Directing Energy Dissipation in Earthquake-Soil-Structure Systems

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CompDyn09

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

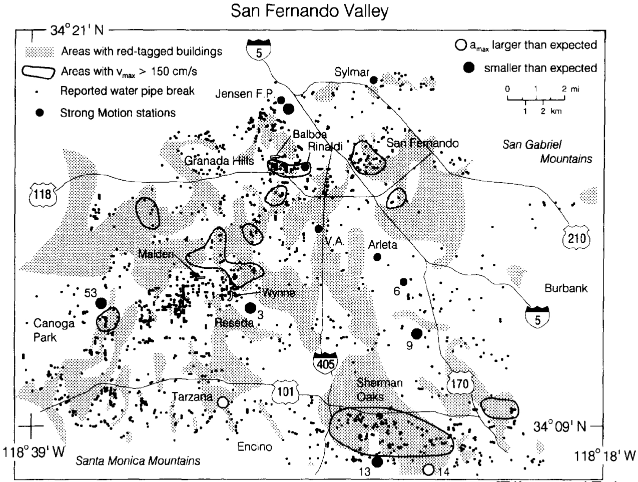
Hypothesis

- Interplay of Earthquake with Soil and Structure plays major role in (catastrophic) 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, we could optimize soil–structure systems for
  - Safety and
  - Economy

First Published Work on Soil–Structure Interaction

- Professor Kyoji Suyehiro
- Ship engineer (Professor of Naval Arch. at U. of Tokyo),
- Was in Tokyo during Great Kantō earthquake (11:58am(7.5), 12:01pm(7.3), 12.03pm(7.2) (shaking until 12:08pm), 1st. Sept. 1923)
- Saw earthquake surface waves travel and buildings sway
- Founding Director of the Earthquake Engineering Research Institute Univ. of Tokyo),
- Records shows 4$\times$ (four) more damage to soft wooden buildings on soft ground

Northridge Example



[Trifunac and Todorovska 1998]

Outline

Seismic Energy at the Source

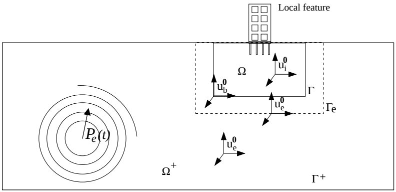
- Large energy releases,
  - Northridge, 1994, $M_{Richter} = 6.7$, $E_r = 6.8 \times 10^{16} J$
  - Loma Prieta, 1989, $M_{Richter} = 6.9$, $E_r = 1.1 \times 10^{17} J$
  - Sumatra-Andaman, 2004, $M_{Richter} = 9.3$, $E_r = 4.8 \times 10^{20} J$
  - Valdivia, Chile, 1960, $M_{Richter} = 9.5$, $E_r = 7.5 \times 10^{20} J$
  - Rhodes, 2008, $M_{Richter} = 6.5$, $E_r = 2.4 \times 10^{16} J$
- 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 $4.2 \times 10^6 J/kg$.
- Rhodes earthquake was $\approx 0.1 kt$.

Seismic Energy and 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.



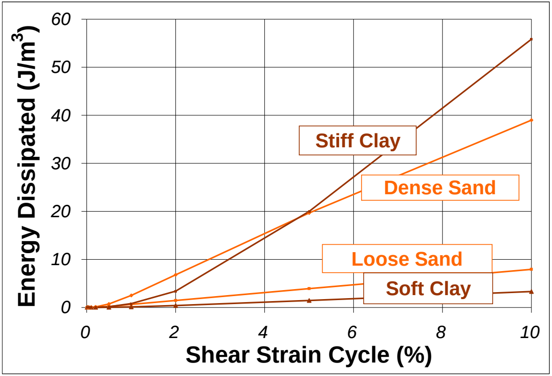
Outline

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:

