Realistic Modeling and Simulation of Earthquake Soil Structure Interaction

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Outline

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Motivation

- Improving seismic design for nuclear installations
- Development of an expert numerical modeling and simulation tool
- Realistic Earthquake Soil Structure Interaction (Real ESSI) Simulator
- Use of high fidelity numerical models in analyzing seismic behavior of soil structure systems
- Accurate following of the flow of seismic energy in the soil structure system
- Direct, in space and time, seismic energy flow in and out of the soil structure system

Hypothesis

- Interplay of the Earthquake, Soil/Rock and Structure in time domain, plays a major role in successes and failures
- Timing and spatial location of energy dissipation determines location and amount of damage
- If timing and spatial location of the energy dissipation can be controlled (directed), we could optimize soil structure system for
  - Safety and
  - Economy

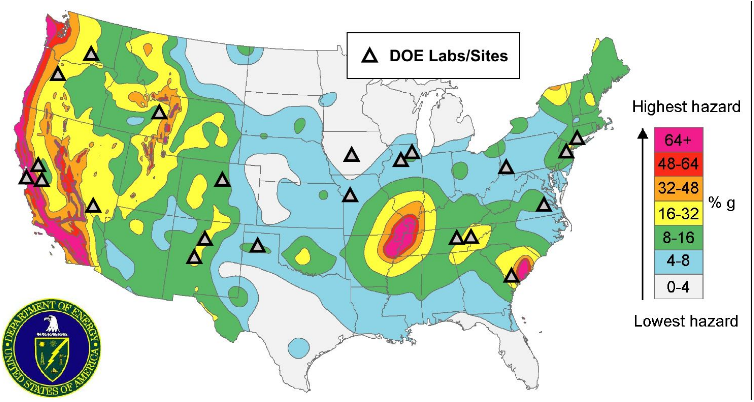
Flow of Seismic Energy Dissipation in SSI System

- Mechanical dissipation outside of SSI domain:
  - reflected wave radiation
  - SSI system oscillation radiation
- Mechanical dissipation/conversion inside SSI domain:
  - plasticity of soil subdomain
  - plasticity/damage of the parts of structure/foundation
  - viscous coupling of porous solid with pore fluid (air, water)
  - viscous coupling of structure/foundation with fluids
- Numerical energy dissipation/production

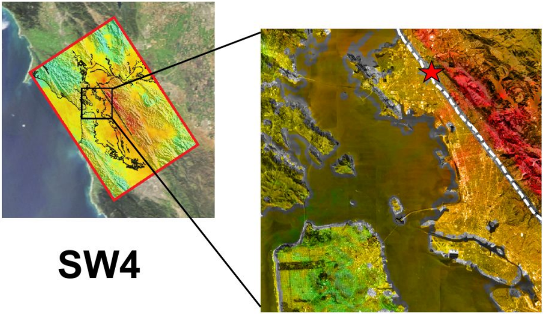
Predictive Capabilities

- 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
- Predictive capabilities with low Kolmogorov Complexity
- Goal: Predict and Inform and not (force) Fit

