Engineering Analysis Toolbox
The Real-ESSI Simulator System

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5th SEECCM
July 2023

Врњачка Бања, Србија

Outline

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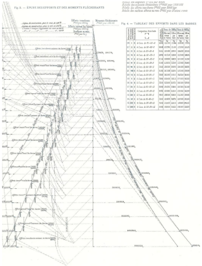
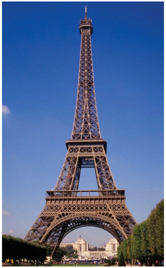
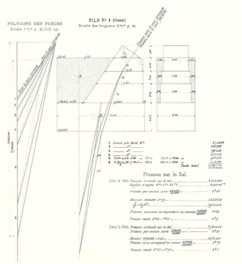
Motivation

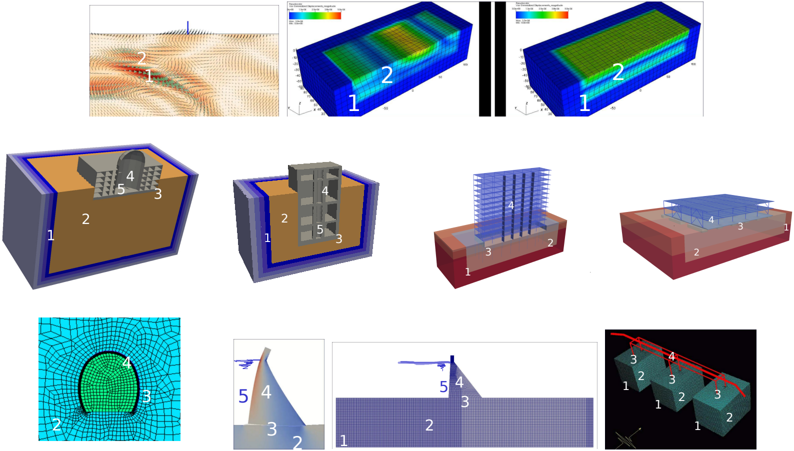
- Safety and economy of infrastructure
- Design, build and maintain sustainable infrastructure
- Responsible Engineer, with Executive Powers
- Engineer with versatile, quality assured analysis tool to
  - Explore design concepts
  - Assess infrastructure performance
- Engineering Analysis to Predict and Inform

Engineer Needs to Know!



Civil Engineering Analysis Challenges



Outline

Introduction

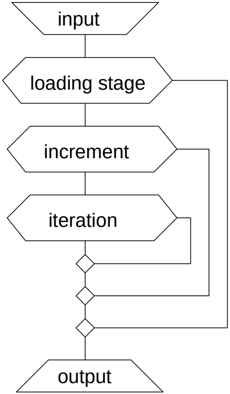
Engineering Analysis Methods and Tools

Engineering Analysis Applications

Summary

Engineering Analysis System

- Statics and dynamics of rock, soil, structures, fluids...
- Linear, Nonlinear, Inelastic
- Deterministic and Probabilistic
- High Performance Computing, HPC
- Reduction of Modeling Uncertainty
- Propagation of Parametric Uncertainty
- QA: Verification and Validation
- Infrastructure safety and economy
- `http://real-essi.us/`



Finite Element Method

- Single Phase FEM: $M_{AacB} \, \ddot{\bar{u}}_{Bc} + K_{AacB} \, \bar{u}_{Bc} = F_{Aa}$

