Modeling and Simulation
Earthquake Soil Structure Interaction

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## Outline

**Introduction**
- Motivation

**Real-ESSI Simulator System**
- Real ESSI Components
- Stochastic Modeling
- High Performance Computing

**Modeling and Simulation Examples**
- Seismic Motions
- Plastic Energy Dissipation

**Conclusion**
- Real-ESSI Simulator System
Outline

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  Seismic Motions
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Conclusion
  Real-ESSI Simulator System
Motivation

Improve modeling and simulation for infrastructure objects
Reduction of modeling uncertainty
Choice of analysis level of sophistication
Goal: Predict and Inform rather than fit
Engineer needs to know!

System for modeling and simulation of Earthquakes and/or Soils and/or Structures and their Interaction:
Real-ESSI, 真简单
http://sokocalo.engr.ucdavis.edu/~jeremic/
Real_ESSI_Simulator/
Motivation

Prediction under Uncertainty

- **Modeling Uncertainty**, Simplifying assumptions
  
  Low, medium, high sophistication modeling and simulation
  
  Choice of sophistication level for confidence in results

- **Parametric Uncertainty**, \( M\ddot{u}_i + C\dot{u}_i + K^{ep}u_i = F(t) \),
  
  Uncertain mass \( M \), viscous damping \( C \) and stiffness \( K^{ep} \)
  
  Propagation of uncertainty in loads, \( F(t) \)
  
  Results are PDFs and CDFs for \( \sigma_{ij}, \epsilon_{ij}, u_i, \dot{u}_i, \ddot{u}_i \)
Motivation

Modeling Uncertainty

- Important (?!?) features are simplified, 1C vs 3C, inelasticity
- Modeling simplifications are justifiable if one or two level higher sophistication model demonstrates that features being simplified out are not important
Motivation

Parametric Uncertainty: Soil Stiffness and Strength

\[ E = (101.125 \times 19.3)^{0.63} \text{ kPa} \]

\[ S_u = (101.125 \times 0.29)^{0.72} \text{ kPa} \]

(cf. Phoon and Kulhawy (1999))
ESSI: 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/interface zone, structure, foundation, dissipators
  Viscous coupling with pore fluids, and external fluids

Numerical, algorithmic energy dissipation/production
Motivation

**Fully Coupled Formulation, u-p-U**

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

Fully Coupled Formulation, u-p-U

\[
(M_s)_{KijL} = \int_\Omega H_K^U (1-n) \rho_s \delta_{ij} H_L^U d\Omega \\
(M_f)_{KijL} = \int_\Omega H_K^U n \rho_f \delta_{ij} H_L^U d\Omega \\
(C_1)_{KijL} = \int_\Omega H_K^U n^2 k_i^{-1} H_L^U d\Omega \\
(C_2)_{KijL} = \int_\Omega H_K^U n^2 k_i^{-1} H_L^U d\Omega \\
(C_3)_{KijL} = \int_\Omega H_K^U n^2 k_i^{-1} H_L^U d\Omega \\
(K_{EP})_{KijL} = \int_\Omega H_K^U n D_{imjn} H_L^U d\Omega \\
(G_1)_{KiM} = \int_\Omega H_{K,i}^U (\alpha - n) H_M^p d\Omega \\
(G_2)_{KiM} = \int_\Omega n H_{K,i}^U H_M^p d\Omega \\
P_{NM} = \int_\Omega H_N^p \frac{1}{Q} H_M^p d\Omega
\]
Energy Dissipation Control

![Graph showing energy dissipation over time](image)

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

Motivation
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Real-ESSI Simulator System
Real ESSI Components
Stochastic Modeling
High Performance Computing

Modeling and Simulation Examples
Seismic Motions
Plastic Energy Dissipation

Conclusion
Real-ESSI Simulator System
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 time domain, linear and 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

Used for:

- Design, linear elastic, load combinations, dimensioning
- Assessment, nonlinear/inelastic, safety margins
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, worldwide

- System description and documentation at
  http://sokocalo.engr.ucdavis.edu/~jeremic/Real_ESSI_Simulator/
Quality Assurance

- Full verification suit for each element, model, algorithm
- Certification process in progress for NQA-1 and ISO-90003-2014
Real-ESSI Components

Real-ESSI Modeling Features

- Solid elements, dry, (un-)saturated, elastic, inelastic
- Structural elements, beams, shells, elastic, inelastic
- Contact elements, dry, coupled/saturated,
- Super element, stiffness and mass matrices
- Material models, soil, concrete, steel...
- Seismic input, 1C and 3C, deterministic or probabilistic
- Energy dissipation calculations
- Solid/Structure – Fluid interaction, full coupling
- Intrusive probabilistic inelastic modeling
Real-ESSI Simulation Features

