Modelling and Simulation Uncertainty

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Outline

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Introduction
- Motivation
- Uncertainties
- Real ESSI Simulator

Modeling and Parametric Uncertainty
- Modeling Uncertainty: 3D Dam/Slope Model, Expert Opinion
- Modeling Uncertainty: Seismic Behavior of Nuclear Power Plants
- Parametric Uncertainty: Wave Propagation

Summary

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

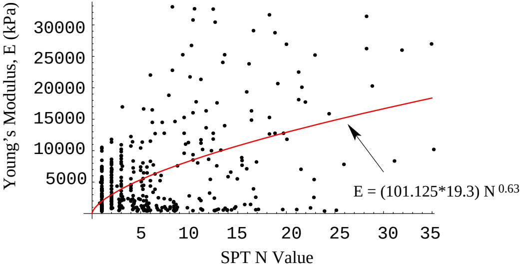
- Verification provides evidence that the model is solved correctly. Mathematics issue.
- Validation provides evidence that the correct model is solved. Physics issue.
- Prediction under Uncertainty (!): use of computational model to predict the state of SSI system under conditions for which the computational 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

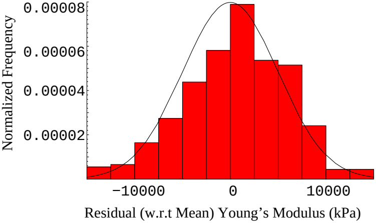
Outline

Modeling Uncertainty

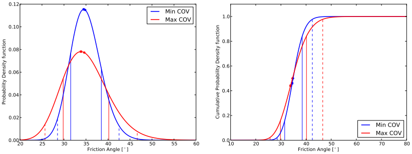
- Simplified modeling: Features (important ?) are neglected (6D ground motions, inelasticity)
- Modeling Uncertainty: unrealistic and unnecessary modeling simplifications
- Modeling simplifications are justifiable if one or two level higher sophistication model shows that features being simplified out are not important

Parametric Uncertainty: Material Stiffness

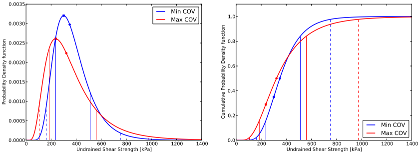




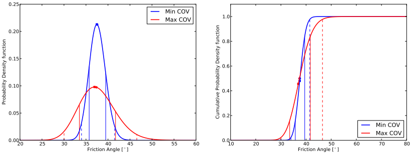
Parametric Uncertainty: Material Properties



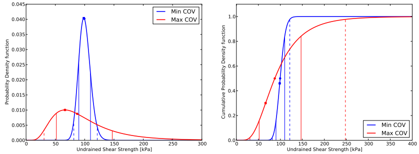
Field ϕ



Field c_u



Lab ϕ



Lab c_u

Outline

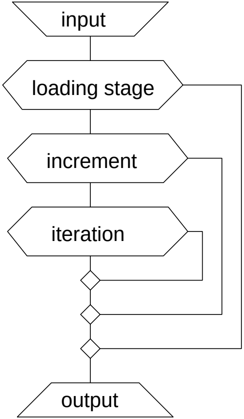
Real ESSI Simulator System

- **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-NRC, US-NSF, CNSC-CCSN, and US-DOE
- The Real ESSI simulator system is designed based on premise of high fidelity 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, سهلٌ جداً.

Real ESSI Modelling



Verification and Validation for High Fidelity Predictive Capabilities

- Verification provides evidence that the model is solved correctly. Mathematics issue.
- Validation provides evidence that the correct model is solved. Physics issue.
- Goal: predictive capabilities with low information (Kolmogorov) Complexity

