Work Interest

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Computer Methods in
Civil & Environmental Engineering,
ECI115
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Outline

Outline

Motivation

Improve modeling and simulation for solids and structures

Reduction of modeling uncertainty

Choice of analysis level of sophistication

Predict and inform, Engineer needs to know!

Design, build and maintain sustainable objects





Prediction under Uncertainty

- Modeling Uncertainty, simplifying assumptions

  Low, medium, high sophistication modeling and simulation

  Choice of sophistication level for confidence in results

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

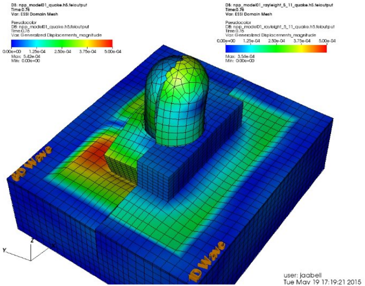
  Uncertain mass M, viscous damping C and stiffness K^{ep}

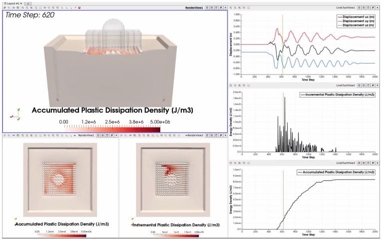
  Propagation of uncertainty in loads, $F(t)$

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

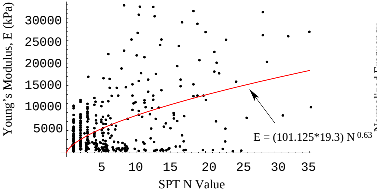
Modeling Uncertainty

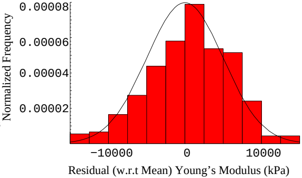
- Important (?!) features are simplified, 1C vs 3C, inelasticity
- Modeling simplifications are justifiable if one or two level higher sophistication model demonstrates that features being simplified out are less or not important



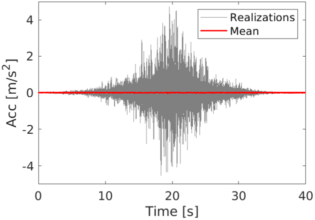


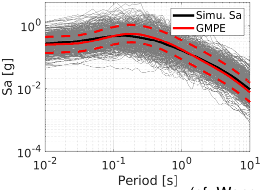
Parametric Uncertainty: Material and Loads





(cf. Phoon and Kulhawy (1999B))





(cf. Wang et al. (2019))

Education and Training

- Lecture Notes: (I) Theory and Computational Formulation, (II) Software and Hardware System, (III) Verification and Validation, (IV) Modeling and Simulation Examples, (V) Application to Practical Engineering Problems.
- Online education, recorded lectures
- Requires time!

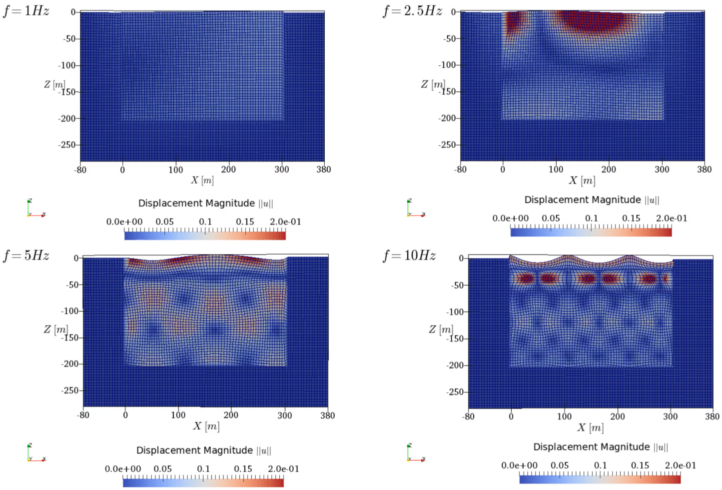
Outline

1C, 2C, 3C, 6C Seismic Motions

All (most) measured motions are full 3C, 6C

What is the effect of neglecting, simplifying 3C/6C to 1C

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



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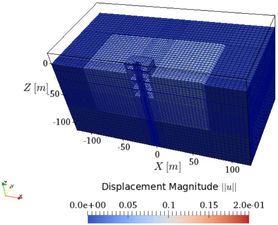
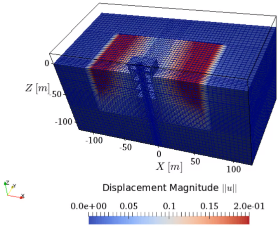
SMR ESSI, Variation in Input Frequency, $\theta = 60^o$

