Динамика тла и конструкције при земљотресима, непоуздани модели, непоуздани параметри и теорија вероватноћа

Борис Јеремић

University of California, Davis, CA, USA
Lawrence Berkeley National Laboratory, Berkeley, CA, USA

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Садржај

Мотивација

- Побољшање моделовања и симулација за системе тла и конструкције
- Развој експертног система за нумеричке анализе
- Употреба прецизних модела за анализе статике и динамике система тла и конструкције
- Циљ је развој методологије за нумеричка предвиђања и информисање корисника, стручњака, а не резултати који прате неку задату линију, на силу

Претпоставка

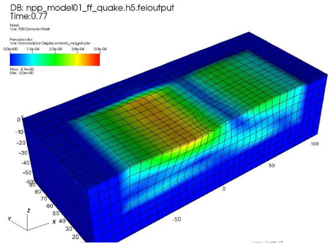
- Интеракција динамичких карактеристика земљотреса, тла и конструкције контролише ниво оштећења конструкције
- Место и време дисипације земљотресне енергије одређује локацију и ниво оштећења конструкције
- Контролисањем проток земљотресне енергије кроз тло и конструкцију, можемо да побољшамо
  - Сигурност
  - Економичност

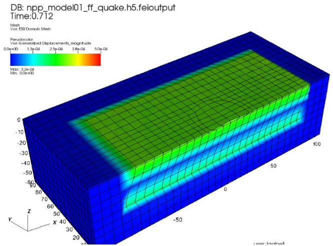
Тачност Моделовања и Симулација

- Верификација: доказ да је модел тачно решен, математички проблем
- Валидације: доказ да је решен прави модел, механички проблем
- Нумеричко анализа: коришћење нумеричког модела за предвиђање стања система за оптерећења која нису коришћена при тестирању (валидацији)
- Предвиђање/анализа уз теорију вероватноћа:
  - Несигурност модела
  - Несигурност параметара

Modeling Uncertainty: Simplified Models

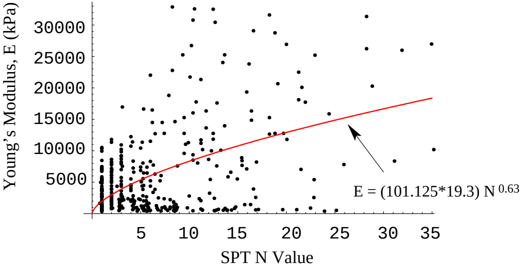
- Simplified modeling: Features (important ?) are neglected (6D ground motions, inelasticity)
- Modeling Uncertainty: unrealistic and unnecessary modeling simplifications
- Modeling simplifications: justifiable iff higher level sophistication model shows are features not important

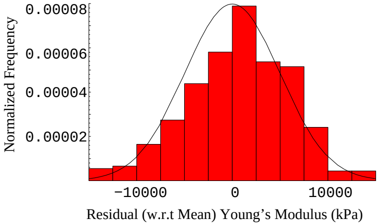




Parametric Uncertainty: Material and Loads

- Significant uncertainty in material and loads
- Need to propagate uncertainty through simulation, to give regulators and engineers information for design, licensing...



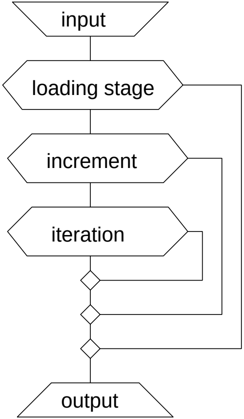


Transformation of SPT *N*-value: 1-D Young's modulus, *E* (cf. Phoon and Kulhawy (1999B))

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 Modeling and Simulation Process



Real ESSI Simulator: DSL

[fragile]

- Domain Specific Language (DSL), Yacc & Lex
- English like modeling and simulation language
- Parser and compiler, can define functions, models, etc.
- Can extend models and methods
- Requires units!

Real ESSI DSL Example

```
model name "UNR Test Setup";
new loading stage "First, static";
add node # 1 at (0*m, 0*m, 0*m) with 6 dofs;
add node # 2 at (0*m, 0*m, 1*m) with 6 dofs;
add element # 1 type beam_elastic with
  nodes (1, 2) cross_section=1.0*m^2
  elastic_modulus=1.0e5*KN/m^2
  shear_modulus=2.0e4*KN/m^2
  torsion_Jx=2*0.083*m^4
  bending_Iy=0.083*m^4 bending_Iz=0.083*m^4
  mass_density=2500.0*kg/m^3
  xz_plane_vector = (0, -1, 0)
  joint_1_offset = (0.0*m, 0.0*m, 0.0*m)
  joint_2_offset = (0.0*m, 0.0*m, 0.0*m);
```

Real ESSI DSL Example

```
fix node No 1 dofs all;
add load # 1 to node # 2 type
  linear Fx=-9*kN;
define load factor increment 0.01;
define solver UMFPack;
define convergence test
  Norm_Displacement_Increment
  tolerance = 1e-5
  maximum_iterations = 20
  verbose_level = 4;
define algorithm Newton;
simulate 100 steps using static algorithm;

dovidjenja;
```

