

Dynamics.  
Linear/Nonlinear analysis of soil structure  
interaction problems.  
Constitutive aspects

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August 2014



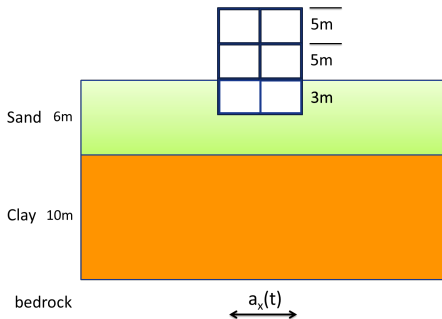


- Example of a building subject to the earthquake (using Domain Reduction Method (DRM))
  - 1 Free field motion as 1D wave propagation problem
    - 1 Basic requirements for mesh size and time step
    - 2 Mesh and BC for rigid base model
    - 3 Application of earthquake signal to the model (relative vs absolute)
    - 4 Signal processing (linear deconvolution, baseline correction, Butterworth filtering)
  - 2 Analysis of reduced model
    - 1 Setting reduced DRM model (exterior and boundary domain setting)
    - 2 Running DRM model
- Pure periodic BC model
- Application of nonlinear models to the problem





# Problem: time history analysis of a building subject to the Loma Prieta earthquake

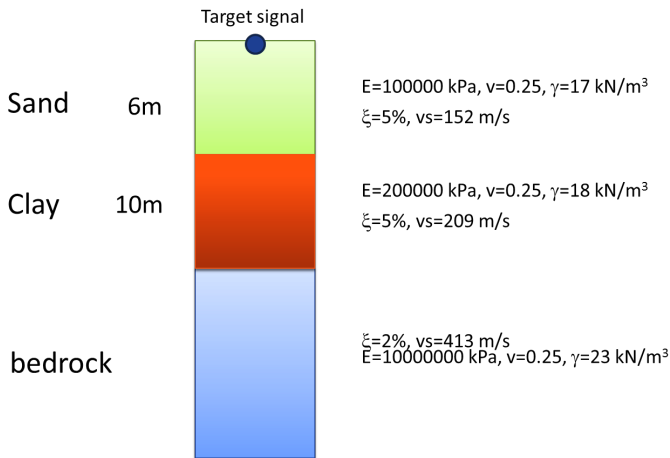


- To run this example we can use so-called Domain Reduction Method (DRM)
- It is the two step analysis that consists of
  - 1 Free field motion analysis
  - 2 Reduced model analysis (structure and small part of subsoil adjacent to it)





# Free field motion: layered subsoil subject to Loma Prieta earthquake (1D) (single phase)





- To trace wave propagation in the medium we need approximately 10 nodes per wavelength
- The mesh size depends on the maximum frequency  $f_{\max}$  that is to be represented
- For typical seismic application  $f_{\max}$  is limited up to 10 Hz
- Hence the maximum mesh size should be smaller than

$$h^e \leq \frac{\lambda}{10} = \frac{v_s}{10 f_{\max}}$$

- Hence the time step limitation can be formulated as follows (in a single time step signal should not pass through more than one element and  $v$  is the maximum wave velocity)

$$\Delta t \leq \frac{h^e}{v}$$





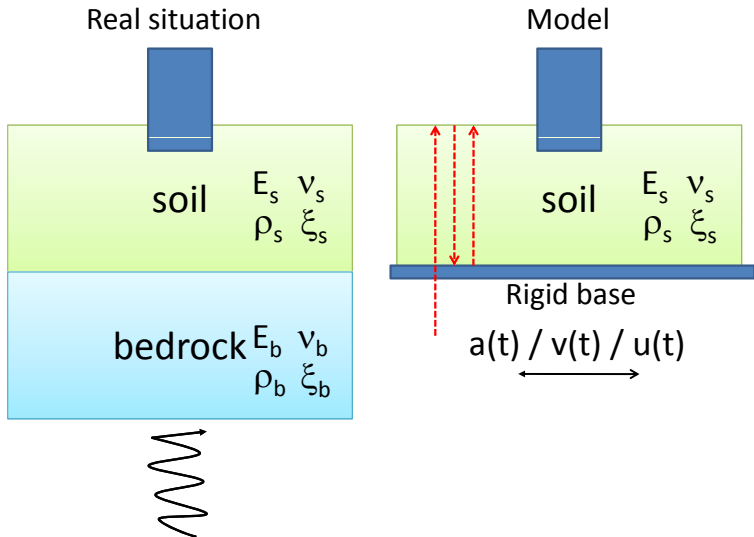
## Material data

Layer	Depth	$E$	$\nu$	$\gamma$	$K_o^{insitu}$	$G$	$\lambda$
	[m]	[kPa]	[-]	[kN/m <sup>3</sup> ]	[-]	[kPa]	[kPa]
Sand	6	$1 \cdot 10^5$	0.25	17	0.5	40000	40000
Clay	10	$2 \cdot 10^5$	0.25	18	0.6	80000	80000
Bedrock	$\infty$	$2 \cdot 10^6$	0.3	23	1.0	3846154	5769231

Layer	Depth	$\rho$	$v_s$	$v_p$	$h^e$	$\bar{h}^e$	$\Delta t$
	[m]	[kN s <sup>2</sup> /m]	[m/s]	[m/s]	[m]	[m]	[s]
Sand	6	1.73	152	263	1.5	1.5	0.010
Clay	10	1.83	209	362	2.1	2.0	0.010
Bedrock	$\infty$	2.34	1281	2396	12.8	12.0	0.009

Hence in sand layer we will use elements with  $\bar{h}^e = 1.5$  m, and for clay  $\bar{h}^e = 2.0$  m





Impedance ratio  $\alpha_z = \frac{\rho_s v_{ss}}{\rho_r v_{sr}} \rightarrow 0$  (complex for nonzero damping)

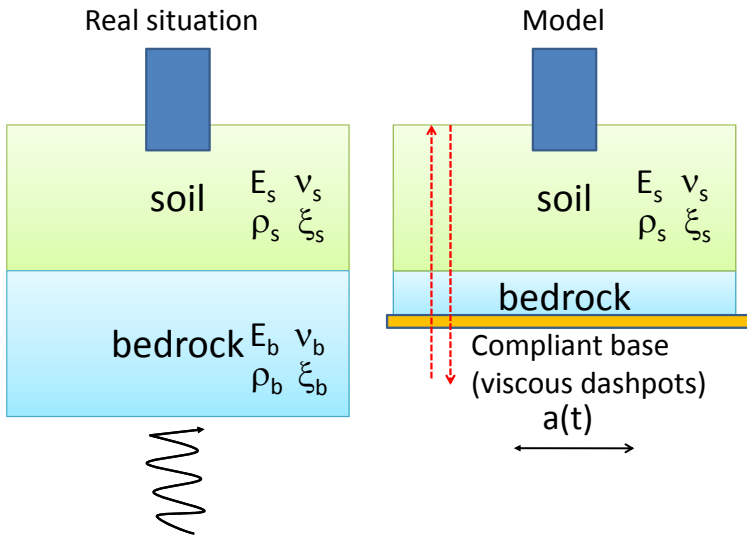


- Nodes at the bottom are fixed
- (a) Motion is imposed by displacement/velocity/acceleration boundary conditions (absolute format)
  - 1 Output: absolute displacements/velocities/accelerations
- (b) Motion is imposed by application of global acceleration to the whole domain (relative format)
  - 1 Output: relative displacements/velocities/accelerations (with respect to the rigid base)





# General comments: Compliant base model



Impedance ratio  $\alpha_z = \frac{\rho_s v_{ss}}{\rho_r v_{sr}} > 0$  (complex for nonzero damping)





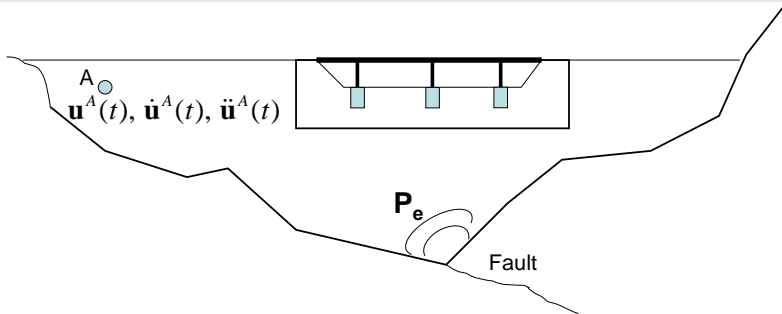
- Nodes at the bottom are free to move
- Viscous dashpots are added to the base
- Motion can exclusively be applied through the acceleration record (seismic input)
  - ① Output: absolute displacements/velocities/accelerations
- Accelerations are integrated to velocities via Newmark method ( $a(t) \rightarrow v_{su}(t)$ )
- Viscous shear tractions are computed and applied to the base
- The input  $a(t)$  does not need to be compatible with  $a(t)$  computed at the base (!)