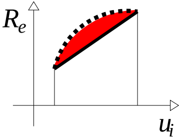
$$\begin{bmatrix} (M_s)_{KijL} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & (M_f)_{KijL} \end{bmatrix} \begin{bmatrix} \ddot{\bar{u}}_{Lj} \\ \ddot{\bar{p}}_N \\ \ddot{\bar{U}}_{Lj} \end{bmatrix} + \begin{bmatrix} (C_1)_{KijL} & 0 & -(C_2)_{KijL} \\ 0 & 0 & 0 \\ -(C_2)_{LjiK} & 0 & (C_3)_{KijL} \end{bmatrix} \begin{bmatrix}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

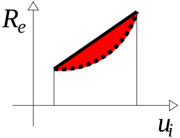
$$+ \begin{bmatrix} (K^{EP})_{KijL} & -(G_1)_{KiM} & 0 \\ -(G_1)_{LjM} & -P_{MN} & -(G_2)_{LjM} \\ 0 & -(G_2)_{KiL} & 0 \end{bmatrix} \begin{bmatrix} \bar{u}_{Lj} \\ \bar{p}_M \\ \bar{U}_{Lj} \end{bmatrix} = \begin{bmatrix} \bar{f}^{solid}_{Ki} \\ 0 \\ \bar{f}^{fluid}_{Ki} \end{bmatrix}$$

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

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

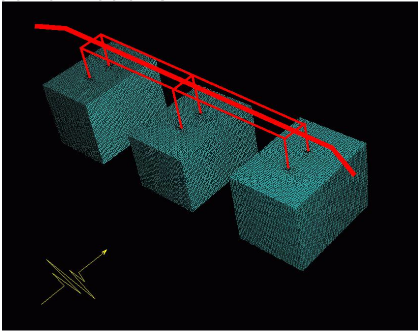




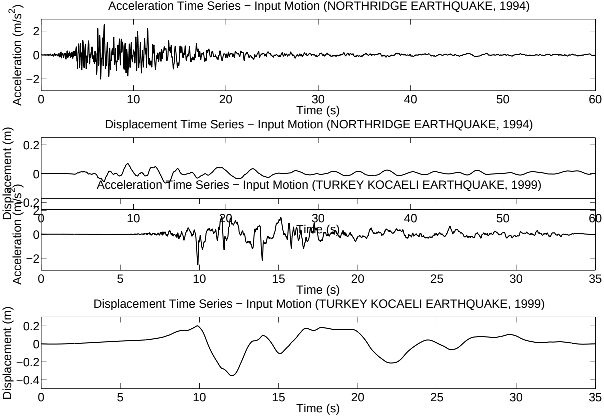
Outline

Earthquake–Soil–Bridge System

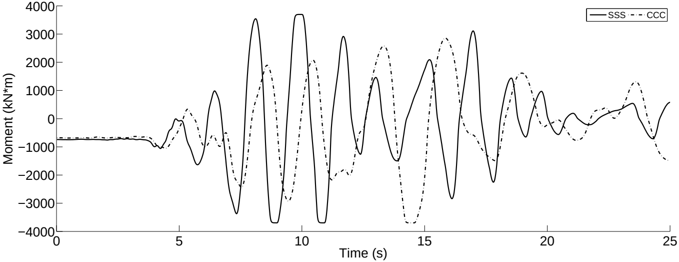
- Inelastic soils (el–pl, Armstrong-Frederick, stiff and soft), inelastic structure (columns), inelastic piles, DRM for seismic input,
- Construction process
- Deconvolution osurface ground motions
- No artificial damping, only plastic dissipation and radiation
- Plastic Domain Decompisition Method for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

