Modeling and Simulation of Static and Dynamic Behavior of Earthquake Soil Structure Systems

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Outline

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Motivation

Improve modeling and simulation for infrastructure objects

Use select fidelity (high $\leftrightarrow$ low) numerical models to analyze static and dynamic behavior of soil/rock structure fluid systems

Reduction of modeling uncertainty, ability to perform desired level of sophistication modeling and simulation

Accurately follow the flow of input and dissipation of energy in a soil structure system

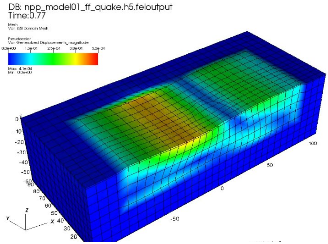
Development of an expert system for modeling and simulation of Earthquakes, Soils, Structures and their Interaction, Real-ESSI: http://real-essi.us/

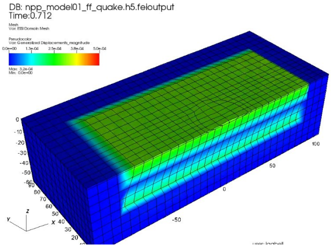
Predictive Capabilities

- 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

Motivation: Modeling Uncertainty, Simplified Models

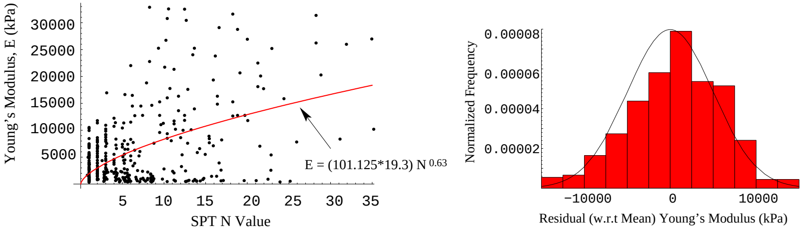
- Simplified modeling: Features (important ?) are neglected (6D ground motions, inelasticity)
- Modeling Uncertainty: unrealistic and unnecessary modeling simplifications
- Modeling simplifications: justifiable iff higher level sophistication model shows are features not important





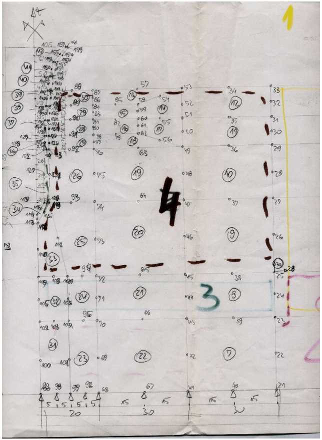
Motivation: Parametric Uncertainty, Material and Load

- Significant uncertainty in material and loads
- Need to propagate uncertainty through simulation, to give regulators and engineers information for design, licensing...



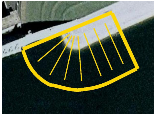
Transformation of SPT *N*-value: 1-D Young's modulus, *E* (cf. Phoon and Kulhawy (1999B))

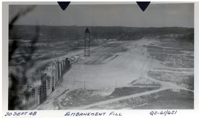
Spillway Dynamic Analysis, ’88-’89

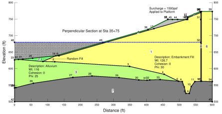


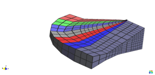
Behkme Dam Project, Iraq, ’89-’90

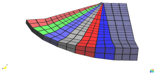
Wolf Creek Dam, ’09-’10

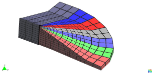


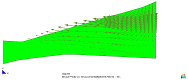


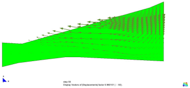


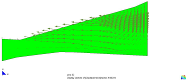












Outline

Real-ESSI Simulator System

The Real-ESSI, Realistic **M**odeling and **S**imulation 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

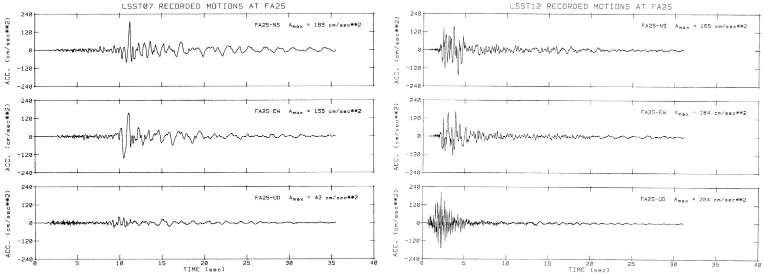
Real-ESSI Simulator System

- Real-ESSI System Components
  - Real-ESSI Pre-processor (gmsh/gmESSI, X2ESSI)
  - Real-ESSI Program (local, remote, cloud)
  - Real-ESSI Post-Processor (Paraview, Python, Matlab)
- Real-ESSI System availability:
  - Educational Institutions: Amazon Web Services (AWS), free
  - Government Agencies, National Labs: AWS GovCloud
  - Professional Practice: AWS, commercial
- Real-ESSI Short Courses, material available online in my lecture notes
- System description and documentation at `http://real-essi.us/`