Real ESSI Simulator Program: Finite Elements

- Dry/single phase solids (8, 20, 27, 8-27 node bricks),
- Saturated/two phase solids (8 and 27 node bricks, liquefaction modeling),
- Truss, Beams, linear and nonlinear
- Nonlinear concrete shell and linear shell (ANDES)
- Contacts (dry and/or saturated soil/rock - concrete, gap opening-closing, frictional slip),
- Base isolators (elastomeric, frictional pendulum)
- Stochastic Elastic-Plastic FEM (1D and 3D solid)

Real ESSI Simulator Program: Material Models

- Elastic (solids): Linear, nonlinear, isotropic and anisotropic
- Elastic-Plastic (solids): 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.
- Elastic-Plastic (structures, 1D fibers): concrete and steel
- Probabilistic Elasto-Plasticity

Real ESSI Simulator Program: Seismic Input

Analytic input of seismic motions using Domain Reduction Method (Bielak et al.)

- Body (P, S) seismic waves
- Surface (Rayleigh, Love, etc.) seismic waves,
- Analytic radiation damping.

Real ESSI Simulator Program: V&V

- Verification: mathematics issue,
  - Each element, model, algorithm and procedure has been extensively verified (math issue),
- Validation: physics issue,
  - Limited, current DOE project will provide a wealth of data for soil, SSI, &c.

Examples

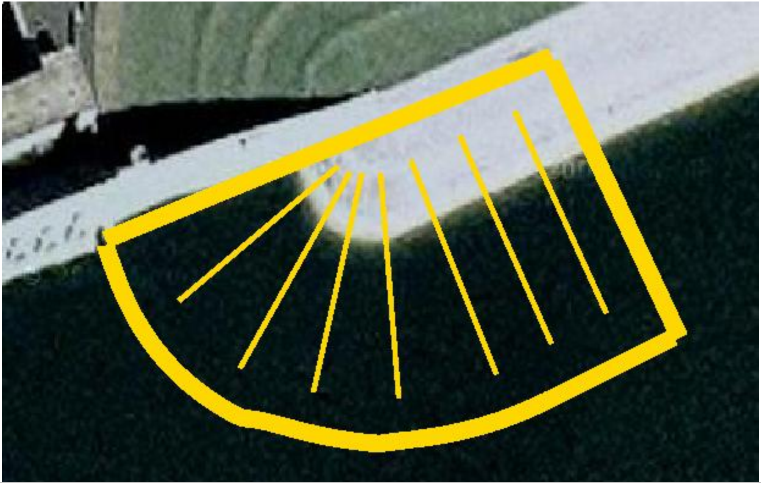
- Earth and Concrete Dam: level of sophistication and the influence of human factor (expert opinion)
- Concrete Bridge: matching of earthquake, soil and structure dynamic characteristics
- Nuclear Power Plant: 3D (6D) vs 1D seismic motions
- Stochastic Elastic Plastic Finite Element Method: risk of undesirable performance

