Uncertainties in Modelling and Simulation of Earthquake Soils Structures Interaction

Boris Jeremić

University of California, Davis
Lawrence Berkeley National Laboratory, Berkeley

Earthquake Research Institute
University of Tokyo
Tokyo, Japan, January 2016

Outline

Outline

Motivation

- Improve seismic design of soil structure systems
- Earthquake Soil Structure Interaction (ESSI) in time and space, plays a major role in successes and failures
- Accurate following and directing (!) the flow of seismic energy in ESSI system to optimize for
  - Safety and
  - Economy
- Development of high fidelity numerical modeling and simulation tools to analyze realistic ESSI behavior: Real ESSI simulator

Predictive Capabilities

- Verification provides evidence that the model is solved correctly. Mathematics issue.
- Validation provides evidence that the correct model is solved. Physics issue.
- 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.
- Modeling and Parametric Uncertainties
- Predictive capabilities with low Kolmogorov Complexity
- Modeling and simulation goal:
  predict and inform, rather than (force) fit

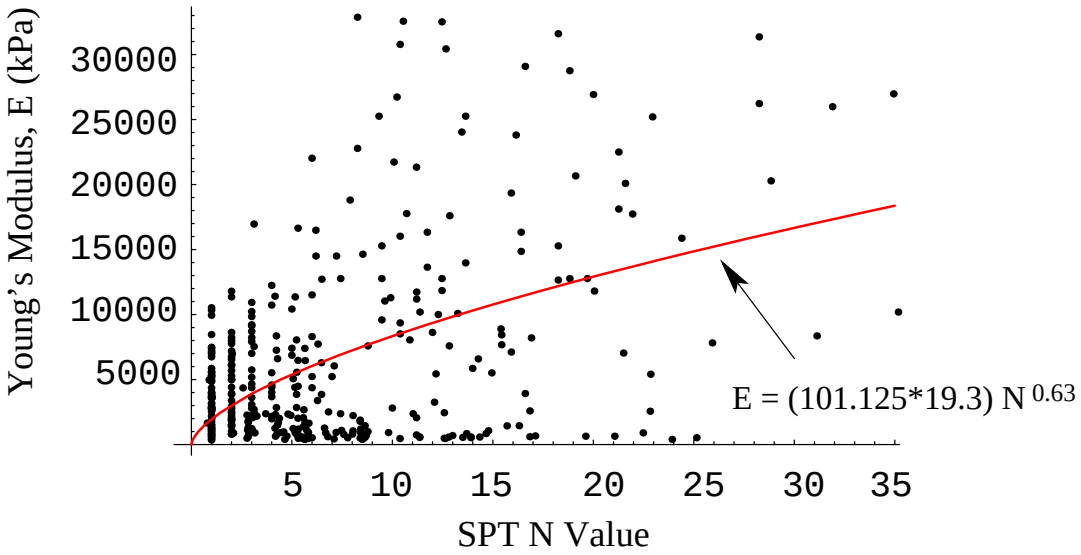
Outline

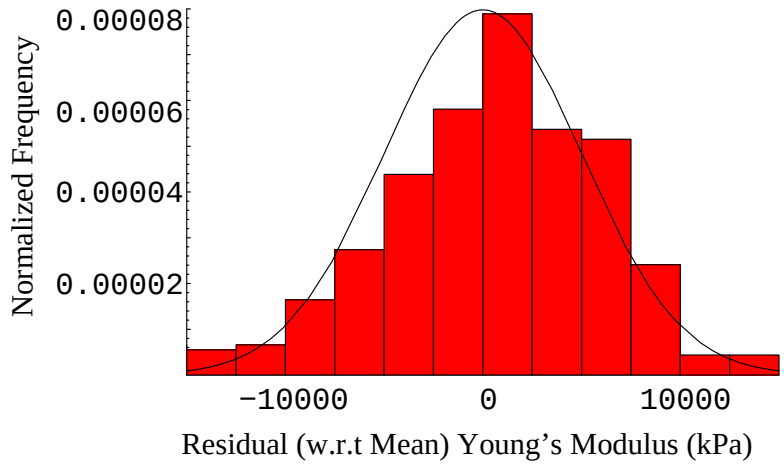
Modeling Uncertainty: Simplified Models

- Simplified modeling: Features (important ?) are neglected (6D 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: Material and Loads

Example: Elastic Stiffness





Transformation of SPT *N*-value: 1-D Young's modulus, *E* (cf. Phoon and Kulhawy (1999B))

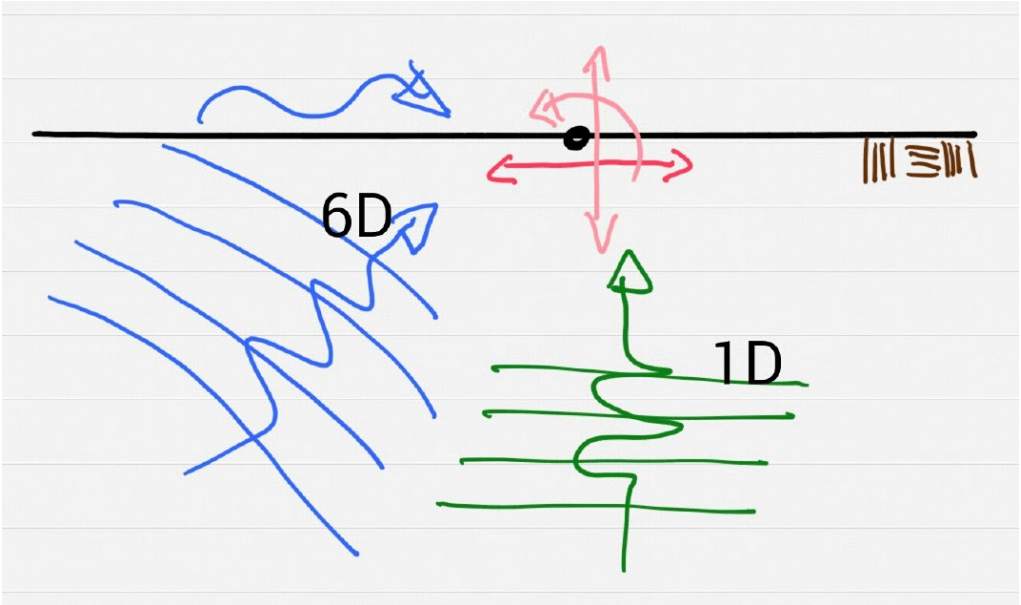
Outline

Modeling and Simulation of Nuclear Power Plants

- Nuclear Power Plants (NPPs) design based on a number of simplified assumptions!
- Linear elastic material behavior
- Seismic Motions: 1D or 3 $\times$ 1D, or real 3D (6D)
- Savings in construction cost possible with more accurate modeling of NPPs
- Improvements in safety of NPPs also possible, even with higher seismic motions, as inelastic effects "eat up" (dissipate) seismic energy

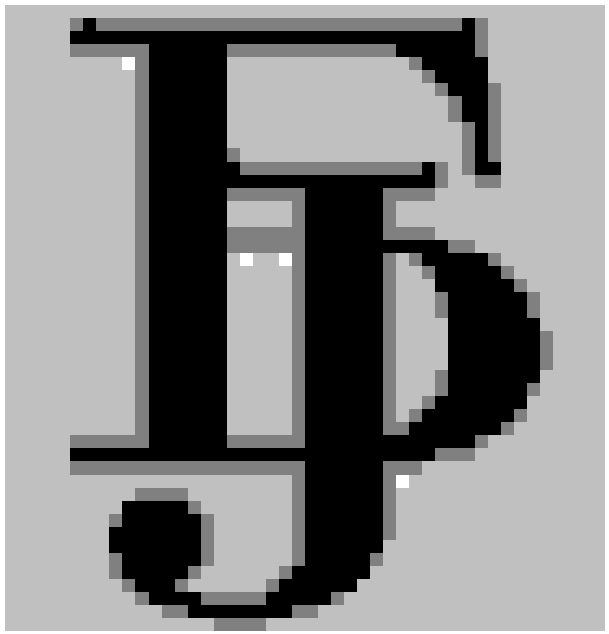
Nuclear Power Plants: 6D or 1D Seismic Motions

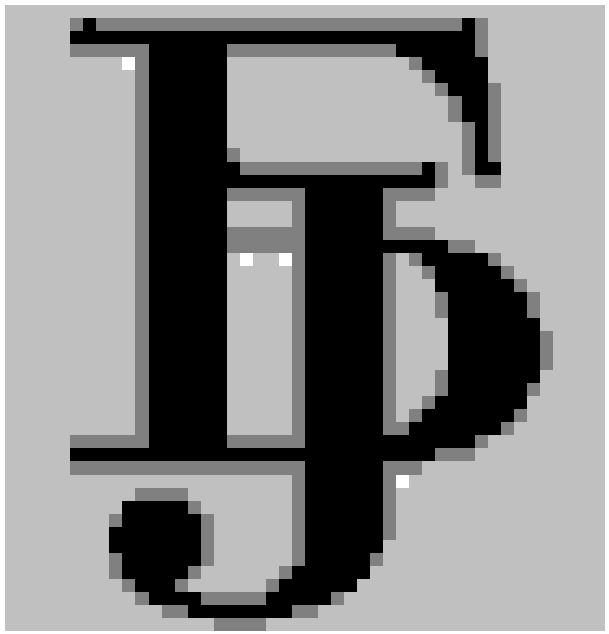
- Assume that a full 6D (3D) motions at the surface are only recorded in one horizontal direction
- From such recorded motions one can develop a vertically propagating shear wave in 1D
- Apply such vertically propagating shear wave to the same soil-structure system



