Earthquake Records on Concrete Dams in Japan: Comparison with Finite-Element Analyses

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Abstract

From 2014 to 2016, EDF was part of the cooperation between French (CFBR) and Japanese (JCOLD) committees on Large Dams occurred on the subject of dam's behavior under earthquake. In Japan, seismic recordings have been conducted on existing dams and JCOLD released in 2014 an update of its databases of earthquake recordings on dams among them 135 gravity dams and 22 arch dams. The dynamic responses of gravity and arch dams are simulated by finite-element analyses using data recorded at the foundation and the responses are compared to the data recorded at sensor located at the dam's crest. Comparisons between analyses and records confirm that the conventional massless foundation/added masses approaches with 5% concrete damping greatly overestimates the response of concrete dam, particularly in the case of gravity dams. The use of more advanced models taking into account the mass of the foundation, viscous-spring boundary input model and potential-based fluid finite elements with absorptive boundaries leads to more adequate values.

Keywords: Japan, Concrete, Earthquake, Analysis, Records.

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.

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.a.i.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 1.a.i.2 and 1.a.i.3, and briefly summarized in Figure 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.

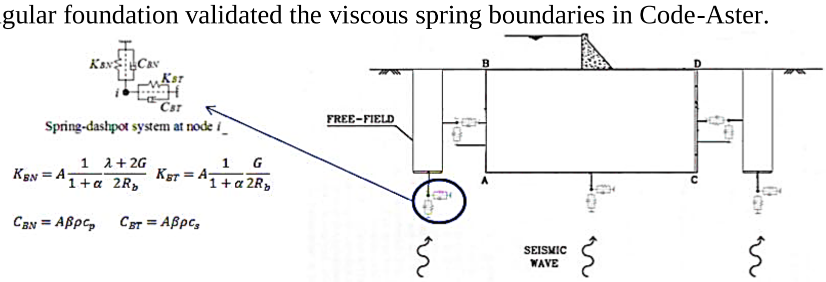

Figure 1: Viscous spring boundary model

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 3-directionnal sensor. 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 Figure 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.

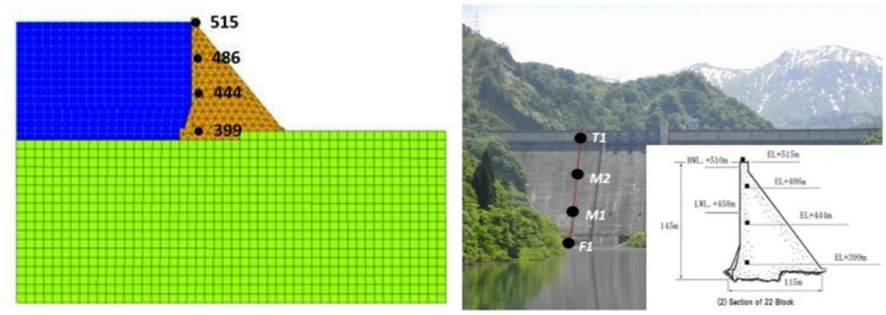

Figure 2 Geometry of the 2D model compare to the gravity dam

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.

Figure 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 (Figure 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).

