Numerical Analysis in Civil Engineering

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Motivation

- Safety and economy of infrastructure
- Improve modeling, analysis
- Essential interaction: soil and structure
- Uncertainties: Modeling/Epistemic, Parametric/Aleatory
- Goal is to predict and inform
- Engineer needs to know!

Infrastructure, the Foundation of our Civilization

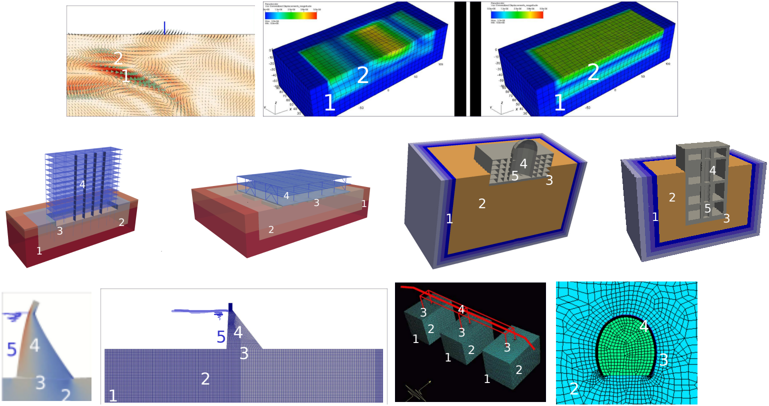



Progress, Resilient Infrastructure

Nov1990

Jul2019

Common Infrastructure Analysis Challenges



Role of Modeling in Civil Engineering

- Physical, experimental Modeling
  - Direct observation of system response
  - Model validation

- Analytical Modeling
  - Clearity and interpretability
  - Model verification, reference solutions

- Numerical Modeling
  - General method for representing realistic system
  - Complex geometry, advanced material behavior

Full Integration of all Three Domains is Essential

- Analytical modeling: understand and verify
- Experimental modeling: observe and validate
- Numerical modeling: analyze realistic system

Numerical Prediction under Uncertainty

- Modeling, Epistemic Uncertainty
  - Model simplifications
  - Choice of sophistication level for confidence in results
  - Verification and Validation

- Parametric, Aleatory Uncertainty
  - $M\,\Delta\ddot{u}_i + C\,\Delta\dot{u}_i + K^{ep}\,\Delta u_i = \Delta F(t)$,
  - Uncertain: mass M, damping C, stiffness K^{ep}, loads $F(t)$
  - Results are PDFs and CDFs for σ_{ij}, ϵ_{ij}, u_i, $\dot{u}_i$, $\ddot{u}_i$

Energy Input and Dissipation

Energy input, forces, loads

Energy dissipation outside SSI domain:
- SSI system oscillation radiation
- Reflected waves radiation

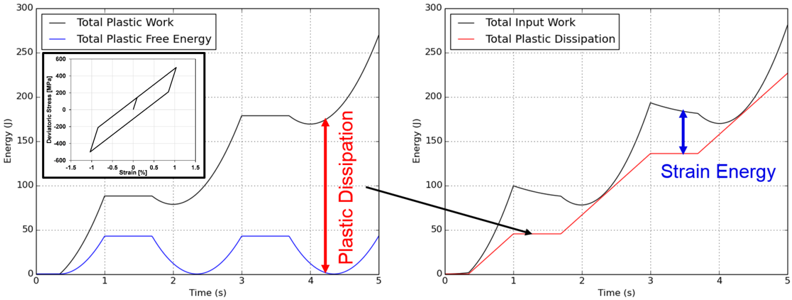
Energy dissipation/conversion inside SSI domain:
- Inelasticity of soil, interfaces, structure, dissipators
- Viscous coupling with internal/pore and external fluids
- Energy deflectors, meta-materials

Numerical energy dissipation/production

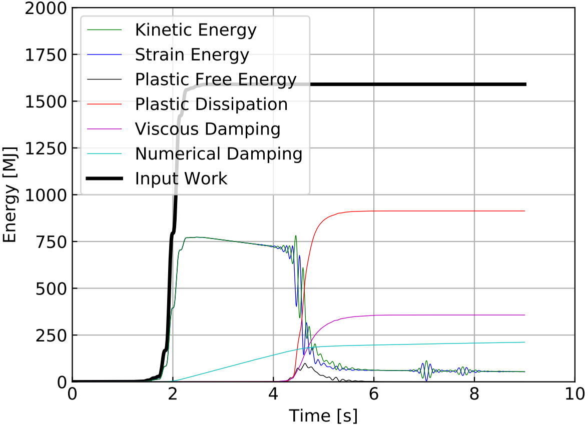
Plastic Energy Dissipation

Plastic work is NOT plastic dissipation !

