Time Domain Nonlinear Earthquake Soil Structure Interaction Analysis

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Outline

Introduction

Real-ESSI Simulator
  Real-ESSI
  Verification and Validation

ESSI Analysis
  Seismic Motions
  Inelasticity
  Probabilistic Modeling

Summary
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Summary
Motivation

Improve modeling and simulation for infrastructure objects
Control modeling, epistemic uncertainty
Propagate parametric, aleatory uncertainty
Predict and inform, Engineer needs to know!
Design, build and maintain sustainable objects
Dedication

Robert P. Kennedy, 1939-2018

"Response of a soil structure system is nonlinear, and I would really like to know what that response is!"

"There are engineers and then there are Engineers!"
Dedication

Nebojša Orbović, 1962-2021

"As an engineer, I have to know, with good accuracy, what will happen to the structure during loading, hence numerical analysis and verification and validation for numerical analysis is really important"

"As an engineer, I have to know what are response sensitivities to modeling parameters."
Engineer Needs to Know!

Engineer needs versatile, quality assured analysis tool
- Explore different design options
- Assess object performance

Choice of analysis/modeling level of sophistication

Predict and Inform
Numerical Prediction under Uncertainty

- Modeling, Epistemic Uncertainty
  - Modeling simplifications
  - Model sophistication
  - Verification and Validation
  - Elastic design does NOT guaranty safe structure!

- 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 $\sigma_{ij}$, $\epsilon_{ij}$, $u_i$, $\dot{u}_i$, $\ddot{u}_i$
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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, free executable downloads:
- MS-Windows
- MacOS
- Linux
- Amazon Web Services

Real-ESSI program, documentation, examples:
http://real-essi.us/
Real-ESSI Simulator Quality Assurance

- Verification available for each element, model, algorithm, ...

- Validation partially available, working with UCSD, TJU...
Real-ESSI Modeling Features

- Solids: dry, saturated/liquefaction, elastic, elastic-plastic
- Structural elements: beams (B,T), shells, elastic, inelastic
- Contact/interface/joint elements: gapping, frictional
- Super element: stiffness and mass matrices
- Material models: soil, rock, concrete, steel...
- Seismic input: 1C and 3C, deterministic or probabilistic
- Energy calculations: input, el-pl, viscous, algorithmic
- Solid/Structure-Fluid interaction, full coupling, OpenFOAM
- Forward probabilistic inelastic modeling
- Backward probabilistic inelastic modeling: Sensitivities
- Input: Domain Specific Language
ESSI Modeling Phases
# Real-ESSI Core Functionality

- Inelastic, nonlinear analysis for professional practice  
- Low/medium/high sophistication models for ESSI analysis  
- 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/interfaces/joints: Bonded, Frictional, Gap open/close
- Loads: Static, Dynamic, Earthquake 1C/3$\times$1C/3C, Restart
- Simulation: explicit/no-equilibrium, Implicit/equilibrium
- Core Functionality Application programs: APs
Real-ESSI Education and Training

- In-person and online courses
- Lecture Notes/Book:
  (I) Theory and Computational Formulation,
  (II) Software and Hardware System,
  (III) Verification and Validation,
  (IV) Modeling and Simulation Examples,
  (V) Application to Practical Engineering Problems.
- Nonlinear SSI workshop at SMiRT26
- Nonlinear SSI short course at SMiRT26
- Documentation and Program at http://real-essi.us/
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Verification and Validation

- Verification: provides evidence that the model is solved correctly. Mathematics issue. Well developed for the Real ESSI Simulator.

- Validation: provides evidence that the correct model is solved. Physics issue. Work in progress (UCSD, TJU, ...)

- Prediction: use of computational model to foretell the state of a physical system under consideration under conditions for which the computational model has not been validated.
V & V Motivation

- How much can we trust model implementations?
- How much can we trust numerical simulations?
- How good are our numerical predictions?
- Can simulation tools be used for improving safety and economy?
- V & V procedures are the primary means of assessing accuracy and building confidence and credibility in modeling and computational simulations
Fundamentals of Verification and Validation
Verification and Validation

V & V Important Documents


## Verification and Validation Summary

- V&V most important for providing confidence in results
- FEM analysis model verification is essential too!
- Numerical analysis should not be used without V&V
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## ESSI Analysis

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## Summary
Realistic Ground Motions
1C vs 6C Free Field Motions

- One component of motions, 1C from 6C
- Excellent fit, wrong dynamics

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

(MP4)
When to use 3C and/or $3 \times 1C$
Seismic Motions

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

![Graphs showing displacement magnitude for different input frequencies](MP4)
**SMR ESSI, 3C vs 3 × 1C**

(OGV)

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**Nonlinear ESSI Analysis**
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Nonlinear ESSI Analysis
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 zone, structure, foundation, dissipators
- Viscous coupling with internal/pore fluids, and external fluids

Numerical energy dissipation/production
Inelasticity

**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
Inelastic Modeling of Soil Structure Systems

- Soil, inelastic, elastic-plastic
  - Dry, single phase
  - Unsaturated, partially saturated
  - Fully saturated

- Contact/interface/joint, 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 reinforced concrete fiber beam
  - Nonlinear/inelastic reinforced concrete solid element
  - Alcali Silica Reaction concrete modeling
Inelasticity

Acceleration Traces, Elastic vs Inelastic

Elastic  Inelastic

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Nonlinear ESSI Analysis
Displacement Traces, Elastic vs Inelastic

