Nonlinear, Inelastic ESSI Analysis

SMiRT26 Tutorial III

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Outline

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Motivation

Improve modeling and simulation for infrastructure objects

Reduction of modeling uncertainty

Choice of analysis level of sophistication

Goal: Predict and Inform

Engineer needs to know!

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."

Hypothesis

- Interplay of the Earthquake, Soil/Rock and Structure in time domain, plays a 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 the energy dissipation can be controlled (directed), we could optimize soil structure system for
  - Safety
  - Economy

ESSI: Energy Input and Dissipation

Energy input, dynamic forcing

Energy dissipation outside SSI domain:

- SSI system oscillation radiation
- Reflected wave radiation

Energy dissipation/conversion inside SSI domain:

- Inelasticity of soil, contact/interface zone, structure, foundation, dissipators
- Viscous coupling, porous solid-pore fluids, solids/structures-external fluids

Numerical, algorithmic energy dissipation/production

Prediction under Uncertainty

- Epistemic, Modeling Uncertainty, Simplifying assumptions
  - Low, medium, high sophistication modeling and simulation
  - Choice of sophistication level for confidence in results
- Alietory, Parametric Uncertainty, $M\ddot{u}_i + C\dot{u}_i + K^{ep}u_i = F(t)$,
  - Uncertain mass M, viscous damping C and stiffness K^{ep}
  - Propagation of uncertainty in loads, $F(t)$
  - Results are PDFs and CDFs for σ_{ij}, ϵ_{ij}, u_i, $\dot{u}_i$, $\ddot{u}_i$

Goal: Reduction of Modeling Uncertainty

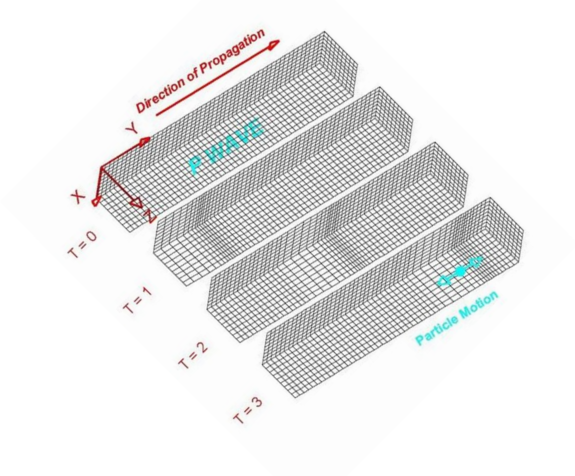
- Modeling Uncertainty: introduced with unnecessary and unrealistic modeling simplification
- Simplified (or inadequate/wrong) modeling: important features are missed (3C (6C) seismic ground motions, inelasticity, etc.)
- Modeling simplifications are justifiable if one, two or higher level sophistication model demonstrates that features being simplified out are not important
- Use of HPC for low modeling uncertainty and direct probabilistic modeling and simulations

Outline

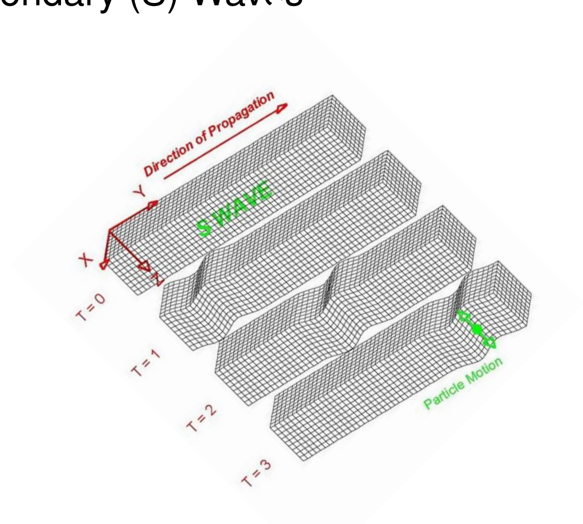
Earthquake Ground Motions

- Body, P and S waves
- Surface, Rayleigh, Love, Stoneley and other waves
- Inclined waves
- 3C/6C waves
- Lack of correlation, incoherence

