High Fidelity Modeling and Simulation of SFS Interaction: Energy Dissipation by Design

Boris Jeremić

with contributions by

Nima Tafazzoli (UCD), Guanzhou Jie (Wachovia Corp), Mahdi Taiebat (UBC), Zhao Cheng (EarthMechanics Inc.)

CompGeoMech group, CEE Dept. UCD

SFSI Auckland, NZ

Outline

Motivation

- Improving seismic design for infrastructure objects
- Use of high fidelity numerical models in analyzing seismic behavior of soil–structure systems
- Accurately (high fidelity modeling and simulations) following the flow of seismic energy in the soil–structure system
- Directing, in space and time, seismic energy flow in the soil–structure system

Hypothesis

- Interplay of Earthquake with Soil and Structure (ESS) in time domain plays major role in failures (and successes).
- Timing and spatial location of energy dissipation determines location and amount of damage.
- If timing and spatial location of energy dissipation can be controlled (directed, designed), we could optimize soil–structure system for
  - Safety and
  - Economy

The Very First Published Work on SFSI

- Professor Kyoji Suyehiro
- Ship engineer (Professor of Naval Arch. at U. of Tokyo),
- Witnessed Great Kantō earthquake (Tokyo, 1st. Sept. 1923 11:58am(7.5), 12:01pm(7.3), 12.03pm(7.2), shaking until 12:08pm)
- Saw earthquake surface waves travel and buildings sway
- Became founding Director of the Earthquake Engineering Research Institute at the Univ. of Tokyo),
- Published records show four times more damage to soft wooden buildings on soft ground then same buildings on stiff soil

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: 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.
- Goal: Develop predictive capabilities with low Kolmogorov Complexity

Seismic Energy Source

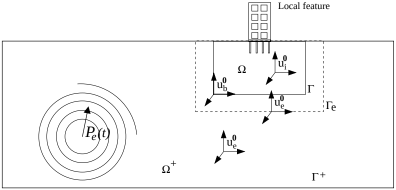
- Large energy releases,
  - Northridge, 1994, $M_{Richter} = 6.7$, $E_r = 6.8 \times 10^{16} J$
  - Loma Prieta, 1989, $M_{Richter} = 6.9$, $E_r = 1.1 \times 10^{17} J$
  - Sumatra-Andaman, 2004, $M_{Richter} = 9.3$, $E_r = 4.8 \times 10^{20} J$
  - Valdivia, Chile, 1960, $M_{Richter} = 9.5$, $E_r = 7.5 \times 10^{20} J$
- Part that energy is radiated as waves ($\approx 1.6 \times 10^{-5}$) and makes it to the surface
- For comparison, specific energy of TNT is $4.2 \times 10^{6} J/kg$.

Seismic Energy Input Into the SFS System

- Kinetic energy flux through closed surface Γ includes both incoming and outgoing waves (using Domain Reduction Method by Bielak et al.)

$$E_{flux} = \left[0; -M_{be}^{\Omega+} \ddot{u}_e^0 - K_{be}^{\Omega+} u_e^0; M_{eb}^{\Omega+} \ddot{u}_b^0 + K_{eb}^{\Omega+} u_b^0\right]_i \times u_i$$

- Alternatively, $E_{flux} = \rho A c \int_0^t \dot{u}_i^2 dt$
- Outgoing kinetic energy is obtained from outgoing wave field (w_i, in DRM)
- Incoming kinetic energy is then the difference.

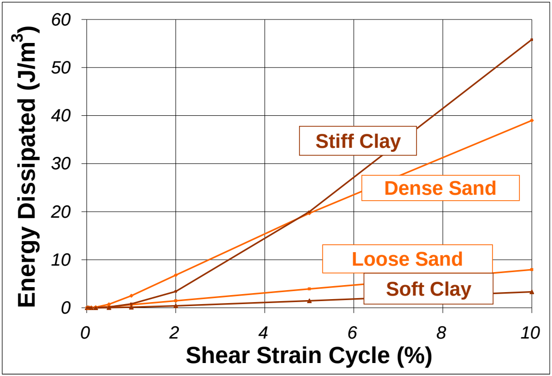


Seismic Energy Dissipation for Soil–Structure Systems

- Mechanical dissipation outside of SFS domain:
  - wave reflection
  - SFS system oscillation radiation
- Mechanical dissipation/conversion inside SFS domain:
  - plasticity of soil (different subdomains)
  - viscous coupling of porous solid with pore fluid (air, water)
  - plasticity/damage of the structure (different parts)
  - viscous coupling of structure with surrounding fluids
  - potential $\leftrightarrow$ kinetic energy
- Numerical energy dissipation/production

Energy Dissipation by Plasticity

- Plastic work ($W = \int \sigma_{ij} d\epsilon_{ij}^{pl}$)
- Energy dissipation capacity for different soils