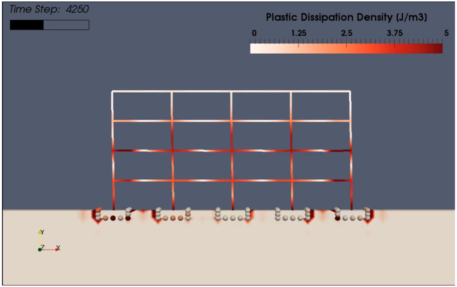
Surface area of $F - \Delta$ or $\sigma - \epsilon$ is NOT plastic dissipation !



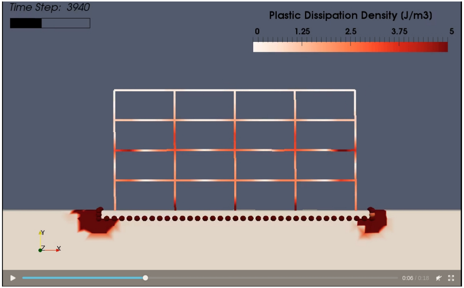
Energy Dissipation Control



Direct Seismic Energy Dissipation to the Soil!

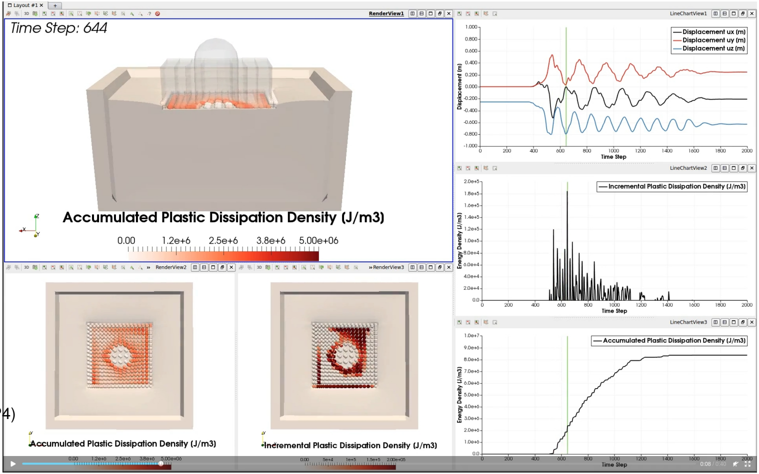


(MP4)



(MP4)

NPP, Energy Dissipation



(MP4)

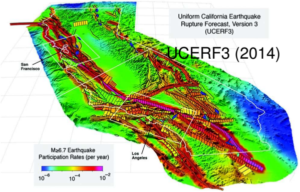
Stochastic Elastic-Plastic Finite Element Method

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

- 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
- Complete probabilistic response
- NO need to decide/define Intensity Measures (IMs) !

Application: Seismic Hazard

Seismic source characterization



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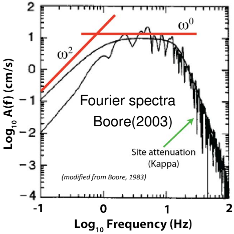
Stochastic ground motion



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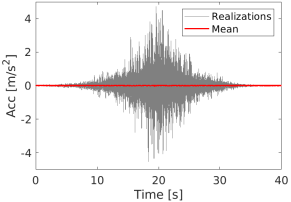
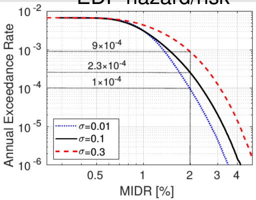


$$\lambda(EDP > z) = \sum N_i(M_i, R_i) P(EDP > z | M_i, R_i)$$

EDP hazard/risk



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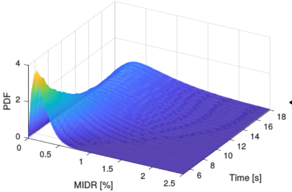
Uncertainty propagation SEPFEM



