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Site effect study of a large rockfill dam: Denis-Perron Dam

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ABSTRACT

In this paper, analyses of strong-motion and ambient noise measurements at the Denis-Perron (SM-3) dam were carried out to evaluate possible site effects and the actual frequency of resonance (F_N) of this earth structure. The Denis-Perron Dam is a rockfill embankment dam standing 171 meters high and 378 meters long. It is the highest earthfill dam in Québec. The dam is built in a narrow valley. Three-component digital strong-motion stations were installed on the dam's crest and on bedrock, on the left abutment. The fundamental vibration frequency in each direction is estimated from a series of three small earthquakes that occurred in 1999 and 2002. The site response is also evaluated with the ambient noise records. Ten sets of ambient noise measurements were conducted using six «Tromino» velocimeters on the dam. A modal analysis regrouping a set of these measurements synchronized together is presented. Vibration modes calculated from the ambient noise measurements in comparison to those obtained for the earthquakes confirm that ambient noise offers a great potential to accurately determine the vibration modes of a large dam. Finally, a 3D numerical modal analysis made it possible to estimate a profile of the average stiffness of the embankment fill taking into account the characteristics of the site and the vibration modes of the dam..

Keywords: Rockfill Dam, Seismic, Ambient noise, Dynamic, Natural Frequencies.

INTRODUCTION

The seismic analysis of an embankment dam requires dynamic parameters of the structure. The dam's vibration modes and the stiffness of the fill materials are essential data. The vibration modes can be obtained from earthquakes recorded on instrumented dams. However, there is very little instrumented dam and the occurrence of seismic events in eastern Canada is relatively low due to the seismic activity of this region. Obtaining seismic data is even more rarely for large dams built in a steep valley.

This article discusses the use of ambient noise to determine the vibration patterns of a large dam built in a steep valley in Quebec. The modal analysis of the ambient noise is performed by synchronizing experimental measurements obtained with each individual velocimeters. The occurrence of 3 microseisms measured on this same dam allows a rigorous validation of analyzes carried out with the experimental ambient noise measurements. Lastly, a 3D modal analysis of the dam and its valley also validates the dam's vibration modes by iteratively adjusting the average stiffness of the embankment.

DENIS-PERRON DAM SITE DESCRIPTION

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 1a) illustrates the plan view of the valley and the dam while figure 1b) shows a section of the valley in the longitudinal axis of the structure. The site area has rugged terrain formed by narrow valleys between rock masses that peak at an average elevation of about 500 m. The region is located in the Grenville Geological Province of the Canadian Shield; it is a tectonically stable zone of crystalline, igneous and metamorphic rocks of the Precambrian age. The bedrock is usually composed by a series of migmatized gneisses and, more rarely, gneisses. Locally, these series are interspersed with intrusive masses consisting of anorthosite, granite and pegmatite.

This dam was instrumented with two accelerometers between 1998 and 2002. An instrument was located on the crest of the embankment while the second station was positioned at the mid-height of the dam on the craggy rock support. The approximate position of the accelerometers is shown (red dots) in figure 1a).

