The Real ESSI Simulator System
Status Report

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Outline

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Motivation

- Improve modeling and simulation for infrastructure objects
- Use of numerical models to analyze statics and dynamics of soil-structure systems
- Reduction of modeling uncertainty
- Desired level of sophistication (high $\leftrightarrow$ low) analysis
- Follow and direct the flow of seismic energy,
- Practical system for modeling and simulation of Earthquakes, Soils, Structures and their Interaction,

  http://real-essi.info/

Predictive Capabilities

- Prediction under Uncertainty: use of computational model to predict the state of SSI system under conditions for which the computational model has not been validated.
- Verification provides evidence that the model is solved correctly. Mathematics issue.
- Validation provides evidence that the correct model is solved. Physics issue.
- Modeling and parametric uncertainties are always present, need to be addressed
- Goal: Predict and Inform rather than (force) Fit

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, 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, worldwide
- System description and documentation at `http://real-essi.info/`

Quality Assurance

- Full verification suit for each element, model, algorithm
- Certification process in progress for NQA-1 and 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

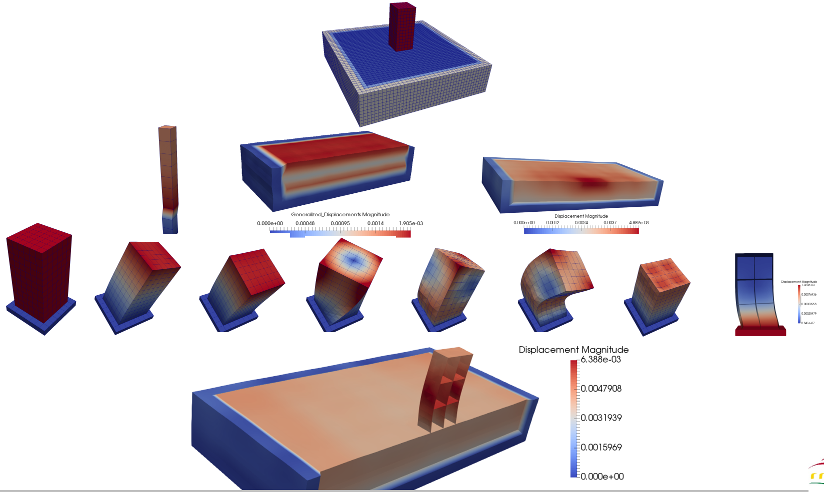
  Fine grained, template mataprograms, small matrix library

  Coarse grained, distributed memory parallel

Real-ESSI Model Development

- Pre-Processing, model development gmsh/gmESSI
- Existing model translation, SASSI$\rightarrow$Real-ESSI
- 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, soon
  - Professional practice
  - Examples available in lecture notes, and documentation
  - Real-ESSI Simulator system, with examples on Amazon Web Services (AWS)
- Full lecture notes (2600+ pages) available online
- Up to date information on Real-ESSI at:

  http://real-essi.info/

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 3×1C), Restart
- Simulation: Explicit no-equilibrium, Implicit equilibrium
- Core Functionality Application programs: APPs

Outline

Existing Simulation Methods for Stochastic PDEs

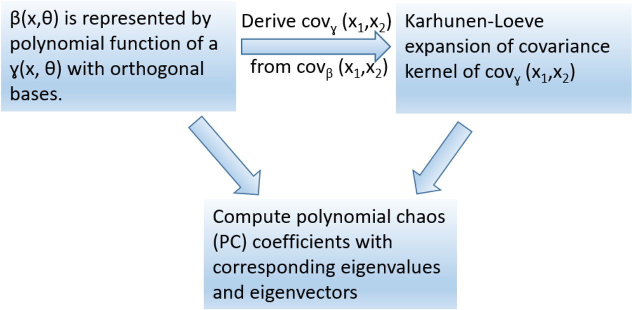
- Analytical, stochastic differential equation approach: difficult to solve with complex random coefficients
- Monte Carlo method : Computationally expensive
- Perturbation approach: Small variation with respect to mean, closure problem
- Stochastic collocation method: Global error minimization
- Stochastic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

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

Note: PC = Polynomial Chaos

Discretization of Input Random Process/Field $\beta(x, \theta)$



Note: $\beta(x, \theta)$ is an input random process with any marginal distribution, with any covariance structure;
$\gamma(x, \theta)$ is a zero-mean unit-variance Gaussian random process.

