



## ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF DAMPING IN ARCH DAMS BASED ON RECORDED EARTHQUAKES

Jean PROULX<sup>1</sup>, Georges R. DARBRE<sup>2</sup> and Nathalie KAMILERIS<sup>3</sup>

### SUMMARY

The earthquake behaviour of three large dams is investigated with an emphasis on damping representation in seismic analyses. Three-dimensional numerical models were prepared for the dam-reservoir-foundation systems and these models were calibrated on the basis of previous, extensive *in-situ* forced- and ambient-vibration dynamic tests. Earthquakes that occurred in the vicinity of the dams were recorded by accelerographs installed at various locations inside the structures and the foundation rock. The recorded free-field ground-motions were then used as inputs to the models and the acceleration responses computed with two different dam-foundation interaction models, i.e. a massless foundation model and an energy-dissipating foundation model (water compressibility is taken into account in both models). The calculated dam motions are compared to the recorded ones and the damping values are varied until a satisfactory match between both is obtained.

### INTRODUCTION

When faced with earthquake-safety evaluations of large dams, engineers must often carry out complete dynamic analyses, taking into consideration dam-reservoir-foundation interaction. One of the difficulties inherent to this process is the selection of proper modeling parameters, such as the concrete modulus and damping; energy dissipation in the upstream direction (wave propagation) and on the reservoir bottom and sides (wave absorption); and energy dissipation in the foundation (material and radiation damping). These parameters can be investigated using actual recorded data on selected dams. Three-dimensional finite-element models can be calibrated by comparing the computed responses to the recorded ones. This paper presents such an investigation, in which three large instrumented arch dams were investigated.

---

<sup>1</sup> Professor, Department of civil engineering, Faculty of engineering, University of Sherbrooke, Sherbrooke, Canada. E-mail: Jean.Proulx@USherbrooke.ca

<sup>2</sup> Safety of Dams, Federal Office for Water and Geology, Bienne, Switzerland.  
E-mail: Georges.Darbre@bwg.admin.ch

<sup>3</sup> Master student, Department of civil engineering, Faculty of engineering, University of Sherbrooke, Sherbrooke, Canada. E-mail: Nathalie.Kamileris@USherbrooke.ca

The Swiss Federal Office for Water and Geology (FOWG) has been involved in long-term research projects on the dynamic behavior of dams since the early 90s. This involved the instrumentation of several large dams with strong-motion sensors [1] and setting up a series of ambient [2, 3] and forced-vibration [4] testing programs. These investigations were carried out with the objective of providing a better understanding of the earthquake behavior of dams and of the relevant modeling requirements. In this respect, one key aspect is the amount of damping that needs to be introduced into finite-element models in the course of seismic safety evaluations.

In the following sections, we address this issue by comparing recorded and computed earthquake motions at three arch dams. The acceleration motions are computed with two different approaches, the differences lying in the way the foundation is modeled.

## INSTRUMENTED ARCH DAMS

### Emosson

The 180-m Emosson dam impounds a  $225 \times 10^6 \text{ m}^3$  reservoir. Completed in 1974, this double-curvature dam with crest length of 550 m consists of 39 blocks with nine inspection galleries. The crest width is 9 m and varies from 35 to 50 m at the base. It is not symmetrical as it includes a gravity-type spillway dam on the right abutment.

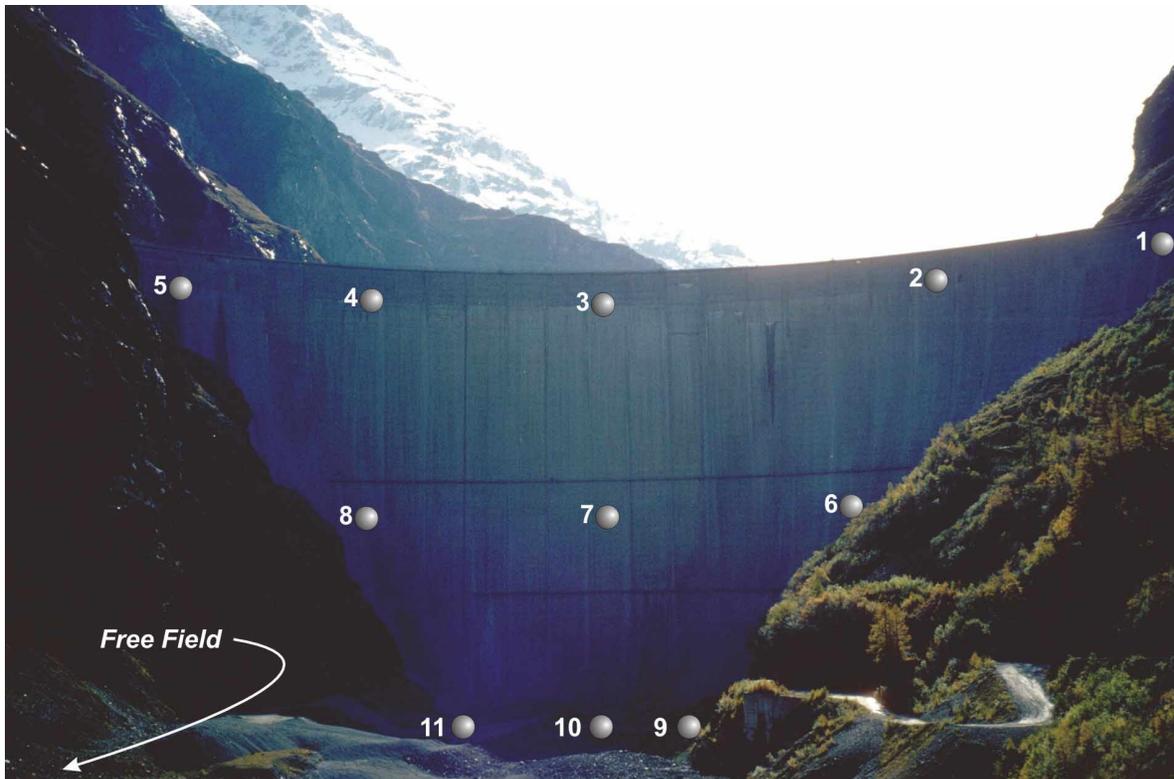
Figure 1 shows an aerial view of the dam and full reservoir together with the location of the accelerographs. The top three instruments (positions 1 to 3) are located in the upper gallery 5 m below the crest, and a fourth one at the base (position 4). An additional free-field instrument is located 2 km downstream. These were triggered by the small Sembrancher earthquake ( $M=3.6$ ), which occurred 10 km away from the dam on February 23, 2001.