*L.H. Mejjia, E.M. Dawson. Earthquake deconvolution for FLAC. 2006 (available on the web).*





# General comments: Domain Reduction Method: General idea

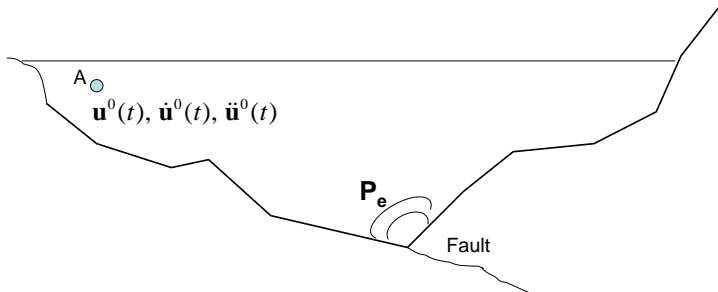


- Goal: **analyze computational model that concerns the structure and only a small adjacent part of subsoil**
- Single and two-phase formulations are supported
- This model with a large subsoil zone and source of load  $P_e(t)$  is decomposed into two models:
  - **Background model**
  - **Reduced model**





# DRM: Background model

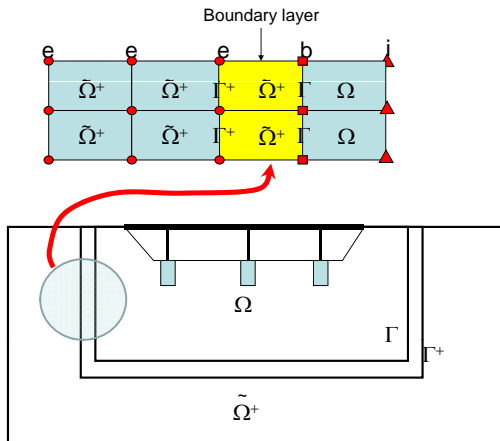


- 1 In the background model **structure is removed**
- 2 **Background model** yields  $\rightarrow$  free field motion:  
 $\mathbf{u}^0(t), \dot{\mathbf{u}}^0(t), \ddot{\mathbf{u}}^0(t)$





# DRM: Reduced model



- 1 Viscous dampers are added to  $\hat{\Gamma}^+$  to cancel wave reflections
- 2 Displ. decomposition in the exterior domain:  $\mathbf{u}_e = \mathbf{u}_e^0 + \mathbf{w}_e$





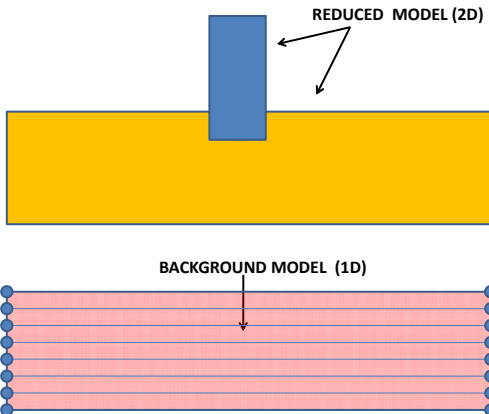
- 1 Continuum in the exterior and boundary layer must work in the elastic mode
- 2 ZSoil freezes stiffness moduli in these zones at the beginning of the analysis
- 3 The interior domain can be analyzed with a suitable nonlinear soil model (HSs, Densification (DNS), HB)
- 4 For HSs, DNS, HB small strain stiffness is automatically taken into account
- 5 For MC we have to adjust stiffness moduli (after static analysis) by hands or by using load time function





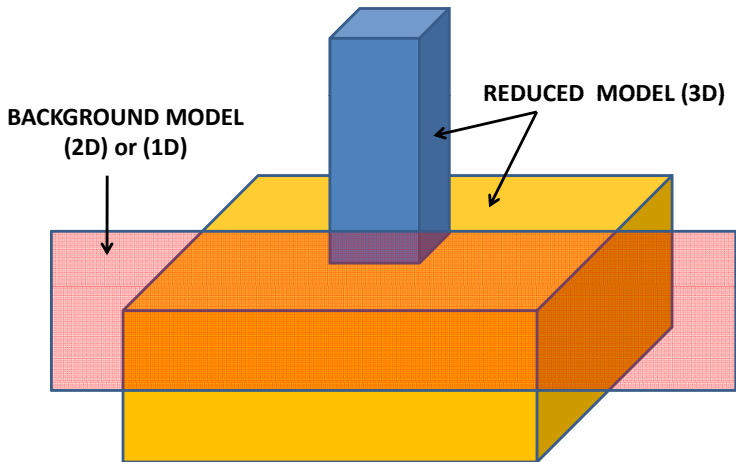
# DRM: Dimensions of background and reduced models

- Space dimension for background model can be lower than for the reduced model





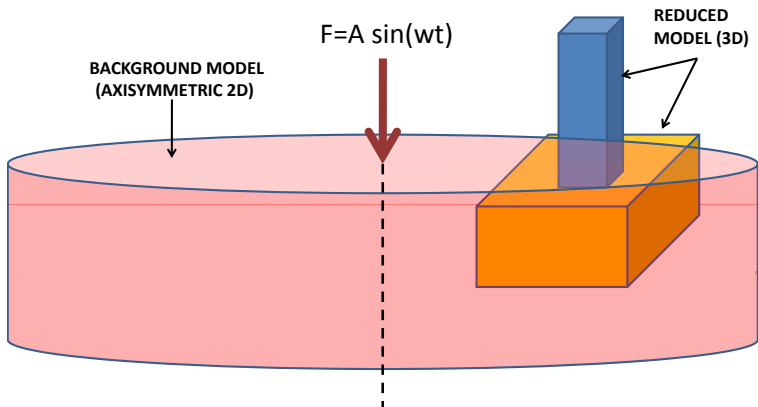
# DRM: Background (2D) Reduced (3D)





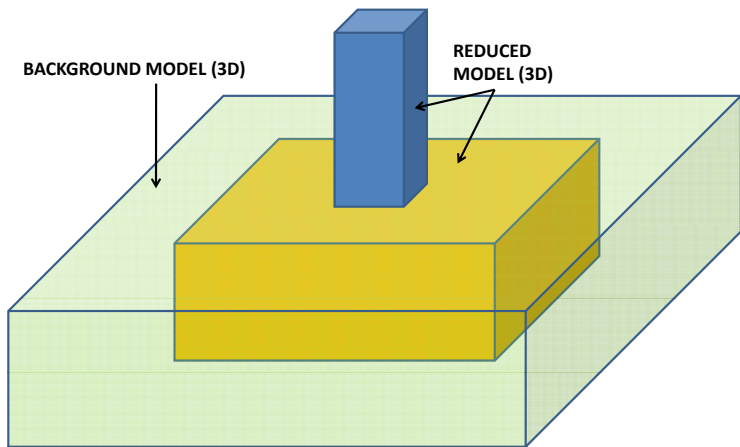


# DRM: Background (2D-axisymmetric) Reduced (3D)



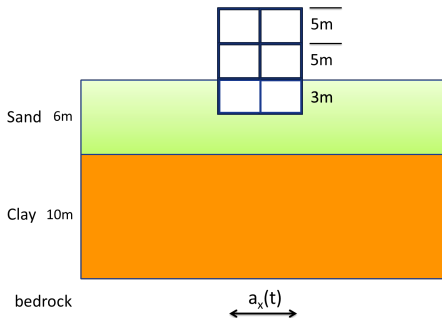


# DRM: Background (3D) Reduced (3D)





## Coming back to our problem



- We will use DRM method
- Rigid base model is analyzed





# Free field motion: Model generation, step by step

- 1 **File/New** - select **Plane strain** model
- 2 Fill **Project preselection** form (set ON option  **Dynamics**)
- 3 Under (**Control/Units**) set units system (use [s] for time unit)
- 4 **File/Save As** : shear-layer-RB-rel.inp

