Dam Safety Interest Group General Meeting

Guidelines for Structural Analysis of Concrete Dams

Boris' part, will merge with Jerzy's PPT slides

CEATI
Orange County, 01Oct2019

Numerical Modeling Approach for Concrete Dams

- Improve modeling and simulation for dam-foundation systems
- Use select fidelity (high ↔ low) numerical models to analyze static and dynamic behavior of Dam-Foundation-Reservoir (DFR) 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
- Develop **Best Practice for Advanced Analysis of Concrete Dams**

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.

Predict and Inform

- Modeling and parametric uncertainties are always present, need to be addressed

- Goal: Predict and Inform rather than (force) Fit

- Chief Engineer, Energoprojekt-Hydroengineering Comp.: "I would love to know a real response of this dam"

- Engineer needs to know!

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

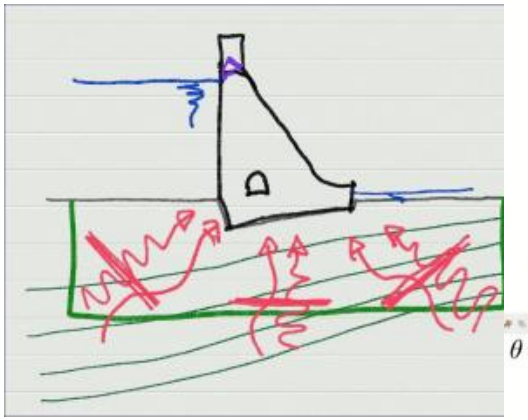
Modeling Effects, Currently Understood

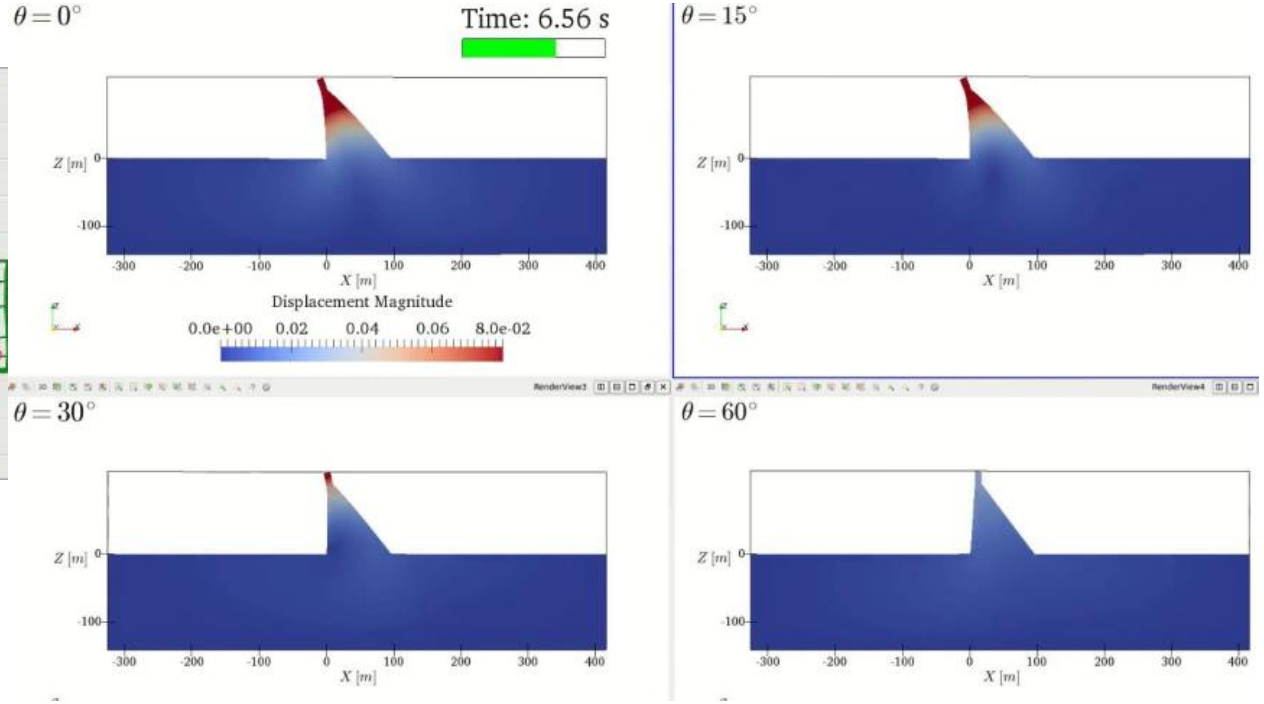
- Mesh size effects
- Boundary conditions, seismic motions input DRM, free field
- Inelastic models for soil, rock, concrete, stele
- Inelastic models for interfaces/joints/contacts
- Mechanical Energy flow in and out of the Dam-Foundation-Reservoir (DFR) system
- Convergence tolerances for both constitutive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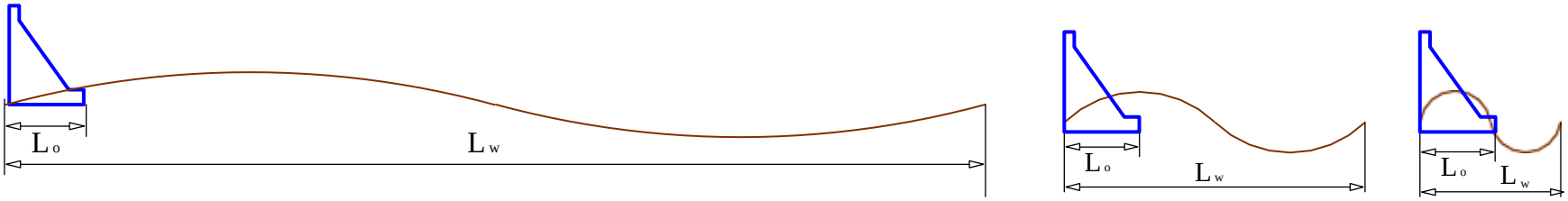
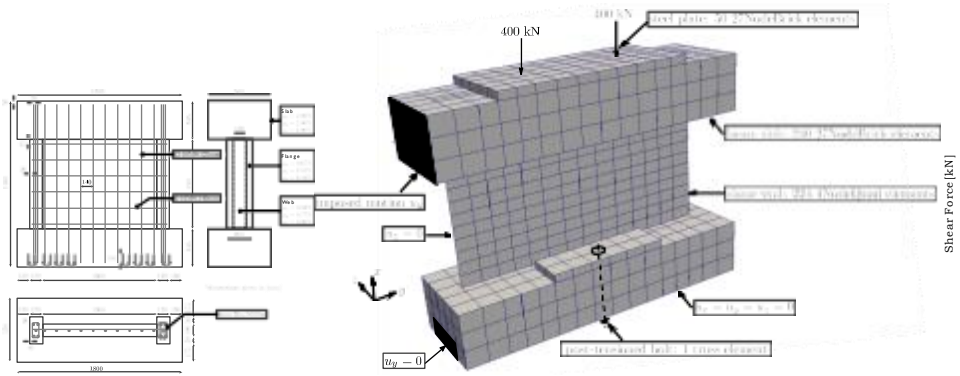
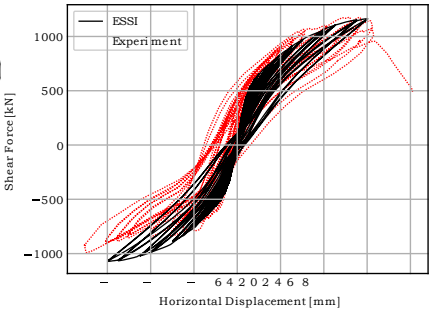
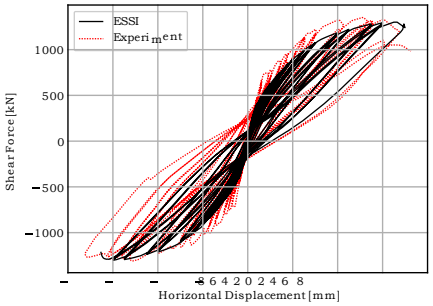
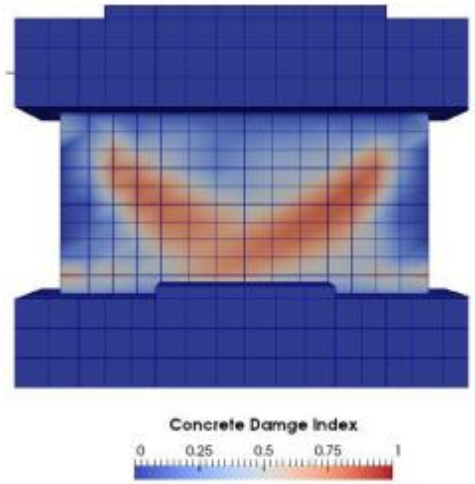


Regular and ASR Concrete

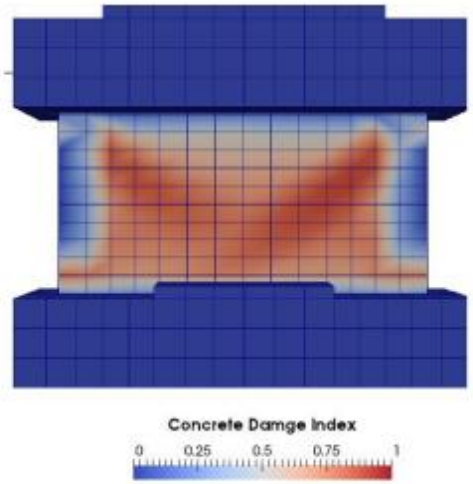




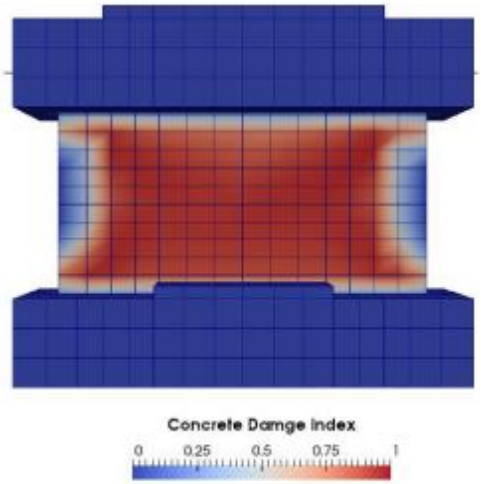




$u_y = 1.4$ mm



$u_y = 1.8$ mm



$u_y = 3.0$ mm

Dry and Wet Interfaces/Joints/Contacts

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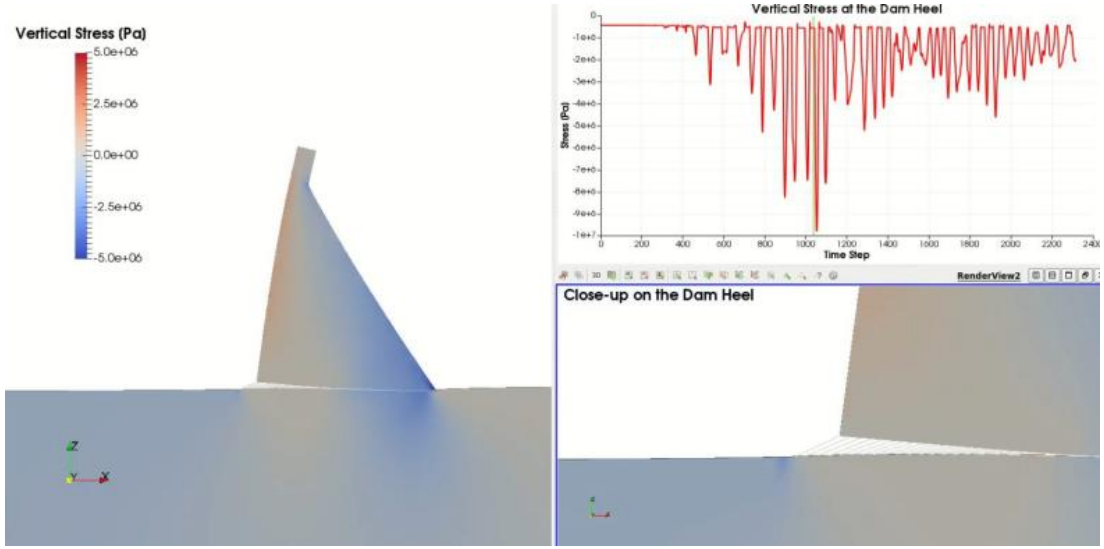
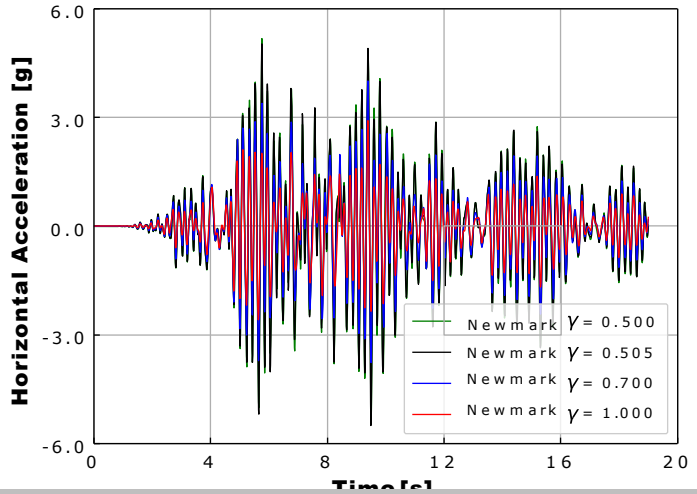
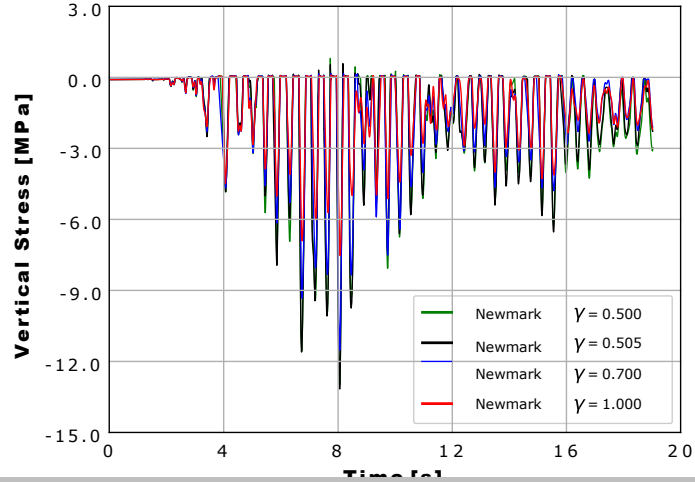
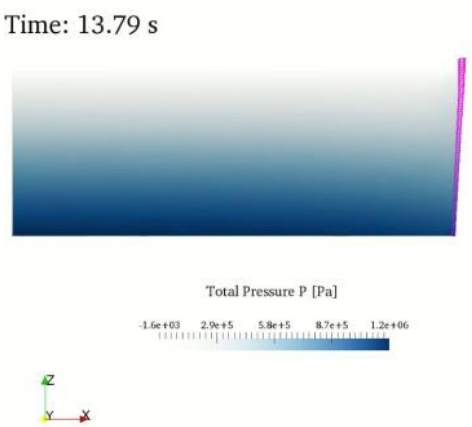
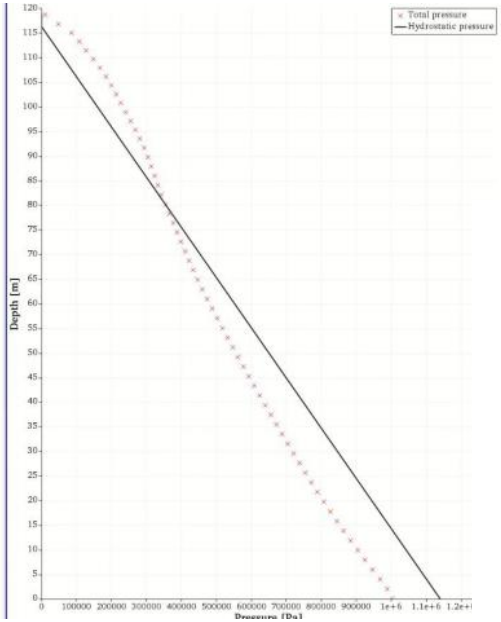






Modeling Full DFR System





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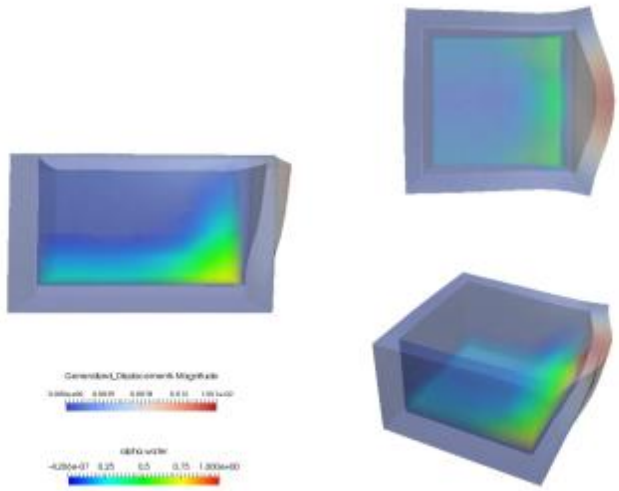

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Propagation of Seismic Energy through DFR System

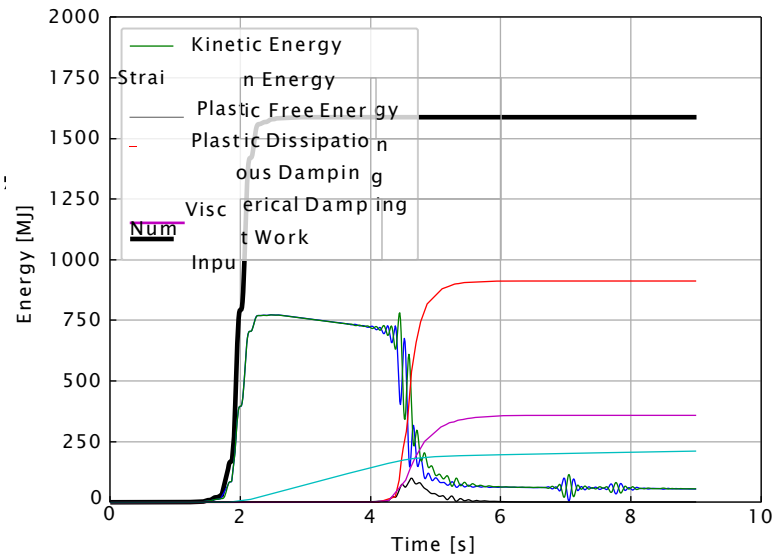
Energy input, dynamic forcing

Energy dissipation outside SSI domain:

- SSI system oscillation radiation
- Reflected wave radiation

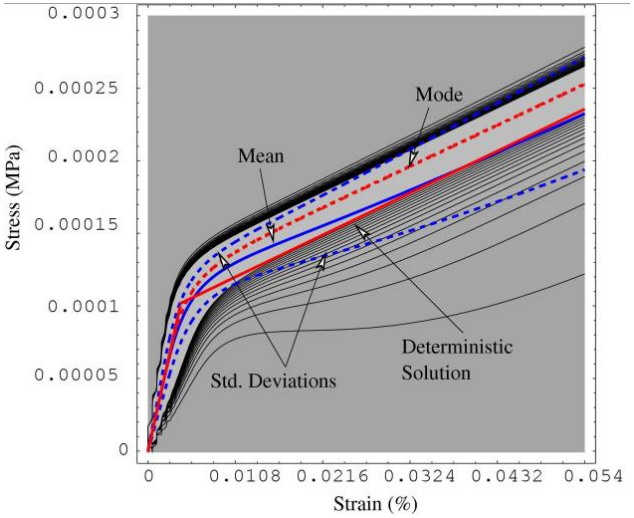
Energy dissipation/conversion inside SSI domain:

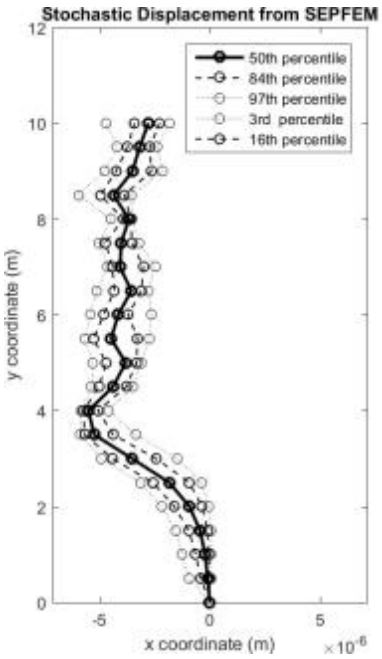
- Inelasticity of rock, soil, interfaces structure, foundation, dissipators
- Viscous coupling with internal/pore fluids
- Viscous coupling with external fluids, reservoir