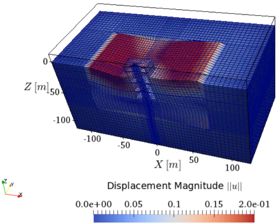
$f = 1Hz$



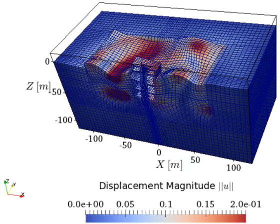
$f = 2.5Hz$



$f = 5Hz$



$f = 10Hz$



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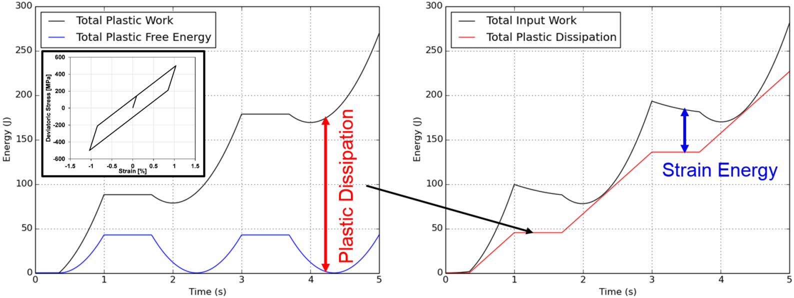
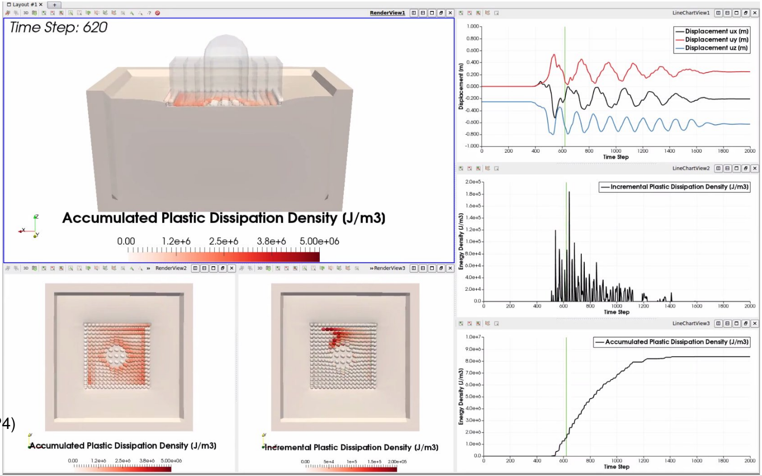
Plastic Energy Dissipation

Single elastic-plastic element under cyclic shear loading

- Difference between plastic work and plastic dissipation
- Plastic work can decrease
- Plastic dissipation always increases



Energy Dissipation for an NPP



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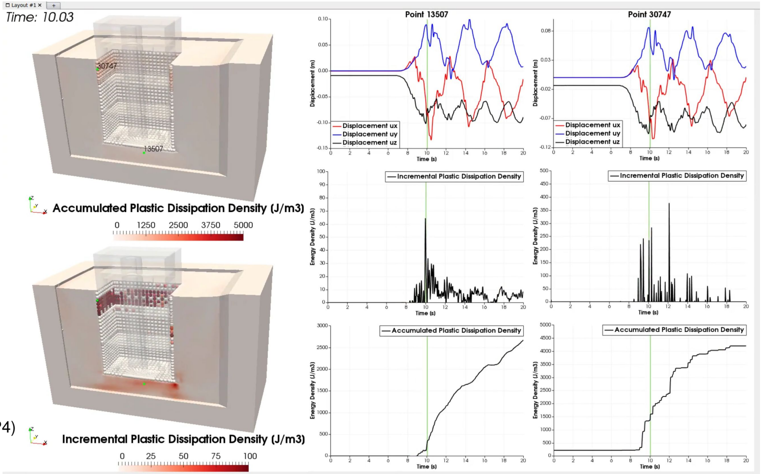
Energy Dissipation for an SMR Model



