Modeling and Simulation
Dam Foundation Reservoir System

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Outline

Introduction
- Motivation
- Modeling and Simulation of ESSI

Seismic Motions, Inelasticity and Uncertainty
- Six Component Seismic Motions
- Inelasticity, Plastic Energy Dissipation and Uncertainty

Pine Flat Dam
- Pine Flat Dam Test Model
- Pine Flat Dam, Additional Modeling and Simulation

Conclusion
- Real-ESSI Simulator System

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

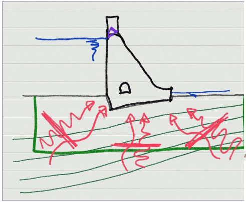
Modeling Effects, Currently Understood

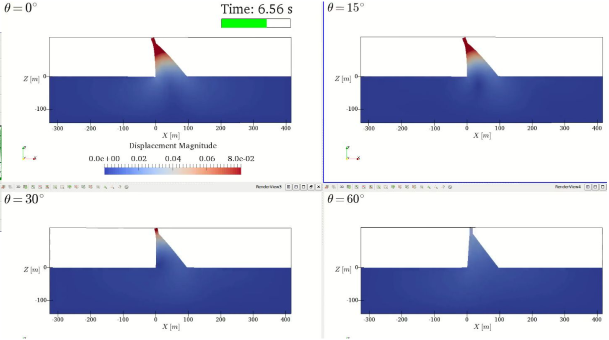
- Mesh size effects
- Boundary conditions, seismic motions input DRM, free field
- Inelastic models for soil, rock, concrete, stele
- Inelastic models for interfaces/joints/contacts
- Mechanical Energy flow in and out of the Dam-Foundation-Reservoir (DFR) system
- Convergence tolerances for both constitutive level and FEM level
- Numerical/algorithmic damping
- Verification of finite elements and algorithms

Modeling Effects that Need More Work

- Full 3C/6C seismic motions
- Models for regular and Alkali-Silica Reaction (ASR) concrete,
- Models for dry and wet interfaces/joints/contacts
- Modeling full DFR system
- Propagation of seismic energy through DFR system
- Propagation of uncertainty in material and loads through DFR system
- Estimations of accuracy of results

Full 3C/6C Seismic Motions





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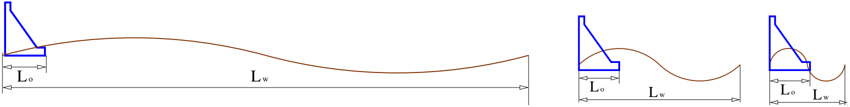
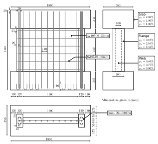
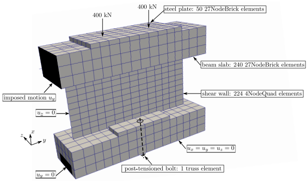
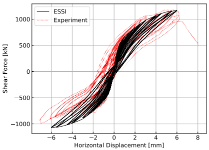
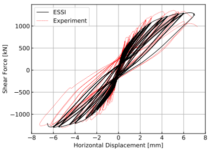


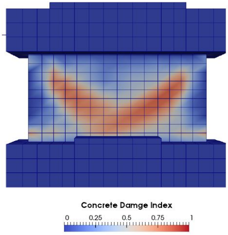
Regular and ASR Concrete



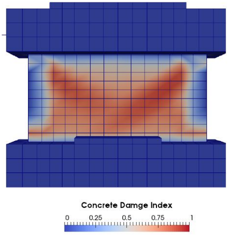




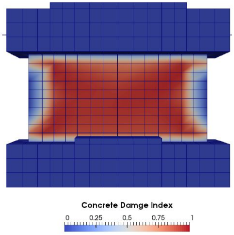




$u_y = 1.4$ mm



$u_y = 1.8$ mm



$u_y = 3.0$ mm

Dry and Wet Interfaces/Joints/Contacts

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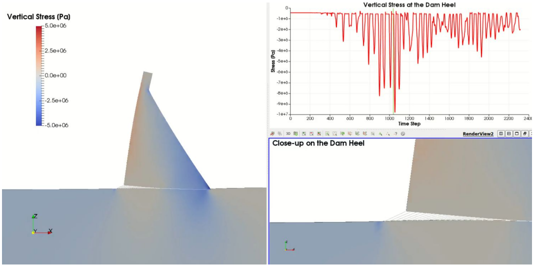
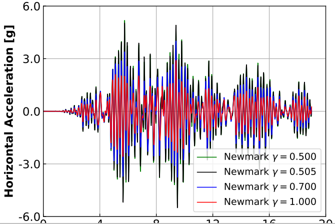
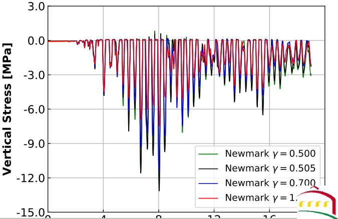
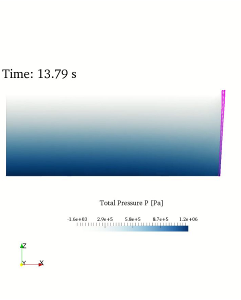
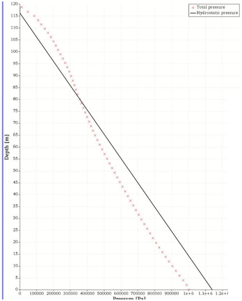


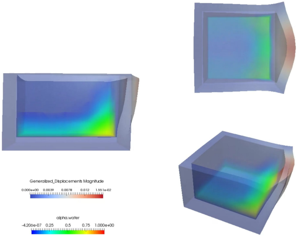




Modeling Full DFR System







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Propagation of Seismic Energy through DFR System

