Modeling and Simulation of Earthquakes, Soils, Structures, and their Interaction

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Outline

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Motivation

Improve modeling and simulation for infrastructure objects

Use of high fidelity numerical modeling and simulation to analyze earthquakes, and/or soils and/or structures and their interaction (ESSI)

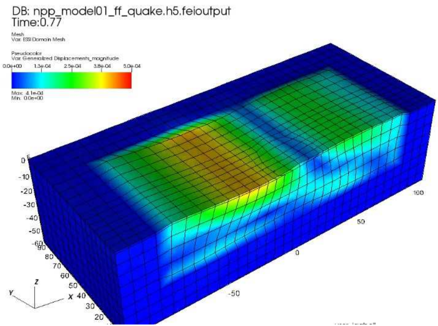
Reduce modeling uncertainty, perform desired level of sophistication modeling and simulation

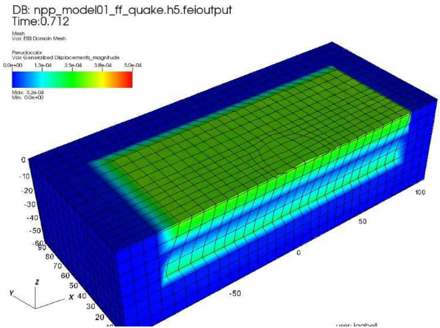
Follow evolution of parametric uncertainty

Le doute n'est pas un état bien agréable, mais l'assurance est un état ridicule. (François-Marie Arouet, Voltaire)

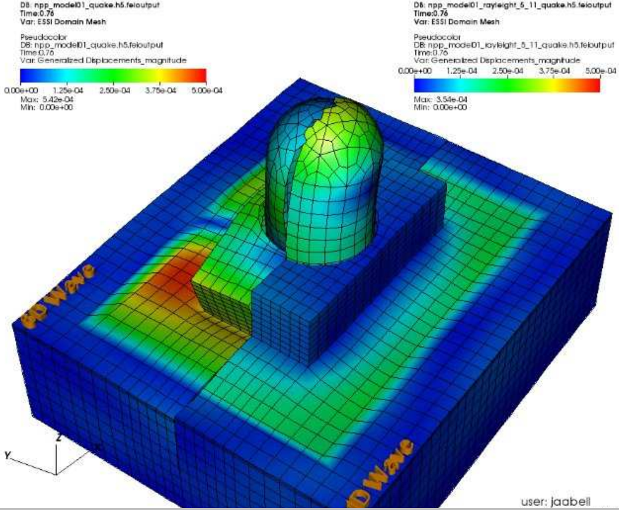
Earthquake Motions, 6C vs 3×1C vs 1C

- Danger of picking one component of motions (1C) from 3C
- Excellent (forced) fit, but not a prediction, information is lost

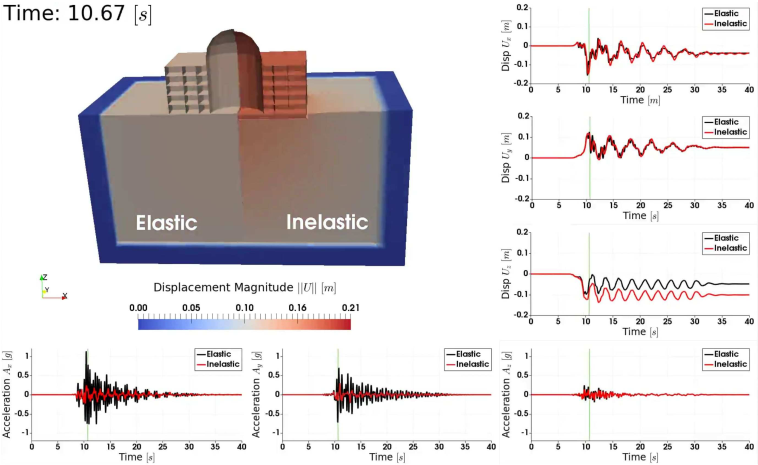




6C vs 1C NPP ESSI Response Comparison

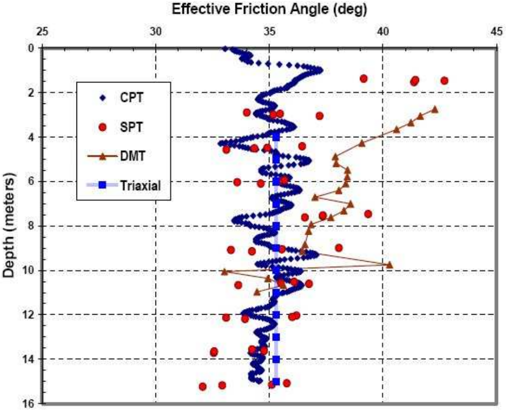


Elastic and Inelastic Response: Differences



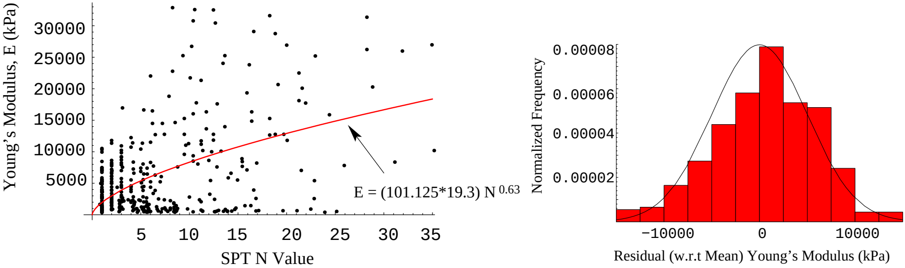
Material Behavior Inherently Uncertain

- Spatial variability
- Point-wise uncertainty, testing error, transformation error