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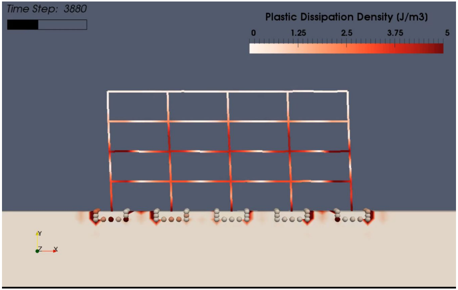
Design Alternatives



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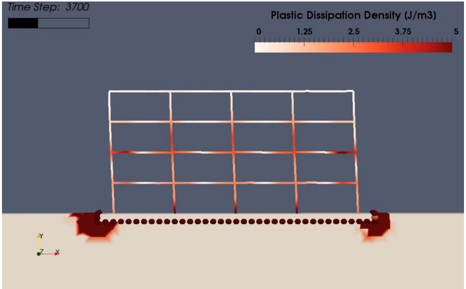

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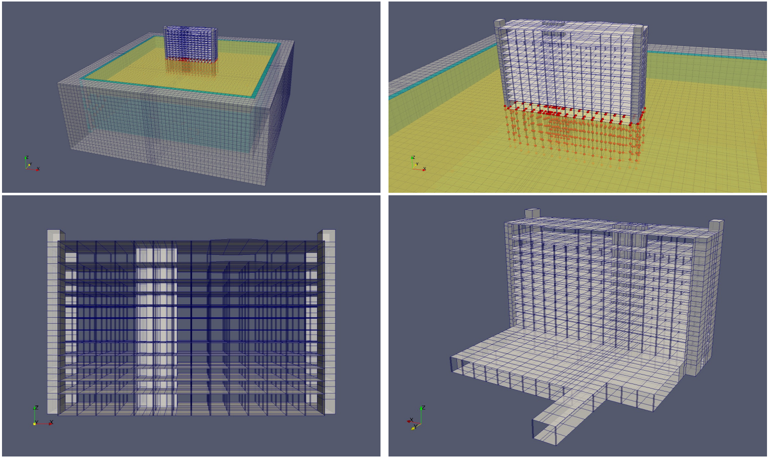
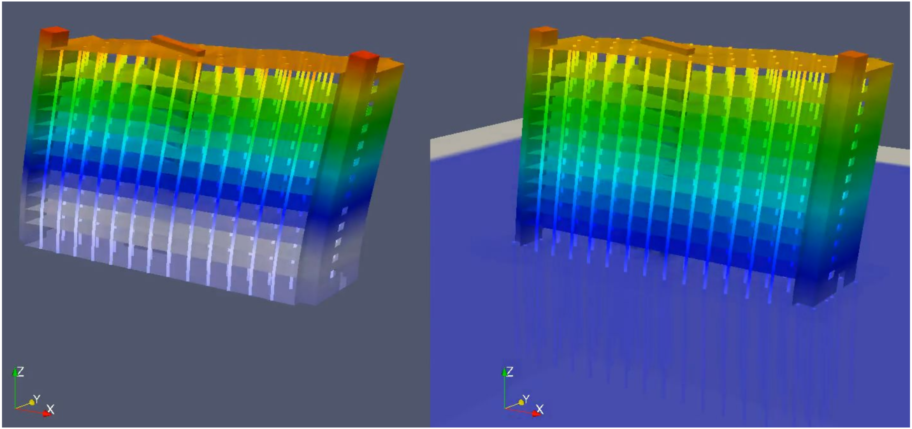
Ventura Hotel, Northridge Earthquake



