Time Domain Nonlinear Earthquake Soil Structure Interaction Analysis

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Outline

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Motivation

Improve modeling and simulation for infrastructure objects

Control modeling, epistemic uncertainty

Propagate parametric, aleatory uncertainty

Predict and inform, Engineer needs to know!

Design, build and maintain sustainable objects



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!"

"There are engineers and then there are Engineers!"


Dedication

Nebojša Orbović, 1962-2021

"As an engineer, I have to know, with good accuracy, what will happen to the structure during loading, hence numerical analysis and verification and validation for numerical analysis is really important"

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

Engineer Needs to Know!

Engineer needs versatile, quality assured analysis tool

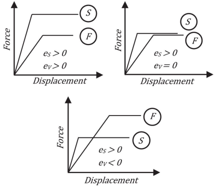
- Explore different design options
- Assess object performance

Choice of analysis/modeling level of sophistication

Predict and Inform

Numerical Prediction under Uncertainty

- Modeling, Epistemic Uncertainty
  - Modeling simplifications
  - Model sophistication
  - Verification and Validation
  - Elastic design does NOT guaranty safe structure!



- 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 σ_{ij}, ϵ_{ij}, u_i, $\dot{u}_i$, $\ddot{u}_i$

Outline

Real-ESSI Simulator System

The Real-ESSI, **Real**istic Modeling and Simulation of **E**arthquakes, **S**oils, **S**tructures and their **I**nteraction Simulator is a software, hardware and documentation system for time domain, linear and nonlinear, elastic and inelastic, deterministic or probabilistic, 3D, modeling and simulation of:

- statics and dynamics of soil,
- statics and dynamics of rock,
- statics and dynamics of structures,
- statics of soil-structure systems, and
- dynamics of earthquake-soil-structure system interaction

Used for:

- Design, linear elastic, load combinations, dimensioning
- Assessment, nonlinear/inelastic, safety margins

Real-ESSI Simulator System

Components

- Real-ESSI Pre (gmsh/gmESSI, X2ESSI)
- Real-ESSI Program (local, remote, cloud)
- Real-ESSI Post (Paraview/pvESSI, Python, Matlab)

Availability, free executable downloads:

- MS-Windows
- MacOS
- Linux
- Amazon Web Services

Real-ESSI program, documentation, examples:

`http://real-essi.us/`

Real-ESSI Simulator Quality Assurance

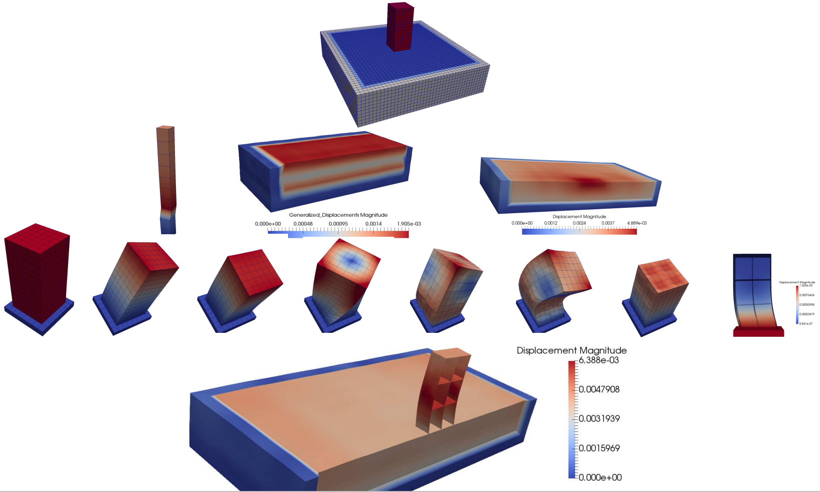
- Verification available for each element, model, algorithm, ...

- Validation partially available, working with UCSD, TJU...

