

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

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Outline

Introduction
Motivation

Modeling and Simulation
Real-ESSI/MS-ESSI Simulator System
Real ESSI Examples

Summary

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- ▶ Improve modeling and simulation for infrastructure objects
- ▶ Use of numerical models to analyze statics and dynamics of soil/rock-structure systems
- ▶ Reduction of modeling uncertainty
- ▶ Desired level of sophistication (high ↔ low) analysis
- ▶ Follow and direct the flow of seismic energy,
- ▶ Practical system for realistic modeling and simulation of Earthquakes, Soils, Structures and their Interaction,
Real-ESSI/MS-ESSI:
<http://real-essi.info/>
<http://ms-essi.info/>
http://sokocalo.engr.ucdavis.edu/~jeremic/Real_ESSI_Simulator/

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

Uncertainties

- ▶ 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 material K^{ep}
 - ▶ Uncertain loads, $F(t)$
 - ▶ Propagate uncertainties to solve for PDFs of σ_{ij} , ϵ_{ij} , u_i , \dot{u}_i , \ddot{u}_i

Motivation

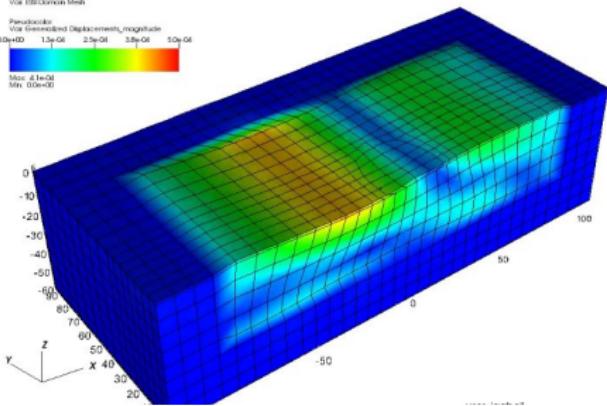
6C vs 1C Free Field Motions

- ▶ One component of seismic motions (1C) from 3C/6C
- ▶ Good, excellent fit

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Time: 0.77

Mesh
Vis: ESSI Domain Mesh

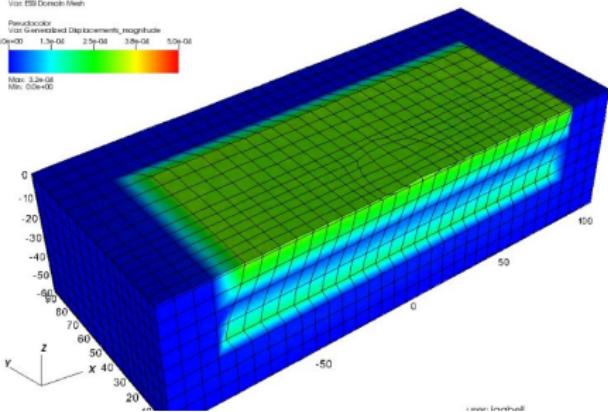
Parabolic
Vis: Generalized Displacements_magnitude
0.0e+00 - 1.3e-01 2.5e-01 3.8e-01 5.0e-01
Max: 4.1e-01
Min: 1.0e-02