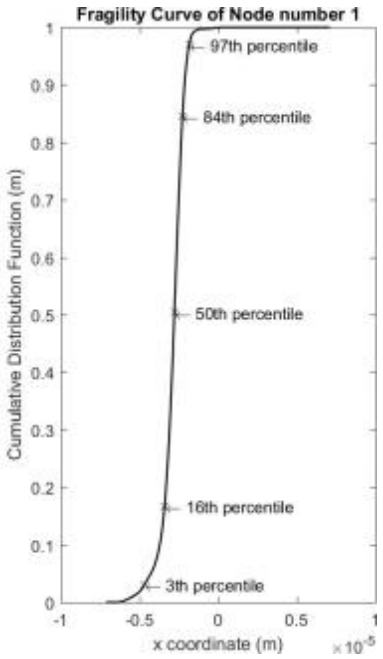


Numerical energy dissipation/production

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

EXTRA SLIDE

Energy Input and Dissipation

Energy input, dynamic forcing

Energy dissipation outside SSI domain:

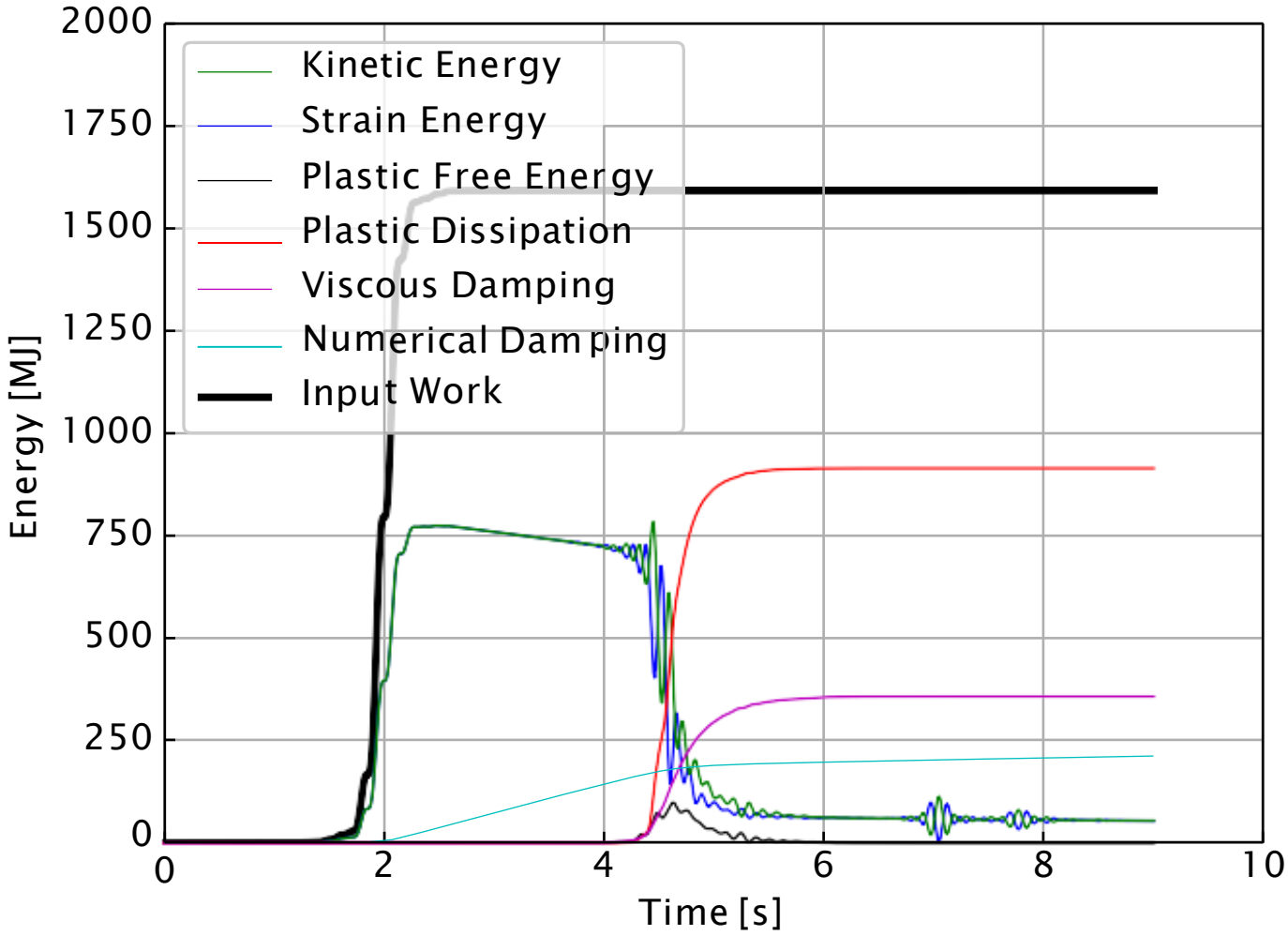
- SSI system oscillation radiation
- Reflected wave radiation

Energy dissipation/conversion inside SSI domain:

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

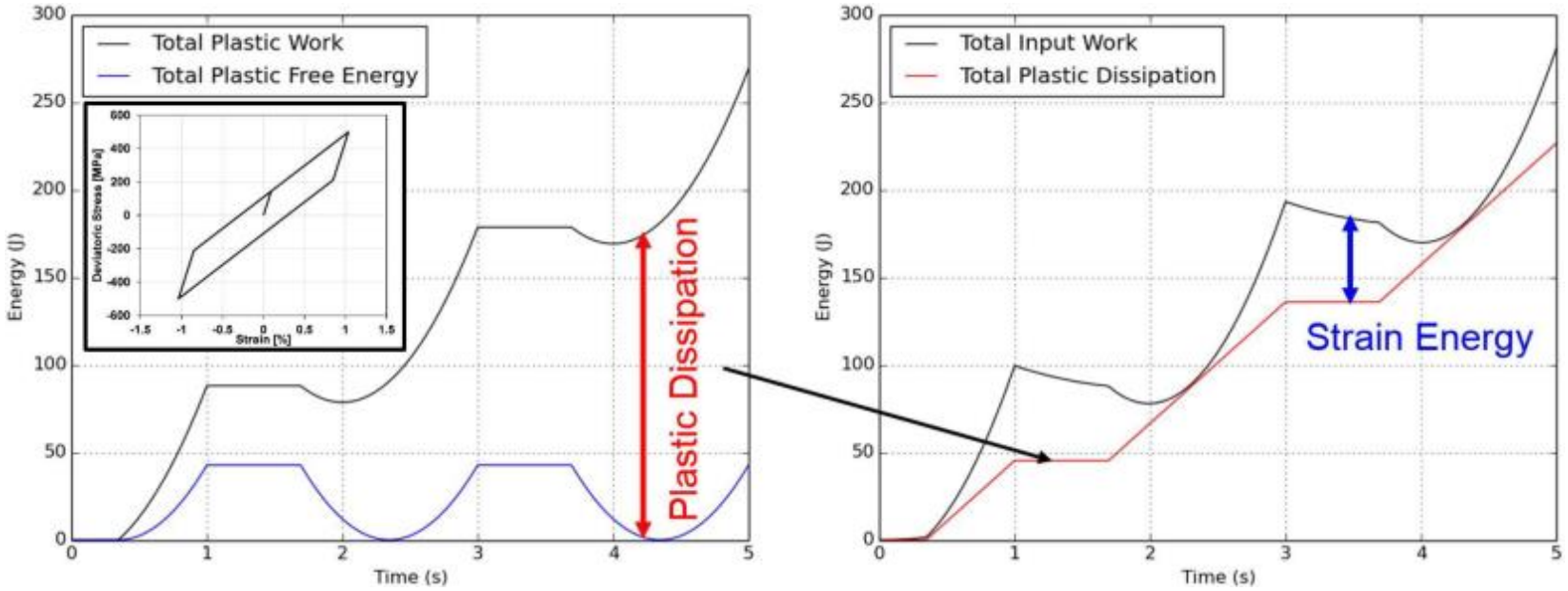
Numerical energy dissipation/production

Energy Dissipation Control

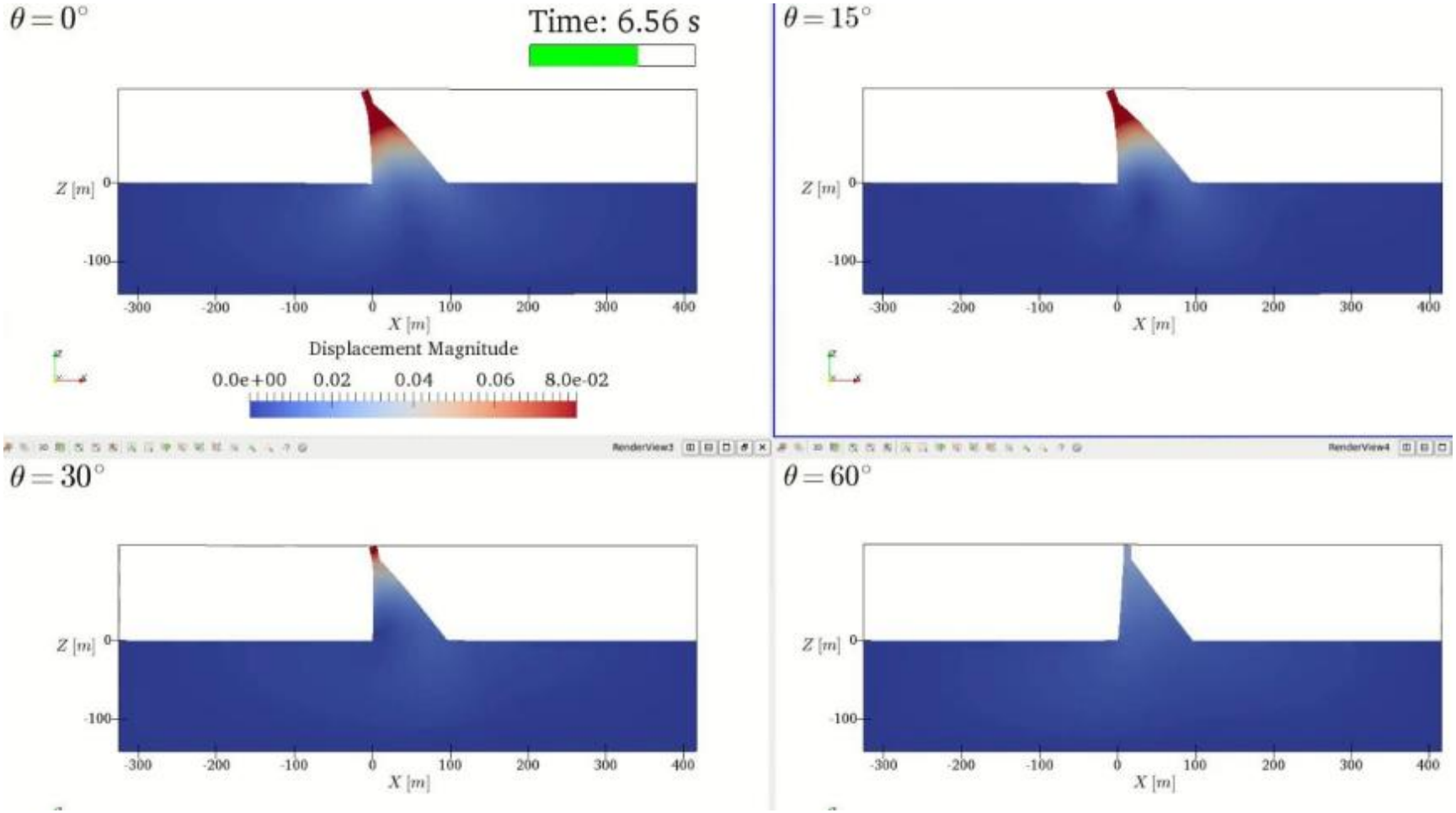


Energy Dissipation on Material Level

- Single elastic-plastic element under cyclic shear loading
  - Difference between plastic work and plastic dissipation
  - Plastic work can decrease
  - Plastic dissipation always increases



Modeling Uncertainty, 6C vs 1C Motions



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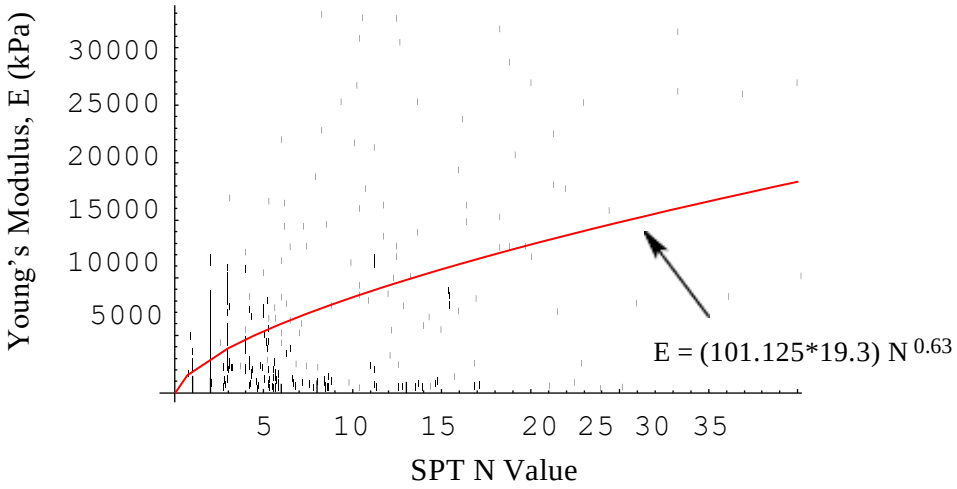
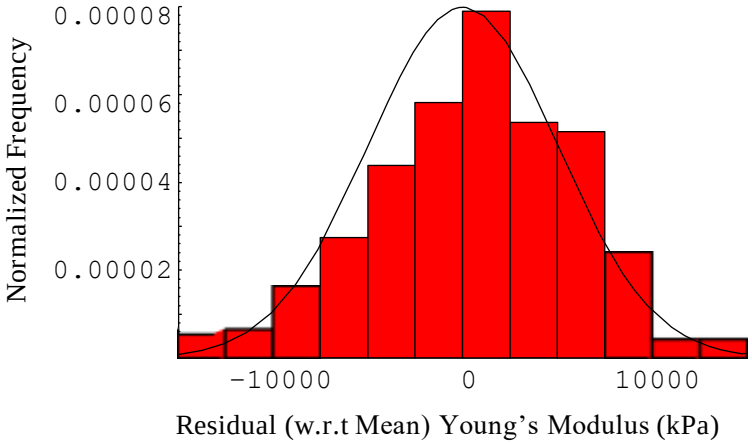
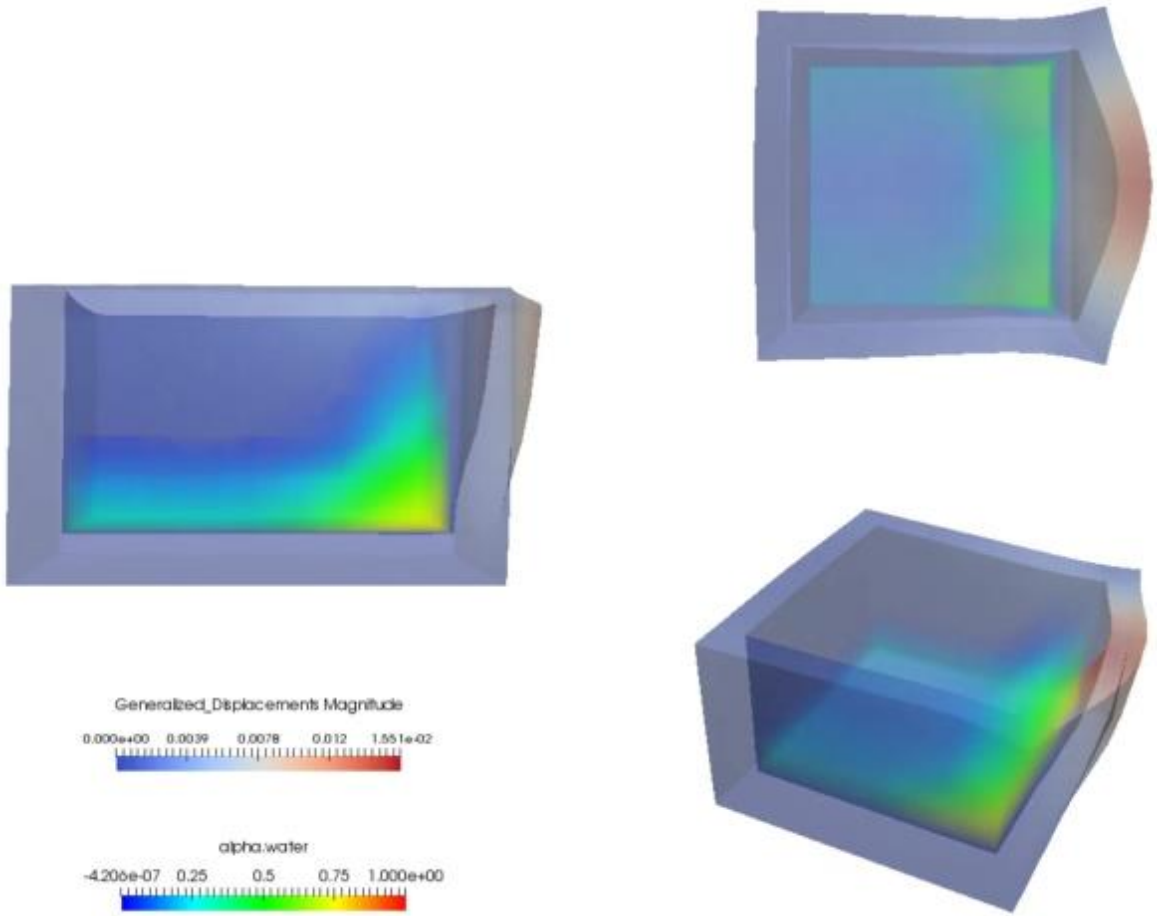
Parametric Uncertainty: Material/Soil Stiffness





cf. Phoon and Kulhawy (1999B)