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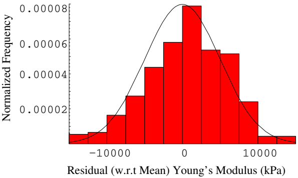
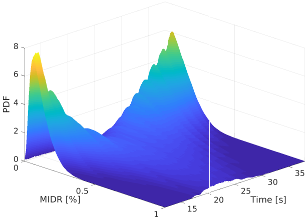
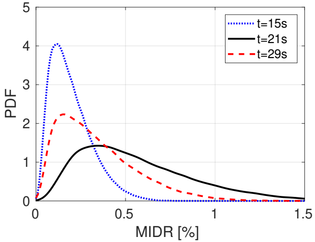
Uncertainty characterization Hermite polynomial chaos

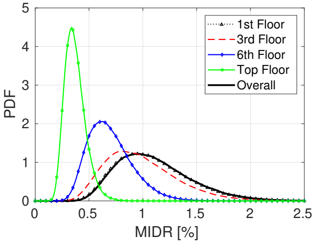


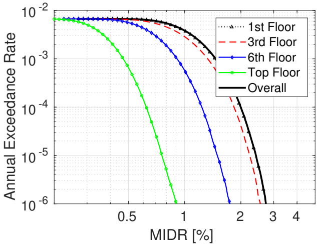
Seismic Risk Analysis

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



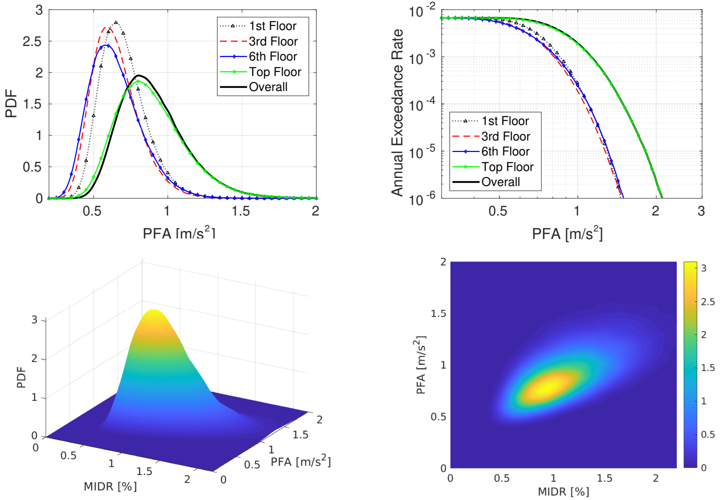






Seismic Risk Analysis

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



Seismic Risk Analysis

- Damage measure 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]	6.66×10^{-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 $\mathbf{1.71\times10^{-3}}/\boldsymbol{yr}$

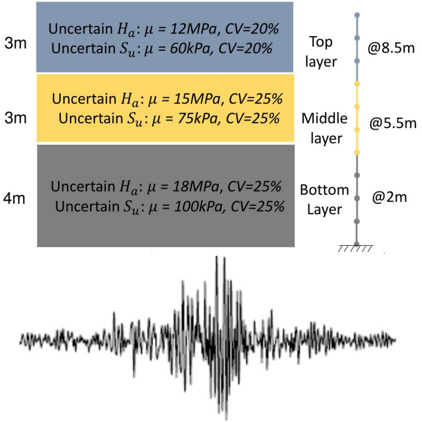
- Seismic risk for DM defined on multiple EDPs can be quite different from that defined on single EDP

Sensitivities, Backward Uncertainty Propagation

- Given forward uncertain response, PDFs, CDFs...
- Contributions of uncertain input to forward uncertainties
- Sensitivity of uncertain response to input uncertainties
- Sobol indices

Application Example: 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 rock motions at depth

- 49% from uncertain rock motions at depth
- 2% from uncertain soil
- 49% from interaction of uncertain rock motions and uncertain soil

Summary

- Engineering analysis to **predict** and **inform**
- Engineer needs to **know**
- **Education** and **Training** is the Key
- `http://real-essi.info`
- Yang, Sinha, Wang, Lacour, Wang, Pisanó, Abell, Sett, Tafazzoli, Jie, Preisig, Tasiopoulou, Watanabe, Luo, Cheng, Yang, Kanellopoulos, Staszewska...
- US-DOE, US-NRC, US-NSF, ATC/US-FEMA, CNSC-CCSN, UN-IAEA, Shimizu, PEER, Caltrans, ENSI-CH-Basler&Hofmann, KEPCO, EDF, CalTeachLab...