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Mesh
Vis: ESSI Domain Mesh

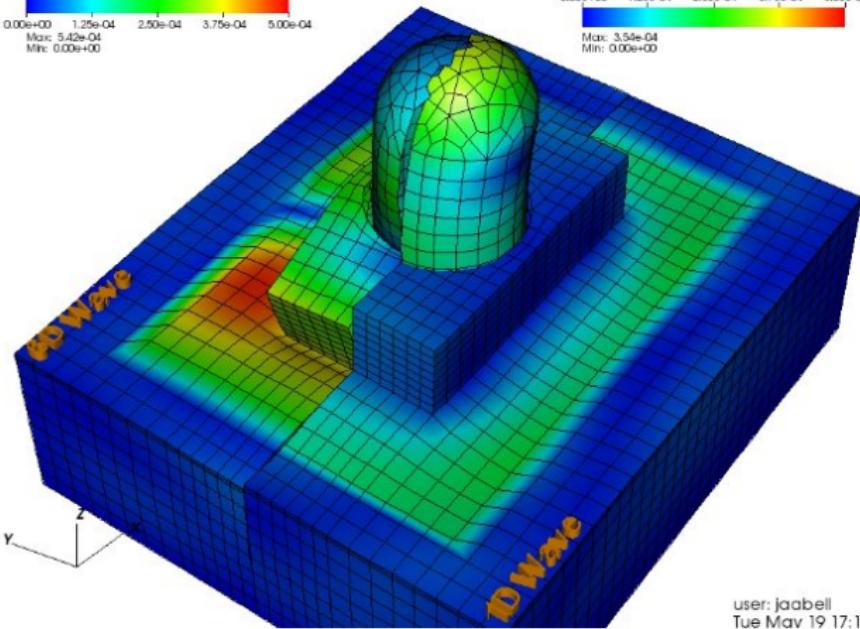
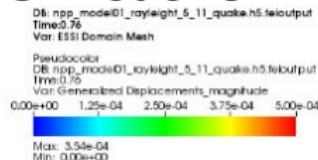
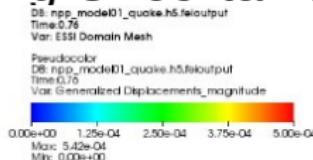
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Max: 3.2e-01
Min: 0.0e+00



(MP4) (MP4)

Motivation

Modeling Uncertainty, 6C vs 1C Motions

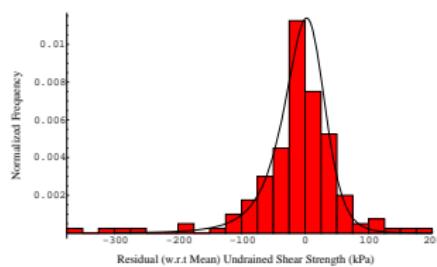
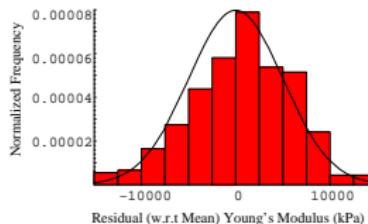
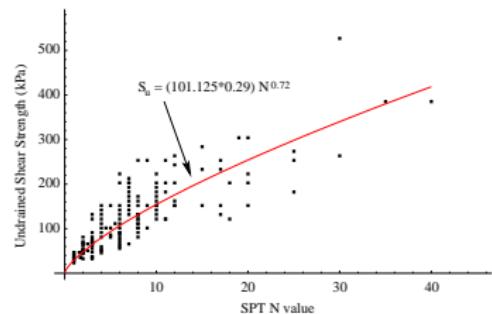
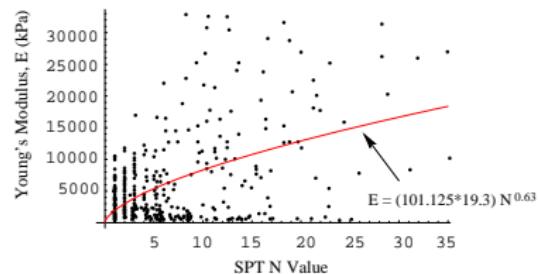