Solid/Structure-Fluid Interaction, Example



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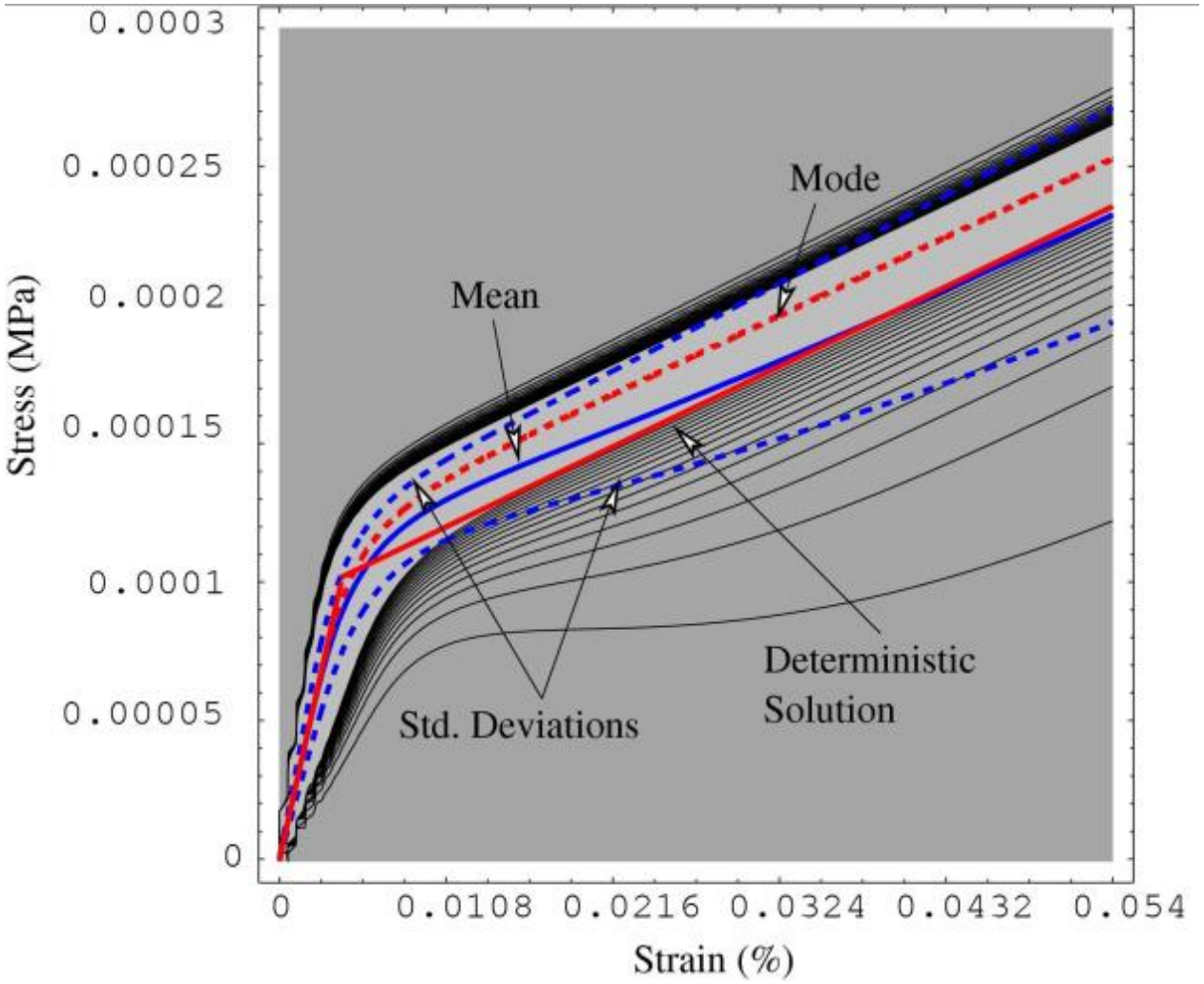
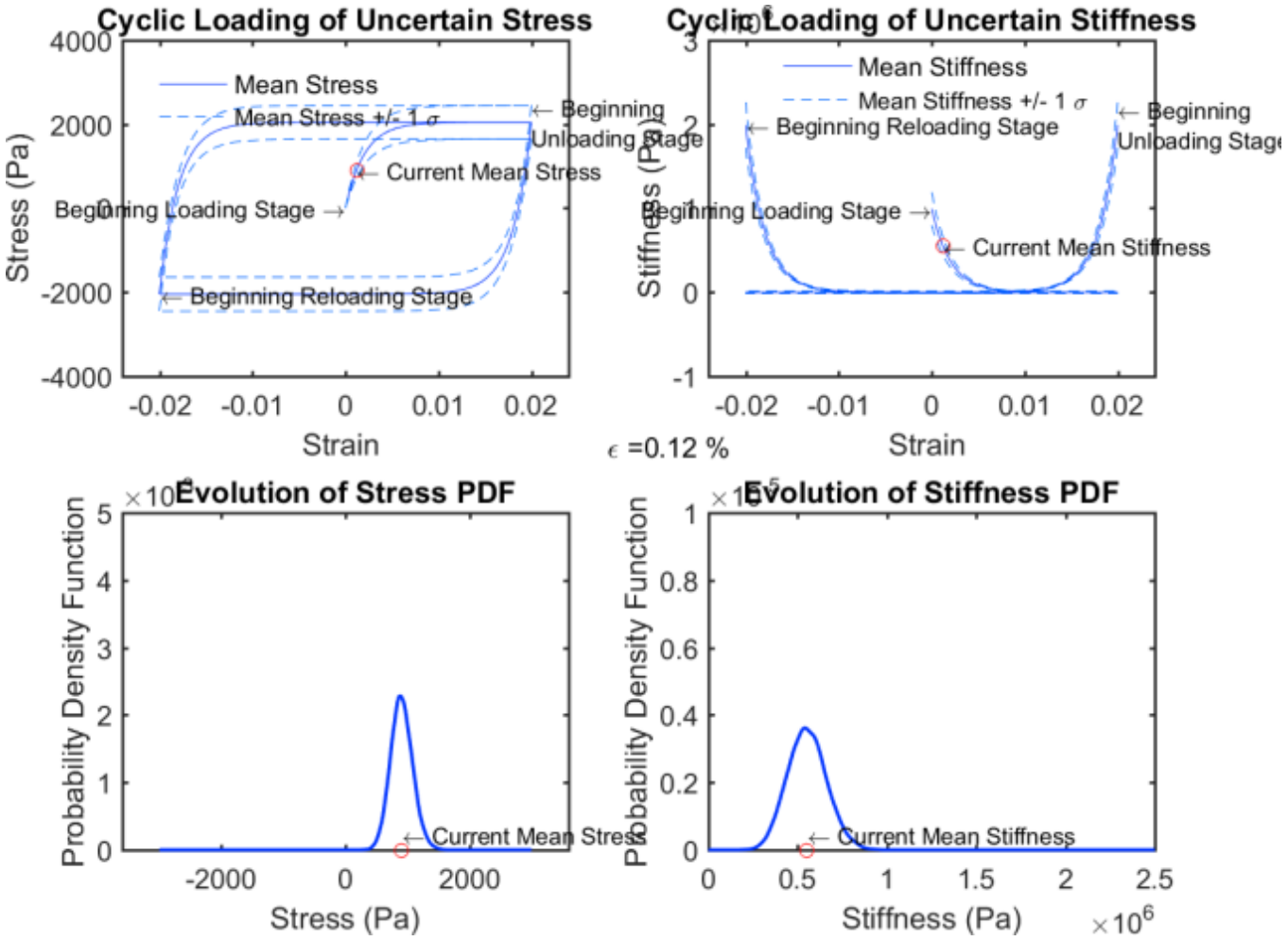
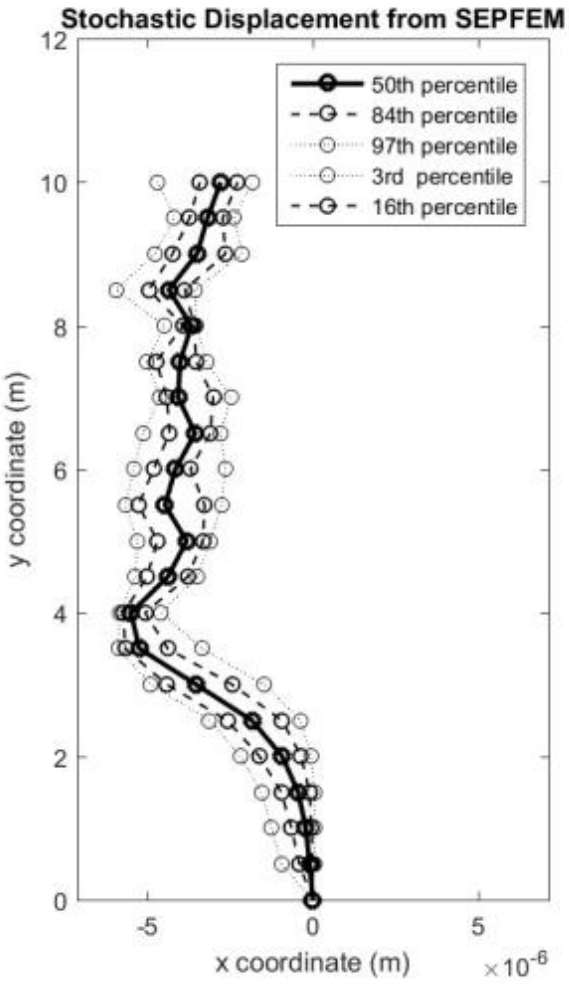
Probabilistic Elastic-Plastic Response

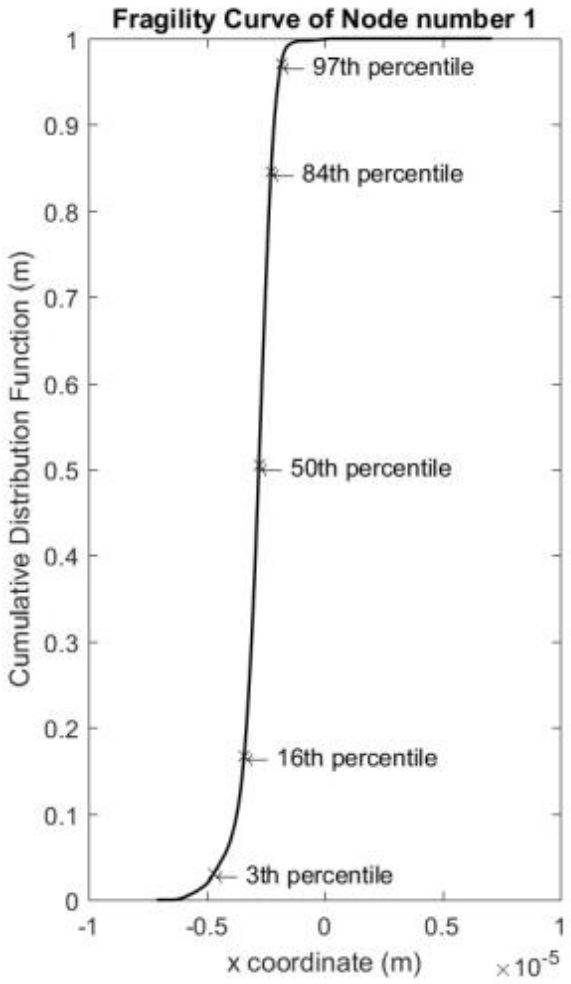


Probabilistic Elastic-Plastic Modeling



SEPFEM: Example in 1D

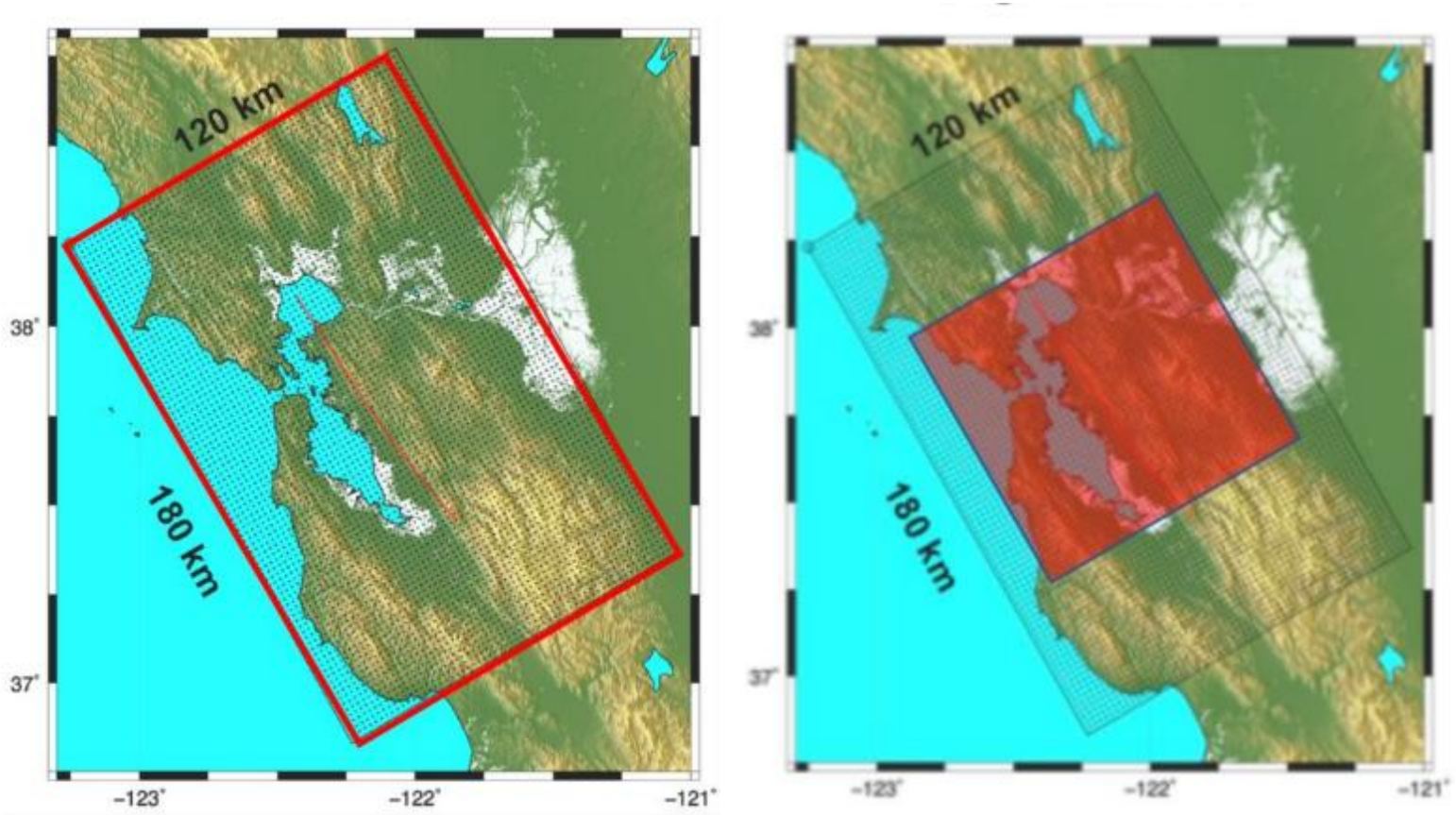




Regional Geophysical Models

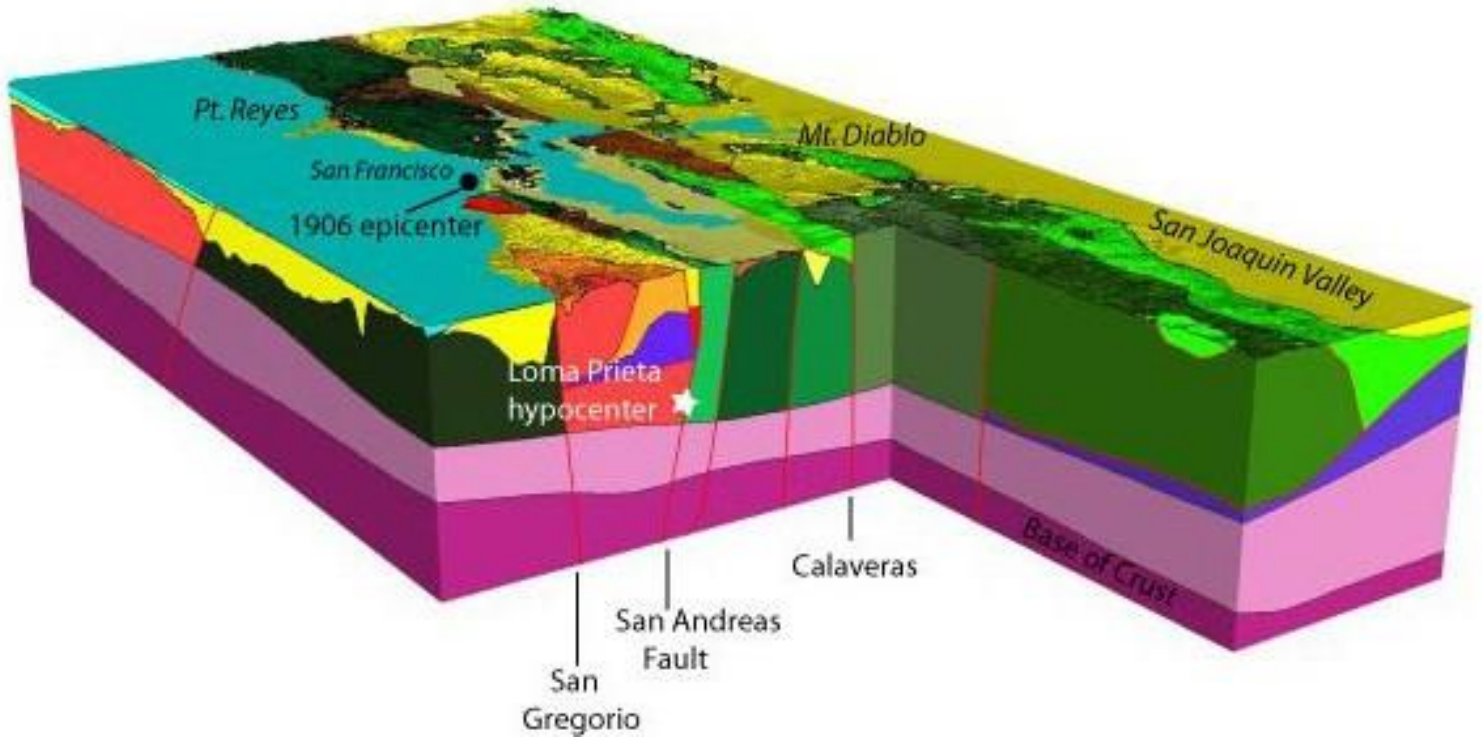
- Free Field seismic motions on regional scale
- Knowledge of geology (deep and shallow) needed
- Developed using SW4 and/or Real-ESSI
- Collaboration with LLNL: Dr. Rodgers, Dr. Pitarka and Dr. Petersson

Regional Geophysical Models



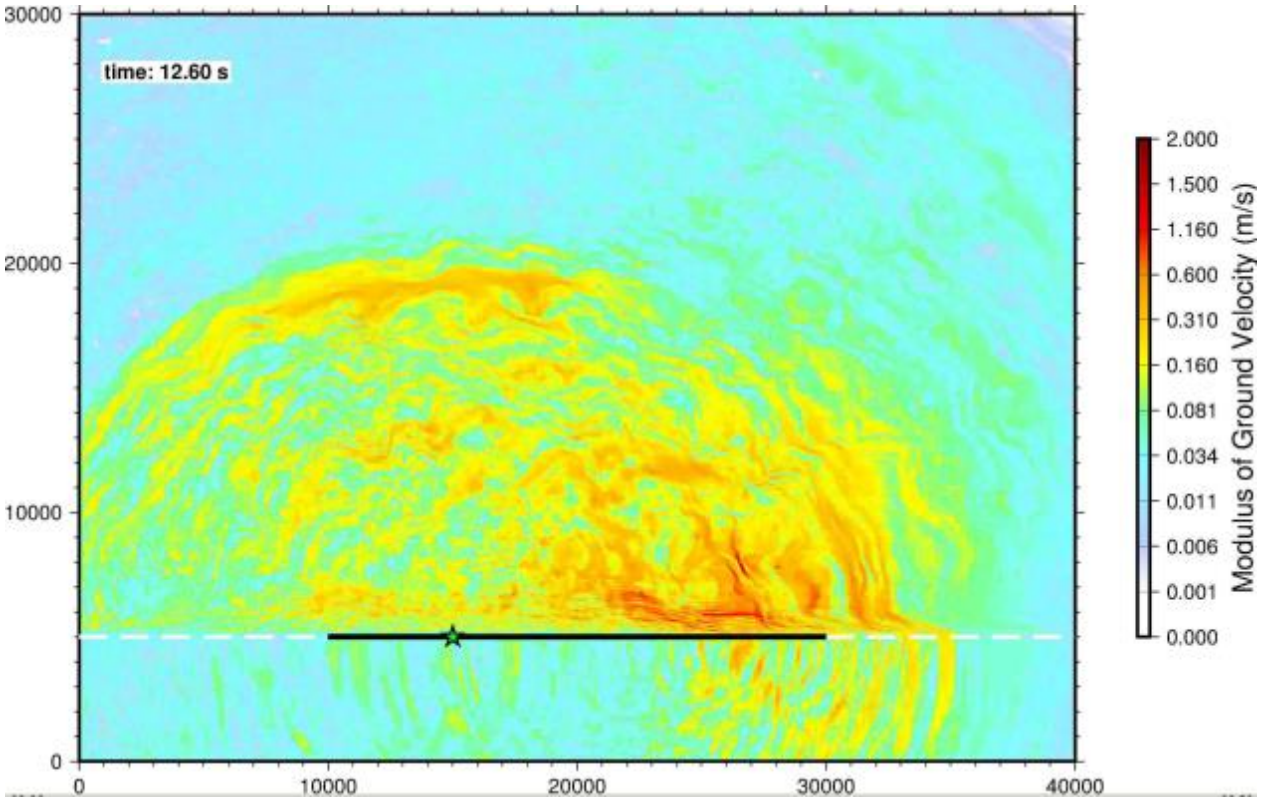
Rodgers and Pitarka

Regional Geophysical Models



USGS

Example Regional Model (Rodgers)