Real-ESSI Modeling Features

- Solids: dry, saturated/liquefaction, elastic, elastic-plastic
- Structural elements: beams (B,T), shells, elastic, inelastic
- Contact/interface/joint elements: gapping, frictional
- Super element: stiffness and mass matrices
- Material models: soil, rock, concrete, steel...
- Seismic input: 1C and 3C, deterministic or probabilistic
- Energy calculations: input, el-pl, viscous, algorithmic
- Solid/Structure-Fluid interaction, full coupling, OpenFOAM
- Forward probabilistic inelastic modeling
- Backward probabilistic inelastic modeling: Sensitivities
- Input: Domain Specific Language

ESSI Modeling Phases



Real-ESSI Core Functionality

- Inelastic, nonlinear analysis for professional practice
- Low/medium/high sophistication models for ESSI analysis
- Set of suggested modeling and simulation parameters
- Investigate sensitivity of response to model sophistication
- Investigate sensitivity of response to model parameters

Real-ESSI Core Functionality Components

- Structural elements: Truss, Beam, Shell, Super-Element
- Soil, solids: elastic, G/G_{max}
- Contacts/interfaces/joints: Bonded, Frictional, Gap open/close
- Loads: Static, Dynamic, Earthquake 1C/3$\times$1C/3C, Restart
- Simulation: explicit/no-equilibrium, Implicit/equilibrium
- Core Functionality Application programs: APs

Real-ESSI Education and Training

- In-person and online courses
- Lecture Notes/Book:
  (I) Theory and Computational Formulation,
  (II) Software and Hardware System,
  (III) Verification and Validation,
  (IV) Modeling and Simulation Examples,
  (V) Application to Practical Engineering Problems.
- Nonlinear SSI workshop at SMiRT26
- Nonlinear SSI short course at SMiRT26
- Documentation and Program at `http://real-essi.us/`

Outline

Verification and Validation

- Verification: provides evidence that the model is solved correctly. Mathematics issue. Well developed for the Real ESSI Simulator.

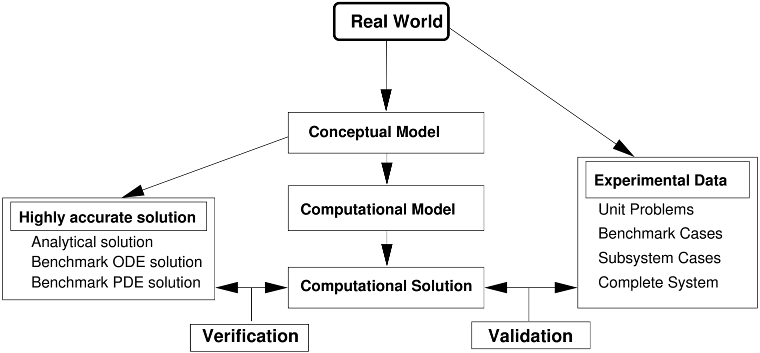
- Validation: provides evidence that the correct model is solved. Physics issue. Work in progress (UCSD, TJU, ...)

- Prediction: 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.

V & V Motivation

- How much can we trust model implementations?
- How much can we trust numerical simulations?
- How good are our numerical predictions?
- Can simulation tools be used for improving safety and economy?
- V & V procedures are the primary means of assessing accuracy and building confidence and credibility in modeling and computational simulations

Fundamentals of Verification and Validation



V & V Important Documents

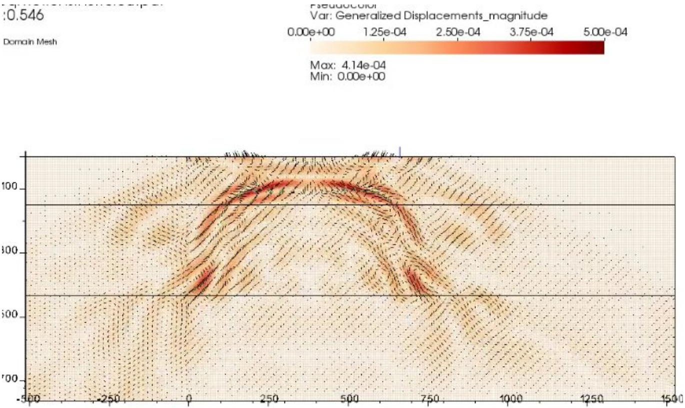
- PJ ROACHE. Verification and Validation in Computational Science and Engineering. Hermosa publishers, (1998).
- WL Oberkampf and CJ Roy. Verification and Validation in Scientific Computing. Cambridge University Press, (2010).
- ASME-VV-10, ASME-VV-20, (2019).
- ISO-90003. ISO/IEC/IEEE 90003, (2018)
- SASSI Verification Project, (2015)

Verification and Validation Summary

- V&V most important for providing confidence in results
- FEM analysis model verification is essential too!
- Numerical analysis should not be used without V&V