Figure 1: Emosson arch dam with accelerograph locations

### Mauvoisin

The 250-m high Mauvoisin dam (currently one of the top three tallest in the world) was completed in 1957 and heightened in 1991. It has 28 blocks for a total crest length of 520 m and a reservoir capacity of  $200 \times 10^6 \text{ m}^3$ . The width is 12 m at the crest and 54 m at the base. The dam is pictured in Figure 2, together with the location of the accelerographs. The top five instruments (positions 1 to 5) are located inside the upper gallery, 14 m below the crest. Three additional ones are located at mid-height (positions 6 to 8), three others at base elevation (9 to 11), and one in the free-field 600 m downstream. All instruments registered the Valpelline earthquake ( $M=4.6$ ) on March 31 1996, which occurred 13 km away from the dam.



**Figure 2: Mauvoisin arch dam with accelerograph locations**

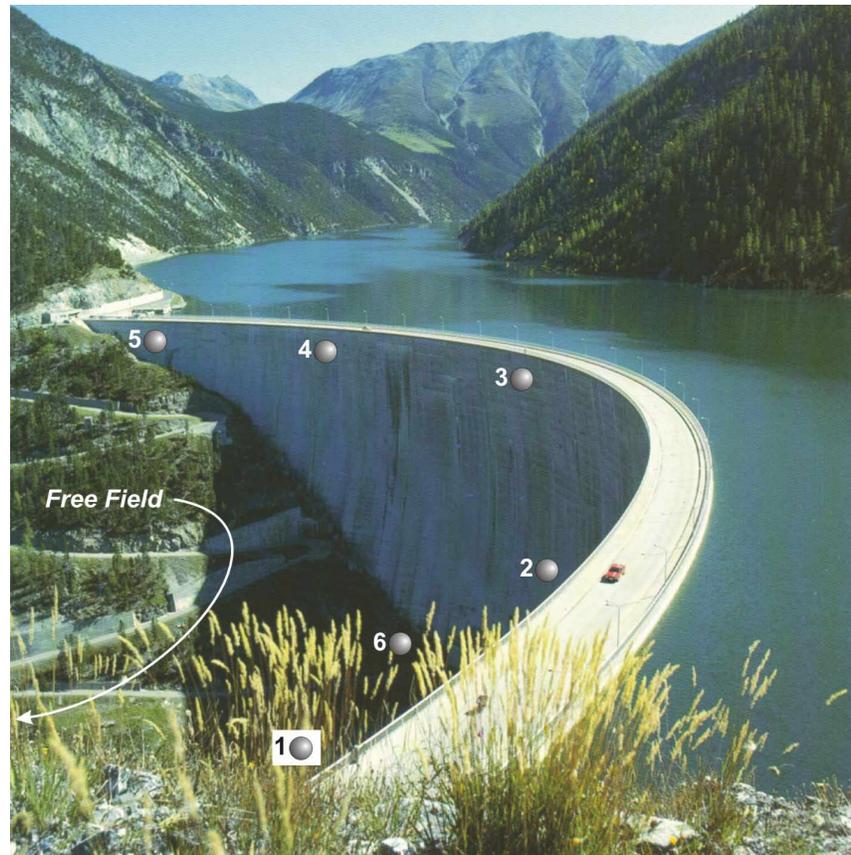
### Punt-dal-Gall

The 130-m high Punt-dal-Gall dam was completed in 1968. It has 30 blocks for a crest length of 540 m. The  $165 \times 10^6 \text{ m}^3$  reservoir has an irregular shape with two “branches” extending in the Southeast and Southwest directions. Figure 3 shows an upstream view of the dam, together with the location of the accelerographs. The top five instruments (positions 1 to 5) are located inside the upper gallery, with two additional ones placed at the base and downstream (free-field), respectively. The Bormio earthquake ( $M=4.9$ ), which occurred 12 km away from the dam, was recorded on December 29, 1999.

## FINITE-ELEMENT MODELING PROCEDURE

Three-dimensional finite-element models were developed for the three dams, including reservoirs and foundations. The geometric features were prepared with the help of FEMAP [5], a specialized tool for pre and post processing. Figure 4 shows the model for Punt-Dal-Gall as an example. The earthquake response calculations were first carried out with EACD-3D [6, 7], a specialized tool that accounts for dynamic dam-

reservoir interaction. The program also considers rock flexibility through a massless foundation model. In a second phase, the responses were obtained with the EACD-3D-96 [8] program, which includes an energy dissipating foundation model. This is achieved by computing a frequency-dependant impedance matrix for the foundation media [8, 9], which is a time-consuming process but leads to a more realistic damping idealization.



**Figure 3: Punt-Dal-Gall arch dam with accelerograph locations**

#### **Use of full-scale dynamic tests results for model calibration**

The model properties were calibrated from ambient- and forced-vibration tests that had been performed earlier [2, 3, 4]. In the case of the Mauvoisin dam, ambient-vibration measurements were obtained twice daily during a six-month period, during a testing program aimed at evaluating the effects of the reservoir level on the resonant frequencies. At Punt-Dal-Gall, three series of ambient-vibration tests were completed for three different water levels in the reservoir.

