Experimental and numerical investigation of dam–reservoir–foundation interaction for a large gravity dam

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Abstract: Forced-vibration tests were completed on Outardes 3 gravity dam, located in northeastern Quebec, Canada. The experimental results were subsequently used as a basis for a numerical correlation study to evaluate the performance of state-of-the-art finite element programs for earthquake analysis of concrete dams. The experimental procedure is presented and involved the recording of acceleration responses on the 84-m-high dam under harmonic loading. Hydrodynamic pressures were also recorded at several locations in the reservoir, up to a distance of 90 m from the dam face. Extensive studies were carried out with two- and three-dimensional models. The effects of several calibration parameters are discussed, including the dam and foundation stiffnesses and damping as well as water compressibility. Numerical results are compared with complete frequency responses for accelerations and pressures obtained on site. It is demonstrated that the two-dimensional approach could only predict the fundamental resonance of the system, and that a three-dimensional model for the dam–reservoir–foundation system including water compressibility could reproduce the experimental behaviour with accuracy. This project complements similar work carried out on a large arch dam, and constitutes direct evidence of water compressibility effects for a large gravity dam.

Key words: forced-vibration tests, gravity dam, dam–reservoir–foundation interaction, frequency responses, acceleration, hydrodynamic pressure, seismic analysis.

1. Introduction

The dynamic behaviour of large dams has been widely studied in the past 20 years. Several analytical methods were developed to take into account the interaction phenomena occurring between the dam, the reservoir, and the foundation in the seismic analysis of such systems. Research programs were undertaken to create an experimental database to validate available numerical models, during which large-scale dynamic tests under forced vibrations were carried out on different concrete dams worldwide. These tests remain the most reliable means of evaluating dam–reservoir–foundation interaction and water compressibility effects.

In spite of the fact that a considerable amount of research has been directed towards the modelling of the dynamic response of large dams, only a limited number of well-documented correlation studies using experimental data are available. Moreover, some technical problems in these experimental programs were reported, especially when hydrodynamic pressure measurements were involved (Hall 1988). However, developments in testing procedures, data acquisition systems, and new solid-state hydrodynamic pressure transducers have spawned reliable and well-detailed experimental studies, based on forced-vibration testing, on Morrow-Point arch dam in the U.S. (Duron and Hall 1988), and recently on Outardes 3 gravity dam in Canada.

Dam–water interaction is often neglected or simplified in the evaluation of the seismic performance of concrete dams, as
the effects of water compressibility lead to complex frequency-dependent problems. Using state-of-the-art numerical models, which take into account energy dissipation by wave propagation in the reservoir, parametric studies have shown that water compressibility and refraction of pressure waves at the reservoir–foundation interface could considerably modify the overall system response (Chopra 1988). Although some experimental results are available, there is a lack of complete measurement data including hydrodynamic pressures in reservoirs to corroborate these findings. The first direct evidence of water compressibility effects for an arch dam was observed at Morrow-Point and the importance of accurately modelling the reservoir was demonstrated in the resulting correlation study (Duron and Hall 1988; Hall 1988).

This article presents large-scale forced-vibration tests on Outardes 3 gravity dam and the evaluation of the performance of state-of-the-art numerical models used for earthquake analysis of concrete dams, on the basis of comparisons with experimental findings. This research project constitutes the first complete series of tests on a gravity dam including hydrodynamic pressure measurements in the reservoir, as well as the first correlation study with a three-dimensional numerical model including water compressibility. Its main objectives were (i) to carry out forced-vibration tests on Outardes 3 dam; (ii) to establish an experimental database for gravity dams including water pressure measurements; (iii) to evaluate the performance of state-of-the-art two- and three-dimensional finite element programs for seismic analysis in predicting the experimental results; and (iv) to study the effects of dam–reservoir interaction including water compressibility for gravity dams.

Figure 1 shows an aerial view of Outardes 3 dam with full reservoir. Part of the Manicouagan-Outardes hydroelectric complex, the dam was chosen for its simple and symmetric geometry. It is located on the Outardes River in northeastern Quebec, 100 km north of Baie-Comeau, between Outardes 2 and Outardes 4 dams. Completed in 1968, it is the largest gravity dam in the province, with 19 unkeyed monoliths, a maximum crest height of 84 m, and a crest length of 300 m. Inspection galleries are located at 20 and 57 m below the crest, as well as at a variable height for the foundation level. The width is 4.6 m at the top and 79 m at the base of the largest monolith. The spillway and hydroelectric power plant are located 2 and 3 km away from the dam, respectively. Water level was at maximum height during all tests, which were carried out in summer time.

