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DIRECT METHOD FOR DYNAMIC SOIL-STRUCTURE INTERACTION BASED ON SEISMIC INERTIA FORCES

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Shaping a Better Energy Future

Direct method for dynamic soil-structure interaction based on seismic inertia forces

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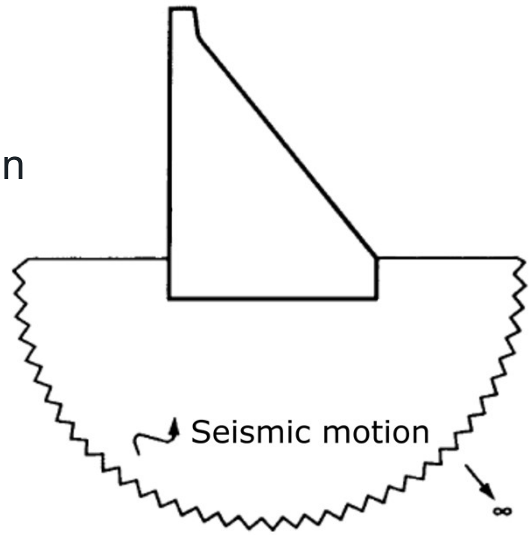
Soil-Structure Interaction (SSI)

Context and Motivation

- Dynamic Soil-Structure Interaction (SSI)
  - Vibrations of the structure interact with seismic motion
  - High impact on seismic response of dams
- SSI FEM modelling critical issues
  - Semi-unbounded size of foundation medium
  - How and where imposing seismic excitation
- Standard massless method
  - FEM modelling of limited portion of foundation medium with no mass
  - Straightforward implementation within commercial FEM software
  - Wave propagation and radiation damping into foundation are ignored
  - Application of design surface ground motion at model bottom boundary
  - Unphysical numerical results leading to dam stress overestimation
- <u>Need of more accurate approaches for SSI in common commercial FEM codes</u>



FEM formulation of SSI problems

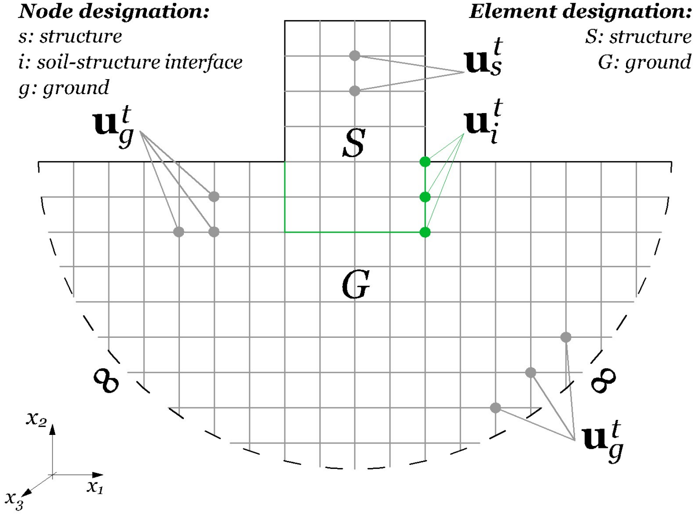
Governing equations in total displacements ($\mathbf{u}^t$)

TIME DOMAIN:

$$\begin{bmatrix} \mathrm{M}_{ss}^S & 0 & 0 \\ 0 & \mathrm{M}_{ii}^{S+G} & 0 \\ 0 & 0 & \mathrm{M}_{gg}^G \end{bmatrix} \begin{Bmatrix} \ddot{\mathrm{u}}_s^t \\ \ddot{\mathrm{u}}_i^t \\ \ddot{\mathrm{u}}_g^t \end{Bmatrix} + \begin{bmatrix} \mathrm{K}_{ss}^S & \mathrm{K}_{si}^S & 0 \\ \mathrm{K}_{is}^S & \mathrm{K}_{ii}^{S+G} & \mathrm{K}_{ig}^G \\ 0 & \mathrm{K}_{gi}^G & \mathrm{K}_{gg}^G \end{bmatrix} \begin{Bmatrix} \mathrm{u}_s^t \\ \mathrm{u}_i^t \\ \mathrm{u}_g^t \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \end{Bmatrix};$$