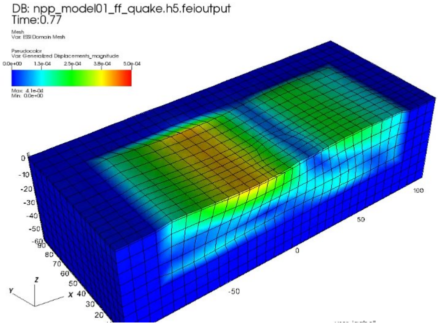
Outline

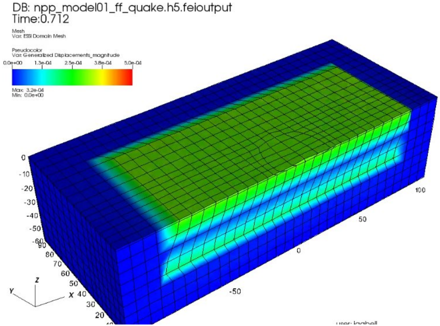
Realistic Ground Motions



1C vs 6C Free Field Motions

- One component of motions, 1C from 6C
- Excellent fit, wrong dynamics





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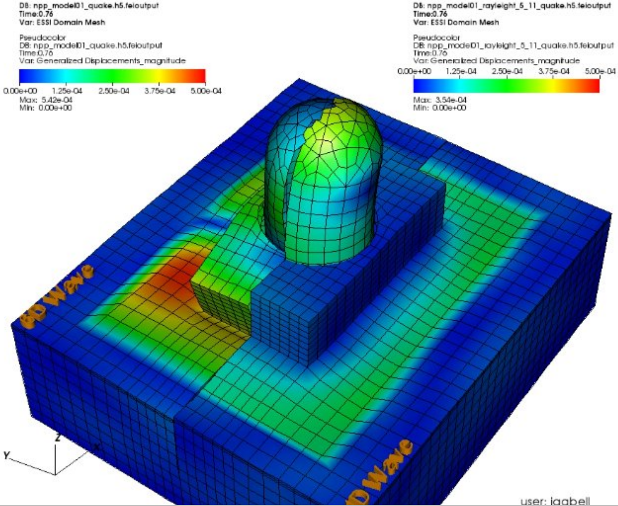
6C vs 1C NPP ESSI Response Comparison



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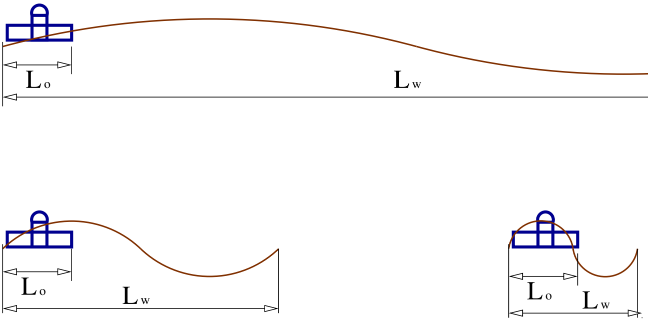
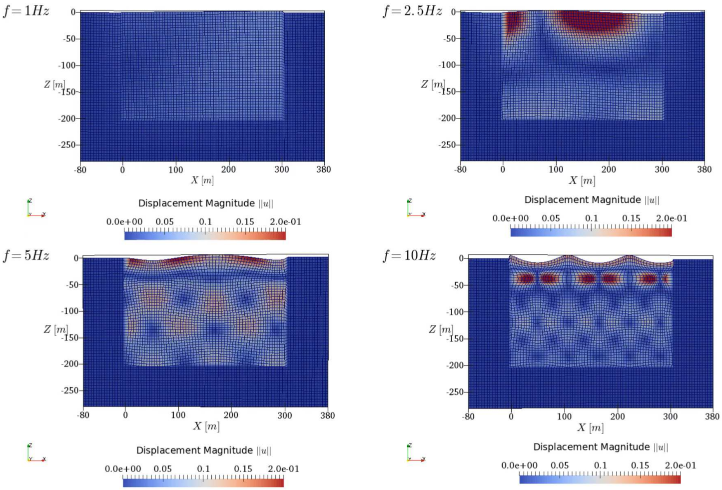
When to use 3C and/or 3×1C



