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FORCED-VIBRATION TESTS OF A LARGE GRAVITY DAM IN WINTER AND SUMMER CONDITIONS

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ABSTRACT

The realistic modelling of the behaviour of large scale structures for dynamic analysis is critical and relies on theoretical considerations, past experience and results of experiments. This puts forth the importance of well-documented and reliable testing procedures. A series of force-vibration large-scale tests was carried out on a 84-m concrete gravity dam in northeastern Quebec (Canada) in summer and winter conditions, with full reservoir. Horizontal acceleration of the dam and hydrodynamic pressure in the impounded water were measured under harmonic loading generated by an eccentric mass shaker. A complete set of frequency responses was obtained at several locations for the dam-reservoir system and was used in a correlation study with specialized 2D and 3D seismic analysis programs. The experimental procedures are presented as well as the evaluation of frequency responses and dynamic properties including resonant frequencies, mode shapes and damping. The use of these results in finite element correlation studies is discussed and comparisons between experimental results obtained in summer and winter conditions are emphasized. The effects of temperature and ice cover on the overall response are highlighted.

KEYWORDS

Dynamic testing, shaker, dam-reservoir-foundation interaction, ice cover, frequency response, hydrodynamic pressure.

INTRODUCTION

Modelling the true behaviour of a civil engineering structure remains the first step and the most difficult in dynamic or seismic analyses. Among the important parameters to be defined are the mass distribution, the damping characteristics, the stiffness of the main load-resisting system, the influence of secondary elements, and various interaction phenomena. Large-scale forced or free-vibration tests provide reliable data for the calibration of such parameters. A considerable amount of research has been carried out in the field of seismic analysis and modelling of various structures in the past decade. The performance of these numerical techniques can only be evaluated and quantified by using dependable full-scale test results. Moreover, experimental findings can also be used as a reference database for auscultation programs based on repeated tests of the same structure to monitor variations in its characteristic properties.

Fig. 1: Aerial view of Outardes 3 gravity dam with full reservoir

Figure 1 shows an upstream view of Outardes 3 gravity dam which consists of 19 monoliths with three inspection galleries at 20 and 57 m below crest and at the foundation level, and has a maximum crest height of 84 m and a total length of 298 m. It is located in a moderate seismic region in northeast Quebec (Canada) and was completed in 1965. A series of forced-vibration tests including hydrodynamic pressure measurements, was carried out in summer conditions at 15 to 25 °C temperatures, with a full reservoir (Proulx *et al.*, 1992), as part of a seismic safety evaluation program.

A correlation study was then undertaken to evaluate the performance of 2D and 3D seismic analysis programs for large dams. The effects of dam-reservoir interaction, including water compressibility, and of several calibration parameters were investigated. Responses computed with the complete dam-reservoir-foundation 3D model accurately reproduced experimental observations (Proulx and Paultre, 1994). Following this study, the complete experimental program was repeated in winter conditions with -15 to -10 °C temperatures, and a 1–1.5 m ice cover. The main objectives of these tests were to evaluate joint motion and ice cover effects on the overall system response.

This paper describes the experimental procedures for both series of tests. A brief description of the correlation study with a specialized 3D program is given. Experimental results from both tests are presented and comparisons between the observed behaviour in summer and winter are emphasized.

EXPERIMENTAL SETUP

The most critical aspect of any experimental procedure is the accuracy and reliability of the instrumentation. In dynamic tests, all instruments are likely to modify what is being recorded, and these modifications have to be taken into consideration when processing the data. This is done by first evaluating the frequency responses of all components of the instrumentation, from the measuring devices

