Nonlinear Earthquake Soil Structure Interaction Analysis for Small Modular Reactors

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Outline

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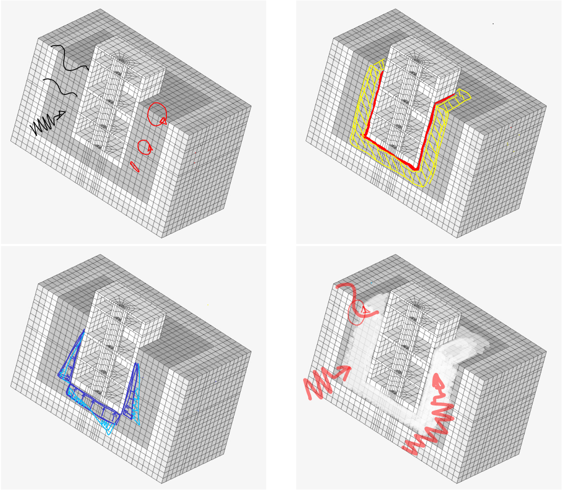
Motivation

- Improve modeling and simulation for Nuclear Facilities
- Develop an expert numerical modeling and simulation tool
- Use of high fidelity numerical models to analyze seismic behavior of soil structure nuclear facilities system
- Reduction of modeling uncertainty, ability to perform high(er) level of sophistication modeling and simulation
- Follow flow of seismic energy in a soil structure system
- Particular issues with SMRs:
  - Seismic motions, body and surface waves
  - Inelastic contact and near field soil zone
  - Underground water, buoyant force
  - uncertain soil, contact...

ESSI Issues for SMRs

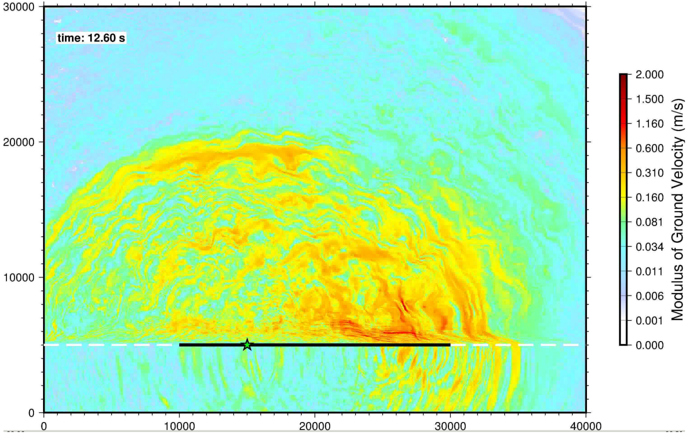


Outline

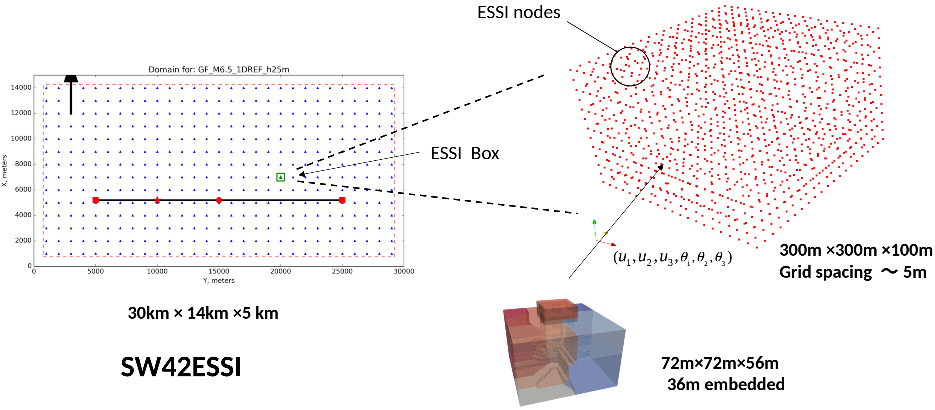
Regional Geophysical Models

- High fidelity free field seismic motions on regional scale
- 3D (6D) and/or $3\times$ 1D and/or 1D motions can also be used
- Knowledge of geology (deep and shallow) needed
- High Performance Computing using SW4 on CORI (LBNL)
- Collaboration with LLNL: Dr. Rodgers, Dr. Pitarka and Dr. Petersson

