Modeling and Simulation
Dam Foundation Reservoir System

Boris Jeremić
University of California, Davis, CA
Lawrence Berkeley National Laboratory, Berkeley, CA

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Outline

Introduction
  Motivation
  Modeling and Simulation of ESSI

Seismic Motions, Inelasticity and Uncertainty
  Six Component Seismic Motions
  Inelasticity, Plastic Energy Dissipation and Uncertainty

Pine Flat Dam
  Pine Flat Dam Test Model
  Pine Flat Dam, Additional Modeling and Simulation

Conclusion
  Real-ESSI Simulator System
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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

- Engineer needs to know!
Motivation: 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
Introduction

Motivation

Modeling Effects, Currently Understood

- Mesh size effects
- Boundary conditions, seismic motions input DRM, free field
- Inelastic models for soil, rock, concrete, stele
- Inelastic models for interfaces/joints/contacts
- Mechanical Energy flow in and out of the Dam-Foundation-Reservoir (DFR) system
- Convergence tolerances for both constitutive level and FEM level
- Numerical/algorithmic damping
- Verification of finite elements and algorithms
Modeling Effects that Need More Work

- Full 3C/6C seismic motions
- Models for regular and Alkali-Silica Reaction (ASR) concrete,
- Models for dry and wet interfaces/joints/contacts
- Modeling full DFR system
- Propagation of seismic energy through DFR system
- Propagation of uncertainty in material and loads through DFR system
- Estimations of accuracy of results
Full 3C/6C Seismic Motions

\[ \theta = 0^\circ \]

\[ \theta = 30^\circ \]

\[ \theta = 60^\circ \]

\( L_0 \) \hspace{1cm} \( L_w \)

Motivation

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(Low.png) (Jeremić et al. Real-ESSI)
Regular and ASR Concrete

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Dry and Wet Interfaces/Joints/Contacts

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Motivation

Modeling Full DFR System

Time: 13.79 s

Total Pressure $P$ [Pa]

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Propagation of Seismic Energy through DFR System

Energy input, dynamic forcing

Energy dissipation outside SSI domain:
- SSI system oscillation radiation
- Reflected wave radiation

Energy dissipation/conversion inside SSI domain:
- Inelasticity of rock, soil, interfaces, structure, foundation, dissipators
- Viscous coupling with internal/pore fluids
- Viscous coupling with external fluids, reservoir

Numerical energy dissipation/production
Motivation

Propagation of Uncertainty in Material and Loads

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Accuracy of Results, Unit Tests

Development of unit tests for components and full dam-reservoir-foundation system
Set of unit test problems, where very accurate solutions exist, in addition to basic verification problems, that are used to verify given numerical modeling approach:

- Wave propagation, free field, 1C and/or 3C
- Wave propagation, dam structure, 1C and/or 3C
- Wave propagation, dam and foundation, 1C and/or 3C
- Material constitutive behavior, concrete
- Material constitutive behavior, rock
Parametric Uncertainty: Soil Stiffness

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

cf. Phoon and Kulhawy (1999B)
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Energy Input and Dissipation

Energy input, dynamic forcing

Energy dissipation outside SSI domain:
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- Inelasticity of soil, contact zone, structure, foundation, dissipators
- Viscous coupling with internal/pore fluids, and external fluids

Numerical energy dissipation/production
Fully Coupled Formulation, $u$-$p$-$U$ 

\[
\begin{bmatrix}
(M_s)_{KijL} & 0 & 0 \\
0 & (M_f)_{KijL} & 0 \\
0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\ddot{u}_{Lj} \\
\ddot{p}_N \\
\ddot{U}_{Lj}
\end{bmatrix}
+ \begin{bmatrix}
(C_1)_{KijL} & 0 & -(C_2)_{LjiK} \\
0 & 0 & (C_3)_{KijL}
\end{bmatrix}
\begin{bmatrix}
\ddot{u}_{Lj} \\
\ddot{p}_N \\
\ddot{U}_{Lj}
\end{bmatrix}
+ \begin{bmatrix}
(K^{EP})_{KijL} & -(G_1)_{KiM} & 0 \\
0 & -(G_2)_{KiL} & 0
\end{bmatrix}
\begin{bmatrix}
\dot{u}_{Lj} \\
\dot{p}_M \\
\dot{U}_{Lj}
\end{bmatrix}
= \begin{bmatrix}
\dddot{u}_{Lj} \\
\dddot{p}_N \\
\dddot{U}_{Lj}
\end{bmatrix}
\]
Fully Coupled Formulation, u-p-U