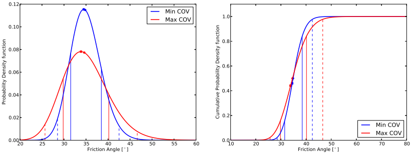
(Mayne et al. (2000)

Parametric Uncertainty: Material and Loads

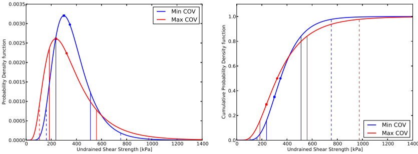


Transformation of SPT *N*-value: 1-D Young's modulus, *E* (cf. Phoon and Kulhawy (1999B))

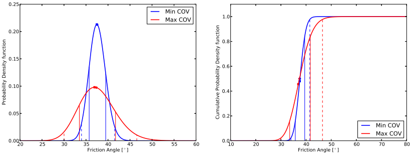
Parametric Uncertainty: Material Properties



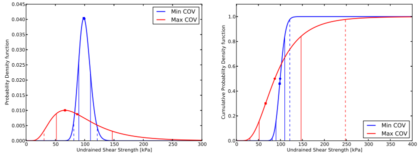
Field ϕ



Field c_u



Lab ϕ

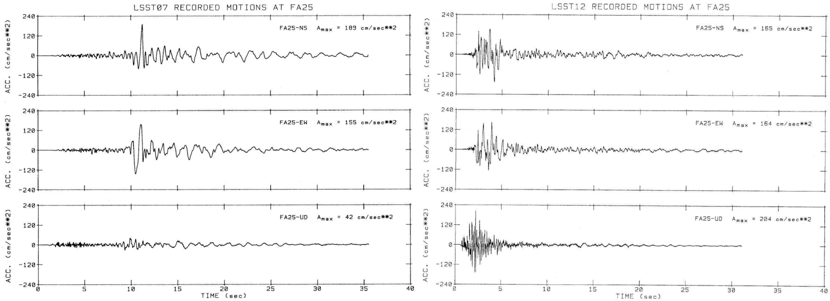


Lab c_u

Outline

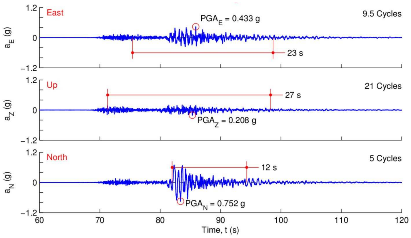
3C (6C) Seismic Motions

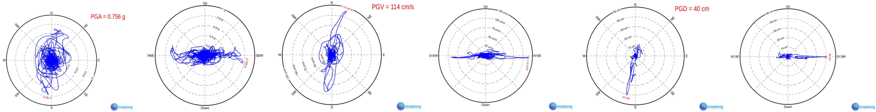
- All (most) measured motions are full 3C (6C)
- Example of an almost 2D motion (LSST07, LSST12)



San Pablo Earthquake, 14Jun2017

Courtesy of `http://www.strongmotioncenter.org/`



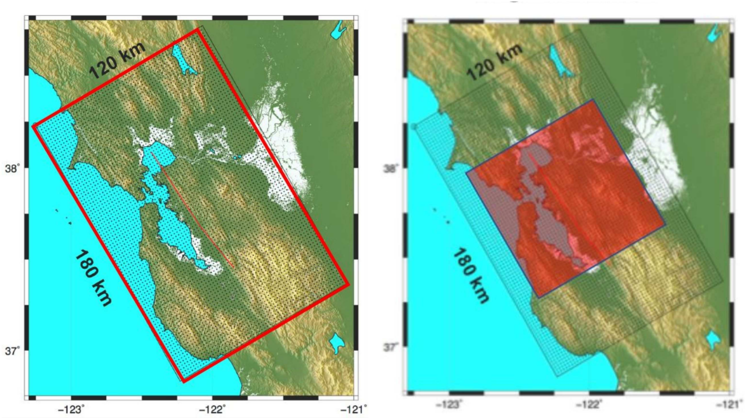


Outline

Regional Geophysical Models

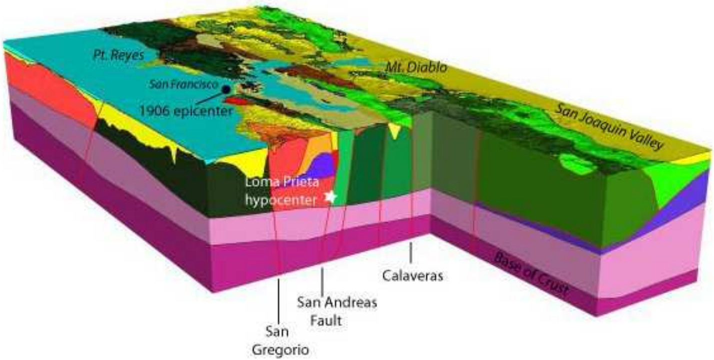
- High fidelity free field seismic motions on regional scale
- Knowledge of geology (deep and shallow) needed
- High Performance Computing using SW4 on CORI (LBNL)
- Collaboration with LLNL: Dr. Rodgers, Dr. Pitarka and Dr. Petersson

