Modeling and Simulation of Static and Dynamic Behavior of 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.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

Motivation: Modeling Uncertainty

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

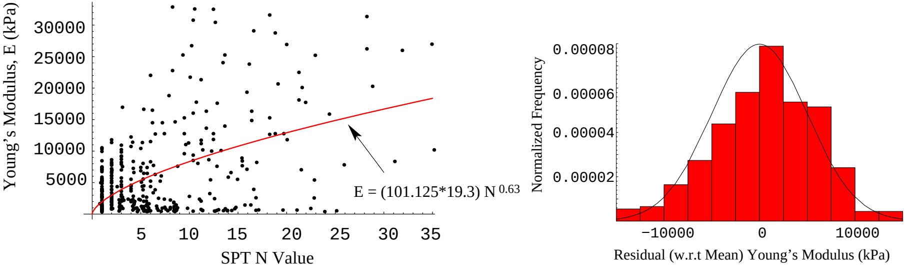
Uncertainties

- Modeling uncertainty, introduced by simplifying assumptions
  - low sophistication modeling and simulation
  - medium sophistication modeling and simulation
  - high sophistication modeling and simulation
  - choice of sophistication level for confidence in analysis results
- Parametric uncertainty, $M\ddot{u}_i + C\dot{u}_i + K^{ep}u_i = F(t)$
  - propagation of uncertainty in material, K^{ep}
  - propagation of uncertainty in loads, $F(t)$
  - results are PDFs and CDFs for σ_{ij}, ϵ_{ij}, u_i, $\dot{u}_i$, $\ddot{u}_i$

Modeling Uncertainty

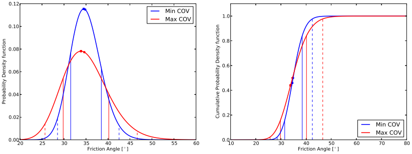
- Simplified modeling: Features (important ?) are neglected (3C, 6C ground motions, inelasticity)
- Modeling Uncertainty: unrealistic and unnecessary modeling simplifications
- Modeling simplifications are justifiable if one or two level higher sophistication model shows that features being simplified out are not important

Parametric Uncertainty: Soil Stiffness

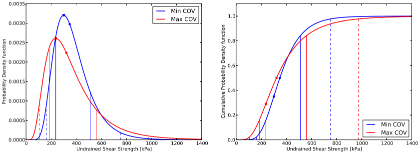


Transformation of SPT *N*-value: 1-D Young's modulus, *E* (cf. Phoon and Kulhawy (1999B))

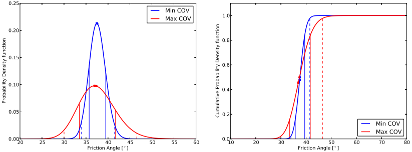
Parametric Uncertainty: Material Properties



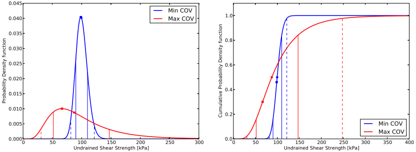
Field ϕ



Field c_u

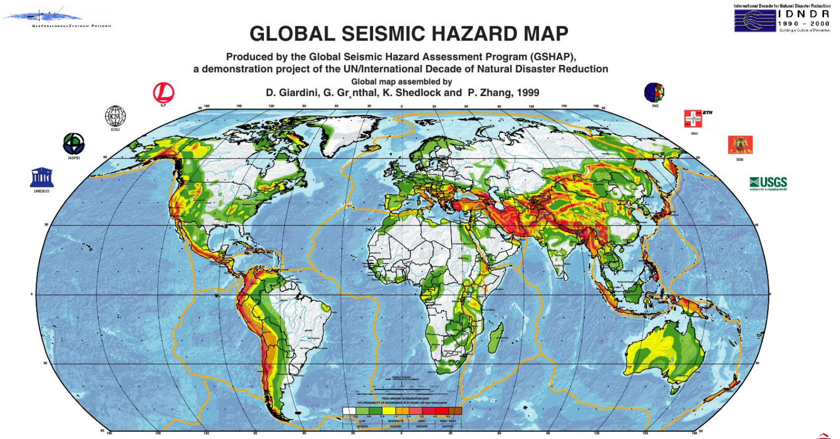


Lab ϕ

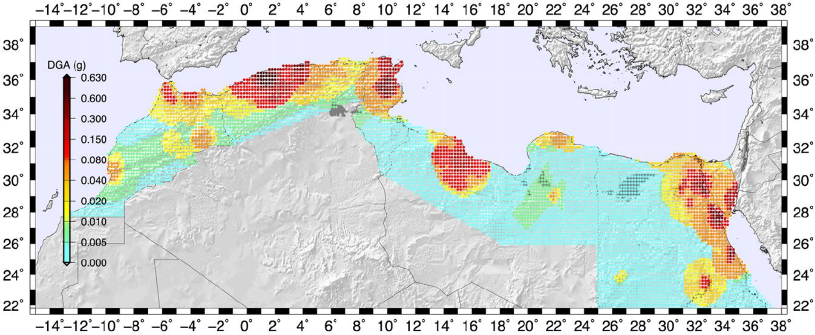


Lab c_u

Motivation: Seismic Hazard



Motivation: Egypt Seismic Design Accelerations



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
  - 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 (online)
- System description and documentation at **`http://real-essi.info/`**