\[(M_s)_{KijL} = \int_{\Omega} H^u_K (1 - n) \rho_s \delta_{ij} H^u_L d\Omega \quad (M_f)_{KijL} = \int_{\Omega} H^u_K n \rho_f \delta_{ij} H^u_L d\Omega \]

\[(C_1)_{KijL} = \int_{\Omega} H^u_K n^2 k^{-1}_{ij} H^u_L d\Omega \quad (C_2)_{KijL} = \int_{\Omega} H^u_K n^2 k^{-1}_{ij} H^u_L d\Omega \]

\[(C_3)_{KijL} = \int_{\Omega} H^u_{K,i} (\alpha - n) H^p_M d\Omega \quad (K^{EP})_{KijL} = \int_{\Omega} H^u_K, m D_{imjn} H^u_L, n d\Omega \]

\[P_{NM} = \int_{\Omega} H^p_N \frac{1}{Q} H^p_M d\Omega \]

Jeremić et al. Real-ESSI
Energy Dissipation Control Mechanisms

Plasticity

Viscous

Numerical
Energy Dissipation Control

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Energy Dissipation on Material Level

Single elastic-plastic element under cyclic shear loading

Difference between plastic work and plastic dissipation

Plastic work can decrease
Plastic dissipation always increases

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Six Component 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
Six Component Seismic Motions

6C Free Field Motions (closeup)

DB: eqmotions.h5.feoutput
Time: 0.558
Mesh: Var ESSI Domain Mesh

Pseudocolor
Var: Generalized Displacements, magnitude

Max: 4.58e-04
Min: 0.00e+00
Six Component Seismic Motions

1C vs 6C Free Field Motions

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

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Six Component Seismic Motions

6C vs 1C NPP ESSI Response Comparison

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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**
Six Component Seismic Motions

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

(MP4)
Six Component Seismic Motions

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

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Numerical energy dissipation/production
Energy Dissipation in NPP Model

Accumulated Plastic Dissipation Density (J/m3)

Incremental Plastic Dissipation Density (J/m3)

(MP4)

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Energy Dissipation for an SMR Model

Accumulated Plastic Dissipation Density (J/m$^3$)

Incremental Plastic Dissipation Density (J/m$^3$)

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Wall, Regular and ASR Concrete

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Real-ESSI Modeling Phases
Uncertainty Propagation through Inelastic System

- Incremental el–pl constitutive equation

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

- Dynamic Finite Elements

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

- Material and load parameters are uncertain
Probabilistic Elastic-Plastic Response

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Probabilistic Elastic-Plastic Modeling

Cyclic Loading of Uncertain Stress

Cyclic Loading of Uncertain Stiffness

Evolution of Stress PDF

Evolution of Stiffness PDF

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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.

\[
\begin{bmatrix}
\sum_{k=0}^{P_d} \langle \Phi_k \psi_0 \psi_0 > K^{(k)} \\
\sum_{k=0}^{P_d} \langle \Phi_k \psi_0 \psi_1 > K^{(k)} \\
\vdots & \vdots & \vdots \\
\sum_{k=0}^{P_d} \langle \Phi_k \psi_P \psi_P > K^{(k)} \\
\end{bmatrix}
\begin{bmatrix}
\Delta u_{10} \\
\vdots \\
\Delta u_{N0} \\
\Delta u_{1Pu} \\
\vdots \\
\Delta u_{NPu}
\end{bmatrix}
= 
\begin{bmatrix}
\sum_{i=0}^{P_f} f_i < \psi_0 \zeta_i > \\
\sum_{i=0}^{P_f} f_i < \psi_1 \zeta_i > \\
\sum_{i=0}^{P_f} f_i < \psi_2 \zeta_i > \\
\vdots \\
\sum_{i=0}^{P_f} f_i < \psi_P \zeta_i > \\
\end{bmatrix}
\]
SEPFEM: Example in 1D

Stochastic Displacement from SEPFEM

Fragility Curve of Node number 1

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Pine Flats Dam, Model

- Material properties provided
- Motions applied through DRM, from bottom
- Energy dissipation, Viscous, Numerical, Radiation
- Load cases as provided
Pine Flats Dam, Static, Displacements

