Modeling and Simulation
Earthquake Soil Structure Interaction

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Beijing, July 2019

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

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

Prediction under Uncertainty

- Modeling Uncertainty, Simplifying assumptions

  Low, medium, high sophistication modeling and simulation

  Choice of sophistication level for confidence in results

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

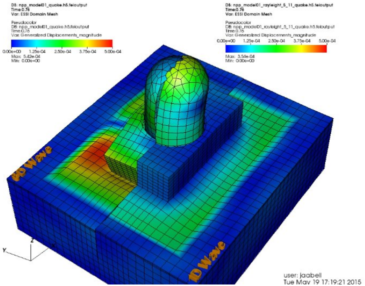
  Uncertain mass M, viscous damping C and stiffness K^{ep}

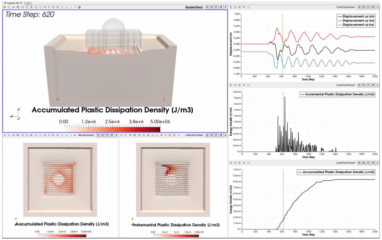
  Propagation of uncertainty in loads, $F(t)$

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

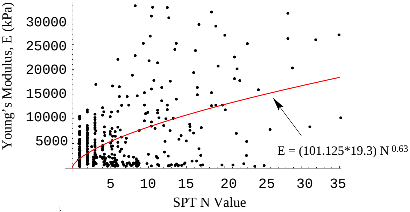
Modeling Uncertainty

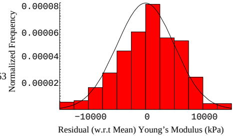
- Important (?!) features are simplified, 1C vs 3C, inelasticity
- Modeling simplifications are justifiable if one or two level higher sophistication model demonstrates that features being simplified out are not important

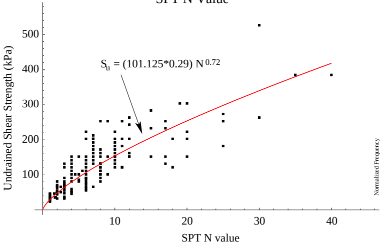


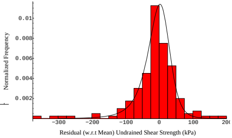


Parametric Uncertainty: Soil Stiffness and Strength









(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

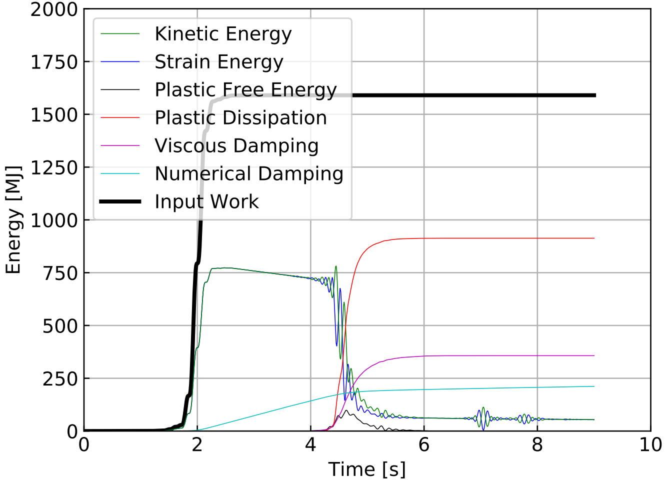
$$
\begin{bmatrix} (M_s)_{KijL} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & (M_f)_{KijL} \end{bmatrix}
\begin{bmatrix} \ddot{\bar{u}}_{Lj} \\ \ddot{\bar{p}}_N \\ \ddot{\bar{U}}_{Lj} \end{bmatrix}
+
\begin{bmatrix} (C_1)_{KijL} & 0 & -(C_2)_{KijL} \\ 0 & 0 & 0 \\ -(C_2)_{LjiK} & 0 & (C_3)_{KijL} \end{bmatrix}
\begin{bmatrix}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

