# Seismic Soil Structure Interaction for Design and Assessment of Nuclear Installations

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UN-IAEA
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# Outline

# Motivation

- Improve modeling and simulation for Nuclear Installations
- Reduction of modeling, epistemic uncertainty
- Propagation of parametric, aleatory uncertainty
- Goal: Predict and Inform
- Engineers, Owners, Regulators need to know!
- Expert analysis tool: **`http://real-essi.us`**

# Dedication

Robert P. Kennedy, 1939-2018

"Response of a soil structure system is nonlinear, and I would really like to know what that response is!"

Nebojša Orbović, 1962-2021

"As an engineer, I have to know what are response sensitivities to modeling parameters."

# Prediction under Uncertainty

## Modeling, Epistemic Uncertainty

Simplifying modeling assumptions

Low, medium, high sophistication analysis

Confidence in results: model sophistication level

## Parametric, Aleatory Uncertainty,

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

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

Uncertain: loads, $F(t)$

Results are PDFs and CDFs for $\sigma_{ij}$, $\epsilon_{ij}$, $u_i$, $\dot{u}_i$, $\ddot{u}_i$

# Quality Assurance for Modeling and Simulation Verification and Validation, V&V

**V&V** is used to build confidence and credibility in modeling and computational simulations

**V&V** procedures are the primary means of assessing accuracy in modeling and computational simulations

**Verification** provides evidence that the model is solved correctly, mathematics issue

**Validation** provides evidence that the correct model is solved, physics issue

# Hypothesis

Earthquake, Soil and Structure Interaction (ESSI), in time domain, plays a major role in successes and failures

Timing and spatial location of energy dissipation determines location and amount of damage

If timing and spatial location of the energy dissipation can be controlled, directed, we could optimize soil structure system for

+ Safety
+ Economy

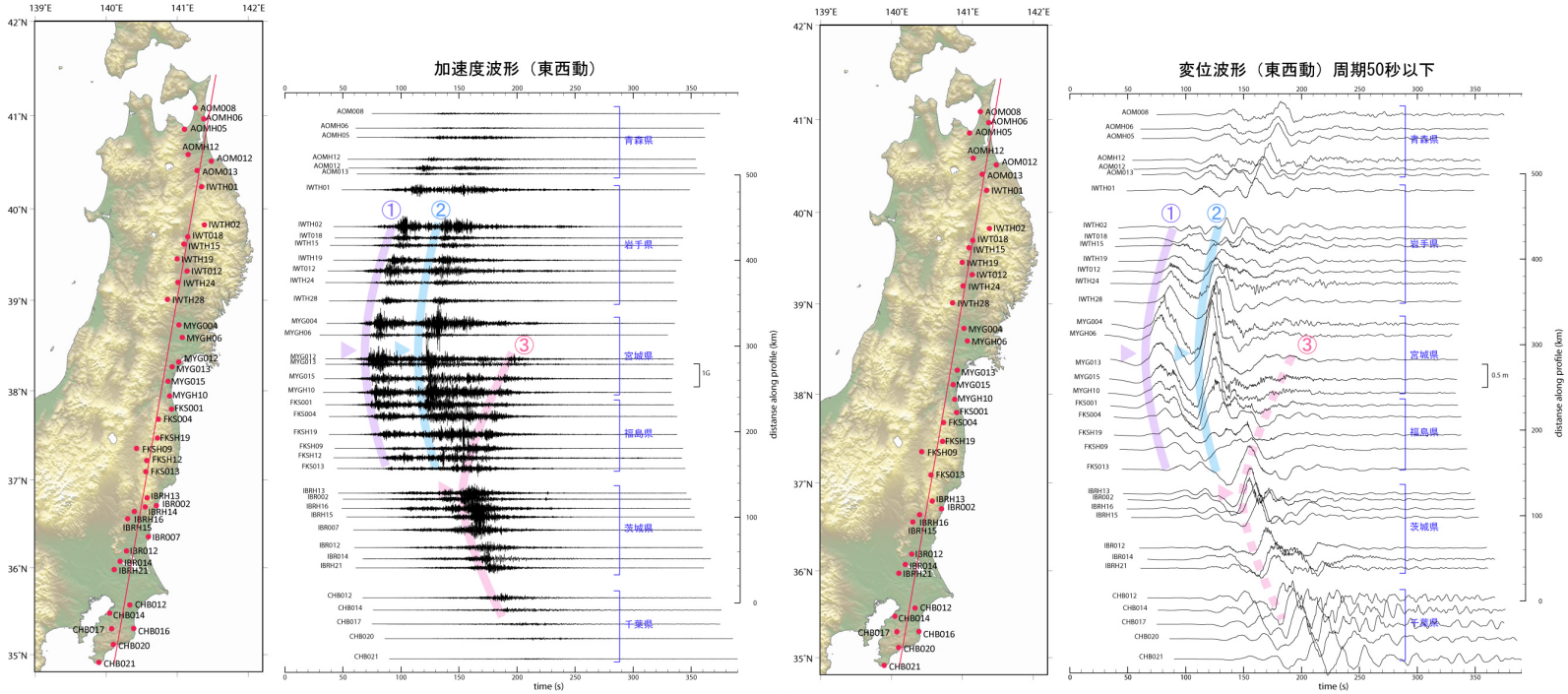
# Seismic Soil Structure Interaction for Design and Assessment of Nuclear Installations

UN-IAEA, EESS, EBP, 2016-2021.
(Pecker, Johnson, Jeremić, Altinyollar, Haddad, Orbović, Fukushima, Coman, Berge-Thierry, Rangelow, Renault, Tyapin, Houston, Ducau, Lee, Caudron, Clement, Potin, ...)