- Self weight
- Water pressure, on dam side and lake bottom

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Displacement [m]</th>
<th>Displacement [in]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top</td>
<td>Heel</td>
</tr>
<tr>
<td>Vert.</td>
<td>-0.0095</td>
<td>-0.0059</td>
</tr>
<tr>
<td>Hor.</td>
<td>0.0101</td>
<td>0.0011</td>
</tr>
<tr>
<td>Vert.</td>
<td>-0.0048</td>
<td>-0.0019</td>
</tr>
<tr>
<td>Hor.</td>
<td>0.0121</td>
<td>0.0031</td>
</tr>
</tbody>
</table>

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Real-ESSI
Static, Displacements and $\sigma_V$
Mesh Refinement Effects
### Pine Flat Dam Test Model

#### Mesh Refinement Effects

<table>
<thead>
<tr>
<th></th>
<th>Displacements [m]</th>
<th>Original</th>
<th>Refined</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dam Top</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Horizontal</td>
<td>0.012121</td>
<td>0.012201</td>
<td>0.66%</td>
</tr>
<tr>
<td></td>
<td>Vertical</td>
<td>-0.009463</td>
<td>-0.009794</td>
<td>3.51%</td>
</tr>
<tr>
<td><strong>Dam Heel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Horizontal</td>
<td>0.003124</td>
<td>0.003287</td>
<td>5.21%</td>
</tr>
<tr>
<td></td>
<td>Vertical</td>
<td>-0.005981</td>
<td>-0.006953</td>
<td>16.25%</td>
</tr>
<tr>
<td><strong>Relative</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Horizontal</td>
<td>0.008996</td>
<td>0.009064</td>
<td>0.76%</td>
</tr>
<tr>
<td></td>
<td>Vertical</td>
<td>-0.003481</td>
<td>-0.003489</td>
<td>0.23%</td>
</tr>
</tbody>
</table>

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Eigen Analysis, Dry

Eigen frequencies:
- (a) 2.46945 Hz
- (b) 3.82403 Hz
- (c) 4.48795 Hz
- (d) 5.25455 Hz
- (e) 5.32023 Hz
- (f) 5.60061 Hz
Pine Flat Dam Test Model

Taft Earthquake, Time History of $\sigma_v$

- Vertical stress at dam heel, there is a tension!
Taft Earthquake, $\sigma_v$ Distribution at $\sigma_{min}$ and $\sigma_{max}$

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D2, Taft Earthquake, Dam and the Reservoir

- Pressures: total at the heel, total at the upstream face, hydrodynamic at the upstream face

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D2, Tafts Earthquake, Dam and the Reservoir

Vertical stress: heel time series, along base for max stress at the heel, for min stress at the heel
D2, ETAF Earthquake, Dam and the Reservoir

- Pressures: total at the heel, total at the upstream face, hydrodynamic at the upstream face
D2, ETAF Earthquake, Dam and the Reservoir

- Vertical stress: heel time series, along base for max stress at the heel, for min stress at the heel

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Numerical Damping Effects, Elastic $\ddot{u}_{\text{top}}^{\text{hor}}$, $\sigma_{\text{v}}^{\text{heel}}$
Numerical Damping Effects, Inelastic $\ddot{u}_{hor}^{top}, \sigma_v^{heel}$
Pine Flat Dam, Dynamic Response with Reservoir

Displacement Magnitude

0 0.06 0.12 0.18 0.24
Pine Flat Dam, Hydrodynamic Pressure

Time: 13.79 s

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Pine Flat Dam, Inelastic Interface, Hydrostatic

(MP4) Vertical Stress (Pa)

Vertical Stress at the Dam Heel

Close-up on the Dam Heel

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Pine Flat Dam, Dynamic Response, Inclined Plane Waves

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 Real-ESSI Simulator System
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

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

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

- System description and documentation at http://real-essi.info/
Real-ESSI Simulator System

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, Pisanó, Abell, Tafazzoli, Jie, Preisig, Tasiopoulou, Watanabe, Cheng, Yang...
► Funding from and collaboration with the US-DOE, US-NRC, US-NSF, CNSC-CCSN, UN-IAEA, and Shimizu Corp. is greatly appreciated,
► http://real-essi.info/
Summary

Numerical modeling to predict and inform, rather than fit
Brave effort of ICOLD, assess numerical analysis of dams!

http://real-essi.info/