**Project preselection**

Preselections

Version type: Basic

Analysis type: Plane Strain

Problem type: Deformation

Project preselection

Frames only     Structures only

Dynamics     Pushover

Show meaningful options only

Show all options (meaningful options in black, other in gray)

Show all options (all in black color)

Project title: Zsoil example

Model description:

Author: ZACE

Company: ZACE

Unit system: STANDARD

OK

**Units**

Unit system name: STANDARD

Add    Delete

Preprocessor		Postprocessor	
Force	kN	Force	kN
Length	m	Length	m
Angle	deg	Angle	deg
Time	s	Time	s
Temperature	C	Temperature	C

Recalculate from old to new units

Save settings in CFG

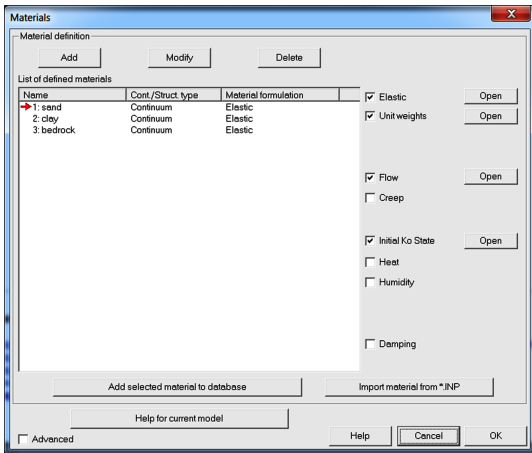
Help    OK    Cancel



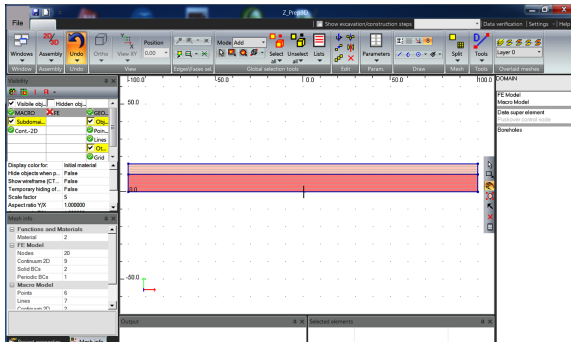


# Free field motion: Setting material data

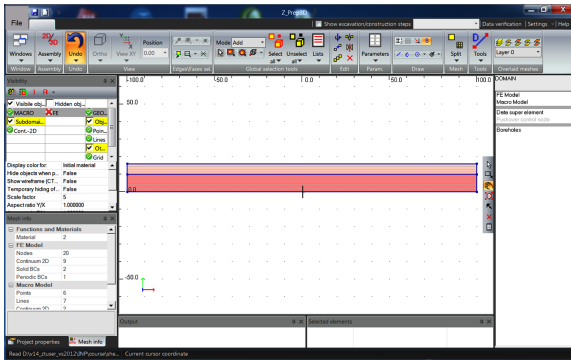
- 1 Add three continuum materials for sand, clay and bedrock via **Assembly/Materials** (material data is given in tabular form in slide 6)



- 1 Use option draw rectangle from ribbon menu **Draw**
- 2 Draw 2 rectangles for sand and clay layers (so far we do not know how big the reduced model should be; hence let us assume  $\pm 100\text{m}$  from the axis of the building)
- 3 Create 2 subdomains using **Macro-model/ Subdomains/ Create continuum inside contour**
- 4 Apply materials to subdomains using ribbon menu **Parameters/Update par.**



- 1 Create virtual meshes  
(4 elements in sand layer, 5 elements in clay layer)  
(use options from ribbon menu **Mesh** or right menu **Subdomain/Mesh/Create virtual mesh**)
- 2 Then convert virtual mesh to the real one





# Free field motion: boundary conditions for rigid base model

- 1 Select 2 nodes at the base and fix them
- 2 Create an auxiliary vertical symmetry plane (at  $x = 0.0$ )
- 3 Select nodes at the left wall (except one at the base)
- 4 Set periodic BC (use FE model/Boundary conditions/Periodic BC/Nodes & Plane option)

The screenshot shows a finite element software interface with a model of a structure. The model is a horizontal bar with a vertical plane of symmetry in the center. The left and right ends of the bar are fixed to the ground, indicated by blue circles and the label "Fixed node". The central vertical line is labeled "Plane of symmetry". The nodes at the ends of the bar are labeled "Master nodes" and "Slave nodes". A red arrow points to the "Periodic BC" button in the software's toolbar.

The "Links" dialog box is open, showing the "Existence function" for various degrees of freedom:

Existence function		
<input checked="" type="checkbox"/> Ux	0	<Edit...>
<input checked="" type="checkbox"/> Uy	0	<Edit...>
<input type="checkbox"/> Uz	0	<Edit...>
<input type="checkbox"/> Rx	0	<Edit...>
<input type="checkbox"/> Ry	0	<Edit...>
<input type="checkbox"/> Rz	0	<Edit...>

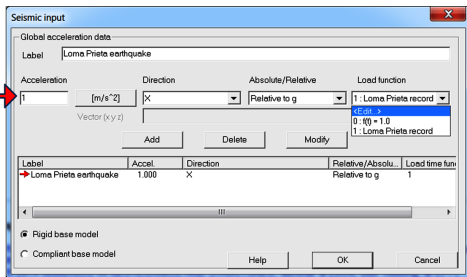






# Free field motion: Let us define seismic input (relative format)

- 1 Go to **Assembly/Seismic input** option
- 2 By using this option our results will be output as relative with respect to the rigid base
- 3 Set scaling factor to 1.0 (or another), define if a given signal is normalized (or not) by  $g$  value and edit the load time function  $a(t)/g$  (or  $a(t)/1\frac{m}{s^2}$ ) (click on *Edit..* in the combo box containing list of load time functions)



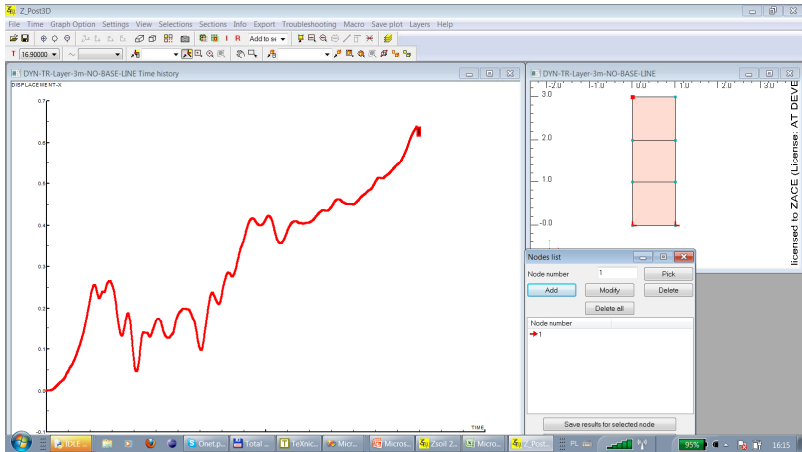
Scaling factor for acceleration record



Before we apply given earthquake record as a seismic input in our model the following operations must be carried out

- 1 Baseline correction and Butterworth filtering on the target earthquake record
- 2 Deconvolution of a given signal to the base (only linear deconvolution is handled in ZSoil)