Synthetic Test Motions

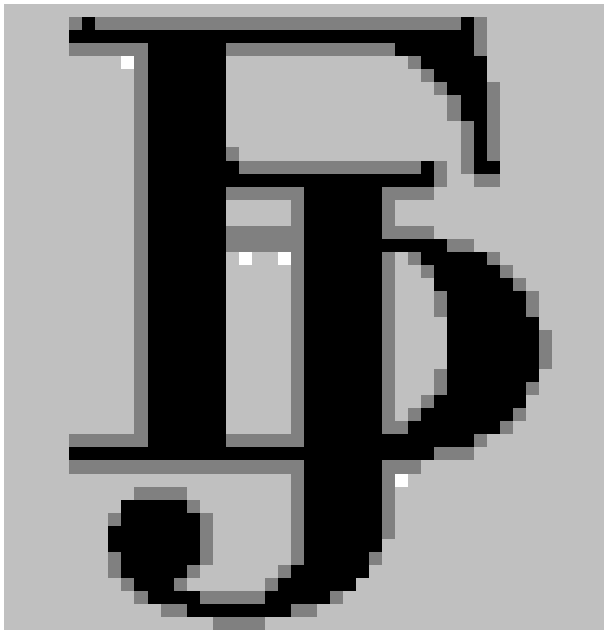
- Develop free field models with sources within
- Sources are simple, point (mostly), line and surface
- Sources will send both P and S waves
- Variation in strike and dip
- Simulation programs, Real ESSI Simulator and SW4

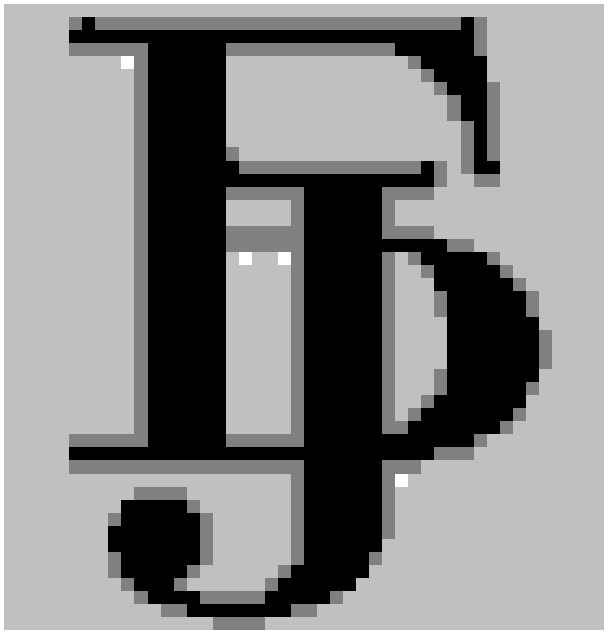




Synthetic Test Motions, 6D vs 1D

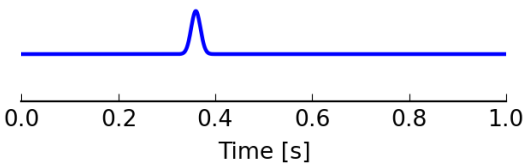
- Danger of picking one component of motions for 1D or 3×1D (it is done all the time!)
- Excellent (forced) fit, but not a prediction and information is lost (goal is to predict and inform and not (force) fit)

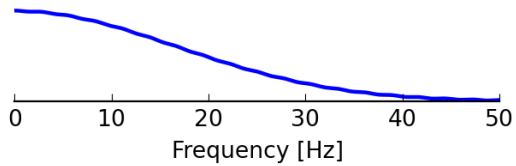




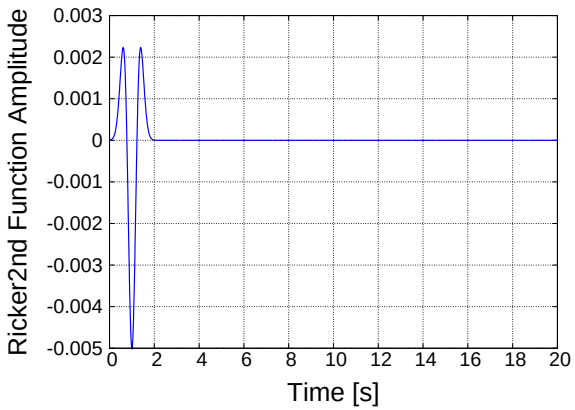
Stress Test Source Signals

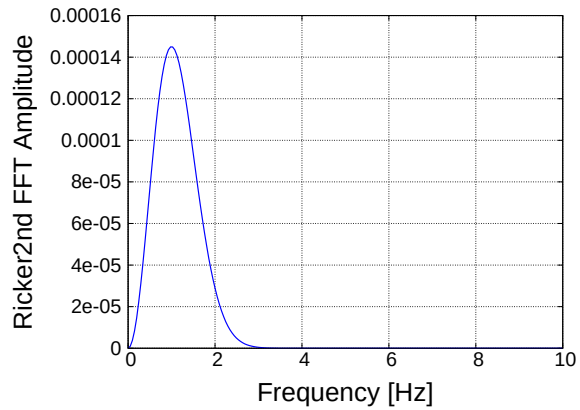
- Gauss



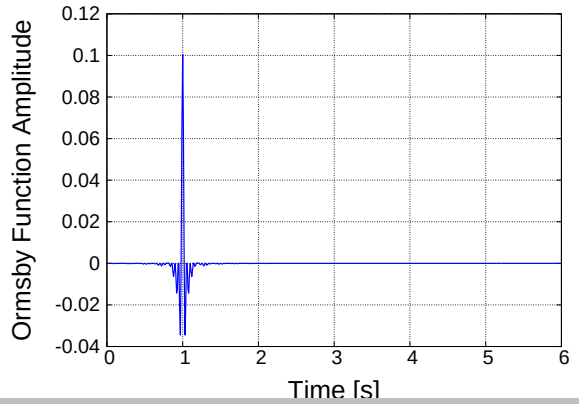


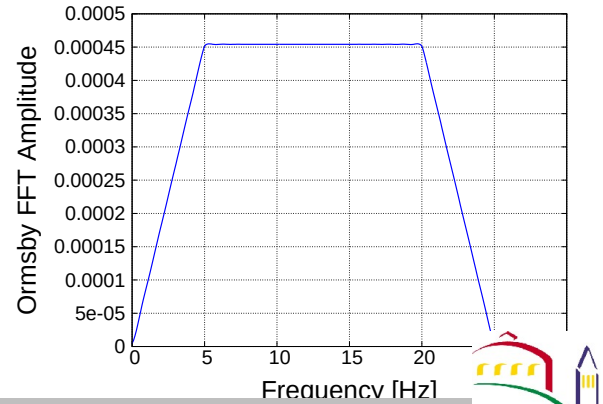
- Ricker (1st, 2nd)





