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Dynamic testing of Outardes 3 gravity dam

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ABSTRACT: Forced vibration tests conducted on Outardes 3 gravity dam (Québec, Canada) have been completed in which an eccentric mass shaker attached on the crest was used to excite the dam. Tests were conducted with the shaker placed at three different locations along the crest. Measurements taken include acceleration responses along the crest and at locations in inspection galleries, and hydrodynamic pressure responses along the upstream dam face and at various distances away from the dam in the reservoir. Details of the experimental procedures employed and a discussion of experimental results are presented.

1 INTRODUCTION

Forced vibration testing can yield reliable data from which evaluations of the dynamic response behavior of concrete dam systems can be made. In particular, careful measurements of both acceleration and hydrodynamic pressure responses in the dam system can be used to investigate both dam-foundation and dam-water interactions. Although a number of vibration tests on gravity dams are reported in the literature, problems with transducers and testing procedures appear in a majority of cases (Hall 1988). Recent advances in test and measurement technology coupled with newly developed experimental techniques for hydrodynamic response measurements have shown greater data reliability and accuracy during forced vibration testing of large concrete dams (Duron 1991a). While these procedures were primarily developed for concrete arch dam systems, the investigation at Outardes 3 dam is the first reported series of tests in which similar procedures were employed on a gravity dam.

Testing was conducted by two independent research teams from the University of Sherbrooke and Harvey Mudd College joined in a collaborative effort. Both teams used separate data acquisition and measurement systems during testing as part of an effort to identify procedures or measurements which may be particularly sensitive to the type of test equipment employed. The tests at Outardes 3 dam were designed to yield a better understanding of dam-water interaction effects on a large gravity dam and to provide a set of reliable data for calibration of finite element models using state-of-the-art analytical techniques for the dynamic behavior of gravity dams.

The Outardes 3 gravity dam was selected for forced vibration testing because of its simple, near symmetric geometry for both the dam and reservoir, its location in a region of moderate seismic activity, and expected important water compressibility effects on the dam response. The investigation at Outardes 3 dam is part of an ongoing research program at the University of Sherbrooke, sponsored by Hydro-Quebec and aimed at gathering measured response data at various concrete dams in order to better understand the dynamic response characteristics of concrete dam systems.

Described below are the experimental procedures employed during testing, a comparison of measured responses obtained using the different data acquisition systems, and a description of the quality and type of data obtained during testing.

2 OUTARDES 3 DAM

Outardes 3 dam is part of the Manicougan-Outardes hydro-electrical complex in the Nort-East of the province of Québec, Canada. This gravity dam is located on the Outardes river, between Outardes 2 and 4 dams, approximately 100 km north of the town of Baie-Comeau. With its 19 monoliths, maximum crest height of 84 m and crest length of 298 m, it is the largest concrete gravity dam in the province of Québec (Fig. 1). The crest is 4.6 m wide, the maximum thickness at the bottom is 79 m, and the total concrete volume is 362 000 m^3. The foundation rock