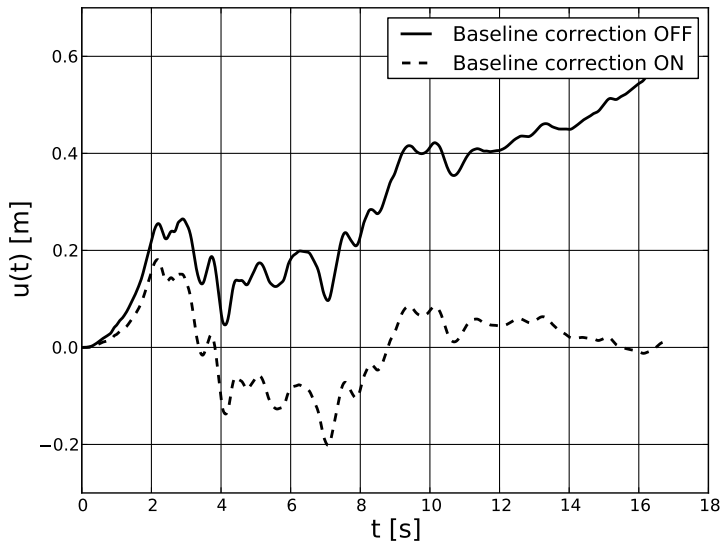
Effect of baseline correction is well visible when earthquake signal is applied as an imposed acceleration (at the base)(absolute format)



Baseline correction is inactive



- Given set of points:  $a_i(t_i)$
- Goal: remove trend line from  $a_i(t_i)$  (cubic polynomial)
- Method: solve optimization problem:  $\sum_i^n \{a_i - \tilde{a}(t_i)\}^2 \rightarrow MIN$
- Trend line equation:  $\tilde{a}(t_i) = a_0 + a_1 * t_i + a_2 * t_i^2 + a_3 * t_i^3$





# Signal processing: Butterworth filter

Signal filtering/baseline correction/linear deconvolution

Baseline correction/Butterworth filtering | Linear deconvolution

Initial Butterworth filtering and baseline correction

Butterworth filter    Low pass    4th order

Frequency f1: 5 Hz

Frequency f2: 25 Hz

Baseline correction

Butterworth filter

Gain

f [Hz]

Update

$a(t)$  (uncorrected)

$a(t)/g$  (after baseline/filtering)

Export to Excel

Web data banks

<http://nsmr.wr.usgs.gov/data.html>

Browse selected data base

Import (from local resources)

Trim left

Trim right (to / from) t = 30

Add zeros left

Add zeros right

dt =

Cancel

OK

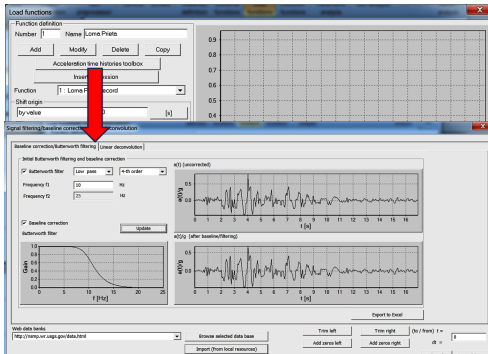
NB. In most cases we will apply low pass filter to cancel high frequencies (in earthquake engineering we usually use 10 Hz low pass BF filter)





# Free field motion: Signal processing: deconvolution

- 1 **Assembly/Load functions** - **Add** a function and label it as *Loma Prieta*
- 2 Press button **Acceleration time histories toolbox** and then in the foregoing dialog box **Import from local resources** record *LomaPrieta-18-10-1989-Station-Corralitos.ear*
- 3 Set ON 4-th order, 10 Hz low pass  **Butterworth filtering**, set ON  **Baseline correction** and **Update** the signal





# Free field motion: Signal processing: deconvolution

- 1 select tab **Linear deconvolution** and fill the form with data
- 2 declare that the signal is given on top of layer 1 (sand) and is to be transferred to top of layer 3 (bedrock)
- 3 use Rayleigh damping (for  $f_1 = 2$  Hz  $\xi_1 = 0.05$  and for  $f_1 = 8$  Hz  $\xi_1 = 0.05$ ) (use button  next to the combo box)
- 4 add quiet zone (**Add zeros left**) to the record at the beginning with  $\Delta t = 6\text{m}/150\frac{\text{m}}{\text{s}} + 10\text{m}/208\frac{\text{m}}{\text{s}} \approx 0.1$  s
- 5 **Run deconvolution** and press **OK** to accept modifications

Signal filtering/baseline correction/linear deconvolution

Baseline correction/Butterworth filtering Linear deconvolution

Rigid base model Target signal is given on top of layer

Compliant base model Signal is to be transferred to top of layer

Soil layers + bedrock (last layer)

Layer	Label	Depth [m]	V-top [m/s]	V-bot [m/s]	E [kN/m <sup>2</sup> ]	$\nu$	gamma	V <sub>S</sub> [m/s]	Damping	Diapha	beta
1	sand	0	16.00	10.00	100000	0.25	17	151.9	Rayleigh	1.00531	0.001592
2	clay	10	10.00	9.0000	200000	0.25	18	206.7	Rayleigh	1.00531	0.001592
3	bedrock		0.0000	0.0000	20000000	0.3	23	1811.0	Rayleigh	0.4021	0.000837

$a(t)$  (filtered)

$a(t)$  (after deconvolution)

Web data banks  
<http://namp.wr.usgs.gov/data.html>    (to / from) t =

dt =

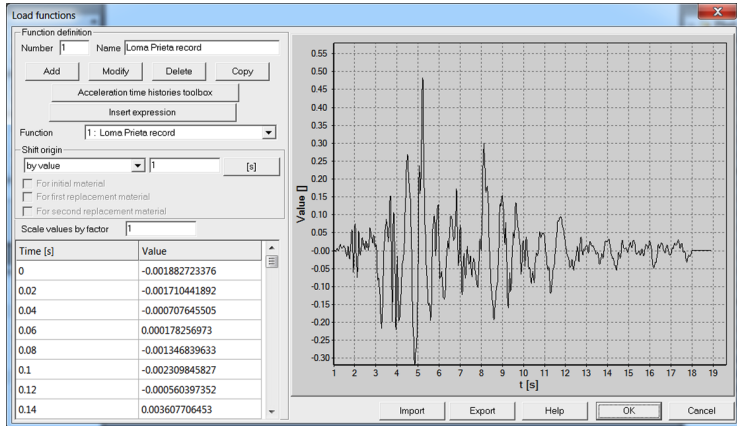






# Free field motion: shifting load time function in time

- In order to be able to reuse this project as a free field motion for the reduced one we need to shift the dynamic driver in time (by 1s for instance)(will be explained later on why..?)





# Free field motion: Drivers

- 1 Set drivers (**Control/Drivers**)
- 2 Note that Default control for each driver can be different (2014)

Drivers definition

Driver	Type	Time start	Time end	Increment	Multiplier	Nonl. solver settings	Dyn. anal. settings
Initial State		1.0000	1.0000	0.1000		Default	...
Dynamics	Driven Load	1.0000 [s]	18.0000 [s]	0.0100 [s]	1.0000	Default	Default

Default for the Initial State

Default for Transient Dynamics

Control

Nonlinear solver settings: Default

Store Raster/Result files each: 1 steps

Convergence norms setup:

Tolerance for solid phase RHS: 0.01

Tolerance for fluid phase RHS: 0.01

Tolerance for energy of solid phase: 0.001

Tolerance for energy of fluid phase: 0.001

For kinematic loading sharpen tolerances by factors

For solid phase RHS: 0.01

For energy of solid phase: 0.01

Initial nonlinear solver setup:

Full Newton-Raphson

BFGS

Initial stiffness

Modified Newton-Raphson

Perform stiffness each: 1 steps

Perform stiffness each: 1 iterations

Initial stiffness (Accelerated)

Max. number of iteration per step: 15

Absolute max. number of iterations: 100

Strategy for divergent steps:

First by another nonlinear solvers (automatically)

Then reduce step size (automatically)

Max reduction trials: 0

Reduction factor: 0.5

Increase dt for Time dep./Transient dyn. drivers when N\_ITER / MAX\_ITER is less than 0.25

Step amplification factor: 1.25

Strategy for slow or lack of convergence:

Automatically increase max. number of iterations

Increase Max. number of iterations by: 5

When number of iterations > absolute max. iter. apply the following amplification factor for RHS norm: 5

Advanced Help OK Cancel

Control

Nonlinear solver settings: Default

Store Raster/Result files each: 1 steps

Convergence norms setup:

Tolerance for solid phase RHS: 0.001

Tolerance for fluid phase RHS: 0.01

Tolerance for energy of solid phase: 0.001

Tolerance for energy of fluid phase: 0.001

For kinematic loading sharpen tolerances by factors

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Step amplification factor: 1.25

Strategy for slow or lack of convergence:

Automatically increase max. number of iterations

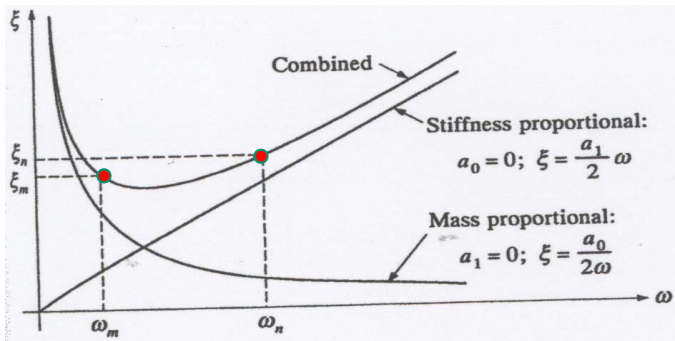
Increase Max. number of iterations by: 5

When number of iterations > absolute max. iter. apply the following amplification factor for RHS norm: 5

Advanced Help OK Cancel



## Specific settings: Rayleigh damping

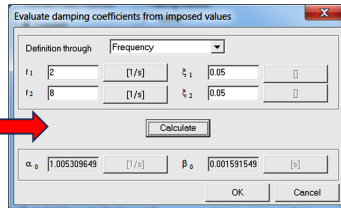
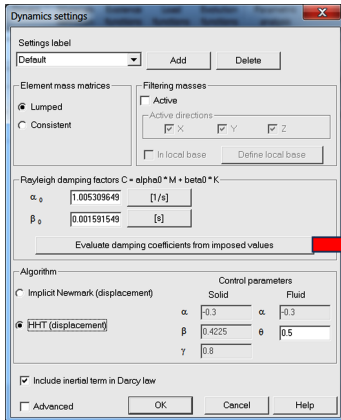


- $\alpha$  (or  $a_0$ ) parameter applies to the mass (low frequency damping, may represent viscous damping)
- $\beta$  (or  $a_1$ ) parameter applies to the stiffness (high frequency damping, may represent hysteretic damping)

NB. If all materials have the same damping coefficients we can set them at the global level in settings for all dynamic drivers (will be done later on). We can do it also at the material level.



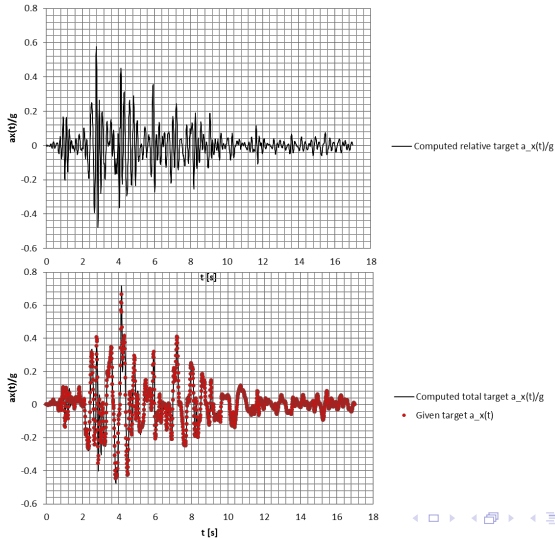
- 1 Set dynamic settings in **Control/Dynamics** menu or by pressing button **...** in column Dynamic analysis settings directly in the list of drivers
- 2 set up global Rayleigh damping coefficients, set ON **HHT** integration scheme





# Free field motion: Computation and postprocessing

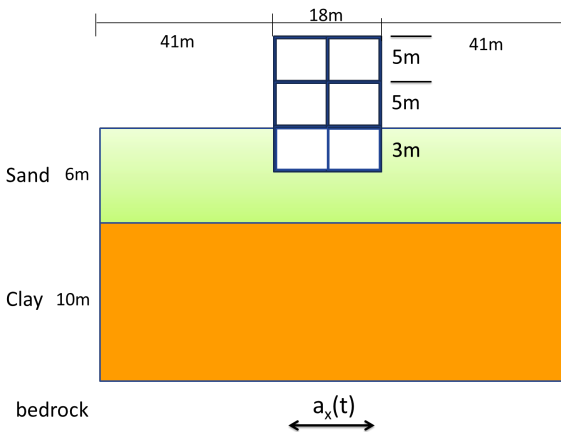
- 1 Displacements, velocities and accelerations are output as relative to the rigid base



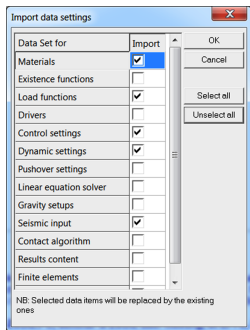


# Reduced model: Geometry of the concrete frame

- 1 Concrete columns  $60 \times 60$ cm (spacing in  $Z$  direction: 6m)
- 2 Concrete beams  $60 \times 100$ cm (spacing in  $Z$  direction: 6m)
- 3 Foundation raft 70 cm



- 1 **File/New**
- 2 Select plane-strain
- 3 In **Project preselection** set ON  **Dynamics**
- 4 **File/Save As** *reduced-RB-rel*
- 5 Import data from free field motion project (in main ZSoil menu use **File/Import data from another \*.inp file**)





## Reduced model: importing meaningful data from free field motion project

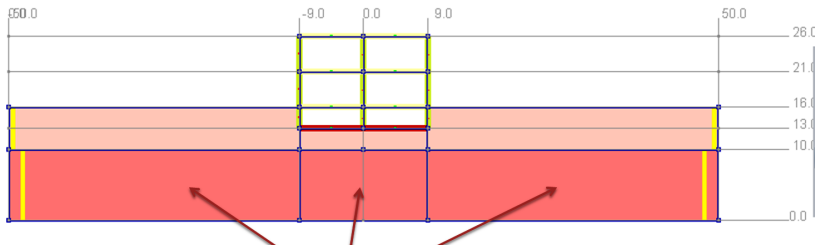
- Add 3 new materials for the raft (material 4), beams (5) and columns (6) (assume  $E = 30000000$  kPa,  $\nu = 0.2$ ,  $\gamma = 24$  kN/m<sup>3</sup>); in group  **Main** select
  - ⊙ **Flexibility based formulation** (single beam per member is sufficient once mass lumping only at connections between beams and columns is a correct assumption)

NB. In ⊙ **Flexibility based formulation** beam elements have 2 nodal points (as in standard) but stress resultants are output in 5 integration points (two of them are placed exactly at the endpoints); mass is lumped at two nodal points; these beam elements are mainly dedicated to structural applications.





- 1 Let us go to the preprocessor
- 2 First we will create construction axes ( $X = \{-50, -9, 0, 9, 50\}$ ,  $Y = \{0, 10, 13, 16, 21, 26\}$ ) (here we have to be coherent with the free field motion geometry !) and then draw the geometry

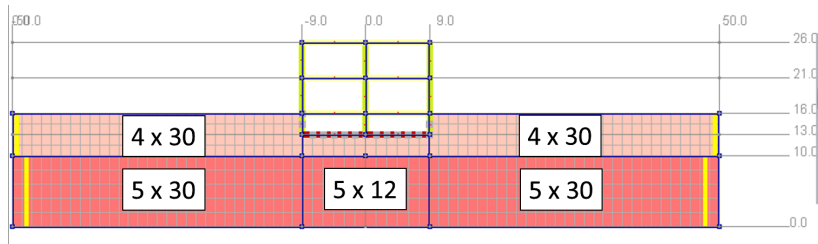


3 subdomains (to have best quality meshes)