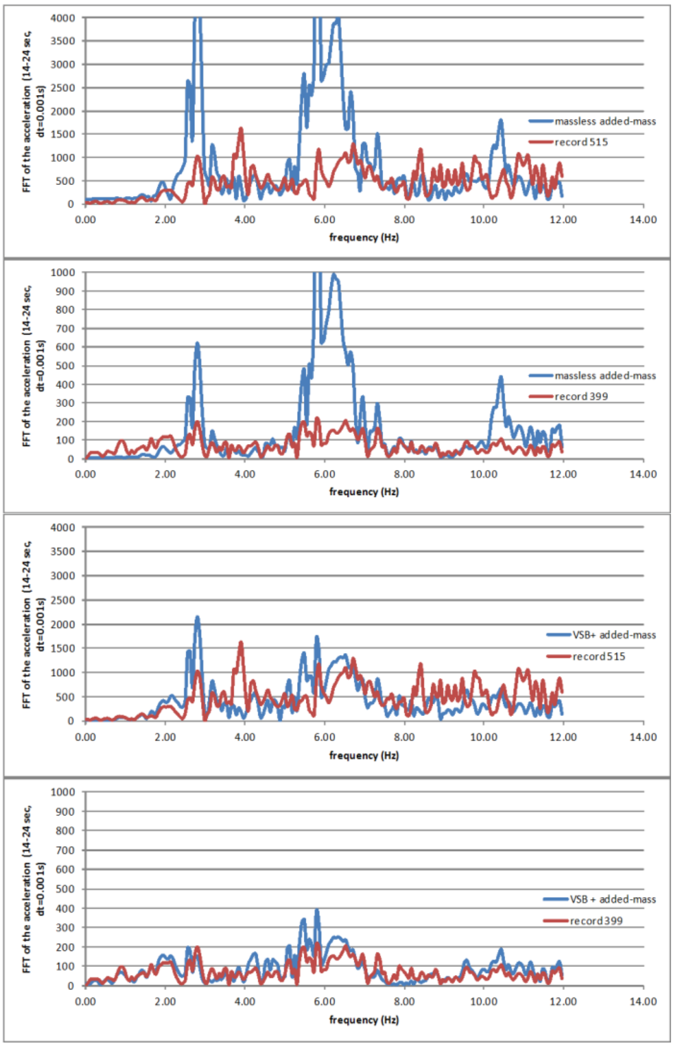

Figure 3comparison of the FFT of the horizontal acceleration, recorded vs computed at the crest (top) and bottom of the dam (bottom) for Massless / added-mass model (left) and VSB / potential fluid model (right),

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 are computed (Figure 4) between the crest of the dam and the input (in that specific case, a white noise is used) in the following case :

- 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 (Figure 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.

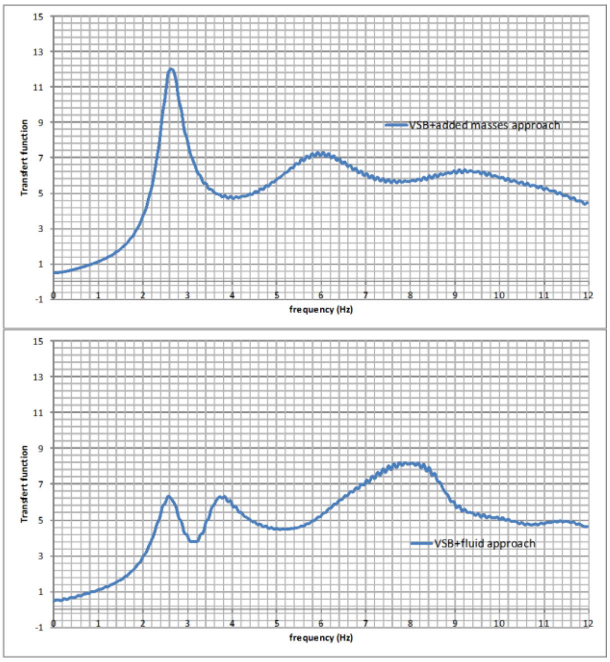

Figure 4. Transfer function: VSB/added masses (left) and VSB/fluid approach (right)

4. 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.

4.1 Earthquake and recording devices

Accelerometers are distributed on the dam (Figure 5). 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.

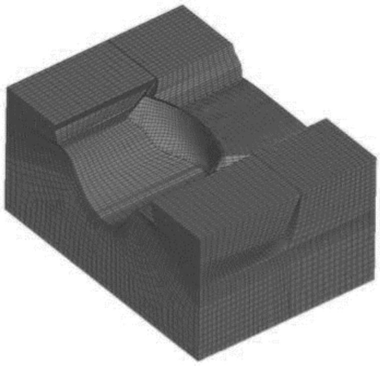

Figure 5 Mesh of the arch dam

4.2. 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 Figure 5. 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.

4.3. 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. Figure 6 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).

4.4. 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 (Figure 7). 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 are slightly overestimated at the first eigenmode around 2 Hz in the river direction but still underestimated it in the lateral direction.