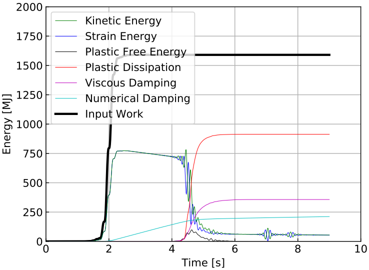
Energy input, dynamic forcing

Energy dissipation outside SSI domain:

- SSI system oscillation radiation
- Reflected wave radiation

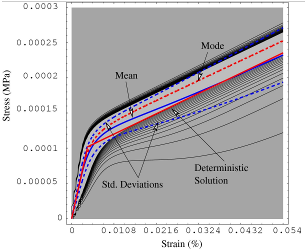
Energy dissipation/conversion inside SSI domain:

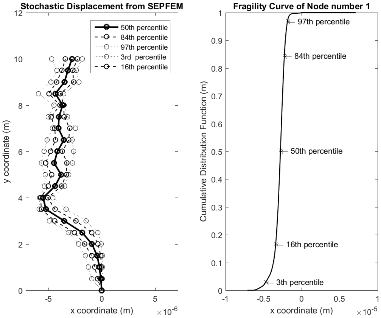
- Inelasticity of rock, soil, interfaces structure, foundation, dissipators
- Viscous coupling with internal/pore fluids
- Viscous coupling with external fluids, reservoir



Numerical energy dissipation/production

Propagation of Uncertainty in Material and Loads





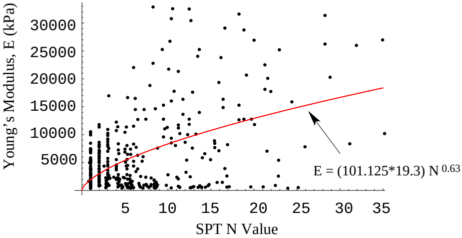
Accuracy of Results, Unit Tests

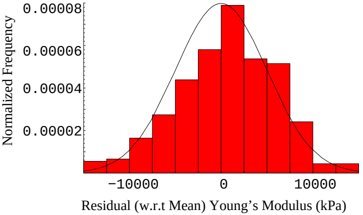
Development of unit tests for components and full dam-reservoir-foundation system

Set of unit test problems, where very accurate solutions exist, in addition to basic verification problems, that are used to verify given numerical modeling approach:

- Wave propagation, free field, 1C and/or 3C
- Wave propagation, dam structure, 1C and/or 3C
- Wave propagation, dam and foundation, 1C and/or 3C
- Material constitutive behavior, concrete
- Material constitutive behavior, rock

Parametric Uncertainty: Soil Stiffness





cf. Phoon and Kulhawy (1999B)

Outline

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

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

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

Fully Coupled Formulation, u-p-U

$$(M_s)_{KijL} = \int_\Omega H^u_K (1-n)\rho_s \delta_{ij} H^u_L d\Omega \quad (M_f)_{KijL} = \int_\Omega H^U_K n \rho_f \delta_{ij} H^U_L d\Omega$$

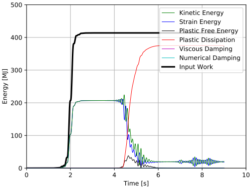
$$(C_1)_{KijL} = \int_\Omega H^u_K n^2 k^{-1}_{ij} H^u_L d\Omega \quad (C_2)_{KijL} = \int_\Omega H^u_K n^2 k^{-1}_{ij} H^U_L d\Omega$$

$$(C_3)_{KijL} = \int_\Omega H^U_K n^2 k^{-1}_{ij} H^U_L d\Omega \quad (K^{EP})_{KijL} = \int_\Omega H^u_{K,m} D_{imjn} H^u_{L,n} d\Omega$$

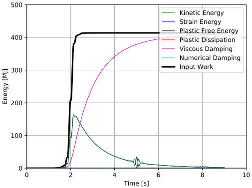
$$(G_1)_{KiM} = \int_\Omega H^u_{K,i} (\alpha - n) H^p_M d\Omega \quad (G_2)_{KiM} = \int_\Omega n H^U_{K,i} H^p_M d\Omega$$

