Forced-Vibration Tests of the Daniel-Johnson Multiple-Arch Dam

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Abstract. The Daniel-Johnson dam is a 1314-m long multiple-arch-buttress dam composed of 14 buttresses and 13 arches with a central arch of 214 m high. The upper part of the dam is composed of gravity dam supported by the arches. Its height, length and the 2 million cubic meters concrete used for its construction make it the largest dam of its type in the world. Hydro-Québec and the University of Sherbrooke carried out forced-vibration tests on the Daniel-Johnson dam that are presented in this paper. The tests aimed to determine the dynamic properties of the dam-reservoir-foundation (DRF) system to be used as a basis for the update of a 3D finite element model of the system. The outstanding size and the complex geometry of the dam are of great interest in this study, because they involved challenges in the experimental work not usually found for smaller dam of simpler geometry. The forced-vibration tests involved the use of an eccentric mass shaker generating forces up to 89 kN. The accurate modal identification of the dam required four different locations of the shaker, 52 measurement stations distributed along the crest of the dam and in the inspection galleries, and overall 13 tests configurations. These tests showed that it is possible to measure useful signals along the whole crest of a very large and massive concrete dam and as far as in the very lower inspection galleries, even with a relatively small excitation force. The analysis procedure of the experimental data were however quite complicated due to the numerous close local and global modes of the multiple-arch dam and their coupling. Twenty-two vibration modes were clearly identified. A 3D finite element model of the DRF system is briefly presented, and was correlated with the measured vibration modes.

Keywords: Modal analysis · Forced-vibration test · Multiple-arch dam · Eccentric mass shaker · 3D dam finite elements model

1 Introduction

In 2002, the Dam Safety Act came into effect for all dams of 1 m-high or more located in the province of Quebec. The main provisions of this Act apply to high capacity dams. The Dam Safety Act imposes a series of actions governing the construction, alteration

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and operation of high-capacity dams. It requires that dam owners regularly maintain in good repair and monitor their structures. The Dam safety Regulation of the Act specifically requires that every high-capacity dams be designed and then be regularly verified to remain stable during the earthquake loading to which it may be subjected in the zone in which it is located. The work presented in this paper was carried out as part of a seismic safety evaluation of a unique multiple arch dam.

Hydro-Québec is a government-owned utility that owns and operates the majority of the hydroelectric powerplants in the province (more than 60). This includes the 2660 MW Manic-5 plant located on the Manicouagan River in northeastern Quebec and supplied by the high-capacity Daniel-Johnson dam (Fig. 1). This structure was constructed between 1959 and 1964 by Hydro-Québec and was inaugurated in 1969 with the hydroelectric plant. It is a multiple-arch-buttress dam composed of 14 buttresses and 13 arches with a central 214 m-high arch. The upper part of the dam is built like a 1314 m-long gravity dam that rests on top of the arches. Its height, its length and the 2 million cubic meters concrete used for its construction make it the largest dam of its type in the world. Most of the reservoir of the dam is located in a former meteor crater of about 197 000 hectares. Around 13 years were necessary to fill the 135 billion cubic meters water in the reservoir.

Fig. 1. Daniel-Johnson dam.

To support the seismic safety evaluation, Hydro-Québec decided to conduct an experimental program to evaluate the dynamic properties of the dam-reservoir-foundation (DRF) system, in collaboration with the Earthquake Engineering and Structural Dynamics Research Center (CRGP) at the University of Sherbrooke because of its experience in characterizing and modelling the dynamic behavior of large concrete dams [1–3]. The aim of this study was to get a 3D finite element model of the DRF system suitable for further seismic analyses.

The forced-vibration tests that were carried out on the Daniel-Johnson multiple-arch dam are the main focus of this paper. The tests aimed to determine the dynamic properties of the DRF system in order to be used as a basis for calibration of a 3D finite element model of the system to be used as part of a seismic safety evaluation. The dynamic tests were carried out with an eccentric mass shaker and accelerations were recorded along the 1.3 km-long dam crest and in selected galleries of the 214 m-high central arch under harmonic loading. The test procedures and data processing are presented. The modal properties (frequencies, mode shapes and damping ratios), are then detailed together with the extraction procedure, which was complicated due to the coupling of the numerous global and local modes of such a complex structure. A 3D finite element model of the dam was finally developed using the computer program ANSYS [4]. It is briefly presented with the main steps that allowed to correlate with the measured dynamic properties.

