Realistic Modeling and Simulation of Earthquakes, Soil, Structures and their Interaction

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Outline

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Motivation

Improve modeling and simulation for infrastructure objects

Modeling sophistication level, epistemic uncertainty

Parametric, aleatory uncertainty

Goal: Predict and Inform

Expert numerical modeling and simulation tool

Engineer needs to know!

Numerical Prediction under Uncertainty

- Modeling, Epistemic Uncertainty

  Modeling simplifications

  Modeling sophistication for confidence in results

- Parametric, Aleatory Uncertainty

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

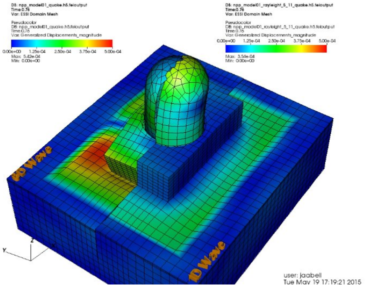
  Uncertain: mass M, viscous damping C and stiffness K^{ep}

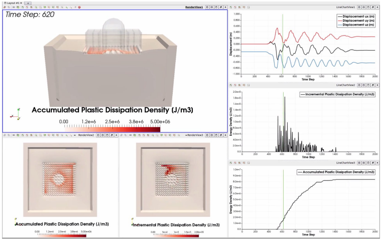
  Uncertain loads, $F(t)$

  Results are PDFs and CDFs for σ_{ij}, ϵ_{ij}, u_i, $\dot{u}_i$, $\ddot{u}_i$

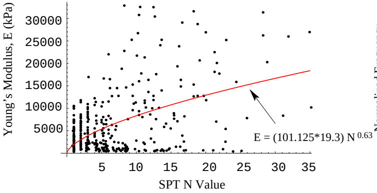
Modeling, Epistemic Uncertainty

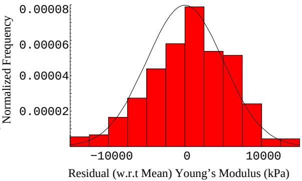
- Important (?!) features are simplified, 1C vs 3C, inelasticity
- Modeling simplifications are justifiable if one or two level higher sophistication model demonstrates that features being simplified out are less or not important



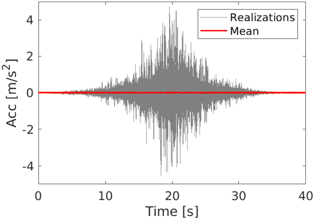


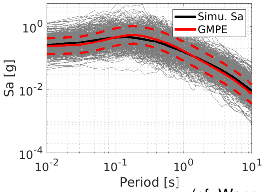
Parametric, Aleatory Uncertainty





(cf. Phoon and Kulhawy (1999B))





(cf. Wang et al. (2019))

Outline

Forward Uncertain Inelasticity

- Incremental el–pl constitutive equation

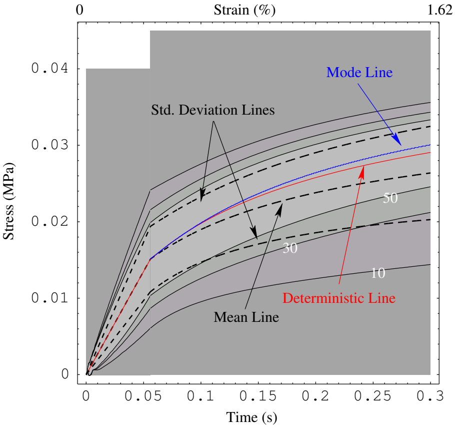
$$\Delta\sigma_{ij} = E^{EP}_{ijkl}\ \Delta\epsilon_{kl} = \left[E^{el}_{ijkl} - \frac{E^{el}_{ijmn} m_{mn} n_{pq} E^{el}_{pqkl}}{n_{rs} E^{el}_{rstu} m_{tu} - \xi_* h_*} \right] \Delta\epsilon_{kl}$$