Брана

Dam, Satellite Photo

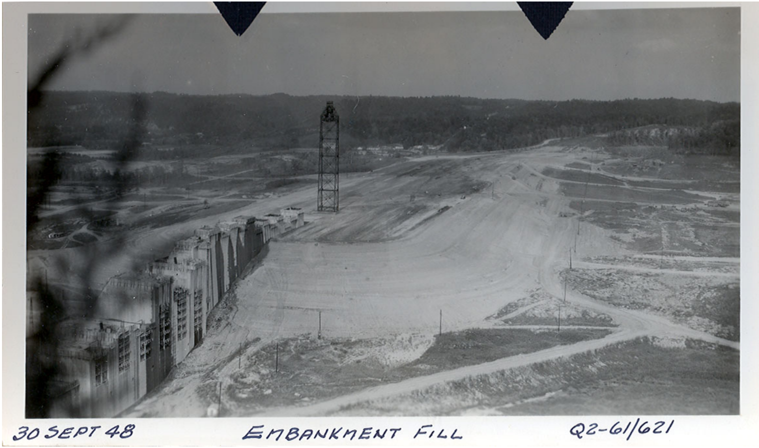
Dam, 3D Slope, Satellite Photo

3D Slope



3D Slope, Ground Photo

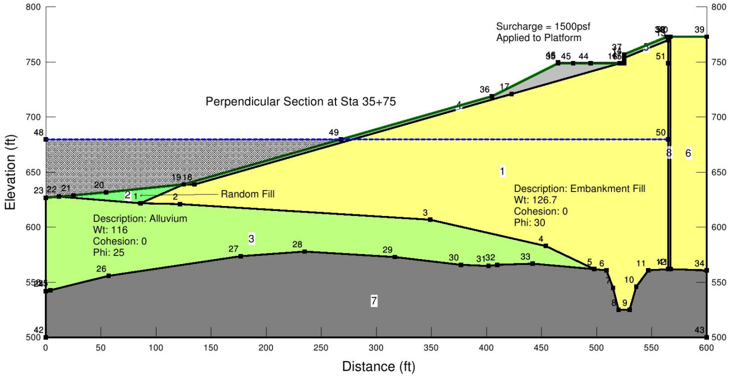
Dam, Construction Photo



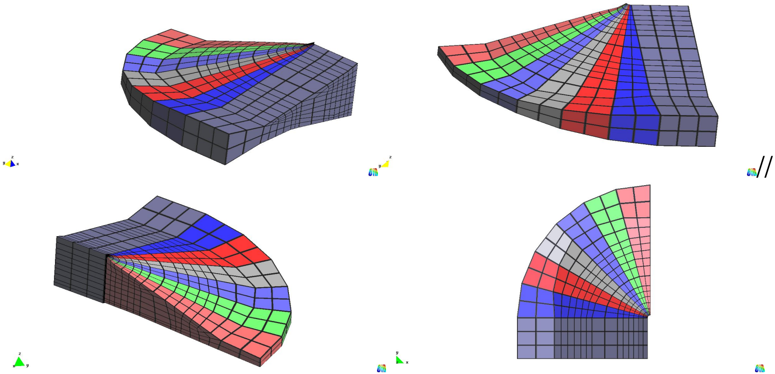
3D Dam – Slope Stability

- 3D earth slope part of a concrete, earth dam
- Movements recorded during lowering of reservoir (and significant rain!)
- 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 (a single) measured shear strength
- Load cases: lowering and raising reservoir, slow and fast
- Dam build using untreated alluvium

Dam, Section

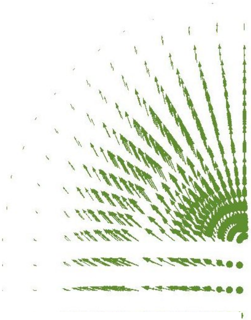

Surcharge = 1500psf
Applied to Platform
Perpendicular Section at Sta 35+75
Random Fill
Description: Alluvium
Wt: 116
Cohesion: 0
Phi: 25
Description: Embankment Fill
Wt: 126.7
Cohesion: 0
Phi: 30
Elevation (ft)
Distance (ft)
800
750
700
650
600
550
500
0
50
100
150
200
250
300
350
400
450
500
550
600

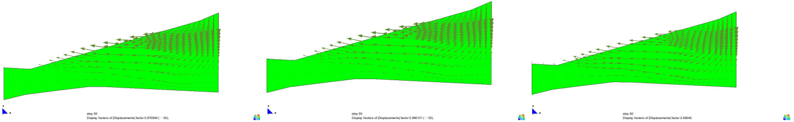
Dam, Model



Dam Slope, Failure Modes

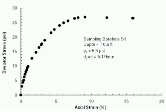
- 3D failure pattern
- 3D has lower FS than 2D (!)
- Original S_u: FS barely enough
- With "increased" S_u, FS a bit higher
- Seismic: immediate slope failure

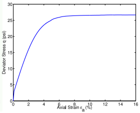


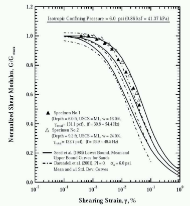


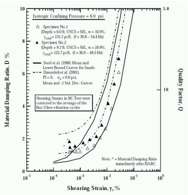
Post-Tensioned Concrete Bridge in Variable Soil

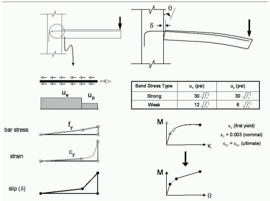
- Linear elastic deck/box girder, concrete, post-tensioned
- Nonlinear frame, r. concrete
- Nonlinear piles, r. concrete
- Nonlinear soil (Sand, Clay)

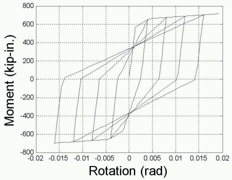


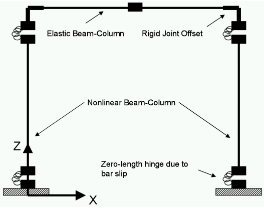






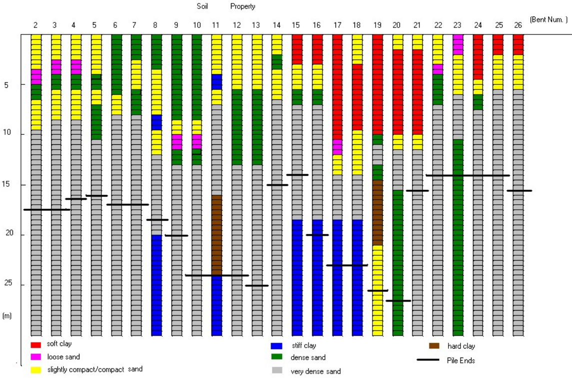






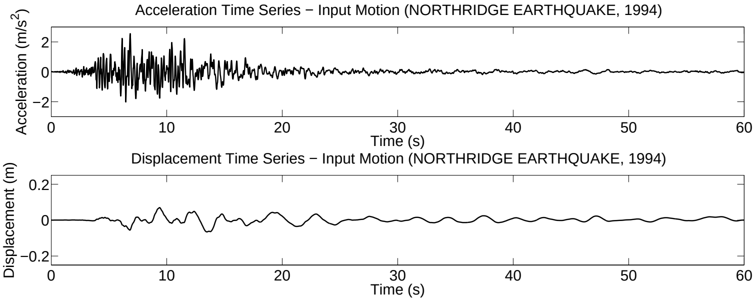
Variable Soil

- Stiff frames (bends) in variable stiffness soils
- Short period earthquake
- Matching EQ, soil and structure stiffness
- Variable soil creates extra demand on main girder