Outline

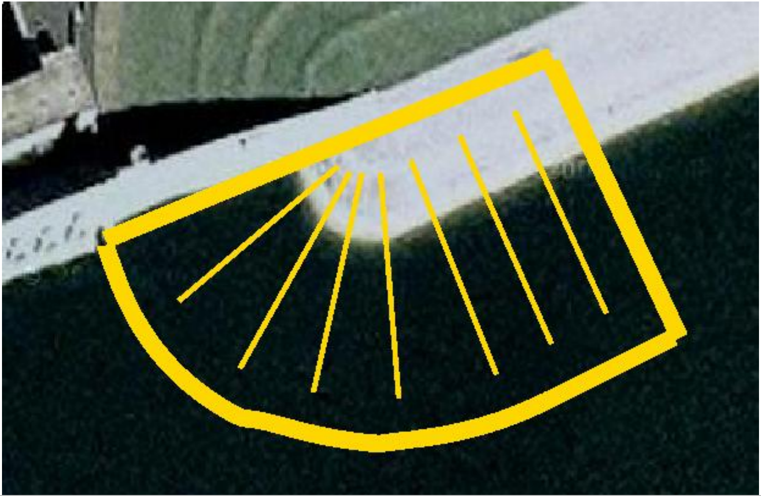
3D Dam – Slope Stability

- 3D earth slope part of a concrete, earth dam
- Movements recorded during lowering of reservoir
- 3D slope unstable (?), no one could tell, all commercial software does 2D slope stability
- 2D vs 3D slope stability
- Shear strength (?) as the only material parameter
- (")Expert(") increased value of measured shear strength
- Load cases: lowering and raising reservoir, slow and fast
- Dam build using untreated alluvium

Dam, Satellite Photo

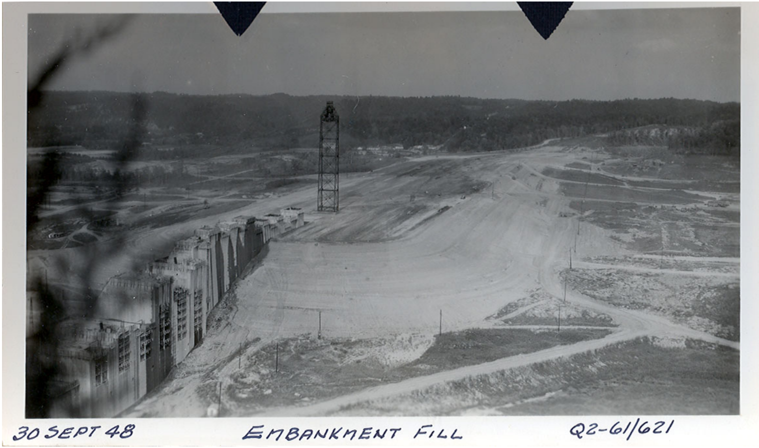
Dam, 3D Slope, Satellite Photo

3D Slope

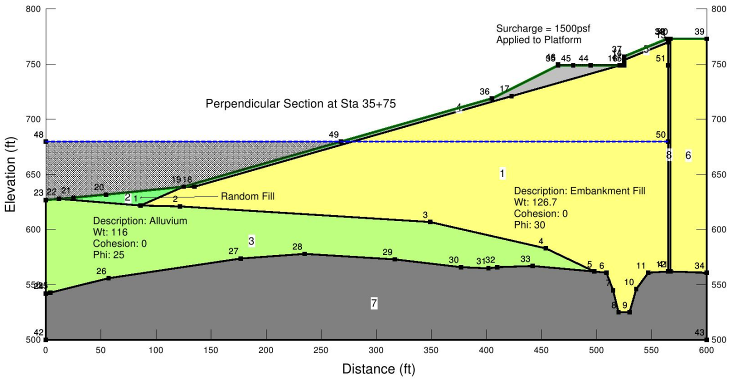


3D Slope, Ground Photo

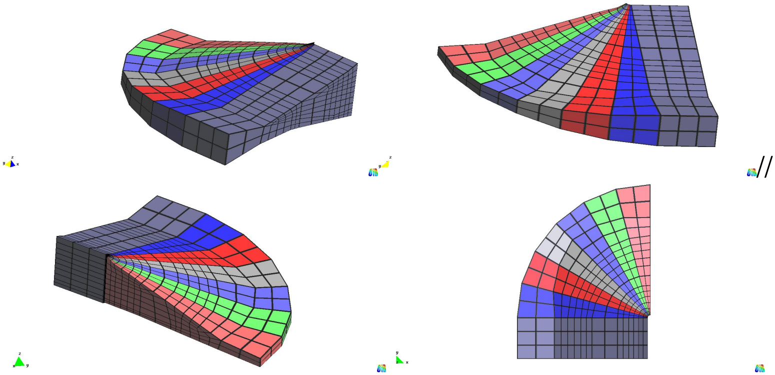
Dam, Construction Photo



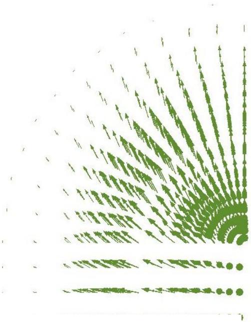
Dam, Section


Surcharge = 1500psf
Applied to Platform
Perpendicular Section at Sta 35+75
Random Fill
Description: Embankment Fill
Wt: 126.7
Cohesion: 0
Phi: 30
Description: Alluvium
Wt: 116
Cohesion: 0
Phi: 25
Elevation (ft)
Distance (ft)

