

Probabilistic Seismic Risk Analysis for Inelastic Soil-Structure Systems

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It is best to use google chrome to view this PDF, so that animation links work!

Introduction
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Uncertain Inelastic Dynamics
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Summary
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Outline

Introduction

Uncertain Inelastic Dynamics

Summary

Motivation

Improve modeling and simulation for nuclear installations

Modeling sophistication level, epistemic uncertainty

Parametric, aleatory uncertainty

One or two levels of sophistication above target

Goal: Predict and Inform

Engineer needs to know!

Numerical Prediction under Uncertainty

- Modeling Uncertainty

- Simplifying assumptions

- Low, medium, high sophistication analysis

- Choice of sophistication level for confidence in results

- Parametric Uncertainty, $M\ddot{u}_i + C\dot{u}_i + K^{ep}u_i = F(t)$,

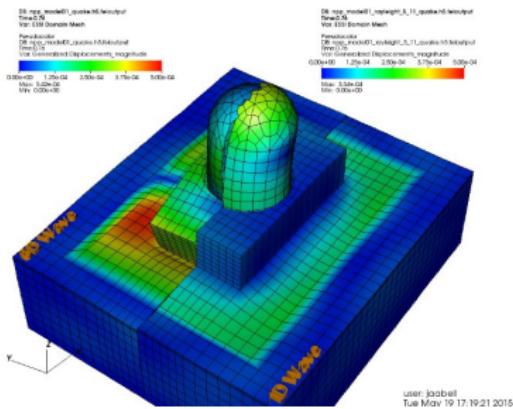
- Uncertain: mass M , viscous damping C and stiffness K^{ep}

- Uncertain: loads, $F(t)$

- Results are PDFs and CDFs for σ_{ij} , ϵ_{ij} , u_i , \dot{u}_i , \ddot{u}_i

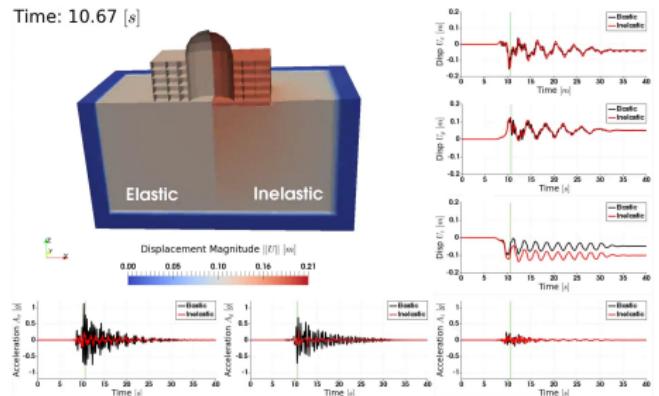
Modeling, Epistemic Uncertainty

6C vs 1C



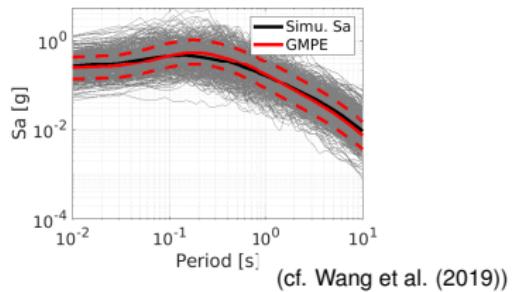
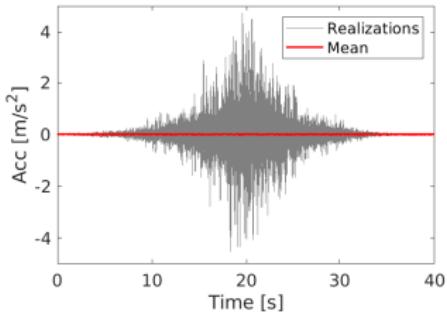
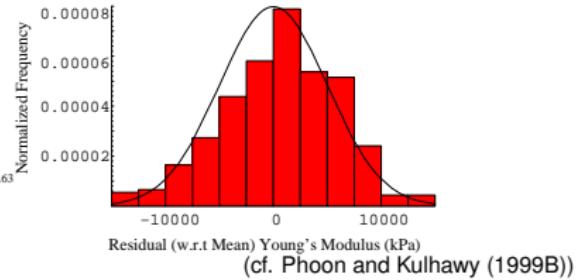
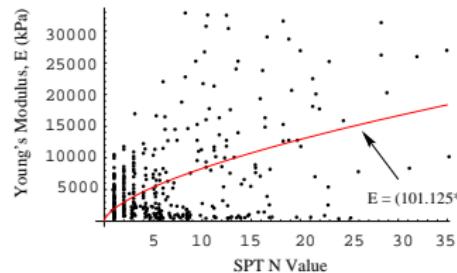
(MP4)

Elastic vs Inelastic



(MP4)

Parametric, Aleatory Uncertainty



Engineer Needs to Know!