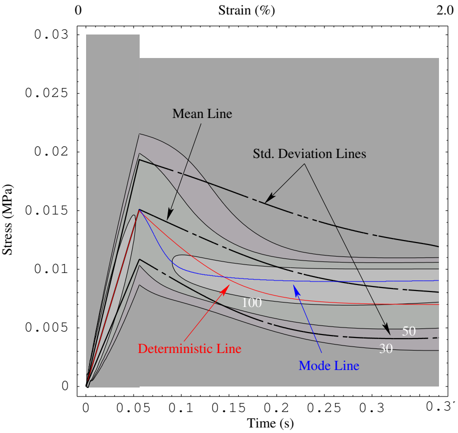
- Dynamic Finite Elements

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

- Material and loads are uncertain

Cam Clay with Random G, M and p_0





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.
- Jeremić et al. 2011

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

Outline

ANOVA Representation

Model with n uncertain inputs ($\boldsymbol{x}$) and scalar output y:

$$y = f(\boldsymbol{x}); \;\; \boldsymbol{x} \in I^n$$

The ANalysis Of VAriance representation (Sobol 2001):

$$f(x_1, ...x_n) = f_0 + \sum_{i=1}^{n} f_i(x_i) + \sum_{1 \leq i < j \leq n} f_{ij}(x_i, x_j) + ...f_{1,...n}(x_1, ...x_n)$$

Sobol Indices

- Sobol' indices $S_{i_1 \dots i_s}$, fractional contributions from random inputs $\{X_{i_1}, ..., X_{i_s}\}$ to the total variance D: $S_{i_1 \dots i_s} = D_{i_1 \dots i_s}/D$
- First order indices $S_i \rightarrow$ individual influence of each uncertain input parameter
- Higher order indices $S_{i_1 \dots i_s} \rightarrow$ mixed influence from groups of uncertain input parameters
- Total sensitivity indices, influence of input parameter X_i

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

Sobol Indices and Polynomial Chaos

PC expansion of response, in 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.

Sobol Sensitivity Analysis

ANOVA $\rightarrow$ Sobol' indices: $S^{PC}_{i_1\dots i_s} = \sum_{\boldsymbol{\alpha}\in\mathscr{S}_{i_1\dots i_s}} y^2_{\boldsymbol{\alpha}} \boldsymbol{E}\left[\Psi^2_{\boldsymbol{\alpha}}\right] / D^{PC}$

Total Sobol' indices: $S^{PC,\text{total}}_{j_1\dots j_t} = \sum_{(i_1,\dots,i_s)\in\mathscr{S}_{j_1,\dots,j_t}} S^{PC}_{i_1\dots i_s}$

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

Outline

Real-ESSI Simulator System

The Real-ESSI, **Real**istic Modeling and Simulation of **E**arthquakes, **S**oils, **S**tructures and their **I**nteraction Simulator is a software, hardware and documentation system for time domain, linear and nonlinear, elastic and inelastic, deterministic or probabilistic, 3D, modeling and simulation of:

- statics and dynamics of soil,
- statics and dynamics of rock,
- 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, safety margins

Real-ESSI Simulator System

Components

- Real-ESSI Pre (gmsh/gmESSI, X2ESSI)
- Real-ESSI Program (local, remote, cloud)
- Real-ESSI Post (Paraview/pvESSI, Python, Matlab)

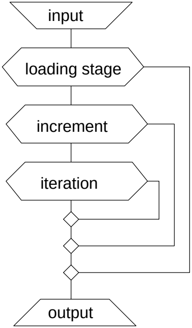
Availability

- Linux Executables
- Amazon Web Services
- Docker Container Image
  - Linux
  - MS-Windows
  - MacOS

Real-ESSI documentation and program available at `http://real-essi.us/`

Real-ESSI Simulation Features

- Static loading stages
- Dynamic loading stages
- Restart, simulation tree
- Solution advancement methods/algorithms, on global and constitutive levels, with and without enforcing equilibrium
- High Performance Computing
  . Fine grained, template mataprograms, small matrix library
  . Coarse grained, distributed memory parallel