$$P_{NM} = \int_\Omega H^p_N \frac{1}{Q} H^p_M d\Omega$$

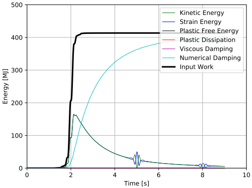
Energy Dissipation Control Mechanisms



Plasticity

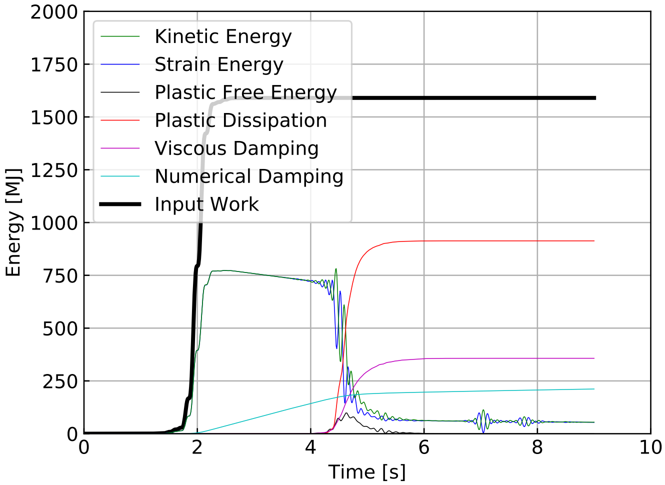


Viscous



Numerical

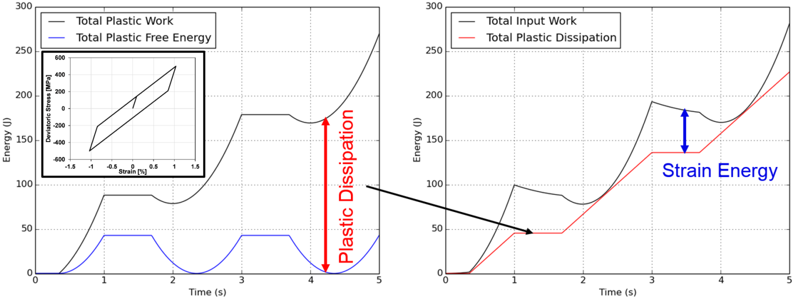
Energy Dissipation Control



Energy Dissipation on Material Level

Single elastic-plastic element under cyclic shear loading

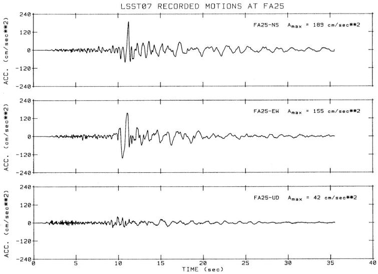
- Difference between plastic work and plastic dissipation
- Plastic work can decrease
- Plastic dissipation always increases

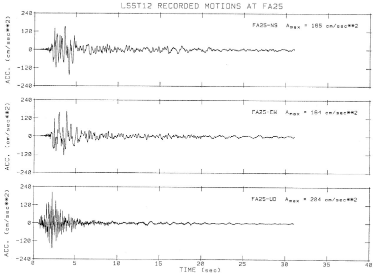


Outline

3C, 6C Seismic Motions

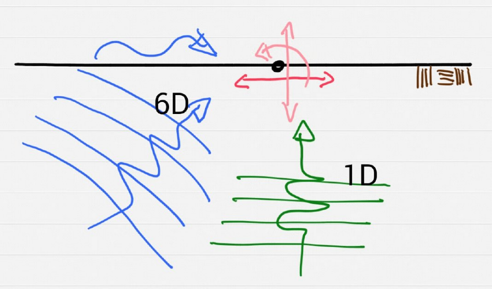
- All (most) measured motions are full 3C, 6C
- One example of an almost 2C motion (LSST07, LSST12)



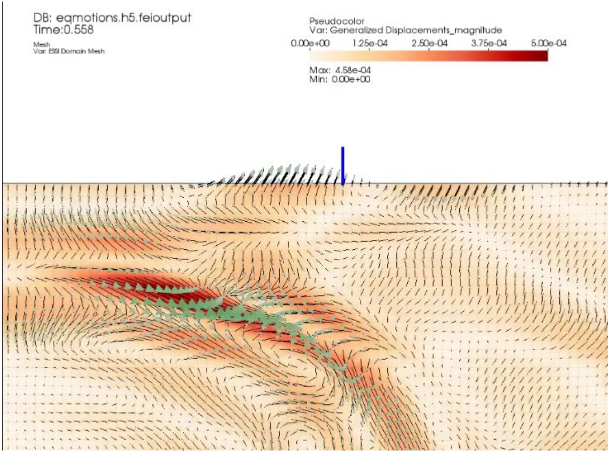


ESSI: 6C or 1C Seismic Motions

- 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)



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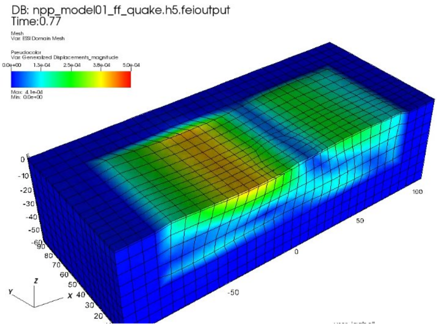
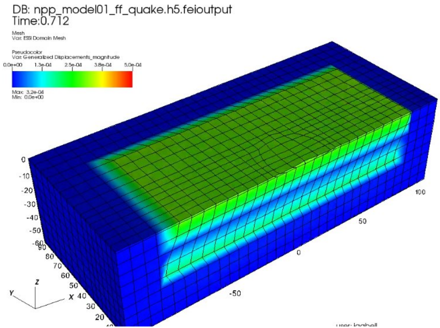
1C vs 6C Free Field Motions

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





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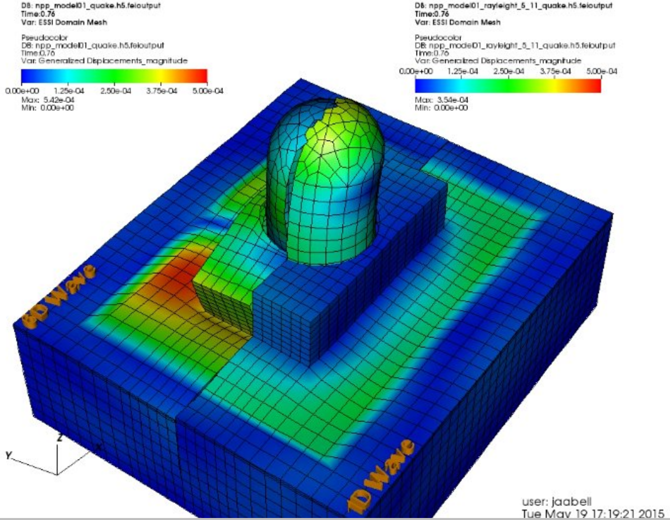
6C vs 1C NPP ESSI Response Comparison



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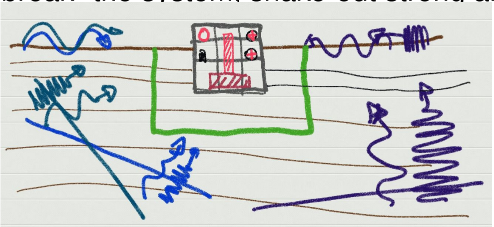
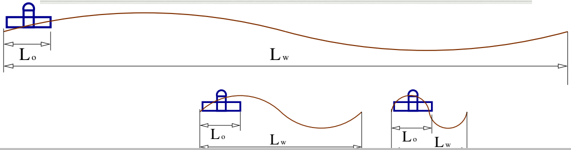
Stress Testing SSI Systems