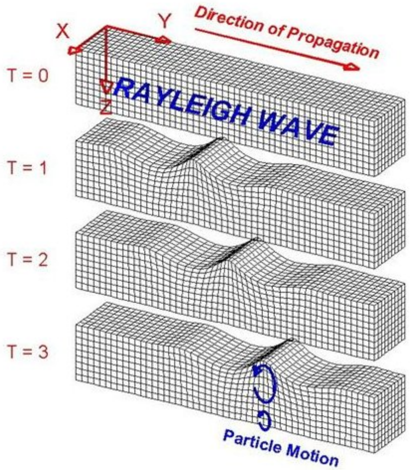
Body Primary (P) Waves



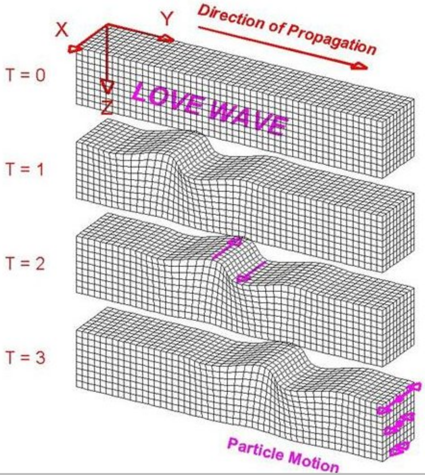
Body Secondary (S) Waves



Surface Rayleigh Waves



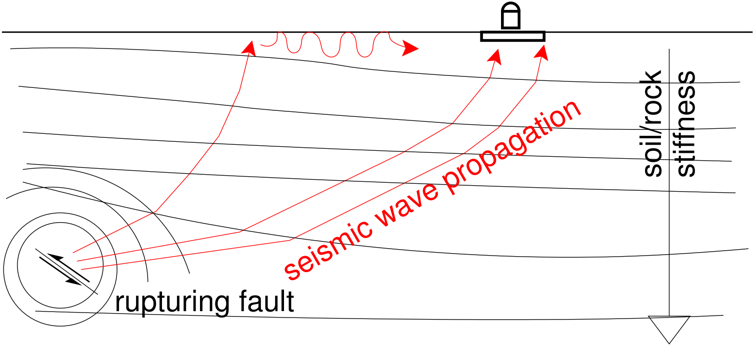
Surface Love Wave



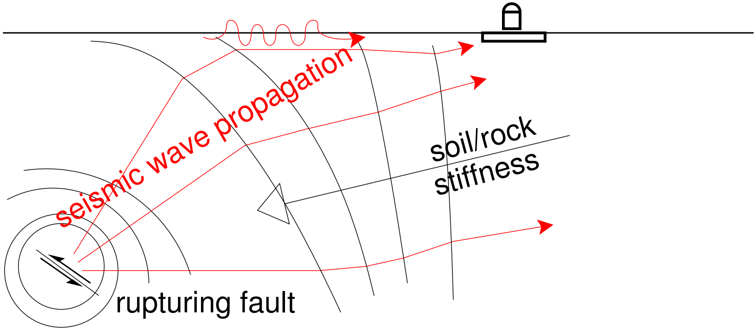
Importance of Surface Waves

- Rayleigh waves are produced by interaction of P- and SV-waves with soil/rock surface
- Love waves are produced by interaction of SH-waves with soil/rock surface
- For realistic geology, surface wave influence is felt close to the epicenter
- Rayleigh waves do carry majority of seismic energy to distance
- Rayleigh waves are responsible for peak accelerations at distance
- Velocity of Rayleigh decreases with increase in frequency

Earthquake Motions, Horizontally Layered Geology



Earthquake Motions with any Geology



3C/6C Inclined Waves

- Deep and shallow geology influences
- Superposition of body and surface waves
- Distance from the causal fault
- 6C, not 3C is a better way to characterize seismic waves

Development of Seismic Motions

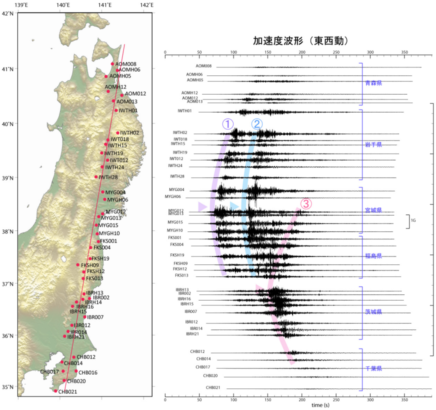
- 1C, 2C, 3×1C, 3C/6C seismic motions
- Knowledge of geology, deep and shallow, needed
- Deconvolution of surface motions
- Convolution of motions from depth
- Regional scale models using Real-ESSI, SW4, fp, etc.
- Stress test motions, Thomson/Haskel solution

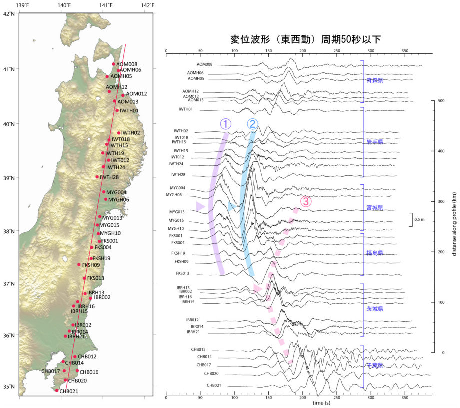
Outline

Earthquake Ground Motions

- Real earthquake ground motions
  - Body waves: P and S waves
  - Surface waves: Rayleigh and Love waves
  - Near surface layer waves: Stoneley waves
  - Lack of correlation, incoherent motions
  - Inclined waves
  - 3C/6C wave fields
- What are the effects of real earthquake ground motions on soil-structure systems ?!

Tohoku Earthquake, Acc, Disp



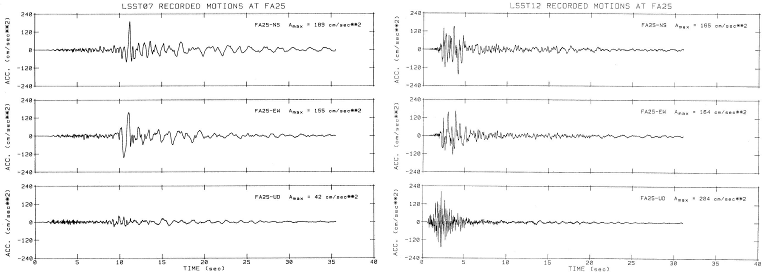


1C, 2C, 3C, 6C Seismic Motions

- All, most measured motions are full 3C, 6C
- What is the effect of neglecting, simplifying out to 1C
- One example of an almost 2C motion (LSST07, LSST12)

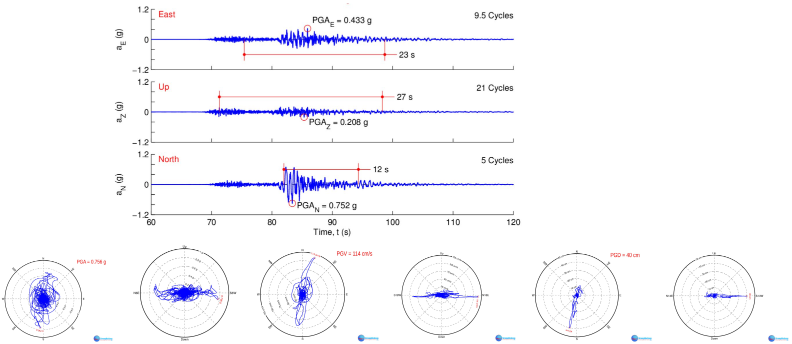
3C (6C) Seismic Motions

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



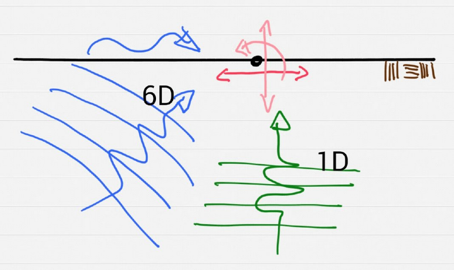
San Pablo Earthquake, 14Jun2017

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



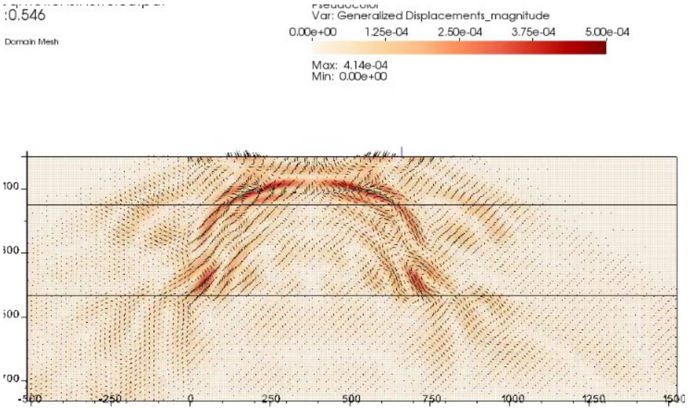
ESSI: 6C or 1C Seismic Motions

- Assume that a full 6C (3C) motions at the surface are only recorded in one horizontal direction
- From such recorded motions one can develop a vertically propagating shear wave (1C) in 1D
- Apply such vertically propagating shear wave to same soil-structure system