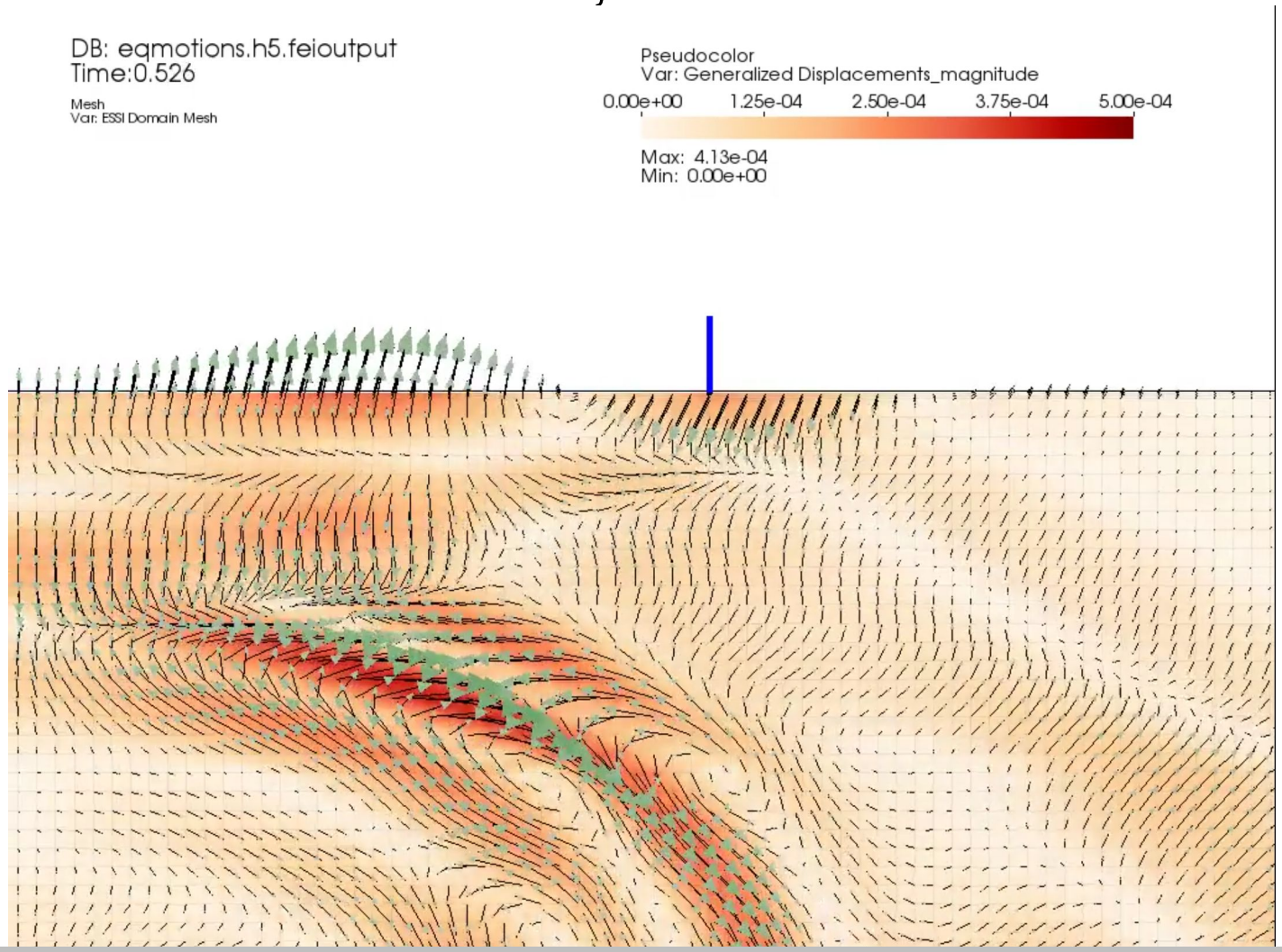
# Outline

# Earthquake Ground Motions

- Body waves: Primary (P) and Secondary (S)
- Surface waves: Rayleigh, Love, Stoneley...

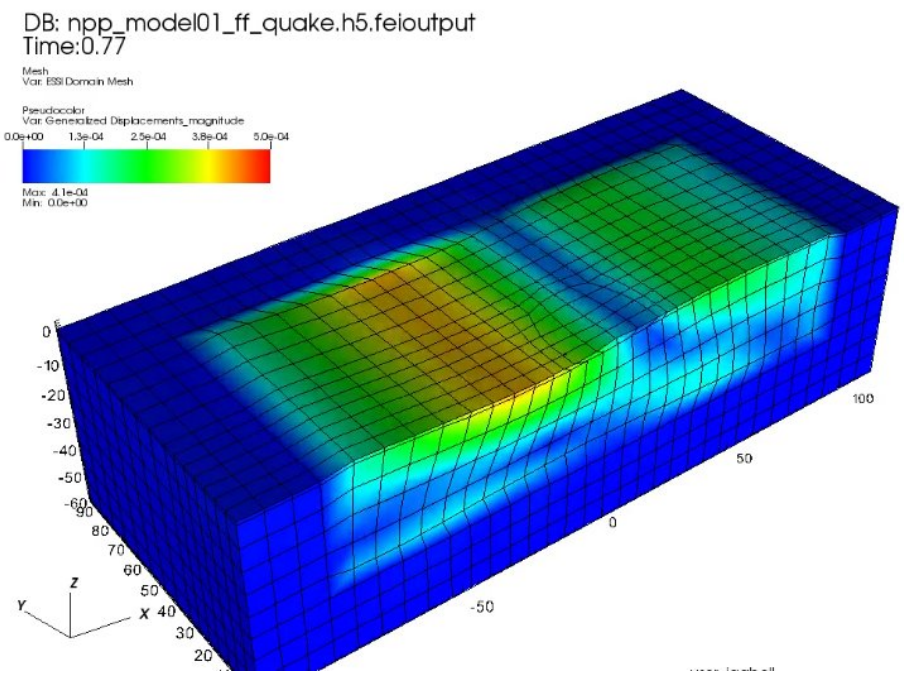


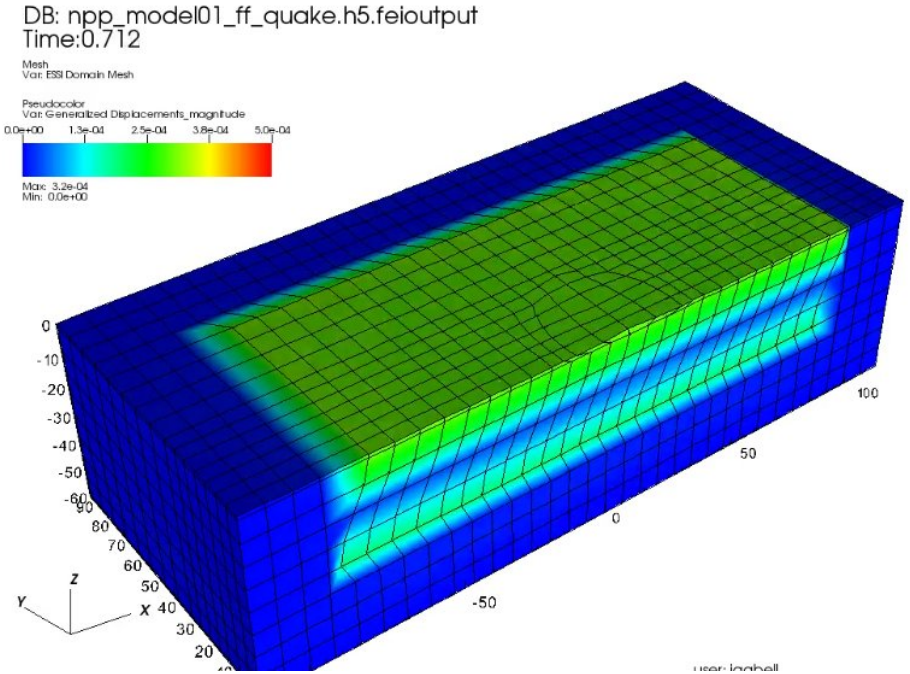
# Realistic Seismic Motions, Inclined P and S Waves