Regional Geophysical Models



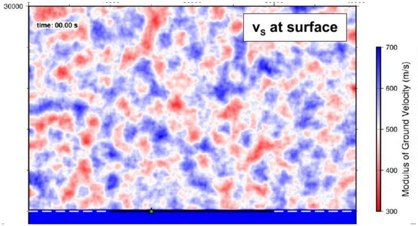
Rodgers and Pitarka

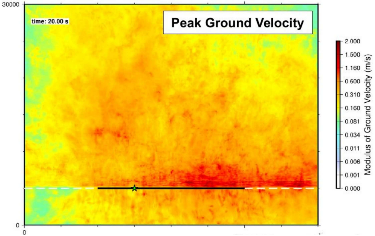
Regional Geophysical Models



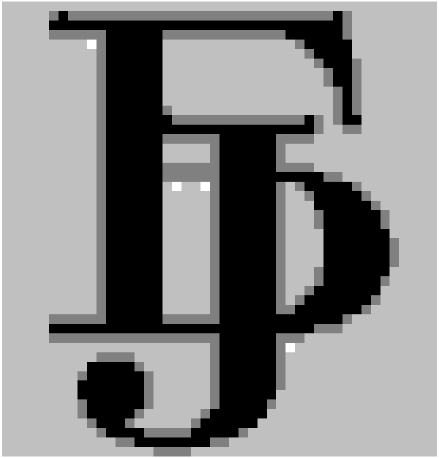
USGS

Example Regional Model

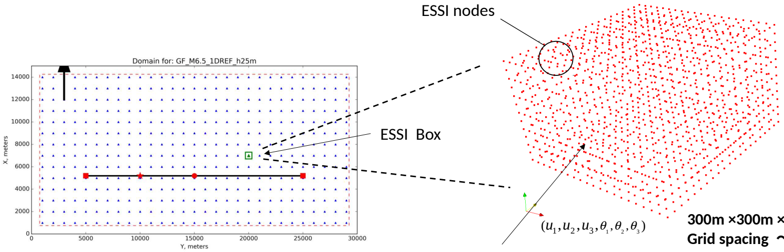




Example Regional Model (Rodgers)



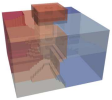
Seismic Motions: SW4 to MS-ESSI



300m ×300m ×100m
Grid spacing ∼ 5m

30km × 14km ×5 km

SW42ESSI

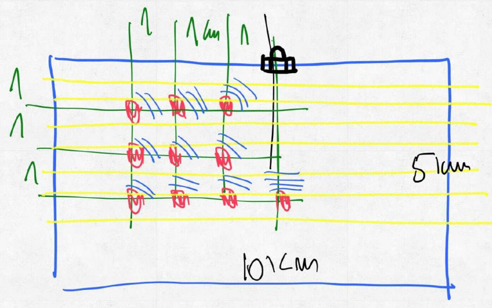


72m×72m×56m
36m embedded

Outline

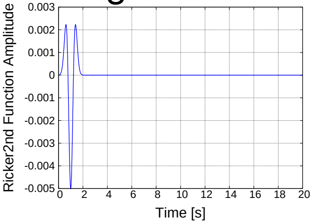
Stress Testing SSI Systems

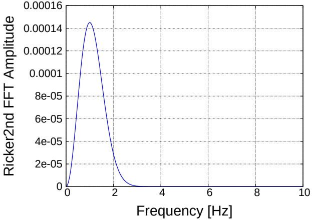
- Excite SSI system with a suite of seismic motions
- Simple sources, variation in strike and dip, P and S waves, surface waves (Rayleigh, Love, etc.)
- Stress test soil-structure system
- Try to "break" the system, shake-out strong and weak links



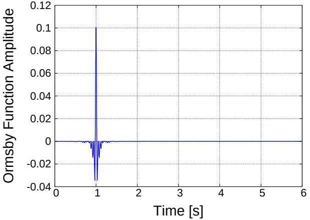
Stress Test Source Signals

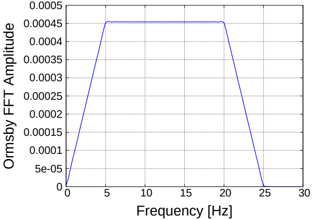
- Ricker





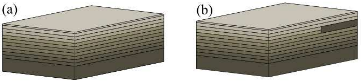
- Ormsby



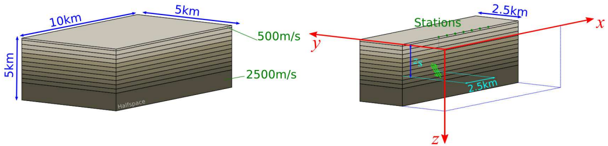


Layered and Dyke/Sill Models

- (a) Horizontal layers
- (b) Dyke/Sill intrusion

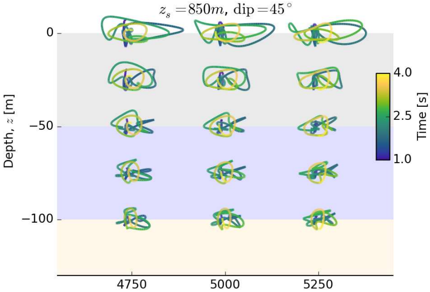


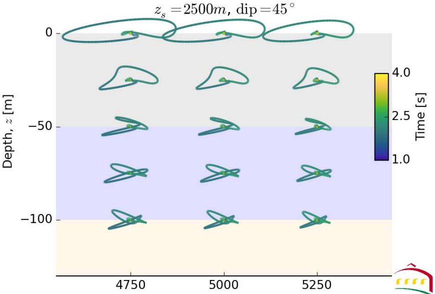
- Source locations matrix (point sources)
- Source strike and dip variation
- Magnitude variations
- Range of frequencies