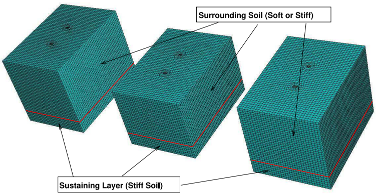


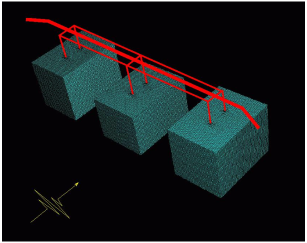
Short Period Earthquake, Northridge

- Usual assumption: soft soil is a problem
- Design: static pushover, single bent, soft soil
- Actual critical behavior: system in stiff and variable soil

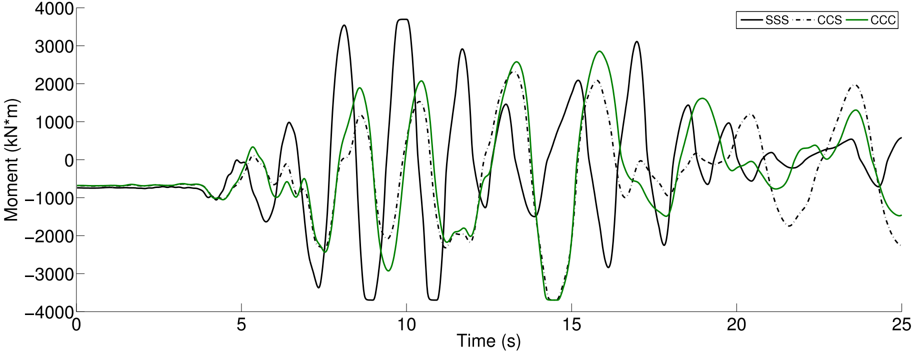


Detailed 3D Bridge Model, 3 Bends

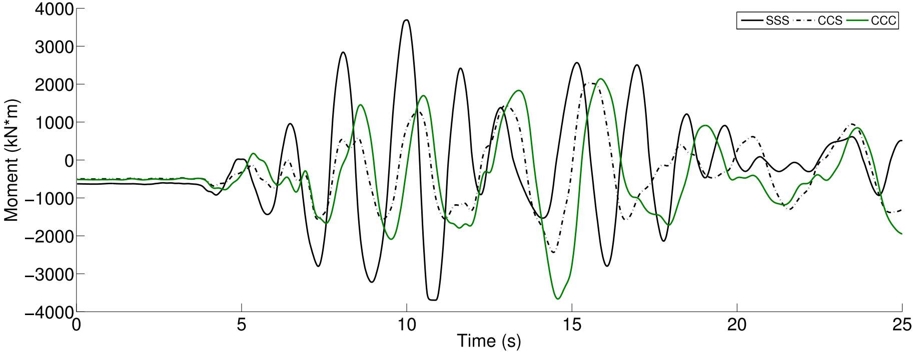




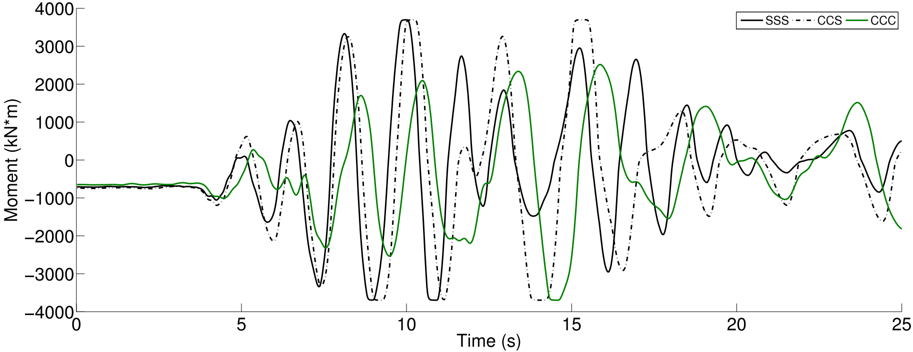
Short Period E.: Moments, Bent #1, SSS, CCS, CCC



Short Period E.: Moments, Bent #2, SSS, CCS, CCC



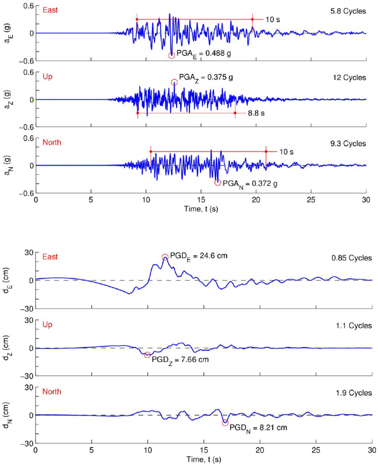
Short Period E.: Moments, Bent #3, SSS, CCS, CCC

