Nuclear Installation Lifecycle: Modeling and Simulation of Design Basis and Beyond Design Basis ESSI Behavior

Yuang Feng, Han Yang, Hexiang Wang, Fangbo Wang,

Boris Jeremić

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

SMiRT25
Charlotte, NC, USA, August 2019

Outline

Introduction

Modeling and Simulation of ESSI for Nuclear Installations

Conclusion

Outline

Introduction

Modeling and Simulation of ESSI for Nuclear Installations

Conclusion

Motivation

Improve modeling and simulation for infrastructure objects

Expert numerical modeling and simulation tool

Control and reduce modeling uncertainty

Goal: Predict and Inform rather than fit

Engineer needs to know!

System for modeling and simulation of Earthquakes and/or Soils and/or Structures and their Interaction:
Real-ESSI, **http://real-essi.info/**

Prediction under Uncertainty

- Modeling Uncertainty, Simplifying assumptions

  Low, medium, high sophistication modeling and simulation

  Choice of sophistication level for confidence in results

- Parametric Uncertainty, $M\ddot{u}_i + C\dot{u}_i + K^{ep}u_i = F(t)$,

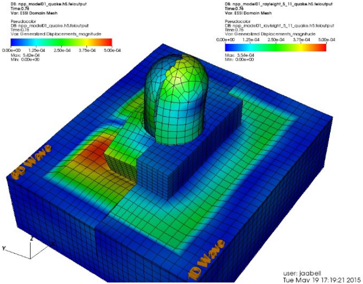
  Uncertain mass M, viscous damping C and stiffness K^{ep}

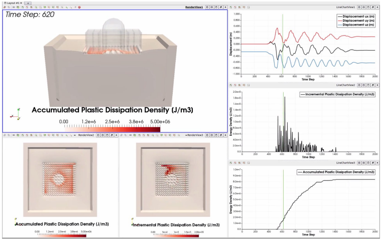
  Propagation of uncertainty in loads, $F(t)$

  Results are PDFs and CDFs for σ_{ij}, ϵ_{ij}, u_i, $\dot{u}_i$, $\ddot{u}_i$

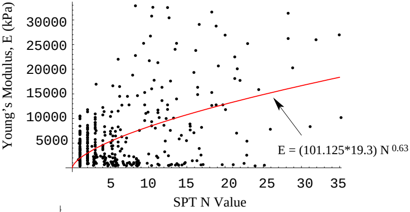
Modeling Uncertainty

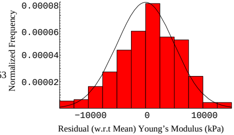
- Important (?!) features are simplified, 1C vs 3C, inelasticity
- Modeling simplifications are justifiable if one or two level higher sophistication model demonstrates that features being simplified out are not important

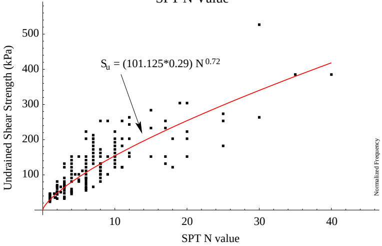


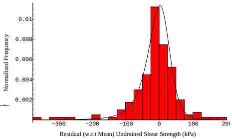


Parametric Uncertainty: Soil Stiffness and Strength









(cf. Phoon and Kulhawy (1999B

Outline

Introduction

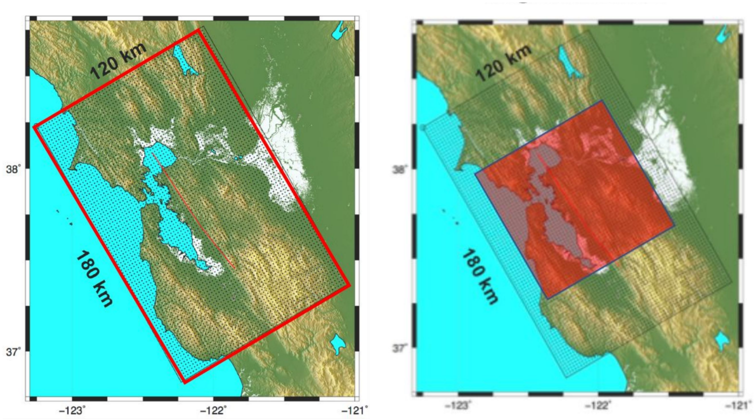
Modeling and Simulation of ESSI for Nuclear Installations

