EXPERIMENTAL EVALUATION OF RESERVOIR LEVEL EFFECTS ON THE DYNAMIC PROPERTIES OF A LARGE ARCH DAM

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SUMMARY

The reliability of state-of-the-art numerical methods used to evaluate the seismic behaviour of dams is measured by correlation with experimental results obtained on existing structures. The Earthquake engineering and structural dynamics research center (CRGP) at the University of Sherbrooke has developed and applied dynamic testing methods for large structures in the past ten years. This paper presents results obtained during a series of forced-vibration tests carried out on Émosson arch dam in Switzerland and, more specifically, the effects of the impounded water level on the dynamic response of the dam. As the reservoir level varies throughout the year at this site, four series of tests were conducted with different water levels in the reservoir. During the tests, the dam-reservoir-foundation system was submitted to a harmonic load provided by an eccentric mass shaker. Horizontal acceleration responses were obtained at several locations on the dam crest and inside selected inspection galleries. Hydrodynamic pressures were also recorded along the upstream face at several depths. In this way, the dynamic response of the dam-reservoir-foundation system was evaluated for empty and full reservoir, as well as two other intermediate water levels. It was observed that, starting with an empty reservoir, the resonant frequencies increased with the raising water level, as the dam stiffness varied with the contraction of the construction joints under increasing hydrostatic pressure. Data also showed that, after a certain water level was reached, this trend was overcome by the added mass of the reservoir and the resonant frequencies decreased. Modal damping and resonant shapes were obtained from the recorded data and a complete database characterizing the dynamic behaviour of Émosson arch dam is now available to validate finite element model predictions and to evaluate the interaction effects that occur between the dam, reservoir and foundation.

INTRODUCTION

The reliability of state-of-the-art numerical methods used to evaluate the seismic behaviour of dams is measured by correlation with experimental results obtained on existing structures. Although the number of instrumented dams has increased in the past decade, very little data were collected to verify these methods. Also, the instrumentation is usually limited to accelerometers placed at a few key locations. By now, it is well known that hydrodynamic pressure and reservoir bottom absorption play an important role in the dynamic response of concrete dams. Experimental investigations, although at a low level of excitation, can be used to obtain reliable data for the calibration of numerical methods.

The Earthquake engineering and structural dynamics research center (CRGP) at the University of Sherbrooke has developed and applied dynamic testing methods for large structures in the past ten years. Several highway bridges, dams and buildings were tested under ambient and forced vibration loading [Paultre and Proulx, 1997]. More recently, an extensive experimental program was designed to provide a reliable database for the characterization of the dynamic behaviour of large concrete dams. This paper presents results obtained during a series of forced-vibration tests carried out on Émosson arch dam in Switzerland and, more specifically, the effects of the impounded water level on the dynamic response of the dam. Acceleration frequency responses

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were obtained at several locations on the dam crest and inside selected inspection galleries while the dam was subjected to horizontal harmonic loading. Hydrodynamic pressures were also recorded on the upstream face. Experimental procedures and the evaluation of dynamic properties are discussed. Resonant frequencies, modal damping and mode shapes are presented for each series of tests and the effects of the water level are discussed.

ÉMOSSON ARCH DAM

Émosson dam is located on the border of France and Switzerland, between Chamonix and Martigny, near the Mont Blanc mountain range (Fig. 1). Completed in 1974, the 180-m high double-curvature arch dam ranks among the 15 tallest in the world. It has 39 blocks, with a crest length of approximately 550 m, nine inspection galleries and a gravity-type spillway on the right bank. The crest width is 9 m and varies from approximately 35 to 50 m at the base. The crest elevation is 1931.5 m above see level and, starting at an elevation of 1905 m, the inspection galleries are evenly spaced at 21 m intervals.

The dam is operated by Électricité d'Émosson S.A., a partnership operated by Switzerland (ATEL) and France (EDF). The reservoir draws its waters from the surrounding glaciers located in both countries through a network of underground galleries and tunnels. Two power plants are operated by Émosson S.A.: the first one in Vallorcine (France), located 805 m below the maximum reservoir level; and the second one in Martigny (Switzerland), located 660 m below the first power plant.