2 Forced-Vibration Tests

2.1 Test Equipment

The equipment used for the forced-vibration tests of the Daniel-Johnson dam is presented below and includes an eccentric-mass shaker, accelerometers, a data acquisition system and a computer that controls and synchronizes the excitation of the shaker and the data acquisition in order to run the tests automatically.

The main objective of the forced-vibration tests was to measure acceleration responses of the DRF system subjected to a harmonic load acting on the dam crest in a desired direction. During the tests of the Daniel-Johnson dam, this force was provided by the MK-12.8A-4600 eccentric mass shaker (ANCO, Inc.) shown in Fig. 2a. Two sets of identical weights rotating in opposite directions about parallel vertical shafts generate a sinusoidal load in only one direction. 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 (Fig. 2b). The maximal force amplitude that can be generated by the shaker is 89 kN, which limits the amount of eccentricity that can be used depending on the excitation frequency. The shaker is powered by a 3.7 kW computer-controlled electric motor at a maximum rotation frequency of 15 Hz.

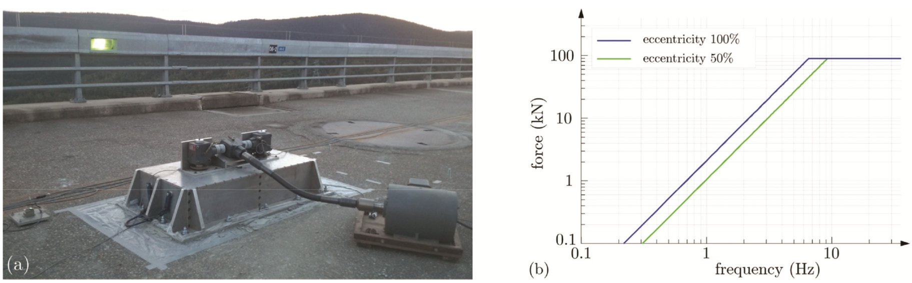


Fig. 2. (a) Eccentric mass shaker on the dam; (b) Generated excitation force.

The tests on the Daniel-Johnson dam were carried out within a frequency range of 1.0 Hz to 8.3 Hz in order to capture the desired modal frequencies determined with a preliminary numerical model of the dam structure. Considering the size of the dam and the need for a good signal to noise ratio even in the lowest frequencies of the test (where the generated harmonic force is the lowest), each sweep of the selected frequency range was completed in two steps using the maximum eccentricity (100%) for 1.0 Hz to 6.0 Hz (loads varying from 2 kN to 75 kN) and half eccentricity (50%) for 5.5 Hz–8.3 Hz (31–72 kN). The shaker was fixed to the dam 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.

The horizontal dynamic responses of the dam excited by the harmonic force of the shaker were recorded by seven low-frequency uniaxial accelerometers with high sensitivity (50 V/g). These transducers allowed to clearly measure the harmonic acceleration responses of the dam with amplitudes ranging from as low as 10^{-5} g to 2×10^{-3} g. They were successively placed in different locations along the whole crest of the dam (measuring in a direction either parallel to, or perpendicular to the exciting force) as well as along two inspection galleries in the center arch (measuring in a direction perpendicular to the arch curvature).

Seven of the eight available acquisition channels were used to record the signals sent by the accelerometers and the last channel was used to record the pulse sent by the shaker once per rotation when the force was maximum. All signals were recorded simultaneously at a sampling rate of 1000 Hz using 20 Hz low-pass hardware filters. This high sampling frequency was required to correctly measure the excitation frequency, using an unfiltered channel. Hardware amplifiers (gain of 10 and 100) were used for the accelerometer channels to improve signal to noise ratios considering the very low level of the acceleration responses.

2.2 Test Procedure

The complete characterization of the modal properties of the Daniel-Johnson dam was carried out by using four different positions of the shaker along the crest. Figure 3 shows 3D views of the dam indicating each position used for the shaker along with the associated direction of the exciting force (red arrow) and associated positions and measurement directions of the accelerometers (yellow boxes). The *X* axis is along the longitudinal direction of the dam crest and the *Y* axis is along the transversal direction of the crest. Note that the buttresses of the dam are numbered from B1 to B14. In the following paragraphs, the arches of the dams will be named by using the number of each adjacent buttress, e.g. A6-7 for the center arch, located between buttresses B6 and B7.