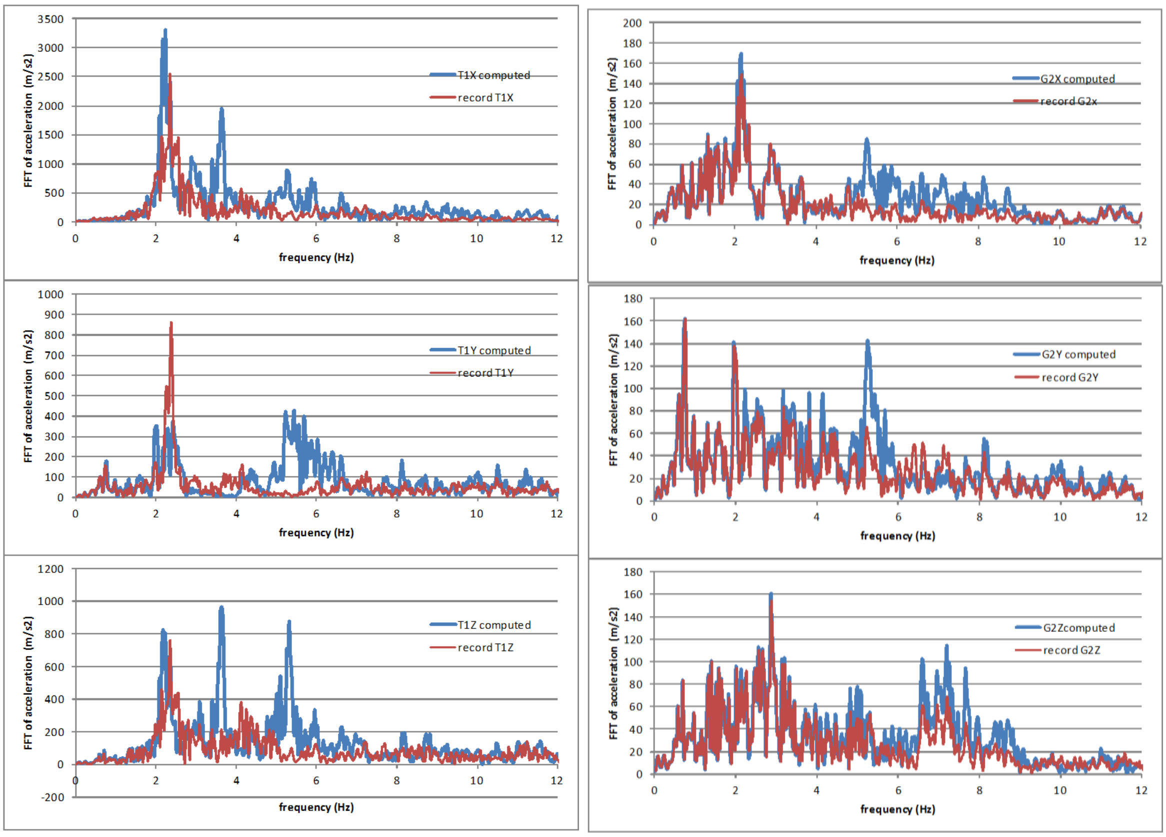

Figure 6. Massless added-mass, comparison of the FFT of the horizontal acceleration, T1 sensor (left) and G2 sensor (right), 3 directions u/s (top), dam axis (middle), vertical (bottom)

