Introduction
000000
0000000

Seismic Motions, Inelasticity and Uncertainty
0000000000
00000000000

Pine Flat Dam
000000000000
0000000

Conclusion
0000

Modeling and Simulation
Earthquake Soil Structure Interaction

Boris Jeremić

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

United States Society on Dams
Chicago, April 2019

Outline

Outline

Motivation

Improve modeling and simulation for infrastructure objects

Use select fidelity (high $\leftrightarrow$ 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

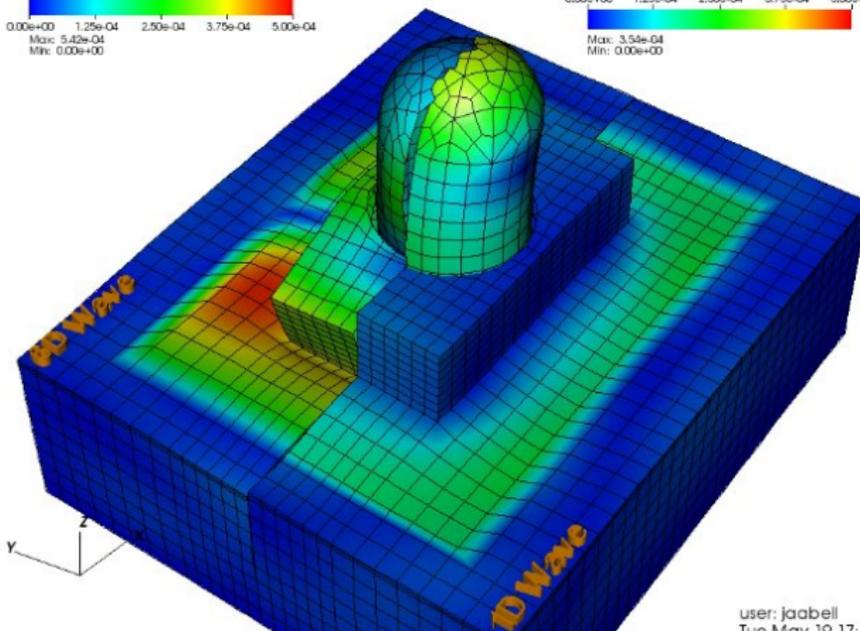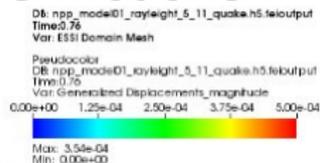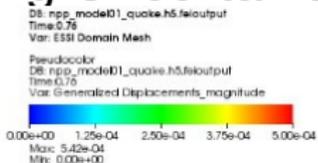► Engineer needs to know!

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

Parametric Uncertainty: Soil Stiffness

$E = (101.125*19.3) N^{0.63}$
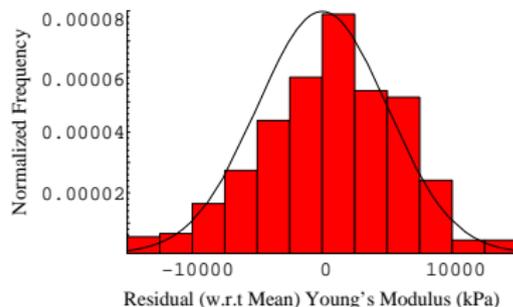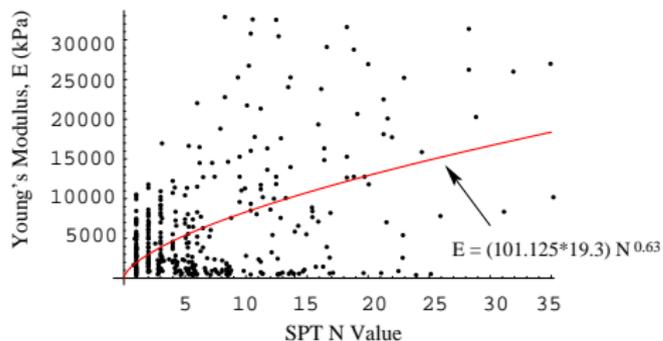
cf. Phoon and Kulhawy (1999B)

Jeremić et al.   UCDAVIS L·B·N·L

Real-ESSI

Introduction
○○○○○●

Seismic Motions, Inelasticity and Uncertainty
○○○○○○○○○○
○○○○○○○○○○○

Pine Flat Dam
○○○○○○○○○○○○○○
○○○○○○○

Conclusion
○○○○

Motivation

Modeling Uncertainty, 6C vs 1C Motions

(MP4)

Outline

Introduction
○○○○○○
○●○○○○○

Seismic Motions, Inelasticity and Uncertainty
○○○○○○○○○○
○○○○○○○○○○○

Pine Flat Dam
○○○○○○○○○○○○
○○○○○○○

Conclusion
○○○○

Modeling and Simulation of ESSI

Energy Input and Dissipation

Energy input, dynamic forcing

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

Energy dissipation/conversion inside SSI domain:
   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

$$
\begin{bmatrix} (M_s)_{KijL} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & (M_f)_{KijL} \end{bmatrix} \begin{bmatrix} \ddot{\overline{u}}_{Lj} \\ \ddot{\overline{p}}_N \\ \ddot{\overline{U}}_{Lj} \end{bmatrix} + \begin{bmatrix} (C_1)_{KijL} & 0 & -(C_2)_{KijL} \\ 0 & 0 & 0 \\ -(C_2)_{LjiK} & 0 & (C_3)_{KijL} \end{bmatrix} \begin{bmatrix} \dot{\overline{u}}_{Lj} \\ \dot{\overline{p}}_N \\ \dot{\overline{U}}_{Lj} \end{bmatrix}
$$

$$
+ \begin{bmatrix} (K^{EP})_{KijL} & -(G_1)_{KiM} & 0 \\ -(G_1)_{LjM} & -P_{MN} & -(G_2)_{LjM} \\ 0 & -(G_2)_{KiL} & 0 \end{bmatrix} \begin{bmatrix} \overline{u}_{Lj} \\ \overline{p}_M \\ \overline{U}_{Lj} \end{bmatrix} = \begin{bmatrix} \overline{f}^{solid}_{Ki} \\ 0 \\ \overline{f}^{fluid}_{Ki} \end{bmatrix}
$$

Fully Coupled Formulation, u-p-U

$$
\begin{aligned}
(M_s)_{KijL} &= \int_\Omega H_K^u (1-n) \rho_s \delta_{ij} H_L^u d\Omega & (M_f)_{KijL} &= \int_\Omega H_K^U n \rho_f \delta_{ij} H_L^U d\Omega \\
(C_1)_{KijL} &= \int_\Omega H_K^u n^2 k_{ij}^{-1} H_L^u d\Omega & (C_2)_{KijL} &= \int_\Omega H_K^u n^2 k_{ij}^{-1} H_L^U d\Omega \\
(C_3)_{KijL} &= \int_\Omega H_K^U n^2 k_{ij}^{-1} H_L^U d\Omega & (K^{EP})_{KijL} &= \int_\Omega H_{K,m}^u D_{imjn} H_{L,n}^u d\Omega \\
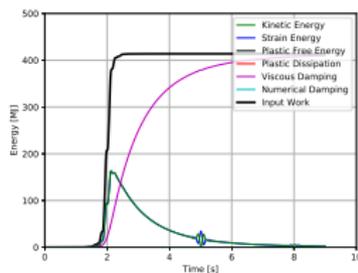(G_1)_{KiM} &= \int_\Omega H_{K,i}^u (\alpha - n) H_M^p d\Omega & (G_2)_{KiM} &= \int_\Omega n H_{K,i}^U H_M^p d\Omega \\
P_{NM} &= \int_\Omega H_N^p \frac{1}{Q} H_M^p d\Omega
\end{aligned}
$$

Energy Dissipation Control Mechanisms
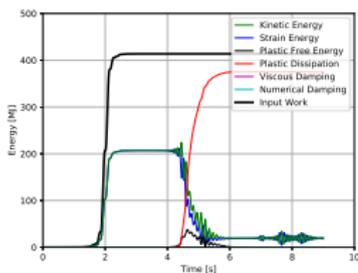
Plasticity   Viscous   Numerical

Energy Dissipation Control

Introduction | Seismic Motions, Inelasticity and Uncertainty | Pine Flat Dam | Conclusion
000000 | 000000000 | 000000000000 | 0000
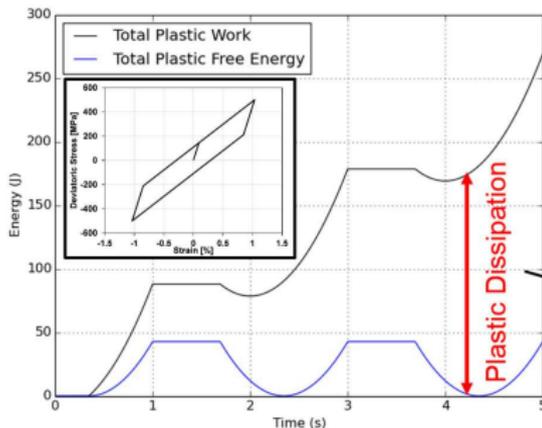0000000●

