Modeling and Simulation of Earthquake Soil Structure Interaction

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Outline

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Motivation

Improve modeling and simulation for infrastructure objects

Reduction of modeling uncertainty

Choice of analysis level of sophistication

Goal: Predict and Inform rather than fit

Engineer needs to know!

System for modeling and simulation of Earthquakes and/or Soils and/or Structures and their Interaction:
Real-ESSI, 真简单

Prediction under Uncertainty

- Modeling Uncertainty, Simplifying assumptions

  Low, medium, high sophistication modeling and simulation

  Choice of sophistication level for confidence in results

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

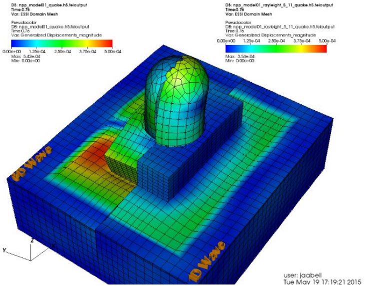
  Uncertain mass M, viscous damping C and stiffness K^{ep}

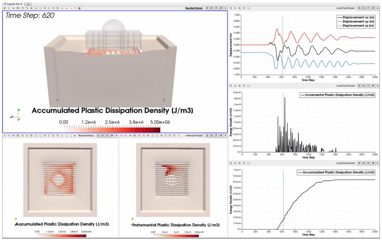
  Propagation of uncertainty in loads, $F(t)$

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

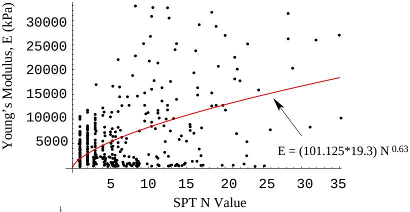
Modeling Uncertainty

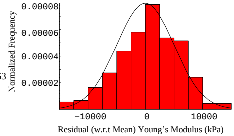
- Important (?!) features are simplified, 1C vs 3C, inelasticity
- Modeling simplifications are justifiable if one or two level higher sophistication model demonstrates that features being simplified out are not important

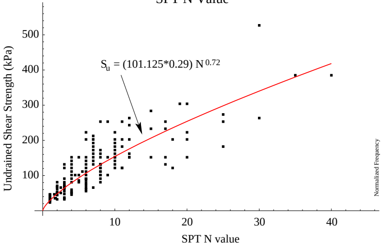


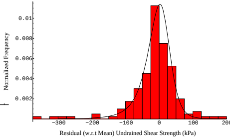


Parametric Uncertainty: Soil Stiffness and Strength









(cf. Phoon and Kulhawy (1999B

ESSI: Energy Input and Dissipation

Energy input, dynamic forcing

Energy dissipation outside SSI domain:

- SSI system oscillation radiation
- Reflected wave radiation

Energy dissipation/conversion inside SSI domain:

- Inelasticity of soil, contact/interface zone, structure, foundation, dissipators
- Viscous coupling with pore fluids, and external fluids

Numerical, algorithmic energy dissipation/production

Fully Coupled Formulation, u-p-U

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

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

Fully Coupled Formulation, u-p-U

$$(M_s)_{KijL} = \int_\Omega H_K^u (1-n)\rho_s \delta_{ij} H_L^u d\Omega \quad (M_f)_{KijL} = \int_\Omega H_K^U n \rho_f \delta_{ij} H_L^U d\Omega$$

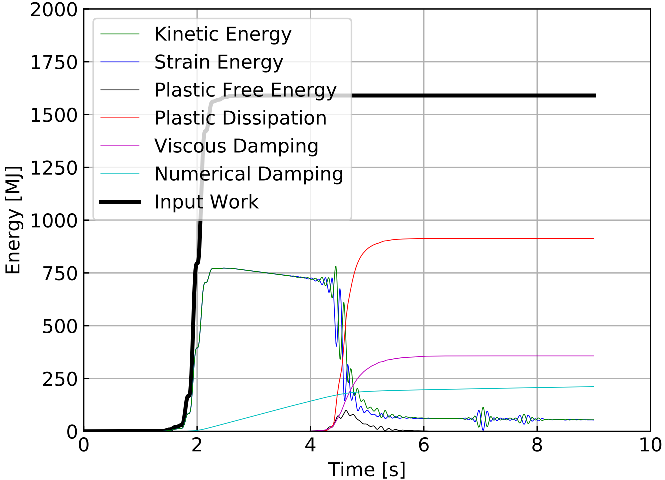
$$(C_1)_{KijL} = \int_\Omega H_K^u n^2 k_{ij}^{-1} H_L^u d\Omega \quad (C_2)_{KijL} = \int_\Omega H_K^u n^2 k_{ij}^{-1} H_L^U d\Omega$$

$$(C_3)_{KijL} = \int_\Omega H_K^U n^2 k_{ij}^{-1} H_L^U d\Omega \quad (K^{EP})_{KijL} = \int_\Omega H_{K,m}^u D_{imjn} H_{L,n}^u d\Omega$$

$$(G_1)_{KiM} = \int_\Omega H_{K,i}^u (\alpha - n) H_M^p d\Omega \quad (G_2)_{KiM} = \int_\Omega n H_{K,i}^U H_M^p d\Omega$$

$$P_{NM} = \int_\Omega H_N^p \frac{1}{Q} H_M^p d\Omega$$

Energy Dissipation Control



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, inelastic, deterministic or probabilistic, 3D, finite element 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/pvESSI, Python)
- Real-ESSI System availability:
  - Educational Institutions: AWS, Linux Image, free
  - Government Agencies, National Labs: AWS GovCloud
  - Professional Practice: AWS, commercial
- Real-ESSI Short Courses, online, worldwide
- `http://sokocalo.engr.ucdavis.edu/~jeremic/Real_ESSI_Simulator/`

Quality Assurance

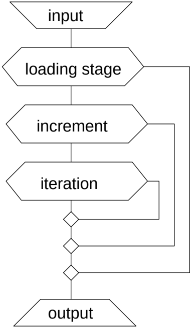
- Full verification suit for each element, model, algorithm
- Certification process
  - ASME NQA-1
  - ISO-90003-2014