# Free Field Motions, 6C vs 1C

- One component of motions, from 6C to 1C
- 1C, excellent fit, wrong mechanics

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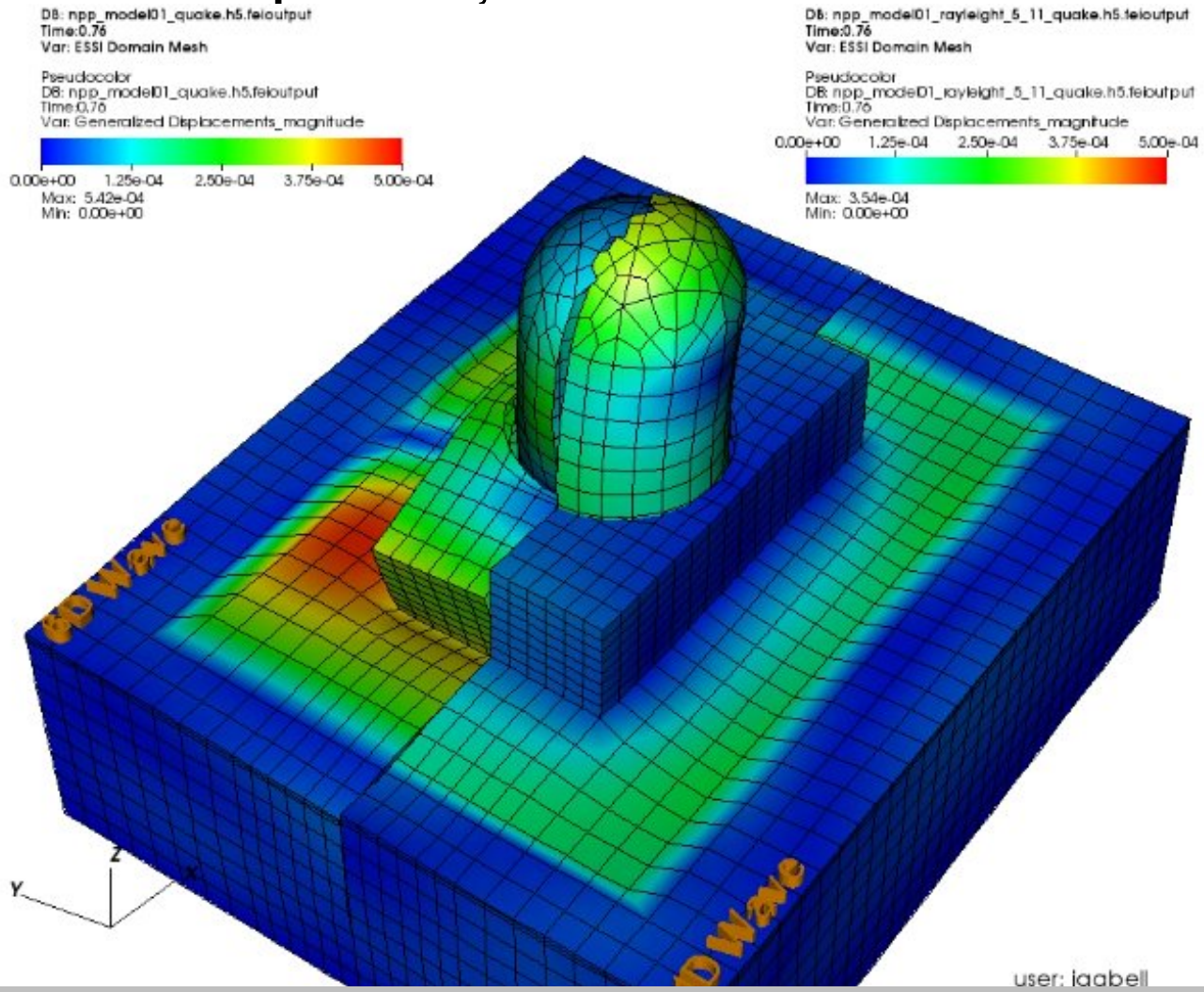
# NPP ESSI Response, 6C vs 1C

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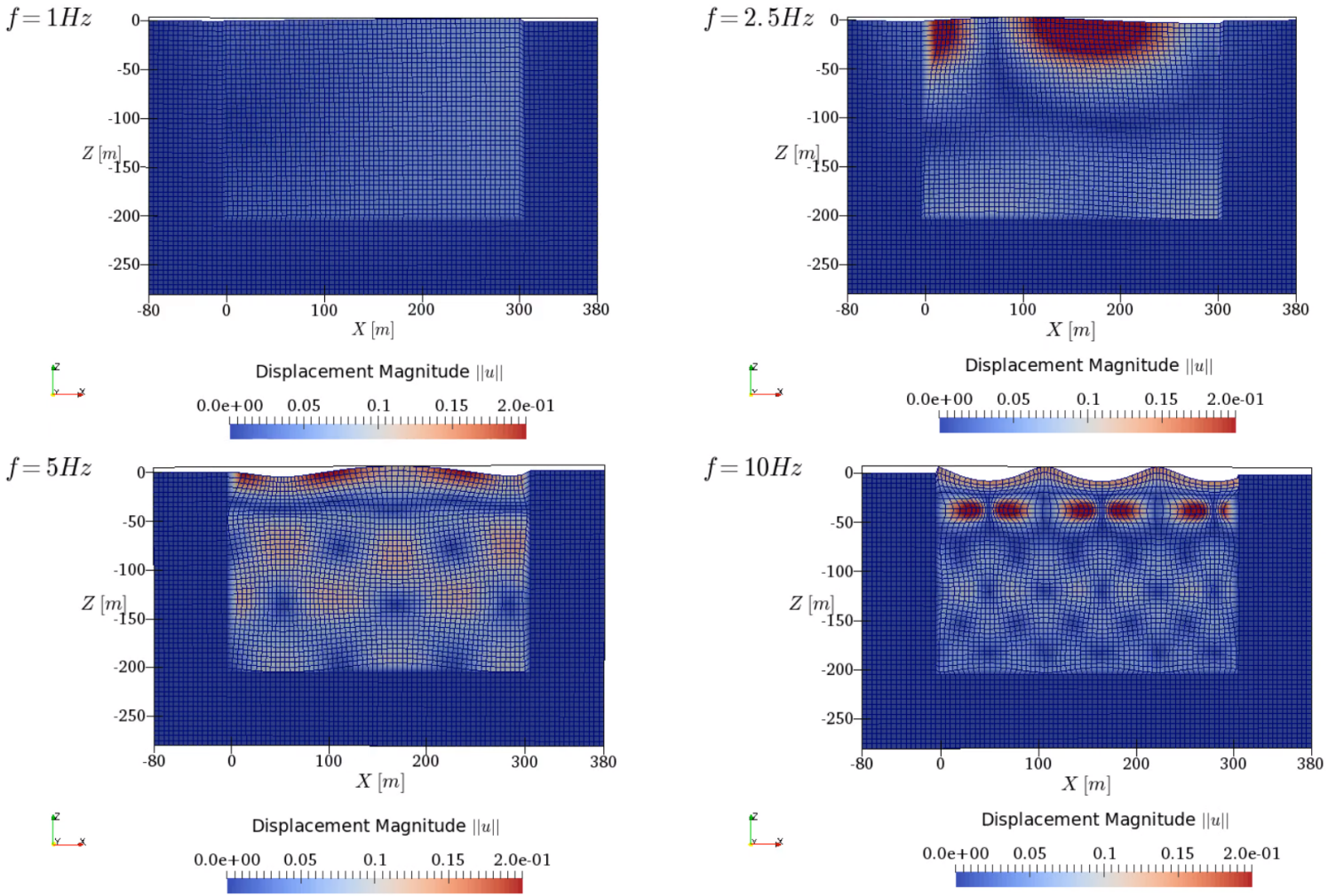
# Free Field, Variation in Input Frequency, $\theta = 60^o$

