

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

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Outline

Introduction
Motivation

Modeling and Simulation
Seismic Motions
Inelasticity

Summary

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Modeling and Simulation

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Motivation

- ▶ Improve safety and economy of infrastructure objects
- ▶ Improve numerical modeling and simulation for infrastructure objects, nuclear installations
- ▶ Quality assurance, verification & validation
- ▶ Practical numerical modeling and simulation system
- ▶ Select level of sophistication numerical models to analyze earthquake soil structure interaction of nuclear installations

Uncertainties

- ▶ Modeling uncertainty, introduced by simplifying assumptions, need for capability to perform lower and higher level of sophistication modeling and simulation
- ▶ Parametric uncertainty, propagation of uncertainty in material K^{ep} and loads $F(t)$, through:
 $M\ddot{u}_i + C\dot{u}_i + K^{ep}u_i = F(t)$, resulting in PDFs and CDFs for σ_{ij} , ϵ_{ij} , u_i , \dot{u}_i , \ddot{u}_i
- ▶ Le doute n'est pas un état bien agréable, mais l'assurance est un état ridicule. (François-Marie Arouet, Voltaire)

Flow of Seismic Energy

- ▶ Seismic energy input into the ESSI system
- ▶ Seismic energy dissipation outside of ESSI system
 - ▶ Wave reflections
 - ▶ Structural oscillations, wave radiation
- ▶ Seismic energy dissipation within ESSI system
 - ▶ Viscous effects (soil, fluid containers...)
 - ▶ Inelastic effects (soil, concrete, contacts, dissipators...)
- ▶ Numerical energy dissipation and production

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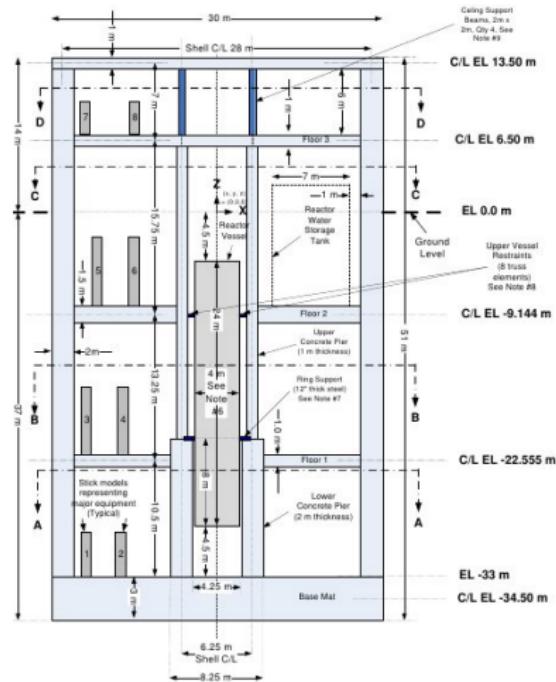


Stress Test Motions and Regional Scale Motions

- ▶ Stress test motions
 - ▶ 3D - 6C, Haskell's solution for plane harmonic waves
 - ▶ 3D - 3×1 C
 - ▶ 3D - 1C
 - ▶ 1D - 1C
 - ▶ High fidelity (?) free field regional scale seismic motions using SW4, courtesy of Dr. Rodgers, Dr. Pitarka and Dr. Petersson (LLNL)
 - ▶ Knowledge of geology and the site is important

Seismic Motions

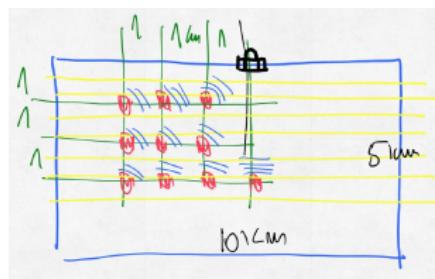
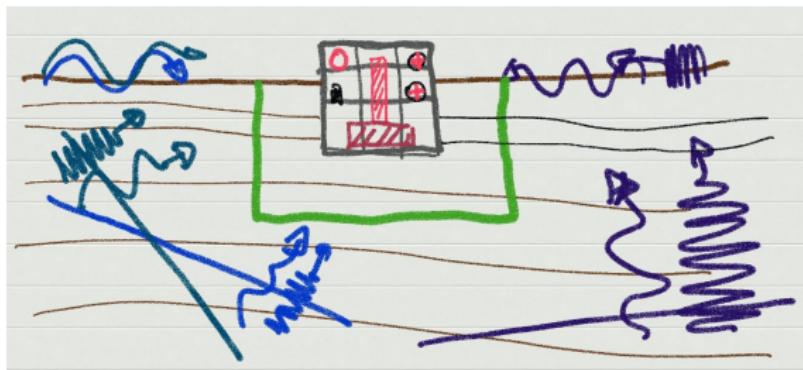
Example Structure, a Small Modular Reactor (SMR)