Real-ESSI Modeling Features

- Solid elements, dry, (un-)saturated, elastic, inelastic
- Structural elements, beams, shells, elastic, inelastic
- Contact elements, dry, coupled/saturated,
- Super element, stiffness and mass matrices
- Material models, soil, concrete, steel...
- Seismic input, 1C and 3C, deterministic or probabilistic
- Energy dissipation calculations
- Solid/Structure – Fluid interaction, full coupling
- Intrusive probabilistic inelastic modeling

Real-ESSI Simulation Features

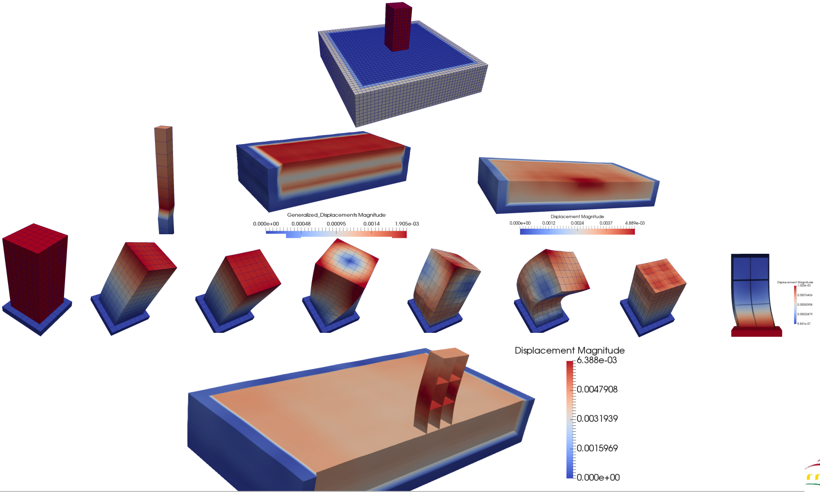
- Static loading stages
- Dynamic loading stages
- Restart, simulation tree
- Solution advancement methods/algorithms, on global and constitutive levels, with and without enforcing equilibrium
- High Performance Computing
  - Fine grained, template mataprograms, small matrix library
  - Coarse grained,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



Real-ESSI 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
- Choose level of sophistication
- Reduce modeling uncertainty
- Model developed in phases
- Verify model components
- Build confidence in inelastic modeling

Real-ESSI Modeling Phases



Real-ESSI Results Post Processing

- All output is saved (stress, strain, displacements, energy...)
- Time histories, scripts to plot or extract in preferred format
- 3D visualization, Paraview with pvESSI plugin

Real-ESSI Training and Education

- Short Courses:
  - Online short course, Fall 2019
  - Examples available in lecture notes, and documentation
- Full lecture notes (2600+ pages) available online
  `http://sokocalo.engr.ucdavis.edu/~jeremic/`

Real-ESSI Core Functionality

- Introduction to inelastic, nonlinear analysis for practicing engineers
- Use of prescribed, required (low, medium, high) fidelity numerical models to analyze ESSI behavior
- Set of suggested modeling and simulation parameters
- Investigate sensitivity of response to model sophistication
- Investigate sensitivity of response to model parameters

Real-ESSI Core Functionality Components

- Structural elements: Truss, Beam, Shell, Super-Element
- Soil, solids: elastic, G/G_{max}
- Contacts: Bonded, Frictional, Gap open/close
- Loads: Static, Dynamic (earthquake, 1C or 3$\times$1C), Restart
- Simulation: Explicit no-equilibrium, Implicit equilibrium
- Core Functionality Application programs: APPs

Outline

Existing Simulation Methods for Stochastic PDEs

- Analytical, stochastic differential equation approach: difficult to solve with complex random coefficients
- Monte Carlo method : Computationally expensive
- Perturbation approach: Small variation with respect to mean, closure problem
- Stochastic collocation method: Global error minimization
- Stochastic Galerkin method: Local error minimization

Uncertainty Propagation through Inelastic System

- Incremental el–pl constitutive equation

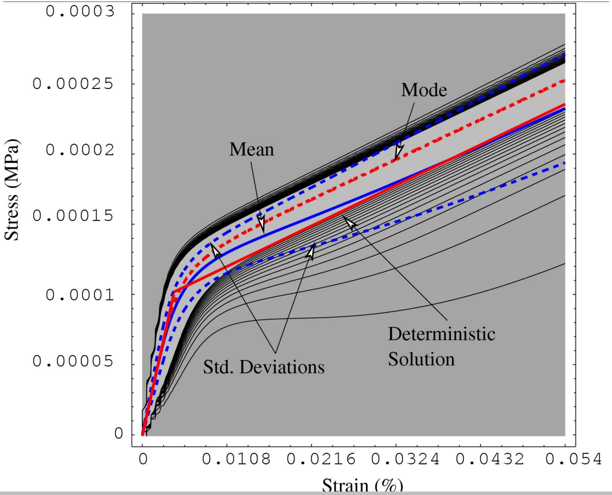
$$\Delta\sigma_{ij} = E^{EP}_{ijkl}\ \Delta\epsilon_{kl} = \left[E^{el}_{ijkl} - \frac{E^{el}_{ijmn} m_{mn} n_{pq} E^{el}_{pqkl}}{n_{rs} E^{el}_{rstu} m_{tu} - \xi_* h_*} \right] \Delta\epsilon_{kl}$$

- Dynamic Finite Elements

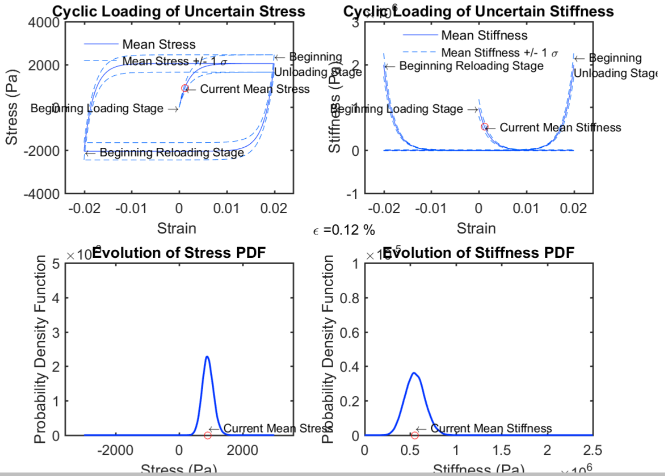
$$M\ddot{u}_i + C\dot{u}_i + K^{ep} u_i = F(t)$$

