International Symposium
Qualification of dynamic analyses of dams and their equipments
and of probabilistic assessment seismic hazard in Europe
31th August – 2nd September 2016 – Saint-Malo

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ISL Ingénierie

Session :

IMPROVING GRAVITY DAMS SIMPLIFIED MODELS : WHY WE SHOULD GO ON


Saint-Malo © Yannick LE GAL

SUMMARY

1.WHY DO WE STILL NEED SIMPLIFIED MODELS?

2.A SIMPLIFIED MODEL WHICH WORKS WELL: ASSESSMENT OF THE SEISMIC SLIDING

THE SLIDING PROBLEM
A SIMPLIFIED MODEL
TESTS AND APPLICATIONS

3.IMPROVING SIMPLIFIED MODELS

SOIL-STRUCTURE INTERACTION
VERTICAL FLUID BEHAVIOR AND FLUID-STRUCTURE INTERACTION

4. CONCLUSIONS AND PERSPECTIVES

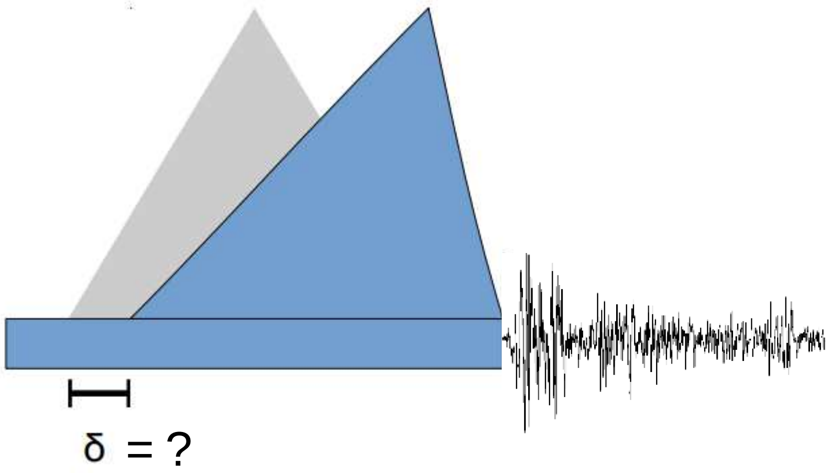
WHY DO WE STILL NEED SIMPLIFIED MODELS?

- **Necessary companion for all more complex simulations, as an error detection tool**
- **Allow to investigate the physics of the problem – instead of only relying on a "black box" that necessary mixes several aspects**
- **Well suited to small or medium-size dams for which data often lack to set-up complex models**
- **Allow investigating the influence of the various parameters**

These reasons explain why we keep doing simplified modeling for the static resistance of gravity dams (whereas they do not entirely capture some important issues like upstream crack propagation)

A SIMPLIFIED MODEL WHICH WORKS WELL: ASSESSMENT OF THE SEISMIC SLIDING

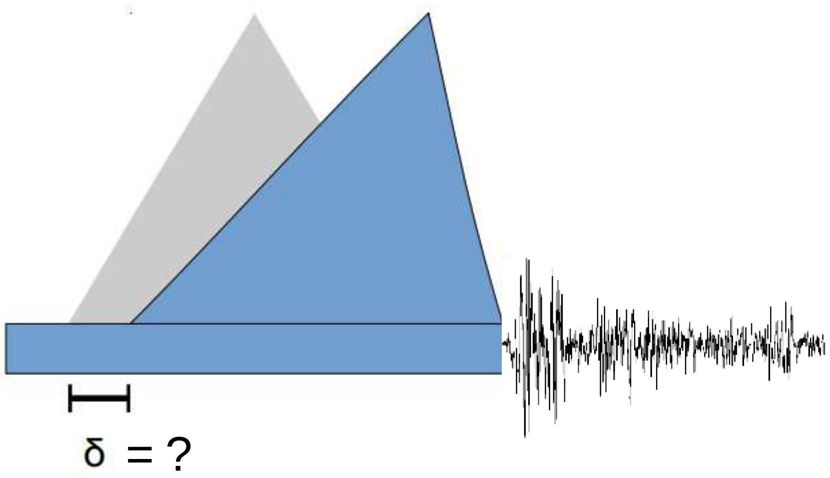
THE SLIDING PROBLEM



- **If it is impossible to meet the non-sliding criterion during the earthquake**
  - The dam may slide over its foundation
  - Along what distance it is likely to slide? mm? cm? m?

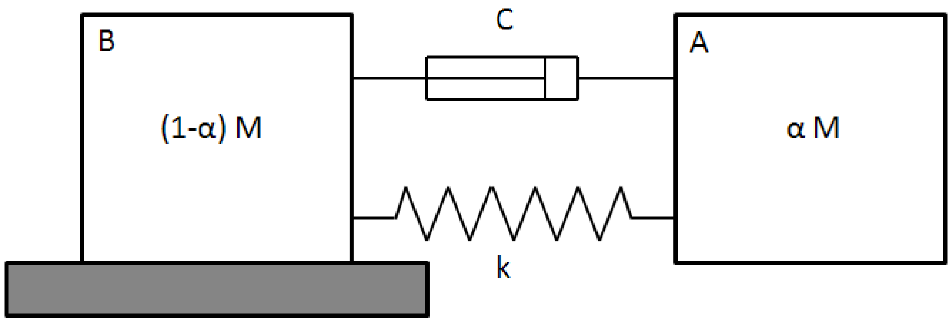
- **Which method could be used to assess this distance?**
  - Finite elements model
  - Newmark’s methods
  - Any other?

A SIMPLIFIED MODEL FOR SLIDING



- **A geometry**
  - 2D section
- **Some hypothesis**
  - The behavior of the reservoir can be approximated by added-masses
  - The shear force at the foundation only depends on the 1st mode
  - The other modes can be considered as rigid modes
  - The earthquake acceleration is horizontal

A SIMPLIFIED MODEL FOR SLIDING



$k = \alpha M\,\omega^2$
$C = 2\,\xi\,\alpha M\,\omega$

- **With only two degrees of freedom**
  - A : the first mode, oscillating
  - B : the other modes, rigid

- **With only four parameters**
  - α : fraction of modal mass of the first mode ($\alpha = m_1/M$ with M : total mass)
  - ω : pulsation frequency of the first mode
  - ξ : damping ratio of the first mode
  - A contact law ?

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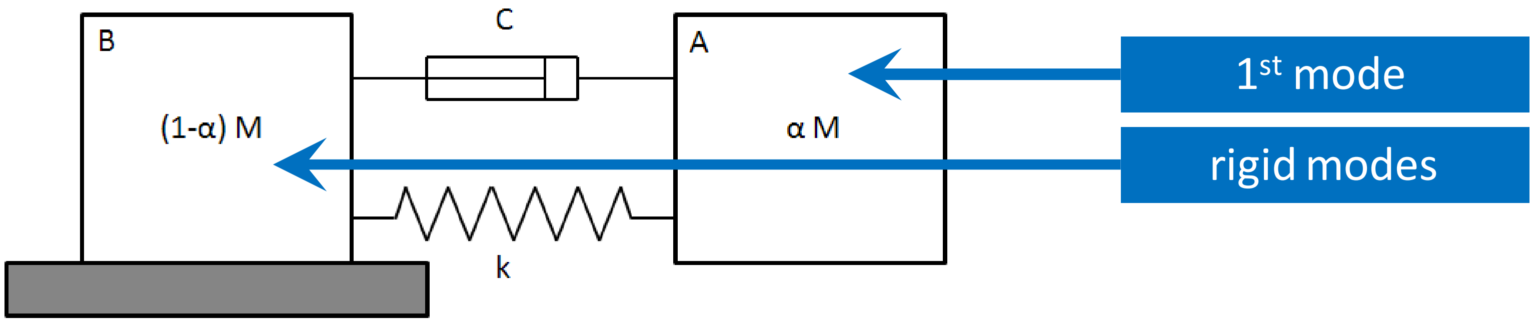

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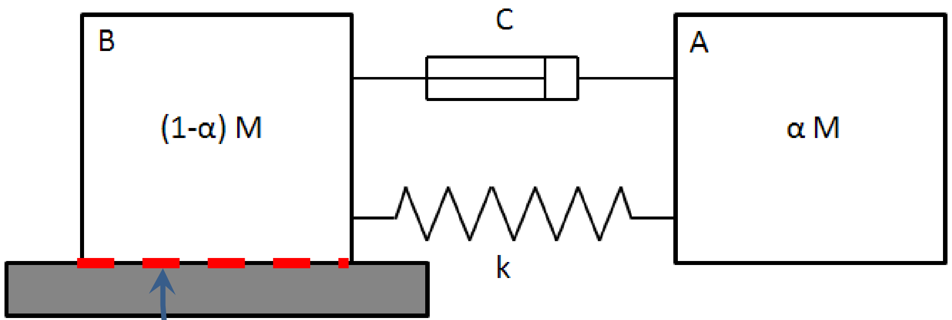
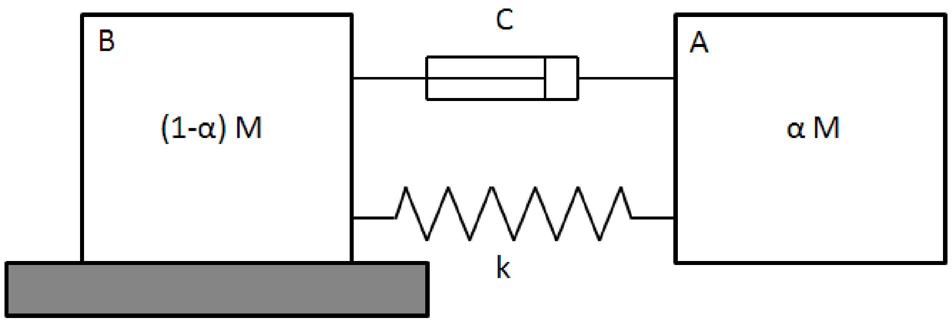