Real ESSI DSL Example

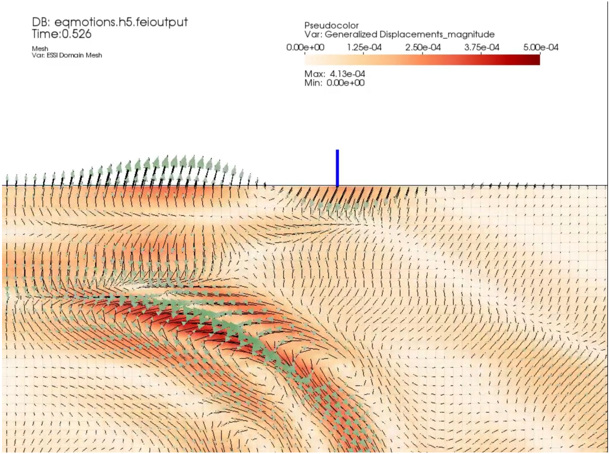

```
model name "SmallTestModel";
new loading stage "First_static";
// Nodal Coordinates
add node # 1 at (0*m, 0*m, 0*m) with 6 dofs;
add node # 2 at (0*m, 0*in, 1000*mm) with 6 dofs;
add element # 1 type beam_elastic with
  nodes (1, 2) cross_section=1.0*m^2
  elastic_modulus=1.0e5*KN/m^2
  shear_modulus=2.0e4*KN/m^2
  torsion_Jx=2*0.083*m^4
  bending_Iy=0.083*m^4 bending_Iz=0.083*m^4
  mass_density=2500.0*kg/m^3
  xz_plane_vector = (0, -1, 0)
  joint_1_offset = (0.0*m, 0.0*m, 0.0*m)
  joint_2_offset = (0.0*m, 0.0*m, 0.0*m);
```

Real ESSI DSL Example

```
fix node No 1 dofs all;
add load # 1 to node # 2 type linear Fy=-9*kN;
define load factor increment 0.01;

define solver UMFPack;

define convergence test
  Norm_Displacement_Increment
  tolerance = 1e-5
  maximum_iterations = 20
  verbose_level = 4;

define algorithm Newton;

simulate 100 steps using static algorithm;

bye;
```

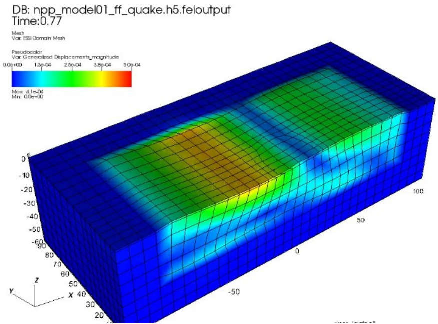
Outline

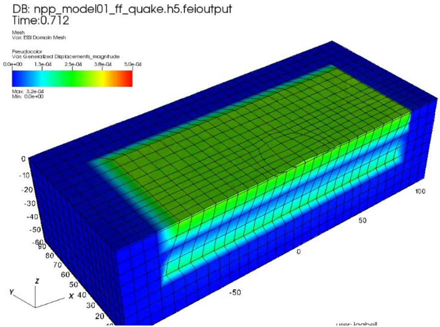
Realistic Ground Motions



1C vs 6C Free Field Motions

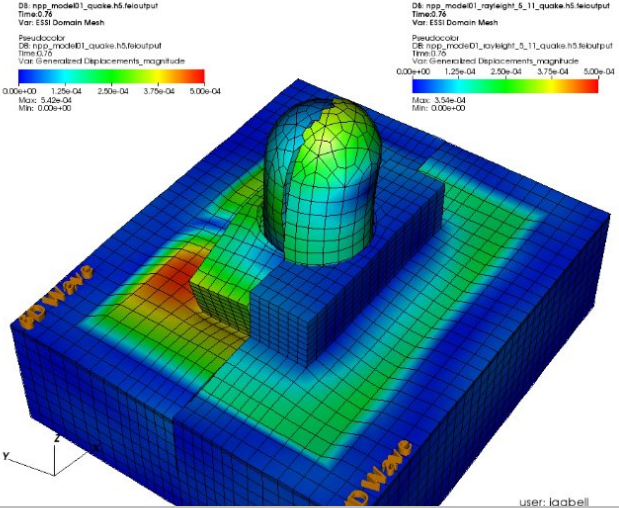
- One component of motions, 1C from 6C
- Excellent fit
- Wrong mechanics





