Earthquake Soil Structure Interaction (ESSI) Modeling and Simulation

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Outline

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Motivation

- Improving seismic design for infrastructure objects
- Use of high fidelity numerical models in analyzing seismic behavior of soil/rock-foundation-structure systems
- Accurate following of the flow of seismic energy in the soil/rock-foundation-structure system
- Directing, in space and time, seismic energy flow in the soil/rock-foundation-structure system

The Very First Published Work on ESSI

- Professor Kyoji Suyehiro
- Ship engineer (Professor of Naval Arch. at U. of Tokyo),
- Witnessed Great Kantō earthquake (Tokyo, 01Sept1923 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,
- His published records (ASCE 1932) show four times more damage to soft wooden buildings on soft ground then same buildings on stiff soil

Hypothesis

- Interplay of the Earthquake with the Soil/Rock, Foundation and Structure in time domain plays major role in successes and failures.
- 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-foundation-structure system for
  - Safety and
  - Economy

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.

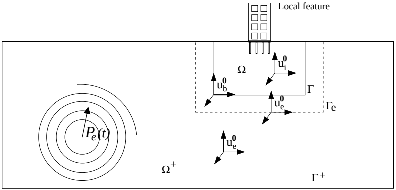
Outline

Seismic Energy Input for the SSI System

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

$$E_{flux} = \left[0; -M^{\Omega+}_{be}\ddot{u}^0_e - K^{\Omega+}_{be}u^0_e; M^{\Omega+}_{eb}\ddot{u}^0_b + K^{\Omega+}_{eb}u^0_b\right]_i \times u_i$$

- 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.

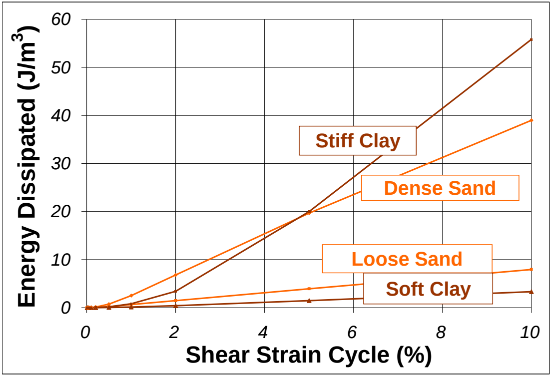


Seismic Energy Dissipation for the SSI System

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

Energy Dissipation by Soil Plasticity

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



Energy Dissipation by Soil 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:

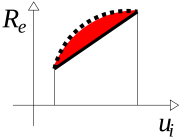
$$\begin{bmatrix} (M_s)_{KijL} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & (M_f)_{KijL} \end{bmatrix} \begin{bmatrix} \ddot{\bar{u}}_{Lj} \\ \ddot{\bar{p}}_N \\ \ddot{\bar{U}}_{Lj} \end{bmatrix} + \begin{bmatrix} (C_1)_{KijL} & 0 & -(C_2)_{KijL} \\ 0 & 0 & 0 \\ -(C_2)_{LjiK} & 0 & (C_3)_{KijL} \end{bmatrix} \begin{bmatrix}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

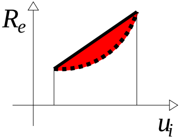
$$+ \begin{bmatrix} (K^{EP})_{KijL} & -(G_1)_{KiM} & 0 \\ -(G_1)_{LjM} & -P_{MN} & -(G_2)_{LjM} \\ 0 & -(G_2)_{KiL} & 0 \end{bmatrix} \begin{bmatrix} \bar{u}_{Lj} \\ \bar{p}_M \\ \bar{U}_{Lj} \end{bmatrix} = \begin{bmatrix} \bar{f}^{solid}_{Ki} \\ 0 \\ \bar{f}^{fluid}_{Ki} \end{bmatrix}$$

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

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: $-0.3\dot{3} \leq \alpha \leq 0, \quad \gamma = 0.5(1 - 2\alpha), \quad \beta = 0.25(1 - \alpha)^2$
- For nonlinear problems, energy cannot be maintained
  - Energy dissipation for steps with reduction of stiffness
  - Energy production for steps with increase of stiffness





Outline

Modeling Uncertainty

- Simplified (or inadequate/wrong) modeling: important features are missed (seismic ground motions, etc.)
- Introduction of uncertainty and (unknown) lack of accuracy in results due to use of un-verified simulation tools (software quality, etc.)
- Introduction of uncertainty and (unknown) lack of accuracy in results due to use of un-validated models (due to lack of quality validation experiments)