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.

FEM and Stochastic Elastic-Plastic FEM, SEPFEM

$$\sum_e [\int_{D_e} N_m(x)\rho(x)N_n(x)d\Omega\ \ddot{u}_n(t) +$$

$$\int_{D_e} \nabla N_m(x)E(x)\nabla N_n(x)d\Omega\ u_n(t) - f_m(t)] = 0$$

$$\sum_{n=1}^{N}\sum_{k=1}^{P_3}\langle\Psi_k\Psi_l\rangle \int_{D_e} N_m(x)\rho(x)N_n(x)d\Omega\ \ \ddot{d}_{nk}(t)\ +$$

$$\sum_{n=1}^{N}\sum_{k=1}^{P_3}\sum_{i=1}^{P_1}\langle\Psi_i\Psi_k\Psi_l\rangle \int_{D_e} B_m(x)a_i(x,t)B_n(x)d\Omega\ \ d_{nk}(t) =$$

$$\sum_{j=1}^{P_2}\langle\Psi_j\Psi_l\rangle f_{mj}(t)$$

SEPFEM

Matrix form:

$$\boldsymbol{M}\ddot{\boldsymbol{d}} + \boldsymbol{K}\boldsymbol{d} = \boldsymbol{f}$$

For damped systems:

$$\boldsymbol{M}\ddot{\boldsymbol{d}} + \boldsymbol{C}\dot{\boldsymbol{d}} + \boldsymbol{K}\boldsymbol{d} = \boldsymbol{f}$$

$$\Downarrow$$

Newmark's method to solve in time domain

where $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are generalized mass, damping and stiffness matrices,
$\boldsymbol{f}$, $\boldsymbol{d}$, and $\ddot{\boldsymbol{d}}$ are generalized force, displacement, and acceleration vectors.

Stochastic Elastic-Plastic Response

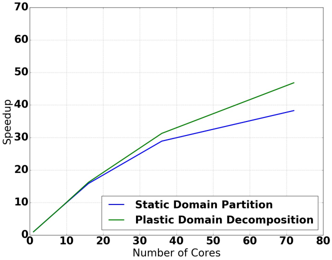
Governing equation: $d\sigma_{ij} = E_{ijkl} d\epsilon_{kl}$

$$E_{ijkl} = \begin{cases} E^{el}_{ijkl} & \text{for elastic} \\ E^{el}_{ijkl} - \dfrac{E^{el}_{ijmn} m_{mn} n_{pq} E^{el}_{pqkl}}{n_{rs} E^{el}_{rstu} m_{tu} - \xi_* h_*} & \text{for elastic–plastic} \end{cases}$$

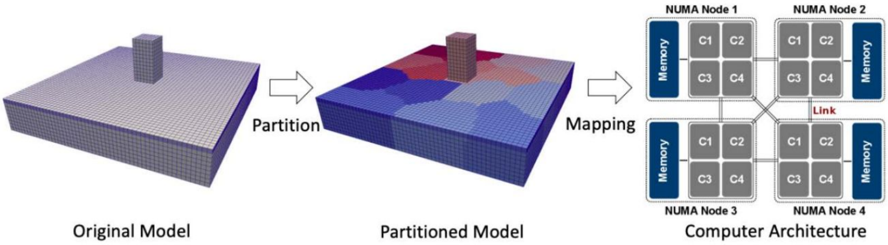
Outline

Course and Fine Grained HPC

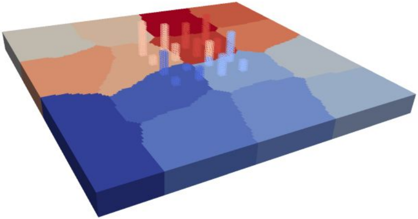
- Hardware Aware Plastic Domain Decomposition (HAPDD) Method
- Small Tensor Library



