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KEY PARAMETERS FOR SINGLE-INPUT EARTHQUAKE ANALYSIS OF ARCH DAMS

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ABSTRACT

In seismic safety analysis and for new constructions, the single-input method is still widely-used to carry out earthquake analysis of concrete dams. It is therefore of utmost importance for practicing engineers to be aware of the influence of each parameter when modeling dam-reservoir-foundation interaction. A long term experimental program was carried out by the Dams division of Swiss Energy, based on an extensive network of strong motion instruments located on several large concrete dams in Switzerland. Using the actual recordings of several small to moderate earthquakes for the past 15 years, as well as results from on-site ambient and forced vibrations tests, a reliable database was created for a few large arch dams. The data includes frequencies, modes shapes and damping values for low-level (linear) excitation and different water levels, as well as several acceleration recordings inside the dam, along the abutments and in a downstream location which can be considered as a free-field. A numerical parametric study was carried out with the 2008 version of EACD-3D, a state-of-the-art program that accounts for dam-reservoir-foundation interaction. Several finite element models were developed for large arch dams using “coarse”, intermediate and finer meshes for the dam and reservoir substructures (the foundation is modeled with boundary elements and includes material and radiation damping). Using the free-field recordings as single-input ground motion, computed accelerations amplitudes and frequency contents were compared to recorded values. The effect of model size, of dam and foundation stiffness and of the various sources of energy dissipation (including material and radiation damping) were investigated.

Introduction

It is now widely accepted that modeling the earthquake response of concrete dams requires an adequate representation not only of the dam itself but also of the reservoir and foundation substructures. State-of-the art three-dimensional finite element programs now include sophisticated models to account for dam-reservoir-foundation interaction (Chopra, 2008). The calibration of such programs and of their key parameters is best accomplished by comparing the computed responses to recorded data obtained from on-site investigation or, in the ideal case, during actual earthquakes.

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A large-scale experimental project on the dynamic response of large concrete dams was initiated in the 90s by the Dams division of Swiss Energy under the direction of Dr. Georges Darbre. Several of the world's largest concrete dams were equipped with networks of triaxial accelerographs strategically placed at several locations inside the dam galleries and in the foundation (Darbre, 1995). Among the instrumented structures are Mauvoisin (250-m arch dam with an 11-sensor configuration shown in Fig 1a), Emosson (180-m arch dam with a minimal 4-sensor configuration shown in Fig 1b) and Grande-Dixence (285-m gravity dam). This strong-motion network has been used for the past 15 years to record several small to moderate earthquakes that occurred in the vicinity of the dams. These recordings, combined with results from on-site investigations that included ambient and forced-vibration tests (Darbre & Proulx, 2001; Darbre *et al.* 2000; Proulx *et al.*, 2001), constitute a unique and reliable database for large concrete dams. The data includes acceleration recordings inside the dams, along the abutments (at several locations in the case of Mauvoisin dam) and in a downstream location which can be considered as a free-field. The project lead to the identification of the key parameters that are needed to calibrate the sophisticated earthquake analysis tools available today. These parameters include frequencies, modes shapes and damping values for low-level (linear) excitation obtained at different water levels.

Figure 1: Mauvoisin (left) and Emosson (right) arch dams
with approximate strong-motion sensor locations.

This paper discusses the influence of the modeling parameters for the earthquake analysis of arch dams using single-input motions obtained from recorded earthquake data. Using three-dimensional numerical models with properties extracted from on-site dynamic test results for a large arch dam in Switzerland, the computed accelerations are compared to recordings of moderate earthquakes. Model parameters for the dam (mesh size, stiffness, and damping) and foundation (damping) are discussed herein. Other important parameters related to the reservoir (geometry, water level, damping by wave propagation and absorption) were previously presented for the same dams and experimental database (Proulx *et al.*, 2004, 2006; Darbre & Proulx, 2001) and are also briefly summarized.

Single-input earthquake analysis

The numerical studies that were first carried-out using the recorded earthquake accelerations were based on so-called “single-input” models, using EACD-96 (Tan and Chopra, 1996), where a single acceleration time-history is used for the ground motion input. This time-history was usually provided by a sensor located in the valley some distance away from the dam. This approach has its limitations: it neglects the canyon effect (non simultaneous motions of the abutments) and it can lead in some cases to overestimated responses, resulting in artificially high damping values required to match the recorded accelerations (Proulx *et al.*, 2006). A multiple-input approach was recently developed by Wang and Chopra (2008) and implemented in the latest version of EACD, which now accounts for spatially-varying ground motion. Using this new program, the input motions could be interpolated from data recorded by sensors located along the abutments, for example. This more realistic approach is very promising, as it accounts for the canyon effect. The data required for multiple-input analysis (several free-field recordings along the canyon) is still very rare, as few dams have such a detailed array of motion sensors. The process of interpolation of recorded ground motion along the abutments is also quite complex. For these reasons, the single-input method is still widely-used in safety analysis and also for new projects. It is therefore of utmost importance for practicing engineers to be aware of the influence of each parameter when using the single-input approach in the context of seismic safety evaluation. These parameters and their effects on the earthquake response are discussed in the following sections.

