13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1862

ANALYTICAL AND NUMERICAL INVESTIGATION OF DYNAMICALLY EXCITED DAMS WITH ICE-COVERED RESERVOIRS

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SUMMARY

This paper examines the dynamic response of a concrete dam impounding an ice-covered reservoir and subjected to forced vibration testing. The analytical research presented is a follow-up to an extensive dynamic testing program carried out on an 84-m high concrete gravity dam located in northeastern Quebec, Canada, under harsh winter conditions, including a 1.0 to 1.5-m-thick ice sheet covering the reservoir. One of the major challenges encountered when analyzing ice–dam–reservoir–foundation interaction is modelling the complex nature of the ice and the boundary conditions governing the ice-covered reservoir motion. The problem is further complicated because there are little or no appropriate observational evidence relevant to ice–dam interaction processes. Some of these challenges are addressed herein using a two-dimensional analytical approach, which investigates the effect due to ice cover, the influence of water compressibility, foundation flexibility, and reservoir bottom absorption. A frequency domain substructure method technique is used and a new boundary condition along the ice-cover–reservoir interface is proposed. The technique developed is implemented in a finite element code specialized in the seismic analysis of concrete dams.

The paper also presents a numerical and parametric study showing the effect of an ice cover on the dynamic response of a concrete dam using the approach developed. The 84-m-high Outardes 3 concrete gravity dam in northern Quebec was chosen as a model for this research. Basic aspects of the numerical model are established and it is shown that the ice cover greatly affects the dynamic response of the ice–dam–reservoir system. Some main features of this influence are emphasized and discussed in a parametric study through the analysis of: (i) acceleration frequency response curves at the dam crest, (ii) hydrodynamic frequency response curves inside the reservoir, and (iii) the hydrodynamic pressure distribution on the upstream face of the dam.

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INTRODUCTION

Dam reservoirs in northern climates are generally covered with ice sheets for significant periods of time during the year. To illustrate this fact for Canada, the map in Figure 1 was prepared in the course of this project by gathering information from different sources.

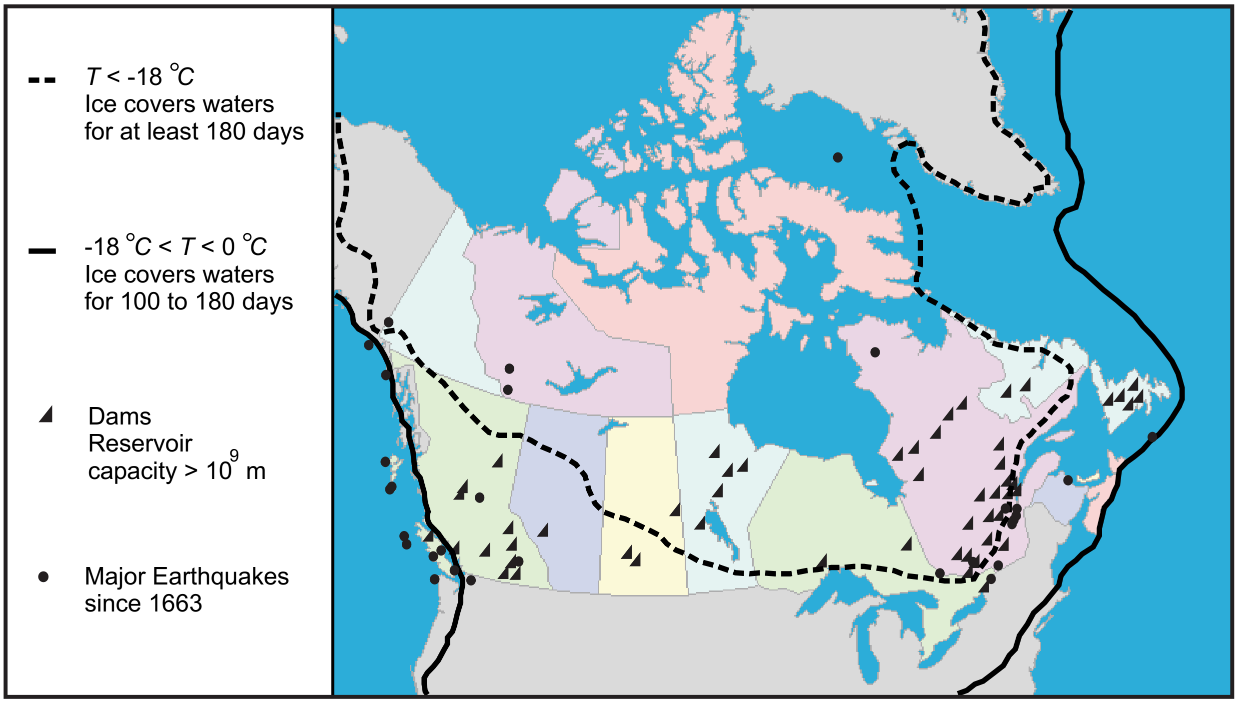

Figure 1. Dams, seismic activity, and ice covers in Canada.

The dashed line on the map indicates the southernmost border of the area where the average temperature of the coldest winter month is -18°C or less and where ice covers navigable waters at least 180 days per year. The solid line represents the southernmost border where the average temperature of the coldest winter month is between -18°C and 0°C and where, consequently, ice covers navigable waters for 100 to 180 days per year [1]. The map also shows dams with reservoir gross capacities exceeding one billion cubic meters, as well as some of the major earthquakes that have occurred in Canada since 1663 [2]. This map clearly shows that most dam reservoirs in Canada are covered with ice sheets for significant periods of time each year, and that some of these dams are located in earthquake prone areas. Consequently, it is of primary importance to ensure that dams that have been or will be built in these areas are designed in a way to withstand the dynamic forces that could be generated under seismic excitation through their interaction with the ice covers and their impounded ice-covered reservoirs. In Quebec, this verification has become even more imperative since the recent adoption of the Quebec Dam Safety Act [3] and the Quebec Dam Safety Regulation [4]. According to these new regulations, dam owners are now more than ever responsible for assessing and controlling the safety of their dams.

Part of the motivation for this study is related to the need to develop theoretical and experimental techniques to help dam owners, consultant engineers, and other concerned community members to ensure dam structural integrity and safety.

SCOPE AND OBJECTIVES

The primary objective of this project is to propose an analytical approach to investigate the effect of ice–covers on the dynamic behaviour of gravity dams. The proposed method had to satisfy the following criteria : (i) to account for ice–dam interaction, as well as ice–reservoir, dam–reservoir and dam–foundation interactions; (ii) to include water compressibility effects as well as energy dissipation mechanisms at reservoir bottom; (iii) to be numerically efficient to be eventually incorporated in specialized dam structural analysis software; (iv) once implemented, to allow for parametric studies to evaluate the contribution of the different substructures to the system's overall dynamic behaviour, and finally (v) to form the ground basis for a 3D numerical model to be used for numerical correlation studies of winter forced vibration tests.