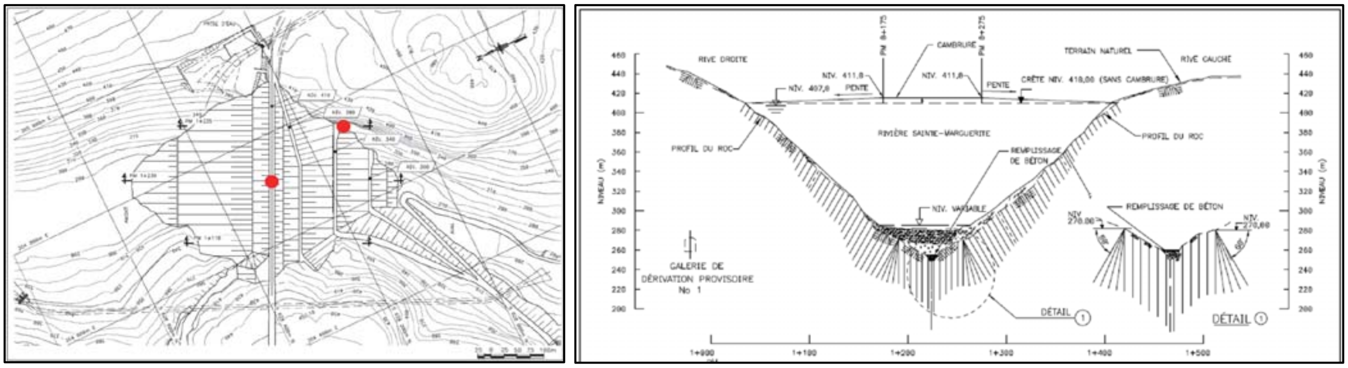


Figure 1.a) Plan view of the Denis-Perron dam, 1b) Longitudinal section of the valley in the central dam axis

EARTHQUAKES EVENTS

Signals processing

The accelerometers were of Altus K2 Kinemetrics type, recording signals in three directions, longitudinal, transverse and vertical with respect to the dam axis. They were instruments equipped with an acquisition system and an analog-digital converter, with a resonant frequency specific to each instrument around 50 Hz. The two instruments were synchronized in time.

This section presents an analysis of transfer functions from signals to estimate the fundamental vibration frequency. A more detailed analysis of these signals is presented by [1].

Between 1998 and 2002, these instruments recorded close to 671 sets of instrumental data. The vast majority of these events were related to blasting activities in the area of this hydro-electric facility. Although blasting activities are suitable for triggering such instruments, the large amount of non-earthquake instrumental data is derived from the fact that instruments were programmed to trigger at a low acceleration of 0.1% g (1 cm/s^2). A detailed analysis of seismic events identified by the Geological Survey of Canada (GSC) has allowed three sets of signals to be related to actual earthquakes. Table 1 lists these events and their main characteristics. The magnitude de Nuttli (M_N) of these earthquakes varies between 4.0 and 5.1.

Table 1: Earthquakes measured at the Denis-Perron dam site

Date	MN	Epicentral distance (km)	Latitude (°)	Longitude (°)
March 16, 1999	5.1	129.2	49.615	– 66.344
January 20, 2002	4.1	146.4	49.487	– 66.954
July 23, 2002	4.0	134.5	49.594	– 66.953

Signals in table 1 were processed according a bandpass filter between 0.3 and 40 Hz and a baseline correction. Figure 2 shows the temporal functions of the three earthquakes studied. Table 2 presents peak accelerations for each earthquake. These are earthquakes of very low amplitude. It is interesting to note that for the first two earthquakes, peak acceleration in the vertical direction exceeds horizontal peak accelerations and that for the third earthquake, the vertical acceleration remains also significant compare to horizontal directions. This is contrary to what is normally observed for free field land condition. In our understanding, this is a 3D effect (called site effect) resulting from the geometry of the steep valley. Elgamal [2] made the same observation for seismological data measured on the La Villita dam, particularly for the weakest earthquake.

Table 2: Peak acceleration of each earthquake

Earthquake	Acc. max Transversal direction			Acc. max Longitudinal direction			Acc. max Vertical direction		
	Rock (g)	Crest (g)	Ratio	Rock (g)	Crest (g)	Ratio	Rock (g)	Crest (g)	Ratio
March 16, 1999	0.0021	0.0118	5.6	0.0022	0.0105	4.7	0.0019	0.0178	9.4
January 20, 2002	0.0004	0.002	5	0.0006	0.0017	2.8	0.0004	0.0045	11.3
July 23, 2002	0.0002	0.0037	18.5	0.0002	0.0039	19.5	0.0002	0.0026	13

Analysis of the fundamental vibration frequencies

For each direction of the earthquakes studied, the transfer function and the fundamental vibration frequency (FN) were calculated by a comparison of the Fast Fourier Transform of the signal on the crest of the dam compared to the one at the bedrock abutment (FFTcrest / FFTrock), calculated by averaging the ratios over a moving range. For each FFT value, it is an average of the Parzen window type defined over a range of frequencies centered on the FFT value. In the present analysis, the selected frequency range is 0.1 Hz (0.05 Hz on both sides of the FFT value).