Modeling and Simulation of ESSI
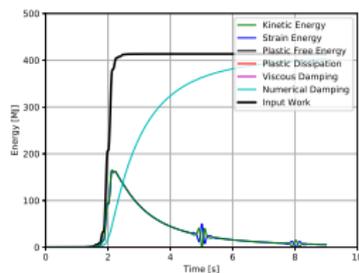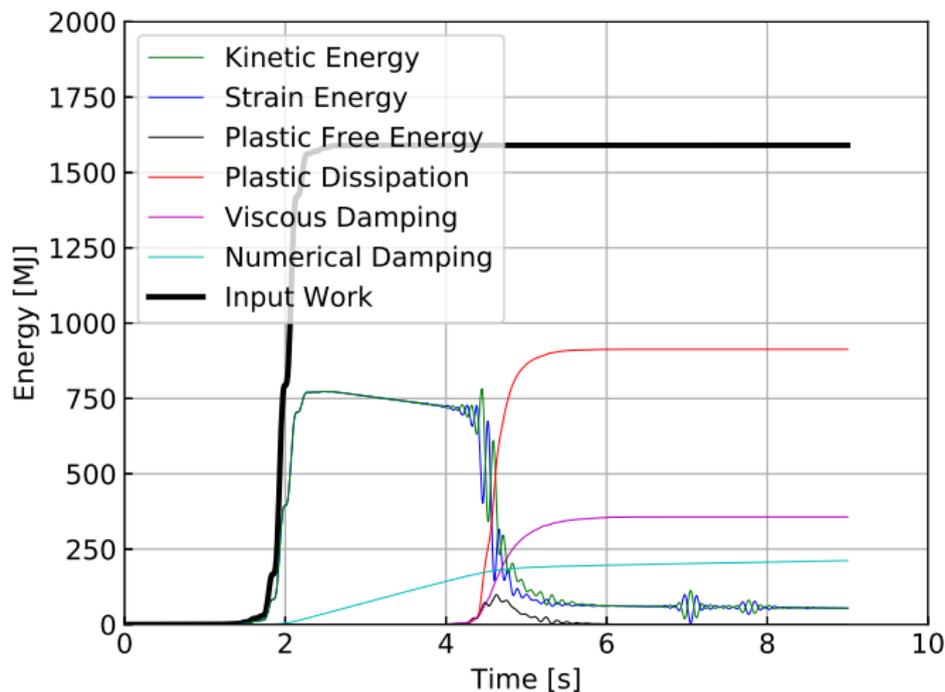
Energy Dissipation on Material Level

Single elastic-plastic element under cyclic shear loading

Difference between plastic work and plastic dissipation
Plastic work can decrease
Plastic dissipation always increases
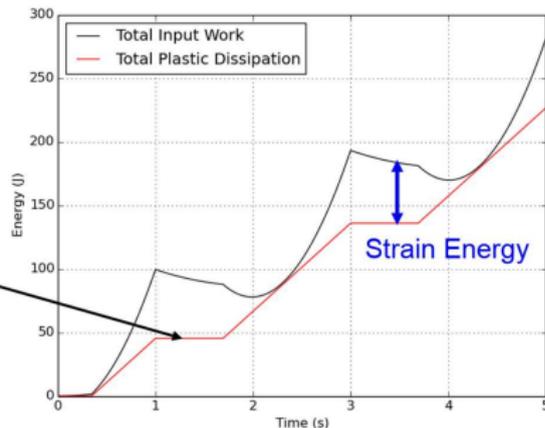
Outline

3C, 6C Seismic Motions

- ▶ All (most) measured motions are full 3C, 6C
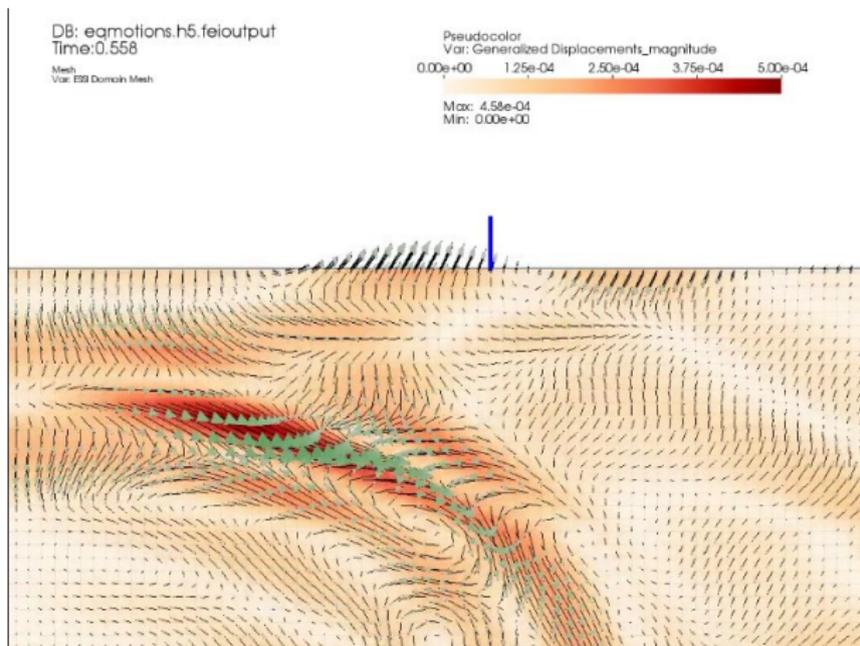- ▶ One example of an almost 2C motion (LSST07, LSST12)
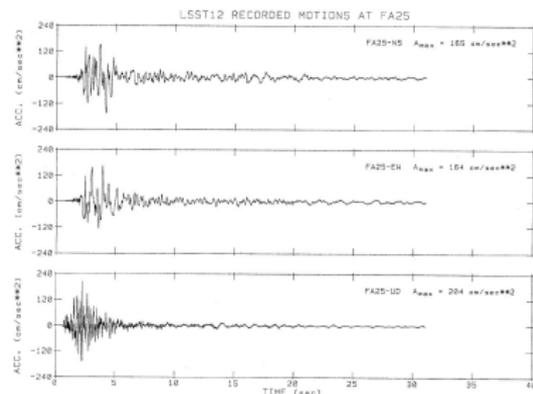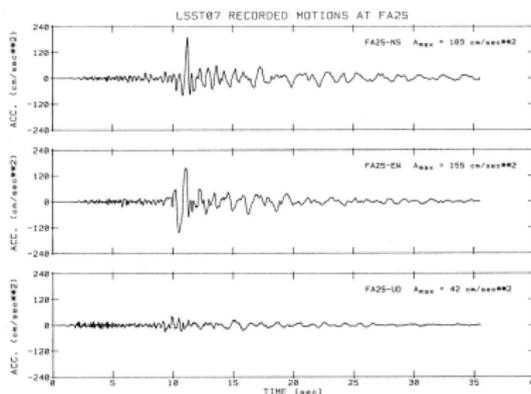
ESSI: 6C or 1C Seismic Motions

▶ 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
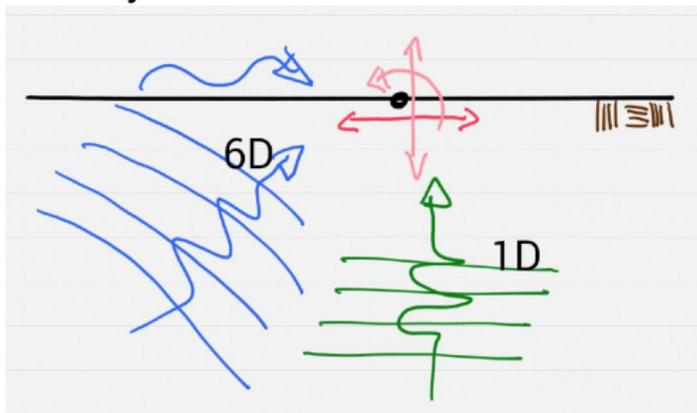
6C Free Field Motions (closeup)

(MP4)

Jeremić et al.

Real-ESSI

Introduction   Seismic Motions, Inelasticity and Uncertainty   Pine Flat Dam   Conclusion
000000   0000●00000   000000000000   0000
0000000   00000000000

Six Component Seismic Motions

1C vs 6C Free Field Motions

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

(MP4) (MP4)

Introduction
000000
0000000

Seismic Motions, Inelasticity and Uncertainty
000000●0000
000000000000

Pine Flat Dam
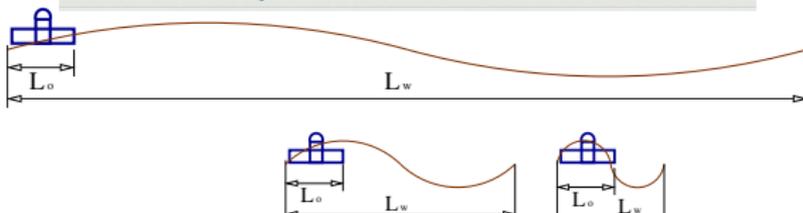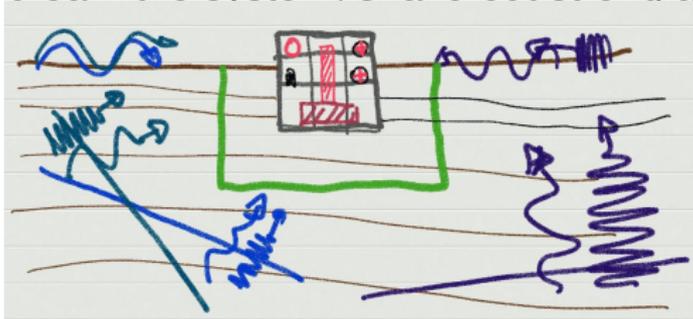000000000000
0000000