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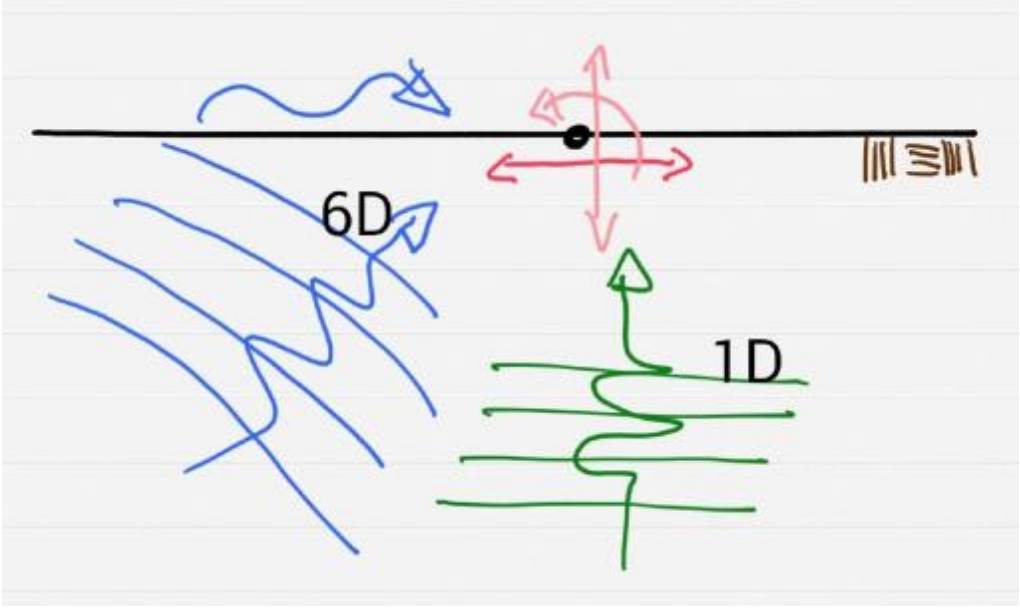
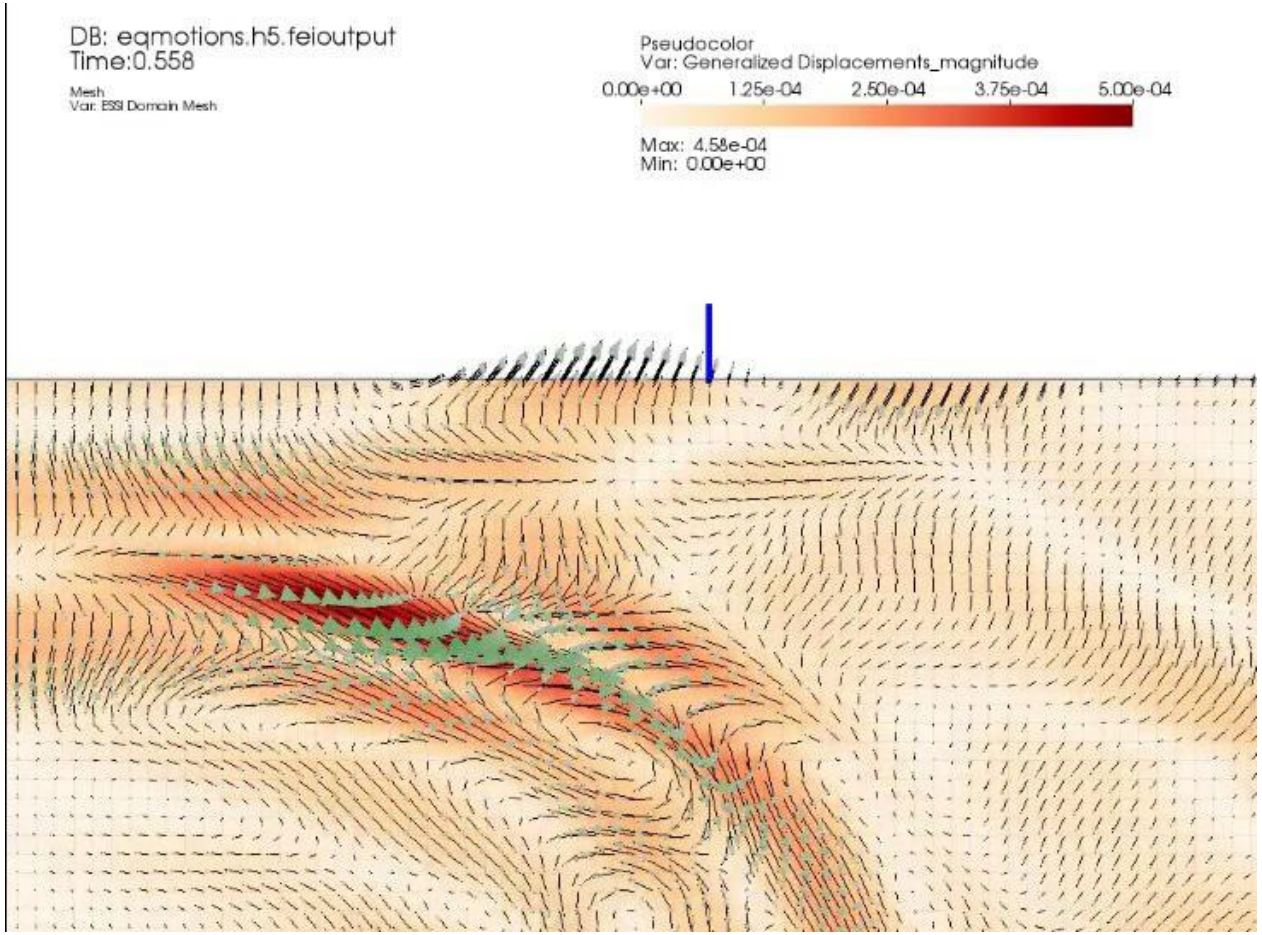
ESSI: 6C or 1C Seismic Motions

- 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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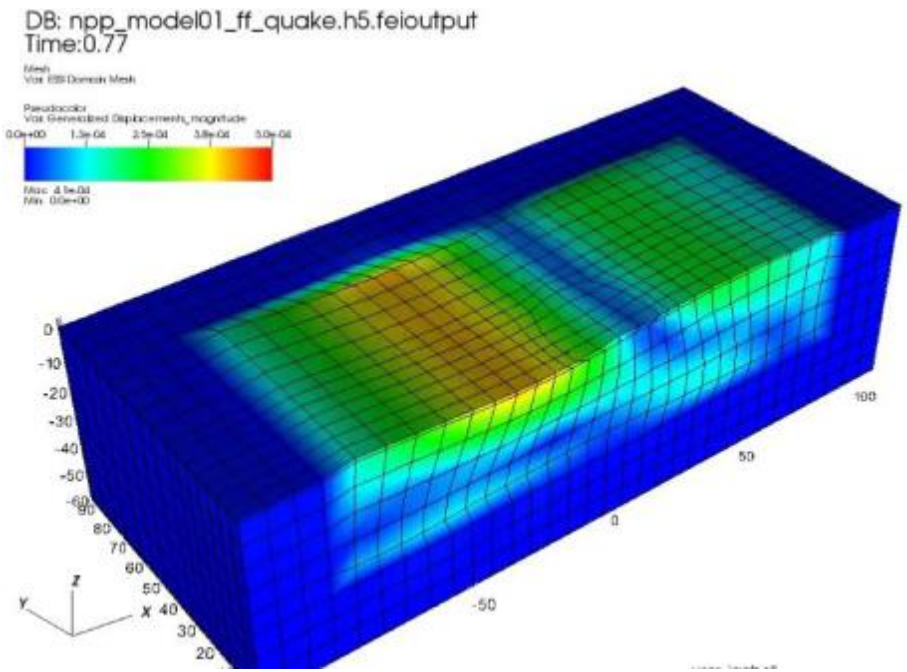
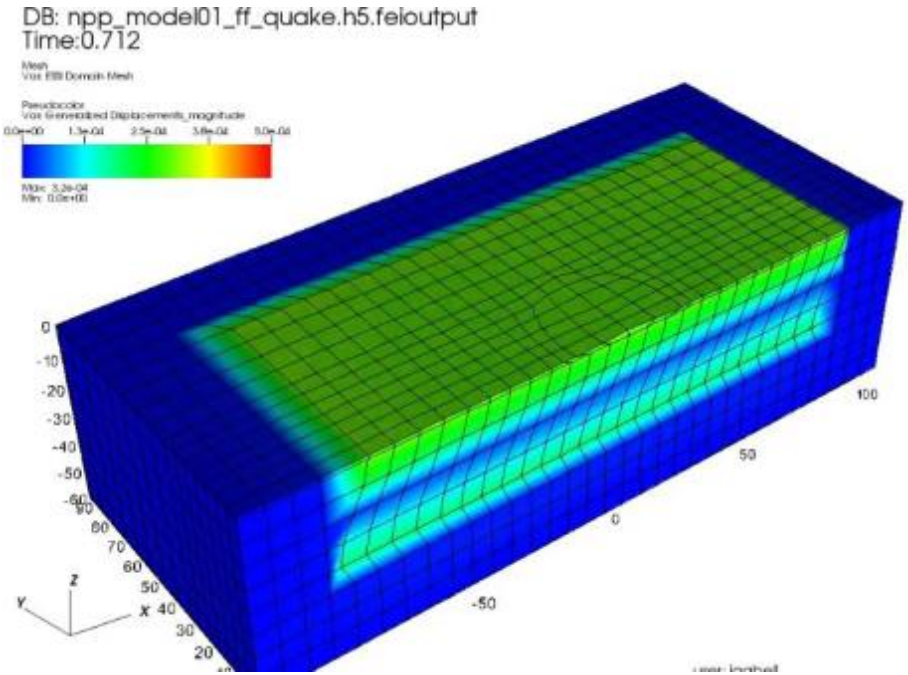
1C vs 6C Free Field Motions

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

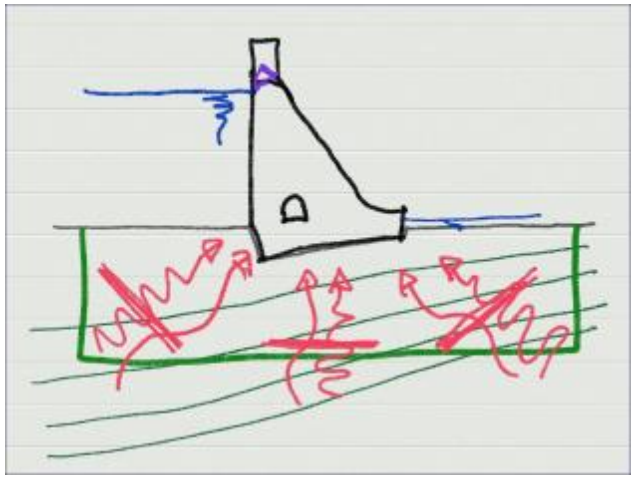


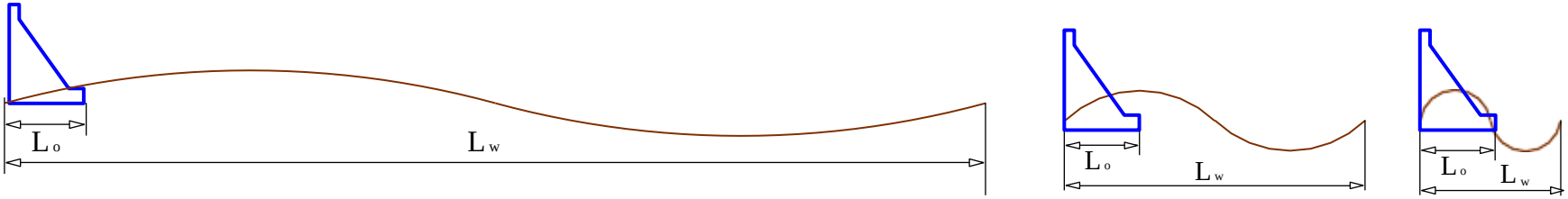


(MP4) (MP4)

Stress Testing Dam-Foundation System

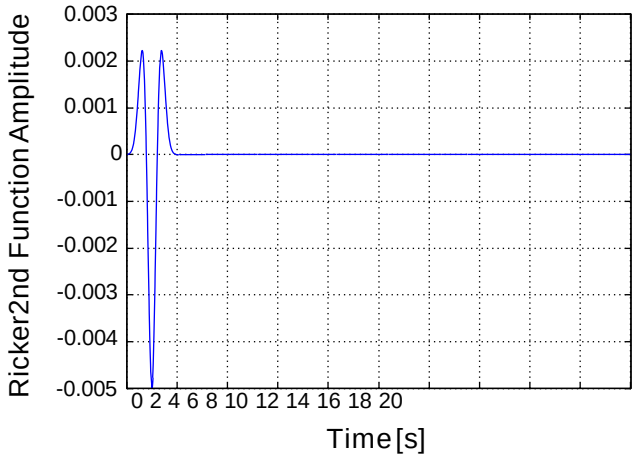
- Excite SSI system with a suite of seismic motions
- Waves: P, SV, SH, Surface (Rayleigh, Love, etc.)
- Variation in inclination, frequency, energy and duration
- Try to "break" the system, shake-out strong and weak links

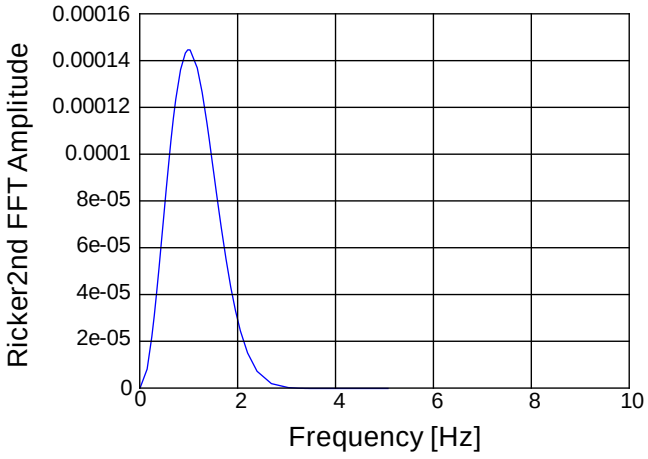




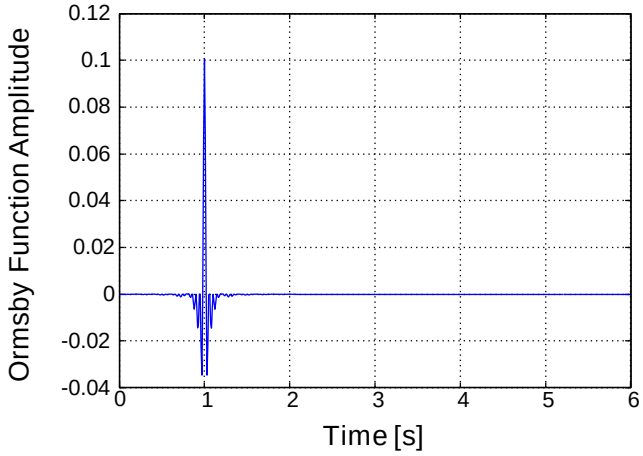
Stress Test Source Signals

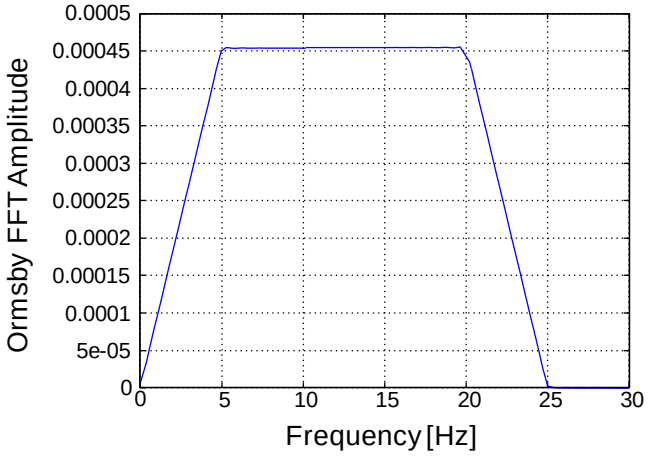
- Ricker



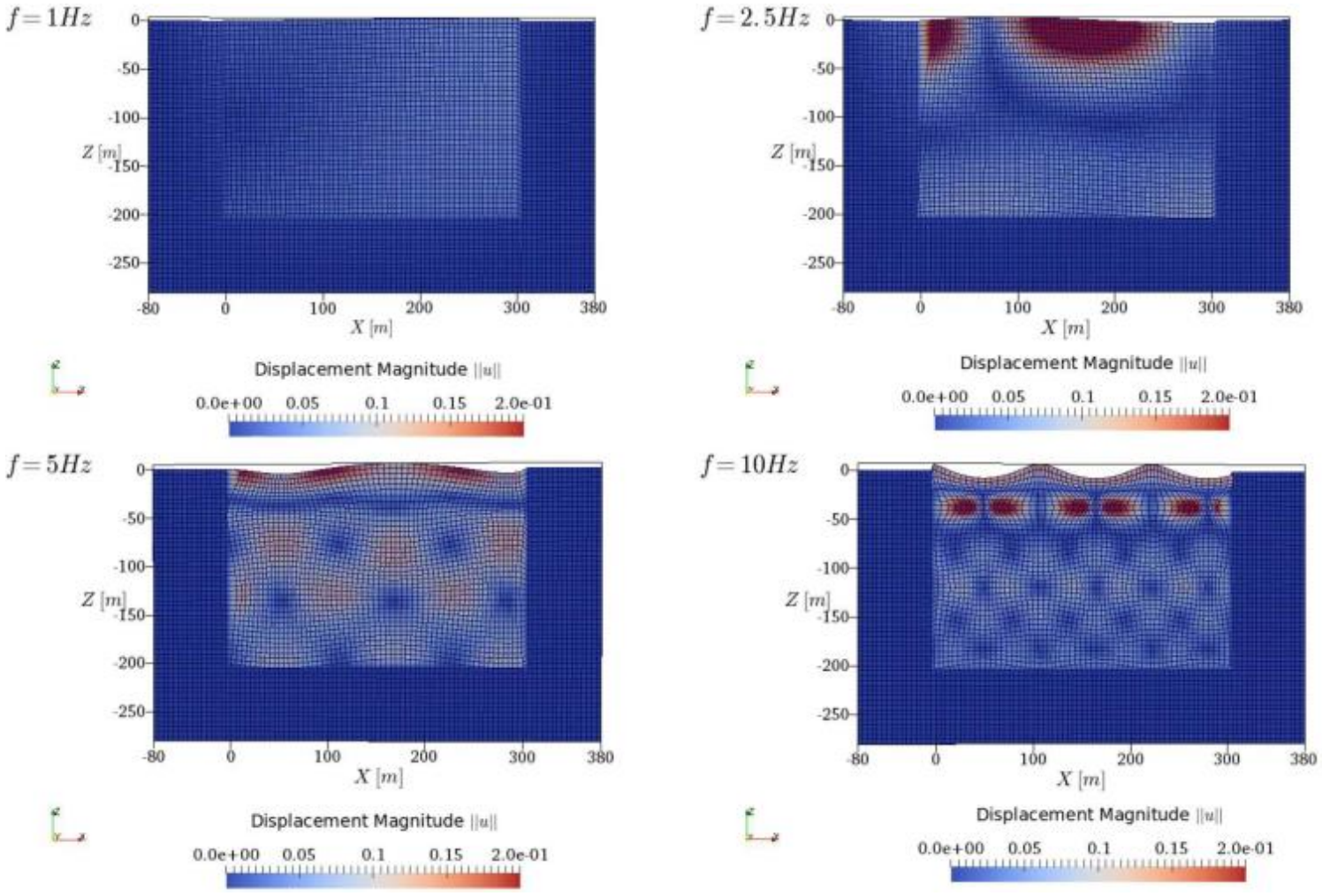


- Ormsby





Free Field, Variation in Input Frequency, θ = 60^o



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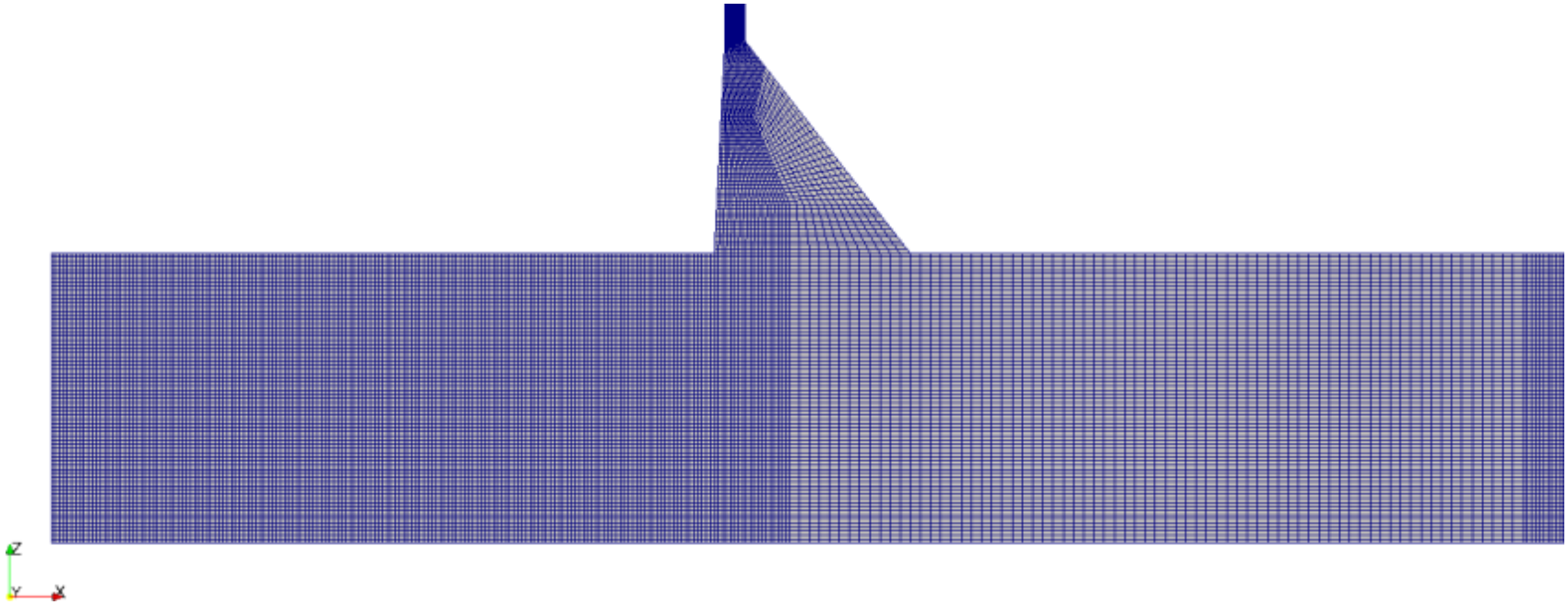
Pine Flats Dam, Model