In the case of Emosson dam, an eccentric mass shaker was used to excite the structure and to obtain complete frequency responses in the structure as well as in the reservoir, for four different water levels. This type of tests is more involved than ambient vibration tests, but generally yields “cleaner” frequency response curves and a better estimate of the overall dam-reservoir-foundation system damping.

Finite-element models were used to compute frequency responses for the dam-reservoir-foundation system, using a modified version of EACD-3D [4]. These responses were then compared to the modal properties extracted from the vibration measurements to obtain the material properties and damping values listed in Table 1. In particular, this calibration process lead to values of 2 to 3% of critical damping for the dam concrete.

**Table 1: Model properties**

Properties	Emosson	Mauvoisin	Punt-dal-Gall
$E_c$ , Dam stiffness modulus, range	29 – 37 GPa <sup>(1)</sup>	29 – 36 GPa	30 – 32.5 GPa
$E_c$ , Dam stiffness modulus, final value	30.9 GPa <sup>(2)</sup>	36 GPa <sup>(3, 4)</sup>	32.5 GPa <sup>(3)</sup>
$\nu_c$ , Concrete Poisson's ratio	0.2	0.167	0.2
$\rho_c$ , Concrete unit mass	2400 kg/m <sup>3</sup>	2400 kg/m <sup>3</sup>	2400 kg/m <sup>3</sup>
$E_r$ , Foundation stiffness modulus, range	45 – 72 GPa <sup>(1)</sup>	18 – 72 GPa	18 – 175 GPa
$E_r$ , Foundation stiffness modulus, final value	70.6 GPa <sup>(2)</sup>	72 GPa <sup>(3)</sup>	75 GPa <sup>(3)</sup>
$\nu_r$ , Foundation Poisson's ratio	0.25	0.25	0.25
$\alpha$ , wave reflection coefficient	0.925 <sup>(2)</sup>	0.9	0.9
$\xi_c$ , damping in dam	2 – 3 % <sup>(2)</sup>	2 – 3 %	2 – 3 %
$\xi_{total}$ , overall required damping	15 %	8 %	8 %

Notes:

(1): From *in-situ* core sample tests during the construction phase (Emosson)

(2): Values obtained from correlation with forced-vibration tests results (Emosson)

(3): Values obtained from correlation with ambient-vibration tests results (Mauvoisin and Punt-Dal-Gall)

(4): In the case of Mauvoisin, a lower value of 25 GPa was also used for the uppermost part of the crest, which was heightened by 12.5 m in 1991.

