Нумеричка анализа интеракције тла и конструкције услед дејства земљотреса

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Српско Удружење за земљотресно инжењерство
СУЗИ
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Outline

Introduction

Real-ESSI Simulator System

Earthquake Soil Structure Interaction
  Seismic Motions
  Plastic Energy Dissipation

Summary
Outline

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  Seismic Motions
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Summary
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!
Hypothesis

- Interplay of the Earthquake, Soil/Rock and Structure in time domain, plays a major 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
  Economy
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, porous solid-pore fluids, solids/structures-external fluids

Numerical, algorithmic energy dissipation/production
Early Work on ESSI

- Professor Kyoji Suyehiro
- Ship engineer (Professor of Naval Arch. at U. of Tokyo),
- Witnessed Great Kantō earthquake, Tokyo, 01Sep1923 11:58(7.5), 12:01(7.3), 12.03(7.2), shaking until 12:08
- Saw earthquake surface waves travel and buildings sway
- Became founding Director of the Earthquake Engineering Research Institute at the Univ. of Tokyo,
- His published records (ASCE 1932) show four times more damage to soft wooden buildings on soft ground then same buildings on stiff soil
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 \( \sigma_{ij}, \epsilon_{ij}, u_i, \dot{u}_i, \ddot{u}_i \)
Goal: Reduction of Modeling Uncertainty

- Modeling Uncertainty: introduced with unnecessary and unrealistic modeling simplification

- Simplified (or inadequate/wrong) modeling: important features are missed (3C (6C) seismic ground motions, inelasticity, etc.)

- Modeling simplifications are justifiable if one, two or higher level sophistication model demonstrates that features being simplified out are not important

- Use of HPC for low modeling uncertainty and direct probabilistic modeling and simulations
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PolicyView
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 time domain, linear and nonlinear, elastic and inelastic, deterministic or probabilistic, 3D, modeling and simulation of Earthquakes, Soils Structures and their Interaction.

Real-ESSI is used for:
- Design, linear elastic, load combinations, dimensioning
- Assessment, nonlinear/inelastic, safety margins

http://real-essi.us/
Verification and Validation

- Verification: provides evidence that the model is solved correctly. Mathematics issue.

- Validation: provides evidence that the correct model is solved. Physics issue.

- 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.

- How good are our numerical predictions?

- Use simulation tools to improve safety and economy?
V & V Motivation

- How much can (should) we trust model implementations (verification)?
- How much can (should) we trust numerical simulations (validation)?
- Can simulation tools be used for improving safety and economy?
- 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
Fundamentals of Verification and Validation
Important Sources


Verification

- Source code management
- Source code verification
- Constitutive integration
- Static and dynamic behavior of single phase solids
- Static and dynamic behavior of fully and partially saturated, fully coupled, porous solid-pore fluid problems
- Static and dynamic behavior of structural elements
- Static and dynamic behavior of special elements (contacts-interfaces/gap-frictional/dry-saturated, isolators/dissipators)
- Static and dynamic FEM solution advancement
- Seismic wave propagation problems
- FEM Model verification, hierarchy of models
Constitutive Integration Verification

- Asymptotic regime of convergence
- Richardson extrapolation
- Grid convergence index
Energy Dissipation Verification: Plastic Work ≠ Plastic Dissipation

Direct violation of the second law of thermodynamics
600 papers since 1990 (!?!?) repeat this error

From a paper on *Soil Dynamics and Earthquake Engineering* (2011)
Dynamic Time Stepping Verification

Based on the amplification matrix $A$, to calculate the analytical solution of damping ratios and period shift.
Example: Hilber-Hughes-Taylor $\alpha = -0.1$
Seismic Input Verification, DRM, EW, NS, UD

Jеремић
Нумериčка анализа интеракције тла и конструкције услед дејства земљотреса
Verification: ANDES Shell

<table>
<thead>
<tr>
<th>$N_{subd}$</th>
<th>$u_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>96.2118</td>
</tr>
<tr>
<td>7</td>
<td>100.096</td>
</tr>
<tr>
<td>101</td>
<td>100.002</td>
</tr>
</tbody>
</table>

Mode 1, $T = 0.999959s$

Mode 1, $T = 0.998022s$
Verification: Irregular Solids and Poisson’s Ratio

<table>
<thead>
<tr>
<th>Force direction</th>
<th>Shape 1</th>
<th>Shape 2</th>
<th>Shape 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical (z)</td>
<td>0.40%</td>
<td>0.85%</td>
<td>0.60%</td>
</tr>
<tr>
<td>Transverse (y)</td>
<td>0.54%</td>
<td>3.67%</td>
<td>0.46%</td>
</tr>
</tbody>
</table>

Poisson’s ratio | 27NodeBrick displacement | Theory displacement | Error |
--- | --- | --- | --- |
0.00 | 8.797E-04 m | 8.784E-04 m | 0.15% |
0.05 | 8.801E-04 m | 8.791E-04 m | 0.11% |
0.10 | 8.799E-04 m | 8.799E-04 m | 0.01% |
0.15 | 8.792E-04 m | 8.806E-04 m | 0.16% |
0.20 | 8.778E-04 m | 8.813E-04 m | 0.40% |
0.25 | 8.758E-04 m | 8.821E-04 m | 0.71% |
0.30 | 8.730E-04 m | 8.828E-04 m | 1.12% |
0.35 | 8.692E-04 m | 8.836E-04 m | 1.63% |
0.40 | 8.641E-04 m | 8.844E-04 m | 2.29% |
0.45 | 8.567E-04 m | 8.851E-04 m | 3.21% |
0.49 | 8.452E-04 m | 8.857E-04 m | 4.58% |