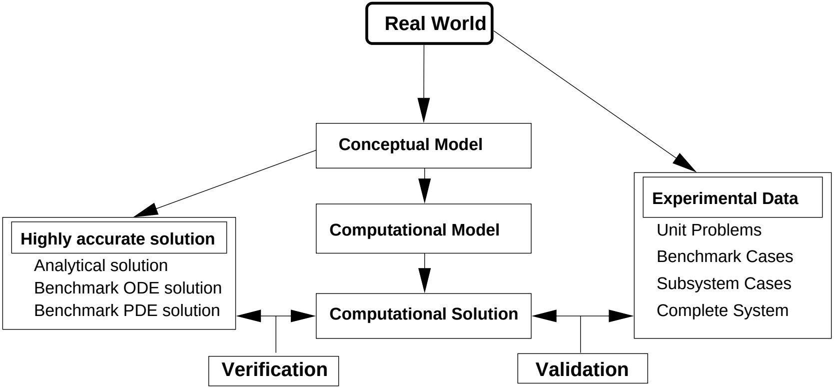
Trusting Simulation Tools, Quality Assurance

- Full verification suit for each element, model, algorithm
- Certification in progress for NQA-1 and ISO-90003-2014
- **Verification**: Mathematics issue. Verification provides evidence that the model is solved correctly.
- **Validation**: Physics issue. Validation provides evidence that the correct model is solved.

Importance of Verification and Validation (V&V)

- V & V procedures are the primary means of assessing accuracy in modeling and computational simulations
- V & V procedures are the tools with which we build confidence and credibility in modeling and computational simulations

Verification and Validation



Oberkampf et al.

Outline

Energy Input and Dissipation

Energy input, static and dynamic forcing

Energy dissipation outside SSI domain:

- SSI system oscillation radiation
- Reflected wave radiation

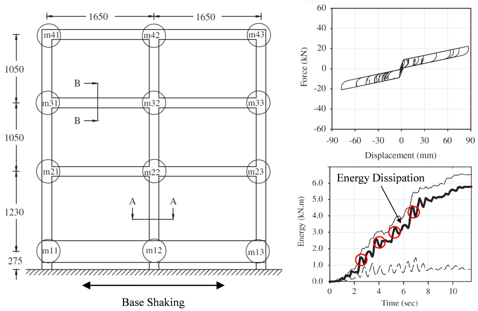
Energy dissipation/conversion inside SSI domain:

- Inelasticity of soil, contact zone, structure, foundation, dissipators
- Viscous coupling with internal/pore fluids, and external fluids

Numerical energy dissipation/production

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

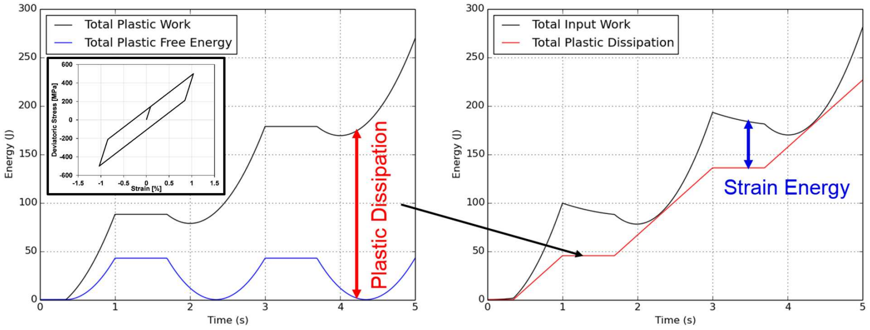
- Negative incremental energy dissipation
- Plastic work is NOT plastic dissipation