Complexity of and Uncertainty in Ground Motions

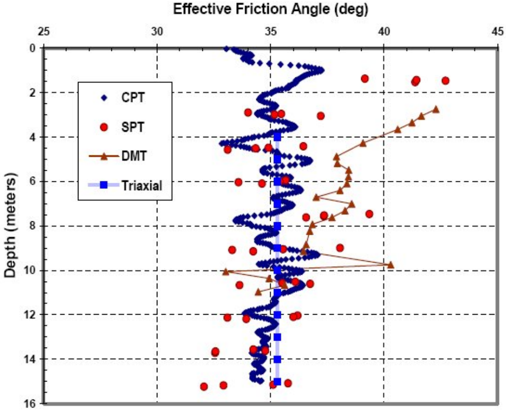
- 6D (3 translations, 3 rotations)
- Vertical motions usually neglected
- Rotational components usually not measured and neglected
- Lack of models for such 6D motions (from measured data))
- Sources of uncertainties in ground motions (Source, Path (rock), soil (rock))

Complexity of and Uncertainty in Material Modeling

- All engineering materials experience inelastic deformations for working loads
- This is even more so for hazard loads (earthquakes)
- Pressure sensitive materials (soil, rock , concrete, etc) can have very complex constitutive response, tying together nonlinear stress-strain with volume response
- Simplistic material modeling (elastic, G/G_{max}, etc.) introduce (significant) uncertainties in response results
- In addition, man-made and natural materials are spatially variable and their material modeling parameters are uncertain

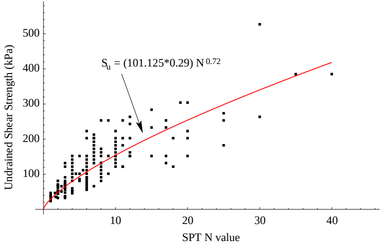
Material Behavior Inherently Uncertain

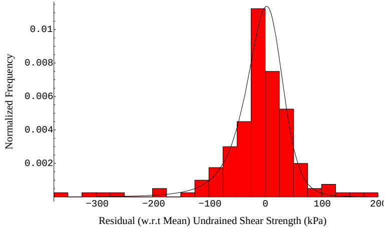
- Spatial variability
- Point-wise uncertainty, testing error, transformation error



(Mayne et al. (2000)

SPT Based Determination of Shear Strength

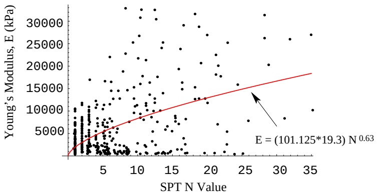


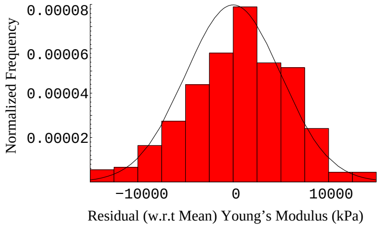


Transformation of SPT N-value $\rightarrow$ un-drained shear strength, s_u (cf. Phoon and Kulhawy (1999B)

Histogram of the residual (w.r.t the deterministic transformation equation) un-drained strength, along with fitted probability density function (Pearson IV)

SPT Based Determination of Young's Modulus





Transformation of SPT *N*-value $\rightarrow$ 1-D Young's modulus, *E* (cf. Phoon and Kulhawy (1999B))
Histogram of the residual (w.r.t the deterministic transformation equation) Young's modulus, along with fitted probability density function

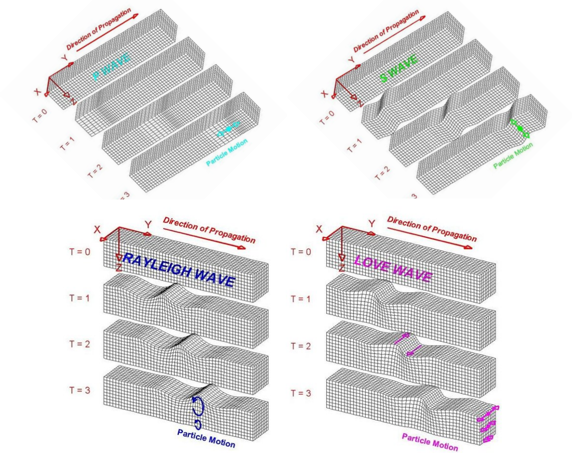
Outline

Earthquake Ground Motions

Realistic earthquake ground motions

- Body waves: P and S waves
- Surface waves: Rayleigh, Love waves, etc.
- Surface waves carry most seismic energy
- Lack of correlation (incoherence)
- Inclined waves
- 3D waves