EXPERIMENTAL BACKGROUND

The analytical research presented here is a follow-up of an extensive dynamic testing program carried out on an 84-m-high concrete gravity dam located in northeastern Quebec, Canada. The experimental work, reported previously by Proulx and Paultre [5] and Paultre et al. [6], consisted of conducting a series of forced vibration tests on the Outardes 3 gravity dam under both summer and severe winter conditions. Owing to the high importance of the issue in evaluating dam seismic safety as discussed earlier, this experimental program represented a first valuable step towards understanding different aspects of ice–dam dynamic interaction. Figure 2 illustrates the experimental setups used under summer and winter conditions. The collected experimental data was then compiled and analyzed to extract valuable information, namely acceleration and hydrodynamic frequency response curves at different locations on the dam and in the reservoir. A first comparison between summer and winter results identified the effects of the ice cover on the dynamic response of the dam–reservoir–foundation system. Modifications in damping and resonance frequencies were observed as well as an additional resonance attributed to the interaction of the dam with the ice cover. The experimental findings also constitute a reliable database that can be valuable in validating theoretical studies of ice–dam–reservoir–foundation interactions and calibrating finite element programs specializing in the dynamic analysis of concrete dams.

MATHEMATICAL FORMULATION

The ice–dam substructure

The aim of this section is to formulate the equations of motion of the ice–dam–reservoir–foundation system using the substructure method, a technique that has been widely used during the last three decades for modelling dam–reservoir–foundation dynamic interaction. The basic idea behind the method is to divide the whole system into substructures and then write the equations of motion for each substructure separately. Overall system response can then be obtained by relating the different substructures through interaction forces arising at common interfaces. It is worth to mentioning that an important merit of the substructure method is its efficiency in analyzing systems with frequency dependent properties such as dam foundations and reservoirs [7]. As illustrated in Figure 3, the system under study consists of four substructures: (i) a concrete dam with a vertical upstream face, (ii) a semi-infinite ice cover of constant thickness, (iii) a semi-infinite reservoir of a constant height, and (iv) a semi-infinite flexible foundation. The ice cover is assumed to extend to infinity, but in order to carry out parametric studies, a finite ice cover length is considered as shown in Figure 3. Both concrete and ice are assumed to have linear, isotropic, elastic behaviour. Nonlinearities due to cracking and reservoir cavitation are not considered in this study. For the sake of clarity and brevity, and in order to effectively isolate the contribution of the ice cover effects to the overall system dynamic behaviour, effects due to foundation flexibility are not included here. Only the basic equations governing the ice–dam–reservoir interaction with a rigid foundation are briefly reviewed. A technique for including foundation flexibility effects in the analysis by idealizing it as a viscoelastic half-plane was described in a previous work [8].

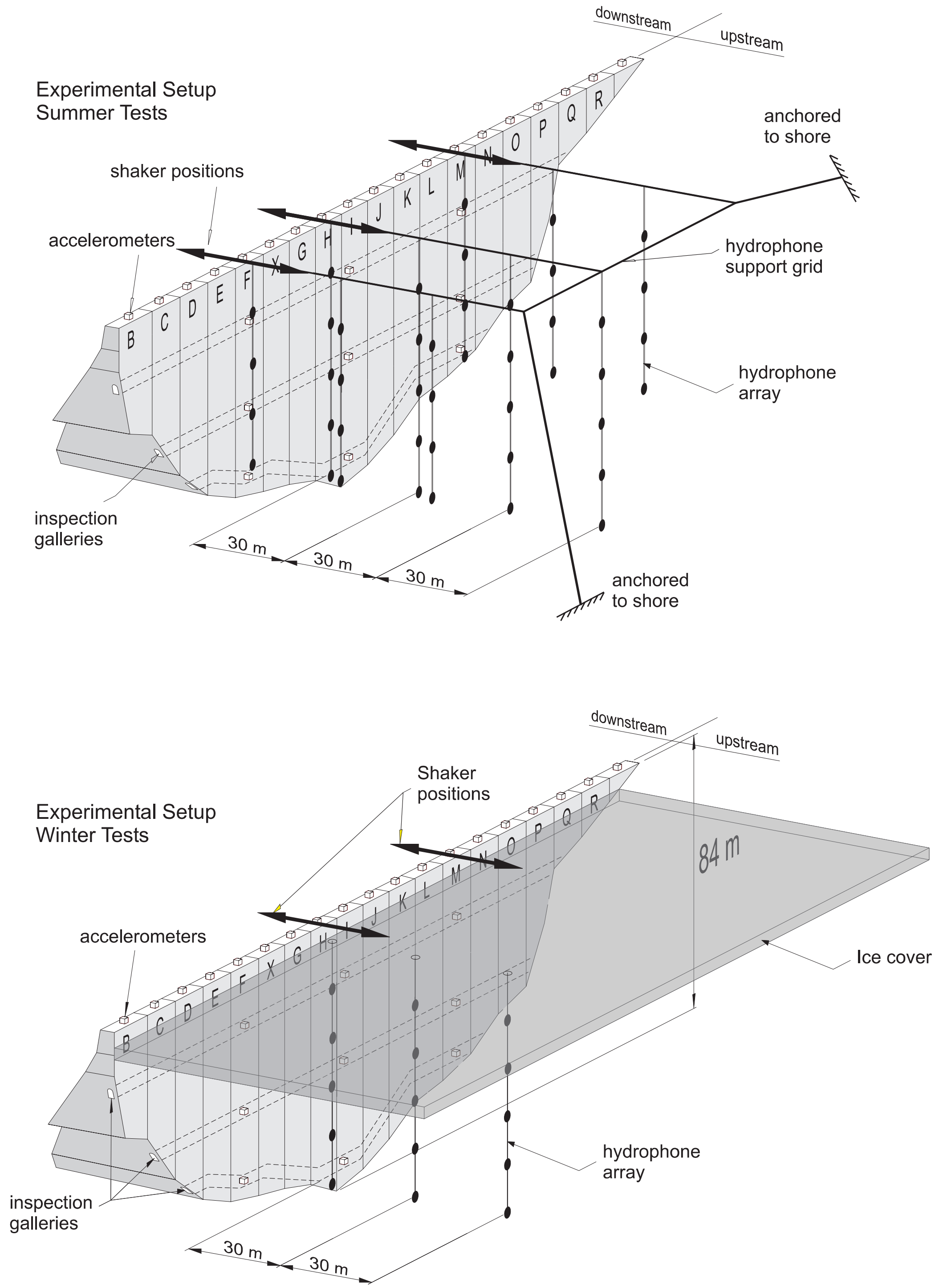

Figure 2. Experimental setups used under summer and winter conditions.