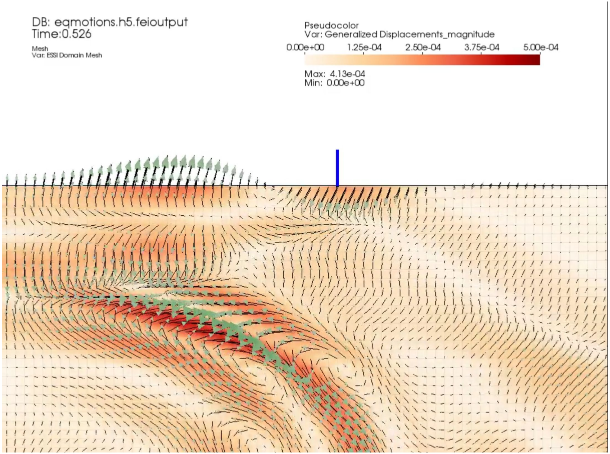
Realistic Ground Motions

- Free field seismic motion models



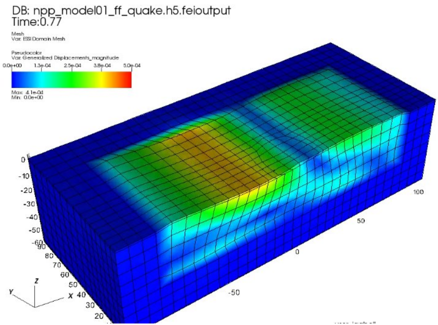
Development of Realistic Motions

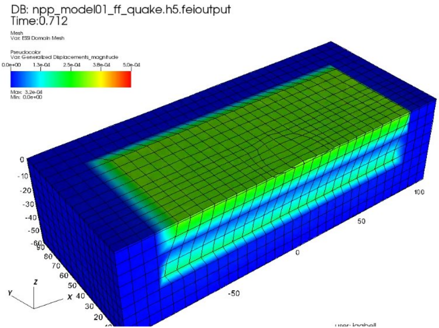
- Sources will send both P and S waves



1C vs 6C Free Field Motions

- One component of motions, 1C from 6C
- Excellent fit, wrong mechanics





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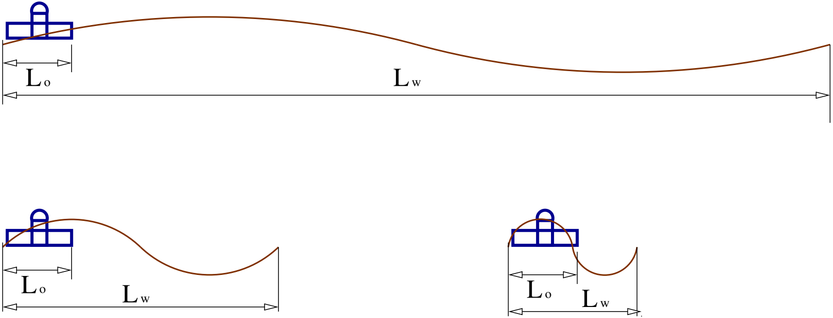
When to use 3C and/or 3×1C

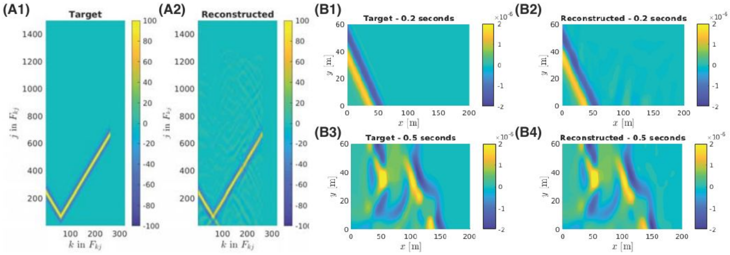


1C vs 3$\times$1C vs 3C Seismic Motions

- 1C is used most frequently
- 3$\times$1C can be used depending on frequency/wave length of interest,
- 3C is more realistic, however it is challenging to define motions in full 3C

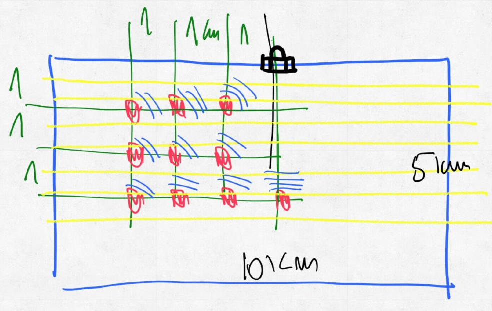
Real Wave Field from Surface Measurements

- Use surface and shallow measurements to develop 3C/6C wave field
- Currently in development, Dr. Han Yang lead



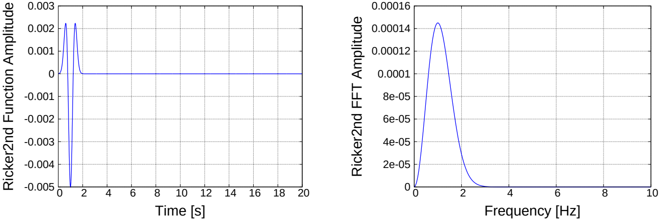
Stress Testing SSI Systems

- Excite SSI system with a suite of seismic motions
- Simple sources, variation in strike and dip, body waves P, S; (near) surface waves (Rayleigh, Love, Stoneley, etc.)
- Stress test soil-structure system

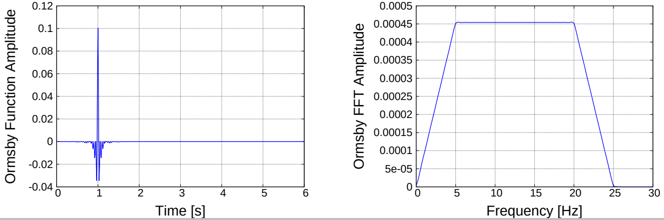


Stress Test Source Signals

- Ricker

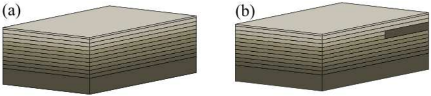


- Ormsby

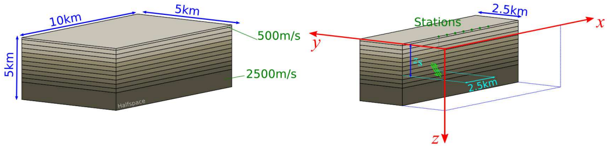


Layered and Dyke/Sill Models

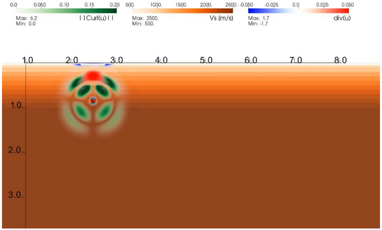
- Horizontal layers
- Dyke/Sill intrusion