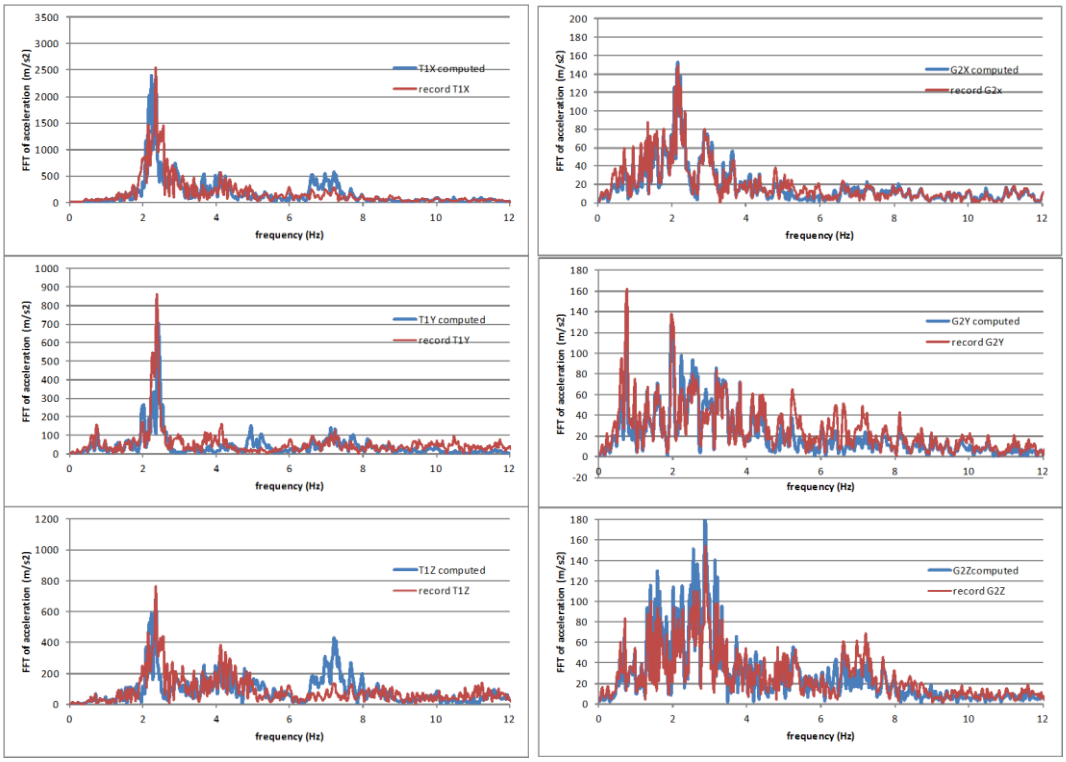

Figure 7 VSB/fluid approach, comparison of the FFT of the horizontal acceleration, T1 sensor (left) and G2 sensor (right), 3 directions u/s (top), dam axis (middle), vertical (bottom)

4.5. EVALUATION OF THE DAMPING

As previously done, 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 for the VSB/added-masses and the VSB/fluid with no concrete damping. The transfer functions are shown in Figure 8.

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%).

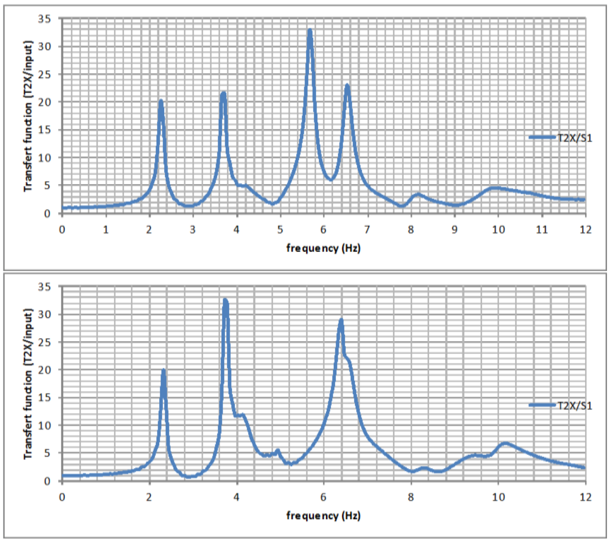

Figure 8. Transfer function: VSB and added masses (left), VSB and potential fluid approach (right)

5. CONCLUSIONS

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.a.i.1, 1.a.i.2, 1.a.i.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.

6. ACKNOWLEDGEMENTS

The study conducted in this paper was made possible by a collaboration between the CFBR (Comité Français des Barrages et Réservoirs) and the JCOLD (Japanese Commission on Large Dams) that took place between 2014 and 2016.

The authors thank the JCOLD, J-Power and Kepco which provided the recorded data, plans and sensor’s layout used in this study.

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