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Motivation

Parametric Uncertainty: Soil Stiffness and Strength

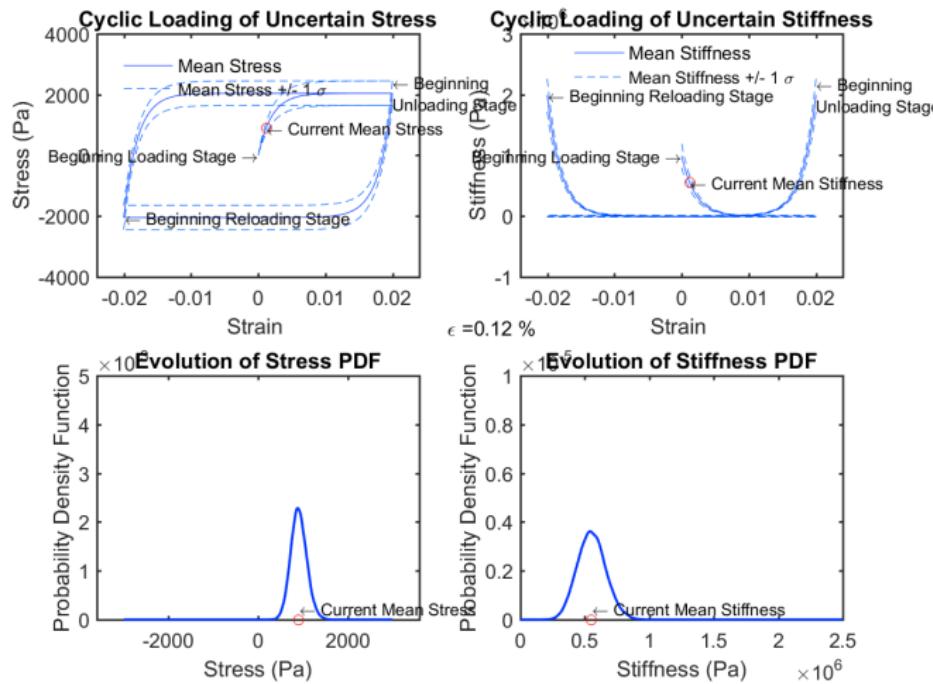


Phoon and Kulhawy (1999)

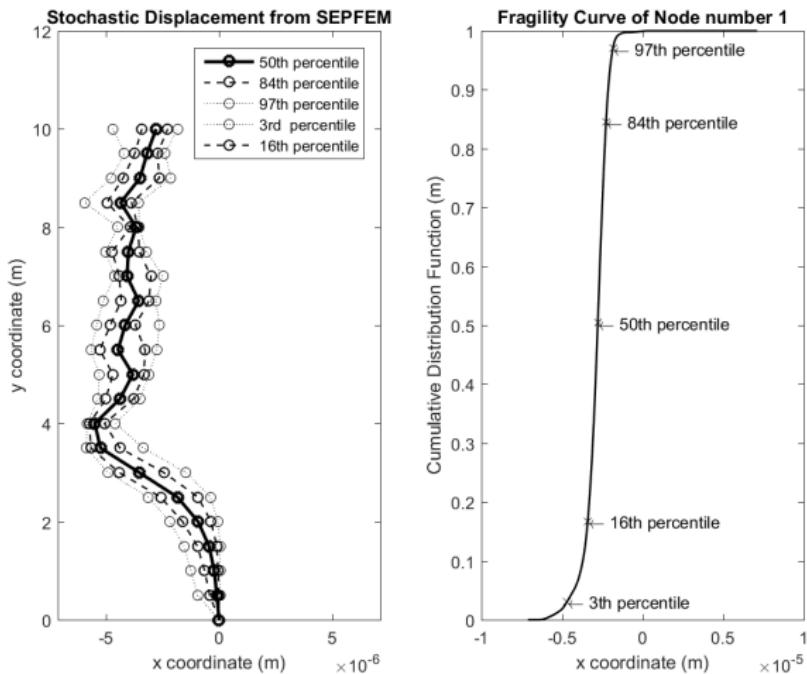


Motivation

SEPFEM : Probabilistic Elastic-Plastic Modeling



SEPFEM : Example in 1D



Real-ESSI/MS-ESSI Simulator System

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Summary

Real-ESSI / MS-ESSI

- ▶ A system for time domain, nonlinear/inelastic, deterministic or probabilistic, 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.
- ▶ Design: linear elastic, load combinations, dimensioning
- ▶ Assessment: inelastic, DBE/BDBE, safety margins
- ▶ More information at:
http://sokocalo.engr.ucdavis.edu/jeremic/Real_ESSI_Simulator/