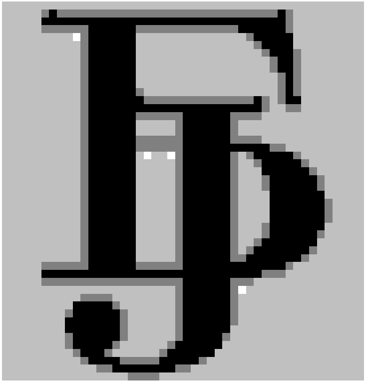
Layered System, Displacement Traces

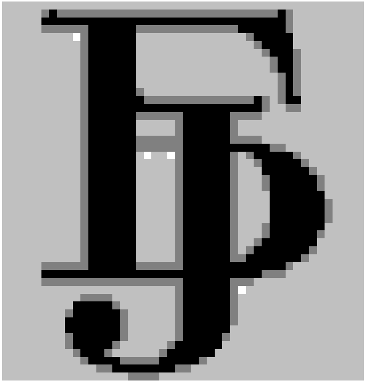
- Epicenter is 2500m away from the location of interest
- Source depth 850m (left) and 2500m (right)
- Different wave propagation path to the point of interest
- Surface waves quite pronounced
- Layered geology did not filter out surface waves





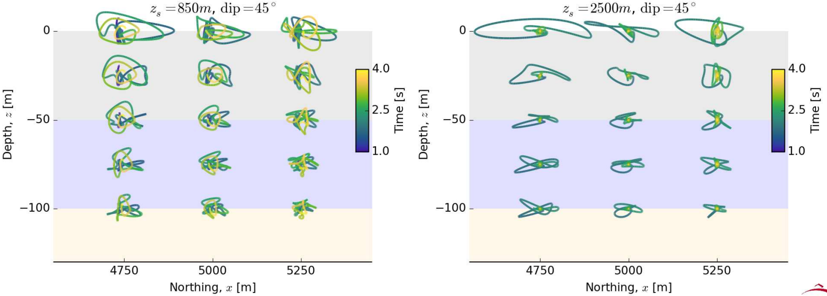
Layered System, Variable Source Depth



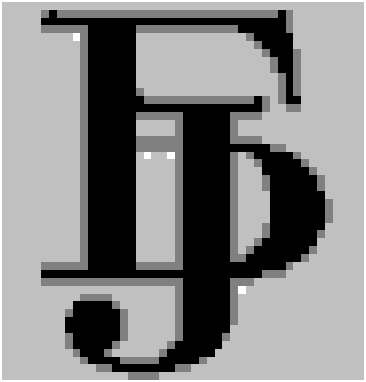


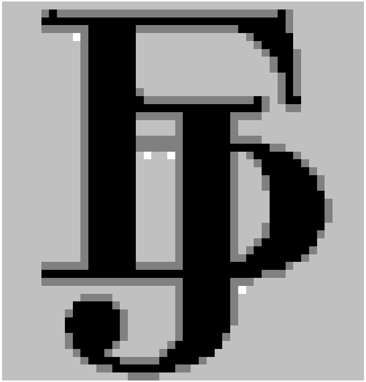
Dyke/Sill Intrusion, Variable Source Depth

- Lower amplitudes than with layered only model!
- Difference in body and surface wave arrivals
- Surface waves present, more complicated wave field



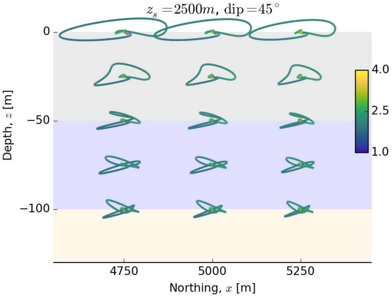
Dyke/Sill Intrusion, Variable Source Depth

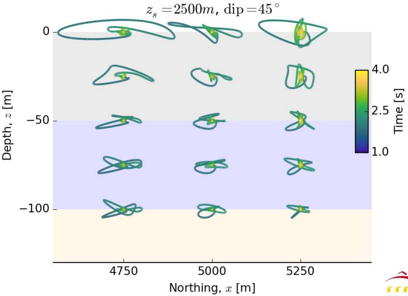




Dyke/Sill as Seismic Energy Sink

- Dyke/Sill (right Fig), made of stiff rock, is an energy sink, as well as energy reflector
- Variable wave lengths behave differently, depending on dyke/sill geometry and location



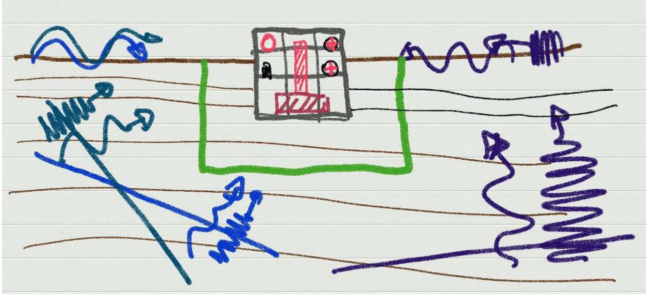


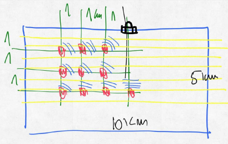
Plane Wave Stress Test Motions

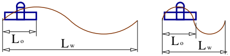
- Plane wave stress test motions: 3D-6C (Haskel's solution for plane harmonic waves) and/or 3D-3$\times$1C and/or 3D-1C and or 1D-1C motions
- Knowledge of geology and the site is important