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

Fully Coupled Formulation, u-p-U

$$
\begin{aligned}
(M_s)_{KijL} &= \int_\Omega H_K^u (1-n)\rho_s \delta_{ij} H_L^u d\Omega \quad (M_f)_{KijL} = \int_\Omega H_K^U n \rho_f \delta_{ij} H_L^U d\Omega \\
(C_1)_{KijL} &= \int_\Omega H_K^u n^2 k_{ij}^{-1} H_L^u d\Omega \quad (C_2)_{KijL} = \int_\Omega H_K^u n^2 k_{ij}^{-1} H_L^U d\Omega \\
(C_3)_{KijL} &= \int_\Omega H_K^U n^2 k_{ij}^{-1} H_L^U d\Omega \quad (K^{EP})_{KijL} = \int_\Omega H_{K,m}^u D_{imjn} H_{L,n}^u d\Omega \\
(G_1)_{KiM} &= \int_\Omega H_{K,i}^u (\alpha - n) H_M^p d\Omega \quad (G_2)_{KiM} = \int_\Omega n H_{K,i}^U H_M^p d\Omega \\
P_{NM} &= \int_\Omega H_N^p \frac{1}{Q} H_M^p d\Omega
\end{aligned}
$$

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, 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://sokocalo.engr.ucdavis.edu/~jeremic/Real_ESSI_Simulator/`

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

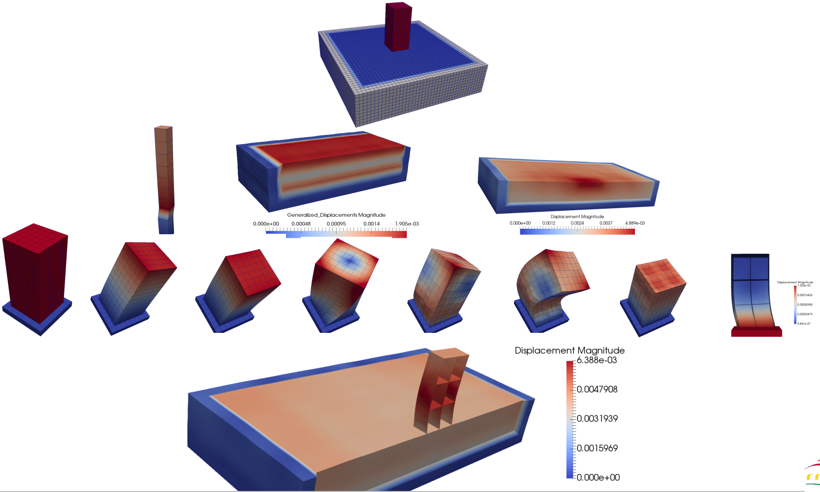
  Fine grained, template mataprograms, small matrix library

  Coarse grained, distributed memory parallel

Real-ESSI Model Development

- Pre-Processing, model development gmsh/gmESSI
- Existing model translation, SASSI→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://sokocalo.engr.ucdavis.edu/~jeremic/Real_ESSI_Simulator/`

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

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

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

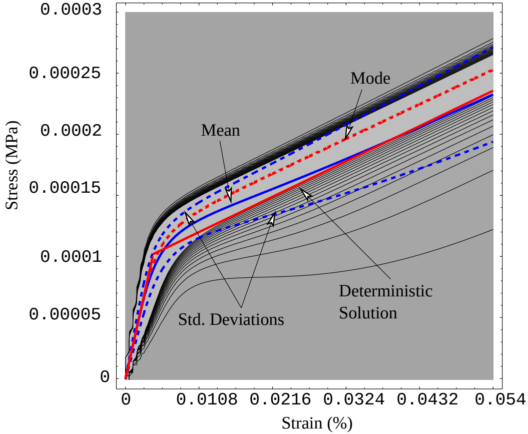
where $a_i(x), f_{mj}(t)$ are known PC coefficients, while $d_{nk}(t)$ are unknown PC coefficients.

Stochastic Elastic-Plastic Response

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

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

Transformation of a Bi–Linear, von Mises Response

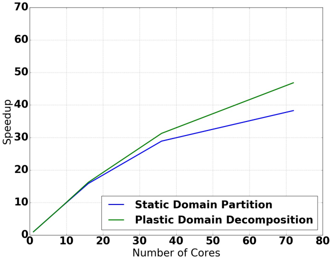


linear elastic – linear hardening elastic-plastic von Mises

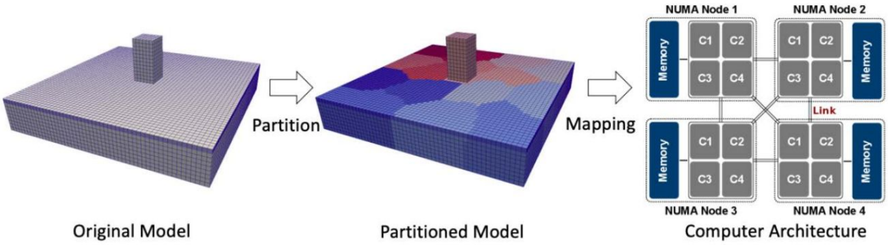
Outline

Course and Fine Grained HPC

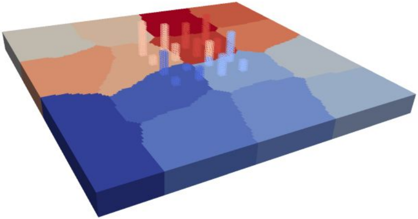
- Hardware Aware Plastic Domain Decomposition (HAPDD) Method
- Small Tensor Library



