EARTHQUAKE RESPONSE OF LARGE ARCH DAMS OBSERVATIONAL EVIDENCE AND NUMERICAL MODELLING

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ABSTRACT :

This paper summarizes a decade of research on the earthquake behavior of large arch dams in Switzerland. This research is based on a network of strong motion instruments located on several large concrete dams including some of the tallest in the world. The accelerograph network was implemented by the Division of Dam Safety in the early to mid 90s. It is being maintained by the Swiss seismological service and has recorded several low to moderate seismic events that occurred in the vicinity of the instrumented dams. In parallel, on-site ambient and forced-vibrations tests were completed on selected arch dams. Brief details of the experimental program are reviewed and the use of the large database is presented. Data obtained from the specific on-site experiments were used to develop state-of-the-art three-dimensional finite-element models for the dam-reservoir-foundation systems. As data was collected during different periods in the year, the effects of the variation of the impounded water level on the dynamic properties were evaluated and quantified. Key parameters for the models were calibrated based on the experimental dynamic properties. Using both massless and energy-dissipating foundation models, free-field acceleration recordings of the various events were used as inputs to the numerical models and the computed motions of the dam were compared to the actual recordings. Possible sources of damping required to corroborate with the recorded motions were investigated. Motion recorded at the foundation and along the abutments as well as results obtained from the numerical study indicate that multiple support excitation plays a key role in the earthquake response of large arch dams.

KEYWORDS: Dams, strong-motion, dynamic tests, modeling, earthquake analysis

1. EARTHQUAKE BEHAVIOR OF LARGE DAMS – FIELD OBSERVATIONS

The validity of the excitations and of the models used in the earthquake analysis of structures can only be confirmed by way of comparison with relevant field observations. Such valuable data are still at the present incomplete and there is a need for field measurements during earthquakes in general and for strong-motion instrumentation in particular. Measurements that are needed relate to the free-field motions from which information on the earthquake recurrence and characteristics can be obtained, as well as to the structural motions from which selected aspects of the earthquake behavior of different types of structures can be studied.

In this context, an extensive network of accelerograph arrays was installed on selected large concrete dams in Switzerland during the 90s. The instrumented dams include some of the largest in the world: Grande-Dixence (285 meters high gravity dam), Mauvoisin (250 meters high arch dam), Emosson (180 meters high arch dam), Punt-dal-Gall (130 meters high arch dam), and Mattmark (120 meters high embankment dam) [Darbre 1995].

The goal of this strong-motion network was to monitor the overall dam behavior during seismic events and to identify the response patterns and governing effects during earthquakes. Specific objectives were: (i) to collect data in order to extract key dynamic properties of the dam-reservoir-foundation systems (frequencies, mode shapes, damping); (ii) to identify the effective input motions as well as the free-field motions at specific sites; and (iii) to establish a set of records covering dam excitation and response that could be used to calibrate finite element earthquake analysis programs. Complementing this effort, ambient vibration and forced vibration testing programs were completed at Mauvoisin [Darbre *et al*. 1998] and Emosson [Paultre *et al*. 1998]. These tests were carried out at different periods of the reservoir filling cycle to investigate water level effects on the dynamic properties of the dams-reservoir-foundation systems.

2. THE SWISS DAMS STRONG MOTION NETWORK

The prediction of the behavior of large structures such as dams during future earthquakes generally requires the use of analytical and numerical techniques that utilize a temporal description of a design earthquake (synthetic accelerogram directly obtained or compatible with a design spectrum). The observational database needed to characterize such earthquakes (amplitudes of motions, strong-motion duration, influence of local geological and soil conditions, attenuation laws and coefficients of wave propagation) is still insufficient.

The Swiss dams strong motion network was established with triaxial accelerographs strategically located to record the input motion as well as the dam response [Darbre 1995]. The instrumentation schemes vary from a minimal 4-sensor configuration (Emosson), to a more detailed 11-sensor configuration (Mauvoisin) where the motion is recorded along the abutments and in several locations inside the dam. Each dedicated strong-motion sensor has digital recording unit with a resolution of 0.00025g and a 50 Hz cutoff frequency. The system has pre and post-event recording capability with adjustable trigger. The instruments have to function not only at locations with dripping water (inside inspection galleries and tunnels), but also - and more challenging – have to function at sites prone to lightning and thus to power surges. Interconnecting the instruments over distances of several hundred meters posed a challenge of similar nature due to the possible occurrence of ground loops. This double challenge was met by carefully designing the instruments for electromagnetic compatibility, electrically isolating them perfectly from their support and using fiber optic cables for the interconnection.