Figure 3 show the transfer functions and the fundamental vibration frequency according to each direction of the three earthquakes. Transfer functions are similar for each earthquake event. The March 16, 1999 event, with the highest magnitude, has slightly higher fundamental vibration frequency values in the horizontal direction that one could be associated with slightly more nonlinear deformations. These small differences between the fundamental vibration frequencies can also be affected by various factors as winter conditions, level of the reservoir, uncertainties of the instruments, etc. Overall, these results from three different events are consistent. These signals, although of small amplitudes, offer the possibility to establish fundamental vibration frequency in each direction and to validate the behavior laws at very small deformations. Table 3 summarize fundamental vibration frequency range for each direction of the three earthquakes components

Table 3: Fundamental vibration frequency range of the three earthquakes components

Direction	Fundamental vibration frequency (Hz)
Transversal	1.55-1.82
Longitudinal	2.00-2.20
Vertical	2.45-2.80

AMBIENT NOISE STUDY

Experimental ambient noise measurements

Ambient noise measurements were carried out on the Denis-Perron dam using six three-components Tromino-type velocimeters. The experimental program consisted of 10 sets of test measurements (T1 to T10) with the 6 instrument devices, 5 sets of measurements which were completed entirely on the dam crest (T1 to T5). For each series of measurements, a master identified instrument (M1) remained stationary at the same location and the other 5 Tromino devices (IN2 to IN5) were moved to various locations and synchronized with this master instrument (M1).

For the measurement series on the downstream face, additional master instruments (IN2, IN3 and IN4) remained stationary. Thus, with these stationary additional master instruments (IN1 to IN4), it became possible to synchronize all the individual series of measurements. Figure 4 illustrates the position of the test experimental measurements on the dam. As part of this project, the experimental data were acquired at a sampling rate of 1024 Hz over a period of 30 minutes with the exception of the last serie (number10), which was acquired on a period of 20 minutes. As presented by[3], measurements with Tromino devices were conducted using the rigid plate support including 3 rods custom steel stems developed for this project and powerful antennas (TP-Link 2.4GHz 8dBi) connected to 6 m long cables were used to allow communication and achieve synchronization between each instrument.

MODAL ANALYSIS

Modal analysis by processing synchronized ambient noise measurements

The Artemis Modal Pro code [4], a software for modal analysis, was used to analyze synchronized ambient noise measurements. Artemis Modal Pro offers the advantage of selecting different modal analysis techniques in both frequency and time domains. The ability to use techniques in these two areas offers the advantageous option of comparing the calculated vibration modes with very different resolution methods. Analyzes of the present study were carried out with two recent developed methods: the "Enhanced Frequency Domain Decomposition - EFDD" in the frequency domain and the "Stochastic Subspace Identification Extended Unweighted Main Component - SSI-UPCX" in the time domain. EFDD method provides estimates of damping ratios as well as improved estimates of natural frequencies and mode shapes.

Figure 5 shows a compilation of vibration modes shape obtained with EFDD and SSI-UPCX estimation technics tested. Artemis provides an option called Modal Assurance Criterion (MAC) diagrams for mode shapes comparison between same or different estimation technics. A very good consistency is observed between the results of these two methods.

Fundamental vibration frequencies determined from a modal analysis by processing synchronized ambient noise measurements on the dam crest are within the range of fundamental vibration frequencies determined from the earthquakes event data.