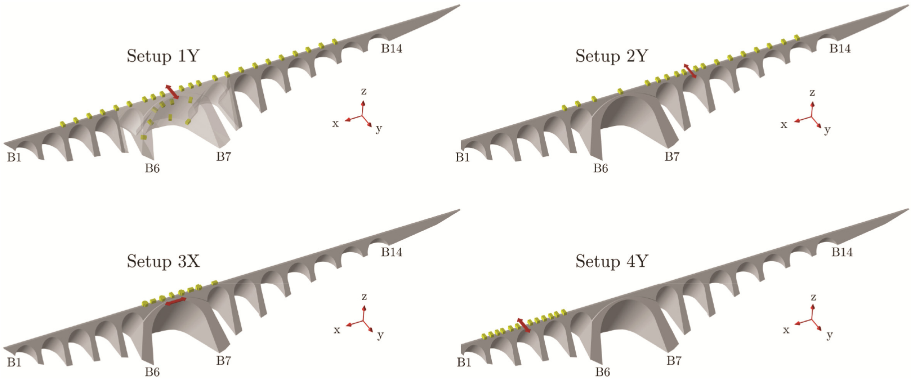


Fig. 3. Positions of the shaker and accelerometers for the four test setups.

The different positions of the excitation force were necessary to excite global modes of the structure (involving most of its 13 arches) as well as local modes (involving only few arches near the shaker) and to ensure that modes were not missed if the excitation force was located at a node of a particular mode shape. The four test setups (Fig. 3) were chosen by considering the results of a preliminary numerical analysis:

- Setup 1Y: the shaker was located at the center of the main arch (A6-7) and oriented to excite in direction *Y*; measurements were done along the crest in direction *Y*; additional measurements were done in inspection galleries 1011 and 800 of the center arch located 57 m and 122 m below the crest, respectively. This setup aimed to characterize most of the first global modes of the dam and the first local modes of the main arch and its adjacent arches A5-6 and A7-8. This position of the shaker was the most likely to produce measurable accelerations in the inspection galleries of the center arch.
- Setup 2Y: the shaker was located at the center of arch A8-9 and oriented to excite in direction *Y*; measurements were done along the crest in direction *Y*. This setup aimed essentially to get the global modes of the dam that have a node at the center of arch A6-7 and hence that were not excited during the tests of setup 1Y.
- Setup 3X: the shaker was located at the center of the main arch (A6-7) and oriented to excite in direction *X* (along the longitudinal crest axis); measurements were done only along the crest of arch A6-7 in directions *X* and *Y*. This setup aimed to characterize the global modes with a strong longitudinal component and the local modes of the center arch identified during the tests of setup 1Y that have a strong *X*-*Y* component coupling.
- Setup 4Y: the shaker was located at the center of arch A3-4 and oriented to excite in direction *Y*; measurements were done along the crest between buttresses B2 and B5 in direction *Y*. This setup aimed to characterize local modes involving the specific arch A3-4 for which a more refined 3D model was developed.

Overall, 36 measurement stations in direction *Y* were defined along the crest of the dam between buttresses B2 and B13 (some were used in several setups), 8 measurement stations in direction X along the crest between buttresses B6 and B8 and 8 in the inspection galleries of the center arch (A6-7). The seven uniaxial accelerometers used were successively moved along the crest of the dam or the inspection galleries for each setup in order to record all locations presented in Fig. 3. A total of thirteen forced vibration tests were needed to complete the experimental study. For each setup, one accelerometer, referred to as the reference accelerometer, remained in the same location, next to the shaker, to ensure the compatibility of the frequency response functions (FRF) of two successive tests.

After having positioned the shaker on the crest and placed the transducers, the procedure for a complete test included a first low-frequency sweep between 1.0 Hz and 6.0 Hz, then a change of the eccentricity of the weights of the shaker, and finally a second high-frequency sweep between 5.5 Hz and 8.3 Hz. The common range of both sweeps (5.5 Hz to 6.0 Hz), was used to verify the compatibility of the FRF measured for both successive sweeps. An increment of 0.025 Hz was used throughout the tests. A complete frequency sweep involved 200 frequency increments for the low-frequency sweep and 113 increments for the high-frequency sweep. For each increment, the signals of the accelerometers and of the shaker pulse were recorded during 4 s, to ensure that the structure reached steady-state and to obtain a sufficient number of cycles for post processing.