- Material and load parameters are uncertain

Probabilistic Elastic-Plastic Response



Probabilistic Elastic-Plastic Modeling



Time Domain Stochastic Galerkin Method

- 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

Polynomial Chaos Representation

Material random field: $D(x,\theta) = \sum_{i=1}^{P1} a_i(x)\Psi_i(\{\xi_r(\theta)\})$

Motion random process: $f_m(t,\theta) = \sum_{j=1}^{P_2} f_{mj}(t)\Psi_j(\{\xi_k(\theta)\})$

Displacement response: $u_n(t,\theta) = \sum_{k=1}^{P_3} d_{nk}(t)\Psi_k(\{\xi_l(\theta)\})$

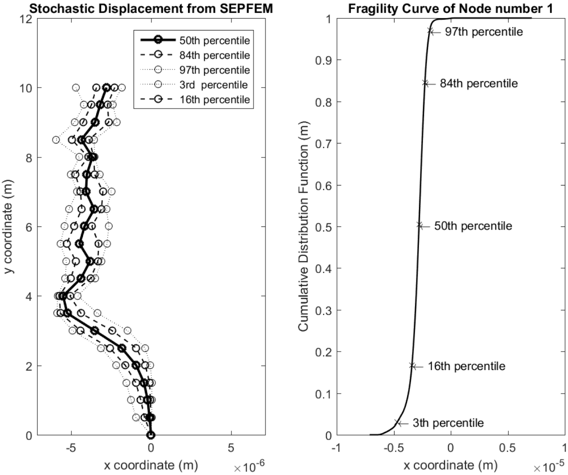
where $a_i(x), f_{mj}(t)$ are known PC coefficients, while $d_{nk}(t)$ are unknown PC coefficients.

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.

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

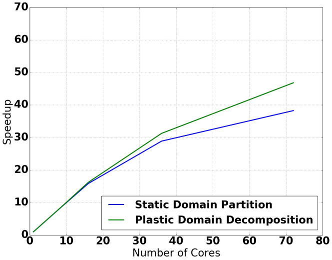
SEPFEM: Example in 1D



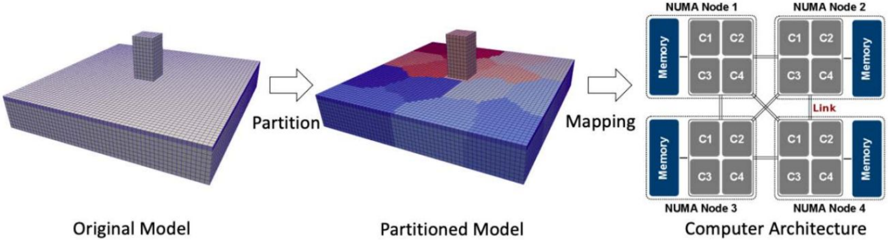
Outline

Course and Fine Grained HPC

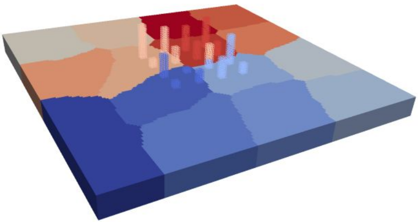
- Hardware Aware Plastic Domain Decomposition (HAPDD) Method
- Small Tensor Library



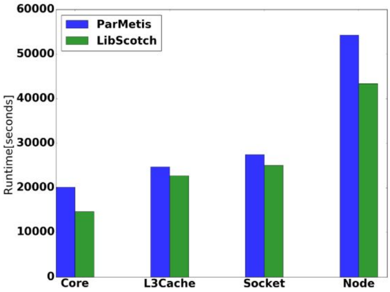
HAPDD


Partition
Mapping
NUMA Node 1
NUMA Node 2
NUMA Node 3
NUMA Node 4
Memory
C1
C2
C3
C4
Link
Original Model
Partitioned Model
Computer Architecture

HAPDD



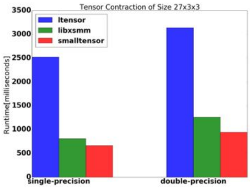
Partitioned Domains



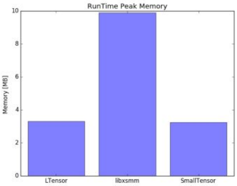
Performance on Different Architectures

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

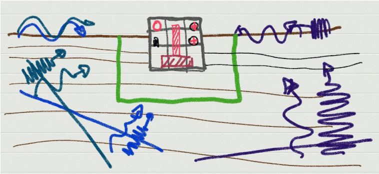


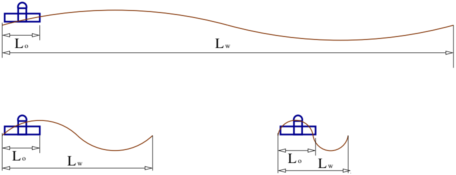
Peak Memory Usage

Outline

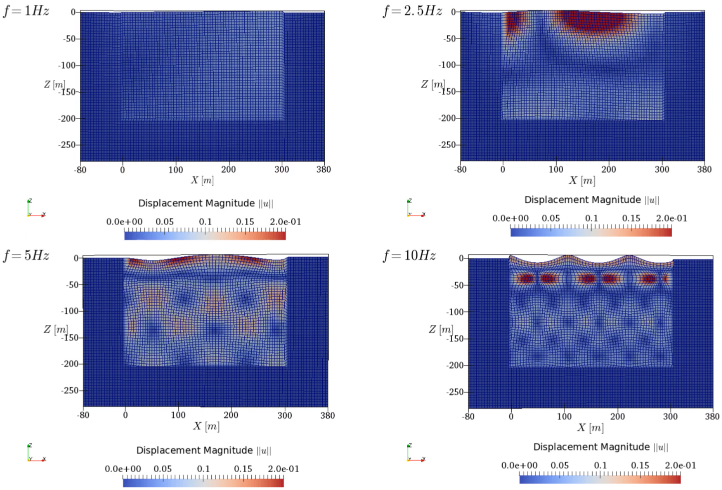
Seismic Motions

- Variation in inclination, frequency, energy, duration...
- Deterministic and Probabilistic
- Stress test the soil-structure system