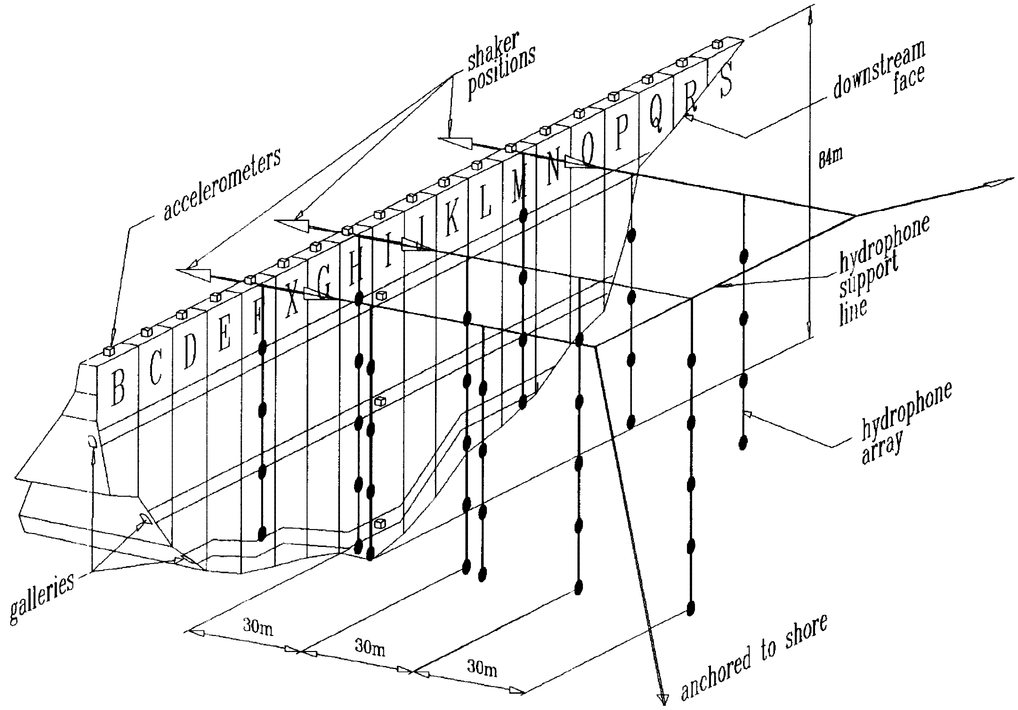

Fig. 2: Outardes 3 gravity dam — Experimental setup

to the analog-digital converters used in the data acquisition system. Corrections for each component of the system are crucial and must be applied in the data processing phase of the experiment.

The instrumentation setup for both series of tests is shown in Fig 2. An eccentric mass shaker generating a sinusoidal force was used to study the dynamic interaction phenomena present in dam-reservoir-foundation systems. This testing technique leads to well-defined frequency response functions for the structure and surrounding media. Acceleration and hydrodynamic pressure responses were measured under a horizontal harmonic load of up to 84 kN at frequencies ranging from 4 to 10 Hz. The dynamic load was provided by two sets of weights rotating around parallel vertical shafts (their eccentricity can be varied to modify the magnitude of the resulting force). The exact frequency of operation was computed from a pulse signal generated by the rotation of the weights.

During both series of tests, the shaker was located on the crest in the centre and at two quarter points (block M only for winter tests). Low-frequency accelerometers were placed on the dam crest on each monolith, inside the inspection galleries, and on the downstream face of the dam (summer tests), to record horizontal acceleration perpendicular to the axis of the dam. These instruments behave like a low-pass filter, reducing the amplitude and modifying the phase significantly for higher frequencies only (Fig 3). Relative joint motions were also investigated by placing accelerometers on both sides of selected construction joints on the crest and by switching the position of the instruments to eliminate calibration errors.

During the winter tests, snow was removed from the crest daily, and any ice accumulation was melted in order to position the accelerometers directly upon the concrete. Specially insulated boxes with thermostat-controlled heaters were placed on top of every accelerometer to keep the operating temperature at approximately 15 °C. Joint motions were also investigated inside different galleries from the crest down to the foundation level.