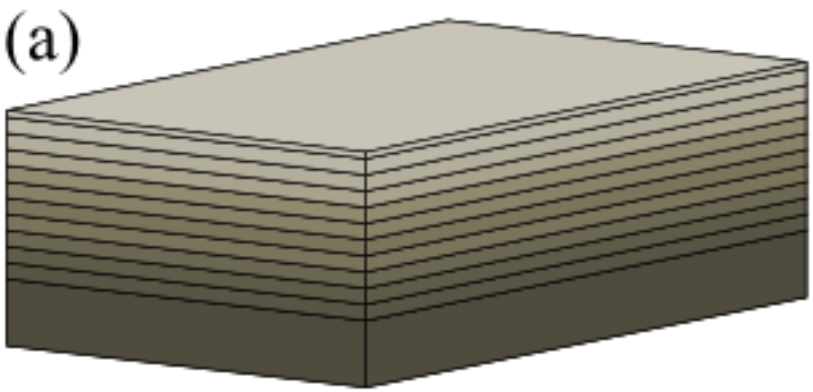
- Ormsby

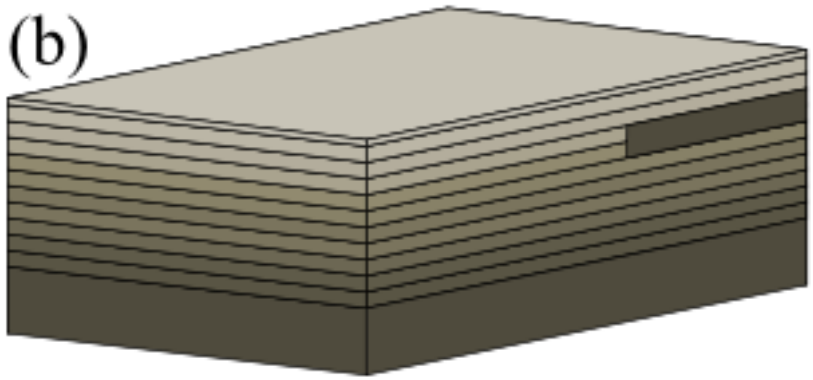




Layered and Dyke/Sill Models

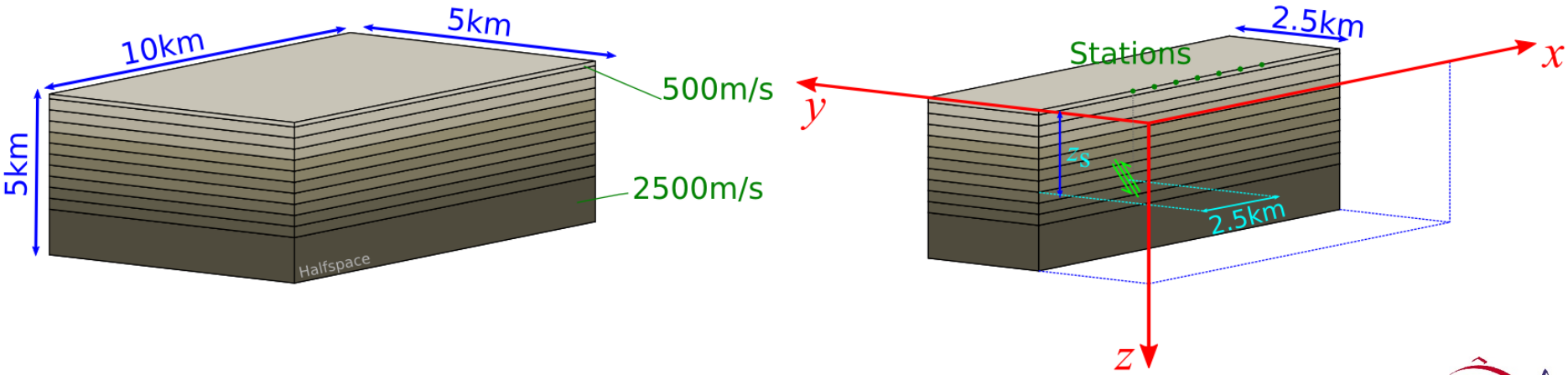
- Uniform soil/rock, to show surface waves
- Horizontally layered geology (a), to show bending/refraction and more surface waves
- Dyke/Sill intrusion within layered geology (b), to show effects of local geology on free field motions





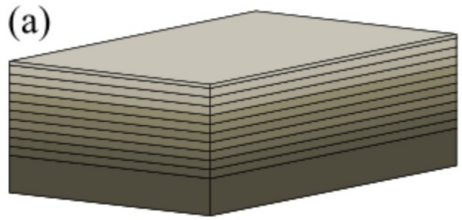
Variable Sources

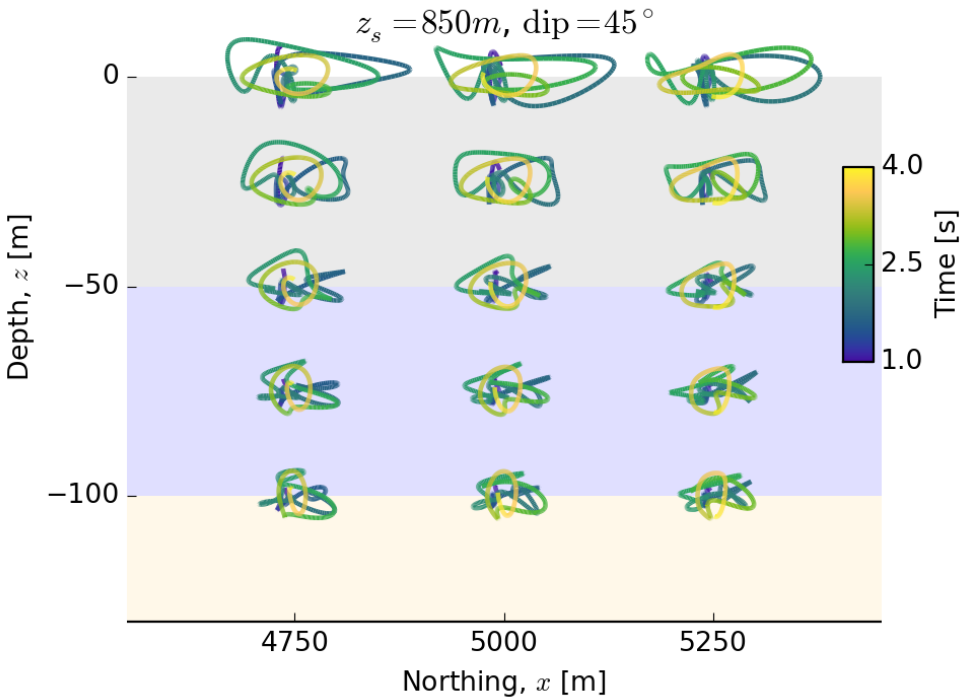
- Epicenter is 2500m away from the location of interest
- Source depth 850m (softer layers) and 2500m (hard rock)
- Variation: source locations, strike and dip, magnitude, frequencies
- Different wave propagation path to the object location

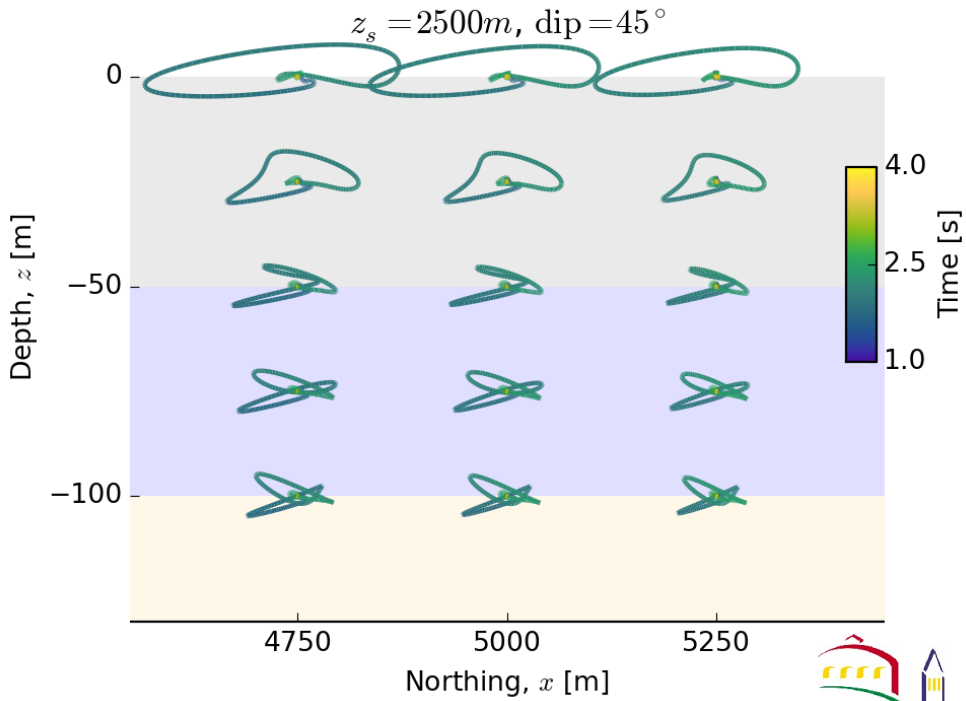


Layered System , Displacement Traces

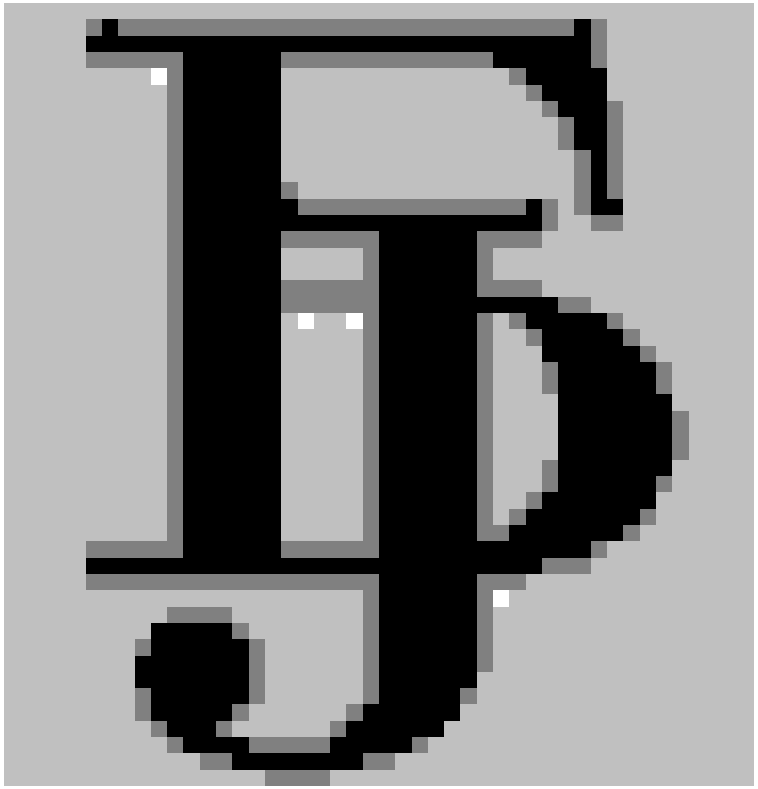
- Surface waves
- Surface waves not filtered out
- Incoherent motions