2. Forced-vibration tests of dams

The U.S. Panel on Earthquake Engineering for Concrete Dams was created to study the seismic performance of concrete dams and to focus the efforts of the scientific community involved in this field (NRC 1990). The themes discussed included the evaluation of linear and nonlinear seismic responses, the gathering of experimental data through dynamic tests and recordings of the effects of seismic events, and the evaluation of the seismic performance of existing dams. The lack of analytical and experimental correlation studies was recognized and the need to generate a database with carefully planned testing programs was stressed. It was also observed that large-scale forced-vibration tests, including hydrodynamic pressure measurements, were the most efficient means to study dam–reservoir interaction.

Hall (1988) published an extensive review on the experimental and analytical behaviour of concrete dams. The lack of reliable and complete experimental data, especially for gravity dams, was put forth, as well as the need to study dam–reservoir interaction. Several experimental methods have been used to evaluate the dynamic properties of large dams, including ambient vibration tests with modal techniques and the use of explosives. Frequencies and mode shapes have been obtained.
successfully and compared with finite element predictions. However, forced-vibration tests under a sinusoidal force generally lead to well-defined frequency response curves, and hence to a better estimate of modal damping. The performance of numerical models can then be evaluated, based not only on the prediction of resonant frequencies and mode shapes, but also on the reproduction of the amplitude and phase of frequency responses measured throughout the dam and reservoir. With modal techniques, transfer functions are usually evaluated for the dam only, and these methods are therefore not appropriate for the evaluation of dam–reservoir interaction. Hence, most correlation studies carried out in the past neglected key parameters, including the contribution of the impounded water, water compressibility, damping arising from wave absorption at the bottom of the reservoir, and dam–foundation interaction.

The project undertaken on Outardes 3 sets out to create a reliable database for a subsequent numerical study, which not only evaluates the effects of dam–reservoir interaction, but at the same time compares the performance of two- and three-dimensional modelling. It is generally assumed that water compressibility effects will play an important role if the ratio of the fundamental frequency of the reservoir and that of the dam with an empty reservoir (for symmetric modes) is below 1.5. Using a preliminary finite element model, and the empirical formula used to determine the fundamental reservoir frequency, \( f_\text{w} = C/AH \) (where \( C \) is the wave propagation velocity in water and \( H \) is the average reservoir height), a value close to 1 was obtained for Outardes 3, indicating that the reservoir contributions could not be neglected for this gravity dam.

3. Experimental procedures

As the quality of experimental data is highly dependent on the testing procedures, a thorough knowledge of all characteristics of the measuring process is necessary to obtain reliable test results. The equipment used during the experimental program at Outardes 3 is discussed below and included an eccentric-mass shaker, accelerometers, hydrophones, a computer-controlled data acquisition system, and appropriate connection cables.

3.1. Eccentric-mass shaker

The main objective of forced-vibration tests is to measure acceleration and pressure responses of the dam–reservoir–foundation system subjected to a harmonic load acting on the dam crest. This force is provided by the MK-12.8A-4600 eccentric-mass shaker (ANCO, Inc.) shown in Fig. 2. Two sets of identical weights rotating about parallel vertical shafts generate 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 tests on Outardes 3 were completed with a frequency range of 4 to 10 Hz, with loads varying from 6.7 to 84 kN. The shaker was fixed to 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.

A three-dimensional upstream view of Outardes 3 dam is shown in Fig. 3, where the 19 monoliths are identified by letters. The instrumentation setup is schematized, and the shaker locations are indicated with large double-headed arrows. Three positions, blocks F, H, and M, were chosen to excite symmetric as well as antisymmetric modes of the dam. Complete frequency sweeps were carried out for each position.

3.2. Accelerometers

Low-frequency servo-accelerometers were used to record horizontal acceleration in a direction parallel to the exciting force. Each instrument was mounted on an aluminum plate...
with three levelling screws. The accelerometers act as low-pass filters with a 50-Hz cutoff frequency with a response as shown in Fig. 4.