- Two phase FEM, u-p-U:

$$\begin{bmatrix} (M_s)_{KijL} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & (M_f)_{KijL} \end{bmatrix} \begin{bmatrix} \ddot{\bar{u}}_{Lj} \\ \ddot{\bar{p}}_N \\ \ddot{\bar{U}}_{Lj} \end{bmatrix} + \begin{bmatrix} (C_1)_{KijL} & 0 & -(C_2)_{KijL} \\ 0 & 0 & 0 \\ -(C_2)_{LjiK} & 0 & (C_3)_{KijL} \end{bmatrix} \begin{bmatrix} \dot{\bar{u}}_{Lj} \\ \dot{\bar{p}}_N \\ \dot{\bar{U}}_{Lj} \end{bmatrix}$$

$$+ \begin{bmatrix} (K^{EP})_{KijL} & -(G_1)_{KiM} & 0 \\ -(G_1)_{LjM} & -P_{MN} & -(G_2)_{LjM} \\ 0 & -(G_2)_{KiL} & 0 \end{bmatrix} \begin{bmatrix} \bar{u}_{Lj} \\ \bar{p}_M \\ \bar{U}_{Lj} \end{bmatrix} = \begin{bmatrix} \bar{f}_{Ki}^{solid} \\ 0 \\ \bar{f}_{Ki}^{fluid} \end{bmatrix}$$

- Equilibrium: $R = F_{external} - F_{internal}$

Energy Input and Dissipation

Energy input, forces, loads

Energy dissipation outside SSI domain:

- SSI system oscillation radiation
- Reflected waves radiation

Energy dissipation/conversion inside SSI domain:

- Inelasticity of soil, interfaces, structure, dissipators
- Viscous coupling with internal/pore and external fluids
- Energy deflectors, meta-materials

Numerical energy dissipation/production

Energy Dissipation

- Rate of plastic energy dissipation:
  $\Phi = \sigma_{ij} \Delta \epsilon_{ij} - \sigma_{ij} \Delta \epsilon_{ij}^{el} - \rho \Delta \psi_{pl} \geq 0$

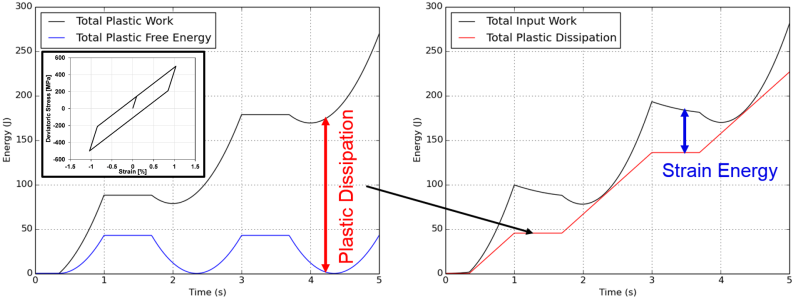
- Increment of viscous energy dissipation/damping:
  $\Delta D_V = C_{ij} \dot{u}_j \Delta u_i$

- Algorithmic, numerical dissipation:
  Newmark, Hilber-Hughes-Taylor, Houbolt, Wilson ...

Plastic Energy Dissipation

Plastic work is NOT plastic dissipation !

Surface area of $F - \Delta$ or $\sigma - \epsilon$ is NOT plastic dissipation !



Forward Uncertainty Propagation

Time Domain Stochastic Elastic-Plastic FEM
$M\ddot{u}_i + C\dot{u}_i + K^{ep}u_i = F(t)$

- Input random field and random 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

Forward Probabilistic Constitutive Solution in 1D

- Zero elastic region elasto-plasticity with stochastic Armstrong-Frederick kinematic hardening
  $\Delta\sigma = \ H_a \Delta\epsilon - c_r \sigma |\Delta\epsilon|; \quad E_t = d\sigma/d\epsilon = H_a \pm c_r \sigma$

- Uncertain: init. stiff. H_a, shear strength H_a/c_r, strain $\Delta\epsilon$:
  $H_a = \Sigma h_i \Phi_i; \quad C_r = \Sigma c_i \Phi_i; \quad \Delta\epsilon = \Sigma \Delta\epsilon_i \Phi_i$

- Resulting stress and stiffness are also uncertain

Forward Probabilistic Stress Solution

- Analytic product, for each stress component,
  $\Delta\sigma_{ij} = E^{EP}_{ijkl}\ \Delta\epsilon_{kl}$

