Modelling and Simulation of Earthquake Soils Structures Interaction Under Uncertainty

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Outline

Motivation
- Introduction
- Uncertainties

Modeling and Parametric Uncertainty
- Modeling Uncertainty: Bridge Model
- Modeling Uncertainty: Nuclear Power Plants
- Parametric Uncertainty

Real ESSI Simulator System
- Real ESSI Simulator
- Verification and Validation

Summary

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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 foretell the state of a physical system under consideration 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 is to inform, not fit

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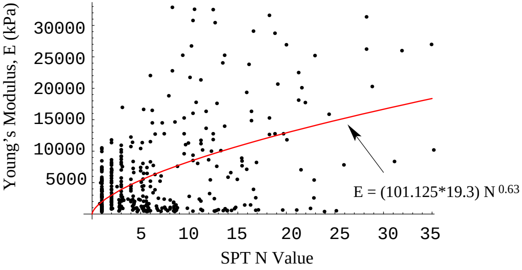
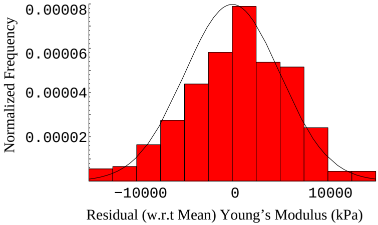
Modeling Uncertainty

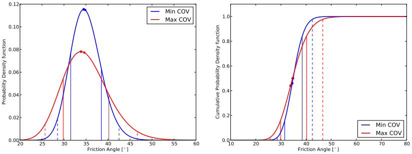
- Simplified modeling: Features (important ?) are neglected (6D ground motions, inelasticity)
- Modeling Uncertainty: unrealistic and unnecessary modeling simplifications
- Modeling simplifications are justifiable if one or two level higher sophistication model shows that features being simplified out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

Parametric Uncertainty: Material Stiffness

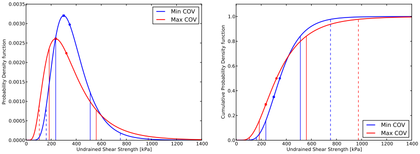




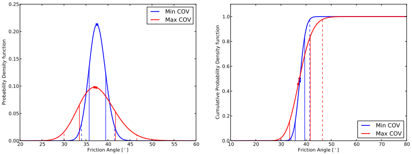
Parametric Uncertainty: Material Properties



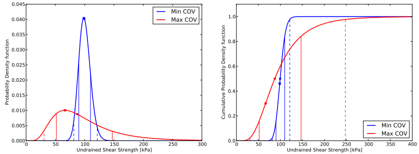
Field ϕ



Field c_u



Lab ϕ



Lab c_u

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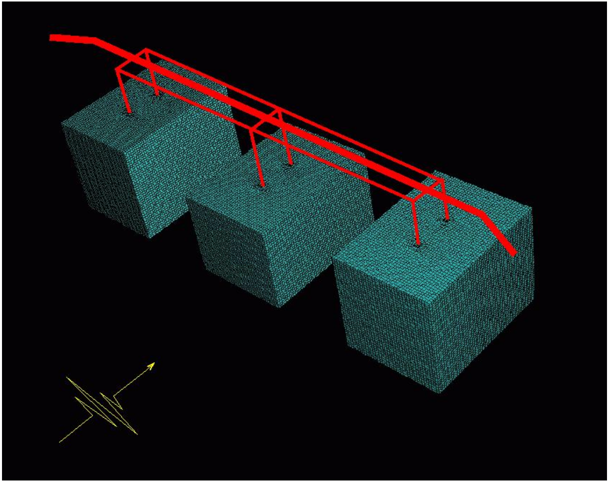
Detailed 3D Bridge Model

