

# Modeling and Simulation of Earthquake Soil Structure Interaction for Nuclear Installations

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# Outline

Introduction

Motivation

Modeling and Simulation

MS-ESSI/Real-ESSI Simulator System

Illustrative Examples

Summary

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# Motivation

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 the flow, input and dissipation, of seismic energy,

Practical system for modeling and simulation of Earthquakes, Soils, Structures and their Interaction,

Real-ESSI/MS-ESSI:

<http://ms-essi.info/>

<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

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## MS-ESSI / Real-ESSI Modeling Features

- ▶ Solid elements, dry, 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
- ▶ All Modeling Features listed at <http://ms-essi.info/>

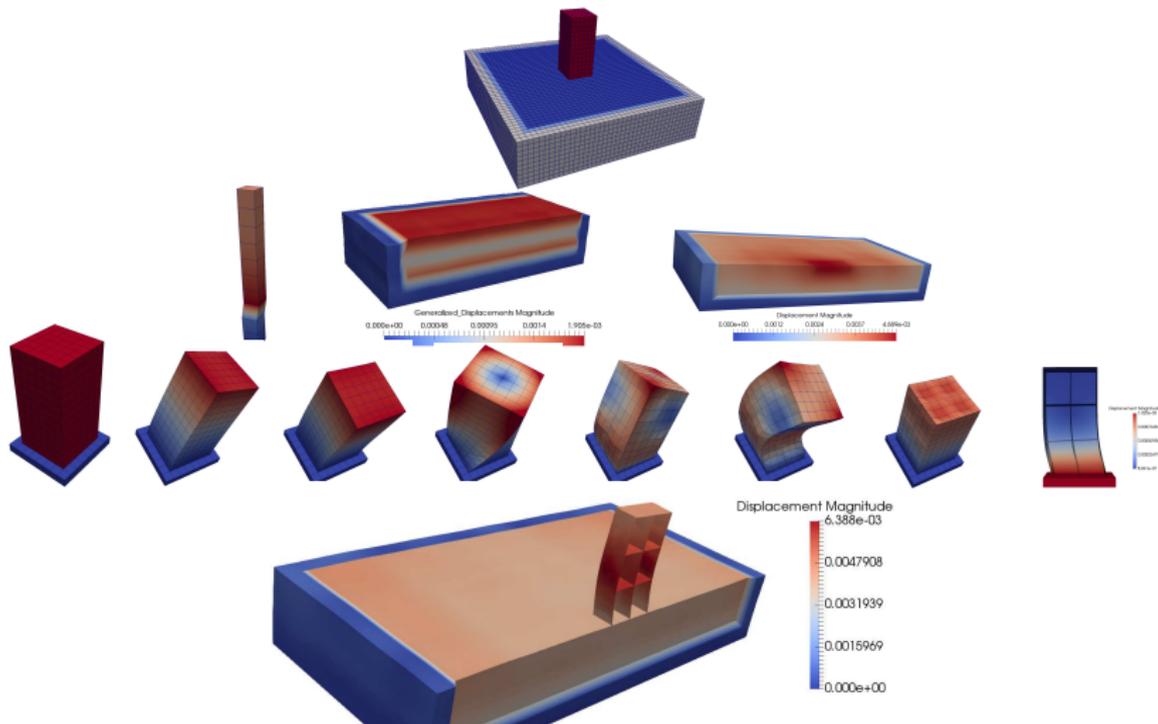
# MS-ESSI / Real-ESSI Simulation Features

- ▶ 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
- ▶ All Simulation Features are listed at <http://ms-essi.info/>

# MS-ESSI / Real-ESSI Model Development

- ▶ Pre-Processing, gmsh/gmESSI, translation (SASSI...)
- ▶ Choose level of sophistication, reduce modeling uncertainty
- ▶ Model developed in phases
- ▶ Verify model components
- ▶ Build confidence in inelastic modeling

# MS-ESSI / Real-ESSI Modeling Phases



# MS-ESSI / Real-ESSI Results Post Processing

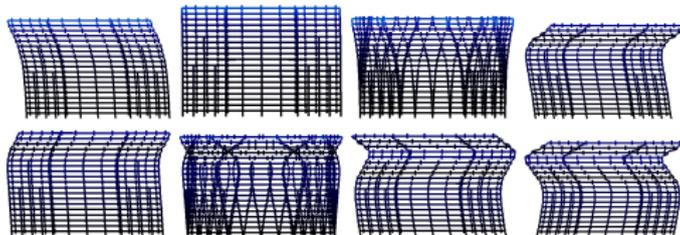
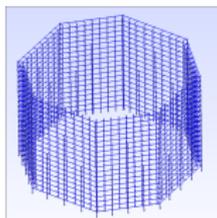
- ▶ All output is saved (stress, strain, displacements, energy...)
- ▶ Time histories, scripts to plot or extract in preferred format
- ▶ 3D visualization, Paraview with pvESSI plugin