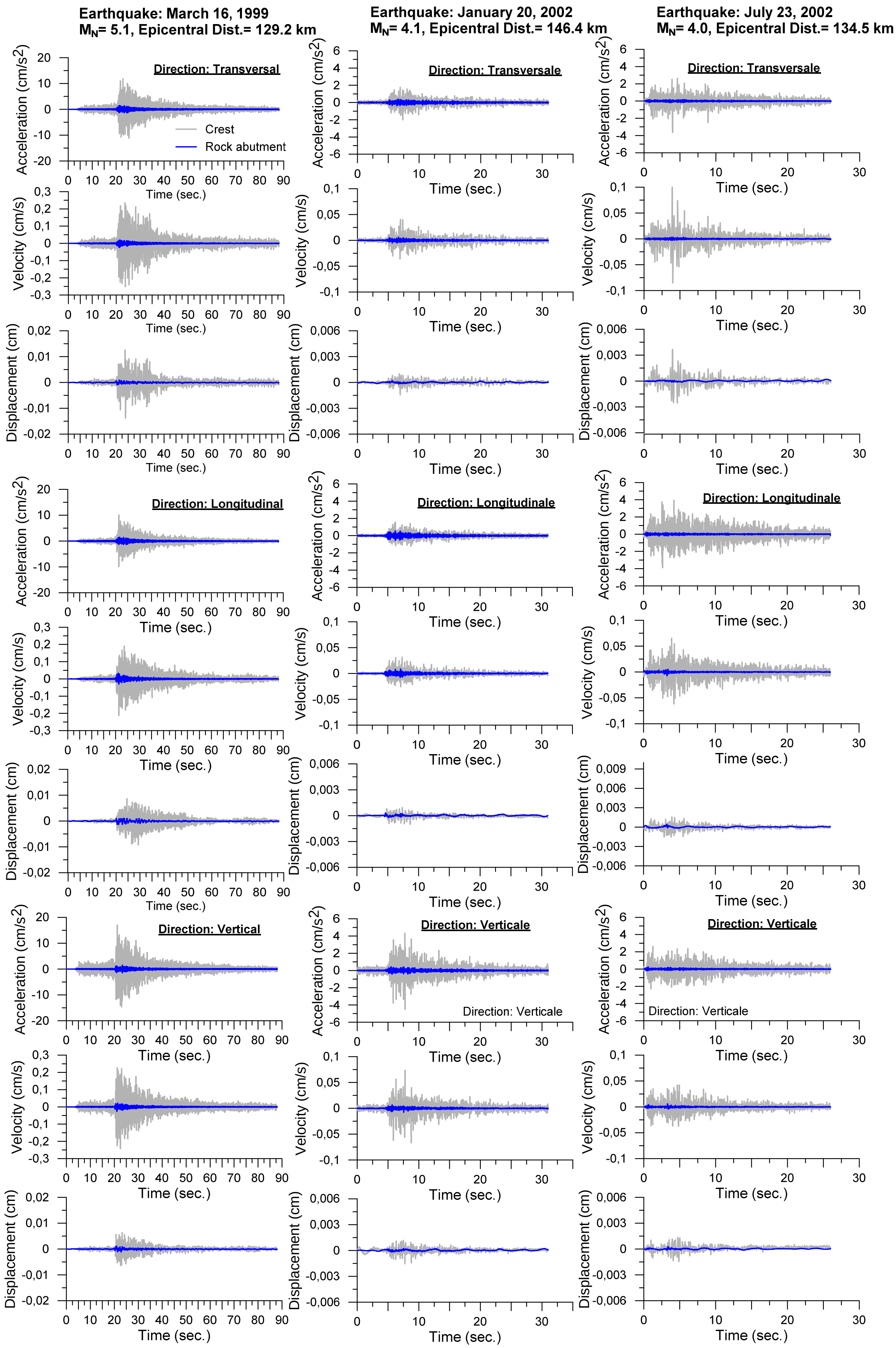


Figure 2.Temporal functions of the three recorded earthquakes on the Denis-Perron dam crest