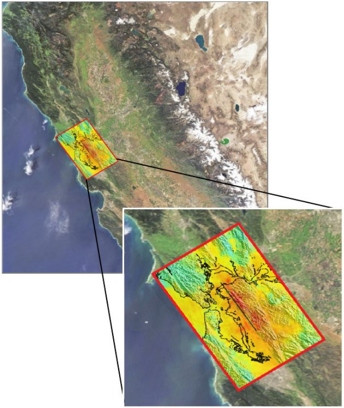
US DOE Motivation

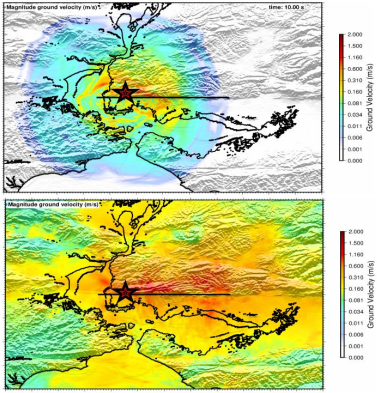


Regional Scale Hazard and Risk Simulations

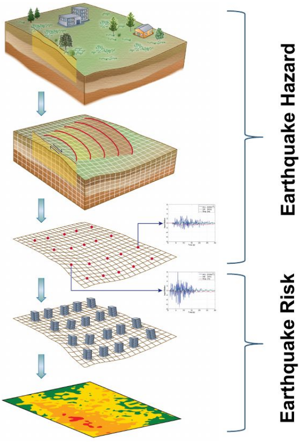


Regional Scale Scenario Earthquakes

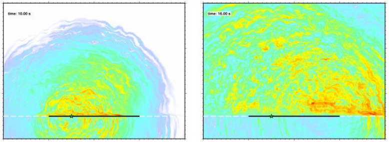




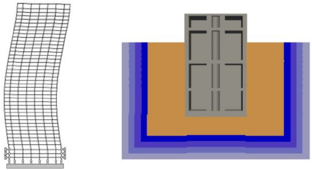
Coupling of Earthquake Hazard and Risk



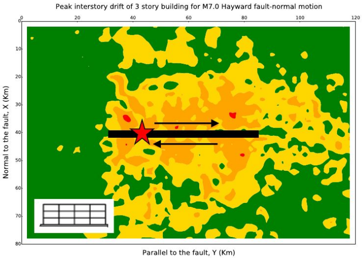
SW4 – 4th order finite difference geophysics code for wave propagation

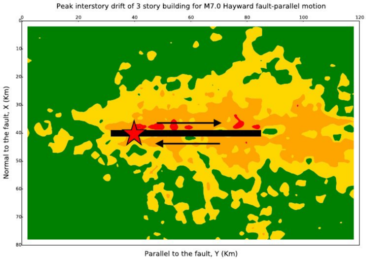


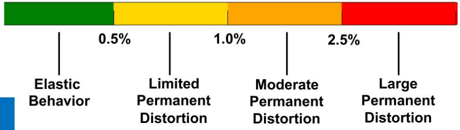
NEVADA & ESSI – finite deformation, inelastic Finite element codes for structures and soils



