12TH CANADIAN CONFERENCE ON EARTHQUAKE ENGINEERING
JUNE 17-20, 2019
CHÂTEAU FRONTENAC
QUÉBEC, QC.
12ÈME CONFÉRENCE CANADIENNE DU GÉNIE PARASISMIQUE
17-20 JUIN 2019
CCEE 2019

The use of ambient vibration instrumentation for dams at Hydro-Québec

Benjamin Miquel[1], Daniel Verret[2]

[1] Structural Eng., Ph.D., Dam Expertise, Hydro-Québec - Montréal, QC, Canada.
[2] Geotechnical Eng., M. A. Sc., Dam Expertise, Hydro-Québec - Montréal, QC, Canada.

ABSTRACT

Ambient vibration instrumentation is a powerful additional tool to better understand the seismic behavior of a structure and consequently better asses its seismic behavior during a major earthquake. This paper presents the global methodology at Hydro-Québec in performing ambient vibration tests, its advantages and disadvantages when compared to more sophisticated in-situ measurements and some improvements that allow measuring clearer signals. Two examples of how those measures are used in ongoing studies are presented.

Keywords: Dam, Seismic, Ambient Vibration, Dynamic, Natural Frequencies.

INTRODUCTION

Many dams have been constructed in highly seismic regions around the world. During their design, no or little considerations were given for seismic loads. Also, numerous aging dams have undergone deterioration since their construction caused for example by thermal loading and/or concrete swelling (Alkali-Aggregate Reaction) in the case of concrete dams.

Because failure of a dam can lead to catastrophic human and economic losses, some countries have created regulatory agencies that require dam owners to perform periodic safety assessment of their facilities. In Québec, the regulation on dam safety, effective since April 2002, imposes the verification of the seismic safety of dams. In 2002, the Québec Dam Safety Act imposes to dam owners of high-capacity dams to undergo a safety reviews every ten years for each dam. In this evaluation, seismic analysis has to be performed to verify that the behavior under such extreme loading is adequate. Also, many dam owners are undertaking major rehabilitation projects to expand the lifespan of their infrastructures. For these projects, state-of-the art seismic analyses have to be performed to validate that the modifications or reinforcements required will allow the dams to withstand a major earthquake. Those analyses should to take into account the effect of aging which adds considerable uncertainty in already complex studies.

During the last decades, there has been a growing interest in the use of geophysics solutions to estimate dynamic properties (natural frequencies, mode shapes and damping ratio) of infrastructures such as building, bridges, and dams. These structural properties can also be obtained by a modal analysis of the structure. The comparison between in situ and numerical results allow validating that the model adequately accounts for mass and rigidity distribution. In other term, this validation assures that at least the linear behavior of the structure is well captured in a seismic analysis allowing an excellent first validation. In 2015, Hydro-Québec has started investigating the use of ambient vibrations instrumentation as an additional tool to feed ongoing seismic reevaluation studies as legally required or for particular studies such as major rehabilitation projects of ageing dams. This paper presents the global methodology in performing ambient vibration tests, its advantages and disadvantages when compared to more sophisticated in-situ measurements and some improvements that allow measuring clearer signals. Two examples of how those measures are used in ongoing studies are given.

AMBIENT VIBRATION ANALYSIS

Overview of ambient vibration and measuring technics

Ambient vibration tests consist in the analysis of the effect of seismic noise on a structure. The seismic noise or micro tremors are mainly caused by human activities (ex. machinery), wind and, in the case of dams, waves propagating in the reservoir. These micro tremors, of very small amplitude, excite the structure which will amplify certain frequencies depending on its dynamic properties. By analyzing recorded signals where dynamic amplification should be important (ex. at crest of a dam for fundamental modes as shown in Figure 1) it is possible to identify the natural frequencies of the structure for which peak amplitudes are found in the frequency domain.

If the noise can be considered as a white noise (i.e. having a flat amplitude spectrum) than the analysis of the recorded effect of this noise on a structure would yield directly to the frequency response function of the structure. This would allow a quick estimation of its naturals frequencies and damping ratios. The main difficulty arises from the fact that the noise is usually not a white noise. Consequently, as it will be shown below, the frequency analysis of the recorded signal will show peak amplitudes that can be caused by dynamic amplification but also by high amplitudes in the noise. This is especially true on a dam where for example the turbines create high amplitude noise at its rotating frequency. Using a single recording station, it is not possible to retrieve the original noise from the recorded signal.