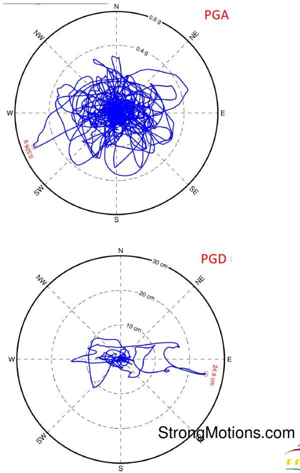


Nuclear Power Plants, Modelling Issues

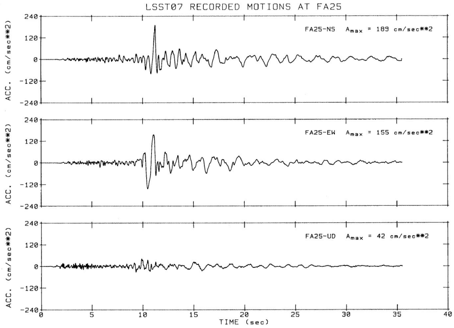
- Nuclear Power Plants (NPPs), early use of SSI analysis (SASSI, CLASSI, &c.)
- State of practice for ESSI analysis of NPPs:
  - Linear elastic material
  - 1D seismic motions
  - Incoherent seismic motions
- Current state of art for ESSI analysis of NPPs:
  - Nonlinear soil, rock, contact, structure
  - 3D (6D) seismic motions
- Seismic motions issue/problem

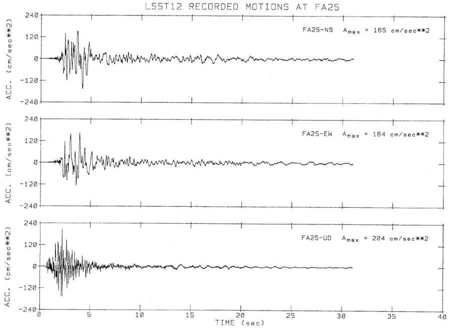
Example Earthquake: M 6.6, Norcia, Italy, 30Oct2016





1D, 2D, 3D Earthquakes?

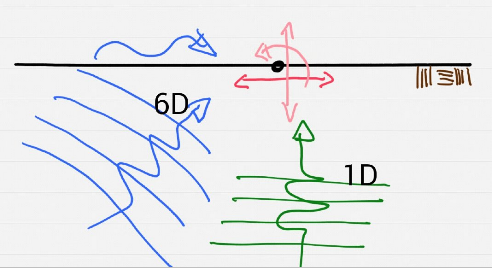




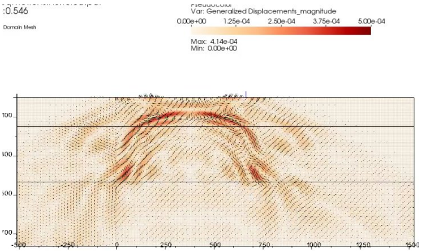
- SMART-1 array, Lotung, Taiwan,
- LSST07: almost 2D (the only one!)
- LSST12: full 3D