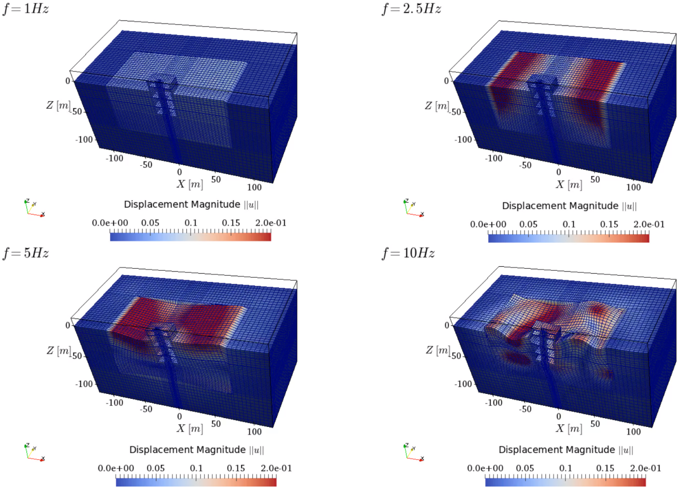


Free Field, Variation in Input Frequency, $\theta = 60^o$



(MP4)

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



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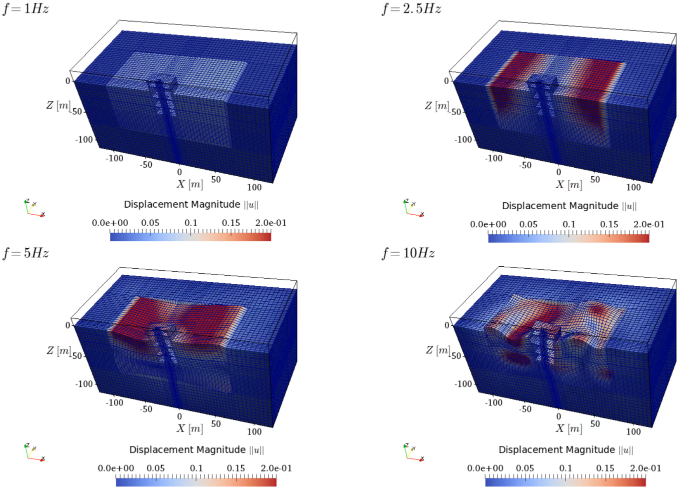
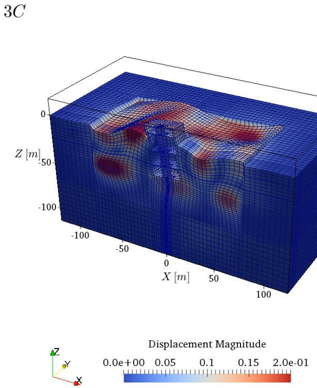
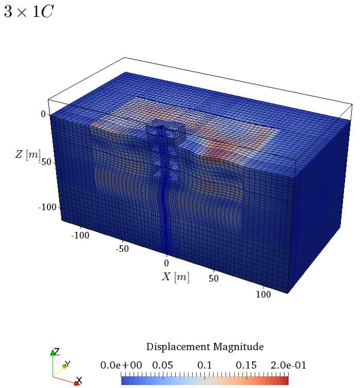
SMR ESSI, Variation in Input Frequency, REAL TIME



(MP4)

SMR ESSI, 3C vs 3×1C

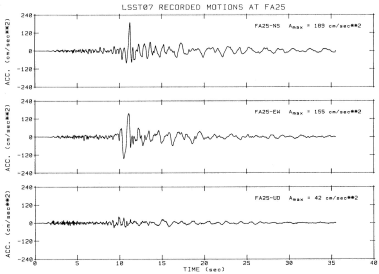


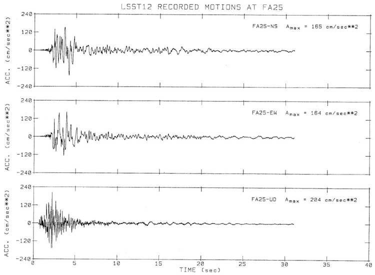


(OGV)

3C, 6C Seismic Motions

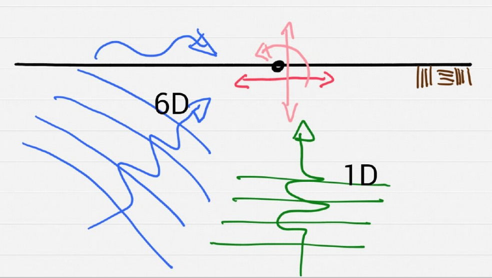
- All (most) measured motions are full 3C, 6C
- One example of an almost 2C motion (LSST07, LSST12)



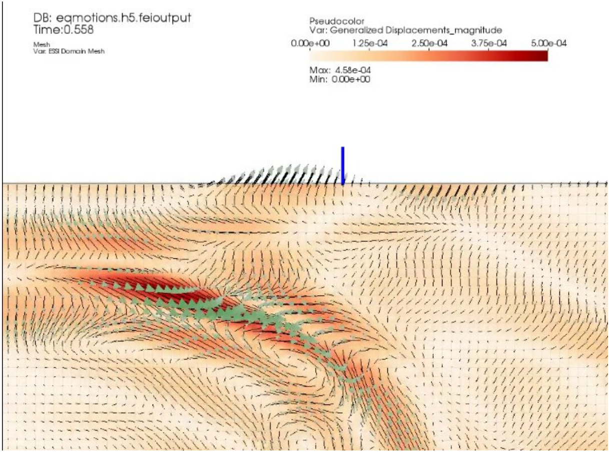


ESSI: 6C or 1C Seismic Motions

- Assume that a full 6C (3C) motions at the surface are only recorded in one horizontal direction
- From such recorded motions one can develop a vertically propagating shear wave (1C) in 1D
- Apply such vertically propagating shear wave to same soil-structure system

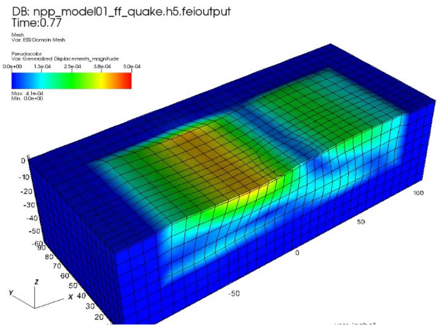


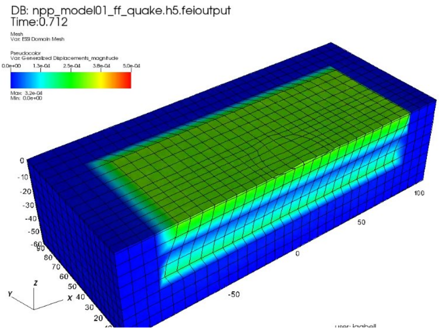
6C Free Field Motions (closeup)