Figure 1 shows a recording of a recent moderate earthquake at the Emosson dam site. The positions of the sensors are illustrated on a finite element model of the dam. Time histories and frequency contents are shown for each sensor component: cross-stream (X), downstream (Y), and vertical (Z). The figure also shows a recording obtained on a smaller dam (Vieux Emosson) located approximately 2 km from Emosson dam. This data can be used to extract the dynamic characteristics of the dams and to calibrate commercial and specialized finite element programs for earthquake analysis (see section 5). The instrumentation configuration at Emosson is minimal, with four sensors inside the dam and a free-field located downstream. At Mauvoisin, however, 11 sensors were used throughout the dam and along the abutments. Using the data recorded at these positions, it is possible to animate the actual dam motion during a seismic event. A program was developed as part of this research project to interpolate the motion for each node in a three-dimensional finite element model of the dam. This interpolation process yields displacement time-histories for all nodal points, which are imported back into a post-processor to generate AVI (movie) files. Figure 2 illustrates frames from such an animation (upstream view and plan view of the deformed dam at a specific point in time). The sensor locations are indicated by small red triangles. Looking at the dam motion – here for the Mauvoisin dam during the same earthquake – we see that the deformed shape is mostly a combination of the first asymmetric and symmetric mode shapes.

3. AMBIENT VIBRATION MEASUREMENTS – WATER LEVEL EFFECTS

In an effort to complement and to corroborate with the experimental findings of the strong-motion network, two ambient-vibration testing programs were completed at the Mauvoisin dam site. 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 water levels varying from 13 to 127 m below the crest [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 Figure 3, where the reservoir filling cycle is plotted over a cross-section of the dam, and the testing period is indicated. 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 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].

