Modeling and Simulation of Earthquakes, Soils, Structures, and their Interaction

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ETH Seminar,
Zurich, Switzerland
May 2018
Outline

Introduction
  Motivation

Seismic Motions
  Observations
  Regional Geophysical Models
  Stress Test Motions

Inelasticity and Energy Dissipation
  Energy Dissipation
  Probabilistic Inelastic Modeling
  Direct Solution for Probabilistic Stiffness and Stress in 1D

Summary
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Summary
Motivation

Improve modeling and simulation for infrastructure objects

Use of high fidelity numerical modeling and simulation to analyze earthquakes, and/or soils and/or structures and their interaction (ESSI)

Reduce modeling uncertainty, perform desired level of sophistication modeling and simulation

Follow evolution of parametric uncertainty

Le doute n’est pas un état bien agréable, mais l’assurance est un état ridicule. (François-Marie Arouet, Voltaire)
Earthquake Motions, $6C$ vs $3 \times 1C$ vs $1C$

- Danger of picking one component of motions ($1C$) from $3C$
- Excellent (forced) fit, but not a prediction, information is lost
6C vs 1C NPP ESSI Response Comparison
Elastic and Inelastic Response: Differences

Time: 10.67 [s]
Material Behavior Inherently Uncertain

- Spatial variability
- Point-wise uncertainty, testing error, transformation error

(Mayne et al. (2000))
Parametric Uncertainty: Material and Loads

Transformation of SPT N-value: 1-D Young’s modulus, $E$ (cf. Phoon and Kulhawy (1999B))

$$E = (101.125 \times 19.3) N^{0.63}$$
Parametric Uncertainty: Material Properties

Field $\phi$

Field $c_U$

Lab $\phi$

Lab $c_U$
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**Summary**
3C (6C) Seismic Motions

- All (most) measured motions are full 3C (6C)
- Example of an almost 2D motion (LSST07, LSST12)
San Pablo Earthquake, 14Jun2017

Courtesy of http://www.strongmotioncenter.org/
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Summary
Regional Geophysical Models

- High fidelity free field seismic motions on regional scale
- Knowledge of geology (deep and shallow) needed
- High Performance Computing using SW4 on CORI (LBNL)
- Collaboration with LLNL: Dr. Rodgers, Dr. Pitarka and Dr. Petersson
Regional Geophysical Models

USGS

Jeremić et al.
MS ESSI
Example Regional Model
Example Regional Model (Rodgers)
Regional Geophysical Models

Seismic Motions: SW4 to MS-ESSI

ESSI nodes

30km × 14km × 5 km

SW42ESSI

Domain for: GF_M6.5_1DREF_h25m

(\(u_1, u_2, u_3, \theta_1, \theta_2, \theta_3\))

300m × 300m × 100m

Grid spacing ~ 5m

72m × 72m × 56m

36m embedded

Jeremić et al.

MS ESSI
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Summary
Stress Testing SSI Systems

- Excite SSI system with a suite of seismic motions
- Simple sources, variation in strike and dip, P and S waves, surface waves (Rayleigh, Love, etc.)
- Stress test soil-structure system
- Try to "break" the system, shake-out strong and weak links
Stress Test Source Signals

**Ricker**

**Ormsby**
Layered and Dyke/Sill Models

- (a) Horizontal layers
- (b) Dyke/Sill intrusion

- Source locations matrix (point sources)
- Source strike and dip variation
- Magnitude variations
- Range of frequencies
Layered System, Displacement Traces

- Epicenter is 2500m away from the location of interest
- Source depth 850m (left) and 2500m (right)
- Different wave propagation path to the point of interest
- Surface waves quite pronounced
- Layered geology did not filter out surface waves
Layered System, Variable Source Depth
Dyke/Sill Intrusion, Variable Source Depth

- Lower amplitudes than with layered only model!
- Difference in body and surface wave arrivals
- Surface waves present, more complicated wave field
Dyke/Sill Intrusion, Variable Source Depth
Dyke/Sill as Seismic Energy Sink

- Dyke/Sill (right Fig), made of stiff rock, is an energy sink, as well as energy reflector
- Variable wave lengths behave differently, depending on dyke/sill geometry and location
Plane Wave Stress Test Motions

- Plane wave stress test motions: 3D-6C (Haskel’s solution for plane harmonic waves) and/or 3D-3×1C and/or 3D-1C and or 1D-1C motions