To circumvent this problem, serval technics are available such as:

- Transfer function method: this method uses two recording stations, one in the structure, the other at structure-foundation interface. The effect of a none white noise can be extracted by dividing in the frequency domain the signal obtained in the structure by the one at foundation. The problem with this technic for dams is that the foundation is not always easily accessible at downstream of a sensor placed at crest (presence of soil deposit, or water) and when it is, it can be close to the powerhouse which will cause the sensor to be solicited by a high noises which will highly affect the signal treatment and results.
- Arrays: this method uses several stations where one is always maintained at the same location (i.e. the master station positioned usually were high amplification is expected) and the other ones can be moved (i.e. slave station). Those stations have to be perfectly synchronized. By calculating the ratio of frequency amplitude between all slaves and the master as well as the phase difference, natural periods, damping ratio and mode shapes can be extracted.
- Forced vibration: this method uses a shaker to excite the structure by sweeping different frequencies of interests (i.e. it doesn't use ambient vibration). Knowing the characteristic of the solicitation, it is possible to output the frequency response function based on recordings at a single station (if only natural periods and damping ratios are of interest) or at different locations (if mode shapes are also of interests which is usually the case using this method). This method is more precise than the use of ambient vibration technics as the source signal is controlled and is of higher amplitude than ambient vibration. It is especially useful when natural periods of a structure are close one to another.

Figure 1: Ambient vibration measurement

The two last technics have already been used with success at Hydro-Québec and are presented elsewhere [1, 2]. Nonetheless, the setup and analysis are more complex and time consuming. Also, for the majority of the required seismic analysis such sophistication is not required and a single recording station has proven to be sufficient particularly in finding the fundamental periods in each direction. Indeed, for a majority of dams with conventional geometries, only the validation of fundamental modes are of interest for two reasons: the fundamental modes excites a great majority of the mass (± 40-60%), and for concrete dams of average height (10 m-30 m), the higher modes have frequencies over 33hz for which the spectral acceleration can be considered equal are very close to the peak ground acceleration (in eastern Canada). Consequently, for these higher modes dynamic amplification can be neglected and the inertial forces associated with these modes can be estimated by a static correction in the seismic analysis [3]. Comparison between numerical/analytical/empirical estimation of the fundamental modes and ones obtained by in-situ measurements allow to validate quickly that hypothesis done in the analysis well capture the studied system such as: (i) effect of appurtenant structures on the response of the water retaining structure (ex. bridge over a spillway); (ii) material properties are adequately estimated ; (iii) depth of deposit.

Technology used at Hydro-Québec
Measures

The acquisition frequency is chosen as 10 times the highest frequency of interest. Due to the high frequency content of earthquakes in Eastern Canada (max. spectral acceleration at 20Hz), and the rigidity of small concrete dams (±20Hz for the fundamental frequency of a 15m dam), an acquisition frequency of 512Hz is usually used.

Based on our experience a 5-10 minutes recording time is sufficient for concreted structures and this time interval is experimentally from 20 -30 minutes actually for embankment dams. As mentioned, the velocimeter device is located were maximum amplification is expected. Mainly, for the fundamental modes in the transversal, longitudinal and vertical direction, the device is positioned on dam crest. It is oriented respecting the orientation of the dam (north direction of the sensor oriented towards the upstream).

Treatment

The TROMINO© velocimeter device is provided with the software Grilla which allows to extract the measures from the sensor and perform a first analysis of the records. The open source software Geopsy developed by the SESAME European Project is also used for more precise treatment.

The first step consists in dividing the signal in windows of same length (A-C in Figure 2). In our experience, windows of 20s yields good results. For each of these windows, a Fast Fourier Transform (FFT) is calculated which allows to observe the frequency amplitudes in the signal as a function of time (D-F in Figure 2). Usually when a window gives very different results than the other windows it is caused by spurious noise (ex. passing of a truck during the acquisition) that should be excluded from the rest of the analysis. This first analysis will also show constant high amplitudes at certain frequencies over time. Those high amplitudes could indicate a natural frequency of the structure but could also be caused by a spurious constant noise coming from an equipment.