FREQUENCY DOMAIN:

$$\begin{bmatrix} \overline{\mathrm{K}}_{ss}^S & \overline{\mathrm{K}}_{si}^S & 0 \\ \overline{\mathrm{K}}_{is}^S & \overline{\mathrm{K}}_{ii}^{S+G} & \overline{\mathrm{K}}_{ig}^G \\ 0 & \overline{\mathrm{K}}_{gi}^G & \overline{\mathrm{K}}_{gg}^G \end{bmatrix} \begin{Bmatrix} \bar{\mathrm{u}}_s^t \\ \bar{\mathrm{u}}_i^t \\ \bar{\mathrm{u}}_g^t \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \end{Bmatrix}; \qquad \overline{\mathrm{K}}_{kl} = \mathrm{K}_{kl} - \omega^2\, \mathrm{M}_{kl};$$



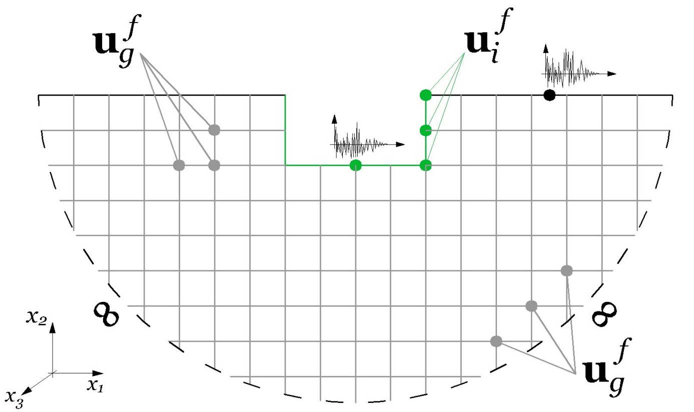
Governing equations of free-field input motion ($\mathbf{u}^f$)

u^f: site response that would have occurred before placing the structure on the site

FREQUENCY DOMAIN:

$$\begin{bmatrix} \overline{\mathrm{K}}_{ii}^G & \overline{\mathrm{K}}_{ig}^G \\ \overline{\mathrm{K}}_{gi}^G & \overline{\mathrm{K}}_{gg}^G \end{bmatrix} \begin{Bmatrix} \bar{\mathrm{u}}_i^f \\ \bar{\mathrm{u}}_g^f \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix};$$

$$\mathrm{K}_{ss}^S\, \bar{\mathrm{u}}_s^f + \mathrm{K}_{si}^S\, \bar{\mathrm{u}}_i^f = 0; \qquad \text{(Pseudo-static transmission)}$$

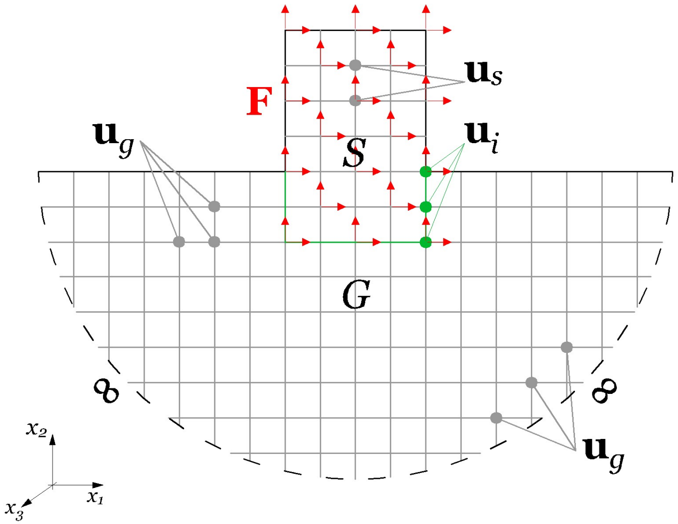


FEM formulation of SSI problems

Governing equations in relative displacements ($\mathbf{u}$)

