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SEISMIC ANALYSES OF CONCRETE DAM, COMPARISON BETWEEN FINITE-ELEMENT ANALYSES AND SEISMIC RECORDS

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Abstract

Currently, in engineering practice, the main approach for dynamic analysis of concrete dams with finite-element method is still based on coarse simplification: fluid-structure interaction is generally taken into account with Westergaard added-masses and soil-structure interaction is considered using massless foundation.

But an increasing number of authors show that these simplified approaches tend to overestimate stresses. Consequently, dam-foundation rock interaction with radiative damping and dam-water interaction considering compressibility of water, partial absorption of hydrodynamic pressure waves by sediments at the lakebed, and semi-unbounded extent of the reservoir and foundation rock domains must be taken into account.

After a brief presentation of a more advanced model taking into account the mass of the foundation, viscous-spring boundary input model and potential-based fluid finite elements with absorptive boundaries, two existing Japanese dams, a gravity dam and an arch dam, are extensively studied. Earthquakes were recorded on each dam, allowing back analyses through comparison of simulated and recorded data at the base and crest of the dams. The dynamic response of each dam is simulated using data recorded at the foundation and the response is compared to the data recorded at sensor located at the dam's crest. Methods are also compared in a stability assessment manner, as done in professional practice.

Comparisons between analyses and records confirm that the conventional massless foundation/added masses approaches with 5% concrete damping greatly overestimates the response of the dam, particularly in the case of gravity dams.

Keywords: dam, dam-water-foundation interaction, finite-element simulation

1. Introduction

Based on seismic records from two existing dams, this paper presents several Finite Element Models (FEM) of these dams and their response to seismic solicitation; the open-source finite-element software Code-Aster is used. Conventional Westergaard added-mass with a massless foundation analyses are done followed by a more elaborate FEM taking into account soil-fluid-structure interaction by means of viscous spring boundary (VSB) and potential-based fluid. Results from both analyses are compared to the actual record at the crest of each dam to assess each method's relevance.

Methods, including the simple pseudo-static approach, are also compared in a stability study manner, as done in engineering practice.

2. Presentation of the fluid-structure interaction and soil-structure interaction method

In order to take into account the fluid-structure interaction, potential-based fluid finite elements are used. The assessment of this formulation for seismic analysis of dam-reservoir systems has been performed by the Ecole Poytechnique of Montreal [1] using test cases based on analytic solutions. The results from this test case have been reproduced using the finite element software Code-Aster used in this study. This formulation allows taking into account compressibility of the water, wave absorption at the end of the reservoir as well as partial absorption by sediments at the bottom of the reservoir.

In order to improve the soil-structure interaction method by taking into account absorption of the wave in the boundaries of the foundation, a viscous spring boundary model is implemented as proposed in [2] and [3], and briefly summarized in Fig. 1. It is employed to absorb the wave energy radiating away from the dam and the foundation. A test case studying the reflection and absorption of a vertically propagating seismic shock in a rectangular foundation validated the viscous spring boundaries in Code-Aster.

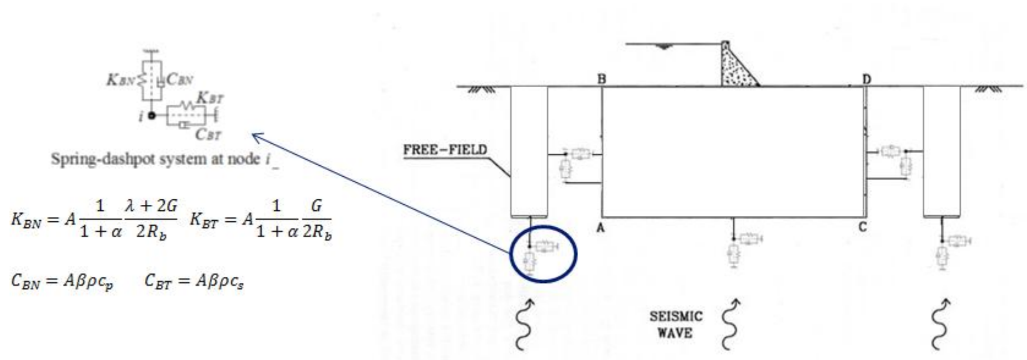

Fig. 1 – Viscous spring boundary model

The description of the VSB and fluid-structure interaction model is limited to this paragraph so as to allow the presentation of the results on the existing dams throughout the rest of this paper.

3. 2D application on a gravity dam

3.1. Geometry of the gravity dam and finite element model, recording devices

The gravity dam studied is 150 m high with a crest of 500 m long. It is equipped with four triaxial sensors. They are positioned at elevation 515 (crest), 486, 444 and 399 (foundation). A 2D model of the dam that displays the sensors' locations is provided Fig. 2.

This study makes use of an earthquake which was recorded at the dam on October the 23th, 2004. An estimation of the dam's first eigenfrequencies was performed using the data from this earthquake. Consequently, concrete's and rock's Young Modulus are set at $E_{concrete}$ = 40000 MPa, E_{rock} = 35000 MPa.

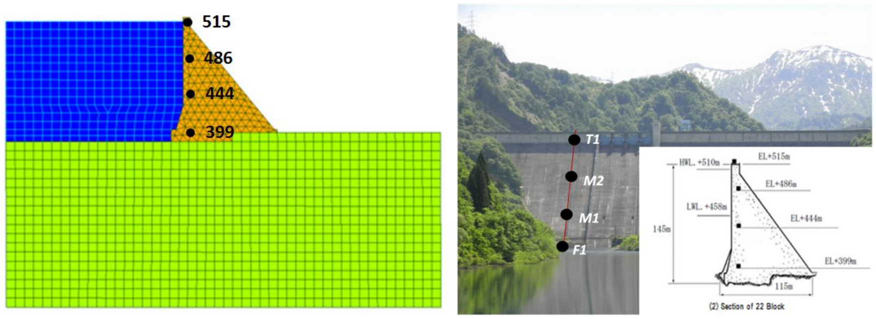

Fig. 2 – Geometry of the 2D model compare to the gravity dam

3.2. Massless foundation and added masses approach

First, a conventional analysis is conducted. The foundation is considered massless and Westergaard added masses are used to take into account the fluid-structure interaction. The concrete's damping value is set at 5 % of the critical value. The input accelerogram is taken at sensor 399.