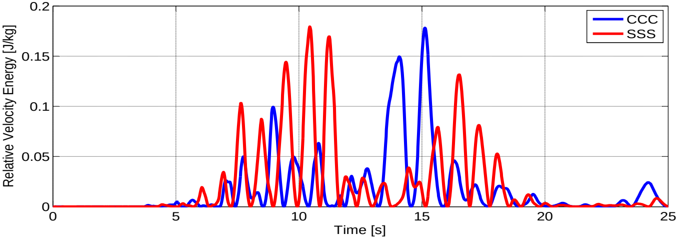


Northridge and Kocaeli Input Motions

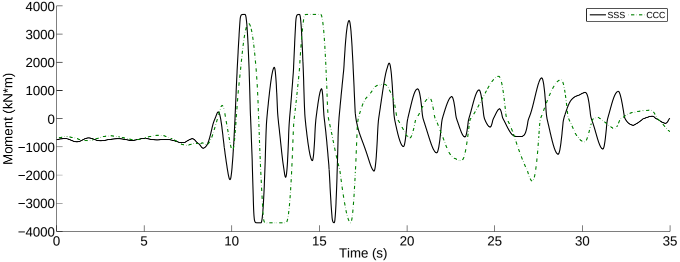


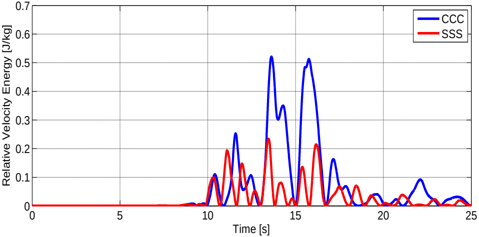
Northridge Energy: Strain (dissipated) and Kinetic





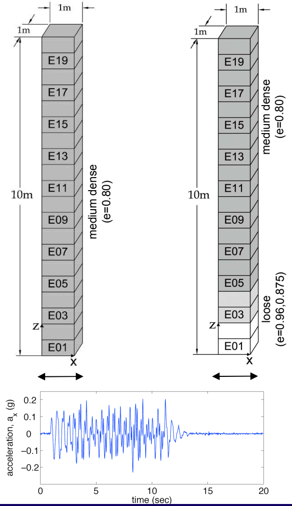
Kocaeli Energy: Strain (dissipated) and Kinetic