In the next sections, the equations of motion are derived for each of the ice–dam and reservoir substructures, and then coupled by means of the interaction forces arising at the ice–reservoir and dam–reservoir interfaces.

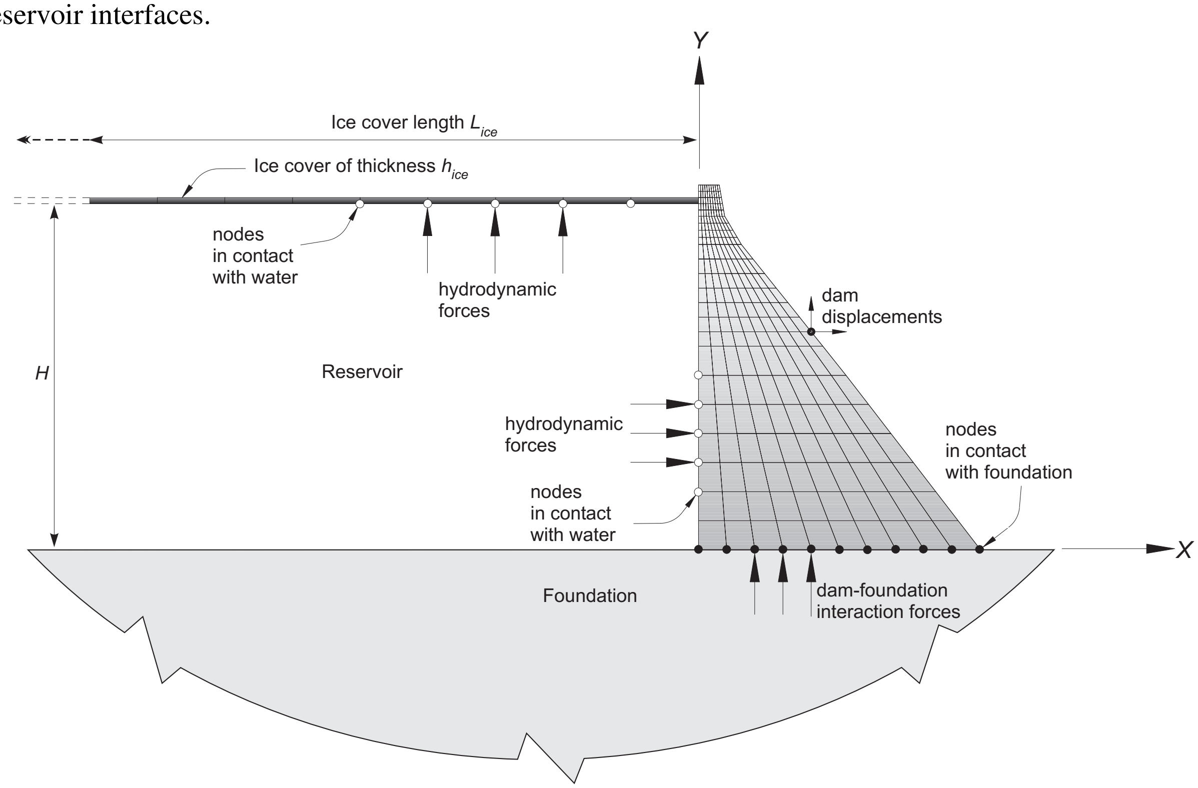

Figure 3. The ice–dam–reservoir–foundation system substructures.

First, the dynamic equilibrium equations governing the linear response of the ice–dam finite element system under forced-vibration testing are written. The eccentric mass shaker load is modeled by a harmonic force applied at dam crest and the reservoir effect is modeled by hydrodynamic loads applied at the dam–reservoir and ice–reservoir interfaces. By expressing the displacements and forces in terms of their complex-valued frequency responses, equilibrium equations are transformed in the frequency domain where the ice–dam substructure is assumed to have a constant hysteretic damping. A modal superposition analysis is then carried out to determine the first natural frequencies and vibration mode shapes, which are solutions to an eigenvalue problem, satisfying classical orthogonality conditions with respect to mass and stiffness matrices, and normalized with respect to the mass matrix. Using corresponding generalized coordinates, the ice–dam displacements are then expressed as a linear combination of the first computed eigenvectors. Taking advantage of the orthogonality properties of the eigenvectors with respect to mass and stiffness matrices, a system of decoupled equations is obtained with generalized coordinates as unknowns to be found as a function of the forced-vibration frequency, the applied harmonic load, the hydrodynamic forces, the system's frequencies, eigenvectors and hysteretic damping. The hydrodynamic forces at the dam–reservoir and ice–reservoir interfaces are to be determined by analyzing the interaction between the ice–dam substructure and the reservoir.

The ice-covered reservoir

Basic equations

The reservoir is modelled as a compressible fluid domain of constant depth and infinite length in the upstream direction. The differential equations governing the movement of water in the reservoir are first derived, along with the reservoir boundary conditions, especially at the ice–reservoir interface. The water in the reservoir is assumed inviscid but compressible, with its motion two-dimensional, irrotational, and limited to small amplitudes. Expressing the hydrodynamic pressure in the frequency domain, it can be shown that the reservoir motion is governed by the familiar Helmholtz equation associated to boundary conditions at the ice-reservoir, dam–reservoir and reservoir–foundation interfaces.

Boundary conditions

The boundary conditions to be satisfied at the dam–reservoir and foundation–reservoir boundaries are those derived by Fenves and Chopra [7], relating the normal derivative of the pressure frequency response to the normal component of the acceleration at the dam–reservoir interface and to a damping coefficient at the reservoir bottom.

The boundary condition at the ice–reservoir interface has to satisfy both the dynamic and kinetic equilibrium of the ice cover. The derivation of this boundary condition, detailed elsewhere [9], uses a velocity potential-based formulation. Expressing the hydrodynamic pressure at the ice–reservoir interface using the linearized Bernoulli equation, and enforcing continuity of the normal velocity at the ice–reservoir interface, it is shown that the dynamic equilibrium at the ice–reservoir interface can be obtained by treating the ice cover as an elastic thin plate floating on water. After some mathematical manipulations, a boundary condition is obtained, relating pressure derivatives, ice cover flexural rigidity, damping at the ice–reservoir interface, ice cover thickness and mass density, water mass density and forced-vibration frequency. The Helmholtz Equation is then solved by separation of variables, leading to a Sturm-Liouville problem, with complex-valued frequency dependent eigenvalues¸ and orthogonal eigenfunctions satisfying special equations developed in the course of the present work [9].