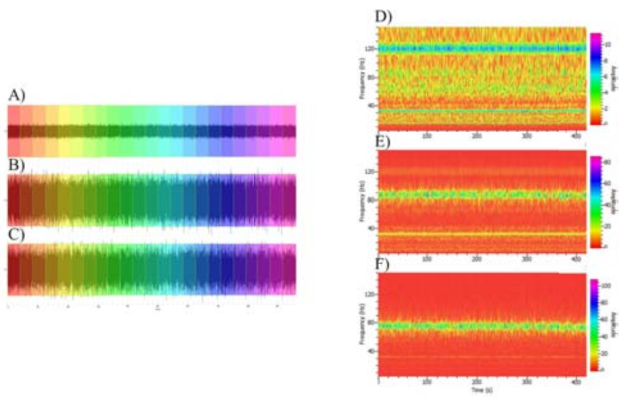

Figure 2: Windowing of signals: A) vertical direction; B) Upstream-downstream direction; C) left-right bank direction; Frequency content as a function of time: D) vertical direction; E) Upstream-downstream direction; F) left-right bank

In order to identify natural frequencies of the structure the first step is to output the power spectral density calculated for each recorded directions and each windows as shown in Figure 3 where the colored lines are the results for each windows, the black line is the average on all windows, and the black dashed lines are the average ± standard deviation. To clarify the global aspect of the curves, as recommended by Geopsy, as smoothing function is applied to the Fourier amplitudes. It consist in performing a moving average on a bandwidth to soften the plot and allow a better interpretation. For this, the Konno and Ohmachi [4] smoothing technique is used and the effect is shown in the left column of Figure 3.

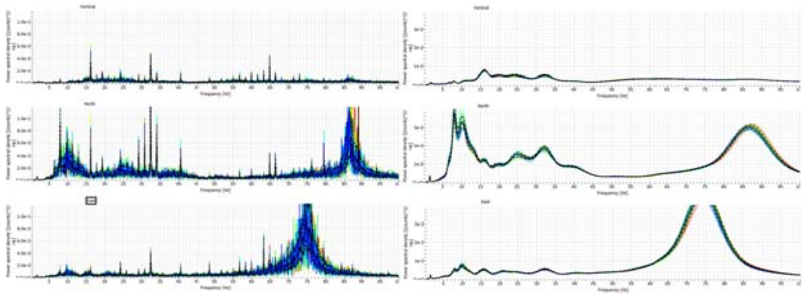

Figure 3: Power spectral density. Left Column : unsmoothed; Right column : smoothed

In the above plot measured at crest of the intake shown in Figure 1, high amplification that could be caused by dynamic amplification can clearly be seen at frequencies ±10Hz and 87Hz in the upstream-downstream direction (North) and ±75Hz in the longitudinal direction of the dam (East). Some other peak seem to be present at 16Hz; 25 Hz and 33Hz.

In order to separate peak amplitudes caused by spurious noise from those caused by dynamic amplification we output directional smoothed power spectral density plots as well as directional smoothed H/V ratios as shown in Figure 4..

The H/V ratio method developed originally by [5] is only recommended for soil deposit. Nonetheless, experience at Hydro-Québec shows that this technic usually leads to good results for dams especially in the identification of fundamental modes. The main reason is believe to be that the fundamental frequency associated with vertical mode shapes is usually much higher than those associated with horizontal fundamental modes. Consequently high amplitudes caused by spurious noise will be present in both horizontal direction and vertical. The H/V ratio will consequently cancel or attenuate the effect of peak caused by spurious noise. This ratio allows, for example, to attenuate the effect of electronic equipment installed at crest of some powerhouses such as transformers. Comparison with natural frequencies obtained by numerical analysis, analytical or empirical formulas is then performed to help identifying natural frequencies obtained by in-situ measurements. This aspect will be addressed in the following section.

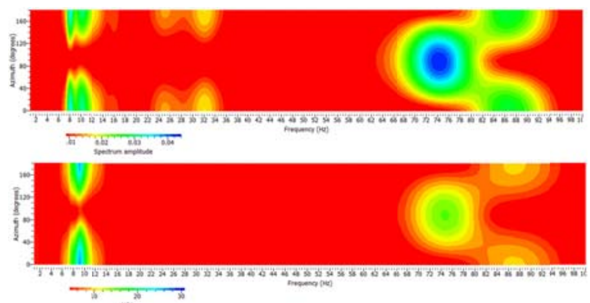

Figure 4: Directional plots: A) Density Spectrum; B) H/V ratio

Impovement for better quality of measure

Based on our experience, the quality of measures on dams can significantly be improves by covering the sensor with an isolated wooden box as shown in Figure 5. The Figure 5 shows the H/V ratio for upstream-downstream direction (N-S/V) and bank direction (E-W/V) and frequency amplitudes as a function of time for a dam in Québec for two measures taken exactly at the same position, one without the isolated box, and the other covering the sensor with the box. It can clearly be seen that the use of the isolated box allows a reduction of spurious noise at frequencies lower than 10Hz. The box prevents noise hitting directly the sensor without having propagated throughout the dam. The effect of the box is mainly seen between frequencies ranging from 1 Hz to 10 Hz that corresponds to noise created by natural meteorological conditions (i.e. wind) or by urban activities [6].