$\mathrm{u} = \mathrm{u}^t - \mathrm{u}^f$: relative/interaction response, i.e. the amount of the total response due to the interaction effects induced by the presence of the structure;

$$\begin{bmatrix} \overline{\mathrm{K}}_{ss}^{S} & \overline{\mathrm{K}}_{si}^{S} & 0 \\ \overline{\mathrm{K}}_{is}^{S} & \overline{\mathrm{K}}_{ii}^{S+G} & \overline{\mathrm{K}}_{ig}^{G} \\ 0 & \overline{\mathrm{K}}_{gi}^{G} & \overline{\mathrm{K}}_{gg}^{G} \end{bmatrix} \begin{Bmatrix} \bar{\mathrm{u}}_s \\ \bar{\mathrm{u}}_i \\ \bar{\mathrm{u}}_g \end{Bmatrix} = - \begin{Bmatrix} -\omega^2 \mathrm{M}_{ss}^{S}\, \bar{\mathrm{u}}_s^f \\ \overline{\mathrm{K}}_{is}^{S}\, \bar{\mathrm{u}}_s^f + \overline{\mathrm{K}}_{ii}^{S}\, \bar{\mathrm{u}}_i^f \\ 0 \end{Bmatrix};$$



Remark: dynamic stiffness submatrices $\overline{\mathrm{K}}_{ig}^{G}$, $\overline{\mathrm{K}}_{gi}^{G}$ and $\overline{\mathrm{K}}_{gg}^{G}$ have theoretically infinite dimensions;

Uniform free-field assumption

$$\bar{\mathrm{u}}^f = \begin{Bmatrix} \bar{\mathrm{u}}_s^f \\ \bar{\mathrm{u}}_i^f \\ \bar{\mathrm{u}}_g^f \end{Bmatrix} = \begin{bmatrix} \mathrm{I} & 0 \\ \mathrm{I} & 0 \\ 0 & \mathrm{I} \end{bmatrix} \begin{bmatrix} \mathrm{r}_i^{x_1} & \mathrm{r}_i^{x_2} & \mathrm{r}_i^{x_3} \\ \mathrm{r}_g^{x_1} & \mathrm{r}_g^{x_2} & \mathrm{r}_g^{x_3} \end{bmatrix} \begin{Bmatrix} \mathrm{v}_{x_1}^f \\ \mathrm{v}_{x_2}^f \\ \mathrm{v}_{x_3}^f \end{Bmatrix};$$

$$\overline{\mathrm{K}}_{is}^{S}\, \bar{\mathrm{u}}_s^f + \overline{\mathrm{K}}_{ii}^{S}\, \bar{\mathrm{u}}_i^f = -\omega^2\, \mathrm{M}_{ii};$$

$$\begin{bmatrix} \overline{\mathrm{K}}_{ss}^{S} & \overline{\mathrm{K}}_{si}^{S} & 0 \\ \overline{\mathrm{K}}_{is}^{S} & \overline{\mathrm{K}}_{ii}^{S+G} & \overline{\mathrm{K}}_{ig}^{G} \\ 0 & \overline{\mathrm{K}}_{gi}^{G} & \overline{\mathrm{K}}_{gg}^{G} \end{bmatrix} \begin{Bmatrix} \bar{\mathrm{u}}_s \\ \bar{\mathrm{u}}_i \\ \bar{\mathrm{u}}_g \end{Bmatrix} = - \begin{Bmatrix} -\omega^2 \mathrm{M}_{ss}^{S}\, \bar{\mathrm{u}}_s^f \\ -\omega^2 \mathrm{M}_{ii}^{S}\, \bar{\mathrm{u}}_i^f \\ 0 \end{Bmatrix};$$

The exciting dynamic forces are the product of the free-field acceleration and the inertial properties of the structure

Equivalence of DM and SM

$$\begin{bmatrix} \bar{K}^S_{ss} & \bar{K}^S_{si} & 0 \\ \bar{K}^S_{is} & \bar{K}^{S+G}_{ii} & \bar{K}^G_{ig} \\ 0 & \bar{K}^G_{gi} & \bar{K}^G_{gg} \end{bmatrix} \begin{Bmatrix} \bar{u}_s \\ \bar{u}_i \\ \bar{u}_g \end{Bmatrix} = - \begin{Bmatrix} -\omega^2 M^S_{ss}\, \bar{u}^f_s \\ \bar{K}^S_{is}\, \bar{u}^f_s + \bar{K}^S_{ii}\, \bar{u}^f_i \\ 0 \end{Bmatrix};$$