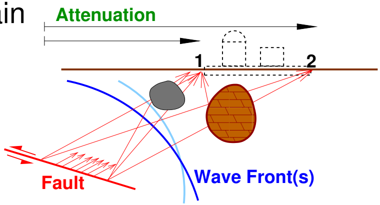
Body (P, S) and Surface (Rayleigh, Love) Waves



Spatial Variability (Incoherence, Lack of Correlation)

Incoherence → frequency domain

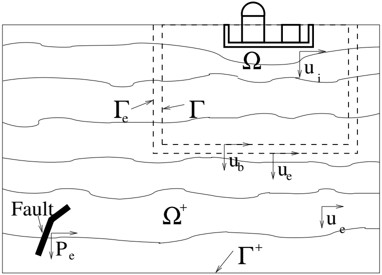
Lack of Correlation → time domain



- Wave passage effects
- Attenuation effects
- Extended source effects
- Scattering effects

Seismic Input

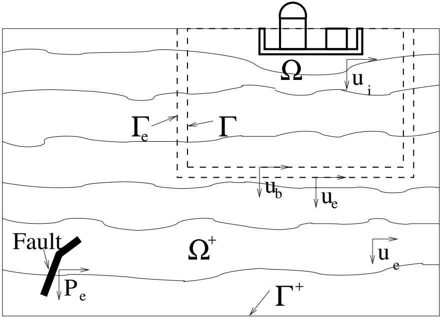
The Domain Reduction Method (Bielak et al.):
The effective force P^{eff}
is a dynamically consistent replacement for the dynamic source forces P_e



$$P^{eff} = \left\{ \begin{array}{c} P_i^{eff} \\ P_b^{eff} \\ P_e^{eff} \end{array} \right\} = \left\{ \begin{array}{c} 0 \\ -M_{be}^{\Omega+} \ddot{u}_e^0 - K_{be}^{\Omega+} u_e^0 \\ M_{eb}^{\Omega+} \ddot{u}_b^0 + K_{eb}^{\Omega+} u_b^0 \end{array} \right\}$$

DRM

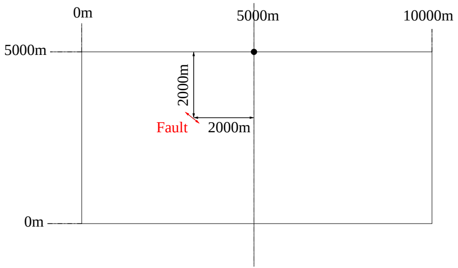
- Seismic forces P_e replaced by P^{eff}
- P^{eff} applied only to a single layer of elements next to Γ.
- The only outgoing waves are from dynamics of the NPP
- Material inside Ω can be elastic-plastic
- All types of seismic waves (body, surface...) are properly modeled



Outline

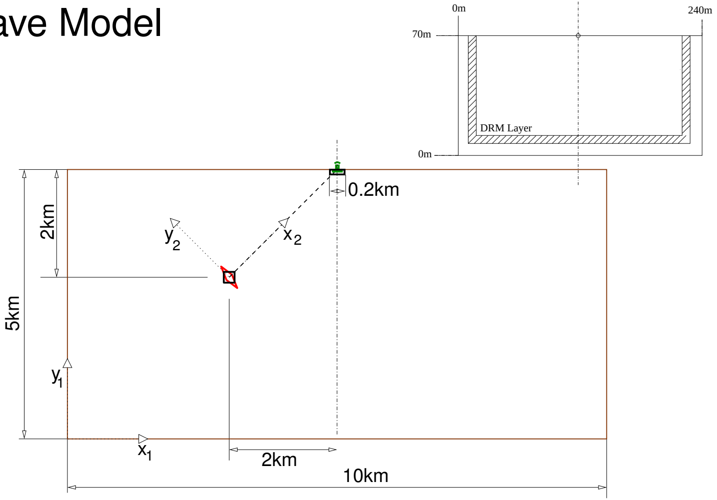
Free Field, Inclined, 3D Body and Surface Waves