(MP4) (MP4)

6C vs 1C NPP ESSI Response Comparison



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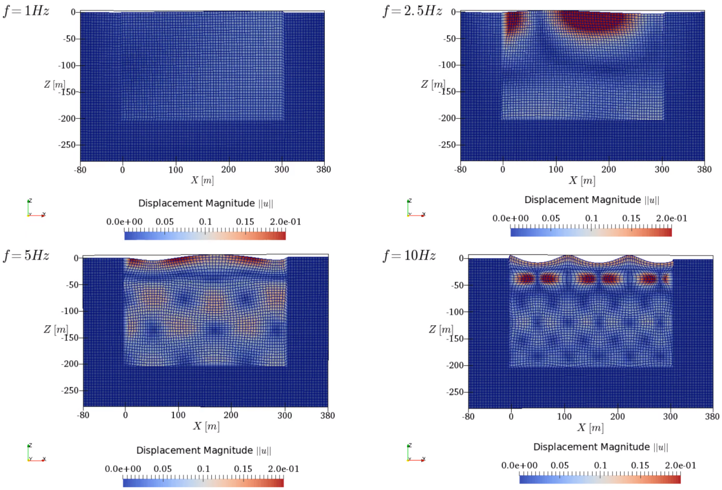
Free Field, Variation in Input Frequency, $\theta = 60^o$



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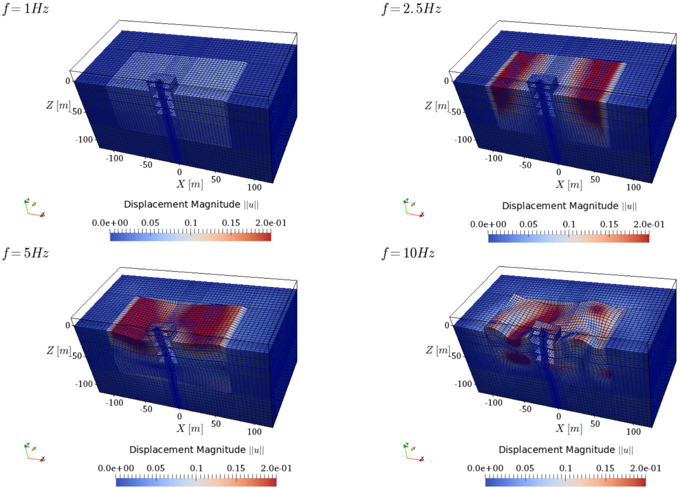
SMR ESSI, Variation in Input Frequency, $\theta = 60^o$



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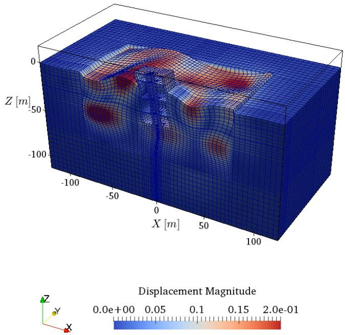
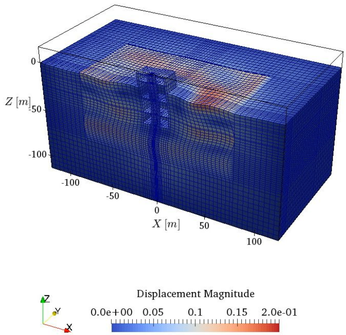
SMR ESSI, 3C vs 3×1C

$3C$



$3 \times 1C$



(OGV)