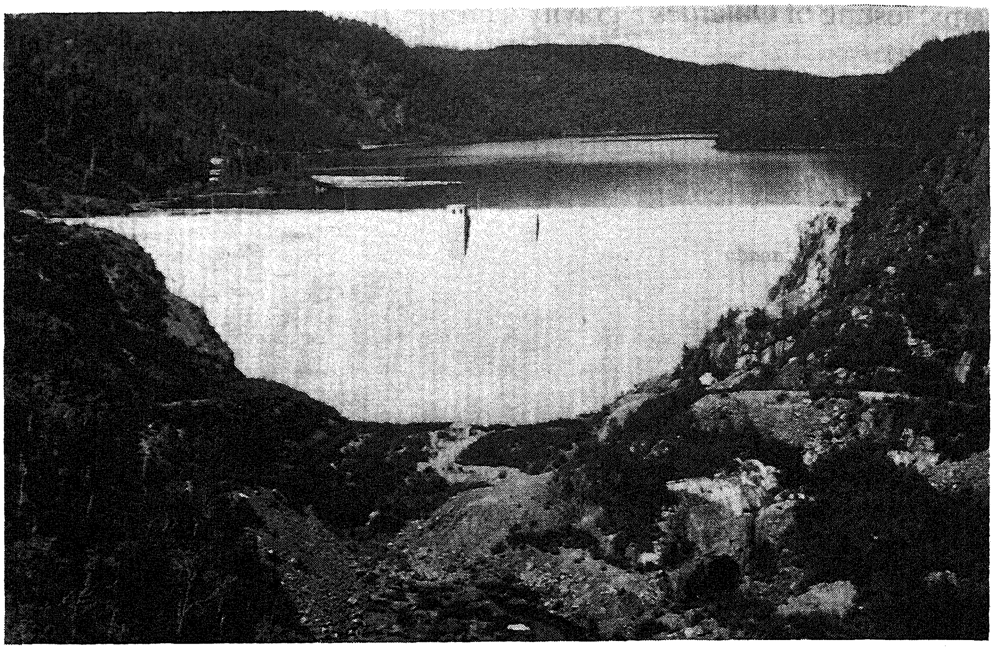

Figure 1: Outardes 3 dam.

consists of anorhositic gabbro and granitic gneiss. The overspill and the power plant are located about 2 and 3 km away respectively. The dam was completed in 1968 and the power plant, which has a total capacity of 1 040 000 HP, was fully operational in 1969. The average flow is 370 m^3/s (maximum flow is 600 m^3/s).

3 EXPERIMENTAL PROCEDURE

Two seperate measurement systems — from University of Sherbrooke (U of S) and Harvey Mudd College (HMC) — were used during the dynamic tests of Outardes 3 dam, and are described in the following. Both systems included a set of accelerometers, a hydrophone array, and a computer controlled data acquisition system. Complete sets of measurements were taken seperately by each team to investigate the reliability and repeatablity of the experimental procedure.

3.1 *Excentric mass shaker*

The excitation was provided by a single MK-12.8A excentric mass shaker (manufactured by ANCO Inc., Culver City California), attached to the crest and placed successively on three different monoliths (H, M and F on Fig 2). These locations were selected with the aid of a three-dimensional finite element model including the foundation rock and added masses for the reservoir (Paultre *et al.* 1991), which indicated significant motions at these monolith positions during both symmetric and antisymmetric responses.

A sinusoidal force of up to 45 kN in continuous operation (0–10 Hz) and up to 90 kN in intermittant operation (0–20 Hz) is generated by the rotation of a set of two excentric masses about parallel vertical shafts. Two matched sets of weights are available: 519 kg-m eccentricity for operation in the 0–10 Hz and 110 kg-m eccentricity for operation in the 0–20 Hz range. The controler provides a frequency control of $\pm$ 0.01Hz. A reed switch is triggerred by the rotation of a notched disk attached to one of the shafts and ouputs a single 5 Volt pulse when the force reaches its maximum value. The base plate of the shaker is anchored on the dam with 12 bolts, and cement grout is used to maintain uniform contact between the surfaces. The direction of the resulting force can be varied by rotating the set of weights. For Outardes 3 dam, the force was perpendicular to the longitudinal axis of the crest.

3.2 *Accelerometers*

To measure horizontal acceleration response, the U of S measurement system used six low frequency SA-102 accelerometers (manufactured by Terra Technology, Redmond, Washington) with a resonant frequency of 50 Hz. These accelerometers were mounted on aluminum plates leveled on the surface by three adjustable screws. An electrical calibration procedure at each accelerometer was needed to minimize