- Development of analytic and numerical 3D, inclined, uncorrelated seismic motions for verification
- Large scale models
- Point shear source
- Stress drop:
  - Wavelet (Ricker, Ormsby, etc)
  - Analytic



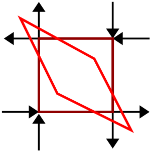
- Seismic input using DRM (Bielak et al (2003))

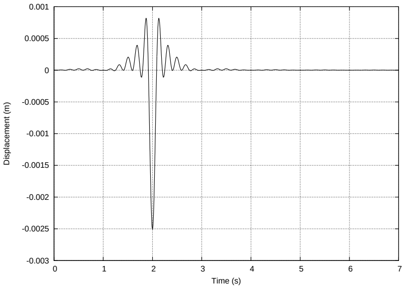
Plane Wave Model

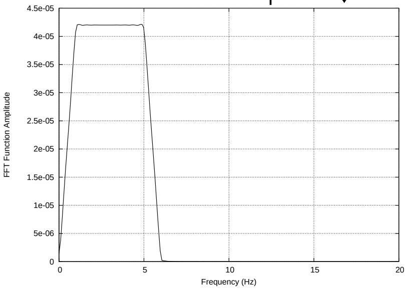


Seismic Source Mechanics

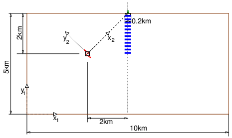
Stress drop, Ormsby wavelet

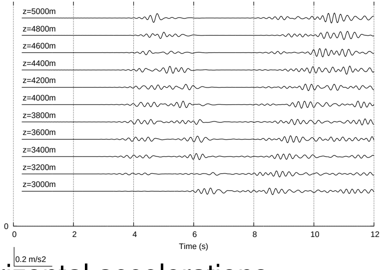




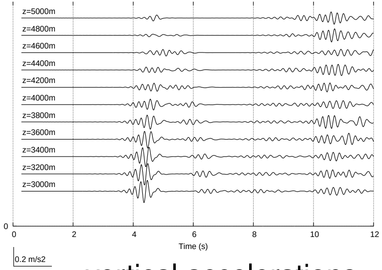


Middle (Structure Location) Plane, Top 2km





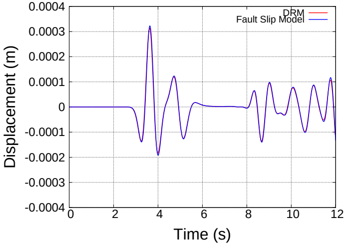
horizontal accelerations



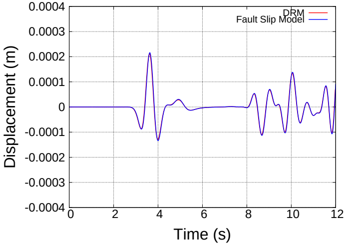
vertical accelerations

Verification: Displacements, Top Middle Point

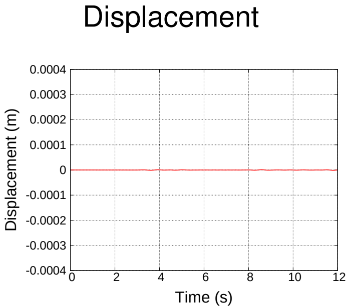
(X)

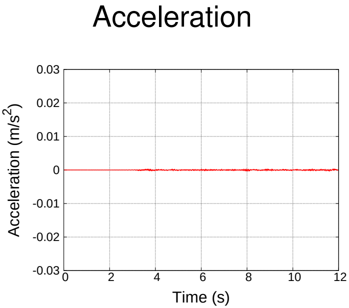


(Z)



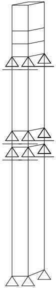
Verification: Disp. and Acc., Out of DRM





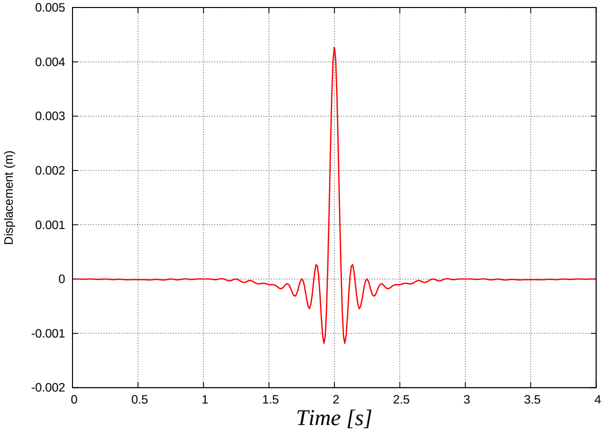
Model Verification: Mesh Size Effects

- Finite element mesh "filters out" high frequencies
- Usual rule of thumb: 10-12 elements needed per wave length
- 1D wave propagation model
- 3D finite elements (same in 3D)
- Motions applied as displacements at the bottom