Mohr-Coulomb : $T_{dyna} < T_{max} - T_{stat} = N \tan(\varphi) - T_{stat}$

- **The limit-acceleration : defined by Newmark (1965)**
  - $a_{lim} = T_{dyna} / M$
  - a_{lim} is the max. « static » acceleration for which the dam does not slide
  - For a dam with vertical upstream face : $$a_{lim} = \frac{(Mg - SP)\tan\varphi - HS_x}{M + M_{added}}$$

A SIMPLIFIED MODEL FOR SLIDING



$k = \alpha M\,\omega^2$

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- **Only four parameters**
  - α : fraction of modal mass of the first mode (M : total mass)
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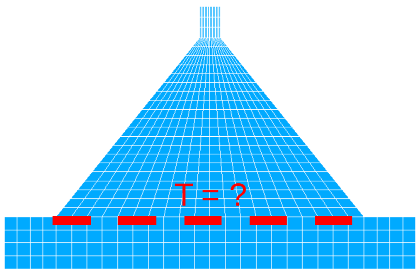
  - ξ : damping ratio of the first mode
  - a_{lim} : limit acceleration

- **A model which is able to estimate the shear force at the foundation**

A « PROOF » : THE SHEAR FORCE

- **Let's compare the shear force at the foundation, in each model**
  - In a finite elements model



$$T = \underline{\Delta}.\left(\underline{\underline{K}}\,\underline{U} + \underline{\underline{C}}\,\underline{\dot{U}}\right)$$

$$= \underline{\Delta}\,\underline{\underline{K}}\left(\underline{D}_1 a_1 q_1(t) + \sum_{i=2}^{N} \underline{D}_i a_i q_i(t)\right)$$

$$+ \underline{\Delta}\,\underline{\underline{C}}\left(\underline{D}_1 a_1 \dot{q}_1(t) + \sum_{i=2}^{N} \underline{D}_i a_i \dot{q}_i(t)\right)$$

$$= \ldots$$

$$= \left(M - m_1\right) a_S(t) + \omega_1^2 m_1 q_1(t) + 2\xi_1 \omega_1 m_1 \dot{q}_1(t)$$

- $\underline{\underline{M}}$; $\underline{\underline{K}}$; $\underline{\underline{C}}$: mass, stiffness & damping matrices
- $\underline{D}_i$: modal base
- $\underline{\Delta}$: influence vector
- $\underline{X}$: nodes displacements vector
- Modal masses : $m_i = \dfrac{\left(\underline{D}_i\,\underline{\underline{M}}\,\underline{\Delta}\right)^2}{\underline{D}_i\,\underline{\underline{M}}\,\underline{D}_i}$
- Participation factors : $a_i = \dfrac{\underline{D}_i\,\underline{\underline{M}}\,\underline{\Delta}}{\underline{D}_i\,\underline{\underline{M}}\,\underline{D}_i}$

Detailed demonstration is given in ref [1]

[1] : Mével, S., (2013). Estimation du glissement sismique d'un barrage-poids. Rapport de projet de fin d'études, École Nationale des Ponts et Chaussées, ISL Ingénierie

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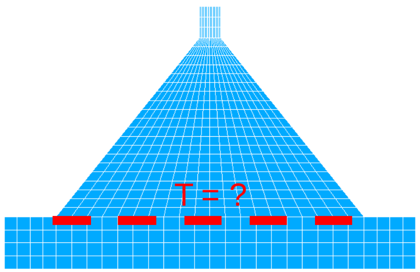

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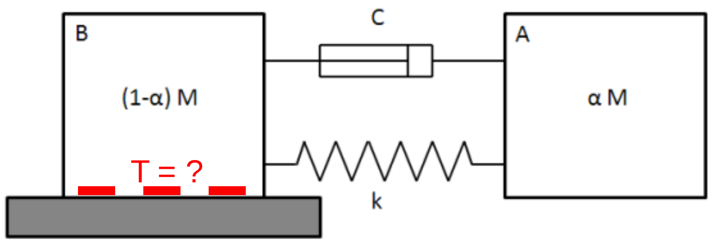
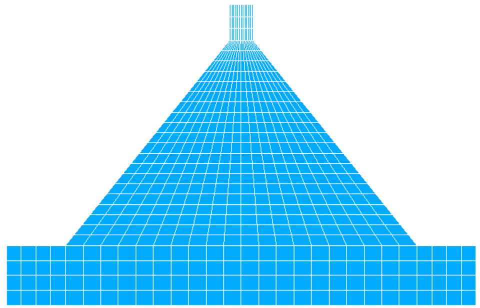
- Same equation for the simplified model !



SHEAR FORCE CALCULATION

- **With an example**
  - Shear force calculated with ANSYS ®
  - Shear force calculated with the simplified method



- **ANSYS model hypothesis**
  - Rayleigh damping propotional to the stiffness matrix
  - Pore-pressures taken into account in the a_{lim} value
  - No fluid domain (only added masses) & infinitely rigid foundation

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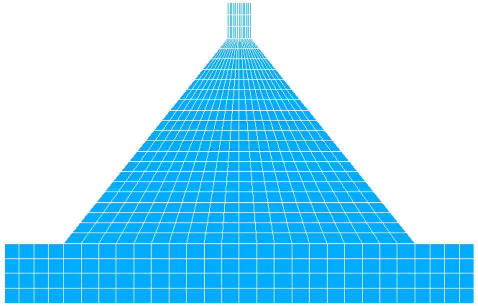

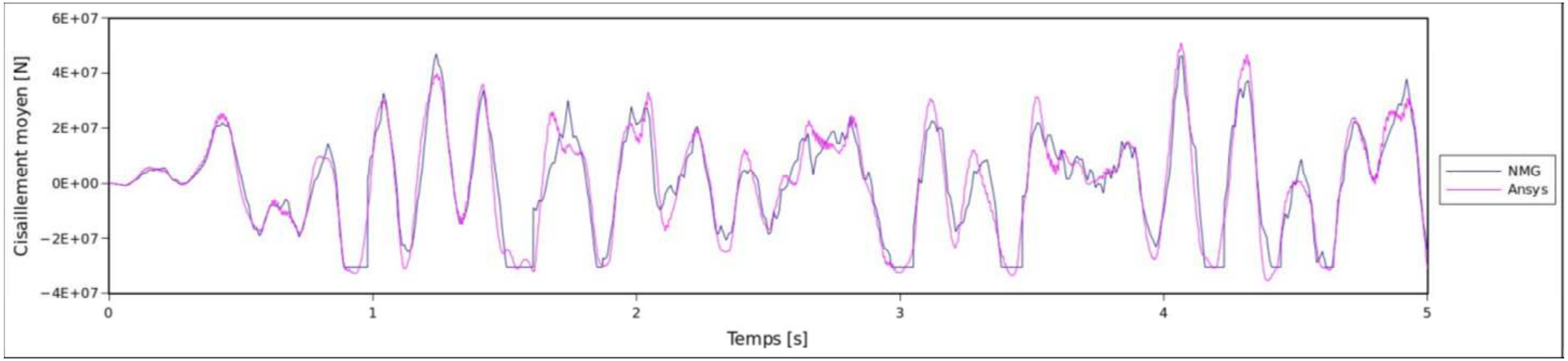

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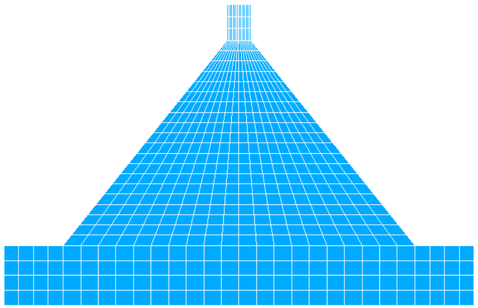

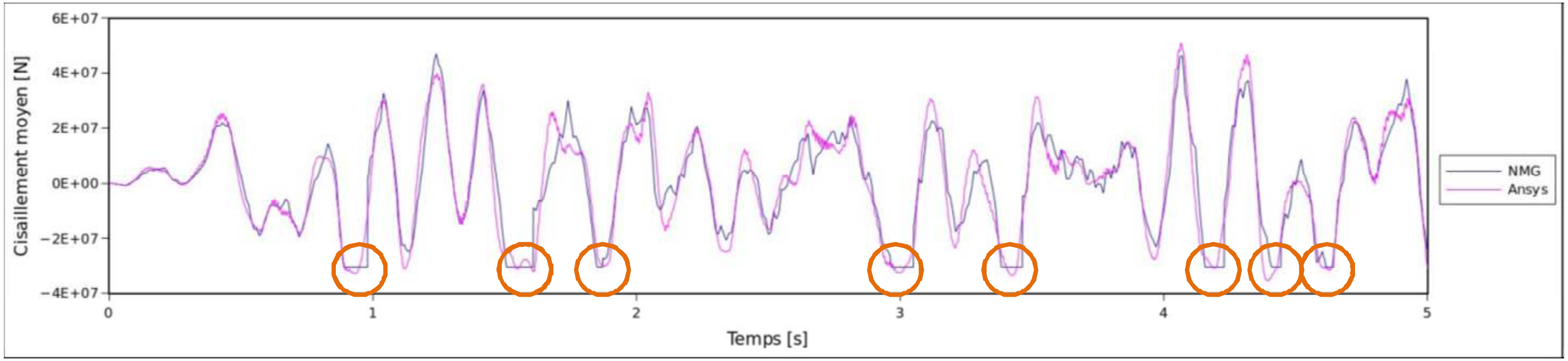

SLIDING !