Also shown on Fig 2 is a set of nylon cables, anchored to both shores and to the dam crest, which were used during the summer tests to suspend arrays of 4 to 5 solid-state hydrophones (with a high-pass

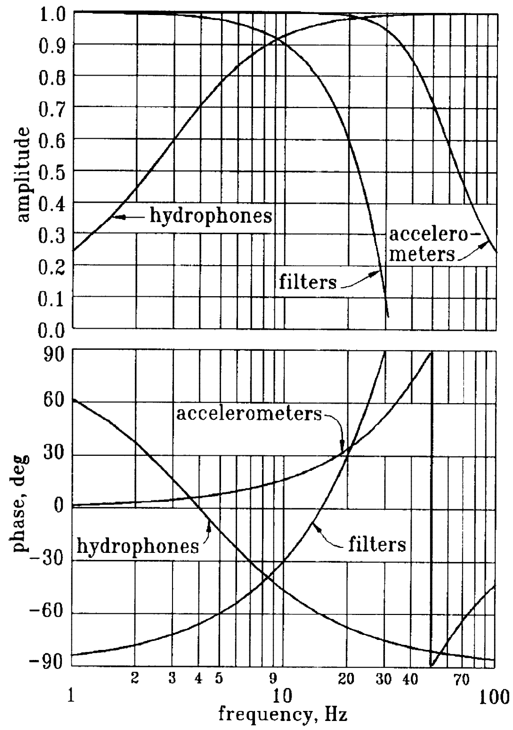

Fig. 3: Frequency responses for equipment components

filter behaviour as shown in Fig 3) at depths of 15, 30, 45, 60 and 75 m. Hydrodynamic pressure responses in the impounded water were obtained along the upstream face at the centre of blocks F, H and M, and at distances of 30, 60 and 90 m from the dam face. During winter tests, the ice cover was drilled with a 15-cm-diameter helicoidal steel blade and the hydrophone arrays were immerged at 3, 30, and 60 m from the dam face along the center of block H.

All instruments were connected to a Hewlett-Packard HP3852a data acquisition system. This recording unit has a 100 kHz aggregate sampling rate and is microcomputer-controlled through an IEEE-488 GPIB interface. It also uses track-and-hold technology which allows for simultaneous sampling and therefore eliminates the need for alignment corrections. Customized programs provide a real-time display of all recorded signals and offer considerable flexibility, as most commercial fully-automated data acquisition packages are not designed for the testing of large-scale structures such as dams, and do not offer control over some important parameters (total number of samples, total time of sampling, etc.). Moreover, some packages do not provide anti-aliasing hardware filtering and only include some types of numerical filter. The filtering process is essential and must take place prior to the analog to digital conversion, as frequencies close to the sampling rate will be aliased in the low range and will not be eliminated by a numerical procedure. Responses for the 20 Hz hardware filters used during both tests were measured and are shown in Fig 3

DATA PROCESSING AND RESULTS

A complete set of frequency response curves for the dam and reservoir was obtained for each shaker position. For each measurement station, frequency responses were obtained by varying the operating frequency of the shaker. Steady-state acceleration and pressure amplitudes are normalized by the excitation force, and the phase lag of each response component is determined with respect to the shaker force. Amplitude and phase modifications of each measurement component are accounted for and corrected using the curves of Fig 3. Figure 4 shows the amplitude and phase response for the dam crest at blocks H and I with the shaker on block H. Each peak represents a resonant frequency of the dam-reservoir-foundation system. Mode shapes can be obtained by computing the steady-state displacement and plotting the resulting values for each station along the crest corresponding to a reference accelerometer at maximum amplitude. Using this method, four modes (two alternating symmetric and antisymmetric shapes) were identified in the 4 to 10-Hz range (Fig 5a). Moving the shaker at the quarter points yielded a clearer definition of the first antisymmetric mode.