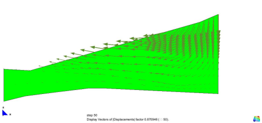
Dam, Model

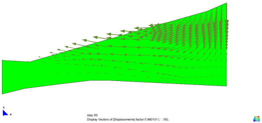


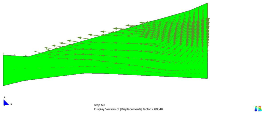
Dam Slope, Failure Modes



- 3D failure pattern
- 3D has lower FS than 2D
- Original S_u FS barely enough,
- With "increased" S_u a bit higher







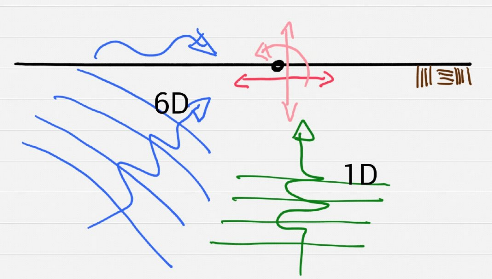
Outline

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

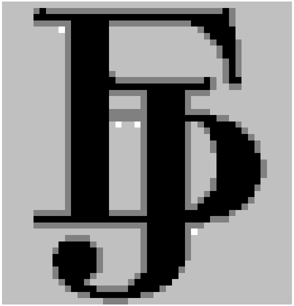
Nuclear Power Plants: 6D or 1D Seismic Motions

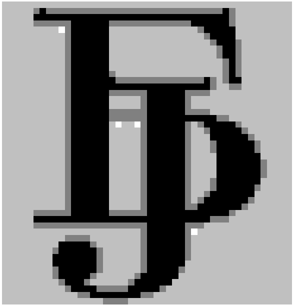
- Assume that a full 6D (3D) motions at the surface are only recorded in one horizontal direction
- From such recorded motions one can develop a vertically propagating shear wave in 1D
- Apply such vertically propagating shear wave to the same soil-structure system



Synthetic Test Motions

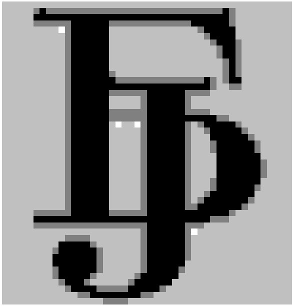
- Develop free field models with sources within
- Sources are simple, point (mostly), line and surface
- Sources will send both P and S waves
- Variation in strike and dip
- Simulation programs, Real ESSI Simulator and SW4

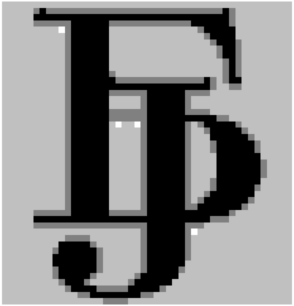




Synthetic Test Motions, 6D vs 1D

- 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)

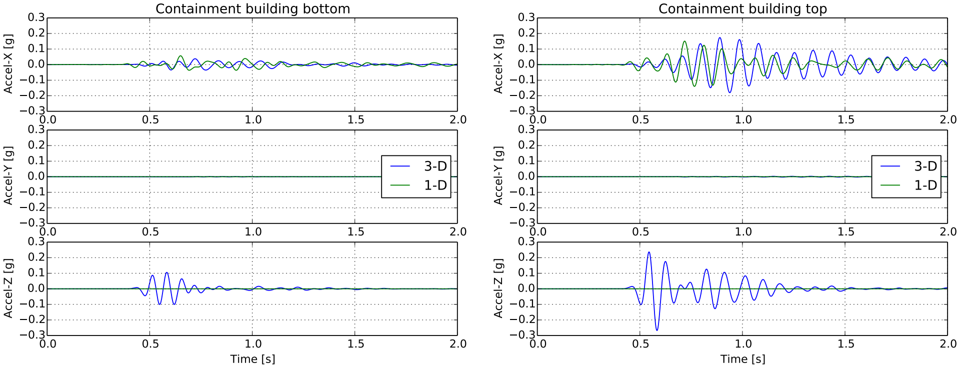




6D vs 1D NPP ESSI Response Comparison

(MP4)