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

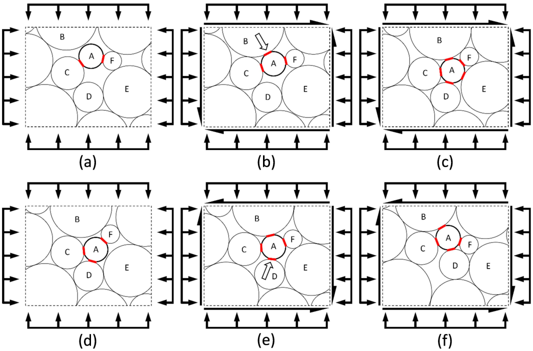
Energy Dissipation on Material Level

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

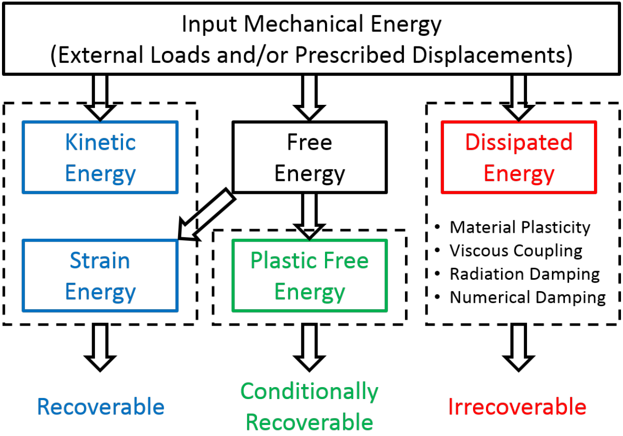


Plastic Free Energy

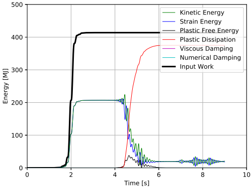
- Multi-scale effect of particle interlocking/rearrangement
- Strain energy on particle level

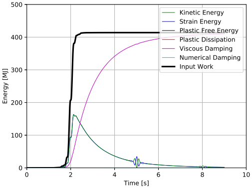


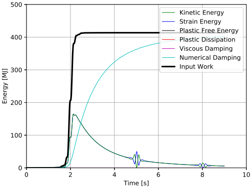
Energy Transformation in Elastic-Plastic Material



Energy Dissipation Control Mechanisms

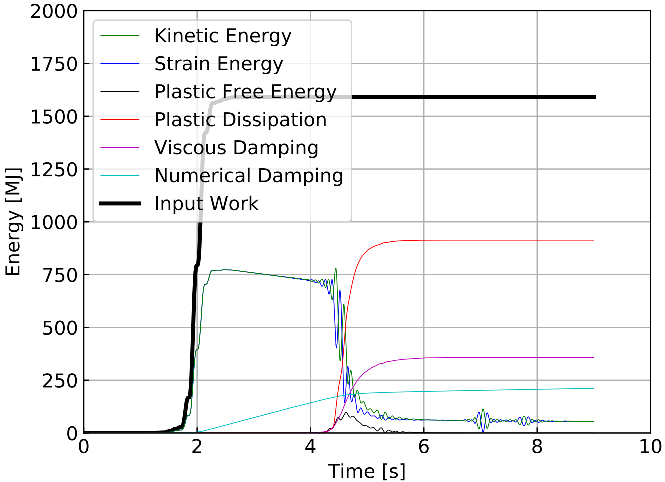






Plasticity Viscous Numerical

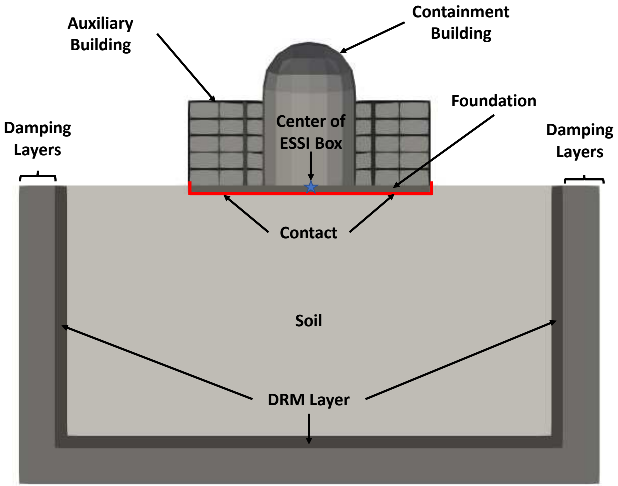
Energy Dissipation Control



Inelastic Modeling for Soil Structure System

- 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 beams
  - Nonlinear/inelastic reinforced concrete walls. plates, shells
  - Alcali Silica Reaction concrete modeling

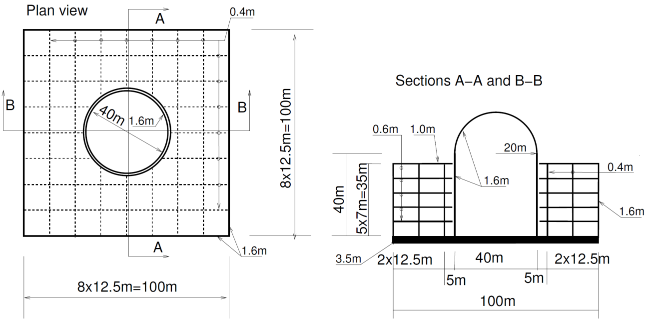
NPP Model


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

Structure Model

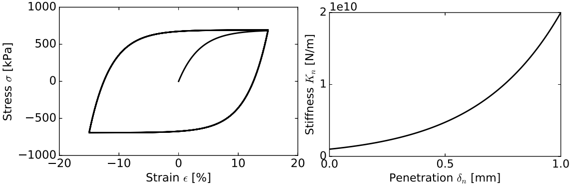
The nuclear power plant structure comprise of