Outline

3D (6D) Seismic Motions

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

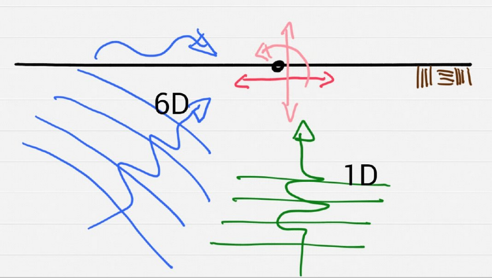


Regional Geophysical Models

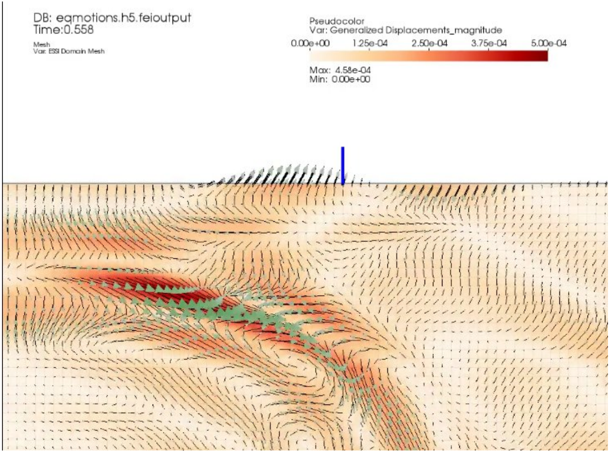
- Free Field seismic motions on regional scale
- Knowledge of geology (deep and shallow) needed
- Developed using Real-ESSI or other regional scale modeling programs (SW4, SCEC...)

ESSI: 6C or 1C Seismic Motions

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

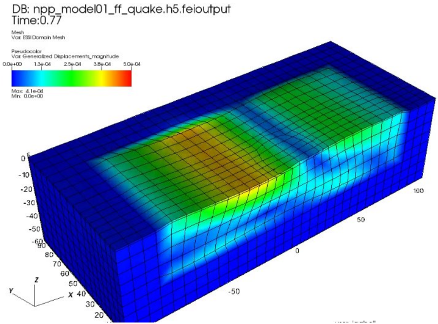


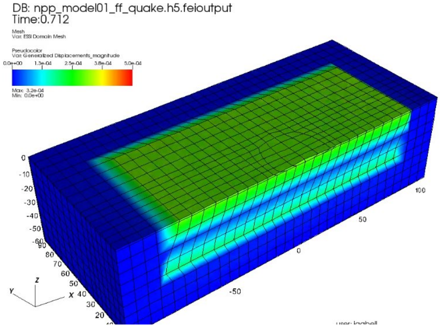
6C Free Field Motions (closeup)



1C vs 6C Free Field Motions

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





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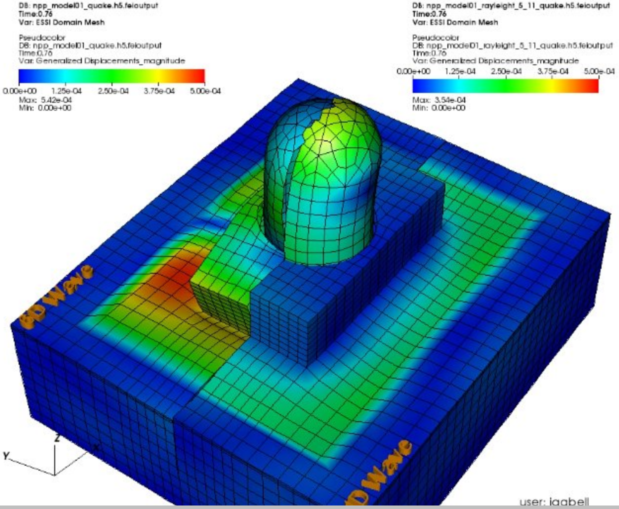
6C vs 1C NPP ESSI Response Comparison



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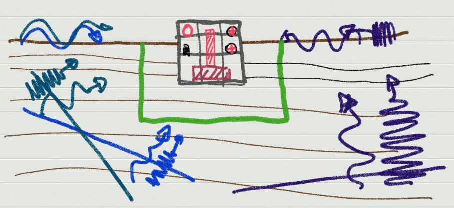
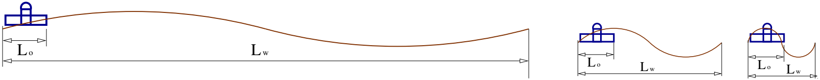
Outline

Stress Testing SSI Systems

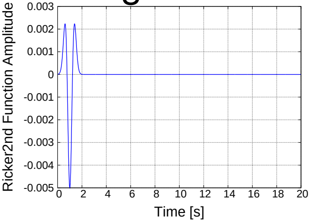
- Excite SSI system with a suite of seismic motions
- Waves: P, SV, Sh, Surface (Rayleigh, Love, etc.)
- Variation in inclination, frequency, energy and duration
- Try to "break" the system, shake-out strong and weak links

