

Seismic Energy Balance for Soil-Structure Interacting (SSI) Systems

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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!"

Nebojša Orbović, 1962-2021



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

Seismic Energy and ESSI System

Energy input, forces/loads, static/dynamic

Energy dissipation outside SSI domain:

- SSI system oscillation radiation

- Reflected waves radiation

Energy dissipation/conversion inside SSI domain:

- Inelasticity of soil, interfaces, structure, dissipators

- Viscous coupling with internal/pore and external fluids

- Energy deflectors, meta-materials/devices

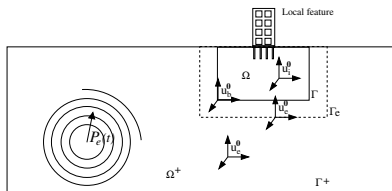
Numerical energy dissipation/production

Seismic Energy and the SFS System

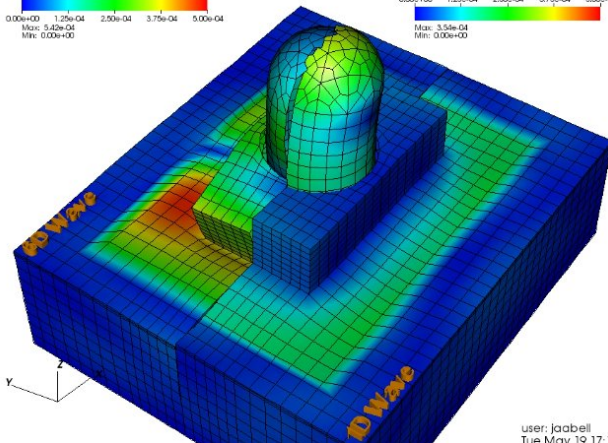
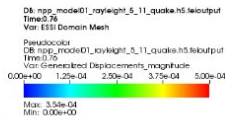
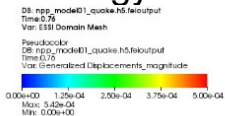
- Kinetic energy flux through closed surface Γ includes both incoming and outgoing waves (using DRM by Bielak et al.)

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

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



Seismic Energy from 3D/6C Seismic Waves



(MP4)

user: jaabell
Tue May 19 17:19:21 2015

Energy Dissipation within ESSI System

- Plastic energy dissipation:

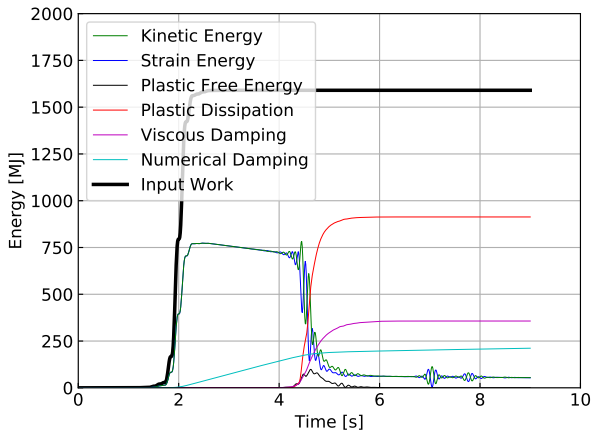
$$\Delta\Phi = \sigma_{ij}\Delta\epsilon_{ij} - \sigma_{ij}\Delta\epsilon_{ij}^{el} - \Delta\psi_{pl} \geq 0$$

- Viscous energy dissipation/damping:

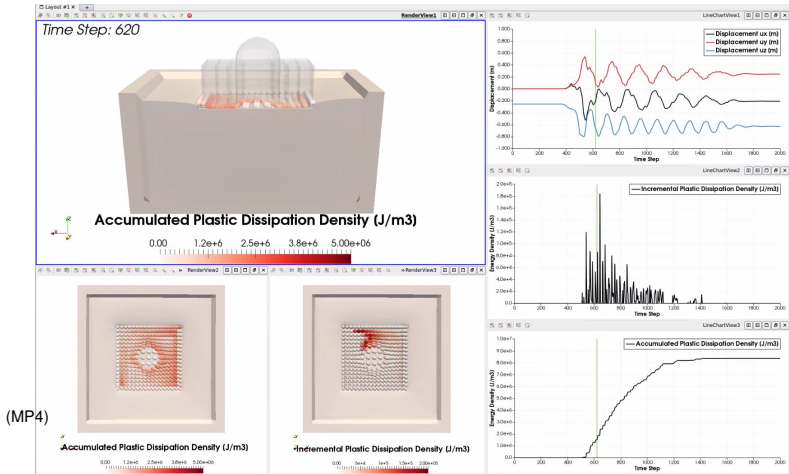
$$\Delta D_V = C_{ij}\dot{u}_j\Delta u_i$$

- Algorithmic, numerical energy dissipation/production:
Newmark, Hilber-Hughes-Taylor, Houbolt, Bathe, Wilson...

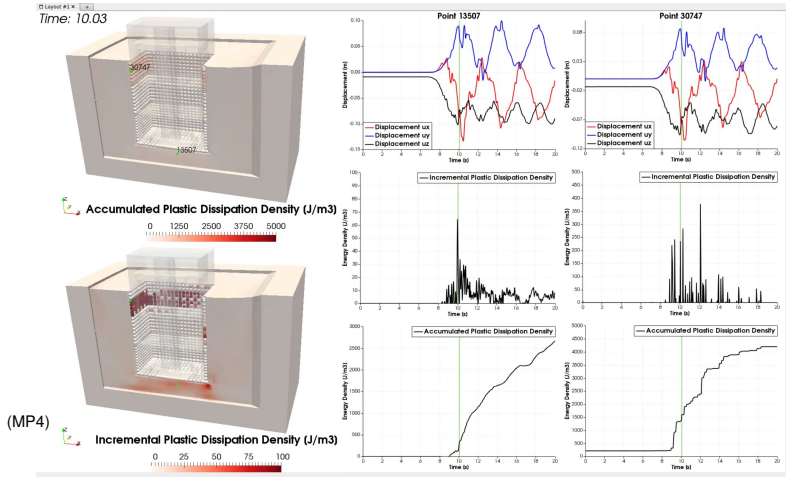
Detailed Seismic Energy Dissipation Control



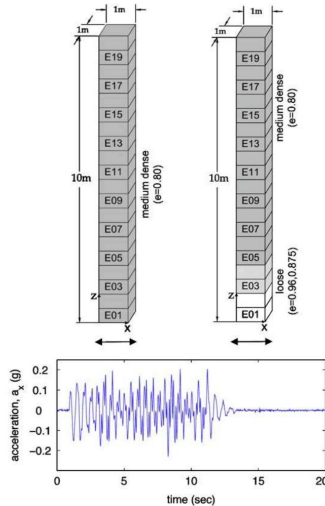
Important Infrastructure, Energy Dissipation



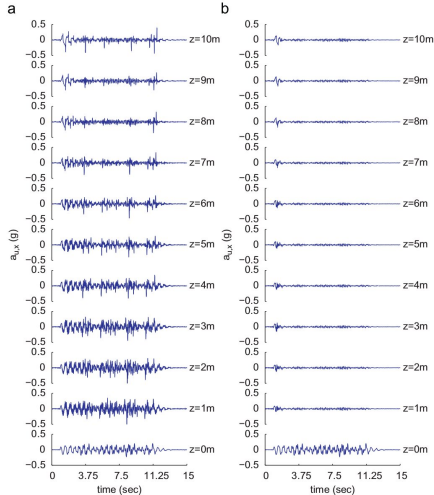
Deeply Embedded Object, Energy Dissipation