Real-ESSI / MS-ESSI Modeling Features

- ▶ Solid elements, dry, (un-) saturated, elastic, inelastic
- ▶ Structural elements, beams, shells, elastic, inelastic
- ▶ Contact elements, dry, coupled/saturated, hard, soft
- ▶ Isolator and Dissipator elements
- ▶ Super element, stiffness and mass matrices
- ▶ Material models, soil, rock, concrete, steel, rubber...
- ▶ Seismic input, 1C, 3C, 6C, deterministic or probabilistic
- ▶ Energy dissipation: material, viscous, algorithmic
- ▶ Solid/Structure – Fluid interaction, full coupling
- ▶ Statics, Dynamics, Eigen, Restart
- ▶ High Performance Computing, fine and coarse grained
- ▶ Pre-Processing, gmsh/gmESSI, model translators
- ▶ Post-processing, Paraview with pvESSI plugin

Real ESSI Examples

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Energy Input and Dissipation

Energy input, static and dynamic forcing

Energy dissipation outside SSI domain:

- ▶ SSI system oscillation radiation
- ▶ Reflected wave radiation

Energy dissipation/conversion inside SSI domain:

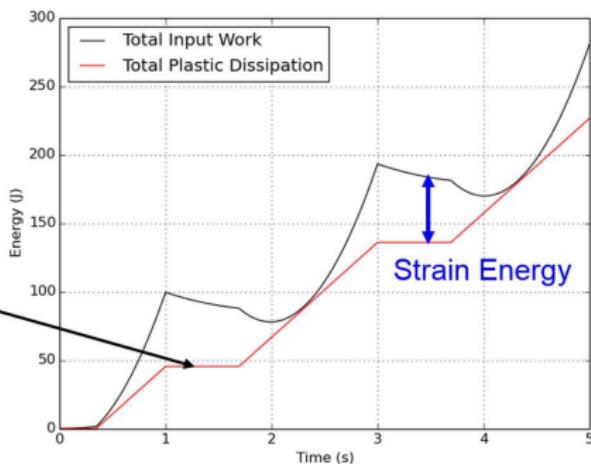
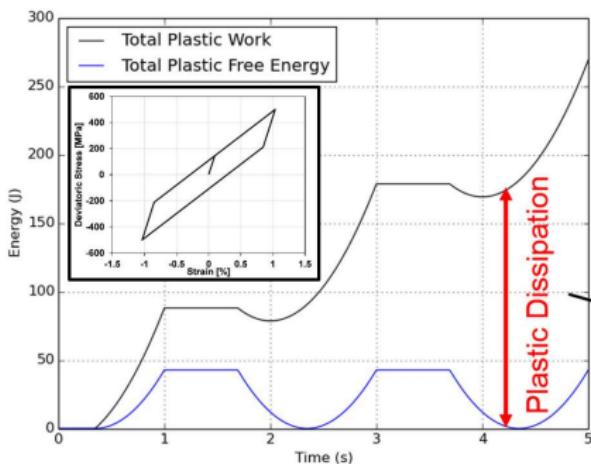
- ▶ Inelastic soil, contacts, structure, foundation, dissipators
- ▶ Viscous coupling with internal and external fluids