Regional Scale Model Coupled with ESSI

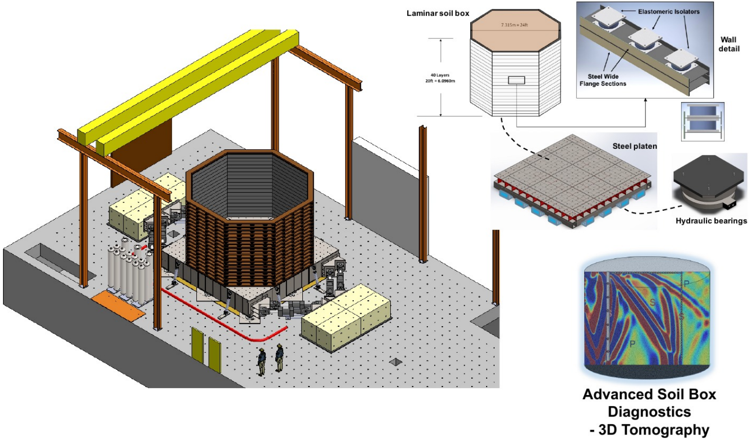




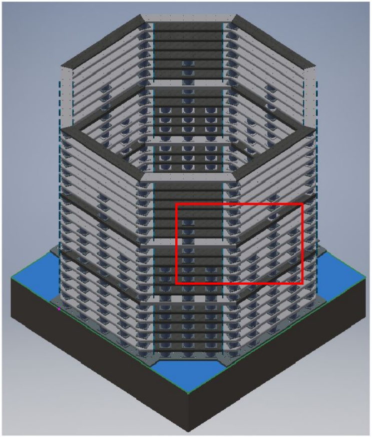


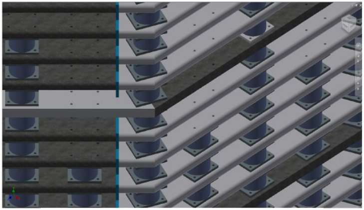
DOE standard 1020 limit states

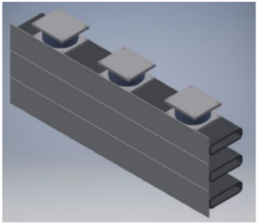
Validation Testing: New Facility at UNR



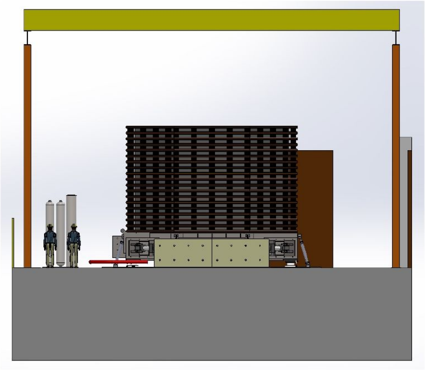
Unique Shear Box Design



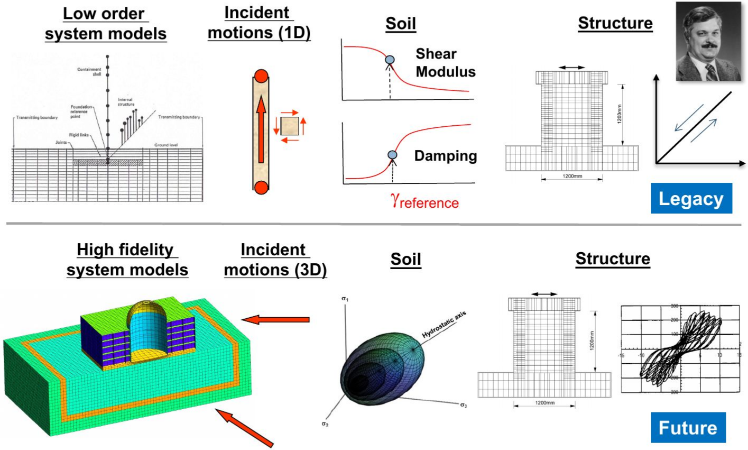




Components at UNR



Progress in Modeling and Simulation



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 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
  - Pre-processor (gmsh/gmESSI, SASSI2ESSI)
  - Simulator (local, remote/cloud)
  - Post-Processor (Paraview, Python, Matlab)
- Real ESSI System availability:
  - Public: Amazon Web Services (AWS, economical!)
  - Government Agencies and National Labs: Local/Remote
- Real ESSI documentation at: `http://real-essi.us/`
- Real ESSI Education and Training

Real ESSI Simulator System, Education and Training

- Special training and education for USA Government Agencies and National Labs
  - US-NRC
  - LBNL (all)
  - LANL
- International
  - UN-IAEA TECDOC
  - Short course at Tongji University in Shanghai, China
  - Visitors from Japan
- Professional practice: Real ESSI Short Course

Real ESSI Short Course, Professional Practice

December 12-14, 2017, San Francisco

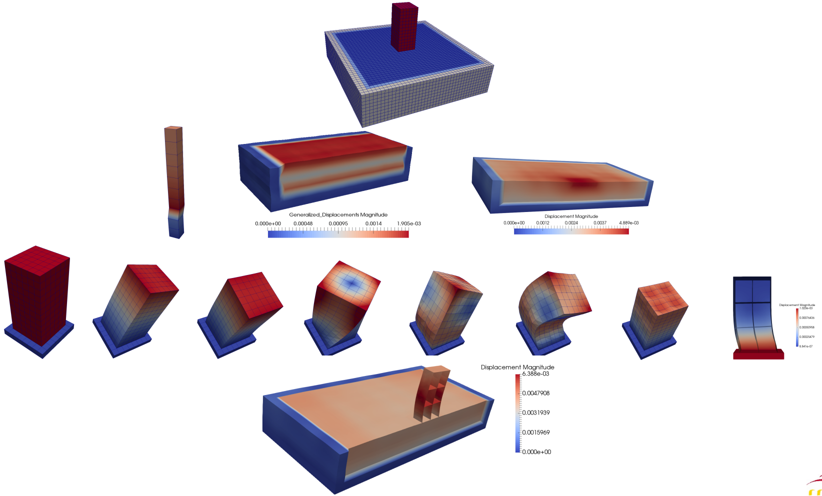
- Day 1: Intro, Setup (AWS), Phased Modeling, ESSI
- Day 2: Ground Motions, 1D, 3×1D, 3D, ESSI
- Day 3: Inelastic Modeling, Soil, Contact, Structures, ESSI

Outline

Modeling Sophistication Levels, Phased Modeling

- Level of sophistication chosen to reduce modeling uncertainty
- Verify code, solutions, methods, elements, material models
- Verify model components
- Model developed in phases (components) and verified
- Gradually building confidence in inelastic modeling
- Use such developed models to predict and inform, rather than force fit

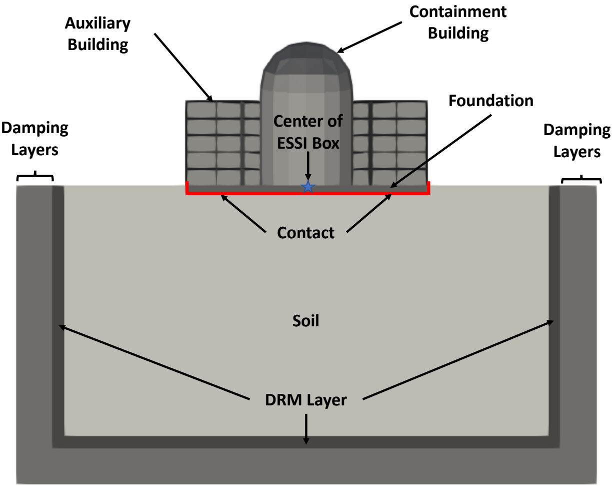
Model Verification and Modeling Phases



Inelastic Modeling for NPP and 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 1D fiber beam
  - Nonlinear/inelastic 2D wall element