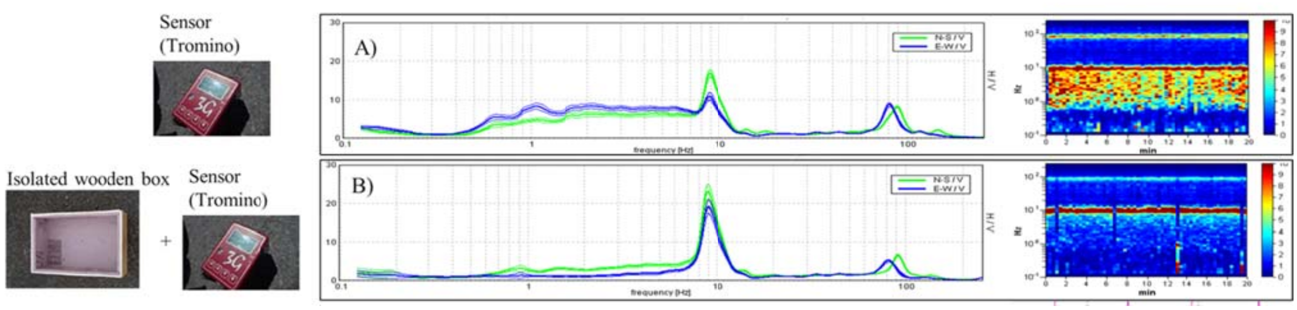

Figure 5: Effect of isolated box on measures: a) Without the box; b) With the box

For an application on an embankment dam, small steel rods underneath the sensor have the main function to ensure a good contact of the instrument with the coarse gravel of the dam crest. A robust system integrating a rigid plate and 3 rods custom steel stems of a length 150 mm x 150 mm was developed as part of a Hydro-Québec research project (Figure 6-A). After installation of this rigid plate system in the field, the velocimeter is leveled with the Tromino small individual steel rods provided with the instrument for a rigid surface such as the concrete surface of the structure.

Also, when several sensors are used on an embankment dam, in order to aloud the communication and achieve synchronization between each instrument, powerful antennas (TP-Link 2.4GHz 8dBi) connected to 6 m long cables had to be used. This arrangement ensured the signal between the instruments covering a distance of more than 500 m.

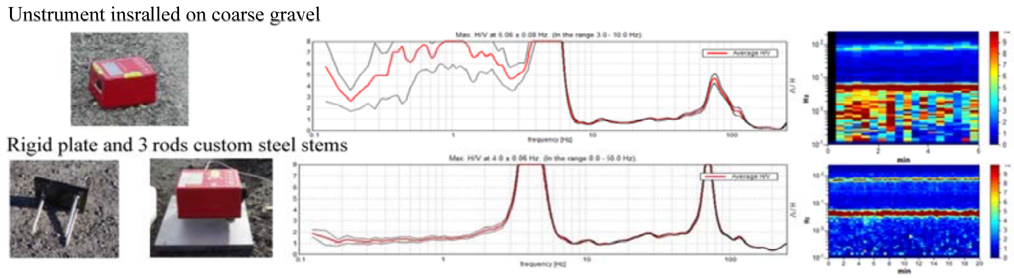

Figure 7: Effect of a rigid plate on measures: A) Without rigid plate; B) With the rigid plate

CASE STUDIES

Spillway

The studied structure is a 12 gates spillway in Québec with spillway piers of approximately 23m height (Figure 8-A). A major rehabilitation project is planned for this spillway that includes the replacement of the steel superstructure on which new gate lifting equipment will be installed. To assure functionality of the spillway after a major earthquake, floor response spectrum were required at piers crest for designing the superstructure.

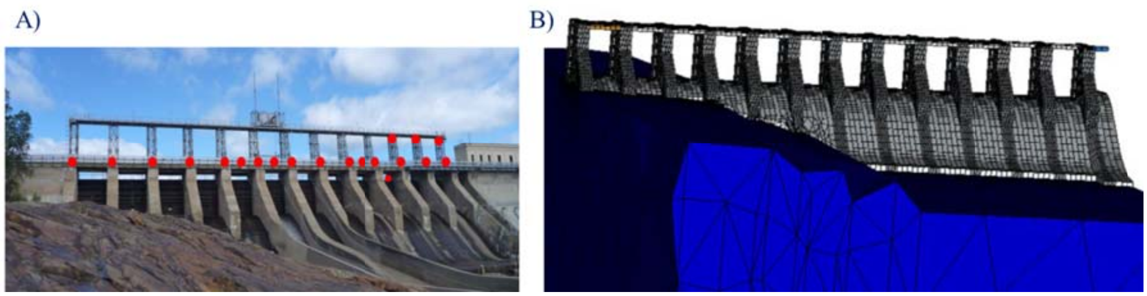

Figure 8: A) Studied spillway and location of measurements(●); B) Numerical model