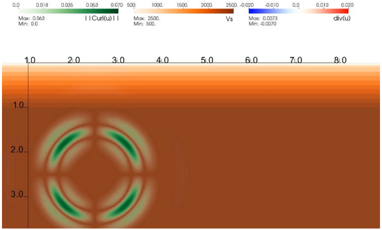


- Source locations matrix, point sources
- Source strike and dip variation
- Magnitude variations
- Range of frequencies



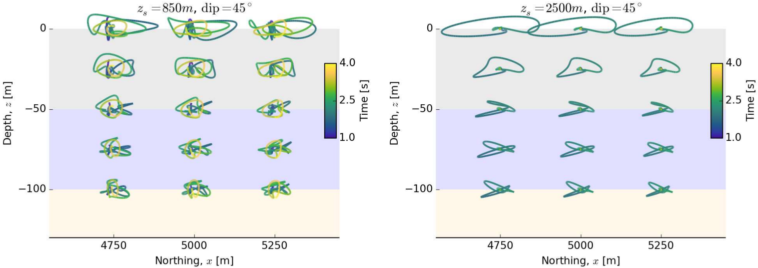
Layered System, Variable Source Depth



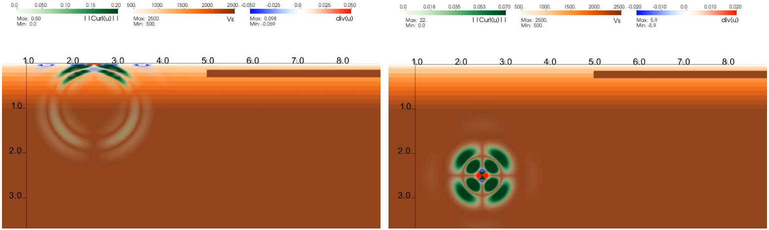


Layered System, Displacement Traces

- 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!

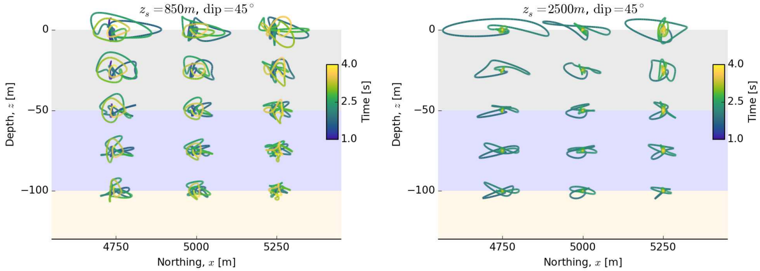


Dyke/Sill Intrusion, Variable Source Depth



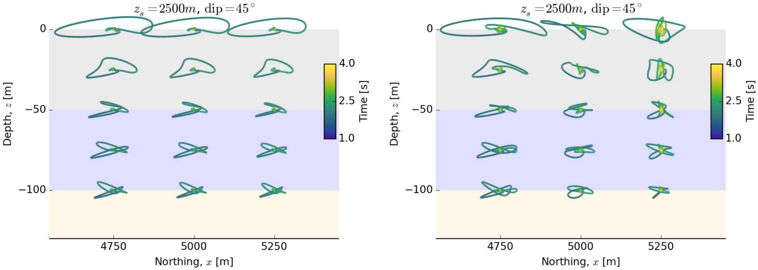
Dyke/Sill Intrusion, Variable Source Depth

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



Dyke/Sill as Seismic Energy Sink

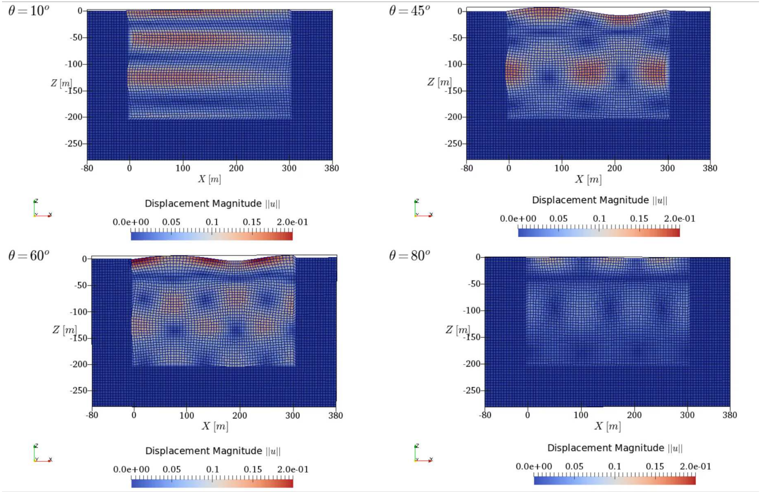
- Dyke/Sill (right Fig), made of stiff rock, is an energy sink, as well as energy reflector
- Variable wave lengths behave differently, depending on dyke/sill geometry and location



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 deep and shalow geology and the soil site is important
- 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



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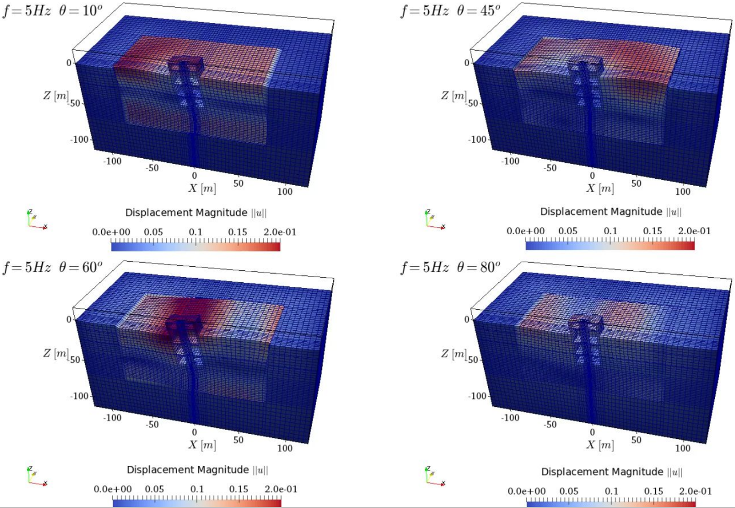
SMR ESSI, Variation in Input Wave Angle, $f = 5$Hz