## Reduced model: meshing (at the macro-level)

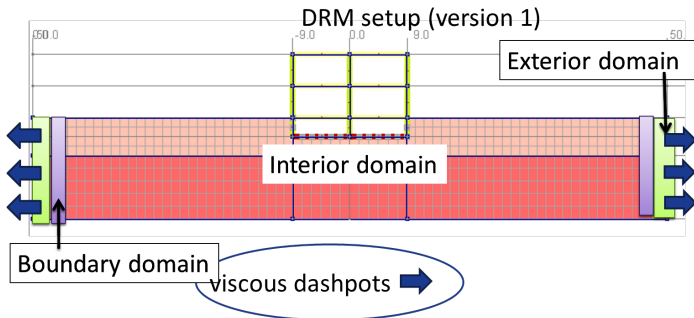
- 1 The optimal situation is when at the left and right walls we have mesh that is compatible with the one used for free field motion
- 2 Therefore in the vertical direction we will have 4 elements in sand layer and 5 elements in the clay layer
- 3 After meshing continuum select all beam macro-elements and create virtual mesh with split parameter equal to 1





# Reduced model: DRM setup (1)

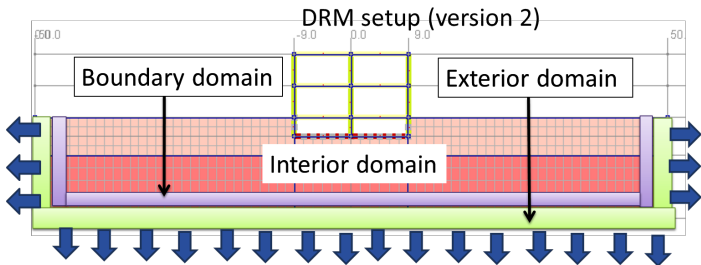
- 1 Here interior domain is extended until the bedrock
- 2 Boundary and exterior layers are located at the left+right vertical walls (single column of elements in each)
- 3 On the exterior domain we have to add viscous dashpots
- 4 In our case setup (1) is optimal





## Reduced model: DRM setup (2)

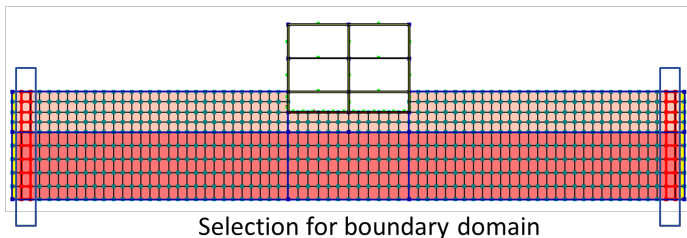
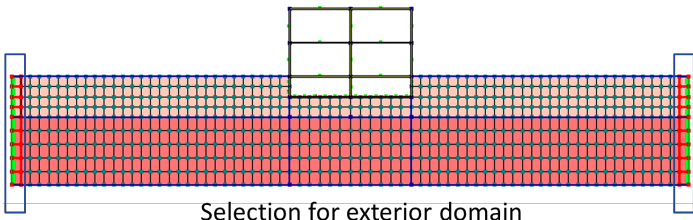
- 1 Here interior domain is far from the bedrock
- 2 Boundary and exterior layers (still single layers of elements) are located around the structure
- 3 On the exterior domain we have to add viscous dashpots





# Reduced model: real mesh, DRM domains

- Once we have FE mesh we can define DRM exterior and boundary domains (**FE model/DRM domains/Create..**)





# Reduced model: existence function and unloading function for horizontal fixities

- 1 Before starting dynamic analysis horizontal fixities must be released but static equilibrium must be preserved
- 2 To do that we need to define one existence function for these fixities in X-direction and one additional load function that will be used as an unloading one for reactions in released fixities

The screenshot displays two overlapping software windows. The top window, titled 'Existence function', contains a table with columns for 'Number', 'Label', and three 'Active period' groups (1, 2, and 3). Each active period has sub-columns for 't1' and 't2'. A row with 'Number' 1 and 'Label' 'BC-horizontal' is shown, with a value of 0 in the first 't2' column and 1 in the second 't2' column. The bottom window, titled 'Load functions', shows a 'Function definition' dialog for 'BC-unloading'. It includes a 'Function' dropdown set to 'BC-unloading', a 'Scale values by factor' field set to 1, and a table with 'Time [s]' and 'Value' columns. The table has two rows: (0, 1) and (20, 1). To the right of the dialog is a graph with 'Value [1]' on the y-axis (0.00 to 1.15) and 't [s]' on the x-axis (0 to 20). A white box with the text 'Unloading function' is overlaid on the graph area.

Number	Label	Active period 1		Active period 2		Active period 3	
		t1	t2	t1	t2	t1	t2
1	BC-horizontal	0	1				

Time [s]	Value
0	1
20	1





# Reduced model: setting variable in time solid BC

- 1 First we apply standard BC (**FE model/Boundary conditions/Solid BC/On box**)
- 2 Then we can select nodes at both vertical walls (except those at the base) and define BC using option (in same menu **On node**)

**Solid boundary condition**

Translational

		Imposed value	LF	EF	Unloading function
<input checked="" type="checkbox"/> X	<input type="checkbox"/> UX	0 [m]	0	1	2
	<input type="checkbox"/> VX	0 [m/s]	0		
	<input type="checkbox"/> AX	0 [m/s <sup>2</sup> ]	0		
<input type="checkbox"/> Y	<input type="checkbox"/> UY	0 [m]	0	0	0
	<input type="checkbox"/> VY	0 [m/s]	0		
	<input type="checkbox"/> AY	0 [m/s <sup>2</sup> ]	0		
<input type="checkbox"/> Z	<input type="checkbox"/> UZ	0 [m]	0	0	0
	<input type="checkbox"/> VZ	0 [m/s]	0		
	<input type="checkbox"/> AZ	0 [m/s <sup>2</sup> ]	0		

Rotation

<input type="checkbox"/> X	<input type="checkbox"/> UX	0 [deg]	0	0	0
	<input type="checkbox"/> VX	0 [deg/s]	0		
	<input type="checkbox"/> AX	0 [deg/s <sup>2</sup> ]	0		
<input type="checkbox"/> Y	<input type="checkbox"/> UY	0 [deg]	0	0	0
	<input type="checkbox"/> VY	0 [deg/s]	0		
	<input type="checkbox"/> AY	0 [deg/s <sup>2</sup> ]	0		
<input type="checkbox"/> Z	<input type="checkbox"/> UZ	0 [deg]	0	0	0
	<input type="checkbox"/> VZ	0 [deg/s]	0		
	<input type="checkbox"/> AZ	0 [deg/s <sup>2</sup> ]	0		

In local base      Define local base





# Reduced model: added masses

- 1 Remaining part of the structure add some mass to the system
- 2 Here we add 6000 kg at each nodal point in structure located on axis of symmetry and 3000 kg in the remaining one

The screenshot shows a 3D finite element analysis (FEA) software interface. The main window displays a meshed structure with a central cutout. The structure is divided into three horizontal rows of nodes. The top row has three nodes labeled 3000kg, 6000kg, and 3000kg. The middle row has three nodes labeled 3000kg, 6000kg, and 3000kg. The bottom row has three nodes labeled 3000kg, 6000kg, and 3000kg. The software interface includes a menu bar, a toolbar, a visibility panel, a mesh info panel, and a command window.

**Visibility Panel:**

- Visible obj:  MACRO,  FE,  Elements,  Cont.-2D,  Beam,  Damper,  Nodes,  Grid
- Hidden obj:  GEO,  Obj,  Lines,  Dt.,  Grid

**Mesh Info Panel:**

- Functions and Materials
  - Load time: 1
  - Existence: 1
  - Material: 6
- FE Model
  - Nodes: 715
  - Continuum 2D: 628
  - Beams: 29
  - Solid BCs: 91
- Macro Model
  - Elements: 95

**Command Window:**

Selected elements: Nodes (6/715) 248 279 280 282 ... Beams (4/29) 1A4







# Reduced model: associate free field motion project with current one

The screenshot displays the Zsoil 2014 v14.03 x64 software interface. The main window shows the 'Project properties' panel on the left, which includes sections for 'Settings', 'Analysis and problem type', 'Project description', and 'Free field motion project'. The 'Free field motion project' section is highlighted, indicating it is the active project. A 'Coming' message is visible below this section.