Conclusion
0000
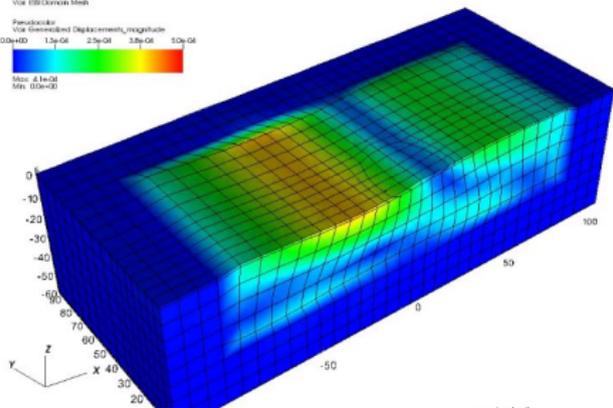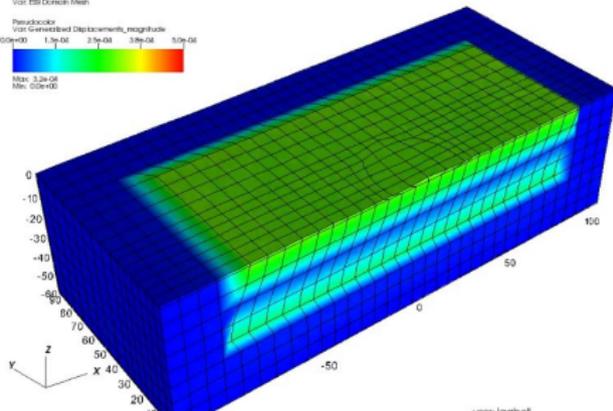
Six Component Seismic Motions

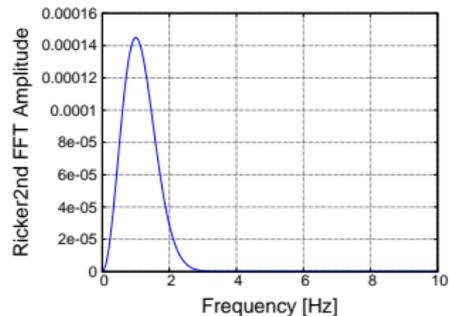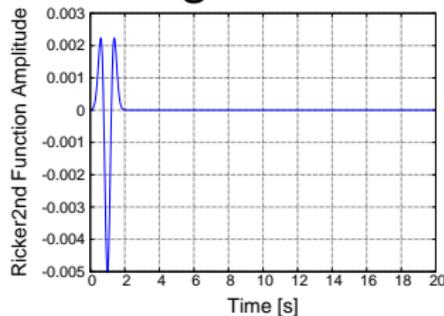# 6C vs 1C NPP ESSI Response Comparison

(MP4)
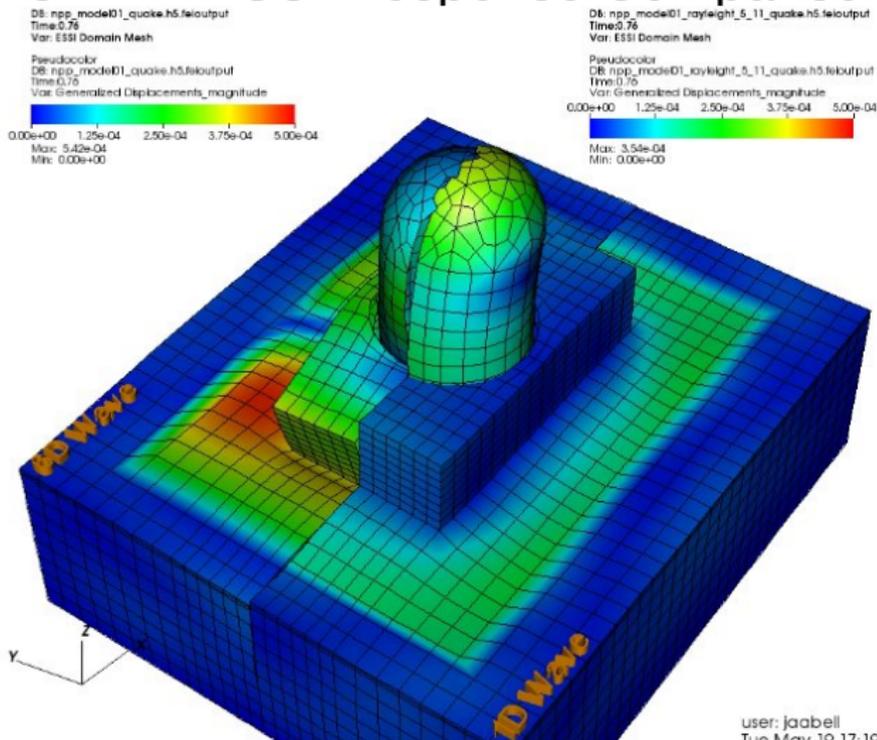
Stress Testing SSI Systems

- ▶ Excite SSI system with a suite of seismic motions
- ▶ Waves: P, SV, SH, Surface (Rayleigh, Love, etc.)
- ▶ Variation in inclination, frequency, energy and duration
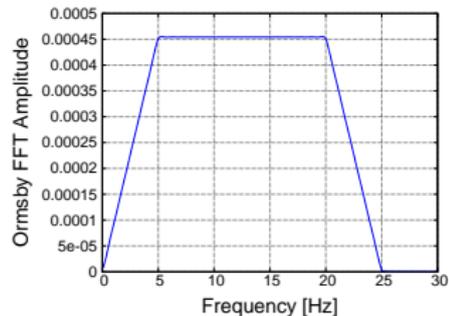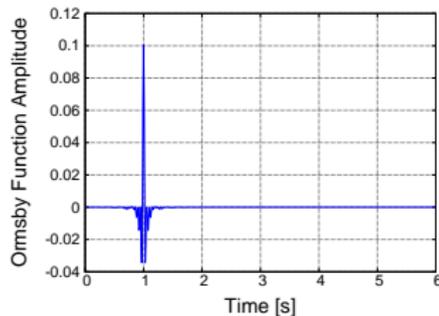- ▶ Try to "break" the system, shake-out strong and weak links
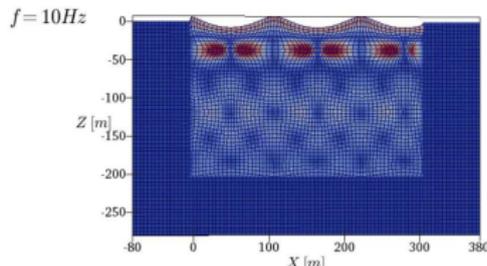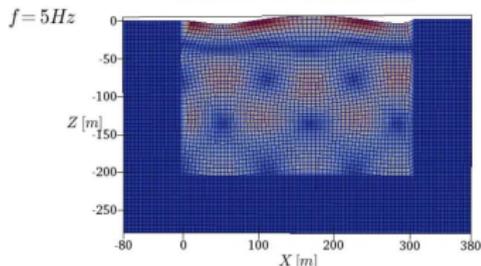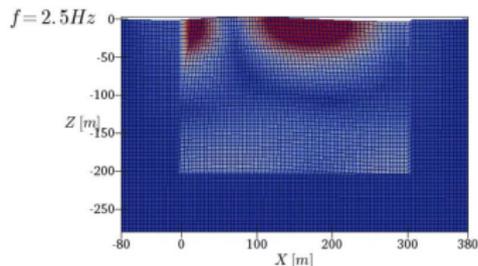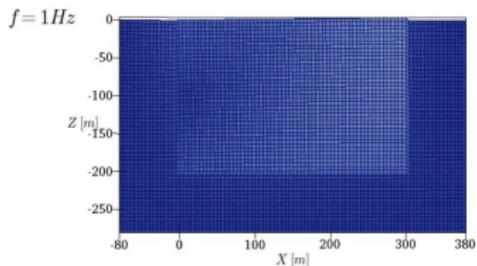
Stress Test Source Signals

▶ Ricker

▶ Ormsby

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

(MP4)

Introduction   Seismic Motions, Inelasticity and Uncertainty   Pine Flat Dam   Conclusion
○○○○○○   ○○○○○○○○○●   ○○○○○○○○○○○○○   ○○○○
○○○○○○○   ○○○○○○○○○○○○○   ○○○○○○○

Six Component Seismic Motions

SMR ESSI, Variation in Input Frequency, $\theta = 60^o$
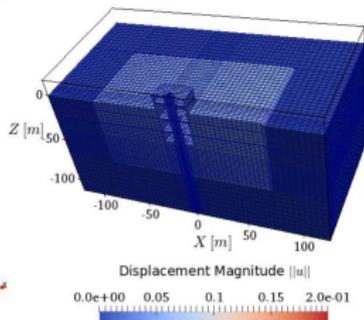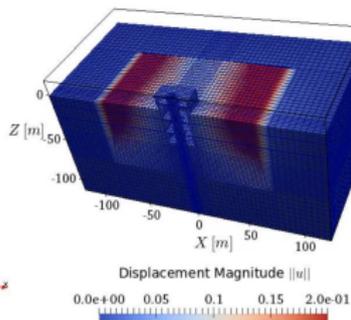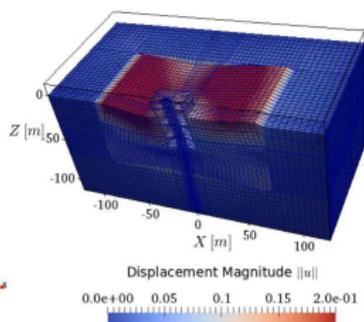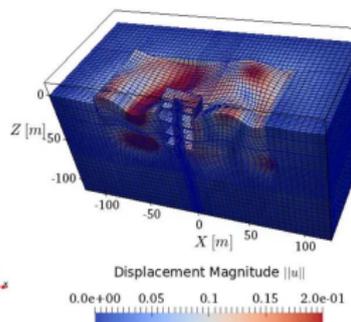
$f = 1\,Hz$

$Z\,[m]$

$X\,[m]$

Displacement Magnitude $||u||$

0.0e+00   0.05   0.1   0.15   2.0e-01

$f = 2.5\,Hz$

$Z\,[m]$

$X\,[m]$

Displacement Magnitude $||u||$

0.0e+00   0.05   0.1   0.15   2.0e-01

$f = 5\,Hz$

$Z\,[m]$

$X\,[m]$

Displacement Magnitude $||u||$

0.0e+00   0.05   0.1   0.15   2.0e-01

$f = 10\,Hz$

$Z\,[m]$

$X\,[m]$

Displacement Magnitude $||u||$

0.0e+00   0.05   0.1   0.15   2.0e-01

(MP4)

Jeremić et al.