- **ANSYS model hypothesis**
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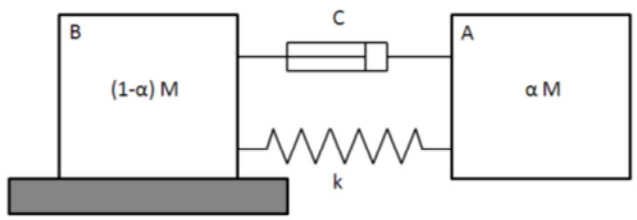
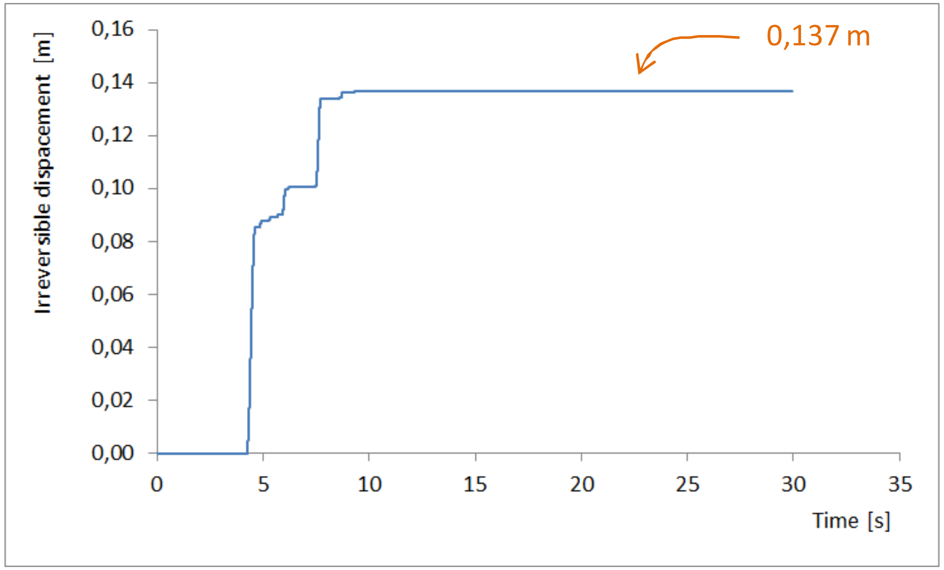
SLIDING CALCULATION

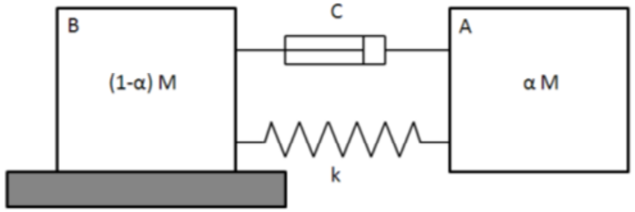


- **The motion integration gives the final irreversible sliding**
  - One or two degrees of freedom
  - Fundamental principle of the dynamics
  - The result *does not* depend on the total mass M !

- **An example of sliding calculation**



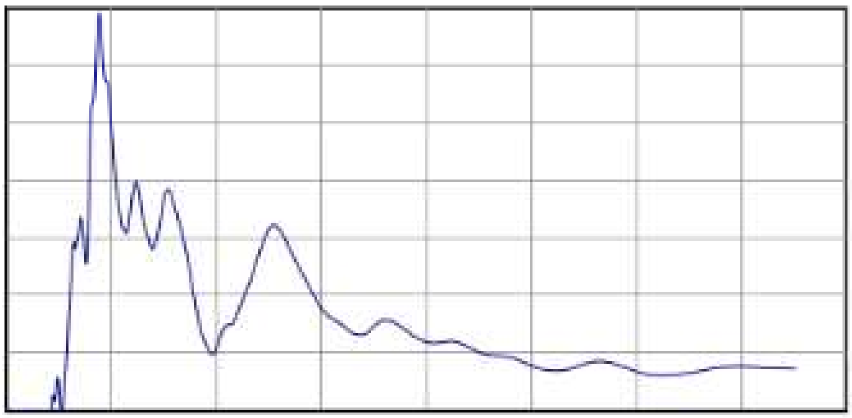
SLIDING CALCULATION



- **Let's define the sliding spectra**
  - A sliding spectrum is drawn for a set of parameters :
    - α
    - ξ
    - a_{lim}
  - The sliding spectra give the final displacement of the mass B as a function of the fundamental frequency f

- **Shape of a sliding spectrum**

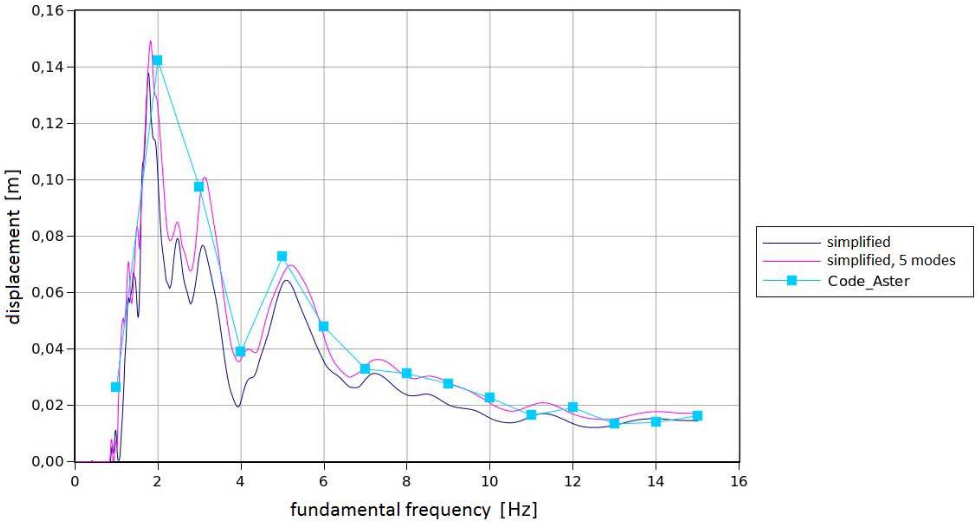
Displacement [m]

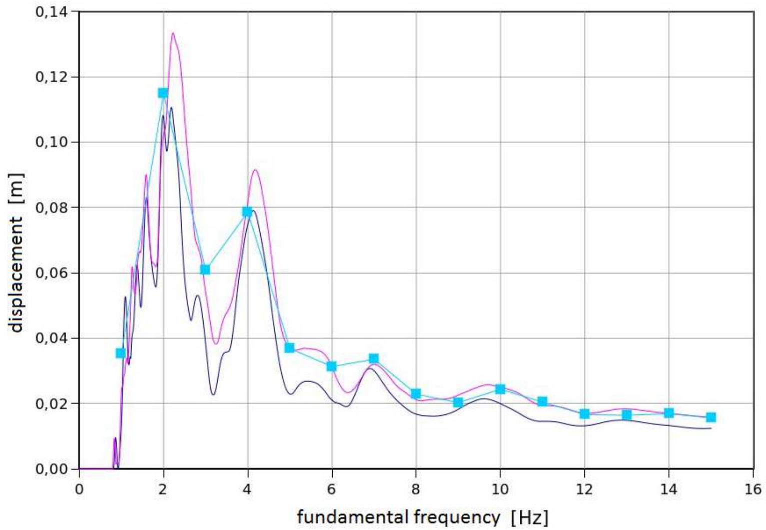


Frequency [Hz]

SLIDING SPECTRA COMPARISON

- **With two examples**
  - Sliding calculated with Code_Aster ® (JOINT_MECA_FROT)
  - Sliding calculated with the simplified method