Stress Test Motions

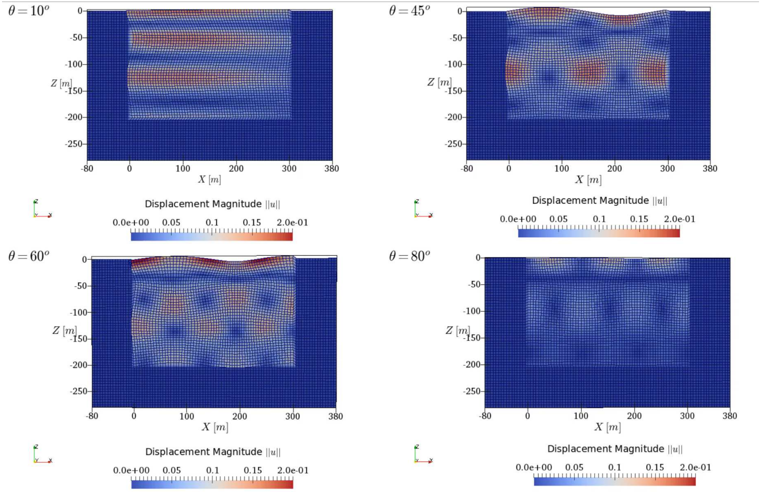
- Variation in inclination, frequency, energy and duration
- Try to "break" the system, shake-out strong and weak links





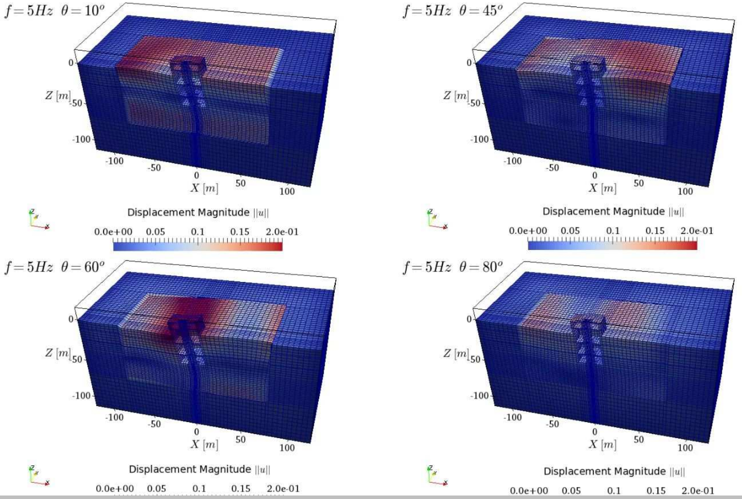


Free Field, Variation in Input Wave Angle, $f = 5$Hz



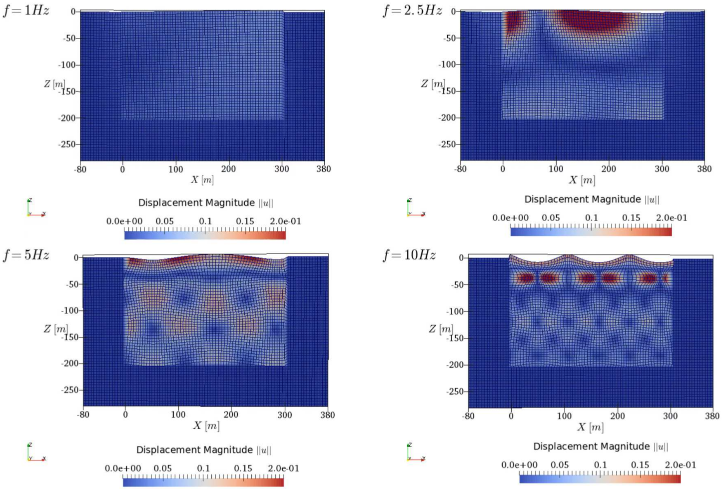
(MP4)

SMR ESSI, Variation in Input Wave Angle, $f = 5$Hz



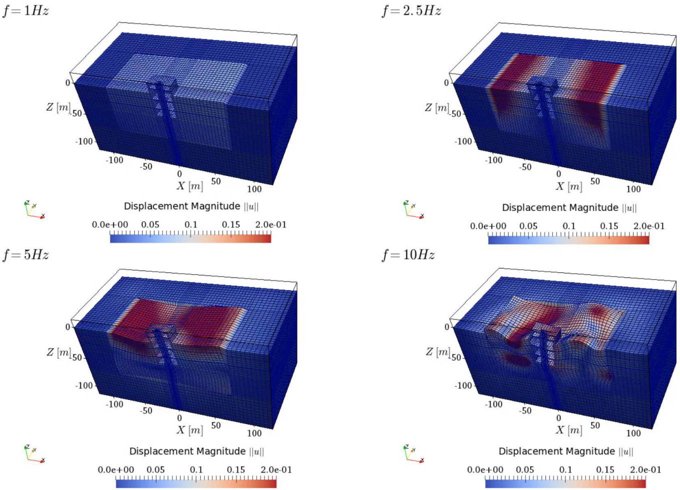
(MP4)