1C vs 6C Free Field Motions

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





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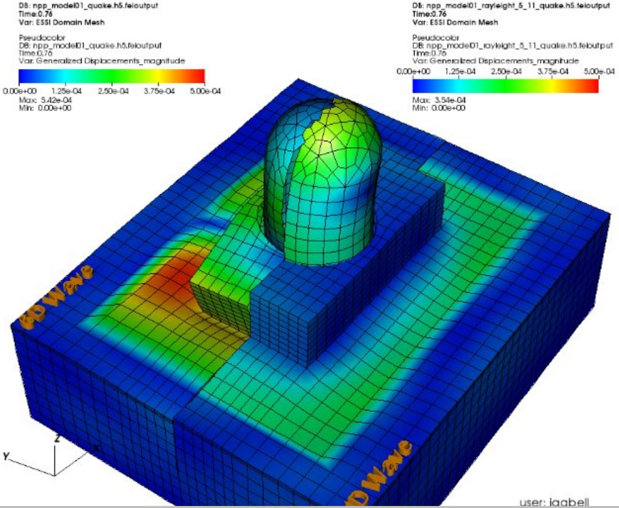
6C vs 1C NPP ESSI Response Comparison



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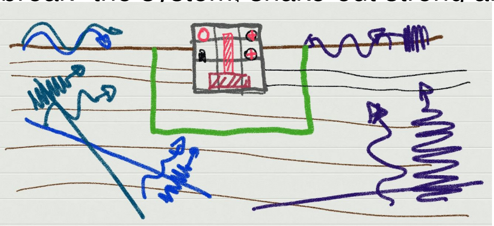
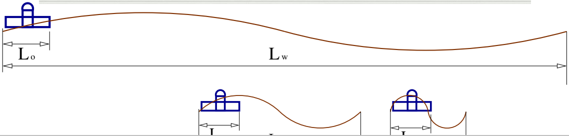
Stress Testing SSI Systems

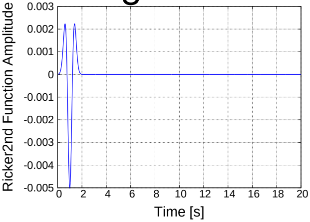
- Excite SSI system with a suite of seismic motions
- Waves: P, SV, SH, Surface (Rayleigh, Love, etc.)
- Variation in inclination, frequency, energy and duration
- Try to "break" the system, shake-out strong and weak links

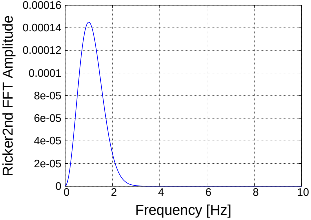




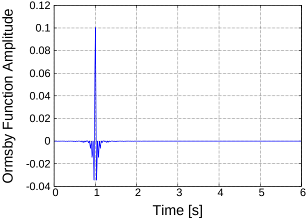
Stress Test Source Signals

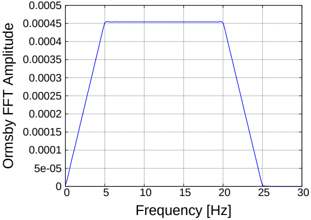
- Ricker





- Ormsby





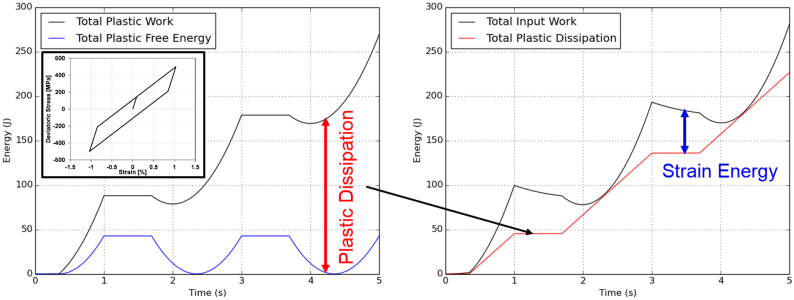
Outline

Energy Input and Dissipation

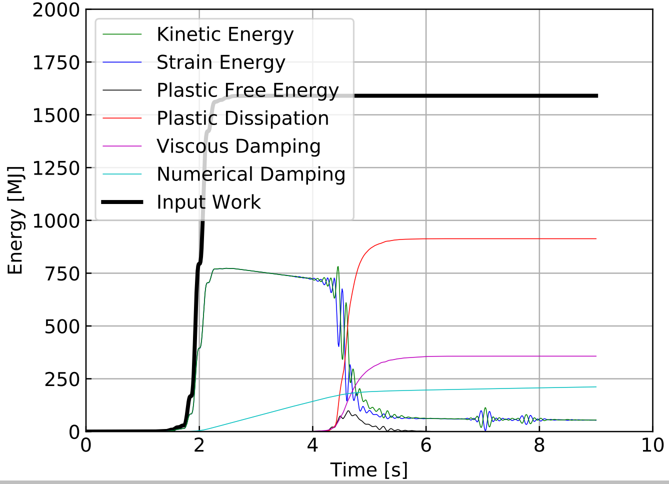
- Energy input, dynamic forcing
- Energy dissipation outside SSI domain:
  - SSI system oscillation radiation
  - Reflected wave radiation
- Energy dissipation/conversion inside SSI domain:
  - Inelasticity of soil, contact zone, structure, foundation, dissipators
  - Viscous coupling with internal/pore fluids, 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
  - Plastic work can decrease
  - Plastic dissipation always increases