2.3 Test Results

The data reduction process involves the computation of frequency response functions for each measurement station and for each test setup. For each frequency increment, a least-squares curve-fitting algorithm was used to calculate the harmonic amplitude and phase of each 4-second recorded time-history. The processing steps are as follows, for each frequency increment: (i) compute the exact excitation frequency from the recorded shaker pulse and calculate the amplitude of the shaker force generated at that frequency (Fig. 2b); (ii) extract the amplitude and phase for each measured response by harmonic curve fitting; (iii) correct the amplitudes and phases for the modifications brought upon by the individual transducers and the filters in the data acquisition unit; and (iv) normalize the response by dividing the amplitude by the excitation force. These steps were repeated during both sweeps of a test to get the complete frequency response curves of the DRF system. Figure 4a and b shows some frequency responses (FRs) obtained for setup 1Y (low-frequency sweep with full lines, high- frequency sweep with dotted lines). These figures show a nearly perfect overlap of the FRs in the common frequency range of both sweeps (5.5 Hz to 6.0 Hz), which validates the testing procedure for a complete sweep from 1.0 Hz to 8.3 Hz using two different eccentricities of the shaker weights. Figure 4b shows the FRs obtained for the reference accelerometer during three of the tests done to complete testing setup 1Y. Again, the nearly perfect overlap of the curves indicates the compatibility of the results of all measurement stations obtained from different sweeps for a specific position of the shaker. It should be noted that useful and significant acceleration responses were measured for all positions of the shaker and all measurement stations (some located almost 500 m away from the exciting force), as well as for stations inside the galleries located well below the crest.

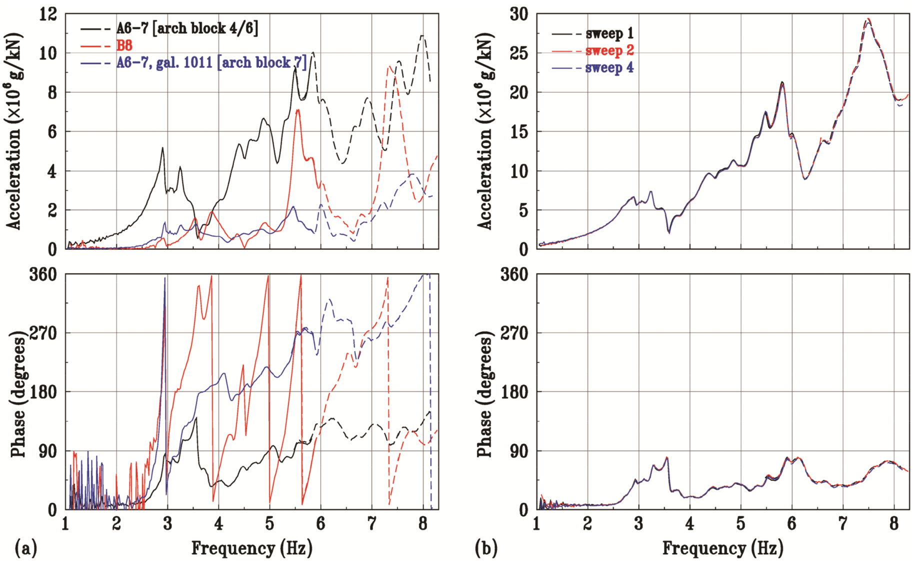


Fig. 4. Frequency responses for (a) setup 1Y (crest and galleries), (b) setup 2Y: reference accelerometer.