6D vs 1D: Containment Acceleration Response



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

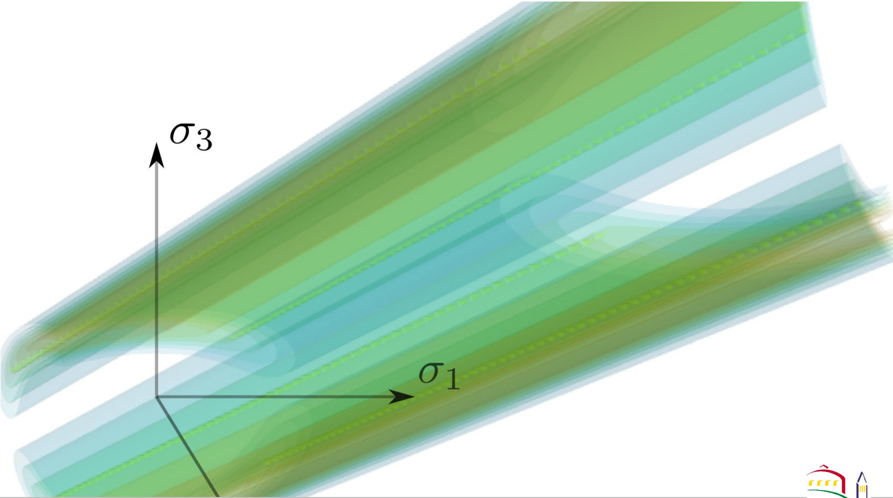
- Incremental el–pl constitutive equation

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

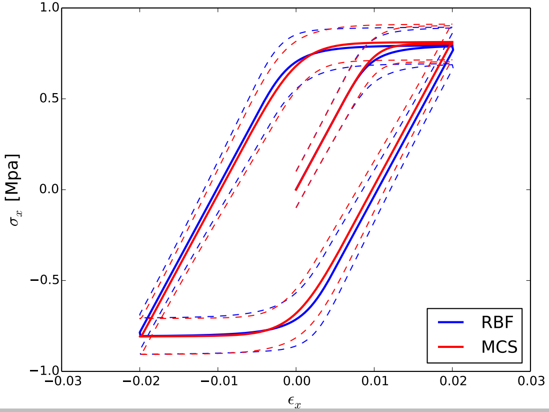
- Dynamic Finite Elements

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

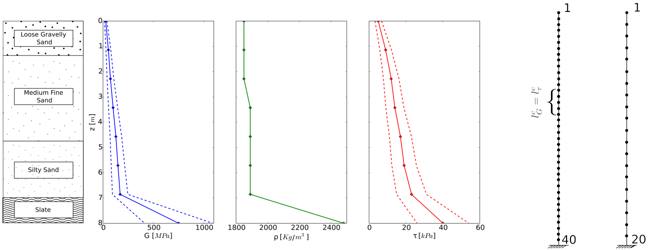
Probabilistic Elasto-Plasticity: von Mises Surface

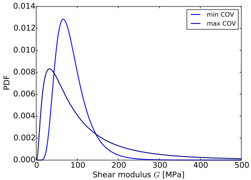


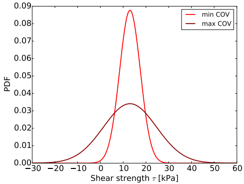
Gradient Theory of Probabilistic Elasto-Plasticity: Verification, Elastic-Perfectly Plastic