Every spring and summer, melted water is collected in the vicinity (and as far as 20 km away from the dam) to be channelled by gravity or pumped to the 225 million m^3 reservoir. Electricity is produced throughout the year, with a peak production period in the fall and winter during which the reservoir is emptied. Figure 2 illustrates this yearly cycle, showing the reservoir volume and level as a function of time. The range of variation of the water level is shown from 74 to 93 and the actual data for the 1997 / 98 season is plotted as a solid curve. Also shown on Fig. 2 are the four different testing periods in September 1997, as well as June, July and August 1998.

Figure 1: Émosson arch dam with almost-full reservoir (September)

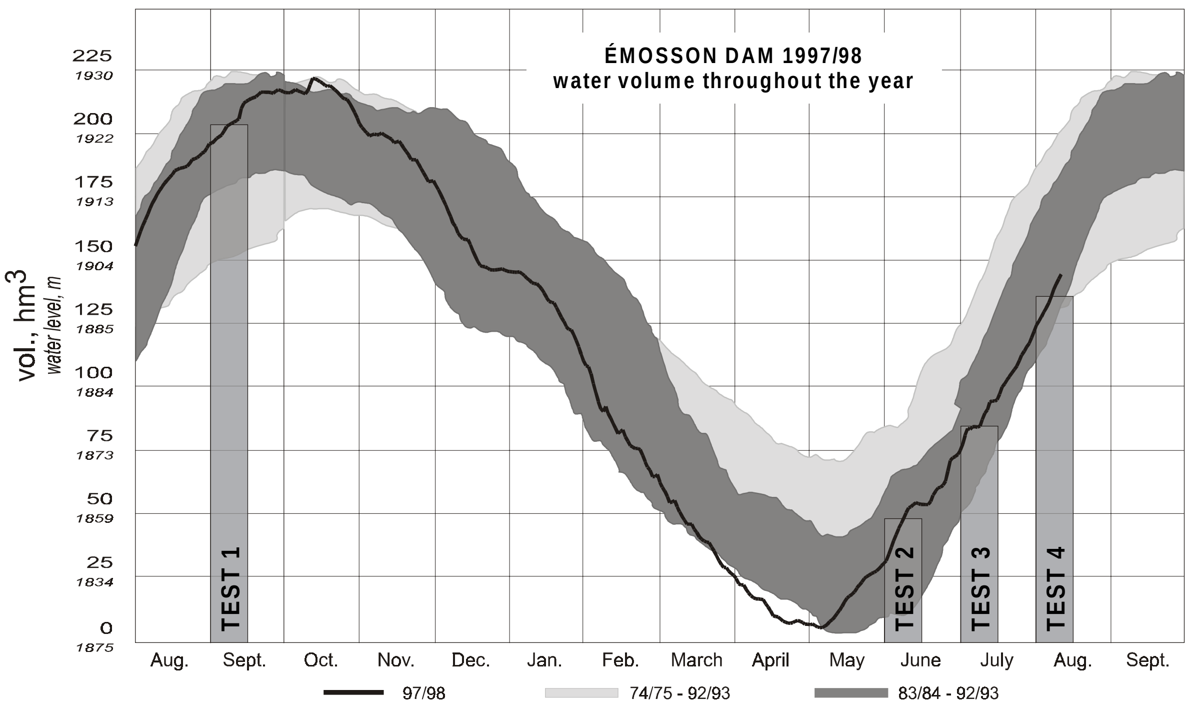

Figure 2: Variation of the reservoir volume and selection of test periods

The earliest possible test dates for the "empty" conditions was the beginning of June, as the access road was still covered with snow in the month of May. The average water levels and volumes observed during the four series are given in Table 1 and were 8 m below maximum level (1931 m) for September 97 as well as 78.7 m and 53.2 m and 33.6 m for June, July and August 98, respectively. Table 1 also shows the variations in the reservoir level and volume during the two-weak test periods. During the June tests, a much larger variation of the reservoir conditions was observed during the tests, as the reservoir is rising much more rapidly for this period. Also, that series of tests was completed with the lake filled at 19% of its capacity, which translates into 50% of its maximum height, due to the shape of the reservoir.