Correlation study and influence of modeling parameters

Reservoir substructure – water level effects

Two ambient-vibration testing programs were completed at the Mauvoisin dam site to complement and corroborate with the experimental findings of the strong-motion network. Like many dams in the Alps, its reservoir goes through an annual filling cycle and reaches its maximum level in Sept./Oct. and its minimum levels in May/June. During the first program, seven series of ambient-vibration measurements were completed over a 16-month period, with varying water levels (Darbre, *et al*. 2000). The second program involved a continuous monitoring program over a 6-month period, using an automated system that was configured to record the accelerations inside the upper gallery, twice a day. The results from both programs are shown in Fig. 2, where the reservoir filling cycle is plotted over a cross-section of the dam, and the testing period is indicated in the left graph. The right graph shows the variation of the resonant frequencies for the first two modes as a function of water level. The data plotted also includes the frequencies extracted from earthquake accelerations recorded by the strong motion network installed at the dam. All data corroborate the observed trend that the stiffening of the dam due to increasing hydrostatic pressure is more important than the added hydrodynamic masses for lower water levels. This trend is then reversed for higher water levels (Darbre & Proulx, 2001).

Modeling the dam-reservoir interaction is controlled by two parameters: reservoir geometry (including water level) and damping. The reservoir level is a fixed parameter. On the other hand, the contribution of the reservoir to the system damping is provided by wave absorption at the bottom of the reservoir and by wave propagation in an infinite or finite reservoir. Since the geometry of the reservoir is known, the only calibration parameter that remains for the reservoir is the amount of energy absorbed by the sediment layer (a parameter that varies between 0 and 1). This quantity was calibrated from forced-vibration tests carried out at Emosson dam (Proulx *et al*, 2001) that lead to values of more than 0.9 (or less than 10% absorption). These values correlated with the fact that reservoirs in these regions contain very little deposit. The onsite investigations have therefore shown that dam-reservoir interaction plays a significant and non-negligible role in the model. Although the calibration process with actual earthquake data relies on parameters that are related to the dam and foundation substructures, it can also be based on the frequency vs. water-level information such as that given by Fig. 2. Models should be calibrated not only on the computed amplitudes, but also on the frequency content of the measured response, when available.