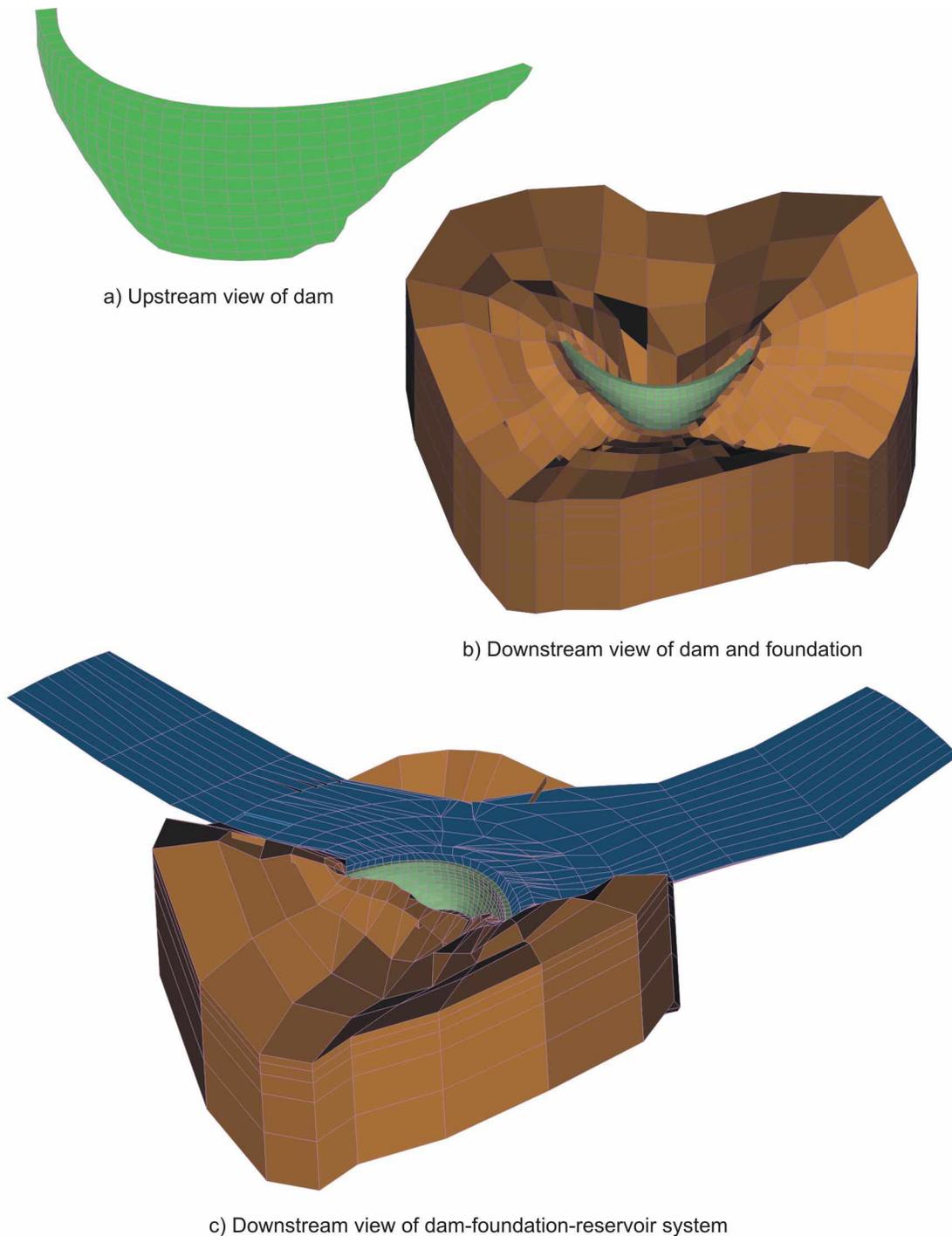
### Earthquake analysis

In order to evaluate the performance of these models, the motions recorded on the foundation rock in the free field (away from the dams) were used as input to the numerical models (with the exception of Emosson, where the base motion was used). The calculated accelerations responses in the dam were then compared with the recorded ones at the same locations. The water levels in the models were adjusted to the actual levels prevailing during the seismic events.

## EARTHQUAKE RESPONSES – MASSLESS FOUNDATION

Using the massless foundation approach, the procedure outlined above led to calculated response motions that were much too large in comparison with the observed ones. A representative example is given in Figure 5 for Mauvoisin dam. The figure shows the acceleration responses at the crest level, for the position of sensor #3 in Figure 2, in the stream direction. The response was calculated with 3% damping for the concrete and using the free-field Valpelline earthquake as input. These results were, at first, surprising, as the models had been calibrated on the basis of ambient- and forced-vibration tests. However, while such calibrations are accurate for stiffness, mass and density, this is less the case for energy-dissipation mechanisms.

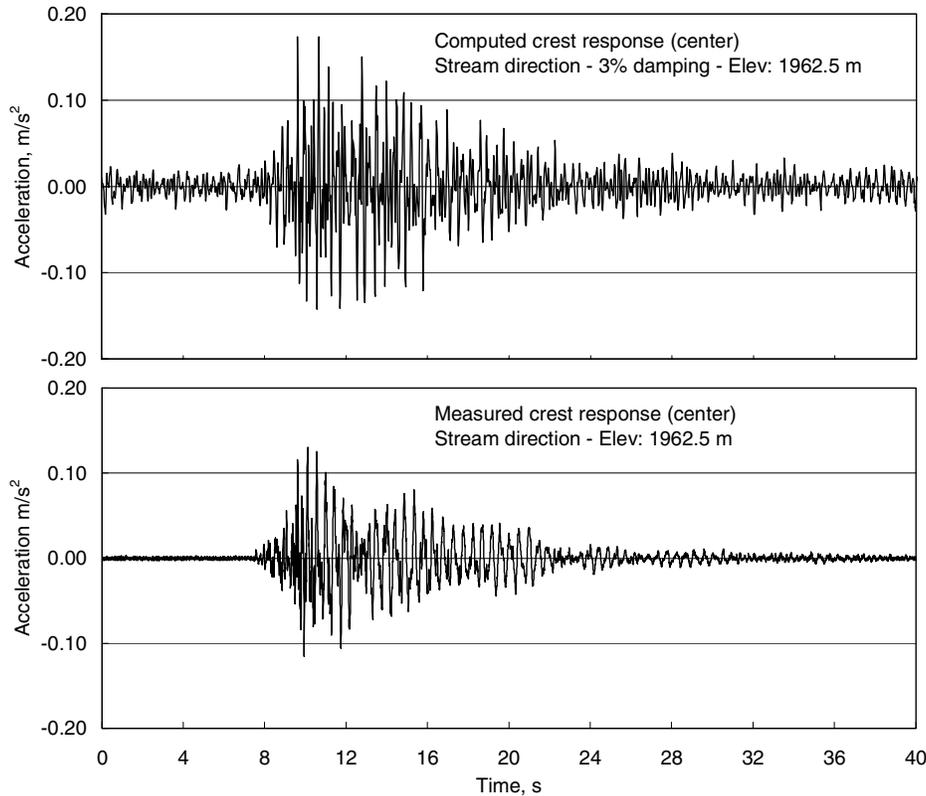
The massless approach does not provide for energy dissipation in the foundation media; its influence is only on the flexibility of the dam-reservoir-foundation system. The only model features that could influence energy dissipation (reservoir parameters and concrete damping) were then sequentially modified until a satisfactory agreement was obtained between the calculated and recorded earthquake responses. The results from this damping calibration are presented in Figures 6 to 9.



**Figure 4: Model of Punt-Dal-Gall arch dam**

**Calibrating the damping with the massless approach**

Changes in the reservoir geometry (upstream length) and boundary conditions affected the calculated responses only marginally and could not explain the observed differences. On the other hand, an increase in concrete damping significantly reduced the computed responses. To the authors' surprise, it was found that damping values of 15% of critical at Emosson, and 8% at Mauvoisin and Punt-dal-Gall needed to be introduced to obtain the sought agreement between calculated and recorded motions.