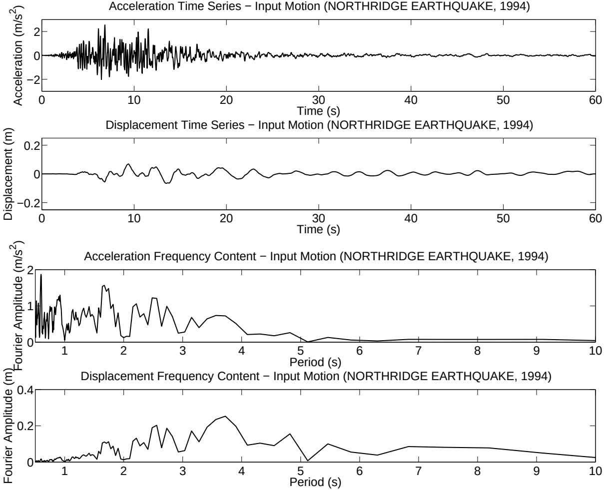


Modeling Issues

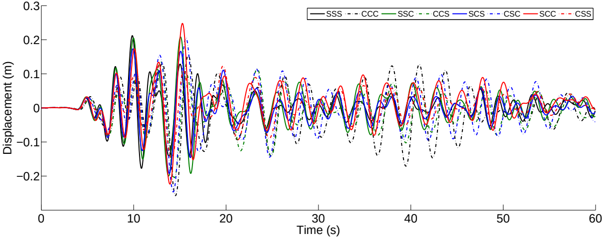
- Construction process
- Deconvolution of given surface ground motions
- No artificial damping (only mat. dissipation, radiation)
- Element size issues (filtering of frequencies)

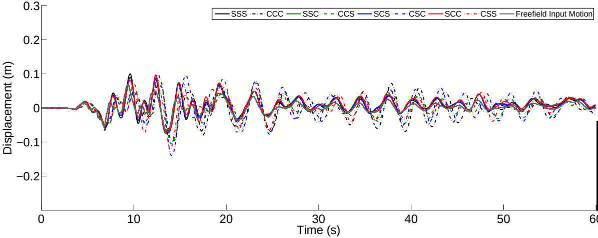
elem. #	elem. size	f_{cutoff}	min. $G^{ep}/Gmax$	γ
12K	1.00 m	10 Hz	1.0	<0.5 %
15K	0.90 m	>3 Hz	0.08	<1.0 %
150K	0.30 m	10 Hz	0.08	<1.0 %
500K	0.15 m	10 Hz	0.02	<5.0 %

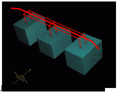
Short Period (Northridge) Input Motions



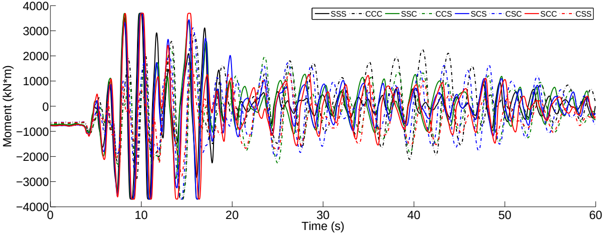
Short Period Eq.: Left Bent, Displacements

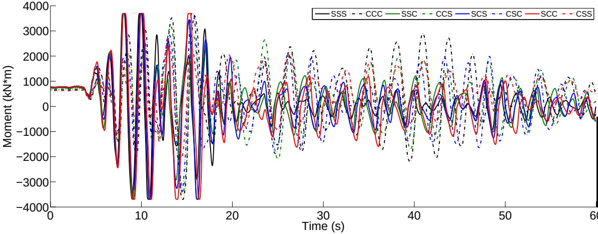


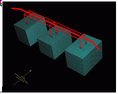




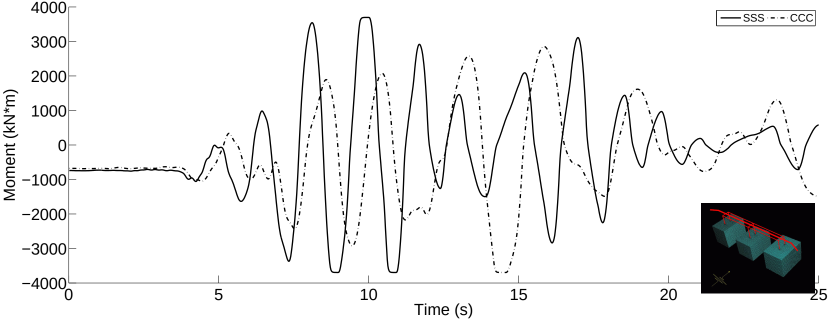
Short Period Eq.: Left Bent, Moments.