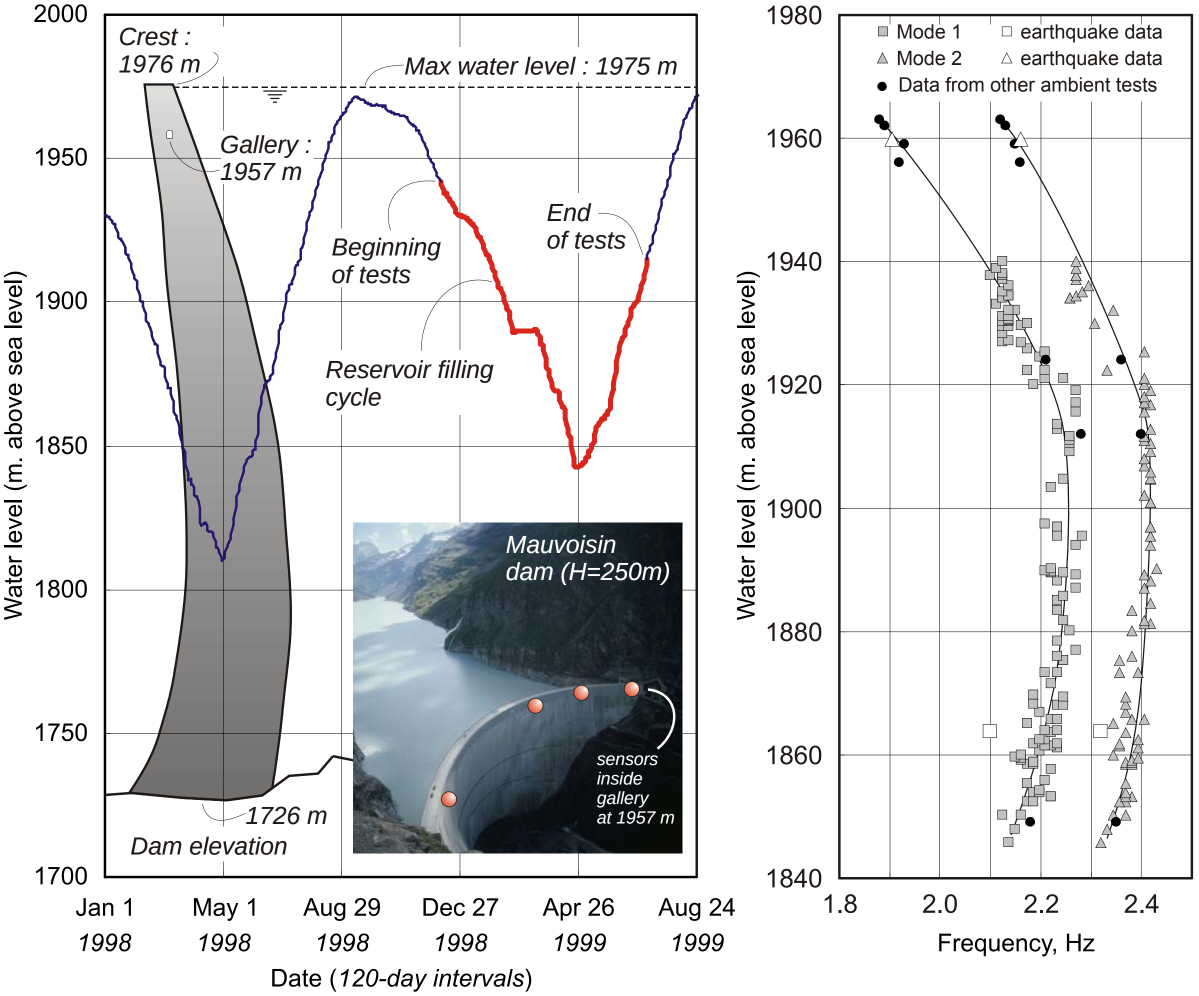

Figure 2: Ambient vibration measurements – effect of water level on resonant frequencies (adapted from Darbre & Proulx, 2001)

Dam and foundation substructures – mesh size and stiffness

Three-dimensional finite element models were created for the dam-reservoir-foundation systems for three large arch dams equipped with the Swiss strong-motion network. Results for Mauvoisin dam are presented herein, but similar investigations were carried-out for two other dams (Émosson and Punt-Dal-Gall). The modeling parameters shown in Table 1 were obtained from on-site vibration testing at Mauvoisin. Two separate values are used for the stiffness modulus of the dam which has a more flexible 12.5-m upper part that was added in 1991 to increase the reservoir capacity. The geometric features were prepared with the help of FEMAP (2009), a specialized tool for pre and post processing. Figure 3 shows two models for Mauvoisin dam: a "coarse" mesh with 35 elements for the dam structure and a more refined (large) mesh with 418 elements. An intermediate 111-element model was also prepared. Moderate earthquakes that occurred within 30 km of the dams and that were recorded by the strong-motion network were used as input. They include the 1996 Valpelline earthquake (M=4.6), and the 2005 Balme earthquake (M=4.9), for which recordings on the dam crest are illustrated in Figures 4 and 5. The water levels in the different reservoir meshes were adjusted to the actual level at the time of the earthquake for each model.

Table 1: Model parameters for Mauvoisin Dam

E_d, Dam stiffness modulus	36 GPa / 25 GPa
Concrete damping	3%
E_f, Foundation stiffness modulus	72 GPa
Foundation damping	5 %
Wave reflection coefficient	0.9