Energy Disipation by Viscous Coupling

- Viscous coupling of porous solid and fluid
- Energy loss per unit volume is $E_{vc} = n^2 k^{-1} (\dot{U}_i - \dot{u}_i)^2$
- Natural in $u - p - U$ formulation:

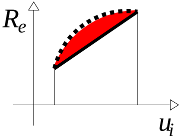
$$\begin{bmatrix} (M_s)_{KijL} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & (M_f)_{KijL} \end{bmatrix} \begin{bmatrix} \ddot{\bar{u}}_{Lj} \\ \ddot{\bar{p}}_N \\ \ddot{\bar{U}}_{Lj} \end{bmatrix} + \begin{bmatrix} (C_1)_{KijL} & 0 & -(C_2)_{KijL} \\ 0 & 0 & 0 \\ -(C_2)_{LjiK} & 0 & (C_3)_{KijL} \end{bmatrix} \begin{bmatrix} \dot{\bar{u}}_{Lj} \\ \dot{\bar{p}}_N \\ \dot{\bar{U}}_{Lj} \end{bmatrix}$$

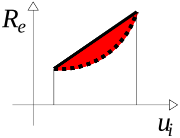
$$+ \begin{bmatrix} (K^{EP})_{KijL} & -(G_1)_{KiM} & 0 \\ -(G_1)_{LjM} & -P_{MN} & -(G_2)_{LjM} \\ 0 & -(G_2)_{KiL} & 0 \end{bmatrix} \begin{bmatrix} \bar{u}_{Lj} \\ \bar{p}_M \\ \bar{U}_{Lj} \end{bmatrix} = \begin{bmatrix} \bar{f}_{Ki}^{solid} \\ 0 \\ \bar{f}_{Ki}^{fluid} \end{bmatrix}$$

$$(C_{(1,2,3)})_{KijL} = \int_\Omega N_K^{(u,u,U)} n^2 k_{ij}^{-1} N_L^{(u,U,U)} d\Omega$$

Numerical Energy Dissipation

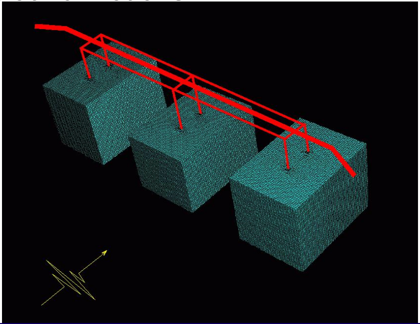
- Newmark and Hilber–Hughes–Taylor can be made non–dissipative for elastic system
  $\alpha = 0.0, \beta = 0.25; \gamma = 0.5,$
- Or dissipative (for elastic) for higher frequency modes:
  - N: $\gamma \geq 0.5, \quad \beta = 0.25(\gamma + 0.5)^2,$
  - HHT: $-0.33 \leq \alpha \leq 0, \quad \gamma = 0.5(1 - 2\alpha), \quad \beta = 0.25(1 - \alpha)^2$
- For nonlinear problems, energy cannot be maintained
  - Energy dissipation for steps with reduction of stiffness
  - Energy production for steps with increase of stiffness



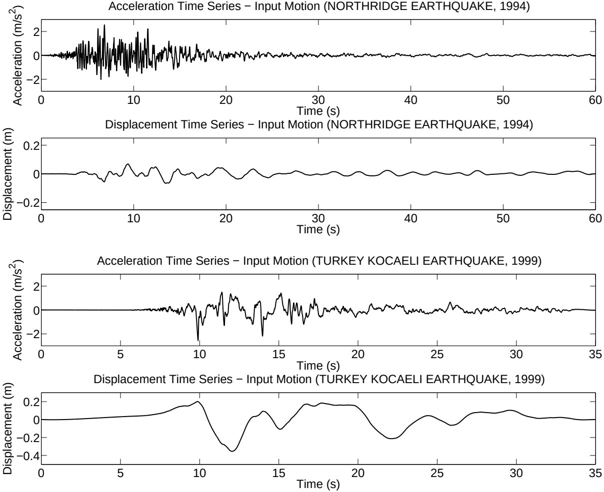


Earthquake–Soil–Bridge System

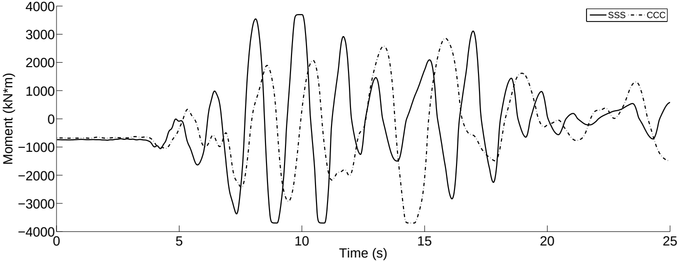
- Inelastic soils (el–pl, Armstrong-Frederick, stiff and soft), inelastic structure (columns), inelastic piles, DRM for seismic input,
- Construction process
- Deconvolution of surface ground motions
- No artificial damping, only plastic dissipation and radiation
- Plastic Domain Decomposition Method for parallel computing
- 1.6 M DOFs (15cm element size)