- Incremental stress: each Polynomial Chaos component is updated incrementally
  $\Delta\sigma_1^{n+1} = \frac{1}{<\Phi_1\Phi_1>}\{\sum_{i=1}^{P_h}\sum_{k=1}^{P_e}\ h_i\Delta\epsilon_k^n < \Phi_i\Phi_k\Phi_1 >$
  $-\sum_{j=1}^{P_g}\sum_{k=1}^{P_e}\sum_{l=1}^{P_\sigma}\ c_j\Delta\epsilon_k^n\sigma_l^n < \Phi_j\Phi_k\Phi_l\Phi_1 >\}$
  ...
  $\Delta\sigma_P^{n+1} = \frac{1}{<\Phi_P\Phi_P>}\{\sum_{i=1}^{P_h}\sum_{k=1}^{P_e}\ h_i\Delta\epsilon_k^n < \Phi_i\Phi_k\Phi_P >$
  $-\sum_{j=1}^{P_g}\sum_{k=1}^{P_e}\sum_{l=1}^{P_\sigma}\ c_j\Delta\epsilon_k^n\sigma_l^n < \Phi_j\Phi_k\Phi_l\Phi_P >\}$

- Stress update:
  $\sum_{l=1}^{P_\sigma}\sigma_i^{n+1}\Phi_i = \sum_{l=1}^{P_\sigma}\sigma_i^n\Phi_i + \sum_{l=1}^{P_\sigma}\Delta\sigma_i^{n+1}\Phi_i$

Backward Uncertainty Propagation, Sensitivities

- Given forward uncertain response, PDFs, CDFs...
- Sensitivity of forward uncertainty to input uncertainties
- The ANalysis Of VAriance representation (Sobol 2001)
- Sobol indices $S_{i_1 \ldots i_s}$, fractional contributions from random inputs $\{X_{i_1}, ..., X_{i_s}\}$ to the total variance D: $S_{i_1 \ldots i_s} = D_{i_1 \ldots i_s}/D$
- First order indices $S_i \rightarrow$ individual influence of each uncertain input parameter
- Higher order indices $S_{i_1 \ldots i_s} \rightarrow$ mixed influence from groups of uncertain input parameters
- Total sensitivity indices, influence of input parameter X_i

$$S_i^{total} = \sum_{\mathscr{S}_i} D_{i_1 \ldots i_s}$$

Sobol Indices and Polynomial Chaos

PC expansion of response, ANOVA form (Sudret 2008)
Multi-dimensional PC bases $\{\Psi_j(\boldsymbol{\xi})\}$ decomposed into products of single dimension PC chaos bases of different orders

$$\Psi_j(\boldsymbol{\xi}) = \prod_{i=1}^{n} \phi_{\alpha_i}(\xi_i)$$

$\phi_{\alpha_i}(\xi_i)$ is the single dimensional, order α_i, polynomial function of underlying basic random variable ξ_i.
From ANOVA representation of probabilistic model response, the PC-based Sobol indices $S^{PC}_{i_1 \ldots i_s}$ are

$$S^{PC}_{i_1 \ldots i_s} = \sum_{\boldsymbol{\alpha} \in S_{i_1, \ldots, i_s}} y^2_{\boldsymbol{\alpha}} \boldsymbol{E}\left[\Psi^2_{\boldsymbol{\alpha}}\right] / D^{PC}$$

Sobol Sensitivity Analysis

Total Sobol indices $S_{j_1 \dots j_t}^{PC,total}$

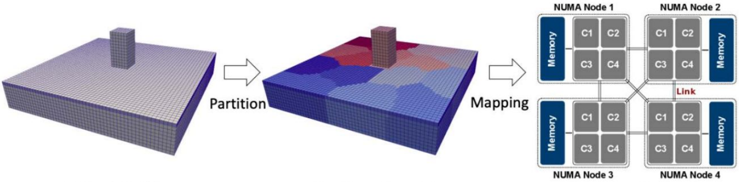
$$S_{j_1 \dots j_t}^{PC,total} = \sum_{(i_1,\dots,i_s) \in S_{j_1,\dots,j_t}} S_{i_1 \dots i_s}^{PC}$$

where $S_{j_1,\dots,j_t} = \{(i_1, \dots, i_s) : (j_1, \dots, j_t) \subset (i_1, \dots, i_s)\}$