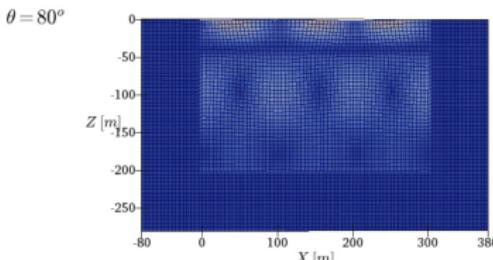
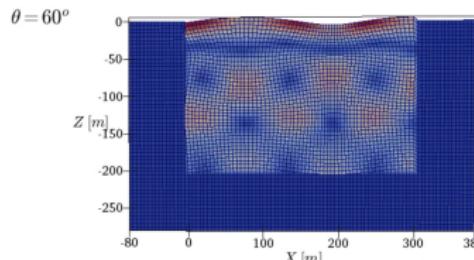
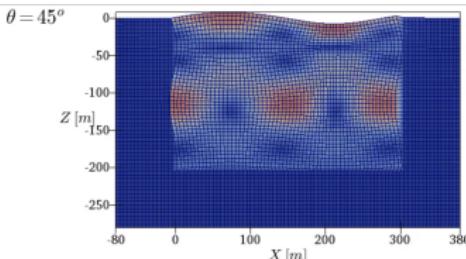
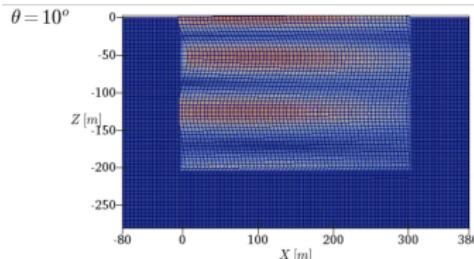
Seismic Motions

Stress Test Motions

- ▶ Variation in inclination, frequency, energy and duration
- ▶ Try to "break" the system, shake-out strong and weak links



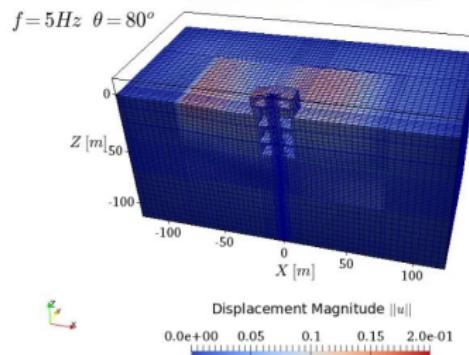
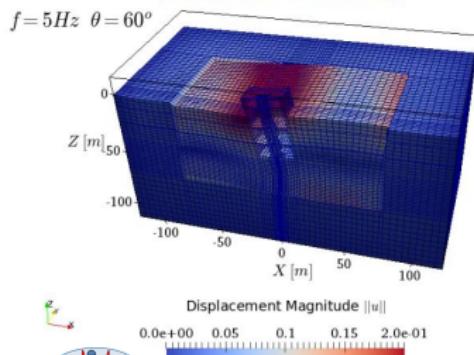
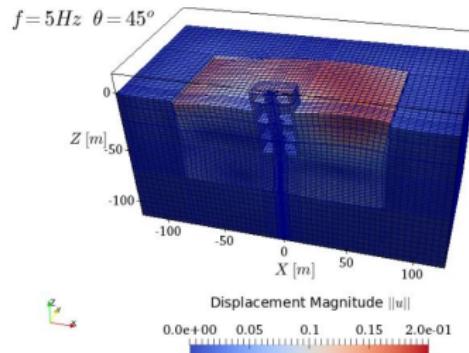
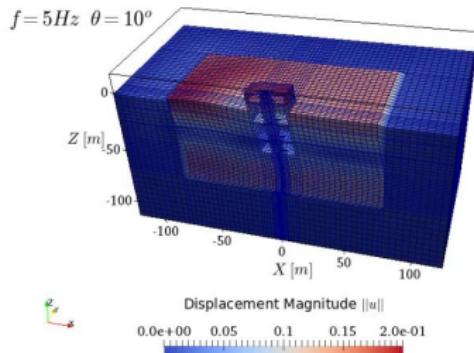
Seismic Motions