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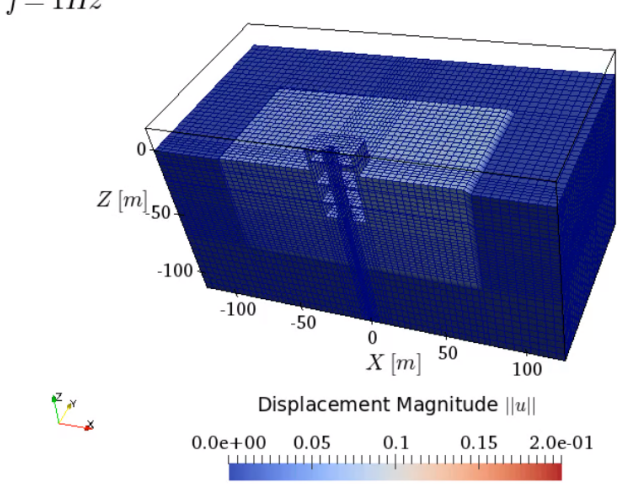
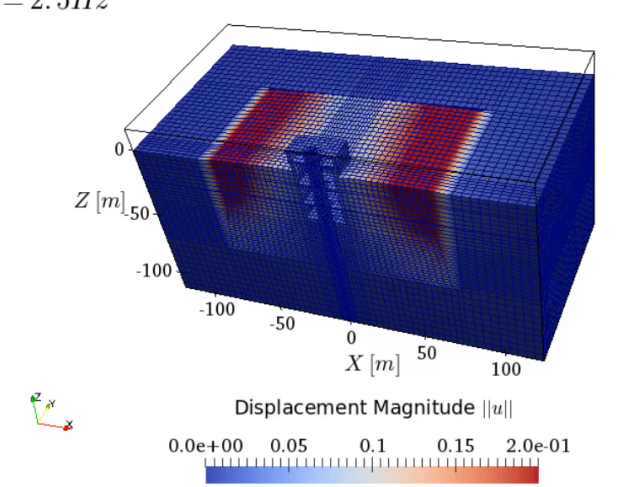
# SMR ESSI, Variation in Input Frequency, $\theta = 60^o$

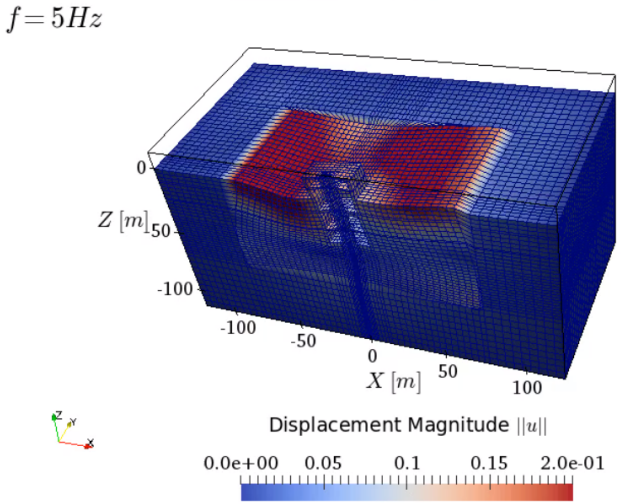
$f = 1Hz$



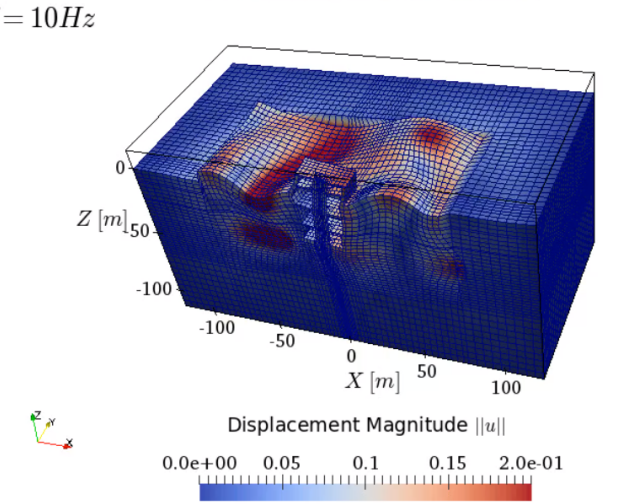

$f = 2.5Hz$




$f = 5Hz$




$f = 10Hz$

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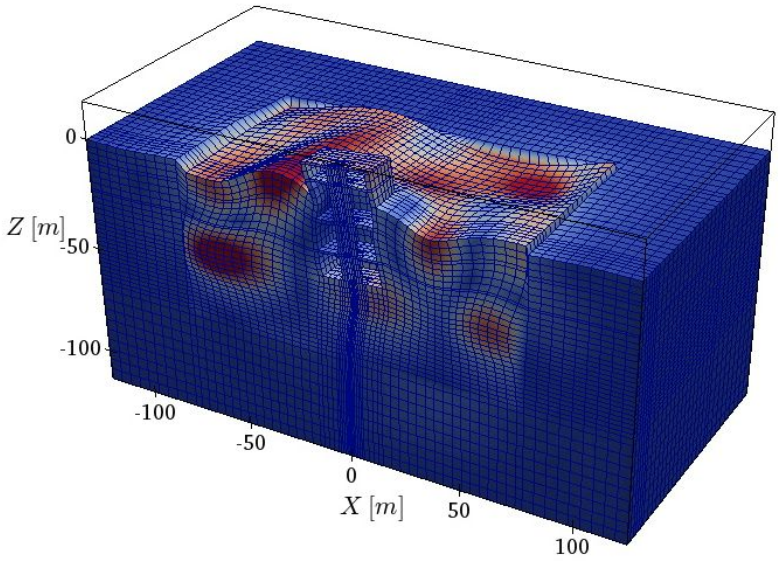
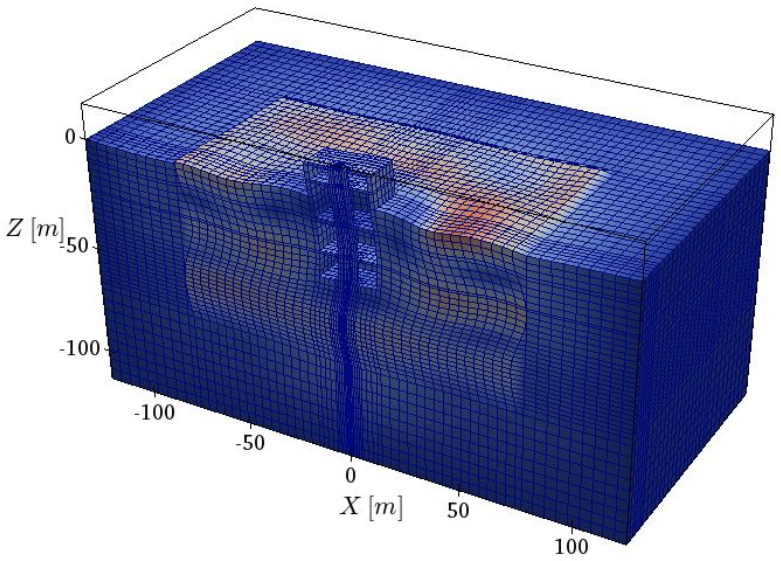
# SMR ESSI Response, 3C vs 3×1C

$3C$




$3 \times 1C$

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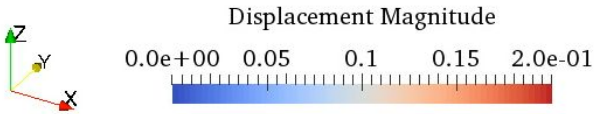
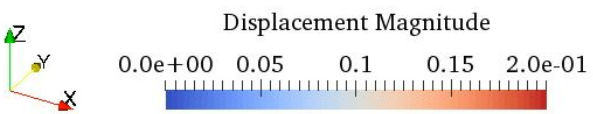