A total of 10 accelerometers were successively placed in the centre of every block on the crest, as well as in the three inspection galleries for blocks F, I, and M. Accelerometers were also placed on the downstream face of the dam for block I, in order to obtain a complete profile of the resonance shape of the cross section. Relative joint motions were also investigated by placing accelerometers on both sides of six selected joints on the crest, and by swapping each pair of instruments to eliminate calibration error problems.

3.3. Hydrophones

An array of solid-state AcquaSense hydrophones was used to record hydrodynamic pressures at several locations in the impounded water. The array consists of eight hydrophones mounted on a 300-m cable at 15-m intervals, starting from one end for a total measurement depth of 120 m. As shown in Fig. 4, each unit acts as a high-pass filter with a 4-Hz cutoff frequency. At full amplitude, the reference pressure is $15.7 \times 10^{-5}$ V/Pa, which translates to a resolution of ±0.1 Pa, taking into account the data acquisition system voltmeter characteristics.

A cable network was used to support the hydrophone arrays, as illustrated in Fig. 3. A cable parallel to the crest was first set up between both shores of the reservoir, 90 m away from the dam face. Three cables, perpendicular to the crest, were placed to join blocks F, H, and M (where the shaker was located) to the first cable. Pressure measurement stations were spaced at 30-m intervals along the three perpendicular cables, starting from the dam face. For each station, the hydrophone array was attached to the perpendicular cable to have the last submerged hydrophone at 15 m below the surface. In this way, five units were used and hydrodynamic pressures were recorded at approximately 15-, 30-, 45-, 60-, and 75-m depths.
The last hydrophone was located approximately 60 m below the surface for blocks F and M.

### 3.4. Data acquisition system

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. Figure 4 shows the frequency response of the 20-Hz low-pass hardware filters used during the tests. A computer program developed during this research work provided a graphical view of the data as well as control of the acquisition process.

### 3.5. Testing procedure

After having positioned the shaker on the crest, rapid sweeps were carried out to obtain an estimate of the resonant frequencies. A 4- to 10-Hz range for the operation frequencies of the shaker was then selected to identify the first four resonances of the dam–reservoir–foundation system, and an increment of 0.05 to 0.1 Hz was used throughout the tests. A complete frequency sweep was then carried out for each measurement station and for all three positions of the shaker on the crest. Up to 70 frequency increments were necessary to cover the full range, and samples were recorded during 4 to 8 s at 1000 Hz.

A time history of raw data is shown in Fig. 5 where the top graphs illustrate the hydrodynamic pressure response at 15- and 75-m depths off block H along the dam face. These samples are shown for 1 s and were recorded when the shaker was operating at 7.62 Hz. The acceleration response measured on the downstream face, 20 m below crest level, is displayed on the third graph, and the shaker pulse, used to compute the exact operation frequency, is shown on the bottom graph. The difference in phase between pressure and acceleration responses is apparent.

Windy conditions on the reservoir can considerably affect hydrodynamic pressure measurements, since the supporting cable network is influenced by small waves. Consequently, most recordings in the reservoir were obtained at night time or at dawn, when the water surface was calm.

Using a depth sonar, a mapping of the reservoir bottom was completed at the end of the tests, for each pressure measurement station and at a distance of 275 m from the dam face along the centre cable. These data were then used to create a three-dimensional reservoir finite element model. It was also found that when comparing the depth measurements with initial topographic surveys at construction time, very little sediment deposits were present at the bottom of the reservoir.

Concrete samples were taken at several locations inside inspection galleries and on the downstream face. Compression tests on these samples indicated an average elastic modulus of 28 000 MPa, with values ranging from 21 000 to 33 000 MPa. Observed aggregate sizes varied from 10–20 mm, for the topmost gallery, to more than 50 mm at the foundation level.

### 3.6. Evaluation of frequency responses

The data-reduction process involves the computation of frequency responses for each measurement station, to be used in the evaluation of the dynamic properties of the dam–reservoir–foundation system, as well as in the subsequent numerical correlation study. A least-squares curve-fitting algorithm was used to calculate the amplitude and phase of each recorded time history. The responses of the instruments were taken into account, and the recorded accelerations and pressures were
corrected for both amplitude and phase modifications caused by the measurement process.