Free Field, Variation in Input Wave Angle, $f = 5\text{Hz}$ 

(MP4)



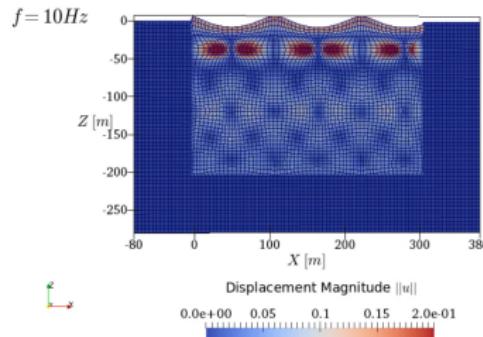
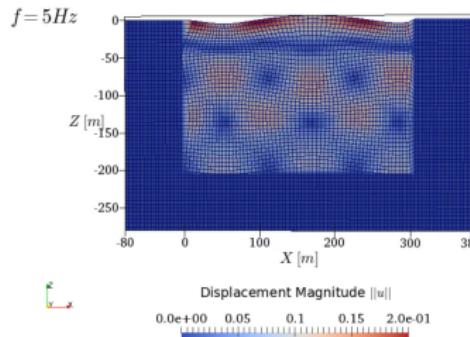
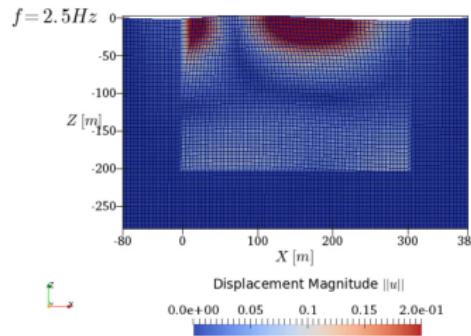
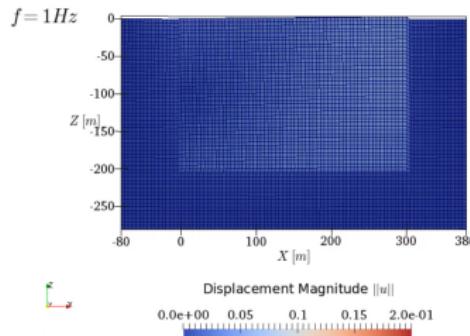
Seismic Motions

SMR ESSI, Variation in Input Wave Angle, $f = 5\text{Hz}$ 

(MP4)



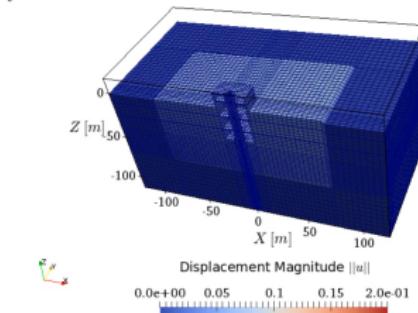
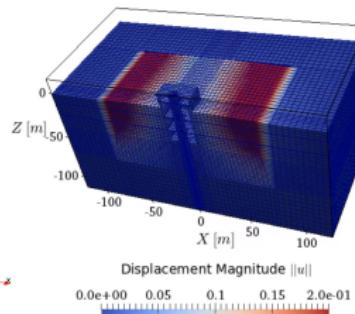
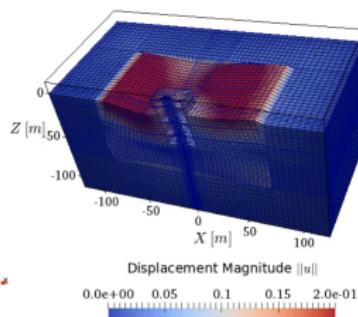
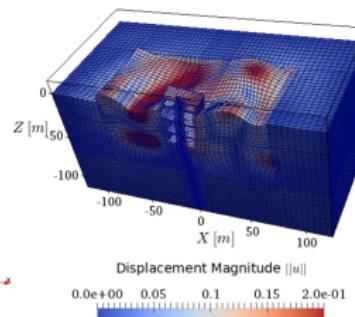
Seismic Motions