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



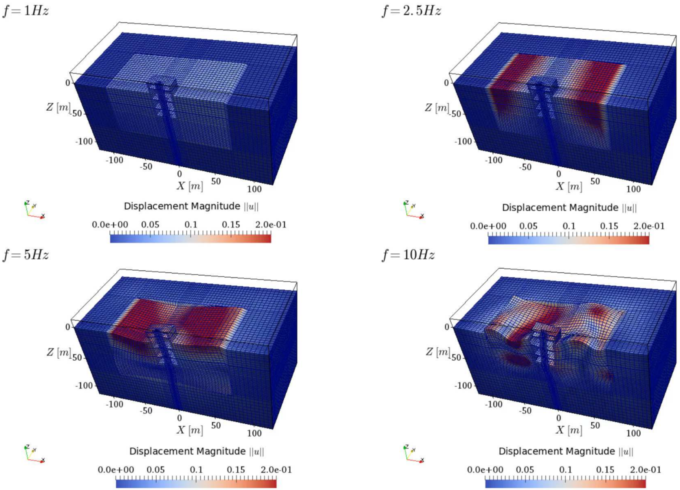
(MP4)

SMR ESSI, Variation in Input Frequency, $\theta = 60^o$

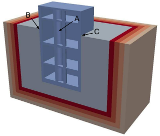


(MP4)

SMR ESSI, Variation in Input Frequency, REAL TIME



(MP4)

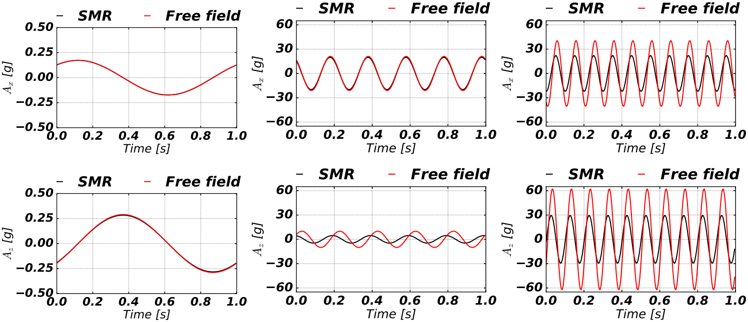


3D wave effects - different frequencies

Acceleration response - Surface center point A

X direction

Z direction



(a) $f = 1Hz \quad \theta = 60^o$ (b) $f = 5Hz \quad \theta = 60^o$ (c) $f = 10Hz \quad \theta = 60^o$

Outline

Seismic Energy Input and Dissipation

Seismic energy input, through a closed boundary

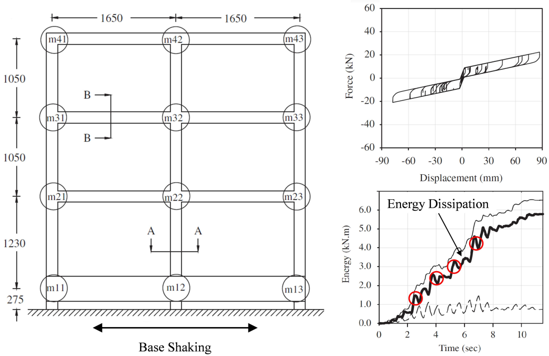
Mechanical dissipation outside SSI domain:
- Reflected wave radiation
- SSI system oscillation radiation

Mechanical dissipation/conversion inside SSI domain:
- Inelasticity of soil and contact zone
- Inelasticity/damage of structure and foundation
- Viscous coupling of fluids and soils and structure

Numerical energy dissipation/production

Incremental Plastic Work: $dW_p = \sigma_{ij}\, d\epsilon_{ij}^{pl}$

- Negative incremental energy dissipation
- Plastic work is NOT plastic dissipation



From a paper on ***Soil Dynamics and Earthquake Engineering*** **(2011)**

Negative Incremental Energy Dissipation!

Direct violation of the second law of thermodynamics

600 papers use Uang and Bertero (1990) and repeat their error

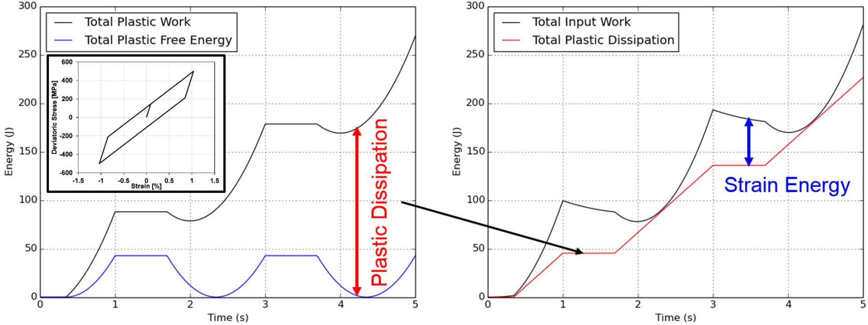
Important form of energy missing: Plastic Free Energy

Observed by Farren and Taylor (1925) and explained by Taylor and Quinney (1934)

