Realistic Modeling and Simulation of Earthquakes, Soil, Structures and their Interaction

Boris Jeremić
University of California, Davis

Duke University
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Outline

Introduction

Uncertain Inelastic Mechanics
  Forward Propagation
  Backward Propagation, Sensitivities

Real-ESSI Simulator

Examples
  Seismic Motions
  Plastic Energy Dissipation
  Sensitivity Analysis

Conclusion
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Motivation

Improve modeling and simulation for infrastructure objects

Modeling sophistication level, epistemic uncertainty

Parametric, aleatory uncertainty

Goal: Predict and Inform

Expert numerical modeling and simulation tool

Engineer needs to know!
Numerical Prediction under Uncertainty

- Modeling, Epistemic Uncertainty
  
  Modeling simplifications
  
  Modeling sophistication for confidence in results

- Parametric, Aleatory Uncertainty

\[ M\ddot{u}_i + C\dot{u}_i + K^{ep} u_i = F(t), \]

Uncertain: mass \( M \), viscous damping \( C \) and stiffness \( K^{ep} \)

Uncertain loads, \( F(t) \)

Results are PDFs and CDFs for \( \sigma_{ij}, \epsilon_{ij}, u_i, \dot{u}_i, \ddot{u}_i \)
Modeling, Epistemic 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 less or not important
Parametric, Aleatory Uncertainty

E = (101.125*19.3) N^{0.63}

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

(cf. Phoon and Kulhawy (1999B))

(cf. Wang et al. (2019))

Jeremić et al.
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Conclusion
Forward Propagation

Forward Uncertain Inelasticity

- Incremental el–pl constitutive equation

\[
\Delta \sigma_{ij} = E_{ij}^{EP} \Delta \epsilon_{kl} = \left[ E_{ij}^{el} - \frac{E_{ij}^{el} m_{mn} n_{pq} E_{pq}^{el}}{n_{rs} E_{rst}^{el} m_{tu} - \xi^* h^*} \right] \Delta \epsilon_{kl}
\]

- Dynamic Finite Elements

\[
M \ddot{u}_i + C \dot{u}_i + K^{ep} u_i = F(t)
\]

- Material and loads are uncertain
Cam Clay with Random $G$, $M$ and $\rho_0$
Stochastic Elastic-Plastic Finite Element Method

- Material uncertainty expanded into stochastic shape funcs.
- Loading uncertainty expanded into stochastic shape funcs.
- Displacement expanded into stochastic shape funcs.
- Jeremić et al. 2011

\[
\begin{bmatrix}
\sum_{k=0}^{P_d} \phi_k \psi_0 \psi_0 & K^{(k)} & \cdots & \sum_{k=0}^{P_d} \phi_k \psi_P \psi_0 & K^{(k)} \\
\sum_{k=0}^{P_d} \phi_k \psi_0 \psi_1 & K^{(k)} & \cdots & \sum_{k=0}^{P_d} \phi_k \psi_P \psi_1 & K^{(k)} \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
\sum_{k=0}^{P_d} \phi_k \psi_0 \psi_P & K^{(k)} & \cdots & \sum_{k=0}^{M} \phi_k \psi_P \psi_P & K^{(k)}
\end{bmatrix}
\begin{bmatrix}
\Delta u_{10} \\
\vdots \\
\Delta u_{N0} \\
\vdots \\
\Delta u_{1P_P} \\
\vdots \\
\Delta u_{MN_P_P}
\end{bmatrix}
= 
\begin{bmatrix}
\sum_{i=0}^{P_f} f_i & \psi_0 \zeta_i \\
\sum_{i=0}^{P_f} f_i & \psi_1 \zeta_i \\
\sum_{i=0}^{P_f} f_i & \psi_2 \zeta_i \\
\vdots & \vdots \\
\sum_{i=0}^{P_f} f_i & \psi_{P_0} \zeta_i 
\end{bmatrix}
\]
Outline

