Modeling and Simulation of Earthquakes, and Soils, and Structures and their Interaction using Real ESSI Simulator System

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Outline

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Motivation

- Improve modeling and simulation for infrastructure objects
- Use of high fidelity numerical models to analyze behavior of soil structure systems
- Reduction of modeling uncertainty, ability to perform high(er) level of sophistication modeling and simulation
- Accurately follow the flow of input and dissipation of energy in a soil structure system
- Development of an expert, rational physics based, system for modeling and simulation

Hypothesis

- Interplay dynamic characteristics of the Dynamic Forcing / Earthquake, Soil/Rock and Structure in time domain, plays a decisive 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

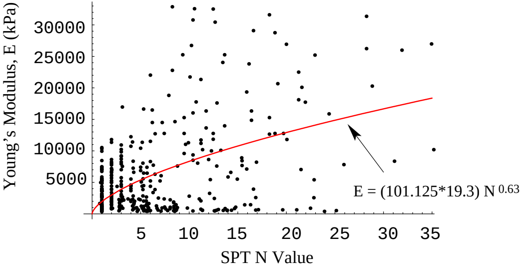
Predictive Capabilities

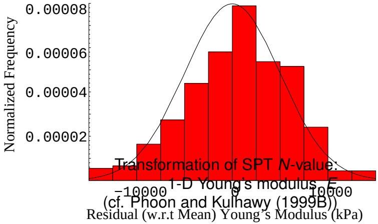
- Prediction under Uncertainty: use of computational model to predict the state of SSI system under conditions for which the computational model has not been validated.
- Verification provides evidence that the model is solved correctly. Mathematics issue.
- Validation provides evidence that the correct 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

Modeling Uncertainty

- Simplified modeling: Features (important ?) are neglected (6D ground motions, inelasticity)
- Modeling Uncertainty: unrealistic and unnecessary modeling simplifications
- Modeling simplifications are justifiable if one or two level higher sophistication model shows that features being simplified out are not important

Parametric Uncertainty: Material Stiffness





Transformation of SPT *N*-value: 1-D Young's modulus, *E* (cf. Phoon and Kulhawy (1999B))

Realistic ESSI Modeling Uncertainties

- Seismic Motions: 6D, inclined, body and surface waves (translations, rotations); Incoherency
- Inelastic material: soil, rock, concrete, steel; Contacts, foundation–soil, dry, saturated slip–gap; Nonlinear buoyant forces; Isolators, Dissipators
- Uncertain loading and material

Outline

Real ESSI Simulator System

The Real ESSI, (**Real**istic modeling and simulation of **E**arthquakes, and **S**oils, and **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, FEMAP2ESSI, ESSI2FEMAP)
  - Simulator (local, remote/cloud)
  - Post-Processor (Paraview, Python, Matlab)
- Real ESSI System availability:
  - Professional Practice and Educational Institutions: Amazon Web Services (AWS, economical!)
  - Government Agencies, National Labs and some Companies: Local/Remote
- Real ESSI Education and Training
- System description and documentation at `http://real-essi.us/`

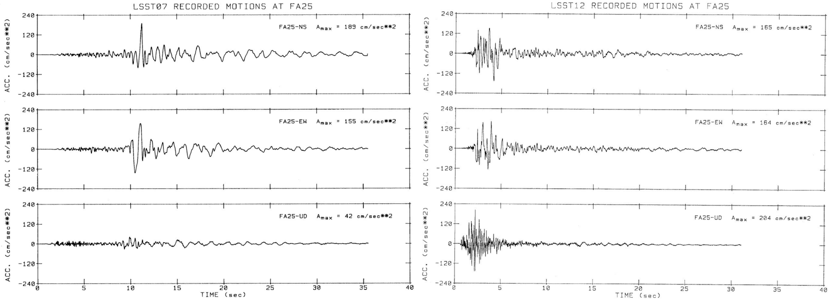
Quality Assurance

- Full verification suit for each element, model, algorithm
- Validation available, however still looking for high quality test data
- Certification in progress for NQA-1 and ISO-90003-2014

Outline

3D (6D) Seismic Motions

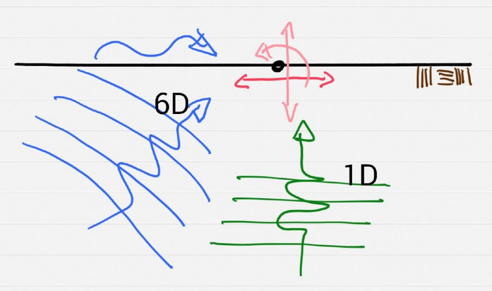
- All (most) measured motions are full 3D (6D)
- One example of an almost 2D motion (LSST07, LSST12)