Dynamic condensation of soil dofs:

$$\boxed{\begin{bmatrix} \bar{K}^S_{ss} & \bar{K}^S_{si} \\ \bar{K}^S_{is} & \bar{K}^S_{ii} + S^G_{ii} \end{bmatrix} \begin{Bmatrix} \bar{u}_s \\ \bar{u}_h \end{Bmatrix} = - \begin{Bmatrix} -\omega^2 M^S_{ss}\, \bar{u}^f_s \\ \bar{K}^S_{is}\, \bar{u}^f_s + \bar{K}^S_{ii}\, \bar{u}^f_i \end{Bmatrix};}$$

SUBSTRUCTURE METHOD (SM) IN RELATIVE COMPONENTS

$S^G_{ii} = \bar{K}^G_{ii} + \bar{K}^G_{ig}\, {\bar{K}^G_{gg}}^{-1}\, \bar{K}^G_{gi}$:dynamic impedance matrix of the unbounded soil region, calculated by a *semi-analytical solution*;

By substituting $u^t = u + u^f$ the more familiar SM in total displacements is retrieved

$$\begin{bmatrix} \bar{K}^S_{ss} & \bar{K}^S_{si} \\ \bar{K}^S_{is} & \bar{K}^S_{ii} + S^G_{ii} \end{bmatrix} \begin{Bmatrix} \bar{u}^t_s \\ \bar{u}^t_i \end{Bmatrix} = \begin{Bmatrix} 0 \\ S^G_{ii}\, \bar{u}^f_i \end{Bmatrix};$$

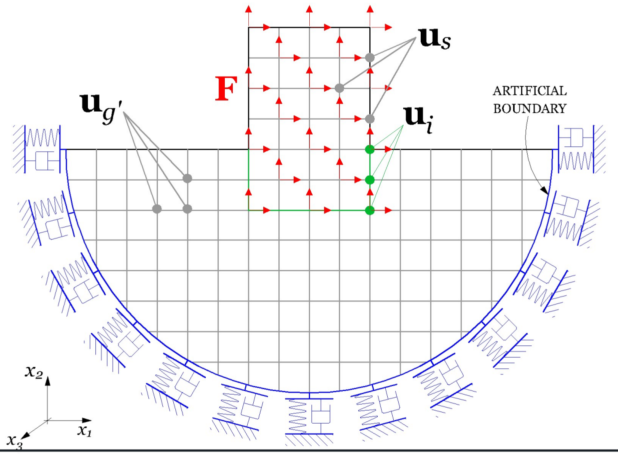
$$\begin{bmatrix} \bar{K}^S_{ss} & \bar{K}^S_{si} & 0 \\ \bar{K}^S_{is} & \bar{K}^{S+G}_{ii} & \bar{K}'^G_{ig'} \\ 0 & \bar{K}'^G_{g'i} & \bar{K}'^G_{g'g'} \end{bmatrix} \begin{Bmatrix} \bar{u}_s \\ \bar{u}_h \\ \bar{u}_{g'} \end{Bmatrix} = - \begin{Bmatrix} -\omega^2 M^S_{ss}\, \bar{u}^f_s \\ \bar{K}^S_{is}\, \bar{u}^f_s + \bar{K}^S_{ii}\, \bar{u}^f_i \\ 0 \end{Bmatrix};$$

Dynamic condensation of soil dofs:

$$\boxed{\begin{bmatrix} \bar{K}^S_{ss} & \bar{K}^S_{si} \\ \bar{K}^S_{is} & \bar{K}^S_{ii} + \bar{S}'^G_{ii} \end{bmatrix} \begin{Bmatrix} \bar{u}_s \\ \bar{u}_i \end{Bmatrix} = - \begin{Bmatrix} -\omega^2 M^S_{ss}\, \bar{u}^f_s \\ \bar{K}^S_{is}\, \bar{u}^f_s + \bar{K}^S_{ii}\, \bar{u}^f_i \end{Bmatrix};}$$

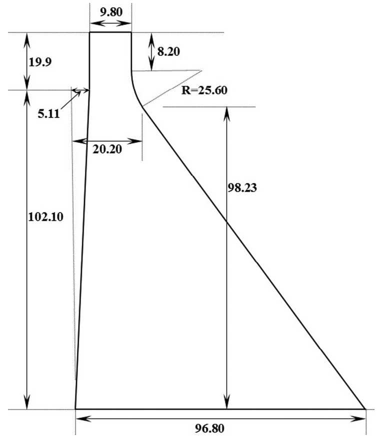
DIRECT METHOD (DM) IN RELATIVE COMPONENTS

