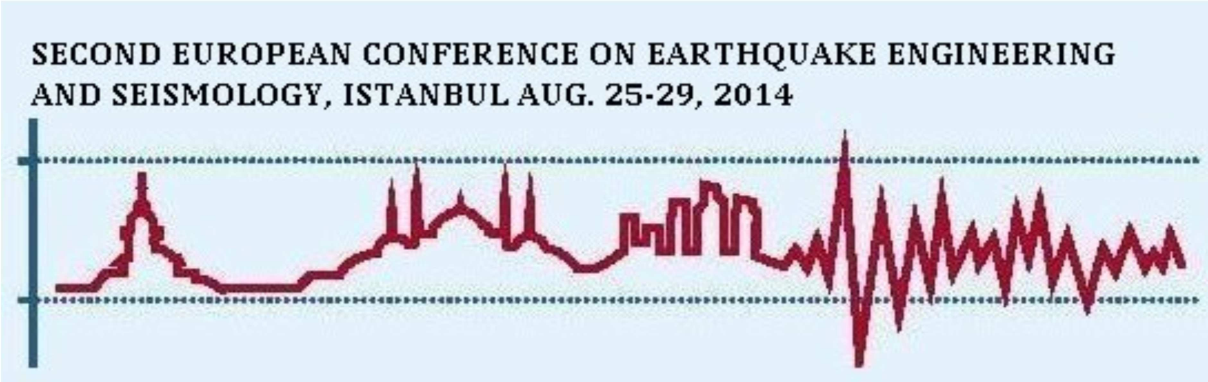

AS-BUILT MODAL CHARACTERISTICS IDENTIFICATION OF AN RCC GRAVITY DAM USING AMBIENT VIBRATION TESTING

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ABSTRACT

The design of structures such as buildings, bridges, dams etc. uses often numerical models whose structural and material parameters are assumed from similar projects or limited material tests. For large civil engineering constructions, further validation and checking of the actual as-built construction can be very useful to assess the model accuracy. The elastic dynamic properties, particularly the natural frequencies and the corresponding mode shapes are a combined measure of the structural characteristics of the construction. These model characteristics can be successfully estimated, especially in elastic range, using the well-known ambient vibration testing. In this paper, a correlation of experimental and numerical modal properties of an RCC gravity dam is presented. The Koudiet Acerdoune dam is located in the northern part of Algeria which is a seismic prone area. The maximum height of the dam is 121 m and a crest length of over than 425 m. First, the simplified design models are presented together with a 3-D finite element model, which has been elaborated and used to determine the analytical modal characteristics. The correlation between experimental and analytical modal data is used to evaluate the accuracy of the different analytical models and their capability to depict the frequencies and vibration modes in transverse and longitudinal directions. The simplified models have the merit to predict reasonably well one or two frequencies with an under-estimate of the fundamental frequency for full reservoir, whereas the anti-node modes were predicted only by the 3-D model.

INTRODUCTION

The elastic dynamic properties, particularly the natural frequencies and the corresponding mode shapes are a combined measure of the structural characteristics of the construction. These model characteristics can be computed using different approaches such as simplified methods and finite elements models. Modal properties can be successfully estimated in the elastic range, using the well-known ambient vibration testing, whose effectiveness is worldwide recognised by numerous cases of acceptable results of many existing buildings, bridges, dams and other structures. This full-scale testing method can be profitably used for many purposes, depending on the specified testing conditions.

Numerous studies used the ambient vibration testing to validate or update numerical models. The main purpose of the model updating procedure is to minimize the differences between the analytically and experimentally determined dynamic characteristics by changing some uncertainty parameters such as material properties or boundary conditions (Altunisik et al. 2011, Jaishi and Ren

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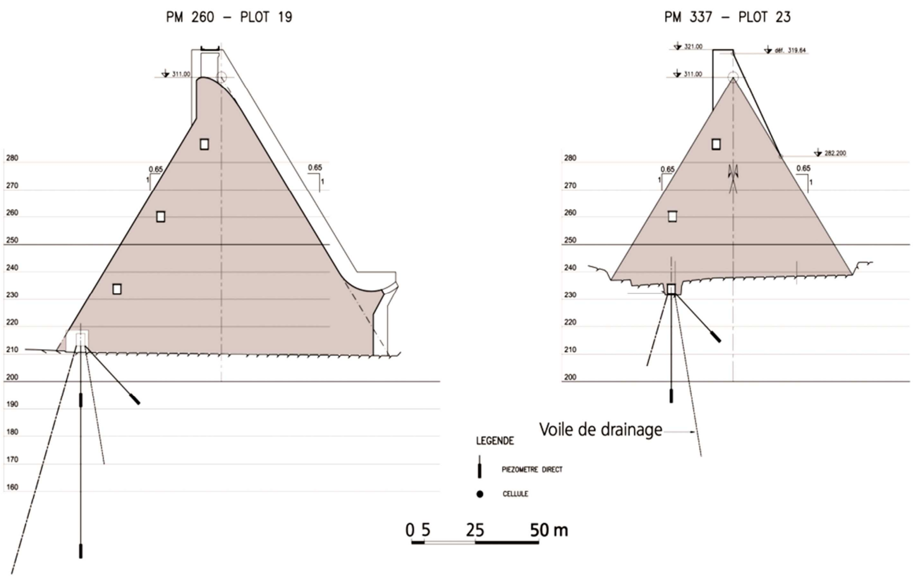
2011, Brownjohn et al. 2003). It has been applied in the field of structural integrity monitoring (SIM), which utilizes measured dynamic responses from a structural system to assess the physical properties of the structure (Salawu 1997, Wiberg 2006).