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



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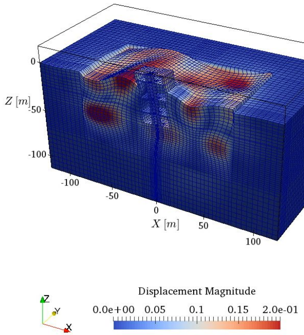
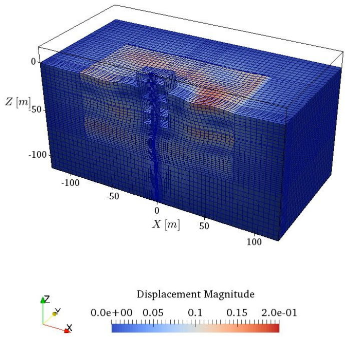
SMR ESSI, 3C vs 3$\times$1C

$3C$



$3 \times 1C$



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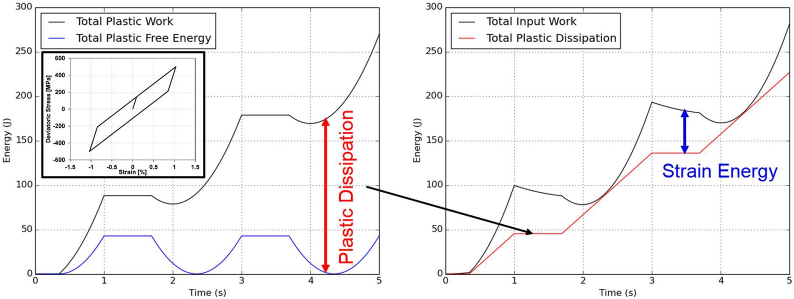
Outline

Energy Input and Dissipation

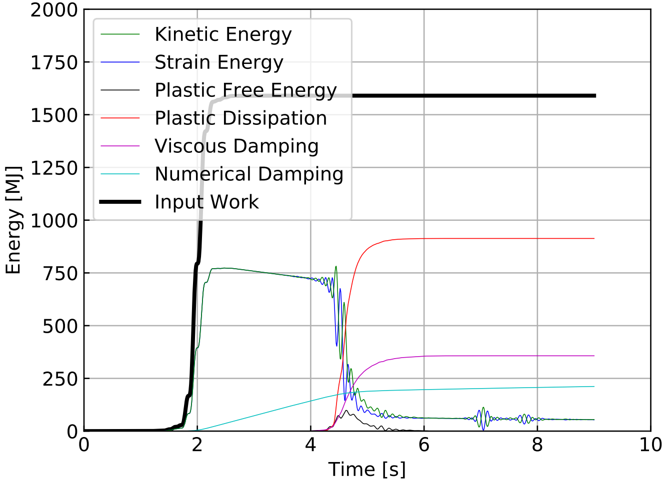
- Energy input, dynamic forcing
- Energy dissipation outside SSI domain:
  - SSI system oscillation radiation
  - Reflected wave radiation
- Energy dissipation/conversion inside SSI domain:
  - Inelasticity of soil, contact zone, structure, foundation, dissipators
  - Viscous coupling with internal/pore fluids, and external fluids
- Numerical energy dissipation/production

Plastic Energy Dissipation

- Single elastic-plastic element under cyclic shear loading
  - Difference between plastic work and plastic dissipation
  - Plastic work can decrease
  - Plastic dissipation always increases



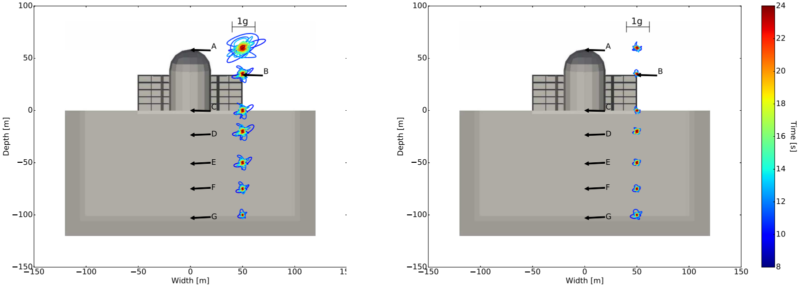
Energy Dissipation Control



Inelastic Modeling of Soil Structure Systems

- Soil, inelastic, elastic-plastic
  - Dry, single phase
  - Unsaturated, partially saturated
  - Fully saturated
- Contact/interface/joint, inelastic, soil/rock – foundation
  - Dry, single phase,
    - Normal, hard and soft, gap open/close
    - Friction, nonlinear
  - Fully saturated, suction, excess pressure, buoyant force
- Structure, inelastic, damage, cracks
  - Nonlinear/inelastic reinforced concrete fiber beam
  - Nonlinear/inelastic reinforced concrete solid element
  - Alcali Silica Reaction concrete modeling