- **Code_Aster model hypothesis**
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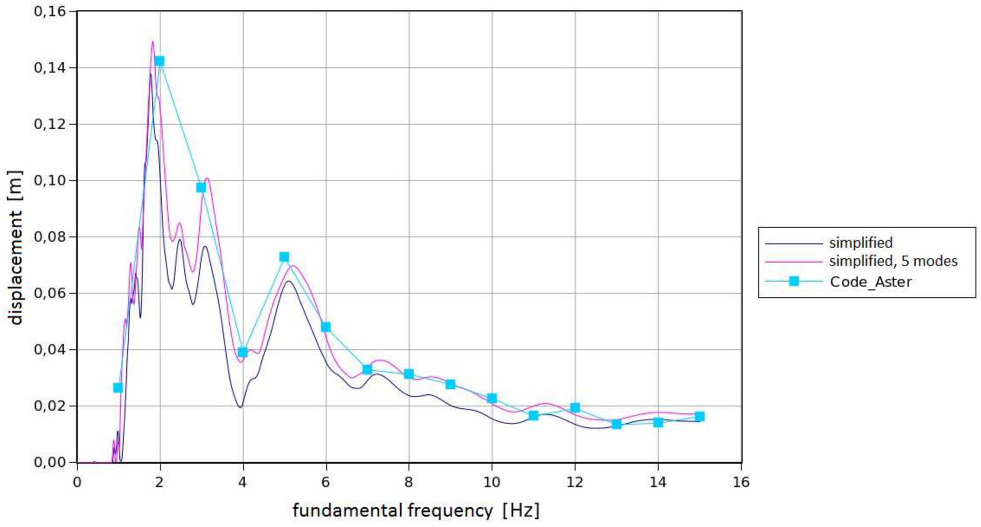
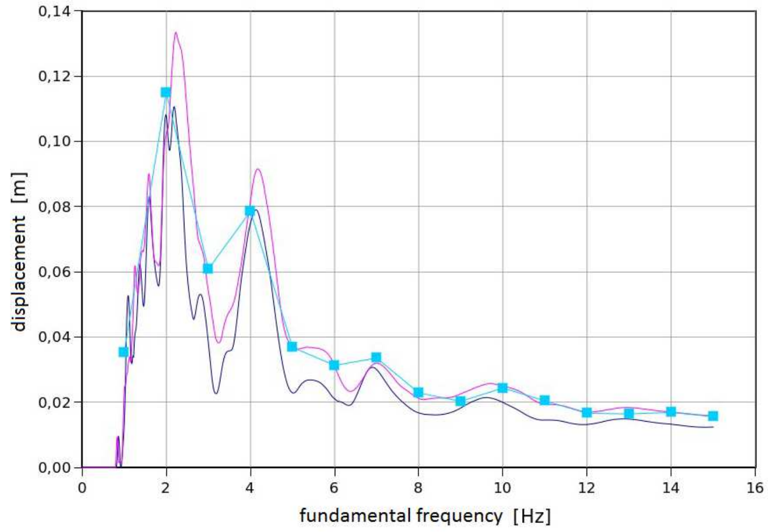
SLIDING SPECTRA PROS AND CONS





- **Sliding spectra :**
  - Are easy to define and to understand
  - Are easy to compute and to use
  - Are computed in less than 10 seconds with a personal computer !
- **But some phenomena are not taken into account, especially :**
  - Soil-structure interaction
  - Fluid-structure interaction
  - Cohesion

SLIDING SPECTRA APPLICATIONS

- **The main advantage of this simplified method is the number of possible applications : parametric & probabilistic studies**

- **Amount of computation for a probabilistic study**
  - For each random parameter defined by its probability distribution

    ~ 10^2 simulations
  - Let's suppose that 2 parameters are defined as random

    ~ 10^4 simulations
  - That-is-to say : 10 000 simulations for :
    - each geometry
    - each foundation resistance hypothesis
    - each accelerogram

- **Some examples are given in ref [2]**

comité français des barrages et réservoirs

[2] : Mével, S., Jellouli, M. (2016). Sûreté d'un barrage-poids vis-à-vis de l'aléa sismique : évaluation probabiliste du glissement par une méthode simplifiée

IMPROVING SIMPLIFIED MODELS

**WHEN AN ANALYTICAL SOLUTION OF A PHENOMENON EXISTS,
EVEN AN APPROXIMATED ONE,
A SIMPLIFIED MODEL CAN BE BUILT**

- **SOIL-STRUCTURE INTERACTION**
  - The Wolf & Deeks Cone (2010)

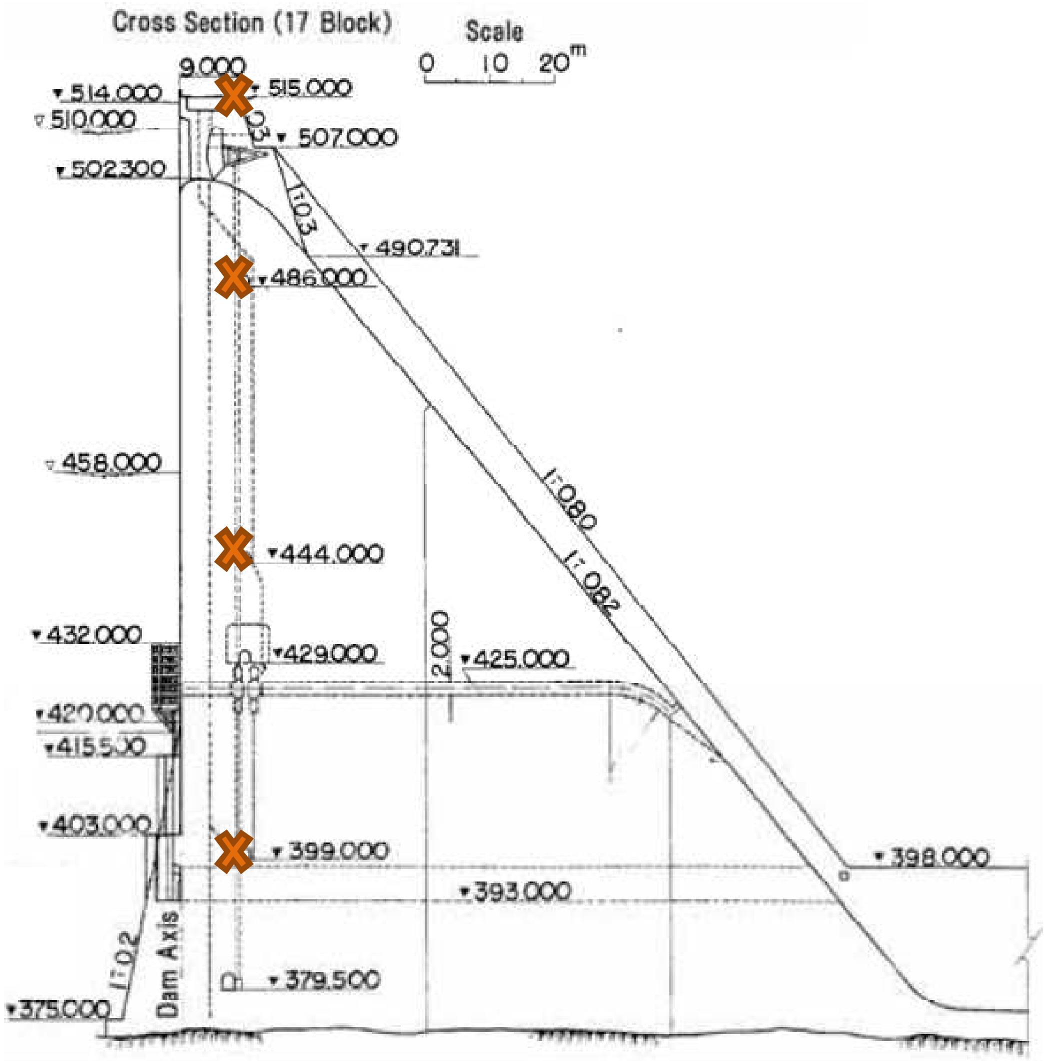
- **VERTICAL FLUID BEHAVIOR**
  - Vertical modes
  - Mean pressure on the dam

- **FLUID-STRUCTURE INTERACTION**

AN EXAMPLE OF REAL RECORDS

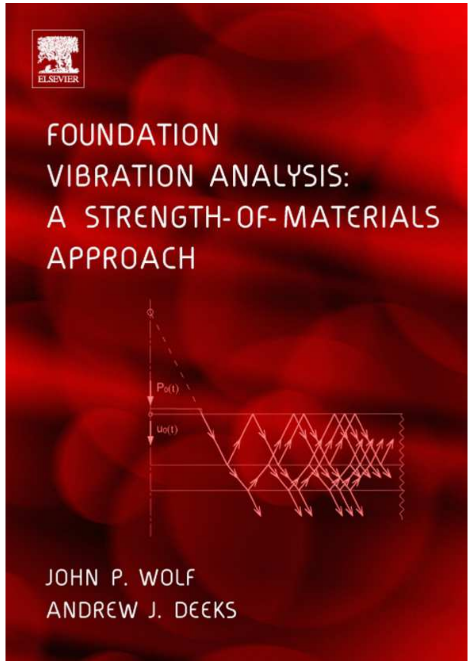
- **TAGOKURA DAM**
  - Concrete gravity dam
  - Height: 145 m
  - Crest length: 462 m

- **RECORDS (3 directions)**
  - El 399 (lower gallery)
  - El 444
  - El 486
  - El 515 (crest)