Ventura Hotel, Northridge Earthquake, nonSSI vs SSI



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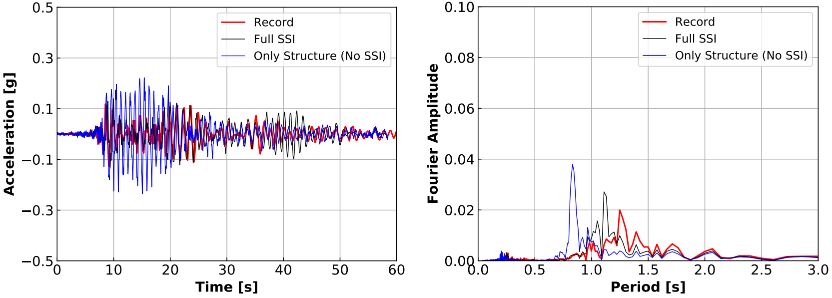
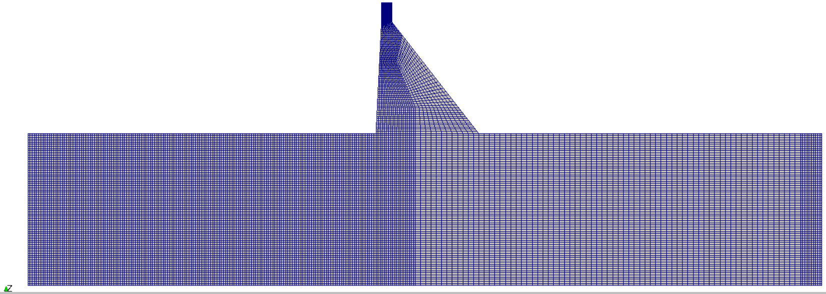
Ventura Hotel, Northridge Earthquake, SSI vs nonSSI

Top floor, long axes response

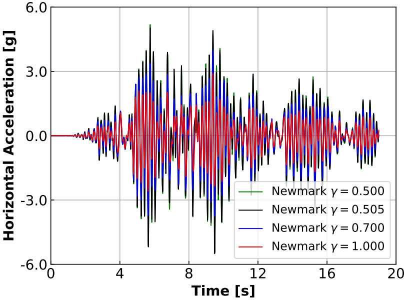


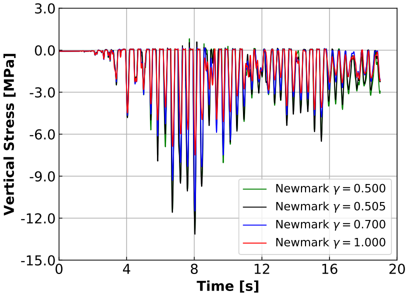
Pine Flats Dam, Model

- Material properties provided
- Motions applied through DRM, from bottom
- Energy dissipation, Viscous, Numerical, Radiation
- Load cases as provided

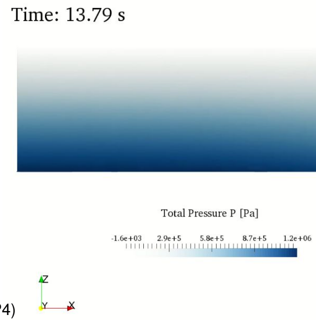


Numerical Damping Effects, Inelastic $\ddot{u}_{hor}^{top}$, σ_v^{heel}





Pine Flat Dam, Hydrodynamic Pressure



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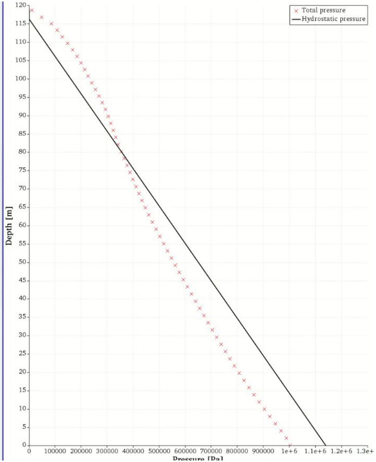
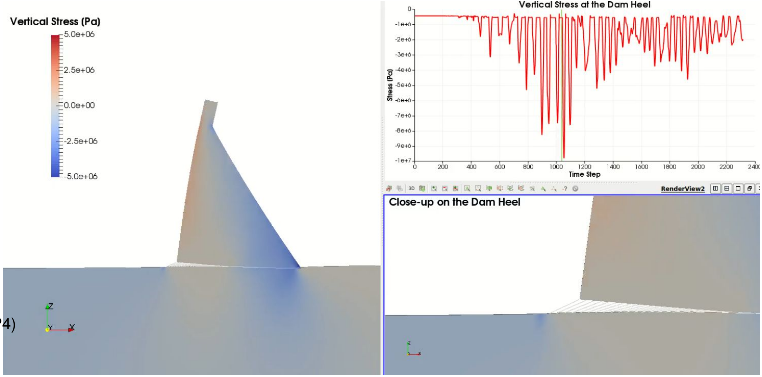