Plastic Work vs. Plastic Energy Dissipation

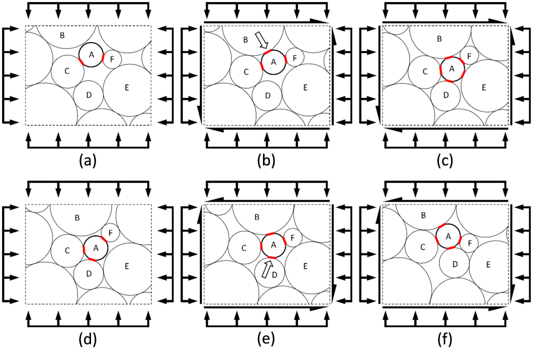
Energy Dissipation on Material Level

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

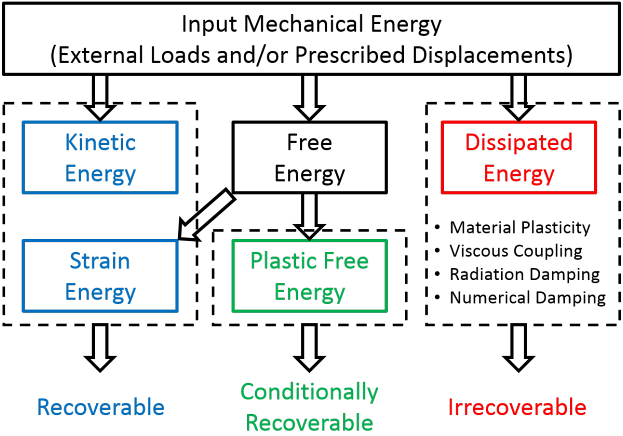


Plastic Free Energy

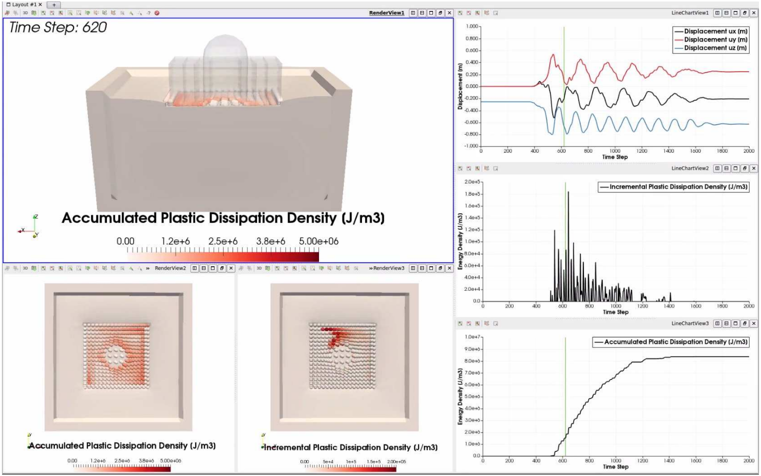
- Multi-scale effect of particle interlocking/rearrangement
- Strain energy on particle level



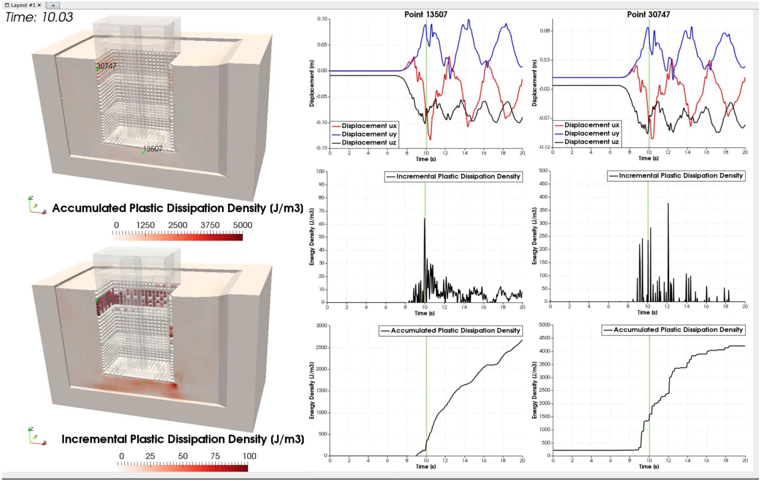
Energy Transformation in Elastic-Plastic Material



Energy Dissipation in Large-Scale Model (NPP)



Energy Dissipation in Large-Scale Model (SMR)



Outline

Uncertainty Propagation through Inelastic System

- Incremental el–pl constitutive equation

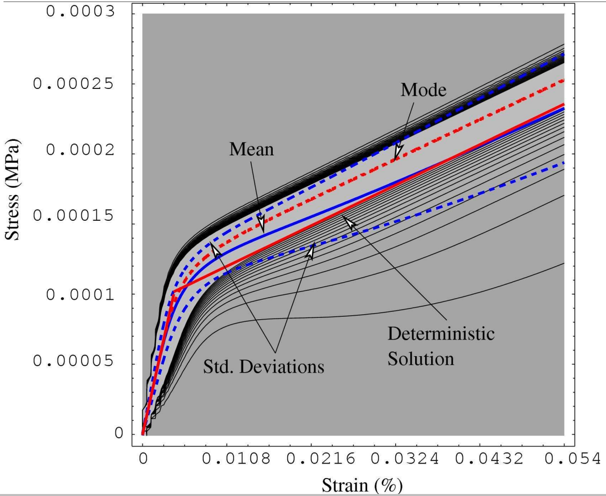
$$\Delta\sigma_{ij} = E^{EP}_{ijkl}\ \Delta\epsilon_{kl} = \left[E^{el}_{ijkl} - \frac{E^{el}_{ijmn} m_{mn} n_{pq} E^{el}_{pqkl}}{n_{rs} E^{el}_{rstu} m_{tu} - \xi_* h_*} \right] \Delta\epsilon_{kl}$$