Algorithmic/Numerical energy dissipation/production

Real ESSI Examples

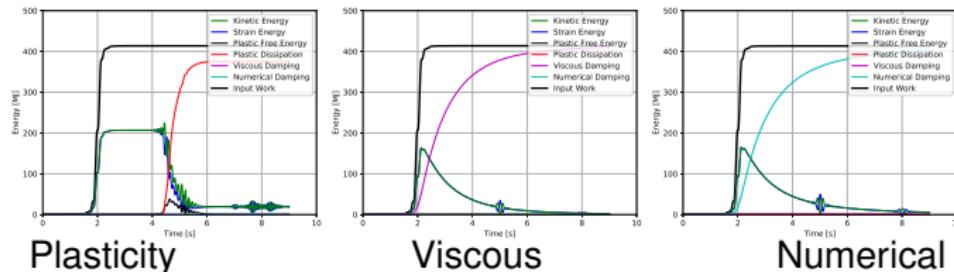
Energy Dissipation on Material Level

Plastic work can decrease, plastic dissipation always increases



Real ESSI Examples

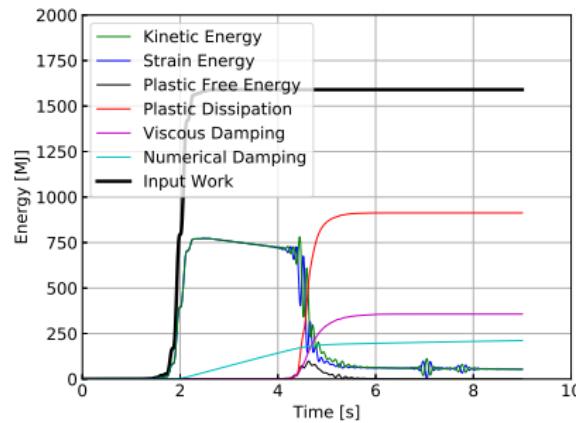
Energy Dissipation Control Mechanisms