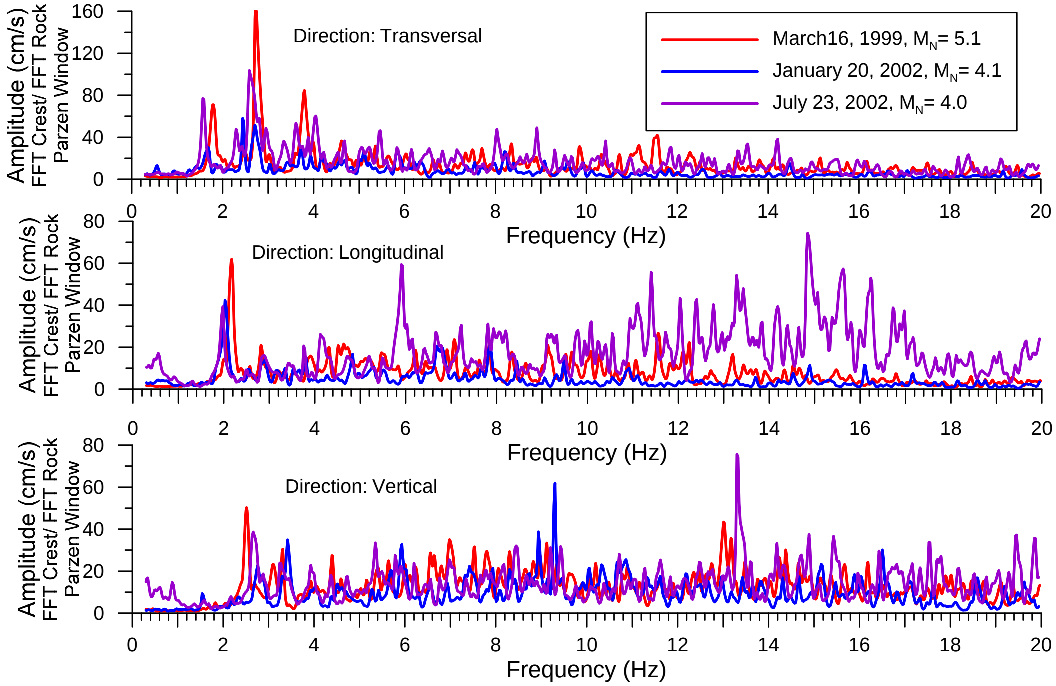


Figure 3: Transfer functions according to the three directions of the three earthquakes

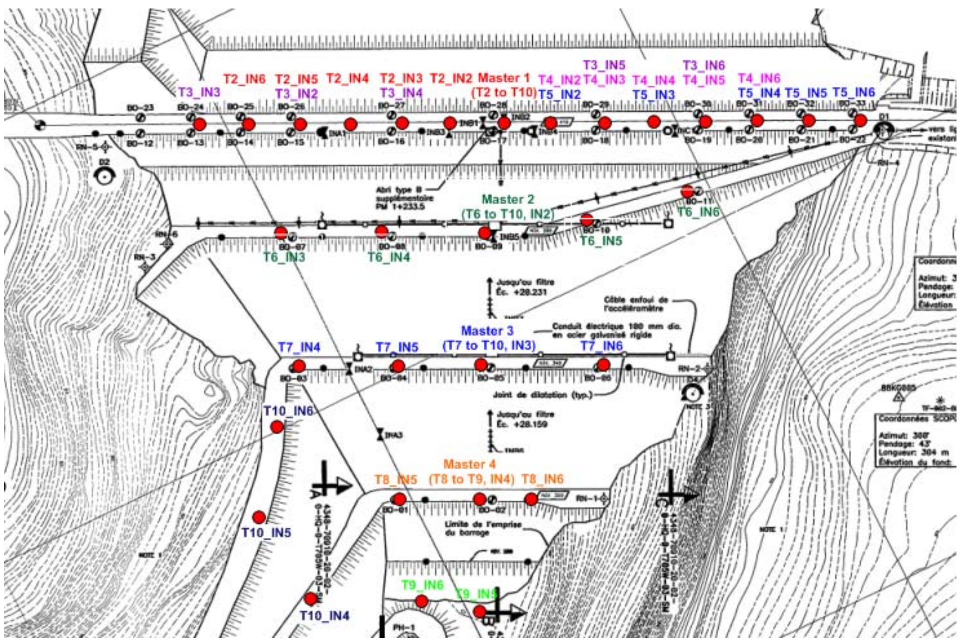
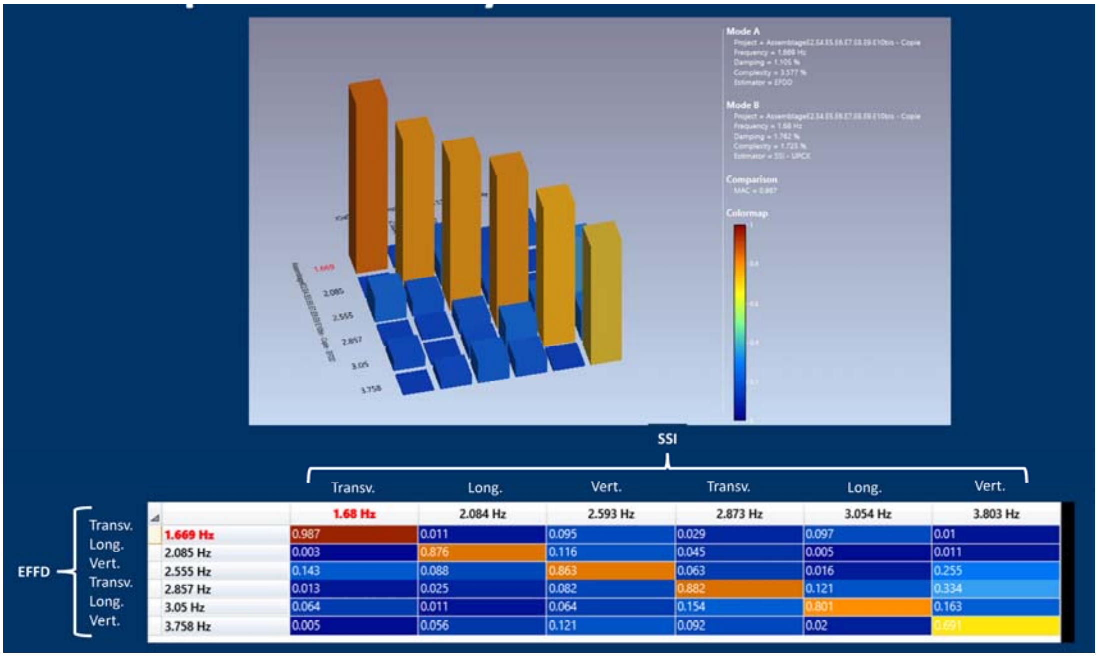