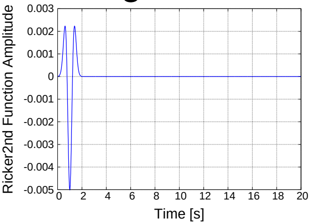
- Excite SSI system with a suite of seismic motions
- Waves: P, SV, SH, Surface (Rayleigh, Love, etc.)
- Variation in inclination, frequency, energy and duration
- Try to "break" the system, shake-out strong and weak links

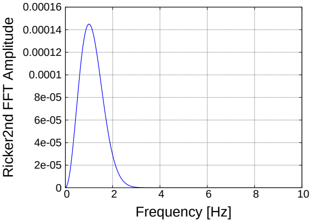




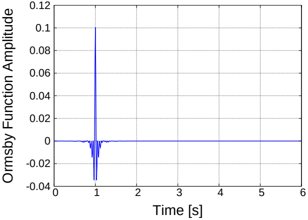
Stress Test Source Signals

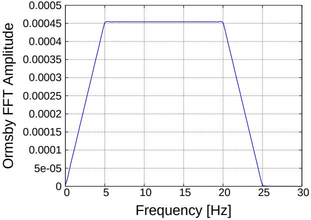
- Ricker



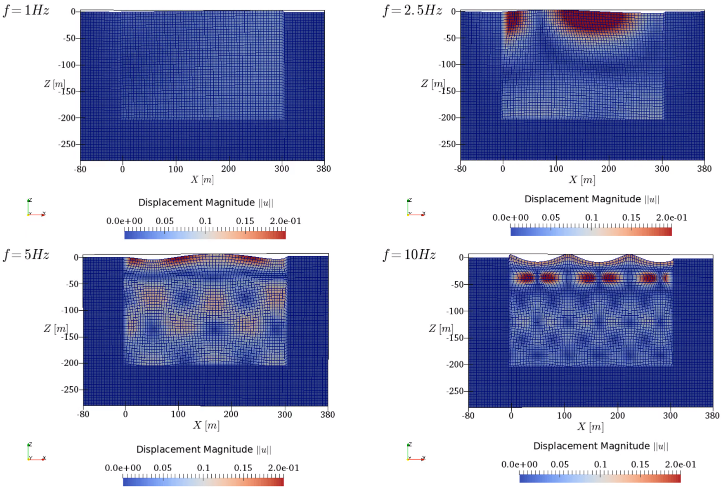


- Ormsby





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



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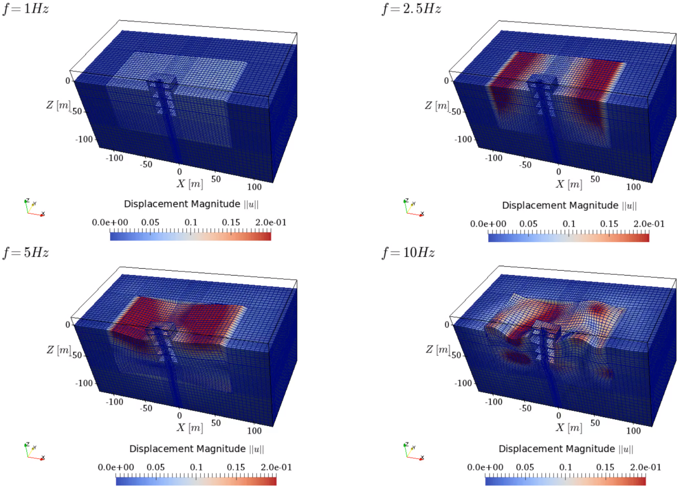
SMR ESSI, Variation in Input Frequency, $\theta = 60^o$



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Outline

Energy Input and Dissipation

Energy input, static and dynamic forcing

Energy dissipation outside SSI domain:

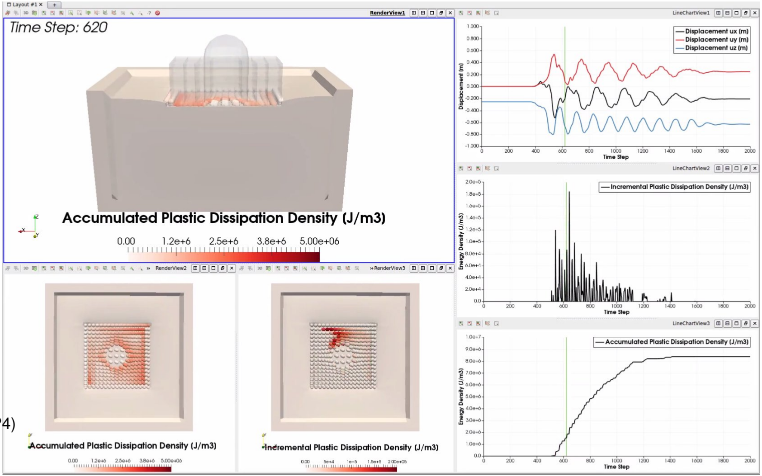
- SSI system oscillation radiation
- Reflected wave radiation