Using PC representation of probabilistic model response, Sobol' sensitivity indices are analytic and inexpensive

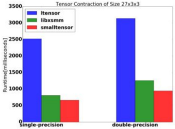
HPC: Course Grained and Fine Grained

- Plastic Domain Decomposition Method

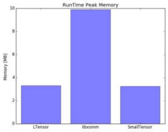


Original Model | Partitioned Model | Computer Architecture

- Small Tensor Library



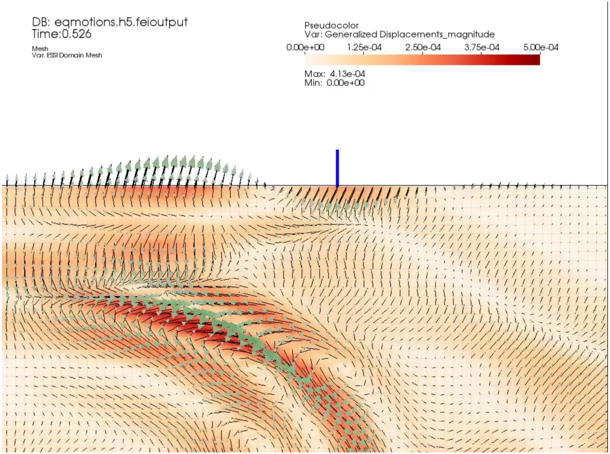
Runtime Performance



Peak Memory Usage

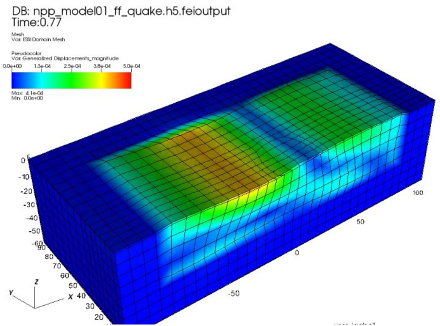
Outline

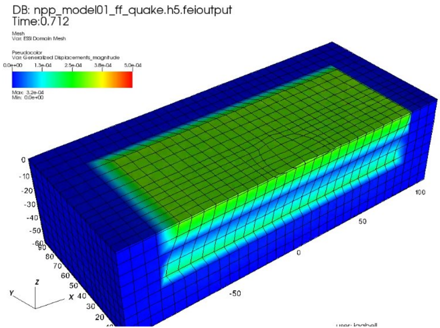
Realistic Ground Motions



1C vs 6C Free Field Motions

- One component of motions, 1C from 6C
- Excellent 1C/1D fit, wrong 3C/3D dynamics





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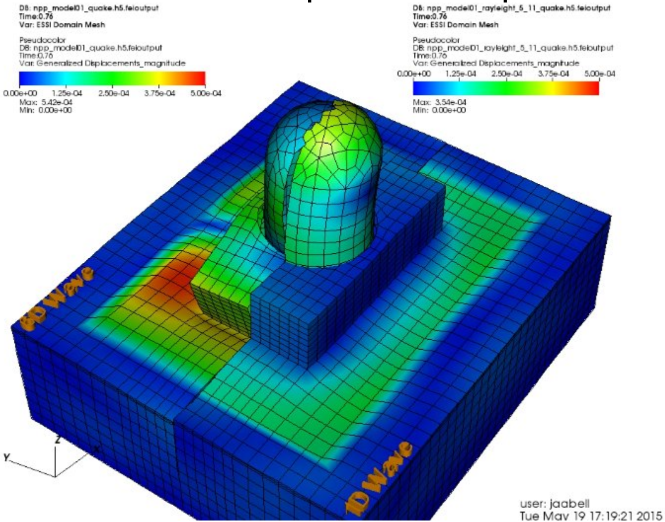
6C vs 1C NPP ESSI Response Comparison