Fig. 3 shows the comparison between the crest acceleration (515) and the bottom acceleration (399); results are presented as Fourier spectra. Numerical results show a great overestimation of the computed response when compared to the recorded response. Overestimations occur mainly at 2.7 Hz (the first eigenmode) and at 6 Hz. Furthermore, the model is not able to reproduce the peak at the crest of 3.9 Hz, probably caused by the reservoir's mode.

3.3. Viscous spring boundary model (VSB) and potential fluid approach

The improved FE method is used. Considering the introduction of damping in the model, the concrete damping is reduce to 1%, which seems more adequate regards to the low intensity of the earthquake. The following assumptions are considered for the fluid-structure interaction : full absorption of the wave at the upstream face of the reservoir (infinite propagation) and no absorption at the bottom of the reservoir by sediments.

The comparison between recorded and computed accelerations (Fig. 3) shows a much better fit between recorded and calculated data than with the previous approach. The acceleration at the bottom and at the crest is on the same range of level and the FFT comparison shows:

- a slight overestimation of the peak around the first eigenfrequency,
- an underestimation of the peak around 4Hz,
- a slight underestimation of the calculated response at high frequencies (from 8Hz).

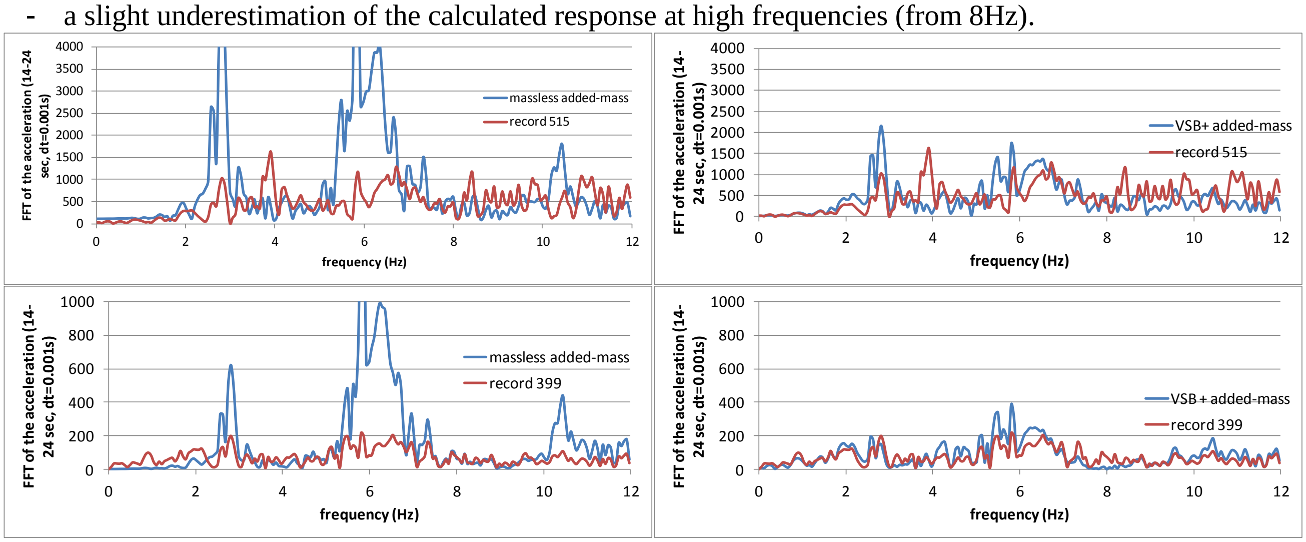

Fig. 3 – Comparison of the FFT of the horizontal acceleration, recorded vs computed at the crest (top) and bottom of the dam (bottom) for Massless / added-mass model (left) and VSB / potential fluid model (right),

3.4. Transfer function and estimation of the damping

In order to evaluate the damping introduce by the new soil-structure but also fluid-structure approaches in the FE analyses, transfer functions (ratio of us/ds acceleration's FFT) are computed (Fig. 4) between the crest of the dam and the input (in that specific case, a white noise is used) with the following methods:

- VSB model with added masses and no concrete damping,
- VSB model with potential fluid and no concrete damping.

Using the half-power bandwidth method, damping introduces by the absorbing boundaries in the foundation is evaluated around 10% for the first mode and up to 20% for higher frequencies. Introduction of the compressible fluid in the FE analyses (Fig. 4) brings:

- A slight increase of the damping (around 2% additional damping on the first eigenmode evaluated with the half-power band method)
- A division of the first peak in 2 sub-ones: the first one is due the structure while the other one come from the reservoir mode,
- An increase of the dam's response around 8 Hz that might come, in that case, of the combination of structure and reservoir modes.

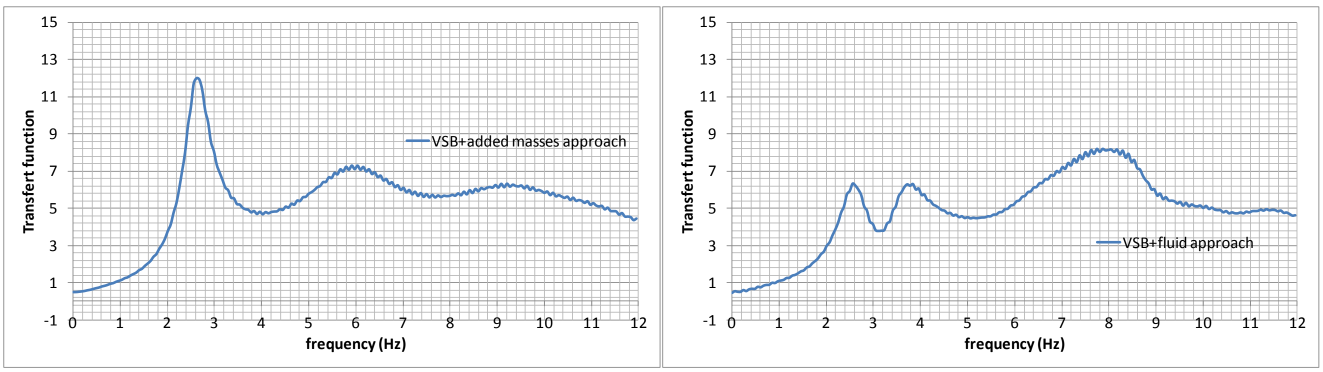

Fig. 4 –Transfer function (ratio betweeb FFT of us/ds crest acceleration and FFT of us/ds input acceleration) VSB-added masses (left) and VSB-fluid approach (right)