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

Energy Dissipation in NPP Model



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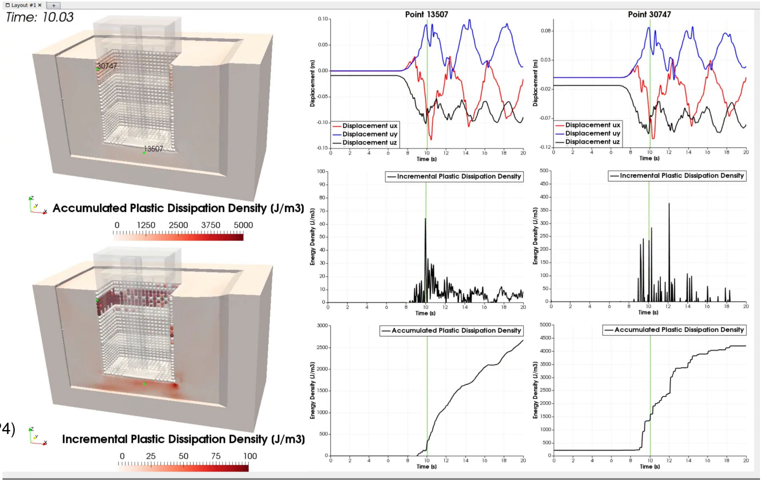
Energy Dissipation for an SMR Model



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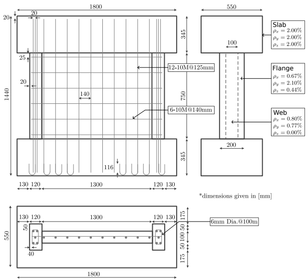
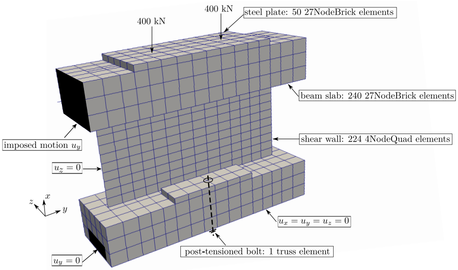
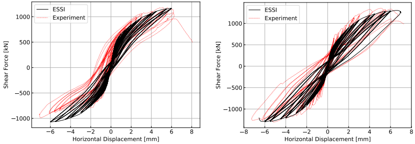
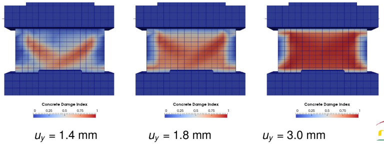
Wall, Regular and ASR Concrete

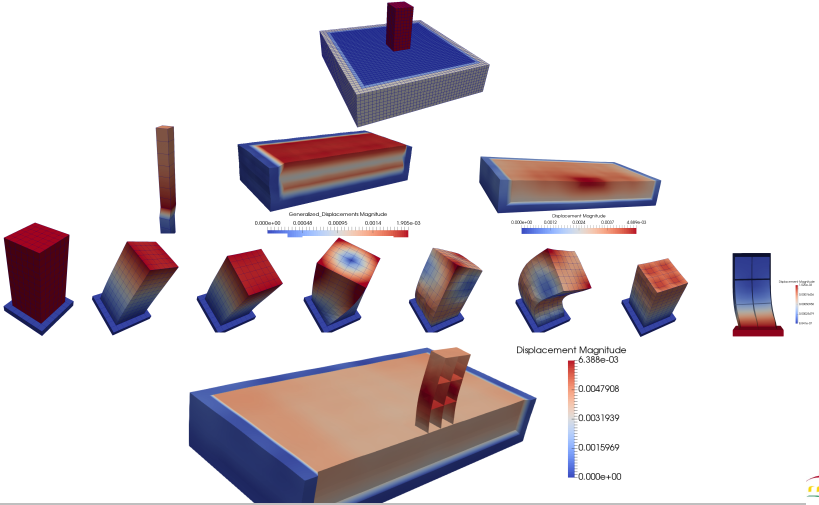








Real-ESSI Modeling Phases



Uncertainty Propagation through Inelastic System

- Incremental el–pl constitutive equation

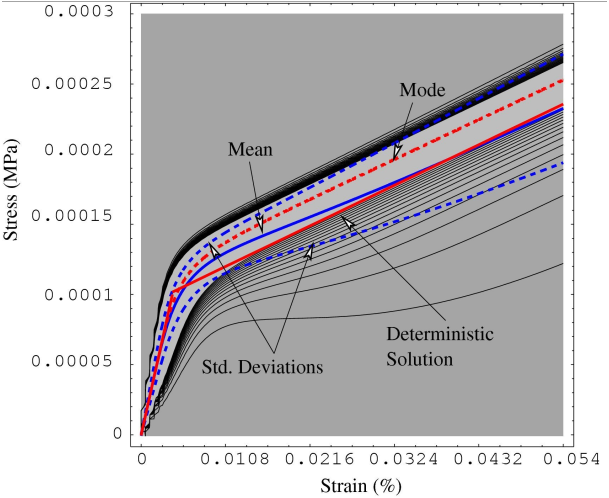
$$\Delta\sigma_{ij} = E^{EP}_{ijkl}\ \Delta\epsilon_{kl} = \left[E^{el}_{ijkl} - \frac{E^{el}_{ijmn} m_{mn} n_{pq} E^{el}_{pqkl}}{n_{rs} E^{el}_{rstu} m_{tu} - \xi_* h_*} \right] \Delta\epsilon_{kl}$$

- Dynamic Finite Elements

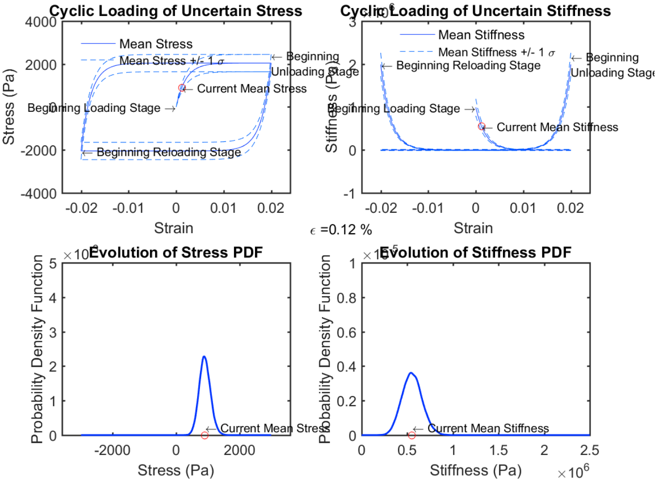
$$M\ddot{u}_i + C\dot{u}_i + K^{ep} u_i = F(t)$$