Table 1: Reservoir characteristics during tests

	June	July	August	September
Reservoir volume				
Average volume (10^3 m^3)	42 655	85 036	132 183	204 325
% of maximum	19 %	38 %	59 %	91 %
Variation during tests (10^3 m^3)	18 934	3861	9688	14 945
Reservoir level				
Average level (m)	1852.8	1878.3	1897.9	1923.5
% of maximum	50 %	67 %	79 %	96 %
Variation during tests (m)	16.4	3.35	3.38	3.25

FORCED VIBRATION TESTS

The experimental program undertaken at Émosson dam involved forced vibration as well as ambient vibration tests. Horizontal acceleration and hydrodynamic pressure responses were recorded while the dam was subjected to a harmonic load generated by an eccentric mass shaker mounted on the crest. This shaker is composed of two sets of identical weights rotating about parallel vertical shafts and generating a sinusoidal load. The amplitude of the resulting force, which is proportional to the square of the rotation frequency, can be adjusted by varying the eccentricity of the weights. The operating frequency was varied from 1 to 10 Hz at Émosson, with loads varying from 2.0 to 100 kN. The shaker was mounted on the crest with 12 anchor bolts and a cement grout was used to level the base plate and to ensure that the resulting force remained in a horizontal plane.

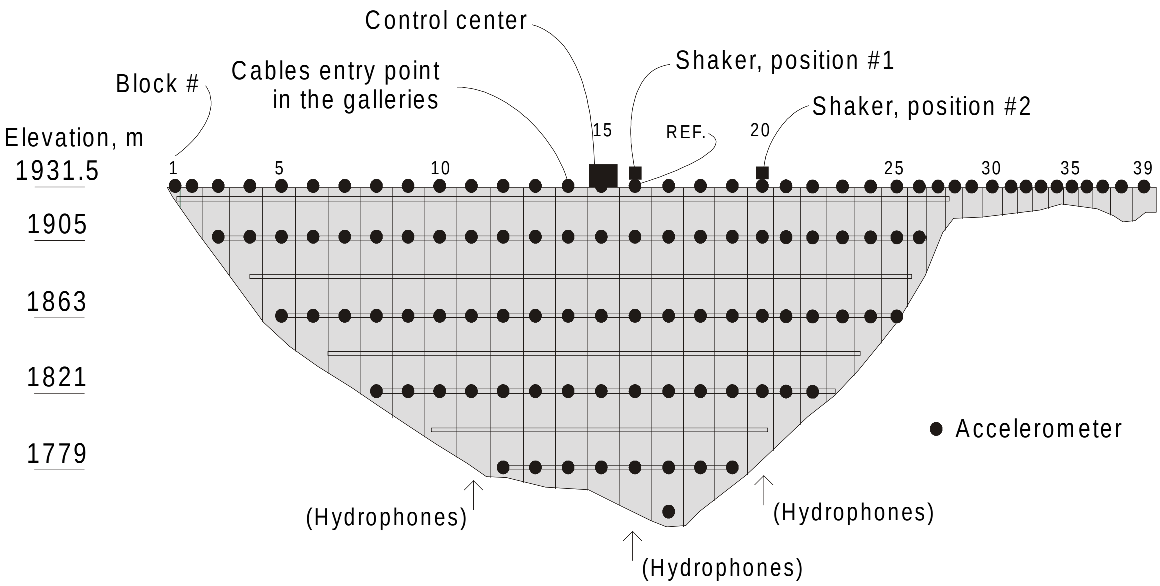

Figure 3: Experimental setup

Figure 3 shows an upstream view of the dam with the instrumentation setup. The 39 concrete monoliths are numbered and the two shaker position used for the series of tests are identified. These positions were selected with the help of a preliminary finite element model completed before the tests. This model was developed to obtain a graphical representation of a selected number of mode shapes for the dam alone, with the assumptions of empty reservoir and a rigid foundation. Key shaker positions could then be selected in order to excite as many symmetric and antisymmetric resonances as possible in the 1- to 10-Hz range. It was determined that blocks 16 and 20 would provide the best locations for the shaker on Émosson dam.