4. Stability assessment and comparison with simplified method

Stability of the dam can be assessed by computing a safety factor at the dam-foundation interface and examining the stresses at the upstream toe. The two numerical methods (added mass and mass foundation & VSB and potential fluid approach) are compared to each other as well as to a simplified pseudo-static calculation.

4.1. Stress and safety factor evaluated from the pseudo-static approach

In order to compare the pseudo-static and the FEM approaches, the following methods are considered for the pseudo-static calculations:

- The PGA of the earthquake is assumed to be 0.09 g (maximum upstream-downstream acceleration recorded)
- In agreement with the French guidelines for gravity dam analysis, the inertial forces are computed with the following assumptions: $F_{horizontal}=0.67\times PGA\times V\times\rho$ & $F_{vertical}=0.2\times PGA\times V\times\rho$
- The hydrodynamic force is computed using Westergaard's formula.

4.2. Stresses and safety factor evaluated from the FE method

From the different FE analyses presented in §3, the nodal forces are extracted at each instant of the earthquake at the dam/foundation contact; it is then possible to evaluate the dynamic forces and the momentums acting on the dam and to assess its global stability. Dynamic forces and momentums are added to the static ones, considering the following assumptions:

- Concrete density is 2400kg/m^3,
- Concrete/foundation friction angle is 45°, with no cohesion
- A 50% reduction of the uplift is considered at the base of the dam to take into account the drainage
- The water level is at 510,67 m

Based on the beam theory and considering a linear repartition of stress, the safety factor against sliding is computed as well as the stress at the upstream toe of the dam. These values are presented on Fig. 5 for the different FE approaches.

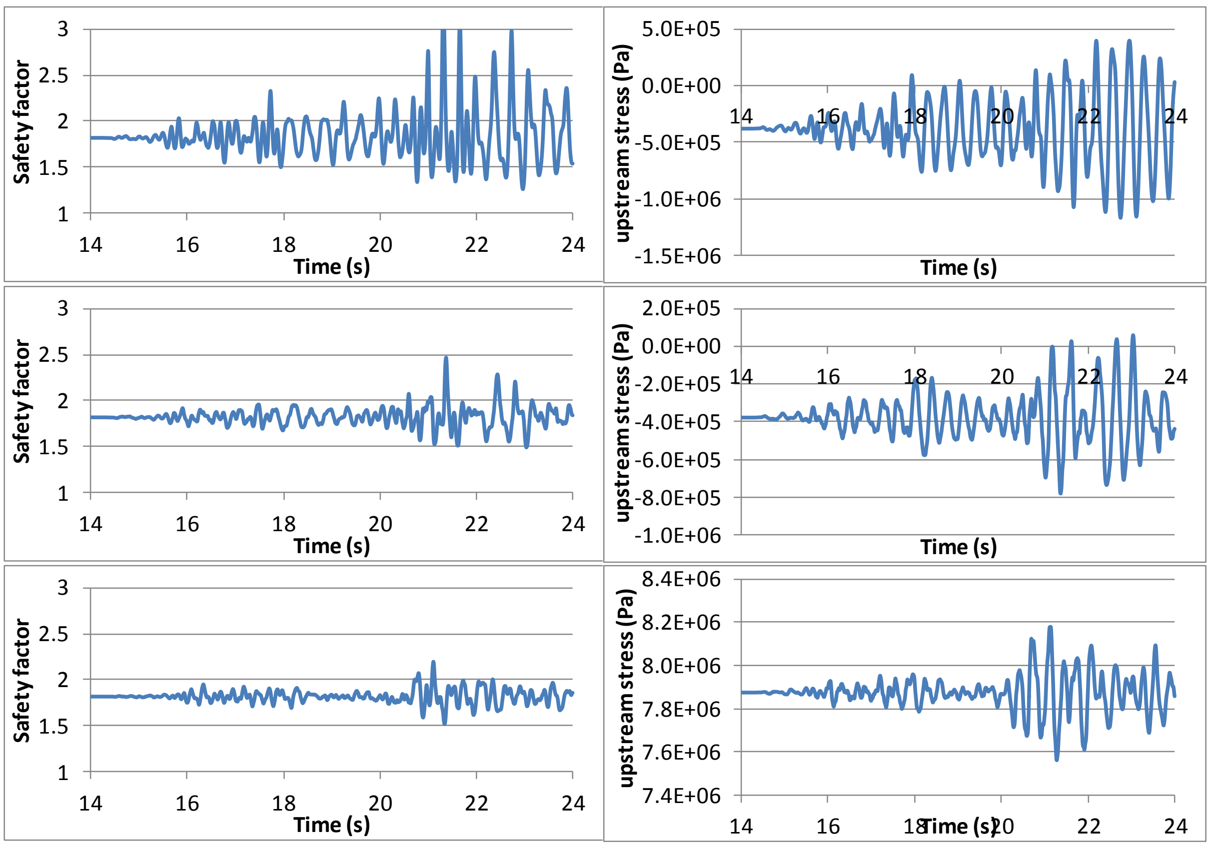

Fig. 5 - Evolution of the safety factor (left) and the upstream toe stress (right)
Massless/added mass (top), VSB/added-mass (middle), VSB/fluid (bottom)

With the massless/added masses approach, the minimum safety factor is 1.26 with a tension stress positive at the upstream toe (up to 0.4 MPa). With the improvement of the FE analyses considering the VSB model and compressible fluid, the safety factor increases to 1.51 and the upstream toe stays in compression (-0.08 MPa). Results are presented Table 1; the stability assessment's results between the different FE models and the pseudo-static method are compared. It is interesting to note that the result of the simplified approach is close from the results obtained with the more complex FE models (VSB+fluid).