$\bar{S}'^G_{ii} = \bar{K}^G_{ii} + \bar{K}'^G_{ig'}\, {\bar{K}'^G_{g'g'}}^{-1}\, \bar{K}'^G_{g'i}$: dynamic impedance matrix of the truncated soil model with transmitting boundaries;



Numerical validation

Case study: Pine Flat Dam

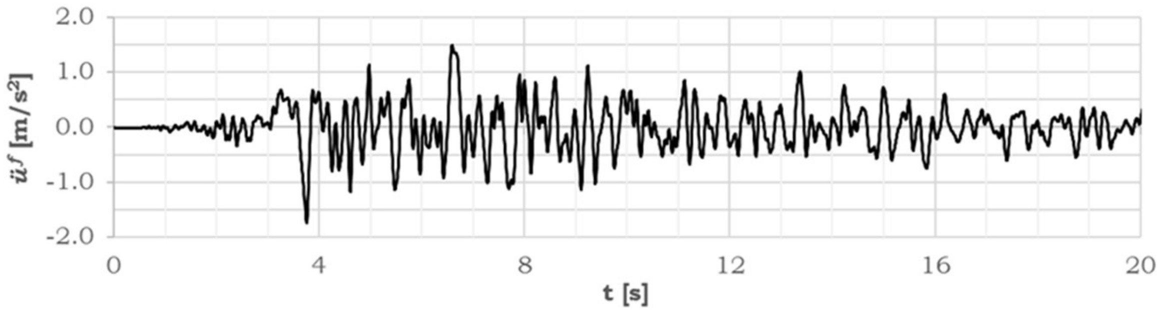


REFERENCE MECHANICAL PROPERTIES OF THE SYSTEM

	Concrete	Rock
Dynamic Young's modulus [GPa]	22.41	68.95
Dynamic Poisson's ratio [1]	0.20	0.33
Mass density [kg/m^3]	2483	2643
Hysteretic damping factor	0.1	0.1

$$\overline{\mathrm{K}}_{kl} = \mathrm{K}_{kl}\,(1 + \mathrm{i}\,\eta) - \omega^2\,\mathrm{M}_{kl};$$

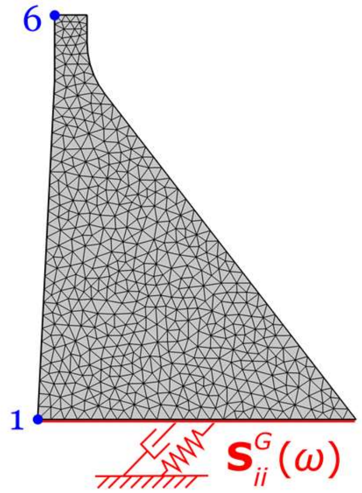
S69E HORIZONTAL COMPONENT OF TAFT GROUND ACCELERATION (1952)



Numerical validation

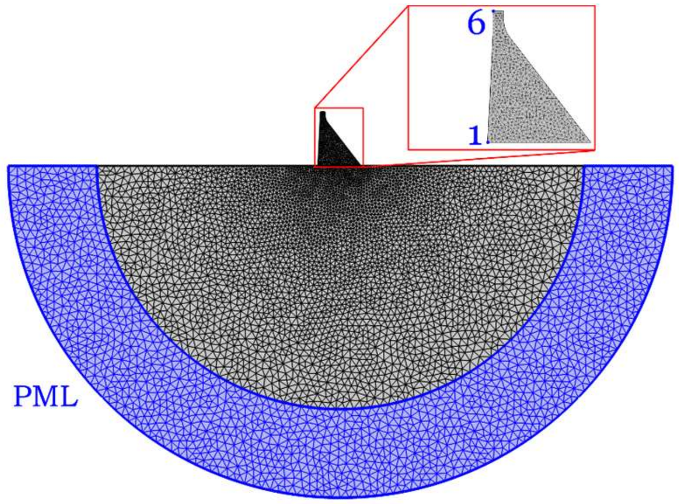
Computational models

SUBSTRUCTURE METHOD



- Autonomous implementation of SM in MATLAB
- Semi-analytical solution for $S_{ii}^{G}(\omega)$
- Frequency Domain analysis
- 972 elements, 536 nodes