Low-frequency servo-accelerometers were used to record horizontal accelerations in the radial direction for each block on the crest, in four selected inspection galleries as well as at the foundation level. These act as low-pass filters with a 50-Hz cutoff-frequency and are mounted on an aluminium plate with three levelling screws. Up to six accelerometers were moved successively to cover all measurement station as shown in Fig. 3, while a reference accelerometer always remained beside the shaker on blocks 16 or 20. More than 2 km of cable were deployed on the crest and inside the inspection galleries through the elevator shaft to connect each measurement station to the control center on block 15.

An array of solid-state AcquaSense hydrophones was used to record hydrodynamic pressures at three different locations on the upstream face of the dam during the September series of tests, with the highest water level. The array consists of eight hydrophones mounted on a 300-m cable at 15-m intervals, the first being submerged 25 m below water level. Each unit acts as high-pass filter with a 4-Hz cutoff frequency. At full amplitude the resolution of each unit is ±0.1 Pa, taking into account the data acquisition system characteristics.

All signals were recorded with an HP3852a data acquisition system, which has an aggregate sampling rate of 100 000 Hz, and track-and-hold capabilities that eliminate measurement delays between individual channels. A computer program developed at the CRGP provides a real-time graphical view of the data as well as control of the shaker and the acquisition process.

A 1- to 10-Hz range for the operation frequencies of the shaker was selected to identify the first seven resonances of the dam reservoir foundation system, and an increment of 0.05 Hz was used throughout the tests. A complete frequency sweep was then carried out for each measurement station and for both positions of the shaker on the crest. Up to 200 frequency increments were necessary to cover the full range for each stations, and acceleration and hydrodynamic pressure responses were recorded during 4 seconds at a sampling rate of 1000 Hz. Finally, for each instrument configuration, ambient vibrations were also recorded for 120 seconds at a sampling rate of 100 Hz to correlate with the forced-vibration tests results. More details of the experimental procedure can be found in Proulx and Paultre [1997].

DYNAMIC PROPERTIES

The data-reduction process involves the computation of frequency responses for each measurement station. The amplitude and phase of each recorded time history were first calculated. The recorded accelerations and pressures were then corrected for both amplitude and phase modifications caused by the measurement process, and the resulting amplitudes were normalized by the exciting force. These steps were repeated for each frequency increment used during the series of tests. In this way, complete frequency response curves were calculated for acceleration and pressure responses, thus characterizing the dam-reservoir-foundation system. Figure 4a illustrates the amplitude of the acceleration frequency response obtained on the crest of block 22 for different water levels. Figure 4b illustrates the response of block 20 obtained at different elevations in the dam (crest level and three inspection galleries). All curves are plotted for the 1- to 10-Hz range used throughout the tests.

The resonant frequencies of the dam-reservoir-foundation system can be readily identified from the peaks displayed in the response curves of Fig. 4. Seven resonances were observed in the testing range and were confirmed with the results of frequency analysis of the ambient vibration recordings. These resonances are given in Table 2, along with modal damping values computed from the frequency response curves. As can be observed in Fig 4b, it is clear that, although the magnitudes differ and a logarithmic scale has been used, there is a consistency between the response curves and resonant frequencies from the crest down to the lowest gallery.

Table 2: Resonant frequencies (Hz) and modal damping (% critical)

Mode	June		July		August		September	
	Freq. (Hz)	Damp. (%)	Freq. (Hz)	Damp. (%)	Freq. (Hz)	Damp. (%)	Freq. (Hz)	Damp. (%)
1	2.07	[1.70]	2.10	[2.01]	2.05	[1.94]	1.88	[2.17]
2	2.29	[2.83]	2.29	[2.10]	2.23	[1.81]	2.14	[1.99]
3	3.17	[2.95]	3.35	[3.21]	3.38	[1.72]	3.25	[1.87]
4	4.27	[2.38]	4.40	[2.14]	4.41	[2.62]	4.10	[2.36]
5	5.56	[2.04]	5.67	[2.29]	5.80	[4.16]	5.40	[2.58]
6	6.82	[2.33]	7.04	[3.69]	7.33	[5.74]	6.79	[2.81]
7	8.32	[2.04]	8.56	[2.92]	9.03	[3.90]	8.34	[3.12]
Avg. damping		[2.32]		[2.62]		[3.13]		[2.41]