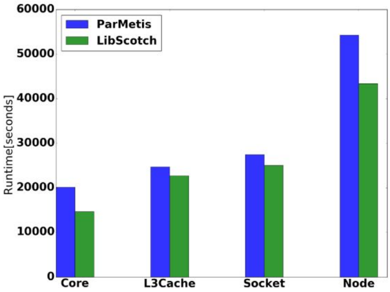
HAPDD


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



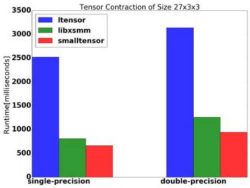
Partitioned Domains



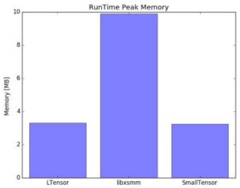
Performance on Different Architectures

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

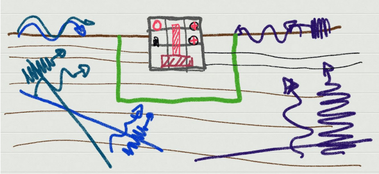


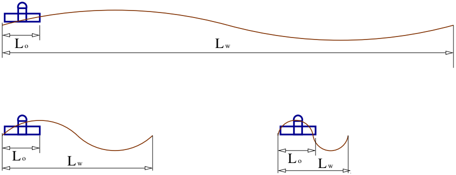
Peak Memory Usage

Outline

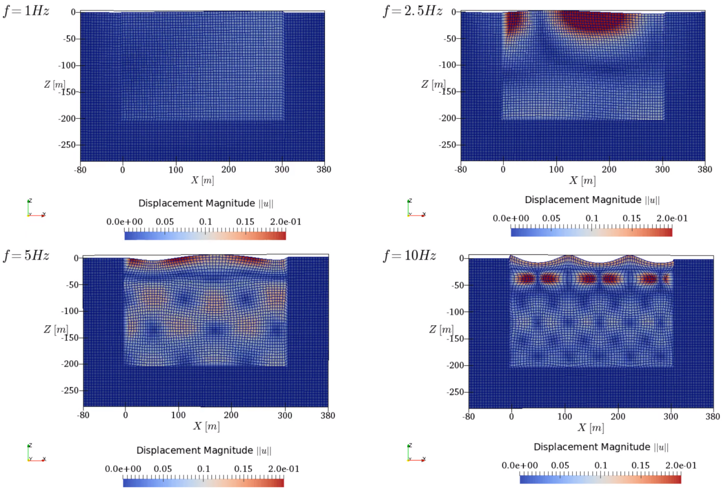
Seismic Motions

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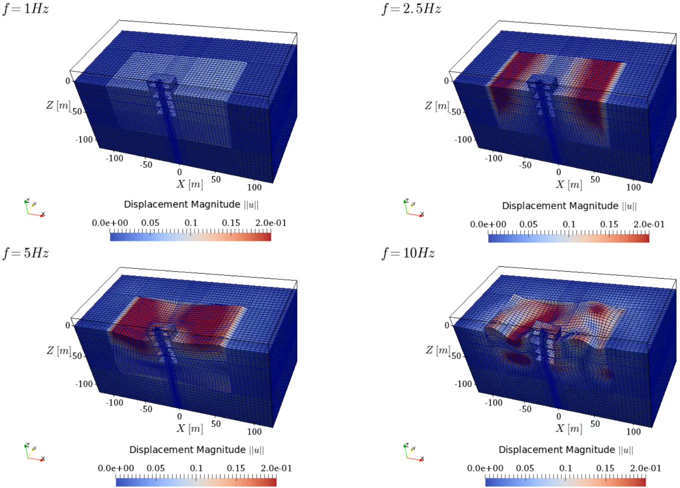
SMR ESSI, Variation in Input Frequency, $\theta = 60^o$