The processing steps are as follows: (i) compute the exact excitation frequency from the recorded shaker pulse and calculate the amplitude of the force generated at that frequency; (ii) compute the amplitude and phase for each measured response for the current frequency; (iii) correct the amplitude and phase for the modifications brought upon by the individual instruments and the filters in the data acquisition unit according to Fig. 4; and (iv) normalize the response, dividing the amplitude by the excitation force. These steps were repeated for each frequency increment used during the tests. In this way, complete frequency response curves were calculated for acceleration and pressure responses, thus characterizing the dam–reservoir–foundation system. Figure 6a illustrates the amplitude and phase of the acceleration response obtained at block H (approximate centre of the dam) with the shaker on the same block. Figure 6d shows the hydrodynamic pressure response for depths of 15 to 60 m at a distance of 60 m from block F.
3.7. Dynamic properties of the dam–reservoir–foundation system

The resonant frequencies of the dam–reservoir–foundation system can be readily identified from the peaks displayed in the response curves of Fig. 6. Four resonances were identified at 4.9, 6.2, 7.6, and 9.1 Hz, respectively. The corresponding modal damping ratios were evaluated with the half-power bandwidth method and values of 2.6%, 2.1%, 2.2%, and 3.1% were found.

The second resonance, which does not appear distinctly in Fig. 6a, was made evident by moving the shaker at block F or M. As shown below, this resonance is associated to an anti-symmetric shape with a node in the centre of the crest, close to block H, corresponding to the first shaker position. The response obtained for block G, with the shaker located at one of the quarter points (block F), is displayed in Fig. 6b. Here, the second resonance stands out, and the corresponding modal damping ratio can be computed. Figure 6c shows the gallery response, and it is clear that, although the magnitudes differ and a logarithmic scale has been used, there is a consistency between the response curves from the crest down to the foundation level.

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. The resulting displacements for each position were then plotted for each resonance. The shapes obtained are compared with the analytical results from the numerical correlation study presented in the next section (Fig. 19). These do not constitute true mode shapes, as the system is responding to a simple harmonic load on the crest.

It is interesting to compare acceleration responses from both sides of a selected joint on the crest (all joints are unkeyed). Figure 7 illustrates the relative peak accelerations measured at the centre and on the boundaries of blocks L and M. A slight difference in motion becomes apparent for the higher resonances, especially for the second antisymmetric mode where the two blocks are in fact slipping in opposite directions under the harmonic load. An evaluation of these motions in winter conditions, with lower temperatures causing joint openings due to individual block contractions, would give more insight into this behaviour.

4. Numerical correlation study

The experimental results obtained on Outardes 3 were used to evaluate the performance of two state-of-the-art finite element programs for earthquake seismic analysis of concrete dams. Both programs rely on a substructure approach, where dam–reservoir–foundation interaction is modelled and water compressibility is considered, and where the equations of motion are solved in the frequency domain. The EAGD-84 program (Fenves and Chopra 1984b) was developed for a two-dimensional analysis of concrete gravity dams, and the EACD-3D program (Fok et al. 1986) uses a three-dimensional approach for concrete dams. These were modified during the research project in order to compute frequency responses that would be generated by a harmonic load on the crest, and to obtain direct comparisons between observed behaviour and numerical predictions.

4.1. Two-dimensional modelling

Figure 8 shows a cross section of a centre block of Outardes 3 dam which was modelled with the EAGD-84 program. In this procedure, a finite element mesh is created for the dam only, and the reservoir and foundation are modelled as frequency-dependent forces acting on the upstream face and bottom of the dam, respectively. The analytical procedure implemented to perform a seismic analysis described in Fenves and Chopra (1984a), which constitutes an extension of the procedures developed in Hall and Chopra (1980) and Chopra et al. (1980), is briefly summarized herein.

4.1.1. Analytical procedure

The equations of motion for the dam are written in the standard matrix form, with the excitation force represented by the ground motion and an added term accounting for both hydrodynamic and dam–foundation interaction forces. These equations are rewritten in complex notation, with a constant hysteretic damping factor for the dam, and are solved in the frequency domain for a unit harmonic acceleration at the base of the dam in the horizontal and (or) vertical directions.

The foundation medium is treated as a viscoelastic half-plane. A frequency-dependent impedance matrix is computed for specified foundation-rock properties (elasticity, density, Poisson’s ratio, hysteretic damping), and added to
the system by expressing the foundation interaction forces in terms of the displacements associated with the degrees of freedom at the base of the dam. The dam–foundation eigenvalue problem is then solved and the system is reduced to a specified number of generalized coordinates.