Outline

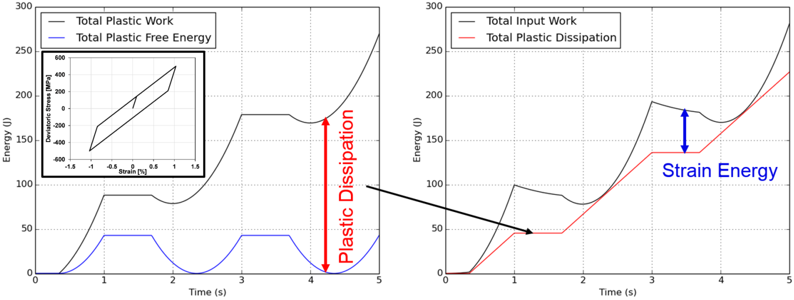
Energy Input and Dissipation

- Energy input, static and dynamic forcing
- Energy dissipation outside SSI domain:
  - SSI system oscillation radiation
  - Reflected wave radiation
- Energy dissipation/conversion inside SSI domain:
  - Inelasticity of soil, interfaces, structure, dissipators
  - Viscous coupling with internal/pore and external fluids
- Numerical energy dissipation/production

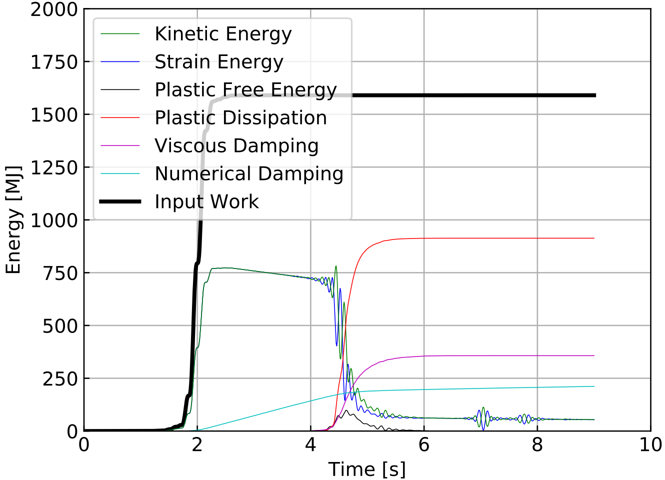
Plastic Energy Dissipation

Single elastic-plastic element under cyclic shear loading

Difference between plastic work and plastic dissipation



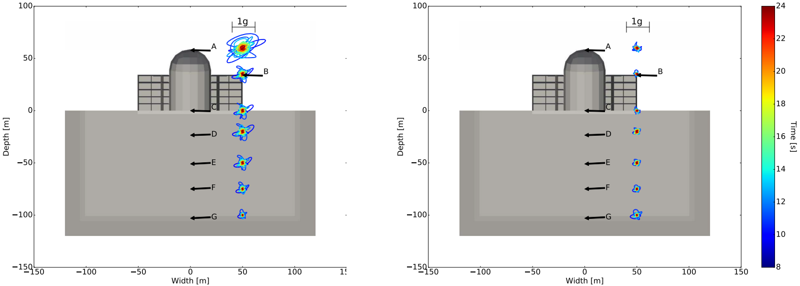
Energy Dissipation Control



Inelastic Modeling of Soil Structure Systems

- Soil, inelastic, elastic-plastic
  - Dry, single phase
  - Unsaturated, partially saturated
  - Fully saturated
- Contact/Interface/Joint, inelastic: dry or saturated
  - Axial, hard and soft, gap open/close
  - Shear, friction, nonlinear
- Structure, inelastic, damage, cracks
  - Inelastic fiber beam
  - Inelastic layer shell
  - Inelastic 3D solid element

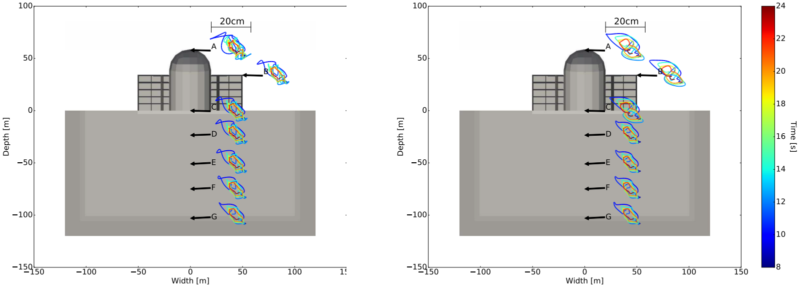
Acceleration Traces, Elastic vs Inelastic



