3D-Deconvolution

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Outline

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Motivation

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

Outline

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

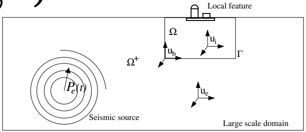
- Earthquake Soil Structure Interaction (ESSI)
- Developments in last 50+ years
- ESSI: Nuclear Power Plants, Dams, Bridges, Buildings
- Domain Reduction Method, DRM (J.Bielak et al.) !

DRM

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

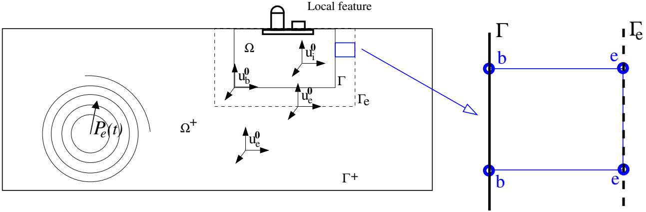
$$
\begin{bmatrix}
K_{ii}^{\Omega} & K_{ib}^{\Omega} & 0 \\
K_{bi}^{\Omega} & K_{bb}^{\Omega} + K_{bb}^{\Omega+} & K_{be}^{\Omega+} \\
0 & K_{eb}^{\Omega+} & K_{ee}^{\Omega+}
\end{bmatrix}
\begin{Bmatrix} u_i \\ u_b \\ w_e \end{Bmatrix} =
$$

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

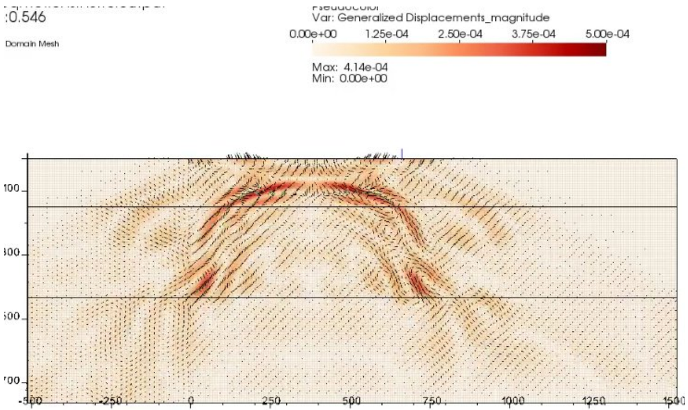


DRM

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



Realistic Seismic Motions



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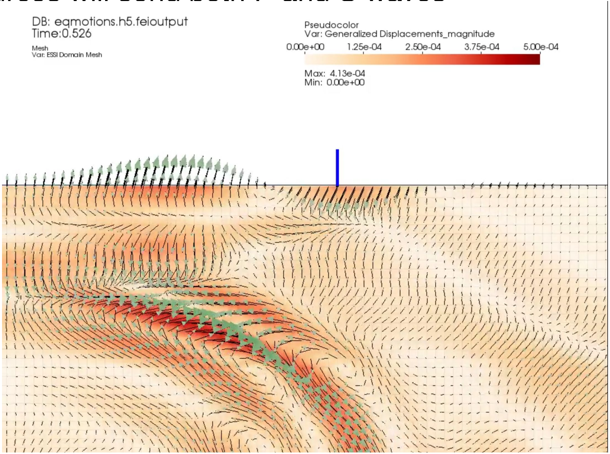
Development of Realistic Seismic Motions

- Sources will send both P and S waves



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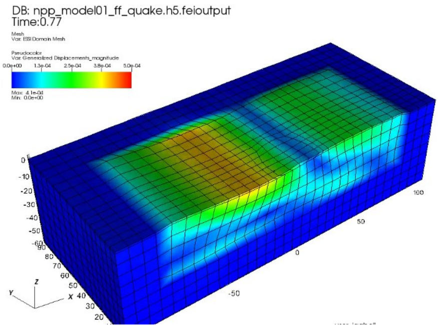
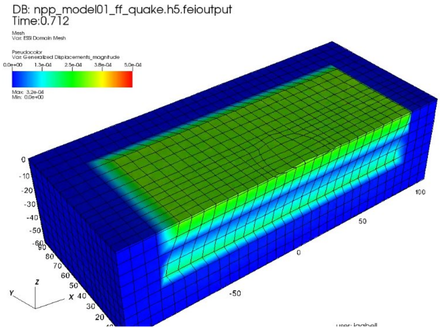
1C vs 6C Free Field Motions