- 1D (?): M 6.9 San Pablo, Guatemala EQ, 14Jun2017

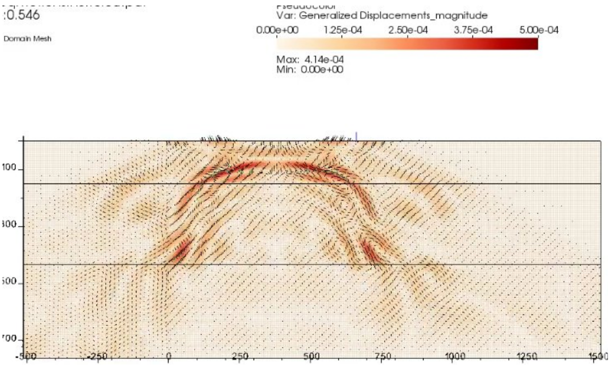
Nuclear Power Plants: 6D or 1D Seismic Motions

- Assume that a full 6D (3D) motions at the surface are only recorded in one horizontal direction
- From such recorded motions one can develop a vertically propagating shear wave in 1D
- Apply such vertically propagating shear wave to the same soil-structure system



Realistic Ground Motions

- Free field seismic motion models



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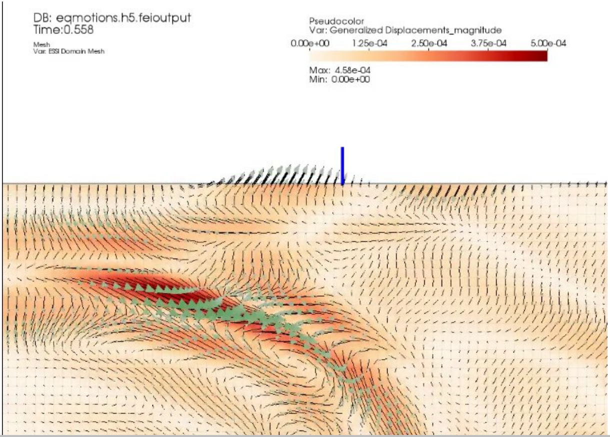
Development of Realistic Motions

- Sources will send both P and S waves



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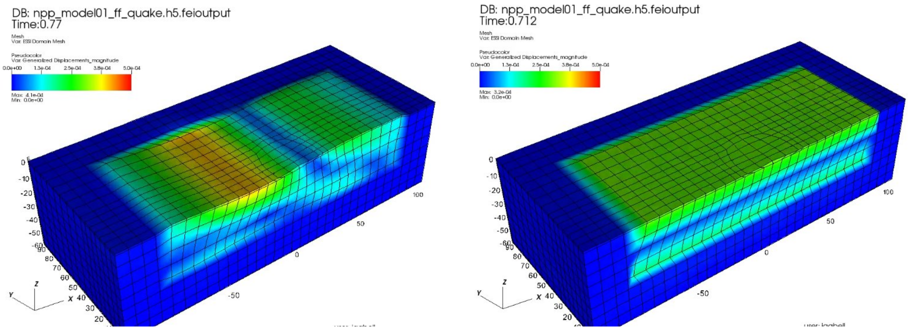
Realistic Earthquake Motions, 6D vs 1D

- One component of motions in 1D from 3D, excellent fit



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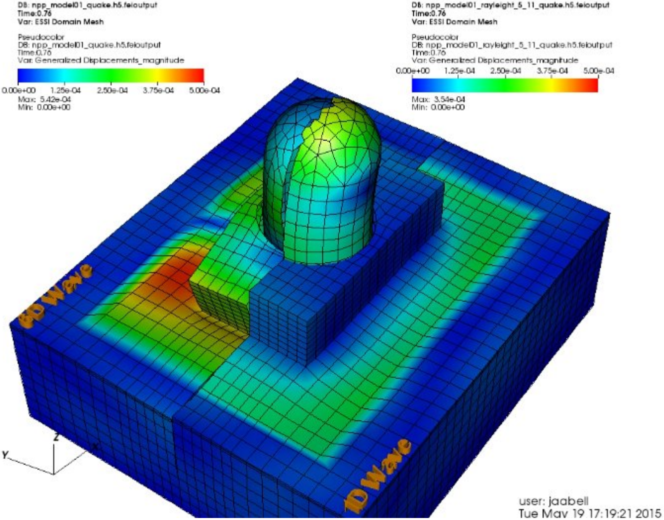
6D vs 1D NPP ESSI Response Comparison