- Static loading stages
- Dynamic loading stages
- Restart, simulation tree
- Solution advancement methods/algorithms, on global and constitutive levels, with and without enforcing equilibrium
- High Performance Computing
  - Fine grained, template mataprograms, small matrix library
  - Coarse grained, distributed memory parallel
Real-ESSI Model Development

- Pre-Processing, model development gmsh/gmESSI
- Existing model translation, SASSI → Real-ESSI
- Choose level of sophistication
- Reduce modeling uncertainty
- Model developed in phases
- Verify model components
- Build confidence in inelastic modeling
Real-ESSI Components

Real-ESSI Modeling Phases
Real-ESSI Results Post Processing

- All output is saved (stress, strain, displacements, energy...)
- Time histories, scripts to plot or extract in preferred format
- 3D visualization, Paraview with pvESSI plugin
Real-ESSI Training and Education

- Short Courses:
  - Online short course, soon
  - Professional practice
  - Examples available in lecture notes, and documentation
  - Real-ESSI Simulator system, with examples on Amazon Web Services (AWS)

- Full lecture notes (2600+ pages) available online

- Up to date information on Real-ESSI at:

  http://sokocalo.engr.ucdavis.edu/~jeremic/Real_ESSI_Simulator/
Real-ESSI Core Functionality

- Introduction to inelastic, nonlinear analysis for practicing engineers
- Use of prescribed, required (low, medium, high) fidelity numerical models to analyze ESSI behavior
- Set of suggested modeling and simulation parameters
- Investigate sensitivity of response to model sophistication
- Investigate sensitivity of response to model parameters
Real-ESSI Core Functionality Components

- Structural elements: Truss, Beam, Shell, Super-Element
- Soil, solids: elastic, $G/G_{max}$
- Contacts: Bonded, Frictional, Gap open/close
- Loads: Static, Dynamic (earthquake, 1C or $3 \times 1C$), Restart
- Simulation: Explicit no-equilibrium, Implicit equilibrium
- Core Functionality Application programs: APPs
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Existing Simulation Methods for Stochastic PDEs

- Analytical, stochastic differential equation approach: difficult to solve with complex random coefficients
- Monte Carlo method: Computationally expensive
- Perturbation approach: Small variation with respect to mean, closure problem
- Stochastic collocation method: Global error minimization
- Stochastic Galerkin method: Local error minimization
Stochastic Modeling

Time Domain Stochastic Galerkin Method

- Input random field/process (non-Gaussian, heterogeneous/non-stationary)
  Multi-dimensional Hermite Polynomial Chaos (PC) with known coefficients

- Output response process
  Multi-dimensional Hermite PC with unknown coefficients

- Galerkin projection: minimize the error to compute unknown coefficients of response process

- Time integration using Newmark’s method
  Update coefficients following an elastic-plastic constitutive law at each time step

Note: PC = Polynomial Chaos
Polynomial Chaos Representation

Material random field: \( D(x, \theta) = \sum_{i=1}^{P_1} a_i(x) \psi_i(\{\xi_r(\theta)\}) \)

Motion random process: \( f_m(t, \theta) = \sum_{j=1}^{P_2} f_{mj}(t) \psi_j(\{\xi_k(\theta)\}) \)

Displacement response: \( u_n(t, \theta) = \sum_{k=1}^{P_3} d_{nk}(t) \psi_k(\{\xi_l(\theta)\}) \)

where \( a_i(x), f_{mj}(t) \) are known PC coefficients, while \( d_{nk}(t) \) are unknown PC coefficients.


**Stochastic Elastic-Plastic Response**

**Governing equation:**

\[ d\sigma_{ij} = E_{ijkl} d\epsilon_{kl} \]

\[
E_{ijkl} = \begin{cases} 
E_{ijkl}^{el} & \text{for elastic} \\
E_{ijkl}^{el} - \frac{E_{ijmn}^{el} m_{mn} n_{pq} E_{pqkl}^{el}}{n_{rs} E_{rstu}^{el} m_{tu} - \xi h} & \text{for elastic–plastic}
\end{cases}
\]
Transformation of a Bi–Linear, von Mises Response

linear elastic – linear hardening elastic-plastic von Mises
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Course and Fine Grained HPC

- Hardware Aware Plastic Domain Decomposition (HAPDD) Method
- Small Tensor Library

![Graph showing speedup vs. number of cores for different domain decomposition methods.](image-url)
HAPDD

Original Model  Partitioned Model  Computer Architecture

Jeremić et al.
Real-ESSI
HAPDD

Partitioned Domains

Performance on Different Architectures

Jeremić et al.