Indeed, since the superstructure is anchored at piers crest, it will be subject to higher accelerations than those at rock due to dynamic amplification in the piers as shown in Figure 9. The methodology used to calculate floor response spectrum is shown in Figure 9 and consists in: (i) developing a numerical model of the spillway: this was done in the finite element software ANSYS where fluid structure was accounted for by using Westergaard added mass method [7]; (ii) selecting ground motions and adjusting them to the design spectrum given by the Geological Survey of Canada for the dam site: the adjustment was done using wavelets in the time domain with the software RSPMatch [8]; and (iii) applying the adjusted ground motions to the numerical model, retrieving accelerations at piers crest, calculating response spectrums and adjusting for uncertainty as proposed by the U.S. Nuclear Commission [9].

Ambient vibration measurements where performed in order to: (i) validate the material properties used in the analysis; (ii) validate the boundary conditions as the adjacent structures are not modelled; and (iii) understand the structural effect of the concrete bridge on the dynamic behavior of the piers. While at construction it is supposed that the span bearings had a certain amount of longitudinal mobility available, the concrete of the dam is affected by a moderate alkali reaction (concrete swelling) which questions their remaining mobility. This aspect could affect considerably the behavior of these piers during an earthquake.

The locations of the ambient measurements are shown in Figure 8-A. Measures were also taken on the superstructure and gates in order to isolate their natural frequencies from the measures on the spillway piers.

The H/V ratios obtained at each piers were compared to frequency response frequency function (FRF) obtained by the finite element analysis at the same location than the measures. After several iteration on the flexibility of bridge elements in contact with the piers, good agreement was obtained when it is assumed that the support do not offer any mobility (i.e. the bridge is rigidly linked to the piers). Example of results obtained for pier 6 are shown in Figure 10. In the upstream direction, peak amplitudes of the H/V ratios (red curve) at high periods (0,1-0,3) are caused by the resonance of the superstructure easily determined by the recording done on this steel structure. Indeed, the measures on the piers are taken closed to base of the superstructure and are consequently affected by its motion.

The fundamental period of the pier is obtained by FRF (black curve) is in accordance with the one measured. The same observation can be done in the longitudinal direction.