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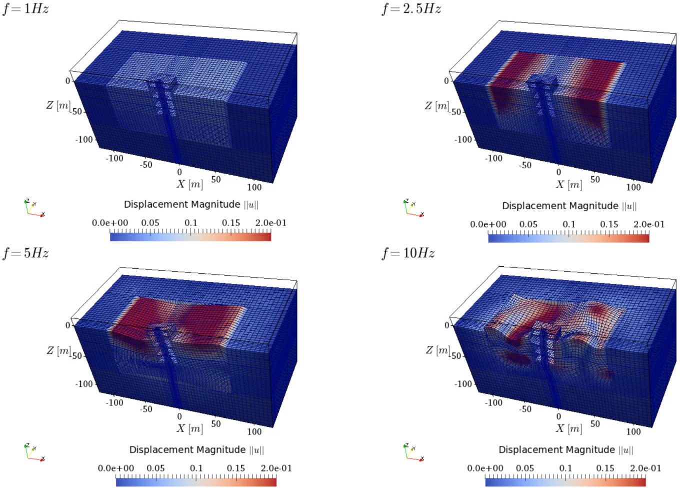
SMR ESSI, Variation in Input Frequency, REAL TIME



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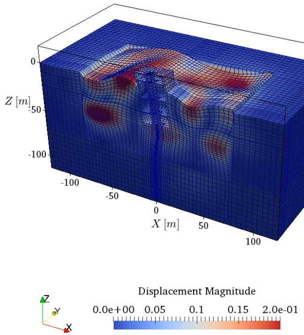
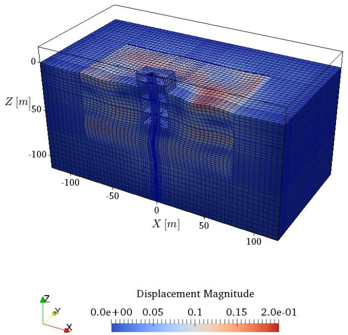
SMR ESSI, 3C vs 3×1C

$3C$



$3 \times 1C$



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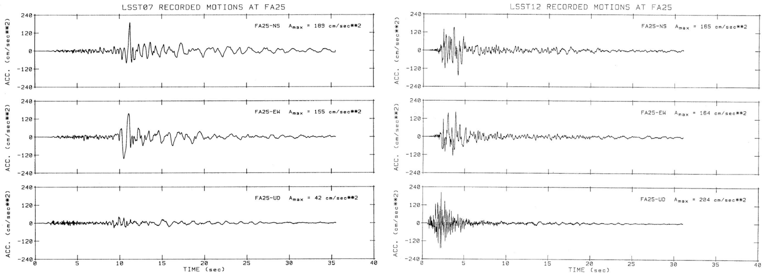
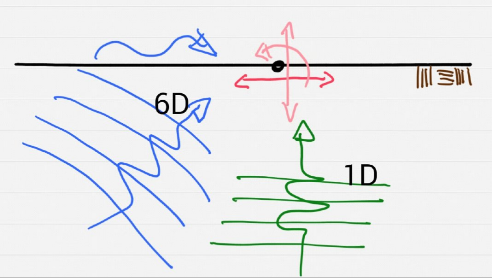
3C, 6C Seismic Motions

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

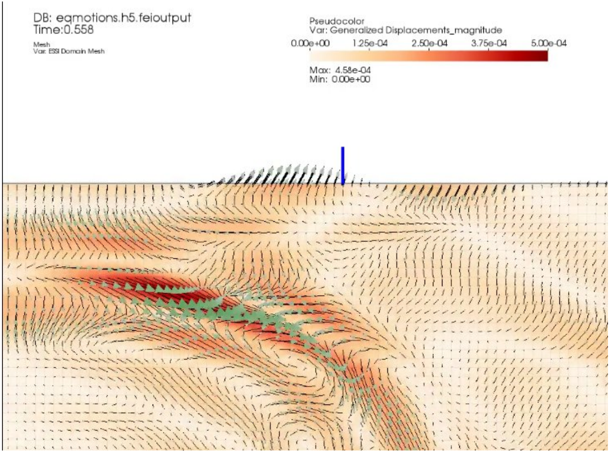


ESSI: 6C or 1C Seismic Motions

- 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

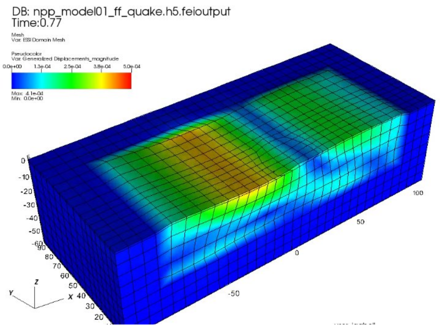


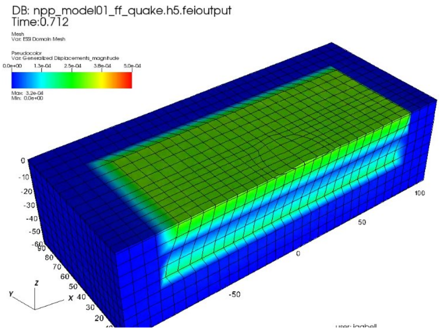
6C Free Field Motions (closeup)