The vertical dynamic stresses on the upstream face of the dam are calculated with the different approaches, including the pseudo-static one: results are compared in Fig. 5. Let's consider that the VSB/fluid approach is the most representative of the actual behaviour of the dam under the considered earthquake:

- The pseudo-static method provides good results at the feet of the dam although it underestimates the stresses at middle-height

- The massless foundation/added masses approach with 5% concrete damping strongly overestimates the stresses: values calculated are 2 or 3 times those from the VSB/fluid approach.

Table 1 – Stability results depending on the method used

	approach	Safety factor (dam/foundation interface)	Effective upstream stress (MPa) At the upstream toe
	Pseudo-static	1.48	0.003
Finite Element	massless added-mass (5% damping)	1.26	0.4
Finite Element	VSB/fluid	1.52	-0.075

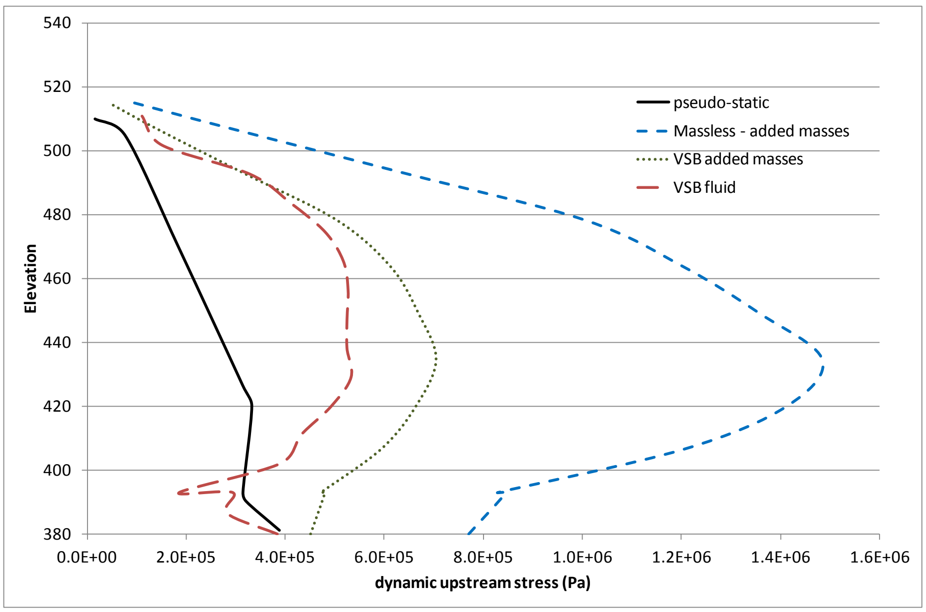

Fig. 6 - Dynamic stresses only on the upstream face of the dam

5. 3D application on the gravity dam

In order to evaluate the ability of the introduced soil-structure and fluid-structure model to deal with 3D finite element model, a comparison between the different approaches and the recorded earthquake is presented on the 3D dynamic analysis of the gravity dam.

The dam's mesh used for this purpose is shown Fig. 7. The following mechanical properties are taken into account: $E_{concrete}$=28000 MPa, E_{rock}=24000 MPa.

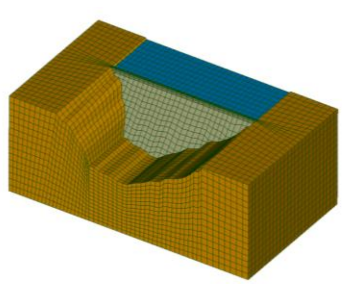

Fig. 7 – 3D mesh of the gravity dam

The earthquake record at elevation 399 will be considered as input data for the FE analysis.

5.1. Massless and added mass approach

As for the 2D analysis, a 5% Rayleigh damping is taken into account for the concrete. This is the only source of damping and results presented on Fig. 8 show that the model strongly overestimates the response of the dam, even at the bottom of the dam and for all the direction.