Following the summer tests, a correlation study was undertaken to investigate the performance of specialized 2D and 3D finite element programs and to investigate the effects of dam-reservoir interaction (Proulx and Paultre, 1994). Figure 5b shows the crest response at block G computed with the EACD program used for 3D seismic analysis of concrete dams (Fok *et al.*, 1986). A substructure approach is used with finite element meshes for the dam, reservoir and foundation. The foundation model is massless, and its stiffness matrix is condensed at the dam-foundation interface. A finite region of the reservoir is modelled, including reservoir bottom absorption, and a constant-depth semi-infinite portion of the reservoir extending upstream is included. The model accounts for water compressibility and radiation damping in the upstream direction. Complex frequency-dependent hydrodynamic forces are computed and added to the system equations, which are solved in the frequency domain. Some modifications were implemented in the program in order to compute frequency response functions for acceleration and hydrodynamic pressure under a concentrated harmonic force applied on the crest. An extensive study was carried out and several calibration parameters were studied. The values retained were those producing the best match with the first experimental resonant frequency. The 2D approach was also investigated, but the three-dimensional nature of the system responses and mode shapes were better modelled with a complete 3D model including dam-reservoir interaction, as shown in Fig 5b. As can be seen, the dam-only and dam-foundation cases clearly overestimate both the amplitude and the resonant frequencies (and underestimate system damping). However, the inclusion of the reservoir with compressible water in the model produces curves which match the overall trend of the observed experimental behaviour and accurately predicts the first modes. Similar results were obtained for various locations in the dam (including the inspection galeries) as well as for pressure responses in the reservoir. The accuracy of the complete 3D model was also put forth by the agreement between measured and computed mode shapes (Proulx and Paultre, 1994).

COMPARING WINTER AND SUMMER RESULTS

As is clearly illustrated in Fig 4, the presence of the ice cover and the lower temperatures during winter tests considerably modified the frequency response of the dam-reservoir-foundation system. A great amount of damping is added to the system and a reduction of the resonant frequencies is observed. Moreover, there is apparently a new resonant frequency associated with the first peak just below 5 Hz on Fig 4a. This new peak can also be observed in Fig 6a for galleries 1, 2 and 3. This phenomenon was reported in a numerical study of the effect of ice on the seismic response of gravity dams (McCullough, 1995), using a 2D model including ice cover, and can be attributed to the additional mass and stiffness at water level. Acceleration responses in galleries 1 and 2 also show this new mode (Fig 6a).

Figure 6b illustrates the measured joint motion around the third resonant frequency at the crest level during winter tests. Similar results were also obtained in the first gallery. Hydrodynamic pressure responses at the dam face (block H) are compared in Fig 7 for both series of tests. The added damping and reduced frequencies are also observed in this case (the amplitude scales are different in order to compare the response shapes).

Based on these preliminary results, it seems that the added damping observed can be partly attributed to the modification of dam-reservoir interaction and of the impounded water boundary conditions by