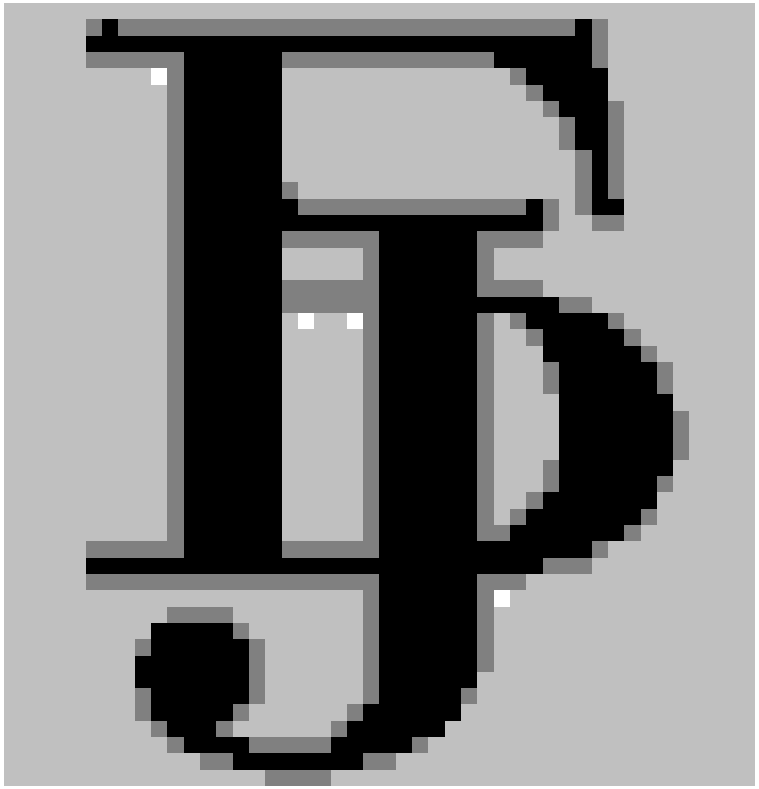






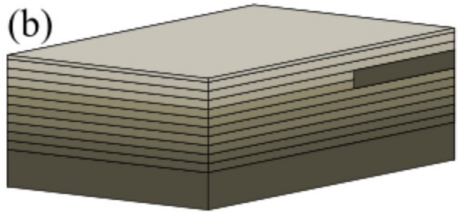
Layered System, Variable Source Depth

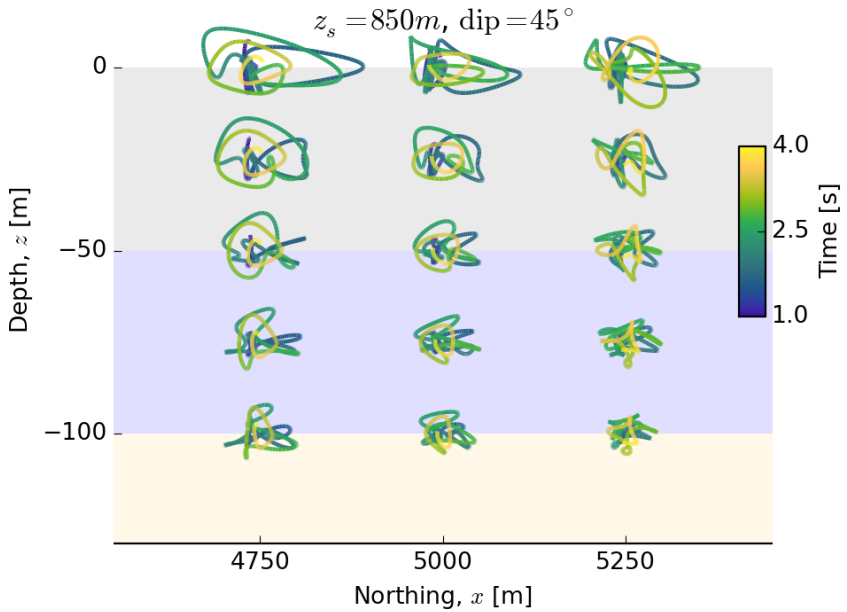


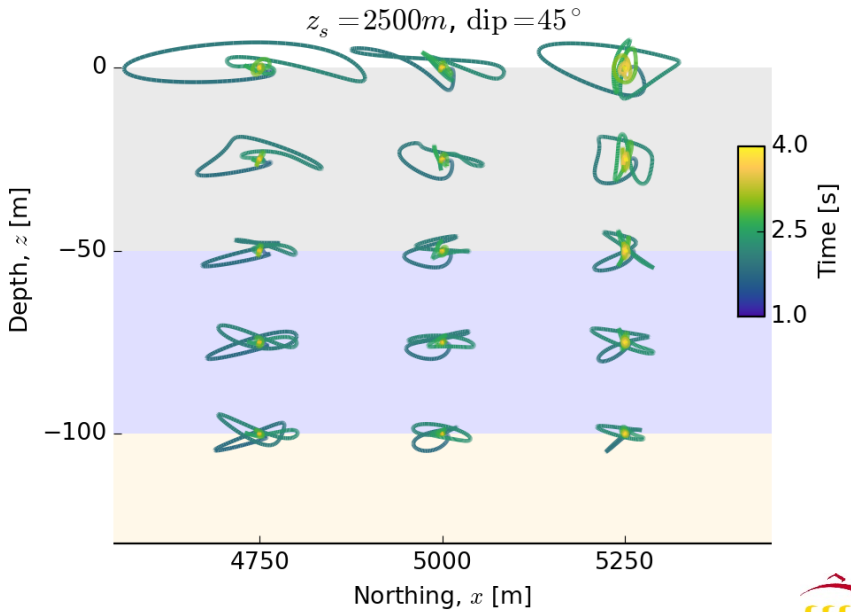


Dyke/Sill Intrusion, Variable Source Depth

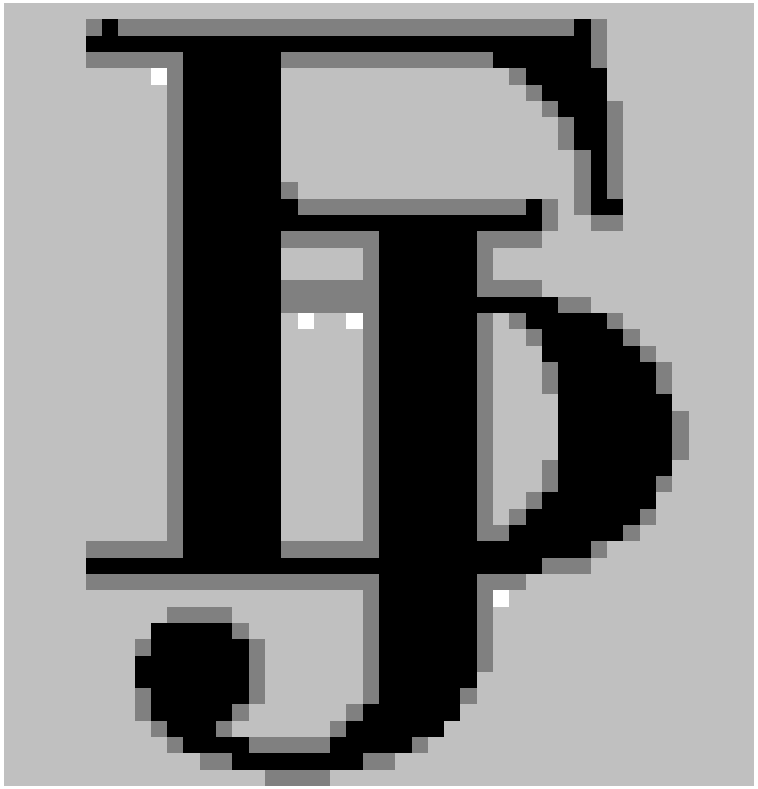
- Incoherent motions
- Surface waves
- Lower amplitudes than with layered only model!