- Dynamic Finite Elements

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

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

Probabilistic Elastic-Plastic Response



3D FPK Equation

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

FPK Equation

- Advection-diffusion equation

$$\frac{\partial P(\sigma,t)}{\partial t} = -\frac{\partial}{\partial \sigma}\left[N_{(1)}P(\sigma,t) - \frac{\partial}{\partial \sigma}\left\{N_{(2)}P(\sigma,t)\right\}\right]$$

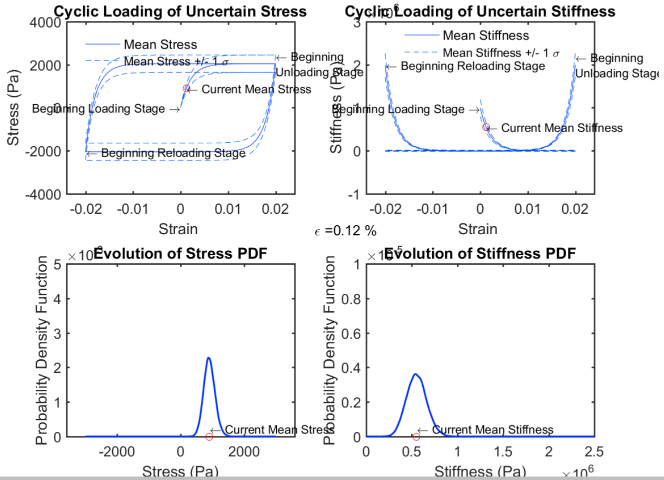
- Complete probabilistic description of response
- Solution PDF is second-order exact to covariance of time (exact mean and variance)
- It is deterministic equation in probability density space
- It is linear PDE in probability density space $\rightarrow$ simplifies the numerical solution process

Outline

Direct Probabilistic Constitutive Modeling in 1D

- Zero elastic region elasto-plasticity with stochastic Armstrong-Frederick kinematic hardening
  $\Delta\sigma = \ H_a \Delta\epsilon - c_r \sigma |\Delta\epsilon|; \qquad E_t = d\sigma/d\epsilon = H_a \pm c_r \sigma$
- Uncertain: init. stiff. H_a, shear strength H_a/c_r, strain $\Delta\epsilon$:
  $H_a = \Sigma h_i \Phi_i; \quad C_r = \Sigma c_i \Phi_i; \quad \Delta\epsilon = \Sigma \Delta\epsilon_i \Phi_i$
- Resulting stress and stiffness are also uncertain

Probabilistic Elastic-Plastic Modeling



Stochastic Elastic-Plastic Finite Element Method

- Material uncertainty expanded into stochastic shape f-ion
- Loading uncertainty expanded into stochastic shape f-ion
- Displacement expanded into stochastic shape f-ion
- Time domain integration using Newmark and/or HHT, in probabilistic spaces

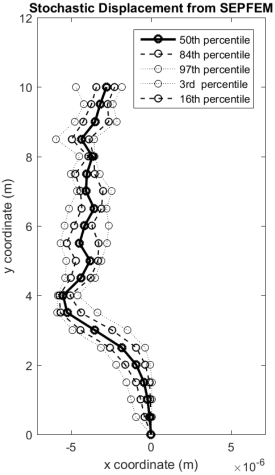
$$\begin{bmatrix} \sum_{k=0}^{P_d} < \Phi_k \Psi_0 \Psi_0 > K^{(k)} & \dots & \sum_{k=0}^{P_d} < \Phi_k \Psi_P \Psi_0 > K^{(k)} \\ \sum_{k=0}^{P_d} < \Phi_k \Psi_0 \Psi_1 > K^{(k)} & \dots & \sum_{k=0}^{P_d} < \Phi_k \Psi_P \Psi_1 > K^{(k)} \\ \vdots & \vdots & \vdots & \vdots \\ \sum_{k=0}^{P_d} < \Phi_k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

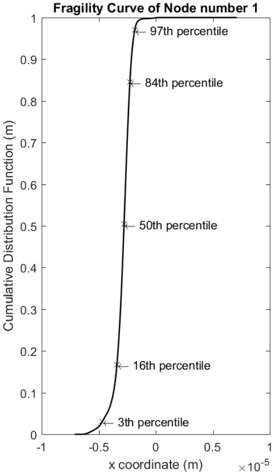
SEPFEM: System Size

- 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	43758
4	4	20	3 108 105
4	4	30	48 903 492
6	6	10	646 646
6	6	20	225 792 840
6	6	30	$1.1058\ 10^{10}$
8	8	10	5 311 735
8	8	20	$7.3079\ 10^{9}$
8	8	30	$9.9149\ 10^{11}$
...	...	...	...

SEPFEM: Example in 1D





Outline

Summary

Importance of using proper models correctly (verification, validation)

Availability of different levels of sophistication of modeling is important for reduction of modeling uncertainty

Development of the MS-ESSI Simulator system
`http://ms-essi.info`

Collaborators: Feng, Abell, Han, Sinha, Wang, Lacour, Pisanó, Kovačević, McCallen, McKenna, Petrone, Rodgers

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