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

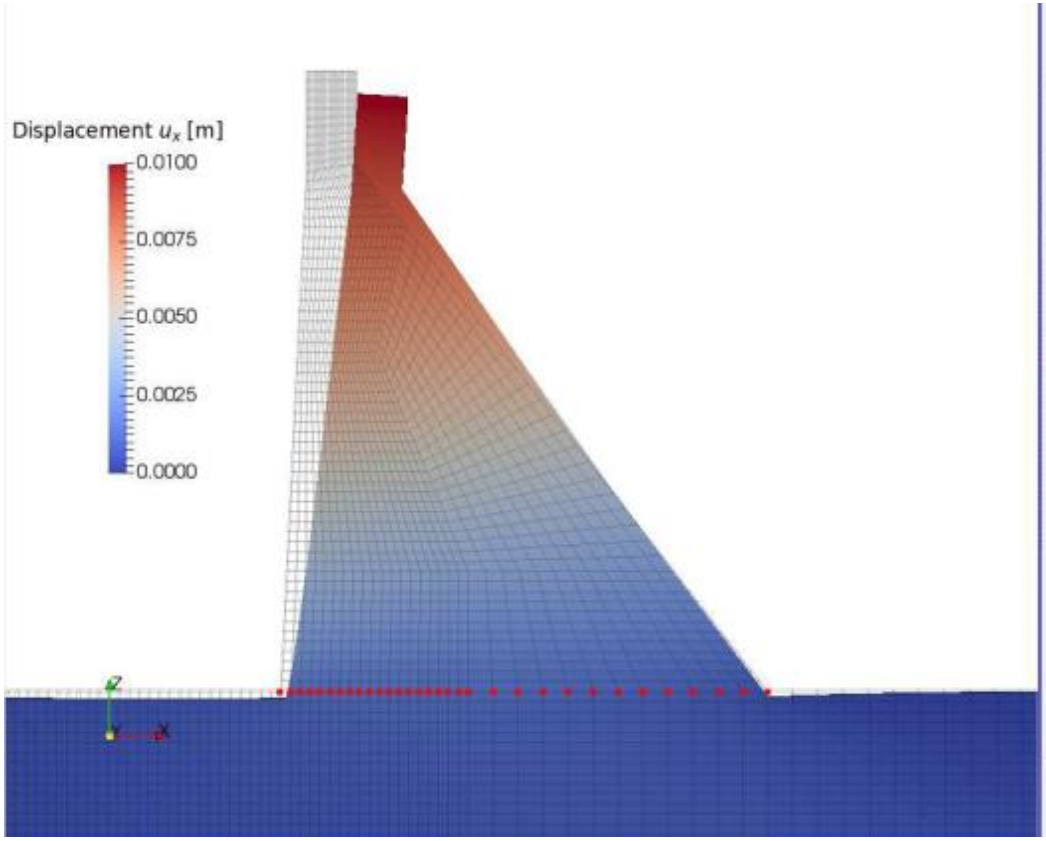


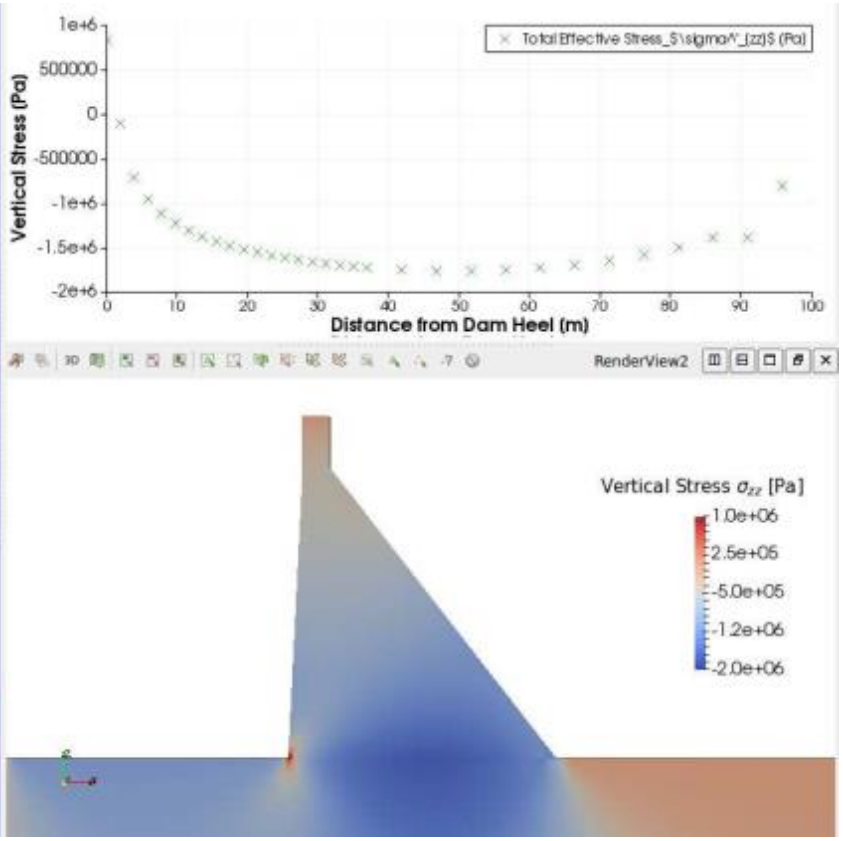
Pine Flats Dam, Static, Displacements

- Selfweight
- Water pressure, on dam side and lake bottom

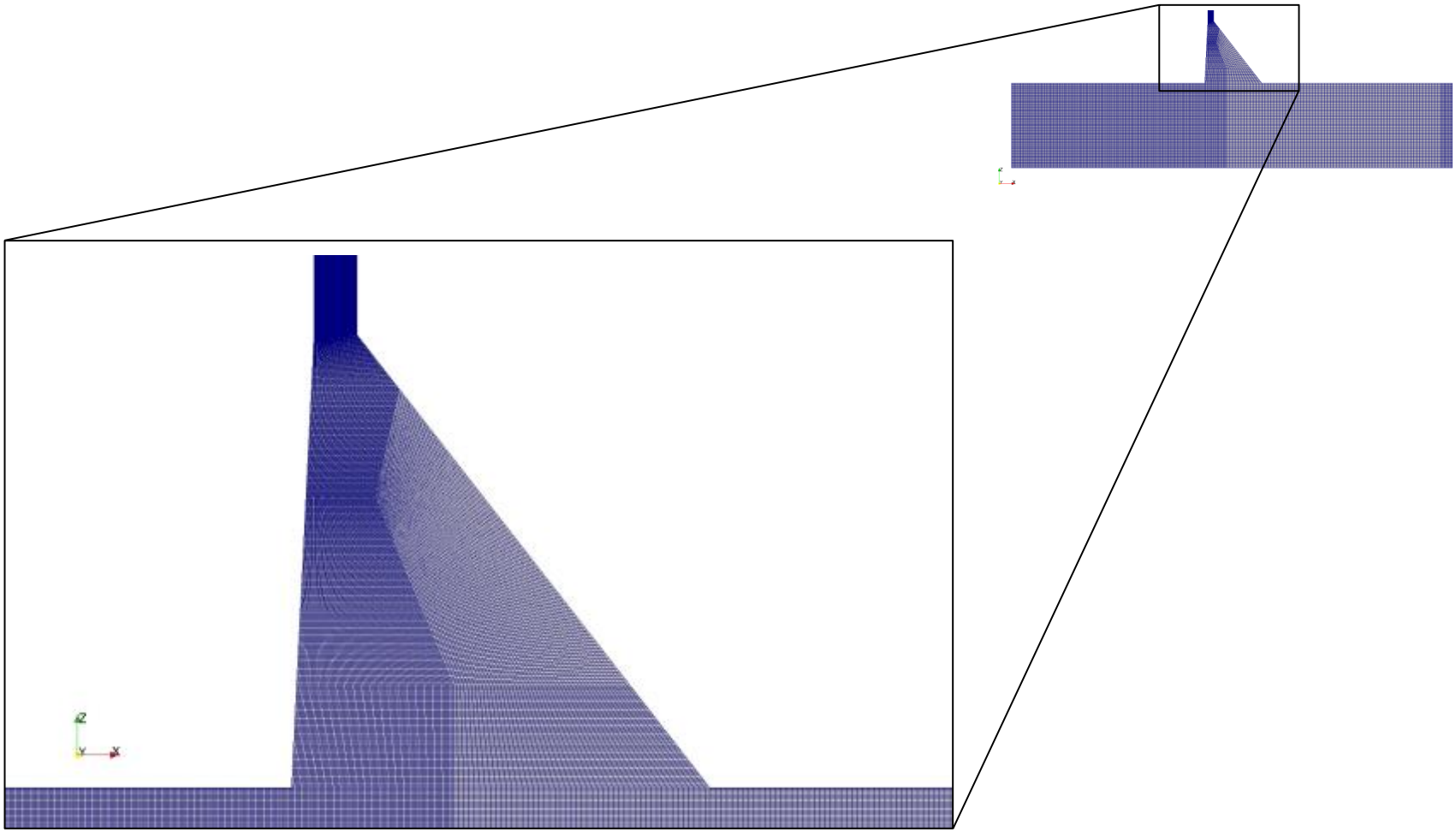
		Disp. [m]			Disp. [in]
		Top	Heel	Rel.	Rel.
Mat. Prop. I (Soft Found.)	Hor.	0.0121	0.0031	0.00900	0.354
	Vert.	-0.0095	-0.0059	-0.00348	-0.137
Mat. Prop, II (Stiff Found.)	Hor.	0.0101	0.0011	0.00904	0.356
	Vert.	-0.0048	-0.0019	-0.00298	-0.117

Static, Displacements and σ_V





Mesh Refinement Effects

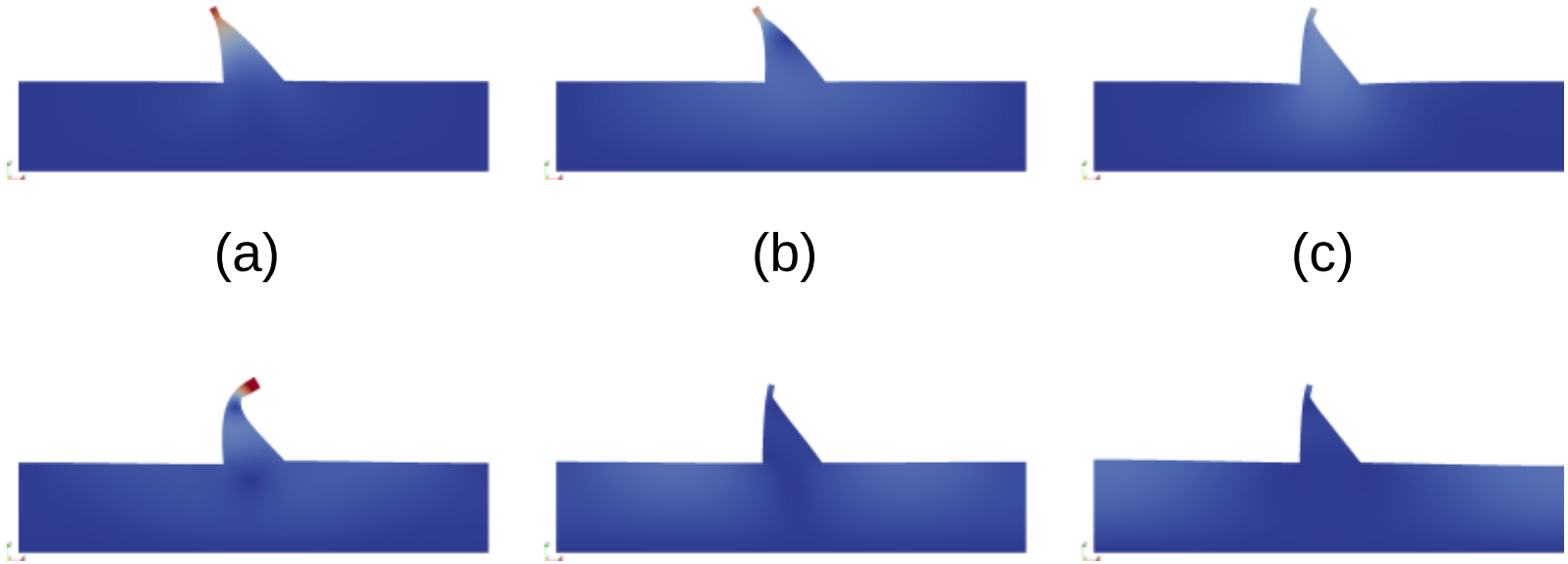


Mesh Refinement Effects

		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,

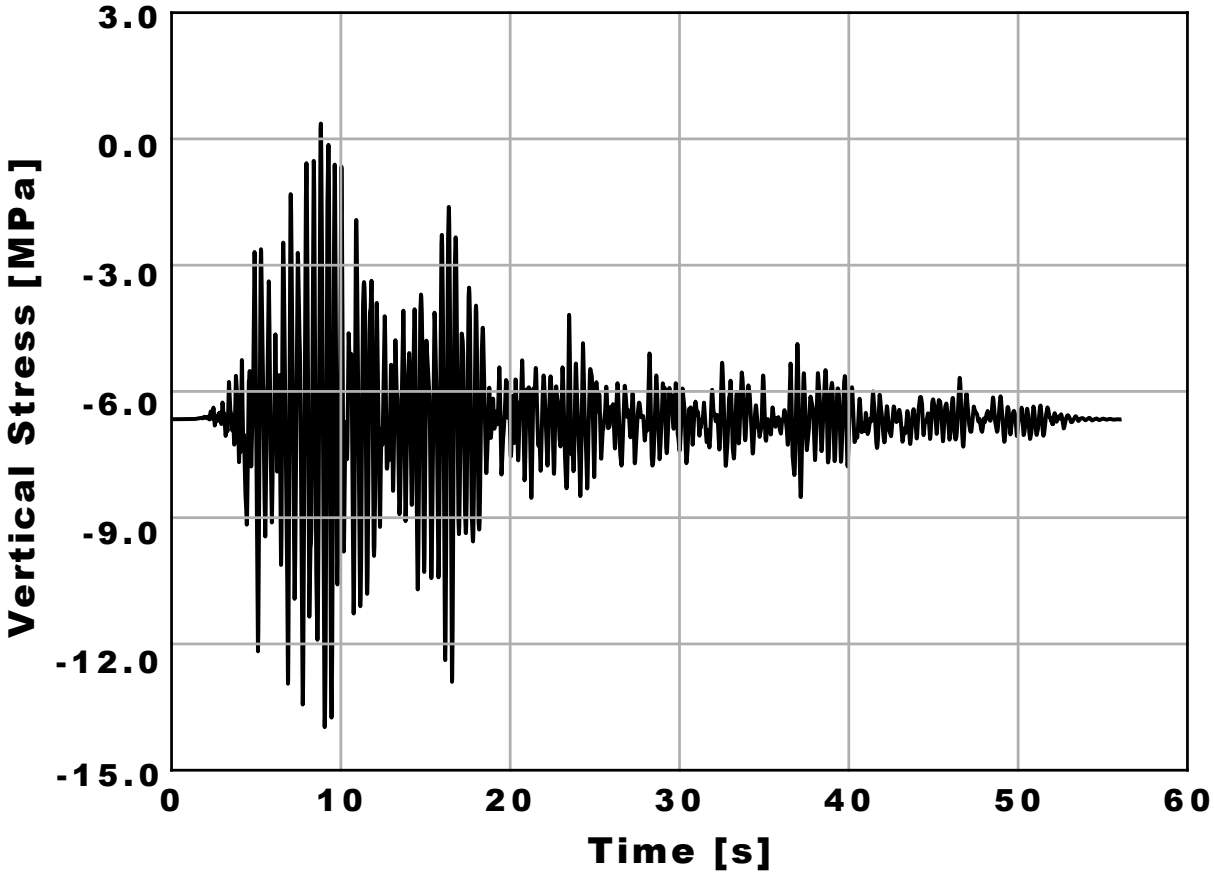


(a) (b) (c)

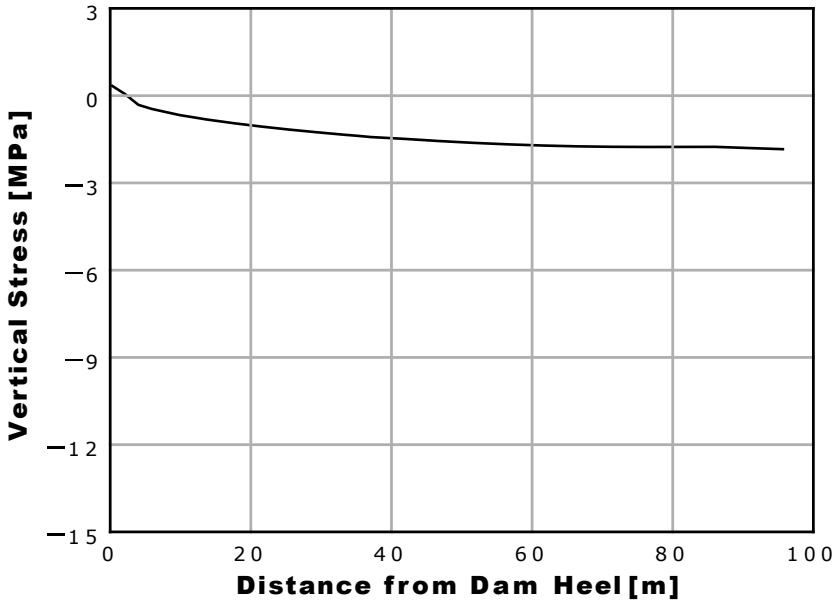
(d) (e) (f)

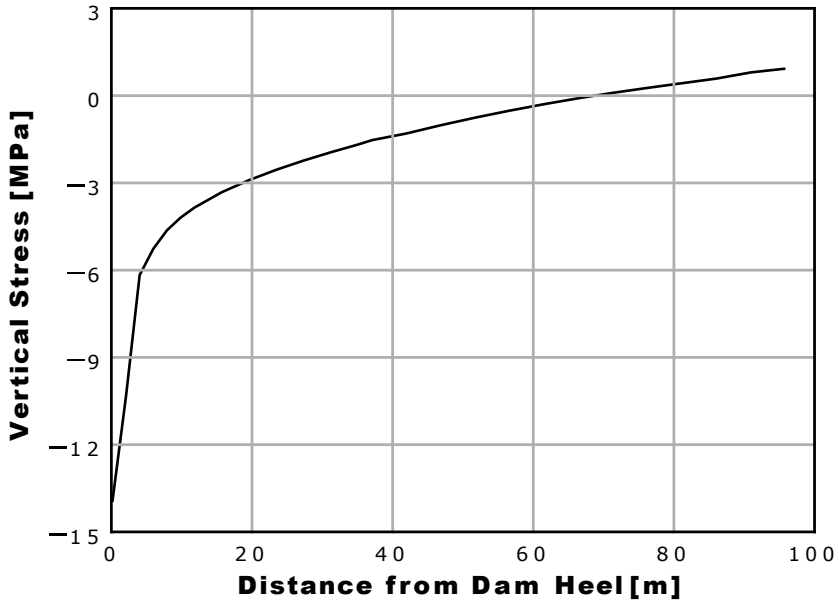
Taft Earthquake, Time History of σ_V

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



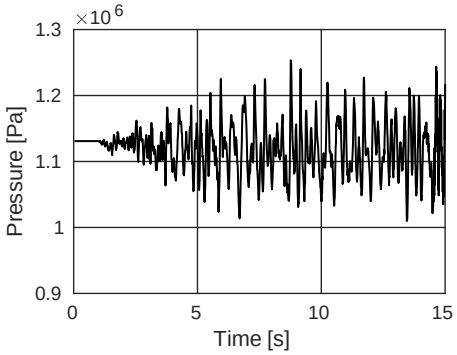
Taft Earthquake, σ_V Distribution at σ_{min} and σ_{max}