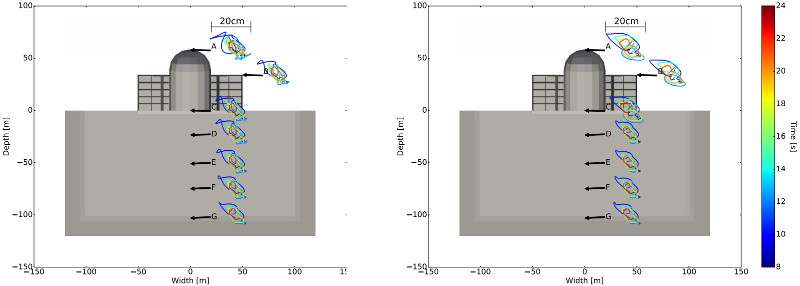
Acceleration Traces, Elastic vs Inelastic



Elastic

Inelastic

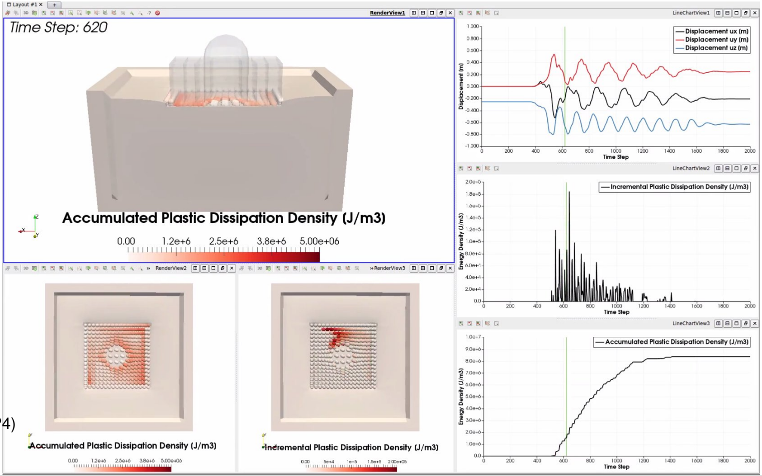
Displacement Traces, Elastic vs Inelastic



Elastic

Inelastic

NPP: Plastic Energy Dissipation



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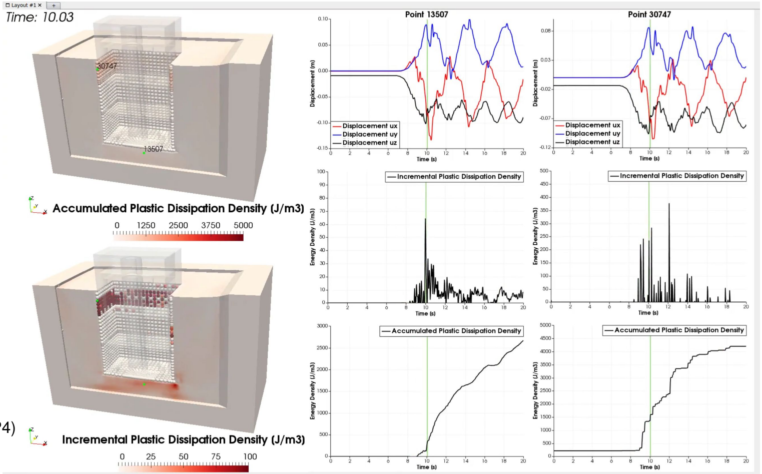
SMR: Plastic Energy Dissipation