- Forward propagation of uncertainty, risk analysis, full probabilistic, nonlinear/inelastic time domain ESSI response (Jeremic et al 2011, Wang et al 2019)
- Backward propagation of uncertainty, sensitivity analysis, relative importance of uncertain input parameters on the variance of probabilistic ESSI response (Sobol 2001, Sudret 2008, Jeremic et al 2022)

Uncertain Inelastic Dynamics

- Incremental el-pl constitutive equation

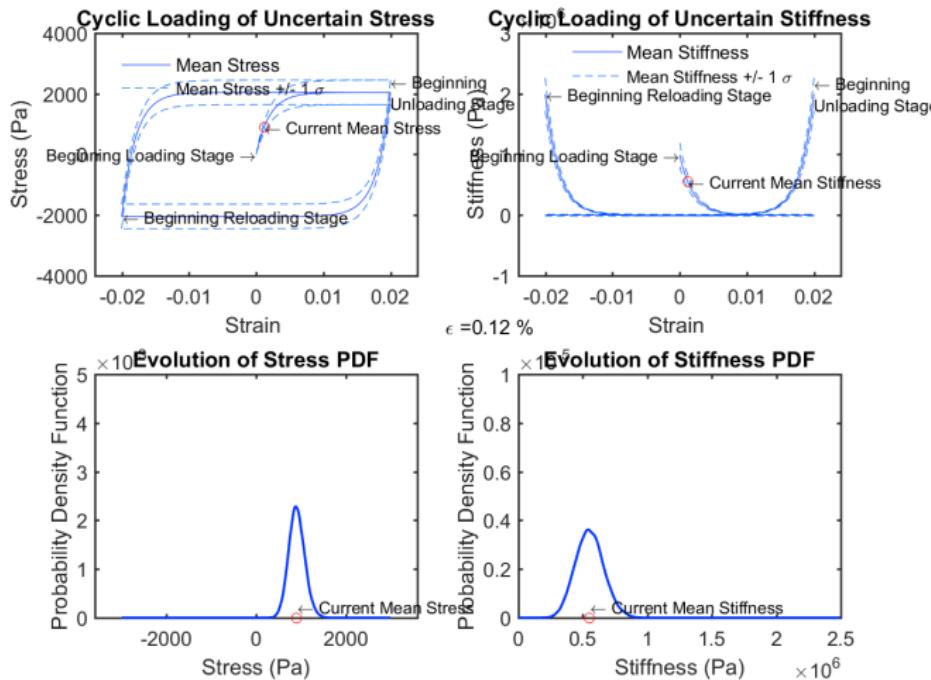
$$\Delta\sigma_{ij} = E_{ijkl}^{EP} \Delta\epsilon_{kl} = \left[E_{ijkl}^{el} - \frac{E_{ijmn}^{el} m_{mn} n_{pq} E_{pqkl}^{el}}{n_{rs} E_{rstu}^{el} m_{tu} - \xi_* h_*} \right] \Delta\epsilon_{kl}$$

- Dynamic Finite Elements

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

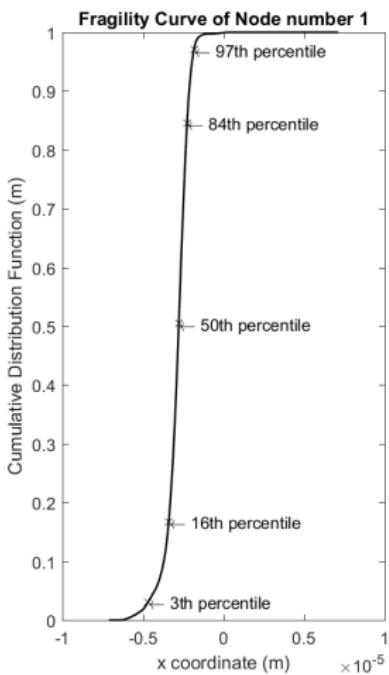
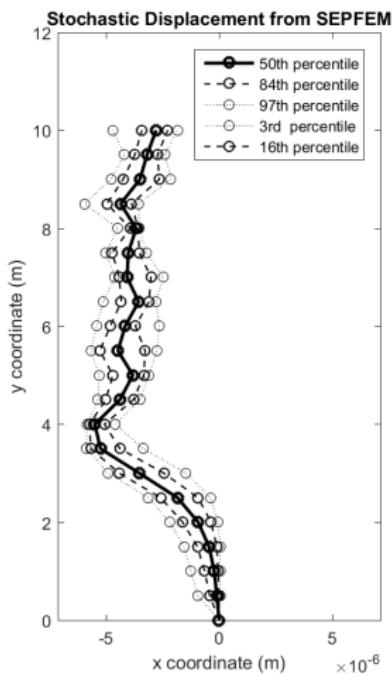
- Materials are uncertain (M, C, K^{ep})
- Loads are uncertain ($F(t)$)