The reservoir is considered to be of constant depth and to extend infinitely in the upstream direction. A closed-form solution is developed for the Helmholtz equation for small amplitude wave propagation in a two-dimensional irrotational fluid medium. The solution to this equation is the hydrodynamic pressure as a function of space and frequency, and can be separated in a component arising from the rigid-body earthquake-induced motion of the dam and components due to relative motion of the upstream face of the dam in each mode. This solution leads to an eigenvalue problem for the reservoir itself, which is to be solved for each excitation frequency considered in the analysis. Added damping arising from wave absorption by the deposit layers on the reservoir bottom is modeled by a parameter, $\alpha$, the value of which varies from 0 to 1 for complete absorption to complete reflection of waves, the latter case corresponding to a reservoir with very little alluvium deposits. The frequency-dependent hydrodynamic forces are then computed from the pressure values at the dam face and added to the generalized system.

The equations are simultaneously solved for the frequency-dependent generalized coordinates. The eigenvectors of the dam–foundation system do not uncouple the equations, as there are off-diagonal terms arising from dam–reservoir and dam–foundation interactions. A Fourier transform of the ground motion is then computed and multiplied by the generalized coordinates. This product is transformed back to the time domain, and a modal summation is carried out to obtain the displacements for the dam mesh.

4.1.2. Performance of the two-dimensional approach

This procedure was modified to take into account a sinusoidal excitation force acting on any degree of freedom of the dam mesh, thus simulating the shaker used in the experimental investigation. The rigid-body component of the hydrodynamic pressure solution vanishes, and the harmonic load vector has a nonzero term at the specific shaker location. Here, the modal summation is carried out in the frequency domain to directly obtain the frequency response of any given degree of freedom of the dam mesh. The magnitude of the force is taken equal to unity in order to obtain normalized responses that can be compared with experimental findings.

The two-dimensional (2-D) model illustrated in Fig. 8 was used to carry out the numerical correlation with the test results obtained at Outardes 3. The amplitude of the frequency response for crest acceleration, calculated with the modified version of EAGD-84, is displayed in Fig 9. This response was computed for the dam on rigid foundation (no foundation interaction) with empty reservoir (no reservoir interaction). The elastic modulus of the dam was taken as the average value obtained from testing of core samples, as described above. A constant hysteretic damping of 3% was considered.

All responses are normalized with respect to the excitation force used during the tests. The effective force transmitted by the shaker to the 2-D model of a given block was calculated with the following procedure. The static displacement of the crest of the 2-D model of the block was first computed for a unit load applied on the crest. The static displacement of the same block under a unit load applied at the same location was then calculated with a 3-D model of the dam. The effective force was taken as the ratio of the 2-D to 3-D static displacements.

Accelerations obtained with plane-strain and plane-stress idealizations are shown in Fig. 9, with similar results and a slightly stiffer response for the plane-strain assumption. Also shown for comparison are the results obtained on site at the centre block. It can be observed that the resonant frequencies and the amplitude are overestimated with this approach, which is often used for gravity dams. The necessity to include reservoir and foundation effects is clearly demonstrated.

Figure 10 shows the effects of dam–reservoir interaction, including reservoir bottom absorption, on the overall response. With water compressibility, the fundamental resonant frequency and amplitudes are reduced by 1.35 Hz and 70%, respectively, owing to the added mass and damping to the system. When the excitation frequency becomes equal to the eigenvalues of the reservoir, which are related to the wave propagation velocity in water, the response takes infinite values for the dam–reservoir model. If water compressibility is neglected, the wave propagation velocity tends towards infinity, and the complex-valued terms added to the system equations become real for all values of the excitation frequency. This corresponds to Westergaard’s solution of added masses on the upstream face of the dam to represent dam–water interaction (1933). As shown in Fig. 10, this widely used approach reduces the fundamental frequency, but still underestimates damping added to the system, and therefore seems inappropriate for Outardes 3 dam.