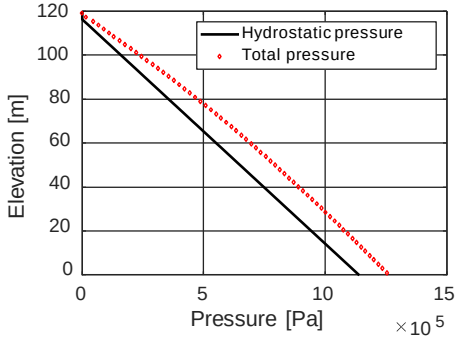


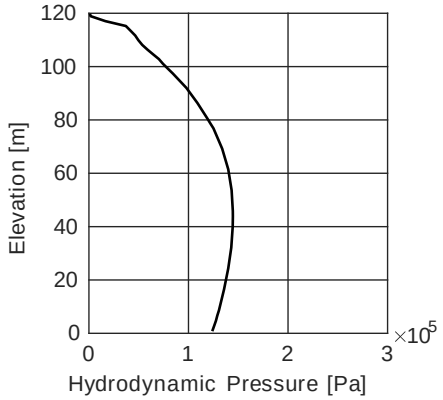


D2, Taft Earthquake, Dam and the Reservoir

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

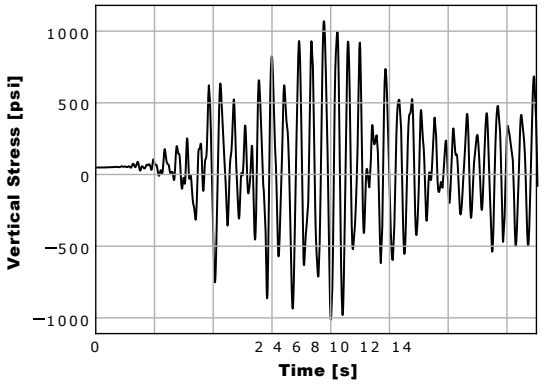


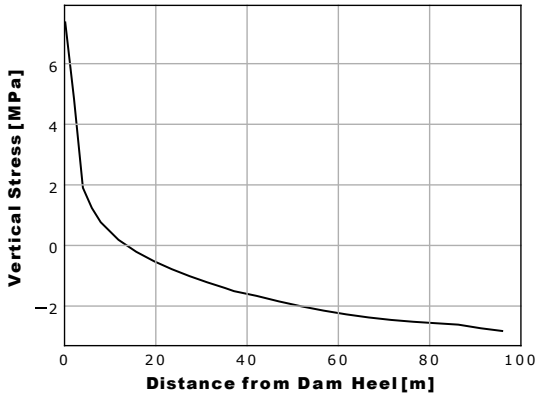


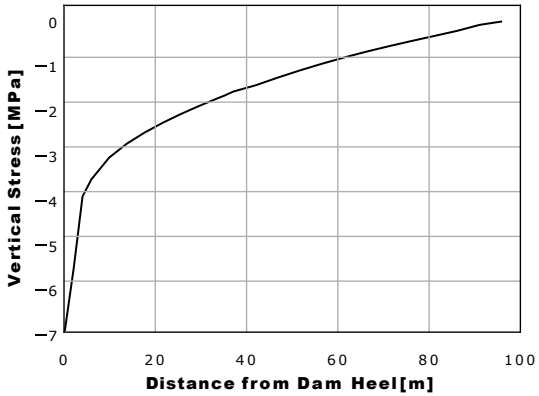


D2, Tafts Earthquake, Dam and the Reservoir

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

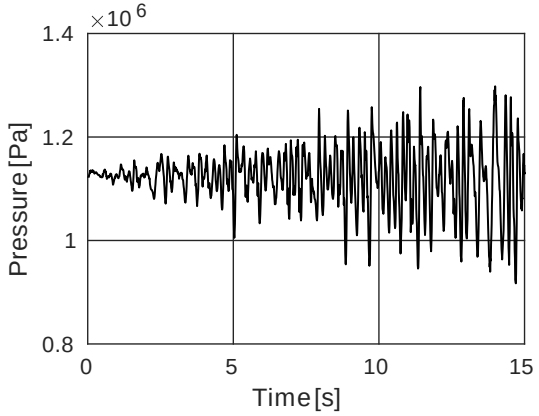


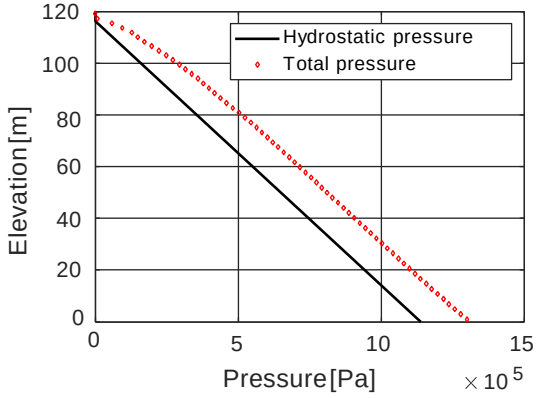


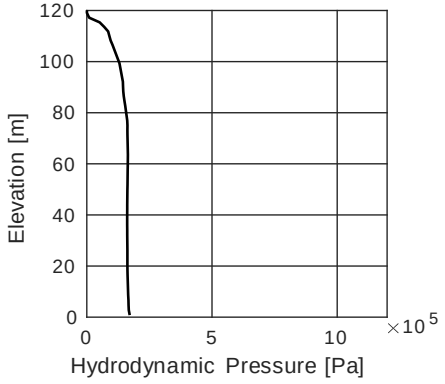


D2, ETAF Earthquake, Dam and the Reservoir

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

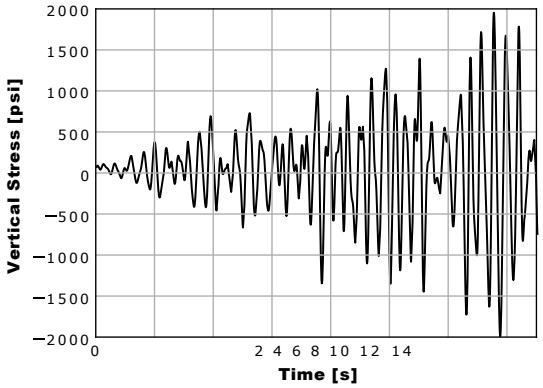


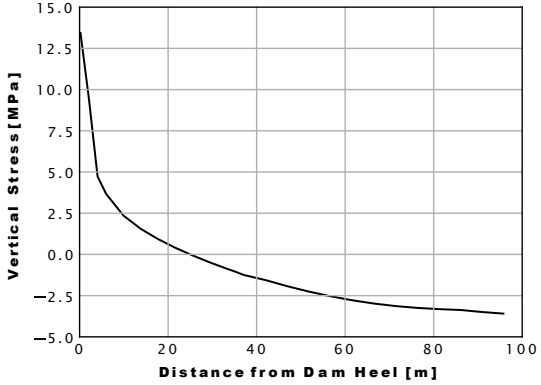


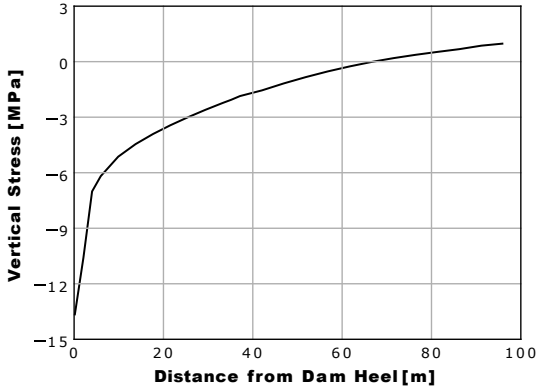


D2, ETAF Earthquake, Dam and the Reservoir

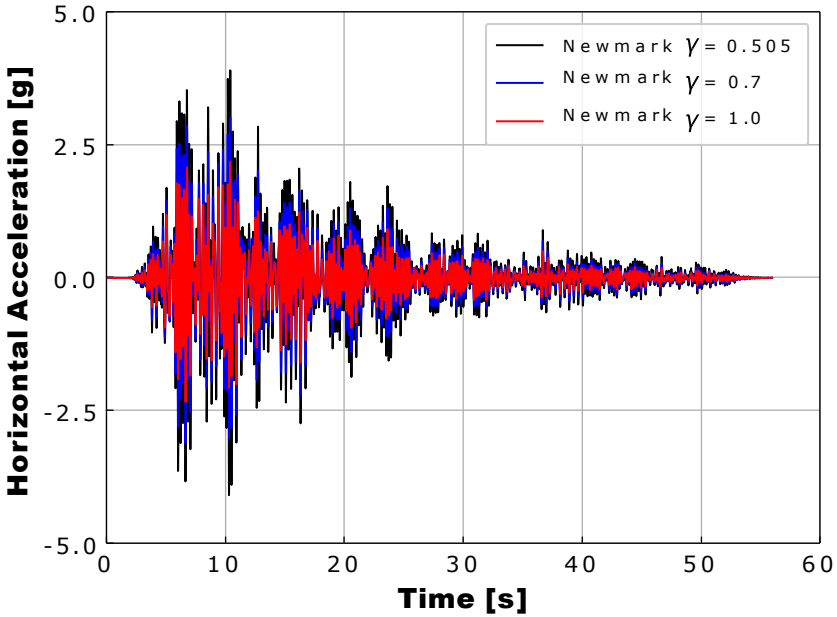
- Vertical stress: heel time series, along base for max stress at the heel, for min stress at the heel

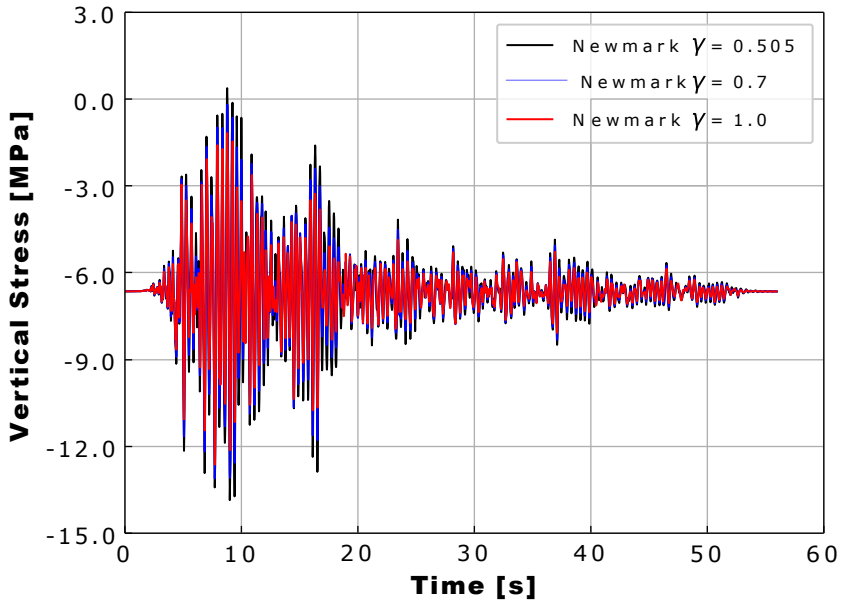




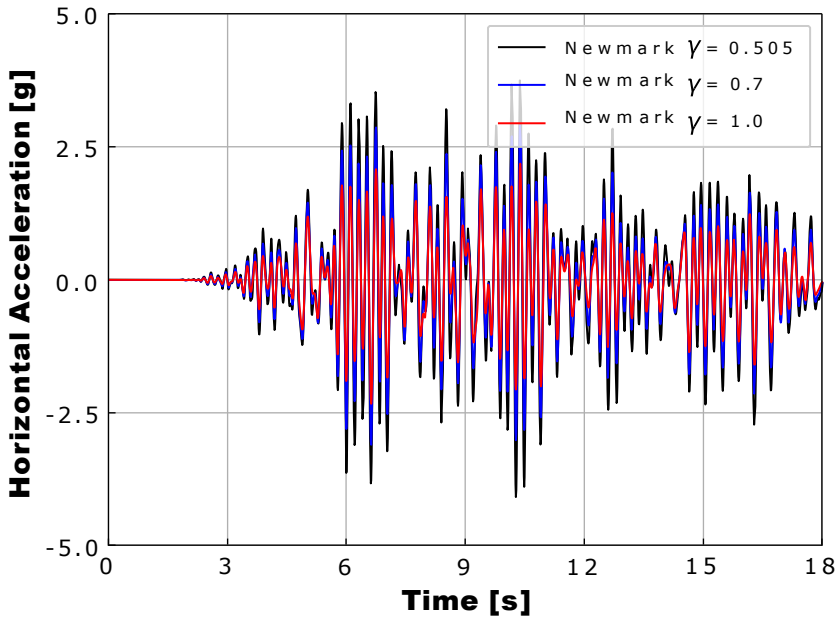


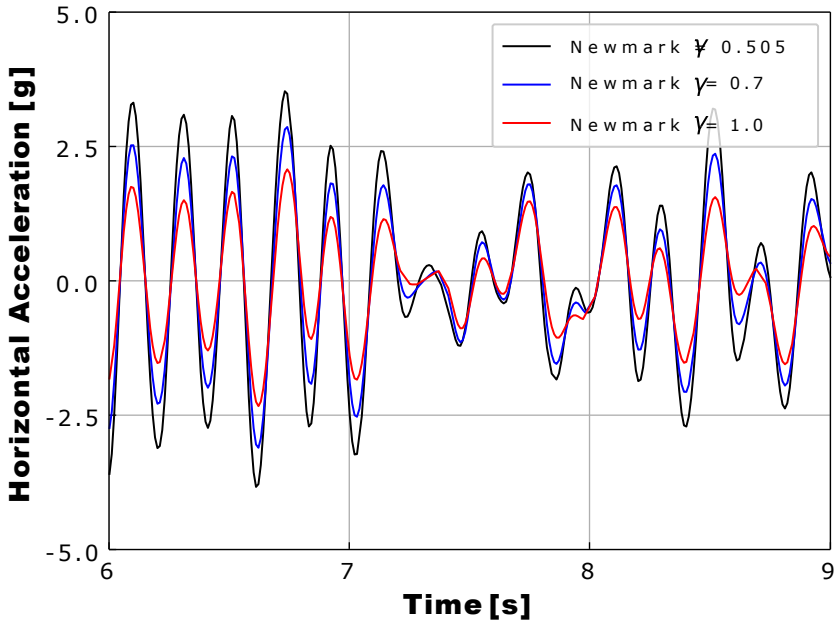
Numerical Damping Effects, Elastic $\ddot{u}_{hor}^{top}$, σ_{v}^{heel}



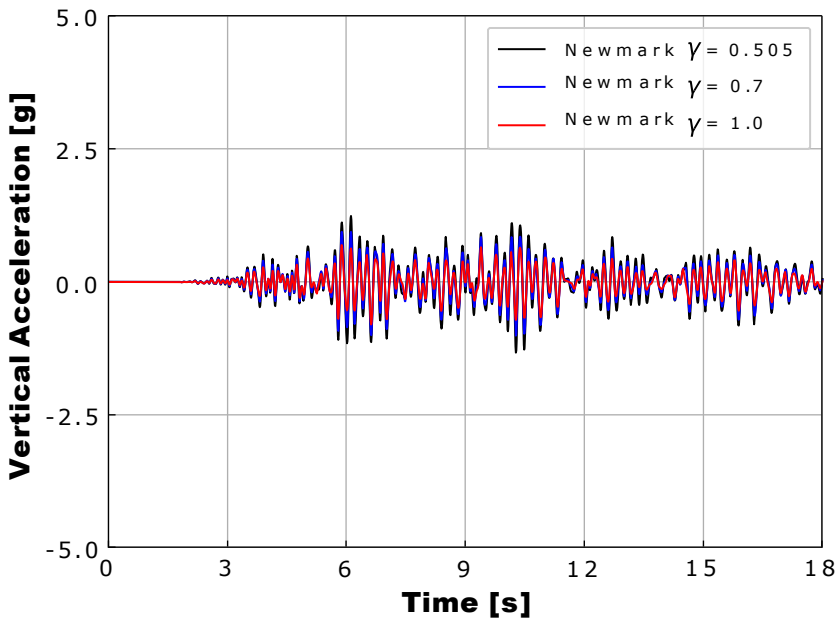


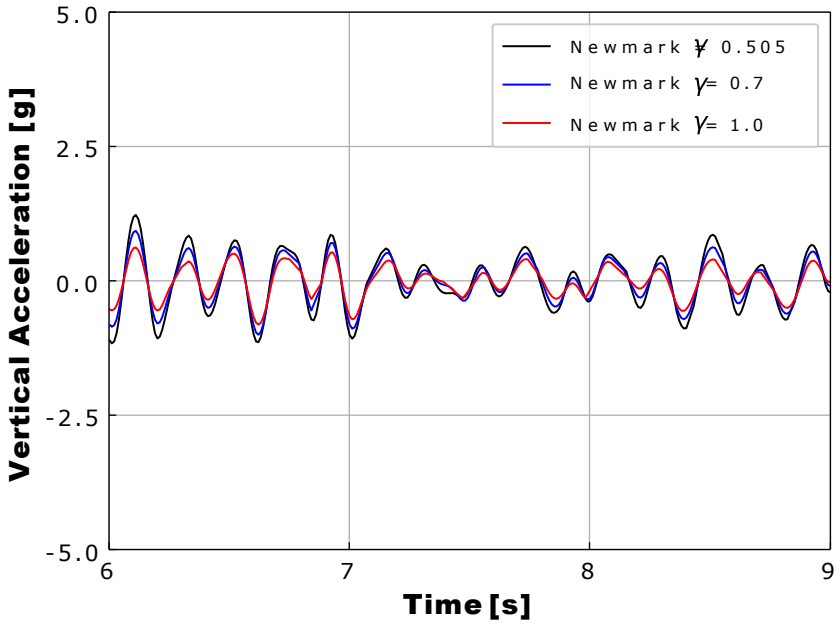
Numerical Damping Effects, Elastic, Details $\ddot{u}^{top}_{horizontal}$