1C vs 6C Free Field Motions

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





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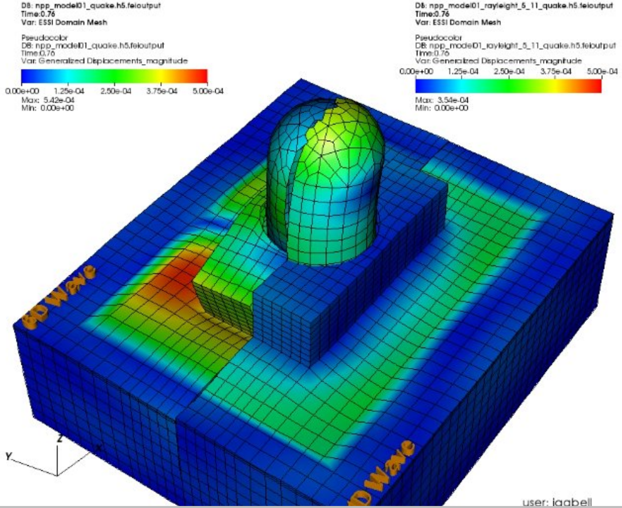
6C vs 1C NPP ESSI Response Comparison



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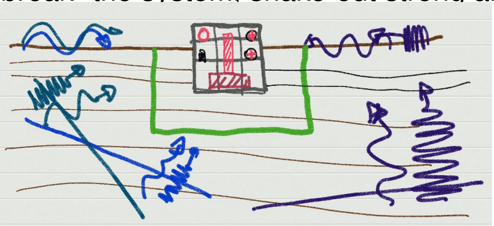
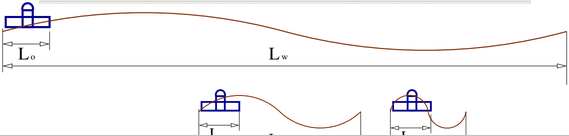
Stress Testing SSI Systems

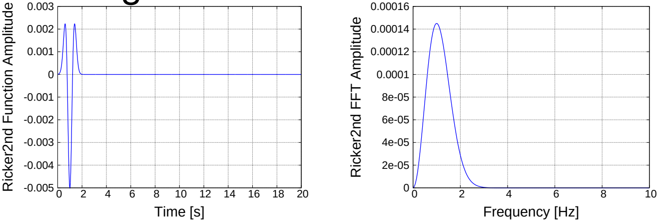
- Excite SSI system with a suite of seismic motions
- Waves: P, SV, SH, Surface (Rayleigh, Love, etc.)
- Variation in inclination, frequency, energy and duration
- Try to "break" the system, shake-out strong and weak links



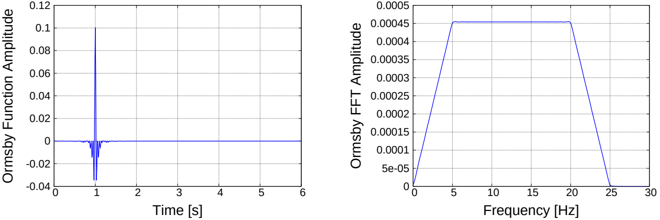


Stress Test Source Signals

- Ricker



- Ormsby



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- Energy dissipation outside SSI domain:
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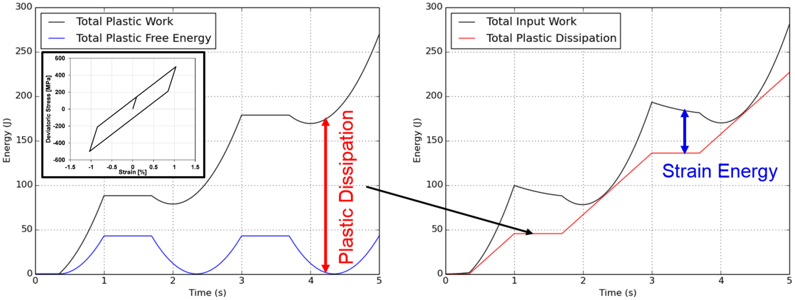
  - Reflected wave radiation
- Energy dissipation/conversion inside SSI domain:
  - Inelasticity of soil, contact zone, structure, foundation, dissipators
  - Viscous coupling with internal/pore fluids, and external fluids
- Numerical energy dissipation/production