Coupling between the ice–dam and the ice–reservoir systems

Coupling the equations obtained for the ice–dam and the ice–reservoir systems yields a system of equations with generalized coordinates as unknowns, to be solved for each forced-vibration frequency. The acceleration and pressure frequency response functions are then obtained by modal summation in the frequency domain. The equations derived are analyzed to understand the effect an ice cover has on the dynamic behaviour of the whole system. They show that this effect can be subdivided into: (i) an added mass effect, (ii) an added load effect and, (iii) an added stiffness effect. As mentioned before, although the ice cover is assumed to extend to infinity as the reservoir, a finite length had to be considered to get a clear understanding of the mass and stiffness effects due to the ice cover.

PARAMETRIC AND NUMERICAL STUDY

Introduction

The mathematical formulation derived to model the effect of an ice cover on the dynamic response of a concrete dam is used herein to conduct a parametric study in which various aspects of ice–dam–reservoir–foundation interaction are addressed. The results of this investigation are expected to give more insight into the relative importance of some parameters on the dynamic behaviour of dams with ice-covered reservoirs.

The Outardes 3 gravity dam described in previous work [5,6] is used as a model for this research. The dynamic behaviour of the dam is examined through the analysis of: (i) acceleration frequency response curves at the dam crest, (ii) hydrodynamic frequency response curves inside the reservoir, and (iii) the hydrodynamic pressure distribution on the upstream face of the dam. These dynamic responses are obtained by using the equations derived, programmed and incorporated in a finite element code specialized for the seismic analysis of concrete dams.

Numerical model

Finite element code

The approach proposed is programmed and implemented in the finite element code EAGD-84 [7], initially developed to determine the elastic response of concrete gravity dam monoliths under the effect of horizontal and/or vertical components of ground motion. The original formulation programmed in EAGD-84 takes account of water compressibility, as well as dam–reservoir and dam–foundation interactions. The code is based on the substructure method, in which the dam is modelled by finite elements, the reservoir as a fluid domain of constant depth and infinite dimension in the upstream direction, and the foundation as an isotropic viscoelastic half-plane [7]. Following the first series of forced vibration tests carried out on the Outardes 3 gravity dam under summer conditions, the 1984 edition of the software was used to analyze the two-dimensional dynamic behaviour of the dam [5]. The software was then modified to produce acceleration frequency response curves at a point in the dam when a harmonic load is applied at a given node of the finite element model. Thus, the effect of an eccentric mass shaker anchored at the dam crest could be simulated, allowing for model calibration against frequency response curves obtained experimentally [5]. After the second series of forced vibration tests on the same dam but under winter conditions, the program was further modified to take account of the presence of an ice sheet covering the reservoir. The new boundary conditions resulting at the ice–reservoir interface as discussed in detail by Bouaanani et al. [9] were programmed. Since part of the experimental measurements was in the form of hydrodynamic frequency response curves, hydrodynamic pressure calculations were completely developed and also programmed. Using the present version of the software, the hydrodynamic frequency response curves can be determined at any point in the reservoir, as well as the distribution of the hydrodynamic pressure on the upstream face of the dam. All the results presented in this paper were produced using the newly modified version of EAGD.

Finite element model

Modelling the gravity dam using EAGD requires that a cross-section of a given monolith be defined and discretized by quadrilateral isoparametric finite elements, including incompatible displacement modes to ensure a better shear behaviour [10]. Node coordinates are defined with reference to global axes and the translations are the two degrees of freedom associated with each node, as shown in Figure 4, which gives an overall view of the Outardes 3 gravity dam and the nomenclature of the various monoliths is also illustrated. The dam and ice finite elements are characterized by their modulus of elasticity, their density, and their Poisson's ratio. The ice–dam substructure is characterized by a constant hysteretic damping coefficient corresponding to a constant modal damping coefficient. It is worth mentioning that finite element modelling of the ice cover, instead of a simplified mass-spring model as proposed by some researchers [11,12], makes it possible to include the contribution of both axial and flexural ice cover vibration modes in the analysis. It should be added that, through this analysis, the dynamic interaction between the ice cover and the reservoir can be rigorously modeled by applying the appropriate boundary conditions along the ice–reservoir interface. The dam finite element model contains 230 quadrilateral isoparametric elements and 264 nodes, 11 of which belong to the dam–foundation interface and 20 to the dam–reservoir interface. The number of elements and nodes used to model the ice cover depends on its length, which is a study parameter. However, for all the cases studied here, a variable nodal spacing along the ice cover was adopted: from dense near the ice–dam interface to gradually coarser towards the other end of the ice cover. The level of the upper ice cover face corresponds to in-situ measurements, giving roughly 2.7 m under dam crest level.

Boundary conditions

The boundary conditions at the dam–reservoir and foundation–reservoir interfaces are the same as those programmed by Fenves and Chopra [7]. The derivation of the boundary condition at the ice–reservoir interface briefly described above and in detail by Bouaanani et al. [9] includes the effect of possible damping at the ice–reservoir interface represented by a viscous damping coefficient. We mention however that in the absence of any experimental data, this damping is neglected herein.

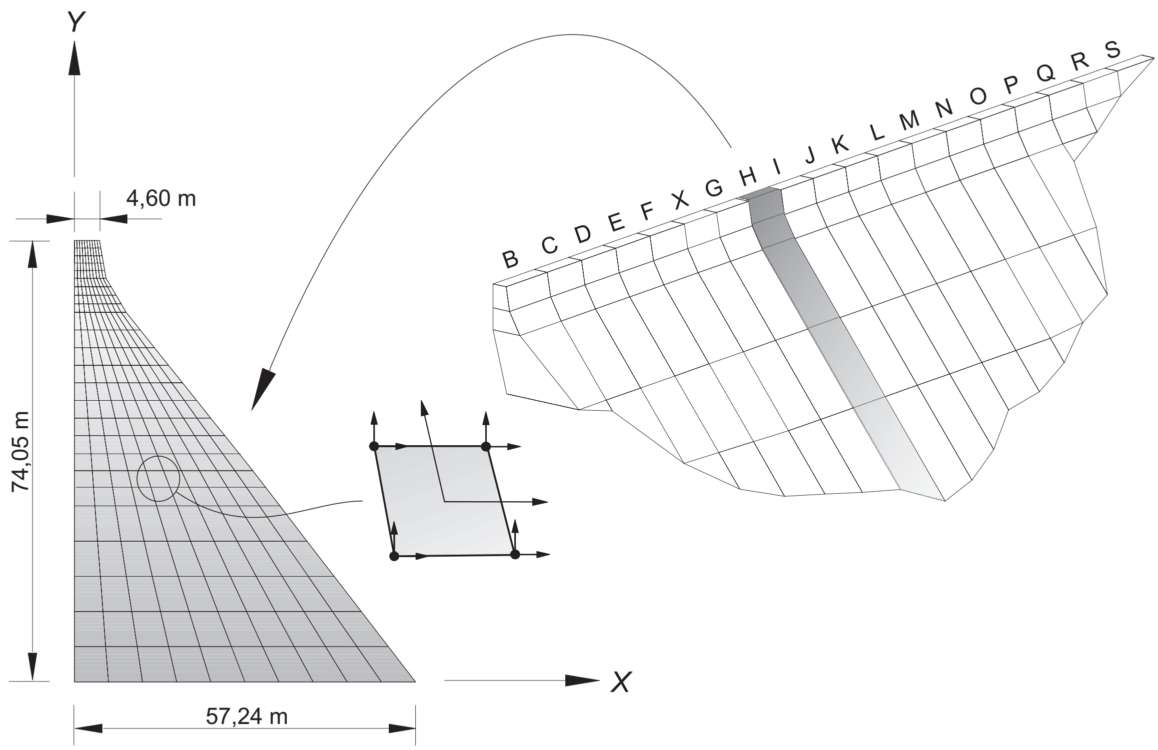

Figure 4. Dimensions of the modelled monolith.