Умеричка анализа интеракције тла и конструкције услед дејства земљотреса
Verification using Boussinesq Solution

8NodeBrick

27NodeBrick

Нумеричка анализа интеракције тла и конструкције услед дејства земљотреса
Wave Propagation, Mesh Size Effects

(Case 1, Vs = 1000 m/s, Cutoff Fq. = 8 Hz, E. Size = 20 m)
Model Verification

Numetric analysis of interaction between soil and structure due to earthquake

Jeremič

Numerička analiza interakcije tla i konstrukcije usled dejstva zemljotresa
V & V Summary

- V&V most important for providing confidence in results
- Numerical modeling program(s) should not be used without extensive/full V&V
- V&V of FEM models is important, essential
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Seismic Motions

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- Introduction
- Real-ESSI Simulator System
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  - Seismic Motions
  - Plastic Energy Dissipation
- Summary

Jeremić

Numerička analiza interakcije tla i konstrukcije usled dejstva zemljotresa
Seismic Motions

Seismic Hazard, World
Earthquake Ground Motions

- Real earthquake ground motions
  - Body, P and S waves
  - Rayleigh, Love, Stoneley, ... waves
  - Lack of correlation, incoherent motions
  - Inclined waves
  - 3C/6C waves

- What are the effects of real earthquake ground motions on soil-structure systems ?!
1C vs 6C Free Field Motions

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

(DB: npp_model101_ff_quake.h5.feloutput
Time: 0.77)

(DB: npp_model101_ff_quake.h5.feloutput
Time: 0.712)
6C vs 1C NPP ESSI Response Comparison

(JMP4)

Jeremić
Нумеричка анализа интеракције тла и конструкције услед дејства земљотреса
When to use 3C and/or 3\(\times1\)C
Free Field, Variation in Input Frequency, $\theta = 60^\circ$

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

(MP4)
SMR ESSI, 3C vs 3×1C

Seismic Motions

(OGV)
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Energy Input and Dissipation

Energy input, dynamic forcing

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  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

Jeremić

Нумеричка анализа интеракције тла и конструкције услед дејства земљотреса
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Plastic Energy Dissipation

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

Нумеричка анализа интеракције тла и конструкције услед дејства земљотреса
Energy Dissipation Control

The diagram illustrates the dissipation of energy in a system over time. The x-axis represents time in seconds (s), and the y-axis represents energy in mega joules (MJ).

Key energy components shown include:
- Kinetic Energy
- Strain Energy
- Plastic Free Energy
- Plastic Dissipation
- Viscous Damping
- Numerical Damping
- Input Work

The graph shows how each component of energy changes over time, with peaks and valleys representing the dissipation of energy due to various mechanisms.
Inelastic Modeling of Soil Structure System

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

- Interface/Contact/Joint, inelastic, gap open/close, slip
  - Dry, single phase,
  - Fully saturated, suction, excess pressure, buoyant force

- Structure, inelastic, damage, cracks, ASR...
  - Nonlinear/inelastic 1D concrete, steel, 3D fiber beams
  - Nonlinear/inelastic 3D concrete, steel, 3D solids, 3D shells

- Solid/Structure-Fluid interaction, open surface
Acceleration Traces, Elastic vs Inelastic

Elastic

Inelastic

Jeremić

Numerička analiza interakcije tla i konstrukcije usled dejstva zemljotresa
Displacement Traces, Elastic vs Inelastic
Energy Dissipation in a Large-Scale Model

Accumulated Plastic Dissipation Density (J/m³)

Incremental Plastic Dissipation Density (J/m³)

Time Step: 620

(MP4)

Numerička analiza interakcije tla i konstrukcije usled dejstva zemljotresa
Energy Dissipation for Design
Design Alternatives

Plastic Energy Dissipation

Time Step: 3880

Plastic Dissipation Density (J/m3)

Time Step: 3700

Plastic Dissipation Density (J/m3)

(MP4)
ASCE-7-21: Low Building

Jeremić

Numerička analiza interakcije tla i konstrukcije usled deјства земљотреса
ASCE-7-21: Low Building Energy Dissipation

Plastic Dissipation Density (J/m³)

0  2.5e+05  5e+05  7.5e+05  1e+06
Ventura Hotel, Northridge Earthquake
Ventura Hotel, Northridge Earthquake, SSI vs nonSSI
Ventura Hotel, Northridge Earthquake, SSI vs nonSSI

Top floor, long axes response

Plastic Energy Dissipation

Earthquake Soil Structure Interaction

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Ventura Hotel, Northridge Earthquake, SSI vs nonSSI

Top floor, long axes response

Record
Full SSI
Only Structure (No SSI)

Record
Full SSI
Only Structure (No SSI)
Pine Flat Dam, Inelastic Interface, Hydrostatic

Vertical Stress (Pa)

Vertical Stress at the Dam Heel

Close-up on the Dam Heel

(MP4)
Plastic Energy Dissipation

Pine Flat Dam, Hydrodynamic Pressure

Time: 13.79 s

Total Pressure P [Pa]

(MP4)
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Закључак

- Numerical modeling to predict and inform, rather than fit

- Инжењер море да зна све о објекту, систему

- Education and Training is the key!


- Хвала СУЗИ на организацији предавања!
  http://suzi-saee.rs/
Хвала на Пажњи

http://sokocalo.engr.ucdavis.edu/~jeremic/za_SUZI_predavanje_Apr2020

http://real-essi.us

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