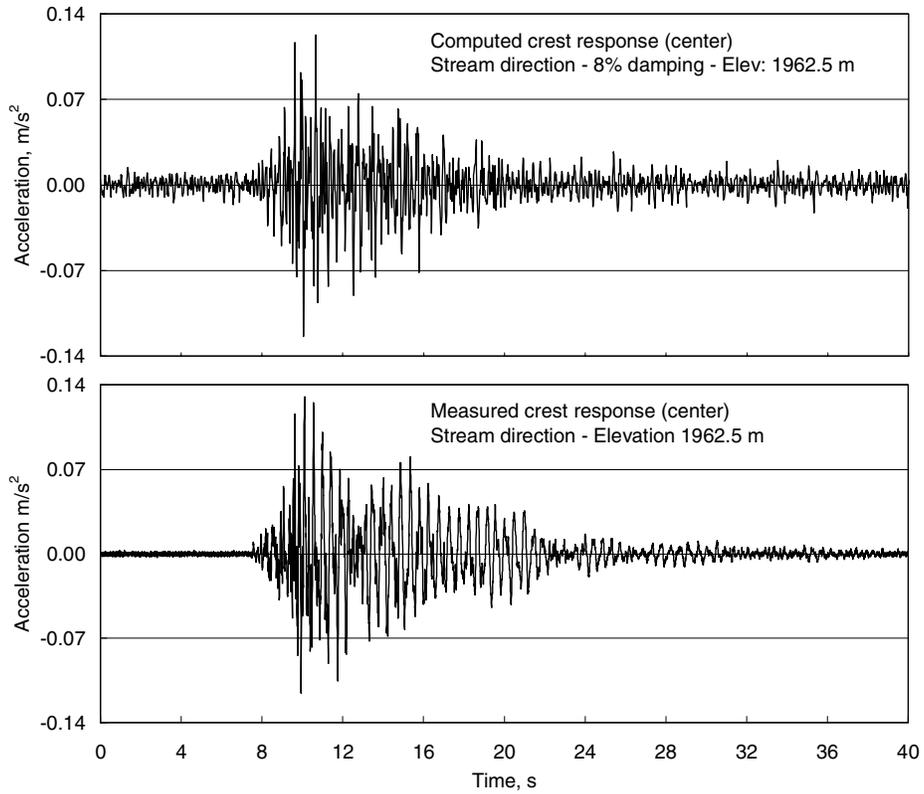
**Figure 5: Measured and computed crest responses at Mauvoisin (3% damping, model with massless foundation)**

The large damping requirements are illustrated in Figures 6 and 7, which are plotted for Mauvoisin dam. The responses shown are for the crest level at the center (sensor #3 in Figure 2) and quarter-point (sensor #4 in Figure 2), respectively, in the stream direction. Figure 8 shows these responses for the center position at the crest level for Eموsson dam (sensor #3, Figure 1); and Figure 9 illustrates the responses for the same position on Punt-Dal-Gall dam (sensor #3, Figure 3). Similar agreements were obtained with the same damping values at the other accelerograph locations and in all directions (stream, cross-stream and vertical).

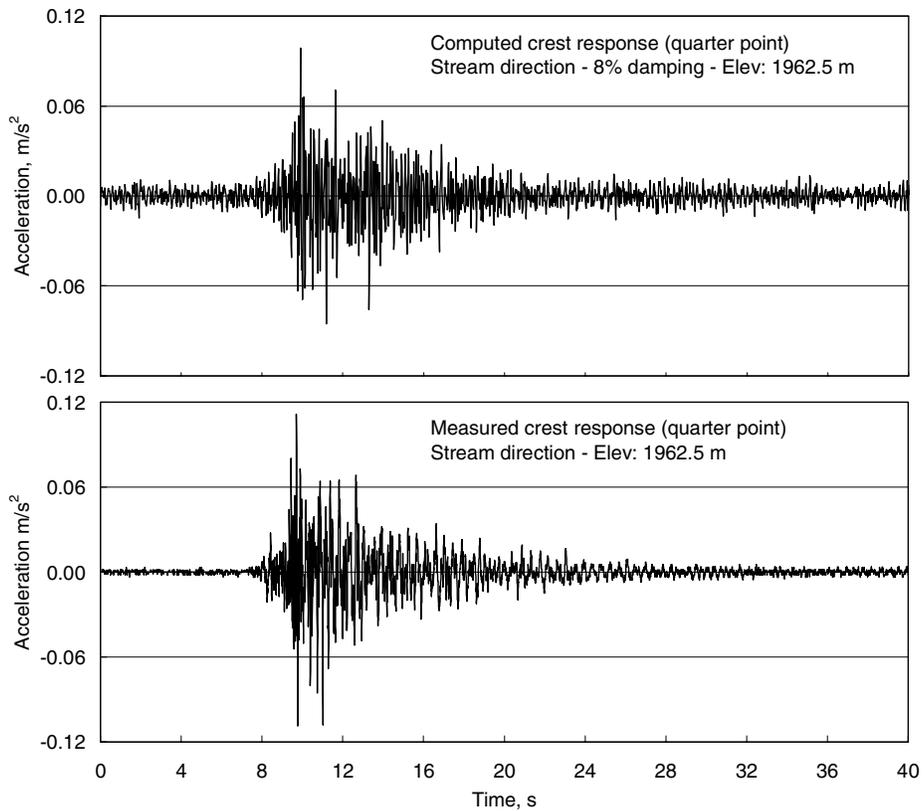
That such large damping values need to be introduced in the models is of utmost significance. It must be emphasized that these are “numerical” values and cannot be solely attributed to energy dissipation in the concrete. The possible sources for the differences between the adjusted concrete damping values (15% and 8%) and the 2 to 3% identified from forced-vibration tests are discussed in a following section.