Energy Dissipation Control

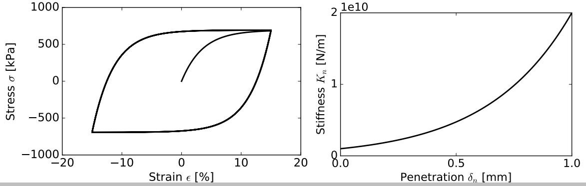


Inelastic Modeling of Soil Structure Systems

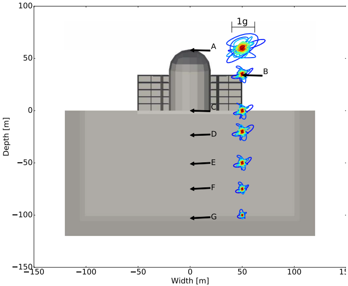
- Soil, inelastic, elastic-plastic
  - Dry, single phase
  - Unsaturated, partially saturated
  - Fully saturated
- Contact, inelastic, soil/rock – foundation
  - Dry, single phase,
    - Normal, hard and soft, gap open/close
    - Friction, nonlinear
  - Fully saturated, suction, excess pressure, buoyant force
- Structure, inelastic, damage, cracks
  - Nonlinear/inelastic 1D reinforced concrete fiber beam
  - Nonlinear/inelastic 3D reinforced concrete solid element
  - Alcali Silica Reaction concrete modeling

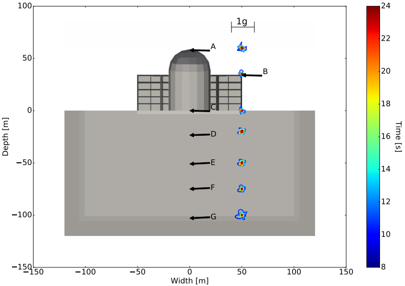
Inelastic Soil and Inelastic Contact

- Shear velocity of soil $V_s = 500 m/s$
- Undrained shear strength (Dickenson 1994) $V_s[m/s] = 23(S_u[kPa])^{0.475}$
- For $V_s = 500 m/s$ Undrained Strength $S_u = 650 kPa$ and Young's Modulus of $E = 1.3 GPa$
- von Mises, Armstrong Frederick kinematic hardening ($S_u = 650 kPa$ at $\gamma = 0.01\%$; $h_a = 30 MPa$, $c_r = 25$)
- Soft contact (concrete-soil), gaping and nonlinear shear



Acceleration Traces, Elastic vs Inelastic

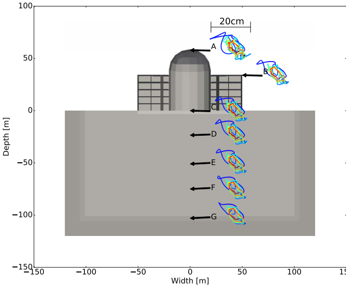


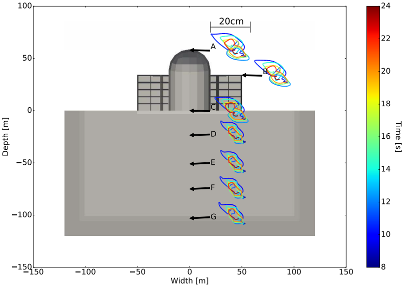


Elastic

Inelastic

Displacement Traces, Elastic vs Inelastic

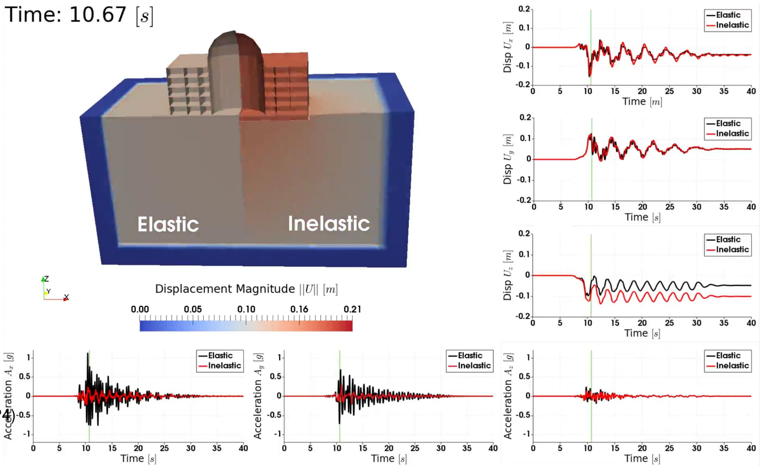




Elastic

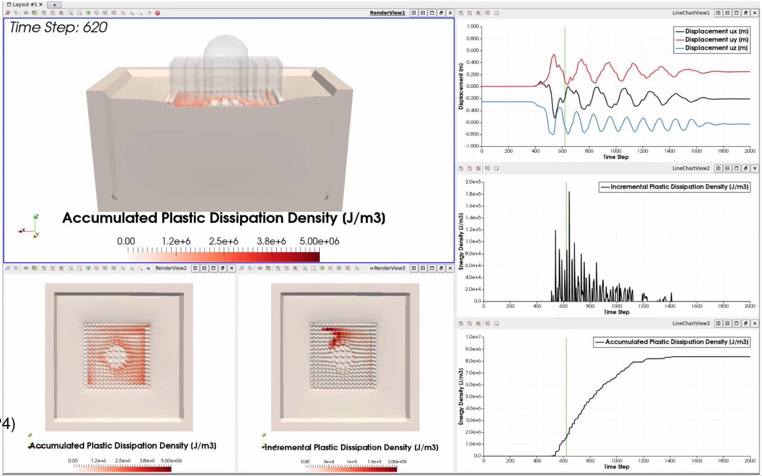
Inelastic

Elastic and Inelastic Response: Differences



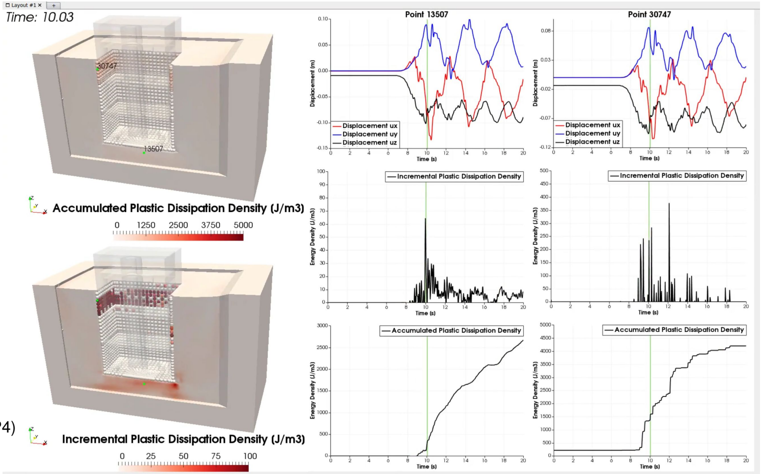
(MP4)