Probabilistic Elastic-Plastic Response



SEPFEM: Example in 1D

(MP4)



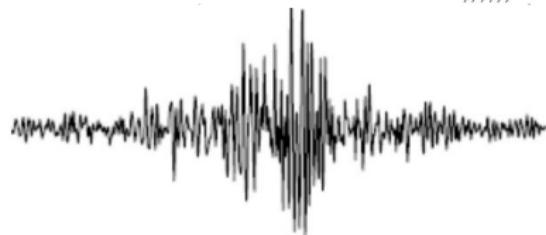
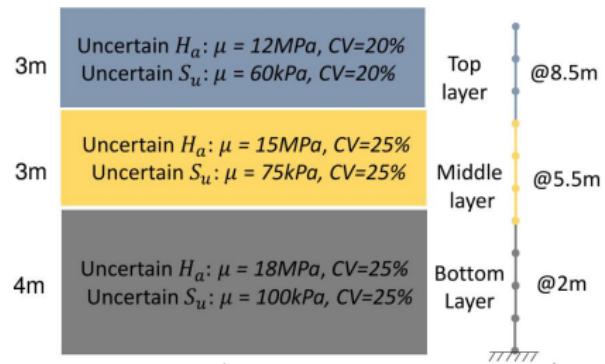
Time Domain Stochastic Galerkin Method

$$\text{Dynamic Finite Elements } M\ddot{u}_i + C\dot{u}_i + K^{ep}u_i = F(t)$$

- Input random field (material) and random process (earthquake): non-Gaussian, heterogeneous/non-stationary, multi-dimensional Hermite polynomial chaos (PC) with known coefficients
- Forward, risk, output response process, multi-dimensional Hermite PC with unknown coefficients
- Backward, sensitivity, ANOVA representation (Sobol 2001, Sudret 2008)

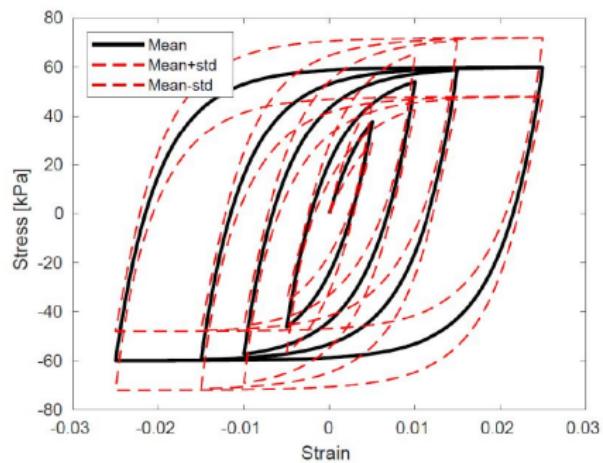
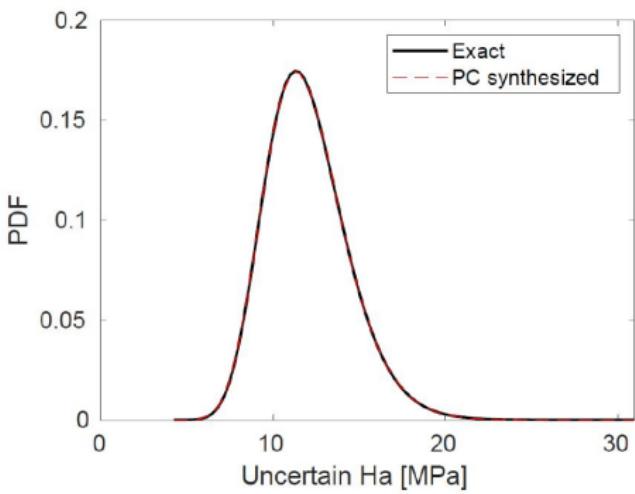
Example: Probabilistic Site Response

- Uncertain material:
uncertain random field,
marginally lognormal
distribution,
exponential correlation
length 10m
- Uncertain seismic
rock motions:
seismic scenario
 $M=7$, $R=50\text{km}$



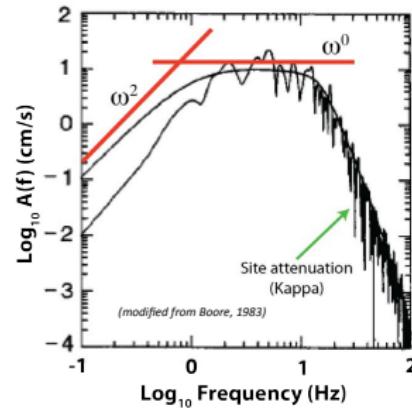
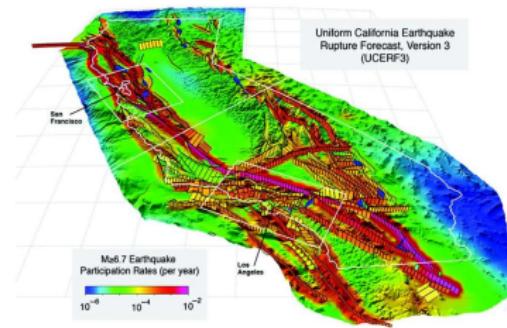
Stochastic Material Parameters