In the center, a file selection dialog titled 'Otwieranie' is open, showing the contents of the folder 'v14\_ztuser\_vs2012 \> INP \> course'. The dialog lists several files, with 'shear-layer-RB-rel.inp' selected. A blue arrow points to this file. The file list is as follows:

Nazwa	Data modyfikacji	Typ	Rozmiar
reduced-RB-rel.inp	2014-08-23 16:42	Plik INP	316 KB
shear-layer-RB-rel.inp	2014-08-23 15:58	Plik INP	41 KB
shear-layer-RB-rel-corr.inp	2014-08-23 16:06	Plik INP	35 KB
shear-layer-RB-rel-uncorr.inp	2014-08-23 16:05	Plik INP	35 KB

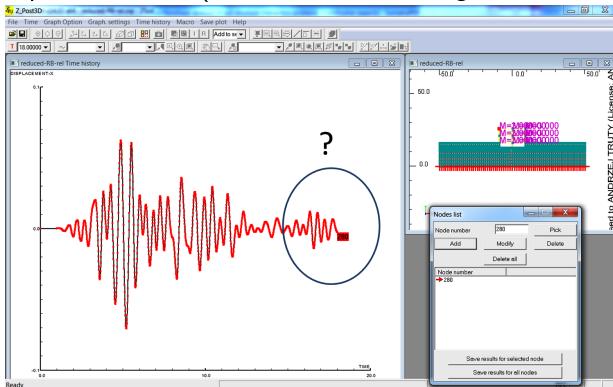
The dialog also shows the file name 'shear-layer-RB-rel.inp' in the 'Nazwa pliku:' field and the file type 'ZSoil Files (\*.inp)'. The 'Otwórz' (Open) button is highlighted.





# Reduced model: computation and analysis of results

- Tracing time histories of relative displacements and accelerations of selected points
- Making envelopes in structures
- Observe parasitic effect of high displacement amplitude at end of shaking visible in displacement/acceleration time history plot for top frame node (this is an effect of rigid base assumption)





- Main sources of nonlinearities
  - 1 In subsoil (plasticity, pore water pressure generation (in fully saturated media) that may lead to liquefaction in case of loose deposits)
  - 2 In structure (cracking)

NB. Once we use nonlinear models for subsoil deconvolution is no more unique (stiffness and damping are stress/strain dependent)





## 1 M-C, H-B models

- here we have to define small strain  $E$  modulus that is larger than static one; to use different stiffness moduli within one computation we can apply a load time function to this parameter
- these models have built in hysteresis effect but for larger strain values; therefore we have to be careful when setting damping parameters; using low frequency damping (to mass) is correct but stiffness proportional damping (if defined) is already included (partially or fully) in the elasto-plastic law; in this case we could define mass proportional damping parameter  $\alpha = 4\pi f\xi$  (at  $f = 2\text{Hz}$  for instance) while keeping  $\beta = 0.0$

## 2 HSs, Densification models

- HSs and Densification models can be used for dynamic analyses but we need to activate  **Small strain stiffness** option in both
- In both cases mass proportional damping is correct while hysteretic damping is fully embedded in the constitutive theory





## Let us try M-C model for subsoil

- Save data file for current reduced model as *reduced-RB-rel-MC.inp* (**File/Save As**)
- Switch elastic model for sand to M-C ( $\phi = 30^\circ$ ,  $c = 1$  kPa,  $\psi = 0^\circ$ ), activate group  **Damping** and set  $\alpha = 1.256$  (5% damping at  $f = 2$  Hz),  $\beta = 0.0$
- Switch elastic model for clay to M-C ( $\phi = 25^\circ$ ,  $c = 10$  kPa,  $\psi = 0^\circ$ ), activate group  **Damping** and set  $\alpha = 1.256$  (5% damping at  $f = 2$  Hz),  $\beta = 0.0$
- In the preprocessor add initial stresses to sand and clay layers (use option **FE model/Initial conditions/Initial stresses**)
- In the preprocessor add contact interface between wall and subsoil





# DRM with M-C model: contact interface

Select continuum element edges adjacent to the concrete wall and then use option **FE model/Interface/On continuum element edges**

The screenshot displays the Z\_Prep3D software interface. The main workspace shows a finite element model of a concrete wall, with two vertical sections highlighted in red. Two blue circles are drawn around these sections. The software interface includes a menu bar, a toolbar, a visibility panel on the left, a main workspace, and a right-hand panel with a tree view and a list of options. The tree view shows 'INTERFACE' selected, and the list of options includes 'On Continuum elem. edges(s)'. The visibility panel on the left shows various options for displaying and hiding objects, including 'MACRO', 'Subdomains', 'Cont.-2D', 'Beam', 'Damper', 'Nodes', 'Node number', 'BC', 'Solid', 'IC', 'Stress', 'Masses', 'Nodal', 'Loc.bases', and 'On beam'. The right-hand panel shows a list of options for the 'INTERFACE' model, including 'Create...', 'On Continuum elem. edges(s)', 'On Structural element(s)', '[Un]/Outline...', 'all', 'Box with 2 Nodes', 'With material', 'With existence function', 'With unloading function', 'With attribute', 'With label', 'On selected edges', 'In zoom box', 'In zoom circle', 'Inside contour', 'Delete...', 'Delete', 'Update...', 'Parameters', 'Scale', 'Show direction', 'Hide direction', 'Standard view', 'Control view', 'Select singular interface nod', 'Link interface node(s)', 'Delete link', 'Delete all links', 'Exclude element(s) from inte', and 'Disable excluded element(s)'. The bottom of the interface shows the 'Output' and 'Selected elements' panels.





- Here we can see that in some periods of shaking plastic zones are active near boundary layer
- What about periodic BC ?





- Save data file for current reduced model as *periodic-RB-rel-MC.inp* (**File/Save As**)
- Go to preprocessor
  - 1 remove DRM domains
  - 2 delete horizontal fixities at left and right wall
  - 3 select nodes at the left wall (except one at the base)
  - 4 create auxiliary symmetry plane at  $x = 0.0$  (use option from ribbon menu **Draw**)
  - 5 use option **FE model/Boundary conditions/Periodic BC/Nodes & Plane**
  - 6 dashpots will not play any role (so we can leave them)
  - 7 quit preprocessor
- Delete free field motion project from project description
- Run analysis

NB. Periodic BC can be used only for flat configurations





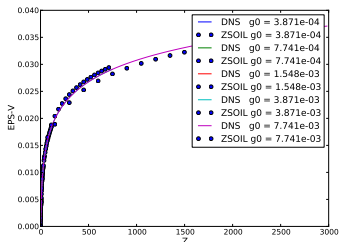
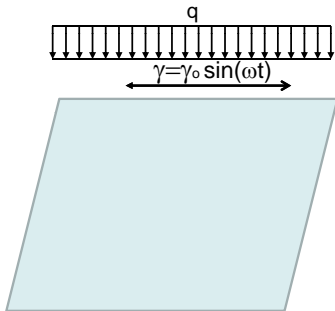


## Let us use HSs and densification models

- For loose sand layer we will use Densification model by Sawicki
- For clay layer HSs model will be used



- Concept of common compaction curve (in simple shear)
- $\varepsilon^{acc} = e_o C_1 \ln(1 + C_2 z)$
- $z = \frac{1}{4} N \gamma_o^2$
- Only the 2 parameters:  $C_1$  i  $C_2$



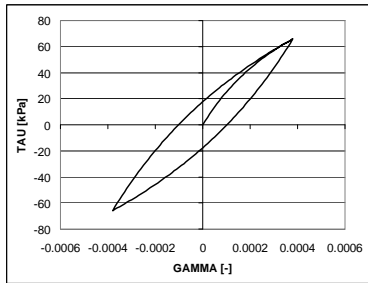
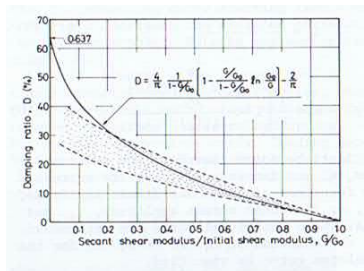
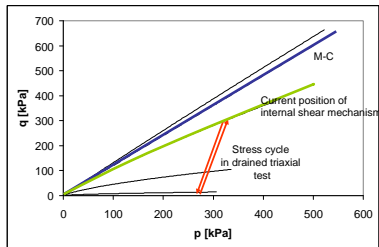
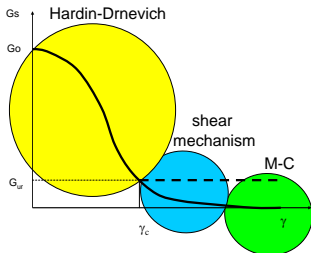