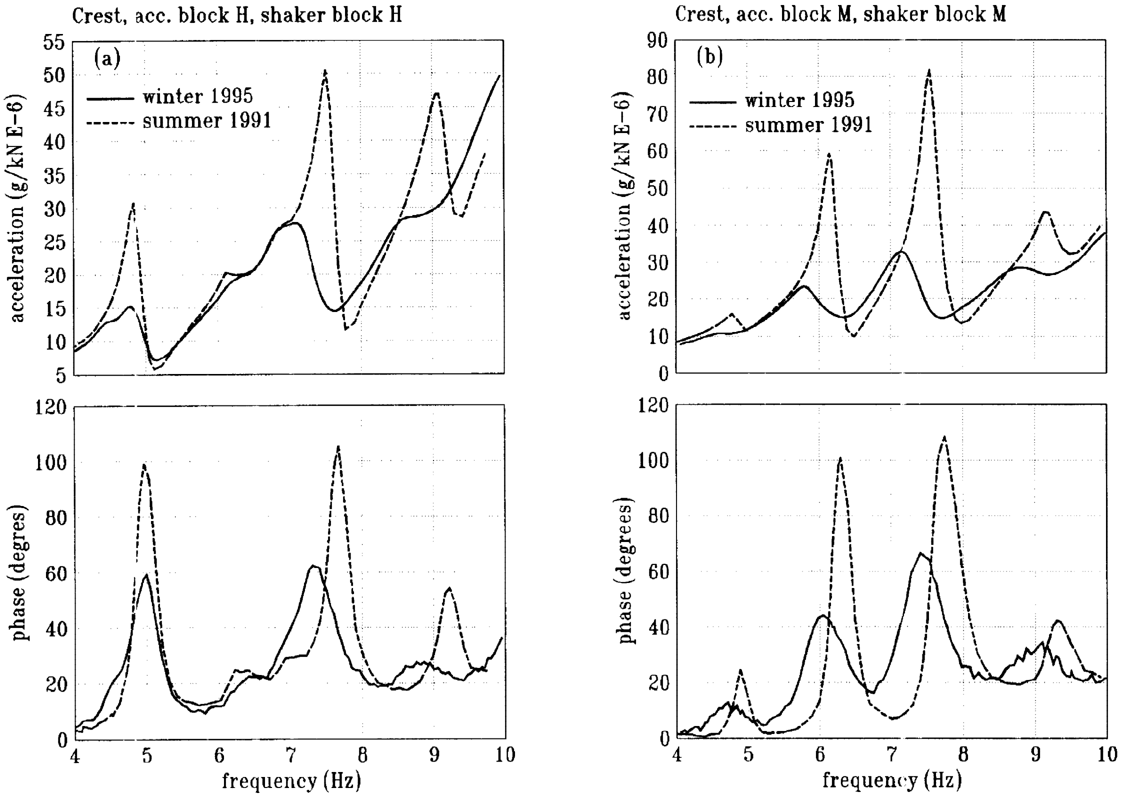

Fig. 4: Crest response — Summer and winter tests.

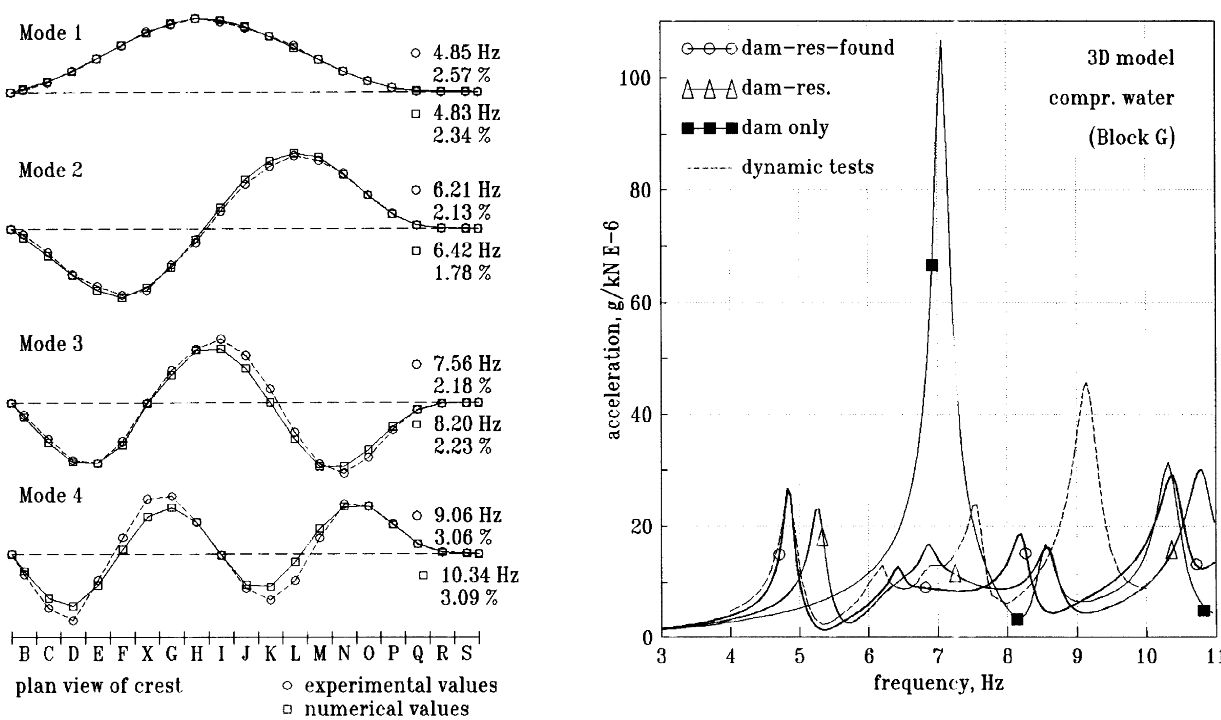

Fig. 5: Experimental mode shapes and 3D finite element model response.