Lognormal distributed random field with PC Dim. 3 Order 2



Stochastic Seismic Motion Development

- UCERF3 (Field et al. 2014)
- Stochastic motions (Boore 2003)
- Polynomial Chaos Karhunen-Loëve expansion
- Probabilistic DRM (Bielak et al. 2003, Wang et al. 2021)



Sensitivity Analysis

Sources of total variance in PGA, in this particular case (!):

49% → uncertain motions at depth/rock

2% → uncertain soil

49% → interaction of uncertain motions and uncertain soil

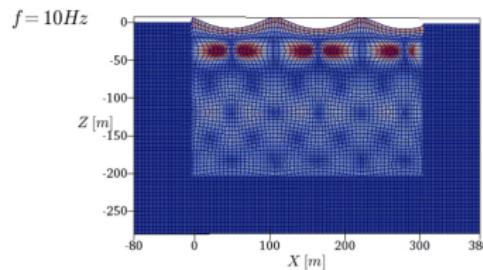
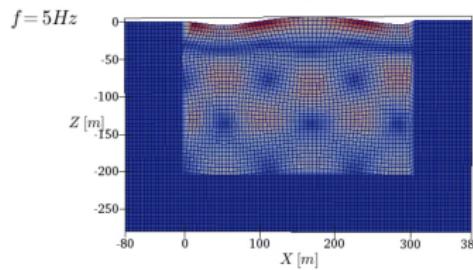
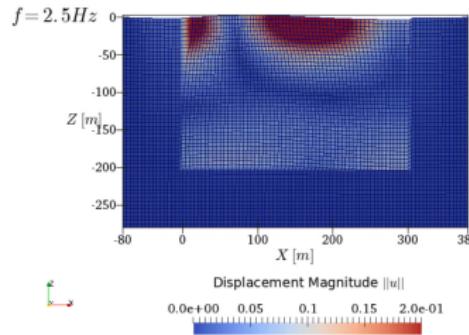
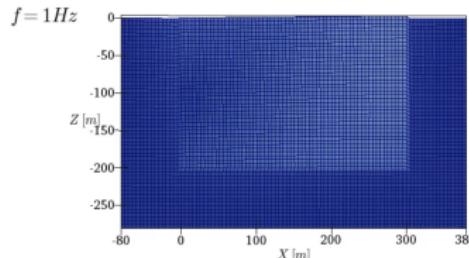
Summary

- Forward uncertainty propagation, risk
- Backward uncertainty propagation, sensitivities
- Modeling and parametric uncertainties
- Predict and inform, Engineer needs to know!
- <http://real-essi.us/>
- US-NSF, US-NRC, US-DOE, US-FEMA, CNSC-CCSN,
UN-IAEA, Shimizu, KEPCO, B&H, Private Funds...
- Bob Kennedy (1939-2018) and Neb Orbović (1962-2021)

Realistic ESSI Analysis

Realistic ESSI Analysis, Examples

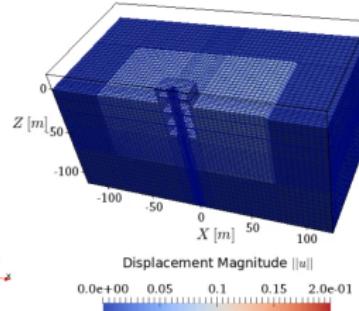
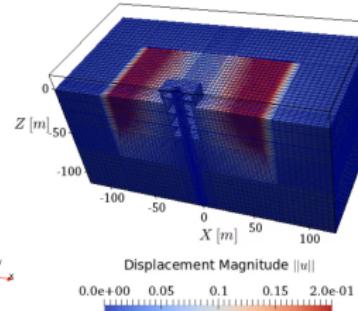
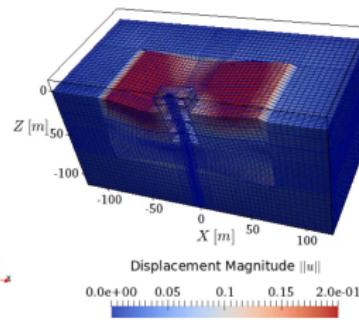
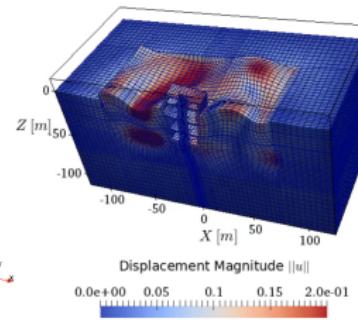
Realistic ESSI Analysis