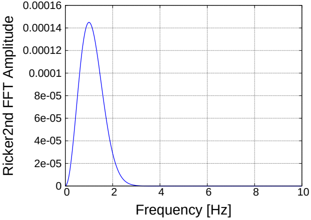




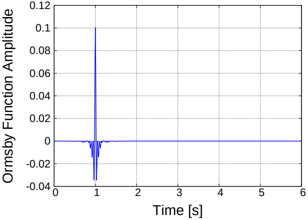
Stress Test Source Signals

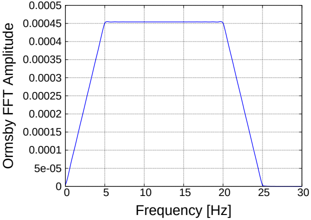
- Ricker





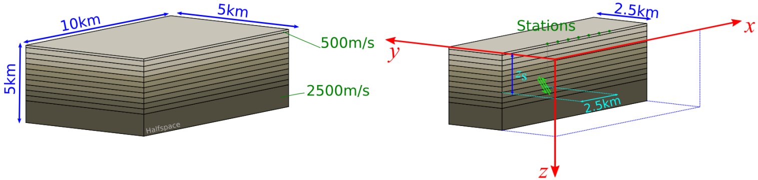
- Ormsby



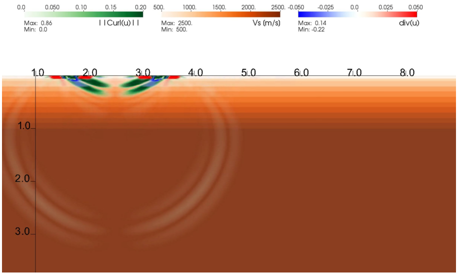


Layered Soil Models

- Point source location matrix
- Plane waves matrix (Thomson and Haskel solution)



Layered System, Variable Source Depth



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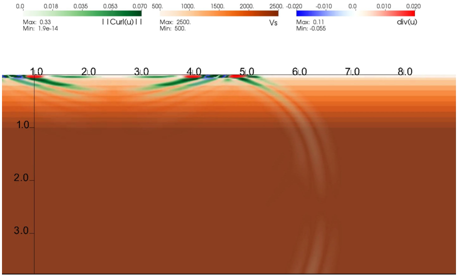

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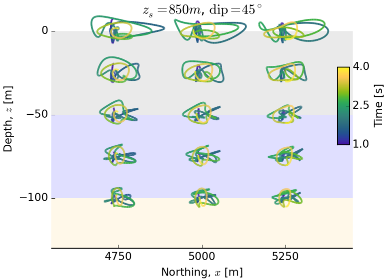
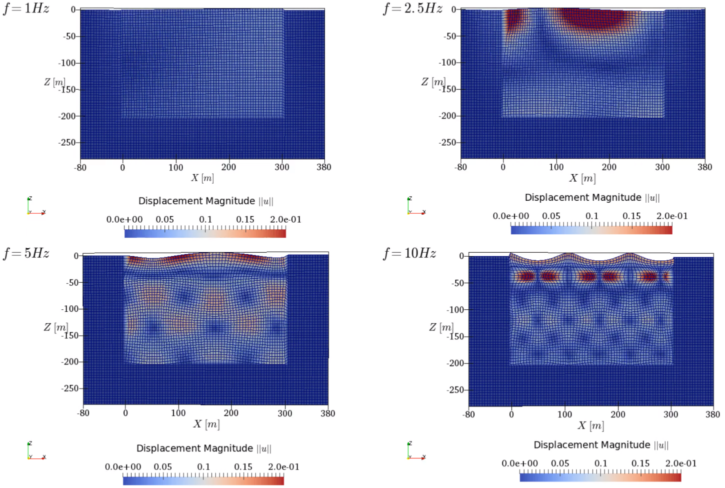
Layered System, Displacement Traces

- Epicenter is 2500m away from the location of interest
- Source depth 850m (left) and 2500m (right)
- Different wave propagation path to the point of interest
- Surface waves quite pronounced
- Layered geology did not filter out surface waves



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



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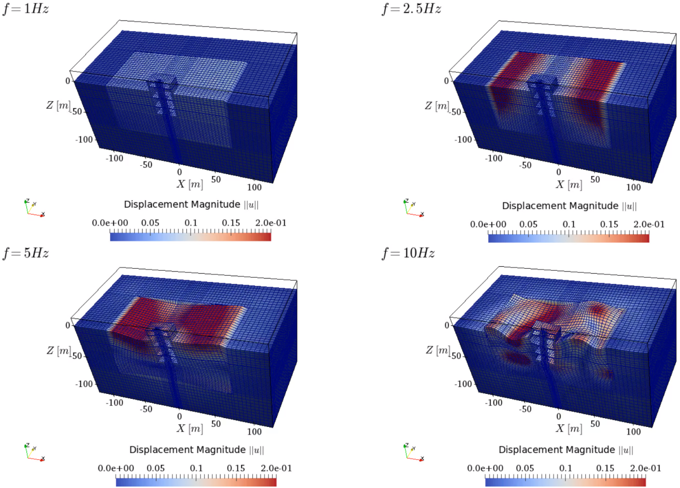
SMR ESSI, Variation in Input Frequency, $\theta = 60^o$