Plasticity

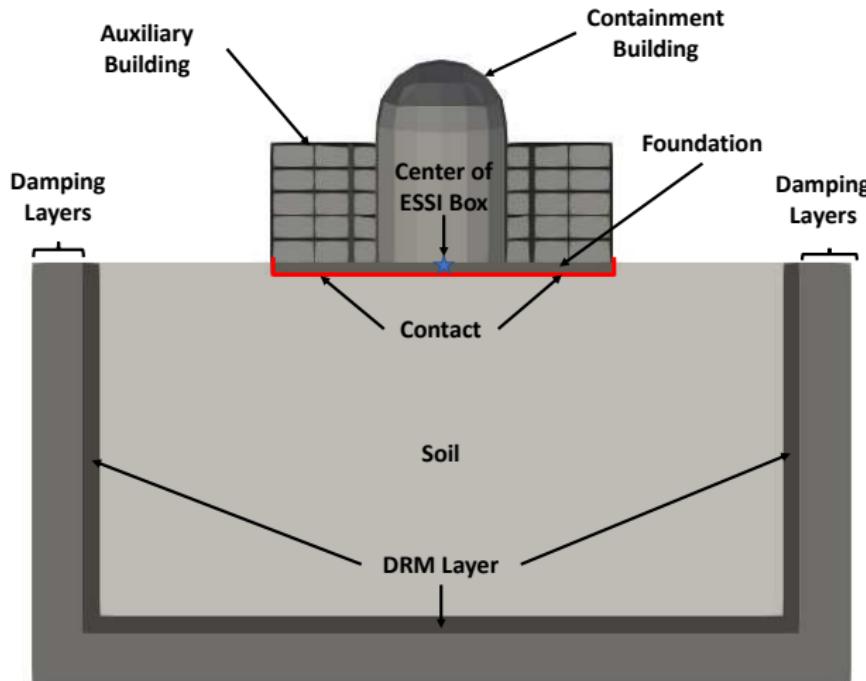
Viscous

Numerical



Real ESSI Examples

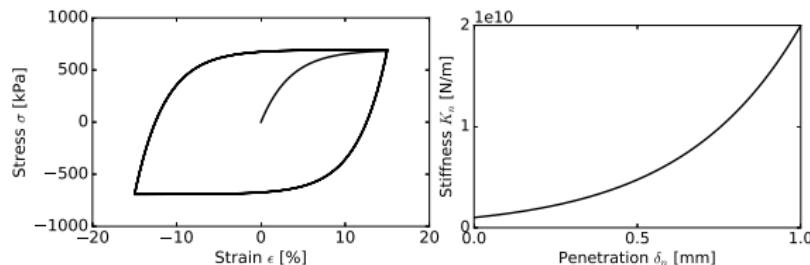
Nuclear Power Plant Model



Real ESSI Examples

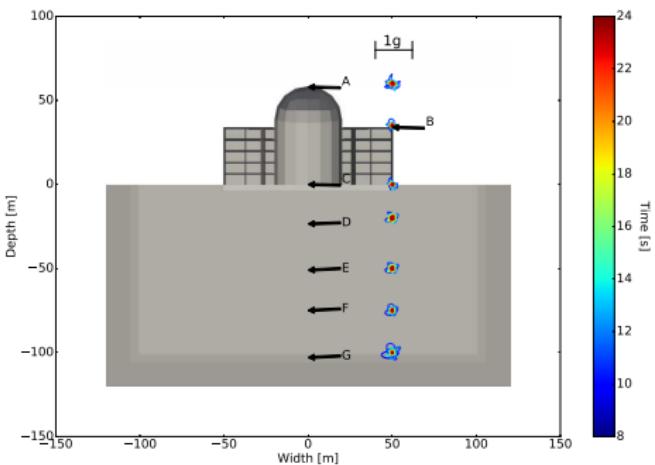
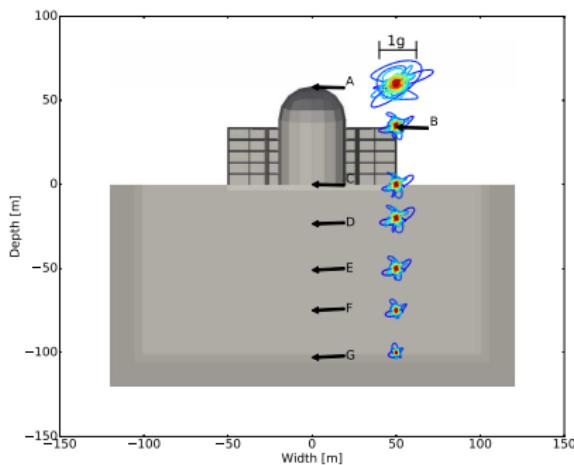
Inelastic Soil and Inelastic Contact