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

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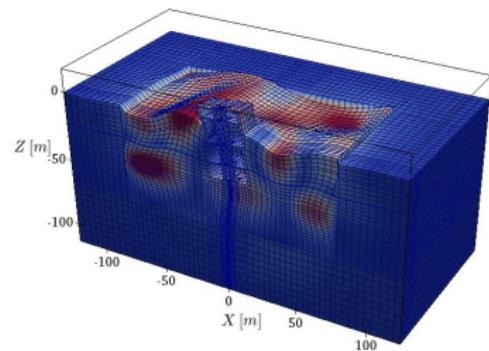
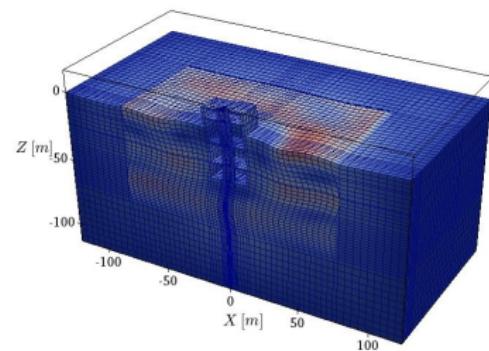


Realistic ESSI Analysis

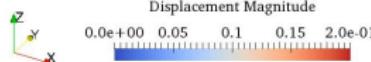
SMR ESSI, Variation in Input Frequency, $\theta = 60^\circ$ $f = 1\text{Hz}$  $f = 2.5\text{Hz}$  $f = 5\text{Hz}$  $f = 10\text{Hz}$ 

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Realistic ESSI Analysis

SMR ESSI, 3C vs $3 \times 1C$ $3C$  $3 \times 1C$ 

(OGV)