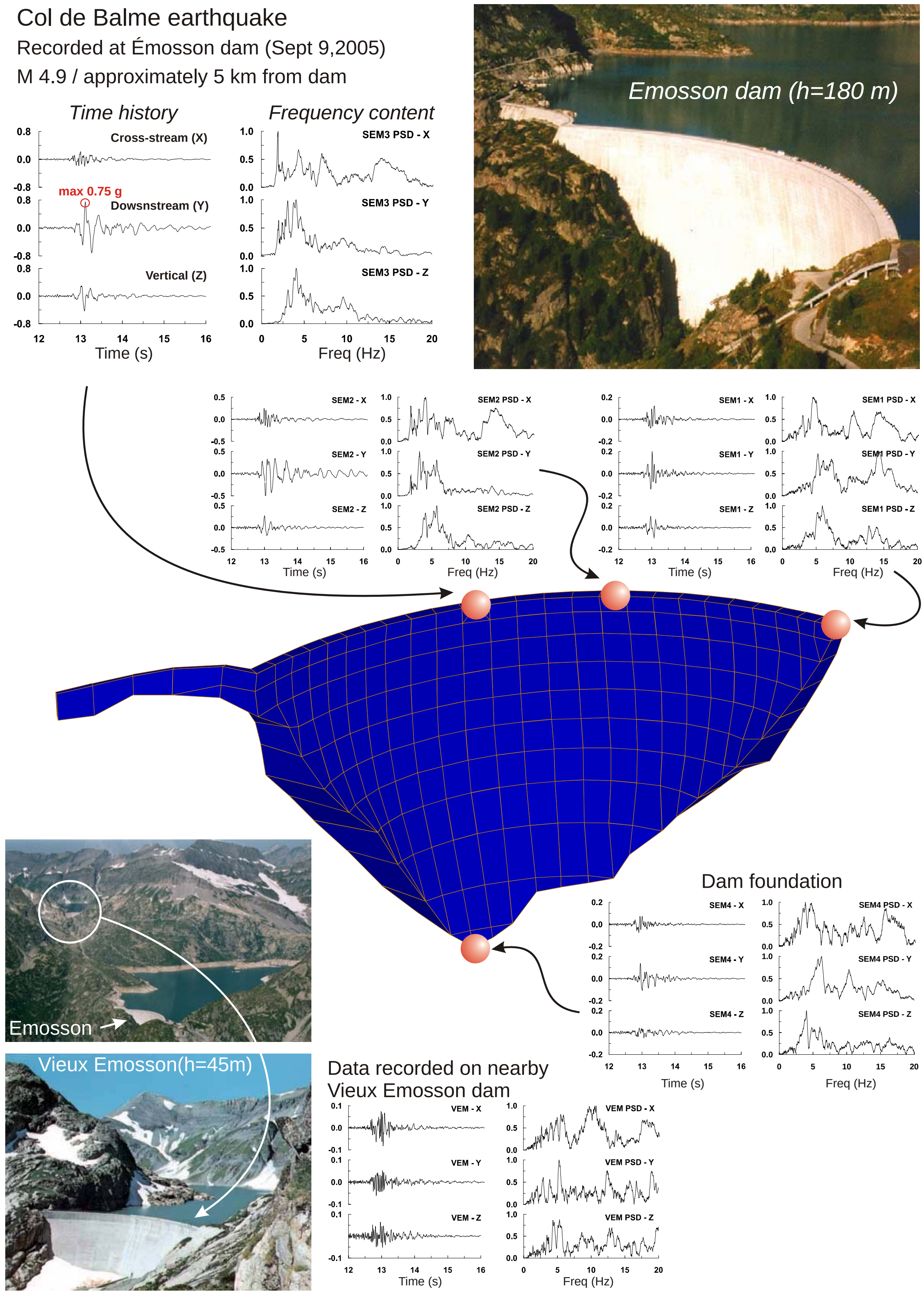

Figure 1: Time histories and frequency content of an earthquake recorded with the strong motion network

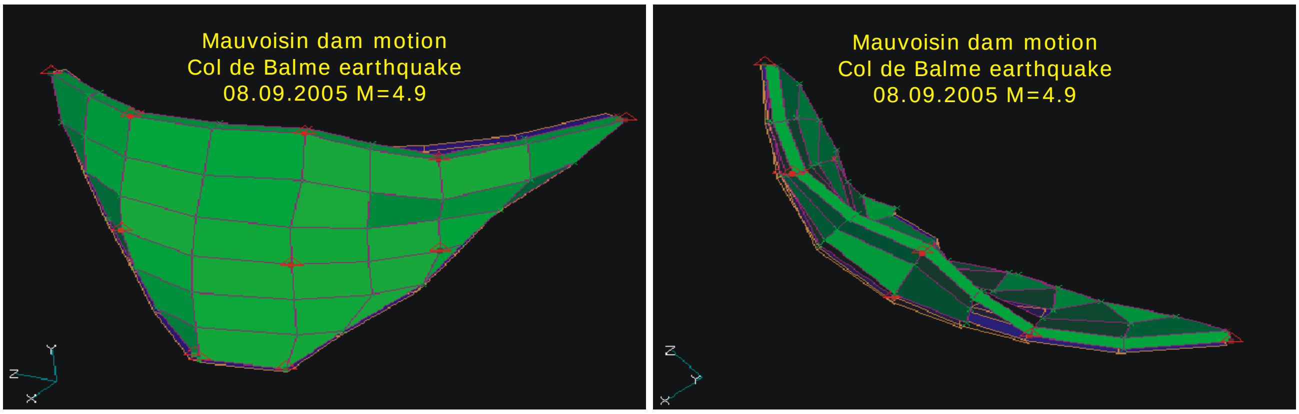

Figure 2 : Animation of actual dam motion during an earthquake (upstream view and top view)