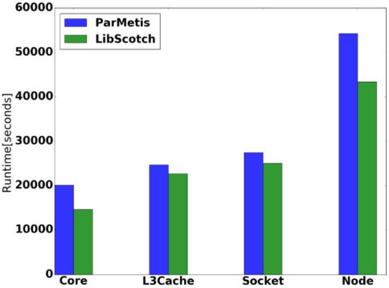
HAPDD


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



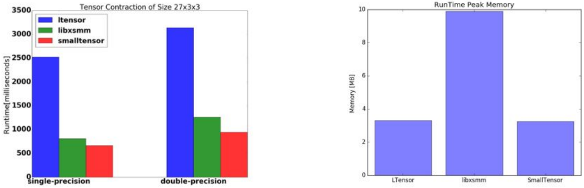
Partitioned Domains



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

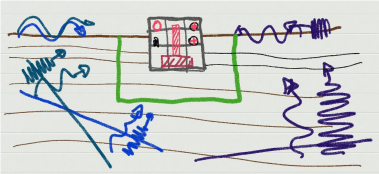


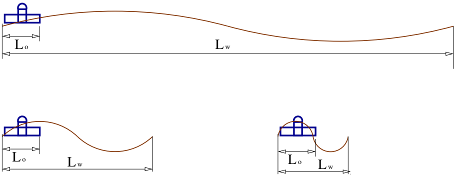
Runtime Performance Peak Memory Usage

Outline

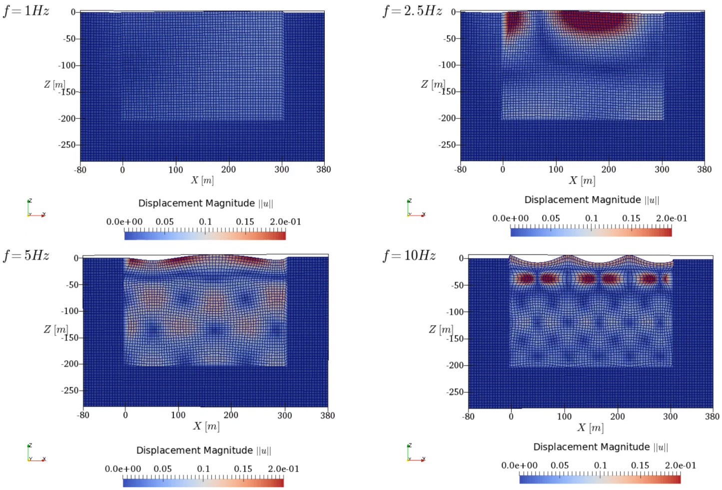
Seismic Motions

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





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



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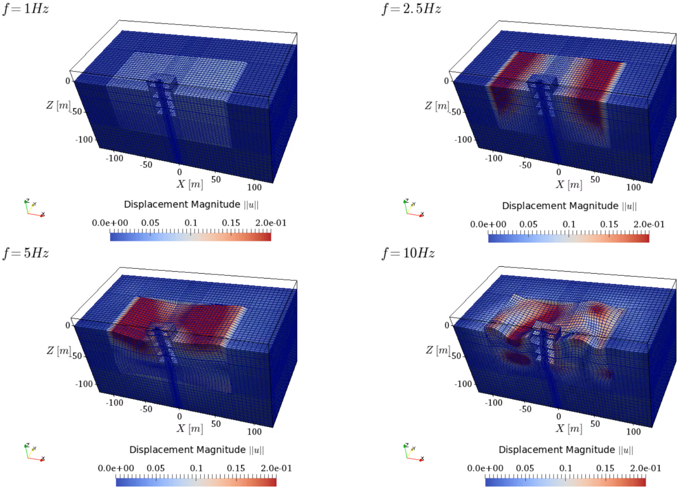
SMR ESSI, Variation in Input Frequency, $\theta = 60^o$



