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

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Outline

Introduction
  Motivation
  Real ESSI Simulator System

Seismic Motions and Energy Dissipation
  Observations and Regional Models
  Energy Dissipation

ESSI Modeling and Simulations
  Buildings
  Liquefaction, Piles

Conclusion
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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

![Graph showing the relationship between SPT N value and Young's modulus, E, with an equation E = (101.125*19.3) N^{0.63}.](image)

Young's Modulus, E (kPa) vs. SPT N Value

- Residual (w.r.t Mean) Young's Modulus (kPa)
- Normalized Frequency

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

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Real ESSI Simulator
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
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Real ESSI Simulator System

The Real ESSI, (Realistic modeling and simulation of Earthquakes, and Soils, and Structures and their Interaction) 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/](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
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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

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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
Realistic Earthquake Motions, 6D vs 1D

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

![Energy Dissipation Control Diagram]

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**Incremental Plastic Work:**

\[ dW_p = \sigma_{ij} d\varepsilon_{ij}^{pl} \]

- 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
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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
- Contact
- Soil
- DRM Layer

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Structure Model

The nuclear power plant structure comprise of

- Auxiliary building, $f_{aux}^1 = 8\text{Hz}$
- Containment/Shield building, $f_{cont}^1 = 4\text{Hz}$
- Concrete raft foundation: 3.5m thick

![Plan view of the structure](image)
Inelastic Soil and Inelastic Contact

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

- $A_x$ [g]
- $A_y$ [g]
- $A_z$ [g]

- Elastic
- Inelastic

- FFT $A_x$ [g]
- FFT $A_y$ [g]
- FFT $A_z$ [g]

- Frequency [Hz]
Acceleration Traces, Free Field
Acceleration Traces, Elastic vs Inelastic
Elastic and Inelastic Response: Differences

Time: 10.67 [s]
Energy Dissipation in a Large-Scale Model (NPP)

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Real ESSI Simulator
Small Modular Reactor

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</tbody>
</table>
SMR: Inelastic ESSI Effects, Top Center
SMR: ESSI Effects, Material Modeling

Material A: nonlinear, vM - AF

Material B: Bilinear

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Real ESSI Simulator
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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Real ESSI Simulator
Buoyant Force Simulation

8 node solid brick (3 dofs)
8 node upU (7 dofs)
Coupled Contact

Displacements UZ
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 $\leftrightarrow$ SSFI $\leftrightarrow$ OpenFoam
Solid/Structure-Fluid Interaction, Example

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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

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Liquefaction, Wave Propagation

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Liquefaction, Excess Pore Pressure Ratio

[Diagram showing two graphs with depth on the y-axis and time on the x-axis, with color scales indicating pressure ratio values.]
Liquefaction, Stress-Strain Response
Pile in Liquefiable Soil, Model

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Pile in Liquefiable Soil, Results

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Real ESSI Simulator
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/](http://real-essi.us/)
- Collaborators: Feng, Lacour, Han, Behbehani, Sinha, Wang, Pisanó, Abell, McCallen, McKenna, Petrone
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