### **EARTHQUAKE RESPONSES – ENERGY DISSIPATING FOUNDATION**

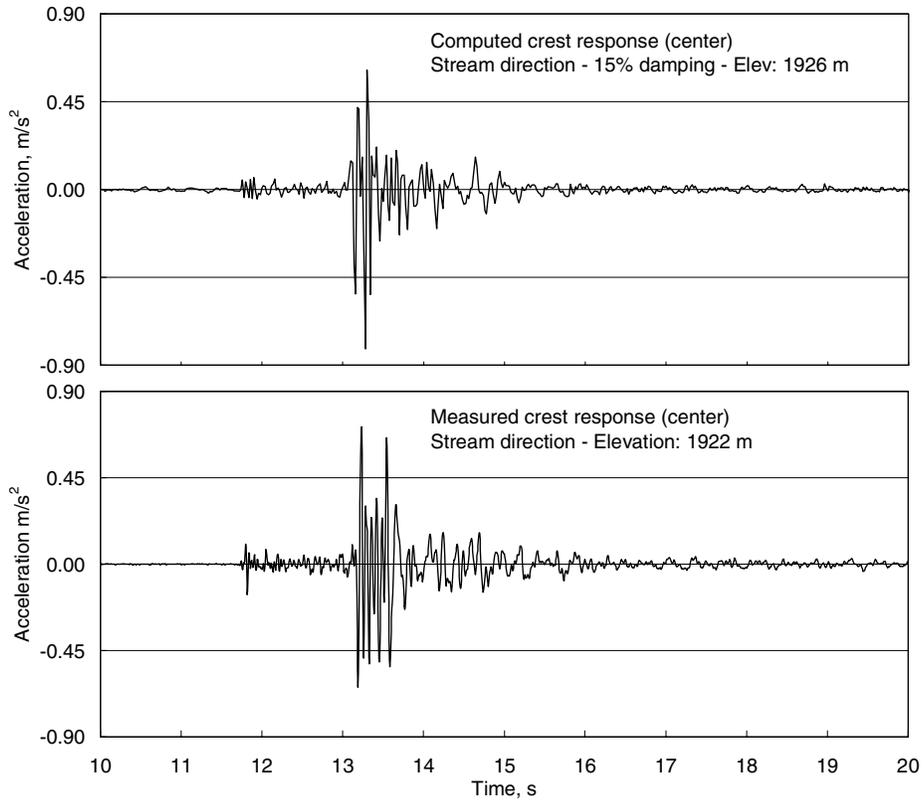
With the EACD-3D-96 program, the foundation is modeled with boundary elements instead of the three-dimensional solid elements that are depicted in Figure 4. The mass of the foundation rock and the foundation material and radiation damping effects are taken into account in the model [8, 9]. A dynamic impedance matrix is computed for a specified excitation frequency range (in our case, 0 to 25 Hz) and frequency increment. The boundary elements are placed at the dam-foundation interface, making the overall modeling procedure much faster. All other aspects of the program are similar to the EACD-3D program. As with the massless approach, the models were used to compute the system responses to the selected earthquake.



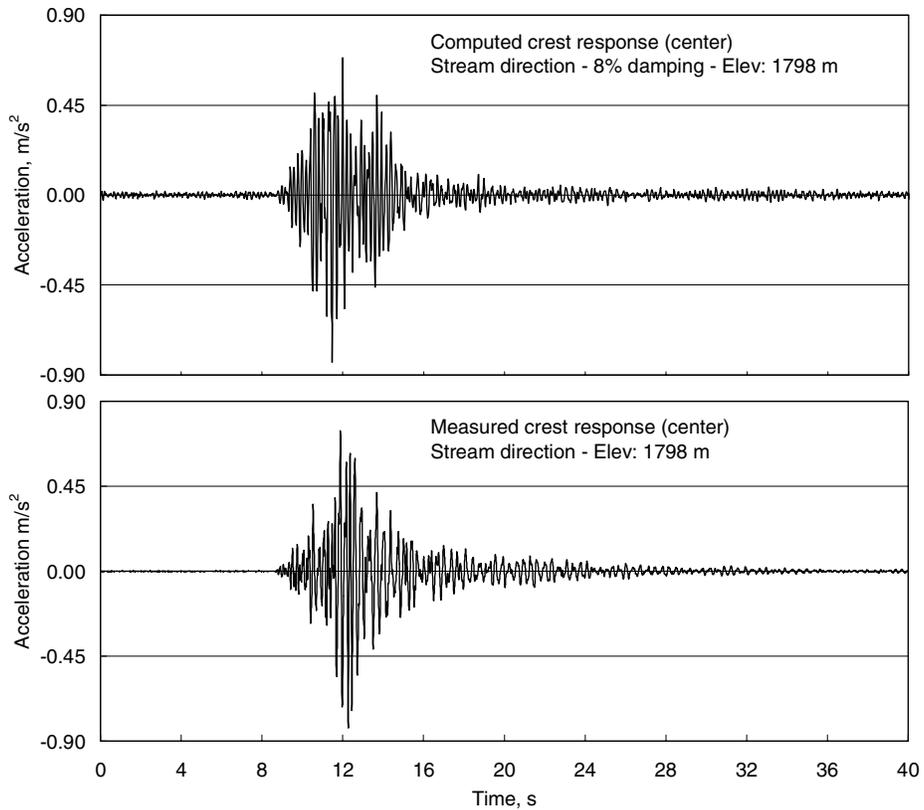
**Figure 6: Crest responses at Mauvoisin (center, 8% damping, massless foundation)**



**Figure 7: Crest responses at Mauvoisin (quarter-pt. 8% damping, massless foundation)**



**Figure 8: Crest responses at Emosson (15% damping, massless foundation)**



**Figure 9: Crest responses at Punt-Dal-Gall (8% damping, massless foundation)**

It is noted that the boundary element approach is very time-consuming. As the number of boundary element increases, computation time will also increase and the models therefore had to be reduced in size. For example, the Mauvoisin model, which had originally approximately 450 dam elements and 1700 foundation elements, was reduced to 35 dam elements and 14 boundary elements for the dam-rock interface. Even with this size reduction, the CPU time is still high: a PC-based version took 6 to 7 hours to compute the foundation impedance matrix on a 3GHz P4 computer.

The objective of this part of the study was to clarify the significance of foundation mass and damping (both material and radiation) in the calculated results. This is presented herein for the Mauvoisin dam.