# MS-ESSI / Real-ESSI Verification

- ▶ Implementation verification
- ▶ Solution verification for each component
  - ▶ Finite elements
  - ▶ Constitutive algorithms
  - ▶ Solution advancement, static and dynamic
- ▶ Error quantification for ranges of modeling parameters
- ▶ Automatic verification, a 13 hour process on multiple CPUs

# MS-ESSI / Real-ESSI Validation

- ▶ Validation partially done, need for high quality data
- ▶ Validation, UNR soil box tests in the near future
  - ▶ Soil testing, range of strains, confinements, stress paths
  - ▶ Contact testing, axial, shear, soil-concrete, formed, poured
  - ▶ Wave propagation through soil, equivalent elastic and inelastic, 1C and 2C, dilatancy influence
  - ▶ Inelastic structural behavior for beams, walls, plates, shells, use of already published high quality test data
  - ▶ ESSI tests for a complete simplified SSI systems



# MS-ESSI / Real-ESSI Training and Education

- ▶ Short Courses:
  - ▶ Online short course this fall/winter
  - ▶ Professional practice
  - ▶ Examples available in lecture notes, and documentation
  - ▶ MS-ESSI system, with examples on Amazon Web Services (AWS)
- ▶ Full lecture notes (2600+ pages) available online
- ▶ Up to date information on Real-ESSI/MS-ESSI at:  
<http://ms-essi.info/>      and      <http://real-essi.info/>

# MS-ESSI / 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

# MS-ESSI / 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

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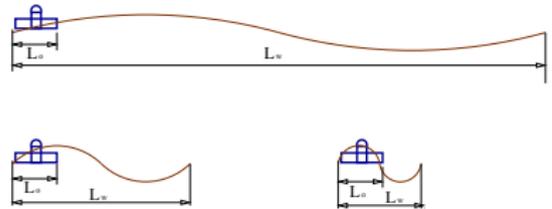
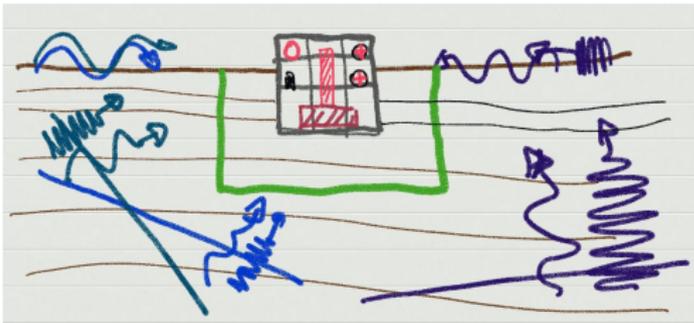
MS-ESSI/Real-ESSI Simulator System

**Illustrative Examples**

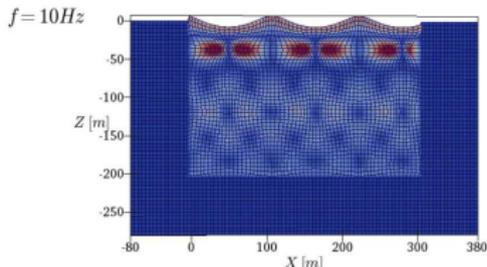
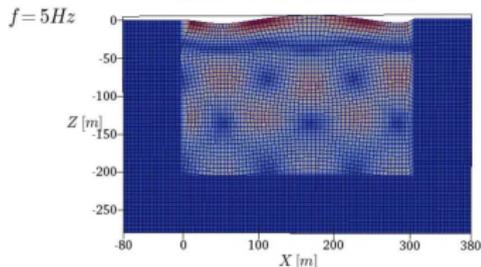
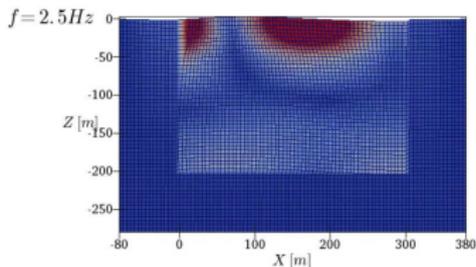
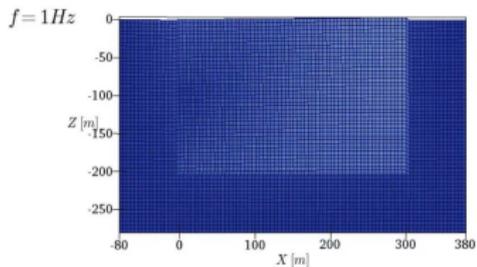
Summary