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





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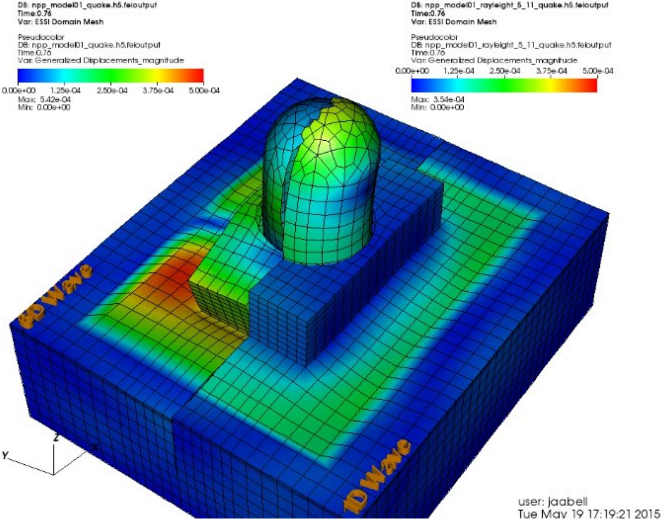
6C vs 1C NPP ESSI Response Comparison



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Outline

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: $\mathbf{Q}\hat{\mathbf{u}} = \hat{\mathbf{F}}$
- $\hat{\mathbf{u}}$ are DoFs in <u>space and time</u>
- $\hat{\mathbf{F}}$ are loads in <u>space and time</u>

3Deconvolution, Discrete Forward Operator

$$\mathbf{Q} = \begin{bmatrix}
\mathbf{I} & 0 & 0 & 0 & 0 & 0 & \dots & 0 & 0 & 0 & 0 & 0 \\
0 & \mathbf{I} & 0 & 0 & 0 & 0 & \dots & 0 & 0 & 0 & 0 & 0 \\
\mathbf{K}_{t_0} & \mathbf{C} & \mathbf{M} & 0 & 0 & 0 & \dots & 0 & 0 & 0 & 0 & 0 \\
\mathbf{L}_1 & \mathbf{L}_2 & \mathbf{L}_3 & \mathbf{Keff}_{t_1} & 0 & 0 & \dots & 0 & 0 & 0 & 0 & 0 \\
a_1\mathbf{I} & \mathbf{I} & 0 & -a_1\mathbf{I} & \mathbf{I} & 0 & \dots & 0 & 0 & 0 & 0 & 0 \\
a_0\mathbf{I} & a_2\mathbf{I} & \mathbf{I} & -a_0\mathbf{I} & 0 & \mathbf{I} & \dots & 0 & 0 & 0 & 0 & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & 0 & 0 & 0 & 0 & 0 & \dots & \mathbf{L}_1 & \mathbf{L}_2 & \mathbf{L}_3 & \mathbf{Keff}_{t_N} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \dots & a_1\mathbf{I} & \mathbf{I} & 0 & -a_1\mathbf{I} & \mathbf{I} \\
0 & 0 & 0 & 0 & 0 & 0 & \dots & a_0\mathbf{I} & a_2\mathbf{I} & \mathbf{I} & -a_0\mathbf{I} & 0
\end{bmatrix} \tag{1}$$

3Deconvolution Methodology, Forward

$$
\begin{aligned}
\mathbf{Keff}_{t_i} &= a_0\mathbf{M} + a_1\mathbf{C} + \mathbf{K}_{t_i} \\
\mathbf{L}_1 &= -a_0\mathbf{M} - a_1\mathbf{C} \\
\mathbf{L}_2 &= -a_2\mathbf{M} - \mathbf{C} \\
\mathbf{L}_3 &= -\mathbf{M} \\
a_0 &= \frac{4}{(\Delta t)^2} \\
a_1 &= \frac{2}{\Delta t} \\
a_2 &= \frac{4}{\Delta t},
\end{aligned}
$$

3Deconvolution Methodology, Inverse

- Objective functional

$$\mathbf{L} = \frac{1}{2}(\hat{\mathbf{u}}_{esti} - \hat{\mathbf{u}}_{targ})^T \mathbf{B} (\hat{\mathbf{u}}_{esti} - \hat{\mathbf{u}}_{targ})$$