Example Regional Model (Rodgers et al, LLNL)



Seismic Motions: SW4 to Real ESSI

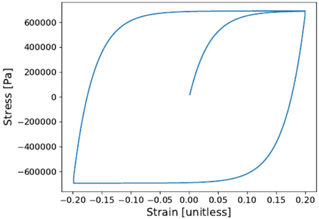


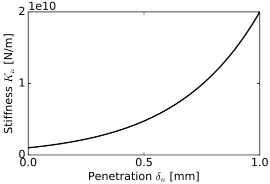
Inelastic Modeling for Components

- Soil 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 and excess pressure (buoyant force)
- Structural inelasticity/damage
  - Nonlinear/inelastic fiber beam
  - Nonlinear/inelastic fiber wall element

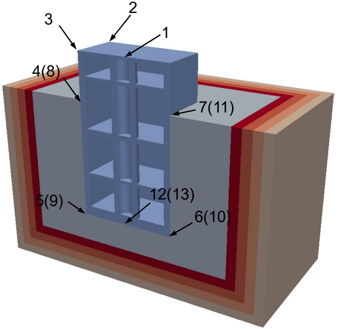
Soil Modeling Parameters

Material parameters	shear wave velocity [m/s]	500
	Young's modulus [GPa]	1.25
	Poisson ratio	0.25
	von Mises radius [kPa]	60
	linear hardening parameter [MPa]	30
	nonlinear hardening parameter	25
Contact parameters	initial normal stiffness [N/m]	1e9
	hardening rate [/m]	1000
	maximum normal stiffness [N/m]	1e12
	tangential stiffness [N/m]	1e7
	normal damping [N/(m/s)]	100
	tangential damping [N/(m/s)]	100
	friction ratio	0.25
Damping parameters	structure layer	5%
	surrounding soil	15%
	DRM layer	20%
	outside layer 1	20%
	outside layer 2	40%
	outside layer 3	60%





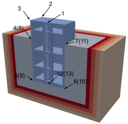
Representative points

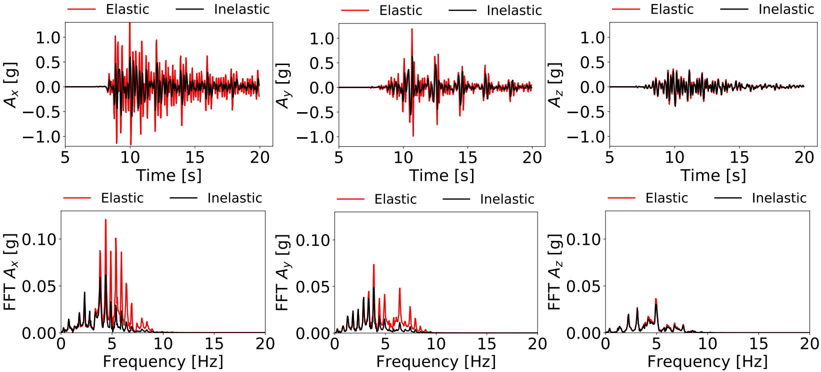


Location of points

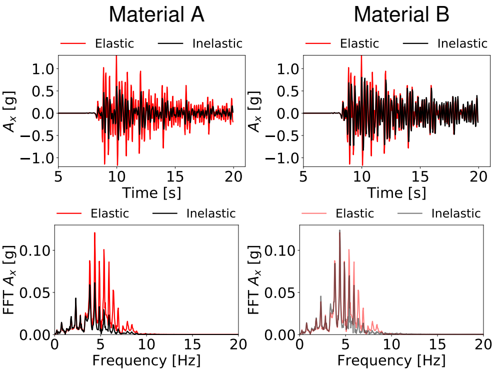
Point ID	X (m)	Y (m)	Z (m)	layer
1	0	0	14	structure
2	15	15	14	structure
3	0	15	14	structure
4	0	15	0	structure
5	0	15	-36	structure
6	0	-15	-36	structure
7	0	-15	0	structure
8	0	15	0	surrounding soil
9	0	15	-36	surrounding soil
10	0	-15	-36	surrounding soil
11	0	-15	0	surrounding soil
12	0	0	-36	structure
13	0	0	-36	surrounding soil