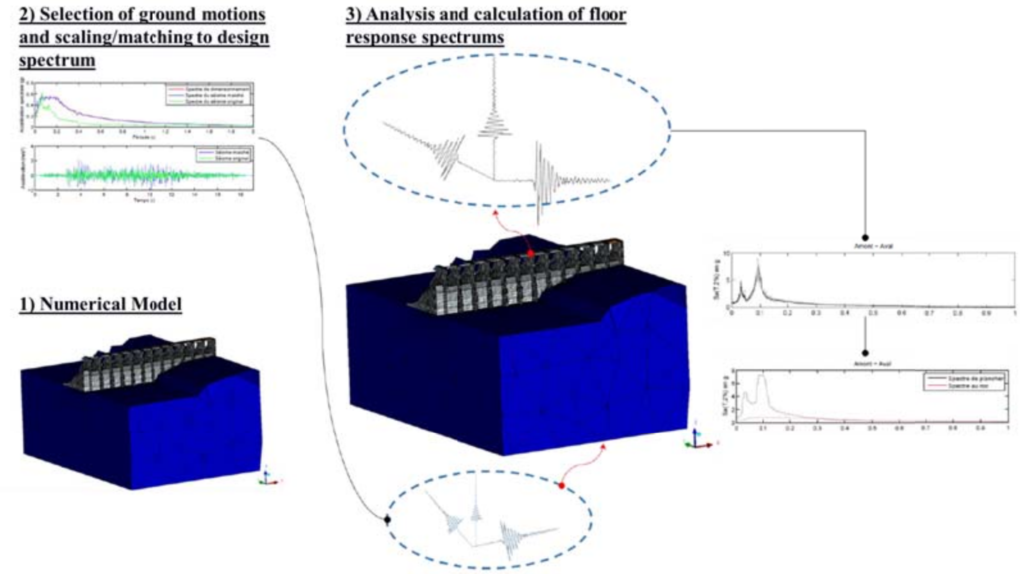

Figure 9: Methodology to calculate floor response spectrum

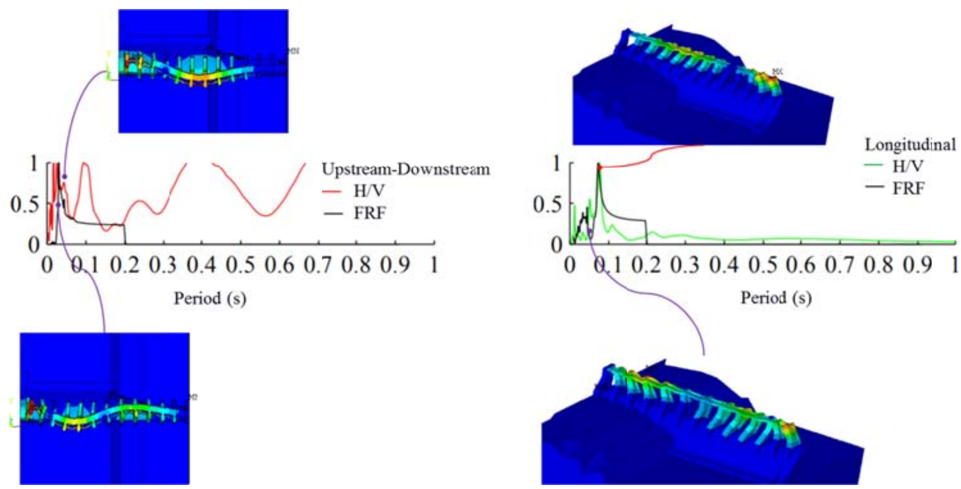

Figure 10: Example of results obtained for pier 6

Large rockfill dam

Denis-Perron Dam is a rockfill embankment 171 m high with a central till core and a crest length of 378 m. It closes the river in a very steep valley. It is built on coarse alluvium at the bottom of the valley except for the core, filters and transitions that are based on remodeled bedrock or concrete. On the banks, the fills are based on the bedrock or colluviums on the right bank downstream side. Figure 11-A illustrates the plan view of the valley and the dam while Figure 11-A shows a section of the valley in the longitudinal axis of the structure.

Experimental measurements of ambient noise were conducted on the Denis-Perron dam crest. For geotechnical application, ambient noise was mostly study for free field land (flat land) to establish the HVSR ratio. In the case of an analysis for a large dam built in a very steep valley, the use of the HVSR ratio is not fundamentally technically well supported. In order to explore the applicability of the ambient noise and the use of the Tromino instrument for a large dam analysis, transfer functions, defined by a comparison of the Fourier spectrum ratio of the embankment surface signal measurement and the bedrock signal measurement (FFT_{Fill} / FFT_{Rock}) were calculated rather than use the HVSR ratio. It is important to mention that in this test program, no ambient noise measurement was performed directly on the bedrock abutment. Transfer functions were calculated based on measurements at the right end of the dam, PM 1 + 085, T3_IN3, where the embankment fill is only a few meters thick. Figure 12 shows transfer functions of ambient noise measurements on the dam crest. While the HVSR method is not recommended for rockfill large dam, as for concrete dams and for the believed reasons discussed previously, good results were obtained using this technic to retrieve the effect of none white noise. HVSR results obtained at the center of the crest are shown in Figure 13 and are in agreement with those obtained with the transfer function method.

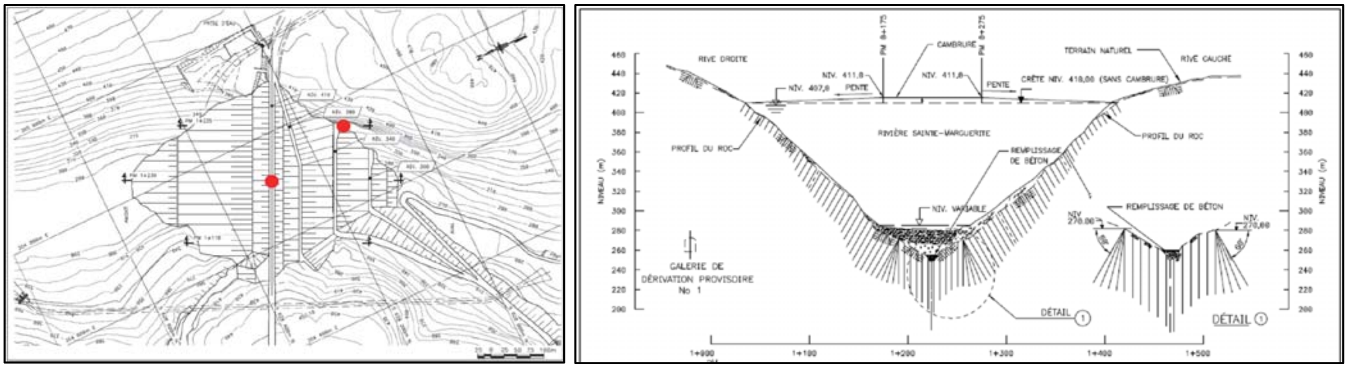

Figure 11: A) Plan view of the Denis-Perron dam, B) Longitudinal section of the valley in the central dam axis