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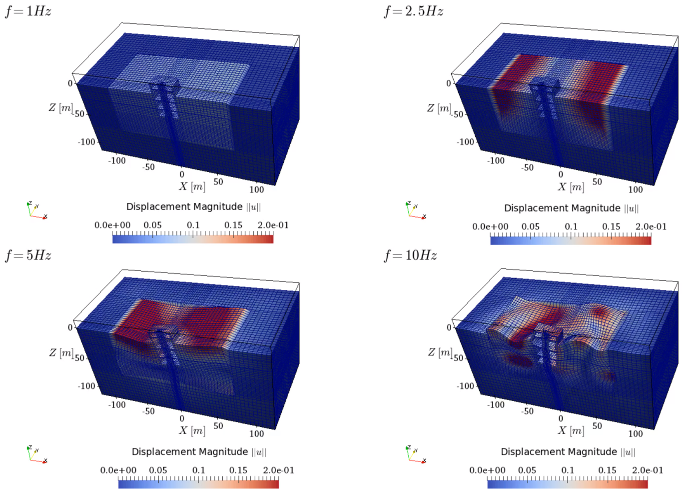
SMR ESSI, Variation in Input Frequency, REAL TIME



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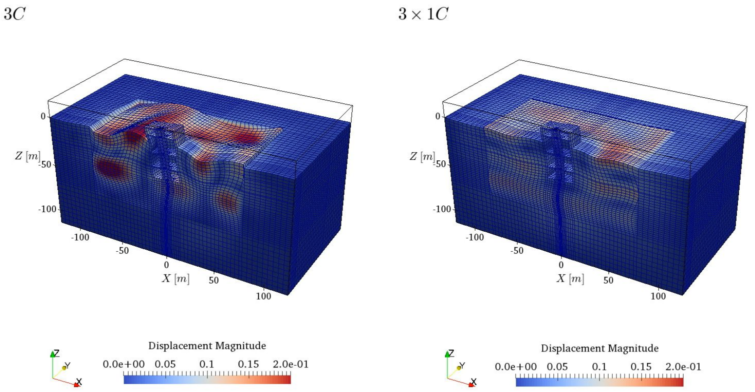
SMR ESSI, 3C vs 3×1C



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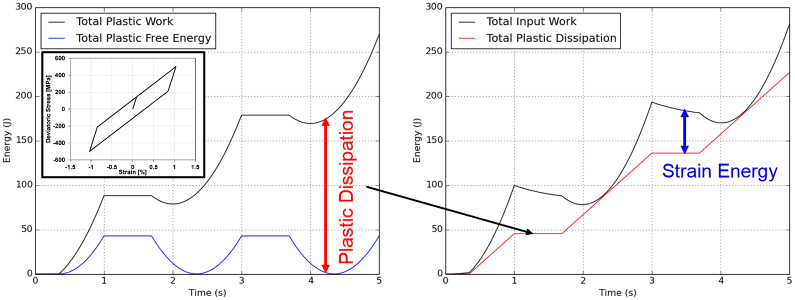
Outline

Energy Input and Dissipation

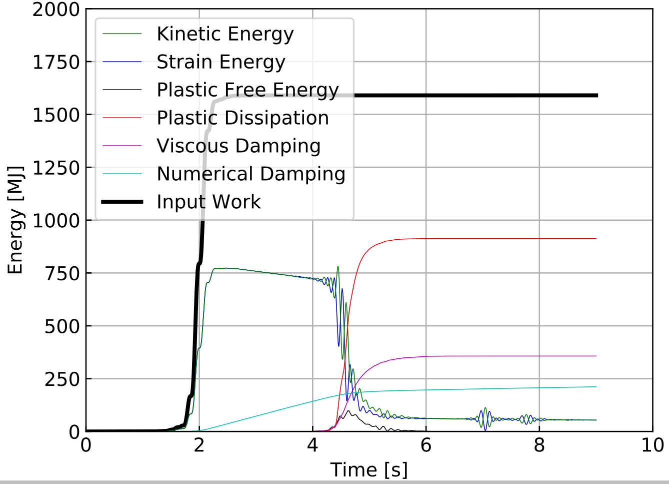
- Energy input, dynamic forcing
- Energy dissipation outside SSI domain:
  - SSI system oscillation radiation
  - Reflected wave radiation
- Energy dissipation/conversion inside SSI domain:
  - Inelasticity of soil, contact zone, structure, foundation, dissipators
  - Viscous coupling with internal/pore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