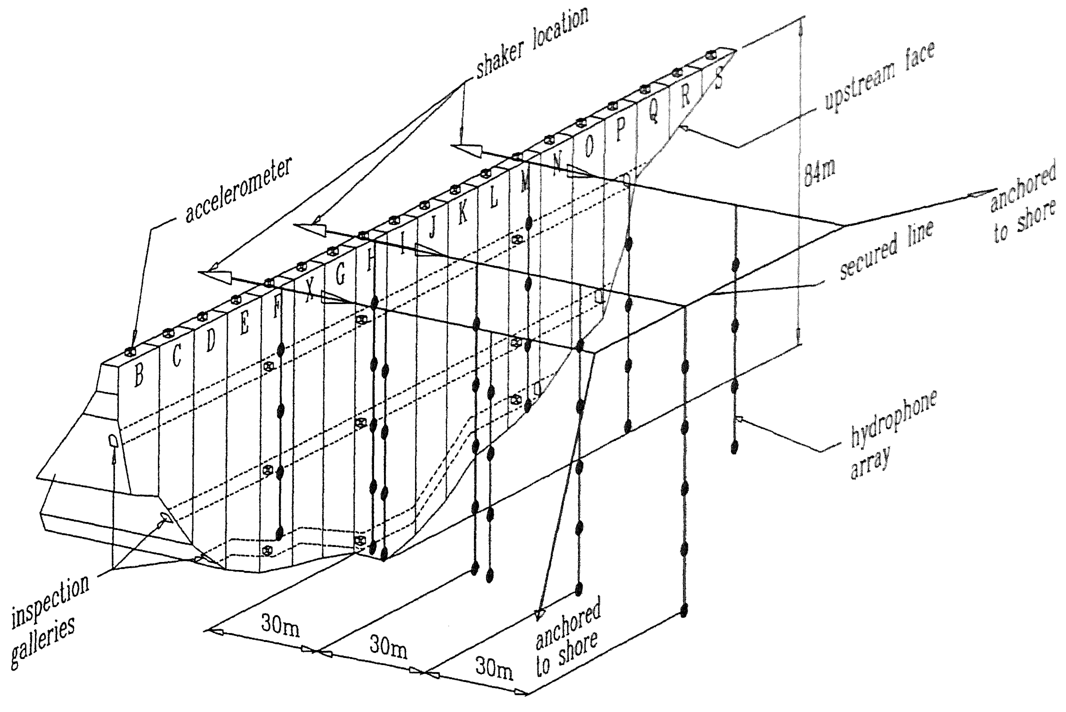

Figure 2: Experimental setup — view of upstream face and reservoir.

unwanted signal bias. The frequency response of the accelerometers is constant in the 0–20 Hz range and a maximum output level of 50 Volts/g was used for the tests at Outardes 3.

The HMC measurement setup used five force balance QA-700 accelerometers (manufactured by Sundstrand Aerospace Instrument Systems, Redmond, Washington), mounted in a similar fashion, with a frequency response constant in the 0-300 Hz range and an output level of 10 Volts/g. No electrical calibration was necessery for these accelerometers and levelling was acheived with a bubble level.

As shown in Fig. 2, accelerometers were placed on the crest at the center of each monolith and in the inspection galleries at the center of monoliths H, M, and F. Accelerometers were also placed on each side of selected monolith joints on the crest for the purpose of measuring motions across the joints, and two accelerometers were placed on the downstream face of the dam at the level of the first two galleries from the top to obtain a better definition of two dimensional resonating shapes. At each location, the accelerometers were oriented to measure motions perpendicular to the longitudinal axis of the dam crest.

3.3 *Hydrophones*

Hydrodynamic response measurements along the upstream dam face and in the reservoir were obtained using two instrument arrays of solid-state hydrophones. Complete details of the design and construction of these arrays can be found in Duron (1991b), however, a brief summary is provided below.

Each hydrophone array consists of eight solid-state hydrophones (manufactured by Halliburton Geophysical Services, Houston, Texas) spaced at 15 m apart along a cable 229 m in length. Typical frequency response characteristics for each hydrophone were chosen with a 4 Hz low frequency cut-off and a $1.46E10^{-4}$ Volts/Pa sensitivity level. Variations in hydrophone response characteristics have been shown to be less than 10% from hydrophone to hydrophone. Because the maximum depth of the reservoir at distances from 0 to 90 m away from the dam face was approximately 67 m, only the bottom five hydrophones on each array were used for acquiring data.