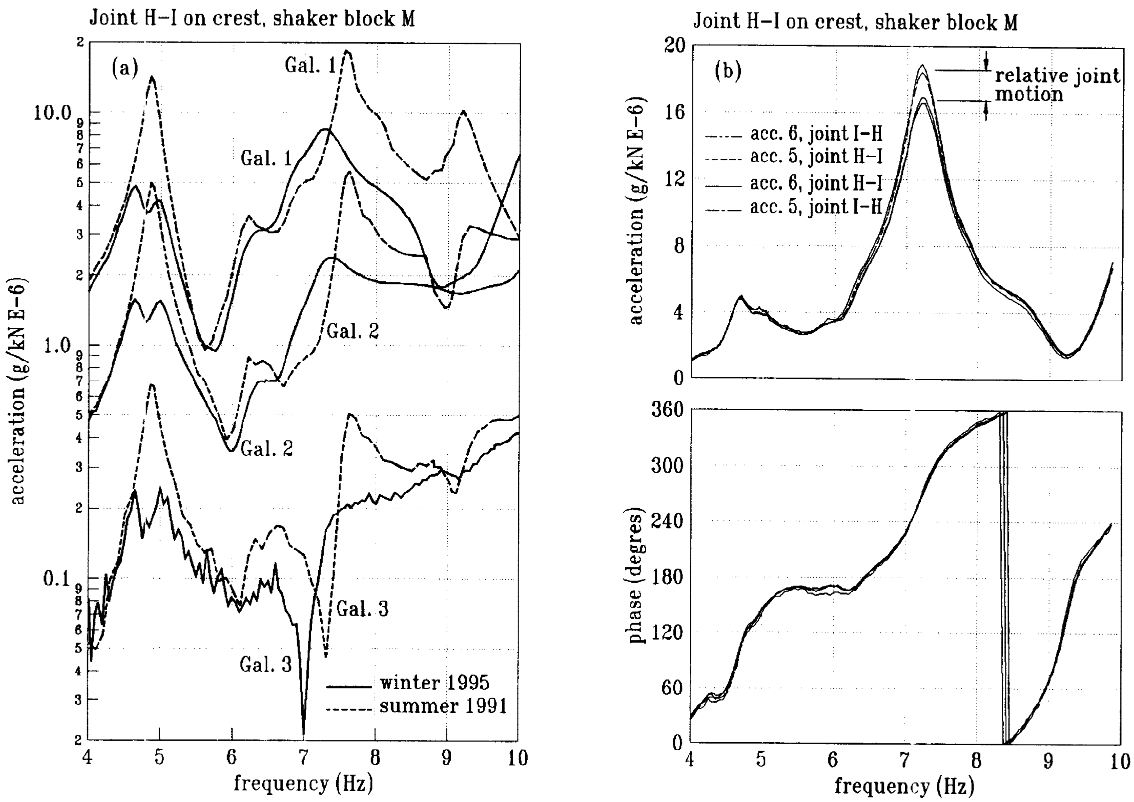

Fig. 6: Gallery responses and joint motions.