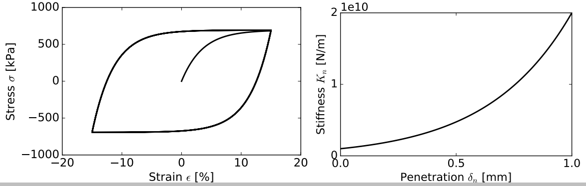


Inelastic Modeling of Soil Structure Systems

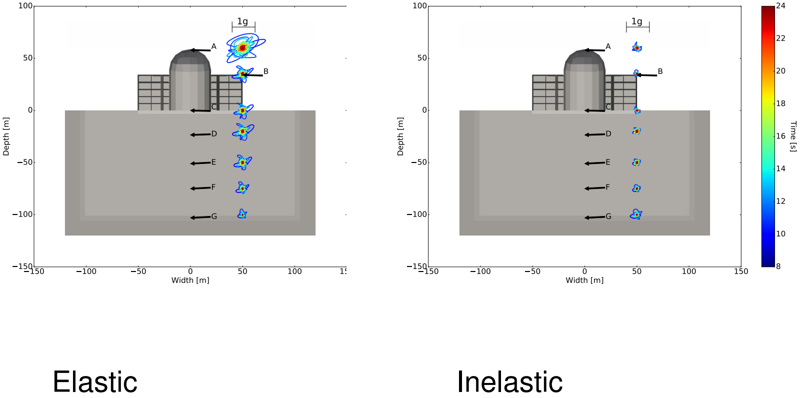
- Soil, inelastic, elastic-plastic
  - Dry, single phase
  - Unsaturated, partially saturated
  - Fully saturated
- Contact, inelastic, soil/rock – foundation
  - Dry, single phase,
    - Normal, hard and soft, gap open/close
    - Friction, nonlinear
  - Fully saturated, suction, excess pressure, buoyant 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

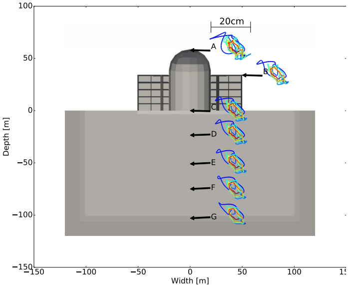
- Shear velocity of soil $V_s = 500 m/s$
- Undrained shear strength (Dickenson 1994) $V_s[m/s] = 23(S_u[kPa])^{0.475}$
- For $V_s = 500 m/s$ Undrained Strength $S_u = 650 kPa$ and Young's Modulus of $E = 1.3 GPa$
- von Mises, Armstrong Frederick kinematic hardening ($S_u = 650 kPa$ at $\gamma = 0.01\%$;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



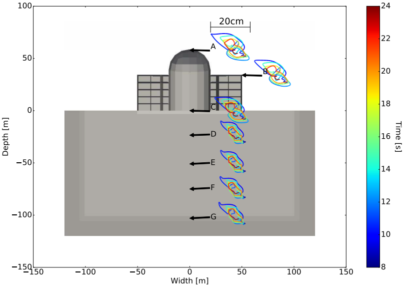
Acceleration Traces, Elastic vs Inelastic