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

(MP4)



Seismic Motions

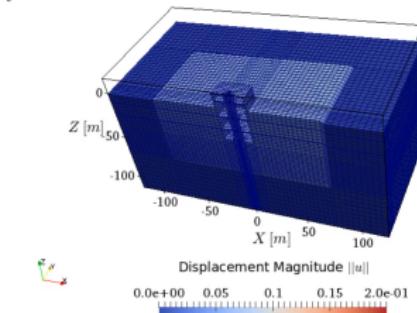
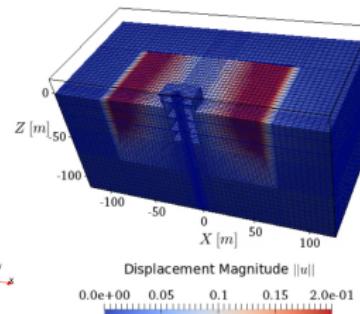
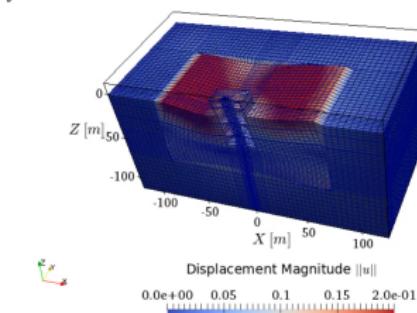
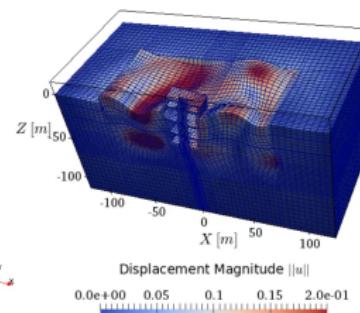
SMR ESSI, Variation in Input Frequency, $\theta = 60^\circ$ $f = 1\text{Hz}$  $f = 2.5\text{Hz}$  $f = 5\text{Hz}$  $f = 10\text{Hz}$ 

(MP4)



Seismic Motions

SMR ESSI, Variation in Input Frequency, REAL TIME

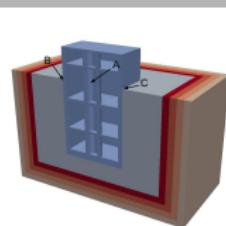
 $f = 1\text{Hz}$  $f = 2.5\text{Hz}$  $f = 5\text{Hz}$  $f = 10\text{Hz}$ 

(MP4)



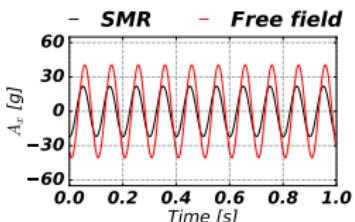
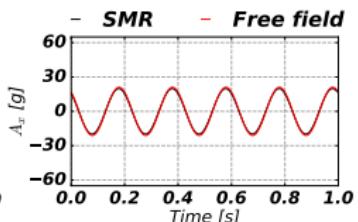
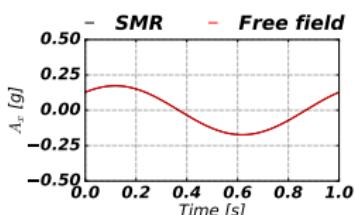
Seismic Motions

Free Field vs ESSI - Different Frequencies

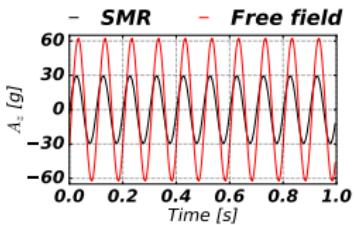
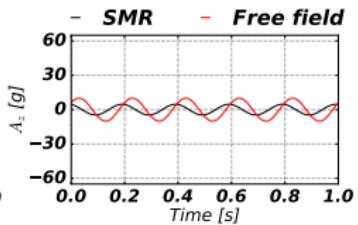
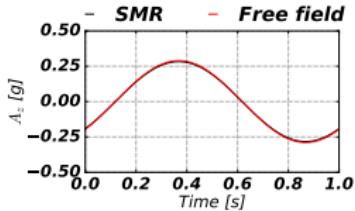