# Outline

# Energy Input and Dissipation

Energy input, dynamic forcing

Energy dissipation outside SSI domain:

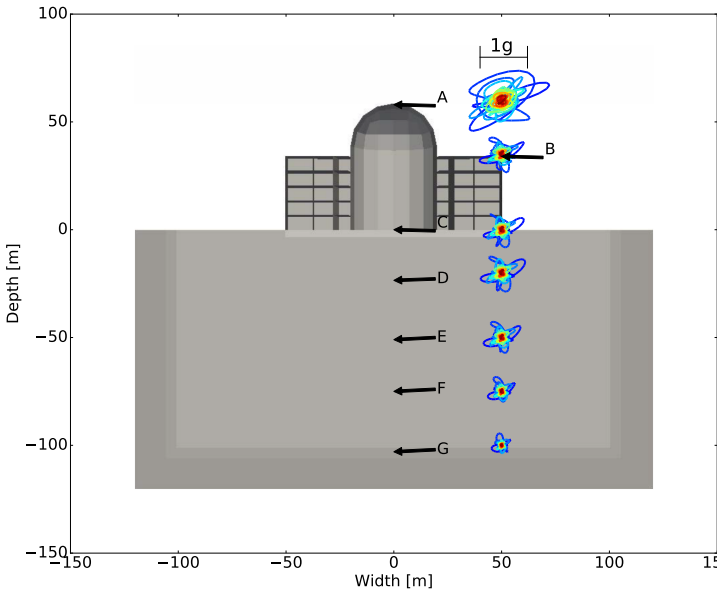
- SSI system oscillation radiation
- Reflected wave radiation

Energy dissipation/conversion inside SSI domain:

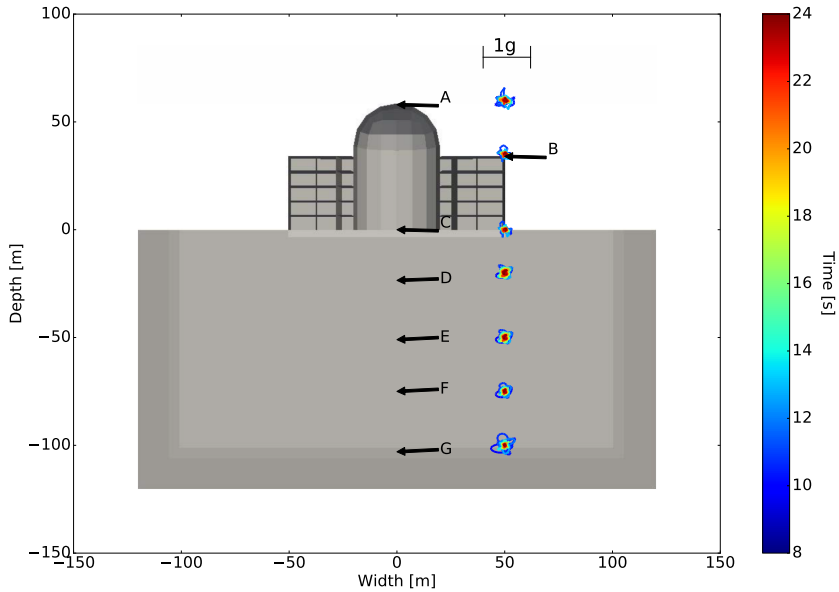
- Inelasticity of soil, interfaces, structure, dissipators
- Viscous coupling with internal/pore and external fluids