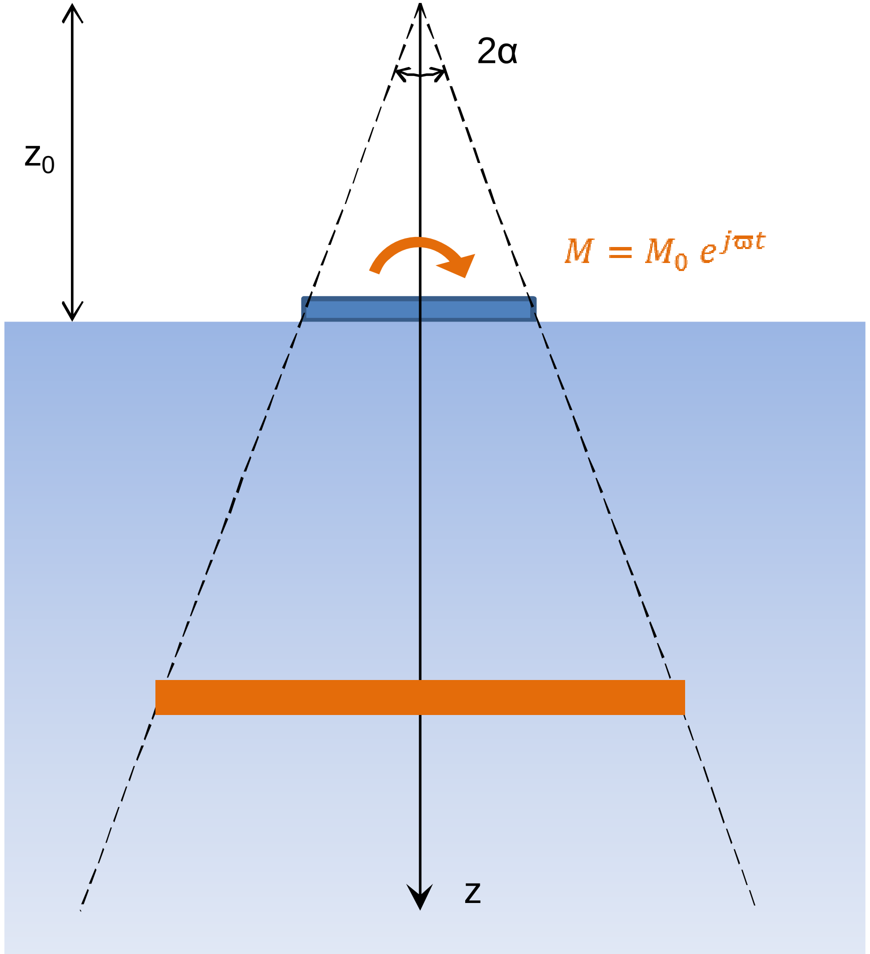
SOIL-STRUCTURE INTERACTION

- **The Wolf & Deeks Cone (2004)**
  - The soil impedance is approximated with
    - springs
    - dampers
    - masses
    - etc.
  - The soil is replaced by a cone-shaped beam of soil
  - Analytical solutions exist for
    - the vertical impedance
    - the horizontal impedance
    - the rocking impedance
    - the rotation impedance
  - Quite accurate representation of the ISS, a lot of comparisons are made



SOIL-STRUCTURE INTERACTION

- **Rocking impedance**



- **Hypothesis**
  - The foundation is rigid
  - The cone behaves as a Bernoulli beam
  - The foundation is only rocking

- **Fundamental equations**
  - Equilibrium (FPD)

$$\frac{\partial M}{\partial z} + \rho I\, \varpi^2 \theta = 0$$

  - Material behavior

$$M = EI \frac{\partial \theta}{\partial z}$$

  - Geometry

$$I = I_0 \left(\frac{z}{z_0}\right)^n$$

n = 3 for 2D models
n = 4 for 3D models

SOIL-STRUCTURE INTERACTION

- **Soil behavior equation**

$$\frac{\partial^2\theta}{\partial z^2} + \frac{n}{z}\frac{\partial\theta}{\partial z} + \frac{\varpi^2\theta}{V_p^2}$$

- **Solution for 2D models : n = 3** → ?

- **Solution for 3D models : n = 4**

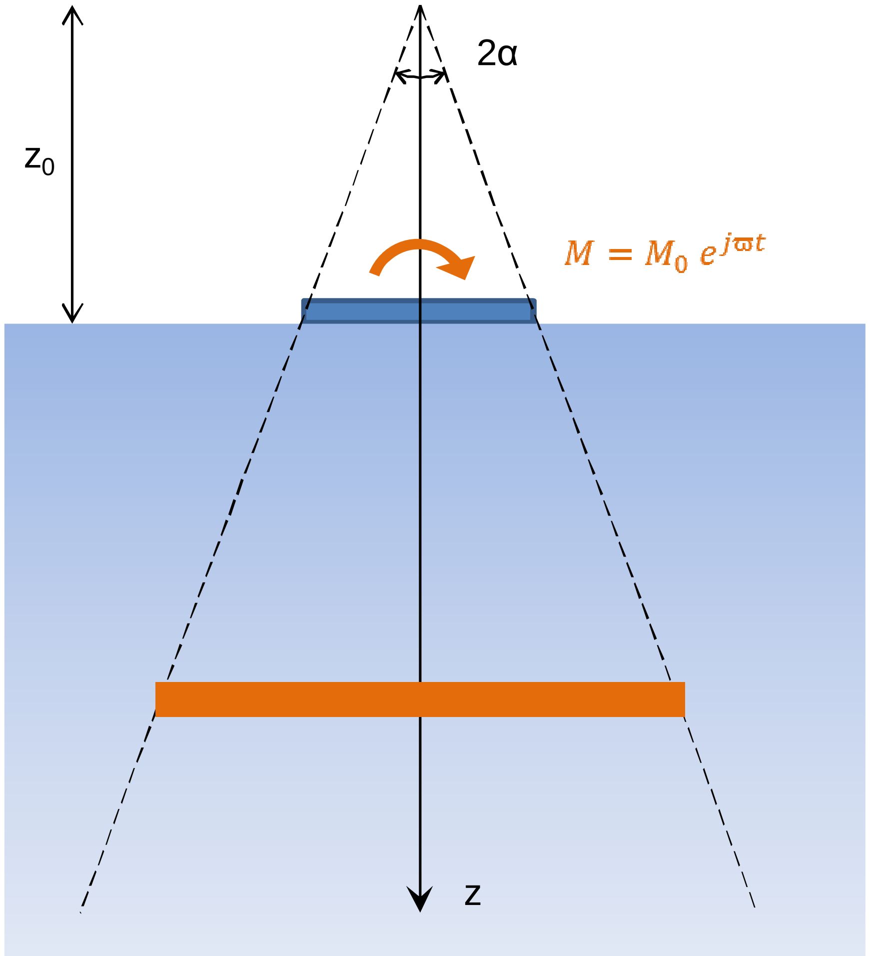
$$\theta(z,\varpi) = \left(\frac{1}{z^3} + j\frac{\varpi}{V_p}\frac{1}{z^2}\right)e^{-j\frac{\varpi}{V_p}z}$$ → Relation between θ and $\partial^2\theta/\partial z^2$

↓

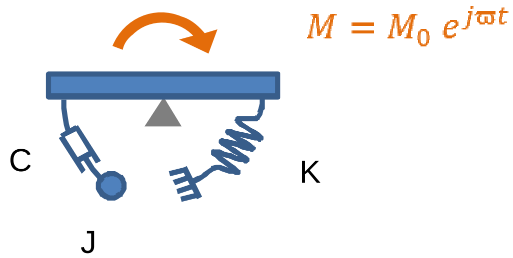
Calibration on the static solution to determines the equivalent soil system ← Analytical expression of impedance