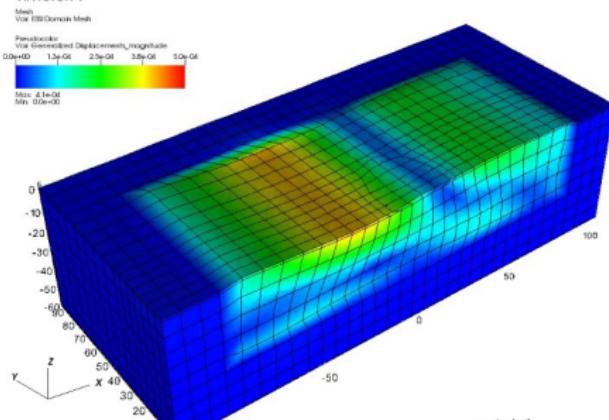


Realistic ESSI Analysis

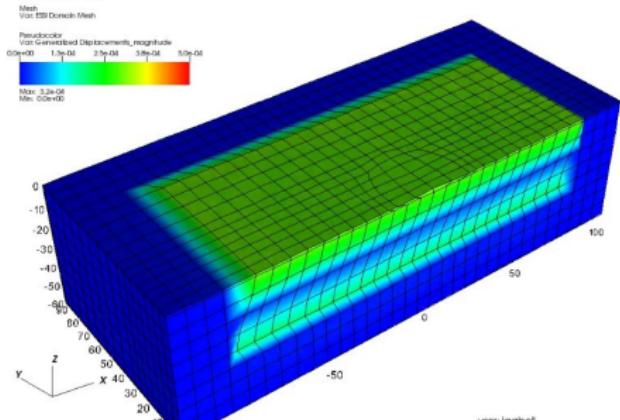
1C vs 6C Free Field Motions

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

DB: npp_model01_ff_quake.h5.feloutput
Time:0.77



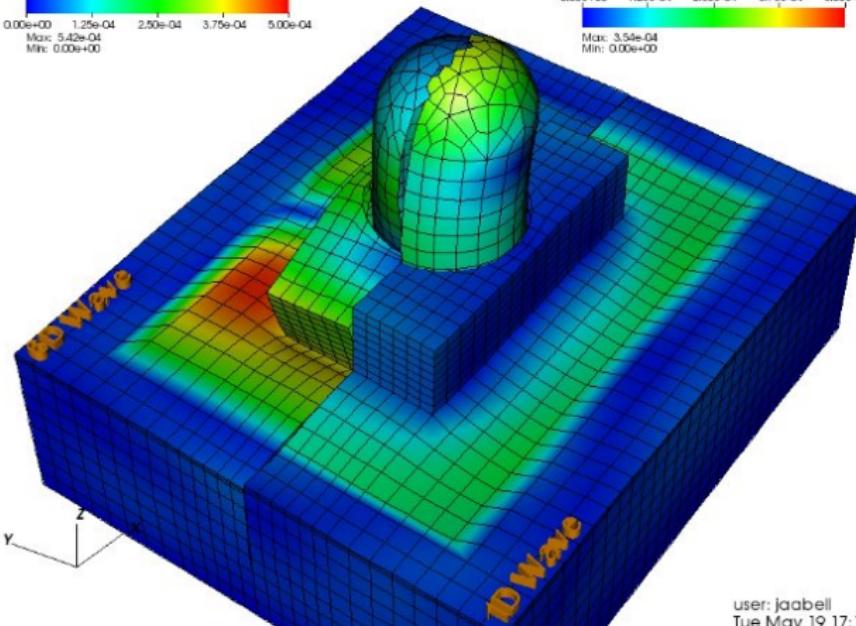
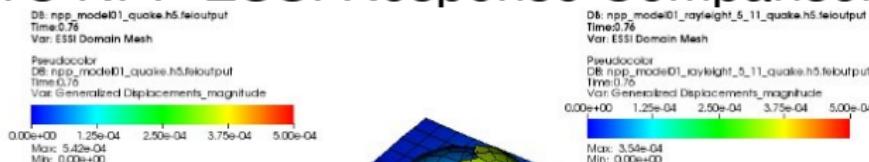
DB: npp_model01_ff_quake.h5.feloutput
Time:0.712



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Realistic ESSI Analysis

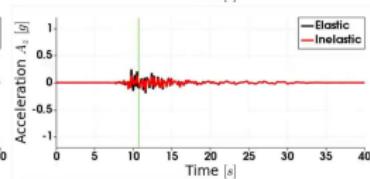
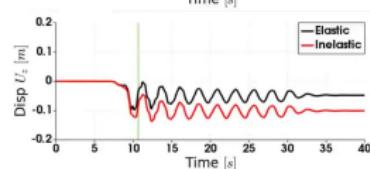
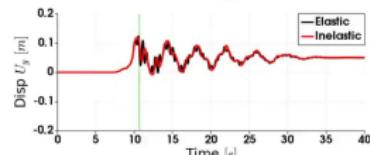
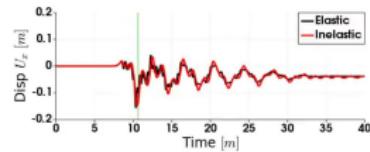
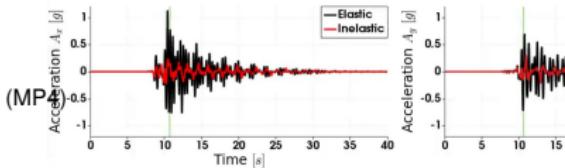
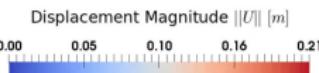
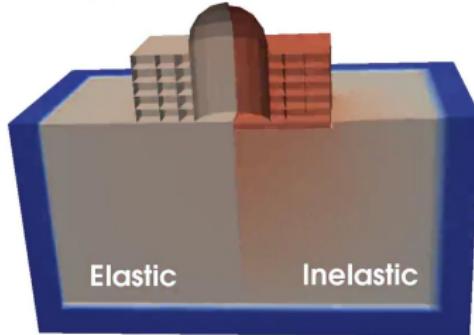
6C vs 1C NPP ESSI Response Comparison

user: jaabel
Tue May 19 17:19:21 2015

Realistic ESSI Analysis

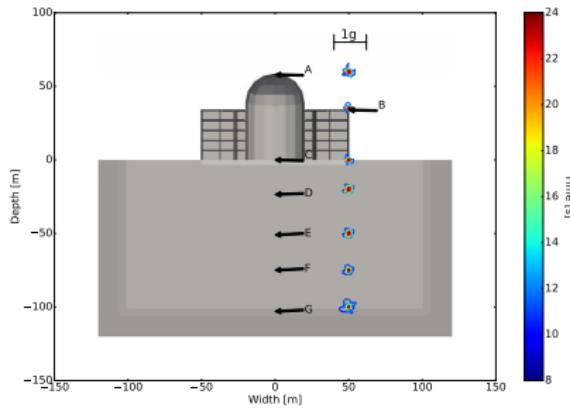
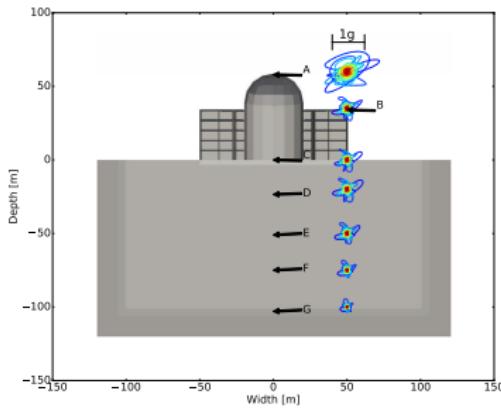
Elastic and Inelastic Response: Differences

Time: 10.67 [s]