Real-ESSI

UCDAVIS L·B·N·L

Outline

Energy Input and Dissipation

Energy input, static and dynamic forcing

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

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

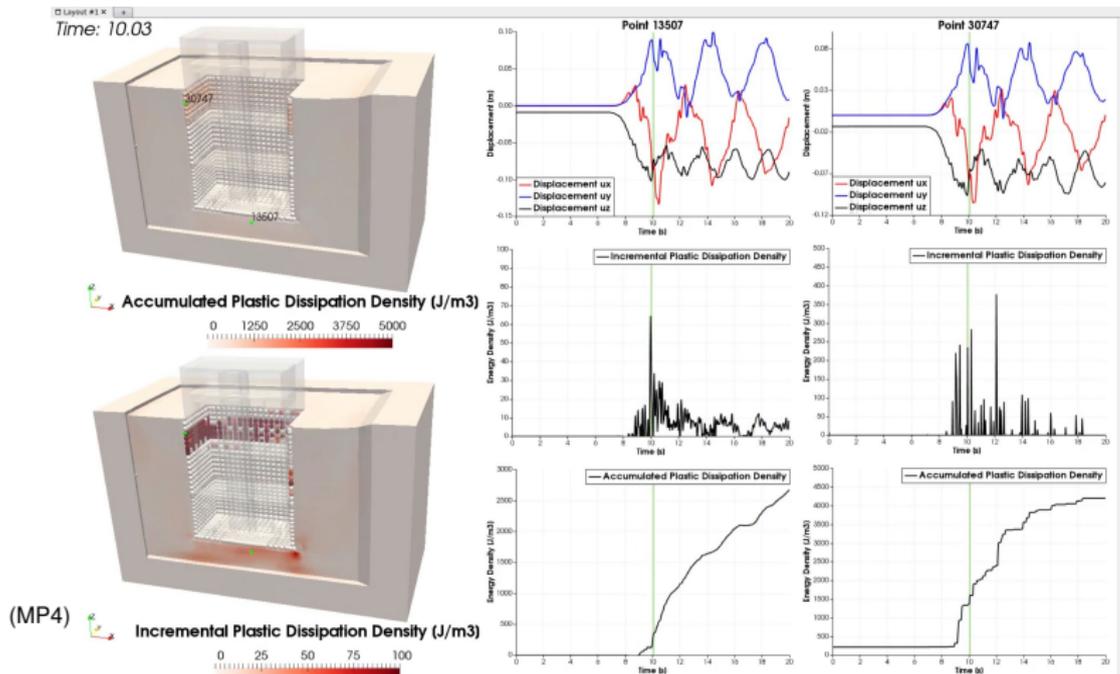Numerical energy dissipation/production

Inelasticity, Plastic Energy Dissipation and Uncertainty

Energy Dissipation in NPP Model

Jeremić et al.

Real-ESSI

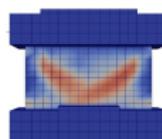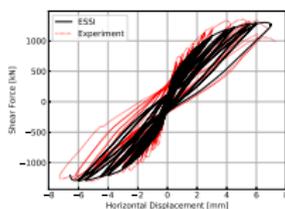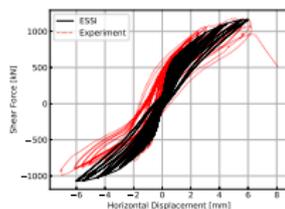| Introduction	Seismic Motions, Inelasticity and Uncertainty	Pine Flat Dam	Conclusion
○○○○○○	○○○○○○○○○○	○○○○○○○○○○○○○	○○○○
○○○○○○○	○○○●○○○○○○○	○○○○○○○	

Inelasticity, Plastic Energy Dissipation and Uncertainty
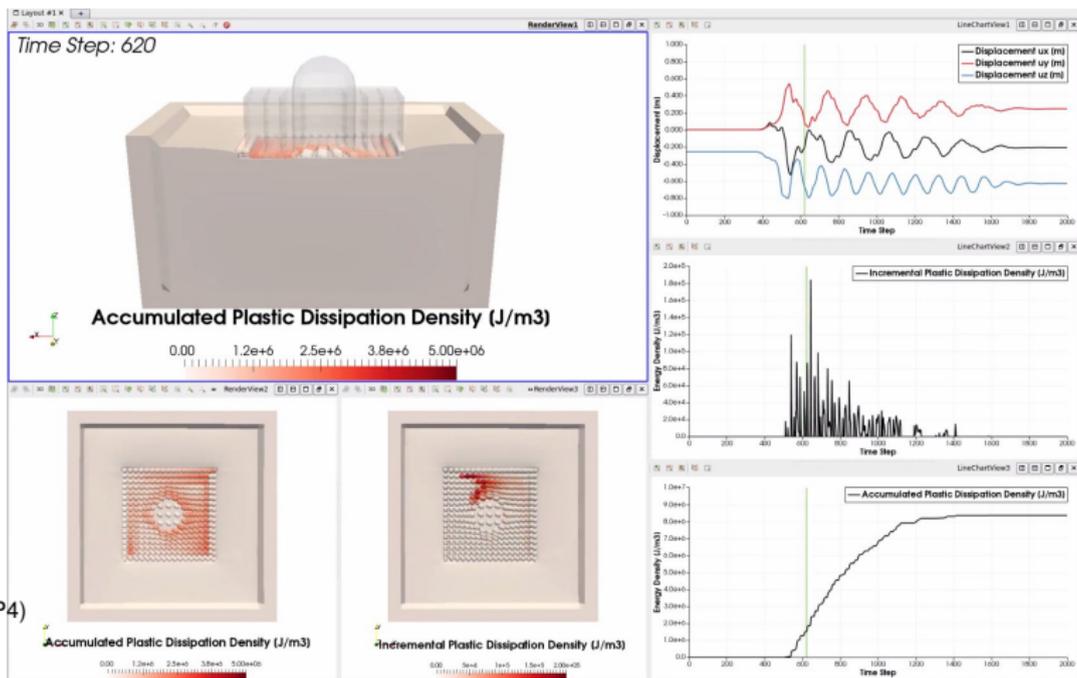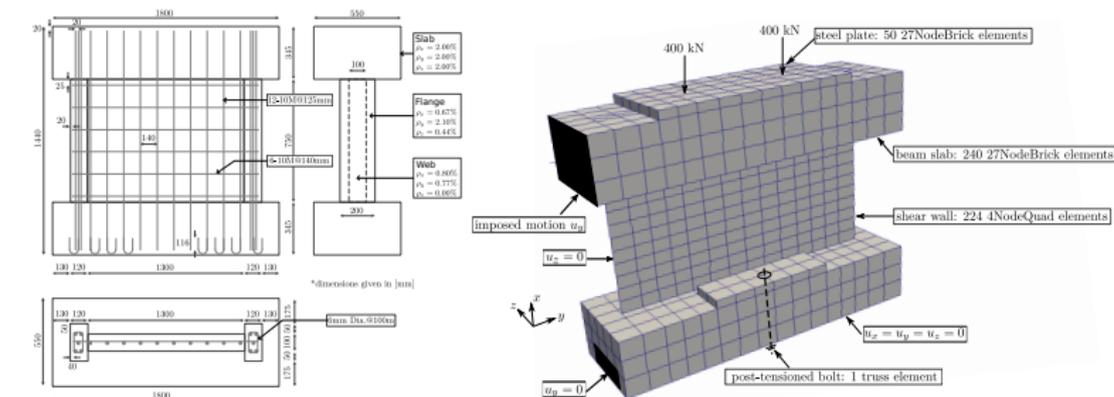
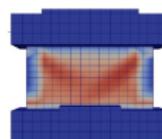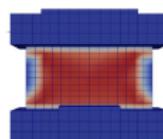# Energy Dissipation for an SMR Model

(MP4)