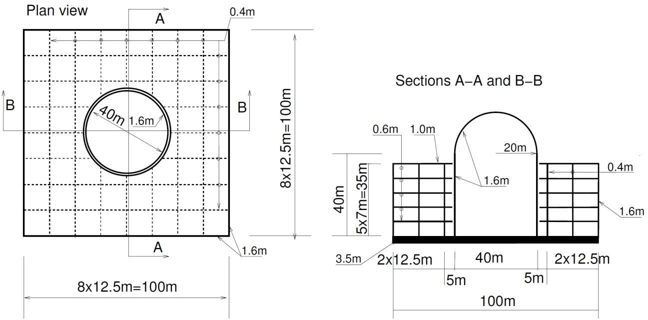
NPP Model


Auxiliary Building
Containment Building
Foundation
Damping Layers
Center of ESSI Box
Damping Layers
Contact
Soil
DRM Layer

Structure Model

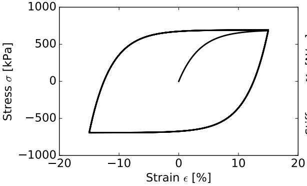
The nuclear power plant structure comprise of

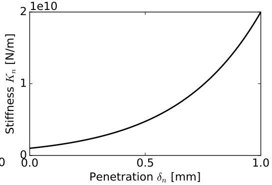
- Auxiliary building, $f_1^{aux} = 8Hz$
- Containment/Shield building, $f_1^{cont} = 4Hz$
- Concrete raft foundation: $3.5m$ thick



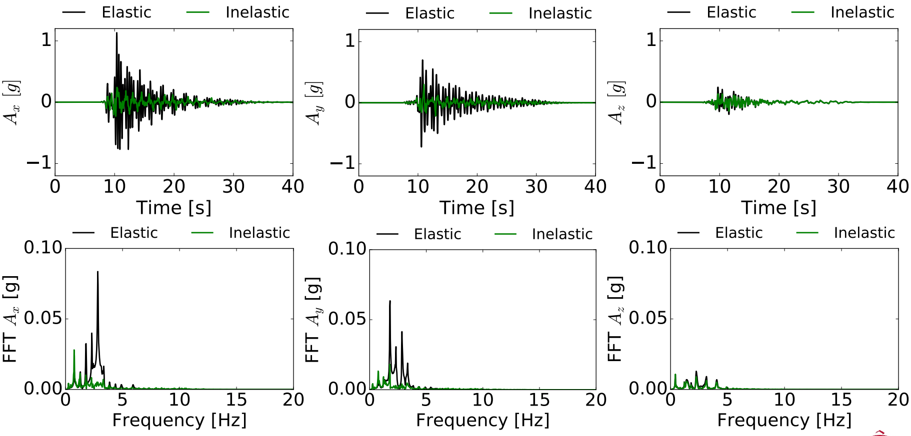
Inelastic Soil and Inelastic Contact

- 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

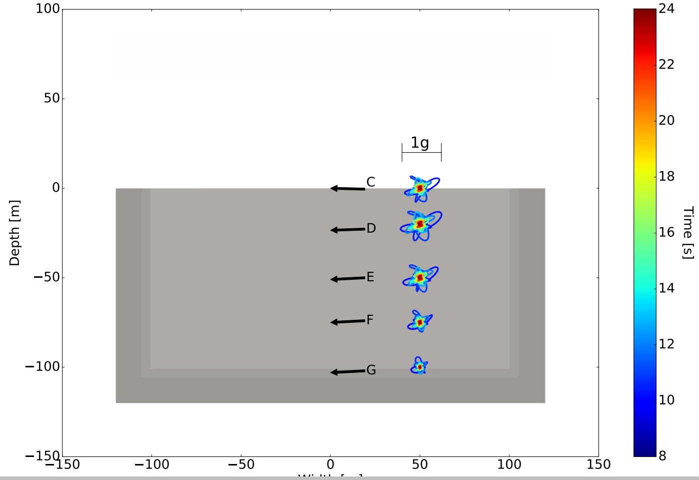




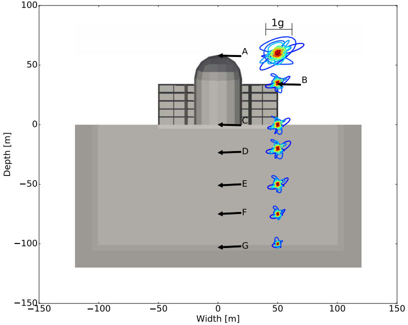
Acc. Response, Top of Containment Building