DIRECT METHOD

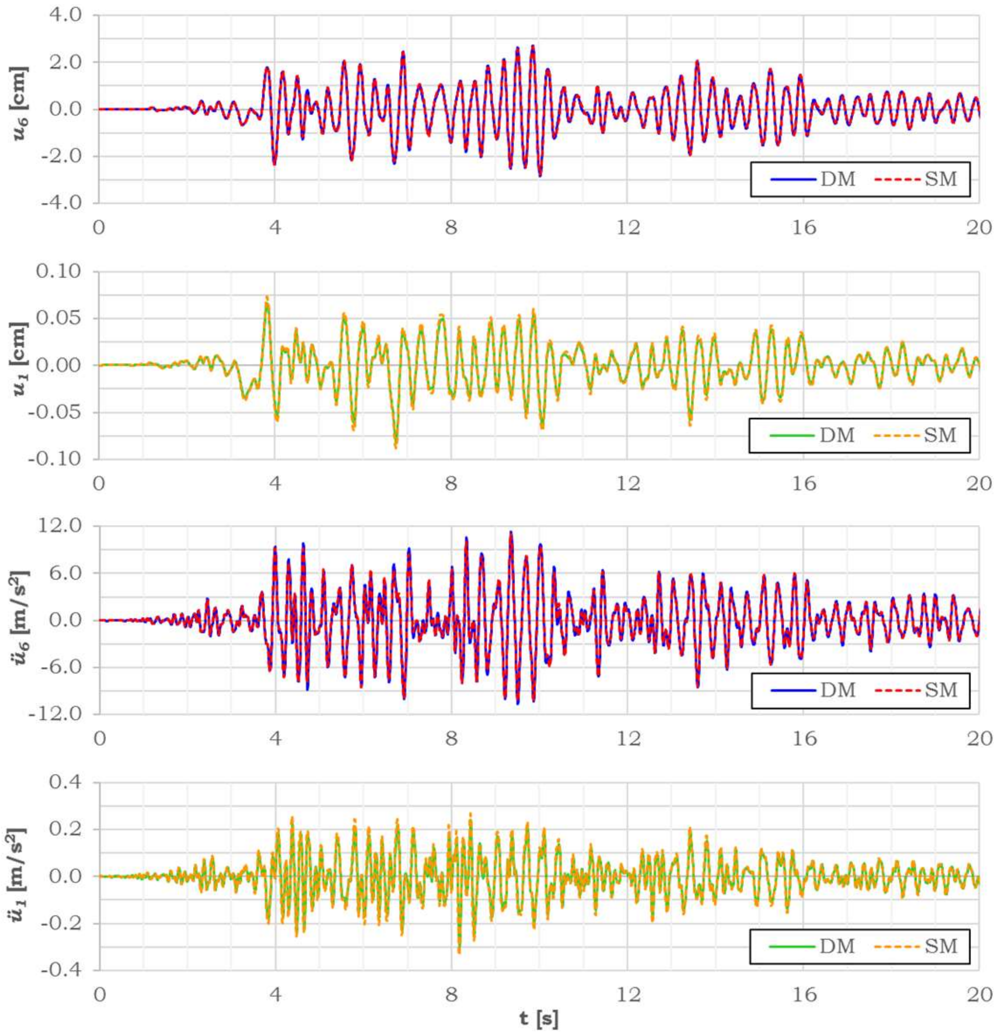


- FEM modelization of DM within COMSOL Multiphysics
- PML transmitting boundary
- Frequency Domain analysis
- 10275 elements, 5284 nodes

Linear triangular FEs; Frequency range= [0, 50] Hz, $\Delta f = 0.012$ Hz

Numerical validation

Results



Conclusions

- Implementation of an alternative version of Direct Method for including SSI effects in seismic analysis of dams
- In case of for uniform free-field motion, the seismic action is modelled by inertial loads applied on the dam only
- Simple implementation within commercial FEM software
- Comparison assessment with respect to widespread SM to verify the rigour of adopted DM
- Exact equivalence between DM and SM, if consistently implemented
- Perfect match of numerical results on benchmark problem of Pine Flat Dam gathered from both methods, confirming exact theoretical derivations

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