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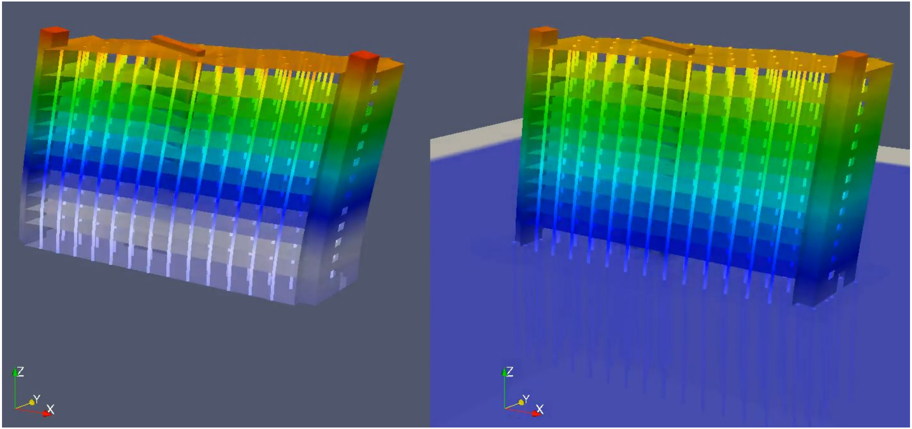
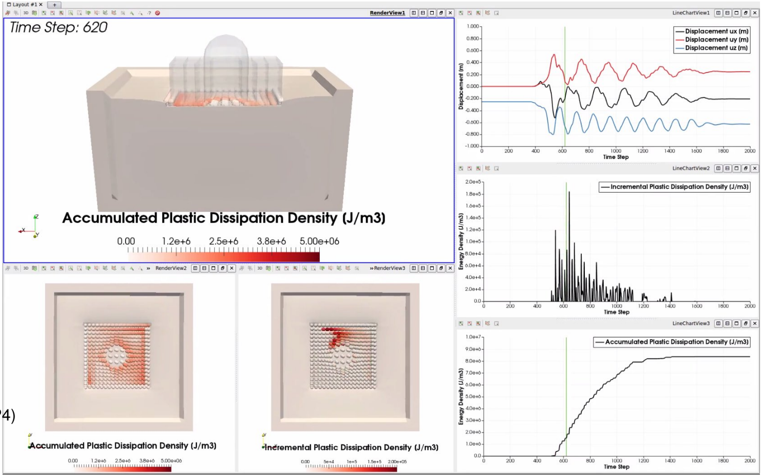
Ventura Hotel, Northridge Earthquake, nonSSI vs SSI



(**MP4**)

NPP Seismic Reponse, Energy Dissipation



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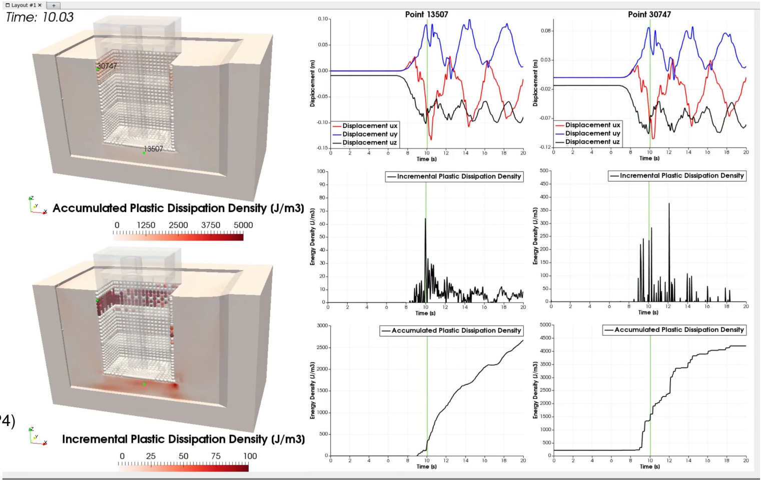
SMR Seismic Reponse, Energy Dissipation