Elastic

Inelastic
NPP: Plastic Energy Dissipation

Inelasticity

(MP4)
SMR: Plastic Energy Dissipation

(MP4)

Incremental Plastic Dissipation Density (J/m3)

Accumulated Plastic Dissipation Density (J/m3)
Energy Dissipation for Design

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Nonlinear ESSI Analysis
Design Alternatives

(MP4)  (MP4)
Regular and ASR Concrete

Inelasticity

\[ u_y = 1.4 \text{ mm} \]
\[ u_y = 1.8 \text{ mm} \]
\[ u_y = 3.0 \text{ mm} \]
Building on Liquefiable Soil

Plastic Strain

Pore Fluid Pressures

(MP4) (MP4)
Solid, Structure-Fluid Interaction, Example

(MP4)

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Probabilistic Modeling

El-PI, Cam Clay with Random \( G, M \) and \( \rho_0 \)

![Graph showing stress-strain behavior with standard deviation lines, mean line, and deterministic line.](image)

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Nonlinear ESSI Analysis
Probabilistic Cyclic Elastic-Plastic Response

**Cyclic Loading of Uncertain Stress**

- Mean Stress
- Mean Stress $\pm \sigma$
- Beginning Loading Stage
- Current Mean Stress
- Beginning Unloading Stage

**Cyclic Loading of Uncertain Stiffness**

- Mean Stiffness
- Mean Stiffness $\pm \sigma$
- Beginning Unloading Stage
- Current Mean Stiffness
- Beginning Reloading Stage

**Evolution of Stress PDF**

- Probability Density Function
- Current Mean Stress

**Evolution of Stiffness PDF**

- Probability Density Function
- Current Mean Stiffness
Stochastic Ground Motion Modeling

- Shift from modeling specific Intensity Measures (IMs) to fundamental characteristics of ground motions
  - Uncertain Fourier amplitude spectra (FAS)
  - Uncertain Fourier phase spectra (FPS)

- No need to define Intensity Measures!

- GMPE studies of FAS, (Bora et al. (2018), Bayless & Abrahamson (2018,2019), Stafford(2017), )

- Stochastic FPS by phase derivative (Boore,2005) (Logistic phase derivative model by Baglio & Abrahamson (2017))

- Near future change from $Sa(T_0)$ to FAS
Application: Seismic Hazard

Seismic source characterization

Stochastic ground motion

Probabilistic Modeling

UCERF3 (2014)

\[ \lambda(\text{EDP} > z) = \sum N_i(M_i, R_i) P(\text{EDP} > z | M_i, R_i) \]

Fourier spectra

Boore (2003)

Site attenuation (Kappa)

(modified from Boore, 1983)

Uncertainty propagation

SEPFEM

Uncertainty characterization

Hermite polynomial chaos

EDP hazard/risk

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

Normalized Frequency

PDF

Annual Exceedance Rate

MIDR [%]

Time [s]

0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0

0.00000 0.00005 0.00010 0.00015 0.00020 0.00025 0.00030 0.00035

0.0000 0.00005 0.0001 0.00015 0.0002 0.00025 0.0003 0.00035

9 \times 10^{-4} 2.3 \times 10^{-4} 1 \times 10^{-4}
Example Soil-Structure/Location

- Fault 1: San Gregorio fault
- Fault 2: Calaveras fault
- Uncertainty: Segmentation, slip rate, rupture geometry, etc.

- 371 total seismic scenarios
- $M 5 \sim 5.5$ and $6.5 \sim 7.0$
- $R_{jb} 20 km \sim 40 km$
Seismic Risk Analysis, Forward Propagation

- No need to define Intensity Measures!

- Damage measure defined on single EDP:

<table>
<thead>
<tr>
<th>DM</th>
<th>MIDR&gt;0.5%</th>
<th>MIDR&gt;1%</th>
<th>MIDR&gt;2%</th>
<th>PFA&gt;0.5m/s²</th>
<th>PFA&gt;1m/s²</th>
<th>PFA&gt;1.5m/s²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk [/yr]</td>
<td>$6.66 \times 10^{-3}$</td>
<td>$3.83 \times 10^{-3}$</td>
<td>$9.97 \times 10^{-5}$</td>
<td>$6.65 \times 10^{-3}$</td>
<td>$1.92 \times 10^{-3}$</td>
<td>$9.45 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

- Damage measure (DM) defined on multiple EDPs:

  $DM : \{\text{MIDR} > 1\% \cup \text{PFA} > 1\text{m/s}^2\}$, seismic risk is $4.2 \times 10^{-3}/\text{yr}$

  $DM : \{\text{MIDR} > 1\% \cap \text{PFA} > 1\text{m/s}^2\}$, seismic risk is $1.71 \times 10^{-3}/\text{yr}$

- Seismic risk for DM defined on multiple EDPs can be quite different from that defined on single EDP.
Sensitivity Analysis, Backward Propagation

- Sensitivity of forward uncertain response to input uncertainties
- Analytic sensitivity analysis development
- 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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- Predict and Inform, Engineer Needs to Know!
- Teacher, Motivator, Supporter: Robert P Kennedy
- Collaborators: Yang, Feng, Behbehani, Sinha, Wang, Wang, Pisanó, Abell, Tafazzoli, Jie, Preisig, Tasiopoulou, Watanabe, Luo, Cheng, Yang, Lizundia, Rangelow, Vögeli, Salamon, Altinyollar, ...
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- http://real-essi.us/