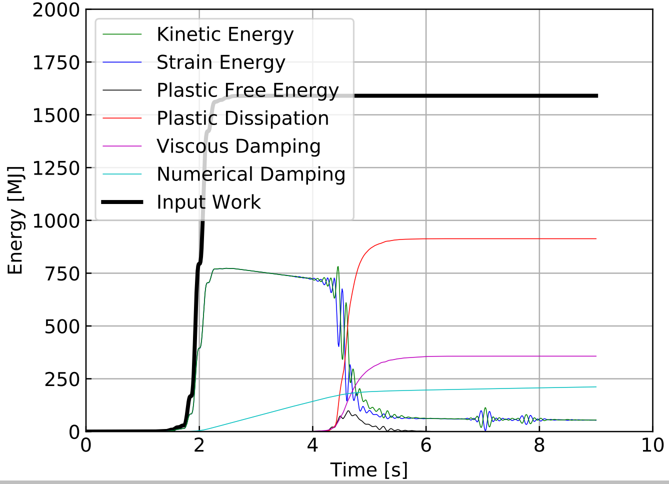
Plastic Energy Dissipation

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

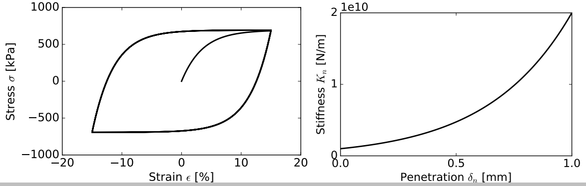


Inelastic Modeling of Soil Structure Systems

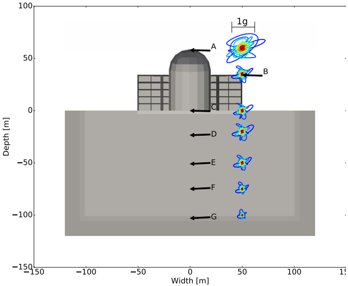
- Soil, inelastic, elastic-plastic
  - Dry, single phase
  - Unsaturated, partially saturated
  - Fully saturated
- Contact, inelastic, soil/rock – foundation
  - Dry, single phase,
    - Normal, hard and soft, gap open/close
    - Friction, nonlinear
  - Fully saturated, suction, excess pressure, buoyant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