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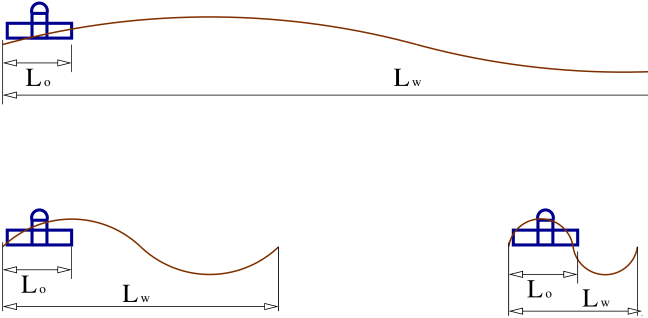
1D vs 3×1D vs 3D Seismic Motions

- 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

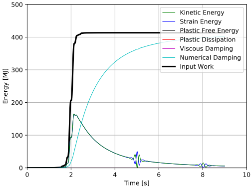


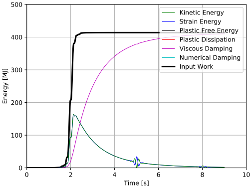
Outline

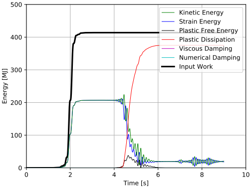
Energy Input and Dissipation

- Energy input, dynamic forcing
- Mechanical dissipation outside SSI domain:
  - SSI system oscillation radiation
  - Reflected wave radiation
- Mechanical dissipation/conversion inside SSI domain:
  - Inelasticity of soil and contact zone
  - Inelasticity/damage of structure and foundation
  - Viscous coupling of porous solid and pore fluids (soil)
  - Viscous coupling of structures with fluids
- Numerical energy dissipation/production

Energy Dissipation Control Mechanisms

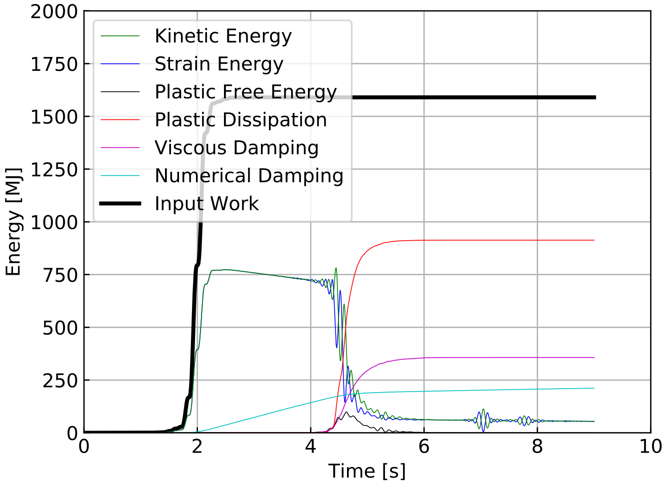






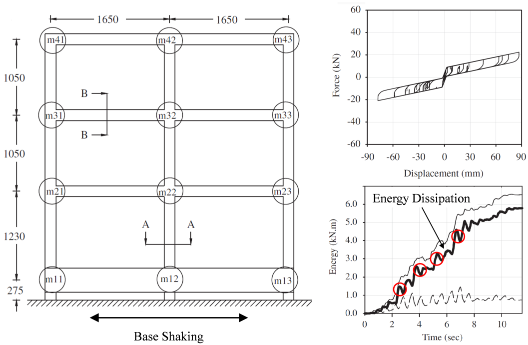
Numerical | Viscous | Plasticity

Energy Dissipation Control



Incremental Plastic Work: $dW_p = \sigma_{ij} \, d\epsilon_{ij}^{pl}$

- Negative incremental energy dissipation
- Plastic work is NOT plastic dissipation



From a paper on *Soil Dynamics and Earthquake Engineering* (2011)

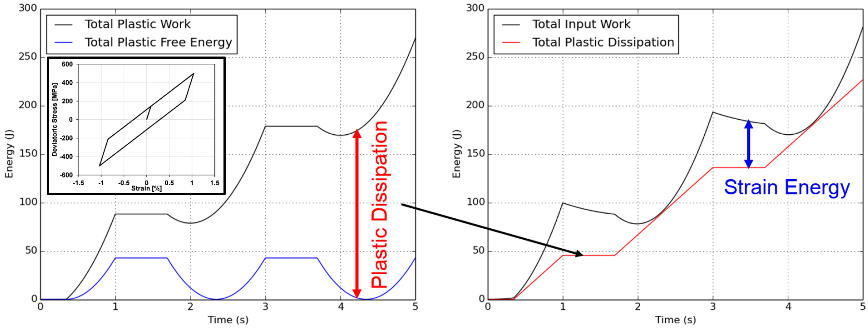
Negative Incremental Energy Dissipation!