A system of nylon cables was setup to support the hydrophone arrays at various positions in the reservoir. First, a stronger cable is secured on both sides of the reservoir, parralel to the crest, at approximatly 95 m from the dam face (Fig 2). Three cable are then

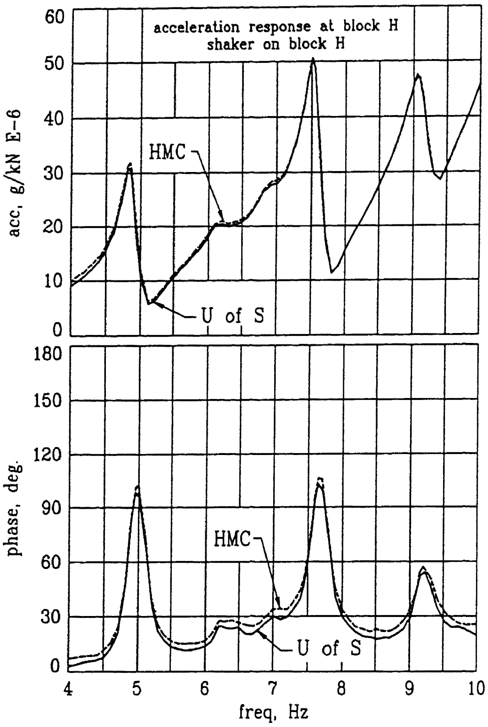

Figure 3: Comparison of measurement systems.

placed at Blocks H, M and F, corresponding to the three shaker positions, between the crest and the secured line. These cables are marked at 15 m intervals and are pulled in tight until the distance separating the crest and the secured line is 90 m. The hydrophone arrays are suspended vertically at various points on these three lines, so that the first hydrophone lies on the bottom of the reservoir. For Outardes 3 dam, measurements were made at 0, 30, 60 and 90 m from the dam face along the center cable, and at 0, 30, and 60 m along the cables at Blocks F and M.

3.4 *Data acquisition system*

The U of S mesurement system is based on the Hewlett-Packard HP3852a data acquisition and control unit. This unit has an internal voltmeter with an aggregate sampling rate of up to 100 kHz for one channel, and can house six HP44730A multiplexer modules with four channels each (additional modules can be added in a seperate main-frame). These include track-and-hold capabilities that eliminate sampling delay and have anti-aliasing filters modified to obtain a cutoff frequency of 20 Hz. Signals are digitalized with a 13 bit precision and stored in the voltmeter's 64 Kb memory. The voltmeter has a 10 Volt maximum range and gain can be set to 1, 10 or 100.

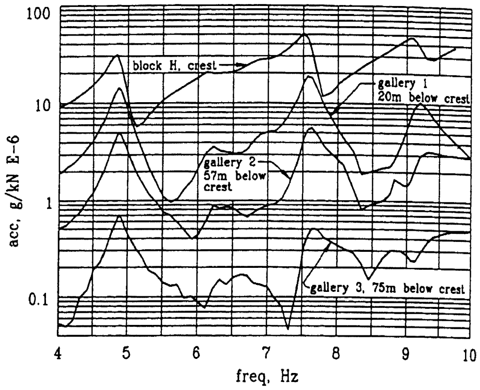

Figure 4: Frequency response for accelerations in the inspection galleries (Block H, shaker at block H).

The HP3852a is entirely programmable and can be controlled by any computer through a GPIB interface port (an IBM PS/2 microcomputer was used to control the HP3852a). The main frame has an expandable memory of 256 Kb were data are stored before they are transfered to the microcomputer. The voltmeter can be triggered and stopped by the keyboard or by an external event. The graphic interface of the data acquisition program developped at the University of Sherbrooke enables real time display of the acquired data, as well as the pulse generated by the shaker. The system is triggered manually, and the pulse is used as a reference to align all signals on the maximum force. Data are stored on the microcomputer hard disk using a data compression scheme reducing total space by a factor of 4.

The HMC data acquisition system employed during testing was the same as described in Duron (1991a). The system consists of a signal conditioning module designed and built at H.M.C., and the Computerscope EGAA system (R.C. Electronics, Goleta, California). Amplification and low-pass filtering, with a cutoff frequency of 10 Hz, is provided by the signal conditioning module which has a selectable gain of 1 to 400. Signals are first filtered using a passive high-pass filter with 0.033 Hz cutoff frequency to eliminate unwanted signal bias associated with imperfect levelling of the accelerometers while not affecting the low frequency components of interest. The EGAA system consists of an analog-to-digital data acquisition card for an IBM compatible microcomputer and associated software to control data acquisition and storage. The A/D board is capable of sampling up to 16 channels of data at an aggregate sampling rate of 1 MHz with a 12 bit accuracy over a ±10 Volt range. Multiple buffers of data are acquired in a burst mode which is triggered by the leading edge of the shaker force pulse.