Wall, Regular and ASR Concrete
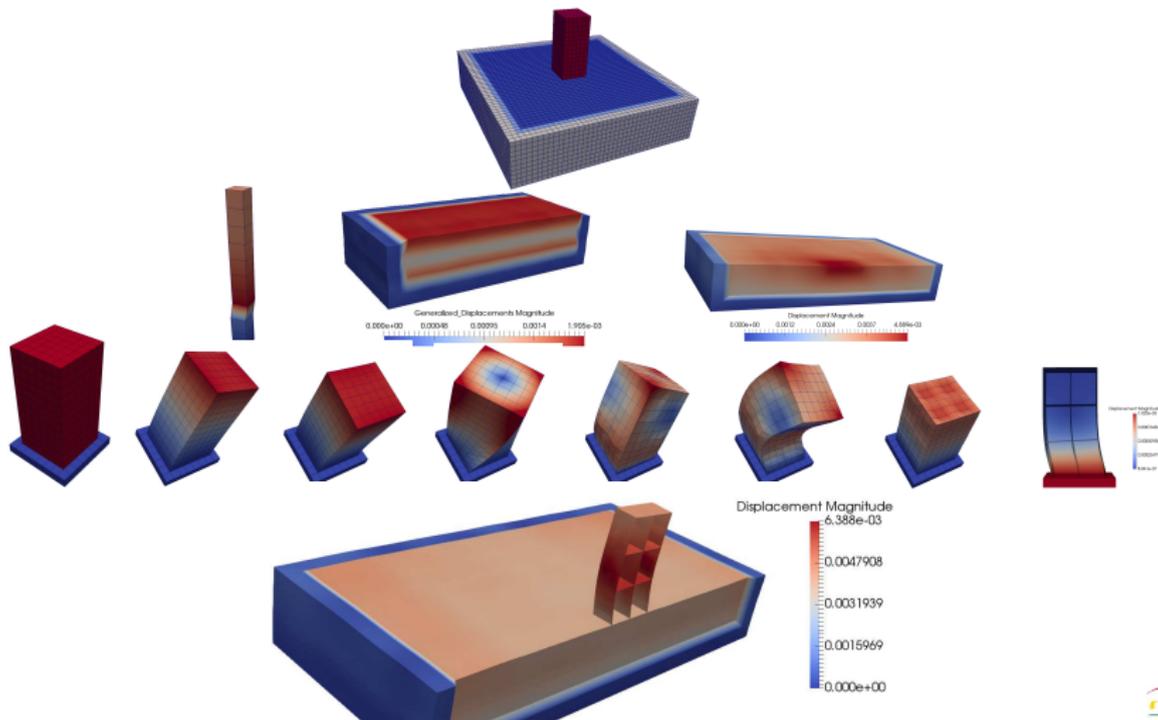

u_y = 1.4 mm u_y = 1.8 mm u_y = 3.0 mm

Real-ESSI Modeling Phases

Uncertainty Propagation through Inelastic System

- Incremental el–pl constitutive equation

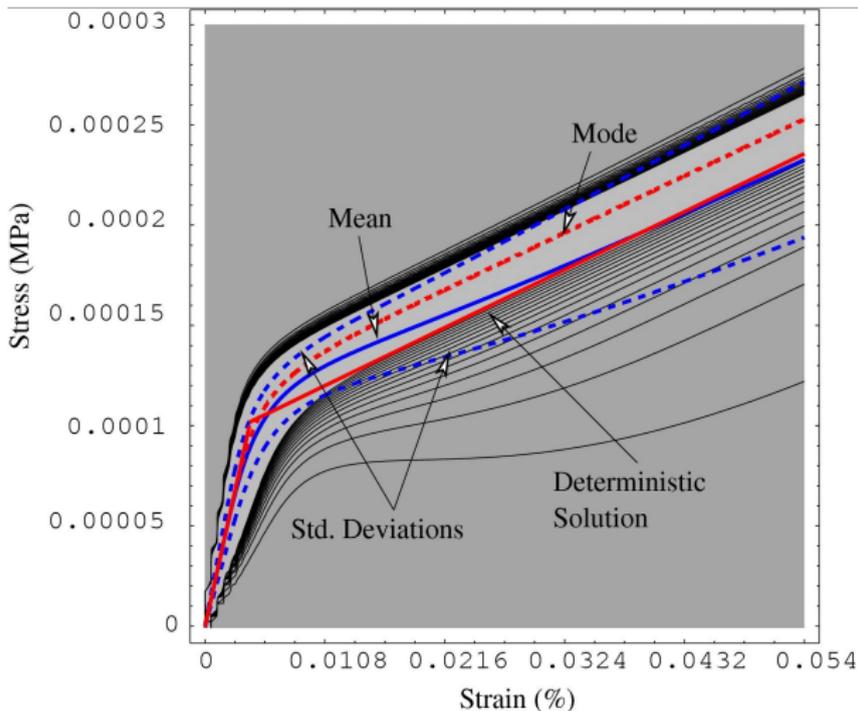$$\Delta\sigma_{ij} = E_{ijkl}^{EP} \, \Delta\epsilon_{kl} = \left[E_{ijkl}^{el} - \frac{E_{ijmn}^{el} m_{mn} n_{pq} E_{pqkl}^{el}}{n_{rs} E_{rstu}^{el} m_{tu} - \xi_* h_*} \right] \Delta\epsilon_{kl}$$
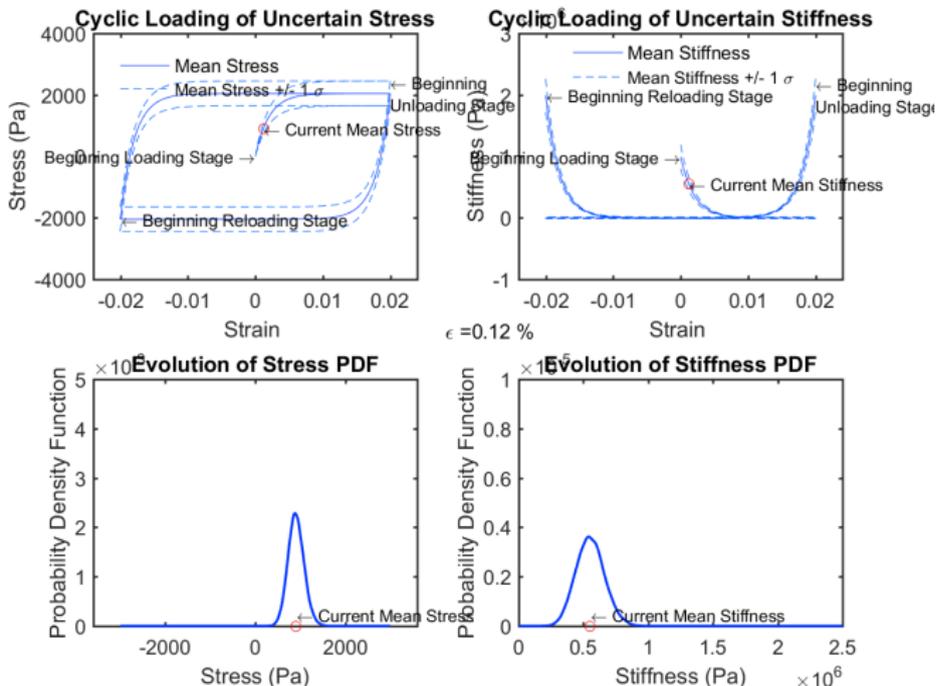
- Dynamic Finite Elements

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

- Material and load parameters are uncertain

Probabilistic Elastic-Plastic Response

# Probabilistic Elastic-Plastic Modeling

Stochastic Elastic-Plastic Finite Element Method

- ► Material uncertainty expanded into stochastic shape funcs.
- ► Loading uncertainty expanded into stochastic shape funcs.
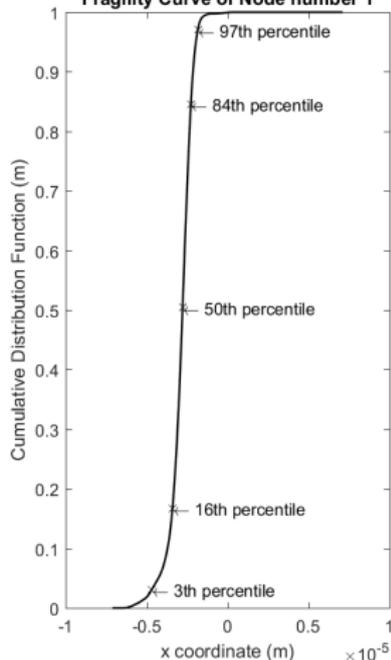- ► Displacement expanded into stochastic shape funcs.

$$
\begin{bmatrix}
\sum_{k=0}^{P_d} <\Phi_k\Psi_0\Psi_0> K^{(k)} & \cdots & \sum_{k=0}^{P_d} <\Phi_k\Psi_P\Psi_0> K^{(k)} \\
\sum_{k=0}^{P_d} <\Phi_k\Psi_0\Psi_1> K^{(k)} & \cdots & \sum_{k=0}^{P_d} <\Phi_k\Psi_P\Psi_1> K^{(k)} \\
\vdots & \vdots & \vdots \\
\sum_{k=0}^{P_d} <\Phi_k\Psi_0\Psi_P> K^{(k)} & \cdots & \sum_{k=0}^{M} <\Phi_k\Psi_P\Psi_P> K^{(k)}
\end{bmatrix}
\begin{bmatrix}
\Delta u_{10} \\
\vdots \\
\Delta u_{N0} \\
\vdots \\
\Delta u_{1P_u} \\
\vdots \\
\Delta u_{NP_u}
\end{bmatrix}
=
\begin{bmatrix}
\sum_{i=0}^{P_f} f_i <\Psi_0\zeta_i> \\
\sum_{i=0}^{P_f} f_i <\Psi_1\zeta_i> \\
\sum_{i=0}^{P_f} f_i <\Psi_2\zeta_i> \\
\vdots \\
\sum_{i=0}^{P_f} f_i <\Psi_{P_u}\zeta_i>
\end{bmatrix}
$$