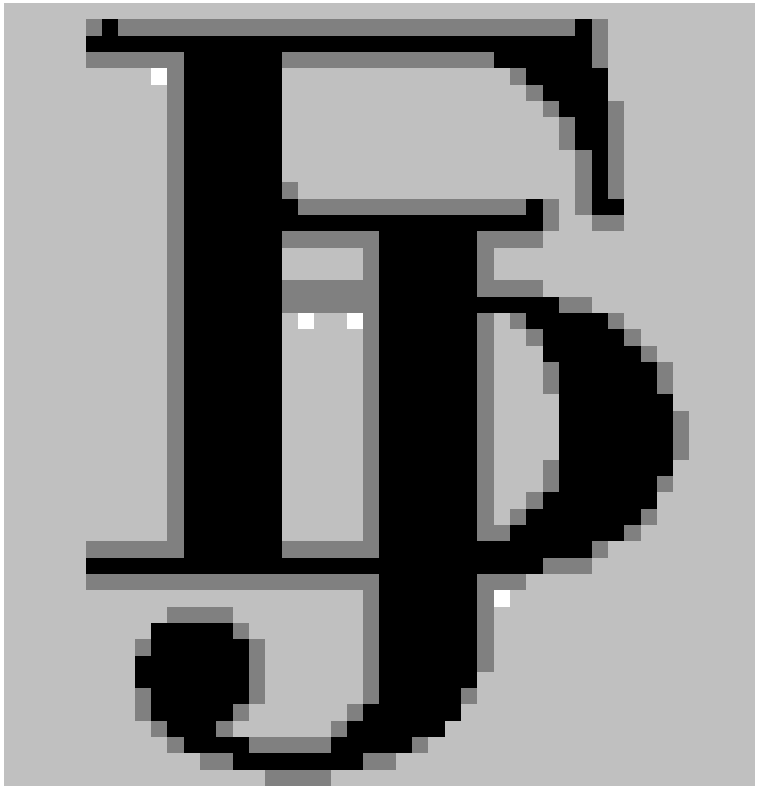






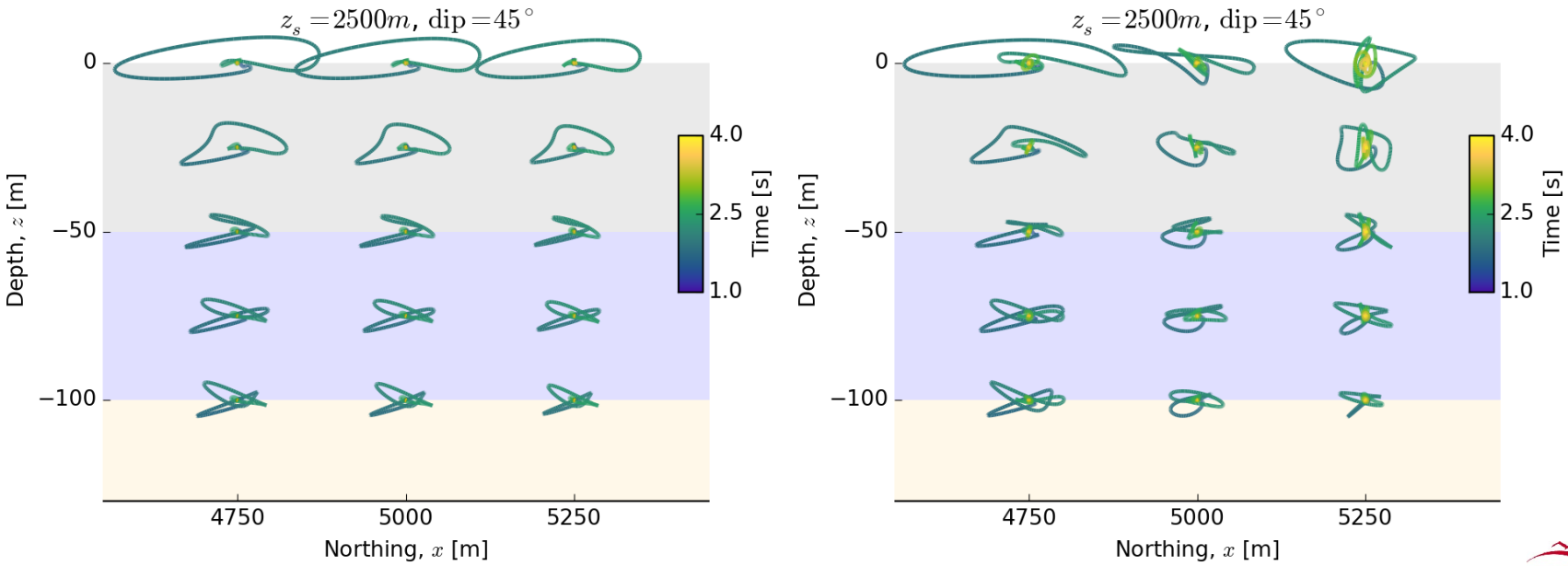
Dyke/Sill Intrusion, Variable Source Depth





Dyke/Sill as Seismic Energy Sink

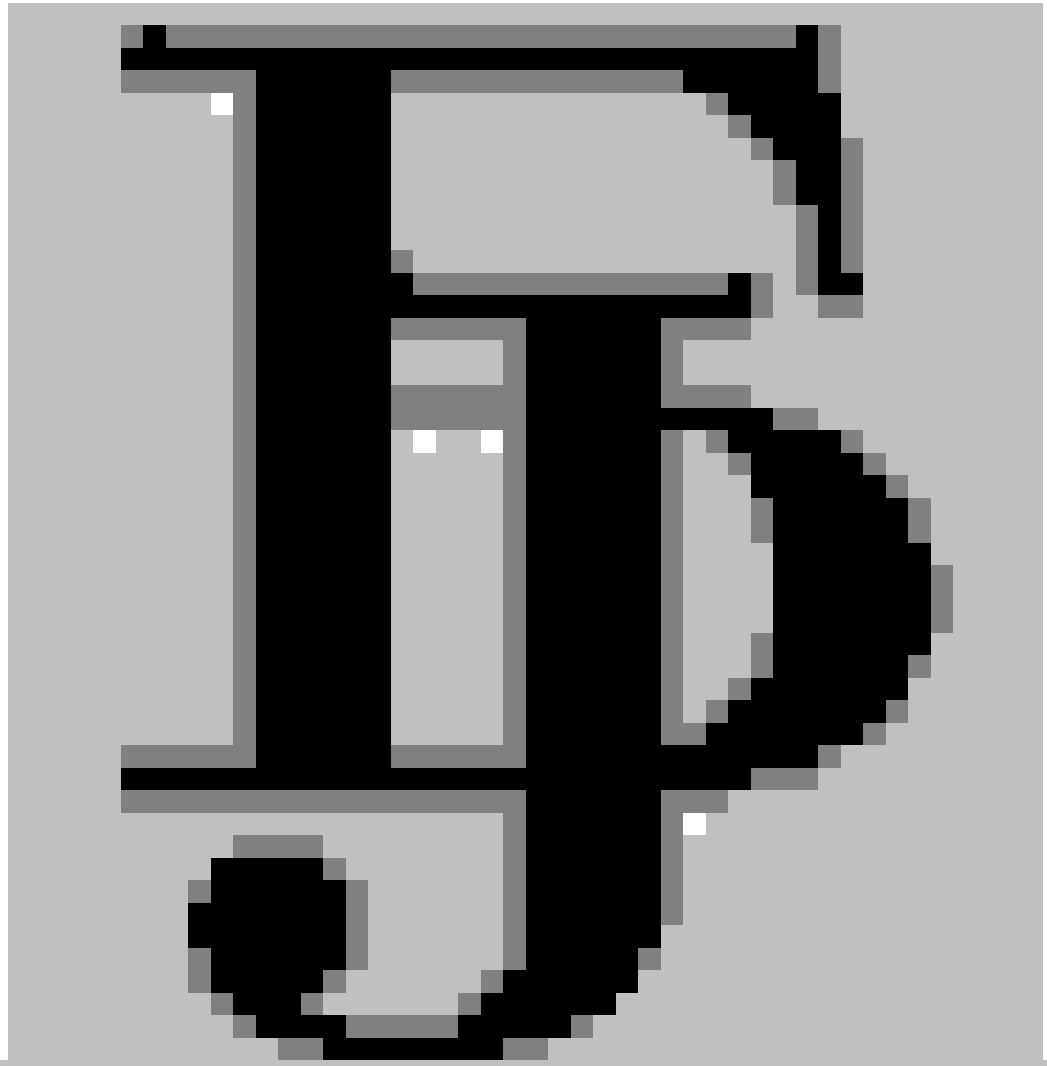
- Dyke/Sill (right Fig), made of stiff rock, is an energy sink, as well as energy reflector
- Variable wave lengths behave differently, depending on dyke/sill geometry and location



Importance of Realistic Seismic Motion Fields

- Developed synthetic (!) free field motions need to excite a number of (all!) possible responses from a nuclear facility
- Knowledge of detailed geology is needed, geometry and material properties, including inelasticity of shallow layers
- Reduction of modeling uncertainty
- Direct use for Realistic ESSI simulations

6D vs 1D NPP ESSI Response Comparison



(MP4)

Outline

Uncertain Material Parameters and Loads

- Decide on modeling complexity
- Determine model/material parameters
- Model/material parameters are uncertain!
  - Measurements
  - Transformation
  - Spatial variability