Real-ESSI
Small Tensor Library

- Benchmark Libraries
  - **LTensor** – Target library
  - **SmallTensor** – Our Small Tensor Library for Computational Mechanics.

- Runtime Performance Comparison

![Runtime Performance](image1)

![Peak Memory Usage](image2)
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Seismic Motions

- Variation in inclination, frequency, energy, duration...
- Deterministic and Probabilistic
- Stress test the soil-structure system
Seismic Motions

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

(MP4)
SMR ESSI, Variation in Input Frequency, $\theta = 60^\circ$
SMR ESSI, Variation in Input Frequency, REAL TIME

Jeremić et al.

Real-ESSI
SMR ESSI, 3C vs 3 × 1C

(OGV)

Jeremić et al.

Real-ESSI
Seismic Motions

3C, 6C Seismic Motions

- All (most) measured motions are full 3C, 6C
- One example of an almost 2C motion (LSST07, LSST12)
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, 1C from 6C
- Excellent fit

(DB: npp_model01_ff_quake.h5.feloutput
Time:0.77)

(DB: npp_model01_ff_quake.h5.feloutput
Time:0.72)

(MP4) (MP4)
6C vs 1C NPP ESSI Response Comparison

(MP4)
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
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Energy input, dynamic forcing

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  Reflected wave radiation

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  Viscous coupling with internal/pore fluids, and external fluids

Numerical energy dissipation/production
Plastic Energy Dissipation

Single elastic-plastic element under cyclic shear loading

Difference between plastic work and plastic dissipation
Plastic work can decrease
Plastic dissipation always increases
Energy Dissipation Control

![Graph showing energy dissipation control with various energy components over time.]

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

Energy [MJ] vs. Time [s]
Inelastic Modeling of Soil Structure Systems

- **Soil, inelastic, 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, excess pressure, buoyant force

- **Structure, inelastic, damage, cracks**
  - Nonlinear/inelastic 1D reinforced concrete fiber beam
  - Nonlinear/inelastic 3D reinforced concrete solid element
  - Alcali Silica Reaction concrete modeling
Inelastic Soil and Inelastic Contact

- Shear velocity of soil \( V_s = 500 \text{m/s} \)
- Undrained shear strength (Dickenson 1994)
  \[ V_s[m/s] = 23(S_u[kPa])^{0.475} \]
- 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
Plastic Energy Dissipation

**Acceleration Traces, Elastic vs Inelastic**

![Elastic Example](image1.png)

![Inelastic Example](image2.png)

Elastic

Inelastic

 Jeremić et al.

Real-ESSI
Plastic Energy Dissipation

**Displacement Traces, Elastic vs Inelastic**

![Displacement traces](image)

**Elastic**

**Inelastic**
Elastic and Inelastic Response: Differences

Time: 10.67 [s]

Displacement Magnitude $||U||$ [m]

Acceleration $A_x$ [g]

Disp. $U_x$ [m]

Disp. $U_y$ [m]

Acceleration $A_y$ [g]

Acceleration $A_z$ [g]

Plastic Energy Dissipation

Jeremić et al.

Real-ESSI
Energy Dissipation in a Large-Scale Model

Accumulated Plastic Dissipation Density (J/m³)

Incremental Plastic Dissipation Density (J/m³)

Time Step: 620

Jeremić et al.

Real-ESSI
Energy Dissipation for an SMR Model

(MP4)

Jeremić et al.

Real-ESSI
Energy Dissipation for Design
Design Alternatives

Plastic Energy Dissipation
Wall, Regular and ASR Concrete

![Diagram of Wall, Regular and ASR Concrete](image)

- Concrete Damage Index
  - $u_y = 1.4\,\text{mm}$
  - $u_y = 1.8\,\text{mm}$
  - $u_y = 3.0\,\text{mm}$
Buoyant Force Simulation

8 node solid brick (3 dofs)

8 node upU (7 dofs)

Coupled Contact
Solid, Structure-Fluid Interaction, Example

(MP4)
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  - Government Agencies, National Labs: AWS GovCloud
  - Professional Practice: AWS, commercial

- Quality Management System, ASME-NQA-1, ISO9003-2018, Certification in progress

- Real-ESSI Short Courses (online, this Fall)

- System description and documentation at
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: Feng, Yang, Behbehani, Sinha, Wang, Wang, Pisanó, Abell, Tafazzoli, Jie, Preisig, Tasiopoulou, Watanabe, Luo, Cheng, Yang...
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