The identification of the resonant frequencies and associated mode shapes and damping ratios is usually straightforward using FRs obtained from forced vibration tests, if the tested structure only has well-separated modes in the tested frequency range. In the particular case of the 13-arch Daniel-Johnson dam with four testing setups, this task proved to be very difficult because of the coupling of several modes in the 1.0 Hz to 8.3 Hz range. The coupling of two close modes or more directly affects the time-history data used to compute the FRs as illustrated in Fig. 5. Figure 5a illustrates one second of a typical raw data recorded during test setup 1Y at 5.828 Hz, which is exactly the frequency of the identified mode #14 which is a relatively isolated mode. The harmonic curve fitting procedure calculated to match the recorded response is very accurate in this case. Figure 5b illustrates the same transducer response at 4.005 Hz, between both closely-spaced modes #5 and #6, where the effects of coupling of both modes are evident and where a decrease in the accuracy of the curve fitting process can be seen for this specific measurement station. As illustrated in Fig. 4a, the large number of vibration modes in the tested frequency range together with mode coupling resulted in FR amplitudes with many peaks having often poorly defined spectral bells and also in complicated evolutions of the calculated phase lags. All of these effects have several consequences on the modal identification process. It is first nearly impossible to trust the phase lag curves to identify the accurate frequency of a mode by finding the phase quadrature between the responses and the excitation force. Therefore, only the peak picking method can be used. Then, for two close modes of similar energy, mode coupling tends to provide FRs with amplitude at a given frequency resulting from a combination of both mode contributions. It can lead to either overestimated or underestimated amplitude values, which can greatly affect the accuracy of the corresponding identified mode shapes at some measurement stations. In the case of coupled modes with a dominant contribution of one of them at a specific measurement station, the spectral bell of the mode of lesser energy will practically be canceled out by the dominant contribution of the other mode. In such a case, the concerned measurement station cannot be considered to identify the mode shape of the mode of lesser energy. These phenomena explain why the mode shapes of the dam could not be extracted systematically by just using the FRs amplitudes of each measurement station at an identified vibration frequency. Thus, the authors had to manually inspect each FR for all measurement stations, for each identified modal frequency, in order to accept or discard the corresponding station, resulting in identified mode shapes where some measurement stations are missing. Finally, the same reasons also explain why in Table 1 some modal damping ratios were not identified for modes that did not result in clear spectral bells on which to apply the half-bandwidth method.

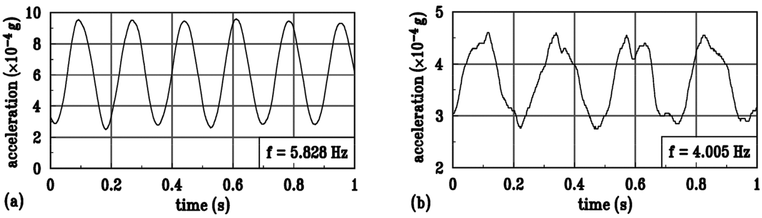


Fig. 5. Effect of mode coupling on the raw time-history response of a typical transducer in setup 1Y.

Table 1. Identified modal properties of the Daniel-Johnson dam used to calibrate the finite element model of the dam.

Mode	1	3	4			5		6		7	10		11
Test setup	3X	1Y	1Y	2Y	3X	1Y	2Y	2Y	3X	1Y	2Y	4Y	4Y
f (Hz)	2.918	3.256	3.535	3.552	3.555	3.868	3.812	4.089	4.069	4.240	4.840	4.793	5.252
σ(Hz)	0.009	0.013	0.038	0.021	0.014	0.056	0.028	0.036	0.035	0.024	0.032	0.012	0.009
ξ	1.31%	2.68%	2.04%	1.77%	1.43%	2.27%	2.94%	–	2.57%	2.11%	2.47%	–	1.63%

Considering previous remarks, the following procedure was applied for each test setup to extract the resonant properties of the dam: (i) extract all FRs peaks for each available measurement station; (ii) group all similar or identical resonant frequencies of the measurement stations to compute a mean resonant frequency f (considered as the identified modal frequency) and its corresponding standard deviation σ (considered as the experimental error); (iii) plot the resonant shapes of the dam for each resonant frequency using the amplitude and phase lag (with respect to the reference accelerometer close to the shaker) of each available measurement station; (iv) discard obviously inaccurate measurements resulting from coupling phenomena on the basis of the spectral bell definition for these specific transducers, of the appearance of the plotted mode shape and of the coherence of the resonant shapes obtained from different testing setups; (v) compute the mean modal damping ratio ξ using the half-power bandwidth method for each available measurement station at each resonant frequency.

Twenty-two (22) resonant frequencies were identified for the Daniel-Johnson dam over the range 1.0 Hz to 8.3 Hz. For practical reasons, the properties of only the eight modes used to calibrate the numerical model of the dam described in the next section are presented in Table 1 and the shapes of only four of them in Fig. 8. These modes are also among the ones identified with the lowest uncertainties, considering the effect of mode coupling explained previously. Some of the identified mode shapes were obtained only from one test setup and others from several setups. In the latter case, the final resonant shapes were extracted by verifying the compatibility of the results from the different test setups and by adequately combining their shape if necessary. Figure 6a is an illustration of the very good coherence for the shapes of mode 4 identified from test setups 1Y and 2Y and justifies that a complete mode shape can be completed by using the results of different setups. Figure 6b shows the combination procedure applied for mode 6 to get a more complete and accurate shape by using the results of setup 3X for the central arch that were not available in test setup 2Y. In Figs. 6 and 8, the modes presented correspond to the lateral and longitudinal deformations of the dam crest. The available measurement stations used to plot the shapes are indicated by filled squares (with station number) that are connected together using a quadratic interpolation for a smoother illustration of the resonant shapes.