Figure 4: Position of the experimental ambient noise measurements

Artemis Modal Pro provides also the advantage of visualizing modal deformed animations. These animations are very consistent with the individual results obtained with the software Grilla to the effect that the upper portion of the dam (berm at level 380 m to the dam crest) is much more excited in comparison to the lower portion of the dam confined in the valley, associated with a site effect.

Modal analysis by numerical retrofit calculation of the 3D valley-dam system

A numerical modal analysis was carried out in order to provide a second validation of the vibration modes obtained from the experimental ambient noise measurements. A three dimensional model of the Denis-Perron valley and dam was developed using the Rhinoceros 3D modeling software [4] and the ANSYS ICEM CFD Meshing software [6]. The modal analysis was



	1.68 Hz	2.084 Hz	2.593 Hz	2.873 Hz	3.054 Hz	3.803 Hz
1.669 Hz	0.987	0.011	0.095	0.029	0.097	0.01
2.085 Hz	0.003	0.876	0.116	0.045	0.005	0.011
2.555 Hz	0.143	0.088	0.863	0.063	0.016	0.255
2.857 Hz	0.013	0.025	0.082	0.882	0.121	0.334
3.05 Hz	0.064	0.011	0.064	0.154	0.801	0.163
3.758 Hz	0.005	0.056	0.121	0.092	0.02	0.691

Figure 5: Compilation of vibration modes calculated with EFDD and SSI-UPCX methods

performed with the ANSYS software [7] using the Finite Element Method (FEM). The geometry of the dam was modeled with mean uniform slopes incorporating the berms. Embankments fill were represented by only one material. Alluvium and colluvium left in place in the narrow furrow at the bottom of the valley were not represented in the numerical model at this stage of analysis. Despite these simplifications, the three dimensional model allows to take into account the geometric effects of the valley. Figure 6 illustrates the three dimensional model of the valley-dam system.

The modal analysis performed is a linear analysis and the foundation model is assumed to be massless. By considering a massless foundation, only its flexibility is taken into account. The modal analysis is affected by the rigidity of the dam-foundation system, the dam mass and the three dimensional geometry dam-valley system. The reservoir has not been taken into account for this modal analysis.