The effects of several parameters were studied, including foundation properties and the wave absorption parameter, $\alpha$. The best results are shown in Fig. 11. The elastic modulus of the foundation rock, $E_f$, at the Outardes 3 site varies from two to three times that of the dam, $E_c = 28 000$ MPa, according to geologic surveys at construction time. A value of $E_f = 2E_c$ was
found to yield the best results with a hysteretic damping factor of 10% for the foundation. Reservoir damping was best modelled with $\alpha = 0.9$, which is consistent with the reservoir depths measured on site, suggesting a thin layer of deposits on the bottom of the reservoir. The amplitude of the fundamental resonance is in agreement with experimental results, but the frequency is underestimated by 20%. As shown in Fig. 11, an increase in the dam stiffness by 10–20% fails to reproduce this frequency and reduces the amplitude at resonance. An increase of the foundation stiffness up to $E_f = 3E_c$ does not improve the analytical correlation. Moreover, the trend in the experimental response is not reproduced for higher frequencies. It is apparent that the 2-D model is limited to an approximate prediction of the fundamental frequency. The calibration of numerical methods is often carried out with 2-D models for gravity dams, including simplified approaches for dam–water interaction, and is generally limited to the first resonance. This seems inadequate to reproduce frequency response functions, as the higher frequencies cannot be predicted because of the three-dimensional nature of the observed mode shapes.

### 4.2. Three-dimensional modelling

The complete 3-D model developed for Outardes 3 gravity dam is shown in Fig. 12. Finite element meshes were created for the dam, as well as parts of the reservoir and foundation. These three distinct models were used with EACD-3D for a
substructure analysis. The foundation is massless and its stiffness matrix is condensed at the dam–foundation interface. A more recent version of the program, EACD-3D-95 (Tan and Chopra 1995), includes foundation mass, but the computational effort involved is still prohibitive at this time and the software is not yet available for distribution. The impounded water is modelled with a 3-D finite element mesh for a finite region of irregular geometry, with a transmission plane between this 3-D mesh and an optional infinite region for large reservoirs. The finite elements used in the reservoir have one degree of freedom per node representing hydrodynamic pressure. The analytical procedure for the 3-D seismic analysis is described in Fok et al. (1985), and the finite element formulation used for the reservoir is detailed in Hall and Chopra (1980). A brief summary is given in the following subsection.

4.2.1. Analytical procedure
The stiffness matrix of the foundation mesh is first computed and a static condensation is performed for the degrees of freedom located on the dam–foundation interface. The mass and stiffness matrices of the dam are then evaluated and the eigenvalue problem of the dam–foundation system is solved to reduce the frequency domain formulation to a specified number of generalized coordinates.

The solution of Helmholtz equation for wave propagation is calculated in matrix form for both the finite and infinite regions of the reservoir. These matrices are comparable to stiffness, mass and damping, for a solid medium. The load vector acting on the reservoir is separated into components generated from the relative dam motion in each mode considered in the analysis and components arising from ground motion in the three global coordinates. An eigenvalue problem is solved for each value of the excitation frequency for the infinite region, and an algebraic equation is solved for the pressures in the finite region. The hydrodynamic forces acting on the dam–reservoir interface are computed from these pressures and added to the reduced frequency-dependent equations.

Fig. 11. Influence of dam stiffness (2-D model).

Fig. 12. (a) Complete 3-D model of the dam–reservoir–foundation system; (b) view of the right-hand side along plane of symmetry.
which are solved for the generalized coordinates. The seismic response can then be computed by taking the Fourier transform of the ground motion, as described above for the 2-D analytical procedure.

4.2.2. Performance of the 3-D approach
Modifications analogous to those implemented in EAGD-84 were added to the EACD-3D program to complete the 3-D numerical correlation with experimental data. In this case, it was also possible to evaluate frequency responses for hydrodynamic pressure, and compare these with the results obtained in the reservoir. An extensive study was completed characterizing the effects of the following parameters on the frequency responses: 

1. the elastic modulus of the dam;
2. its structural damping;
3. the elastic modulus of the foundation;
4. water compressibility; and
5. wave absorption at the bottom of the reservoir. The influence of water level as well as the extent of the foundation and reservoir models was also investigated.

Figures 13 and 14 show the effects of the foundation and reservoir, respectively, on the frequency response at the crest level on block G with the shaker positioned on block H. The calibration of the 3-D model was based on the complete frequency response. Generally, researchers have used individual resonant frequencies for numerical correlation studies, or calibrated the models for each resonance separately, with phase comparisons almost always ignored. However, the reliability of the numerical model should be evaluated for the full

Fig. 15. Influence of water compressibility (3-D model).