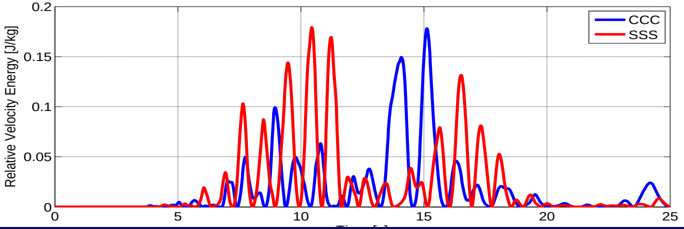


Northridge and Kocaeli Input Motions

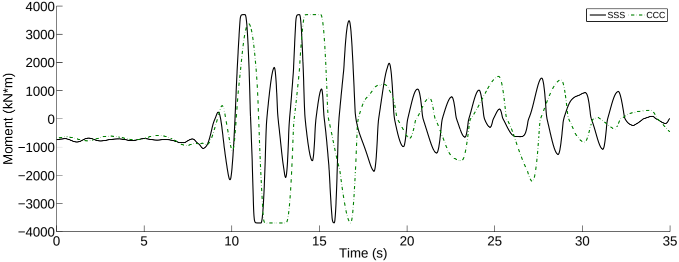


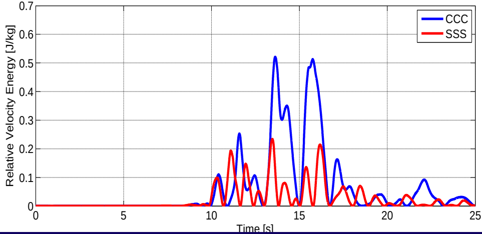
Northridge Energy: Strain (dissipated) and Kinetic



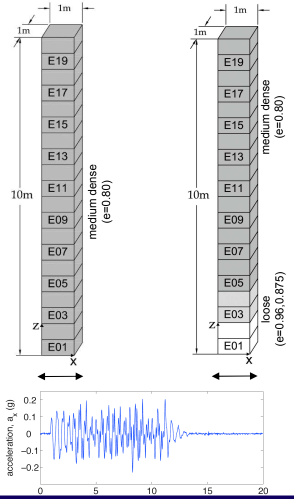


Kocaeli Energy: Strain (dissipated) and Kinetic

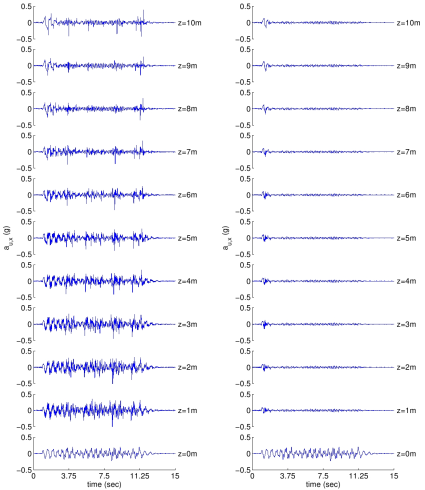




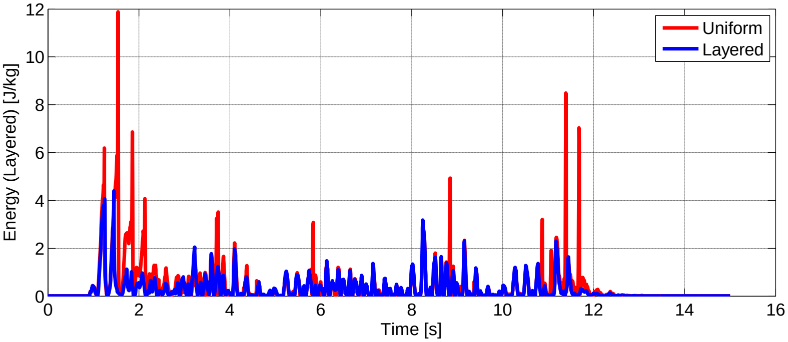
Uniform and Layered Soils



Acceleration Time History



Kinetic Energy at the Surface



Summary

- **Interplay** of **Earthquake**, **Soil** and **Structure** in **time domain** plays a decisive role in catastrophic failures and great successes
- **Opportunity to improve design through high fidelity simulations**: design, direct the flow of seismic energy in the SFS systems
- **Ability to direct** seismic energy flow, in space and time, for a complete SFS system will lead to an increase in safety and economy
- **Public domain tools**, such as FEI and **`www.OpenHazards.com`**