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

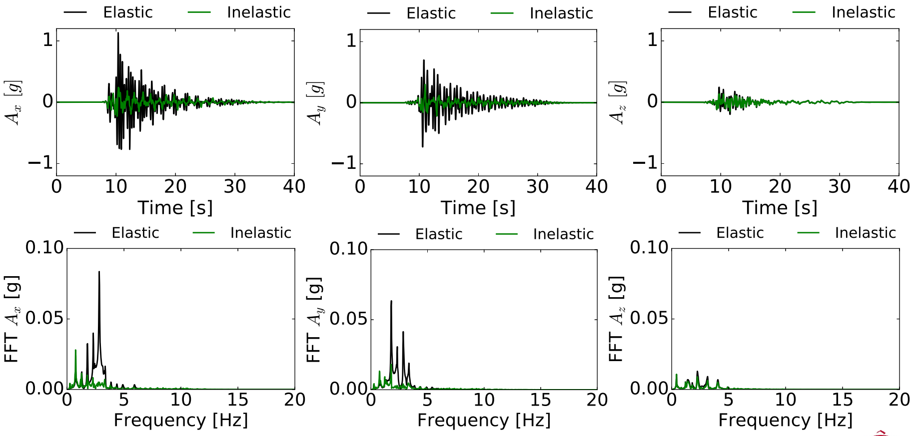


Inelastic Soil and Inelastic Contact

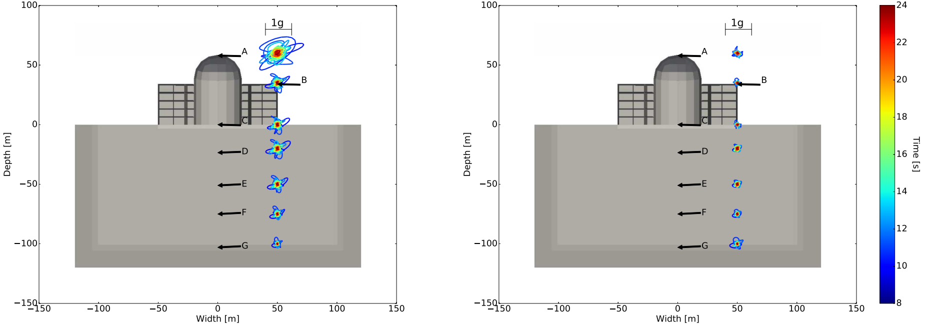
- Shear velocity of soil $V_s = 500 m/s$
- Undrained shear strength (Dickenson 1994) $V_s[m/s] = 23(S_u[kPa])^{0.475}$
- For $V_s = 500 m/s$ Undrained Strength $S_u = 650 kPa$ and Young's Modulus of $E = 1.3 GPa$
- von Mises, Armstrong Frederick kinematic hardening ($S_u = 650 kPa$ at $\gamma = 0.01\%$;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



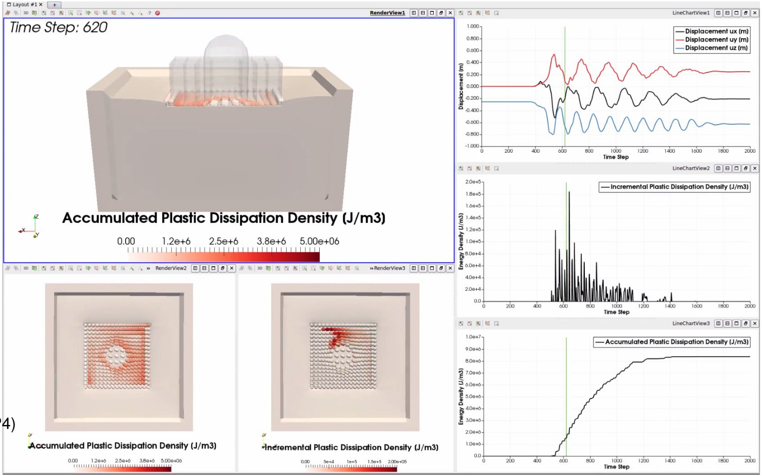
Acc. Response, Top of Containment Building



Acceleration Traces, Elastic vs Inelastic



Energy Dissipation in NPP Model



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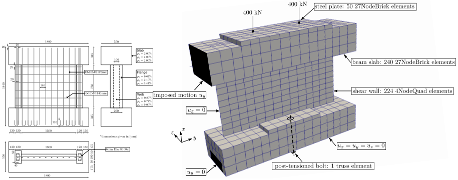
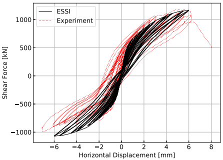
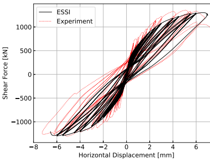
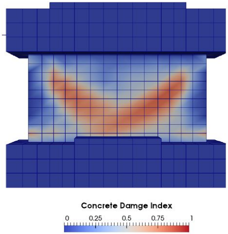
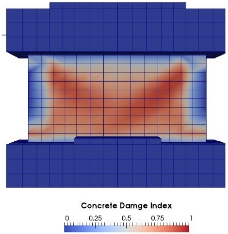
Wall, Regular and ASR Concrete