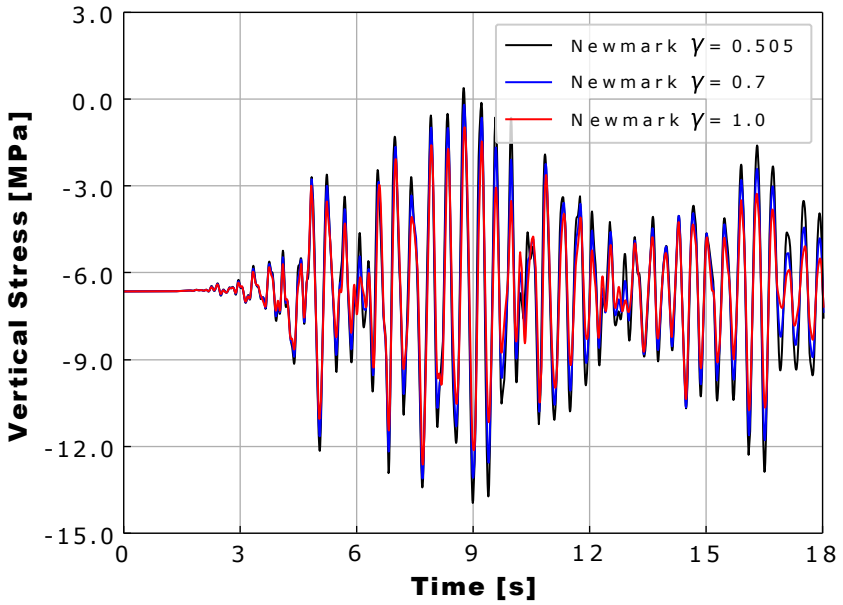


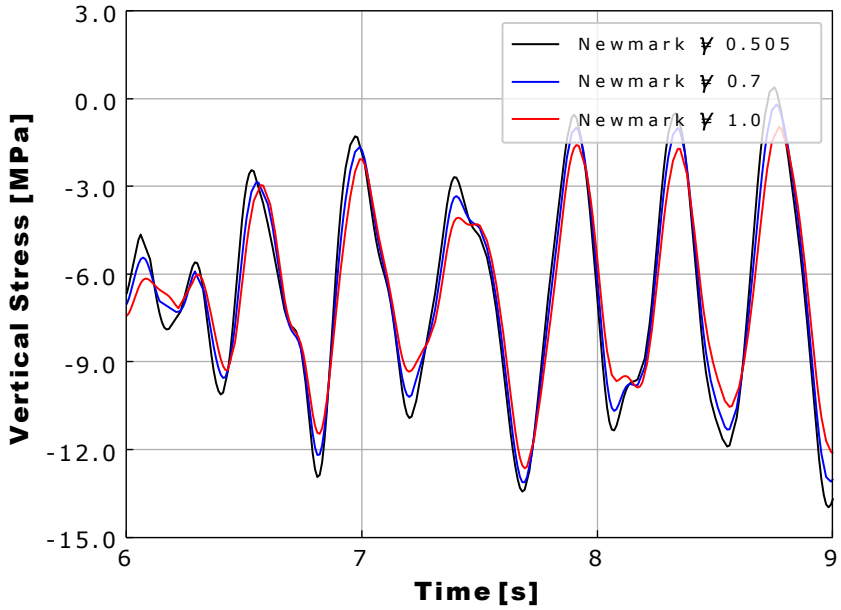
Numerical Damping Effects, Elastic, Details $\ddot{u}^{top}_{vertical}$



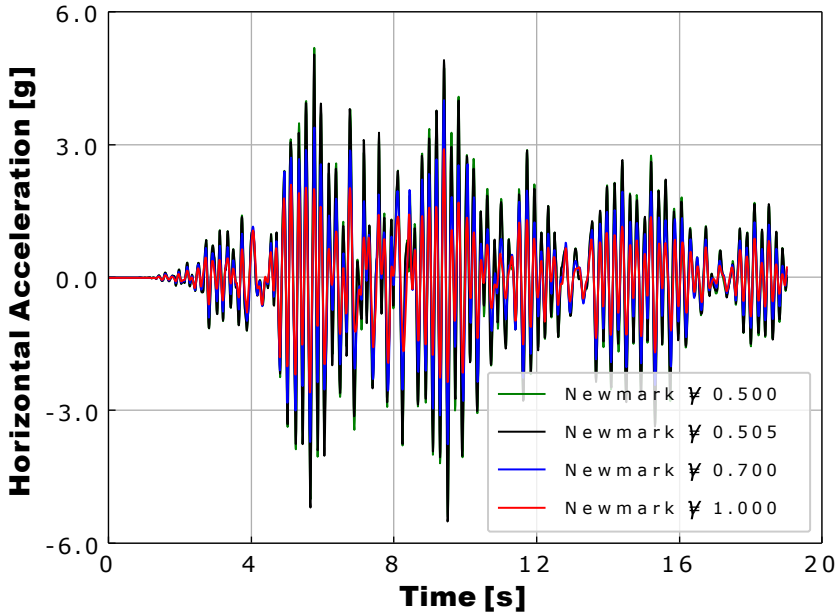


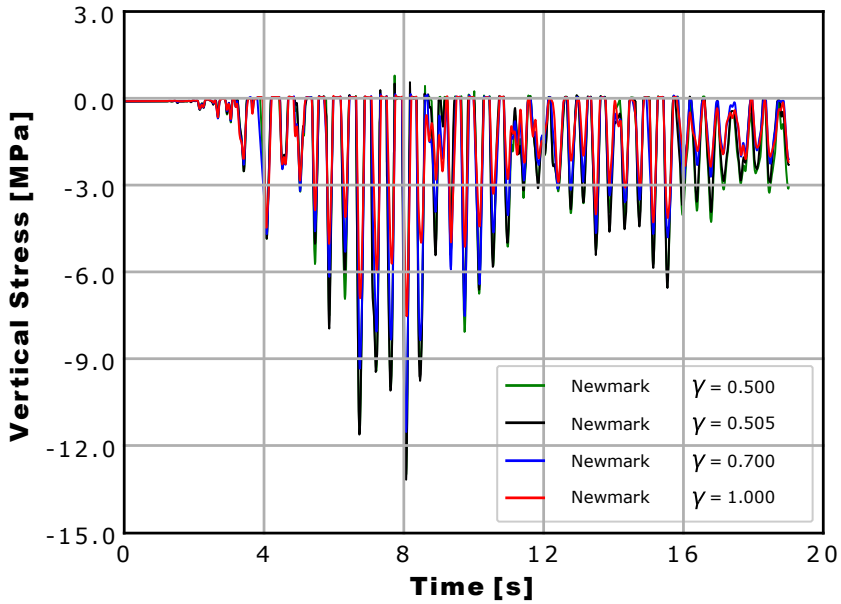
Numerical Damping Effects, Elastic, Details, σ_v^{heel}



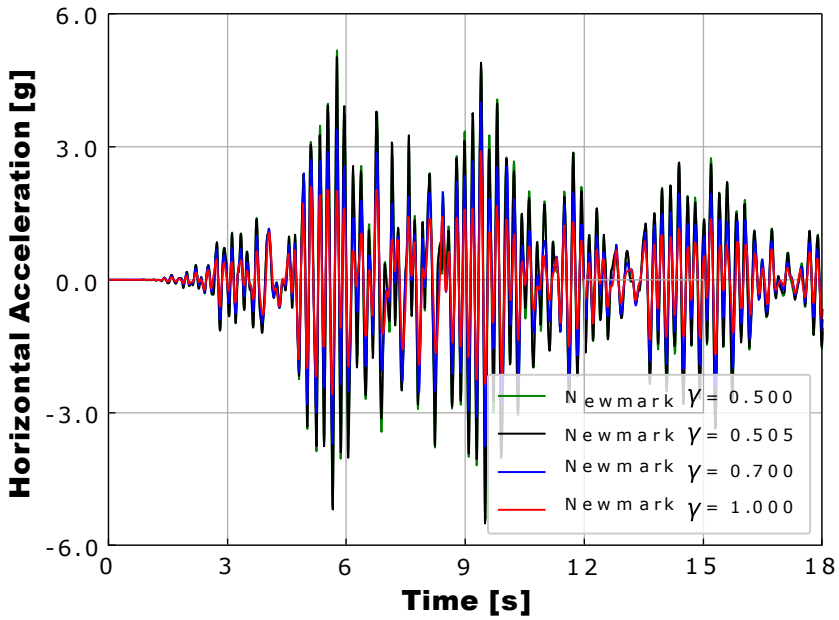


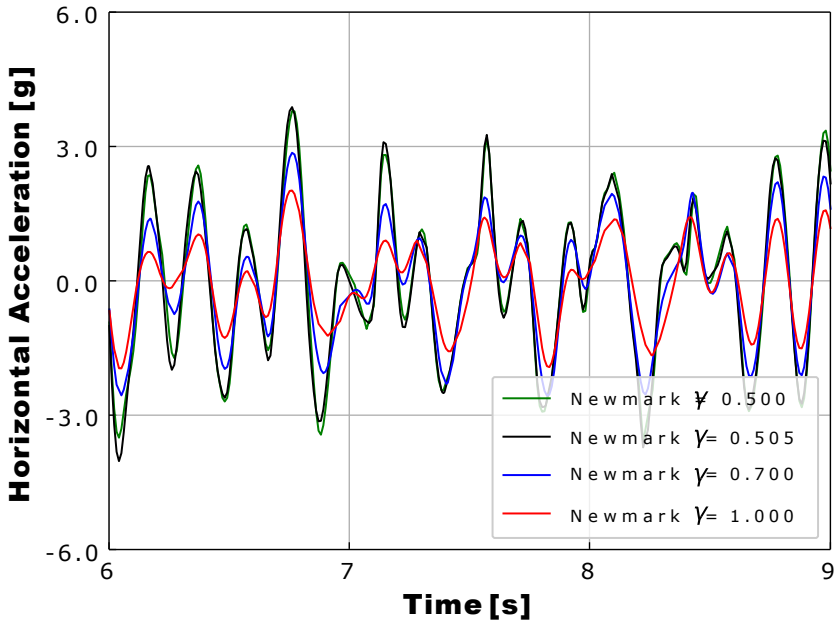
Numerical Damping Effects, Inelastic $\ddot{u}^{top}_{hor}$, σ^{heel}_{v}



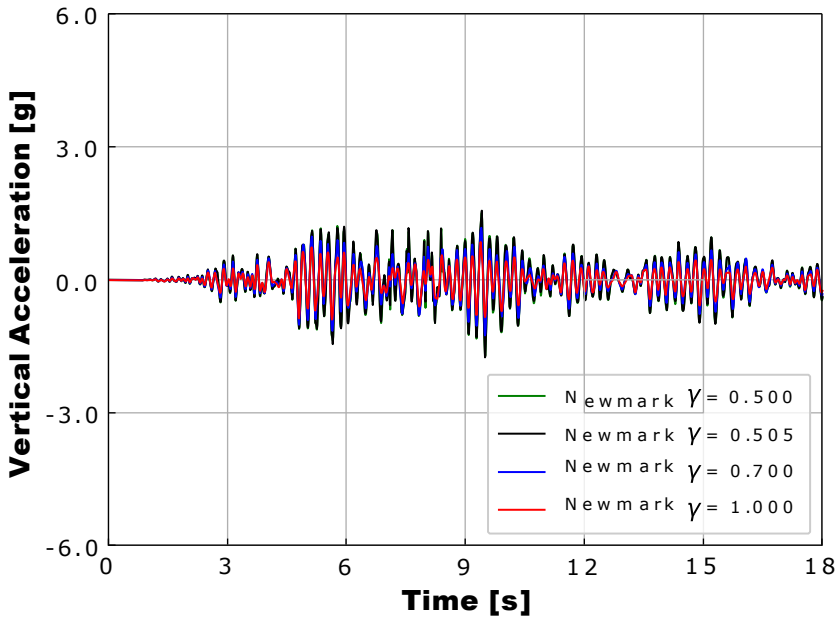


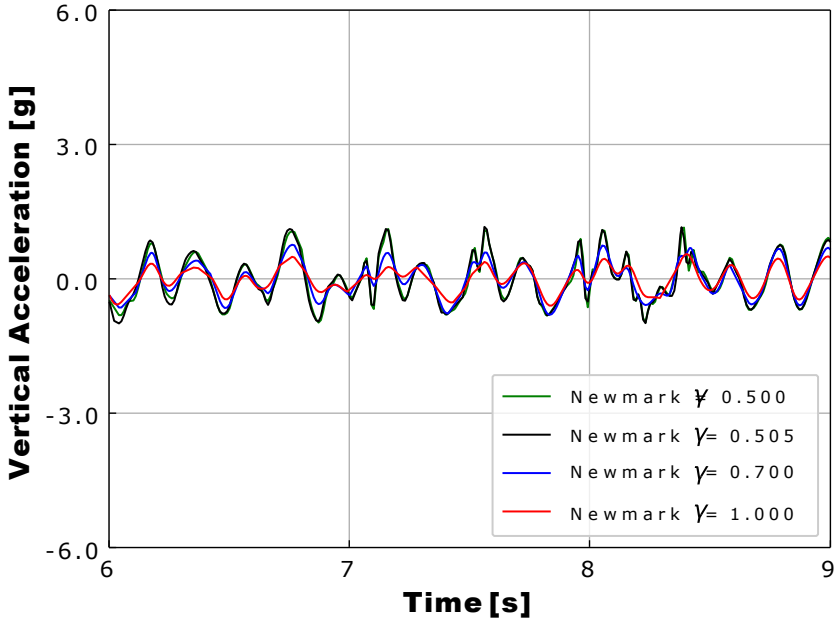
Numerical Damping Effects, Inelastic, Details $\ddot{u}^{top}_{horizontal}$



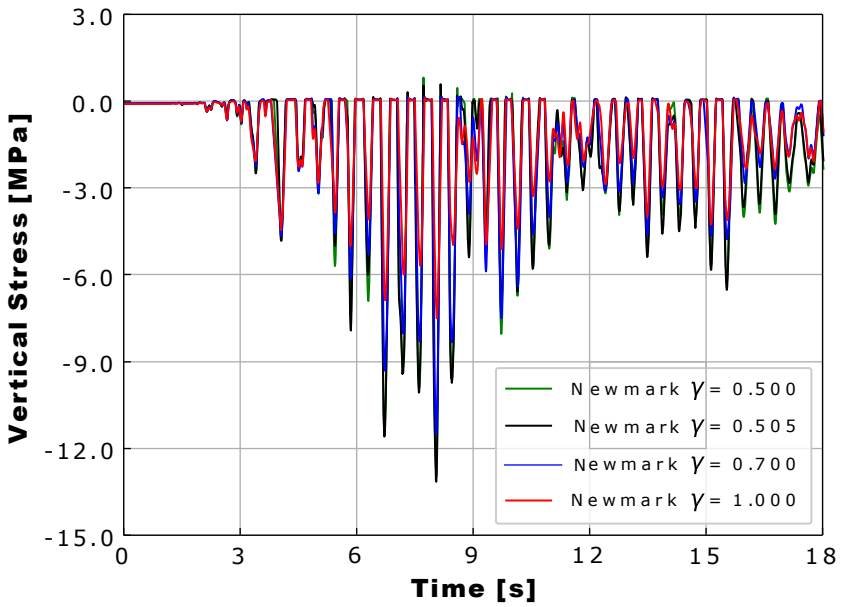


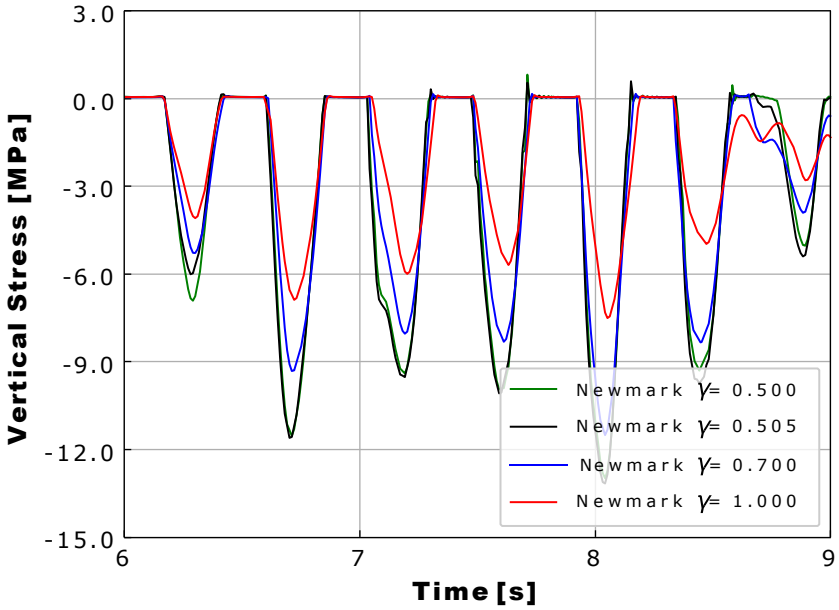
Numerical Damping Effects, Inelastic, Details $\ddot{u}^{top}_{vertical}$



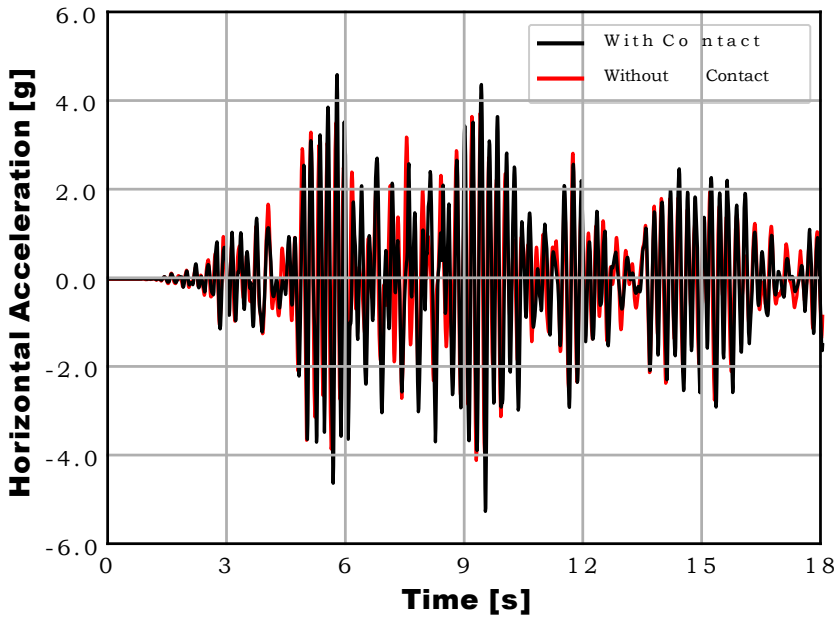


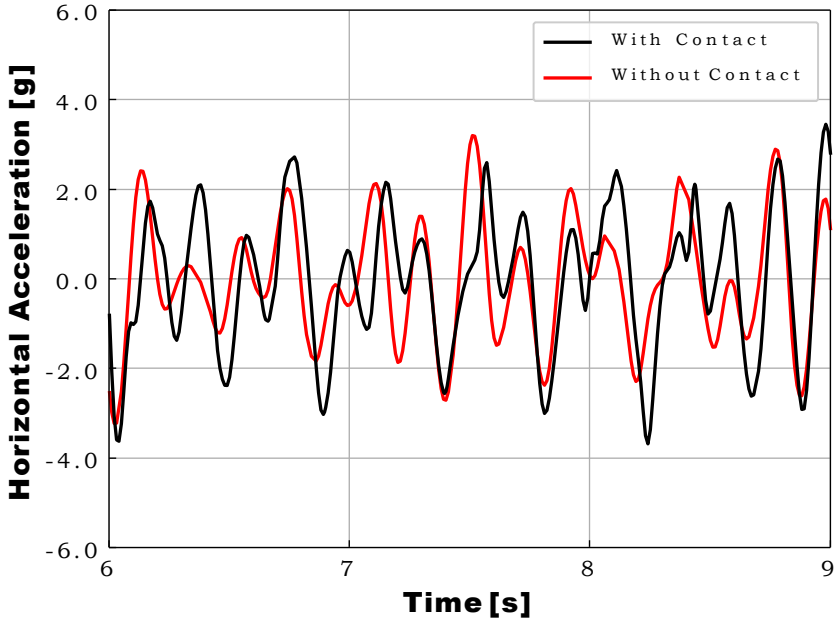
Numerical Damping Effects, Inelastic, Details, σ_V^{heel}