# Seismic Motions

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

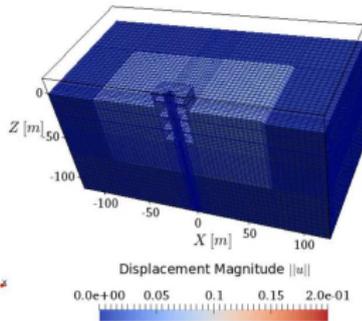
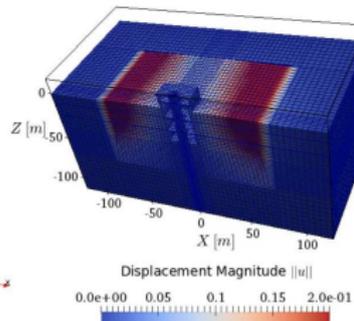
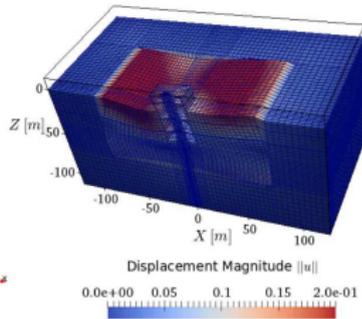
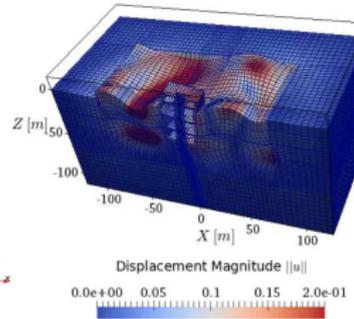


## Illustrative Examples

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

(MP4)

## Illustrative Examples

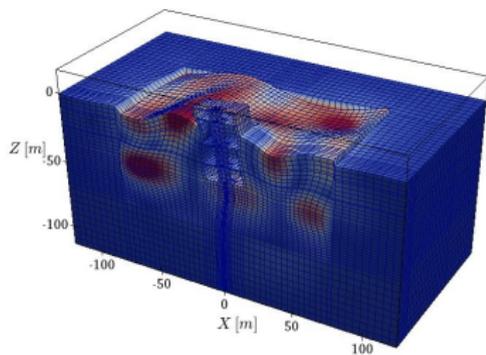
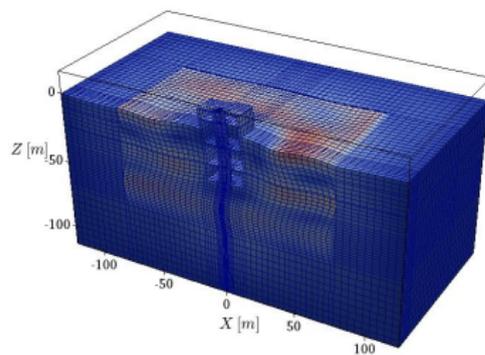
SMR ESSI, Variation in Input Frequency,  $\theta = 60^\circ$  $f = 1\text{Hz}$  $f = 2.5\text{Hz}$  $f = 5\text{Hz}$  $f = 10\text{Hz}$ 

(MP4)