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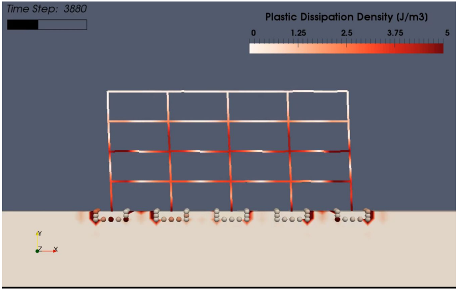
Design Alternatives



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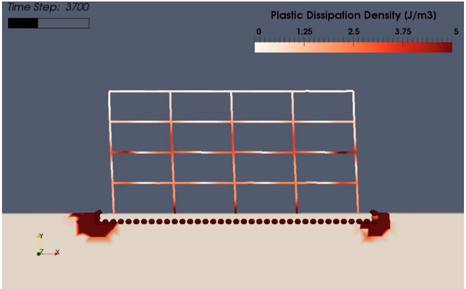

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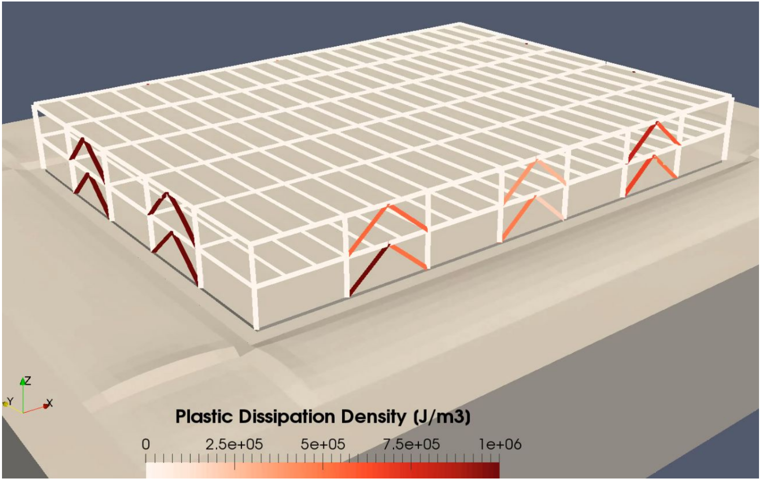
ASCE-7-21, Low Building: BRB Energy Dissipation



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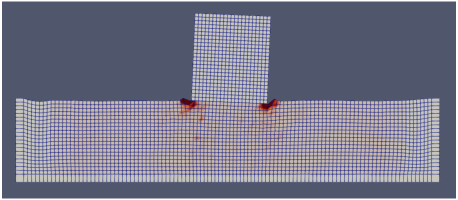
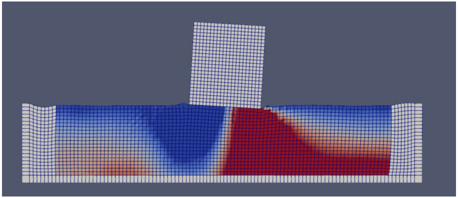
Building on Liquefiable Soil

Plastic Strain



Pore Fluid Pressures



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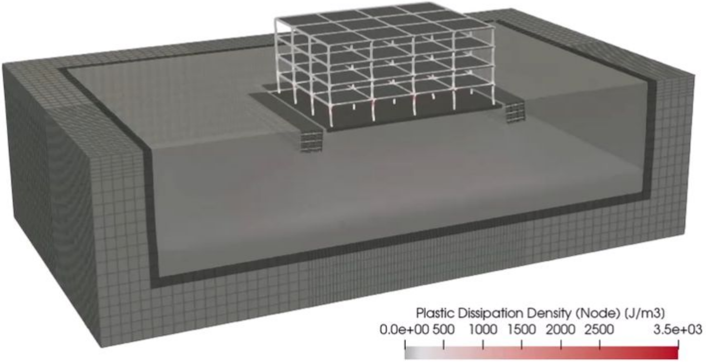
Building with Metamaterial Deflectors