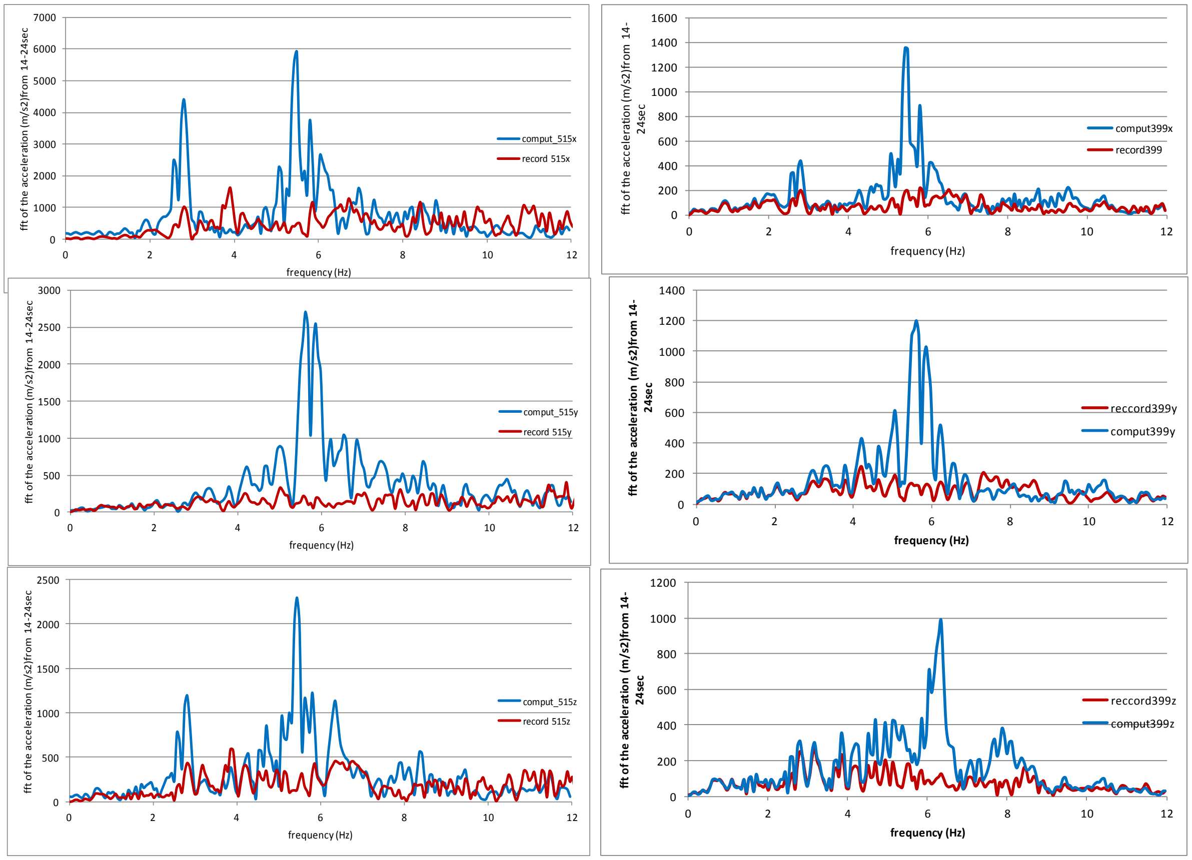

Fig. 8 – Massless foundation / added masses, gravity dam 3D FFT comparison of the accelerations, recorded vs computed 515 (left) and 399 (right), directions u/s (top) dam axis (middle) vertical (bottom)

5.2. Viscous-spring boundary model and potential fluid approach

Results of the VSB model with a 1% damping in the concrete are shown in Fig. 9. It is interesting to note that the accelerations computed at the crest of the dam are in good agreement with the recorded ones, in the 3 directions. At the bottom of the dam, values are in the same range in the horizontal directions but globally overestimated in the vertical direction.

It has to be said that the situation is quite different in a 3D model than on the 2D one presented in the previous chapter. The geometry of the valley is clearly influencing the transmission of the wave from the bottom to the top of the foundation. Even without the dam, the acceleration computed in the top of the foundation is probably not equal to twice the injected one anymore. That means that a deconvolution procedure should be introduced to improve the quality of the results. It has not been done yet considering the quality of the result already obtained.

The FE model also has a significant tendency to underestimate the response of the dam from 8 to 11 Hz. This was already the case in the 2D analyses previously leaded and will need to be investigated in further studies. It does not come from the Rayleigh damping formulation used here, adjusted for the frequencies 3 and 13 Hz.

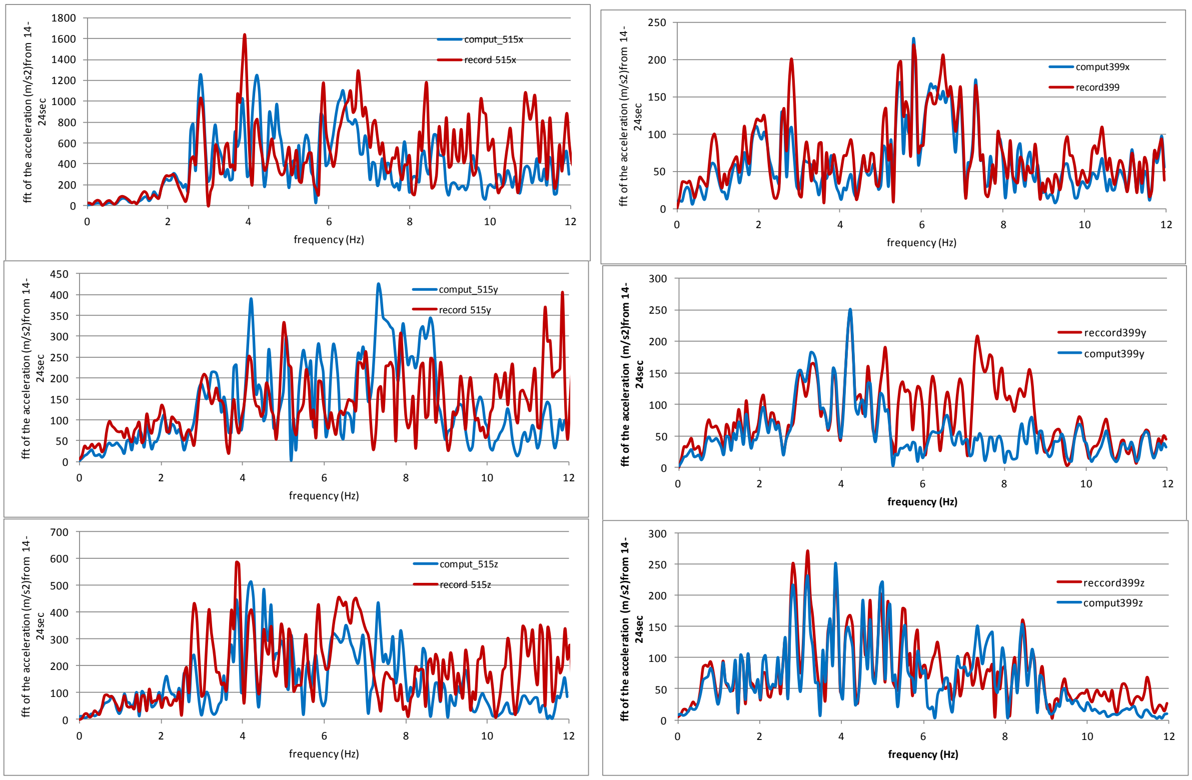

Fig. 9 – VSB/fluid approach, gravity dam 3D FFT comparison of the accelerations, recorded vs computed 515 (left) and 399 (right), directions u/s (top) dam axis (middle) vertical (bottom)