As reported by [8], this method has been used extensively for two and three dimensional dynamic analysis of concrete dams. In the present study, this method is applied for a three dimensional large rockfill dam. The stiffness of the embankments was gradually adjusted following a prismatic shear beam model as described in [9]. Figure 7 illustrates the schema of this model. The dam stiffness was also related to the parameter $K_{2\,max}$ computed with the standard relation (1) proposed by [10] (modified to be adimensional), whose stiffness is related with the effective mean stress (σ'_m) and the atmospheric pressure (P_{atm}). For this analysis, K_{2max} was increased iteratively until the fundamental vibration frequencies computed with Ansys coincided as closely as possible with those computed with earthquake events and by processing ambient noise data.

$$G_{max} = P_{atm} \cdot 21.7 \cdot K_{2max} \cdot \sqrt{\frac{\sigma'_m}{P_{atm}}} \qquad (1)$$

Table 4 presents the three dimensional modal analysis results of the Denis-Perron Dam. The best retrofit of the fundamental vibration frequencies during the modal analysis is obtained using a K_{2max} of 130 (figure 8a)). Although this stiffness is an average value representative of an entire horizontal fill layer, as illustrated on the figure 8b), this K_{2max} value compares relatively well with published test results conducted on Oroville dam fill materials 8. The fundamental vibration frequency presented in the table 1 for each direction is very close to the results obtained with earthquake events and by processing ambient noise measurements. Modal analyses indicate also than more than 80 % of the dam mass is mobilized for the fundamental vibration frequency and almost the entire mass (more than 98 %) is mobilized when the second vibration mode is included.

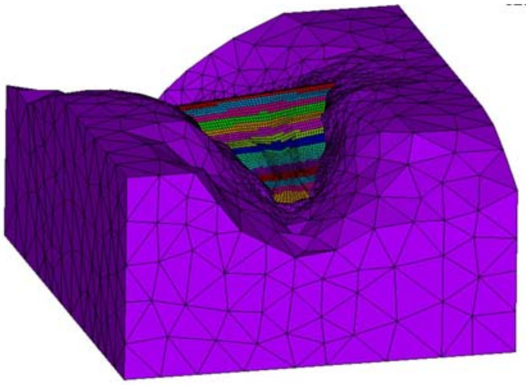


Figure 6: 3D model of the dam-valley system

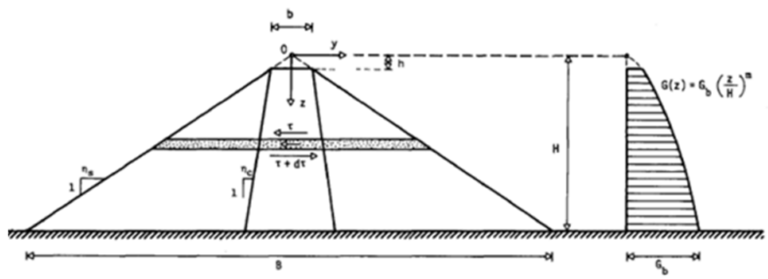


Figure 7: Prismatic shear beam mode, [9]

Table 4: 3D Denis-Perron dam modal analysis results with ANSYS

Mode	Frequency	Mass Contribution		
		Transversal	Longitudinal	Vertical
1	1.83	80.8	0.00	0.1
2	2.16	0.0	94.2	0.1
3	2.34	0.0	0.35	0.1
4	2.44	0.0	0.01	91.6
5	2.79	0.8	0.05	0.0
6	2.86	0.1	5.08	0.0
7	2.96	17.4	0.00	0.3
8	3.06	0.2	0.00	4.7
9	3.14	0.0	0.01	0.2
10	3.34	0.7	0.35	2.9