Acceleration response - Surface center point A

X direction

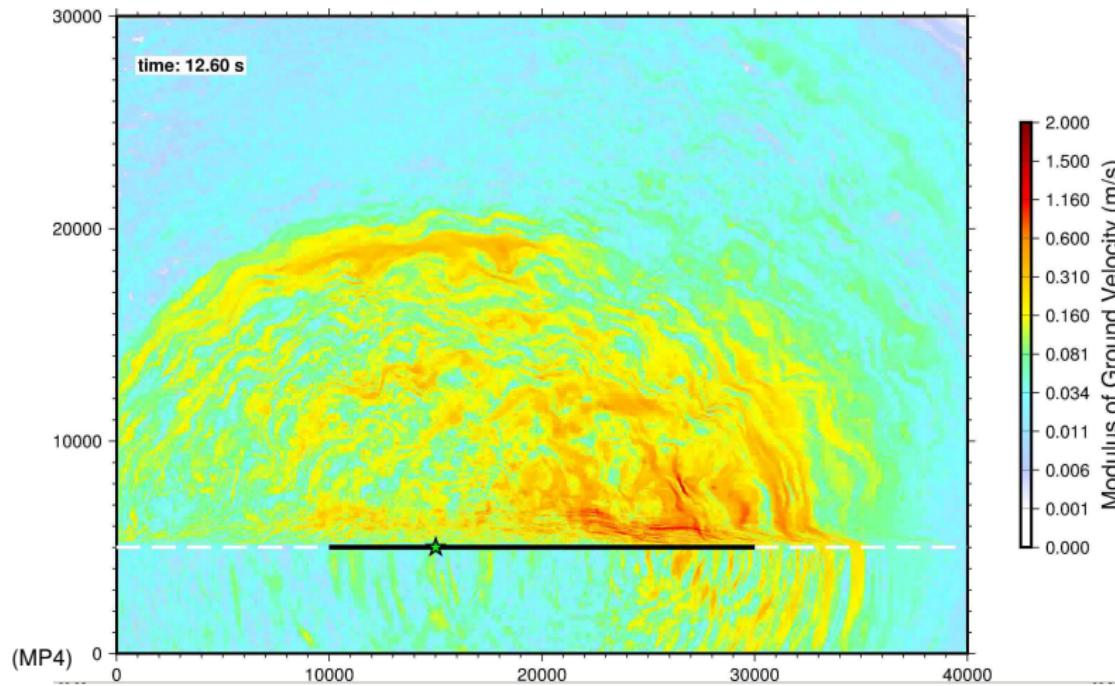


Z direction

(a) $f = 1\text{Hz} \quad \theta = 60^\circ$ (b) $f = 5\text{Hz} \quad \theta = 60^\circ$ (c) $f = 10\text{Hz} \quad \theta = 60^\circ$