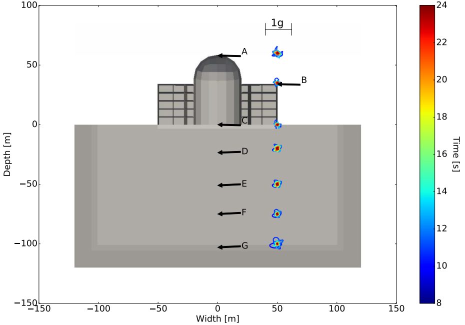


Acceleration Traces, Free Field

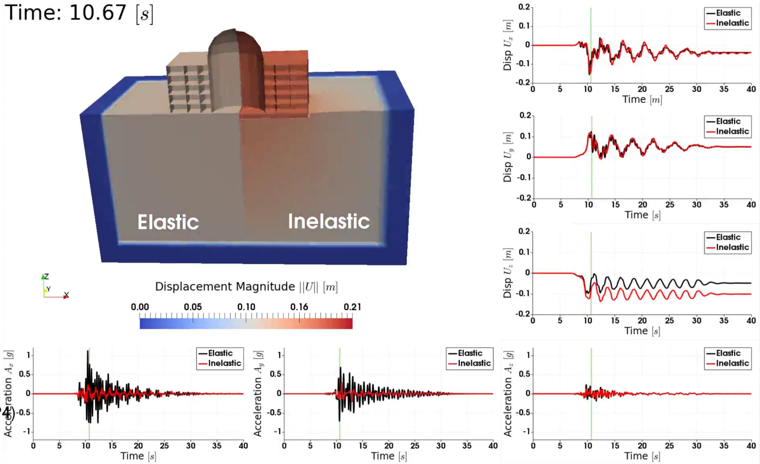


Acceleration Traces, Elastic vs Inelastic





Elastic and Inelastic Response: Differences



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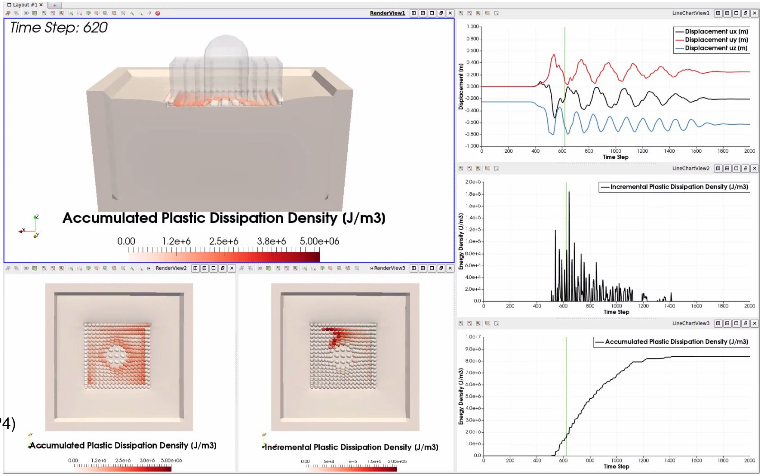
Energy Dissipation in Large-Scale Model (NPP)



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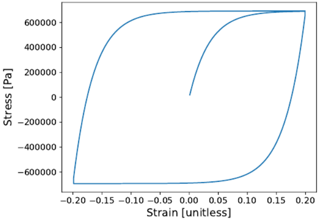
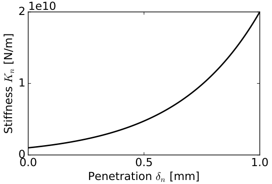
  - Nonlinear/inelastic 2D wall element