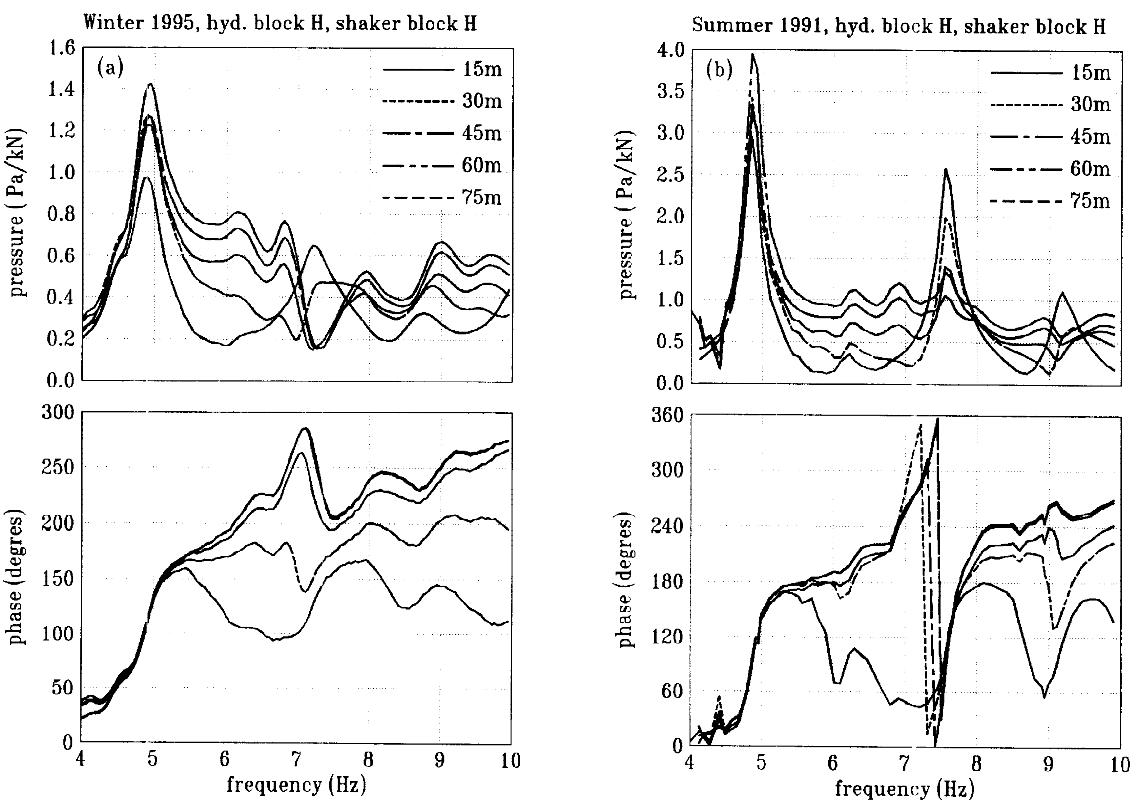

Fig. 7: Hydrodynamic pressure — Summer and winter tests.

the ice cover. The downward shift in the resonant frequencies can be attributed to a reduced overall stiffness due to joint openings induced by lower temperatures, and added reservoir mass due to the ice cover.

A correlation study is underway at the University of Sherbrooke during which the non linear behaviour due to vertical joint motion will be investigated. The modelling of the ice cover is also being developed and added to the complete dam-reservoir-foundation 3D model, to be compared with the experimental results obtained during the winter tests.

CONCLUSIONS

During this research project, forced-vibration tests have been carried out on a concrete gravity dam in both winter and summer conditions. A complete set of frequency responses, including hydrodynamic pressure measurements, was obtained for many locations on the dam crest, inside the galleries, on the downstream face, and in the impounded water. A comparison between winter and summer experimental results has shown that a considerable amount of damping is added to the system by the presence of the ice cover and that some joint motion is apparent and contributes to a downshift of resonant frequencies.

The reliability of the experimental procedures and the quality of the results obtained from well-documented large-scale dynamic tests are the basis of the evaluation of the seismic performance of structures. These can only be ensured by well-defined and complete experimental investigations, including corrections for the individual response of each component of the measuring system. The experimental data obtained on Outardes 3 fully characterizes the dynamic behaviour of the dam-reservoir-foundation system in winter and summer conditions, and can be used effectively to evaluate the performance of state-of-the-art finite element programs for seismic analysis.

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