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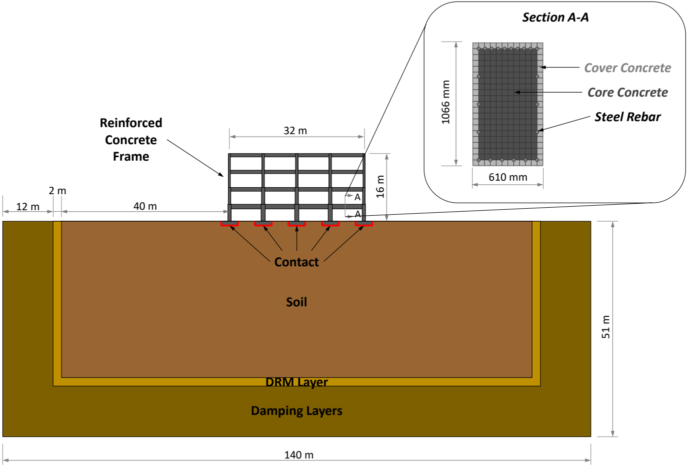
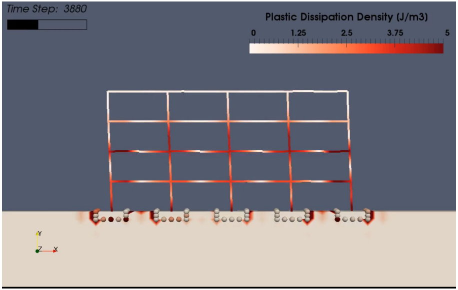
Energy Dissipation for Design



Design Alternatives



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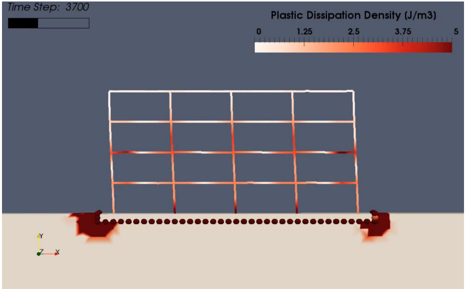

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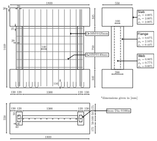
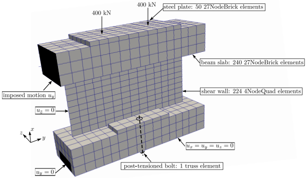
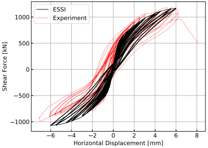
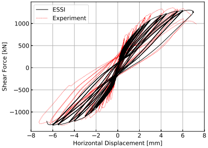
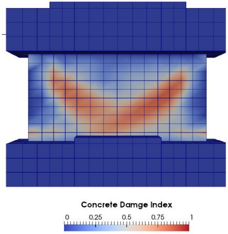
Regular and ASR Concrete

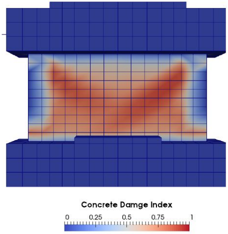


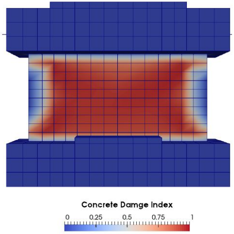








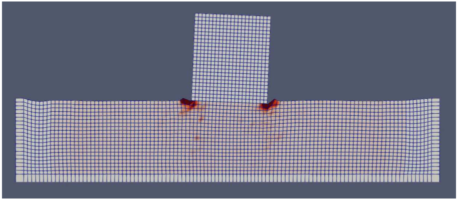




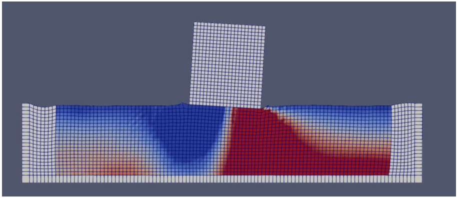
$u_y = 1.4$ mm $u_y = 1.8$ mm $u_y = 3.0$ mm

Building on Liquefiable Soil

Plastic Strain



Pore Fluid Pressures



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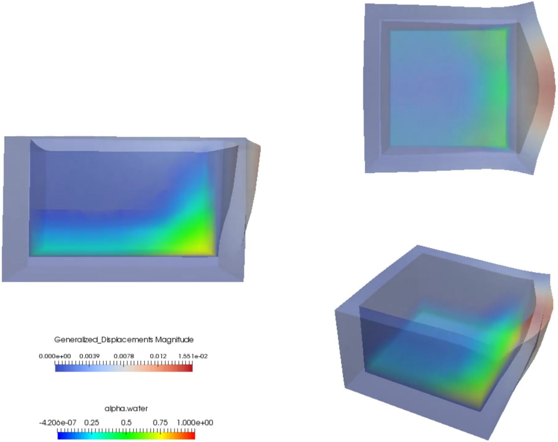
Solid, Structure-Fluid Interaction, Example