5.3. Comparison of the stress results

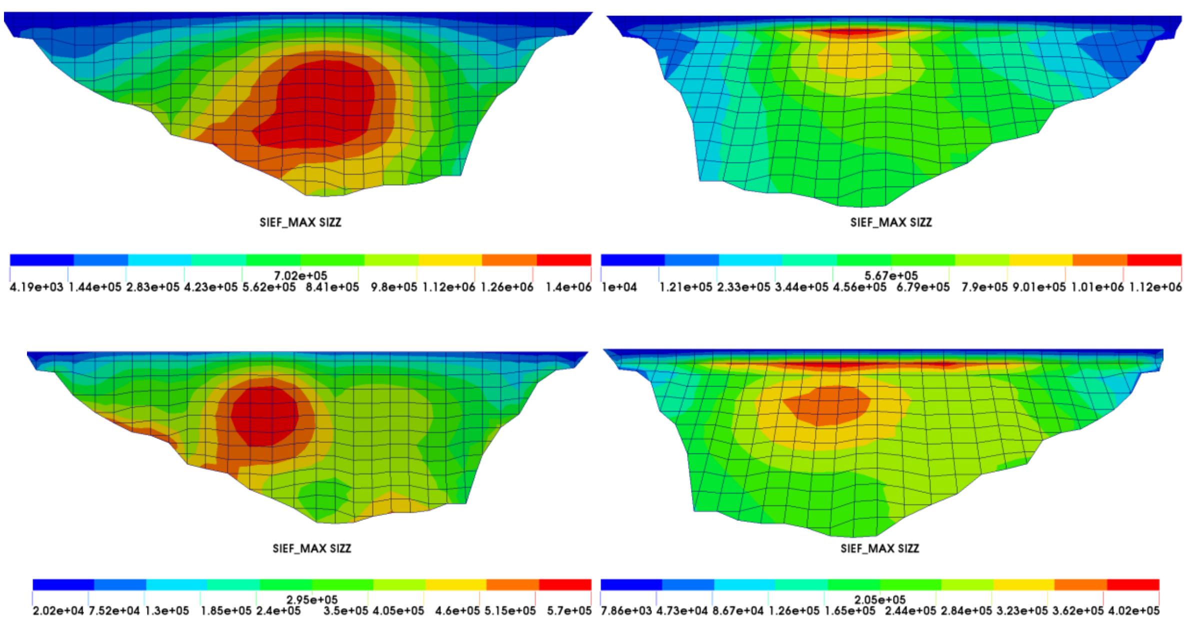

Fig. 10 - vertical tensile stresses on the upstream (left) and downstream (right) face of the gravity dam with massless/added masses (top) and VSB+fluid approach (bottom)

Fig. 10 compares the maximal vertical dynamic stresses (without static) on the upstream and downstream faces of the gravity dam during the earthquake considered for both approaches proposed. Dynamic stresses computed with the conventional approach are almost twice in average the computed stresses by the improved model.

6. 3D Application on the arch dam

Since the mechanical behaviour of an arch dam is strongly different than the behaviour of a gravity dam, the same type of analysis are lead on a 150 m high arch dam with a crest of more than 350 m long, in order to evaluate the numerical approaches in such a case.

6.1. Earthquake and recording devices

Accelerometers are distributed on the dam (Fig. 11). For the rest of the study, it should be noted that: X is the river direction, Y the bank to bank direction and Z the vertical direction. These devices recorded in the end of an earthquake which occurred off the coast Japan in the Sea of Japan with a high magnitude, on March, the 25th, 2007.

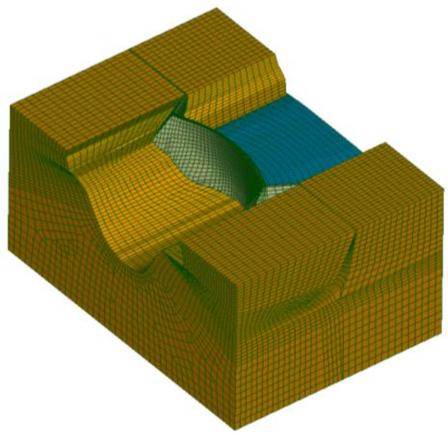

Fig. 11 - Mesh of the arch dam

6.2. Presentation of the 3D model of the arch dam

In order to evaluate the response of the viscous-spring boundary / fluid potential model in the case of an arch dam, the dynamic linear analysis is performed with the mesh presented in Fig. 11. Results from the massless foundation/Westergaard added masses approach are also presented for comparison. The maximal size of each element is around 20 m.

Earthquake records from the G2 sensor (in the right bank of the dam) are considered as input for the analyses. The response of the numerical analyses will mainly be evaluated by comparison of the recorded dam response at the crest of the dam, at the T1 sensor.

The following mechanical properties are taken into account: $E_{concrete}$= 30000 MPa, E_{rock} = 20000 MPa.

6.3. Massless foundation and added masses approach

First, a conventional analysis is provided considering the foundation massless and the Westergaard added masses to take into account fluid-structure interaction. A 5% Rayleigh damping (adjusted at the frequencies 3 and 13 Hz) is considered for the concrete. Fig. 12 compares the recorded and computed acceleration (in the frequency domain) at the crest and at the right bank of the dam, where the input is coming from.

This approach leads to rather good results in comparison with the record, particularly in the river direction for the first eigenmode of the dam. But it is also interesting to note that the FE model provides some peaks that do not appear in the records (around 5-6 Hz in every direction for example).

6.4. Viscous-spring boundary model and potential fluid approach

Considering the results shown in the previous analyses with the VSB model, 1% concrete damping is taking into account in this approach, considering that this model introduces additional damping from the wave radiation at the boundaries.

The introduction of the viscous-spring boundary model in the FE analyses brings first improvements of the results:

- The coherence between recorded and computed acceleration is good in the right bank. There is no need of adapting the input data using deconvolution
- The overestimated peak between 5 and 6 Hz are no present anymore
- The results is slightly overestimated at the first eigenmode around 2 Hz in the river direction but still underestimated it in the lateral direction.