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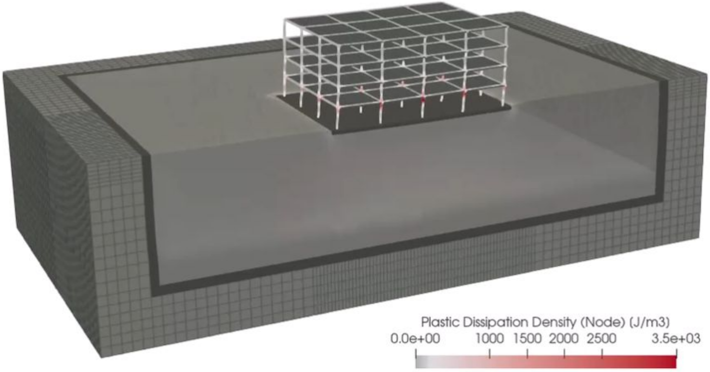
Building without Metamaterial Deflectors



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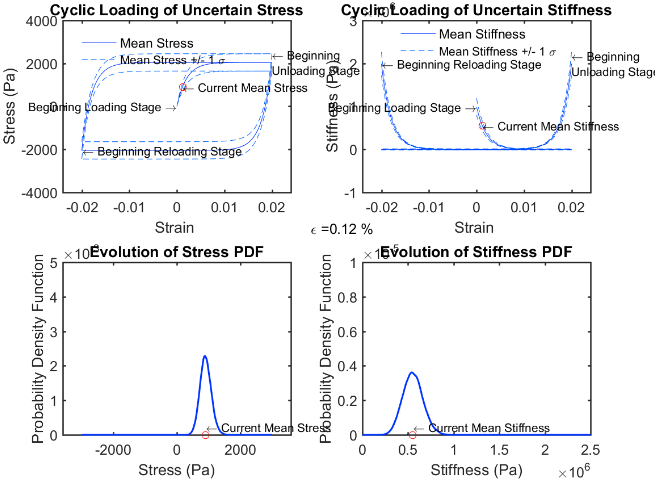
Probabilistic Elastic-Plastic Response



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SEPFEM: Example in 1D

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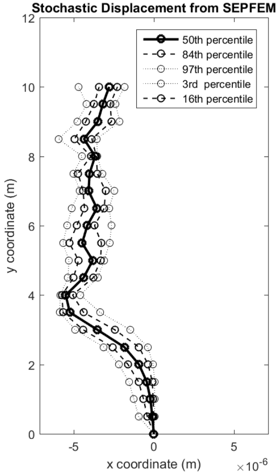
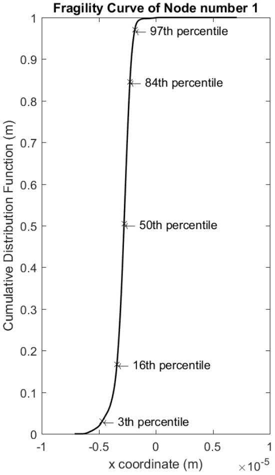
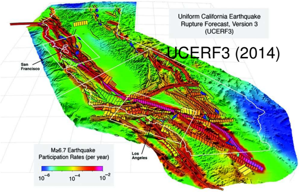