SOIL-STRUCTURE INTERACTION

- **Rocking impedance**



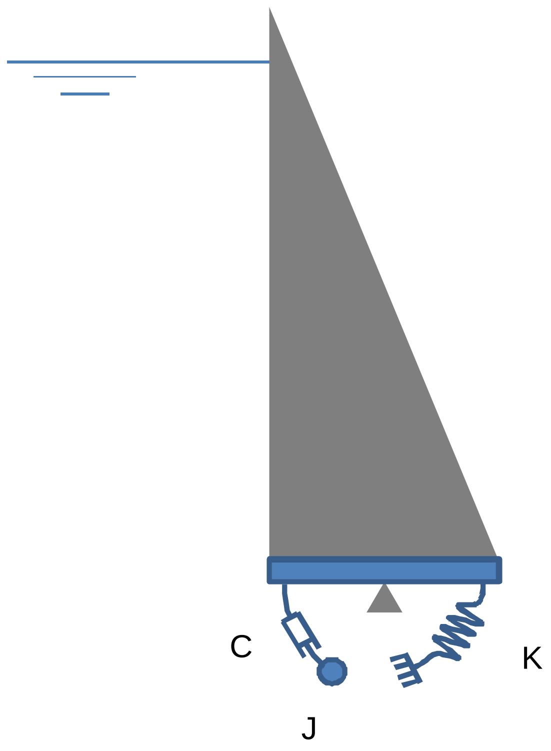
- **Equivalent soil system**

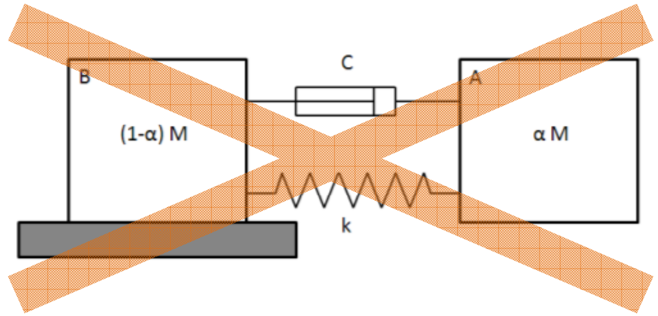


C, J, K are defined analytically, and *does not* depend on ϖ

SOIL-STRUCTURE INTERACTION

- **How to simply represent the dam?**

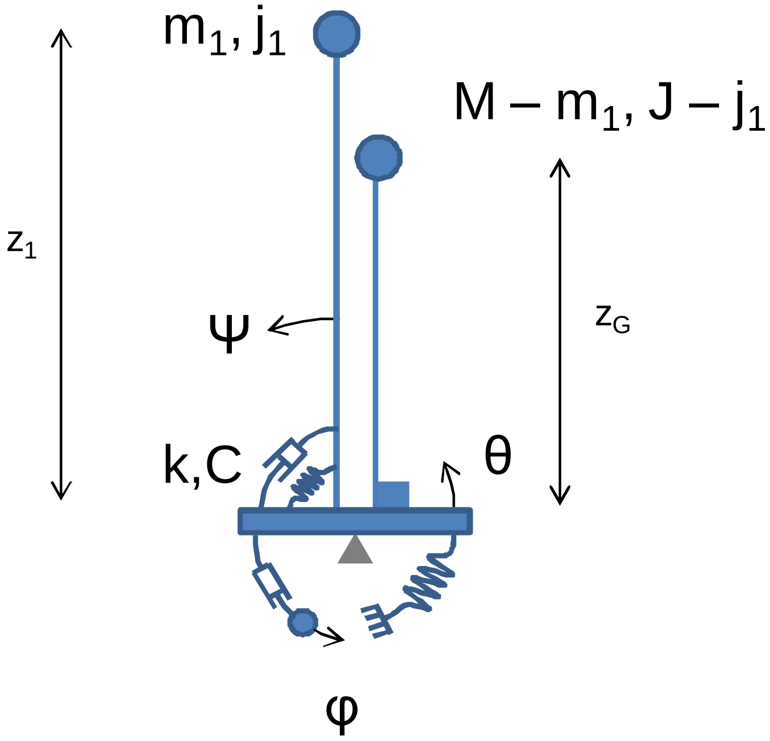




This simple model is no longer valid:
it should model the total momentum at the foundation, not the shear force

SOIL-STRUCTURE INTERACTION

- **How to simply represent the dam?**



- **Parameters**
  - M : total mass
  - m_1 : first modal mass

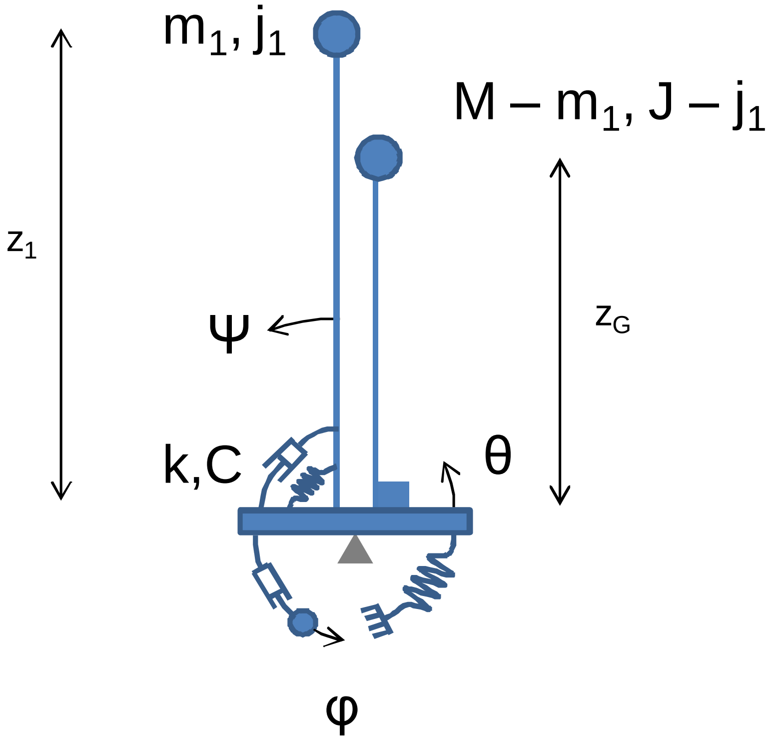
$$m_1 = \frac{\left(\underline{D}_1 \underline{\underline{M}}\, \underline{\Delta}\right)^2}{\underline{D}_1 \underline{\underline{M}}\, \underline{D}_1}$$

  - J : total moment of inertia
  - j_1 : first modal moment of inertia

$$j_1 = \frac{\left(\underline{D}_1 \underline{\underline{M}}\, \underline{B}\right)^2}{\underline{D}_1 \underline{\underline{M}}\, \underline{D}_1}$$

  - k, C : first mode of the dam on a rigid foundation

SOIL-STRUCTURE INTERACTION



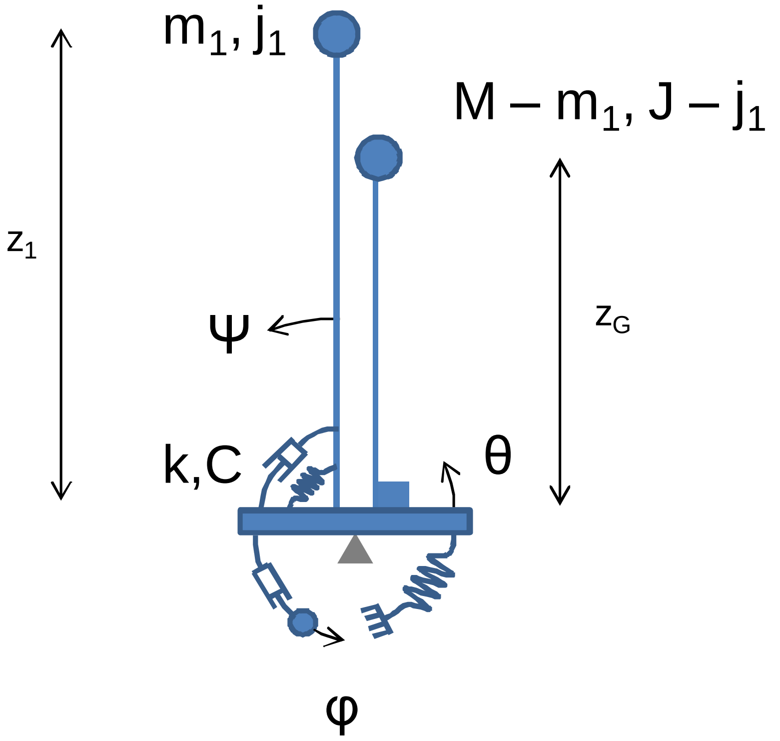
- **Elevation z_1 and z_0**
  - $z_1 = (j_1 / m_1)^{0,5}$
  - z_G = elevation of the centre of gravity
- **The « demonstration » is similar to the one presented for the first model**
- **Crest horiz. displacement**

$$d_c = \theta H + \delta z_1 \psi$$

$$\delta = a_1 D_1 (z = H)$$

SOIL-STRUCTURE INTERACTION

- **What is the effect of the SSI?**
  - Transfer function between the horiz. acceleration and the crest acc.



- **Matrices of the simplified system**
  - $\underline{\underline{M}}, \underline{\underline{C}}, \underline{\underline{K}}$

- **Motion equation**

$$\left(-\varpi^2 \underline{\underline{M}} + j\underline{\underline{C}}\varpi + \underline{\underline{K}}\right).\underline{X} = \underline{\Delta}'\, a(\varpi)\, e^{j\varpi t}$$

- **Crest horiz. displacement**

$$d_c = \theta H + \delta z_1 \psi = \underline{R}.\underline{X}$$

$$d_c = \underline{R}.\left(-\varpi^2 \underline{\underline{M}} + j\underline{\underline{C}}\varpi + \underline{\underline{K}}\right)^{-1} \underline{\Delta}'\, a(\varpi)\, e^{j\varpi t}$$