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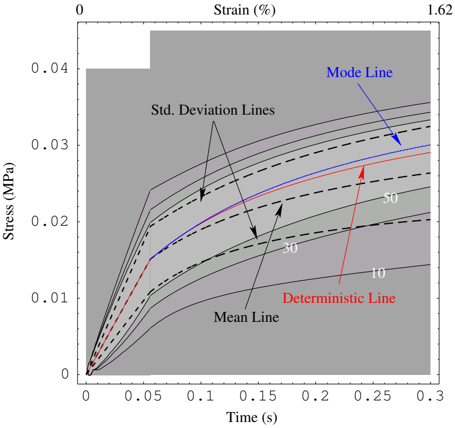
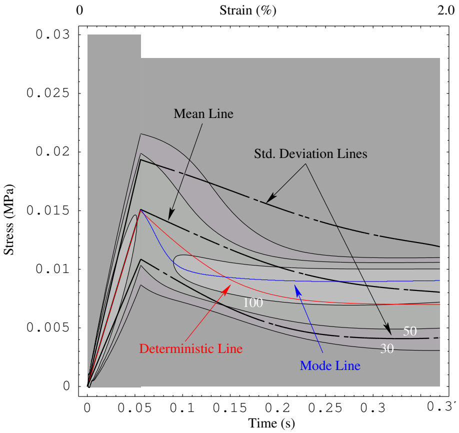
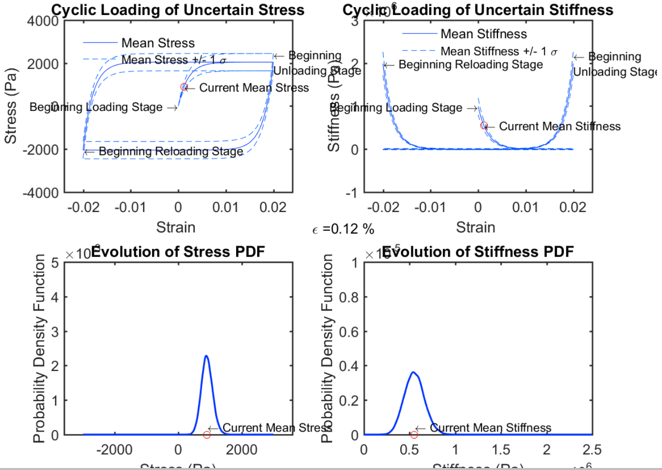
Outline

El-Pl, Cam Clay with Random G, M and p_0





Probabilistic Cyclic Elastic-Plastic Response



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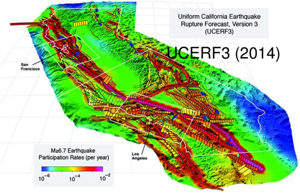
Stochastic Ground Motion Modeling

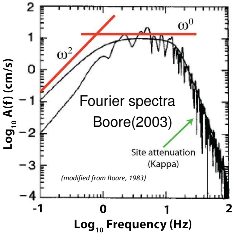
- Shift from modeling specific Intensity Measures (IMs) to fundamental characteristics of ground motions
  - Uncertain Fourier amplitude spectra (FAS)
  - Uncertain Fourier phase spectra (FPS)
- No need to define Intensity Measures!
- GMPE studies of FAS, (*Bora et al. (2018)*, *Bayless & Abrahamson (2018,2019)*, *Stafford(2017)*,)
- Stochastic FPS by phase derivative (Boore,2005) (Logistic phase derivative model by *Baglio & Abrahamson (2017)*)
- Near future change from $\boldsymbol{Sa}(\boldsymbol{T_0})$ to **FAS**

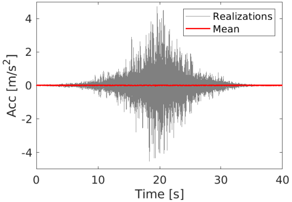
Application: Seismic Hazard

Seismic source characterization



Stochastic ground motion



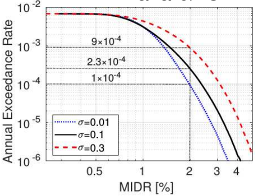


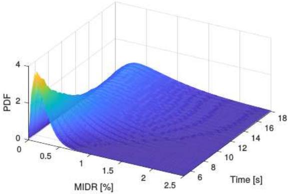
$$\lambda(EDP > z) = \sum N_i(M_i, R_i) P(EDP > z | M_i, R_i)$$