Energy Dissipation in a Large-Scale Model



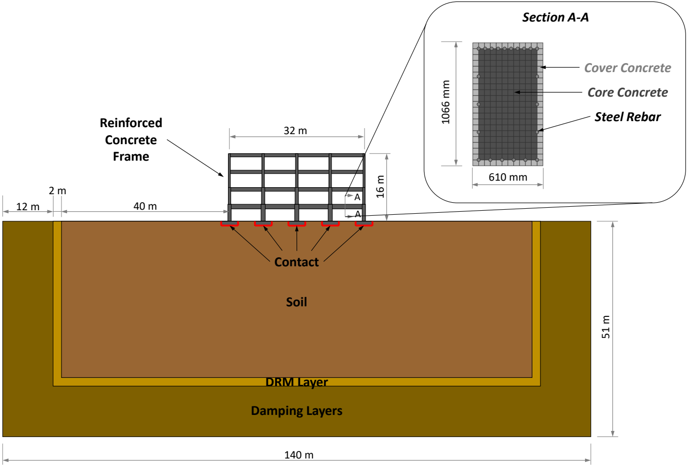
(MP4)

Energy Dissipation for an SMR Model

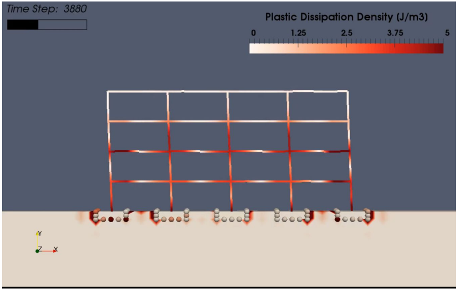


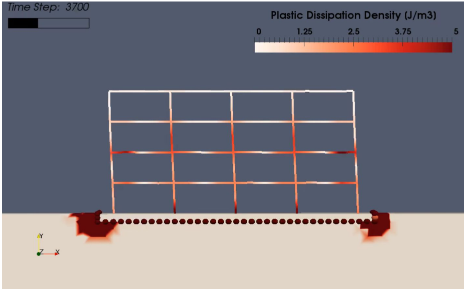
(MP4)

Energy Dissipation for Design

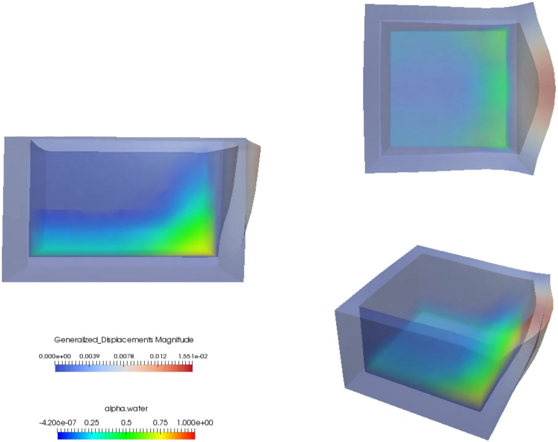


Design Alternatives





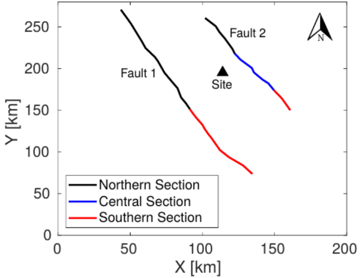
Solid, Structure-Fluid Interaction, Example



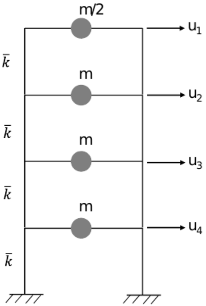
(MP4)

Outline

Uncertain Model Description



(a) Faults configuration



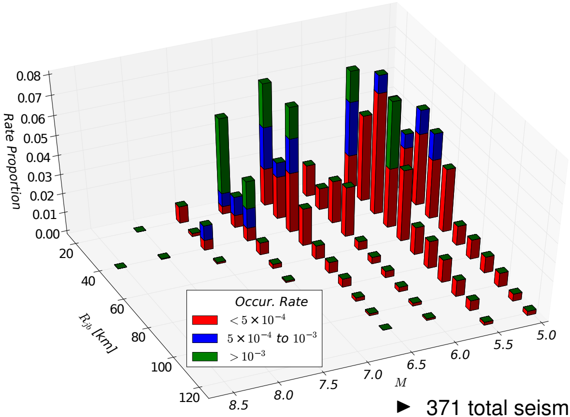
(b) Building structure

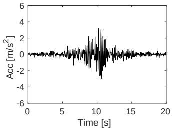
$$Cov_k = \begin{bmatrix} 1.0 & 0.6 & 0.3 & 0.2 \\ 0.6 & 1.0 & 0.5 & 0.2 \\ 0.3 & 0.5 & 1.0 & 0.7 \\ 0.2 & 0.2 & 0.7 & 1.0 \end{bmatrix}$$

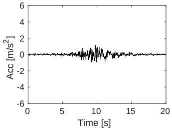
- Fault 1: San Gregorio fault
- Fault 2: Calaveras fault
- Uncertainty: Segmentation, slip rate, rupture geometry, etc.

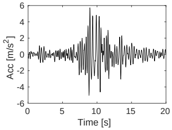
- $Vs_{30} = 620 m/s$
- $m = 100 kips/g$
- $\bar{k} = 168 kip/in$

Seismic Source Characterization



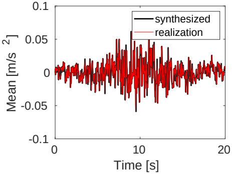




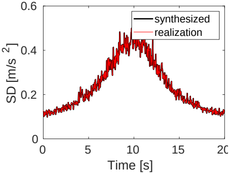


- 371 total seismic scenarios
- M 5 ∼ 5.5 and 6.5 ∼ 7.0
- R_{jb} 20km ∼ 40km

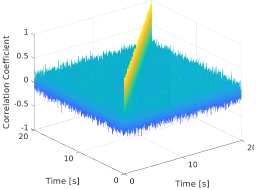
Stochastic Ground Representation



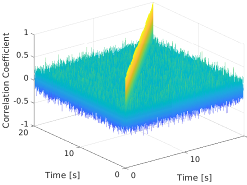
Acc. marginal mean



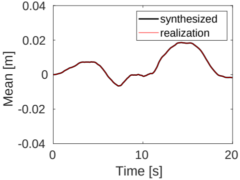
Acc. marginal S.D.