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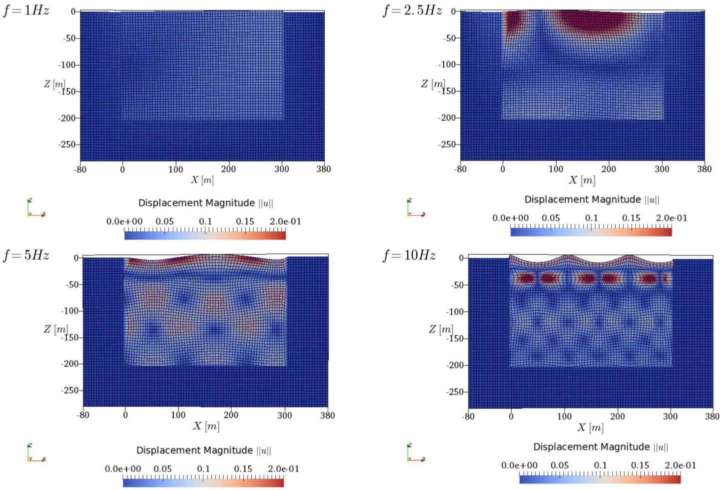
Free Field, Variation in Input Frequency, $\theta = 60^o$



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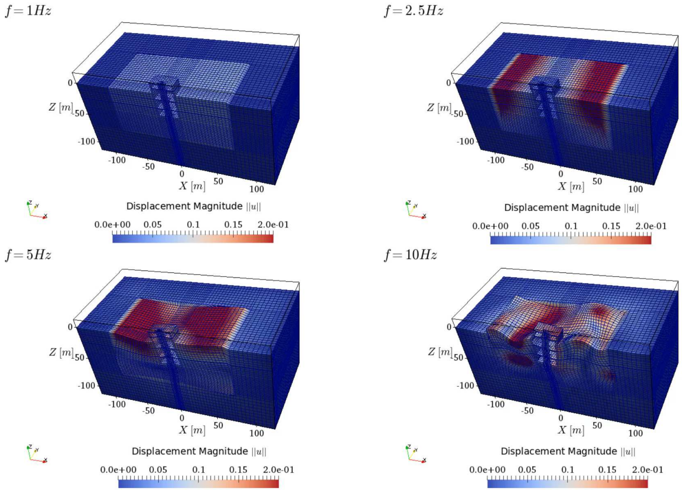
SMR ESSI, Variation in Input Frequency, $\theta = 60^o$



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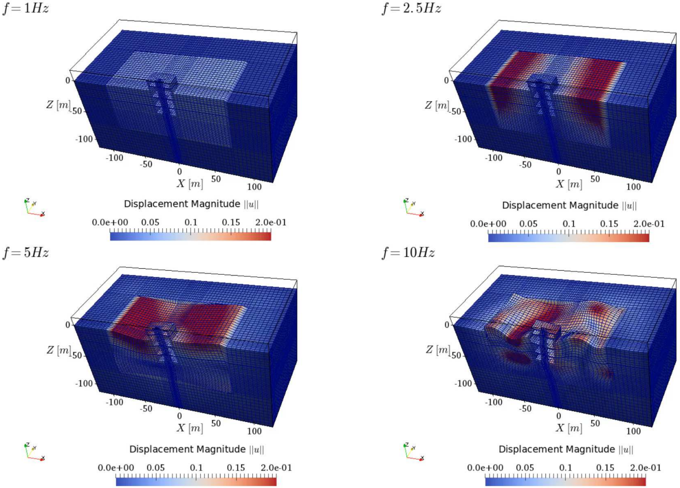
SMR ESSI, Variation in Input Frequency, REAL TIME



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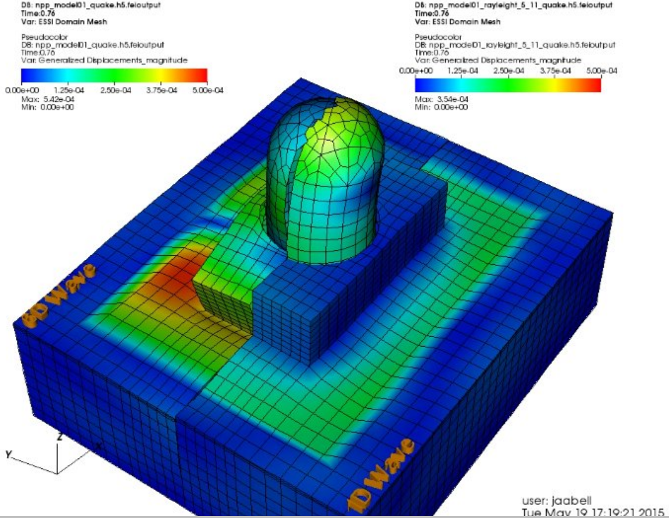
6C vs 1C NPP ESSI Response Comparison



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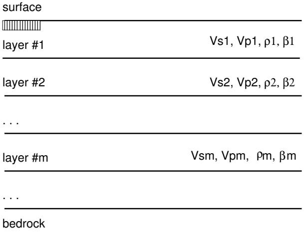
Outline

Ground Motions for ESSI Analysis

- 1C, 3×1C, 3C/6C, convolution or de-convolution
- 1C, or 3×1C wave field de-convolution from surface soil motions, then use DRM
- 1C, or 3×1C wave field de-convolution from surface rock outcrop motions, then convolution up the soil column then use DRM
- 3D with a full 3C wave field convolution using DRM
- Wave fields defined on linear elastic deep geology

1C Wave Propagation



- Wave equation: $\rho \partial^2 u / \partial t^2 = G \partial^2 u / \partial z^2 + \eta \partial^3 u / (\partial z^2 \partial t)$
- Assume harmonic oscillations: $u(z,t) = U(z) \cdot e^{i\omega t}$
- Obtain: $(G + i\omega\eta) \partial^2 u / \partial z^2 = \rho \omega^2 U$
- Solution is a wave equation for a harmonic motions of frequency ω: $u(z,t) = Ee^{i(kz+\omega t)} + Fe^{-i(kz-\omega t)}$
- Complex wave number $k^2 = \rho\omega^2 / (G + i\omega\eta)$ and η is viscosity.

1C Wave Propagation, contd.