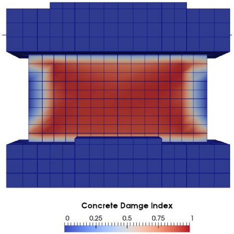












$u_y = 1.4$ mm $u_y = 1.8$ mm $u_y = 3.0$ mm

Outline

Fully Coupled Formulation, u-p-U

- Fully saturated soil
- Partially, un-saturated soil

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

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

Fully Coupled Formulation, u-p-U

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

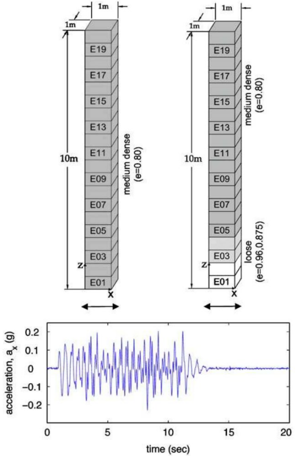
$$(C_1)_{KijL} = \int_\Omega H_K^u n^2 k_{ij}^{-1} H_L^u d\Omega \quad (C_2)_{KijL} = \int_\Omega H_K^u n^2 k_{ij}^{-1} H_L^U d\Omega$$

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

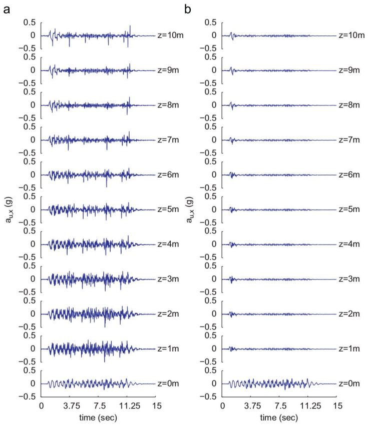
$$(G_1)_{KiM} = \int_\Omega H_{K,i}^u (\alpha - n) H_M^p d\Omega \quad (G_2)_{KiM} = \int_\Omega n H_{K,i}^U H_M^p d\Omega$$