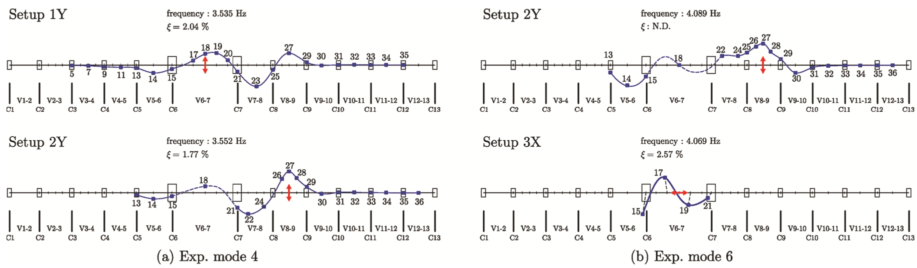
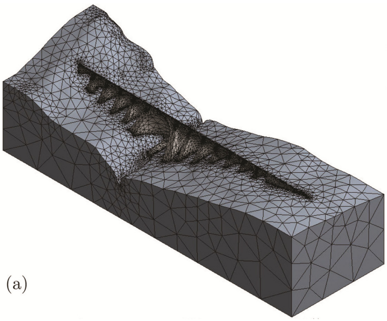


Fig. 6. Coherence and combination of mode shapes from different test setups.

3 Calibrated Numerical Model

The identified modal properties of the DRF system were used as a basis for the calibration of a finite element model of the DRF system developed with the finite element software ANSYS v14.5 [4]. The development of such a finite element model was not straightforward and included many steps to get the most appropriate model for time-history seismic analyses. The adequate model was selected based (i) on the accuracy of the modal properties compared to those measured experimentally; (ii) on the effective influence of some approximations on time-history results; and (iii) on the required computation time considering that numerous time-history calculations are required for a seismic evaluation.

Figure 7a presents the finite element model developed for the dam-foundation system. The model was developed by using the detailed 3D geometry of the dam meshed with 10-nodes quadratic tetra elements. The vertical contraction joints of the dam crest between the arches were accounted for by not connecting the nodes defining both faces of a joint. The surface rock of the foundation was represented in a realistic manner from in situ topographic data. The dam-foundation interface is made up of coincident surfaces between the dam and the foundation. The foundation dimensions were sized such that its side and bottom faces were located at a distance from the dam at least equal to the maximum dam height. Massless foundations were considered in order to simplify further seismic time-history analyses by avoiding deconvolution of the accelerograms [5]. Values of the elastic moduli for the dam concrete E_c and the rock E_r equal to 40 GPa were obtained from a preliminary parametric study.



(a)

Nb of elements	175 187
Nb of nodes	236 381
Dam-Foundation	Quadratic tetrahedron elements(SOLID 187)
Reservoir	Linear prism elements (FLUID 30)
Dam concrete	Linear elastic, E_c=44 GPa, ν_c=0.20, ρ_c=2400 kg/m^3
Rock	Linear elastic, E_r=40 GPa, ν_r=0.25, ρ_r=0 kg/m^3
Water	Incompressible, ρ_c=1000 kg/m^3, c=1.44x10^6 m/s
Bound. Cond. Reservoir	Zero gradient pressure on all sides of reservoir, except on dam-reservoir interface; zero pressure on the upper side of the reservoir.
Dam-Foundation	Fixed conditions in the three directions on all sides.

(b)

Fig. 7. Features of the calibrated finite element model of the dam-foundation-reservoir system.