Displacement Traces, Elastic vs Inelastic

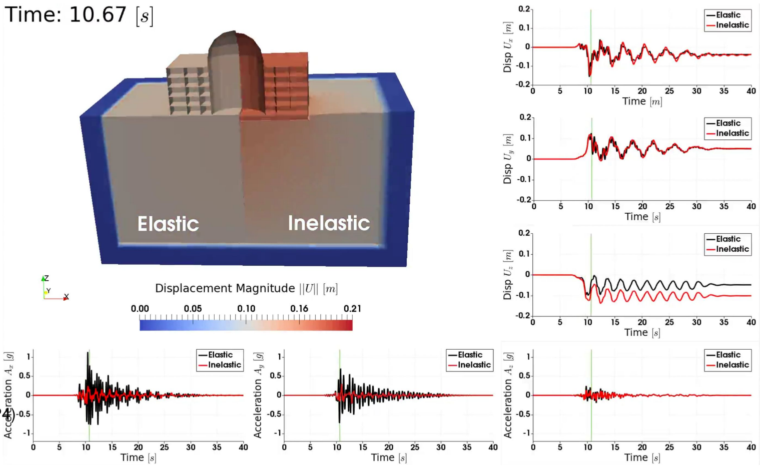


Elastic



Inelastic

Elastic and Inelastic Response: Differences



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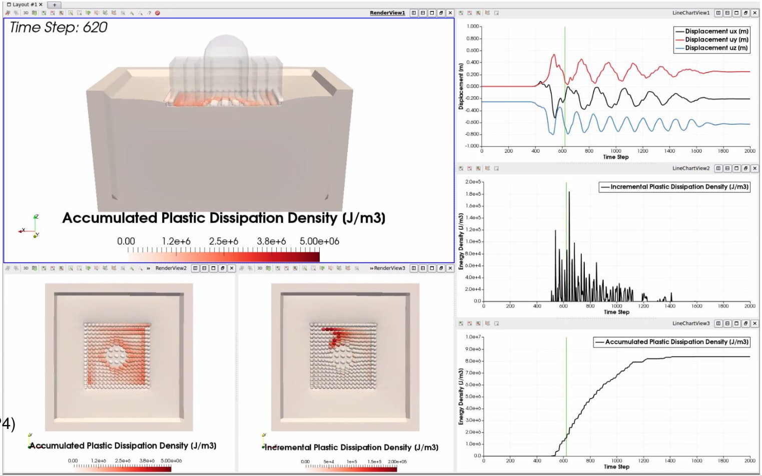
Energy Dissipation in a Large-Scale Model



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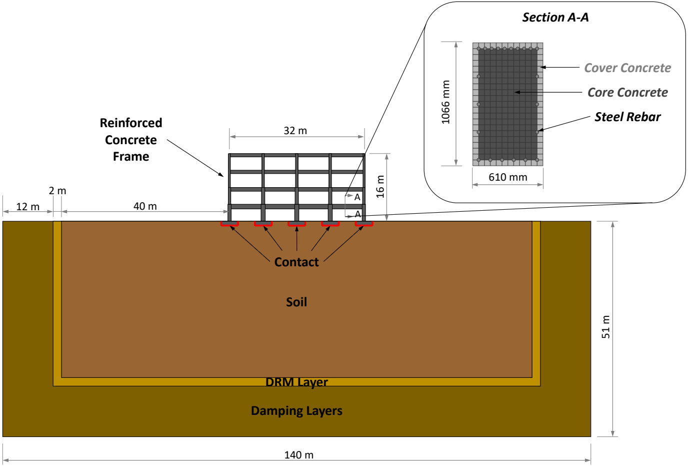
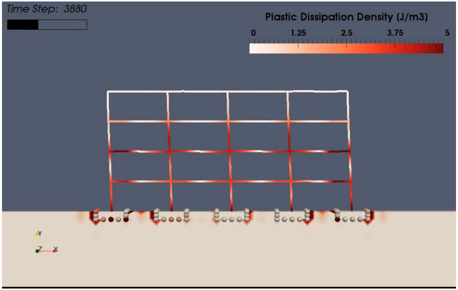
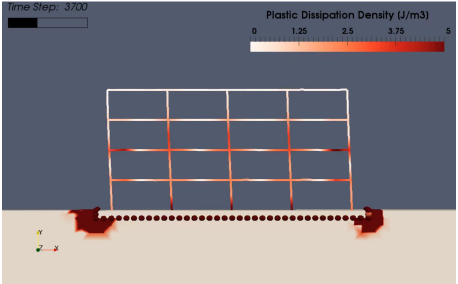
Energy Dissipation for Design