Numerical energy dissipation/production

# Accelerations, Elastic vs Inelastic

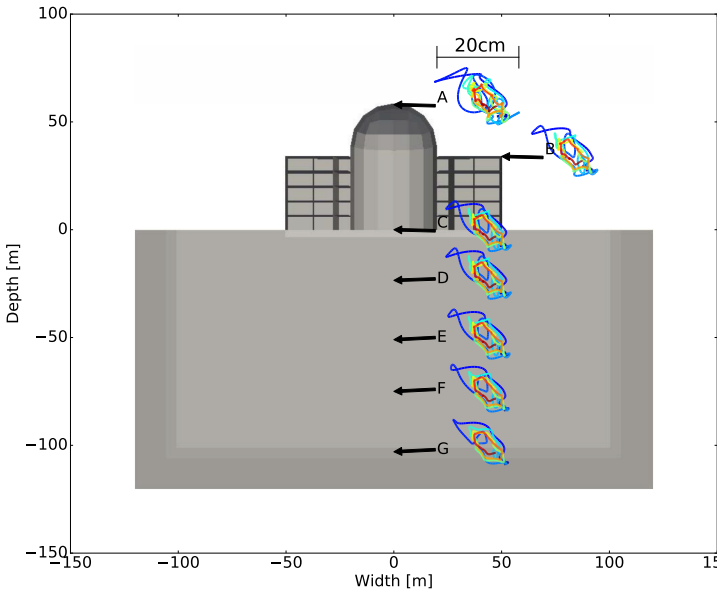



Elastic

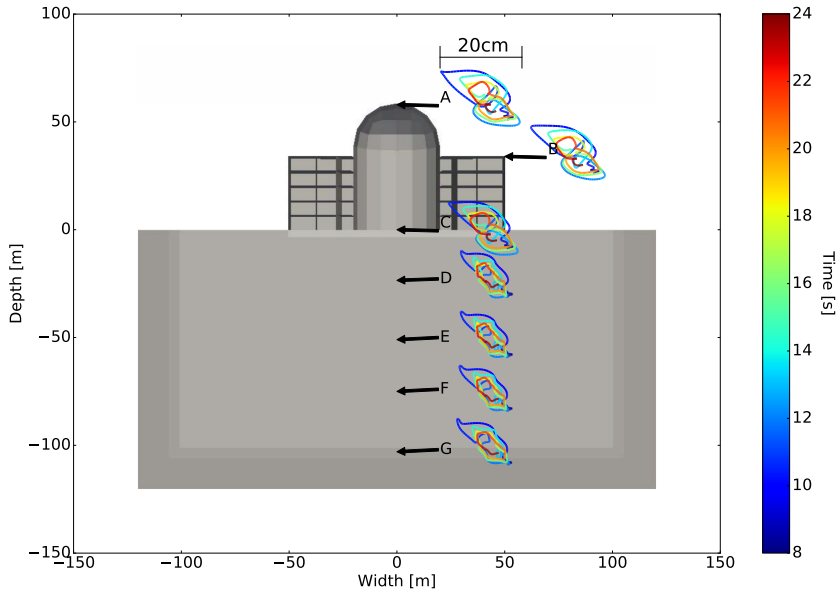



Inelastic

# Displacements, Elastic vs Inelastic

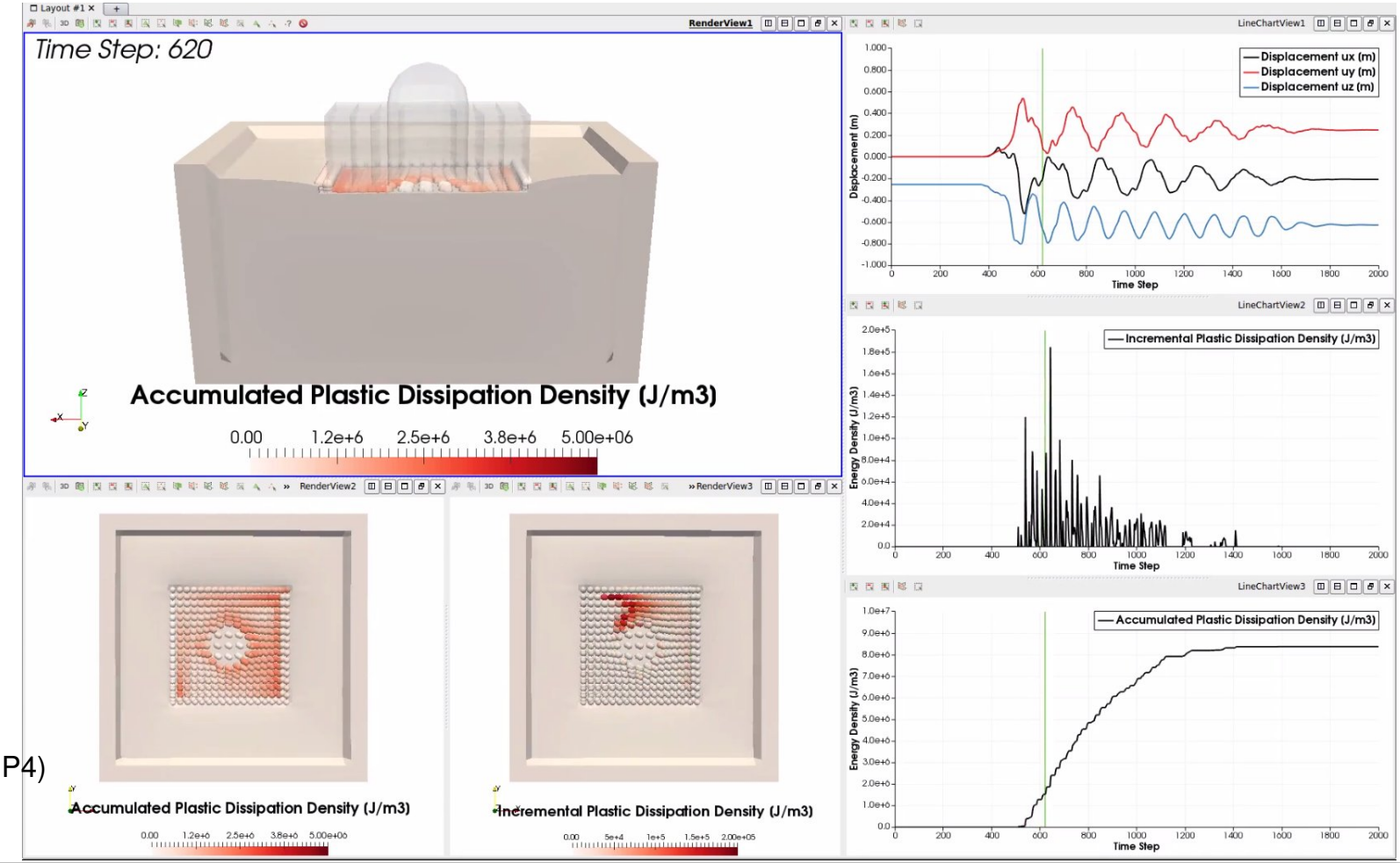



Elastic




Inelastic

# ESSI for an NPP, Plastic Energy Dissipation

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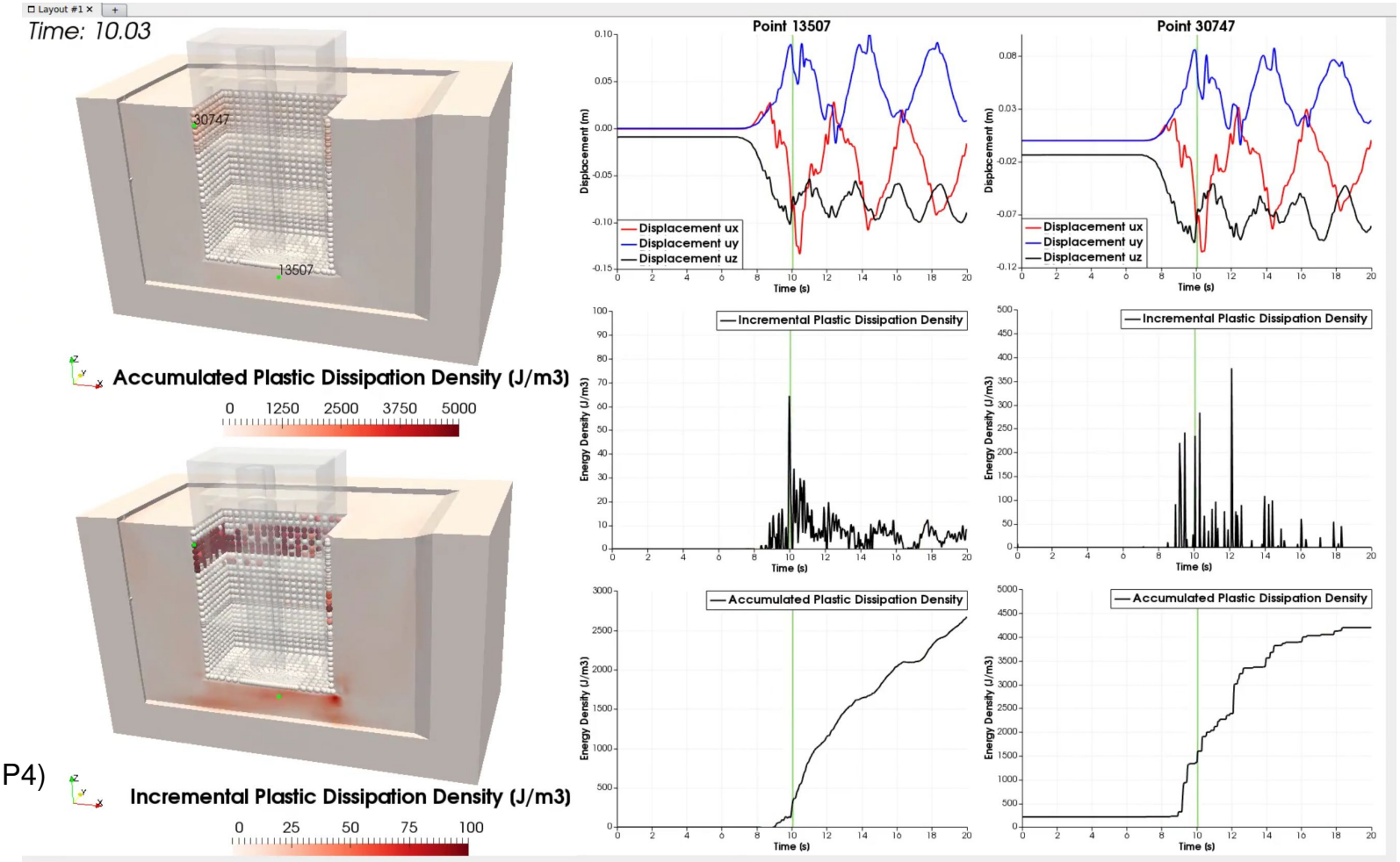
# ESSI for an SMR, Plastic Energy Dissipation