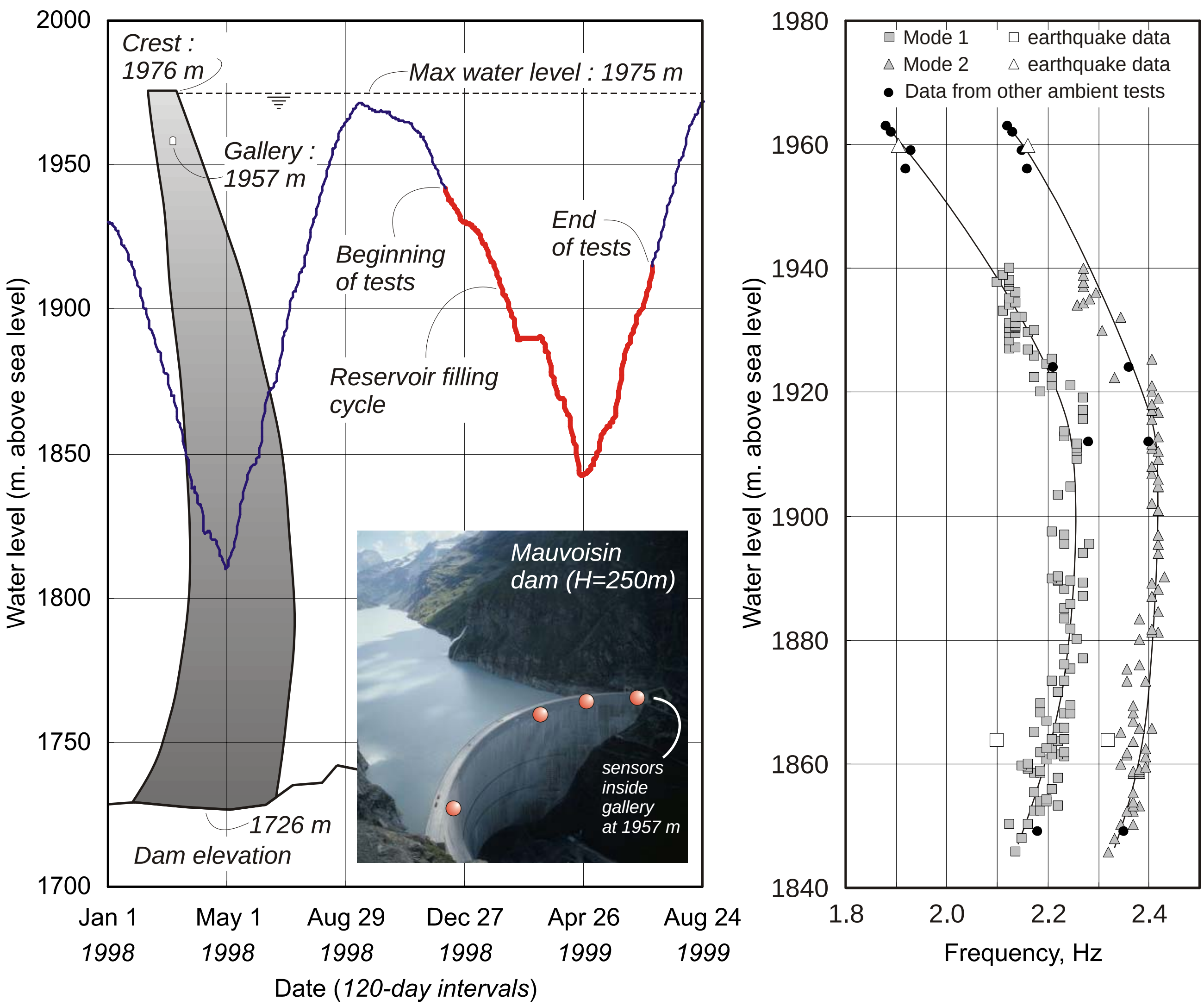

Figure 3: Ambient vibration measurements – effect of water level on resonant frequencies
(adapted from Darbre & Proulx, 2001)