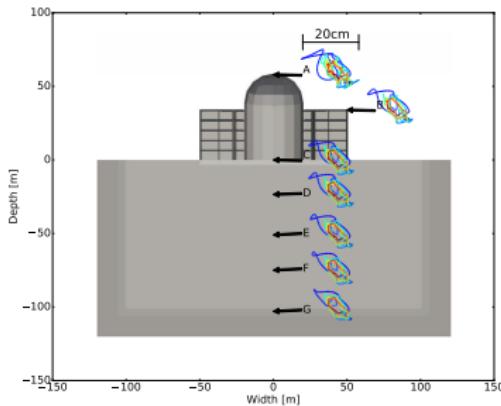
Realistic ESSI Analysis

Acceleration Traces, Elastic vs Inelastic

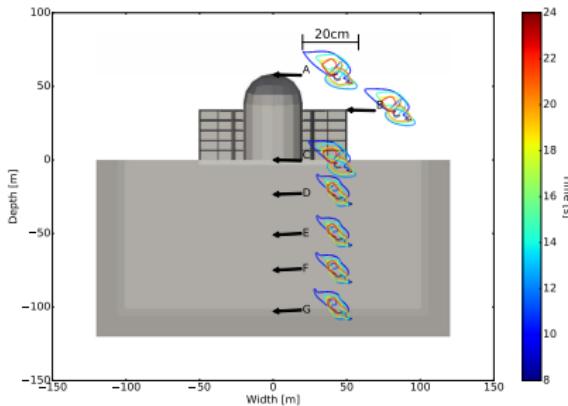


Realistic ESSI Analysis

Displacement Traces, Elastic vs Inelastic



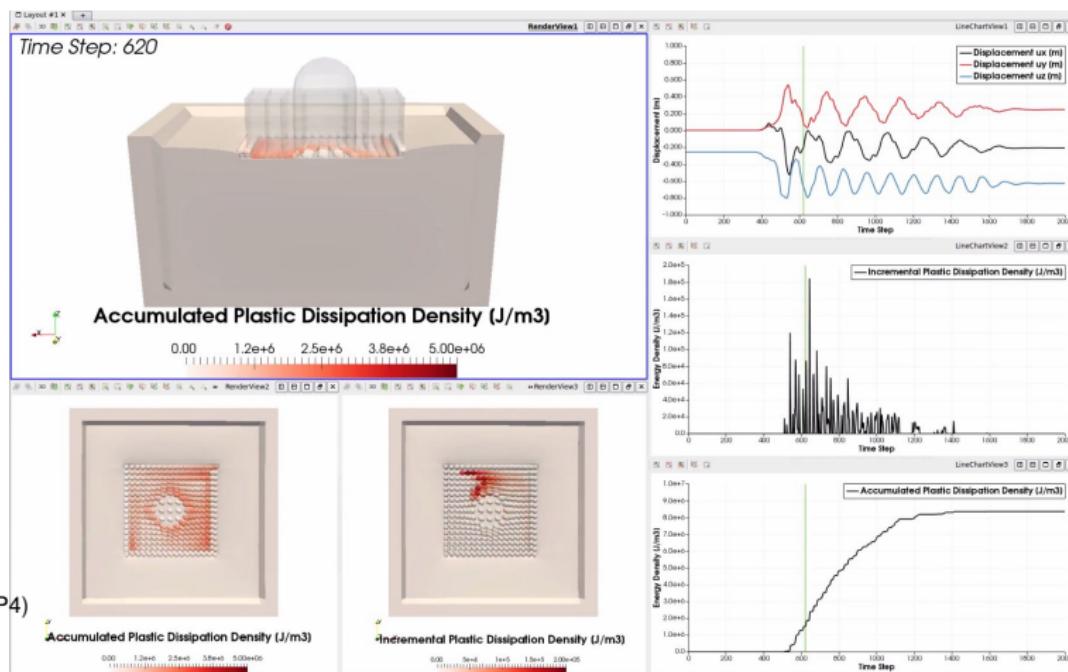
Elastic



Inelastic, Permanent Deformation

Realistic ESSI Analysis

Energy Dissipation in a Large-Scale Model



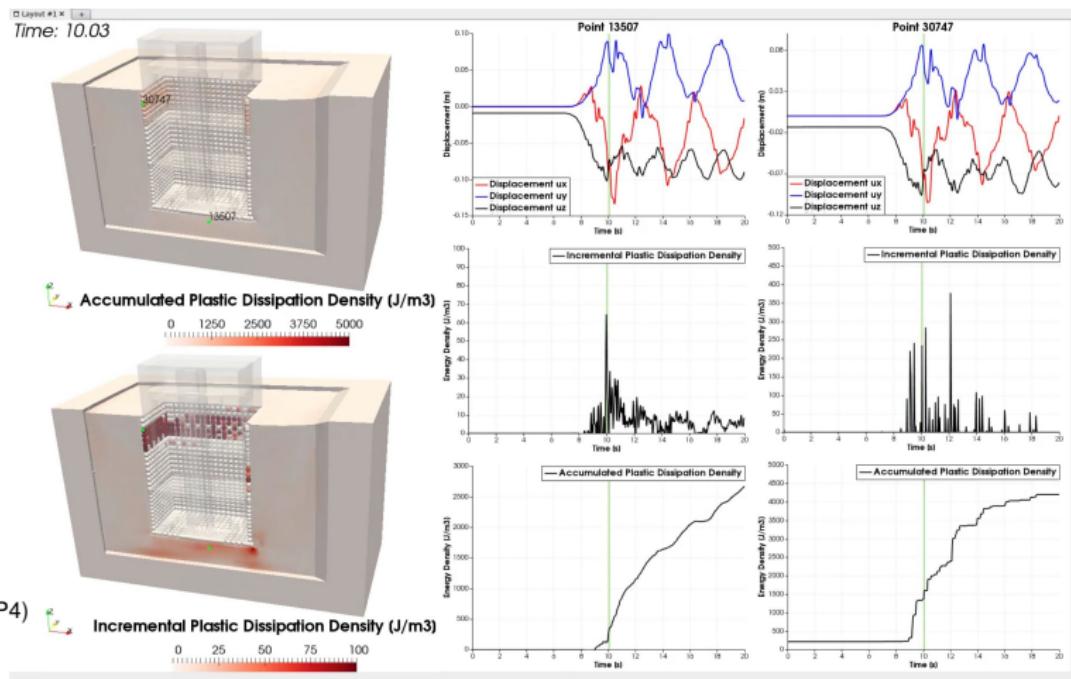
Jeremić, Wang and Yang

Forward and Backward Probabilistic ESSI

UCDAVIS

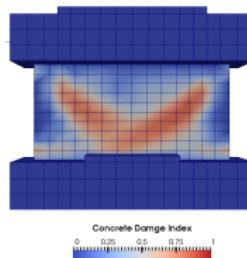
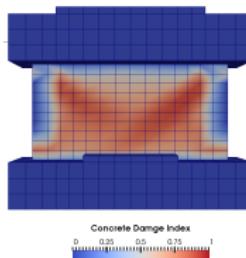
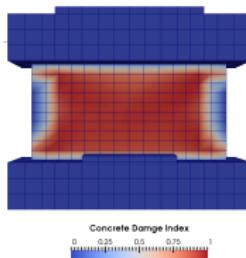