On the other hand, the finite element modelling of the ice cover requires the definition of a boundary condition at its far upstream end. Ideally, this condition should take account of the friction of the ice cover at the reservoir border and allow for energy dissipation at this location using appropriate impedance functions. This effect could also be simulated with a reasonable degree of accuracy by truncating the ice cover at a given distance from the dam face and finding the adequate transmitting boundaries. These questions are difficult to address, because of the complexity of the dynamic behaviour of the ice cover and its interaction with the reservoir border, associated with the lack of related experimental evidence. For the present research, it is legitimate to assume that the ice cover is clamped at its far upstream end, due to the small deformations induced in the ice cover during the *in-situ* dynamic testing.

Ice-cover properties

Due to a lack of adequate experimental data, the ice mechanical properties were adopted directly from the literature, and are namely those of a columnar ice, of type S2 at an ambiant temperature of -10°C. Choosing this type of ice was motivated by results from other studies related to ice covers in Canada [13]. Determining the ice cover thickness represents another difficulty since it is far from being uniform for a given reservoir. Our field observations indicate a variation within 1 m. In addition to thickness variability of the ice cover itself, a considerable amount of snow located within a 2 to 3-m wide strip along the dam face was also observed. An average ice cover thickness of 1.37 m (4.5 ft) was adopted; its mass density was varied artificially to include the effects of snow loading and thickness variability. Finally, in order to account for the ice added mass effect different ice cover lengths were considered.

Parametric study

Effect of the ice modulus of elasticity

It is logical to expect the ice modulus of elasticity to be an important parameter in characterizing the ice cover contribution to the system's global stiffness. As discussed in Bouaanani et al. [8,9], the literature abounds with dispersed values for quantifying this parameter. In an attempt to cover the most possible cases within the framework of this research, the ice modulus of elasticity was varied within a broad interval, ranging from 475 MPa to 16 150 MPa.

In order to evaluate the contribution of the ice cover to the system total stiffness, the effect of variations of the ice modulus of elasticity on the acceleration frequency response curves at the dam crest (without including reservoir effects) is examined first. Some of the results of this analysis are illustrated in Figure 5, in which the acceleration frequency response curve at the dam crest without ice cover is also plotted for purposes of comparison.

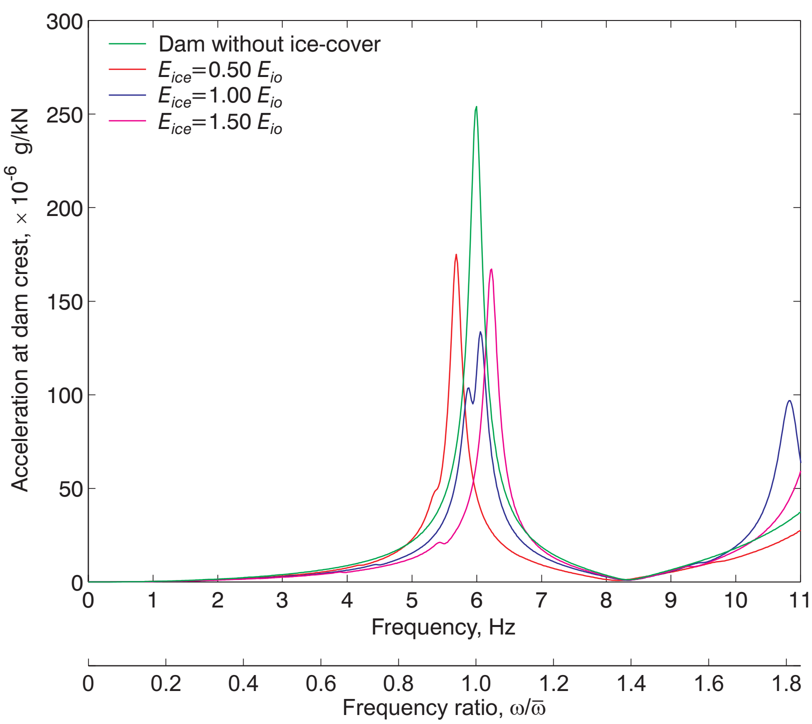

Figure 5. Effect of the ice modulus of elasticity on the acceleration frequency response curves.

As can be seen from these curves, variations in the ice modulus of elasticity influence the shape of the frequency response curves and reveal additional resonant modes with more or less pronounced peaks, depending on the value of the ice modulus of elasticity. To gain better insight into these findings, it is useful to determine the first natural frequencies of the ice–dam system and to identify the corresponding mode shapes on the frequency response curves.

For the sake of clarity when discussing the results in what follows, principal resonances refer to significant peaks on the frequency response curves and secondary resonances to all the other peaks. Principal resonances in each case will be ranked according to their descending amplitude, and termed first principal resonance, second principal resonance, and so forth. By examining the first 15 vibration frequencies of the ice–dam system obtained by increasing the ice elastic modulus on a wide range, and comparing them to the corresponding first 15 vibration frequencies of the dam without ice–cover, we observed that the frequency of each mode increases at each variation step of the ice modulus of elasticity. Basically, this means that, as expected, a higher ice modulus of elasticity stiffens the ice–dam system. Another important observation arising from the comparison of the acceleration frequency response curves in Figure 5, is that, in all examined cases, the amplitude of the ice–dam principal resonance is lower than that of the fundamental mode of the dam without ice cover. Again, as expected, the presence of the ice cover reduces the amplitudes of the horizontal motion at the dam crest.

The next step in the analysis was to identify the mode shapes corresponding to the calculated frequencies. An example of this process is presented in Figure 6 where the modes are identified on the acceleration frequency response curves at the dam crest for a given value of ice modulus of elasticity. The acceleration frequency response curve at the dam crest without ice cover and the corresponding fundamental frequency are also illustrated in the same figure. These investigations showed that the peaks on the frequency response curves correspond, generally, to the vibration of the dam at a frequency near that of its fundamental mode without ice cover. It can then be concluded that, for the range of forced vibration frequencies considered (0 to 10 Hz) only a few modes correspond to significant peaks on the frequency response curves. The other modes correspond, indeed, to the vibration of the ice cover alone and do not imply a significant resonance of the combined ice–dam system. This can be clearly seen by comparing the vibration frequencies and mode shapes of the ice cover alone clamped at both ends and those of the ice–dam system as illustrated in Figure 7. It is apparent from these results that only two of the first 10 modes presented (occurring at 5.88 Hz and 6.05 Hz in this case), correspond to the two peaks on the frequency response curve shown in Figure 6.