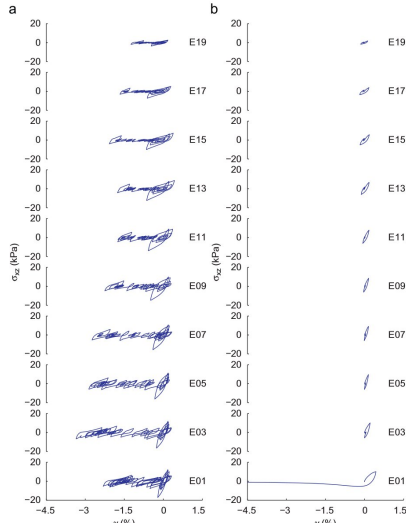
Liquefaction as Seismic Shield



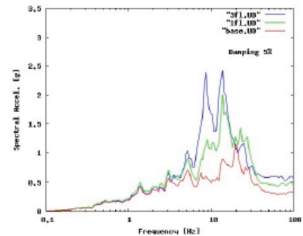
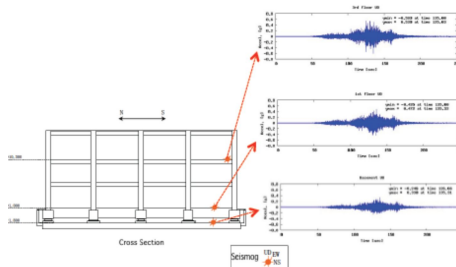
Liquefaction, Wave Propagation



Liquefaction, Stress-Strain Response



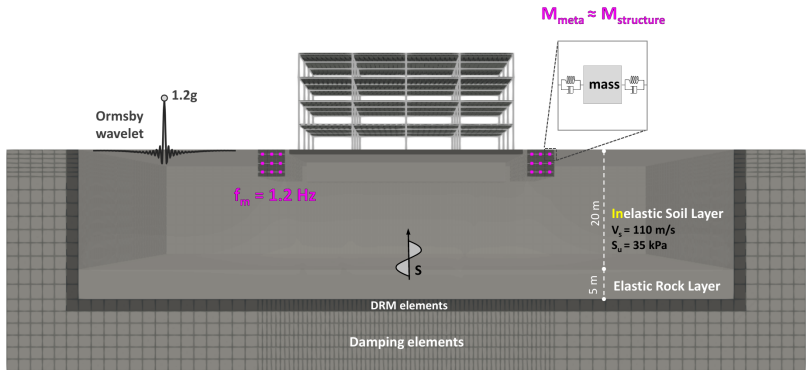
Base Isolation



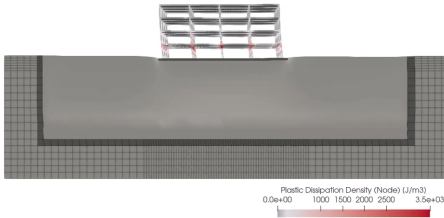
Fukushima NPP building: V-amp. 80% [JAEE/LLNL, 2012]



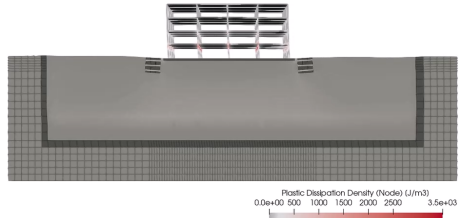
Metadevice/Metamaterial Seismic Shielding



Metadevice/Metamaterial Shielding



without

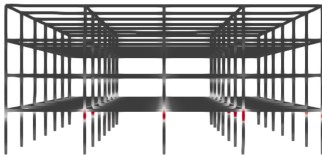


with

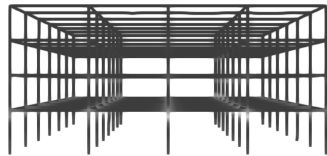
[Kanellopoulos et al., ETH]

Metadevice/Metamaterial Shielding

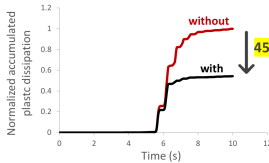
without metamaterials



with metamaterials



Plastic Dissipation Density (Node) (J/
0.0e+00 500 1000 1500 2000 2500



Plastic Dissipation Density (Node) (J/m³)
00 500 1000 1500 2000 2500 3.5e+03



Summary

- Sophisticated, realistic analysis: improve design, safety
- Seismic energy flow for design and assessment
- Education and Training is the Key !
- Analysis tool: Real-ESSI Simulator
(<http://real-essi.us>)