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Outline

Energy Input and Dissipation

Energy input, dynamic forcing

Energy dissipation outside SSI domain:
- SSI system oscillation radiation
- Reflected wave radiation

Energy dissipation/conversion inside SSI domain:
- Inelasticity of soil, contact zone, structure, foundation, dissipators
- Viscous coupling with internal/pore fluids, and external fluids

Numerical energy dissipation/production

Fully Coupled Formulation, u-p-U

$$
\begin{bmatrix} (M_s)_{KijL} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & (M_f)_{KijL} \end{bmatrix}
\begin{bmatrix} \ddot{\bar{u}}_{Lj} \\ \ddot{\bar{p}}_N \\ \ddot{\bar{U}}_{Lj} \end{bmatrix}
+
\begin{bmatrix} (C_1)_{KijL} & 0 & -(C_2)_{KijL} \\ 0 & 0 & 0 \\ -(C_2)_{LjiK} & 0 & (C_3)_{KijL} \end{bmatrix}
\begin{bmatrix} \dot{\bar{u}}_{Lj} \\ \dot{\bar{p}}_N \\ \dot{\bar{U}}_{Lj} \end{bmatrix}
$$

$$
+
\begin{bmatrix} (K^{EP})_{KijL} & -(G_1)_{KiM} & 0 \\ -(G_1)_{LjM} & -P_{MN} & -(G_2)_{LjM} \\ 0 & -(G_2)_{KiL} & 0 \end{bmatrix}
\begin{bmatrix} \bar{u}_{Lj} \\ \bar{p}_M \\ \bar{U}_{Lj} \end{bmatrix}
=
\begin{bmatrix} \bar{f}^{solid}_{Ki} \\ 0 \\ \bar{f}^{fluid}_{Ki} \end{bmatrix}
$$

Fully Coupled Formulation, u-p-U

$$(M_s)_{KijL} = \int_\Omega H_K^u (1-n)\rho_s \delta_{ij} H_L^u d\Omega \quad (M_f)_{KijL} = \int_\Omega H_K^U n \rho_f \delta_{ij} H_L^U d\Omega$$

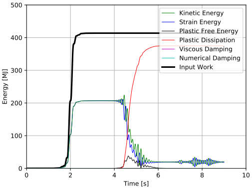
$$(C_1)_{KijL} = \int_\Omega H_K^u n^2 k_{ij}^{-1} H_L^u d\Omega \quad (C_2)_{KijL} = \int_\Omega H_K^u n^2 k_{ij}^{-1} H_L^U d\Omega$$

$$(C_3)_{KijL} = \int_\Omega H_K^U n^2 k_{ij}^{-1} H_L^U d\Omega \quad (K^{EP})_{KijL} = \int_\Omega H_{K,m}^u D_{imjn} H_{L,n}^u d\Omega$$

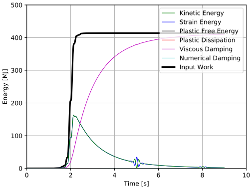
$$(G_1)_{KiM} = \int_\Omega H_{K,i}^u (\alpha - n) H_M^p d\Omega \quad (G_2)_{KiM} = \int_\Omega n H_{K,i}^U H_M^p d\Omega$$