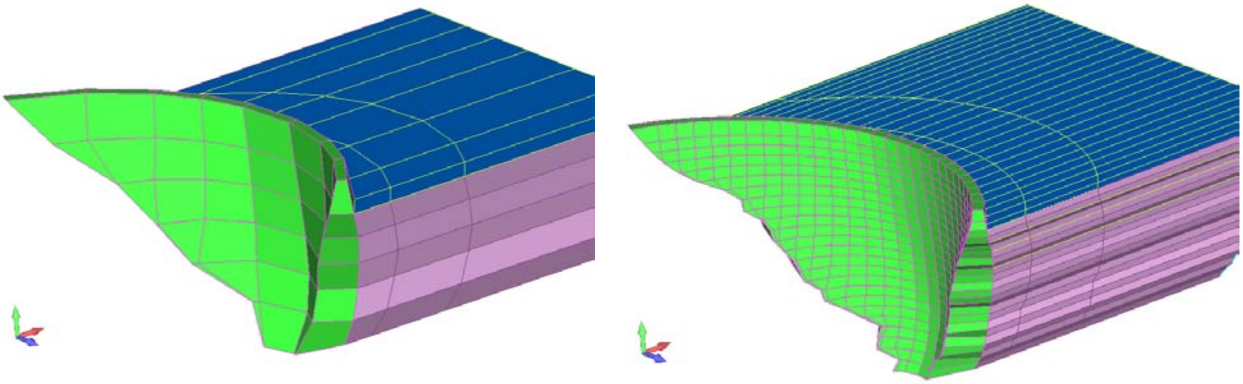

Figure 3: 3D models for Mauvoisin dam: "Large" and "Coarse" models

The earthquake response calculations were carried out with EACD-3D-2008 (Wang and Chopra, 2008), a specialized program that accounts for dynamic dam-reservoir-foundation interaction, and spatially-varying ground motion (multiple input). The program was used in single-input mode for this investigation. The foundation model provides energy dissipation, which is achieved by computing a frequency-dependant impedance matrix for the foundation substructure for specific damping values (Tan and Chopra, 1996). A previous correlation study with an earlier version of EACD-3D which considered only the rock flexibility through a massless foundation model showed that artificially large values of damping, added in the dam substructure, were needed to corroborate with the experimental data (up to 15%, Proulx, *et al.*, 2004). This is not the case with a foundation model that includes radiation and material damping. In this case the energy dissipation is properly accounted for and the program adequately reproduces the recorded data with "reasonable" damping values (Table 1), provided that the dam-reservoir-foundation system is properly modeled.

Figure 4 shows a comparison between the computed and measured responses for Mauvoisin dam, using the M=4.6 Valpelline earthquake record obtained by a “free-field” sensor located 600 m in the downstream valley, as single-input motion. Graph (e) shows the time-history of the horizontal acceleration recorded inside the top gallery of the dam at the center of the crest (sensor #3) in the stream direction. Graphs (a) and (c) show the acceleration time-histories computed for the same location, for the “coarse” (35-element) model and the larger (418-element) models, respectively. The modeling parameters from Table 1 are used (3% damping in the concrete and 5% in the foundation). It is clear that the finer mesh results in a much better correlation with the measured data, both in amplitude and frequency content. This can be partially explained by the fact that the finer model adequately represents the frequency response of the dam-reservoir-foundation system, as shown in graphs (b), (d) and (f).