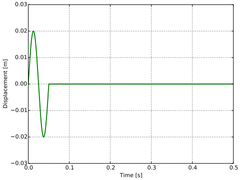


Wave Propagation Through Uncertain Soil

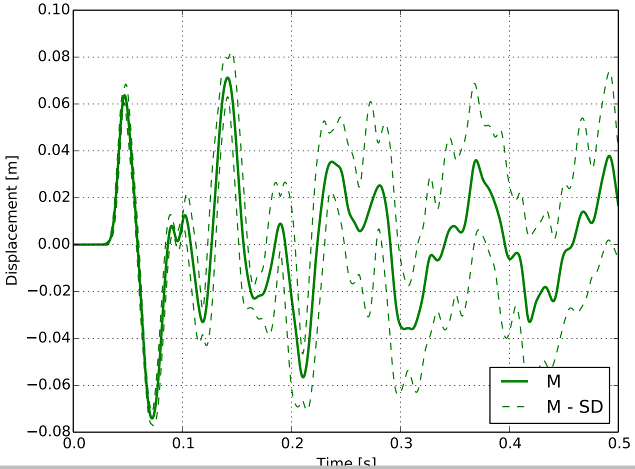




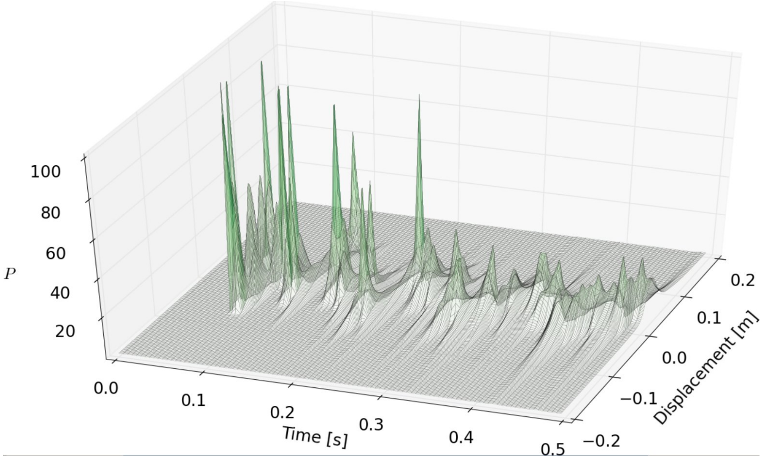




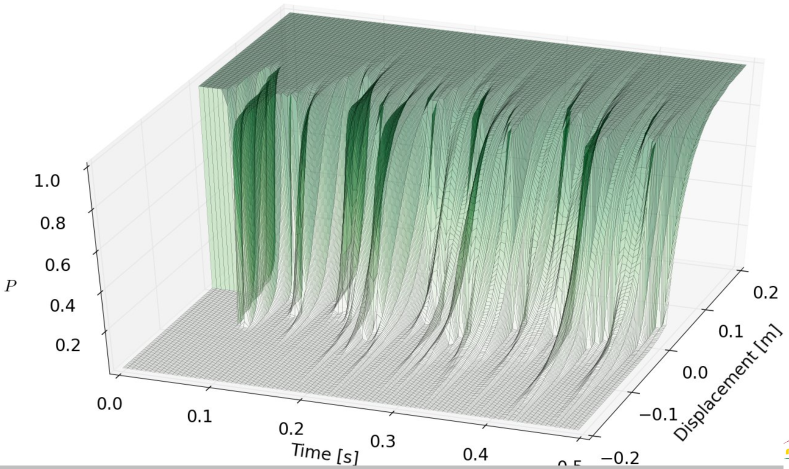
Uncertain Elastic Response at the Surface (COV = 120%)



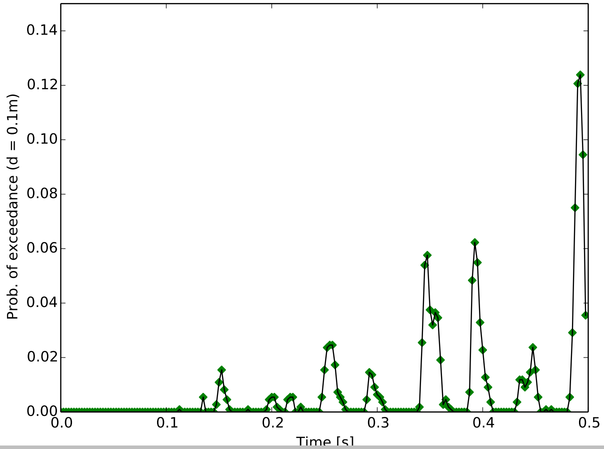
Displacement PDFs at the Surface (COV = 120%)



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



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



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

Acknowledgement

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- Collaborators: Prof. Yang, Dr Cheng, Dr. Jie, Dr. Tafazzoli, Prof. Pisanò, Mr. Watanabe, Mr. Vlaski, Mr. Orbović, and UCD students: Mr. Abell, Mr. Karapiperis, Mr. Feng, Mr. Sinha, Mr. Luo, Mr. Lacour, Mr. Yang, Ms. Behbehani

- Real ESSI Simulator: `http://sokocalo.engr.ucdavis.edu/~jeremic/Real_ESSI_Simulator/`