- Knowledge of geology and the site is important
Stress Test Motions

- Variation in inclination, frequency, energy and duration
- Try to "break" the system, shake-out strong and weak links
Free Field, Variation in Input Wave Angle, $f = 5\text{Hz}$
SMR ESSI, Variation in Input Wave Angle, $f = 5\text{Hz}$

\[
\begin{align*}
&f = 5\text{Hz} \quad \theta = 10^\circ \\
&f = 5\text{Hz} \quad \theta = 45^\circ \\
&f = 5\text{Hz} \quad \theta = 60^\circ \\
&f = 5\text{Hz} \quad \theta = 80^\circ
\end{align*}
\]
Stress Test Motions

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

- $f = 1\, \text{Hz}$
- $f = 2.5\, \text{Hz}$
- $f = 5\, \text{Hz}$
- $f = 10\, \text{Hz}$
SMR ESSI, Variation in Input Frequency, $\theta = 60^\circ$
SMR ESSI, Variation in Input Frequency, REAL TIME

\( f = 1\text{Hz} \)

\( f = 2.5\text{Hz} \)

\( f = 5\text{Hz} \)

\( f = 10\text{Hz} \)

(MP4)
3D wave effects - different frequencies

Acceleration response - Surface center point A

(a) $f = 1\text{Hz} \quad \theta = 60^\circ$

(b) $f = 5\text{Hz} \quad \theta = 60^\circ$

(c) $f = 10\text{Hz} \quad \theta = 60^\circ$
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Summary
Seismic Energy Input and Dissipation

Seismic energy input, through a closed boundary

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

Mechanical dissipation/conversion inside SSI domain:
  - Inelasticity of soil and contact zone
  - Inelasticity/damage of structure and foundation
  - Viscous coupling of fluids and soils and structure

Numerical energy dissipation/production
Energy Dissipation

Incremental Plastic Work: $dW_p = \sigma_{ij} d\varepsilon_{ij}^{pl}$

- Negative incremental energy dissipation
- Plastic work is NOT plastic dissipation

From a paper on *Soil Dynamics and Earthquake Engineering* (2011)
Negative Incremental Energy Dissipation!

Direct violation of the second law of thermodynamics

600 papers use Uang and Bertero (1990) and repeat their error

Important form of energy missing: Plastic Free Energy

Observed by Farren and Taylor (1925) and explained by Taylor and Quinney (1934)

Plastic Work vs. Plastic Energy Dissipation
Energy Dissipation on Material Level

Single elastic-plastic element under cyclic shear loading

Difference between plastic work and dissipation

Plastic work can decrease, dissipation always increases

![Graphs showing energy dissipation](image-url)
Plastic Free Energy

- Multi-scale effect of particle interlocking/rearrangement
- Strain energy on particle level
Energy Transformation in Elastic-Plastic Material

- Input Mechanical Energy
  (External Loads and/or Prescribed Displacements)

  - Kinetic Energy
  - Strain Energy
  - Free Energy
  - Plastic Free Energy
  - Dissipated Energy
    - Material Plasticity
    - Viscous Coupling
    - Radiation Damping
    - Numerical Damping

- Recoverable
- Conditionally Recoverable
- Irrecoverable
Energy Dissipation in Large-Scale Model (NPP)
Energy Dissipation in Large-Scale Model (SMR)
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<th>Inelasticity and Energy Dissipation</th>
<th>Summary</th>
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Probabilistic Inelastic Modeling

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**Inelasticity and Energy Dissipation**

- Energy Dissipation
- Probabilistic Inelastic Modeling
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**Summary**
Uncertainty Propagation through Inelastic System

- Incremental el–pl constitutive equation

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

- Dynamic Finite Elements

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

- What if all (any) material and load parameters are uncertain
Probabilistic Elastic-Plastic Response
Probabilistic Inelastic Modeling