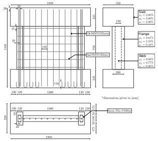


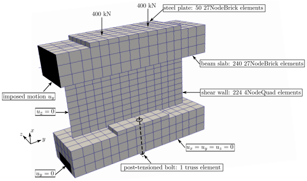
Design Alternatives

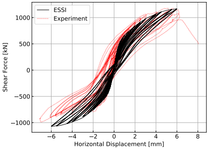


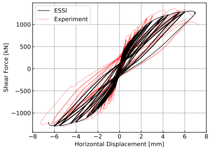


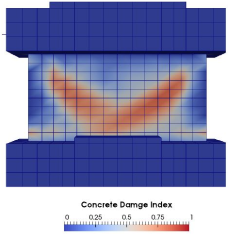
Wall, Regular and ASR Concrete



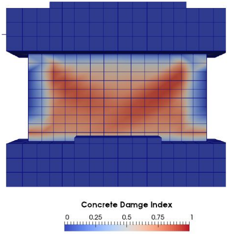




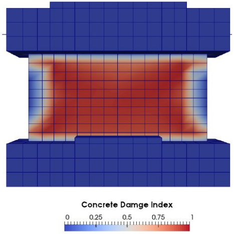




$u_y = 1.4$ mm

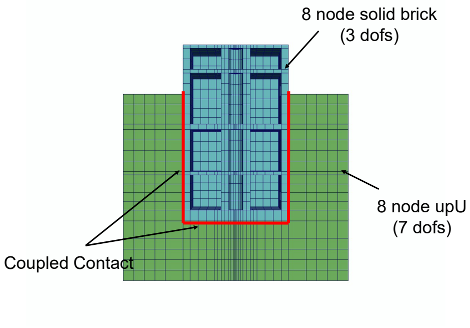


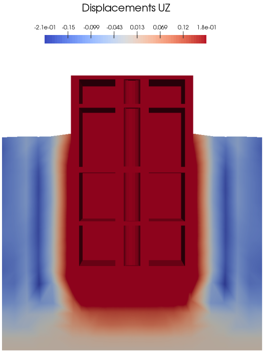
$u_y = 1.8$ mm



$u_y = 3.0$ mm

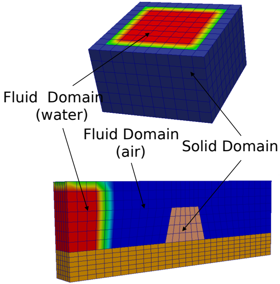
Buoyant Force Simulation



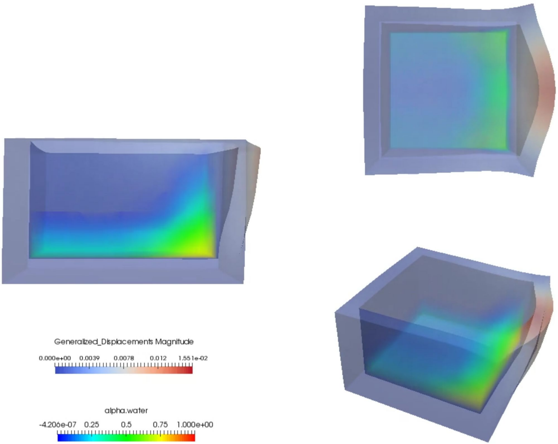


Solid, Structure-Fluid Interaction: gmFoam

- Mesh separation
  - integrated geometry model
  - FEM & FVM mesh conversion
  - handle discontinuous mesh
- Incorporate gmESSI
- Interface geometry extraction
- Interface class **SSFI** in Real-ESSI
- Real-ESSI $\leftrightarrow$ SSFI $\leftrightarrow$ OpenFoam