Introduction

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ANOVA Representation

Model with $n$ uncertain inputs ($\mathbf{x}$) and scalar output $y$:

$$y = f(\mathbf{x}); \quad \mathbf{x} \in I^n$$

The ANalysis Of VAriance representation (Sobol 2001):

$$f(x_1, \ldots, x_n) = f_0 + \sum_{i=1}^{n} f_i(x_i) + \sum_{1 \leq i < j \leq n} f_{ij}(x_i, x_j) + \ldots f_{1,\ldots,n}(x_1, \ldots, x_n)$$
Sobol Indices

- Sobol’ indices $S_{i_1...i_s}$, fractional contributions from random inputs $\{X_{i_1}, \ldots, X_{i_s}\}$ to the total variance $D$: $S_{i_1...i_s} = D_{i_1...i_s}/D$

- First order indices $S_i \rightarrow$ individual influence of each uncertain input parameter

- Higher order indices $S_{i_1...i_s} \rightarrow$ mixed influence from groups of uncertain input parameters

- Total sensitivity indices, influence of input parameter $X_i$

$$S_{i}^{\text{total}} = \sum_{\mathcal{I}_i} D_{i_1...i_s}$$
Sobol Indices and Polynomial Chaos

PC expansion of response, in ANOVA form (Sudret 2008)

Multi-dimensional PC bases \( \{\psi_j(\xi)\} \) decomposed into products of single dimension PC chaos bases of different orders

\[
\psi_j(\xi) = \prod_{i=1}^{n} \phi_{\alpha_i}(\xi_i)
\]

\( \phi_{\alpha_i}(\xi_i) \) is the single dimensional, order \( \alpha_i \), polynomial function of underlying basic random variable \( \xi_i \).
Sobol Sensitivity Analysis

\[
\text{ANOVA } \rightarrow \text{ Sobol' indices: } S^\text{PC}_{i_1...i_s} = \sum_{\alpha \in \mathcal{I}_{i_1...i_s}} y^2_\alpha \mathbb{E} \left[ \psi^2_\alpha \right] / D^\text{PC}
\]

Total Sobol' indices: \[ S^\text{PC, total}_{j_1...j_t} = \sum_{(i_1,...,i_s) \in \mathcal{I}_{i_1,...,i_s}} S^\text{PC}_{i_1...i_s} \]

Using PC representation of probabilistic model response, Sobol’ sensitivity indices are analytic and inexpensive
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Introduction

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Examples
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Conclusion
Real-ESSI Simulator System

The Real-ESSI, **Real**istic Modeling and Simulation of **Earthquakes**, **Soils**, **Structures** and their **Interaction** Simulator is a software, hardware and documentation system for time domain, linear and nonlinear, elastic and inelastic, deterministic or probabilistic, 3D, 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

Components
- Real-ESSI Pre (gmsh/gmESSI, X2ESSI)
- Real-ESSI Program (local, remote, cloud)
- Real-ESSI Post (Paraview/pvESSI, Python, Matlab)

Availability
- Linux Executables
- Amazon Web Services
- Docker Container Image
  - Linux
  - MS-Windows
  - MacOS

Real-ESSI documentation and program available at http://real-essi.us/
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 DSL Example

```plaintext
model name "SmallTestModel";
new loading stage "First_static";

// Nodal Coordinates
add node # 1 at (0*m, 0*m, 0*m) with 6 dofs;
add node # 2 at (0*m, 0*in, 1000*mm) with 6 dofs;
add element # 1 type beam_elastic with
    nodes (1, 2) cross_section=1.0*m^2
    elastic_modulus=1.0e5*KN/m^2
    shear_modulus=2.0e4*KN/m^2
    torsion_Jx=2*0.083*m^4
    bending_Iy=0.083*m^4 bending_Iz=0.083*m^4
    mass_density=2500.0*kg/m^3
    xz_plane_vector = (0, -1, 0)
    joint_1_offset = (0.0*m, 0.0*m, 0.0*m)
    joint_2_offset = (0.0*m, 0.0*m, 0.0*m);
```