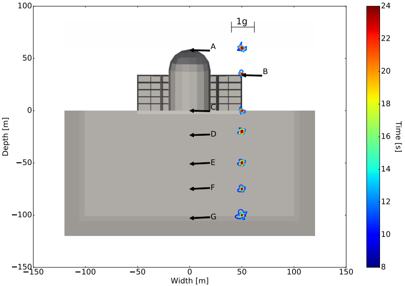
Inelastic Soil and Inelastic Contact

- 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

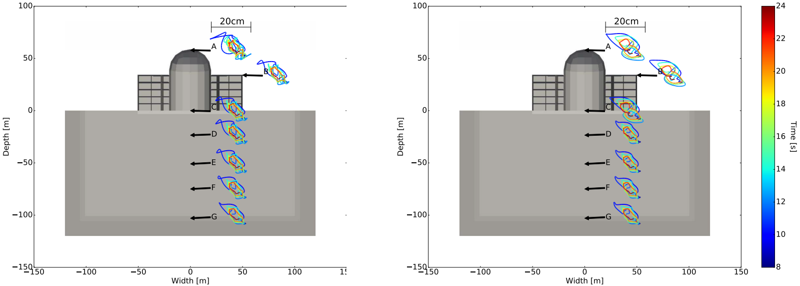




Elastic

Inelastic

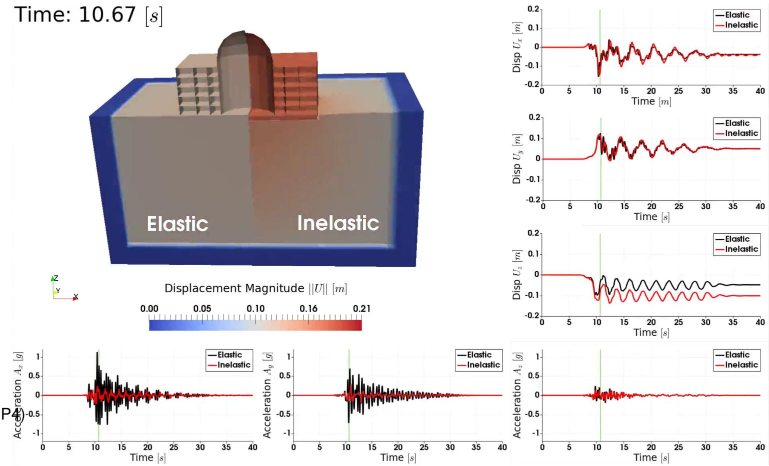
Displacement Traces, Elastic vs Inelastic



Elastic

Inelastic

Elastic and Inelastic Response: Differences



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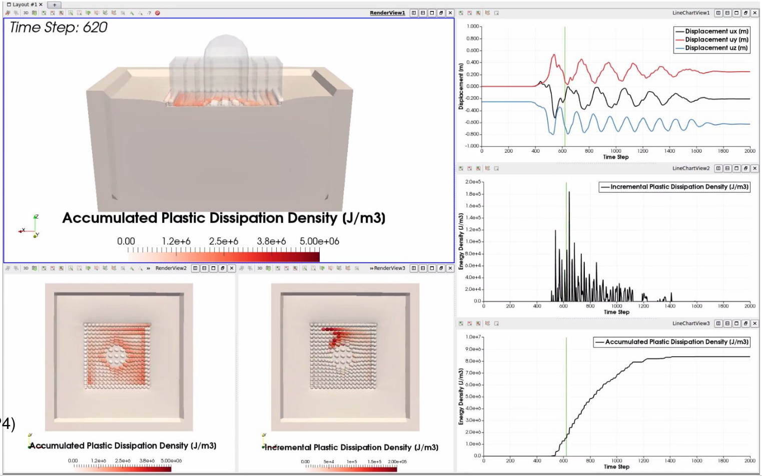
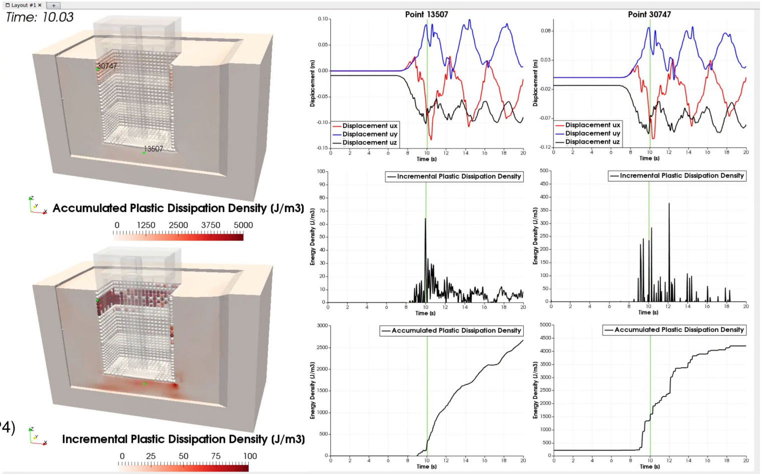
Energy Dissipation in a Large-Scale Model



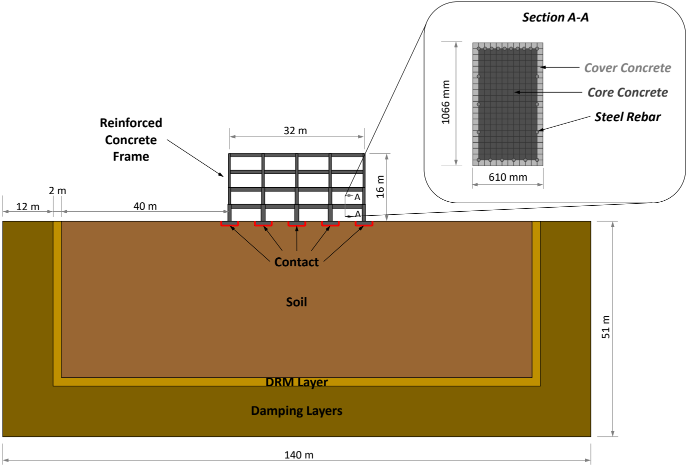
(MP4)