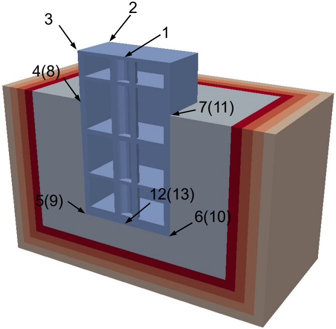
Soil Modeling Parameters

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%





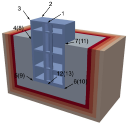
Representative points

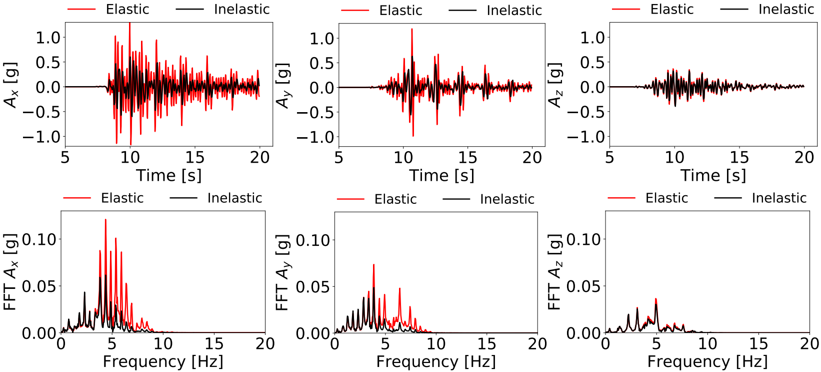


Location of points

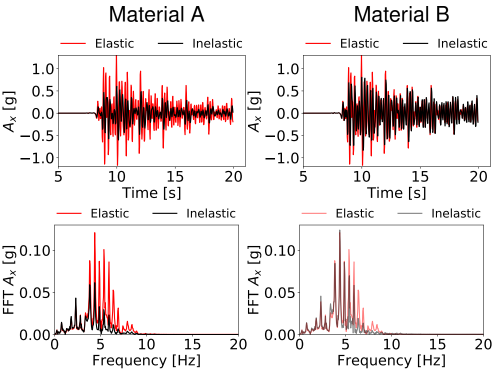
Point ID	X (m)	Y (m)	Z (m)	layer
1	0	0	14	structure
2	15	15	14	structure
3	0	15	14	structure
4	0	15	0	structure
5	0	15	-36	structure
6	0	-15	-36	structure
7	0	-15	0	structure
8	0	15	0	surrounding soil
9	0	15	-36	surrounding soil
10	0	-15	-36	surrounding soil
11	0	-15	0	surrounding soil
12	0	0	-36	structure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