Pine Flat Dam, Inelastic Interface, Hydrostatic



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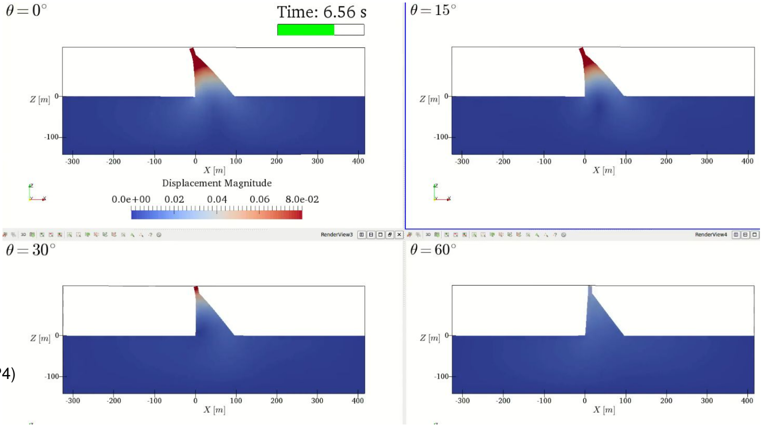
Pine Flat Dam, Inclined Plane Waves



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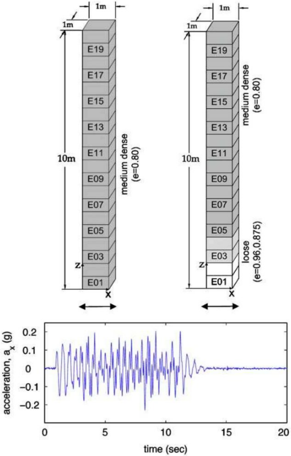
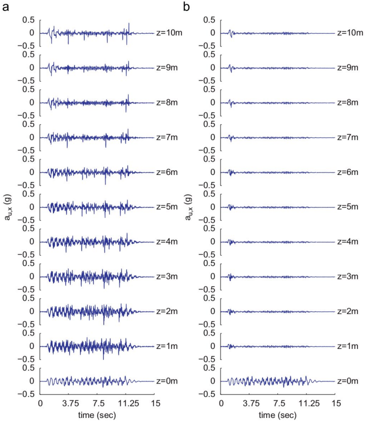
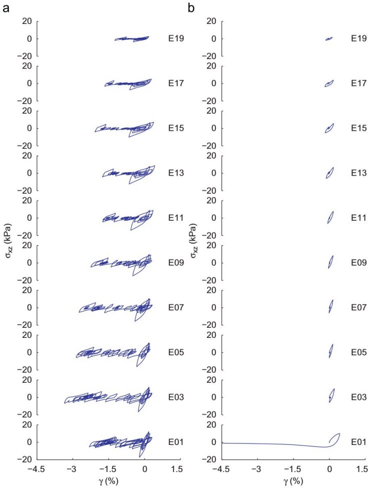
Liquefaction as Base Isolation, Model