]Real ESSI Simulator

Real ESSI: Finite Elements

- Dry/single phase solids (8, 20, 27, 8-27 node bricks), elastic and/or inelastic
- Saturated/two phase solids (8 and 27 node bricks, liquefaction modeling), elastic and/or inelastic
- Truss, elastic
- Beams (six and variable DOFs per node), elastic, inelastic
- Shell (ANDES) with 6DOF per node, linear elastic, inelastic shell soon
- Contacts (dry and/or saturated soil/rock - concrete, gap opening-closing, frictional slip), inelastic
- Base isolators (elastomeric, frictional pendulum), inelastic

Real ESSI: Material Models

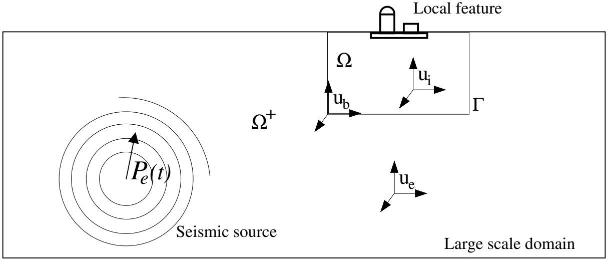
- Linear and nonlinear, isotropic and anisotropic elastic
- Elastic-Plastic (von Mises, Drucker Prager, Rounded Mohr-Coulomb, Leon Parabolic, Cam-Clay, SaniSand, SaniClay, Pisanò...). All elastic-plastic models can be used as perfectly plastic, isotropic hardening/softening and kinematic hardening models.
- Viscous damping solids, Rayleigh and Caughey damping

Real ESSI: Solution Advancement Algorithms

- Constitutive
  - Explicit, Implicit, Sub-incrementation, Line Search
- Nonlinear Static FEM
  - No equilibrium iteration
  - Equilibrium Iterations (full Newton, modified N, Initial Stiff.)
  - Hyperspherical constraint (arch length, displacement control, load control)
  - Line Search
  - Convergence criteria: displacement, load, energy
- Nonlinear Dynamic FEM
  - No equilibrium iteration
  - Equilibrium Iterations (full Newton, modified N, Initial Stiff.)
  - Constant or variable time stepping
  - Convergence criteria: displacement, load, energy

Real ESSI: Seismic Input

- Analytic input of seismic motions (both body (P, S) and surface (Rayleigh, Love, etc., waves), including analytic radiation damping using Domain Reduction Method (Bielak et al.)



Real ESSI Simulator Program: Parallel, HPC

- High Performance Parallel Computing: both parallel and sequential version available, however, for high fidelity modeling, parallel is really the only option. Parallel Real ESSI Simulator runs on clusters of PCs and on large supercomputers (Distributed Memory Parallel machines, all top national supercomputers). Plastic Domain Decomposition Method (PDD, dynamic computational load balancing) for elastic-plastic computations with multiple types of finite elements and on variable speed CPUs (and networks)

Real ESSI Simulator Program: Probabilistic/Stochastic

- Constitutive: Euler-Lagrange form of Fokker-Planck (forward Kolmogorov) equation for probabilistic elasto-plasticity (PEP)
- Spatial: stochastic elastic plastic finite element method (SEPFEM)

Uncertainties in material and load are analytically taken into account. Resulting displacements, stress and strain are obtained as very accurate (second order accurate for stress) Probability Density Functions. PEP and SEPFEM are not based on a Monte Carlo method, rather they expand uncertain input variables and uncertain degrees of freedom (unknowns) into spectral probabilistic spaces and solve for PDFs of resulting displacement, stress and strain in a single run.

Verification

- Code Verification (code coverage, memory leaks and pointer assignment testing, static argument list testing, &c.)
- Solution verification (finite elements, constitutive integration, material models, algorithms, seismic input, &c.) based on analytic, closed form solutions
- Method of manufactured solutions for elasto-plastic verification
- Parameter bounds (finite elements, material models, algorithms, &c.)
- Develop error plots for elements, models, algorithms over a range of parameter

Validation

- Traditional Experiments
  - Improve the fundamental understanding of physics involved
  - Improve the mathematical models for physical phenomena
  - Assess component performance
- Validation Experiments
  - Model validation experiments
  - Designed and executed to quantitatively estimate mathematical model's ability to simulate well defined physical behavior
  - The simulation tool (Real ESSI Simulator) (conceptual model, computational model, computational solution) is the customer
  - New US-DOE project to validate inelastic seismic wave propagation and soil-structure interaction