$$P_{NM} = \int_\Omega H_N^p \frac{1}{Q} H_M^p d\Omega$$

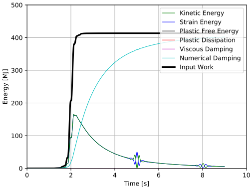
Energy Dissipation Control Mechanisms



Plasticity

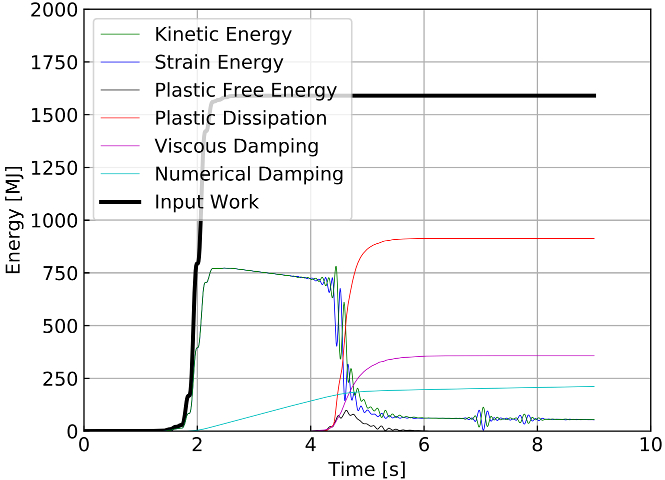


Viscous



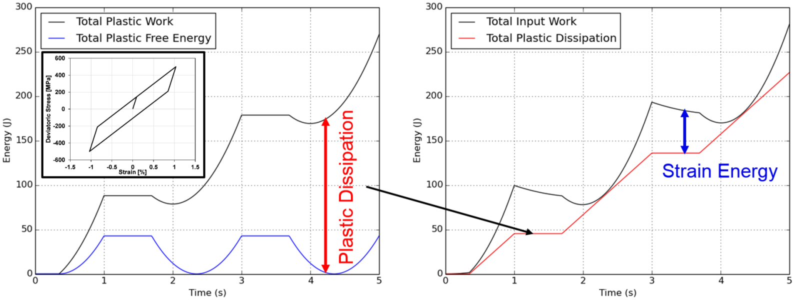
Numerical

Energy Dissipation Control



Energy Dissipation on Material Level

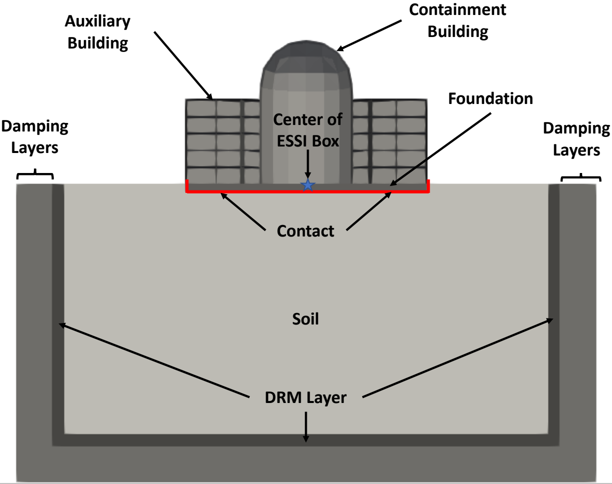
- Single elastic-plastic element under cyclic shear loading
  - Difference between plastic work and plastic dissipation
  - Plastic work can decrease
  - Plastic dissipation always increases



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 reinforced concrete fiber beam
  - Nonlinear/inelastic 2D reinforced concrete element
  - Alcali Silica Reaction concrete modeling

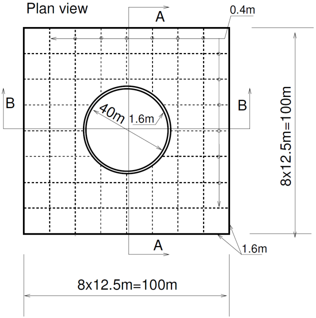
NPP Model

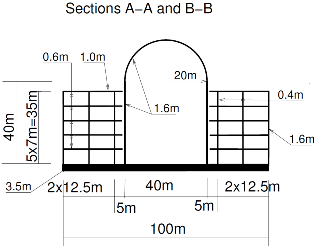

Auxiliary Building
Containment Building
Foundation
Damping Layers
Center of ESSI Box
Damping Layers
Contact
Soil
DRM Layer

Structure Model

The nuclear power plant structure comprise of

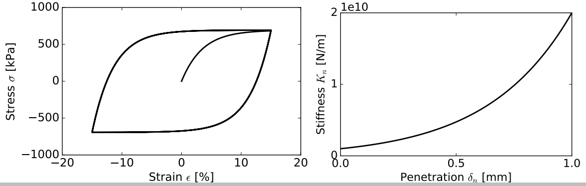
- Auxiliary building, $f_1^{aux} = 8Hz$
- Containment/Shield building, $f_1^{cont} = 4Hz$
- Concrete raft foundation: $3.5m$ thick



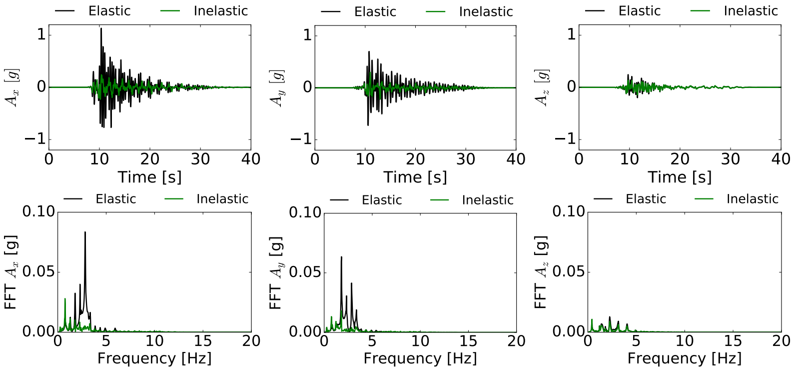


Inelastic Soil and Inelastic Contact

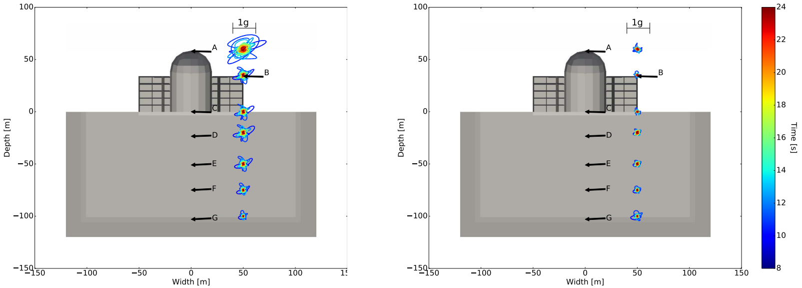
- Shear velocity of soil $V_s = 500 m/s$
- Undrained shear strength (Dickenson 1994)
  $V_s[m/s] = 23(S_u[kPa])^{0.475}$
- For $V_s = 500 m/s$ Undrained Strength $S_u = 650 kPa$ and Young's Modulus of $E = 1.3 GPa$
- von Mises, Armstrong Frederick kinematic hardening ($S_u = 650 kPa$ at $\gamma = 0.01\%$;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