- Direct violation of the second law of thermodynamics
- 600 papers since 1990 (!?!) repeat this error
- Important form of energy missing: Plastic Free Energy
- First described by Taylor and Quinney in 1925 and then 1934!
- Plastic Work vs. Plastic Energy Dissipation

Energy Dissipation on Material Level

Single elastic-plastic element under cyclic shear loading

- Difference between plastic work and dissipation
- Plastic work can decrease, dissipation always increases

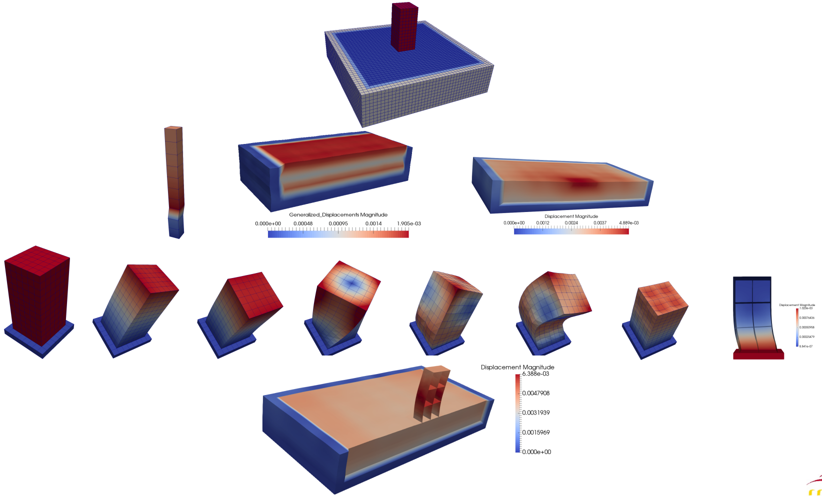


Outline

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

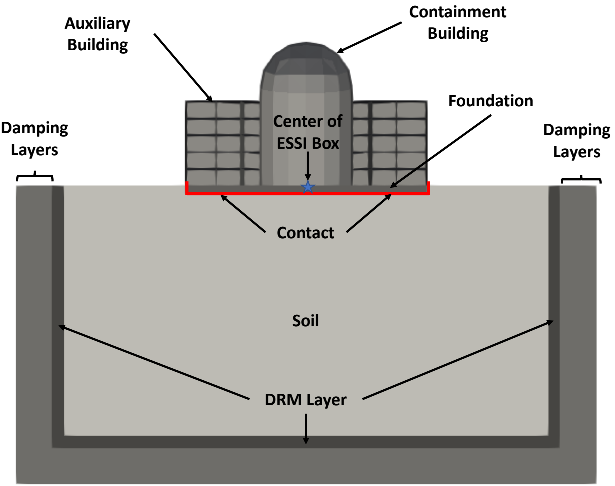
Model Verification and Modeling Phases



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

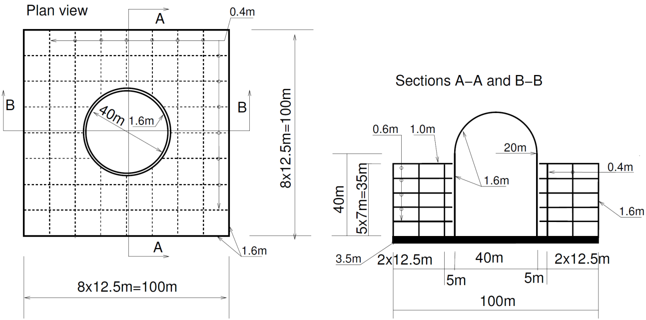
NPP Model


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

Structure Model

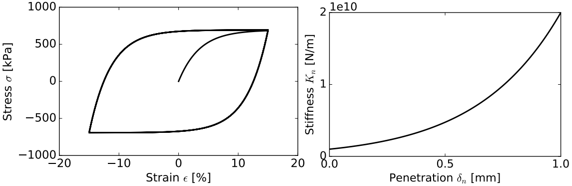
The nuclear power plant structure comprise of