<table>
<thead>
<tr>
<th>$f$ (Hz)</th>
<th>$\xi$ (%)</th>
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<td>12.58</td>
<td>1.69</td>
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*Modal damping, in percent of critical, evaluated from frequency response curves with half-bandwidth method.
†Incompressible water.
‡Compressible water.

Table 1. Experimental and numerical frequencies.

<table>
<thead>
<tr>
<th>Dam only</th>
<th>Dam–foundation</th>
<th>Dam–reservoir–foundation$^\dagger$</th>
<th>Dam–reservoir–foundation$^\ddagger$</th>
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<tr>
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<td>1.69</td>
<td>12.19</td>
<td>1.86</td>
<td>10.80</td>
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frequency range, taking into account both the amplitude and the phase of the response at several locations on the dam and in the reservoir.

It is clear from Fig. 13 that the inclusion of the reservoir is necessary, as the responses obtained for the cases of the dam on rigid or flexible foundations overestimate the frequency and amplitude, and do not reproduce the observed behaviour. The inclusion of the flexible foundation reduces resonant frequencies, but the massless model, which eliminates lower frequency additional modes for the foundation, does not add
enough damping into the system, and the amplitudes at resonance are overestimated without reservoir interaction. The variation of the foundation elastic modulus within a reasonable range of two to three times the dam modulus does not improve the numerical predictions, with only 0.1 Hz and 2% differences for frequency and amplitude, respectively.

The effects of the reservoir, with compressible water, are displayed in Fig. 14 and an excellent match is obtained for the fundamental frequency. Moreover, this is the only way to produce good agreement over the full frequency range, not only for the system resonances but also for modal damping and phase. Table 1 summarizes the analytical predictions for the 3-D model, and the effects of the calibration parameters are described below.

Figure 15 illustrates the effects of water compressibility. The incompressible model corresponds to Westergaard’s solution of real frequency-independent added masses on the upstream face. It is clear that this hypothesis underestimates the damping present in the system and overestimates the fundamental frequency. The consideration of water compressibility, which introduces radiation damping in the upstream direction, is therefore required for Outardes 3 dam.

Additional damping is introduced in the system by wave absorption at the bottom of the reservoir. Figure 16 illustrates the responses obtained for various values of the $\alpha$ parameter, ranging from 0 (complete absorption) to 1 (complete reflection). The experimental response corresponds to a range of $\alpha$ values between 0.75 and 1, with the best results obtained for $\alpha = 0.93$. This is consistent with the 2-D model observations that there is little absorption occurring at the reservoir–foundation interface. For $\alpha = 1$, the only damping present in the reservoir is attributed to radiation, which will occur for excitation frequencies above the fundamental resonance of the reservoir. This resonance was equal to 6 Hz for Outardes 3 dam, which explains the large amplitude observed for the fundamental frequency in Fig. 16 for the case of $\alpha = 1$, where damping is introduced into the system for frequencies above 6 Hz.

Comparisons of experimental and analytical acceleration
responses, for both amplitude and phase, are shown in Fig. 17 for the galleries and the downstream face of the dam. Similar results were obtained for all measurement stations. The first resonance was closely matched, and the response curves were slightly shifted for higher frequencies by 0.1 to 1 Hz. The phase was also predicted with the same accuracy.

Hydrodynamic pressure responses were also computed with the modified version of EACD-3D. Figure 18 illustrates a comparison of experimental (left graphs) and numerical (right graphs) pressures computed for 15, 30, 45, and 75 m below the surface at the upstream face along block H. Very good agreement was observed, even for the topmost hydrophone, which was out of phase with respect to the other transducers for higher frequencies. Such consistency between numerical predictions and measured responses was observed at distances of up to 90 m from the dam face, and confirms the validity of the reservoir model and the importance of water compressibility.

Resonance shapes can be computed from the numerical responses with a procedure analogous to the one used with experimental data. Figure 19a illustrates a plan view of the crest with experimental and analytical resonance shapes. Two symmetric and two antisymmetric shapes were identified on site and are reproduced by the numerical model. These shapes are plotted for a given time which corresponds to the maximum amplitude of the reference accelerometer located next to the shaker.

Figure 19a also shows an elevation view of block I, in the centre of the dam, with similar comparisons. The vertical shapes are completed by two measurement points on the downstream face, and the responses are always in phase with the upstream face. These can be compared with the mode shapes obtained with the 2-D model, where the second and third resonances show out-of-phase motions for both faces and are not obtained experimentally. To the authors’ knowledge, this is the first report of such measurements for a gravity dam.