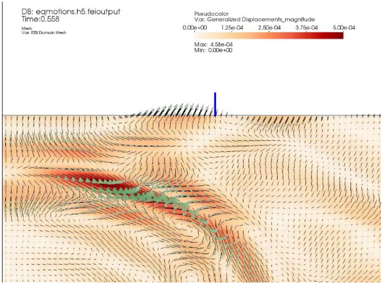
3D (6D) or 1D Seismic Motions for NPPs

- 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



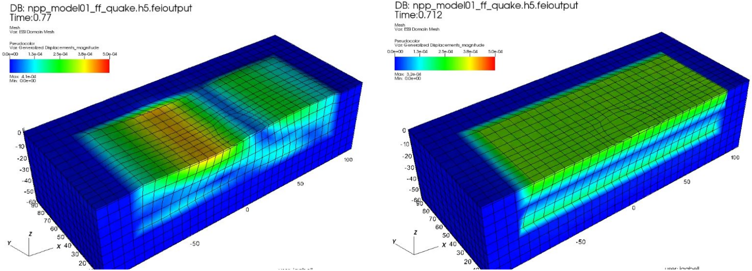
Synthetic (Realistic) Test Motions



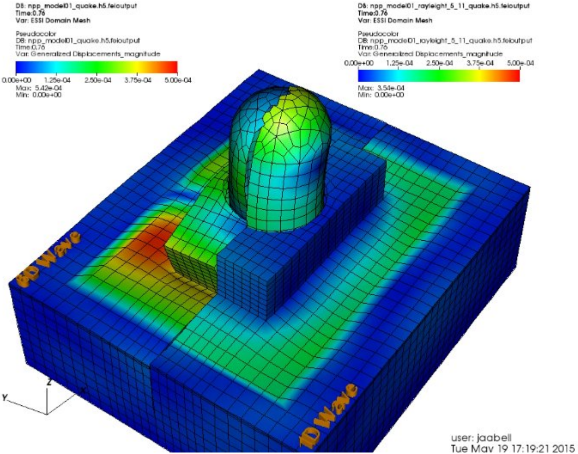


Synthetic Test Motions, 6D vs 1D

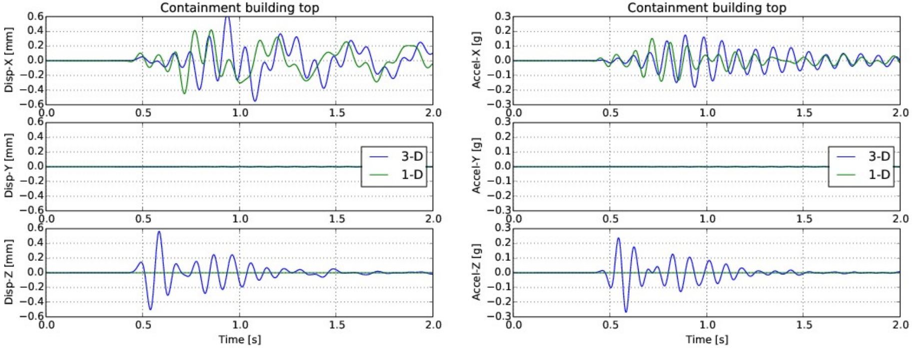
- Danger of picking one component (1D) of motions
- Excellent (forced) fit, but it is not a prediction



6D vs 1D NPP ESSI Response Comparison



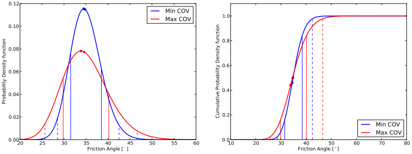
6D vs 1D NPP ESSI, Top of Containment, Differences



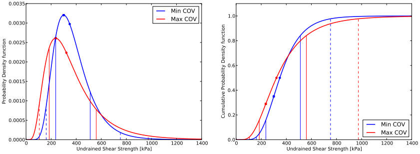
Uncertain Material Parameters and Loads

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

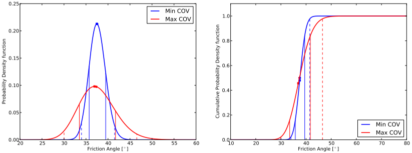
Parametric Uncertainty: Material Properties



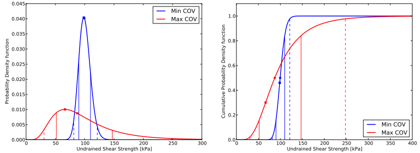
Field ϕ



Field c_u



Lab ϕ



Lab c_u

Uncertainty Propagation through Inelastic System

- Incremental el–pl constitutive equation

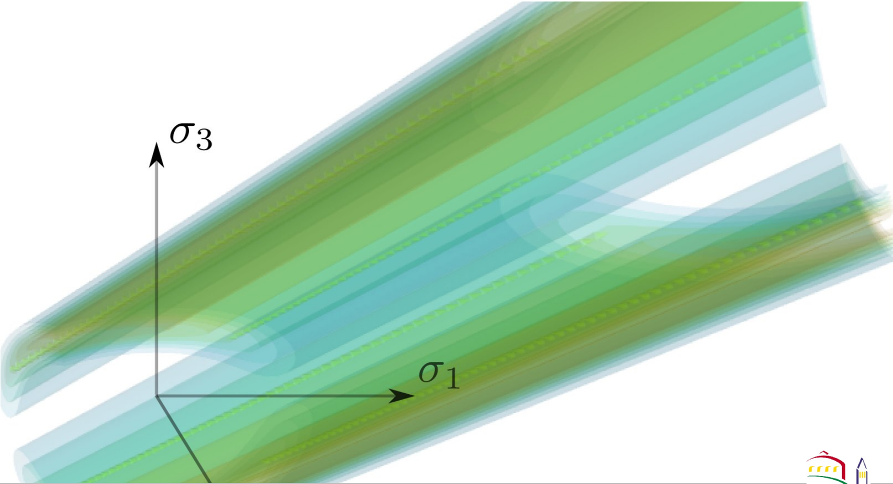
$$\Delta\sigma_{ij} = E^{EP}_{ijkl} = \left[E^{el}_{ijkl} - \frac{E^{el}_{ijmn} m_{mn} n_{pq} E^{el}_{pqkl}}{n_{rs} E^{el}_{rstu} m_{tu} - \xi_* h_*} \right] \Delta\epsilon_{kl}$$