## Illustrative Examples

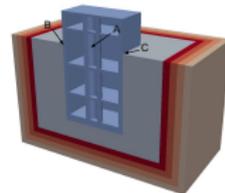
SMR ESSI, 3C vs  $3 \times 1C$ 

3C

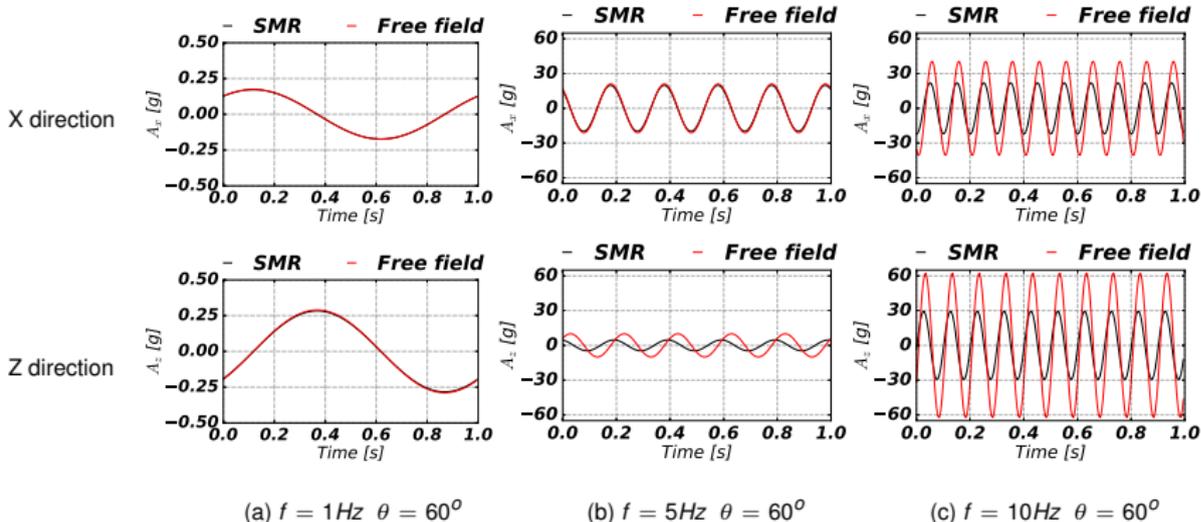
 $3 \times 1C$ 

(OGV)

# Free Field vs ESSI - Different Frequencies



Acceleration response - Surface center point A



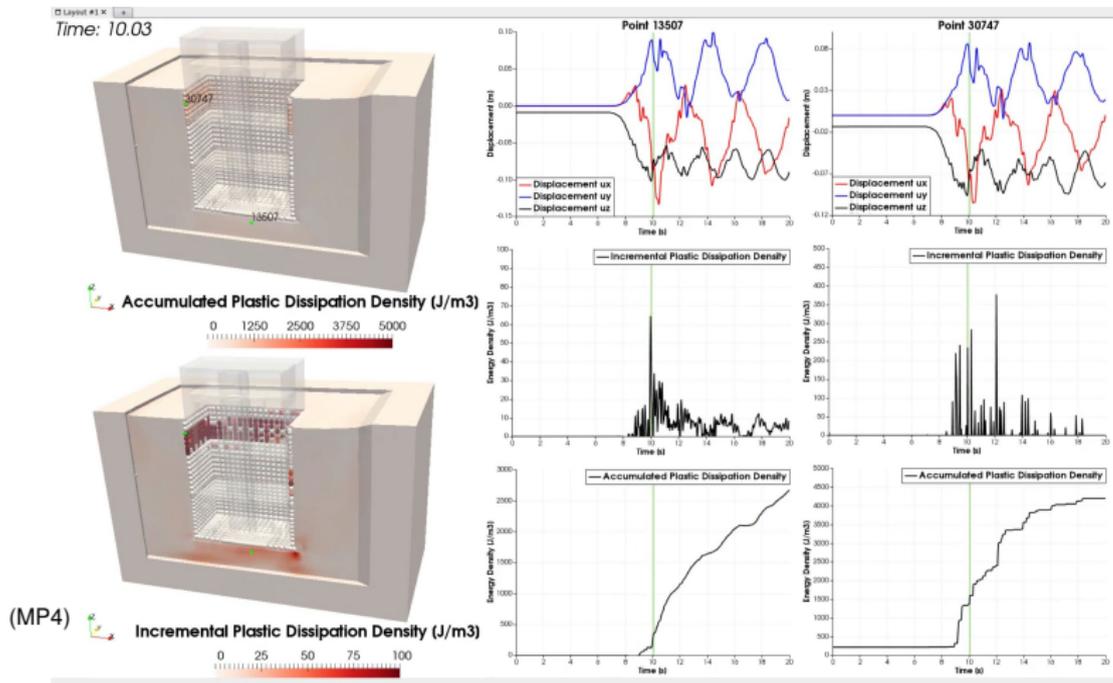
(a)  $f = 1\text{Hz}$   $\theta = 60^\circ$