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

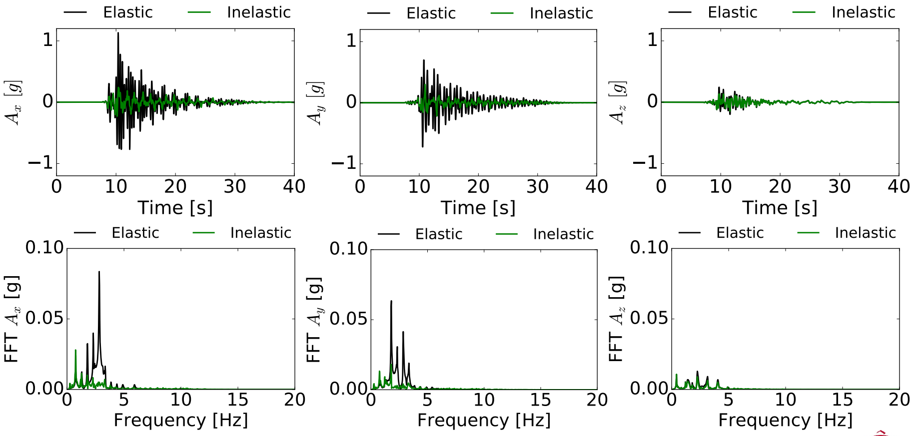


Inelastic Soil and Inelastic Contact

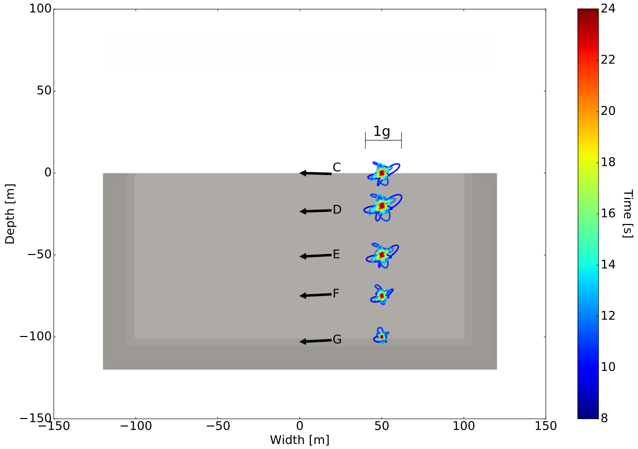
- Shear velocity of soil $V_s = 500 m/s$
- Undrained shear strength (Dickenson 1994) $V_s[m/s] = 23(S_u[kPa])^{0.475}$
- For $V_s = 500 m/s$ Undrained Strength $S_u = 650 kPa$ and Young's Modulus of $E = 1.3 GPa$
- von Mises, Armstrong Frederick kinematic hardening ($S_u = 650 kPa$ at $\gamma = 0.01\%$;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



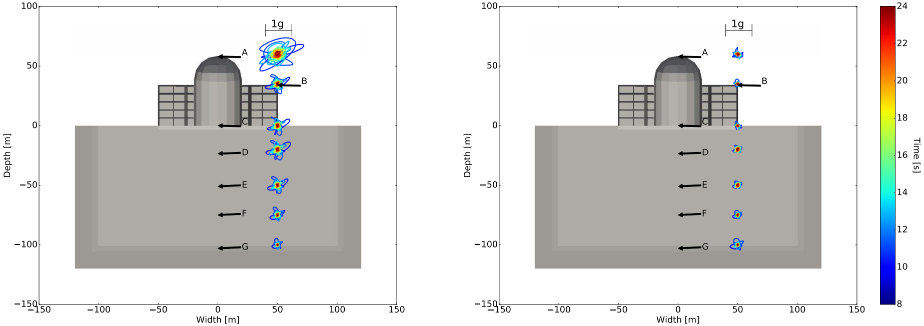
Acc. Response, Top of Containment Building



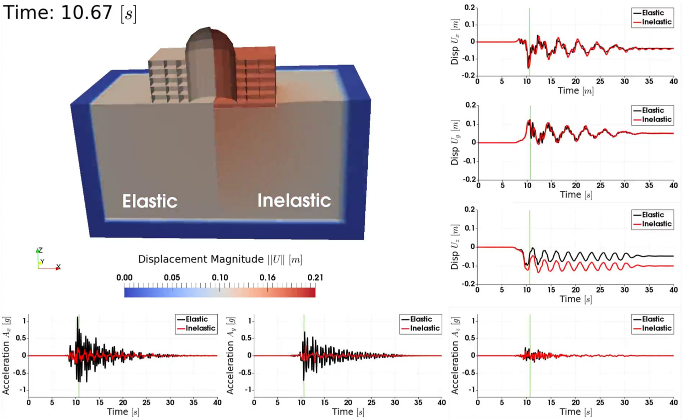
Acceleration Traces, Free Field



Acceleration Traces, Elastic vs Inelastic



Elastic and Inelastic Response: Differences



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Energy Dissipation in a Large-Scale Model (NPP)