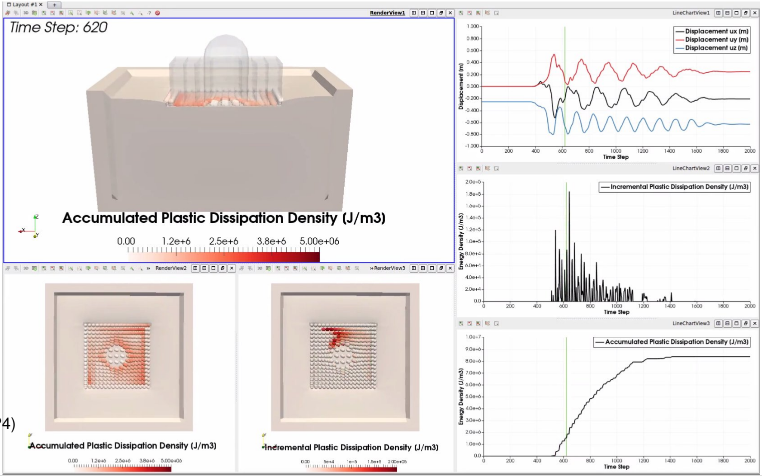
Acc. Response, Top of Containment Building



Acceleration Traces, Elastic vs Inelastic



Energy Dissipation in Large-Scale Model (NPP)



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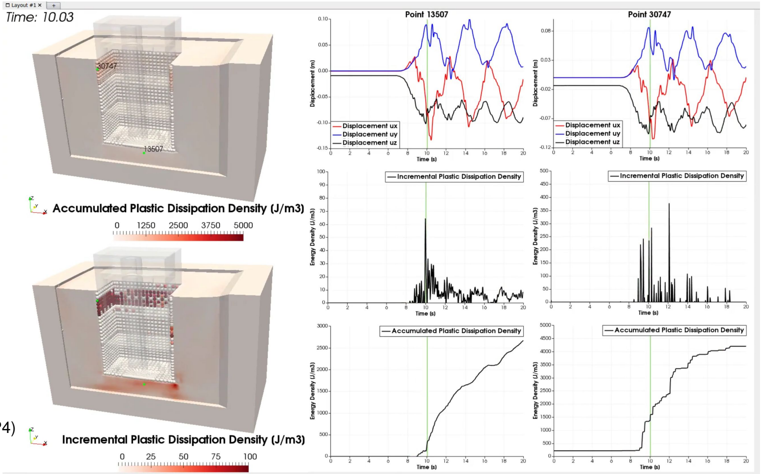
Energy Dissipation for a SMR



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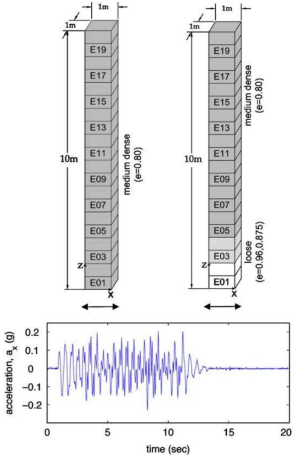
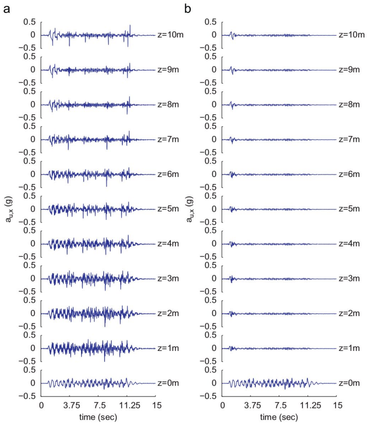
Outline