Conclusion

Regional Geophysical Models

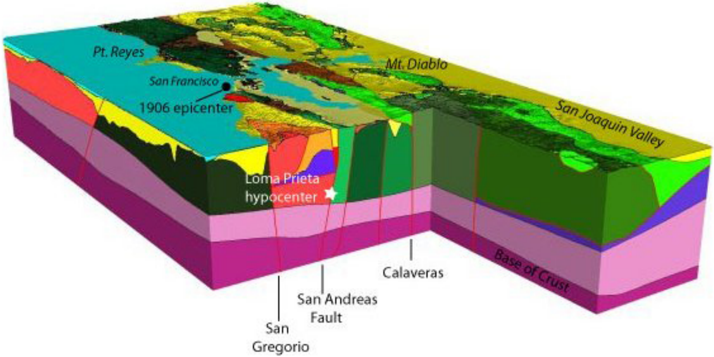
- Free Field seismic motions on regional scale
- Knowledge of geology (deep and shallow) needed
- Developed using SW4 and/or Real-ESSI
- Collaboration with LLNL: Dr. Rodgers, Dr. Pitarka and Dr. Petersson

Regional Geophysical Models



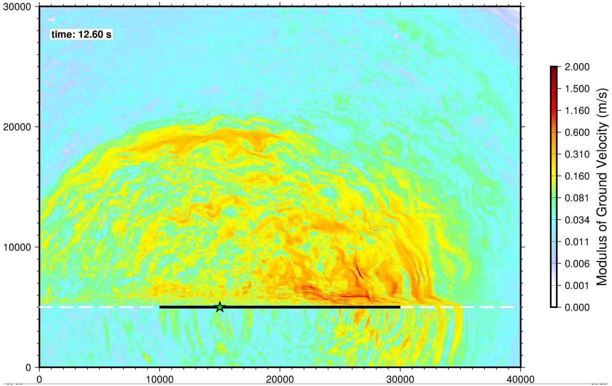
Rodgers and Pitarka

Regional Geophysical Models



USGS

Example Regional Model (Rodgers)



(MP4)

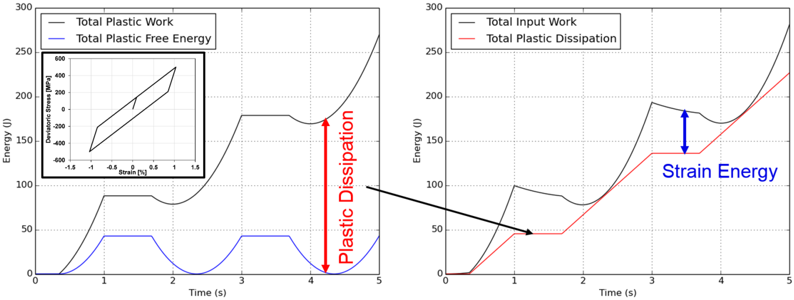
Energy Input and Dissipation

- 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

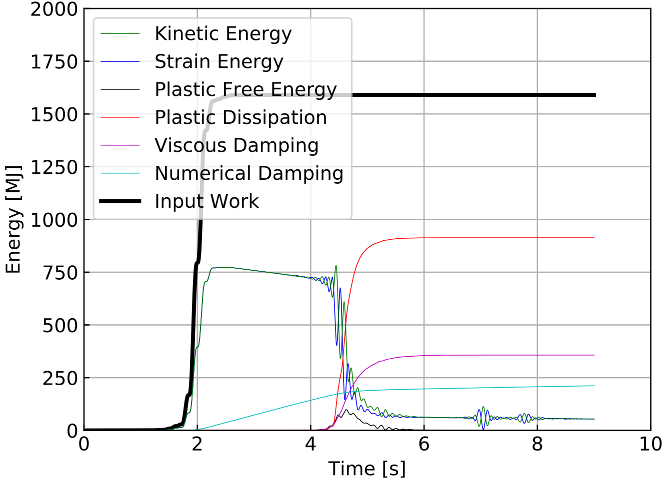
Plastic Energy Dissipation

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

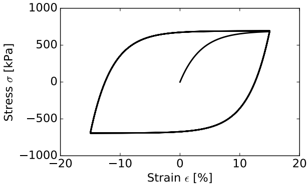


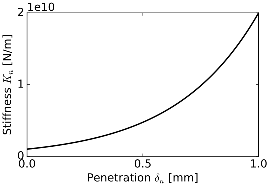
Inelastic Modeling of Soil Structure Systems