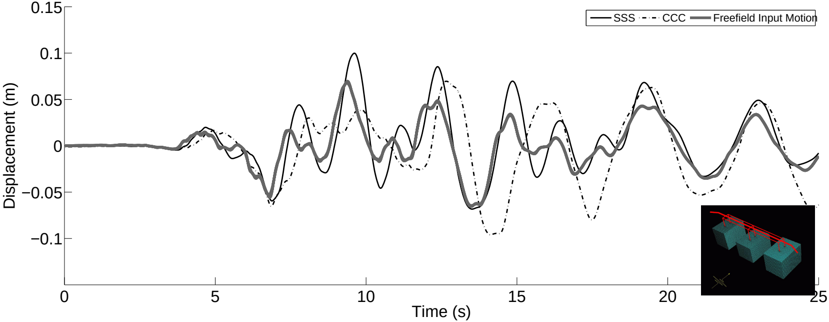




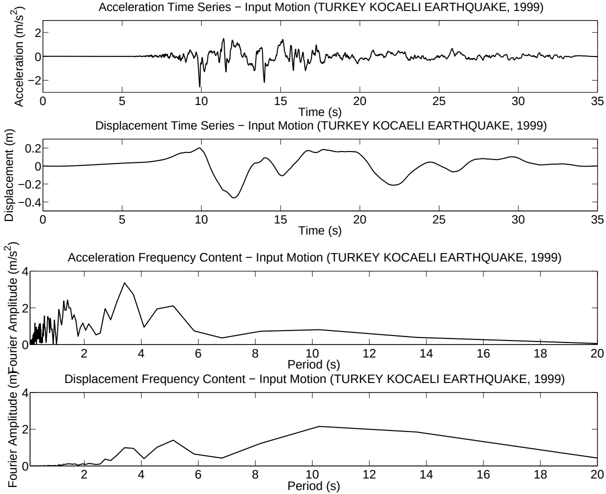
Short Period E.: Left Bent, Bending Moments



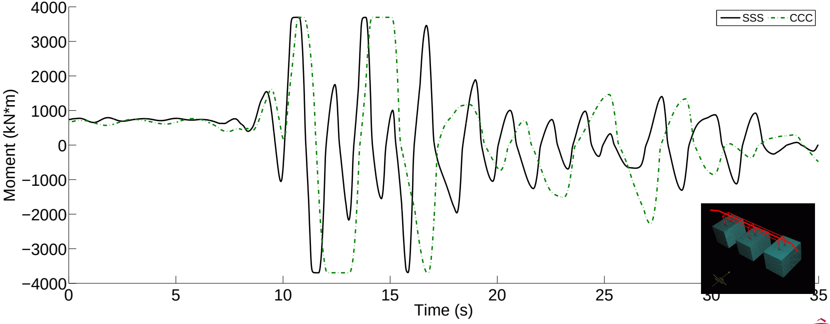
Short Period E.: Left Bent, Free Field vs Real Disp.



Long Period (Kocaeli) Input Motions



Long Period E.: Left Bent, Bending Moments.



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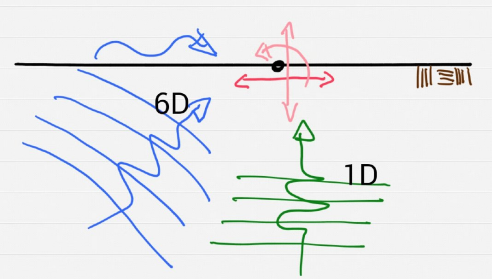
Modeling and Simulation of Nuclear Power Plants

- Nuclear Power Plants (NPPs) design based on a number of simplified assumptions!
- Linear elastic material behavior
- Seismic Motions: 1D or $3 \times 1D$
- Significant savings in construction cost possible with more accurate modeling of NPPs
- Improvements in safety of NPPs also possible

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



6D Free Field Motions

(MP4)

6D Free Field Motions (closeup)

(MP4)

6D Free Field at Location

(MP4)

6D Earthquake Soil Structure Interaction

(MP4)

1D Free Field at Location

(MP4)