(b)  $f = 5\text{Hz}$   $\theta = 60^\circ$

(c)  $f = 10\text{Hz}$   $\theta = 60^\circ$

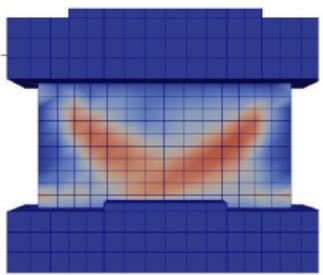
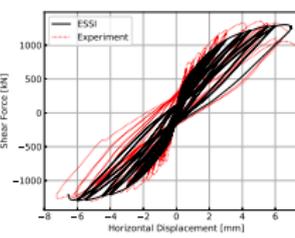
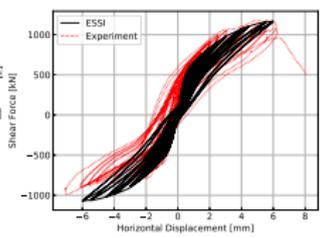
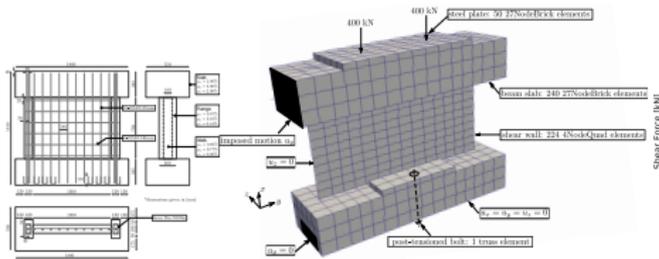
Illustrative Examples

# SMR, Inelastic Response, Energy Dissipation

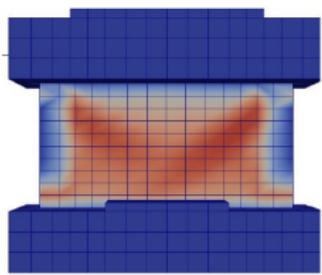


Illustrative Examples

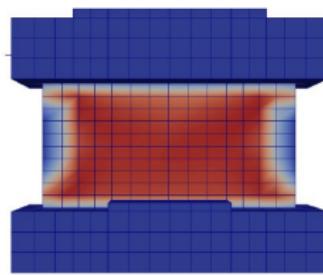
# Wall, Regular and ASR Concrete



$u_y = 1.4 \text{ mm}$

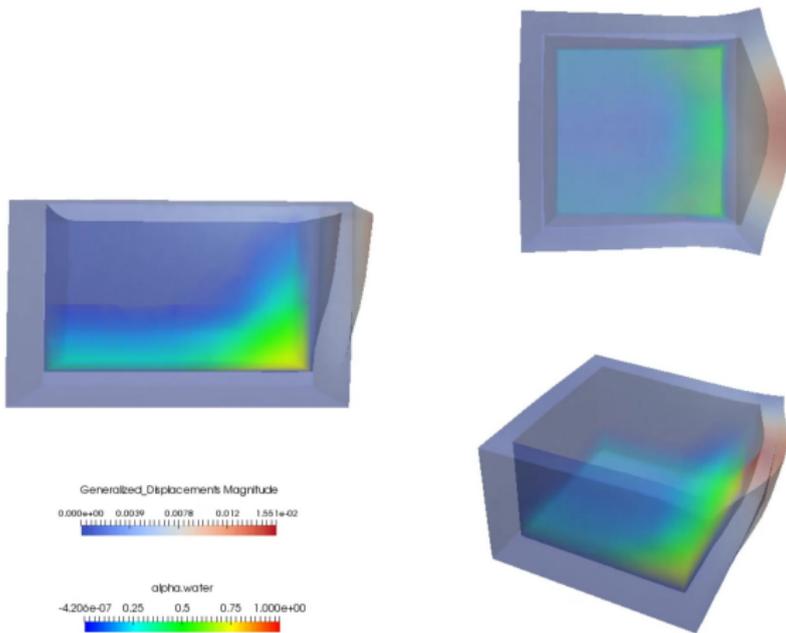


$u_y = 1.8 \text{ mm}$



$u_y = 3.0 \text{ mm}$

# Solid/Structure – Fluid Interaction



(MP4)

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- ▶ Numerical modeling to predict and inform, rather than fit
- ▶ Inelastic/nonlinear analysis done in phases
- ▶ Education and Training is the key!
- ▶ Real-ESSI/MS-ESSI Simulator System:  
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<http://real-essi.info/>