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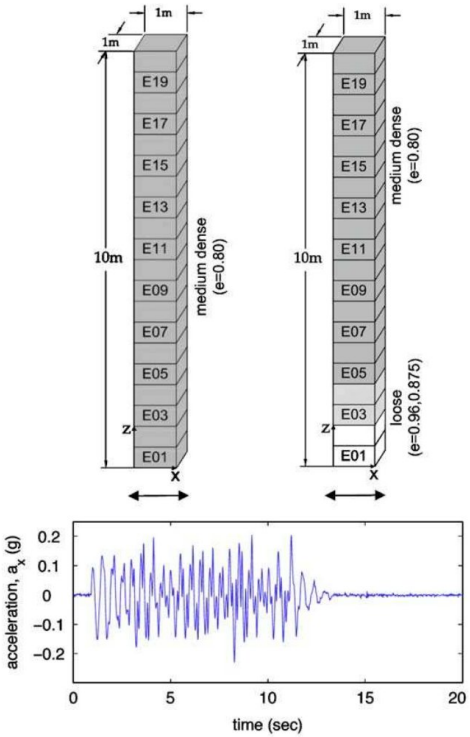
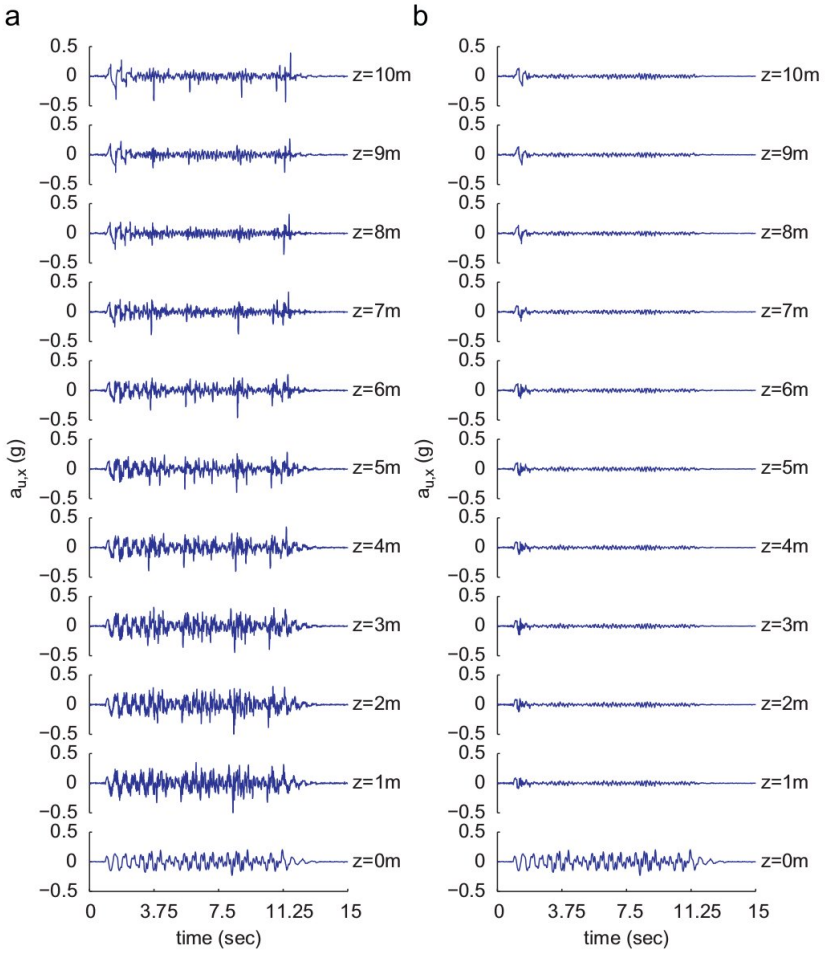
# Liquefaction as Base Isolation