4. FORCED VIBRATION MEASUREMENTS – MODEL CALIBRATION

Ambient vibration tests are a fast and inexpensive way to obtain the dynamic characteristics of a civil engineering structure. Forced-vibration test on the other hand, with a controlled input load, lead to complete frequency responses for the structure, from which frequencies, mode shapes, and especially damping can be extracted with a high level of accuracy. Data from such tests are extremely valuable for the calibration of numerical procedures used to carry out earthquake analysis and seismic safety evaluation. The Emosson dam was selected for a series of four consecutive forced-vibration tests over a 12-month period. Figure 4 illustrates the experimental setup, where accelerometers were placed inside the dam on each block, and hydrophone arrays were placed in the reservoir along the upstream face of the dam. The goal of these tests was to measure the dynamic response of the dam-reservoir-foundation (DRF) system in the 0-10 Hz range, using an eccentric-mass shaker located in different positions on the crest. The graph in Figure 4 shows the normalized acceleration frequency responses for the dam crest obtained for different water levels. Resonant frequencies and mode shapes were obtained from these results, and the system damping was also evaluated. These key parameters were then used to calibrate a 3D finite element model for the DRF system. Using the calibrated models, energy dissipation in the reservoir and dam-foundation interaction effects were investigated [Proulx *et al* 2001].