- Dynamic Finite Elements

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

- What if all (any) material and load parameters are uncertain

Probabilistic Elasto-Plasticity: von Mises Surface



Probabilistic Stress Solution: Eulerian–Lagrangian form of FPK Equation

$$
\begin{aligned}
\frac{\partial P(\sigma_{ij}(x_t,t),t)}{\partial t} = \frac{\partial}{\partial \sigma_{mn}} \Bigg[\Bigg\{ \Bigg\langle \eta_{mn}(\sigma_{mn}(x_t,t), E_{mnrs}(x_t), \epsilon_{rs}(x_t,t)) \Bigg\rangle \\
+ \quad \int_0^t d\tau Cov_0 \left[\frac{\partial \eta_{mn}(\sigma_{mn}(x_t,t), E_{mnrs}(x_t), \epsilon_{rs}(x_t,t))}{\partial \sigma_{ab}}; \right. \\
\left. \eta_{ab}(\sigma_{ab}(x_{t-\tau}, t-\tau), E_{abcd}(x_{t-\tau}), \epsilon_{cd}(x_{t-\tau}, t-\tau) \right] \Bigg\} P(\sigma_{ij}(x_t,t),t) \Bigg] \\
+ \quad \frac{\partial^2}{\partial \sigma_{mn} \partial \sigma_{ab}} \Bigg[\Bigg\{ \int_0^t d\tau Cov_0 \Big[\eta_{mn}(\sigma_{mn}(x_t,t), E_{mnrs}(x_t), \epsilon_{rs}(x_t,t)); \\
\eta_{ab}(\sigma_{ab}(x_{t-\tau}, t-\tau), E_{abcd}(x_{t-\tau}), \epsilon_{cd}(x_{t-\tau}, t-\tau)) \Big] \Bigg\} P(\sigma_{ij}(x_t,t),t) \Bigg]
\end{aligned}
$$

(Jeremić et al. 2007, Sett and Jeremić 2010, Sett et al. 2007, 2011)

Eulerian–Lagrangian FPK Equation and (SEP)FEM

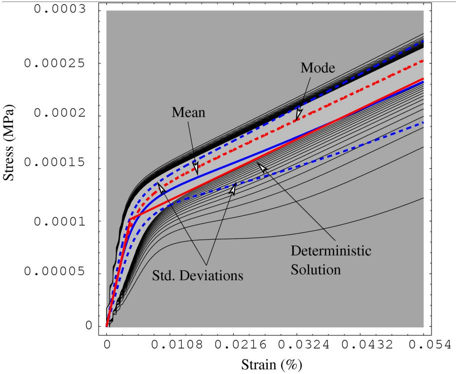
- Advection-diffusion equation

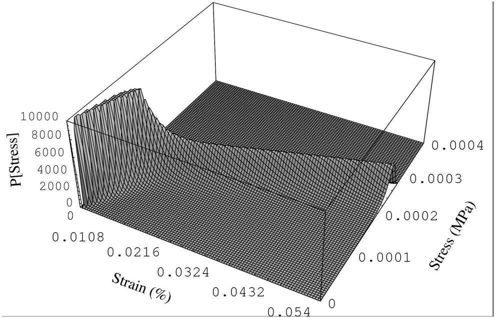
$$\frac{\partial P(\sigma_{ij},t)}{\partial t} = -\frac{\partial}{\partial \sigma_{ab}}\left[N_{ab}^{(1)}P(\sigma_{ij},t) - \frac{\partial}{\partial \sigma_{cd}}\left\{N_{abcd}^{(2)}P(\sigma_{ij},t)\right\}\right]$$

- **Complete** probabilistic description of response
- **Second-order exact** to covariance of time (exact mean and variance)
- Any uncertain FEM problem ($\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{F}$) with
  - uncertain material parameters (stiffness matrix **K**),
  - uncertain loading (load vector **F**)

  can be analyzed using PEP and SEPFEM to obtain PDFs of DOFs, stress, strain...

Probabilistic Elastic-Plastic Response





Spectral Stochastic Elastic–Plastic FEM

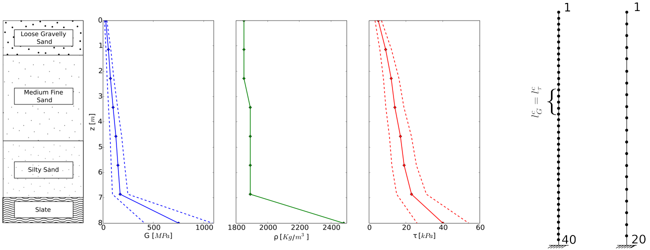
- Minimizing norm of error of finite representation using Galerkin technique (Ghanem and Spanos 2003, Sett et al. 2011):

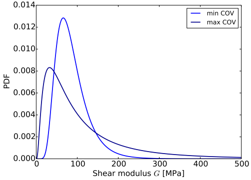
$$\sum_{n=1}^{N} K_{mn}^{ep} d_{ni} + \sum_{n=1}^{N} \sum_{j=0}^{P} d_{nj} \sum_{k=1}^{M} C_{ijk} K'^{ep}_{mnk} = \langle F_m \psi_i[\{\xi_r\}] \rangle$$

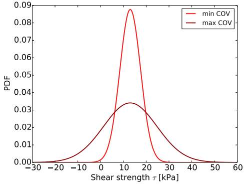
$$K_{mn}^{ep} = \int_D B_n E^{ep} B_m dV \qquad K'^{ep}_{mnk} = \int_D B_n \sqrt{\lambda}_k h_k B_m dV$$

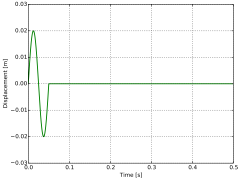
$$C_{ijk} = \langle \xi_k(\theta) \psi_i[\{\xi_r\}] \psi_j[\{\xi_r\}] \rangle \qquad F_m = \int_D \phi N_m dV$$