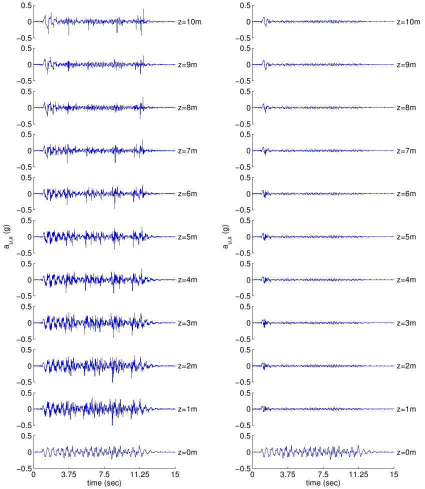


Outline

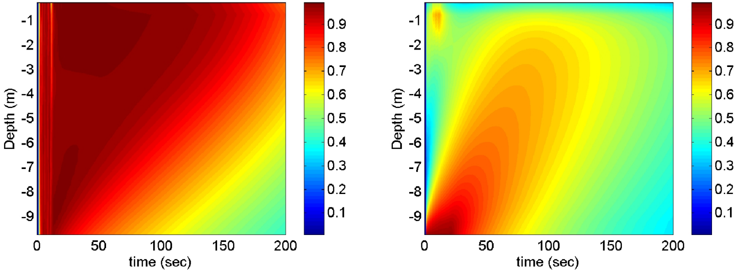
Uniform and Layered Soils

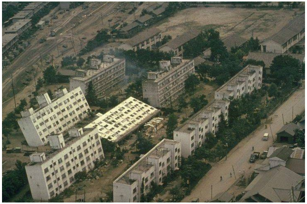


Acceleration Time History

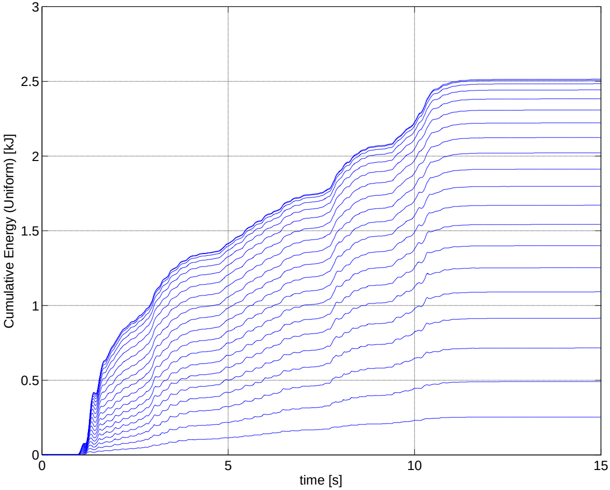


Excess Pore Pressure Ratio

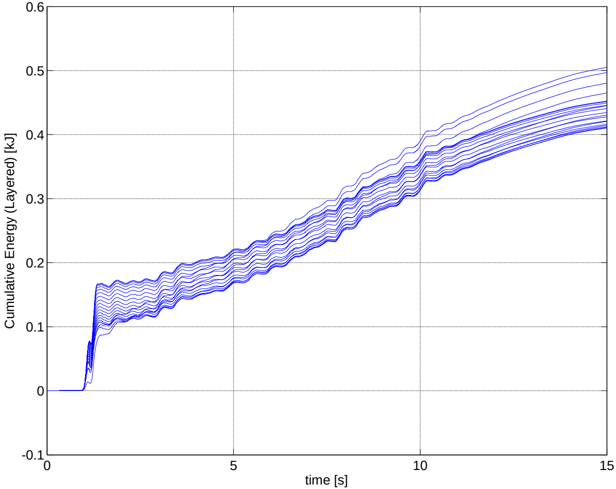




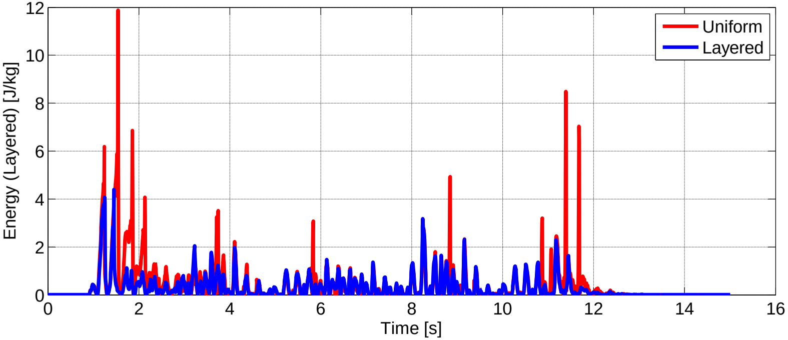
Plastic Energy Dissipation in Uniform Soils



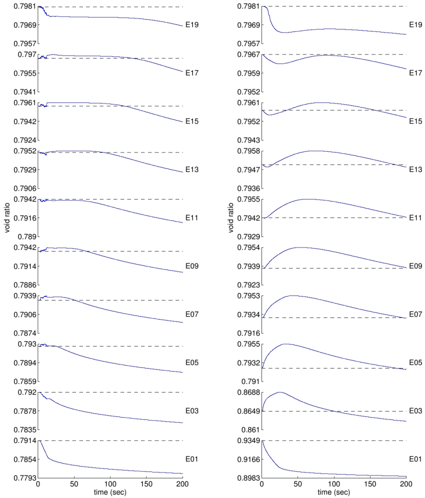
Plastic Energy Dissipation in Layered Soils



Kinetic Energy at the Top



Void Ratio Variation (Potential Energy)



Summary

- **Interplay** of **Earthquake**, **Soil** and **Structure** plays a major role in catastrophic failures and great successes
- **Opportunity to improve design**: following the flow of seismic energy in the soil–structure systems
- **Directing** in space and time, seismic energy flow in the soil–structure system might/will lead to increase in safety and economy

Colossus of Rhodes: What if?