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Real-ESSI
Real ESSI DSL Example

```plaintext
1. fix node No 1 dofs all;
2. add load #1 to node #2 type linear \( F_y = -9 \times 10^3 \) kN;
3. define load factor increment 0.01;
4. define solver UMFPack;
5. define convergence test
   Norm_Displacement_Increment
   tolerance = 1e-5
   maximum_iterations = 20
   verbose_level = 4;
7. define algorithm Newton;
8. simulate 100 steps using static algorithm;
9. bye;
```
<table>
<thead>
<tr>
<th>Introduction</th>
<th>Uncertain Inelastic Mechanics</th>
<th>Real-ESSI Simulator</th>
<th>Examples</th>
<th>Conclusion</th>
</tr>
</thead>
</table>

Seismic Motions

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- Introduction
- Uncertain Inelastic Mechanics
  - Forward Propagation
  - Backward Propagation, Sensitivities
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- Examples
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  - Plastic Energy Dissipation
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Realistic Ground Motions
Seismic Motions

1C vs 6C Free Field Motions

- One component of motions, 1C from 6C
- Excellent fit
- Wrong mechanics
6C vs 1C NPP ESSI Response Comparison
Free Field, Variation in Input Frequency, $\theta = 60^\circ$

(MP4)
SMR ESSI, Variation in Input Frequency, $\theta = 60^\circ$
SMR ESSI, 3C vs 3×1C

(OGV)

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Real-ESSI
Outline

Introduction

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Real-ESSI Simulator

Examples
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Conclusion
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, interfaces, structure, dissipators
- Viscous coupling with internal/pore 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
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**

**Figure**

Jeremić et al. (2023) Real-ESSI
Inelastic Modeling of Soil Structure Systems

- Soil, inelastic, elastic-plastic
  Dry, single phase
  Unsaturated, partially saturated
  Fully saturated
- Contact/Interface/Joint, inelastic: dry or saturated
  Axial, hard and soft, gap open/close
  Shear, friction, nonlinear
- Structure, inelastic, damage, cracks
  Inelastic fiber beam
  Inelastic layer shell
  Inelastic 3D solid element
Acceleration Traces, Elastic vs Inelastic

Elastic

Inelastic
Plastic Energy Dissipation

Displacement Traces, Elastic vs Inelastic

Elastic

Inelastic

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Real-ESSI
NPP: Energy Dissipation

Accumulated Plastic Dissipation Density (J/m³)

Time Step: 620

(MP4)
Energy Dissipation for Design
Design Alternatives

Plastic Energy Dissipation

(MP4) (MP4)

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Outline

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Real-ESSI Simulator

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Conclusion
Sensitivity Analysis

Stochastic Site Response

- Uncertain material: uncertain random field, marginally lognormal distribution, exponential correlation length 10m
- Uncertain seismic rock motions: seismic scenario M=7, R=50km
Sensitivity Analysis

Stochastic Material Parameters

Lognormal distributed random field with PC Dim. 3 Order 2

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Real-ESSI
Stochastic Seismic Motion Development

- UCERF3 (Field et al. 2014)
- Stochastic motions (Boore 2003)
- Polynomial Chaos Karhunen-Loève expansion
- Probabilistic DRM (Bielak et al. 2003, Wang et al. 2021)
Sensitivity Analysis

Stochastic Seismic Motions

![Graph showing stochastic seismic motions](image)

- **Realizations**
- **Mean**

![Graph showing Sa vs. Period](image)

- **Simu. Sa**
- **GMPE**
Sensitivity Analysis

Total variance in PGA, in this case (!), dominated by uncertain ground motions

49% from uncertain rock motions at depth

2% from uncertain soil

49% from interaction of uncertain rock motions and uncertain soil
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Real-ESSI Simulator

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Conclusion
Appropriate Quotes

François-Marie Arouet, Voltaire: "Le doute n’est pas une condition agréable, mais la certitude est absurde."

Max Planck: "A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."

Niklaus Wirth: "Software is getting slower more rapidly than hardware becomes faster."
Summary

- Numerical modeling to predict and inform

- Education and Training is the key!


- Funding from and collaboration with the US-NSF, US-DOE, US-NRC, US-FEMA/ATC, CNSC-CCSN, CH-ENSI/Basler&Hofmann, UN-IAEA, and Shimizu Corp. is greatly appreciated,

http://sokocalo.engr.ucdavis.edu/~jeremic