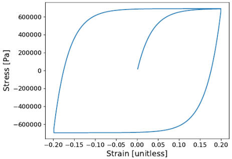
SMR: Inelastic ESSI Effects, Top Center



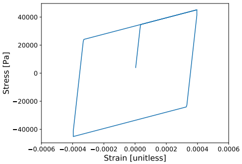


SMR: ESSI Effects, Material Modeling



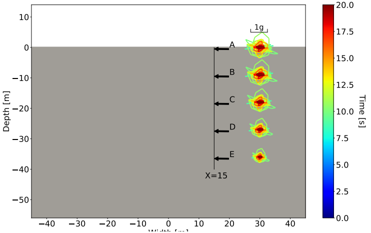


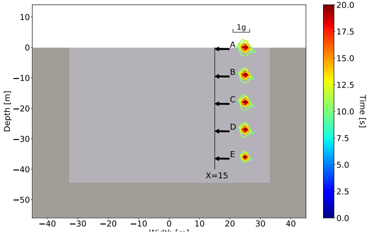
Material A: nonlinear, vM - AF



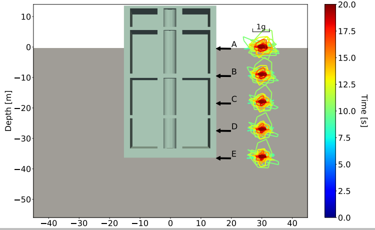
Material B: Bilinear

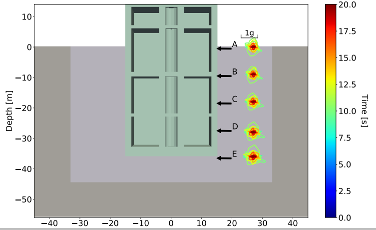
SMR: Accelerations Along Depth





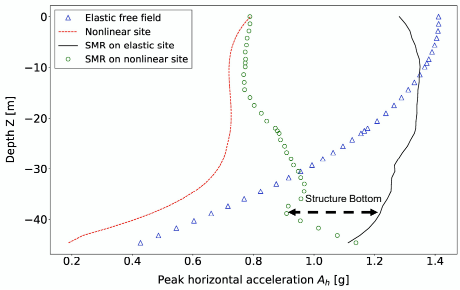
Nonlinear site effects

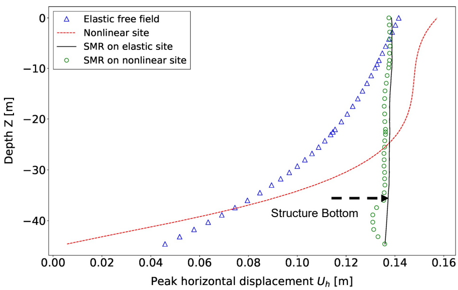




SSI effects

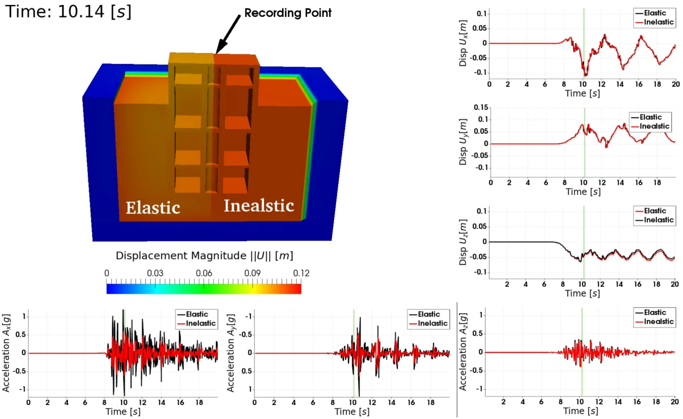
Depth variation - PGA & PGD





- 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



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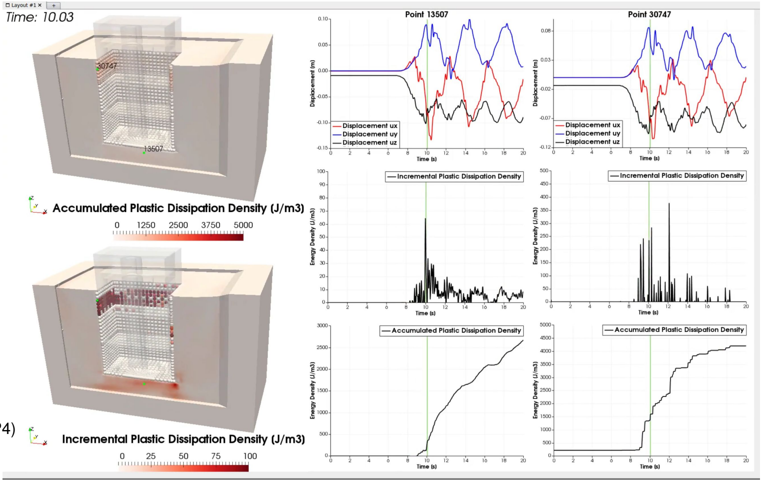
Energy Dissipation for an SMR



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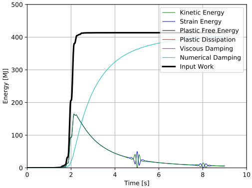
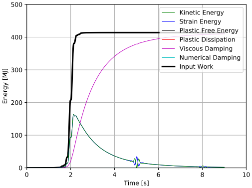
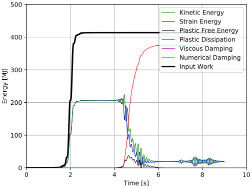
Energy Dissipation Control Mechanisms