Uncertainty Propagation through Inelastic System

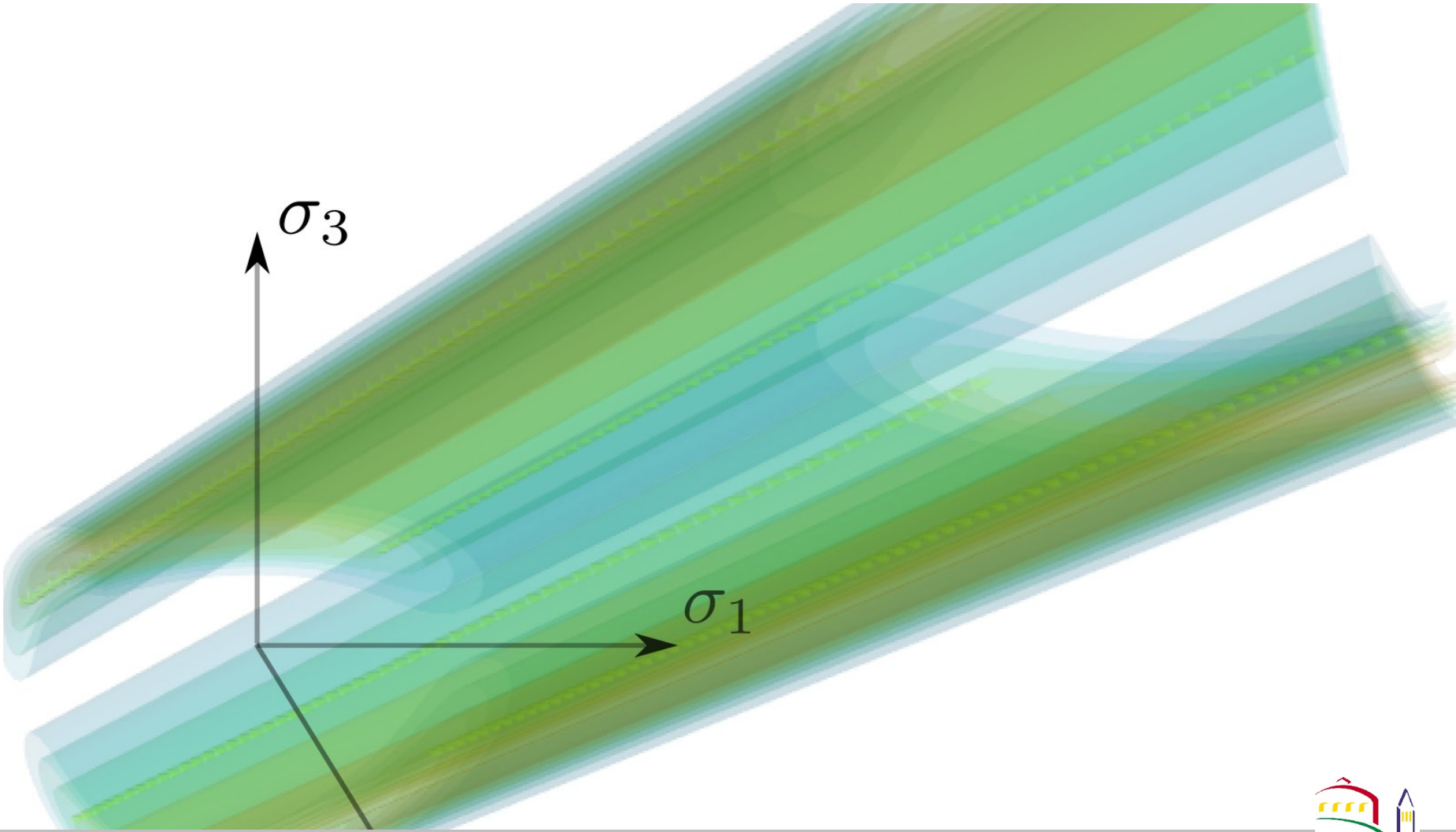
- Dynamic Finite Elements

$$\mathbf{M\ddot{u}} + \mathbf{C\dot{u}} + \mathbf{K}^{ep}\mathbf{u} = \mathbf{F}$$

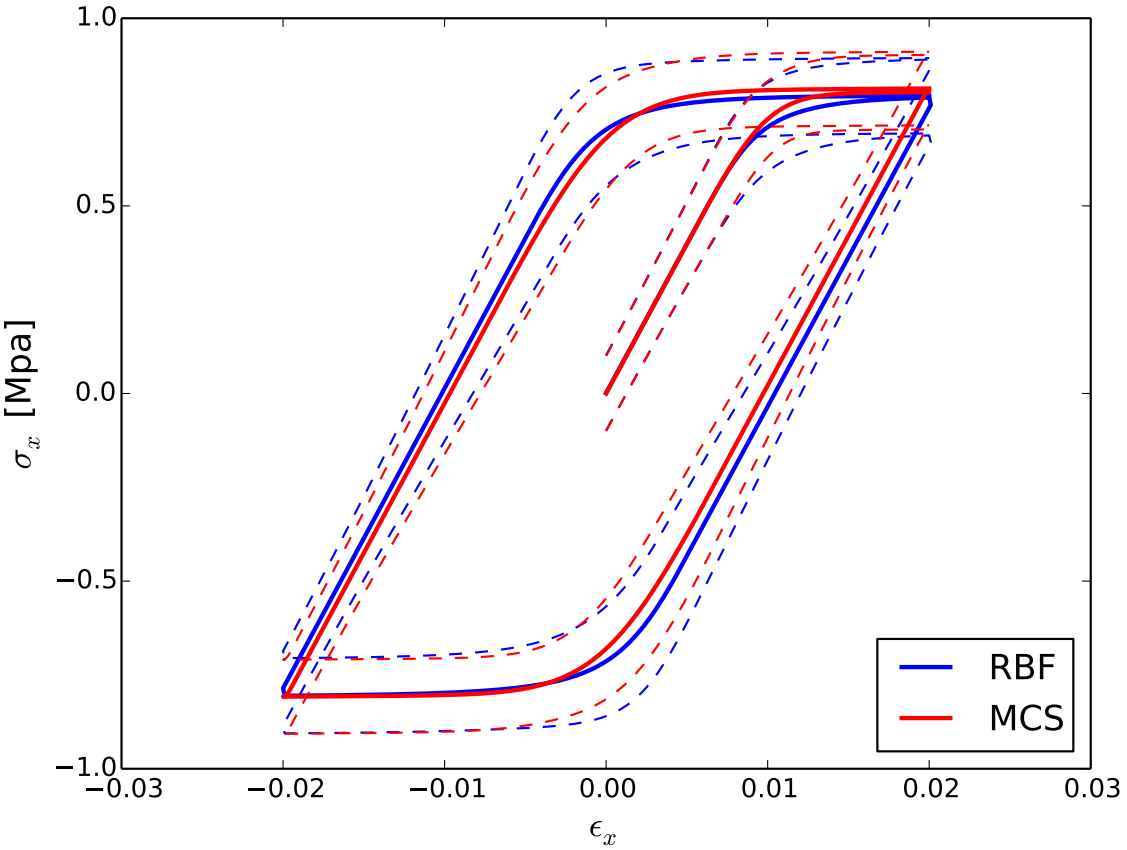
- Incremental elastic-plastic constitutive equation

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

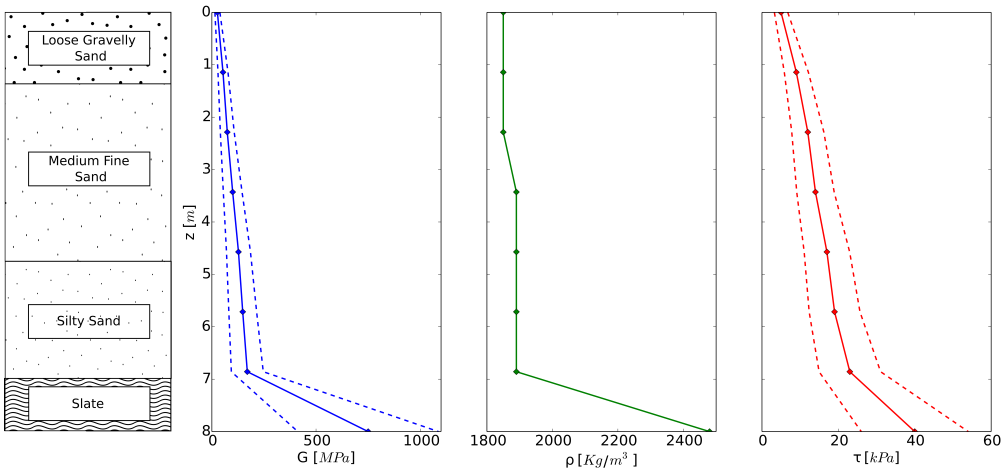
Probabilistic Elasto-Plasticity: von Mises Surface

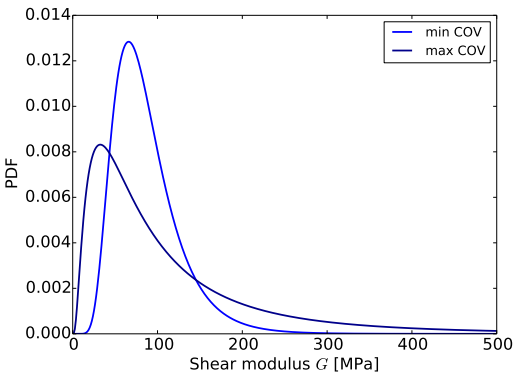


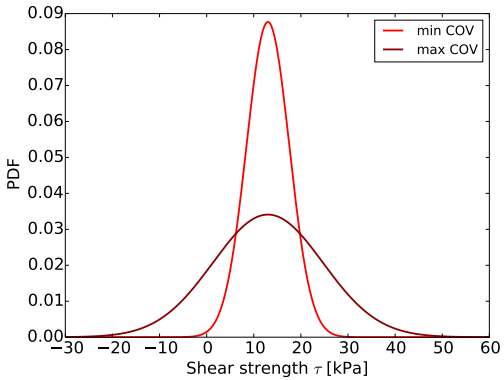
Gradient Theory of Probabilistic Elasto-Plasticity: Verification, Elastic-Perfectly Plastic