The influence of the variation of the water level in the reservoir is illustrated in Figure 4a, which shows a significant difference in the amplitude at each resonance. Also, as can be observed in Table 2, the resonant frequencies are also modified as the dam-reservoir system is modified. These frequencies are plotted against water level height in Fig. 5, and a non-linear trend is obtained for each mode. As the water level increases in the reservoir, resonant frequencies should decrease due to the additional mass added to the dam-reservoir system. However, in the lower part of the curves shown in Fig. 5, the resonant frequencies are shown to increase with the water level.

Starting with the data obtained in June and July (lowest water levels), it is believed that the increase in the resonant frequencies is associated with an increase in the stiffness of the dam due to the contraction of the construction joints under increasing hydrostatic pressure. After a certain water level is reached, sometime between the July and August tests, this phenomenon is overcome by the added mass of the reservoir and the resonant frequencies begin to decrease, as can be observed with the August and September data. This behaviour is more apparent for higher resonances, although the critical water level at which the turning point occurs is approximately the same for all modes. Similar results were reported by De Smet *et al* [1998] following a series of ambient vibration tests of Mauvoisin arch dam in Switzerland.

The resonant shapes of the dam can be plotted using the amplitude and phase information of each measurement station for a given frequency. The steady-state displacement and the phase lag, with respect to a reference accelerometer close to the shaker, were computed for all series of tests. The resulting radial displacements for each measurement position were then plotted for each resonance and are shown in Fig 6. The four shapes for each mode correspond to the four series of tests carried out at Émosson dam. Four symmetric mode shapes as well as three antisymmetric modes shapes can be observed. It should be mentioned that these shapes do not constitute true mode shapes, as the system is responding to a simple harmonic load on the crest, but they can be compared with eigenvalue analysis results. Slight node shifts are noticeable in Fig. 6 between different series of tests.

A numerical correlation study is currently underway at the CRGP, based on the experimental findings presented herein. This study is conducted with complete three-dimensional finite element models that include dam-reservoir-foundation interaction. These models are calibrated with the complete set of dynamic properties obtained at Émosson : continuous frequency response curves, resonant frequencies and their associated modal damping values, and mode shapes.