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

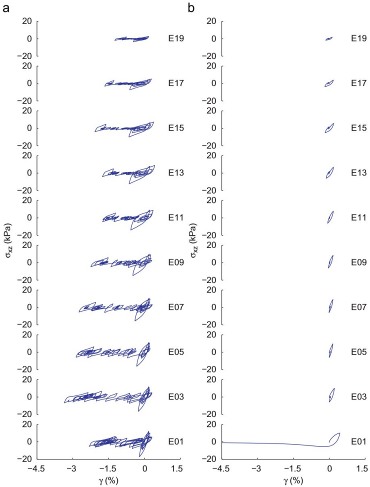
Liquefaction as Base Isolation, Model



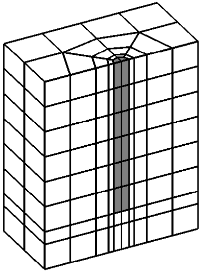
Liquefaction, Wave Propagation

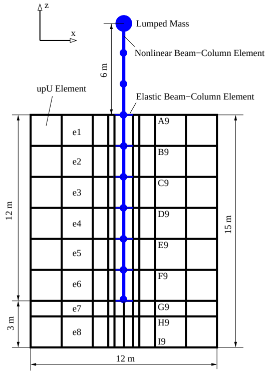


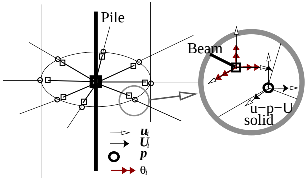
Liquefaction, Stress-Strain Response



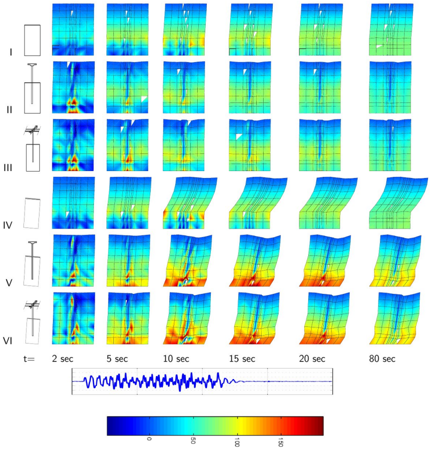
Pile in Liquefiable Soil, Model



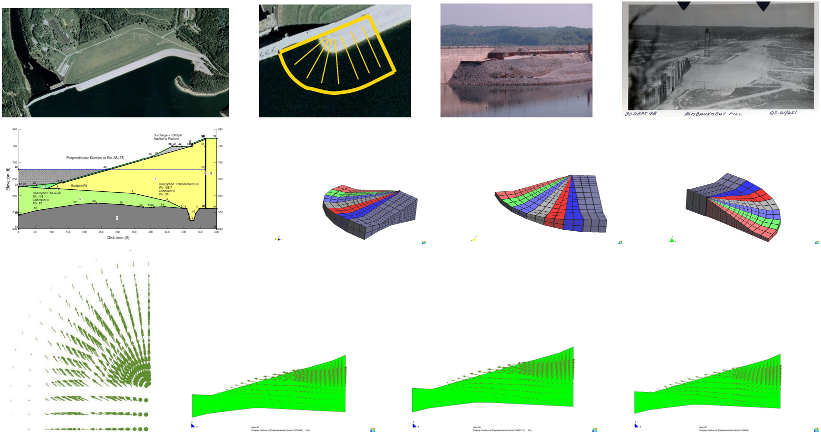




Pile in Liquefiable Soil, Results

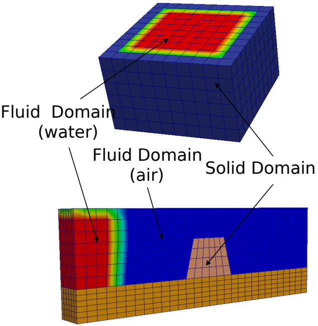


Dam, 3D Slope Stability

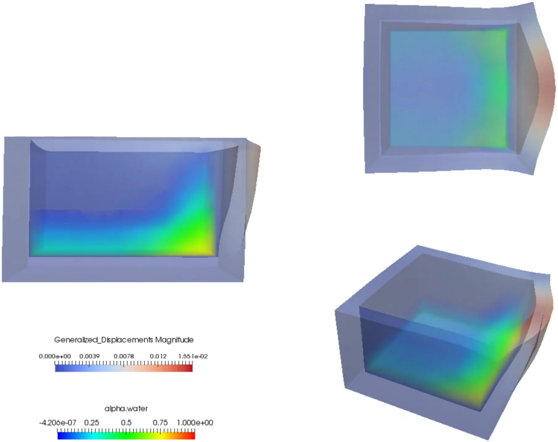


Solid/Structure-Fluid Interaction: gmFoam

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



Solid/Structure-Fluid Interaction, Example



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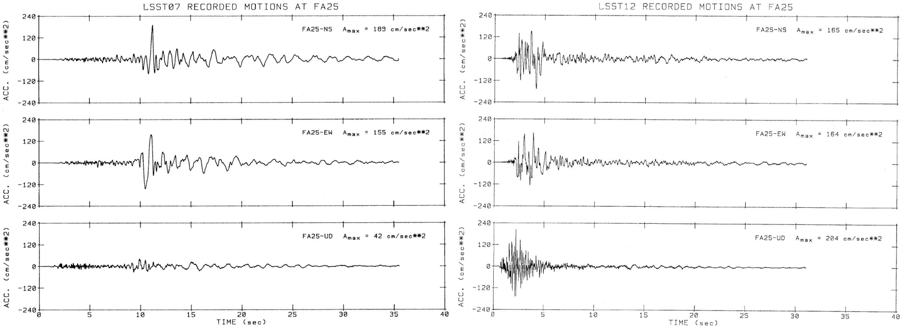
Outline

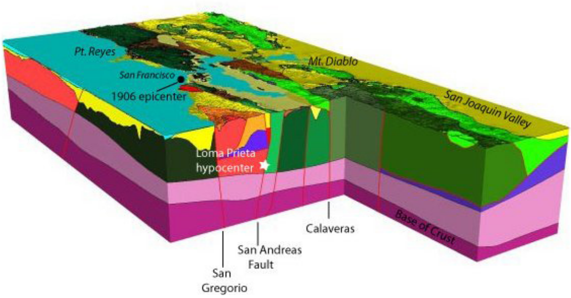
3D (6D) Seismic Motions

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



Regional Geophysical Models

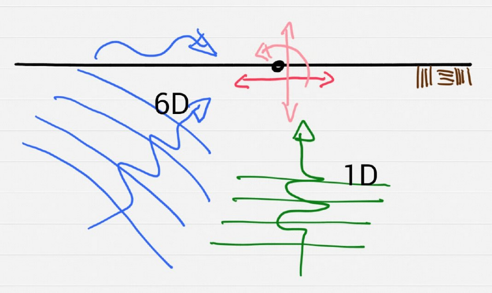
- Free Field seismic motions on regional scale
- Knowledge of geology (deep and shallow) needed



USGS

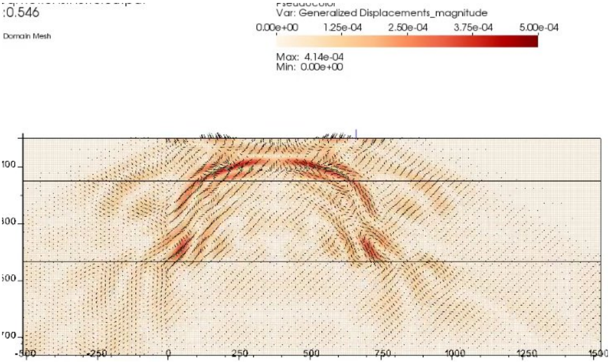
ESSI: 6C or 1C Seismic Motions

- Full 6C (3C) motions, recorded only in 1C
- Develop vertically propagating shear wave, 1C
- Apply 1C shear wave to ESSI system



