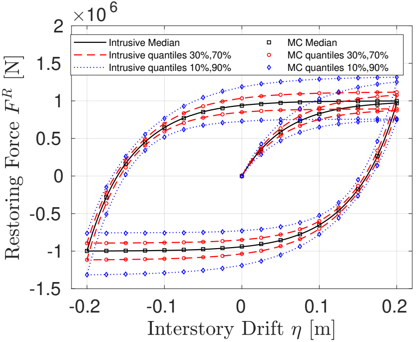


Dis. synthesized Cov.

Stochastic Material Modeling

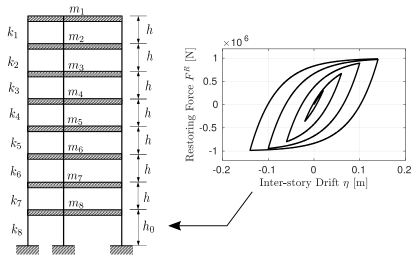


(a) Frame



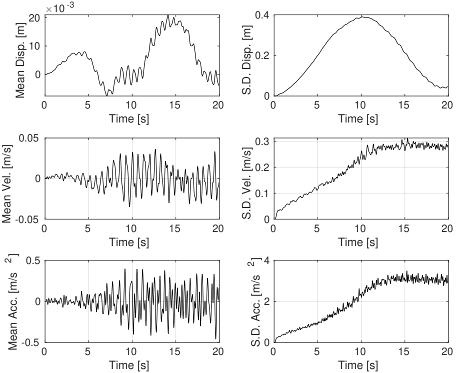
(b) Interstory response

Probabilistic Dynamic Structural Response



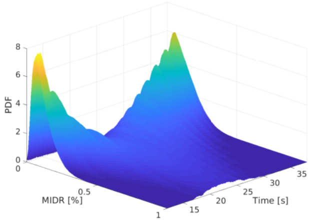
- Coefficient of variation 15% for H_a and C_r
- Time domain stochastic El-Pl FEM analysis (SEPFEM)

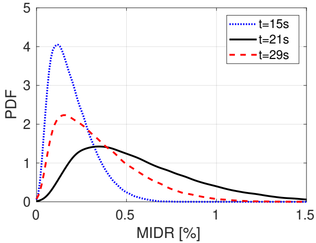
Probabilistic response of top floor from SFEM

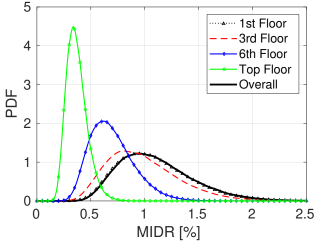


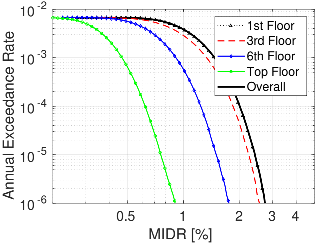
Seismic Risk Analysis

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



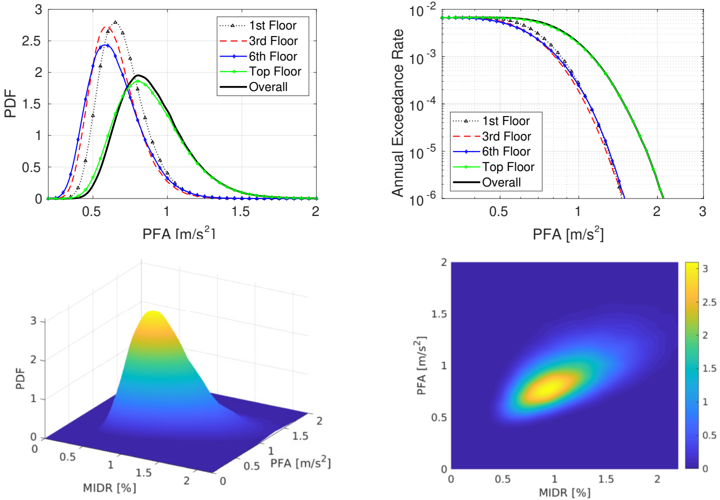






Seismic Risk Analysis

Engineering demand parameter (EDP): Peak floor acceleration (PFA)



Seismic Risk Analysis

- Damage measure (DM) defined on multiple EDPs:

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

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

- Damage measure defined on single EDP:

DM	MIDR>0.5%	**MIDR>1%**	MIDR>2%	PFA>0.5m/s^2	**PFA>1m/s^2**	PFA>1.5m/s^2
Risk [/yr]	6.66×10^{-3}	$\mathbf{3.83\times10^{-3}}$	9.97×10^{-5}	6.65×10^{-3}	$\mathbf{1.92\times10^{-3}}$	9.45×10^{-5}

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

Summary

Probabilistic analysis to predict and inform

Stochastic Elastic-Plastic Finite Element Method and presented examples will be publicly available within the Real-ESSI Simulator, Global Release 21.01, Jan2021

Real-ESSI program, is available on AWS and as a Docker container for Linux, MS Windows and MacOS,

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

Support from and collaboration with the US-DOE, US-NRC, US-NSF, ATC/US-FEMA, CNSC-CCSN, CH-ENSI, UN-IAEA is greatly appreciated