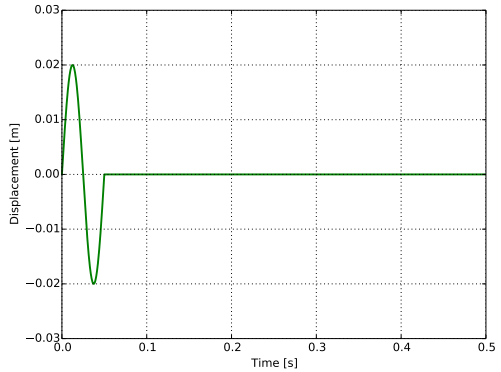


Wave Propagation Through Uncertain Soil

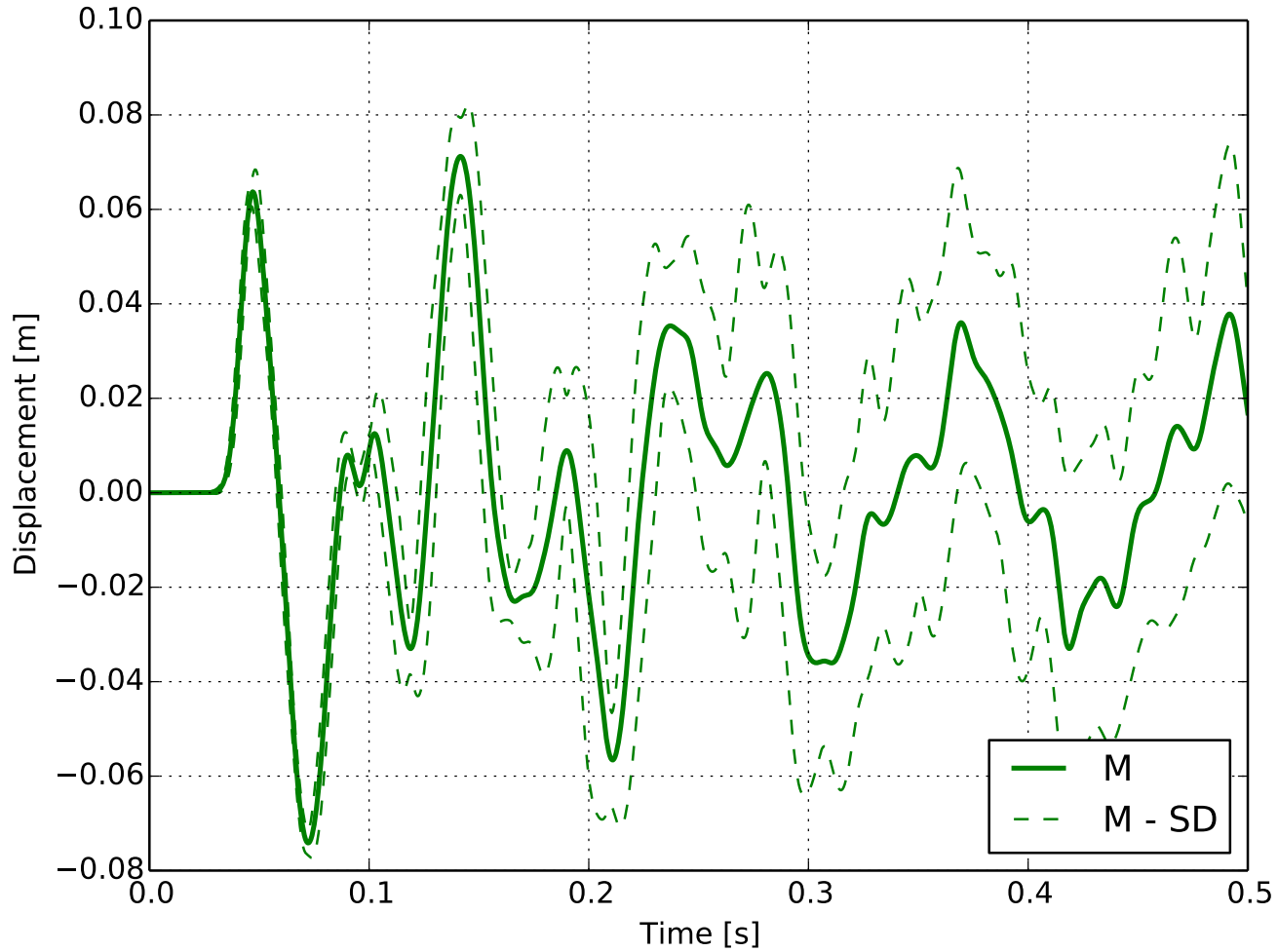




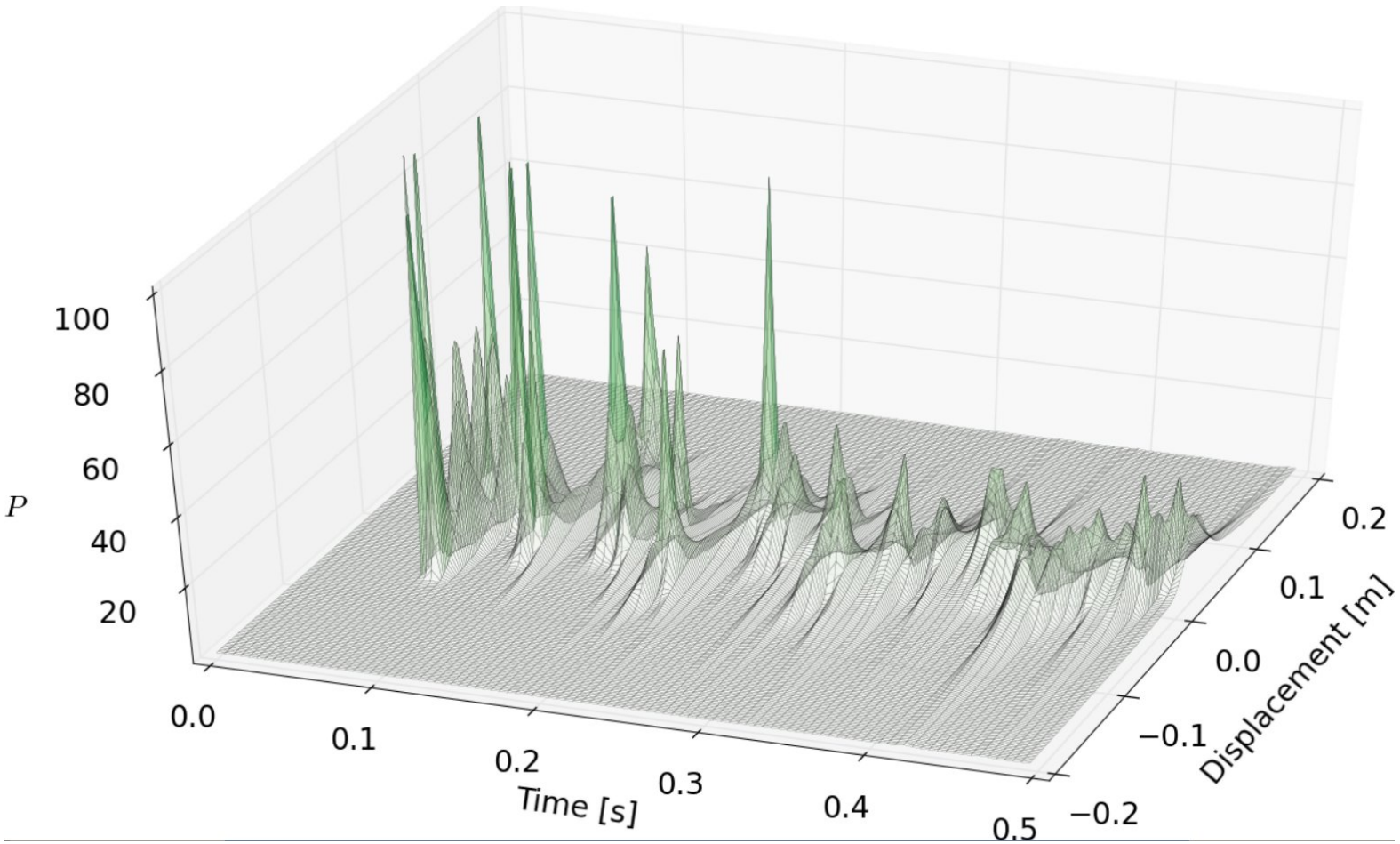




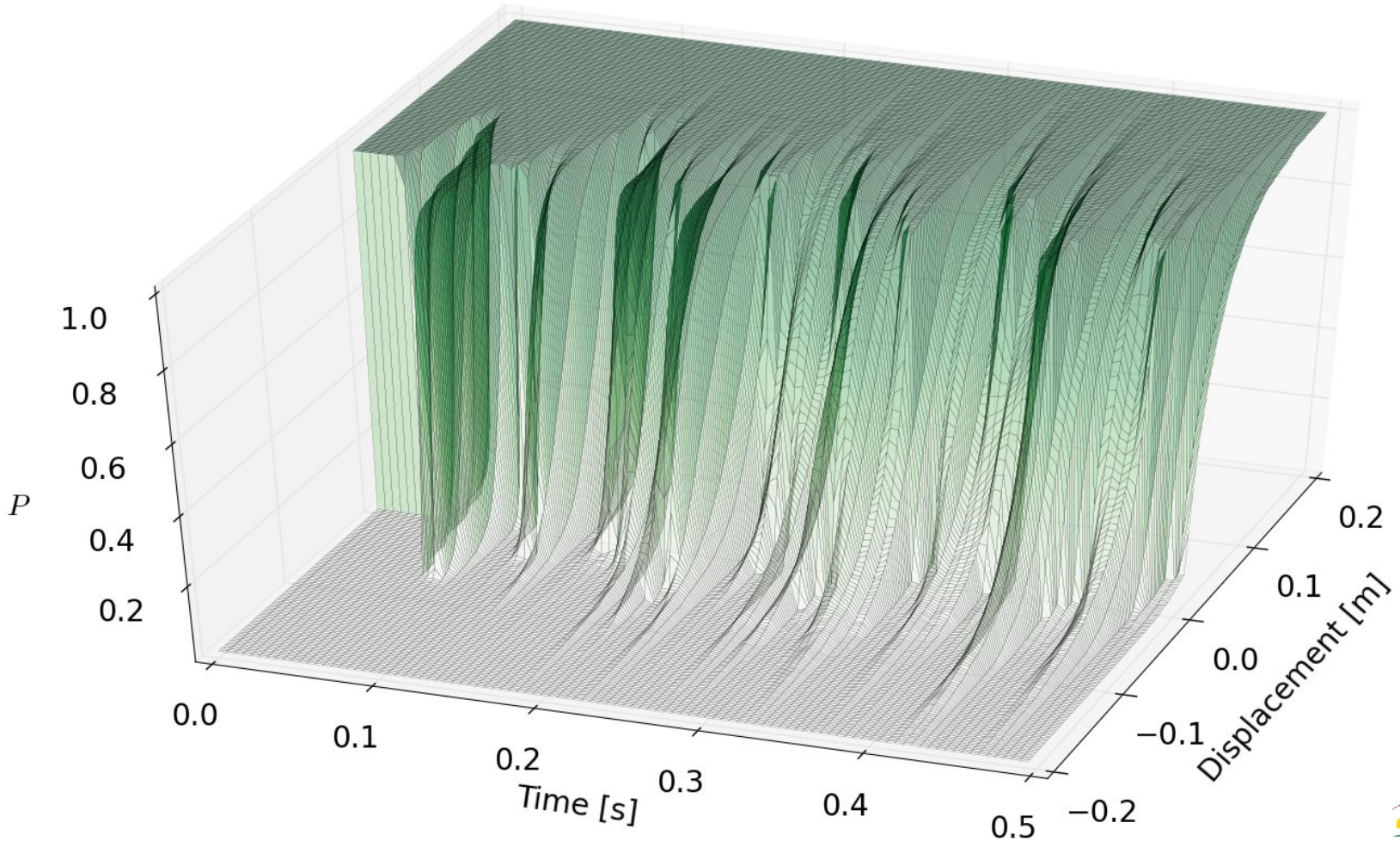
Uncertain Elastic Response at the Surface (COV = 120%)



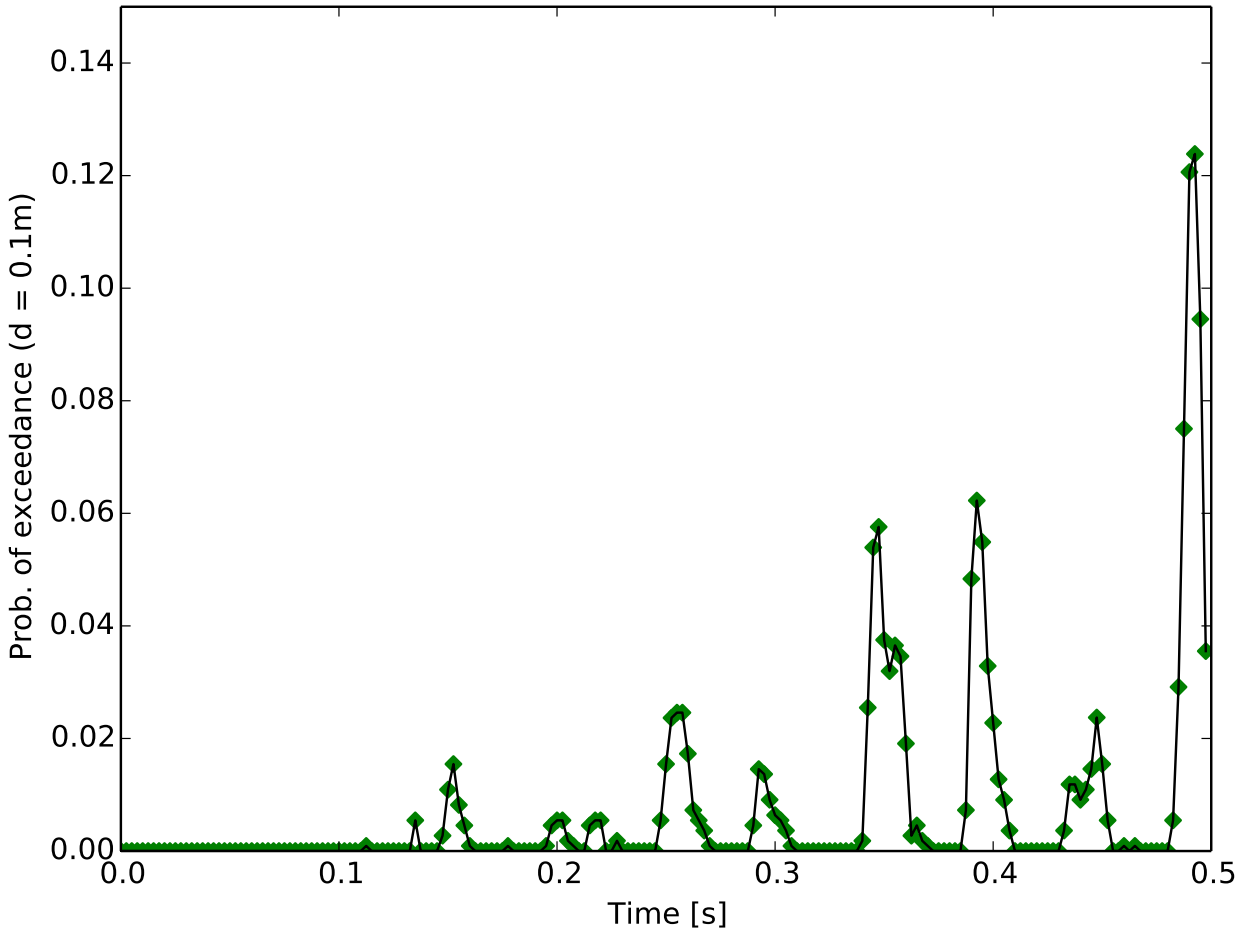
Displacement PDFs at the Surface (COV = 120%)



Displacement CDFs (Fragilities) at the Surface (COV = 120%)



Probability of Exceedance, $disp = 0.1m$ (COV = 120%)



Outline

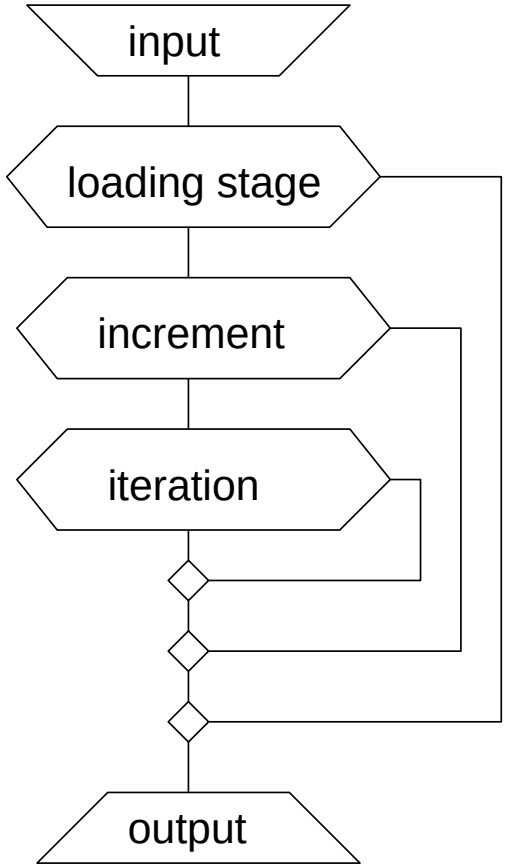
Real ESSI Simulator System

- **The Real ESSI-Program** is a 3D, nonlinear, time domain, parallel finite element program specifically developed for Hi-Fi modeling and simulation of Earthquake Soil/Rock Structure Interaction problems for NPPs (infrastructure objects) on ESSI-Computers.
- **The Real ESSI-Computer** is a distributed memory parallel computer, a cluster of clusters with multiple performance processors and multiple performance networks.
- **The Real ESSI-Notes** represent a hypertext documentation system (Theory and Formulation, Software and Hardware, Verification and Validation, and Case Studies and Practical Examples) detailing modeling and simulation of ESSI problems.

Real ESSI Simulator System

- Developed with funding from US-DOE, US-NRC, US-NSF and CNSC-CCSN
- The Real ESSI simulator system is designed based on premise of high fidelity, high performance, modeling and simulation
- Reduction of modeling uncertainty and propagation of parametric uncertainty
- Real ESSI simulator, also known as Врло Просто, 真简单 , অতি সহজ, Muy Fácil, Molto Facile, 本当に簡単 , Πραγματικά Εύκολο, बहुत ही आसान , آسان واقعی, Très Facile, Вистински Лесно, Wirklich Einfach.

Real ESSI Modelling



Real ESSI: Components

- Variety of solid, structural and special finite elements
- Variety of material models
- Variety of static and dynamic solution advancement algorithms
- Seismic (realistic) input using DRM
- High performance parallel computing for elastic-plastic FEM and multiple performance CPUs and networks using Plastic Domain Decomposition method
- Stochastic Elastic-Plastic Finite Element Method (SEPFEM)
- Extensive Verification, working on Validation

Concluding Remarks

- Modeling and simulation of infrastructure object requires high sophistication
- Uncertainties (modeling and parametric) influences results
- Those uncertainties need to be addressed and propagated to results and used in decision making
- Goal is to predict and inform, and not force fit