SEPFEM: Example in 1D
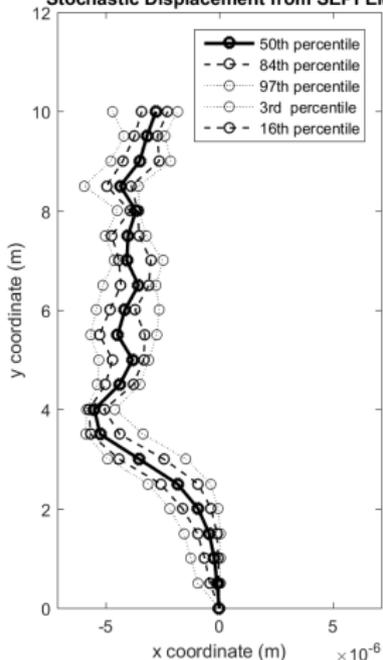
Outline

Pine Flats Dam, Model

- ► Material properties provided
- ► Motions applied through DRM, from bottom
- ► Energy dissipation, Viscous, Numerical, Radiation
- ► Load cases as provided

Introduction   Seismic Motions, Inelasticity and Uncertainty   **Pine Flat Dam**   Conclusion
000000   000000000   000●000000000   0000
0000000   00000000000   0000000

Pine Flat Dam Test Model
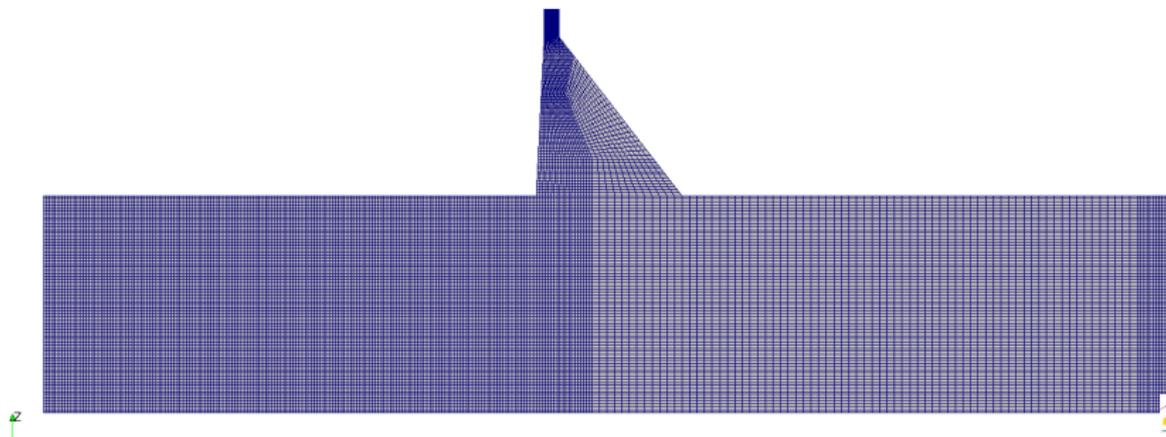
Pine Flats Dam, Static, Displacements

- ▶ Self weight
- ▶ Water pressure, on dam side and lake bottom
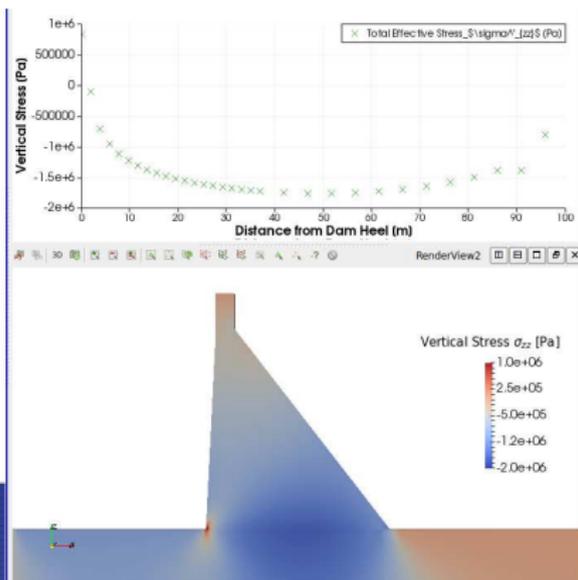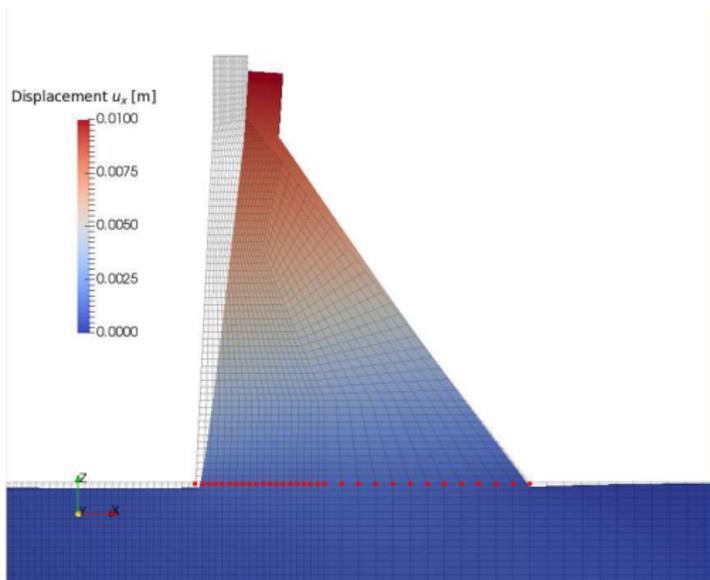
| | | Disp. [m] | | | Disp. [in] |
		Top	Heel	Rel.	Rel.
Mat. Prop. I	Hor.	0.0121	0.0031	0.00900	0.354
(Soft Found.)	Vert.	-0.0095	-0.0059	-0.00348	-0.137
Mat. Prop. II	Hor.	0.0101	0.0011	0.00904	0.356
(Stiff Found.)	Vert.	-0.0048	-0.0019	-0.00298	-0.117

Introduction   Seismic Motions, Inelasticity and Uncertainty   Pine Flat Dam   Conclusion
000000   0000000000   0000000000000   0000
0000000   00000000000   0000000

Pine Flat Dam Test Model

Static, Displacements and σ_v

Mesh Refinement Effects
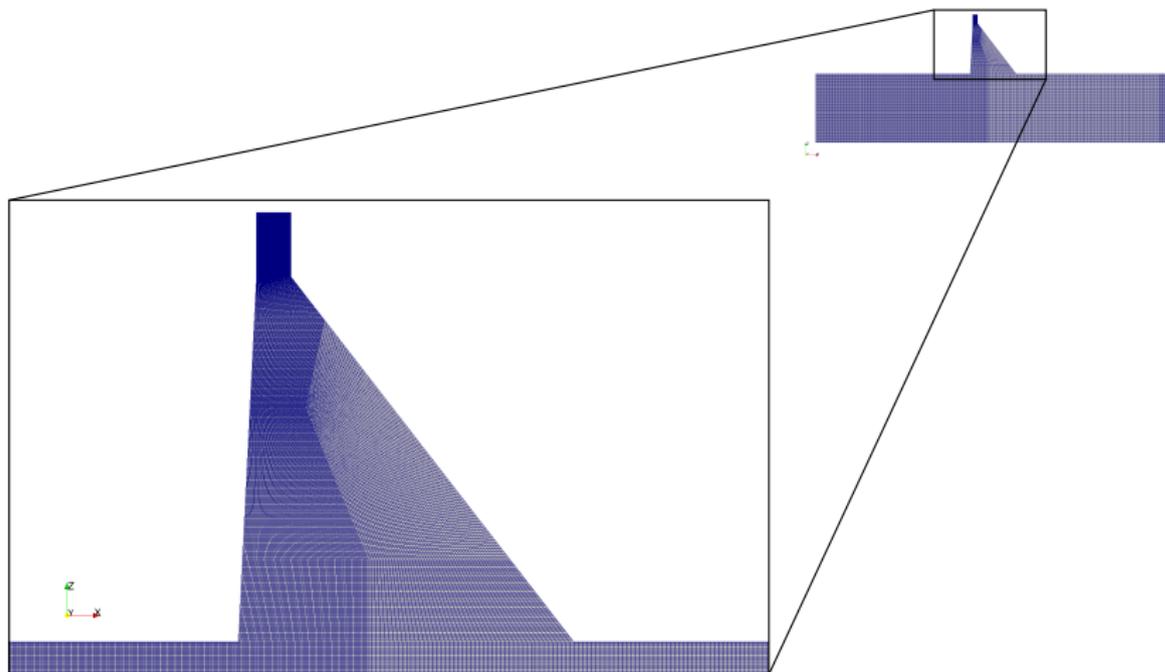
Mesh Refinement Effects

		Displacements [m]		
		Original	Refined	Difference
Dam Top	Horizontal	0.012121	0.012201	0.66%
	Vertical	-0.009463	-0.009794	3.51%
Dam Heel	Horizontal	0.003124	0.003287	5.21%
	Vertical	-0.005981	-0.006953	16.25%
Relative	Horizontal	0.008996	0.009064	0.76%
	Vertical	-0.003481	-0.003489	0.23%