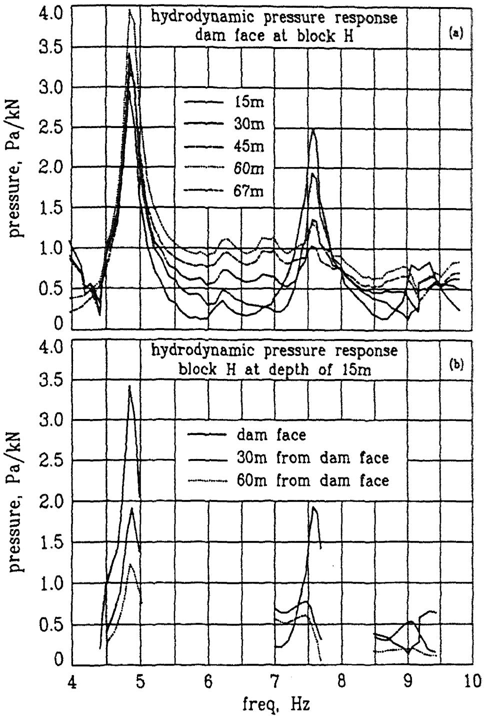

Figure 5: Frequency response for hydrodynamic pressure.

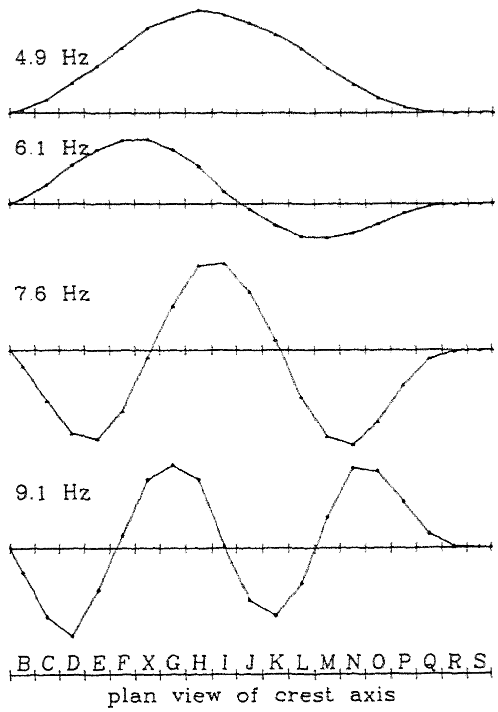

Figure 6: First four resonnance shapes for crest.

3.5 *Testing procedure*

Prior to final testing, preliminary frequency sweeps were performed to identify resonances in the dam system. For each test, a frequency increment of 0.1 Hz was used except in the vicinity of resonant peaks where a smaller increment of 0.05 Hz was used. Typical frequency sweeps ranged from 4 to 10 Hz and required approximately 40 minutes to complete. Data were sampled at 1000 Hz over 4 seconds for accelerometer data, and over 8 seconds for hydrophone data.

A least square curve fitting algorithm was used to compute the amplitude, phase relative to the exciting force, and signal offset for each data channel. Phase and amplitude corrections for the antialiasing filters, amplifiers, accelerometers, and hydrophones are accounted for. Magnitude and phase frequency response curves are then constructed for every measurement station. Data reduction and calibration software was developped by both research teams.

When measuring hydrodynamic pressure responses, windy conditions can adversely affect the signal quality of the hydrophone measurements. In order to maximize the signal to noise ratio for each measurement, it is necessary to isolate the hydrophone array from surface wave effects which can produce excessive motions along the cable. These motions result in long period, large amplitude signals superimposed on the hydrodynamic responses. The cable system employed to position the array could not satisfactorily isolate the hydrophone arrays from these effects and as a result, the majority of the hydrodynamic response measurements were taken during periods of calm conditions; typically late at night or at dawn.