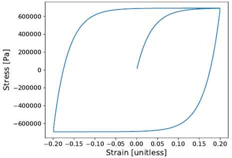
SMR: Inelastic ESSI Effects, Top Center



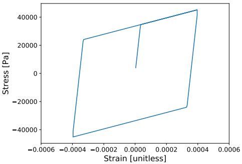


SMR: ESSI Effects, Material Modeling



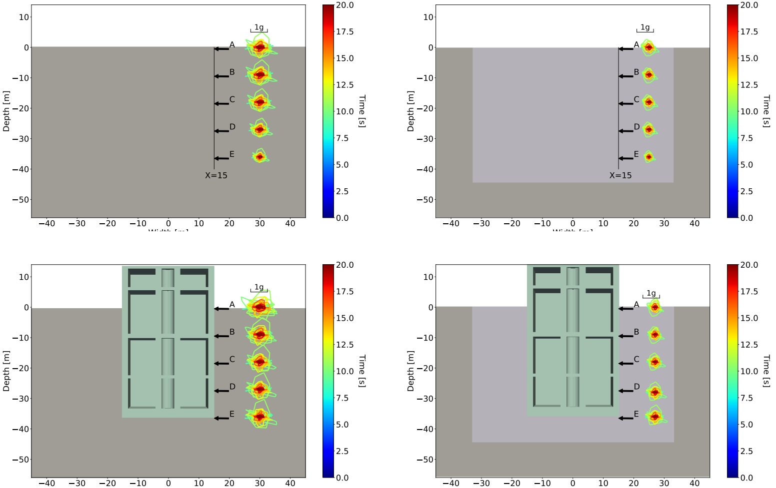


Material A: nonlinear, vM - AF



Material B: Bilinear

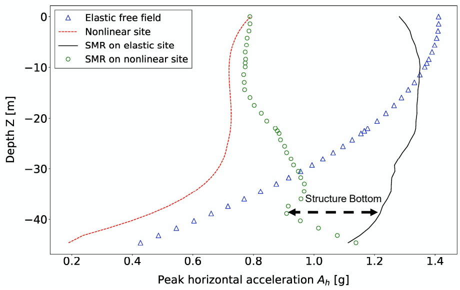
SMR: Accelerations Along Depth

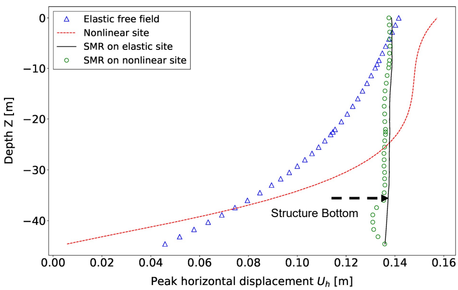


Nonlinear site effects

SSI effects

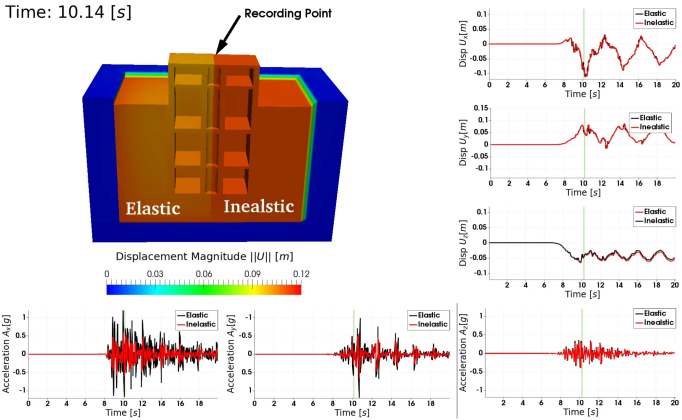
Depth variation - PGA & PGD



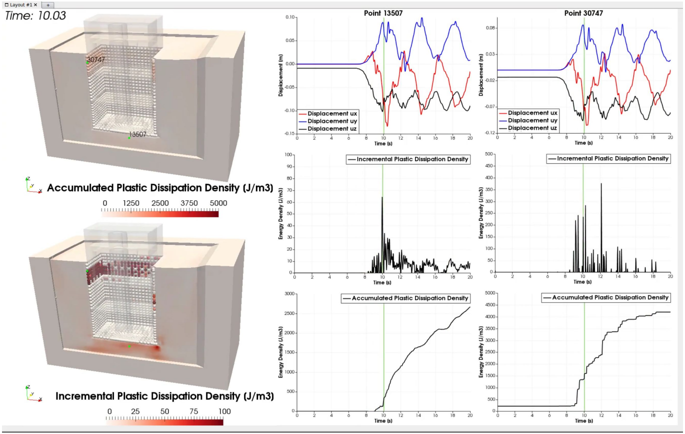


- The PGA & PGD of SSI systems are (very) different from free field motions,
- Material nonlinearity has significant effect on acceleration response.

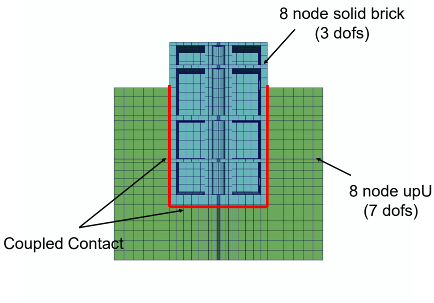
Elastic and Inelastic Response: Differences

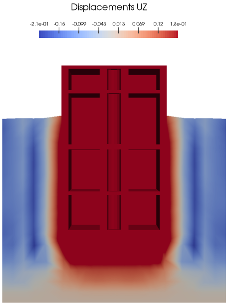


Energy Dissipation for an SMR



Buoyant force simulation