Solid, Structure-Fluid Interaction, Example



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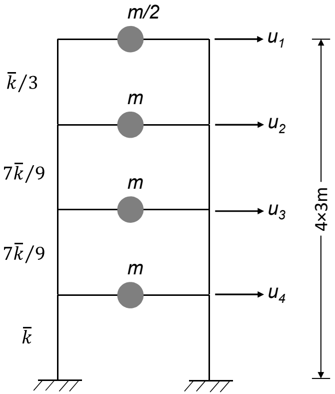
Outline

Uncertain Stiffness



Lognormal random field for stiffness $\bar{k}$:
Marginal mean: 9.84 MN/m
Marginal COV: 10%
Correlation structure:

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

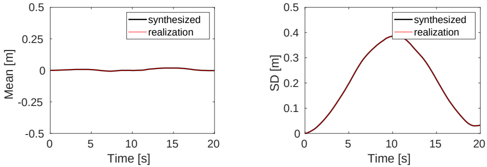
PC rep: dimension 4 order 2

Uncertain Motion

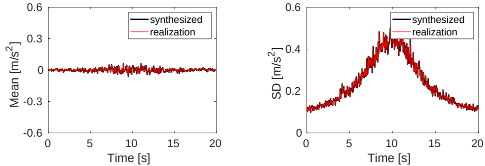
Uncertain bedrock seismic motion:

- Stochastic ground motion modeling
- Marginal PDF: Gaussian $\rightarrow$ order 1
- PC dimension 150 order 1 to quantify motion random process

PC synthesized statistics $\Longleftarrow$ of bedrock motion



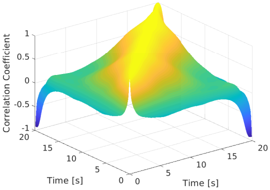
(a) Displacement



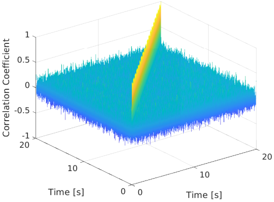
(b) Acceleration

Uncertain Motion: Non-stationary Correlation Structure

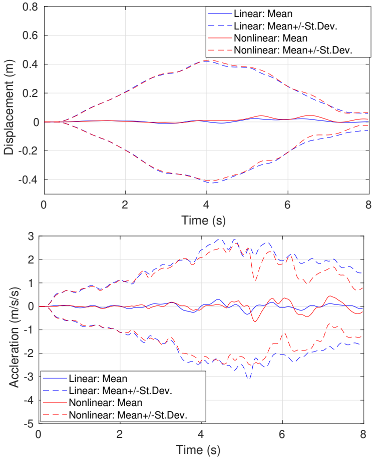
Displacement



Acceleration

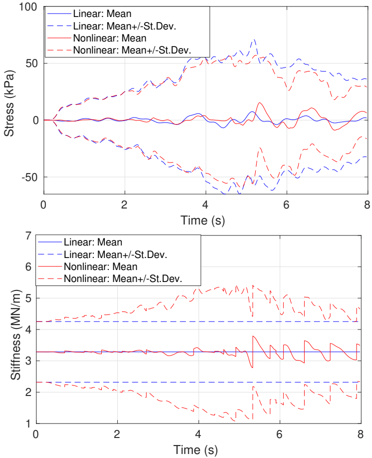


Uncertain Response on Top



- Smaller St.Dev. for nonlinear case
- Magnitude of mean is negligible compared to standard deviation

Evolution of Stress and Stiffness at Top Floor



- Smaller St.Dev. of stress for nonlinear case
- Larger St.Dev. of stiffness introduced by nonlinearity

Outline

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: Wang, Feng, Yang, Behbehani, Sinha, Wang, Pisanó, Abell, Yang, Cheng, Jie, Tafazzoli, Preisig, Tasiopoulou, Watanabe
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