As shown on Fig. 2, 44 hydrophone stations were chosen in the reservoir, 19 accelerometer stations on the dam crest and 3 stations for the 3 inspection gallery levels. In addition, 8 acceleromter stations were chosen to evaluate joint motion on both sides of joints E-F, F-X, I-H, and L-M, for a total of 80 measurement stations for each shaker position. The two accelerometer on the downstream face were placed at joint I-H when the shaker was located on Block H.

For the first shaker position (Block H), both the U of S and the HMC systems were used independantly and two complete sets of measurements for all stations were taken. Figure 3 shows a comparison of measured acceleration responses taken at Block H obtained by placing one SA-102 accelerometer and one QA-700 accelerometer side by side. Although not presented here, similar comparisons made at other locations on the dam also indicate good agreement. Based on this agreement between measurement systems, subsequent tests (when the shaker was moved to Blocks F ans M) were carried out in a collaborative manner combining all 11 accelerometers and both hydrophone arrays for each series of measurements.

Following the forced vibration tests, water depth measurements were made at various points in the reservoir to obtain an approximation of the reservoir geometry. These measurements were carried out with a depth sounder, along the cables used for supporting the hydrophone arrays and along the centerline at distances of up to 275 m from the dam face.

4 EXPERIMENTAL RESULTS

The experimental results are presented here to demonstrate the quality of the data and the effectiveness of the experimental procedure. Correlation with analytical procedures including dam-reservoir interaction and finite element modelling of the system are currently underway at the University of Sherbrooke. All data presented here is obtained directly from measurements taken and no smoothing on the data has been performed.

The measured acceleration response at Block H with the shaker located at Block H indicates resonant peaks at 4.9, 7.6, and 9.1 Hz (Fig. 3) with damping values of 2.57, 2.18 and 3.06% of critical respectively. The smaller peak between 6 and 6.5 Hz is associated with the fundamental antisymmetric response shape of the dam at 6.1 Hz with 2.13% damping (not shown here). Figure 4 is a comparison of acceleration responses measured in each of the galleries. Reduced magnitudes in the lower galleries compared to crest response magnitudes are shown and resonant frequencies indicated in each curve are consistent with those identified in the measurements taken along the crest.

Figure 5(a) is a comparison of measured hydrodynamic responses obtained on the dam face behind Block H at depths of 15, 30, 45, 60, and 67m below the water surface. Each response indicates resonant frequencies which are consistent with those on the dam at 4.9, 7.9, and 9.1 Hz. Shown in Fig. 5(b) is a comparison of measured hydrodynamic responses about each of the resonant peaks taken behind Block H on the dam face, and at 30 and 60 m away from the dam all at a depth of 15 m. While the pressure amplitudes are shown to decay as a function of distance from the dam, the responses are reliable and consistent with measured responses on the dam. The measured responses in the reservoir will be used in evaluations of dam-water interaction effects.

Figure 6 illustrates the resonating shapes obtained from the amplitude and phase information for each accelerometer on the crest. It can be seen that the first and third shapes are symmetric and the second and forth are antisymmetric, which correlates well with the mode shapes obtained by finite element analysis.

5 CONCLUSIONS

The forced vibration tests conducted on Outardes 3 dam have successfully demonstrated the applicability of newly developed techniques to the testing of large concrete gravity dams. The good agreement shown between both the magnitude and the phase of the acceleration responses obtained by both research teams suggests that the differences in accelerometer characteristics (10 Volts/g and 300 Hz cutoff for the QA-700 versus 50 Volts/g and 50 Hz for the SA-102) do not significantly affect data quality. The use of a single vibrator placed at different locations along the crest of a long gravity dam appears to yield satisfactory measurements. Some modal interference from closely spaced resonances was observed during testing with the shaker at Block H, however these effects were eliminated when the shaker was moved to Blocks F and M. This collaborative effort by two research teams from two different countries has put forth the need for the developement of standardized procedures for dynamic testing of large dams.

6 ACKNOWLEDGEMENTS

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