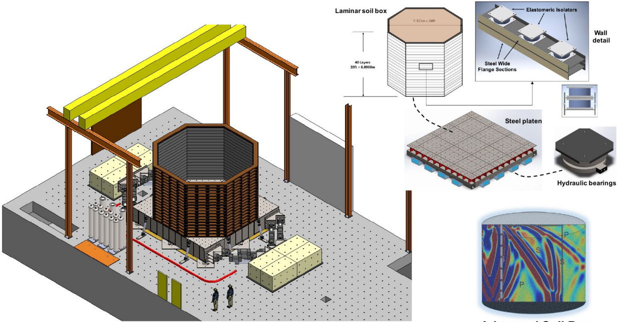
Outline

US-DOE: ESSI Modeling of NPPs/SMRs

The Real ESSI Simulator System (UCD/LBNL)

Modeling from seismic source to NPP (LLNL/UCD/LBNL)

High Quality Validation test (UNR/UCD/LBNL)



Advanced Soil Box Diagnostics
- 3D Tomography

Summary

- Importance of inelastic modeling (soil, contact, structure) for SMR behavior
- Importance of seismic wave fields (3D/6D, 3×1D, 1D) for SMR behavior
- Numerical modeling and simulation used to predict and inform and rather than to (force) fit
- Real ESSI Simulator system http://real-essi.info
- Funding/support from and collaboration with the US-DOE, US-NRC, CNSC-CCSN, US-NSF, UN-IAEA, and Shimizu Corp. is greatly appreciated,
- More on modeling and simulation for SMRs at the: Nonlinear/Inelastic Earthquake Soil Structure Interaction (ESSI) short course, this fall in San Francisco, more info at http://real-essi.info