### Mauvoisin dam results

When applicable, the model parameters were kept identical to the ones used with the massless approach. Table 2 lists the properties for the Mauvoisin model. The foundation damping properties were changed until a satisfactory match between observed and computed responses was reached (no change in concrete properties). Several foundation matrices were thus computed, using a range of 5 to 20% viscous damping for the foundation rock. Figure 10 shows the responses obtained for the crest level (center position, sensor#3 in Figure 2). The top two graphs illustrate the acceleration motions computed with a constant 3% damping ratio for the concrete, and with 5% and 20% in the foundation rock, respectively. As can be observed when comparing the top and bottom graphs, the response is largely overestimated with the 5% foundation damping model. When the damping is increased to 20%, the response is somewhat reduced, but still overestimated. An additional increase in damping is needed and this can be achieved by a substantial increase in the foundation damping (up to 40%) or a slight increase in the dam concrete damping. Clearly these values have no physical basis. It can thus be concluded that the origin of the large overestimate of dam response when using "realistic" values of material parameters in the massless-foundation model does not stem (solely) from foundation damping (material and radiation). This is discussed further below.

**Table 2: Model properties for Mauvoisin dam with the energy-dissipating foundation approach**

<b>Properties</b>	<b>Mauvoisin</b>
$E_c$ , Dam stiffness modulus	36 GPa <sup>(1)</sup>
$\nu_c$ , Concrete Poisson's ratio	0.167
$\rho_c$ , Concrete unit mass	2400 kg/m <sup>3</sup>
$\xi_c$ , damping in dam	3 %
$E_r$ , Foundation stiffness modulus	72 GPa <sup>(1)</sup>
$\nu_r$ , Foundation Poisson's ratio	0.25
$\rho_r$ , Foundation unit mass	2500 kg/m <sup>3</sup>
$\xi_r$ , damping in foundation, range	5 – 20 %
$\alpha$ , wave reflection coefficient	0.9

Note:

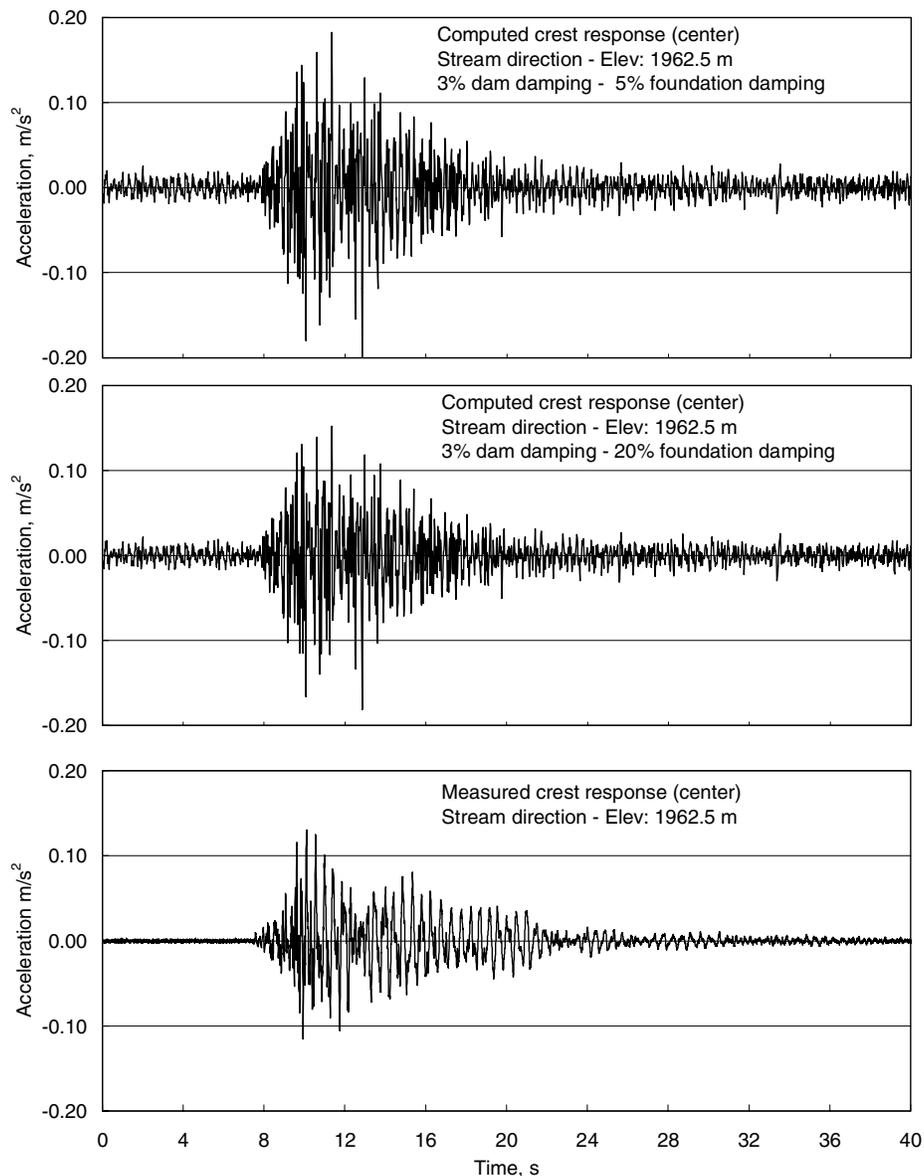
(1): Values calibrated from dynamic tests

## DISCUSSION ON DAMPING

### Damping sources

The damping values identified from forced-vibration tests already include the contribution of the dissipation of energy in the foundation by waves traveling towards infinity. The same holds true for energy dissipated within the foundation by material damping, although the levels of motions are larger during the recorded earthquakes. These energy-dissipating sources are accounted for with the boundary element approach, but are neglected with the massless foundation approach.