Figure 19b illustrates the vertical hydrodynamic pressure profiles for each resonance. These were computed with the procedure used for acceleration responses, and they are plotted using the same accelerometer for reference time. The distributions at the first resonance are similar to the theoretical pressure profile for an infinite reservoir. Subsequent profiles, at the dam face, are characterized by the presence of a node located between 15 and 30 m below the surface; this phenomenon is also noticeable on the pressure responses for which the topmost hydrophone was out of phase with respect to the other units. This situation occurs for frequencies above the fundamental reservoir resonance and corresponds to the introduction of radiation damping in the system.

The validity of the complete 3-D numerical approach, including water compressibility and wave absorption at the reservoir–foundation interface, was confirmed by this correlation study. It is evident that 3-D modelling is much more involved, but it was essential for the reproduction of the experimental frequency responses of Outardes 3 gravity dam, given the three-dimensional nature of its behaviour under low-amplitude forced-vibration tests.

5. Conclusions

An extensive dynamic testing program was carried out on Outardes 3 gravity dam in order to evaluate state-of-the-art numerical methods for modelling dam–reservoir–foundation interaction. Complete frequency responses for both amplitude and phase were measured under harmonic loading and four resonances were identified for the dam–reservoir–foundation system. Continuous frequency response functions were also measured for hydrodynamic pressure at several locations in the reservoir up to a distance of 90 m from the dam face.

A numerical correlation study was carried out to evaluate the performance of 2-D and 3-D models, as well as the effects of various calibration parameters. Results obtained with the 2-D model showed that the added mass and damping introduced by a compressible reservoir model were necessary to predict the amplitude of the response at the fundamental resonance with reasonable accuracy. The 2-D program also demonstrated the importance of wave absorption at the bottom of the reservoir. However, this approach was limited to the computation of the amplitude at the first resonance. Moreover, higher frequencies were not reproduced, and the overall trend of the response (frequency spacing, relative amplitudes of the resonances) was not present in the numerical results. Lastly, a widely used solution of real-valued frequency-independent added masses was shown to overestimate the amplitude by as much as 400% for Outardes 3 dam.

A parametric study was carried out with a complete 3-D model including a massless foundation and a compressible reservoir. The numerical correlation showed that not only was the fundamental resonance matched for both amplitude and phase, but the overall trends in acceleration and pressure responses were reproduced with this approach. The dam–reservoir (with simplified added masses) and the dam–foundation cases were shown to largely overestimate the amplitudes and resonances of the response. The inclusion of water compressibility and wave absorption at the bottom of the reservoir was essential in reproducing the observed behaviour at Outardes 3 dam.

Although test results have indicated that only the 3-D model could reproduce the observed behaviour of the dam, it must be appreciated that this conclusion applies to low-amplitude harmonic forced vibrations. For earthquake analysis of gravity dams with unkeyed construction joints, a 2-D model is reasonable if sliding of vertical blocks is expected. However, this research indicates that a state-of-the-art 3-D analysis should perhaps be carried out where justified by the importance of the project or for a critical safety evaluation.

The number of key parameters required to adequately model a large concrete dam such as Outardes 3, even for 2-D modelling, justifies the need to carry out forced-vibration tests. This type of investigation constitutes a fast and economical method to calibrate such parameters as mass and stiffness distribution, water compressibility, foundation stiffness, and system damping.

The numerical correlation was carried out in the frequency domain during this project in order to compare predicted and measured frequency responses. However, relative joint motion that can occur under strong ground motion leads to a nonlinear problem. It is therefore important to obtain reliable data to calibrate numerical methods in the time domain. Although some motion was detected during the tests carried out on Outardes 3, a new series of tests in winter conditions was recently completed, and the experimental results are being used to...
study the effects of temperature on joint motion and the effects of the ice cover on the overall response.

**Acknowledgements**

The financial support of Hydro-Québec and of the Natural Sciences and Engineering Research Council of Canada is gratefully acknowledged. The authors also thank S. Raphael, O. Im, T. Mai Phat, and L.-M. Landry, all of Hydro-Québec, and Professor Z. Duron of Harvey Mudd College, for their cooperation during this research project.

**References**