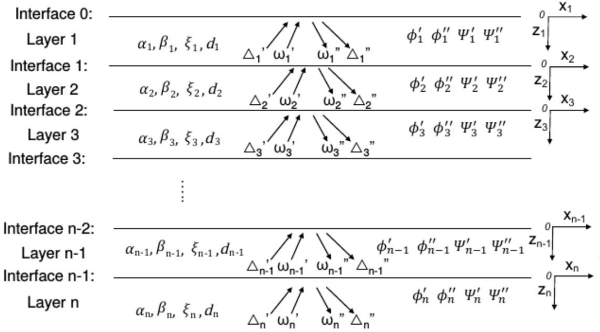
- Solutions for top and bottom of each layer m:

$$u_m(z = 0) = (E_m + F_m)e^{i\omega t}$$

$$u_m(z = h_m) = (E_m \cdot e^{ik_m h_m} + F_m e^{-ik_m h_m}) \cdot e^{i\omega t}$$

- Note: solution is valid for a linear elastic or equivalent elastic material

3C, Inclined Plane Wave, Layered Ground



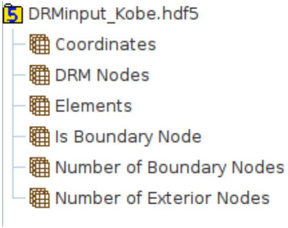
- Thomson/Haskel ('50/'53) propagator matrix technique
- $\alpha_i, \beta_i, \xi_i, d_i$ are P, SV wave velocities, damping ratio and thickness for the i^{th} layer

3C, Inclined Plane Wave, Layered Ground, Contd.

- DRM layer geometry, boundary and exterior nodes
- Engineering site characteristics
- Inclined incident seismic wave:
  - Input wave potential, harmonic
  - Input time series signal

DRM Layers

- HDF5 file containing required info on DRM layer
- Same DRM input format for 1C, 2×1C, 3×1C DRM motions



Engineering Site Characteristics

Layers: Five column, plain text file

- S wave velocity
- P wave velocity
- Density
- Damping
- Layer thickness

```
// Format of Soil Profile:
//Vs    Vp      rho     damp    thickness
500     816.5   2100    0.0     100
750     1403.1  2300    0.0     200
1000    2081.7  2500    0.0

// Last layer is the bedrock.
// User should NOT give thickness for the last layer.

// in documentation, from surface to bottom
```

NOTE: This ground profile has to be the same as profile of DRM leyrs and inner soil layers used in wave propagation model!

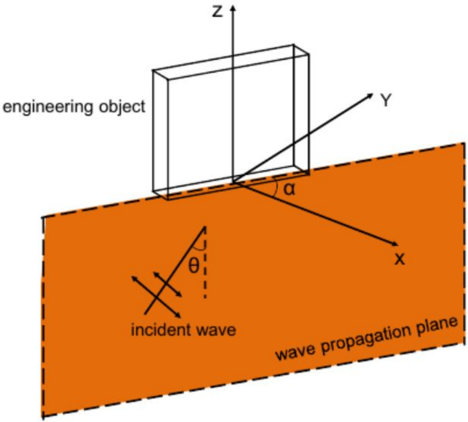
3C, Inclined Plane Wave, Harmonic, Convolution

```
add wave field # 1 type inclined_plane_wave with
    anticlockwise_angle_of_SV_wave_plane_from x = 30
    SV_incident_magnitude = 10*m^2
    SV_incident_angle = 60
    SV_incident_frequency = 5/s
    motion_time_step = 0.005*s
    number_of_time_steps = 1001
    soil_profile_filename = "soil_profile.txt"
    soil_surface at z = 0*m
    unit_of_vs_and_vp = 1*m/s
    unit_of_rho = 1*kg/m^3
    unit_of_damping = absolute
    unit_of_thickness = 1*m;
```

3C, Inclined Plane Wave, Time Signal, Convolution

```
add wave field # 1 type inclined_plane_wave with
    anticlockwise_angle_of_SV_wave_plane_from x = 0
    SV_incident_acceleration_filename = "Kobe_acc.txt"
    unit_of_acceleration = 1*m/s^2
    SV_incident_displacement_filename = "Kobe_disp.txt"
    unit_of_displacement = 1*m
    SV_incident_angle = 15
    add_compensation_time = 0.5*s
    soil_profile_filename = "soil_profile.txt"
    soil_surface at z = 0*m
    unit_of_vs_and_vp = 1*m/s
    unit_of_rho = 1*kg/m^3
    unit_of_damping = absolute
    unit_of_thickness = 1*m;
```

3C, Inclined Plane Wave, Geometry



Generate DRM Input, Convolution

- Using developed wave fields

- Generate DRM input, effective forces P_{eff}

```
generate DRM motion file from wave field # 1 hdf5_file = "DRMinput.hdf5";
```

1C, 3×1C Seismic Wave De-Convolution

```
add wave field # 1 with
    acceleration_filename = "Kobe_acc.txt"
    unit_of_acceleration = 1*m/s^2
    displacement_filename = "Kobe_disp.txt"
    unit_of_displacement = 1*m
    add_compensation_time = 2*s
    motion_depth = 0*m
    monitoring_location = within_soil_layer
    soil_profile_filename = "soil_profile.txt"
    unit_of_Vs = 1*m/s
    unit_of_rho = 1*kg/m^3
    unit_of_damping = absolute
    unit_of_thickness = 1*m;
```

Generate DRM Input, 1C, $3\times1C$, De-Convolution

```
generate domain reduction method motion file
  from wave field
  # 1 in direction ux
  soil_surface at z = 0*m
  hdf5_file = "DRMinput_Kobe.hdf5";
```

```
generate domain reduction method motion file
  from wave field
  # 1 in direction ux
  # 2 in direction uy
  # 3 in direction uz
  soil_surface at z = 0*m
  hdf5_file = "DRMinput_Kobe.hdf5";
```

Outline

Methods for Seismic Input, 1C, 3×1C, 3C/6C

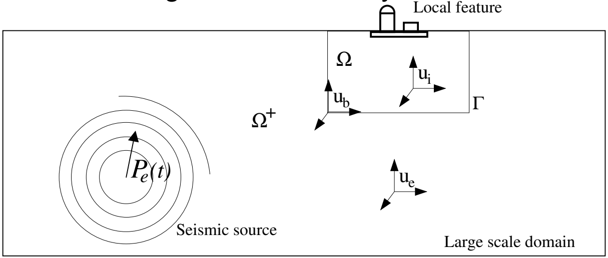
- Relative accelerations
- Prescribed displacements
- Prescribed accelerations
- Free field column coupled with 2D models via dampers
- Domain Reduction Method