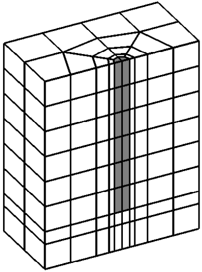
Liquefaction, Wave Propagation

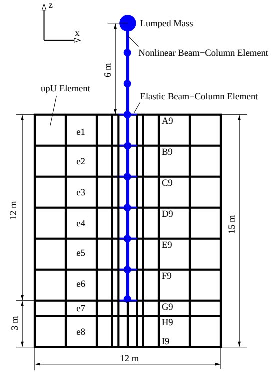


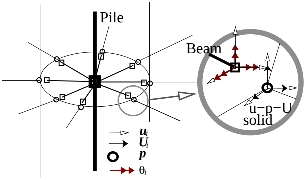
Liquefaction, Stress-Strain Response



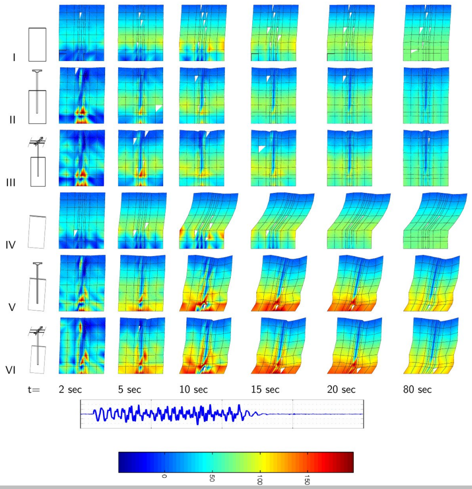
Pile in Liquefiable Soil, Model



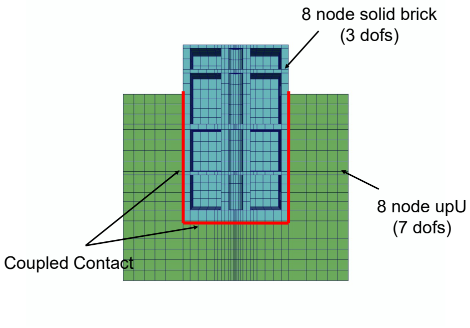


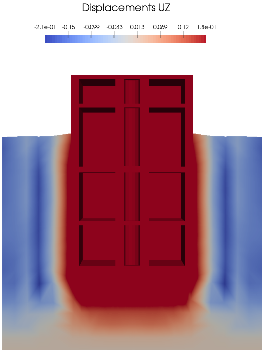


Pile in Liquefiable Soil, Pinning Effects

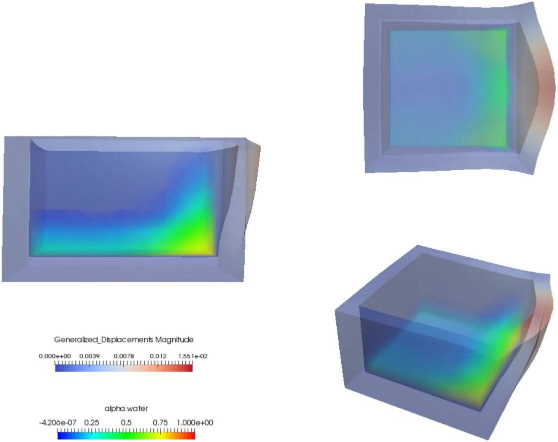


Buoyant Force Simulation





Solid, Structure-Fluid Interaction, Example



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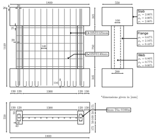
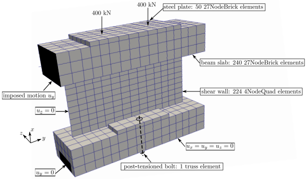
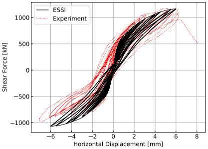
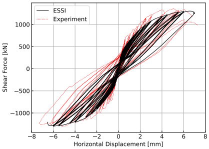
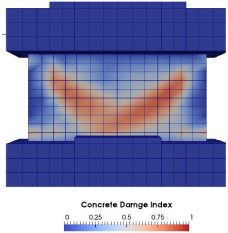
Regular and ASR Concrete



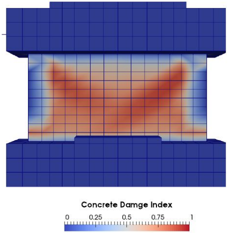




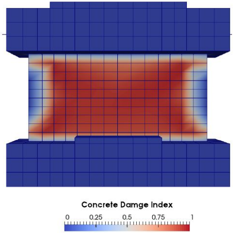




u_y = 1.4 mm



u_y = 1.8 mm

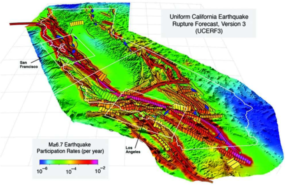


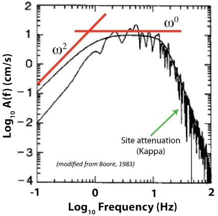
u_y = 3.0 mm

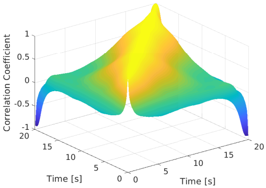
Outline

Stochastic Seismic Motion Development

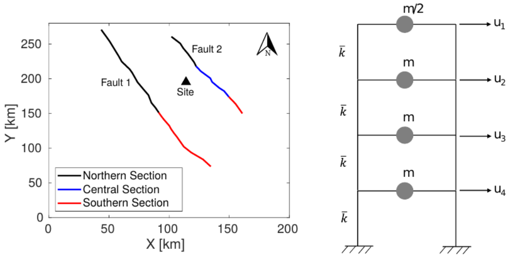
- UCERF3 (Field et al. 2014)
- Stochastic motions (Boore 2003)
- Polynomial Chaos Karhunen-Loève expansion
- Domain Reduction Method for P_{eff} (Bielak et al. 2003)