6.5. Evaluation of the damping

As previously done §3.4, and in order to evaluate the damping introduced by the new soil-structure in the FE analyses of the arch dam, transfer functions are computed between the crest of the dam and the input (as done in §3.4) for the VSB/added-masses and the VSB/fluid with no concrete damping. The transfer functions are shown in Fig. 14.

Using the half-power bandwidth method, the damping introduced by the absorbing boundaries in the foundation goes from 3% for the first peak to 1Hz for higher frequencies. That shows that in the case of the arch dam, damping coming from the soil-structure effect is of less importance than for the gravity dam (around 10%).

6.6. Comparison of the stress results

Fig. 15 compares the maximum vertical and principal dynamic stresses (without static) on the upstream face of the arch dam dam during the earthquake considered for both approaches proposed. In comparison with the gravity dam's results, there are not so big differences between the approaches for the vertical stresses. In the case of the maximum tensile stresses, which mainly occur in the crest's centre of the dam, simplified analysis leads to an overestimation of almost twice compare to the most complex analysis.

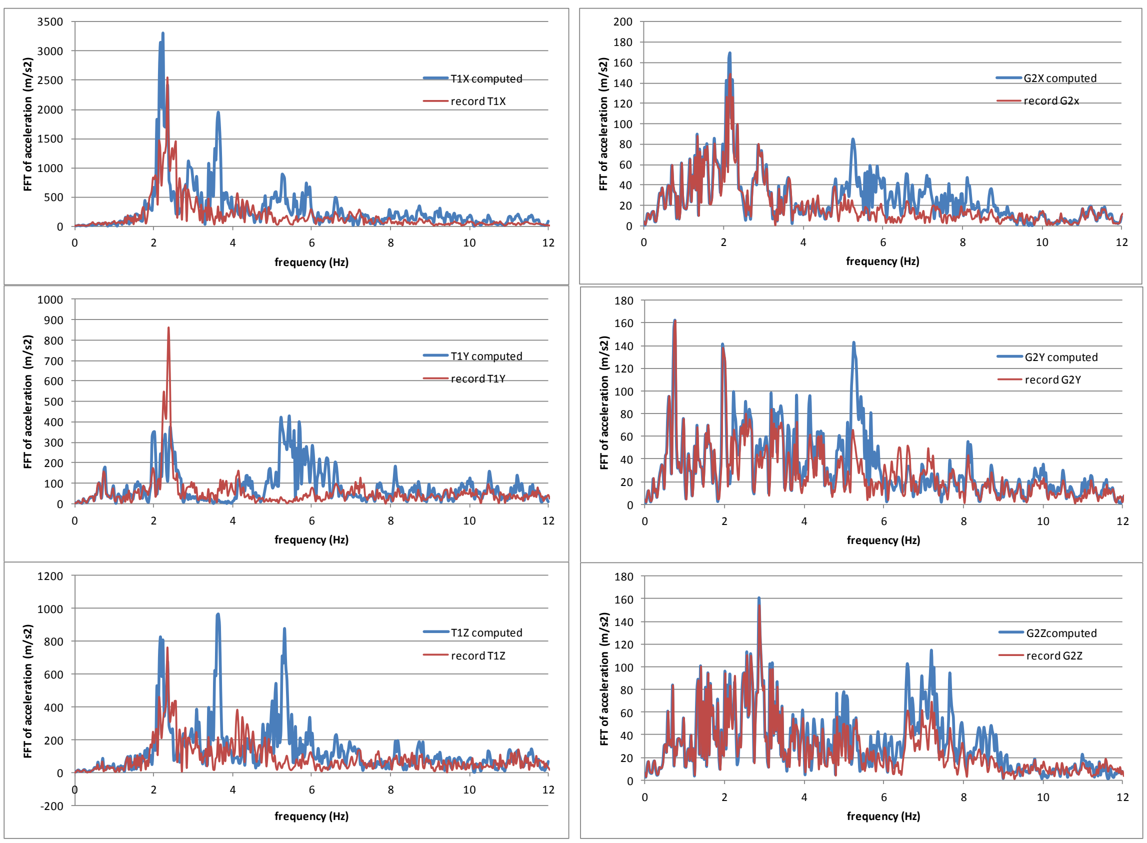

Fig. 12 – Massless added-mass, comparison of the FFT of the horizontal acceleration,
T1 sensor (left) and G2 sensor (right), 3 directions u/s (top), dam axis (middle), vertical (bottom)