- Soil, inelastic, elastic-plastic
  - Dry, single phase
  - Unsaturated, partially saturated
  - Fully saturated
- Contact, 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 1D reinforced concrete fiber beam
  - Nonlinear/inelastic 3D reinforced concrete solid element
  - Alcali Silica Reaction concrete modeling

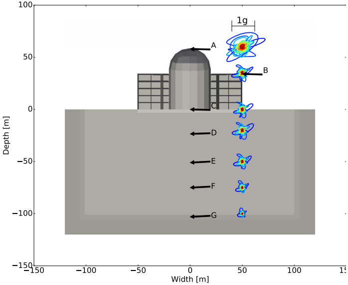
Inelastic Soil and Inelastic Contact

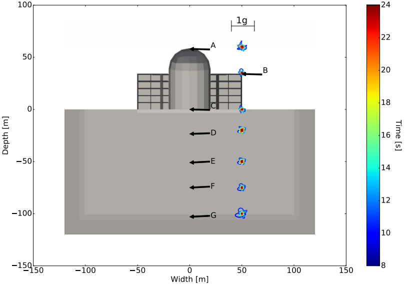
- Shear velocity of soil $V_s = 500 m/s$
- Undrained shear strength (Dickenson 1994) $V_s[m/s] = 23(S_u[kPa])^{0.475}$
- For $V_s = 500 m/s$ Undrained Strength $S_u = 650 kPa$ and Young's Modulus of $E = 1.3 GPa$
- von Mises, Armstrong Frederick kinematic hardening ($S_u = 650 kPa$ at $\gamma = 0.01\%$; $h_a = 30 MPa$, $c_r = 25$)
- Soft contact (concrete-soil), gaping and nonlinear shear





Acceleration Traces, Elastic vs Inelastic

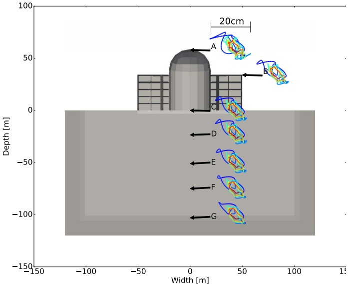


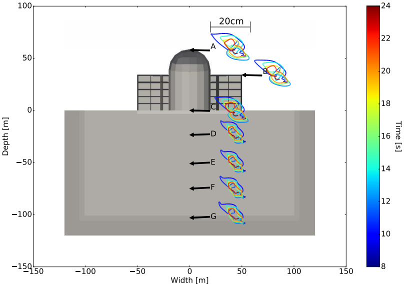


Elastic

Inelastic

Displacement Traces, Elastic vs Inelastic

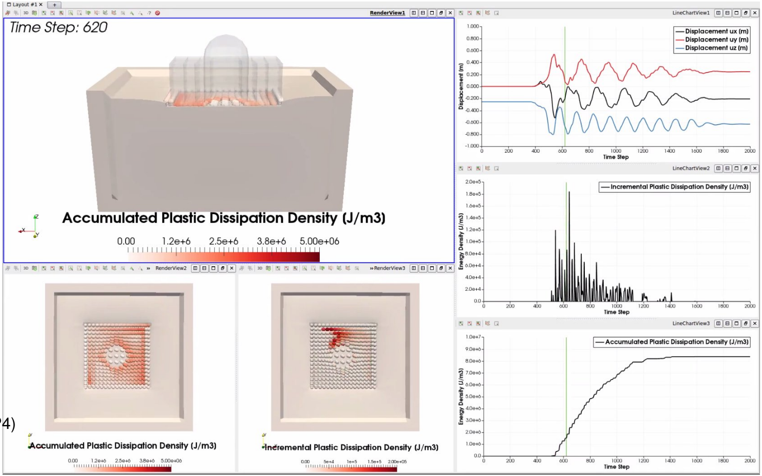




Elastic

Inelastic

Energy Dissipation in a Large-Scale Model



(MP4)