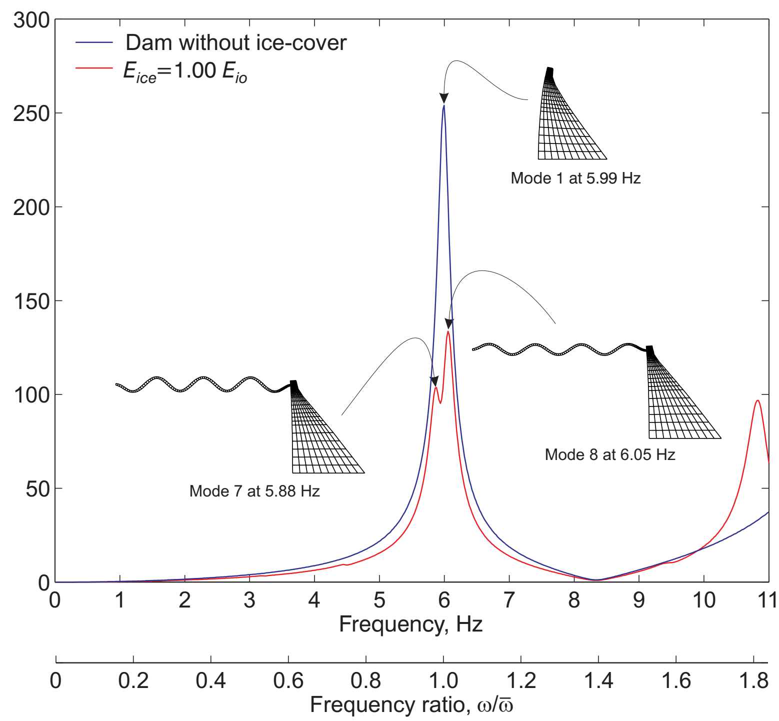

Figure 6. Mode identification for a given value of ice modulus of elasticity.

So far we have excluded reservoir effects from the analysis. Let us examine now the case where the reservoir is filled with water. An example of the acceleration frequency response curves obtained at the dam crest with a full reservoir is illustrated in Figure 8. By comparing these curves with those obtained for an empty reservoir (as in Figure 5), it can be concluded that the resonant frequencies are generally lower when the reservoir is full and that the corresponding amplitudes are smaller because of the added mass effect due to the reservoir as explained in [9]. We also note that, similarly to an empty reservoir, the frequency response curves generally show one or two principal resonances depending on the value of the ice modulus of elasticity. By examining the frequency response curves we showed that variations in ice modulus of elasticity have an effect on the frequency and amplitude of the second principal resonance, as well as, a lesser effect on the frequency and the amplitude of the first principal resonance. Moreover, all the principal resonances have amplitudes lower than that of the fundamental mode of the dam without ice cover.

It is also interesting to investigate the effect of the variations of ice modulus of elasticity on the frequency response curves of the hydrodynamic pressure and on its distribution on the upstream face of the dam. Figure 9 shows the frequency response curve of the normalized hydrodynamic pressure at 3 m from the upstream face of the dam and at 15 m below the ice–reservoir interface for different values of ice modulus of elasticity. To preserve the generality of the results presented herein, the hydrodynamic pressure is normalized with respect to both the exciting force and the hydrostatic pressure at the bottom of the reservoir. Again, Figure 9 shows that an increase in ice modulus of elasticity involves a reduction in the amplitudes of the principal resonances, a slight increase in the corresponding frequencies, and a modification of the frequencies of the second principal resonances. We also note that all the principal hydrodynamic resonances have amplitudes lower than those of the fundamental resonance of the dam without ice cover.

Figure 10 illustrates the effect of variations in the ice modulus of elasticity on the distribution of the hydrodynamic pressure on the upstream face of the dam at the system's first principal resonance. First of all, these curves show that the hydrodynamic pressure at the ice–reservoir interface is not equal to zero, as is the case for a free-surface reservoir. Sun [14] had already predicted such hydrodynamic amplification for offshore platforms. Then we examined the values of the hydrodynamic pressures calculated at the ice–reservoir interface and at the reservoir bottom as well as the corresponding amplifications, presented in terms of a percentage of the pressure at the reservoir bottom for each calculation case and comparing to the hydrodynamic pressures at the reservoir bottom with a free surface. The results demonstrate that the amplification ratios of the hydrodynamic pressure at ice–reservoir interface remain practically constant independently of the values of ice modulus of elasticity.

It can also be seen that, for all the calculated cases, the value of the hydrodynamic pressure at the bottom of the ice-covered reservoir is lower than that obtained for a free-surface reservoir. Therefore, we can conclude that the ice cover causes the hydrodynamic pressure to increase in the vicinity of the ice–reservoir interface and to diminish closer to the reservoir bottom. Finally, by examining the variation of the hydrodynamic pressure as a function of the ice modulus of elasticity, both at the ice–reservoir interface and reservoir bottom, the hydrodynamic pressure in the reservoir globally decreases with increasing ice cover stiffness.

Effect of other parameters

Following the same procedure outlined above for studying the influence of ice cover modulus of elasticity on the dynamic response of the gravity dam, the effect of other parameters was also investigated, namely the concrete modulus of elasticity, the mass density and the length of the ice cover, and the foundation flexibility. A detailed description of the results obtained is presented in Bouaanani et al. [8,15].