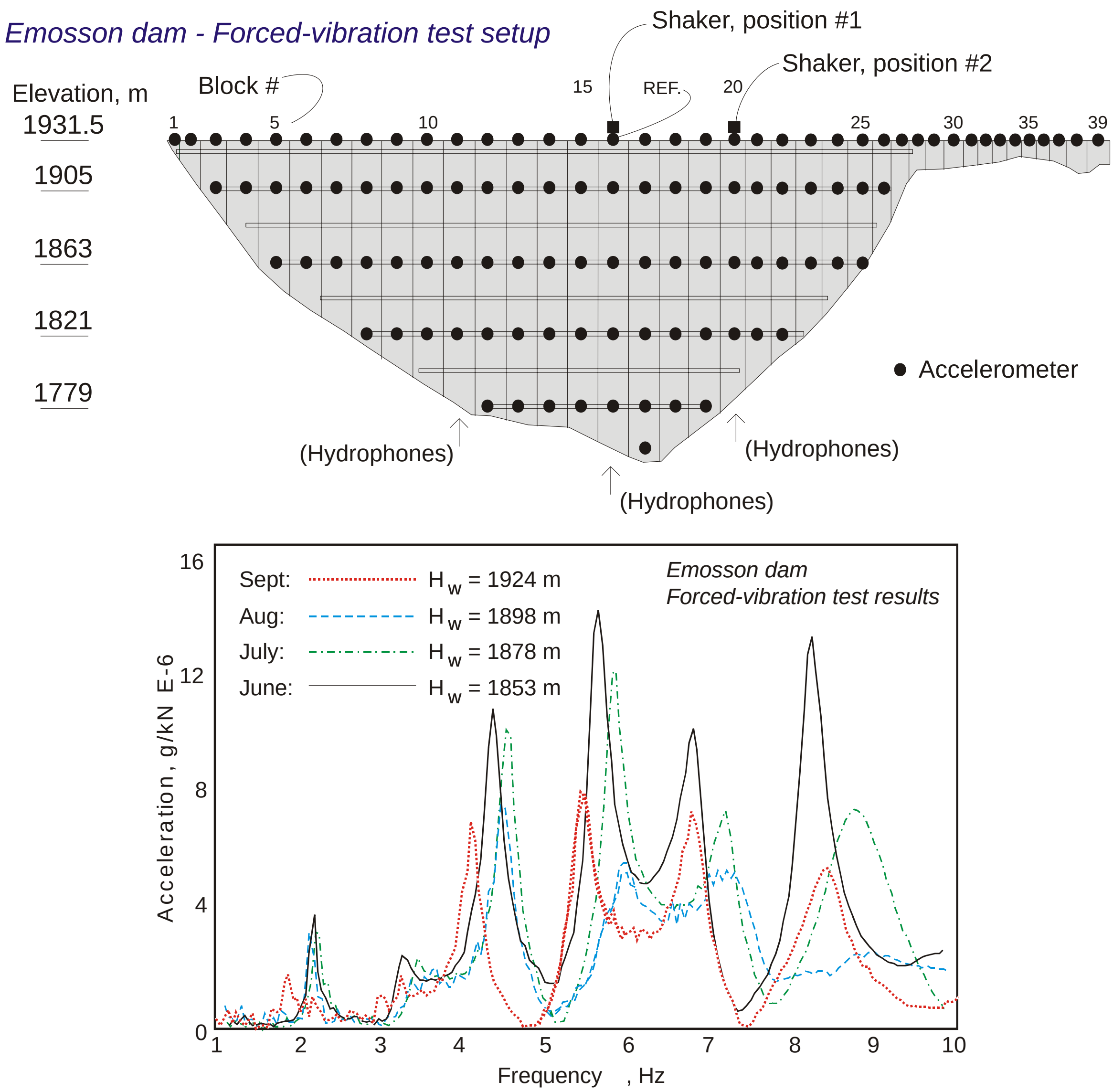

Figure 4: Forced vibration test setup and frequency responses for different water levels (adapted from Proulx *et al*, 2001)

5. EARTHQUAKE ANALYSIS – COMPARISON WITH STRONG MOTION RECORDINGS

With the observational evidence acquired from the strong-motion network and the complementary data obtained with ambient and forced-vibration tests, a numerical investigation was undertaken. Three arch dams were selected (Mauvoisin, Emosson, and Punt-dal-Gall), and 3D models were developed for each DRF system, with complete meshes for the dams, the reservoir and the foundation. The well-known earthquake analysis programs EACD-85 (massless foundation) and EACD-96 (energy dissipating foundation) [Fok, *et al*, 1986; Tan & Chopra, 1996] were used for this numerical study. Data from the on-site experiments at Emosson and Mauvoisin were used to calibrate the basic properties of the models, such as the concrete and foundation stiffness, the amount of energy dissipated in the reservoir and the target values for the overall amount of damping in the system. Using strong-motion network data corresponding to four low to moderate earthquakes that occurred in the vicinity of the dams, the free-fields records were used as input to the finite element models. Acceleration time-histories were computed for specific nodal points of the dam mesh and were compared to the actual sensor recordings. As most parameters were previously calibrated from ambient and forced-vibration test results, the emphasis of the comparison was on the evaluation of the dam and foundation damping that was necessary to match the experimental results [Proulx *et al* 2004, Proulx *et al*, 2006].

Figure 5 shows a 3D models for Mauvoisin dam along with the acceleration recording of the 1996 Valpelline earthquake (M=4.6). The first - more refined - model was used with the massless approach (along with a 3D mesh for the reservoir and the foundation that are not depicted in the figure). The main findings for this dam and the two other arch dams was that a large amount of additional damping needed to be artificially introduced into the dam model to match the recorded acceleration (the middle graph shows the response computed with 8% damping). The second model represents a coarse mesh that was used with the energy dissipating foundation model. This model accounts for radiation and material damping in the foundation and the concrete damping is kept at a “reasonable” level (3%). The bottom graph shows that the response was still overestimated with 20% damping in the foundation model. Due to limitations in computing power at the time of this investigation, the dam mesh used with the energy dissipating foundation was very coarse, and this resulted in a model with a resonance frequency slightly higher (stiffer model) that the observed frequency at the time of the earthquake (Fig 3). Moreover, lowering the concrete modulus increased the computed acceleration response. A much finer model would be needed to compare with the massless approach, and this investigation is currently underway.

From the shape and the dimensions of the dam-foundation interface, various aspects of soil-structure interaction can significantly contribute to the earthquake response of a dam. The topography of the canyon and the inertial and energy dissipation properties of the foundation rock lead to a non-uniform motion at the interface. The motions at the abutments are also affected by the response of the dam. These effects combine into the total effective input motion along the interface, whose observation is still largely missing. Figure 6 shows acceleration records along the abutments at Mauvoisin dam during the Valpelline earthquake. Such data could be used to develop a new multiple support excitation approach, where the effective input motion would be accounted for.

6. CONCLUSION

With its careful design and maintenance, the Swiss dams strong motion network is still in operation after roughly 15 years. It provides reliable experimental data to study the earthquake behavior of large concrete dams, with free-field and dam motion recordings of low to moderate earthquakes. The observational program of the SFOE that included several on-site ambient and forced-vibration testing programs provided insight into the effects of dam-reservoir and dam-foundation interaction. Finite element models were developed for three large arch dams and calibrated with results from the dynamic tests. Earthquake analysis were performed using two state-of-the-art finite element programs that account for dam-reservoir-foundation interaction with different approaches for the foundation rock model. The effects of energy dissipation in the reservoir and in the foundation were identified. The single input motion approach has its limitations, however, and further progress in the prediction of the seismic response of arch dams are dependent on the way that the earthquake motion is introduced in the dam-reservoir-foundation system.