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



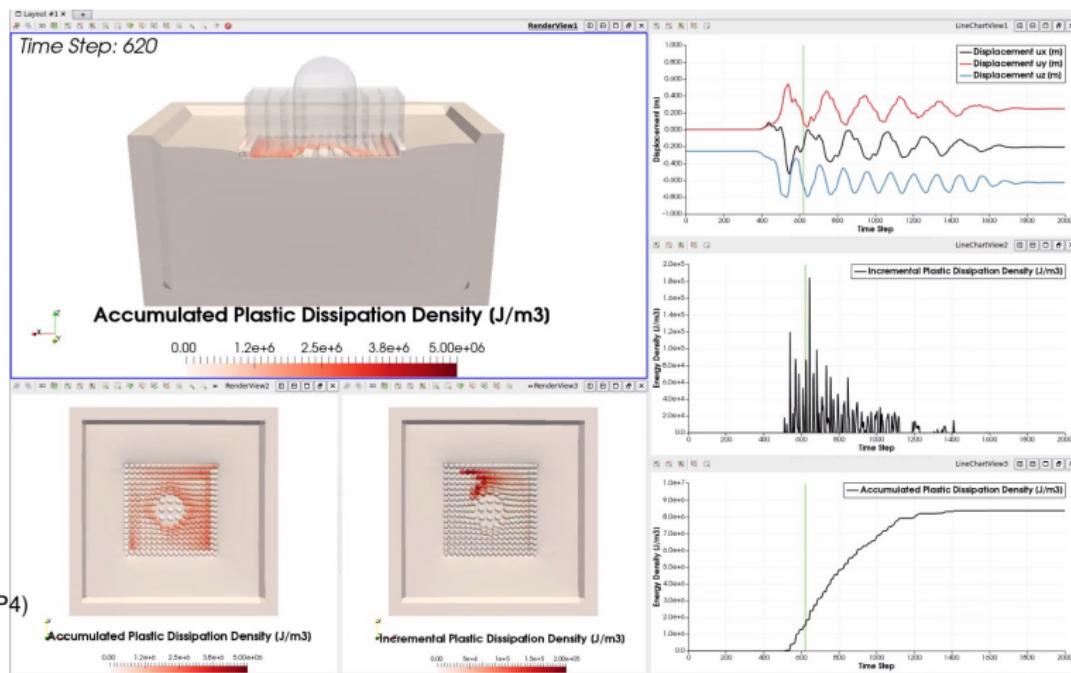
Real ESSI Examples

Acceleration Traces, Elastic vs Inelastic



Real ESSI Examples

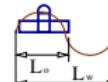
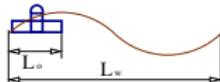
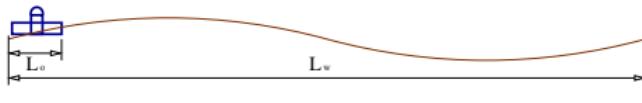
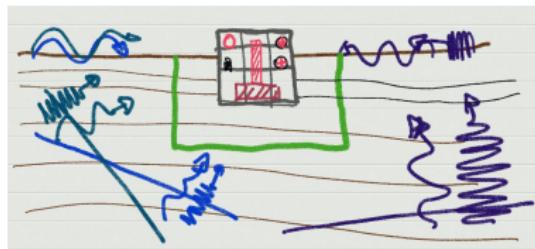
Energy Dissipation in NPP Model



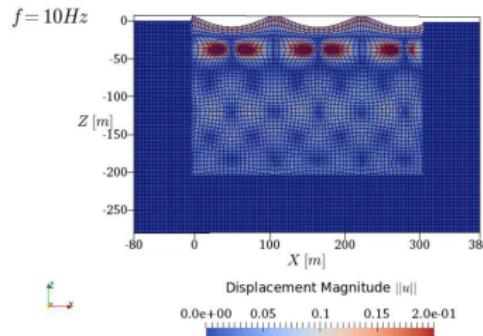
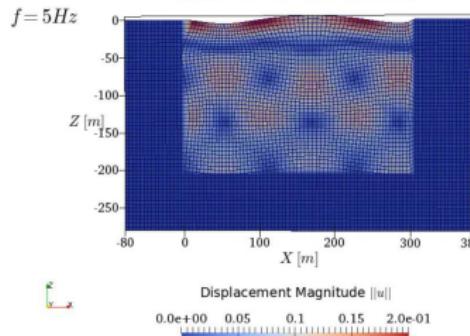
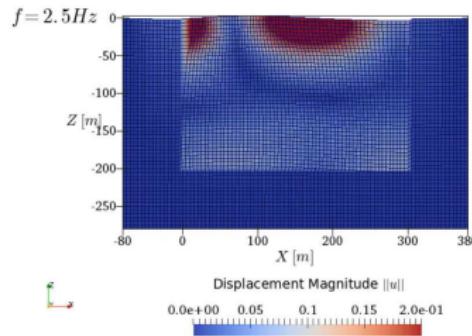
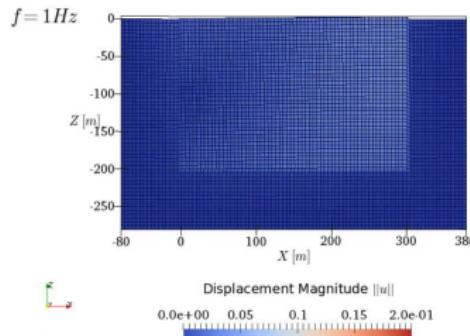
Real ESSI Examples