Elastic

Inelastic

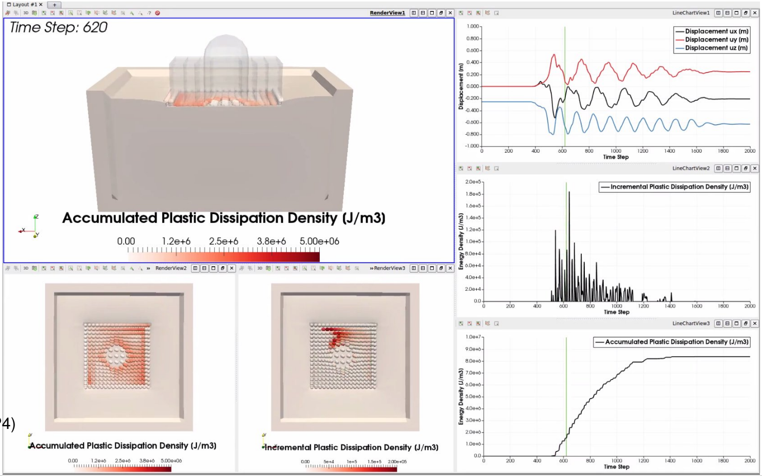
Displacement Traces, Elastic vs Inelastic



Elastic

Inelastic

NPP: Energy Dissipation



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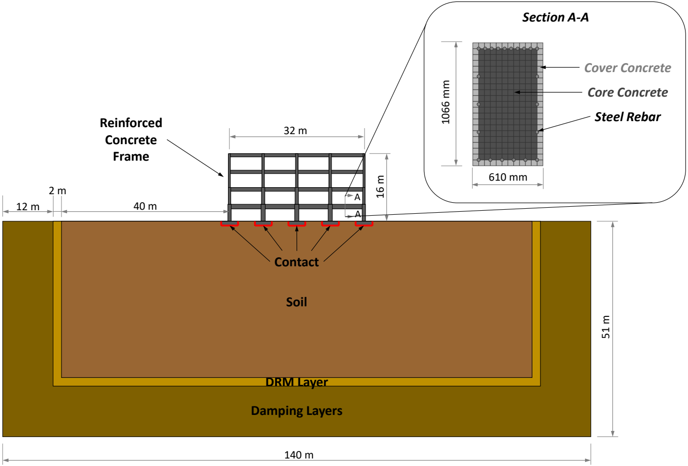
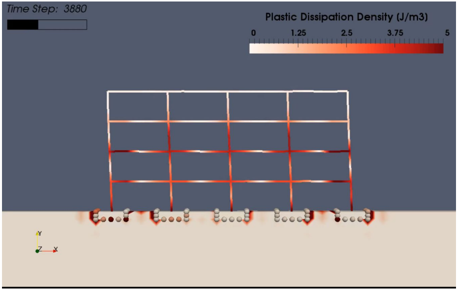
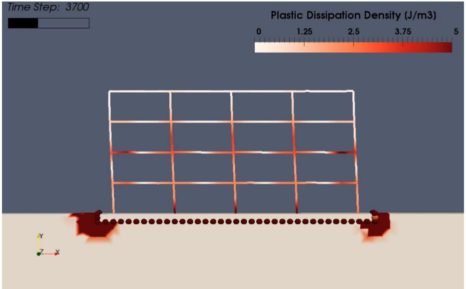
Energy Dissipation for Design



Design Alternatives





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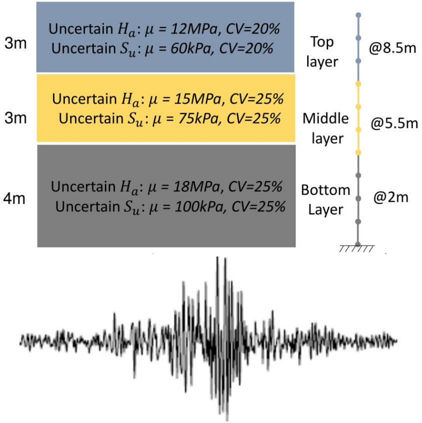
Outline