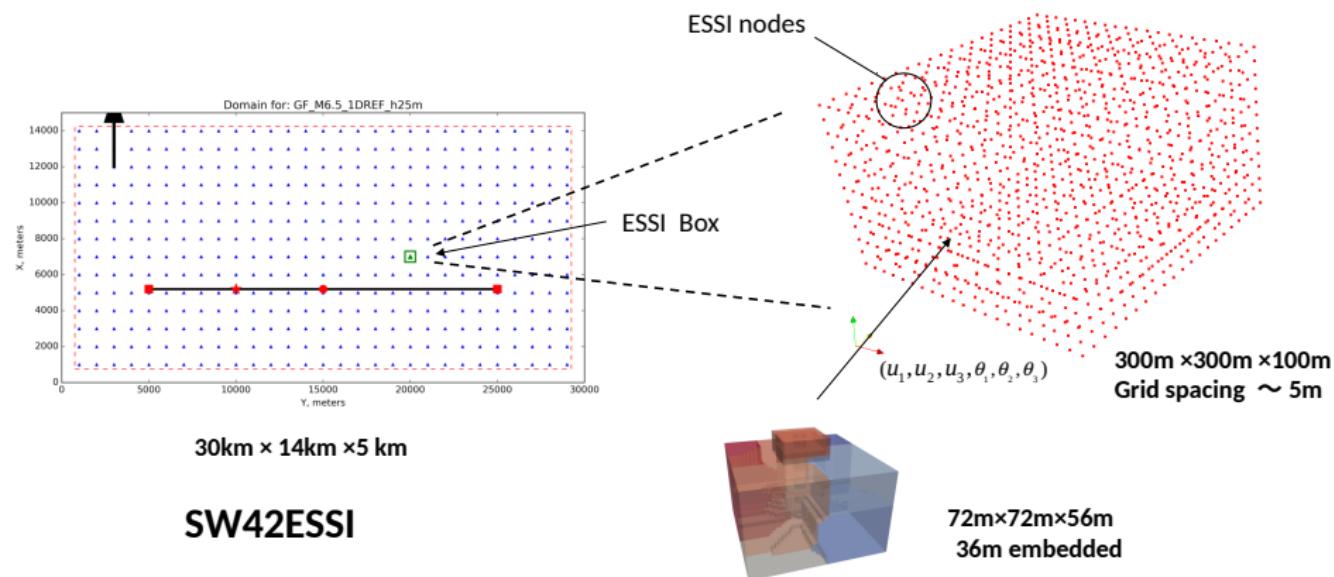
Seismic Motions

Example Regional Model (Rodgers et al, LLNL)



Seismic Motions

Seismic Motions: SW4 to MS-ESSI



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Inelasticity

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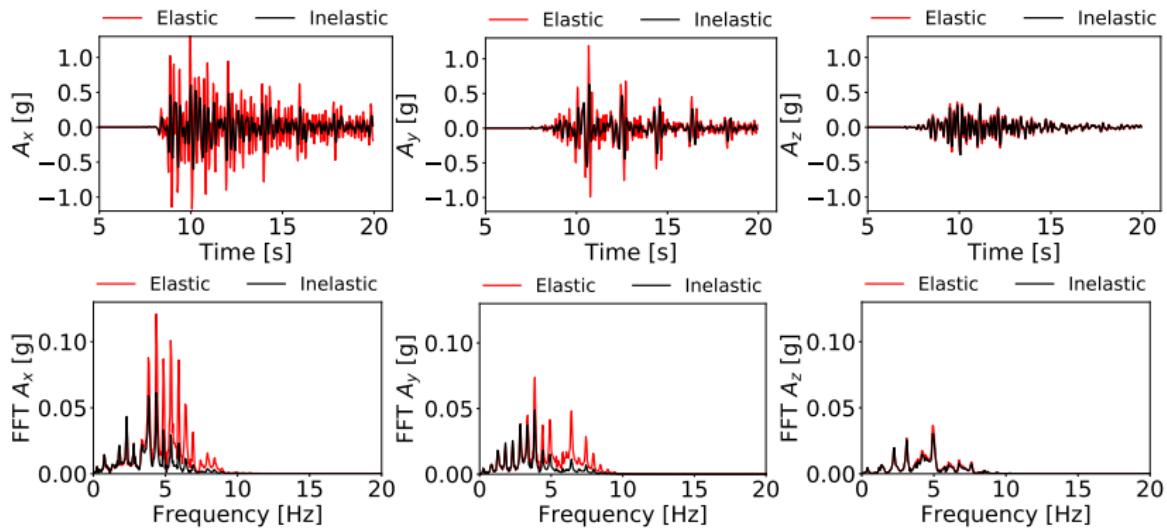
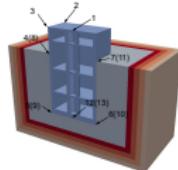
Inelasticity

Inelastic Modeling for Components

- ▶ Soil elastic-plastic
 - ▶ Dry, single phase
 - ▶ Unsaturated (partially saturated)
 - ▶ Fully saturated
- ▶ Contact, inelastic, soil/rock – foundation
 - ▶ Dry, single phase, normal/axial (hard and soft, gap open/close), friction/shear (inelastic)
 - ▶ Fully saturated, suction and excess pressure (dynamic buoyant force)
- ▶ Structural inelasticity/damage
 - ▶ Nonlinear/inelastic fiber beam
 - ▶ Nonlinear/inelastic fiber wall element