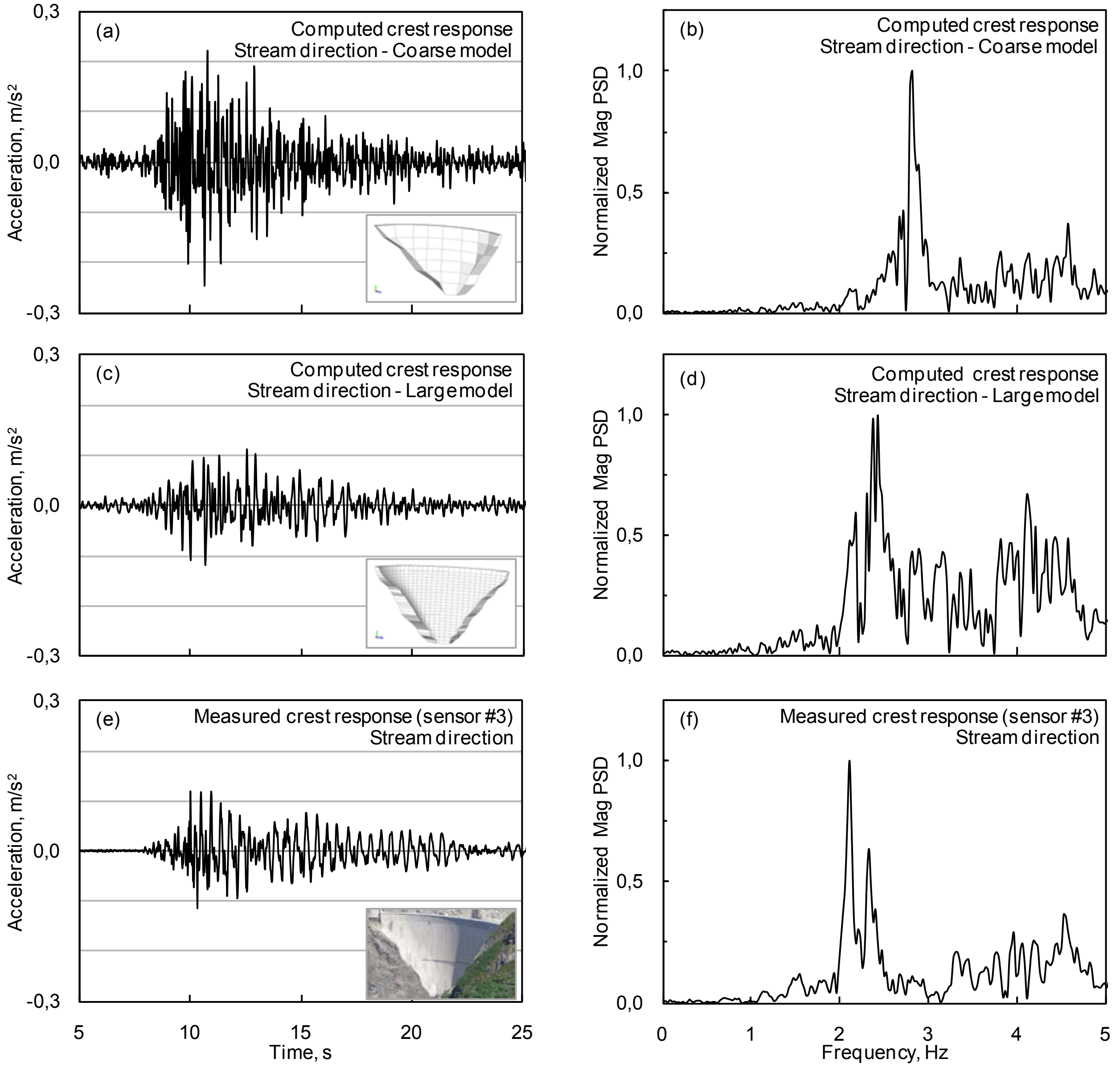

Figure 4: Acceleration responses and frequency contents for Mauvoisin (Valpelline earthquake)

The Power spectral density (PSD) magnitudes in Figure 4 are normalized with respect to the maximum value (graph (f)). The first resonance at approximately 2.1 Hz is not matched by the coarse (more rigid) model, but is closely obtained with the larger model. The concrete and foundation unit weights are well-known, and the options for this model would be to artificially reduce either the dam or foundation stiffness (this is discussed on the next page).

Figure 5 shows similar results on the same dam, but using a different earthquake recording as input motion (the M=4.9 Balme event). This earthquake triggered a response of 0.75g on the crest of Emosson dam, but was considerably attenuated at the Mauvoisin site, located 30 km away, resulting in amplitudes approximately 50% smaller than the Valpelline earthquake. The results corroborate the observations in Figure 4, with the coarse model (graphs (a) and (b)) leading to an overestimation of the response amplitudes and higher frequency content with respect to the recorded data (graphs (e) and (f)).