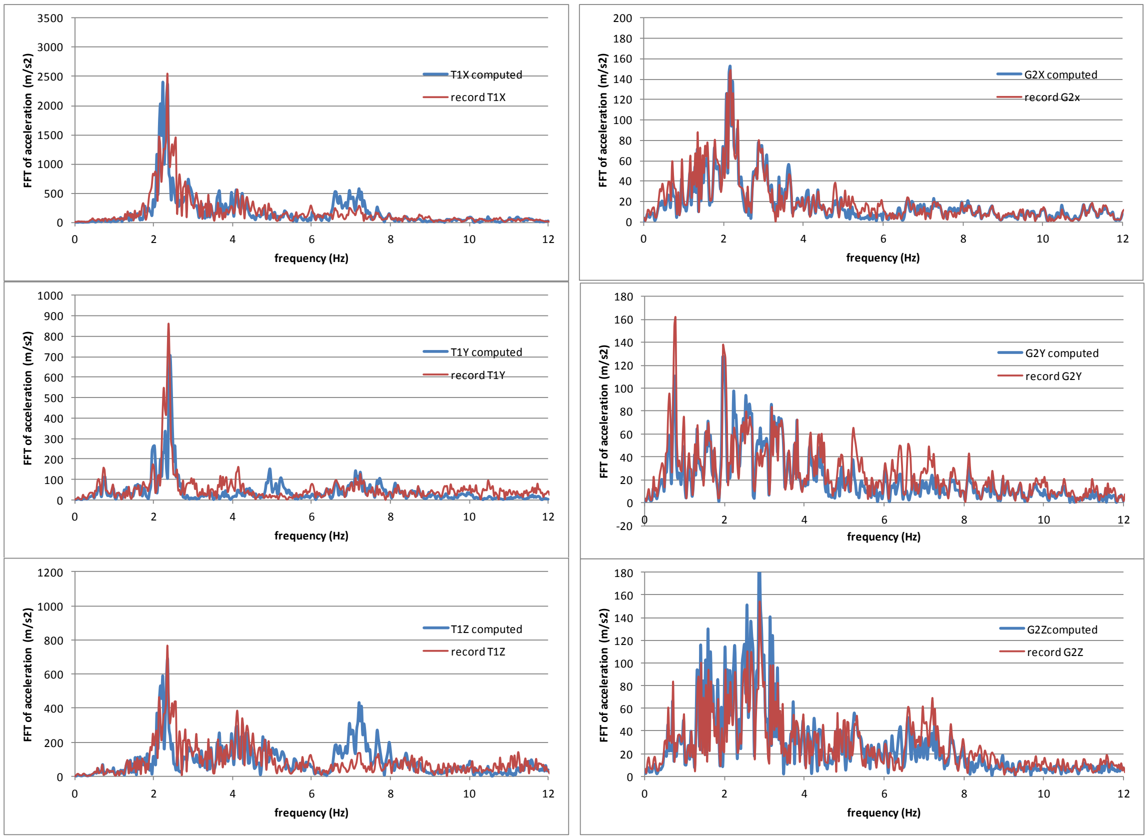

Fig. 13 - VSB/fluid approach, comparison of the FFT of the horizontal acceleration,
T1 sensor (left) and G2 sensor (right), 3 directions u/s (top), dam axis (middle), vertical (bottom)

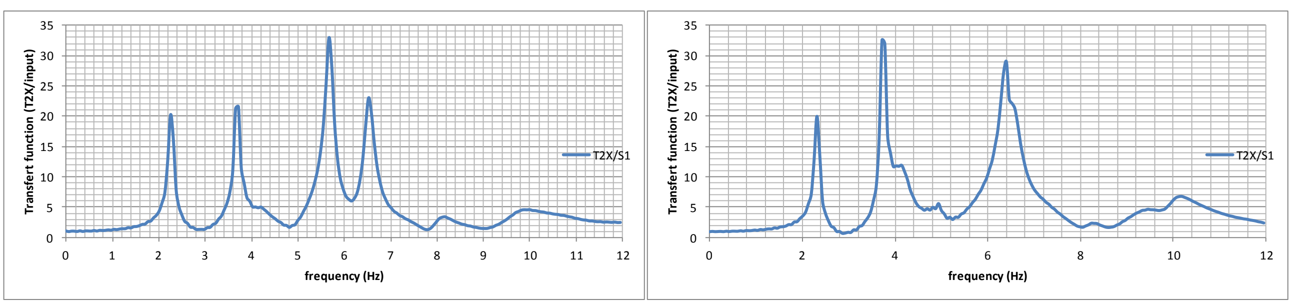

Fig. 14 –Transfer function : VSB and added masses (left), VSB and potential fluid approach (right)

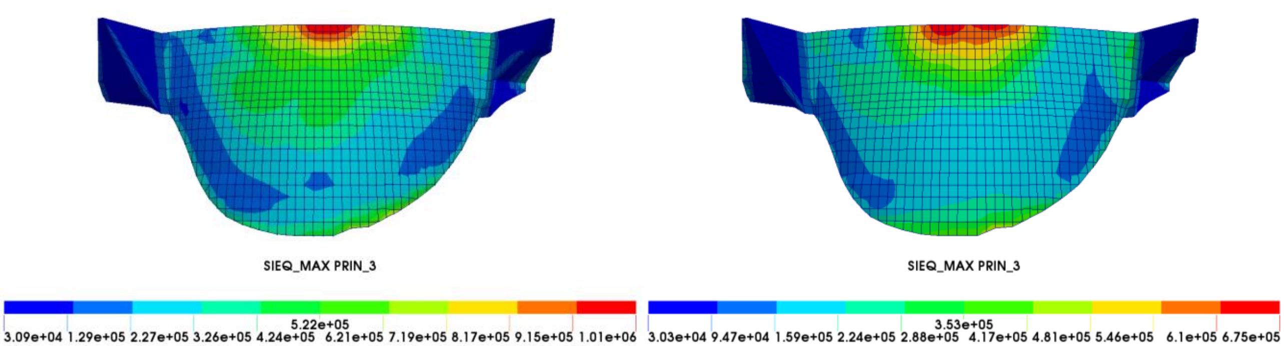

Fig. 15- Principal tension stresses on the upstream face of the arch dam with massless/added masses (left) and VSB+potential fluid (right) approaches

7. Conclusion

This paper presents comparisons between recorded earthquake in Japan, on a gravity dam and an arch dam and FE analyses performed with different approaches in 2D and 3D: conventional analyses with massless foundation / Westergaard added masses are carried out, but also more accurate analyses with better soil-structure and fluid-structure interaction considering viscous-spring-boundaries and potential base fluid finite-element. Theses finite-element models have been based on the bibliography [1], [2], [3] and validated on test cases.

Comparisons between FE analyses and records confirm that the conventional massless foundation/added masses approaches with 5% concrete damping greatly overestimates the response of the dam, particularly in the case of gravity dams. The use of viscous-spring boundaries in the foundation (with its masse) and potential based fluid finite element to represent soil-fluid-structure interaction leads to very good results compare to the earthquake records on dams. With such method, a low damping value of the concrete (probably between 1 to 2-3 %) seems more adequate for low intensity earthquake, considering that geometrical damping introduced by the absorbing boundaries already increases the global damping of the FE model.

It seems also important to remind that in the case of more complexes models introducing the input as wave propagation through the foundation, there might be a need of deconvolution process in 3D analyses to be sure that the input earthquake is correctly applied at the feet of the dam.

8. Acknowledgements

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