Numerical

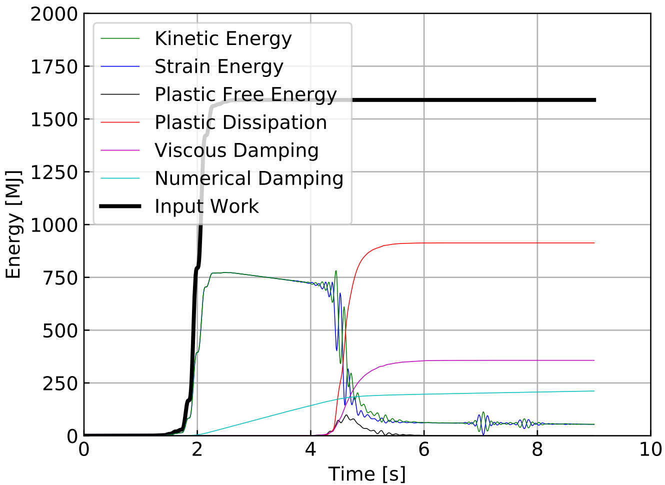


Viscous

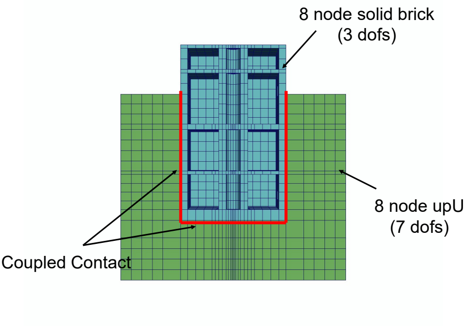


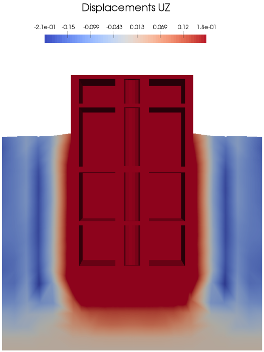
Plasticity

Energy Dissipation Control



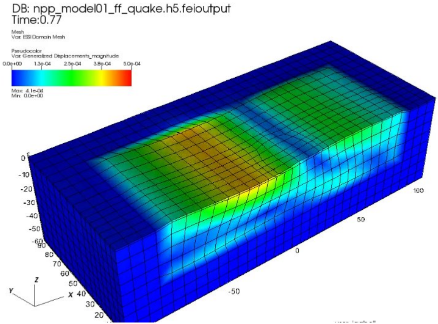
Buoyant Force Simulation





1D vs 3D Seismic Motions

- One component of motions (1D) from 3D
- Excellent fit



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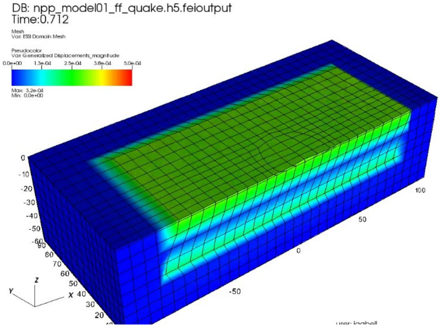

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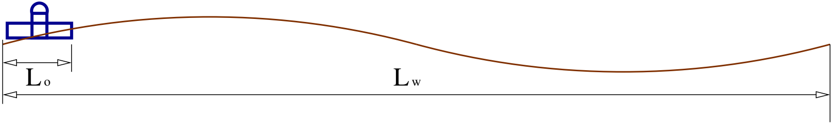
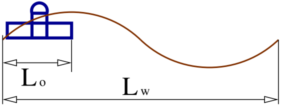
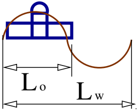
1D vs 3×1D vs 3D Seismic Motions

- 1D is required by the code
- 3×1D can be used depending on frequency/wave length of interest,
- 3D is more realistic, however it is challenging to define motions in full 3D

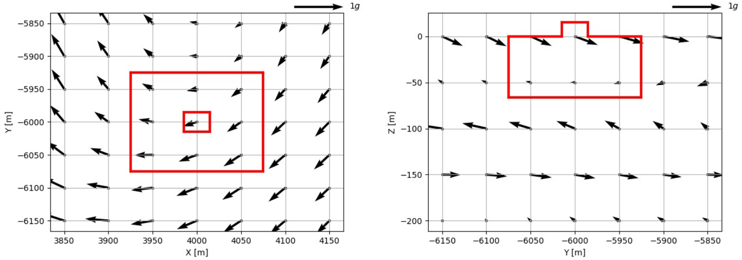
When to use 3D and/or 3×1D



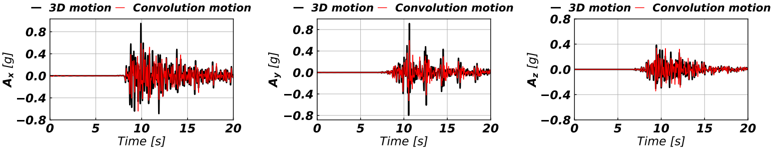




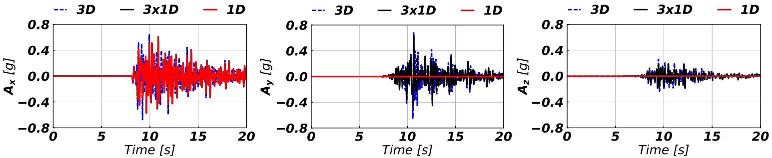
1D vs 3D, Bottom Control Point



Free Field 3D vs 1D Convolution From Base Point



3D vs 3×1D vs 1D, Top of SMR



Summary

- Numerical modeling to predict and inform, rather than fit
- Change of demand due to inelastic effects
  - Reduction of dynamic motions
  - Increase in deformations
- Sophisticated inelastic/nonlinear modeling and simulations need to be done carefully and in phases
- Education and Training is the key!
- `http://real-essi.us/`