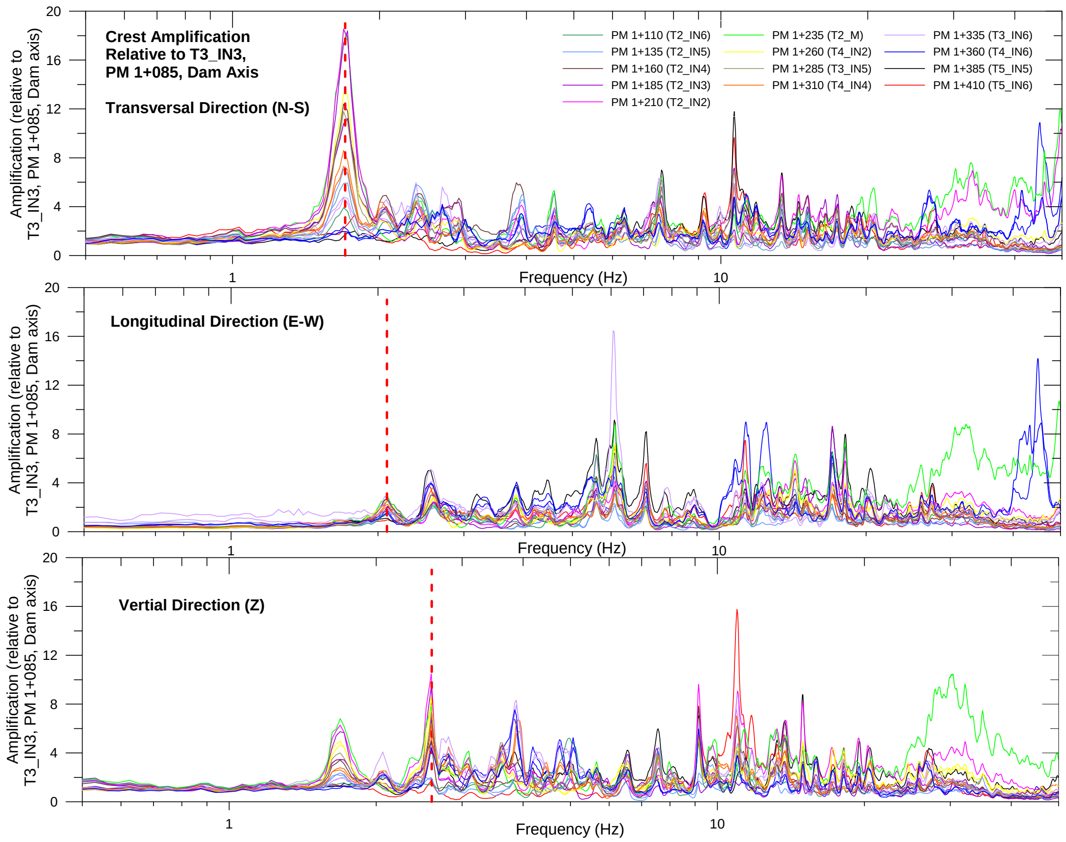

Figure 12: Transfer functions calculated from ambient noise measurements of top of the Denis-Perron dam

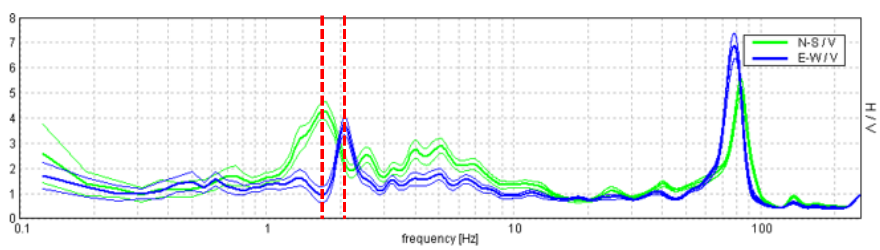

Figure 13: H/V ratio – Measure at center of crest: -Transversal direction; - Longitudinal direction