Seismic Motions

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

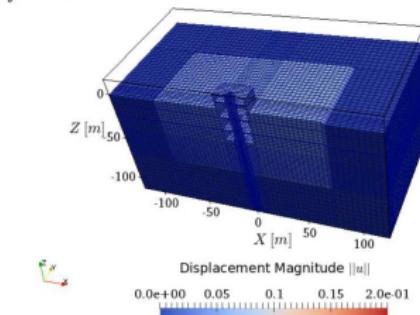
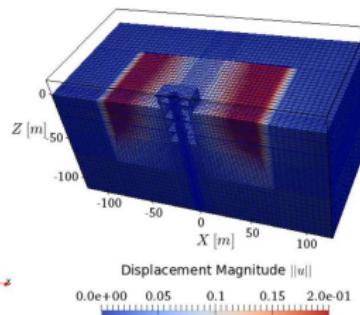
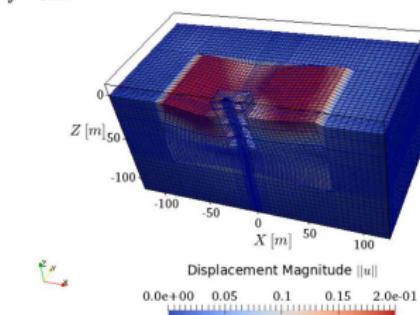
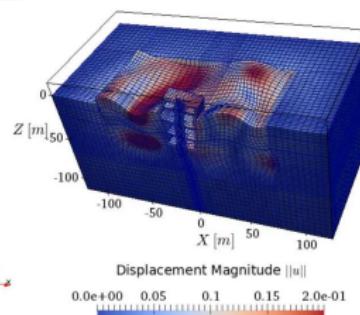


Real ESSI Examples

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

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Real ESSI Examples

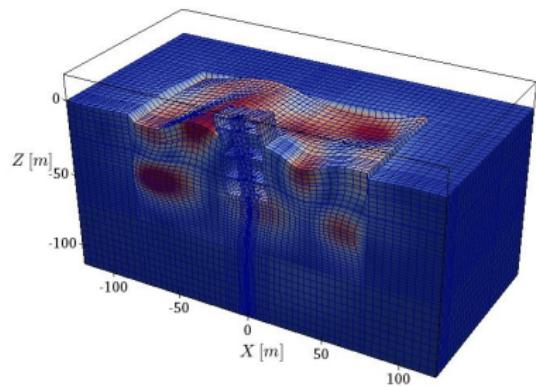
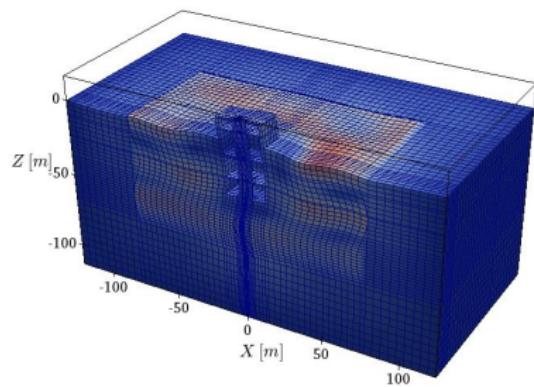
SMR ESSI, Variation in Input Frequency, $\theta = 60^\circ$ $f = 1\text{Hz}$  $f = 2.5\text{Hz}$  $f = 5\text{Hz}$  $f = 10\text{Hz}$ 

(MP4)

Real ESSI Examples

SMR ESSI, 3C vs $3 \times 1C$

3C

 $3 \times 1C$ 

(OGV)



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- ▶ Numerical modeling to predict and inform, rather than fit
- ▶ Education and Training is the key!
- ▶ Real-ESSI/MS-ESSI Simulator System:
<http://real-essi.info/>
<http://ms-essi.info/>
http://sokocalo.engr.ucdavis.edu/~jeremic/Real_ESSI_Simulator/
- ▶ Collaboration with and financial support from the US-DOE, US-NRC, US-NSF, Caltrans, CNSC-CCSN, UN-IAEA, ILEE, Shimizu, Basler&Hofmann