- Model is derived directly from HSs (Schanz, Vermeer)
- Deviatoric plastic flow rule is adopted ( $\psi = 0^\circ$ )
- Model is equipped with a current shear yield surface controlled in addition by an external M-C surface
- $E_{ur} = E_{ur}^{ref} \left( \frac{p}{\sigma_{ref}} \right)^m$
- $E_o = E_o^{ref} \left( \frac{p}{\sigma_{ref}} \right)^m$
- Elastic stiffness modulus  $E$  varies from  $E_o \div E_{ur}$
- All volume changes are due to explicit densification mechanism





# Global construction of densification model





Model is very flexible and can be used in different contexts  
(not only for loose deposits)

- **Standard Mohr-Coulomb**

$(E(p) + \langle \text{small-strain} \rangle + \langle \text{densification} \rangle)$

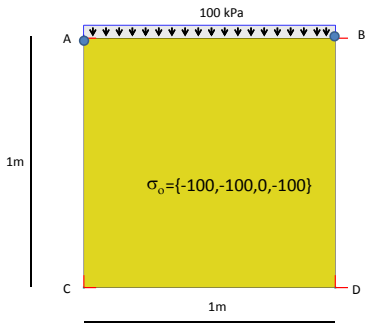
- **M-C + hardening**

$(E(p) + \langle \text{small-strain} \rangle + \langle \text{densification} \rangle)$

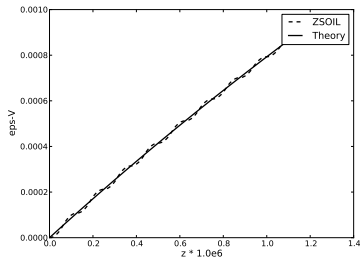
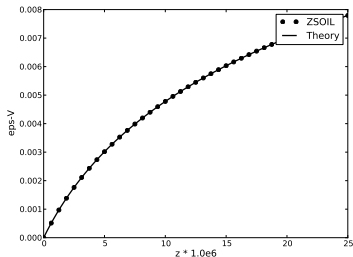




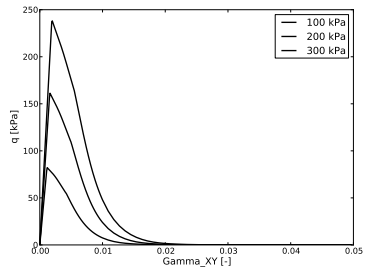
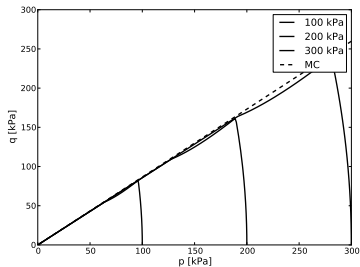
# Simple shear test (static) (drained case)



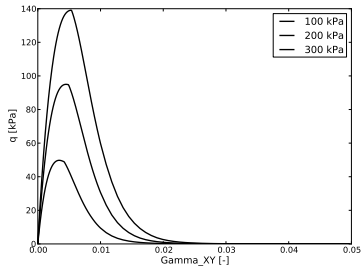
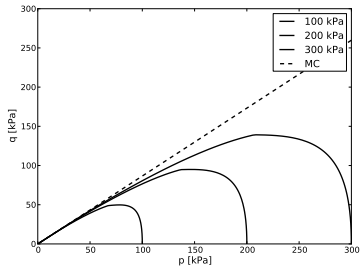
- $u_x^A = u_x^B = 10^{-3} \sin(2 * \pi * t)$
- $t = 0..100s$ , step 0.25s
- $u_y^A = u_y^B$
- $C_1 = 8.7 * 10^{-3}$ ,  
 $C_2 = 2 * 10^5$
- $m_{ij}$  - nonisotropic



Internal shear mechanism is inactive (no notion of  $E_{50}$  is included)



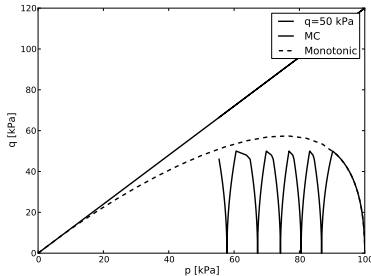
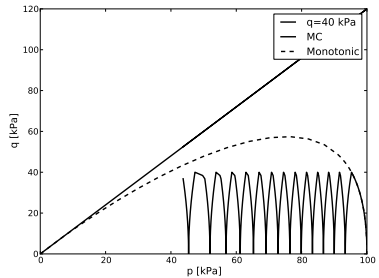
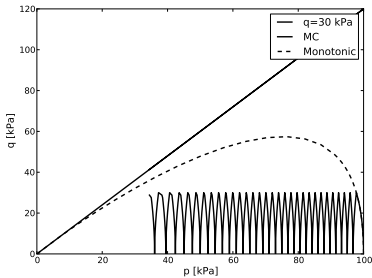
Internal shear mechanism is active (effect of  $E_{50}$  is included)





# Cyclic undrained simple shear test

Internal shear mechanism is active (effect of  $E_{50}$  is included)





## So let us use HSs and densification models

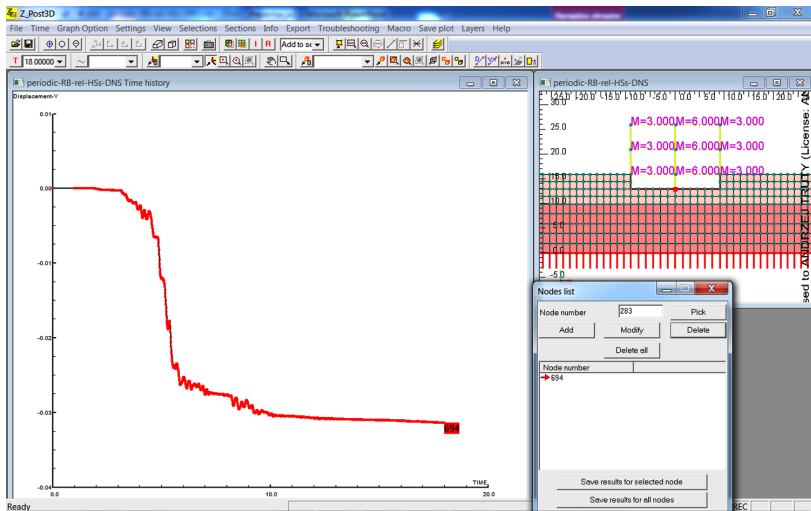
- Here we will use periodic BC so let us reuse data prepared for M-C model and make corrections for materials (save data as *periodic-RB-rel-HSs-DNS.inp*)
- For sand layer Densification model is used  
 $E_o^{ref} = 200000 \text{ kPa}$ ,  $\nu = 0.25$ ,  $m = 0.5$ ,  $\gamma_{0.7} = 10^{-4}$ ,  
 $E_{ur}^{ref} = 60000 \text{ kPa}$ ,  $E_{50}^{ref} = 20000 \text{ kPa}$ ,  $OCR = 1.0$ ,  $K_o^{SR} = 0.5$ ,  $C_1 = 8.7 \cdot 10^{-3}$ ,  $C_2 = 2 \cdot 10^5$
- Assume  $e_o = 0.57$  for sand (this is needed for densification law)
- For clay layer HSs model is used  
 $E_o^{ref} = 240000 \text{ kPa}$ ,  $\nu = 0.25$ ,  $m = 0.5$ ,  $\gamma_{0.7} = 2 \cdot 10^{-4}$ ,  
 $E_{ur}^{ref} = 80000 \text{ kPa}$ ,  $E_{50}^{ref} = 30000 \text{ kPa}$ ,  $E_{oed} = 30000 \text{ kPa}$ ,  
 $OCR = 20.0$ ,  $K_o^{SR} = K_o^{NC} = 0.577$
- Assume  $e_o = 0.48$  for clay
- Let's run and analyze permanent settlement of the building





# Permanent settlements

Densification model allows description of permanent settlements





# Permanent horizontal movement

Densification model allows description of permanent settlements