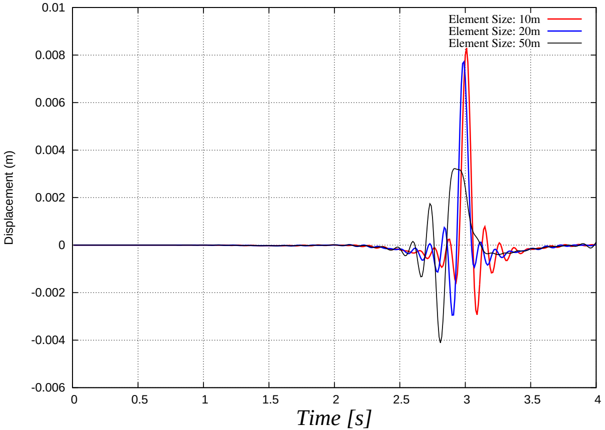


case	model height [m]	V_s [m/s]	El.size [m]	f_{max} (10el) [Hz]
3	1000	1000	10	10
4	1000	1000	20	5
6	1000	1000	50	2

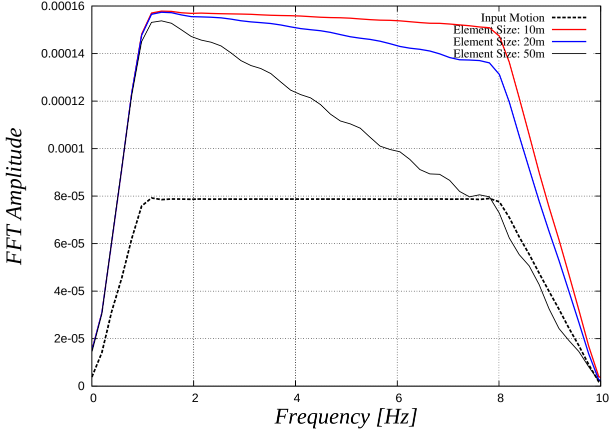
Cases 3, 4, and 6, Ormsby Wavelet Input Motions