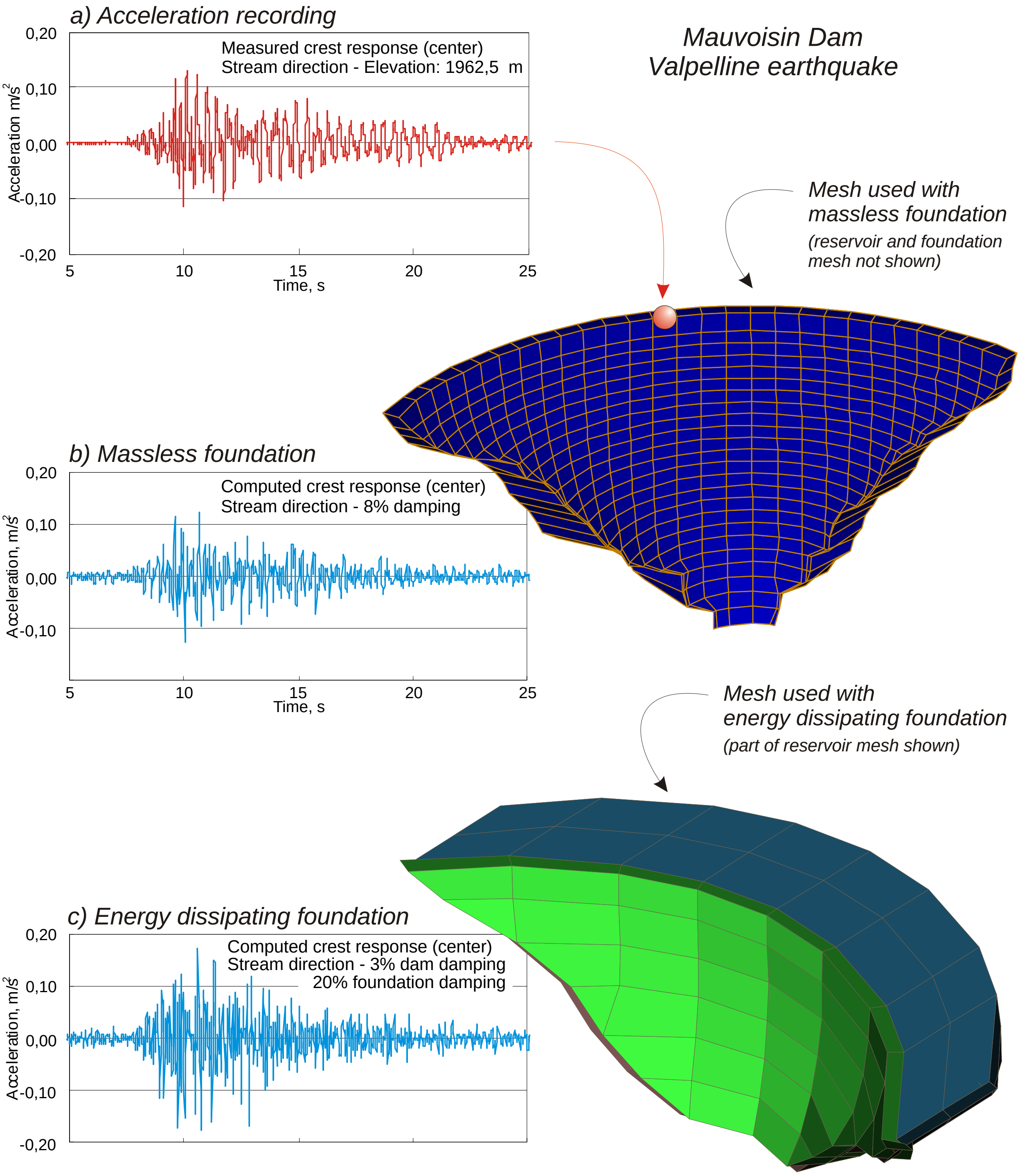

Figure 5: Earthquake analysis – Comparison of recorded and computed crest accelerations