Uncertain Model Description



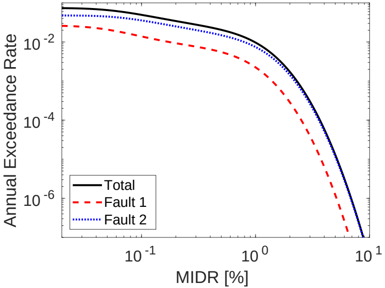
(a) Faults configuration (b) Building structure

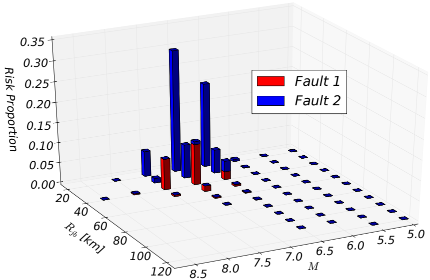
$$Cov_k = \begin{bmatrix} 1.0 & 0.6 & 0.3 & 0.2 \\ 0.6 & 1.0 & 0.5 & 0.2 \\ 0.3 & 0.5 & 1.0 & 0.7 \\ 0.2 & 0.2 & 0.7 & 1.0 \end{bmatrix}$$

- 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 Risk, Maximum Interstory Drift Ratio (MIDR)

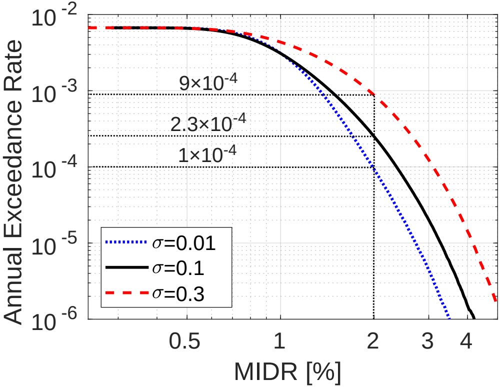




$$\lambda(MIDR > 1\%) = 9.7 \times 10^{-3}$$
$$\lambda(MIDR > 2\%) = 1.7 \times 10^{-3}$$
$$\lambda(MIDR > 4\%) = 5.9 \times 10^{-5}$$

Risk de-aggregation for $\lambda(MIDR > 1\%)$

Seismic Risk, Uncertain Material



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 loads are uncertain

Time Domain Stochastic Galerkin Method

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

- Input random field/process(non-Gaussian, heterogeneous/ non-stationary)

  Multi-dimensional Hermite Polynomial Chaos (PC) with known coefficients

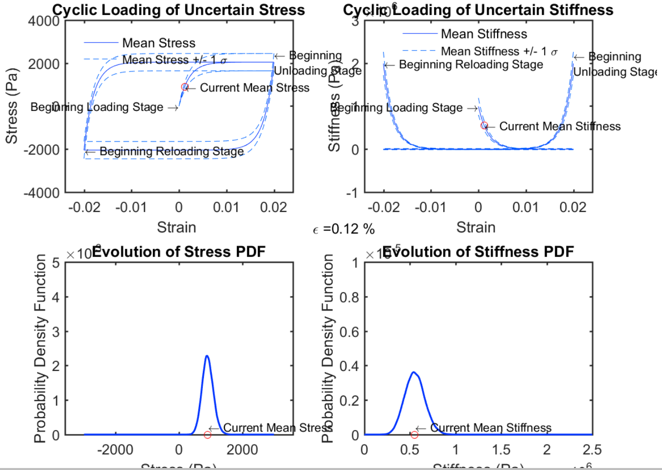
- Output response process

  Multi-dimensional Hermite PC with unknown coefficients

- Galerkin projection: minimize the error to compute unknown coefficients of response process
- Time integration using Newmark's method

  Update coefficients following an elastic-plastic constitutive law at each time step

Probabilistic Elastic-Plastic Response



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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