6C Realistic Ground Motions

- Free field seismic motion models



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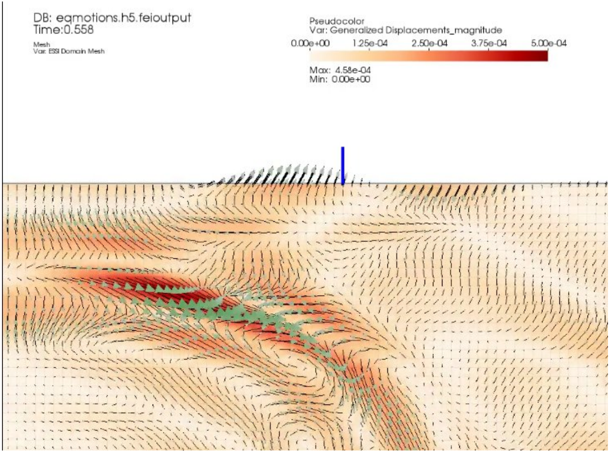
6C Realistic Ground Motions (closeup)



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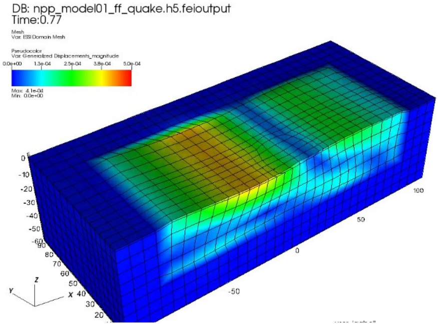
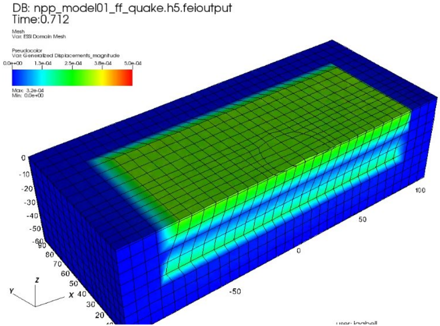
6C vs 1C Free Field Motions

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





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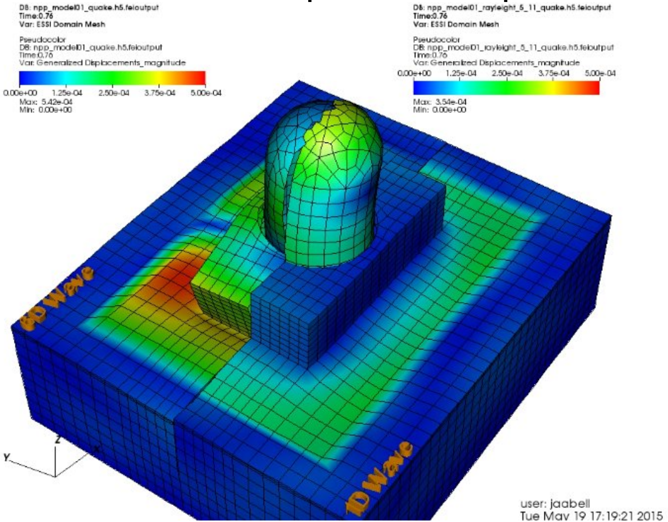
6C vs 1C NPP ESSI Response Comparison



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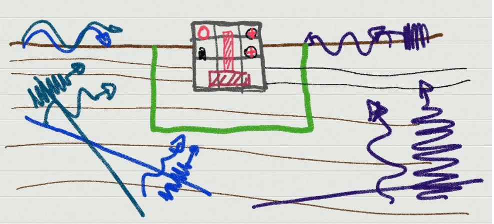
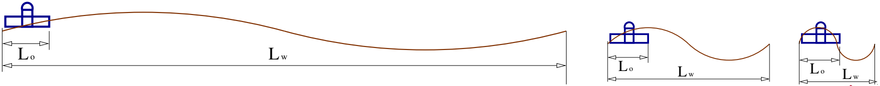
Outline

Stress Testing SSI Systems

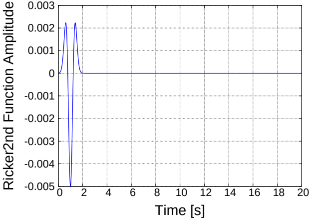
- Excite SSI system with a suite of seismic motions
- Waves: P, SV, Sh, Surface (Rayleigh, Love, etc.)
- Variation in inclination, frequency, energy and duration
- Try to "break" the system, shake-out strong and weak links