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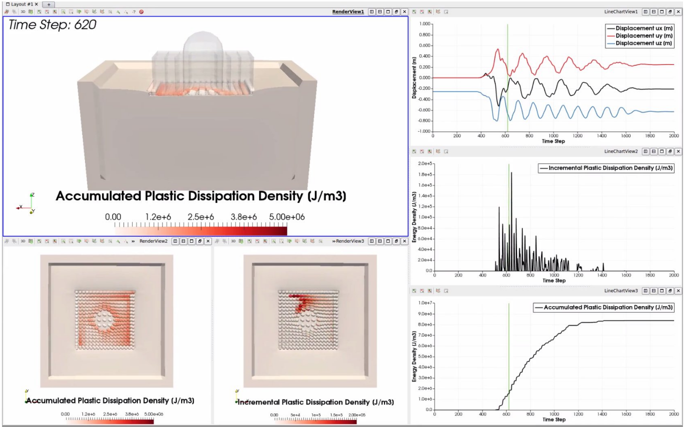
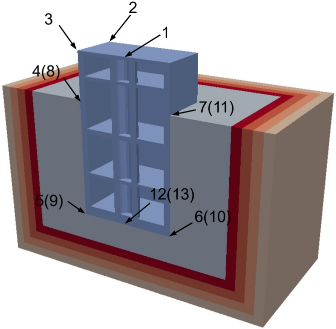


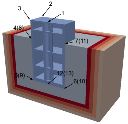
Small Modular Reactor

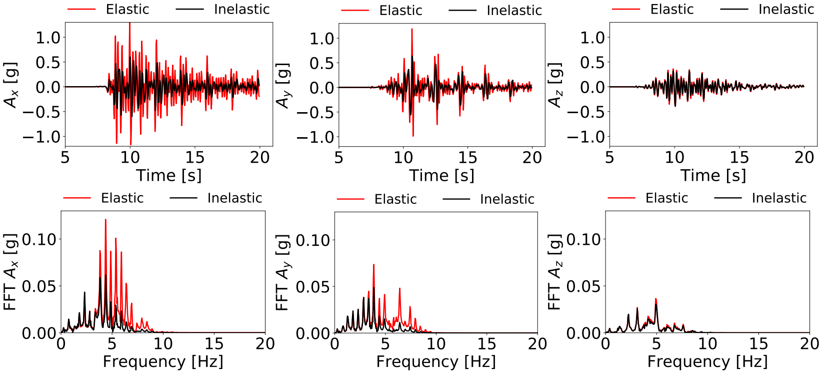


Location of points

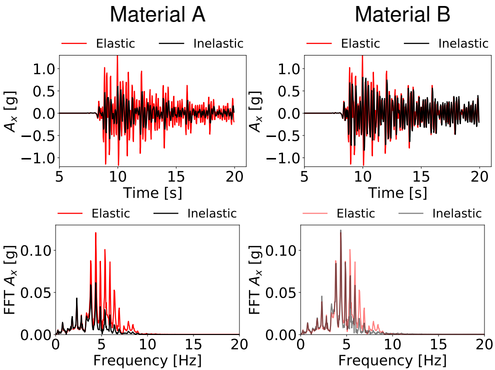
Point ID	X (m)	Y (m)	Z (m)	layer
1	0	0	14	structure
2	15	15	14	structure
3	0	15	14	structure
4	0	15	0	structure
5	0	15	-36	structure
6	0	-15	-36	structure
7	0	-15	0	structure
8	0	15	0	surrounding soil
9	0	15	-36	surrounding soil
10	0	-15	-36	surrounding soil
11	0	-15	0	surrounding soil
12	0	0	-36	structure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