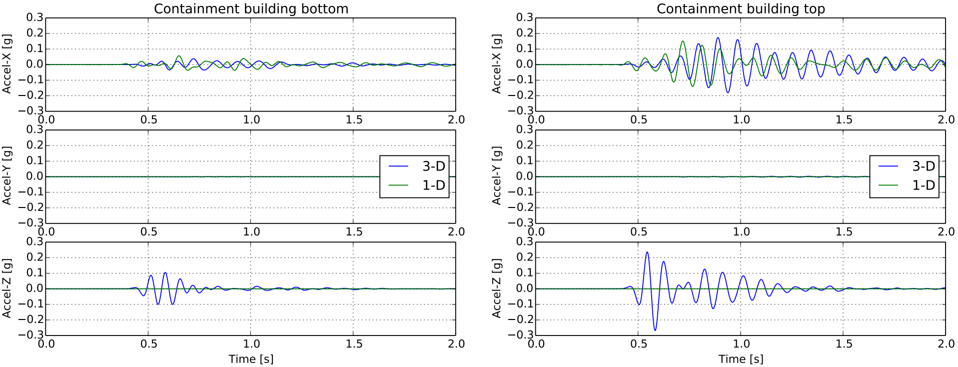
1D ESSI of NPP

(MP4)

6D vs 1D NPP ESSI Response Comparison

(MP4)

6D vs 1D: Containment Acceleration Response



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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

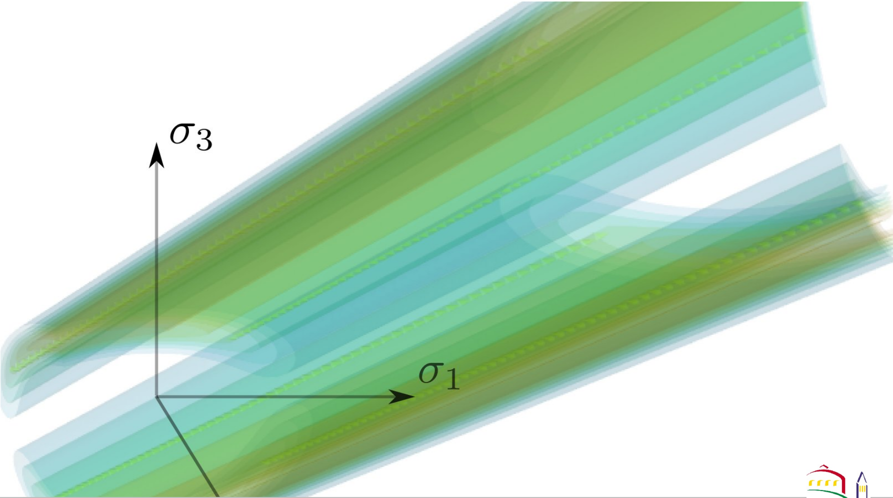
- Incremental el–pl constitutive equation

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

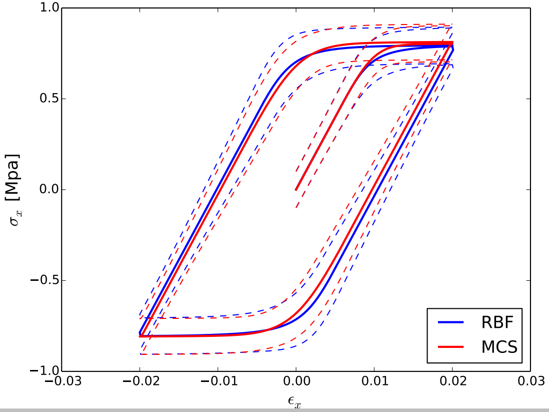
- Dynamic Finite Elements

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

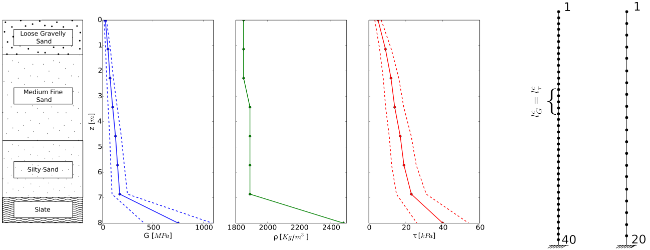
Probabilistic Elasto-Plasticity: von Mises Surface