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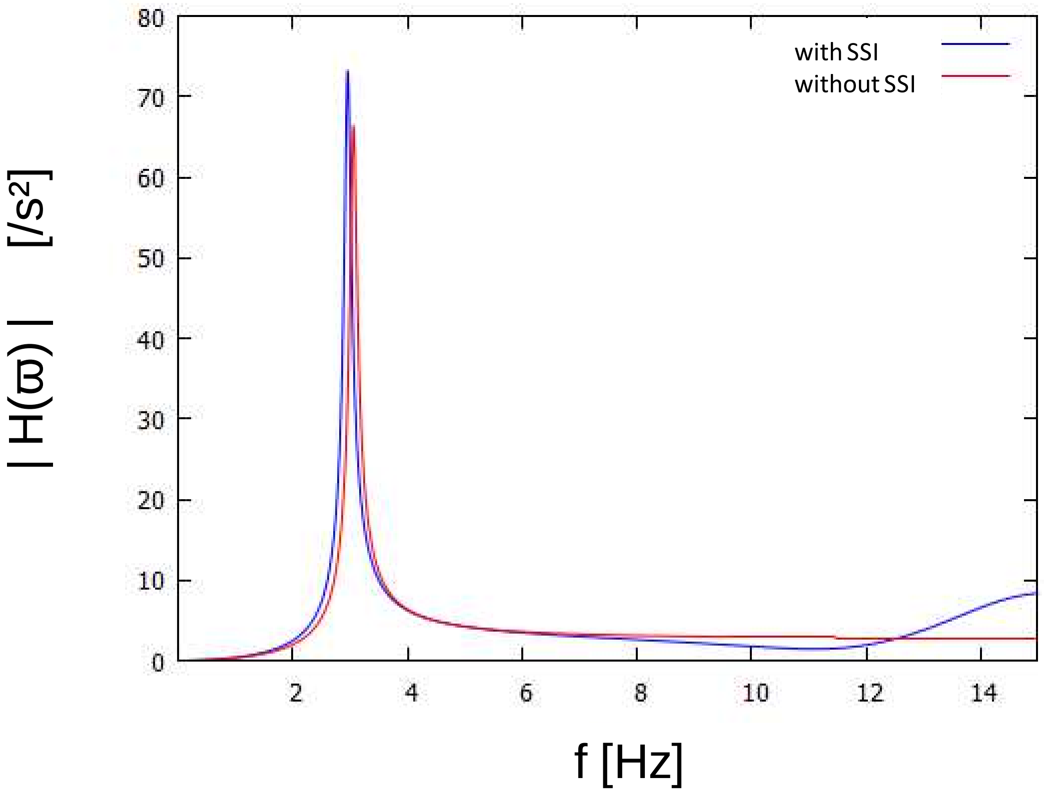

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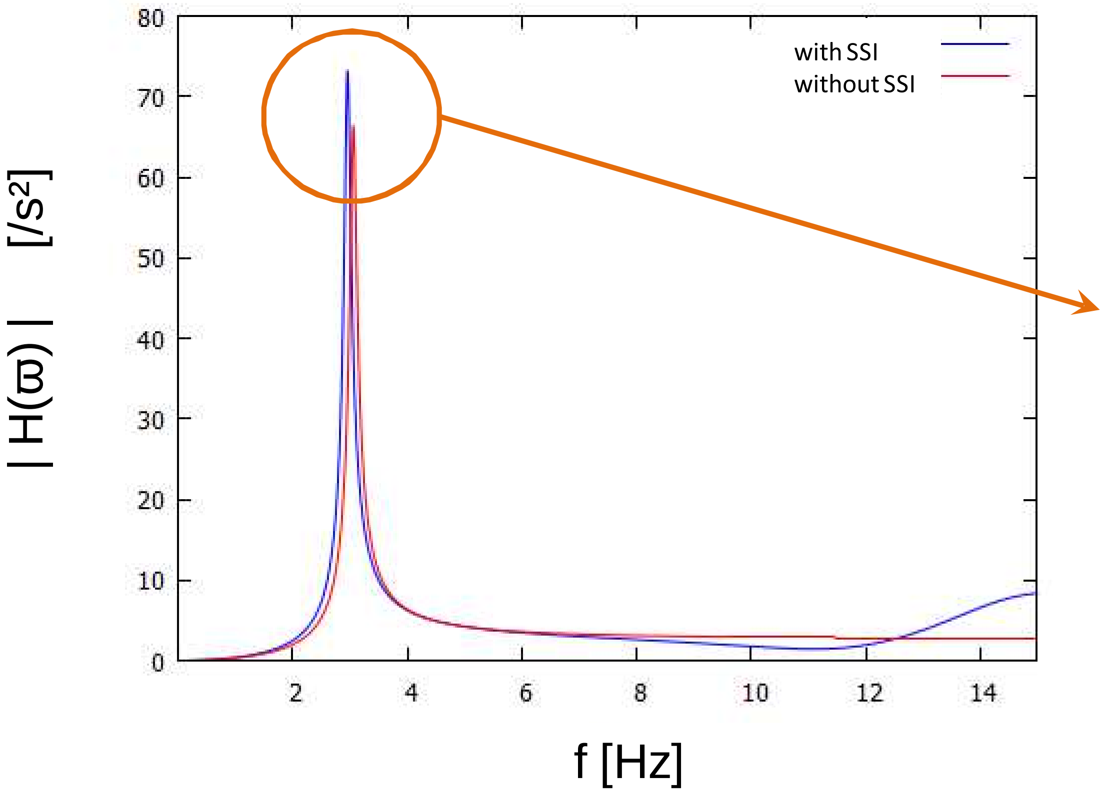


In this case (Tagokura):

- Almost no SSI damping
- Almost no effect on the fundamental frequency

SOIL-STRUCTURE INTERACTION

- **What is the effect of the SSI?**

  - In the Tagokura case : almost no effect of the rocking impedance

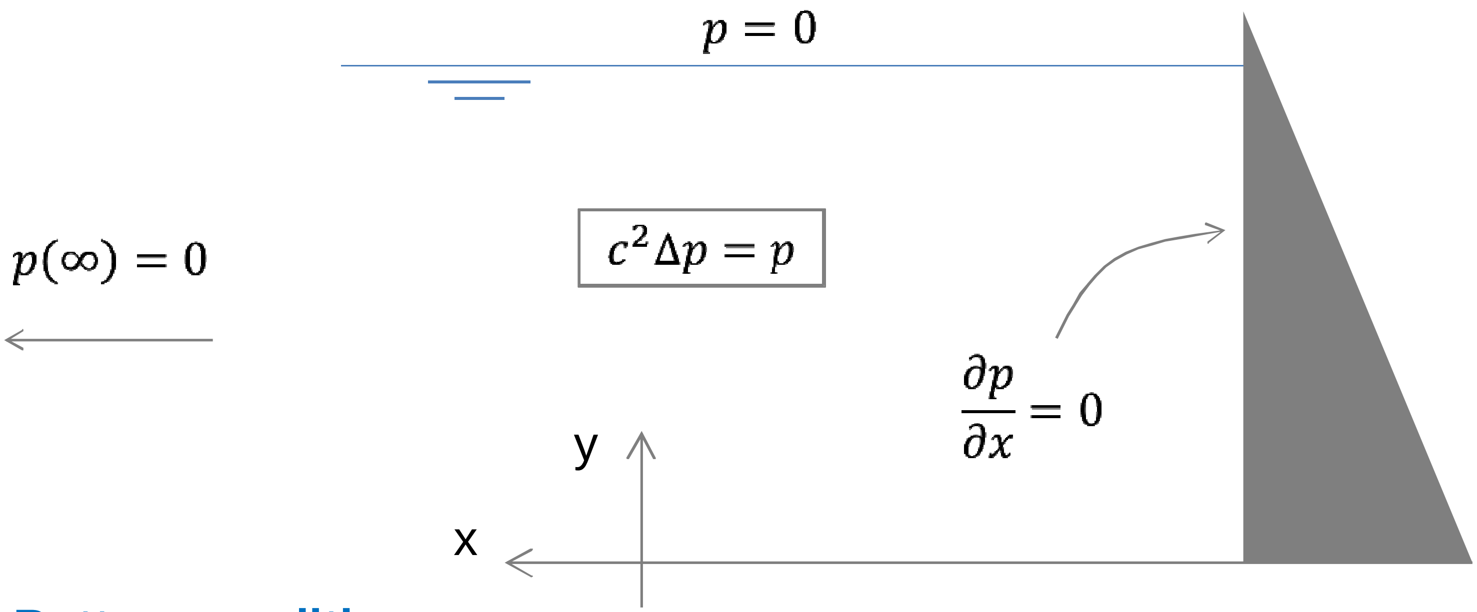
  - The horizontal impedance may have more effect : *to be continued*

VERTICAL FLUID BEHAVIOR

- **The vertical earthquake effect on a reservoir has been investigated by ref [4]**
- **Vertical acceleration generates a vertical response of the reservoir**
- **This response generates a pressure on the upstream face**

[4] : Pasbani, K., Ghorbani, A. (2012). Hydrodynamic analysis of reservoir due to vertical component of earthquake using an analytical method

VERTICAL FLUID BEHAVIOR



- **Bottom condition**
  - Total absorption = Sommerfeld → $\frac{\partial p}{\partial y} + \frac{1}{C}\frac{\partial p}{\partial t} = -\rho a_y$
  - Total reflection = Rigid condition → $\frac{\partial p}{\partial y} = -\rho a_y$
  - Realistic behavior → $\frac{\partial p}{\partial y} + \frac{h}{C}\frac{\partial p}{\partial t} = -\rho a_y$

VERTICAL FLUID BEHAVIOR

- **Pressure in the fluid**
  - Under vertical acceleration, the pressure *does not* depend on x

$$P(y,t) = \frac{\cos\lambda H - \cot\lambda H \sin\lambda y}{\lambda \cot\lambda H - j\varpi \frac{h}{C}} \rho\, a_y(\varpi) e^{j\varpi t} \qquad \lambda = \frac{\varpi}{C}$$