The Domain Reduction Method (DRM)

- Work by Bielak et al. (2003) at CMU.
- DRM features:
  - General 3C seismic input (P, S, Love, Rayleigh, Stoneley...)
  - Nonlinear, elastic-plastic ESSI
  - Minimal outgoing waves, only radiation of structural oscilation energy
- Consistent replacement for seismic moment released from hypocenter with forces on a single layer of elements around ESSI system

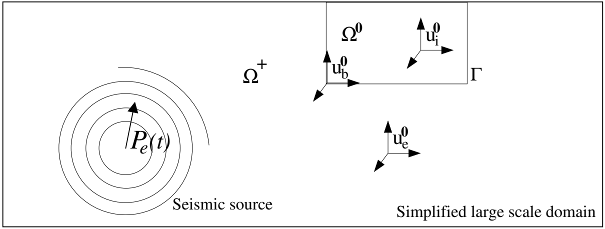
Domain Reduction Method

- Large physical domain is to be analyzed for dynamic behavior.
- Source of disturbance is a known time history of a force field $P_e(t)$.
- Source of loading, fault is far away from the local feature



DRM

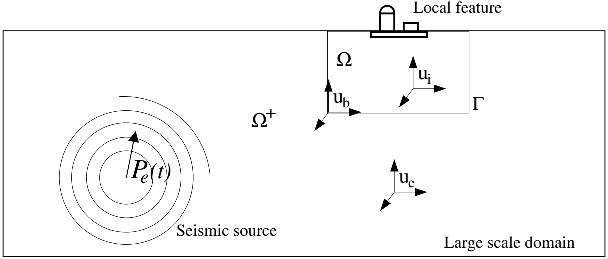
- Remove local feature, create a free field model
- Domain inside the boundary Γ is named Ω_0.
- Outside boundary Γ, is Ω^+.
- Outside domain Ω^+ is the same as in the original model,
- Simplification, is done on the domain inside boundary Γ.



DRM

Equations of motions for a complete system

$$\left[\ M\ \right]\left\{\ \ddot{u}\ \right\}+\left[\ K\ \right]\left\{\ u\ \right\}=\left\{\ P_e\ \right\}$$

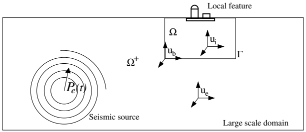


DRM

Eq. of motions for each subdomain (interior, boundary and exterior of Γ)

$$\begin{bmatrix} M_{ii}^{\Omega} & M_{ib}^{\Omega} & 0 \\ M_{bi}^{\Omega} & M_{bb}^{\Omega} + M_{bb}^{\Omega+} & M_{be}^{\Omega+} \\ 0 & M_{eb}^{\Omega+} & M_{ee}^{\Omega+} \end{bmatrix} \begin{Bmatrix} \ddot{u}_i \\ \ddot{u}_b \\ \ddot{u}_e \end{Bmatrix} +$$

$$+ \begin{bmatrix} K_{ii}^{\Omega} & K_{ib}^{\Omega} & 0 \\ K_{bi}^{\Omega} & K_{bb}^{\Omega} + K_{bb}^{\Omega+} & K_{be}^{\Omega+} \\ 0 & K_{eb}^{\Omega+} & K_{ee}^{\Omega+} \end{bmatrix} \begin{Bmatrix} u_i \\ u_b \\ u_e \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ P_e \end{Bmatrix}$$



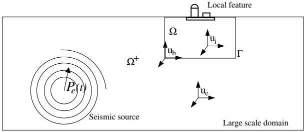
DRM

Separate previous equation into two domains Ω (inside):

$$\begin{bmatrix} M_{ii}^{\Omega} & M_{ib}^{\Omega} \\ M_{bi}^{\Omega} & M_{bb}^{\Omega} \end{bmatrix} \begin{Bmatrix} \ddot{u}_i \\ \ddot{u}_b \end{Bmatrix} + \begin{bmatrix} K_{ii}^{\Omega} & K_{ib}^{\Omega} \\ K_{bi}^{\Omega} & K_{bb}^{\Omega} \end{bmatrix} \begin{Bmatrix} u_i \\ u_b \end{Bmatrix} = \begin{Bmatrix} 0 \\ P_b \end{Bmatrix}$$

and Ω^+ (outside):

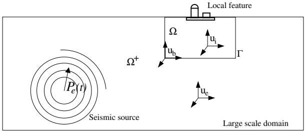
$$\begin{bmatrix} M_{bb}^{\Omega+} & M_{be}^{\Omega+} \\ M_{eb}^{\Omega+} & M_{ee}^{\Omega+} \end{bmatrix} \begin{Bmatrix} \ddot{u}_b \\ \ddot{u}_e \end{Bmatrix} + \begin{bmatrix} K_{bb}^{\Omega+} & K_{be}^{\Omega+} \\ K_{eb}^{\Omega+} & K_{ee}^{\Omega+} \end{bmatrix} \begin{Bmatrix} u_b \\ u_e \end{Bmatrix} = \begin{Bmatrix} -P_b \\ P_e \end{Bmatrix}$$



DRM

For this separation to work one needs to enforce

- compatibility of displacements
- equilibrium, through action–reaction forces P_b

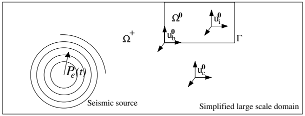


DRM

- Simplified interior domain without local feature, u_i^0, u_b^0, u_e^0 and P_b^0
- The equations of motion in the outside domain Ω^+ for the auxiliary problem:

$$\left[\begin{array}{cc} M_{bb}^{\Omega+} & M_{be}^{\Omega+} \\ M_{eb}^{\Omega+} & M_{ee}^{\Omega+} \end{array} \right] \left\{ \begin{array}{c} \ddot{u}_b^0 \\ \ddot{u}_e^0 \end{array} \right\} +$$

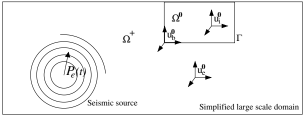
$$+ \left[\begin{array}{cc} K_{bb}^{\Omega+} & K_{be}^{\Omega+} \\ K_{eb}^{\Omega+} & K_{ee}^{\Omega+} \end{array} \right] \left\{ \begin{array}{c} u_b^0 \\ u_e^0 \end{array} \right\} = \left\{ \begin{array}{c} -P_b^0 \\ P_e \end{array} \right\}$$



DRM

Using second part of previous equation to obtain the dynamic force P_e as:

$$P_e = M_{eb}^{\Omega+} \ddot{u}_b^0 + M_{ee}^{\Omega+} \ddot{u}_e^0 + K_{eb}^{\Omega+} u_b^0 + K_{ee}^{\Omega+} u_e^0$$