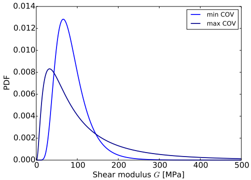


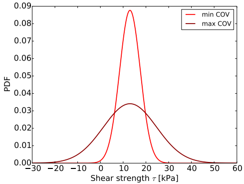
Gradient Theory of Probabilistic Elasto-Plasticity: Verification, Elastic-Perfectly Plastic

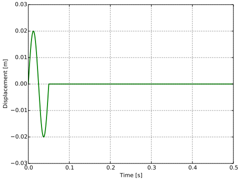


Wave Propagation Through Uncertain Soil

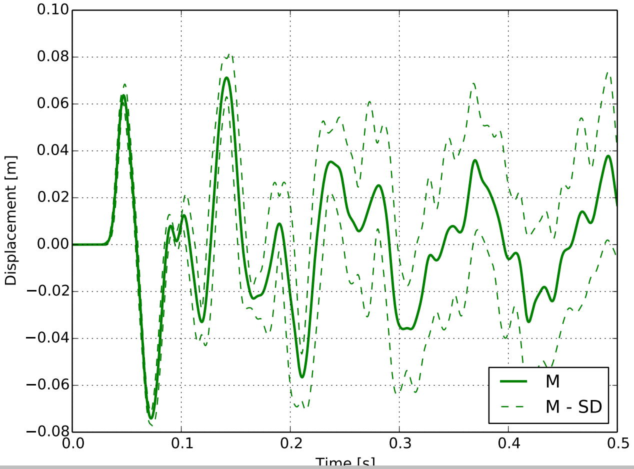




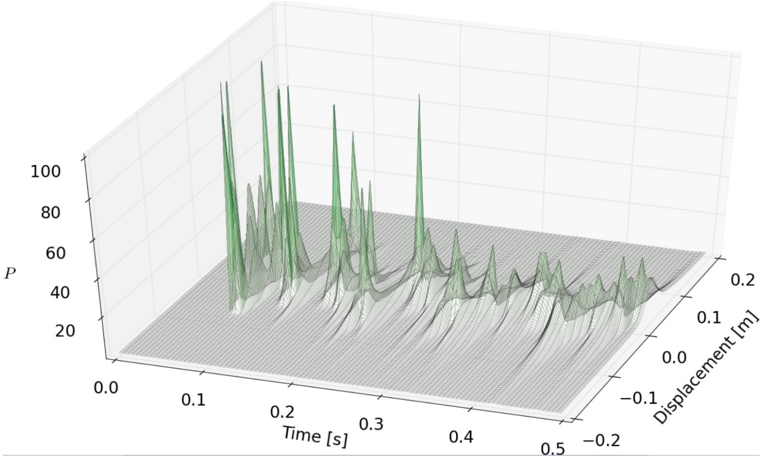




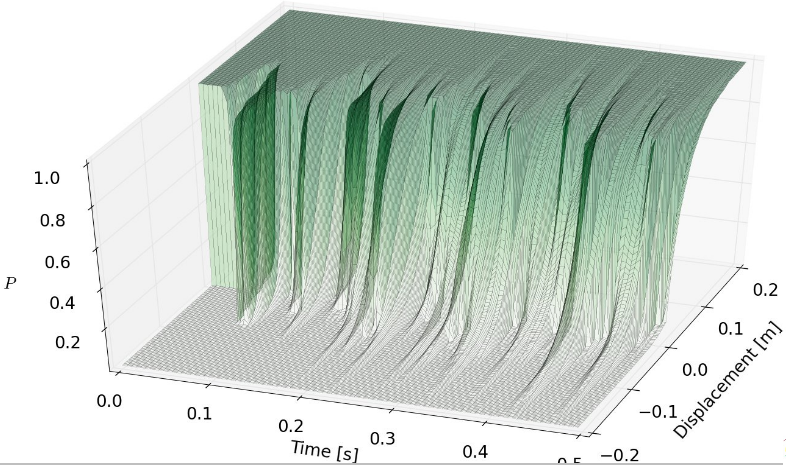
Uncertain Elastic Response at the Surface (COV = 120%)