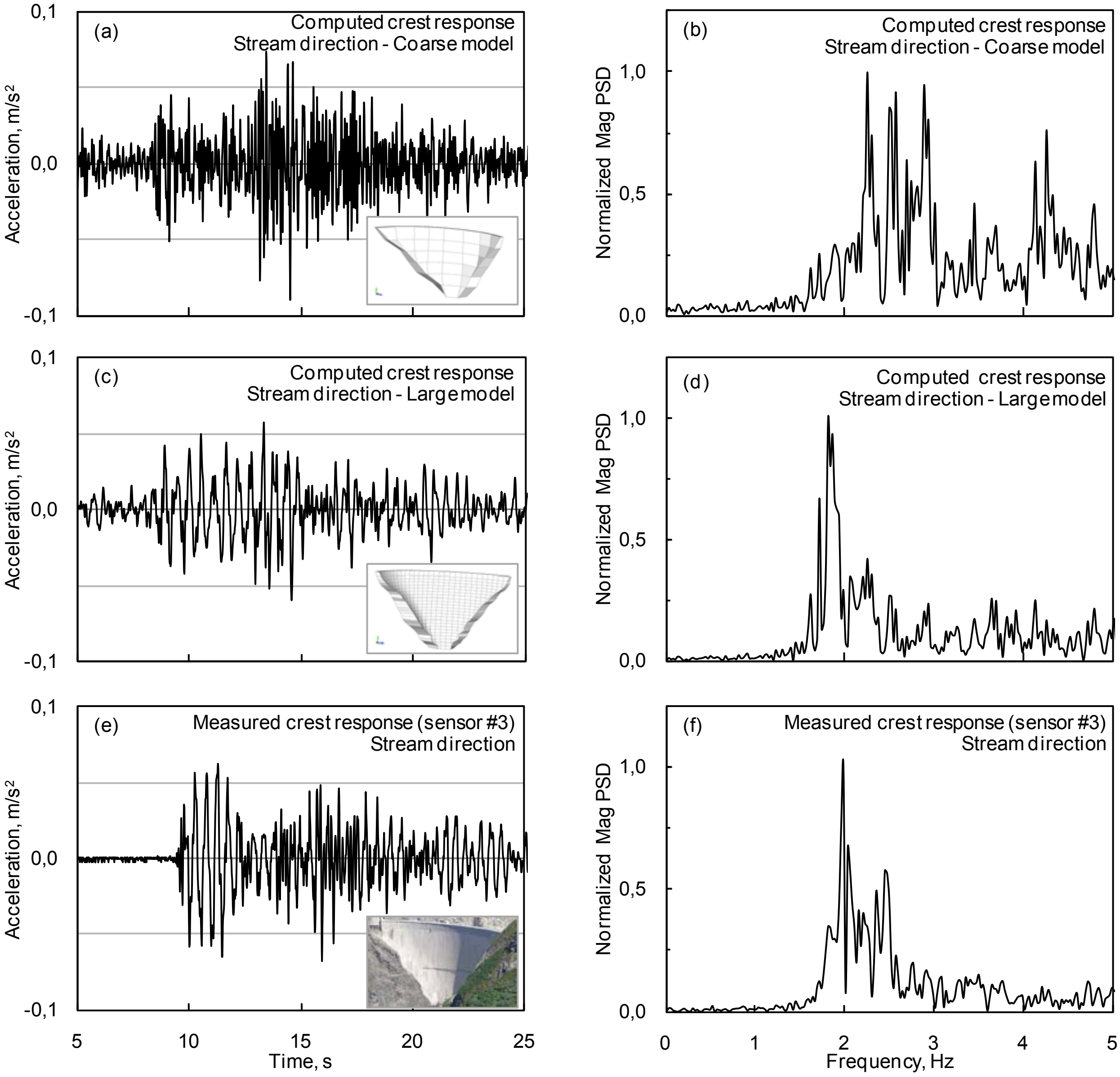

Figure 5: Acceleration responses and frequency contents for Mauvoisin (Balme earthquake)

Calibration of the “coarse” model in order to match the measured frequency requires a significant reduction of the concrete stiffness, as shown in Figure 6 (graphs (a) to (f)). Graphs (a) and (b) were calculated with the concrete stiffness values found in Table 1, indicated as 1.0 E_d. Graphs (c) and (d) were obtained with a value of 0.6 E_d, and graphs (e) and (f) represent the actual earthquake record. The first resonance in graph (d) is very close to the one computed from the measured values, but this is only achieved with a 40% stiffness reduction in the dam model, which is an artificial calibration. On the other hand, reducing the foundation stiffness does not provide a significant change in the frequency, as shown in graphs (g) to (l) in Figure 6. With a 40% reduction of the foundation stiffness (graph (i) and (j)), the amplitudes and the fundamental frequency are still both overestimated. Similar results were also obtained with the Balme earthquake. A more refined mesh is therefore required, with at least two elements per block in the dam substructure, to obtain a reasonable correlation with the frequency content.