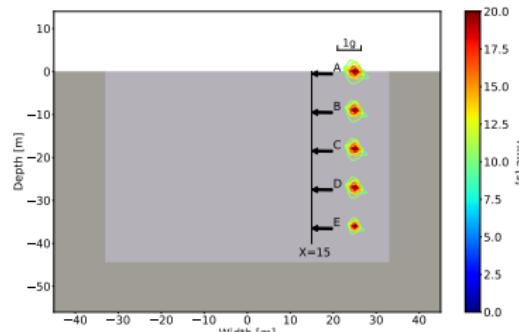
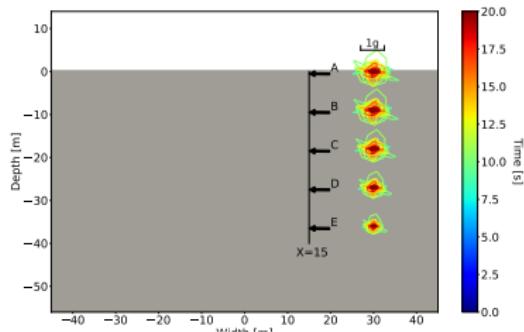
Inelasticity

SMR: Inelastic ESSI Effects, Top Center

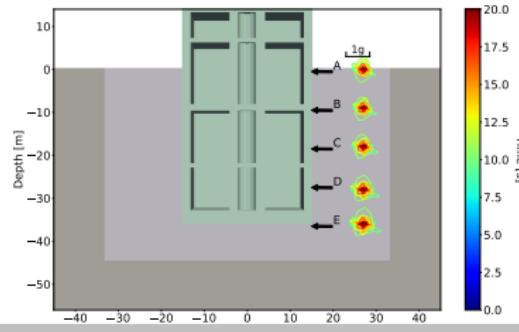
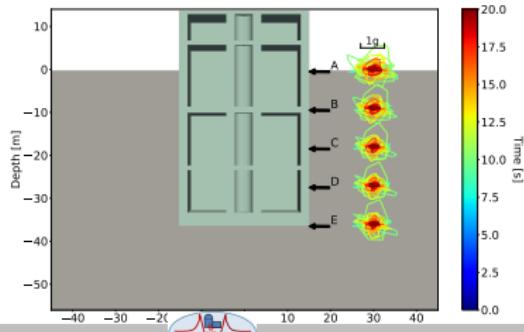