Some amount of energy is expected to be dissipated during large earthquake trough nonlinear behavior in the dam concrete itself. However, this cannot be the case at the level of motions recorded here in dams that are perfectly sound. Concrete damping can thus not be significantly different from the values identified from forced-vibration tests.



**Figure 10: Measured and computed crest response at Mauvoisin  
Energy dissipating foundation model**

### **Averaging effect**

With the massless approach, part of the additional damping introduced into the system accounts for the damping sources mentioned above. However, it is directly accounted for in the energy-dissipating foundation model; the response is however still grossly overestimated if no other energy dissipation is introduced.

It is believed that the additional damping required for both approaches is related to the averaging effect of the input motion along the canyon walls. This contribution to motion reduction can be attributed to different effects related to the way the earthquake waves propagate in the foundation and are affected by the canyon and the dam (motion incoherence and non uniformity, kinematic interaction).

It is recalled that in these analyses, the input motion is introduced uniformly along the outside boundaries of the models. This corresponds to the present state-of-the-art for the earthquake analysis of dams. Because of the averaging effect, the input motion to be used in the models should actually be “lower” than any point-motion recorded in the foundation. In the absence of proper account of such an averaging process, a match between recorded and computed dam motion can only be obtained by artificially increasing the overall damping as a substitute.

### **Difference in damping demands for individual dams**

For the massless approach, the difference in the required model, “numerical” damping at Emosson as compared to Mauvoisin and Punt-dal-Gall is striking. It was thought that the fact that the input used at Emosson was not a true free-field but the recorded ground motion at the foot of the dam, could explain this difference. This assumption was checked at Mauvoisin, where the recorded base motion was also used as an input to the model. However, this did not lead to a higher damping demand. At this stage, the difference in damping demands (Emosson vs. Mauvoisin and Punt-dal-Gall) cannot be explained.

## **CONCLUSIONS AND PRACTICAL IMPLICATIONS**

This paper has presented numerical analyses of the earthquake response of three large arch dams, based on seismic events that occurred in their vicinity. Three-dimensional numerical models were developed for the dams and calibrated with dynamic properties obtained from in-situ investigations that involved ambient- and forced-vibration measurements. The recorded free-field and base accelerations were used as input ground motions and the responses were computed at several dam locations and compared with the recorded ones. Two approaches were used: first a massless foundation with only flexibility effects, and then an energy-dissipating foundation model, accounting for material and radiation damping. With both methods, it was found that high damping values were needed in order to match the observed acceleration responses (8 to 15% in the dam concrete for the first approach; and more than 20% for the energy dissipating foundation model). This is believed to indirectly account for the averaging of the input earthquake motion, which is not directly modeled.

While more data are needed to sustain the use of high damping values in earthquake safety assessment of arch dams, the findings tend to indicate that current modeling practice may entail some amount of hidden conservatism. At the same time, it must be kept in mind that attention has been focused on motion responses in the paper. The same effects that can lead to motion averaging can also lead to differential abutment motions. Their occurrence would be detrimental to the state of stress in the dam and somewhat counterbalance the beneficial effect of the higher damping demand. It is therefore recommended to avoid increasing energy dissipation in safety evaluations of arch dams before this aspect is also investigated.

## ACKNOWLEDGEMENTS

The authors thank the Forces Motrices de Mauvoisin SA, Emosson SA and Engadiner Kraftwerke AG, for their support throughout the research project. The continuous monitoring system at Mauvoisin was installed by the Swiss Federal Laboratories for Materials (EMPA). The accelerograph arrays are operated by the Swiss Seismological Service. The forced-vibration tests at Emosson were carried out in collaboration with the Natural Sciences and Engineering Research Council of Canada, FOWG, EDF, Hydro-Québec and Emosson S.A. Ms. Nathalie Roy and Mr. Mathieu Primeau helped prepare the models of Mauvoisin and Punt-dal-Gall.

## REFERENCES

1. Darbre, G.R., De Smet C.A.M., and Kraemer, C. "Natural frequencies measured from ambient vibration response of the arch dam of Mauvoisin." *Earthquake Engineering and Structural Dynamics* 2000; 29: 577–586.
2. Darbre, G.R. "Strong-motion instrumentation of dams." *Earthquake Engineering and Structural Dynamic* 1995; 24: 1101–1111.
3. Darbre, G.R. and Proulx, J. "Continuous ambient-vibration monitoring of the arch dam of Mauvoisin." *Earthquake Engineering and Structural Dynamics* 2001; 31: 475–480.
4. Proulx, J., Paultre, P., Rheault, J., and Robert Y. "An experimental investigation of water level effects on the dynamic properties of a large arch dam." *Earthquake Engineering and Structural Dynamics* 2001; 30: 1147–1166.
5. Fok, K.L., Hall, J.F., and Chopra, A.K. "EACD-3D, A Computer Program for Three-Dimensional Earthquake Analysis of Concrete Dams." Report #UCB/EERC-86/09, University of California, Berkeley, California, July 1986.
6. Fok, K.L., and Chopra, A.K. "Earthquake Analysis and Response of Concrete Arch Dams." Report #UCB/EERC-85/07, University of California, Berkeley, Calif., July 1985.
7. FEMAP : Finite Element Modeling And Postprocessing. SDRC, Exton, PA.
8. Tan, H., and Chopra, A.K. "EACD-3D-96, A Computer Program for Three-Dimensional Earthquake Analysis of Concrete Dams." Report #UCB/SEMM-1996/06, Department of Civil and Environmental Engineering, University of California, Berkeley, California, 1996.
9. Tan, H., and Chopra, A.K. "Earthquake analysis of arch dams including dam-water-foundation rock interaction". *Earthquake Engineering and Structural Dynamics*, 1995; 24: 1453—1474.