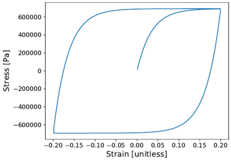
SMR: Inelastic ESSI Effects, Top Center



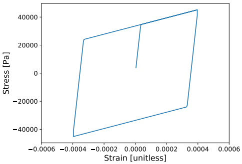


SMR: ESSI Effects, Material Modeling



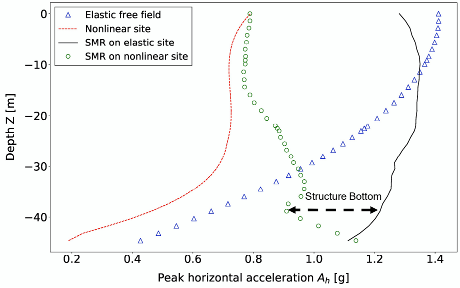


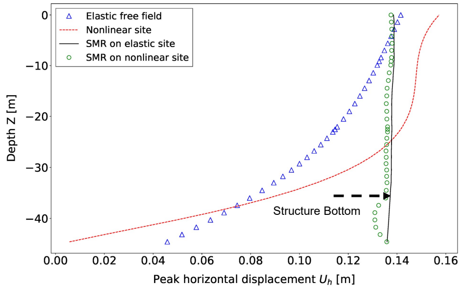
Material A: nonlinear, vM - AF



Material B: Bilinear

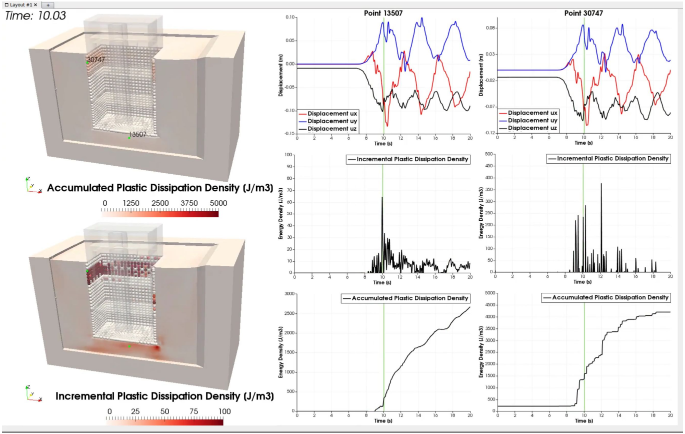
Depth variation - PGA & PGD





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

Energy Dissipation for an SMR



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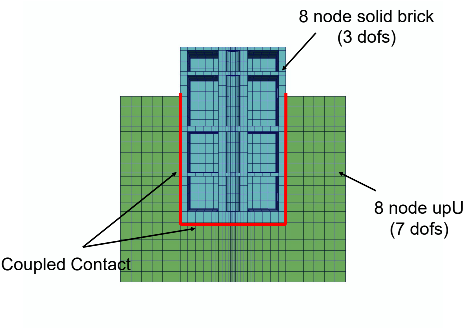
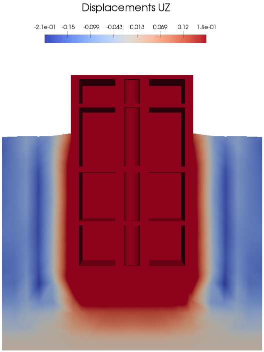
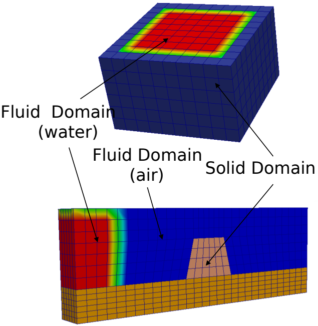
Buoyant Force Simulation



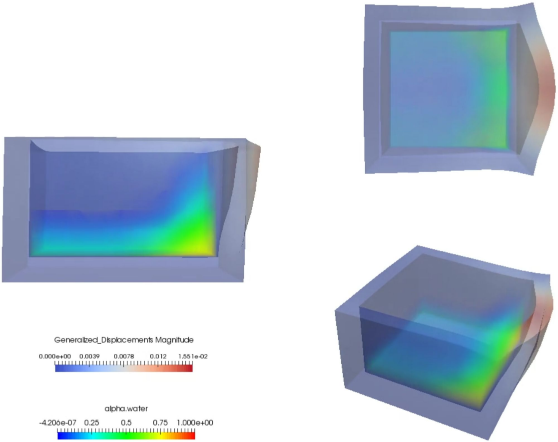


Solid/Structure-Fluid Interaction: gmFoam

- Mesh separation
  - integrated geometry model
  - FEM & FVM mesh conversion
  - handle discontinuous mesh
- Incorporate gmESSI
- Interface geometry extraction
- Interface class **SSFI** in RealESSI
- RealESSI $\Longleftrightarrow$ SSFI $\Longleftrightarrow$ OpenFoam



Solid/Structure-Fluid Interaction, Example



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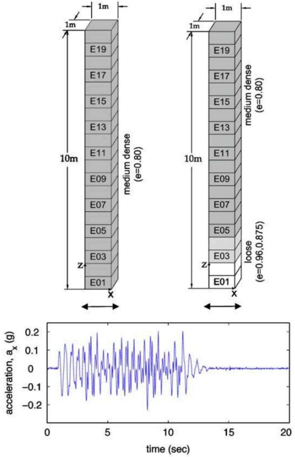
Outline