  - Eigenvalues are given by $\cos\lambda H = 0$

$$f = \frac{1}{4}\frac{\pi C}{H}\ ;\ \frac{3}{4}\frac{\pi C}{H}\ ;\ \frac{5}{4}\frac{\pi C}{H}\ ; \ldots$$

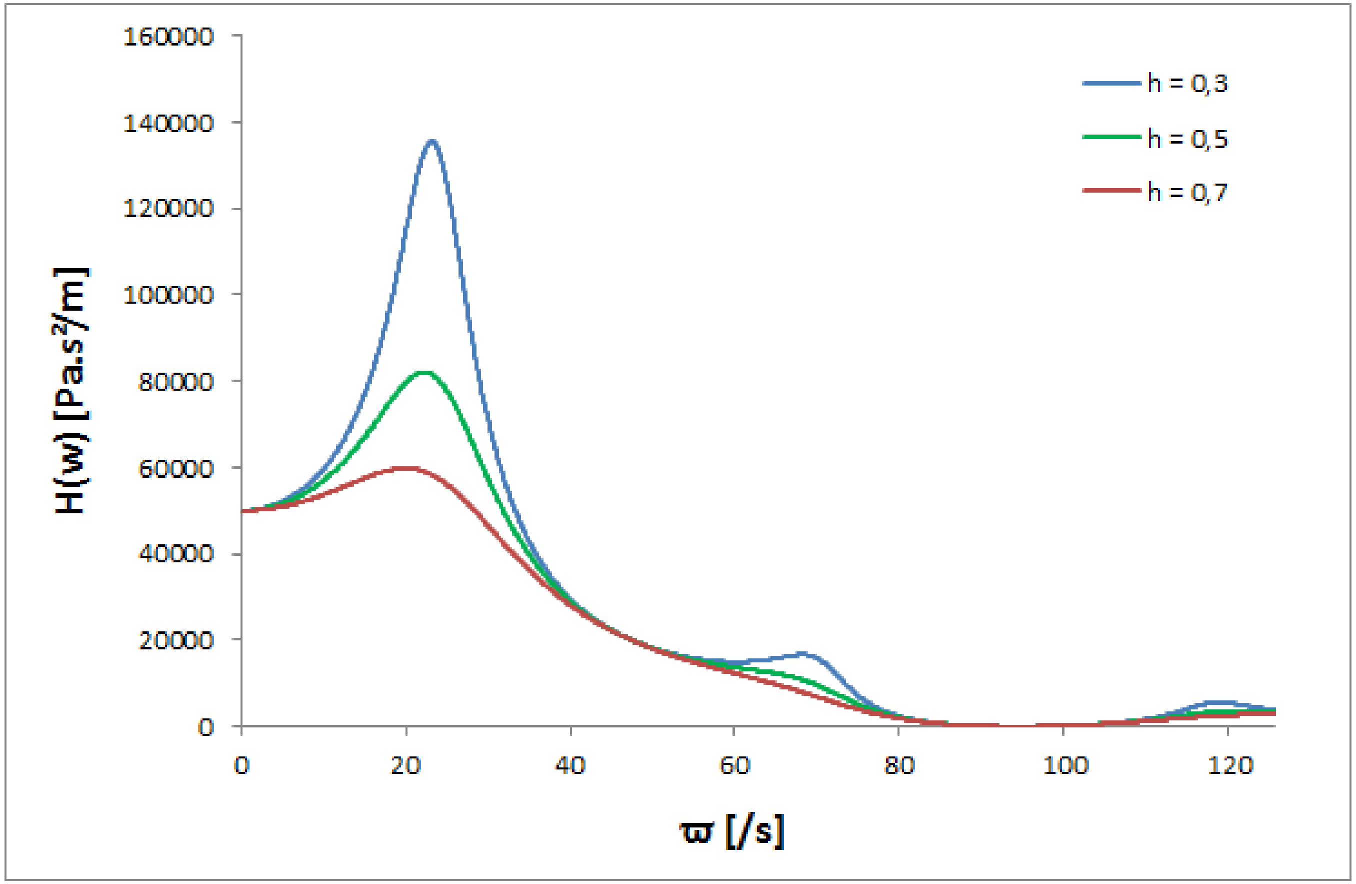
  - The mean pressure on the upstream face is

$$\bar{P}(t) = \int P(y,t)dy$$

  - The mean pressure is a force-sollicitation on the dam

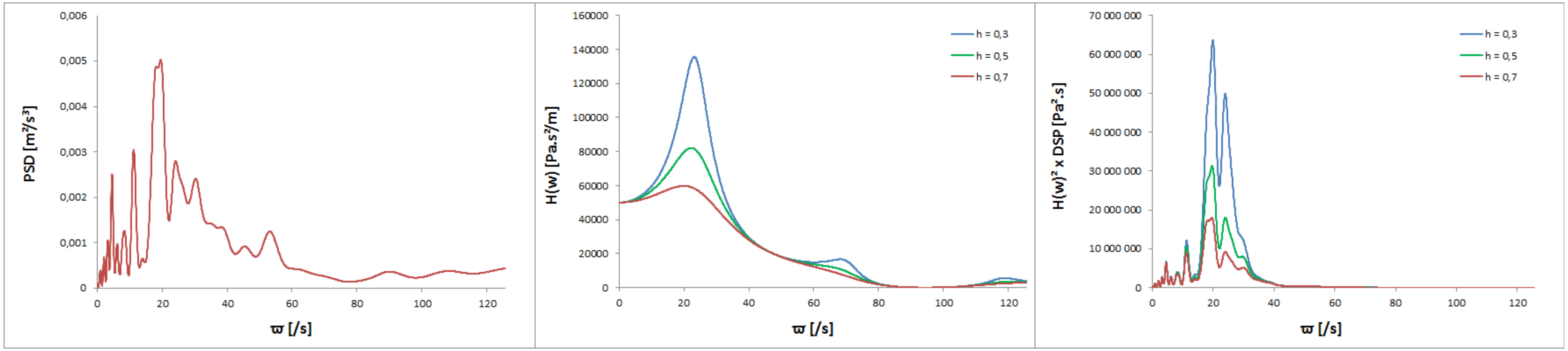
VERTICAL FLUID BEHAVIOR

- **Mean pressure v.s. vertical acceleration : transfer function**
  - Influence of the parameter h



VERTICAL FLUID BEHAVIOR

- **Rough estimation of the mean pressure on the upstream face**
  - Assuming that the vertical acceleration is a stochastic function, the value of the mean pressure on the upstream face can be estimated using the Power Spectral Density



$$E(\max(\bar{P})) = peak \times \int |H(\varpi)|^2 PSD(\varpi)d\varpi = \begin{cases} 14\% & \text{of } \rho g H/2 \text{ for } h = 0{,}3 \\ 10\% & \text{of } \rho g H/2 \text{ for } h = 0{,}5 \\ 08\% & \text{of } \rho g H/2 \text{ for } h = 0{,}7 \end{cases}$$

$peak \approx 3$

With a vertical PGA = 0,08 g

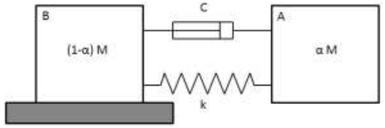
FLUID-STRUCTURE INTERACTION

- **First approximation : Westergaard**
  - Valid under strict conditions

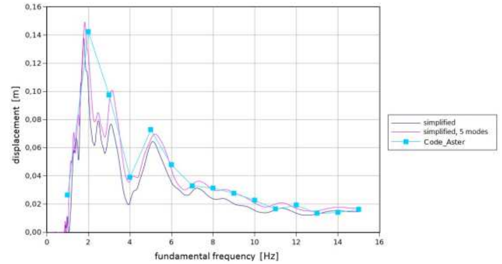
- **For high dams**
  - General analytical solutions have been proposed, see ref [5] and [6]
  - So, simplified models could be built
  - To be continued…

[5] : Pasbani, K. (2011). An analytical solution for earthquake-induced hydrodynamic pressure on gravity dams
[6] : Vieira Ribeiro, P., M., Da Silva, S., F., Pedroso, L., J. (2009). Analytical and numerical studies of dams reservoir interaction in concrete gravity dams

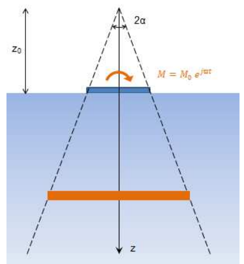
CONCLUSIONS AND PERSPECTIVES



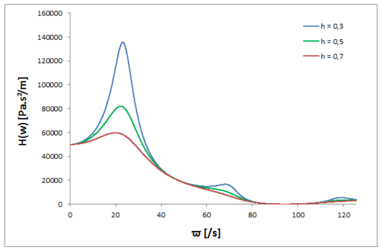
- **We believe that simplified models can usefully be further developed**



- **Historical simplified dynamic models have been developed by others, for gravity or earthfill dams, and have proven being useful**
- **Some applications (parametric & probabilistic studies) need simplified models**



- **For gravity dams, a first 2D simplified model incorporating various aspects of dam dynamics has been developed and compared to more complex FEM models**



- **Several aspects still have to be incorporated (SSI, FSI, under-pressures). It has not been implemented so far, but it seems possible**
- **The PN represents a unique opportunity to keep working on these methods**


THANK YOU FOR
YOUR ATTENTION