- Material and load parameters are uncertain

Probabilistic Elastic-Plastic Response



Probabilistic Elastic-Plastic Modeling

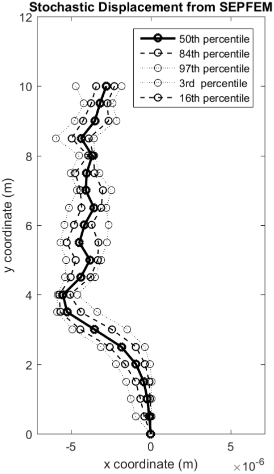


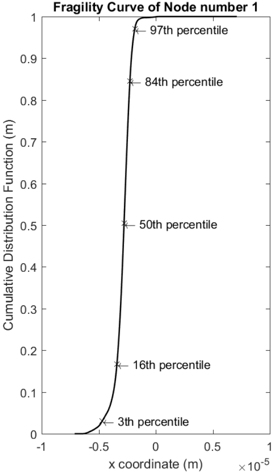
Stochastic Elastic-Plastic Finite Element Method

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

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

SEPFEM: Example in 1D

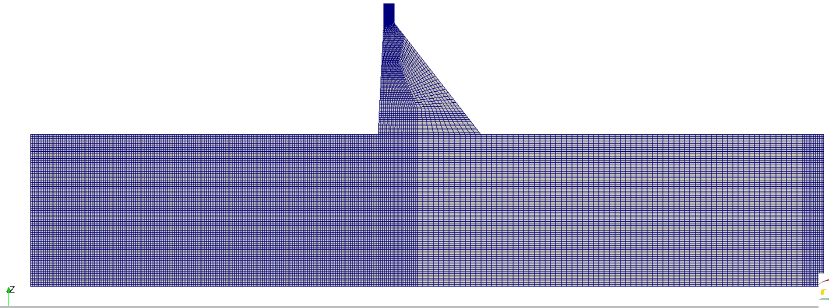




Outline

Pine Flats Dam, Model

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

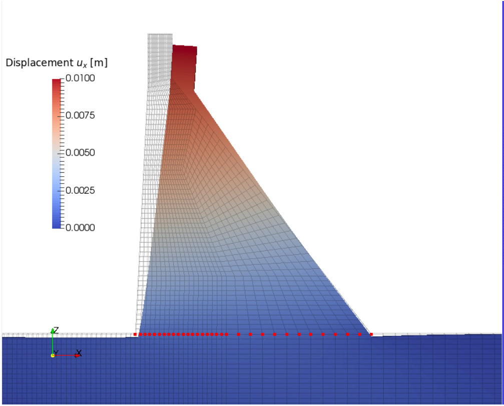


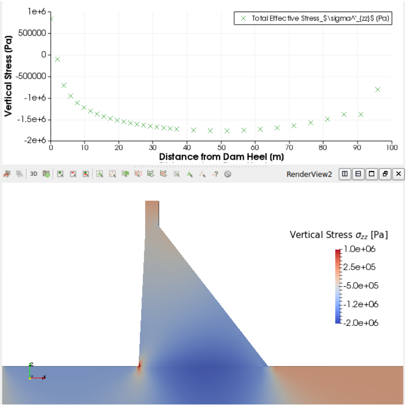
Pine Flats Dam, Static, Displacements

- Self weight
- Water pressure, on dam side and lake bottom

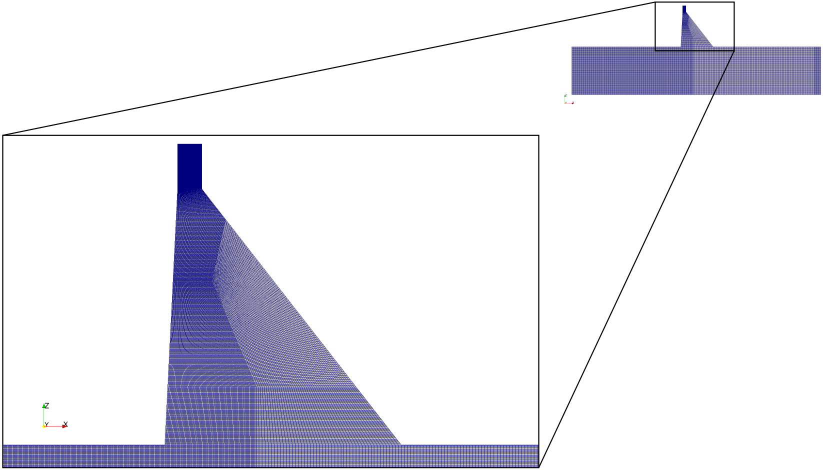
		Disp. [m]			Disp. [in]
		Top	Heel	Rel.	Rel.
Mat. Prop. I	Hor.	0.0121	0.0031	0.00900	0.354
(Soft Found.)	Vert.	-0.0095	-0.0059	-0.00348	-0.137
Mat. Prop, II	Hor.	0.0101	0.0011	0.00904	0.356
(Stiff Found.)	Vert.	-0.0048	-0.0019	-0.00298	-0.117