Wave Propagation Through Uncertain Soil

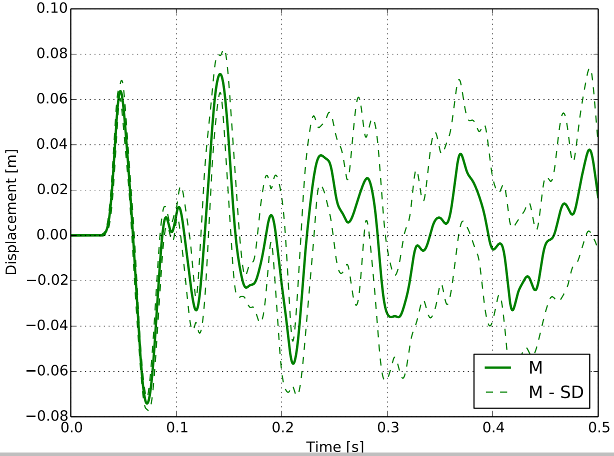




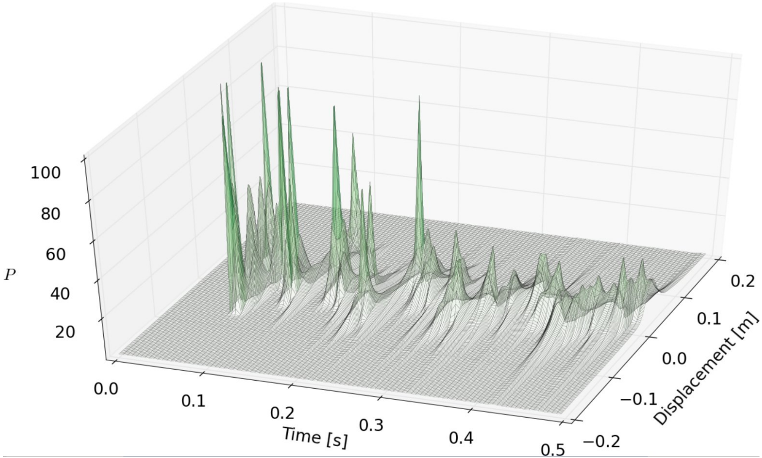




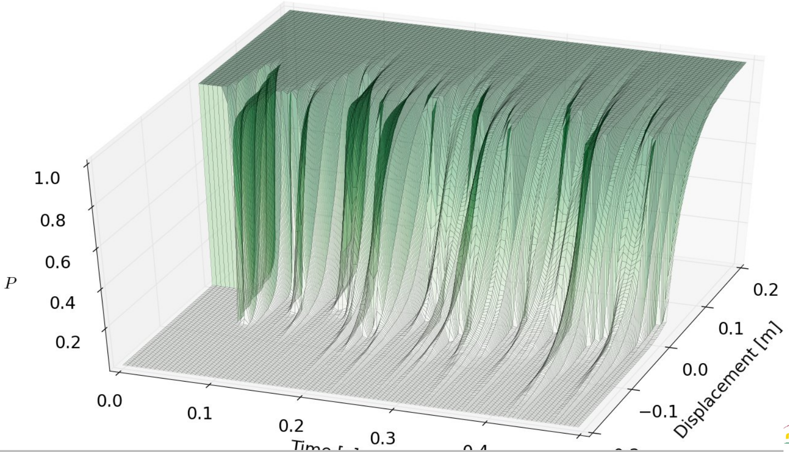
Uncertain Response at the Surface (COV = 120%)



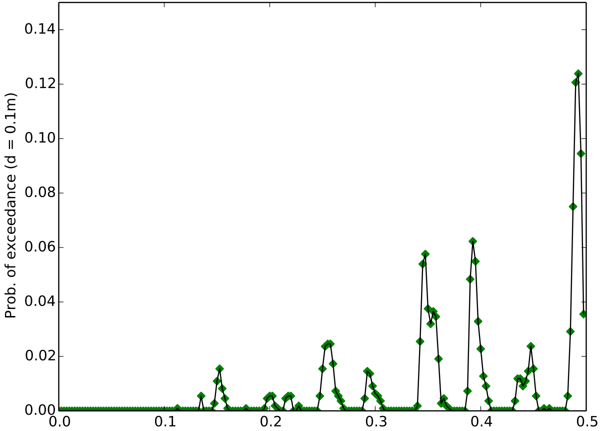
Displacement PDFs at the Surface (COV = 120%)



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



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



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Summary

- High fidelity modeling and simulation allows reduction of modeling uncertainty and direct propagation of parametric uncertainties through the dynamic ESSI system
- Development and expert use of high fidelity modeling and simulation numerical tools: Real ESSI Simulator System
- Education and training of users (researchers, designers, regulators, owners) will prove essential
- Collaborators: Yang, Cheng, Jie, Sett, Taiebat, Tafazzoli, Karapiperis, Abell, Pisanò, Feng, Sinha, Lacour, Yang, Behbehani, Wang, Petrone, Wong, McKenna, McCallen
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