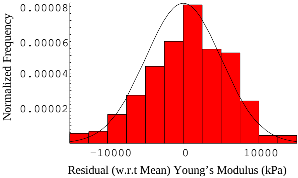
Uncertainty propagation
SEPFEM

Uncertainty characterization
Hermite polynomial chaos

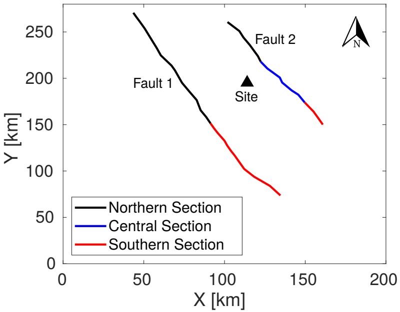
EDP hazard/risk

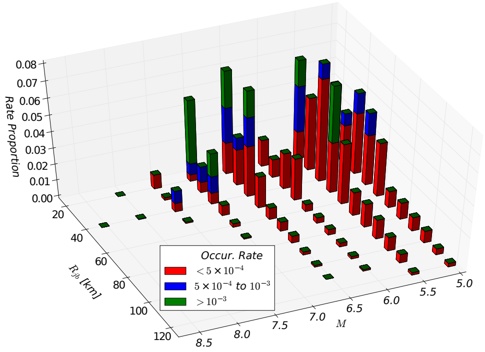






Example Soil-Structure/Location





- Fault 1: San Gregorio fault
- Fault 2: Calaveras fault
- Uncertainty: Segmentation, slip rate, rupture geometry, etc.

- 371 total seismic scenarios
- M 5 $\sim$ 5.5 and 6.5 $\sim$ 7.0
- R_{jb} 20km $\sim$ 40km

Seismic Risk Analysis, Forward Propagation

- No need to define Intensity Measures!

- Damage measure defined on single EDP:

DM	MIDR>0.5%	**MIDR>1%**	MIDR>2%	PFA>0.5$\mathrm{m/s^2}$	**PFA>1$\mathbf{m/s^2}$**	PFA>1.5$\mathrm{m/s^2}$
Risk [/yr]	6.66×10^{-3}	$\mathbf{3.83\times10^{-3}}$	9.97×10^{-5}	6.65×10^{-3}	$\mathbf{1.92\times10^{-3}}$	9.45×10^{-5}

- Damage measure (DM) defined on multiple EDPs:

  DM : $\{\text{MIDR} > 1\% \cup \text{PFA} > 1\mathrm{m/s^2}\}$, seismic risk is $\mathbf{4.2 \times 10^{-3}/yr}$

  DM : $\{\text{MIDR} > 1\% \cap \text{PFA} > 1\mathrm{m/s^2}\}$, seismic risk is $\mathbf{1.71 \times 10^{-3}/yr}$

- Seismic risk for DM defined on multiple EDPs can be quite different from that defined on single EDP.

Sensitivity Analysis, Backward Propagation

- Sensitivity of forward uncertain response to input uncertainties
- Analytic sensitivity analysis development
- Total variance in PGA, in this case, dominated by uncertain ground motions

  49% from uncertain rock motions at depth

  2% from uncertain soil

  49% from interaction of uncertain rock motions and uncertain soil

Outline

Summary

- Predict and Inform, Engineer Needs to Know!
- Teacher, Motivator, Supporter: Robert P Kennedy
- Collaborators: Yang, Feng, Behbehani, Sinha, Wang, Wang, Pisanó, Abell, Tafazzoli, Jie, Preisig, Tasiopoulou, Watanabe, Luo, Cheng, Yang, Lizundia, Rangelow, Vögeli, Salamon, Altinyollar, ...
- Much appreciated is collaboration with and funding from the USDOE, USNRC, USNSF, USFEMA, USBR, ETHZ, CNSC/CCSN, UN-IAEA, CH-ENSI/IFSN, Basler&Hofmann and Shimizu Corp.
- `http://real-essi.us/`