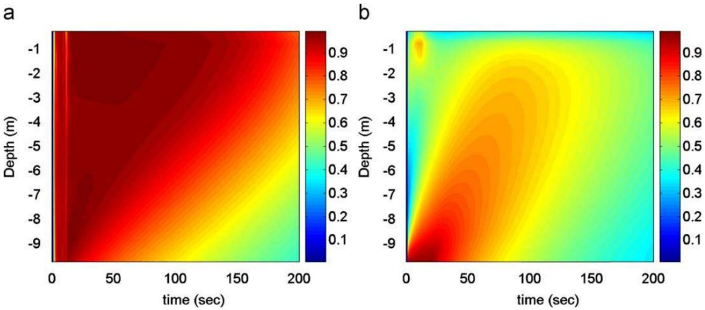
Liquefaction as Base Isolation, Model



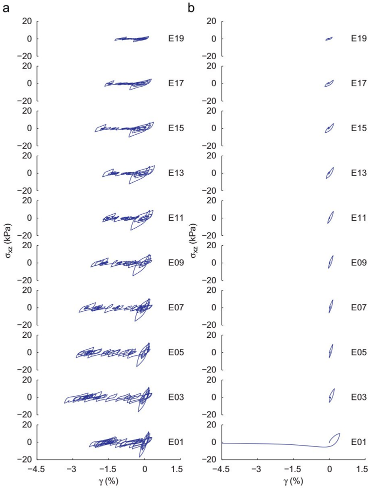
Liquefaction, Wave Propagation



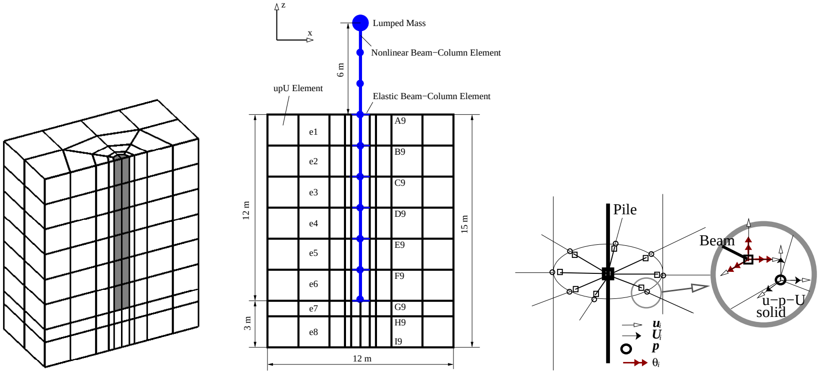
Liquefaction, Excess Pore Pressure Ratio



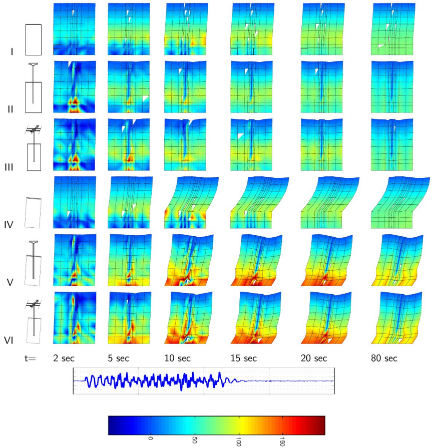
Liquefaction, Stress-Strain Response



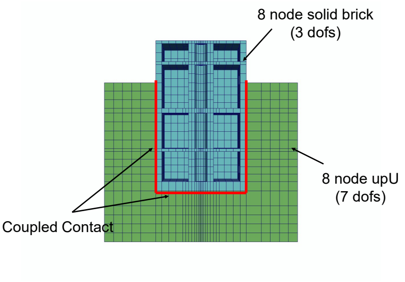
Pile in Liquefiable Soil, Model

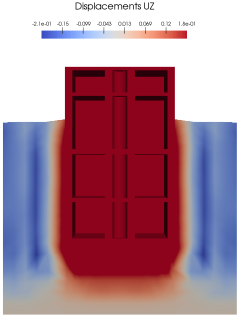


Pile in Liquefiable Soil, Pinning Effects

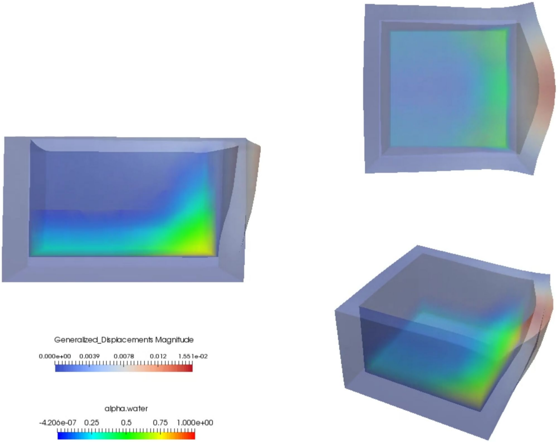


Buoyant Force Simulation





Solid/Structure-Fluid Interaction, Example

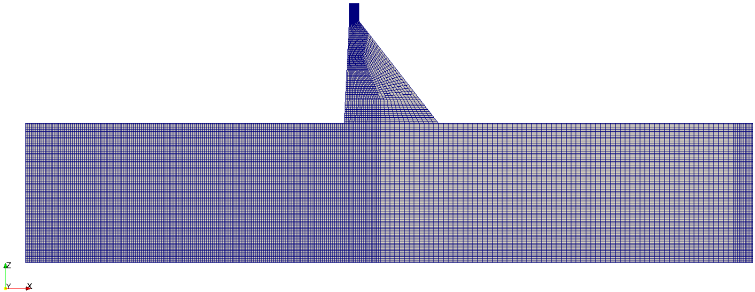


(MP4)

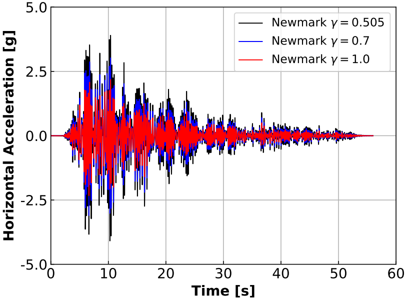
Outline

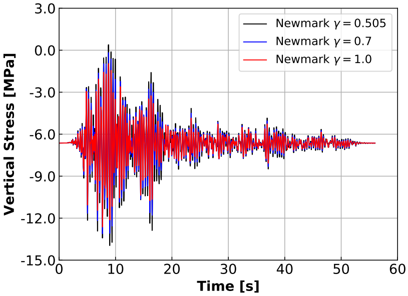
Concrete Dam, Model

- 3D solids, with BCs for 2D analysis
- Linear elastic and inelastic material and interfaces
- Energy dissipation: material, viscous, numerical, radiation
- Seismic input, 1C, 3C, 6C, 3×1C, using DRM