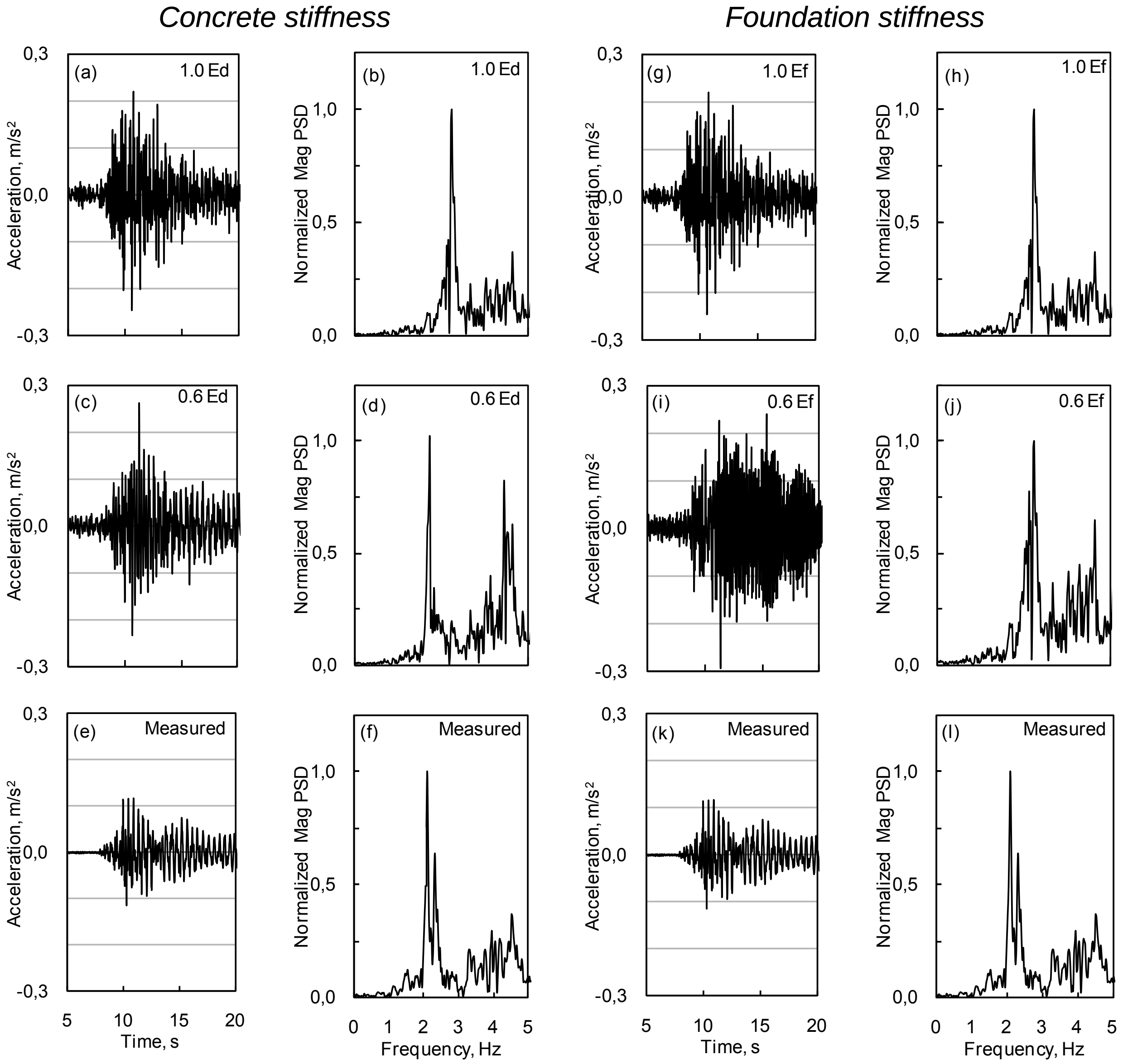

Figure 6: Effect of the stiffness modulus of the concrete and foundation substructures on the horizontal crest response of the “coarse” model.

Foundation and concrete damping

Figure 6 shows that a larger, more refined mesh is needed to reproduce the measured amplitudes. The “coarse” model, even calibrated on the fundamental frequency by reducing the concrete stiffness, still overestimates the response. Further damping would need to be added to the system, either in the foundation or dam substructures, since the reservoir damping is related to parameters that are either fixed (geometry and water level) or calibrated from on-site vibration testing (wave absorption coefficient).

The effects of damping are shown in Figure 7, where the foundation and concrete damping ratios were varied independently, while the other parameters (Table 1) were kept constant. Graph (a) shows the maximum amplitudes of the horizontal acceleration response of Mauvoisin dam subjected to the Valpelline earthquake, using the large model. Impedance matrices were computed for 5, 10 and 20% damping in the foundation, respectively. Damping in the dam concrete was kept constant at 3%. The amplitudes are normalized with respect to the measured values. With 5% damping, the large model correctly predicts the actual earthquake record (amplitude equal to 1.0), and this value decreases with 10 and 20% damping. The intermediate model (111 elements, graph (b)) shows the same behavior, with slightly smaller amplitudes. The “coarse” model (graph (c)), however, overestimates the amplitudes by a factor of 2.0, and the additional damping (up to 20%) reduces the response, but not nearly enough to match the measured values. It is also clear from graphs (a) to (c) that the effect of foundation damping is more pronounced for the smaller models.

Concrete damping has similar effects for the three models, as shown in graphs (d) to (f). In this case, the foundation damping was kept at 5% and the concrete damping was increased from 1 to 3%. At 3% damping, the large model accurately predicts the recorded response. The effect of concrete damping is also more pronounced for the coarse mesh.