Cases 3, 4, and 6, Surface Motions

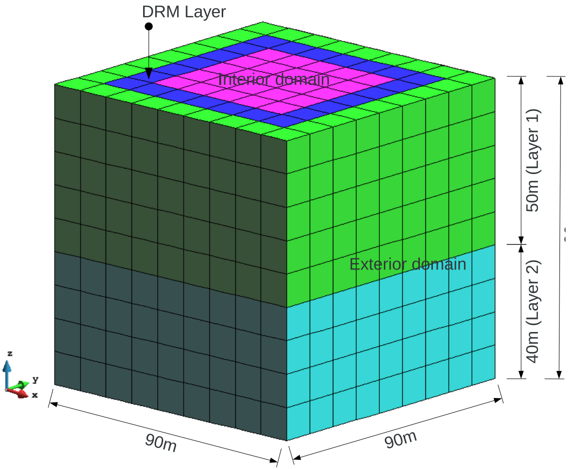


Cases 3, 4, and 6, Input and Surface Motions, FFT



Outline

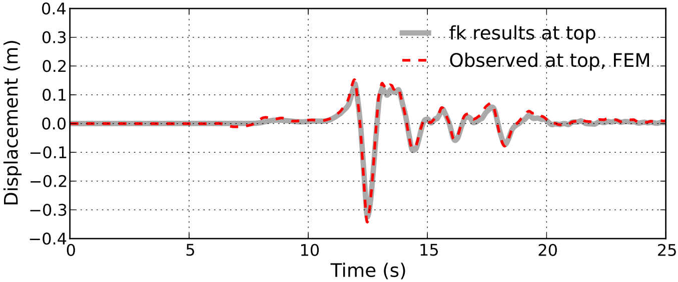
Northridge 3D FE Model



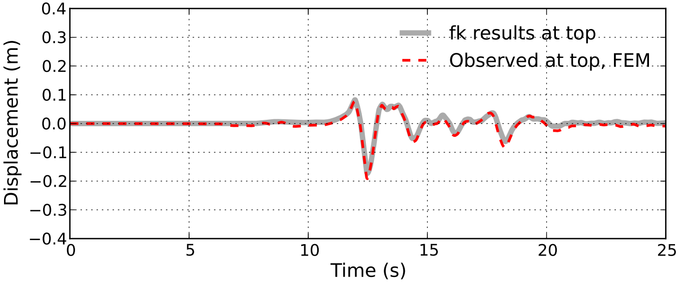
Northridge 3D Model Properties

- Model Properties
  - 90 m $\times$ 90 m $\times$ 90 m dimension
  - Vs1 = 300 m/s, Vs2 = 400 m/s
  - Poisson's ratio1 = 0.25, Poisson's ratio2 = 0.25
- Input Wave Properties
  - Northridge earthquake source properties
  - Generated using fk program

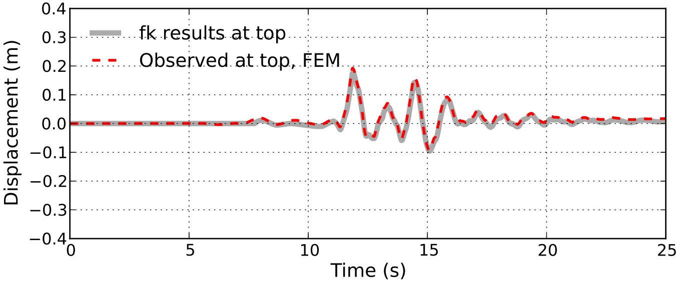
FEM Results, EW Component



FEM Results, NS Component



FEM Results, UD Component



Outline

ESSI Simulator System

- **The ESSI-Program** is a 3D, nonlinear, time domain, parallel finite element program specifically developed for Hi-Fi modeling and simulation of Earthquake Soil/Rock Structure Interaction problems for infrastructure objects on ESSI-Computer.
- **The ESSI-Computer** is a distributed memory parallel computer, a cluster of clusters with multiple performance processors and multiple performance networks.
- **The ESSI-Notes** represent a hypertext documentation system (Theory and Formulation, Software and Hardware, Verification and Validation, and Case Studies and Practical Examples) detailing modeling and simulation of ESSI problems.

ESSI Simulator Program: Finite Elements

- Dry/single phase solids (8, 20, 27 8-27 node bricks),
- Saturated/two phase solids (8 and 27 node bricks, liquefaction modeling),
- Shell with 6DOF per node,
- Beams (six and variable DOFs per node),
- Truss,
- Contacts (dry or saturated soil/rock - concrete, gap opening-closing, frictional slip),
- Base isolators (elastomeric, frictional pendulum)

ESSI Simulator Program: Material Models and Seismic Input

- Material Models
  - Linear and nonlinear, isotropic and anisotropic elastic
  - Elastic-Plastic (von Mises, Drucker Prager, Rounded Mohr-Coulomb, Leon Parabolic, Cam-Clay, SaniSand, SaniClay, Pisanò...). All elastic-plastic models can be used as perfectly plastic, isotropic hardening/softening and kinematic hardening models.
- Analytic input of seismic motions (both body (P, S) and surface (Rayleigh, Love, etc., waves), including analytic radiation damping.

ESSI Simulator Program: V&V, Parallel

- Verification and Validation: each element, model, algorithm and procedure has been extensively verified (math issue) and validated (physics issue). Verification and Validation is documented in detail in ESSI Notes.
- High Performance Parallel Computing: both parallel and sequential version available, however, for high fidelity modeling, parallel is really the only option. Parallel ESSI Simulator runs on clusters of PCs and on large supercomputers (Distributed Memory Parallel machines, all top national supercomputers).

ESSI Simulator Program: Probabilistic/Stochastic

- Constitutive: Euler-Lagrange form of Fokker-Planck (forward Kolmogorov) equation for probabilistic elasto-plasticity (PEP)
- Spatial: stochastic elastic plastic finite element method (SEPFEM)

Uncertainties in material and load are analytically taken into account. Resulting displacements, stress and strain are obtained as very accurate (second order accurate for stress) Probability Density Functions. PEP and SEPFEM are not based on a Monte Carlo method, rather they expand uncertain input variables and uncertain degrees of freedom (unknowns) into spectral probabilistic spaces and solve for PDFs of resulting displacement, stress and strain in a single run.

