3D-Deconvolution

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Outline

Introduction

Seismic Motions
  Realistic Wave Propagation
  3Deconvolution

Summary
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Summary
Motivation

- Improve analysis and design for infrastructure
- Control modeling, epistemic uncertainty
- Propagate parametric, aleatory uncertainty
- Predict and inform, Engineer needs to know!
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Seismic Motions

- Knowledge about seismic motions (?)
- Uncertainty in seismic motions (!)
- Simplifying assumptions, 1D/2D/3D; 1C, 2C, 3C, $3 \times 1C$, 6C
- Seismic energy input and dissipation within ESSI systems
- Seismic motions have critical importance for ESSI analysis
ESSI Analysis

- Earthquake Soil Structure Interaction (ESSI)
- Developments in last 50+ years
- ESSI: Nuclear Power Plants, Dams, Bridges, Buildings
- Domain Reduction Method, DRM (J.Bielak et al.)
Introduction

Seismic Motions

Summary

Realistic Wave Propagation

**DRM**

\[
\begin{bmatrix}
 M_{ii}^\Omega & M_{ib}^\Omega & 0 \\
 M_{bi}^\Omega & M_{bb}^\Omega + M_{bb}^\Omega^+ & M_{be}^\Omega^+ \\
 0 & M_{eb}^\Omega^+ & M_{ee}^\Omega^+ \\
 K_{ii}^\Omega & K_{ib}^\Omega & 0 \\
 K_{bi}^\Omega & K_{bb}^\Omega + K_{bb}^\Omega^+ & K_{be}^\Omega^+ \\
 0 & K_{eb}^\Omega^+ & K_{ee}^\Omega^+ \\
\end{bmatrix}
\begin{bmatrix}
 \ddot{u}_i \\
 \ddot{u}_b \\
 \ddot{w}_e \\
\end{bmatrix}
+ 
\begin{bmatrix}
0 \\
0 \\
0 \\
\end{bmatrix}
= 
\begin{bmatrix}
0 \\
0 \\
0 \\
\end{bmatrix}
+ 
\begin{bmatrix}
0 \\
0 \\
0 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
 M_{be}^\Omega^+ \ddot{u}_e^0 - K_{be}^\Omega^+ u_e^0 \\
 M_{eb}^\Omega^+ \ddot{u}_b^0 + K_{eb}^\Omega^+ u_b^0 \\
\end{bmatrix}
\]

Large scale domain
Local feature
Seismic source
DRM

- Seismic forces $P_e$ replaced by $P^{\text{eff}}$
- $P^{\text{eff}}$ applied only to a single layer of elements next to $\Gamma$
- Only outgoing waves from structural oscillations
- Material inside $\Omega$ can be elastic-plastic
- Any wave field can be input/imposed
- Neglect the outside ($\Omega^+$) problems
Realistic Seismic Motions

(MP4)
Development of Realistic Seismic Motions

- Sources will send both P and S waves
1C vs 6C Free Field Motions

- One component of motions, 1C from 6C
- Excellent fit, wrong physics
6C vs 1C NPP ESSI Response Comparison

(MP4)
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3-Deconvolution

- 1D/1C deconvolution developed long time ago
- Develop 3D/3C seismic waves from limited number of motion measurements, surface, depth
- 3D/3C deconvolution provides many analysis opportunities
- Utilize DRM features and the PDE-constrained optimization to develop DRM forces $P_{eff}$
- C.Jeong et al. recent work on inverse modeling
3Deconvolution Methodology

- Full-waveform inversion

- Inversion modeling is a minimization process

- Minimize misfits between motions at sensors/nodes
  - Measured, real motions and
  - Motions induced by developed effective forces $P_{eff}$
3Deconvolution Methodology, Forward

- State problem: \( Q \hat{u} = \hat{F} \)
- \( \hat{u} \) are DoFs in space and time
- \( \hat{F} \) are loads in space and time
$$Q = \begin{bmatrix}
I & 0 & 0 & 0 & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & 0 \\
0 & I & 0 & 0 & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & 0 \\
K_{t_0} & C & M & 0 & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & 0 \\
L_1 & L_2 & L_3 & \text{Keff}_{t_1} & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & 0 \\
a_1 I & I & 0 & -a_1 I & I & 0 & \ldots & 0 & 0 & 0 & 0 & 0 \\
a_0 I & a_2 I & I & -a_0 I & 0 & I & \ldots & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \ldots & L_1 & L_2 & L_3 & \text{Keff}_{t_N} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \ldots & a_1 I & I & 0 & -a_1 I & I \\
0 & 0 & 0 & 0 & 0 & 0 & \ldots & a_0 I & a_2 I & I & -a_0 I & 0
\end{bmatrix}$$

(1)
3Deconvolution Methodology, Forward

\[ \text{Keff}_{t_i} = a_0 M + a_1 C + K_{t_i} \]

\[ L_1 = -a_0 M - a_1 C \]

\[ L_2 = -a_2 M - C \]

\[ L_3 = -M \]

\[ a_0 = \frac{4}{(\Delta t)^2} \]

\[ a_1 = \frac{2}{\Delta t} \]

\[ a_2 = \frac{4}{\Delta t}, \]
**3Deconvolution Methodology, Inverse**

- Objective functional

\[
L = \frac{1}{2} (\hat{u}_{est} - \hat{u}_{targ})^T B (\hat{u}_{est} - \hat{u}_{targ})
\]

- \(B\) is a square matrix, pairing sensor locations

- Lagrangian functional to solve minimization problem

- Forward step, predictor

- Backward step, checker, corrector
3Deconvolution Methodology, Benefits

- Leveraging DRM features ($w = 0$) to improve accuracy
- HPC/parallel implementation in the Real-ESSI Simulator
- Still working on improving efficiency and accuracy
- Large computational cost in 3D/3C
- Wirth’s law/observation and Moore’s law/observation
3DDeconvolution Methodology, Trials
Seismic Energy Input into ESSI System

- Accurate seismic energy input into the ESSI system
  3Deconvolution
  DRM

- Analysis of energy dissipation with ESSI system

- Application: buildings, bridges, tunnels, dams, NPPs...
Seismic Energy Dissipation Alternatives

-Time Step: 3880 Plastic Dissipation Density (J/m3)
-Time Step: 3700 Plastic Dissipation Density (J/m3)

(MP4) (MP4)
NPP Energy Dissipation Benefits

Accumulated Plastic Dissipation Density (J/m3)

Displacement vs Time Step

Incremental Plastic Dissipation Density (J/m3)

Time Step: 620

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Energy Dissipation Devices

(MP4)
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- Improve analysis of ESSI systems
- 3D/3C deconvolution → 3Deconvolution
- Realistic dynamic motions, seismic, etc.
- Accurate energy input and dissipation analysis
- 3Deconvolution available within http://real-essi.us
- NSF project with Prof. Jeong CMichUniv.