Energy Dissipation for an SMR Model

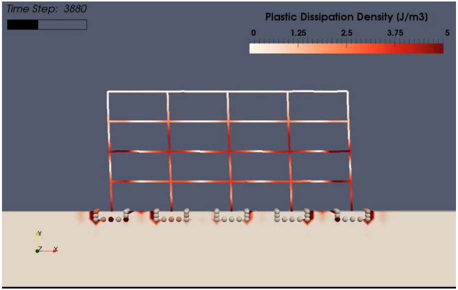


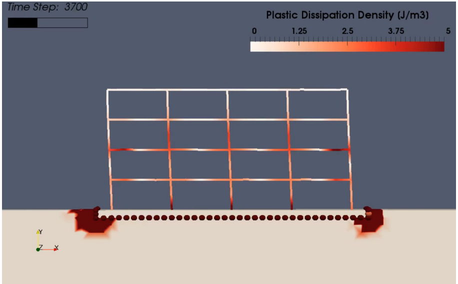
(MP4)

Energy Dissipation for Design

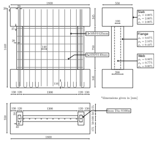
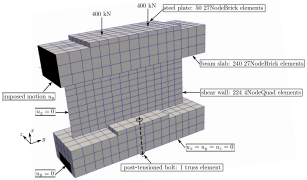


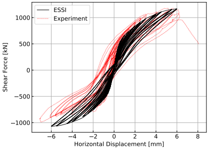
Design Alternatives

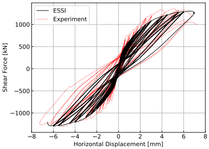


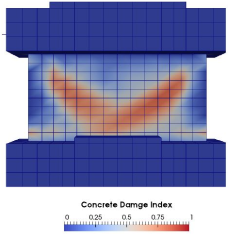


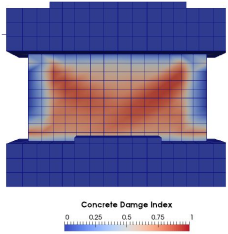
Wall, Regular and ASR Concrete

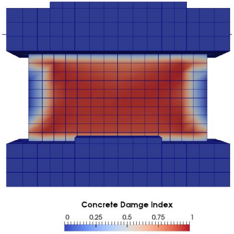







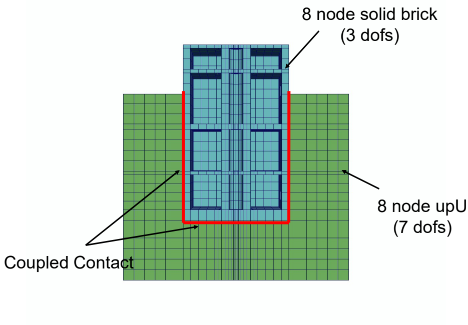


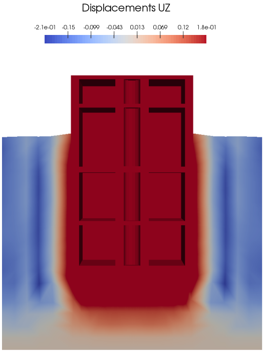




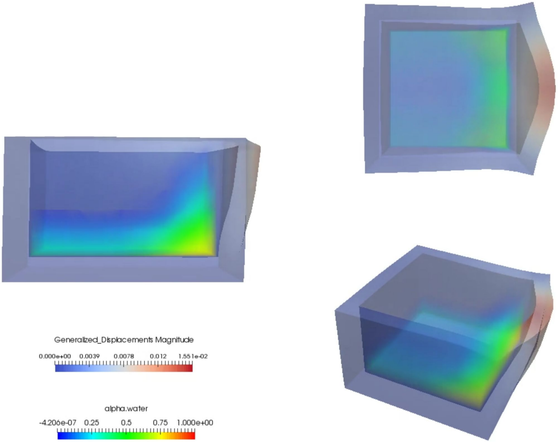
u_y = 1.4 mm u_y = 1.8 mm u_y = 3.0 mm

Buoyant Force Simulation





Solid, Structure-Fluid Interaction, Example



(MP4)

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, Python, Matlab)
- Real-ESSI System availability:
  - Educational Institutions: Amazon Web Services (AWS), free
  - Government Agencies, National Labs: AWS GovCloud
  - Professional Practice: AWS, commercial
- Quality Management System, ASME-NQA-1, ISO9003-2018, Certification in progress
- Real-ESSI Short Courses (online, this Fall)
- System description and documentation at `http://sokocalo.engr.ucdavis.edu/~jeremic/Real_ESSI_Simulator/`

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/Real_ESSI_Simulator/` ; `http://real-essi.info/`

Thank You