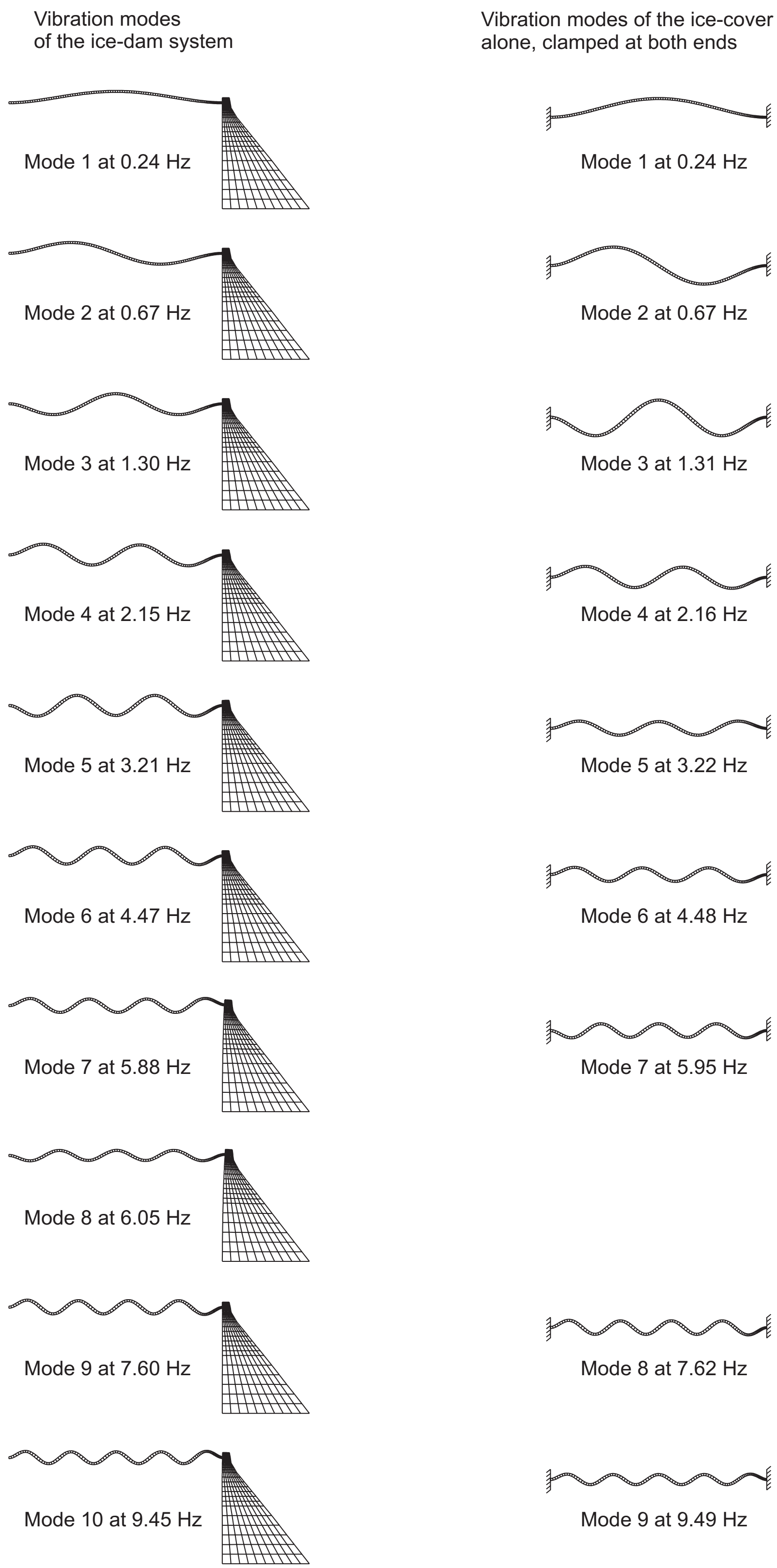

Figure 7. Vibration modes of the ice–dam system and ice cover alone, clamped at both ends.

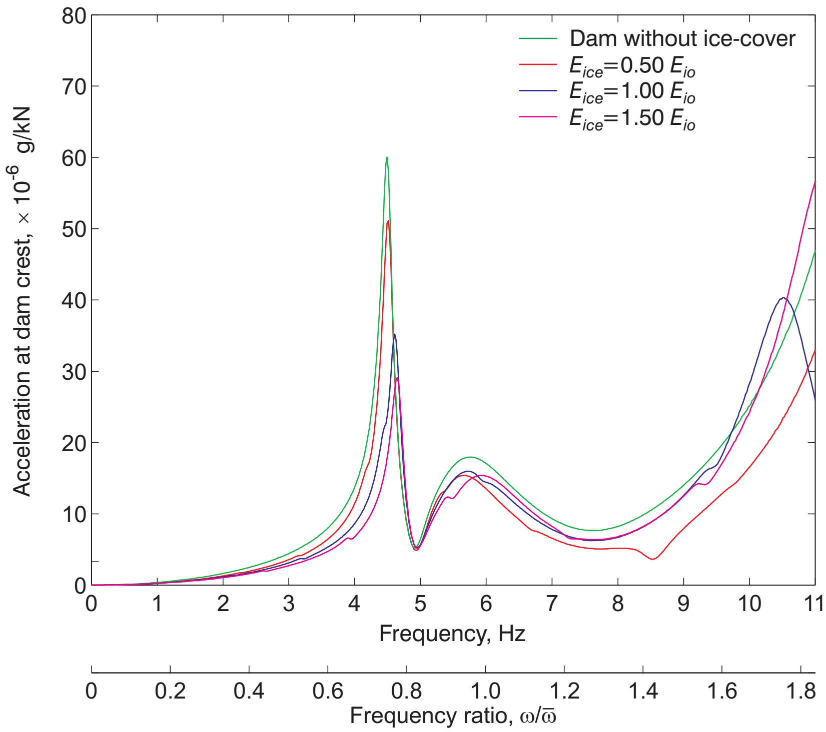

Figure 8. Effect of the ice modulus of elasticity on the acceleration frequency response curves at the dam crest, with a full reservoir and a rigid foundation.

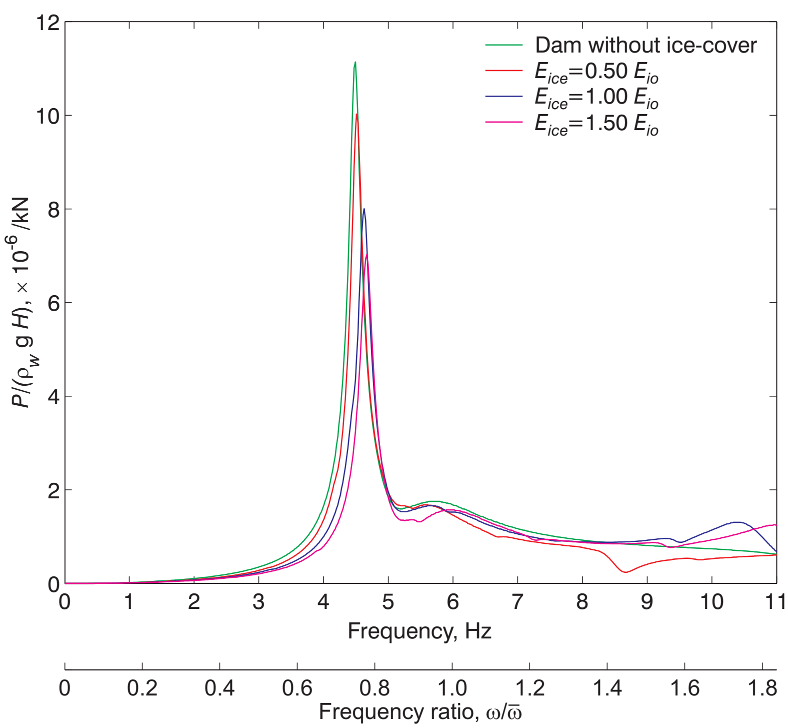

Figure 9. Effect of the ice modulus of elasticity on the frequency response curves of the normalized hydrodynamic pressure 3 m from the upstream face of the dam and 15 m below the ice–reservoir interface, with a full reservoir and a rigid foundation.