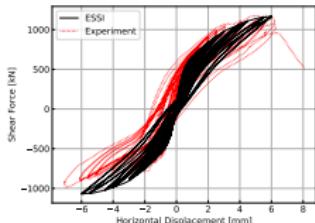
Realistic ESSI Analysis

Energy Dissipation for an SMR Model

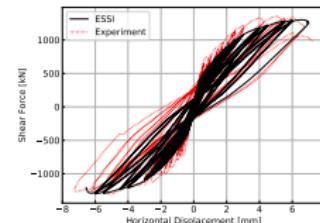


Realistic ESSI Analysis

Concrete Walls, ASR Concrete

damage at: $u_y = 1.4 \text{ mm}$  $u_y = 1.8 \text{ mm}$  $u_y = 3.0 \text{ mm}$ 

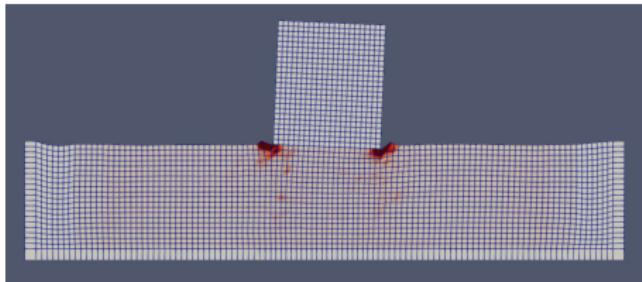
Regular concrete



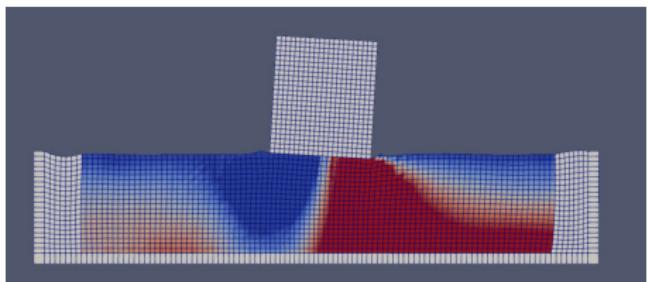
ASR Concrete

Building on Liquefiable Soil

Plastic Strain



Pore Fluid Pressures



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Realistic ESSI Analysis

Structure-Fluid Interaction