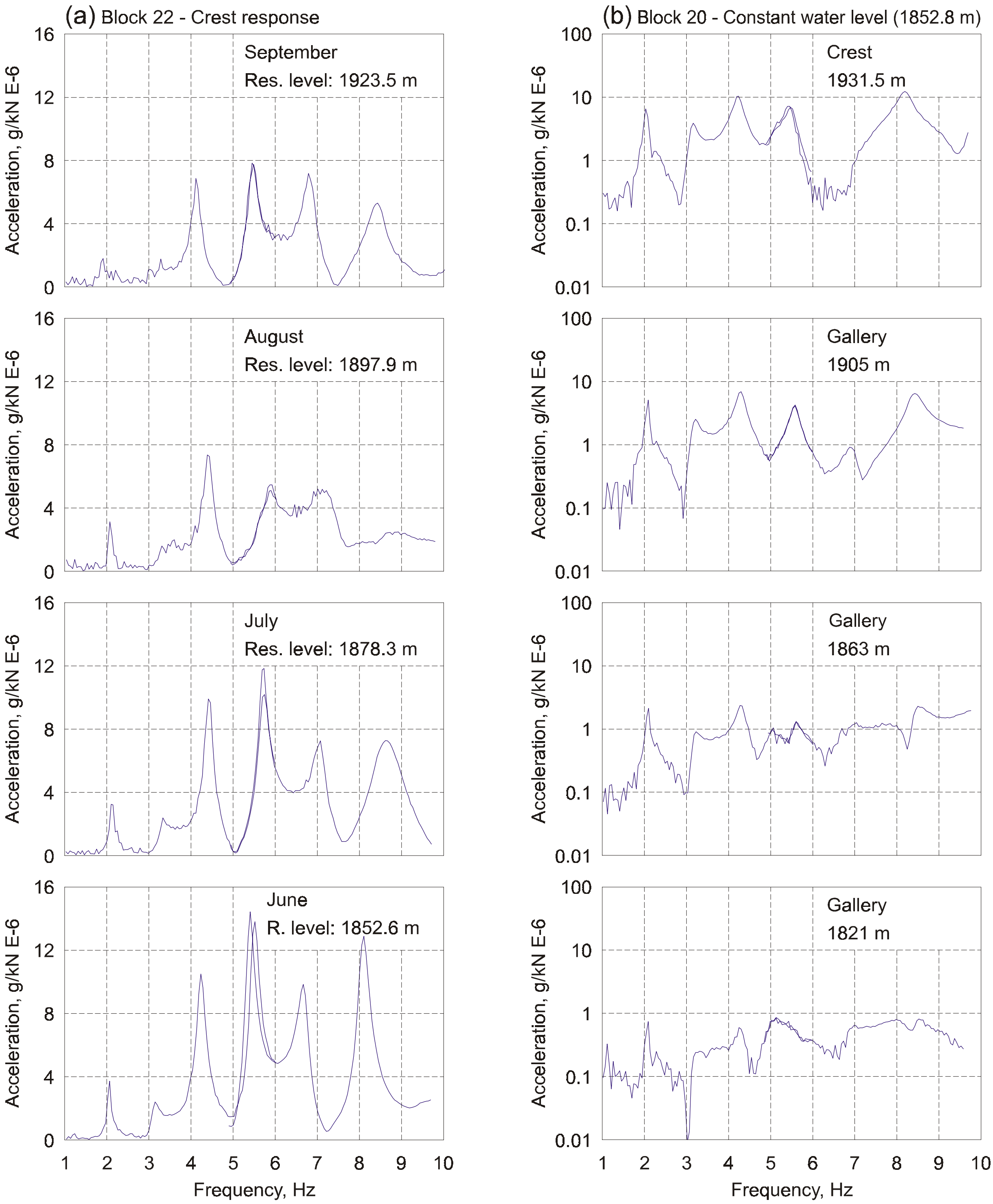

Figure 4: Frequency responses for blocks (a) 22 and (b) 20

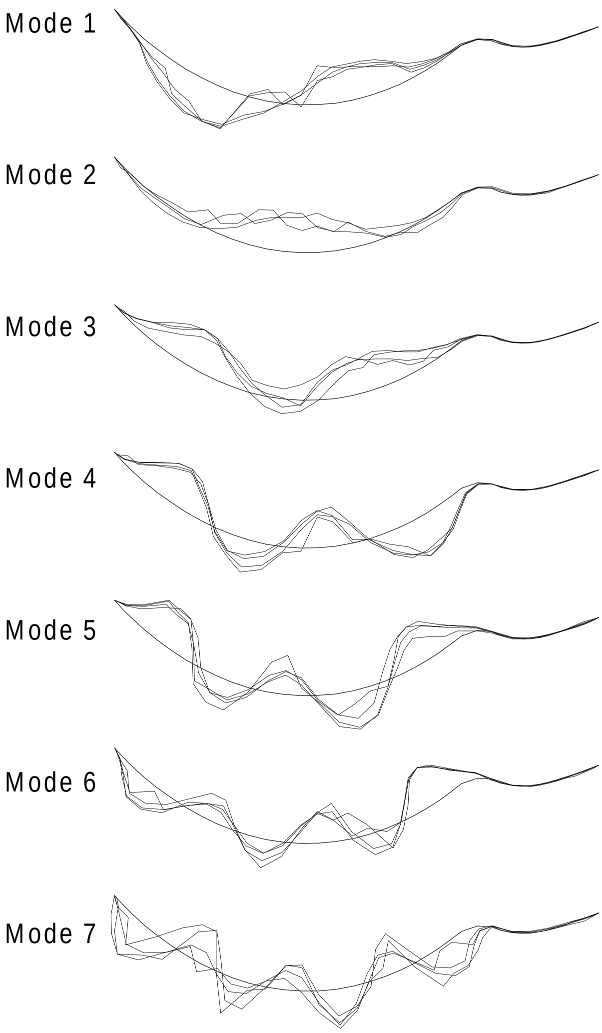

Figure 5: Experimental resonance shapes

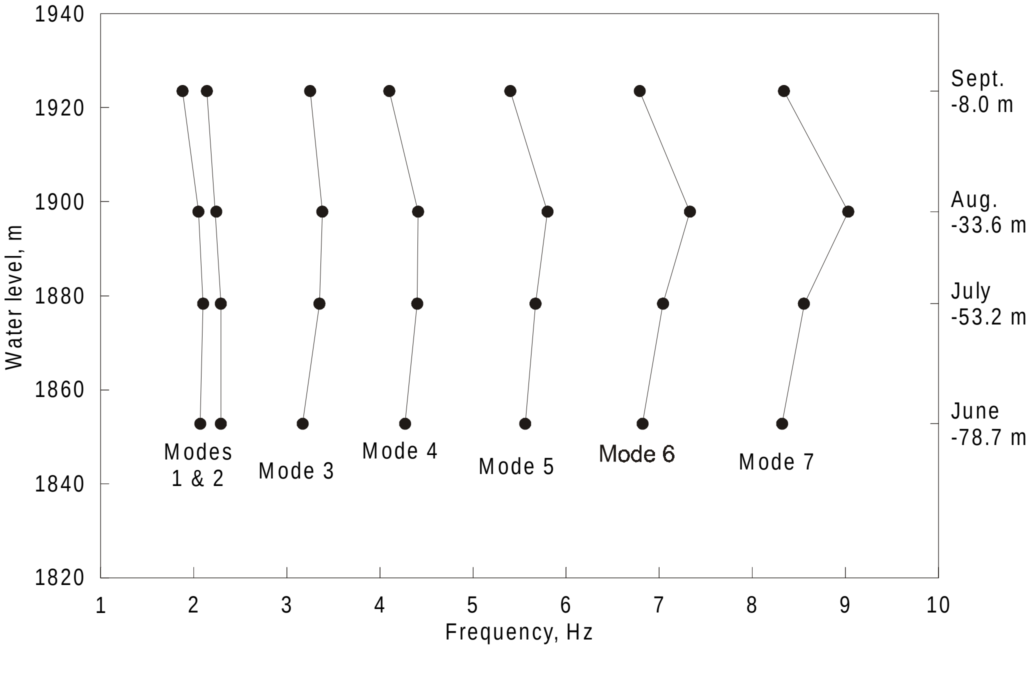

Figure 6: Effect of water level on resonant frequencies

CONCLUSIONS

Full-scale forced and ambient vibration tests were carried out on the 180-m Émosson arch dam with four different water levels. The testing program was undertaken to evaluate the effects of the reservoir level on the dynamic properties of the dam and to obtain reliable experimental data to validate state-of-the-art finite element programs used in the seismic analysis of concrete dams. Acceleration frequency responses were obtained at several locations on the dam crest and inside selected inspection galleries while the dam was subjected to horizontal harmonic loading. Hydrodynamic pressures were also recorded on the upstream face.

It was observed that, starting with an empty reservoir, resonant frequencies increased with the rising water level as the dam stiffness varied with the contraction of the construction joints under increasing hydrostatic pressure. Data also showed that, after a certain water level was reached, this trend was overcome by the added mass of the reservoir and the resonant frequencies decreased. Modal damping and resonant shapes were computed from the recorded data for all series of tests.

A complete database characterizing the dynamic behaviour of Émosson arch dam is now available to evaluate state-of-the art numerical programs developed for seismic analysis and safety evaluation of concrete dams. In particular, recordings obtained for different water levels will be used to validate three-dimensional finite element models for the dam-reservoir-foundation system as part of the ongoing research project at the CRGP. Parametric studies based on the experimental frequency responses for acceleration and hydrodynamic pressure will be used to isolate dam-reservoir and dam-foundation effects. This will lead to a better understanding of these complex interaction phenomenons, which is essential in the seismic safety evaluation of concrete dams.

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