Static, Displacements and σ_V





Mesh Refinement Effects

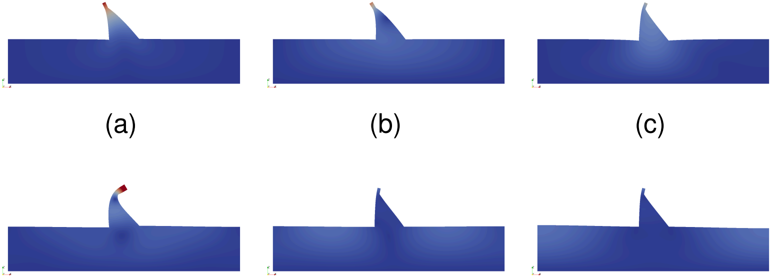


Mesh Refinement Effects

		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,

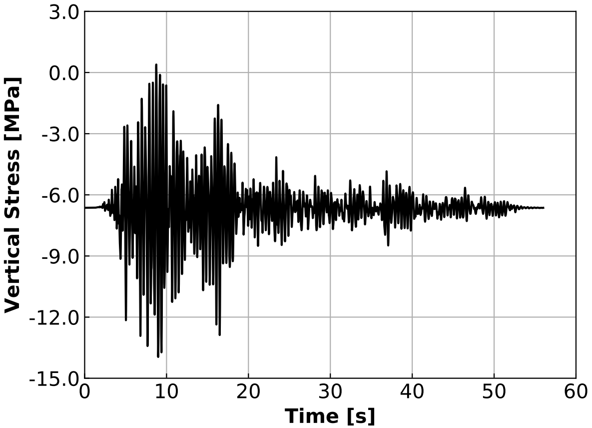


(a) (b) (c)

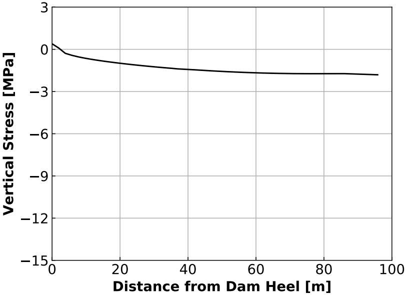
(d) (e) (f)

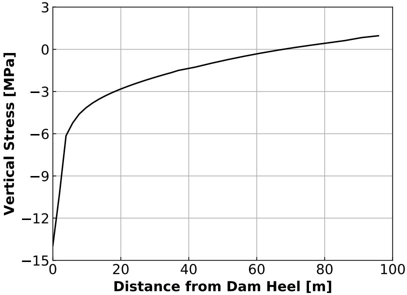
Taft Earthquake, Time History of σ_V

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



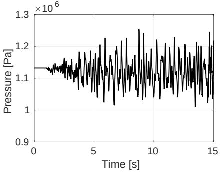
Taft Earthquake, σ_V Distribution at σ_{min} and σ_{max}

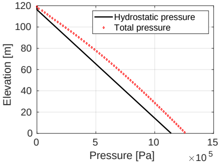


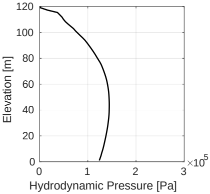


D2, Taft Earthquake, Dam and the Reservoir

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

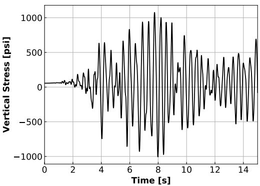


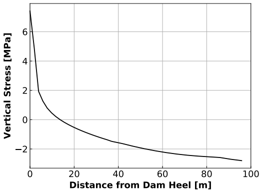


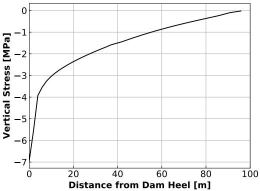


D2, Tafts Earthquake, Dam and the Reservoir

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

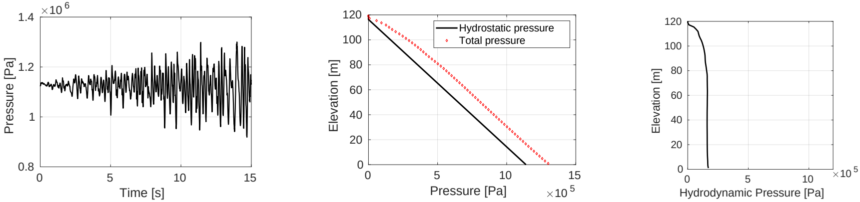






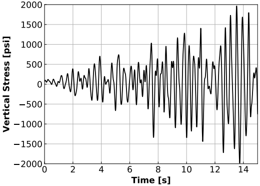
D2, ETAF Earthquake, Dam and the Reservoir

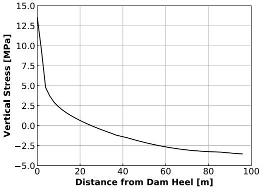
- Pressures: total at the heel, total at the upstream face, hydrodynamic at the upstream face