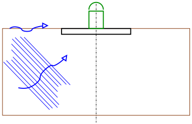
Outline

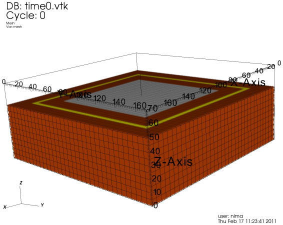
Few Illustrative Examples

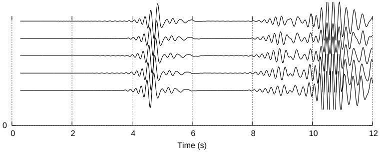
- Slip between foundation slab and the soil/rock underneath
- Passive seismic isolation by liquefaction
- Structural response in liquefied soil

Nuclear Power Plant with Base Slip

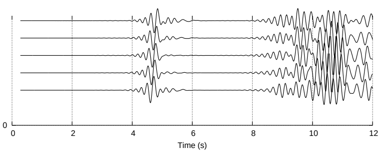
- Low friction zone between concrete foundation and soil/rock
- Inclined, 3D, body and surface, seismic wave field (wavelets: Ricker, Ormsby; real seismic, etc.)





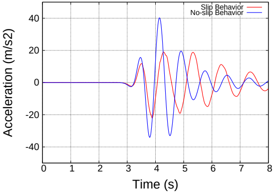


horizontal

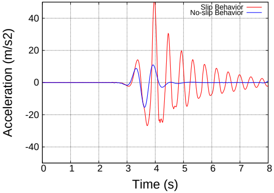


vertical

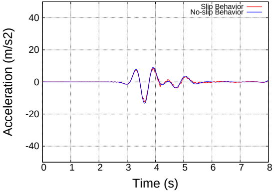
Acc. Response for a Full 3D (at 45°) Ricker Wavelet



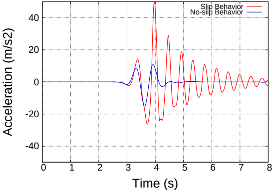
top X



top Z

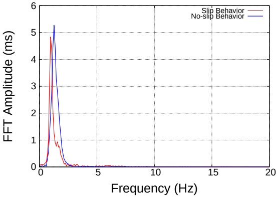


bottom X

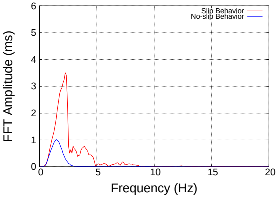


bottom Z

FFT Response for a Full 3D (at 45°) Ricker Wavelet



top X



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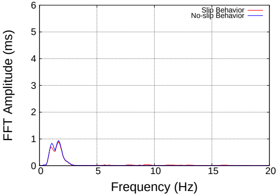
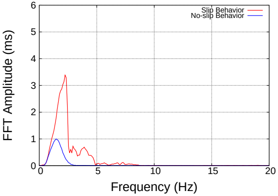
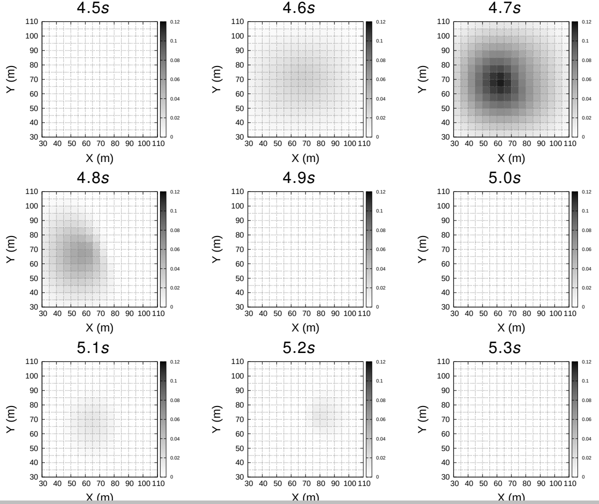