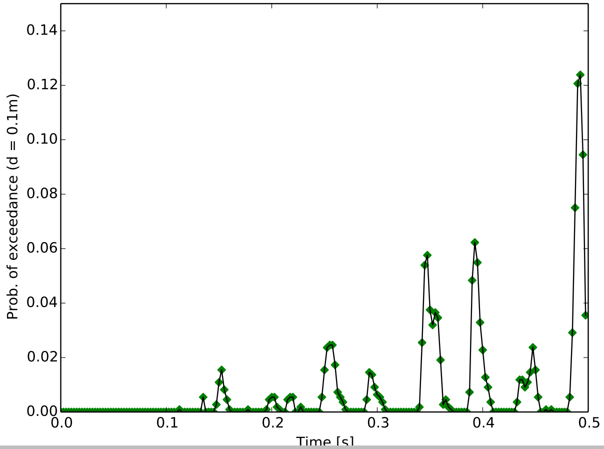
Displacement PDFs at the Surface (COV = 120%)



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



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



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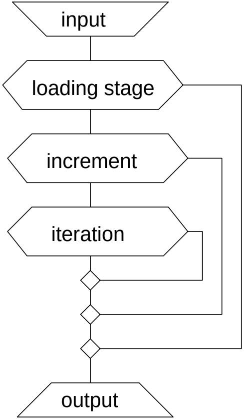
Real ESSI Simulator System

- **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

- Philosophy of the Real ESSI simulator modeling and simulation system is to predict and inform, not fit
- Real ESSI simulator, also known as Врло Просто, 真简单, 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



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
- Shell (ANDES) with 6DOF per node, linear elastic
- Contacts (dry and/or saturated soil/rock - concrete, gap opening-closing, frictional slip), inelastic
- Base isolators (elastomeric, frictional pendulum), inelastic

Real ESSI: Material Models

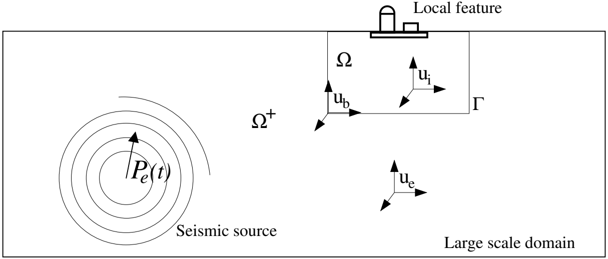
- Linear and nonlinear, isotropic and anisotropic elastic
- Elastic-Plastic (von Mises, Drucker Prager, Rounded Mohr-Coulomb, Leon Parabolic, Cam-Clay, SaniSand, SaniClay, Pisanò...). All elastic-plastic models can be used as perfectly plastic, isotropic hardening/softening and kinematic hardening models.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

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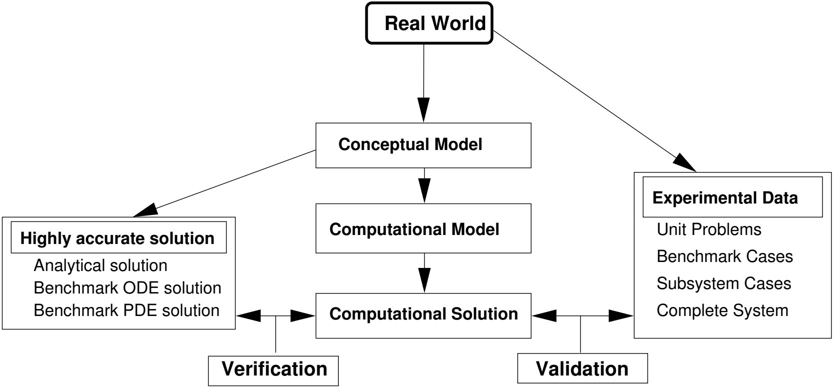
High Fidelity Predictive Capabilities

- 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

Fundamentals of Verifications and Validation



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

Concluding Remarks

- Modeling and parametric uncertainty influences results of numerical predictions and must be taken into account
- Goal is to predict and inform, not fit

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