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

SEPFEM: Example in 1D

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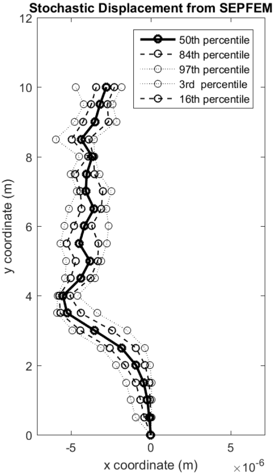
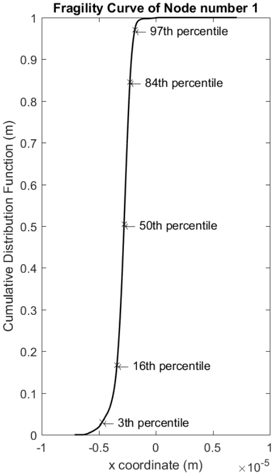




Outline

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

Real-ESSI System Components

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

Real-ESSI System availability: Linux Executables, AWS, Docker containers, DesignSafe/TACC

Real-ESSI education and training: theory and applications

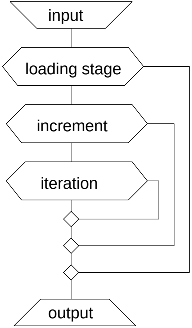
Real-ESSI documentation and program available at `http://real-essi.us/`

Real-ESSI Modeling Features

- Solid elements: dry, (un-)saturated, elastic, inelastic
- Structural elements: beams, shells, elastic, inelastic
- Contact/interface/joint elements: Bonded; Shear/Frictional (EPP, EPH, EPS); Gap/Normal; dry, coupled/saturated,
- Super element: stiffness and mass matrices
- Material models: soil, rock, concrete, steel...
- Seismic input: 1C and 3C, deterministic or probabilistic
- Energy dissipation: elastic-plastic, viscous, algorithmic
- Solid/Structure-Fluid interaction, full coupling, OpenFOAM
- Intrusive probabilistic inelastic modeling

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: Domain Specific Language, DSL

Domain Specific Language (DSL), Yacc & Lex

English like modeling and simulation language

Parser and compiler, can define functions, models, etc.

Can extend models and methods

Requires units!

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*m, 1*m) with 6 dofs;

// add beam element
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

```
// Boundary Conditions
fix node No 1 dofs all;
// Loads
add load # 1 to node # 2 type
  linear Fx=-9*kN;
define load factor increment 0.01;
// Simulation details
define solver UMFPack;
define convergence test
  Norm_Displacement_Increment
  tolerance = 1e-5
  maximum_iterations = 20
  verbose_level = 4;
define algorithm Newton;

// go!
simulate 100 steps using static algorithm;
// finish gracefully
bye;
```

Real-ESSI Model Development

- Pre-Processing, model development gmsh/gmESSI
- Existing model translation, SASSI→Real-ESSI
- Self documenting input language
- Units required for all input variables
- All variables and constants need to be defined by user
- Sophistication level of choice
- Model developed in phases
- Verify model components
- Build confidence in inelastic modeling

Real-ESSI Results Post Processing

All (!) output is saved (stress, strain, displacements, energy...)

Time histories, scripts to plot or extract in preferred format, Python, Matlab...

3D visualization, Paraview with pvESSI plugin

Verification and Validation

Verification: provides evidence that the model is solved correctly. Mathematics issue. Extensive for Real-ESSI.

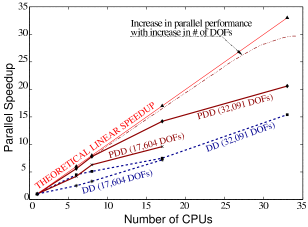
Validation: provides evidence that the correct model is solved. Physics issue. In progress, need high quality test

Prediction: use of computational model to foretell the state of a physical system under consideration under conditions for which the computational model has not been validated.

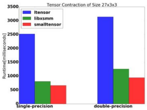
Course Grained and Fine Grained HPC

Hardware Aware Plastic Domain Decomposition Method

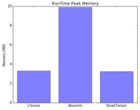
Small Tensor Library



- Benchmark Libraries
  - **LTensor** – Target library
  - **LIBXSMM** – State-of-Art Small Linear Algebra for Machine Learning.
  - **SmallTensor** – Our Small Tensor Library for Computational Mechanics.
- Runtime Performance Comparison



Runtime Performance



Peak Memory Usage

Outline

Summary

Engineering analysis

Use Statics, Mechanics of Materials, ...

Education and Training is the key

Engineer needs to know

Let's learn Mechanics of Materials!