7. ACKNOWLEDGEMENTS

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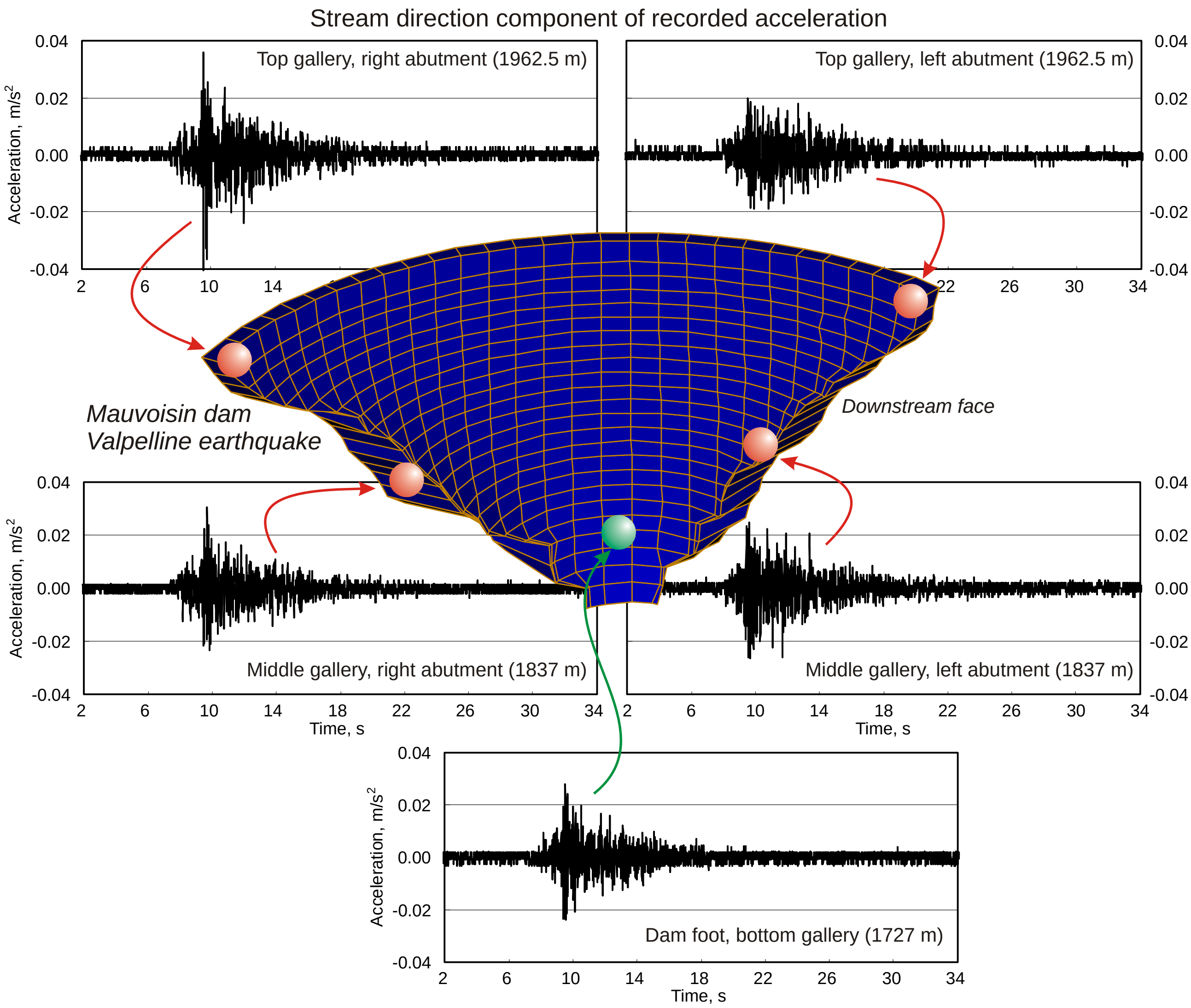

Figure 6: Acceleration records along the abutments of Mauvoisin dam

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