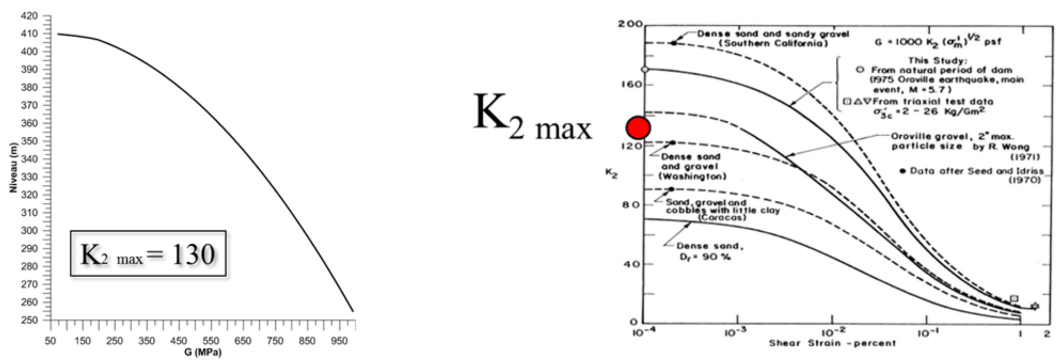


Figure 8:. a) Stiffness evaluation of the embankment dam, b) K_{2max} comparison based on [11]

VIBRATION MODES RESULTS COMPARISON

Table 5 compiles vibration frequencies of the Denis-Perron dam calculated according to different methods. The similarity of frequencies between the different methods is impressive.

In comparison to values established from real earthquakes which are considered reference values or verification values, based on these results, ambient noise measurements appear very promising to determine vibration frequencies. Ambient noise measurements are easy, relatively inexpensive and quick to perform and do not present any risk of damage to the dam. But above all it takes into account the site effects, i.e. geometry of the valley and the dam, foundation condition and stiffness of embankment fills. Second vibration mode could be only estimated after completing modal analysis with Artemis Pro software. From the earthquake data analyses or analyses of each ambient noise individual measurements data with Grilla software, it is very difficult to establish with certainty the second mode of vibration. The modal analysis with the software Artemis Pro offers analyzes that determine the higher modes taking into account a set of ambient noise measurements on a dam with its own characteristics (height, geometry, zoning, fill materials rigidity, shape of the valley, etc.).

The numerical modal analysis with a simplified 3D model in ANSYS also makes it possible to check the coherence between the estimation of the materials stiffness and the fundamental and superior dam modes of vibration confirmed with the analyses of real earthquakes and ambient noise measurements.

Table 5: Summary of vibration frequencies of the Denis-Perron dam

Direction	Fundamentals vibration frequency (Hz)				Second mode of vibration (Hz)			
	Earthquakes	Ambient Noise (Grilla) by[3]	Ambient Noise Modal analysis (Artemis Pro)	Modal analysis (Ansys)	Earthquakes[1]	Ambient Noise[1] (Grilla) by [3]	Ambient Noise Modal analysis (Artemis Pro)	Modal analysis (Ansys)
Long.	1.55 - 1.82	1.79 - 1.82	1.67 - 1.68	1.83	2.33 – 2.74	2.7 – 2.9	2.86 - 2.87	2.96
Trans.	2.00 - 2.20	2.07 - 2.10	2.08 - 2.09	2.16	2.84 – 2.92	3.1	3.05	2.86
Vert.	2.45 - 2.80	2.59	2.56 - 2.59	2.43	3.10 – 3.45	3.6 – 3.8	3.76 - 3.80	3.86

Note 1: Second vibration mode estimated after completing modal analysis with Artemis Pro software.

CONCLUSION

It has been possible to measure ambient noise on a large rockfill dam in a steep valley. Processing of these signals made it possible to study the Denis-Perron 3D dam site effects and to determine the modes of vibration of this structure. The study of 3 real earthquakes makes it possible to validate analyses results obtained with the experimental ambient noise measurements. The study of 3 real earthquakes measured on the dam in 1999 and 2002 makes it possible to validate analyses results obtained with the experimental ambient noise measurements as well as those of the numerical 3D modal analysis.

This first validation of the potential for using ambient noise to establish the dynamic parameters of a large dam with real earthquakes by Hydro-Québec shows that this technology can be applied to embankment dams. Results of this work offer a very promising alternative for establishing dynamic parameters of an embankment dam without the need for a more conventional practice, namely the costly installation and maintenance of accelerometers in areas of low occurrence of seismic events as in eastern Canada.

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