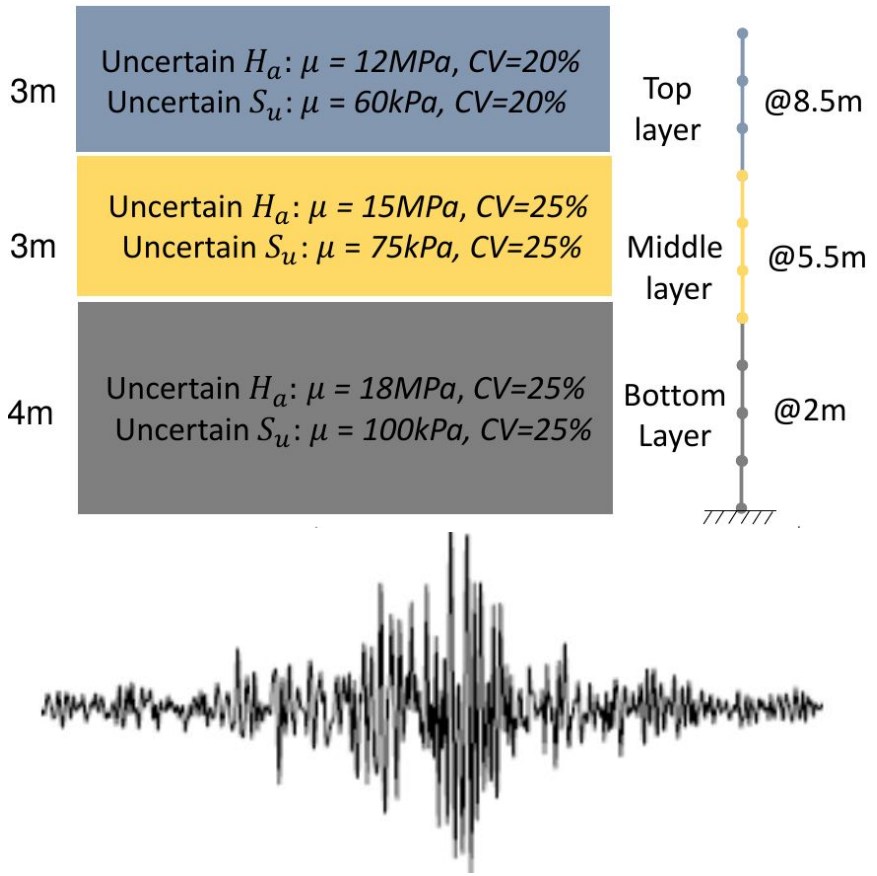


# Outline

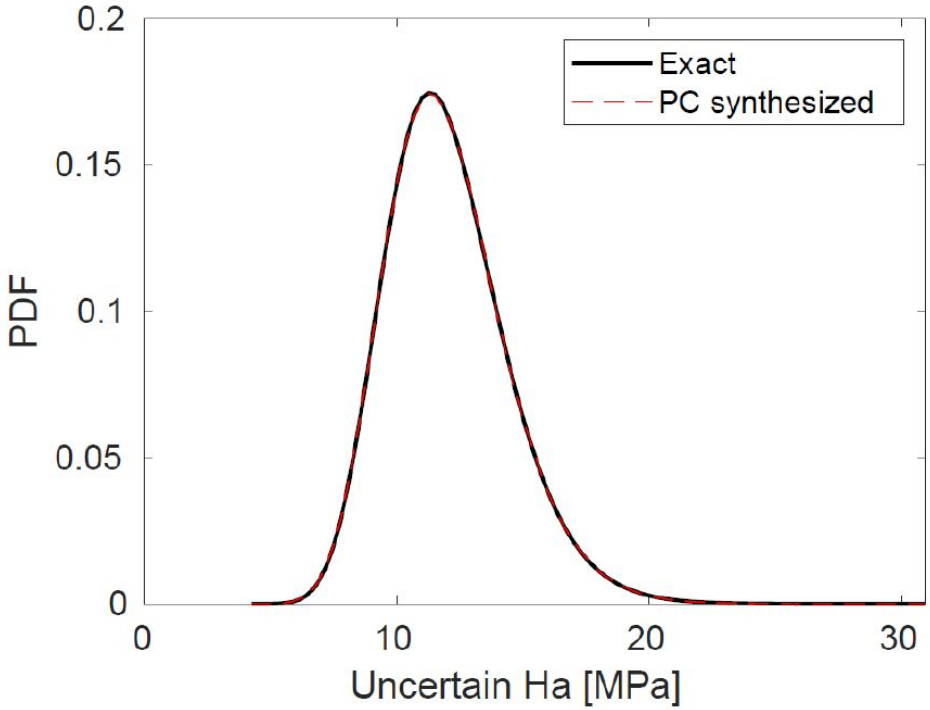
# Probabilistic Site Response

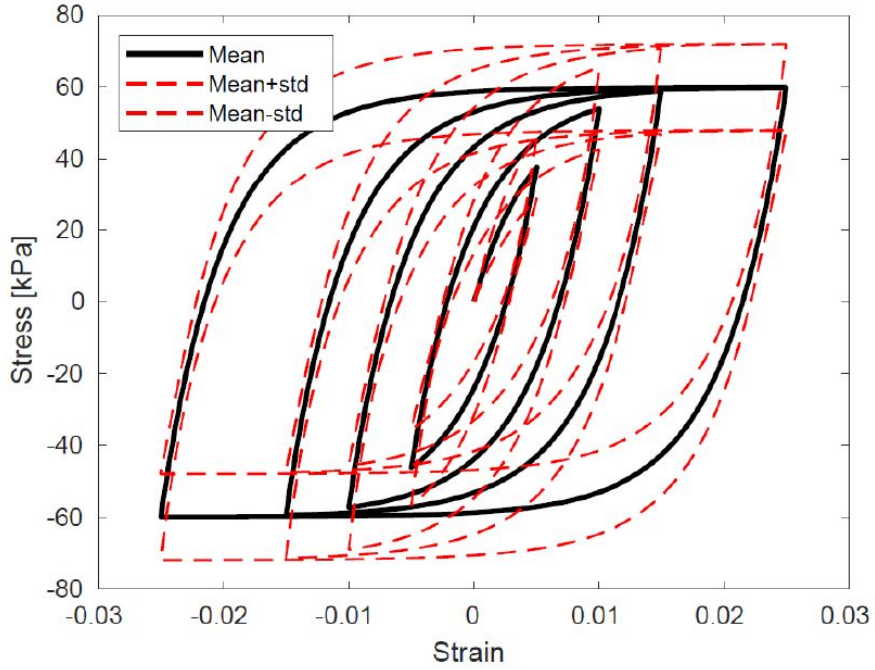
- Uncertain material: uncertain random field, marginally lognormal distribution, exponential correlation length 10m
- Uncertain seismic rock motions: seismic scenario M=7, R=50km



# Uncertain Material Parameters

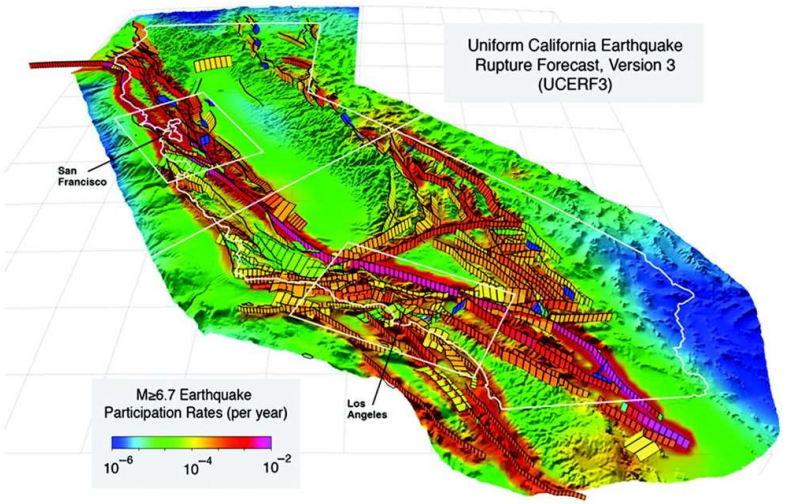
## Lognormal distributed random field with PC Dim. 3 Order 2

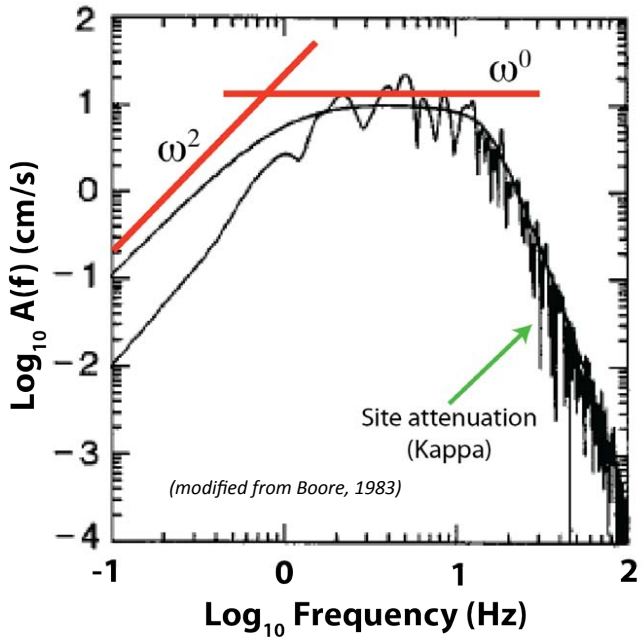


# Uncertain Seismic Motion Development

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



# Sensitivity Analysis

Total variance in PGA, in this case (!), dominated by uncertain ground motions

- 49% variance from uncertain rock motions at depth
- 2% variance from uncertain soil
- 49% variance from interaction of uncertain rock motions and uncertain soil

# Outline

# US-DOE/UCD International Forum on Earthquakes - Soil/Rock - Structure - Interaction Analysis for Nuclear Installations

Conversation, consultation, debate on ESSI analysis

- State of the art
- State of practice
- Current and future needs
- Current and future developments

Online and In-Person

- Invited presentations, recorded, Nov–Dec 2021
- Online discussion, Jan–Jun 2022
- In person symposium, July 2022, at the SMiRT-26 in Berlin,

Organizers will contact many of you

Email me to ensure participation: **Jeremic@ucdavis.edu**

# Conclusion

Numerical analysis to predict and inform

Engineers, Owners, Regulators need to know!

Education and Training is the key!

Funding from and collaboration with agencies and companies: US-DOE, CNSC-CCSN, UN-IAEA, CH-ENSI, US-NSF, US-FEMA, US-NRC, Shimizu, Basler&Hofmann, and KEPCO is greatly appreciated!

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