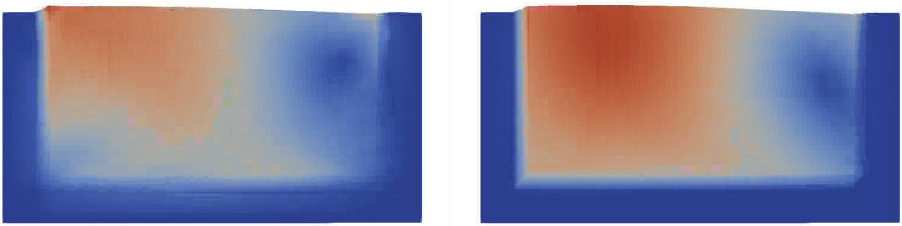
B is a square matrix, pairing sensor locations

- Lagrangian functional to solve minimization problem
- Forward step, predictor
- Backward step, checker, corrector

3Deconvolution Methodology, Benefits

- Leveraging DRM features ($\mathbf{w} = 0$) 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

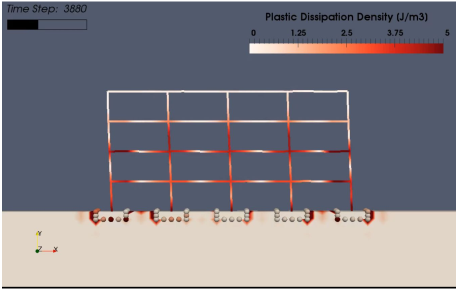
3Deconvolution Methodology, Trials

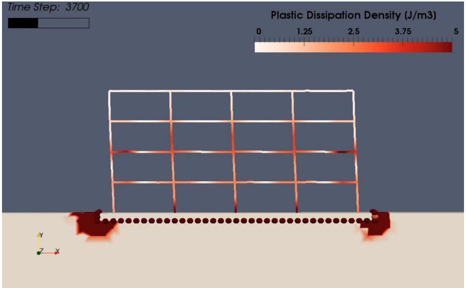


Seismic Energy Input into ESSI System

- 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





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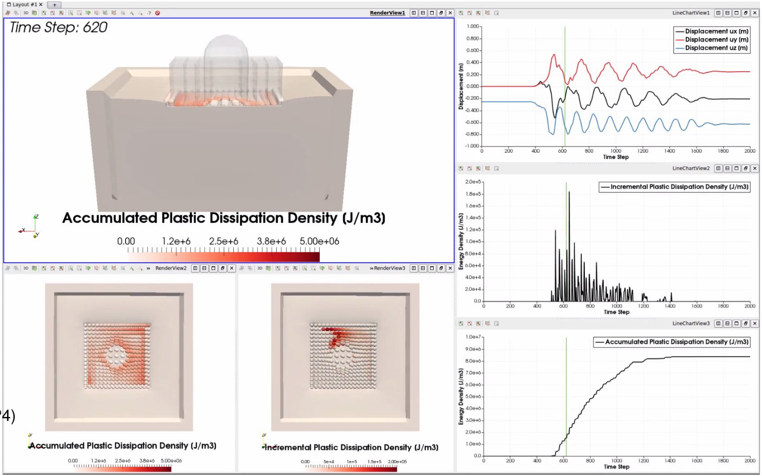
NPP Energy Dissipation Benefits



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Energy Dissipation Devices

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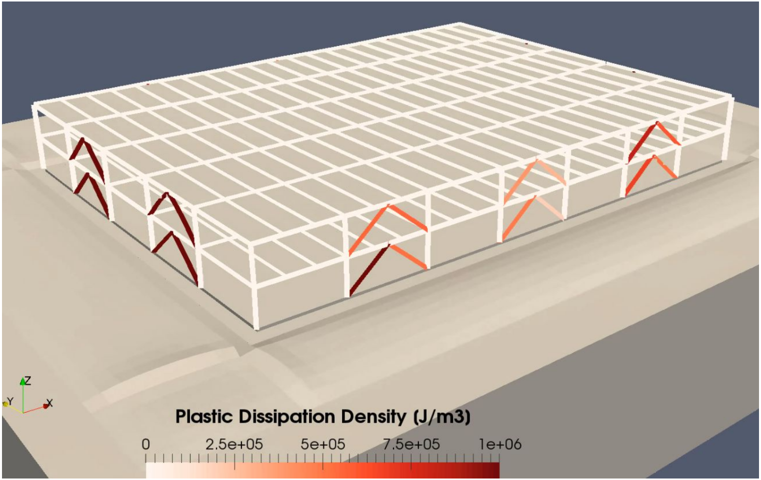

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Summary

- Improve analysis of ESSI systems
- 3D/3C deconvolution $\rightarrow$ 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.