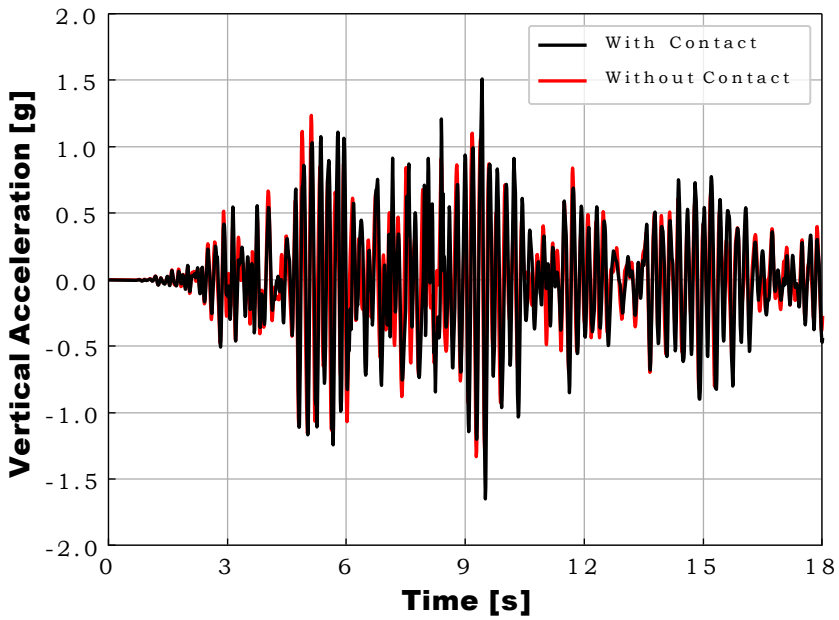


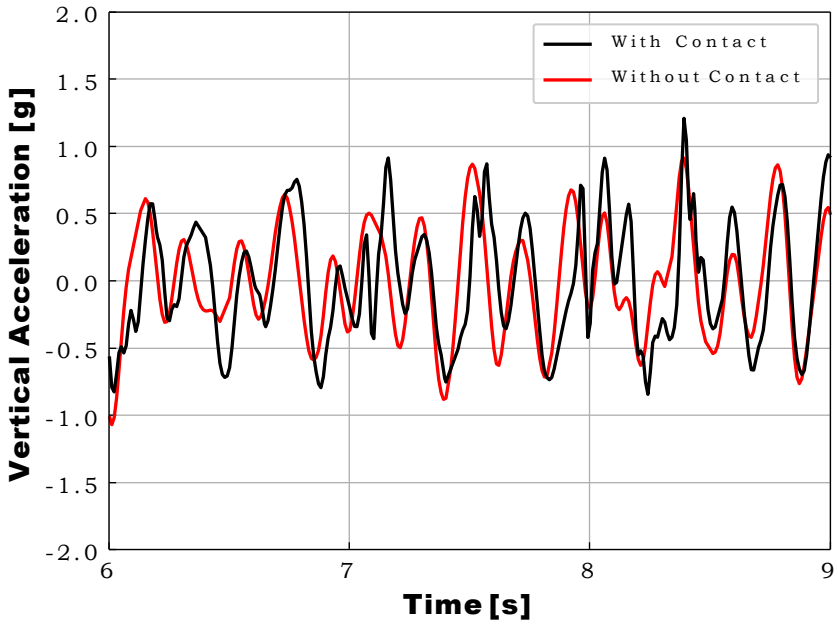
Inelastic vs Elastic, Details $\ddot{u}^{top}_{horizontal}$



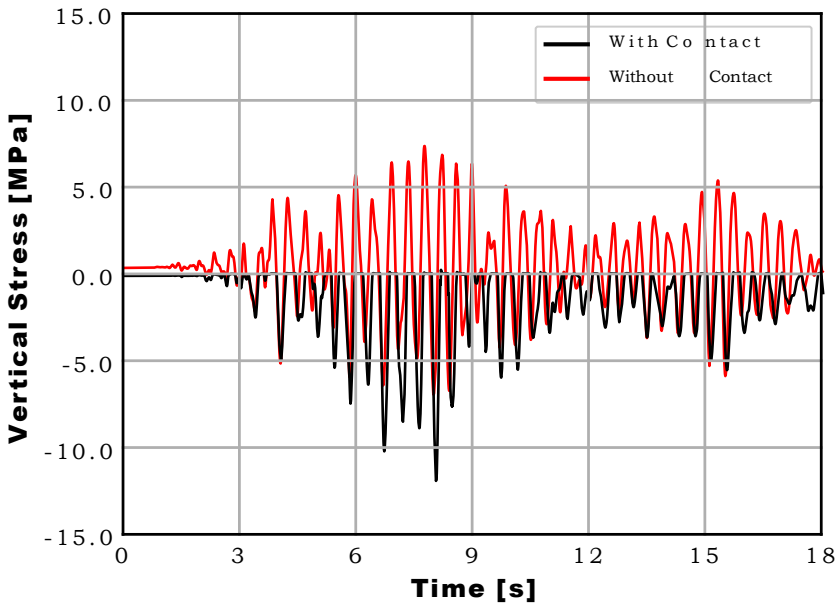


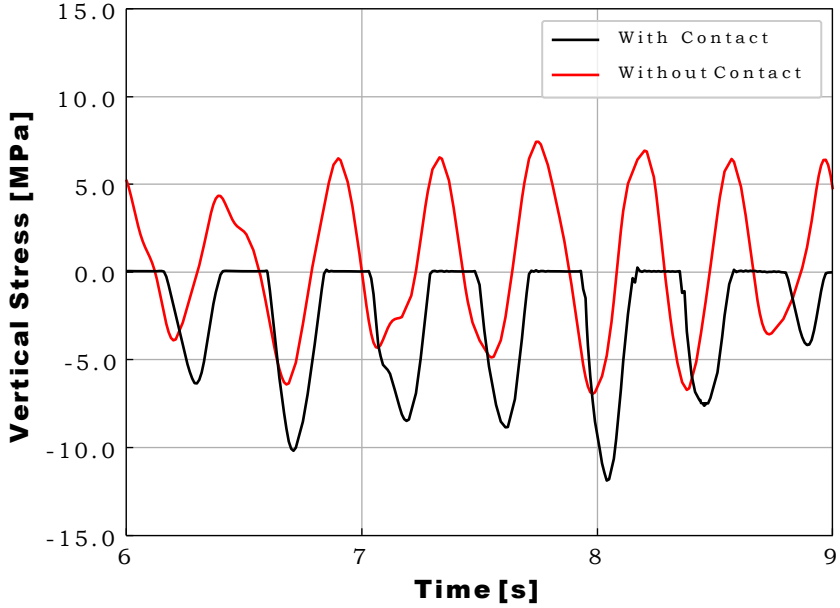
Inelastic vs Elastic, Details $\ddot{u}^{top}_{vertical}$



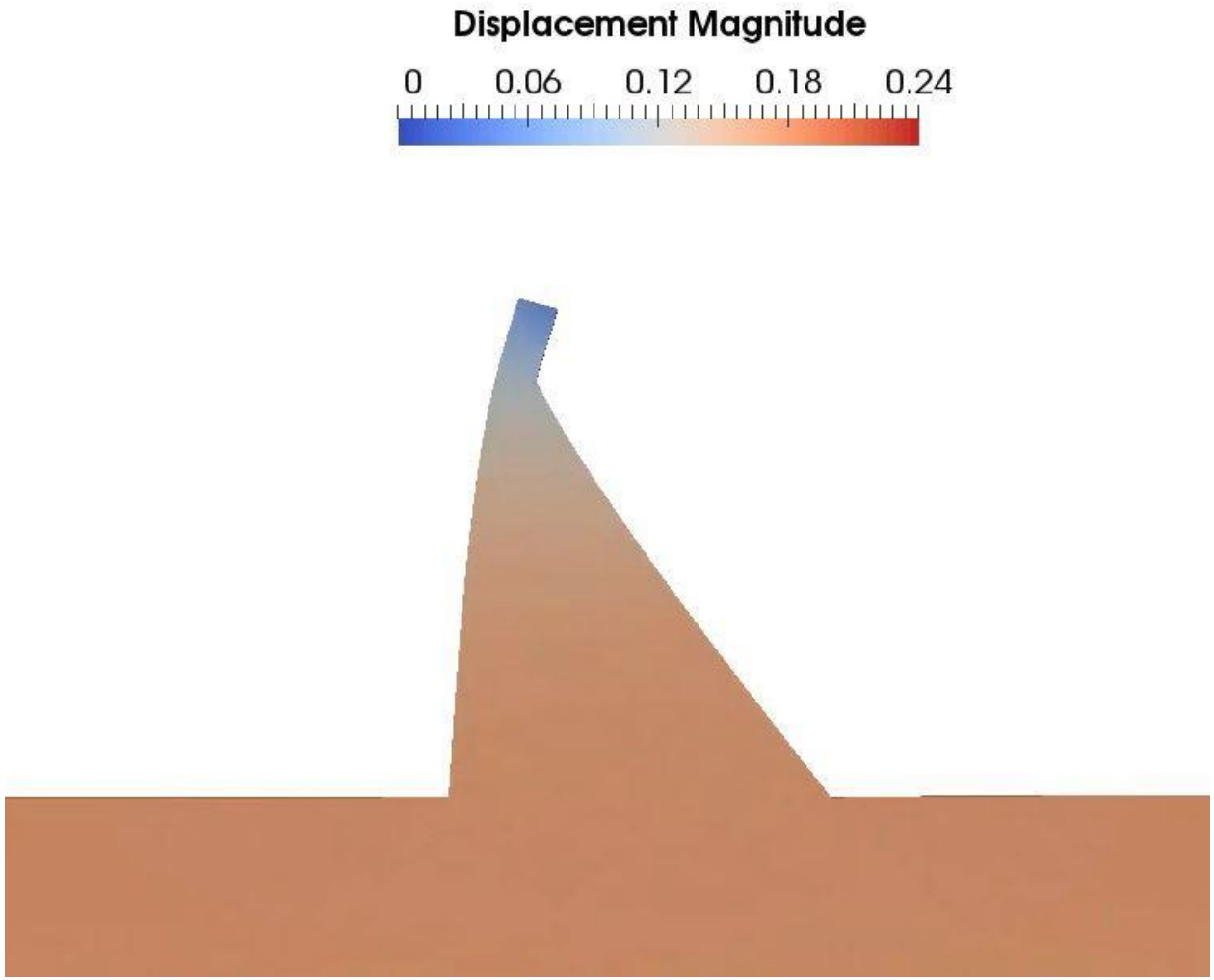


Inelastic vs Elastic, Details σ_v^{heel}



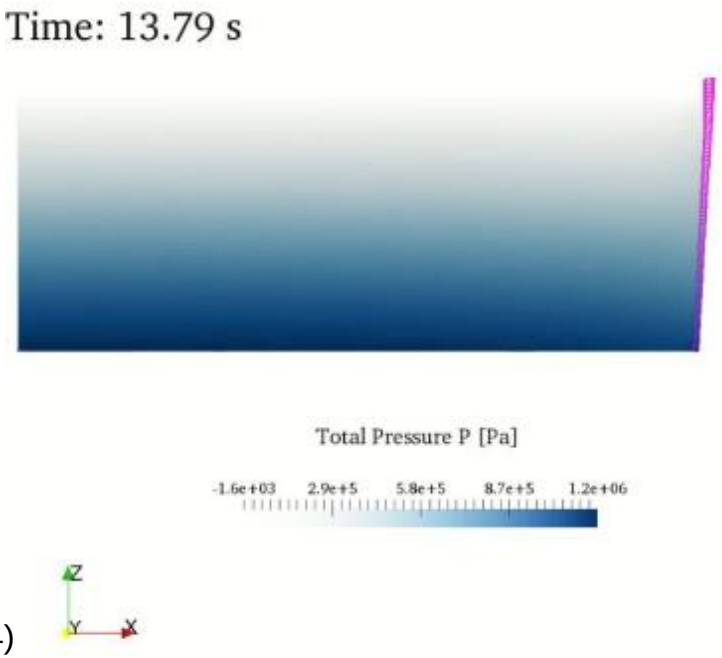


Pine Flat Dam, Dynamic Response with Reservoir

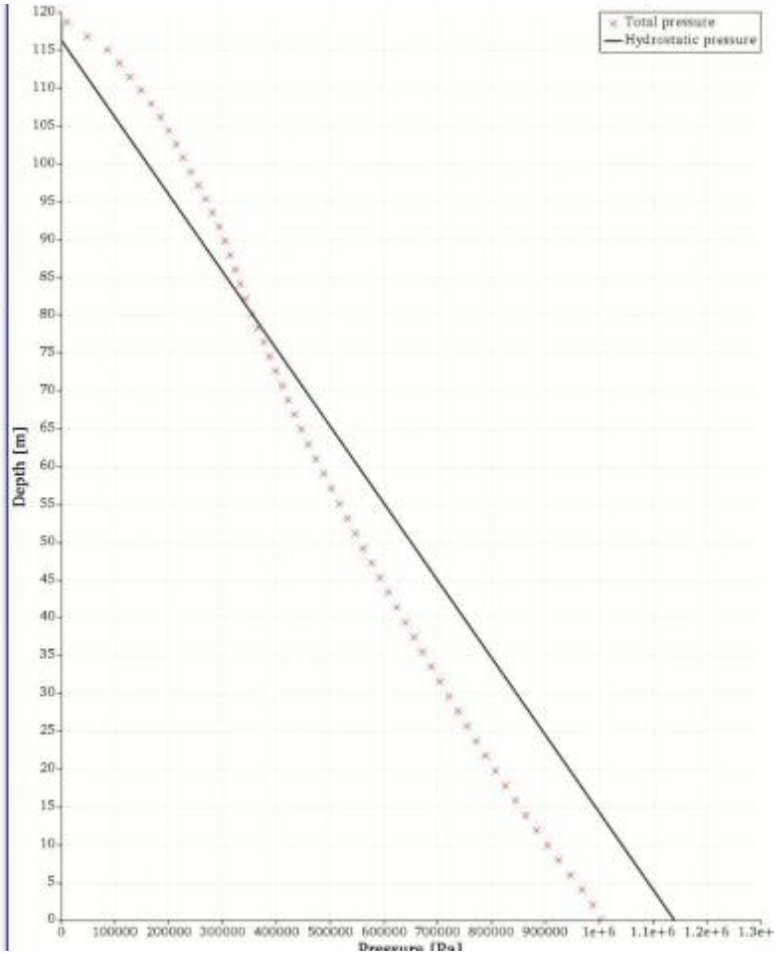


(MP4)

Pine Flat Dam, Hydrodynamic Pressure

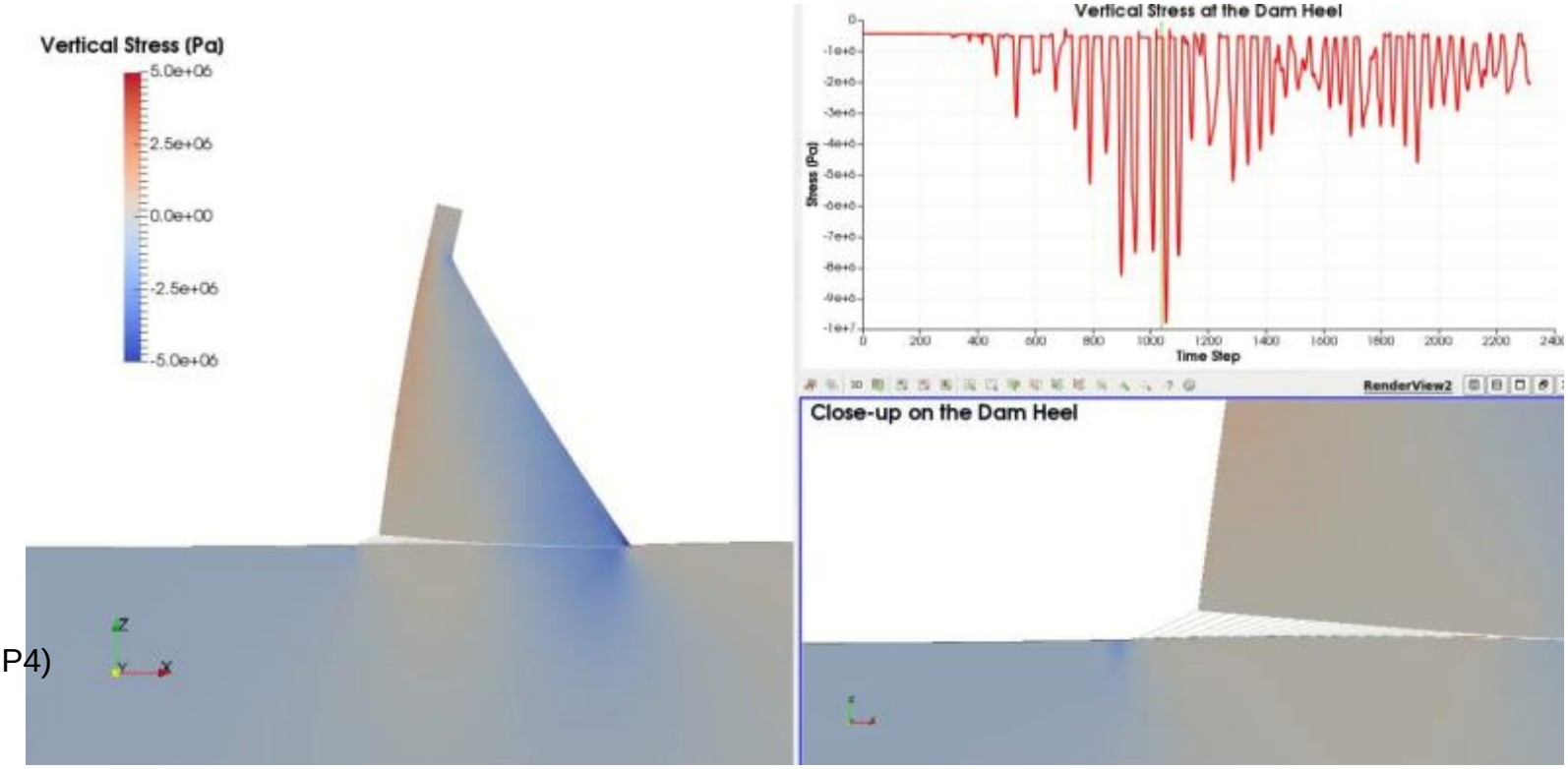


(MP4)

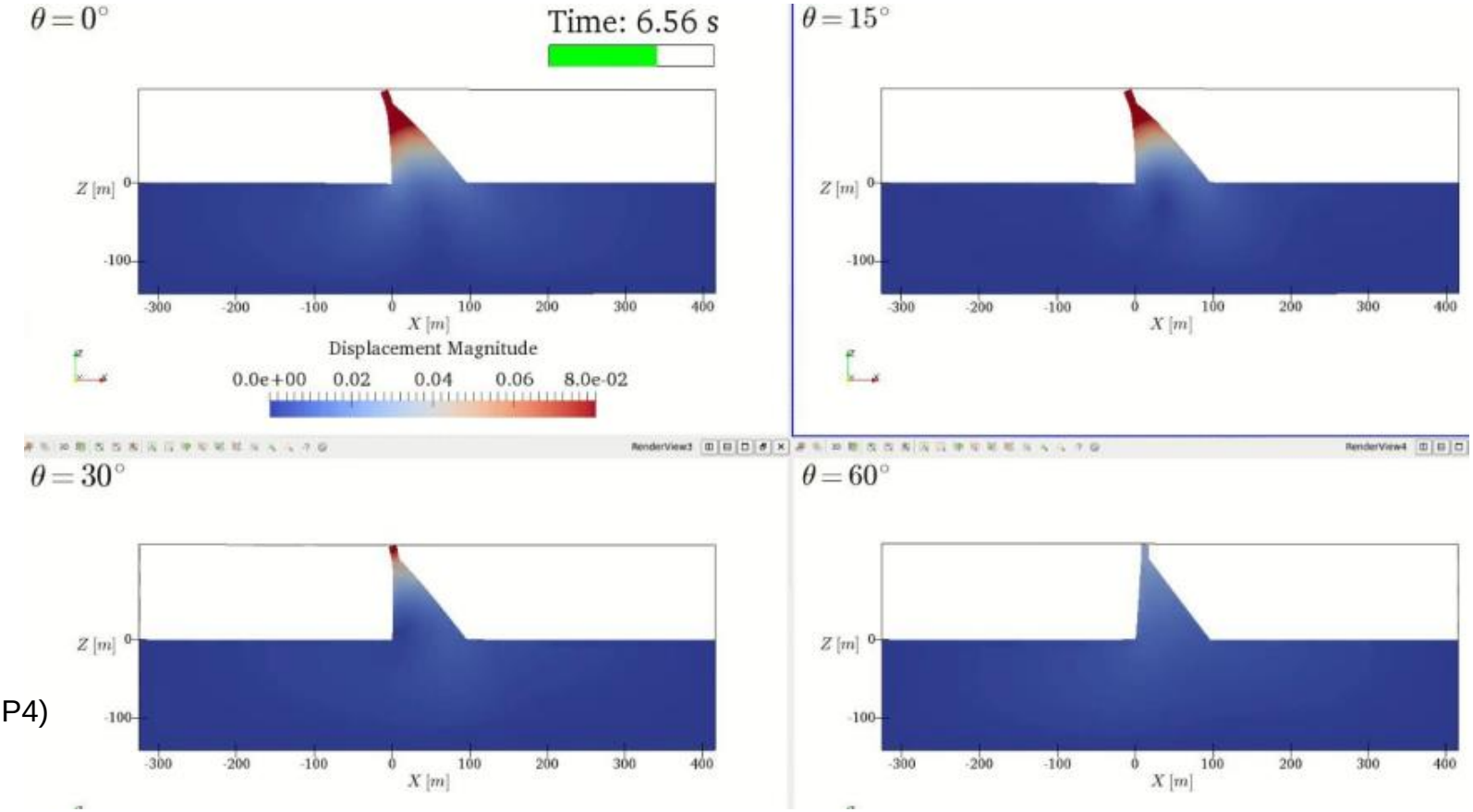


Pine Flat Dam, Inelastic Interface, Hydrostatic

(MP4)



Pine Flat Dam, Dynamic Response, Inclined Plane Waves



(MP4)