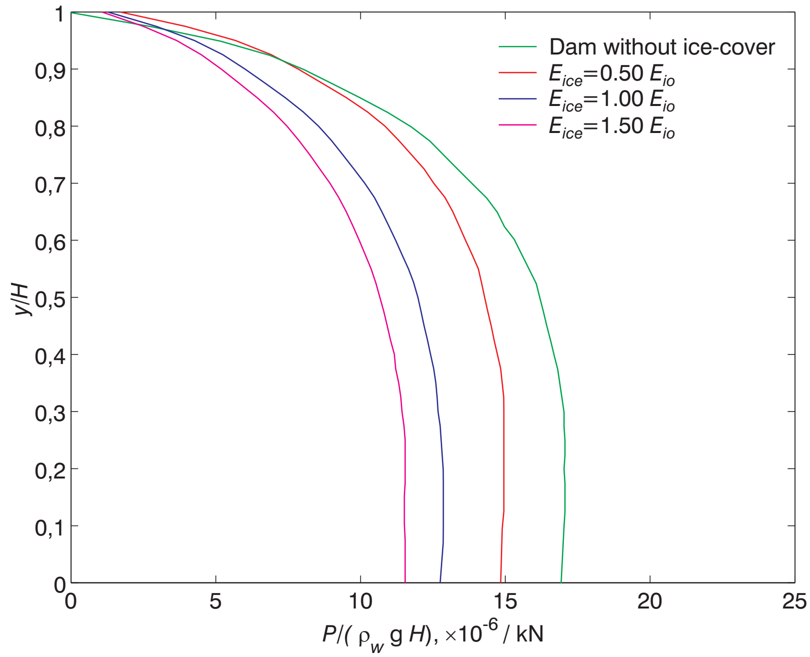

Figure 10. Effect of the variation of Eice on the distribution of the hydrodynamic pressure on the upstream face of the dam at the system's first principal resonance.

CONCLUSIONS

The primary objective of this work was to develop a theoretical approach to model the effects of ice covers on concrete gravity dams. In addition, the technique proposed takes account of water compressibility and reservoir bottom absorption. During this work, some challenges were encountered, namely:

- Difficulties related to modelling the ice cover because of its highly complex nature. The mechanical properties had then to be varied within broad ranges to cover most possible cases.
- Developing a comprehensive susbstructure formulation in which the effects of the ice cover are combined to those of the reservoir and the foundation.
- Derivation of a new boundary condition at the ice–reservoir interface. This boundary condition had to take into account the dynamic equilibrium at the interface, the flexibility of the ice cover, and possible damping at this location.

These challenges were addressed by using a two-dimensional analytical approach, which takes into account the effects of an ice cover, the influence of water compressibility, foundation flexibility, and reservoir bottom absorption. A frequency domain substructure method technique is developed and a new boundary condition along the ice-cover–reservoir interface is proposed. The technique developed is implemented in a finite element code specialized for the seismic analysis of concrete dams.

The paper also presents some results regarding the dynamic behaviour of concrete dams with ice-covered reservoirs, obtained by using the approach proposed. The Outardes 3 gravity dam was chosen as a model for this numerical study. After having mentioned the modifications made to the software, the basic elements of the numerical model were established. A parametric study was then carried out in order to appreciate the influence of various factors on the dynamic behaviour of the ice-dam-reservoir system. It can be clearly concluded that the ice cover greatly affects the dynamic response of the ice–dam–reservoir system, and some basic trends of this influence were emphasized and discussed. It is worth mentioning however, that the work described herein is preliminary and was intended to establish a base-line study to be extended for investigating dynamic interactions in two- and three-dimensional ice–dam–reservoir–foundation systems.

REFERENCES

1. U.S. Army Corps of Engineers. "Ice engineering." 1999; EM 1110-2-1612.
2. The Atlas of Canada, http://atlas.gc.ca/site/english/index.html.
3. Gouvernement of Quebec. "Quebec dam safety act, Bill 93." May 30, 2000.
4. Gouvernement of Quebec. "Quebec dam safety regulation." Gazette officielle du Quebec, March 27, 2002; 134(13).
5. Proulx, J. and Paultre, P. "Experimental and numerical investigation of dam–reservoir–foundation interaction for a large gravity dam." Canadian Journal of Civil Engineering, 1997, 24(1): 90-105.
6. Paultre P., Proulx, J., and Carbonneau, C. "An experimental evaluation of ice cover effects on the dynamic behaviour of a concrete gravity dam." Earthquake engineering and structural dynamics, 2002, 31(12): 2067–2082.
7. Fenves, G. and Chopra, A.K. "Earthquake analysis and response of concrete gravity dams." Report No. UCB/EERC-84/10, 1984, University of California, Berkeley, 213 p.
8. Bouaanani, N., Paultre, P., and Proulx, J. "Two-dimensional modelling of ice cover effects for the dynamic analysis of concrete gravity dams." Earthquake Engineering and Structural Dynamics, 2002, 31(12): 2083–2102.
9. Bouaanani, N., Paultre, P., and Proulx, J. "Dynamic response of a concrete dam impounding an ice-covered reservoir, Part I. Mathematical modelling." Canadian Journal of Civil Engineering (Submitted).
10. Wilson, E.L., Taylor, R.L. Doherty, W.P., and Ghaboussi J. "Incompatible displacement models." Numerical and Computer Methods in Structural Mechanics, 1973, Academic Press, New York, p.43–57.
11. McCullough, F., Léger, P., and Tinawi, R. "Influence of ice covers on the seismic behaviour of gravity dams (in French)." Report No. EPM/GCS-1996-05, 1996, Department of Civil Engineering, École Polytechnique de Montréal, Montréal, 185 p.
12. Croteau, P. "Dynamic interactions between floating ice and offshore structures." Report No. UCB/EERC-83/06, 1983, University of California, Berkeley, 335 p.
13. Michel, B. "Ice mechanics." 1978, Les Presses de l'Université de Laval, Quebec, 499 p.
14. Sun, K. "Effects of ice layer on hydrodynamic pressure of structures." ASCE Journal of Cold Regions Engineering, 1993, 7(3): 63-76.
15. Bouaanani, N., Paultre, P., and Proulx, J. "Dynamic response of a concrete dam impounding an ice-covered reservoir, Part II. Parametric and numerical study." Canadian Journal of Civil Engineering (Submitted).