DRM

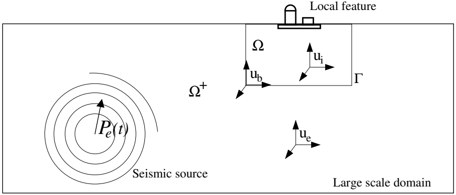
The total displacement, u_e, can be expressed as the sum of the

- free field u_e^0 (from the background, simplified model) and
- residual field w_e (coming from the local feature)

Change of variables

Superposition in the outside domain, not inside!

$$u_e = u_e^0 + w_e$$

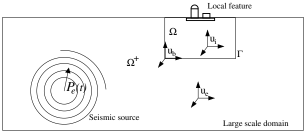


DRM

Substitution into previous dynamic equations

$$\begin{bmatrix} M_{ii}^{\Omega} & M_{ib}^{\Omega} & 0 \\ M_{bi}^{\Omega} & M_{bb}^{\Omega} + M_{bb}^{\Omega+} & M_{be}^{\Omega+} \\ 0 & M_{eb}^{\Omega+} & M_{ee}^{\Omega+} \end{bmatrix} \begin{Bmatrix} \ddot{u}_i \\ \ddot{u}_b \\ \ddot{u}_e^0 + \ddot{w}_e \end{Bmatrix} +$$

$$\begin{bmatrix} K_{ii}^{\Omega} & K_{ib}^{\Omega} & 0 \\ K_{bi}^{\Omega} & K_{bb}^{\Omega} + K_{bb}^{\Omega+} & K_{be}^{\Omega+} \\ 0 & K_{eb}^{\Omega+} & K_{ee}^{\Omega+} \end{bmatrix} \begin{Bmatrix} u_i \\ u_b \\ u_e^0 + w_e \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ P_e \end{Bmatrix}$$



DRM

Move free field motions u_e^0 to the right hand side

$$
\begin{bmatrix} M_{ii}^{\Omega} & M_{ib}^{\Omega} & 0 \\ M_{bi}^{\Omega} & M_{bb}^{\Omega} + M_{bb}^{\Omega+} & M_{be}^{\Omega+} \\ 0 & M_{eb}^{\Omega+} & M_{ee}^{\Omega+} \end{bmatrix} \begin{Bmatrix} \ddot{u}_i \\ \ddot{u}_b \\ \ddot{w}_e \end{Bmatrix} +
\begin{bmatrix} K_{ii}^{\Omega} & K_{ib}^{\Omega} & 0 \\ K_{bi}^{\Omega} & K_{bb}^{\Omega} + K_{bb}^{\Omega+} & K_{be}^{\Omega+} \\ 0 & K_{eb}^{\Omega+} & K_{ee}^{\Omega+} \end{bmatrix} \begin{Bmatrix} u_i \\ u_b \\ w_e \end{Bmatrix} =
\begin{Bmatrix} 0 \\ -M_{be}^{\Omega+} \ddot{u}_e^0 - K_{be}^{\Omega+} u_e^0 \\ -M_{ee}^{\Omega+} \ddot{u}_e^0 - K_{ee}^{\Omega+} u_e^0 + P_e \end{Bmatrix}
$$

DRM

Substitute P_e

$$\begin{bmatrix} M_{ii}^{\Omega} & M_{ib}^{\Omega} & 0 \\ M_{bi}^{\Omega} & M_{bb}^{\Omega} + M_{bb}^{\Omega+} & M_{be}^{\Omega+} \\ 0 & M_{eb}^{\Omega+} & M_{ee}^{\Omega+} \end{bmatrix} \begin{Bmatrix} \ddot{u}_i \\ \ddot{u}_b \\ \ddot{w}_e \end{Bmatrix} +$$

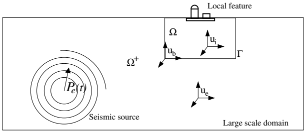
$$\begin{bmatrix} K_{ii}^{\Omega} & K_{ib}^{\Omega} & 0 \\ K_{bi}^{\Omega} & K_{bb}^{\Omega} + K_{bb}^{\Omega+} & K_{be}^{\Omega+} \\ 0 & K_{eb}^{\Omega+} & K_{ee}^{\Omega+} \end{bmatrix} \begin{Bmatrix} u_i \\ u_b \\ w_e \end{Bmatrix} =$$

$$\begin{Bmatrix} 0 \\ -M_{be}^{\Omega+} \ddot{u}_e^0 - K_{be}^{\Omega+} u_e^0 \\ M_{eb}^{\Omega+} \ddot{u}_b^0 + K_{eb}^{\Omega+} u_b^0 \end{Bmatrix}$$

DRM

The right hand side is the dynamically consistent replacement force, so called effective force, P^{eff} for the source forces P_e

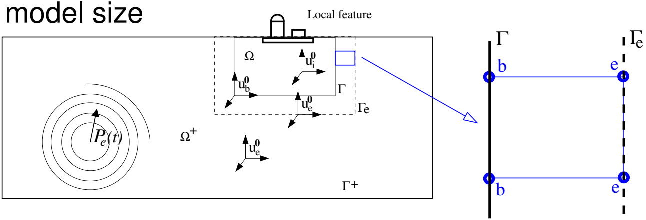
$$P^{eff} = \left\{ \begin{array}{c} P_i^{eff} \\ P_b^{eff} \\ P_e^{eff} \end{array} \right\} = \left\{ \begin{array}{c} 0 \\ -M_{be}^{\Omega+} \ddot{u}_e^0 - K_{be}^{\Omega+} u_e^0 \\ M_{eb}^{\Omega+} \ddot{u}_b^0 + K_{eb}^{\Omega+} u_b^0 \end{array} \right\}$$



DRM

DRM features:

- Seismic forces P_e replaced by P^{eff}
- P^{eff} applied only to a single layer of elements next to Γ.
- Only outgoing waves from structural oscilations
- Material inside Ω can be elastic-plastic
- Any wave field can be input
- We can also neglect the outside (Ω^+) problems thus reducing model size



Seismic Motions, Summary

- Realistic seismic motions
- Three translations, three rotations, 6C
- DRM used as an effective method for motions input
- ESSI analysis with 1C, 3$\times$1C, and 3C/6C seismic motions

Outline

Summary

- Numerical modeling to predict and inform
- Education and Training is the key!
- The Road Ahead: Nonlinear ESSI in Practice
- Afternoon SMiRT workshop on Nonlinear ESSI in Practice
- `http://real-essi.us`