3D FPK Equation

\[
\frac{\partial P(\sigma_{ij}(x_t, t), t)}{\partial t} = \frac{\partial}{\partial \sigma_{mn}} \left[ \left\{ \langle \eta_{mn}(\sigma_{mn}(x_t, t), D_{mnrs}(x_t), \epsilon_{rs}(x_t, t)) \rangle \right\} + \int_0^t d\tau \text{Cov}_0 \left[ \frac{\partial \eta_{mn}(\sigma_{mn}(x_t, t), D_{mnrs}(x_t), \epsilon_{rs}(x_t, t))}{\partial \sigma_{ab}} \right] \eta_{ab}(\sigma_{ab}(x_t-\tau, t-\tau), D_{abcd}(x_t-\tau), \epsilon_{cd}(x_t-\tau, t-\tau)) \right] P(\sigma_{ij}(x_t, t), t) \right] + \frac{\partial^2}{\partial \sigma_{mn} \partial \sigma_{ab}} \left[ \left\{ \int_0^t d\tau \text{Cov}_0 \left[ \eta_{mn}(\sigma_{mn}(x_t, t), D_{mnrs}(x_t), \epsilon_{rs}(x_t, t)) \right] \right\} \eta_{ab}(\sigma_{ab}(x_t-\tau, t-\tau), D_{abcd}(x_t-\tau), \epsilon_{cd}(x_t-\tau, t-\tau)) \right] P(\sigma_{ij}(x_t, t), t) \right]
\]
FPK Equation

- Advection-diffusion equation

$$\frac{\partial P(\sigma, t)}{\partial t} = -\frac{\partial}{\partial \sigma} \left[ N(1) P(\sigma, t) - \frac{\partial}{\partial \sigma} \left\{ N(2) P(\sigma, t) \right\} \right]$$

- Complete probabilistic description of response
- Solution PDF is second-order exact to covariance of time (exact mean and variance)
- It is deterministic equation in probability density space
- It is linear PDE in probability density space → simplifies the numerical solution process
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Direct Probabilistic Constitutive Modeling in 1D

- Zero elastic region elasto-plasticity with stochastic Armstrong-Frederick kinematic hardening
  \[ \Delta \sigma = H_a \Delta \epsilon - c_r \sigma |\Delta \epsilon|; \quad E_t = d\sigma / d\epsilon = H_a \pm c_r \sigma \]

- Uncertain: init. stiff. \( H_a \), shear strength \( H_a / c_r \), strain \( \Delta \epsilon \):
  \[ H_a = \sum h_i \Phi_i; \quad C_r = \sum c_i \Phi_i; \quad \Delta \epsilon = \sum \Delta \epsilon_i \Phi_i \]

- Resulting stress and stiffness are also uncertain
Probabilistic Elastic-Plastic Modeling
Stochastic Elastic-Plastic Finite Element Method

- Material uncertainty expanded into stochastic shape f-ion
- Loading uncertainty expanded into stochastic shape f-ion
- Displacement expanded into stochastic shape f-ion
- Time domain integration using Newmark and/or HHT, in probabilistic spaces

\[
\begin{align*}
\sum_{k=0}^{P_d} & \phi_k \psi_0 \psi_0 > K^{(k)} \\
\sum_{k=0}^{P_d} & \phi_k \psi_0 \psi_1 > K^{(k)} \\
\sum_{k=0}^{P_d} & \phi_k \psi_0 \psi_P > K^{(k)} \\
\vdots & \\
\sum_{k=0}^{M} & \phi_k \psi_P \psi_P > K^{(k)}
\end{align*}
\]

\[
\begin{bmatrix}
\Delta u_{10} \\
\vdots \\
\Delta u_{NP_u}
\end{bmatrix}
= 
\begin{bmatrix}
\sum_{i=0}^{P_f} f_i < \psi_0 \zeta_i > \\
\sum_{i=0}^{P_f} f_i < \psi_1 \zeta_i > \\
\sum_{i=0}^{P_f} f_i < \psi_2 \zeta_i > \\
\vdots \\
\sum_{i=0}^{P_f} f_i < \psi P_u \zeta_i >
\end{bmatrix}
\]
SEPFEM: System Size

- SEPFEM offers a complete solution (single step)
- It is NOT based on Monte Carlo approach
- System of equations does grow (!)

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<th># KL terms load</th>
<th>PC order displacement</th>
<th>Total # terms per DoF</th>
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<td>5 311 735</td>
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</tbody>
</table>
SEPFEM: Example in 1D

Stochastic Displacement from SEPFEM

Fragility Curve of Node number 1

Jeremić et al.
MS ESSI
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Importance of using proper models correctly (verification, validation)

Availability of different levels of sophistication of modeling is important for reduction of modeling uncertainty

Development of the MS-ESSI Simulator system
http://ms-essi.info

Collaborators: Feng, Abell, Han, Sinha, Wang, Lacour, Pisanó, Kovačević, McCallen, McKenna, Petrone, Rodgers