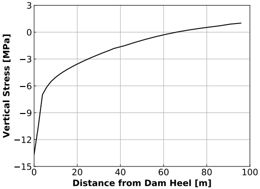


D2, ETAF Earthquake, Dam and the Reservoir

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

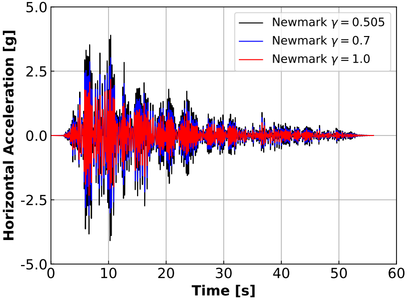


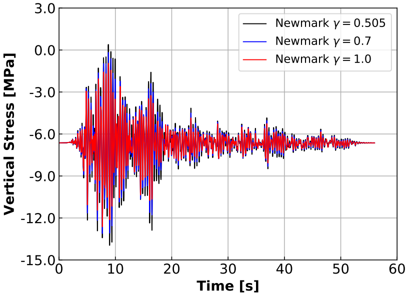




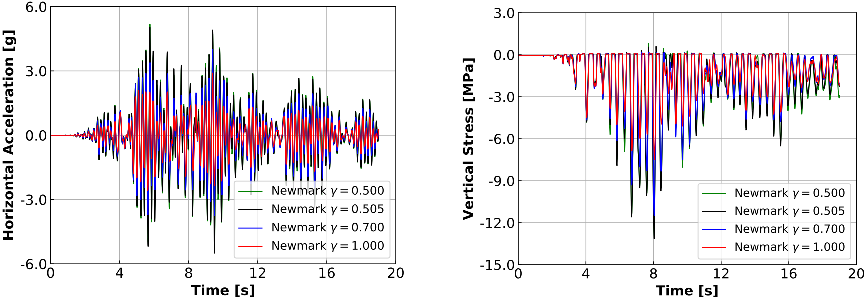
Outline

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

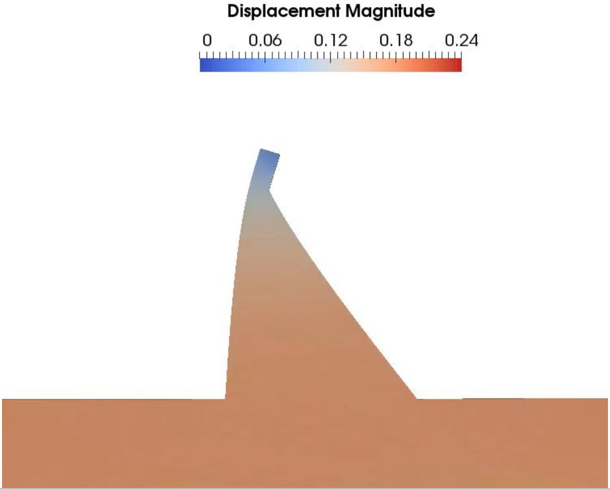




Numerical Damping Effects, Inelastic $\ddot{u}_{hor}^{top}$, σ_v^{heel}

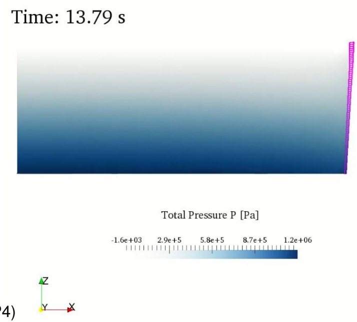


Pine Flat Dam, Dynamic Response with Reservoir

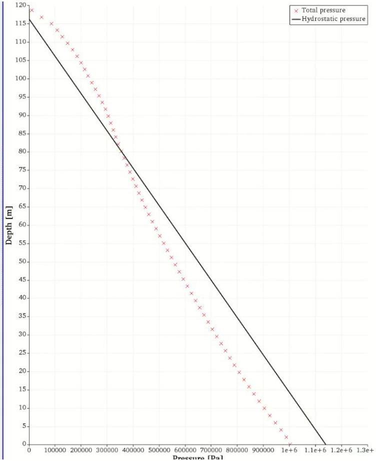


(MP4)

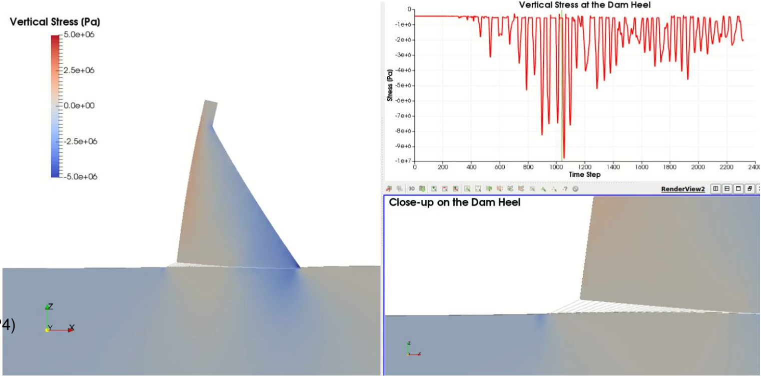
Pine Flat Dam, Hydrodynamic Pressure



(MP4)

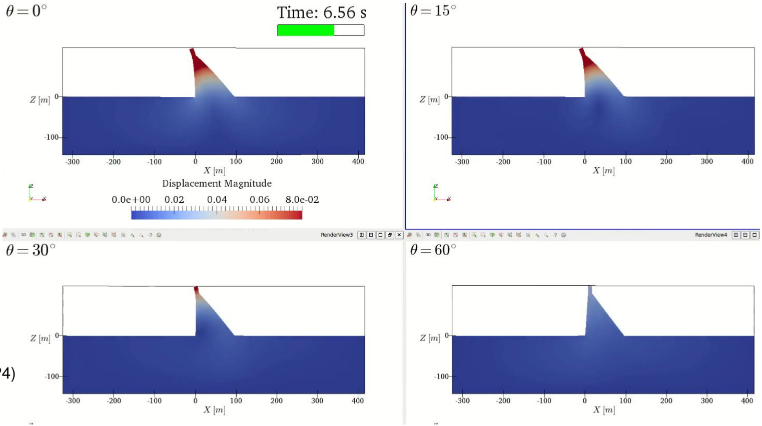


Pine Flat Dam, Inelastic Interface, Hydrostatic



(MP4)

Pine Flat Dam, Dynamic Response, Inclined Plane Waves



(MP4)

Outline

Real-ESSI Simulator System

The Real-ESSI, Realistic **M**odeling and **S**imulation of **E**arthquakes, **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/`

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/`

Summary

Numerical modeling to predict and inform, rather than fit

Brave effort of ICOLD, assess numerical analysis of dams!

Education and Training is the key

`http://real-essi.info/`