A detailed analysis was carried out to select the appropriate modelling method for the impounded reservoir of the DRF system. Two widely used approaches were considered: the direct finite element modelling of the reservoir as well as the added mass approach [6]. For the finite element approach, fluid linear or quadratic prism elements were used to mesh the reservoir, with both compressible and incompressible water models. The added mass approach is a simplified modelling assumption of the reservoir that allows to greatly reduce the required calculations, compared to a complete finite element model of the reservoir, by significantly reducing the number of elements. However, it requires that the added masses be determined independently for each direction, and that time-history analyses be performed in each direction independently. Modal analyses and a benchmark seismic time-history analysis carried out on the DRF system for the different models of the reservoir showed that: (i) compressibility of water may affect the predicted vibration modes of the DRF system, but it has only a slight effect on the seismic time-history results; (ii) the use of linear fluid elements produces dynamic results similar to those obtained with quadratic ones, but with half the computation time; (iii) added mass models can provide satisfactory estimations of the maximum time history responses with significantly shorter computation times per analysis, but they are not the most appropriate for such a complex arch dam, because it requires that each direction be studied independently.

The authors concluded that the best approach in terms of accuracy of the dynamic behavior and of computation time was to model the reservoir by finite element with linear acoustic fluid elements with incompressible water. The resulting finite element model of the DRF system was finally refined by adjusting the preliminary calibrated value of the elastic modulus of the dam concrete to $E_c = 44$ GPa. All features of the final finite element model are given in Fig. 7b. The whole process allowed to efficiently correlate eight of the identified experimental modes (four modes illustrated in Fig. 8), including frequencies and mode shapes.

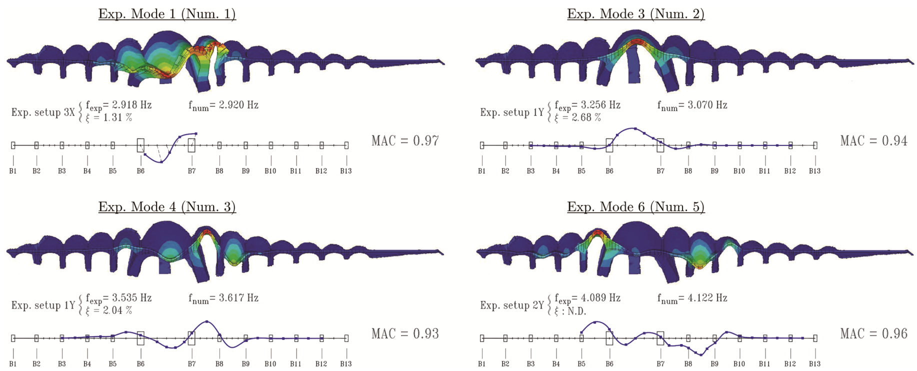


Fig. 8. Comparison of four of the eight experimental and numerical mode shapes used for model updating.

4 Conclusions

This paper presented the experimental modal analysis of the Daniel-Johnson multiple-arch concrete dam. This dam, composed of 14 buttresses and 13 arches with a 214 m-high central arch and a 1314 m-long crest is among the largest multiple-arch dams in the world. The outstanding size and the complex geometry of the dam lead to challenges in the experimental work. Forced-vibration tests were carried out on the dam, and involved the use of an eccentric mass shaker located at several positions along the crest of the dam in order to characterize the modal properties of the DRF system. These tests showed that it is possible to measure useful signals along the whole crest of a very large dam and as well as in the lowest inspection galleries, even with a relatively small excitation force. The analysis procedure of the experimental data were however quite complicated due to the numerous closely spaced local and global modes of the multiple-arch dam. Mode coupling provided difficulties in the analysis of the frequency response functions that could not be completed automatically. A particular modal extraction procedure was applied, including manual choices about the reliable measurement stations for each mode to extract accurate mode shapes. The results from the four different test setup corresponding to four different locations of the shaker were also combined for specific resonant frequencies to get complete mode shapes. Twenty-two vibration modes were finally identified, including modal frequencies, mode shapes and modal damping ratios.

The identified modal properties of the DRF system were used as a basis for the calibration of a finite element model of the DRF system developed with ANSYS v14.5. The modelling work was carried out on the basis of a detailed 3D dam-foundation geometry. Different methods were considered to model the interactions of the dam-foundation system with the reservoir, including several finite element models of the reservoir and the added mass approach. From modal and time-history analyses, the authors concluded that a finite element model of the reservoir with incompressible water and linear elements was the most suitable model for the seismic analyses of the complex Daniel-Johnson dam, both in terms of accuracy and of computation time. The whole process allowed to efficiently correlate the model results with eight of the identified experimental mode shapes and frequencies, making the finite element model suitable for the subsequent seismic safety analyses.

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