For all measurements on the top of the crest, fundamental vibration frequencies in the transverse direction varies between 1.69 Hz and 1.72 Hz with a slight increase in the frequency near each bank abutment (PM 1 + 385 and PM 1 + 410). The fundamental vibration frequencies in the longitudinal direction vary between 2.07 Hz and 2.10 Hz with also a slight increase in the frequency near each left bank abutment. In the vertical direction, fundamental frequency is about 2.59. The latter is not perceptible for signals (PM 1 + 110 and PM 1 + 135) near the reference point (PM 1 + 085, T3_IN3) on the right abutment. Fundamental vibration frequencies in the transverse direction have a greater relative amplification than in the other directions. Amplitudes of the fundamental vibration frequencies in the vertical direction are significant relative to horizontal frequencies, particularly compared to the longitudinal direction. In our understanding, this is a 3D effect (called site effect) resulting from the geometry of the steep valley. This observation is consistent with the vertical peak acceleration observed by [10] for Denis-Perron earthquakes event and by [11] for seismological data measured on the La Villita dam, particularly for the weakest earthquake. Fundamental vibration frequencies determined from the ambient noise measurements on the dam crest are within the range of the fundamental vibration frequencies determined from earthquakes event as presented by [10].

CONCLUSIONS

After 3 years experimenting the use of ambient vibration measurements to feed ongoing studies, this technology has clearly become an important additional tool to better understand the behavior of our structures and at least validate that we are able to adequately predict the linear seismic behavior of our structures. The use of a single station has proven to be sufficient in most case to output the fundamental modes of a structure and this for both concrete and earth dams of various heights and geometry. The advantage of the single station method is the simplicity of the setup that allows taking measurements during a normal inspection of a dam. Results can be obtained quickly with a simple treatment of the measured signals. The downside of this method is that mode identification can be difficult in some cases as mode shape identification is not possible. Nonetheless, the simplicity of the geometry of most of our dams allows usually a very good estimation of the natural frequencies using analytical/empirical formulas or finite element analysis. When great differences are obtained, modelling hypothesis should be reviewed (ex. 2D vs 3D; boundary conditions; mechanical properties). After the successful use of a single station in our practice, Hydro-Québec is starting to investigate the use of an array of sensors on both concrete and earth dams.

ACKNOWLEDGMENTS

The authors wish to acknowledge Hydro-Québec for sharing instrumental measurements and allow publication of this paper.

REFERENCES

[1] Proulx, J., and Paultre, P. (1997). "Experimental and numerical investigation of dam-reservoir-foundation interaction for a large gravity dam". Canadian Journal of Civil Engineering, 24(1), 90–105.

[2] Gauron,O., Boivin, Y., Ambroise, S., Paultre,P., Proulx,J. Roberge, M., and Roth, S.-N. (2017) "Forced-vibration tests of the Daniel-Johnson multiple-arch dam". International Conference on Experimental Vibration Analysis for Civil Engineering Structures, San Diego, USA.

[3] Fenves, G., and Chopra, A. (1984). "Earthquake analysis and response of concrete gravity dams, Report No.UCB/EERC-84/10". Earthquake Engineering Research Center, University of California, Berkeley, CA.

[4] Konno, K., and Ohmachi, T. (1998). "Ground motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremors" *Bull. seism. Soc. Am.,* vol. 88, pp. 228-241.

[5] Nogoshi, M. and Igarashi, T. (1971). "On the amplitude characteristics of microtremor (part 2)". Journal of seismological Society of Japan, 24, 26-40., vol. 24, pp. 26-40.

[6] Bonnefoy-Claudet, S., Cotton, F., and Bard, P.-Y. (2006). "The nature of noise wavefield and its applications for site effects studies - A literature review". Earth-Science Reviews, vol. 79, p. 205–227.

[7] Westergaard, H. (1933). "Water pressures on dams during earthquakes". Transactions(ASCE).

[8] Abrahamson, N.A. (2009). "User Manual for RSPMatch09".

[9] U.S. Nuclear regulatory Commission. (1978). "Development of floor design response spectra for seismic design of floor-supported equipement or components". Regulatory Guide 1.122.

[10] Verret, D., LeBoeuf, D. and Péloquin, É. (2015), Effets de Site du Barrage en Enrochement Denis-Perron (SM-3), Québec, Annual conference of Canadian Geotechnical Society, Québec, Canada

[11] Elgamal, A.W. (1992). Three-Dimensional Seismic Analysis of La Villita Dam. Journal of Geotechnical Engineering 118(12), 22.