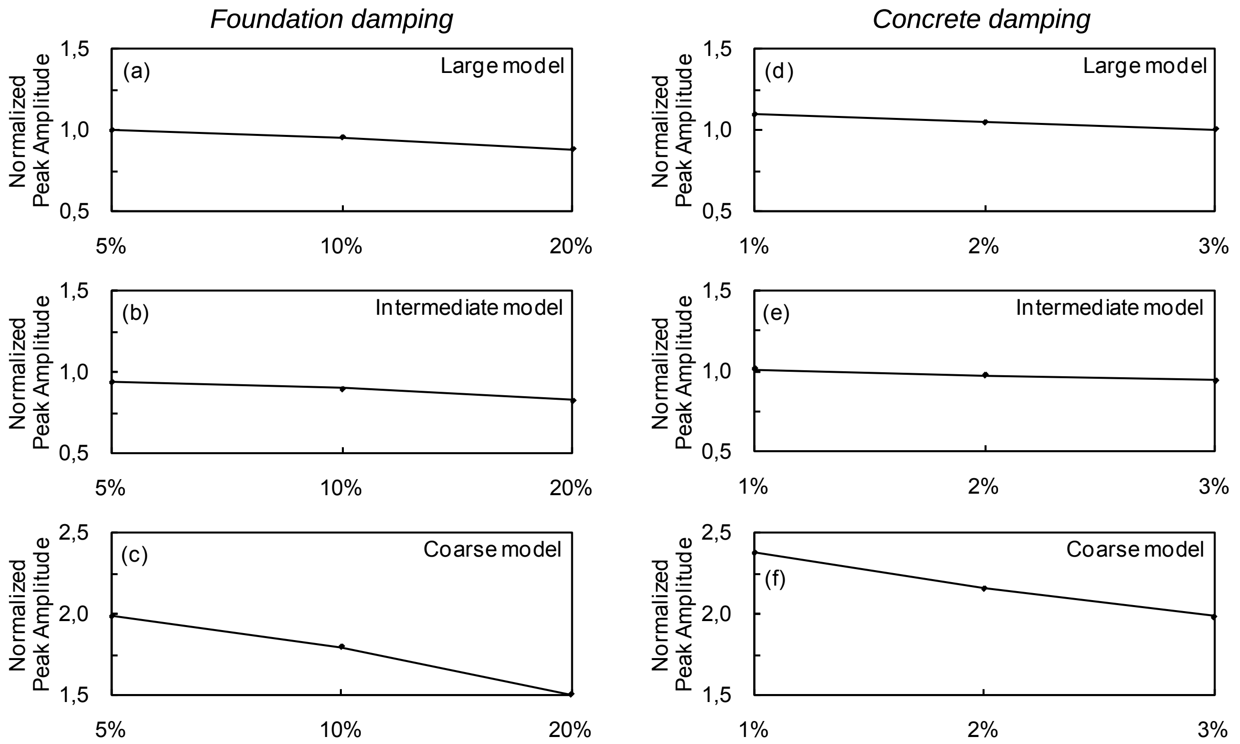

Figure 7: Effect of foundation and concrete damping

Conclusions

Using the latest version of the EACD program and single-input ground motion, a parametric study was carried out for large arch dams located in Switzerland and equipped with networks of strong-motion sensors. 3D finite-element models were developed for the dam and reservoir, including, “coarse”, intermediate and large meshes. A dynamic impedance matrix was computed for the foundation for 5, 10 and 20% damping values. The models were first calibrated with results obtained from on-site investigations and used to evaluate the effects of the key parameters for the dam and foundation (the importance of water level and reservoir geometry were reported in previous studies). Computed accelerations were compared to sensor recordings. Results showed that, although the computation of a foundation impedance matrix can be time consuming, especially for larger models (over a larger frequency range), the use of a finer, more complex mesh (at least two elements per block) is essential to predict the response in terms of amplitude and frequency content. In the case of the large model, “reasonable” damping values of 3% for concrete and 5% for the foundation were needed to reproduce the recorded accelerations. The smaller (coarse) models were more sensitive to an increase in damping values, but trying to correlate with experimental data lead to artificially high demands in damping. On-site vibration testing and monitoring networks are therefore very valuable. They provide crucial information needed to calibrate key parameters in finite element models used for earthquake safety analysis.

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FEMAP, Pre- and post-processor for engineering finite element analysis. Siemens-PLM Software

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