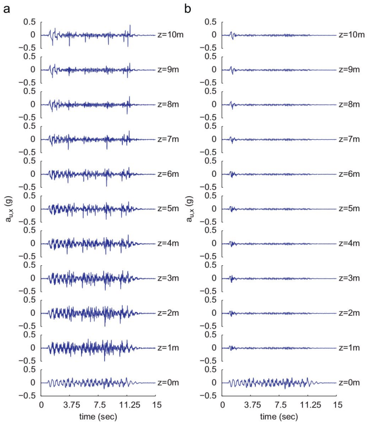
Saturated Soil and Liquefaction

- For fully and partially saturated layers of loose to medium sand, with fines, silt, and with in-between layers of low permeability clay, liquefaction is likely
- Liquefaction: uniform and differential settlements!
- Liquefaction: base isolate objects
- Piles in liquefied soil, pile pinning effects

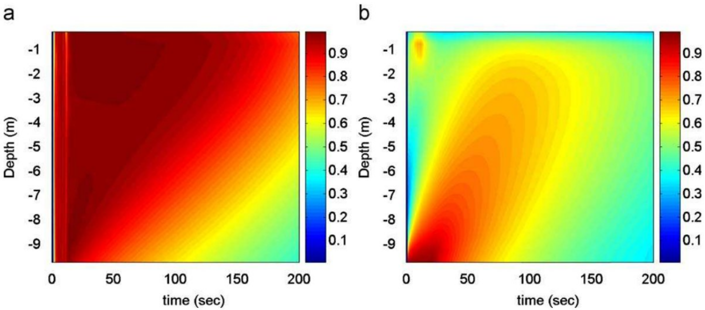
Liquefaction as Base Isolation, Model



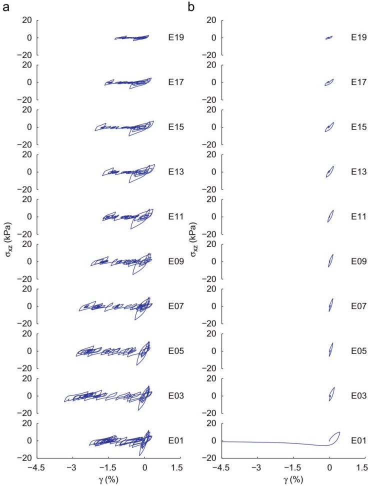
Liquefaction, Wave Propagation



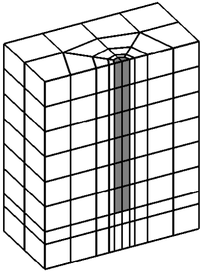
Liquefaction, Excess Pore Pressure Ratio

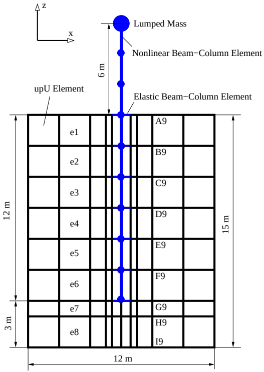


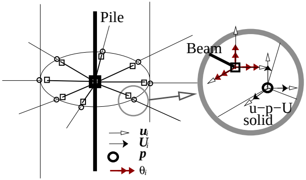
Liquefaction, Stress-Strain Response



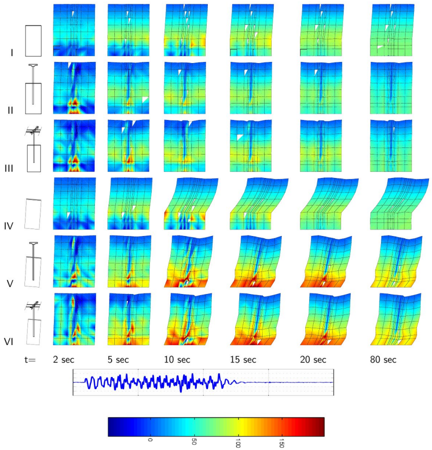
Pile in Liquefiable Soil, Model







Pile in Liquefiable Soil, Results



Summary

- Numerical modeling to predict and inform, rather than fit
- Sophisticated inelastic/nonlinear modeling and simulations need to be done carefully and in phases
- Education and Training is the key!
- `http://real-essi.us/`
- Collaborators: Feng, Lacour, Han, Behbehani, Sinha, Wang, Pisanó, Abell, McCallen, McKenna, Petrone
- Funding from and collaboration with the US-DOE, US-NRC, US-NSF, CNSC-CCSN, UN-IAEA, and Shimizu Corp. is greatly appreciated,