Inelasticity

SMR: Accelerations Along Depth



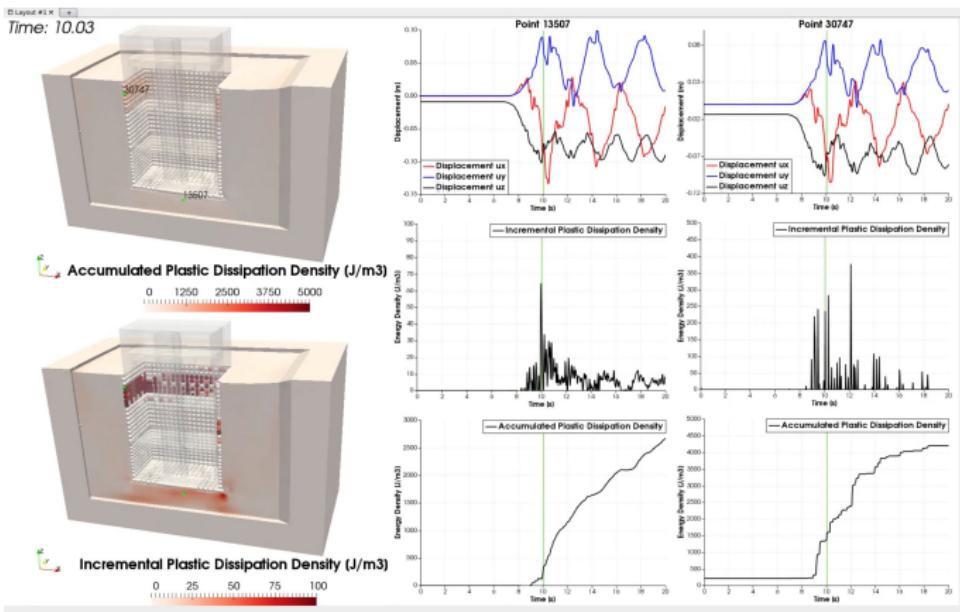
Nonlinear
site
effects



Nonlinear
ESSI
effects

Inelasticity

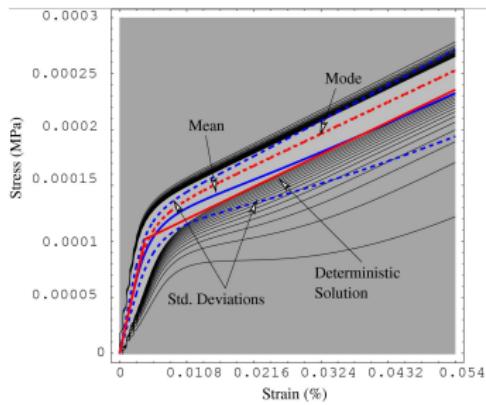
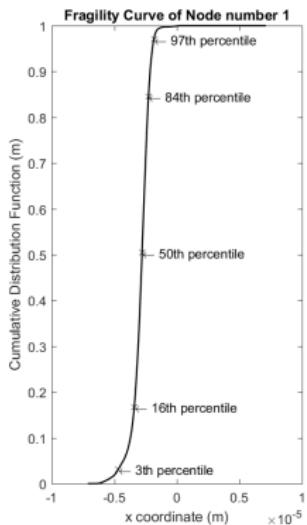
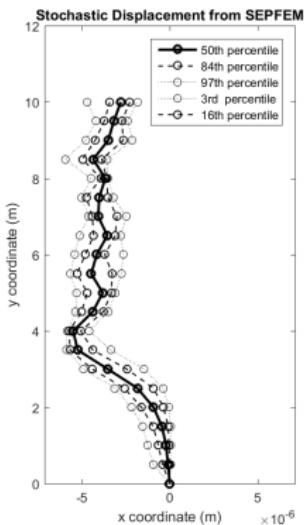
Energy Dissipation for an SMR



Inelasticity

Stochastic Elastic-Plastic Finite Element Method

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



(MP4)

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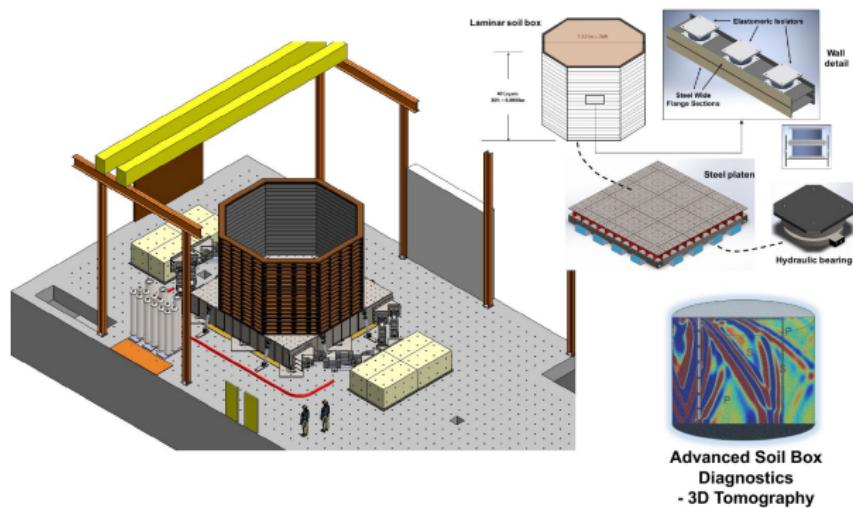
Summary

- ▶ Seismic wave fields, 3C/6C, $3 \times 1C$ and 1C, for ESSI behavior
- ▶ Inelastic ESSI behavior, soil, contact and structure
- ▶ MS-ESSI Simulator: <http://ms-essi.info>
- ▶ Funding from and collaboration with the DOE, NRC, CNSC-CCSN, NSF and IAEA is greatly appreciated
- ▶ Collaborators: Feng, Han, Wang, Sinha, Lacour, Abell, Pisanò, Orbović, McCallen, Petrone, McKenna

US-DOE: ESSI of Nuclear Installations

The MS-ESSI Simulator: <http://ms-essi.info>

High Quality Validation test (UNR/UCD/LBNL)



Advanced Soil Box
Diagnostics
- 3D Tomography