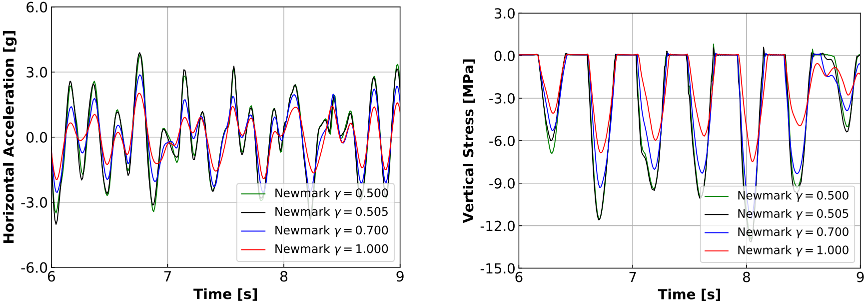


Numerical Damping Effects, Dry, Elastic $\ddot{u}_{hor}^{top}$, σ_v^{heel}

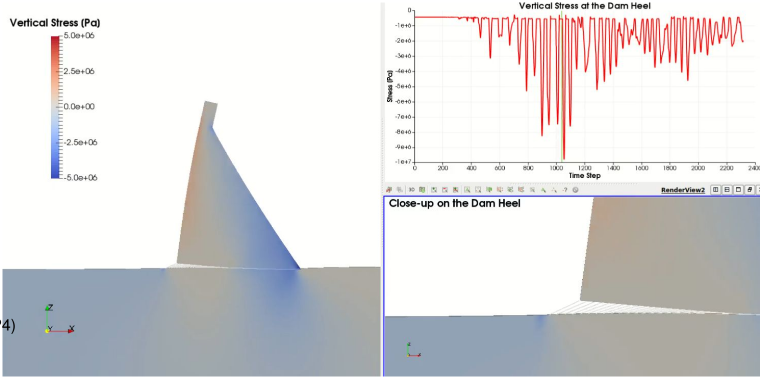




Numerical Damping Effects, Wet, Inelastic $\ddot{u}_{hor}^{top}$, σ_v^{heel}



Concrete Dam, Inelastic Interface, Hydrostatic



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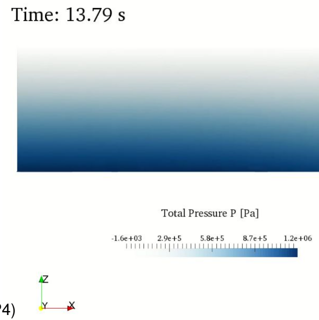
Pine Flat Dam, Hydrodynamic Pressure



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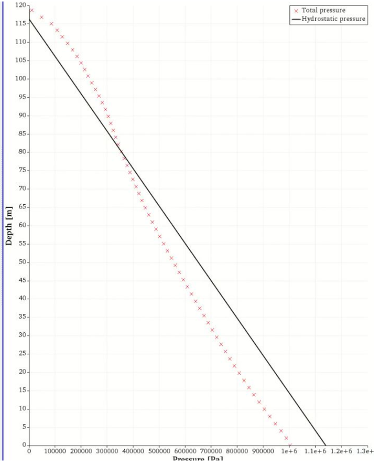
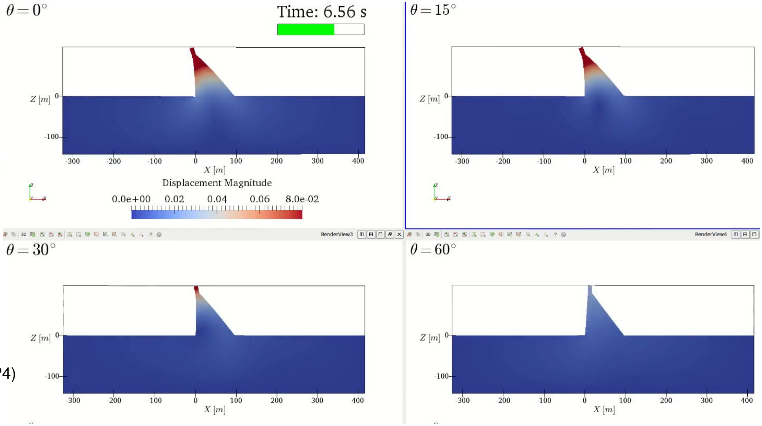


Seismic Response, Inclined Plane Waves



(MP4)

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!
- Collaborators: Yang, Preisig, Tafazzoli, Feng, Yang, Behbehani, Sinha, Wang, Pisanó, Abell, ...
- Funding from and collaboration with the US-DOE, US-NRC, US-NSF, CNSC-CCSN, UN-IAEA, CH-ENSI and Shimizu Corp. is greatly appreciated,
- `http://real-essi.us/`