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,

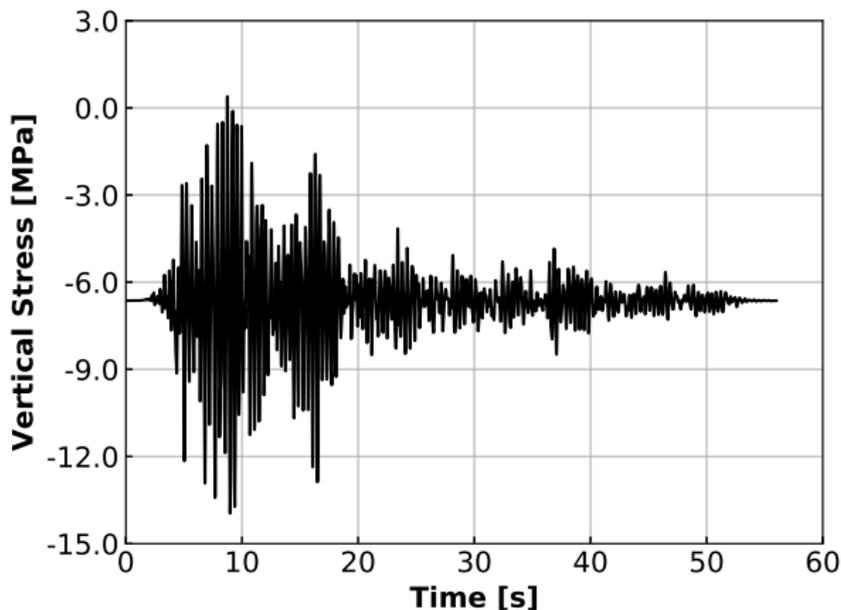(a)   (b)   (c)
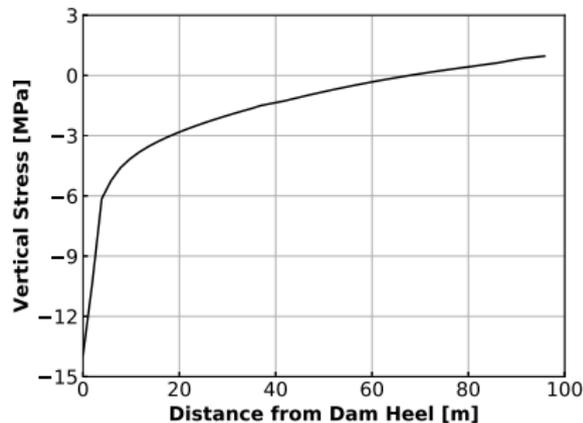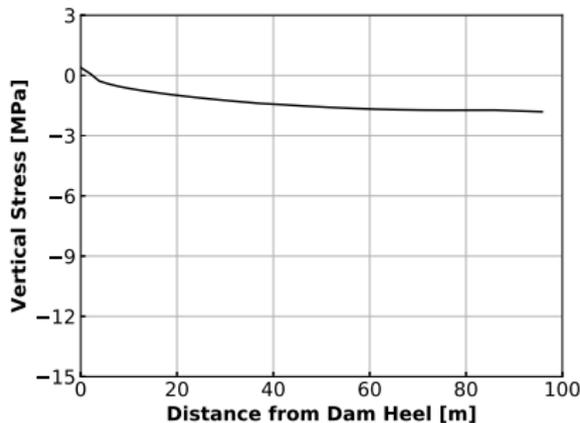
(d)   (e)   (f)

Introduction   Seismic Motions, Inelasticity and Uncertainty   Pine Flat Dam   Conclusion
000000   0000000000   00000000●00000   0000
0000000   00000000000   0000000

Pine Flat Dam Test Model

Taft Earthquake, Time History of σ_v

▶ Vertical stress at dam heel, there is a tension!

Taft Earthquake, σ_v Distribution at σ_{min} and σ_{max}
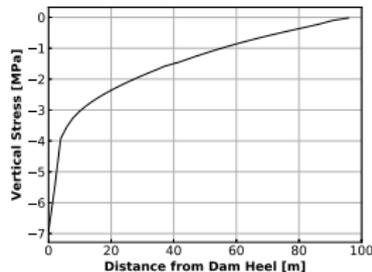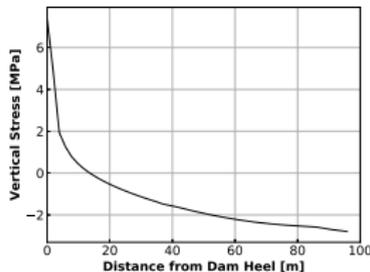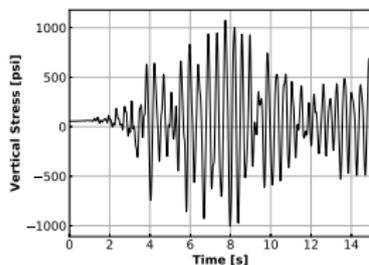
D2, Taft Earthquake, Dam and the Reservoir

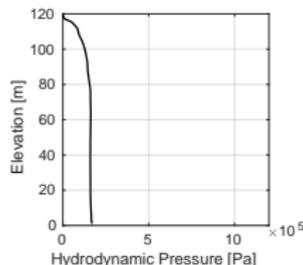▶ Pressures: total at the heel, total at the upstream face, hydrodynamic at the upstream face
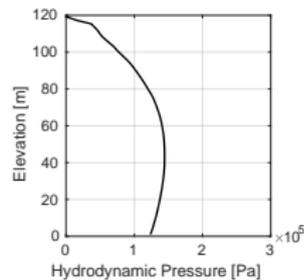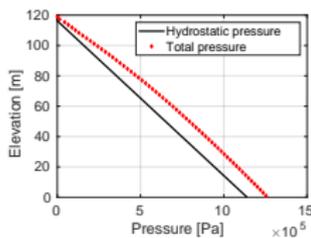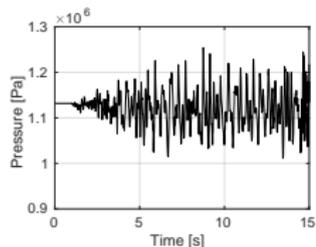
D2, Tafts Earthquake, Dam and the Reservoir

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

Pine Flat Dam Test Model

D2, ETAF Earthquake, Dam and the Reservoir

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

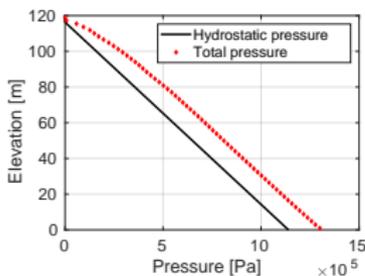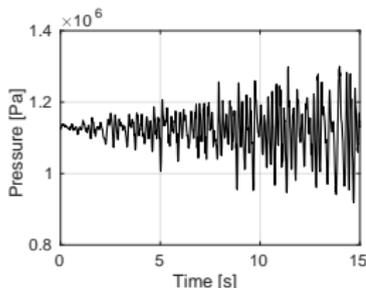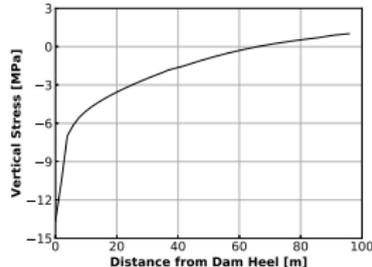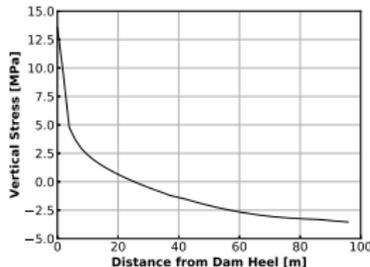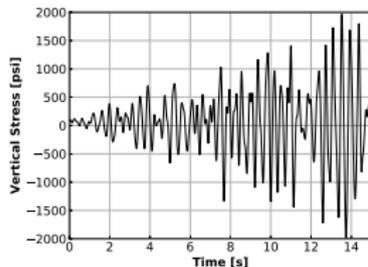# D2, ETAF Earthquake, Dam and the Reservoir

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

Introduction   Seismic Motions, Inelasticity and Uncertainty   **Pine Flat Dam**   Conclusion
000000   000000000   000000000000   0000
0000000   00000000000   ●000000

Pine Flat Dam, Additional Modeling and Simulation

Outline

Numerical Damping Effects, Elastic $\ddot{u}_{hor}^{top}$, σ_v^{heel}

Pine Flat Dam, Additional Modeling and Simulation
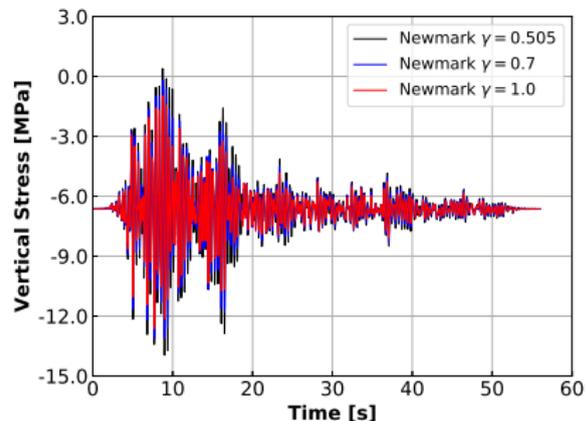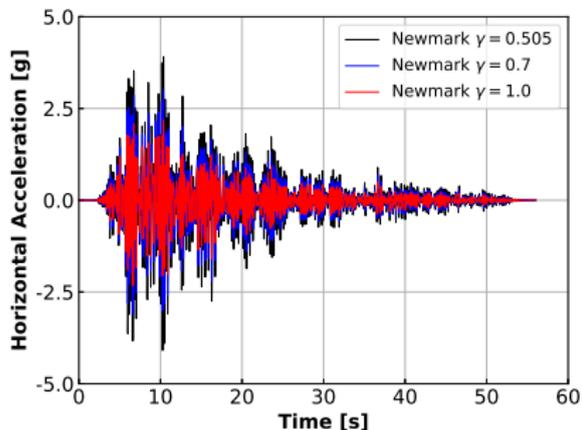
Numerical Damping Effects, Inelastic $\ddot{u}_{hor}^{top}$, σ_v^{heel}