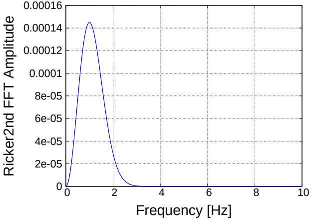




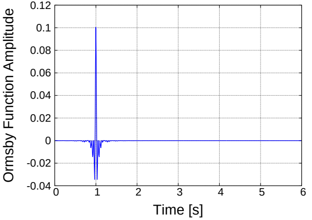
Stress Test Source Signals

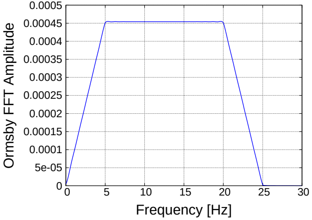
- Ricker



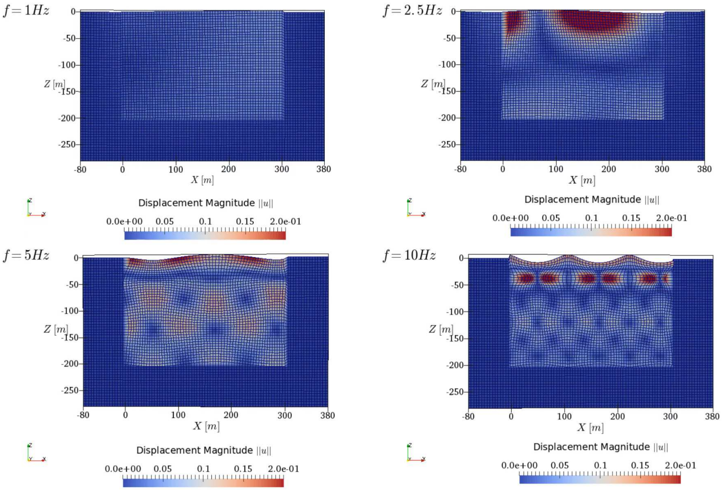


- Ormsby



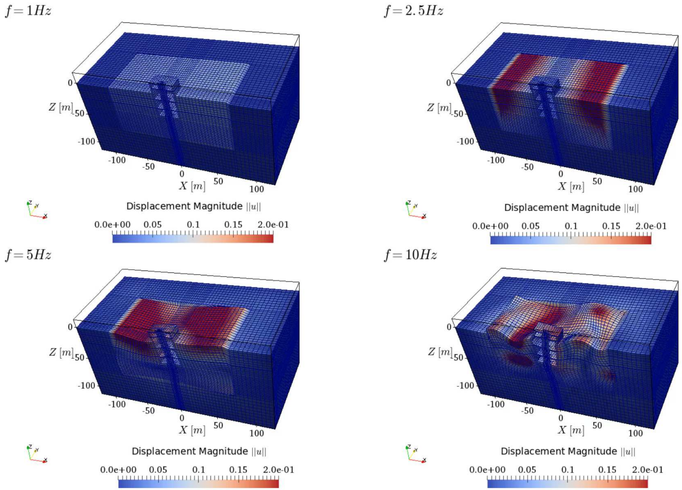


Free Field, Variation in Input Frequency, $\theta = 60^o$



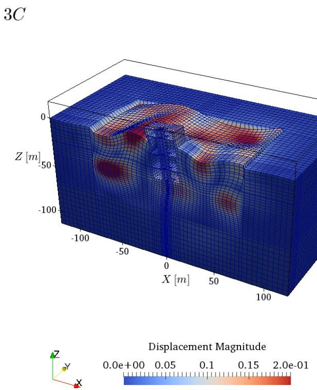
(MP4)

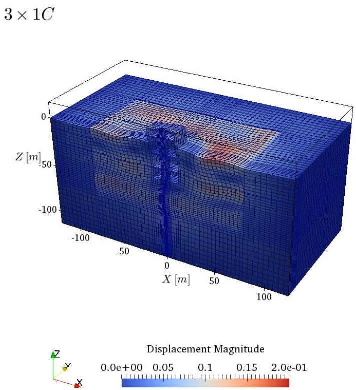
SMR ESSI, Variation in Input Frequency, $\theta = 60^o$



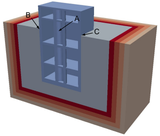
(MP4)

SMR ESSI, 3C vs 3×1C





(OGV)

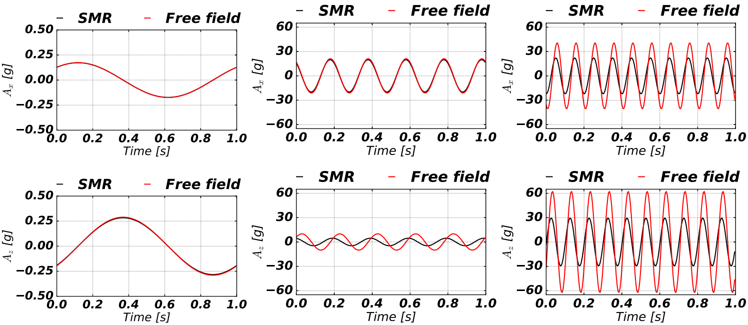


Free Field vs ESSI - Different Frequencies

Acceleration response - Surface center point A

X direction

Z direction



(a) $f = 1Hz \;\; \theta = 60^o$

(b) $f = 5Hz \;\; \theta = 60^o$

(c) $f = 10Hz \;\; \theta = 60^o$

Summary

- Numerical modeling to predict and inform, rather than fit
- Education and Training is the key!
- Funding from and collaboration with the US-DOE, US-NRC, CNSC-CCSN, US-NSF, Caltrans, UN-IAEA, and Shimizu Corp. is greatly appreciated,
- Real-ESSI/MS-ESSI Simulator System: **`http://real-essi.info/`**
- Lecture Notes, Book: **`http://sokocalo.engr.ucdavis.edu/~jeremic/LectureNotes/`**