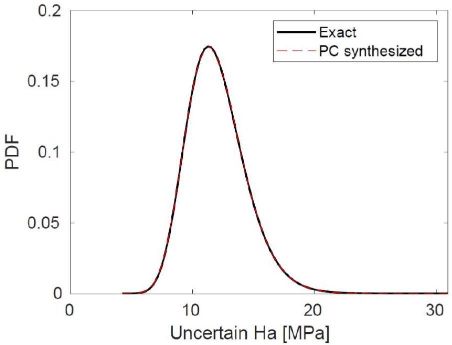
Stochastic Site Response

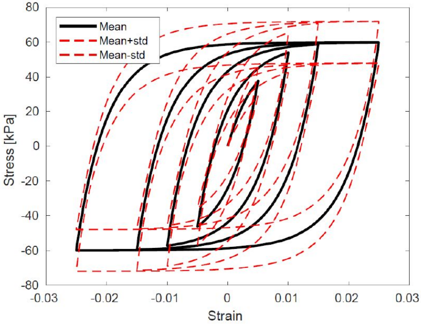
- Uncertain material: uncertain random field, marginally lognormal distribution, exponential correlation length 10m
- Uncertain seismic rock motions: seismic scenario M=7, R=50km



Stochastic Material Parameters

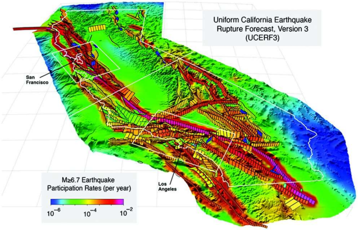
Lognormal distributed random field with PC Dim. 3 Order 2

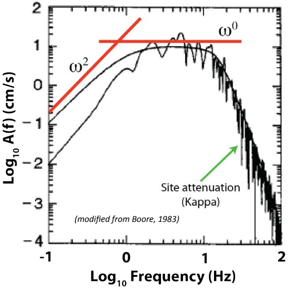




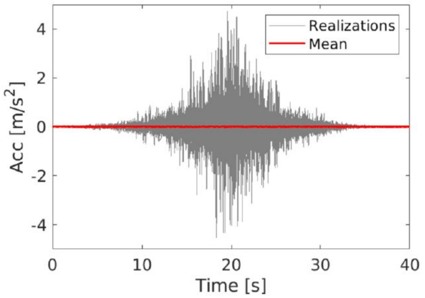
Stochastic Seismic Motion Development

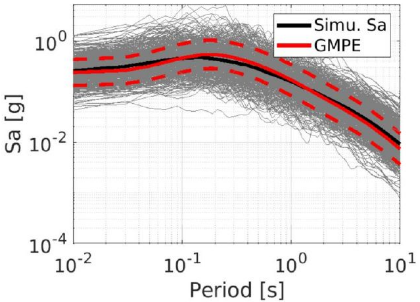
- UCERF3 (Field et al. 2014)
- Stochastic motions (Boore 2003)
- Polynomial Chaos Karhunen-Loève expansion
- Probabilistic DRM (Bielak et al. 2003, Wang et al. 2021)





Stochastic Seismic Motions





Sensitivity Analysis

Total variance in PGA, in this 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

Appropriate Quotes

François-Marie Arouet, Voltaire: "Le doute n'est pas une condition agréable, mais la certitude est absurde."

Max Planck: "A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."

Niklaus Wirth: "Software is getting slower more rapidly than hardware becomes faster."

Summary

- Numerical modeling to predict and inform
- Education and Training is the key !
- Collaborators: Feng, Yang, Behbehani, Lacour, Sinha, Wang, Wang, Pisanó, Abell, Tafazzoli, Jie, Preisig, Tasiopoulou, Watanabe, Luo, Cheng, Yang.
- Funding from and collaboration with the US-NSF, US-DOE, US-NRC, US-FEMA/ATC, CNSC-CCSN, CH-ENSI/Basler&Hofmann, UN-IAEA, and Shimizu Corp. is greatly appreciated,

  http://sokocalo.engr.ucdavis.edu/~jeremic