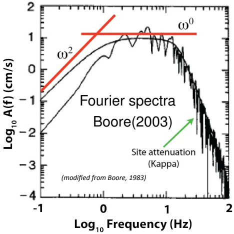


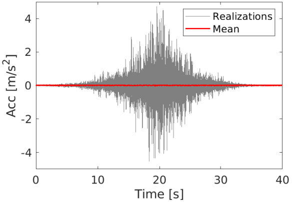
Application: Seismic Hazard

Seismic source characterization



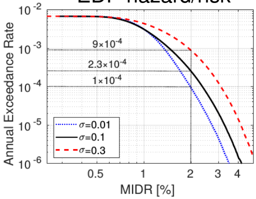
Stochastic ground motion



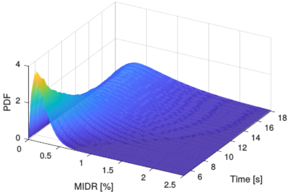


$$\lambda(EDP > z) = \sum N_i(M_i, R_i) P(EDP > z | M_i, R_i)$$

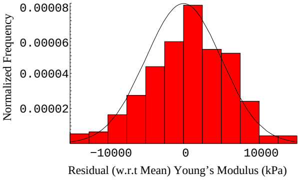
EDP hazard/risk



Uncertainty propagation SEPFEM

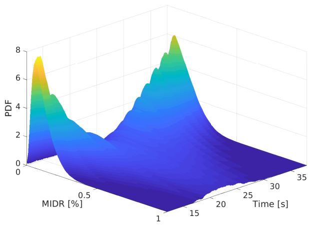


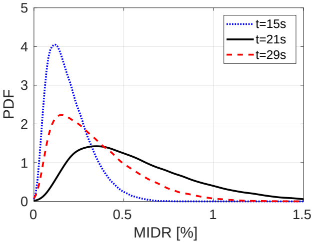
Uncertainty characterization Hermite polynomial chaos

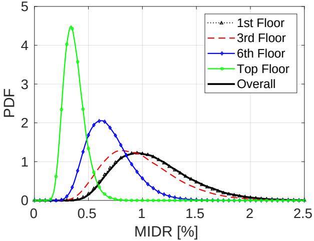


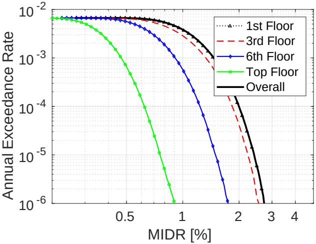
Seismic Risk Analysis

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>0.5$\mathrm{m/s^2}$	**PFA>1$\mathrm{m/s^2}$**	PFA>1.5$\mathrm{m/s^2}$
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}

- Damage measure (DM) defined on multiple EDPs:

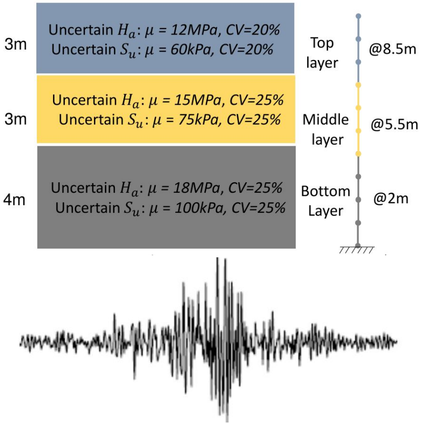
  DM : $\{\text{MIDR} > 1\% \cup \text{PFA} > 1\mathrm{m/s^2}\}$, seismic risk is $\mathbf{4.2\times10^{-3}}/\boldsymbol{yr}$

  DM : $\{\text{MIDR} > 1\% \cap \text{PFA} > 1\mathrm{m/s^2}\}$, seismic risk is $\mathbf{1.71\times10^{-3}}/\boldsymbol{yr}$

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

Sensitivity Example: Probabilistic 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

Outline

Summary

- Engineering analysis to predict and inform
- Engineer needs to know
- Education and Training is the Key
- Collaborators: Feng, Yang, Behbehani, Sinha, Wang, Lacoure, Wang, Pisanó, Abell, Tafazzoli, Jie, Preisig, Tasiopoulou, Watanabe, Luo, Cheng, Yang
- Funding from and collaboration with the US-DOE, US-NRC, US-NSF, ATC/US-FEMA, CNSC-CCSN, CH-ENSI, UN-IAEA, is greatly appreciated