bottom X

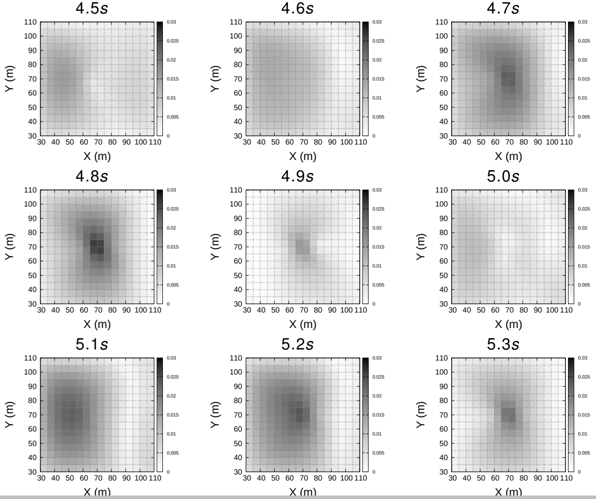


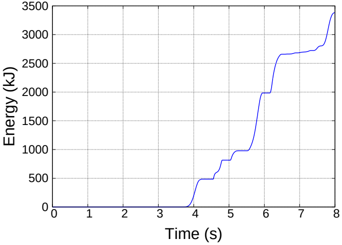
bottom Z

Gaping Response (45° Ricker Wavelet)



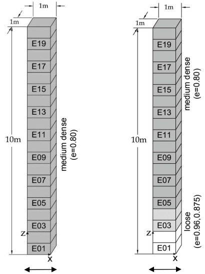
Slipping Response and Energy Dissipated (45° Ricker)

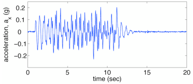


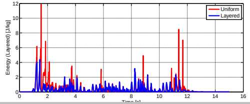


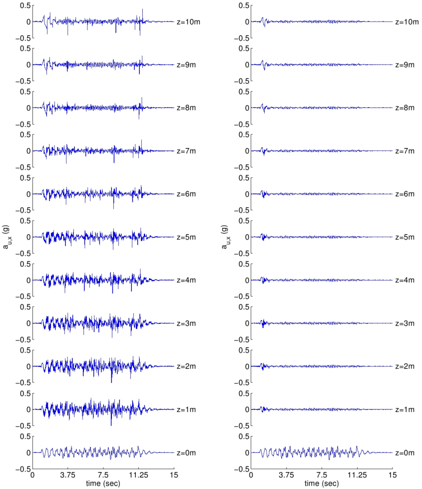
Outline

Passive Base Isolation in Uniform and Layered Soils

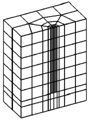


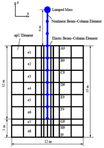


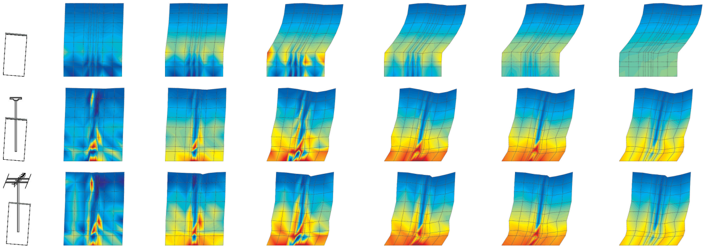




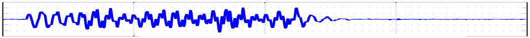
Pile in Liquefiable Sloping Ground



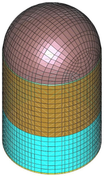


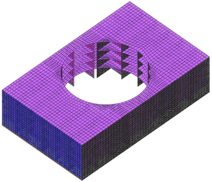


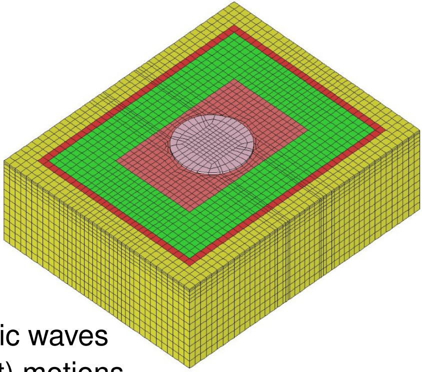
t= 2 sec 5 sec 10 sec 15 sec 20 sec 80 sec



Current NPP Model(s)







- 3D, Inclined,
  Body and Surface seismic waves
- Uncorrelated (incoherent) motions
- Foundation slip – gap
- Isolators, dissipators
- Saturated dense vs loose soil with buoyant forces
- Piles and pile groups

Summary

- **Interplay** of **Earthquake**, **Soil**, and **Structure**, in time domain, plays a decisive role in seismic performance of infrastructure objects
- Improve **design** (**safety** and **economy**) through **high fidelity**, modeling and simulation
- **ESSI Simulator System**, extensively **Verified** and **Validated** is used for modeling, simulations, design and regulatory decision making
- **Education** and **training** of users (designers, regulators, owners) will prove essential

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