Introduction Seismic Motions, Inelasticity and Uncertainty Pine Flat Dam Conclusion
○○○○○○ ○○○○○○○○○○ ○○○○○○○○○○○○○ ○○○○
○○○○○○○ ○○○○○○○○○○○ ○○○●○○○

Pine Flat Dam, Additional Modeling and Simulation
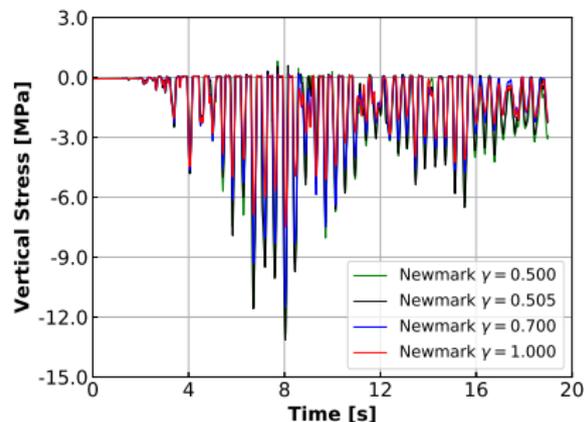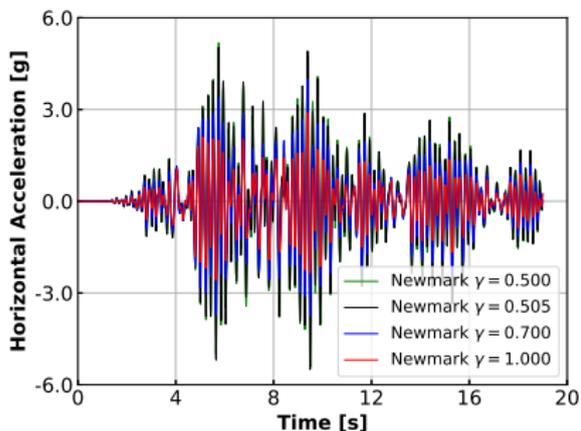
Pine Flat Dam, Dynamic Response with Reservoir

(MP4)

Pine Flat Dam, Hydrodynamic Pressure

Time: 13.79 s

Total Pressure P [Pa]

-1.6e+03 2.9e+5 5.8e+5 8.7e+5 1.2e+06

(MP4)

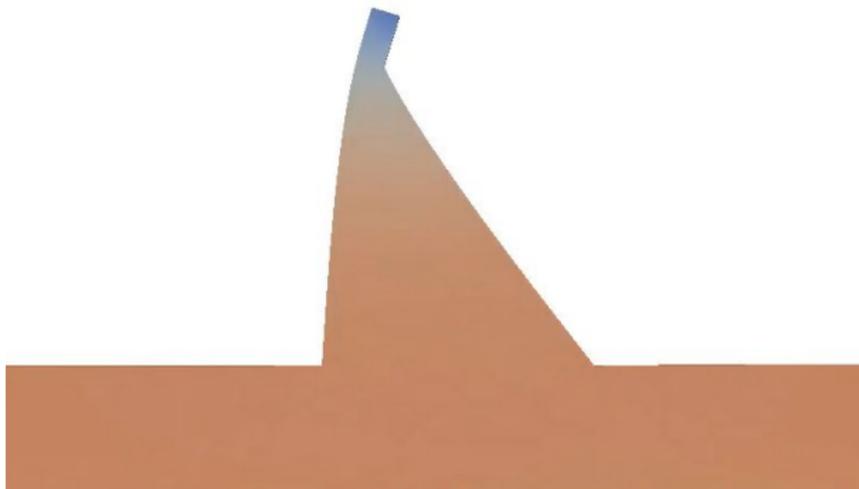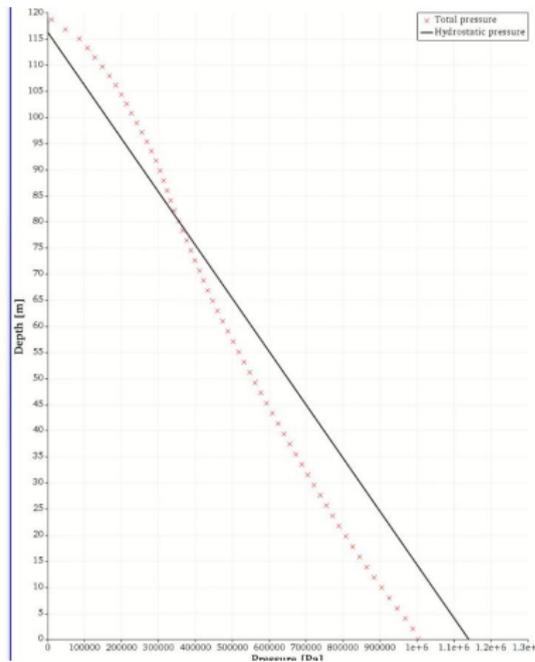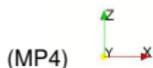# Pine Flat Dam, Inelastic Interface, Hydrostatic

(MP4)
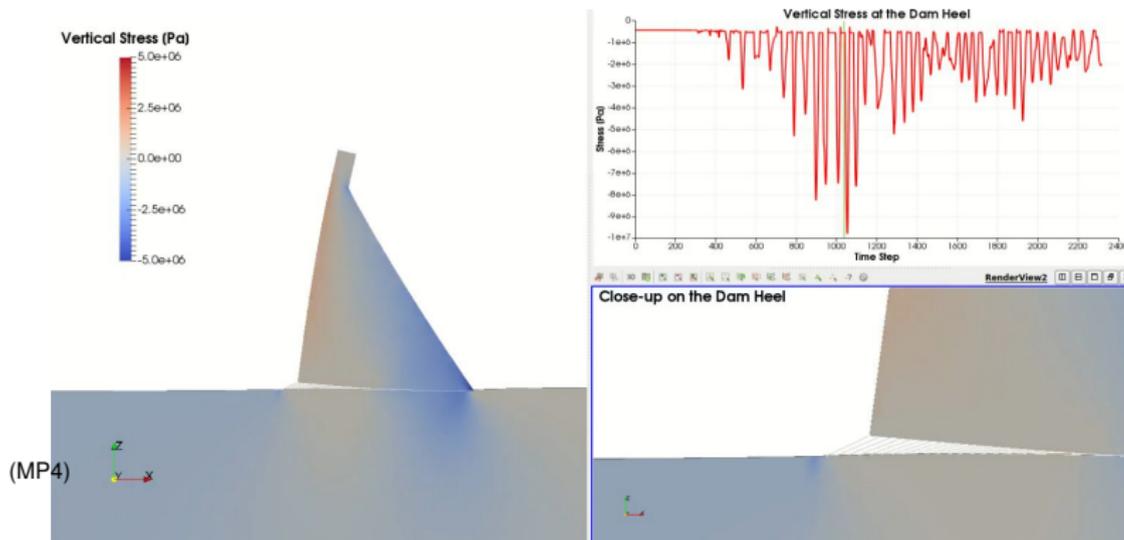
Pine Flat Dam, Dynamic Response, Inclined Plane Waves
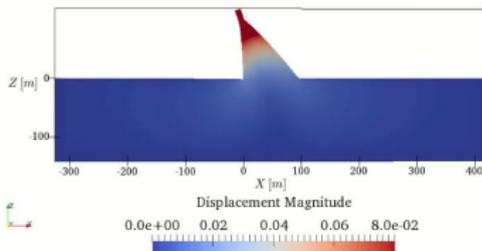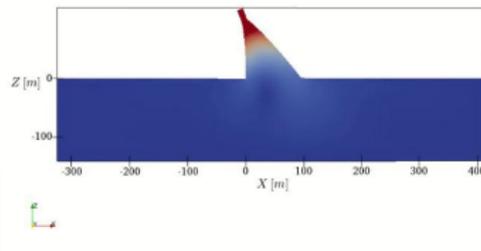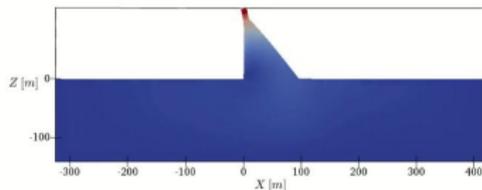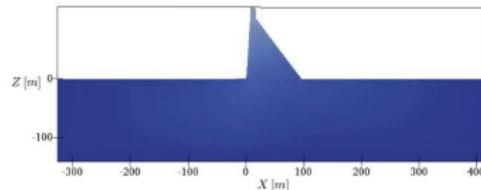
Introduction   Seismic Motions, Inelasticity and Uncertainty   Pine Flat Dam   **Conclusion**
000000   0000000000   0000000000000   ●000
0000000   00000000000   0000000

Real-ESSI Simulator System

Outline

Real-ESSI Simulator System

Real-ESSI Simulator System

The Real-ESSI, Realistic **M**odeling and **S**imulation of
Earthquakes, **S**oils, **S**tructures and their **I**nteraction. 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/`

Introduction   Seismic Motions, Inelasticity and Uncertainty   Pine Flat Dam   **Conclusion**
000000   000000000   000000000000   000●
0000000   00000000000   0000000

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/