Uncertainty Propagation through Inelastic System

- Incremental el–pl constitutive equation

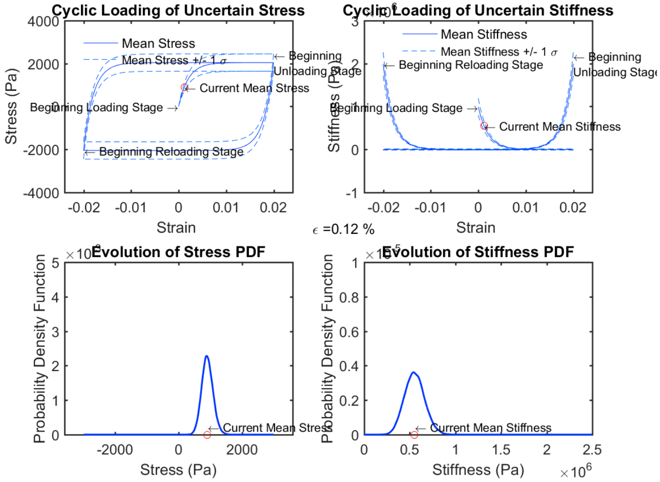
$$\Delta\sigma_{ij} = E^{EP}_{ijkl}\ \Delta\epsilon_{kl} = \left[E^{el}_{ijkl} - \frac{E^{el}_{ijmn} m_{mn} n_{pq} E^{el}_{pqkl}}{n_{rs} E^{el}_{rstu} m_{tu} - \xi_* h_*} \right] \Delta\epsilon_{kl}$$

- Dynamic Finite Elements

$$M\ddot{u}_i + C\dot{u}_i + K^{ep} u_i = F(t)$$

- Material and load parameters are uncertain

Probabilistic Elastic-Plastic Modeling



Stochastic Elastic-Plastic Finite Element Method

- Material uncertainty expanded into stochastic shape funcs.
- Loading uncertainty expanded into stochastic shape funcs.
- Displacement expanded into stochastic shape funcs.

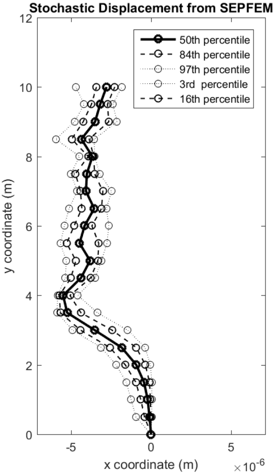
$$\begin{bmatrix} \sum_{k=0}^{P_d} < \Phi_k \Psi_0 \Psi_0 > K^{(k)} & \dots & \sum_{k=0}^{P_d} < \Phi_k \Psi_P \Psi_0 > K^{(k)} \\ \sum_{k=0}^{P_d} < \Phi_k \Psi_0 \Psi_1 > K^{(k)} & \dots & \sum_{k=0}^{P_d} < \Phi_k \Psi_P \Psi_1 > K^{(k)} \\ \vdots & \vdots & \vdots & \vdots \\ \sum_{k=0}^{P_d} < \Phi_k \Psi_0 \Psi_P > K^{(k)} & \dots & \sum_{k=0}^{M} < \Phi_k \Psi_P \Psi_P > K^{(k)} \end{bmatrix} \begin{bmatrix} \Delta u_{10} \\ \vdots \\ \Delta u_{N0} \\ \vdots \\ \Delta u_{1P_u} \\ \vdots \\ \Delta u_{NP_u} \end{bmatrix} = \begin{bmatrix} \sum_{i=0}^{P_f} f_i < \Psi_0 \zeta_i > \\ \sum_{i=0}^{P_f} f_i < \Psi_1 \zeta_i > \\ \sum_{i=0}^{P_f} f_i < \Psi_2 \zeta_i > \\ \vdots \\ \sum_{i=0}^{P_f} f_i < \Psi_{P_u} \zeta_i > \end{bmatrix}$$

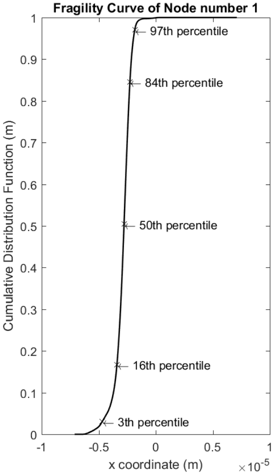
SEPFEM: System Size

- SEPFEM offers a complete solution (single step)
- It is NOT based on Monte Carlo approach
- System of equations does grow (!)

# KL terms material	# KL terms load	PC order displacement	Total # terms per DoF
4	4	10	43,758
4	4	20	3,108,105
4	4	30	48,903,492
6	6	10	646,646
6	6	20	225,792,840
...	...	...	...

SEPFEM: Example in 1D





Outline

Introduction

Modeling and Simulation of ESSI for Nuclear Installations

Conclusion

Summary

- Numerical modeling to predict and inform, rather than fit
- Engineer needs to know
- Model, simulate and understand full life cycle of an object
- Funding from and collaboration with the US-DOE, US-NRC, US-NSF, US-BR, US-FEMA CNSC-CCSN, UN-IAEA, and Shimizu Corp. is greatly appreciated,
- More info: **`http://real-essi.info/`**