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

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Outline

Introduction
  Motivation
  Real-ESSI Simulator System

Inelasticity
  Energy Dissipation
  Coupled Systems

Seismic Motions
  6C vs 1C Motions
  Stress Test Motions

Summary
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Motivation

Improve modeling and simulation for infrastructure objects

Use select fidelity (high ↔ 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
Motivation

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 \( \sigma_{ij}, \epsilon_{ij}, u_i, \dot{u}_i, \ddot{u}_i \)
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 $\phi$

Lab $\phi$

Field $c_u$

Lab $c_u$
Motivation: Seismic Hazard

GLOBAL SEISMIC HAZARD MAP

Produced by the Global Seismic Hazard Assessment Program (GSHAP),
a demonstration project of the UN/International Decade of Natural Disaster Reduction
Global map assembled by
D. Giardini, G. Grünthal, K. Shedlock and P. Zhang, 1999
Motivation: Egypt Seismic Design Accelerations
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Real-ESSI Simulator System

The Real-ESSI, (Realistic Modeling and Simulation of Earthquakes, Soils, 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
  - 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

Real World

Conceptual Model

Highly accurate solution
Analytical solution
Benchmark ODE solution
Benchmark PDE solution

Computational Model

Computational Solution

Experimental Data
Unit Problems
Benchmark Cases
Subsystem Cases
Complete System

Verification

Validation

Oberkampf et al.

Jeremić et al.

Real-ESSI
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Summary
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

Input Mechanical Energy
(External Loads and/or Prescribed Displacements)

- Kinetic Energy
- Strain Energy
- Free Energy
- Plastic Free Energy

Dissipated Energy
- Material Plasticity
- Viscous Coupling
- Radiation Damping
- Numerical Damping

Recoverable
Conditionally Recoverable
Irrecoverable
Energy Dissipation Control Mechanisms

Plasticity  
Viscous  
Numerical
Energy Dissipation Control

![Energy Dissipation Control Graph](image)

- Kinetic Energy
- Strain Energy
- Plastic Free Energy
- Plastic Dissipation
- Viscous Damping
- Numerical Damping
- Input Work

**Axes:**
- Time [s]
- Energy [MJ]

**Legend:**
- Kinetic Energy (green)
- Strain Energy (blue)
- Plastic Free Energy (gray)
- Plastic Dissipation (red)
- Viscous Damping (magenta)
- Numerical Damping (cyan)
- Input Work (black)

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Real-ESSI
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
Structure Model

The nuclear power plant structure comprise of:

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

**Introduction**

**Inelasticity**

**Seismic Motions**

**Summary**

**Energy Dissipation**

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Real-ESSI
Energy Dissipation

**Acceleration Traces, Elastic vs Inelastic**

![Diagram showing acceleration traces for elastic and inelastic motions with depth and time axes.](image-url)
Energy Dissipation in NPP Model

(MP4)

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Wall, Regular and ASR Concrete

$u_y = 1.4 \text{ mm}$  
$u_y = 1.8 \text{ mm}$  
$u_y = 3.0 \text{ mm}$
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Fully Coupled Formulation, u-p-U

- Fully saturated soil
- Partially, un-saturated soil

\[
\begin{bmatrix}
(M_s)_{KijL} & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & (M_f)_{KijL}
\end{bmatrix}
\begin{bmatrix}
\ddot{u}_{Lj} \\
\ddot{p}_N \\
\ddot{U}_{Lj}
\end{bmatrix}
+ \begin{bmatrix}
(C_1)_{KijL} & 0 & -(C_2)_{KijL} \\
0 & 0 & 0 \\
-(C_2)_{LjiK} & 0 & (C_3)_{KijL}
\end{bmatrix}
\begin{bmatrix}
\ddot{u}_{Lj} \\
\ddot{p}_N \\
\ddot{U}_{Lj}
\end{bmatrix}
+ \begin{bmatrix}
(K^{EP})_{KijL} & -(G_1)_{KiM} & 0 \\
-(G_1)_{LjM} & -(P_{MN}) & -(G_2)_{LjM} \\
0 & -(G_2)_{KiL} & 0
\end{bmatrix}
\begin{bmatrix}
\ddot{u}_{Lj} \\
\ddot{p}_M \\
\ddot{U}_{Lj}
\end{bmatrix}
= \begin{bmatrix}
\ddot{f}_{solid}^{Ki} \\
0 \\
\ddot{f}_{fluid}^{Ki}
\end{bmatrix}
\]
Coupled Systems

Fully Coupled Formulation, $u-p-U$

\[
(M_s)_{KijL} = \int_{\Omega} H_K^U (1 - n) \rho_s \delta_{ij} H_L^U d\Omega \quad (M_t)_{KijL} = \int_{\Omega} H_K^U n \rho_t \delta_{ij} H_L^U d\Omega
\]

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

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

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

\[
P_{NM} = \int_{\Omega} H_N^p \frac{1}{Q} H_M^p d\Omega
\]
Liquefaction as Base Isolation, Model
Liquefaction, Wave Propagation
Liquefaction, Stress-Strain Response

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Real-ESSI
Pile in Liquefiable Soil, Model

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Real-ESSI
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 $\iff$ SSFI $\iff$ OpenFoam
Solid/Structure-Fluid Interaction, Example

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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

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Real-ESSI
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 vs 1C Motions

6C Realistic Ground Motions

- Free field seismic motion models
6C Realistic Ground Motions (closeup)
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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Introduction

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Summary
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, $\theta = 60^\circ$

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Real-ESSI
SMR ESSI, Variation in Input Frequency, $\theta = 60^\circ$
SMR ESSI, 3C vs 3×1C

(OGV)
Free Field vs ESSI - Different Frequencies

Acceleration response - Surface center point A

(a) $f = 1\,\text{Hz} \quad \theta = 60^\circ$

(b) $f = 5\,\text{Hz} \quad \theta = 60^\circ$

(c) $f = 10\,\text{Hz} \quad \theta = 60^\circ$
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/