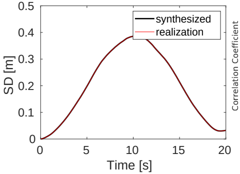
Acc. realization Cov.



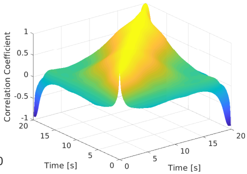
Acc. synthesized Cov.



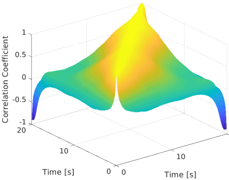
Dis. marginal mean



Dis. marginal S.D.

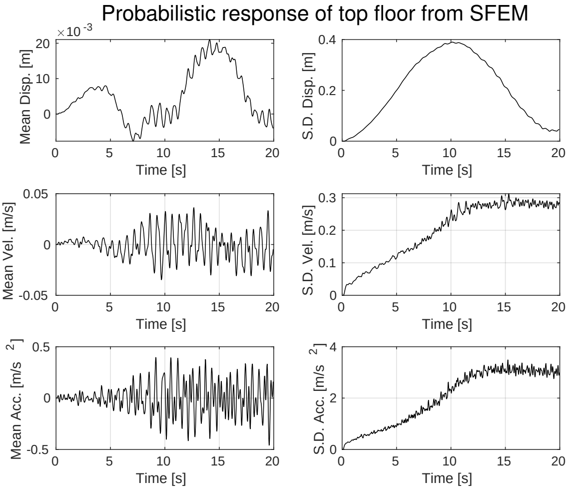


Dis. realization Cov.

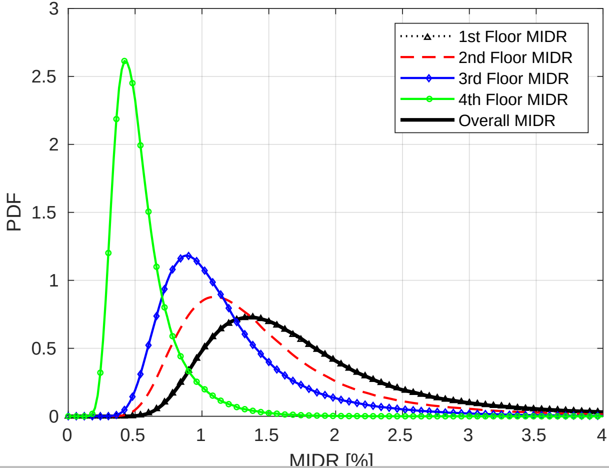


Dis. synthesized Cov.

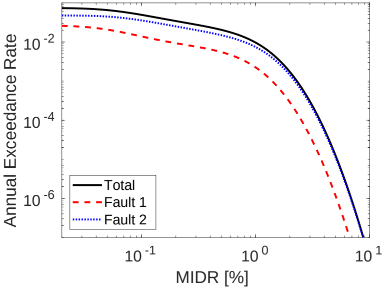
Probabilistic Dynamic Response

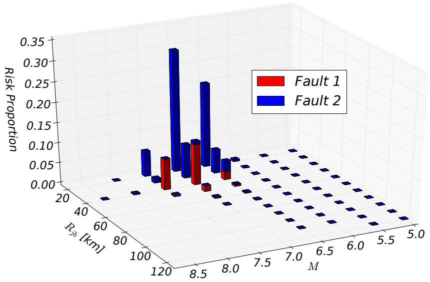


Maximum Inter-story Drift Ratio (MIDR)



Seismic Risk Analysis

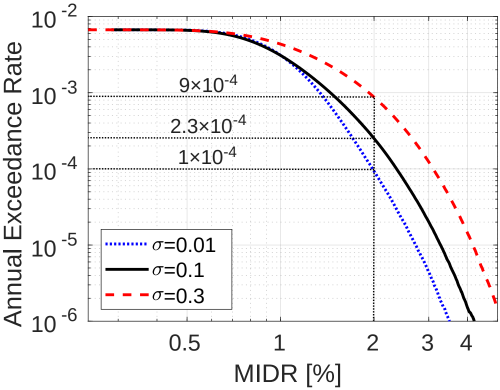




$$\lambda(MIDR > 1\%) = 9.7 \times 10^{-3}$$
$$\lambda(MIDR > 2\%) = 1.7 \times 10^{-3}$$
$$\lambda(MIDR > 4\%) = 5.9 \times 10^{-5}$$

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

Seismic Risk, Uncertain Material



Outline

Real-ESSI Simulator System

The Real-ESSI, Realistic **M**odeling and **S**imulation of **E**arthquakes, **S**oils, **S**tructures and their **I**nteraction. Simulator is a software, hardware and documentation system for high fidelity, high performance, time domain, nonlinear/inelastic, deterministic or probabilistic, 3D, finite element 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

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/pvESSI, Python, Matlab)
- Real-ESSI System availability:
  - Educational Institutions: Amazon Web Services (AWS), free
  - Government Agencies, National Labs: AWS GovCloud
  - Professional Practice: AWS, commercial
- Real-ESSI Short Courses (online, this Fall)
- System description and documentation at `http://sokocalo.engr.ucdavis.edu/~jeremic/Real_ESSI_Simulator/`

Science Quotes

- 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." (Science advances one funeral at a time)
- François-Marie Arouet, Voltaire: "Le doute n’est pas une condition agréable, mais la certitude est absurde."
- Niklaus Wirth: "Software is getting slower more rapidly than hardware becomes faster."

Summary

- Numerical modeling to predict and inform, rather than fit
- Sophisticated inelastic/nonlinear modeling and simulations need to be done carefully and in phases
- Education and Training is the key!
- Collaborators: Feng, Yang, Behbehani, Sinha, Wang, Wang, Pisanó, Abell, Tafazzoli, Jie, Preisig, Tasiopoulou, Watanabe, Luo, Cheng, Yang...
- Funding from and collaboration with the US-DOE, US-NRC, US-NSF, CNSC-CCSN, UN-IAEA, and Shimizu Corp. is greatly appreciated,
- `http://sokocalo.engr.ucdavis.edu/~jeremic`