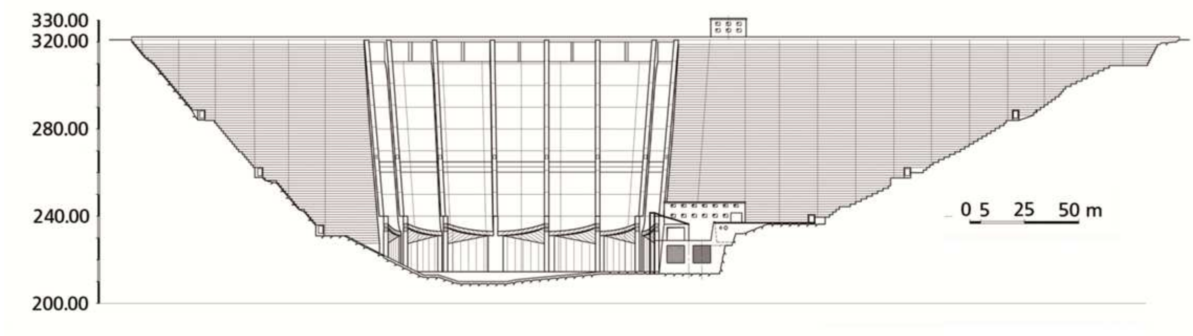
Within the framework of structural identification, ambient vibration testing has also been used in conjunction with neural networks to extract structural characteristics such as building eccentricities (Bourahla and Boukhemacha 2005). In the context of the present study, this technique has been used to assess the dynamic characteristics of a newly constructed RCC dam in order to compare the simple design model and 3-D model frequencies with those measured on the as-built dam.

KOUDIAT ACERDOUNE DAM DESCRIPTION

The Koudiat Acerdoune Roller Compacted Concrete dam is the second most important hydraulic project in Algeria after Beni-Haroun Dam. With a maximum height of 121 m and a length of more than 425 m, the Koudiat Acerdoune dam has a 640 million m^3 capacity to provide drinking water for 34 cities located in the region of Bouira , Médéa , M'Sila ,Tizi-Ouzo, Bougazoul with a population about 800 000 inhabitants. It provides also the irrigation of about 18 000 hectares of farmland.
The Koudiet Acerdoune dam is located in the northern part of Algeria, which is a seismic prone area (Boinay and Frossard 2009).



(a) Cross section (b) Dam profile



(c) Dam elevation

Figure 1. Dam geometry configuration

Figure 2. A general view of Koudiat Acerdoune dam

SIMPLIFIED APPROACH

Several calculations are performed, in preliminary design stage. The first approach is a simplified method for pre-dimensioning gravity dams in seismic areas (Tardieu et al. 1993). The main assumptions adopted for this method are the following:

• The dam is considered as a simple resonator (triangular prism) with two degrees of freedom (translation and bending parallel to the dam axis).
• The height of the prism "H" is the height of the normal water level
• The dam is founded on rigid bedrock.
• The effects of earthquake bank-to-bank horizontal component are not taken into account.
• The hydrodynamic effect is taken into account

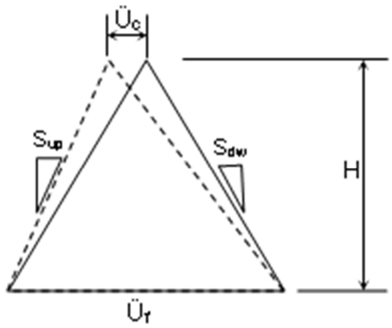


Figure 3. Scheme of the dam for simplified approach

Taking into account the feedback from different sites, the material characteristics used are as follow:
• RCC mass density : = 2.35 t/m^3
• RCC dynamic elastic modulus : Ed = 29 000 MPa (Zdiri et al. 2007)

The first frequencies of the fundamental vibration mode for this simplified method are given as follows:

$$\text{Empty dam reservoir } N = 0.23\, S / H \tag{1a}$$
$$\text{Full dam reservoir } N = 0.17\, S / H \tag{1b}$$

where S = 2263 m/s is the shear wave velocity and H is the normal water level immediately upstream of the dam.

The computed frequencies are 4.3Hz for empty dam reservoir and 3.18 Hz for full dam reservoir.

FINITE ELEMENT MODELS

First 2D model was elaborated using a FE software SAP 2000 to identify plane upstream-downstream mode shapes and frequencies. The foundation is assumed to be rigid. Then a 3D model is generated to predict antinode mode shapes.

Hydrodynamic forces are modeled using nodal masses equivalent to inertia forces of a water volume attached to the dam. The approximate parabolic distribution pressure is given by the equation below (Zangar 1953) :

$$P = \frac{1}{2} awhC_m \left[\frac{y}{h}\left(2 - \frac{y}{h}\right) + \sqrt{\frac{y}{h}\left(2 - \frac{y}{h}\right)} \right] \tag{2}$$

With : a acceleration due to earthquake
y distance below surface
h total depth of reservoir
w unit weight of water
C_m is the maximum value of “C” the coefficient of pressure distribution for constant slope

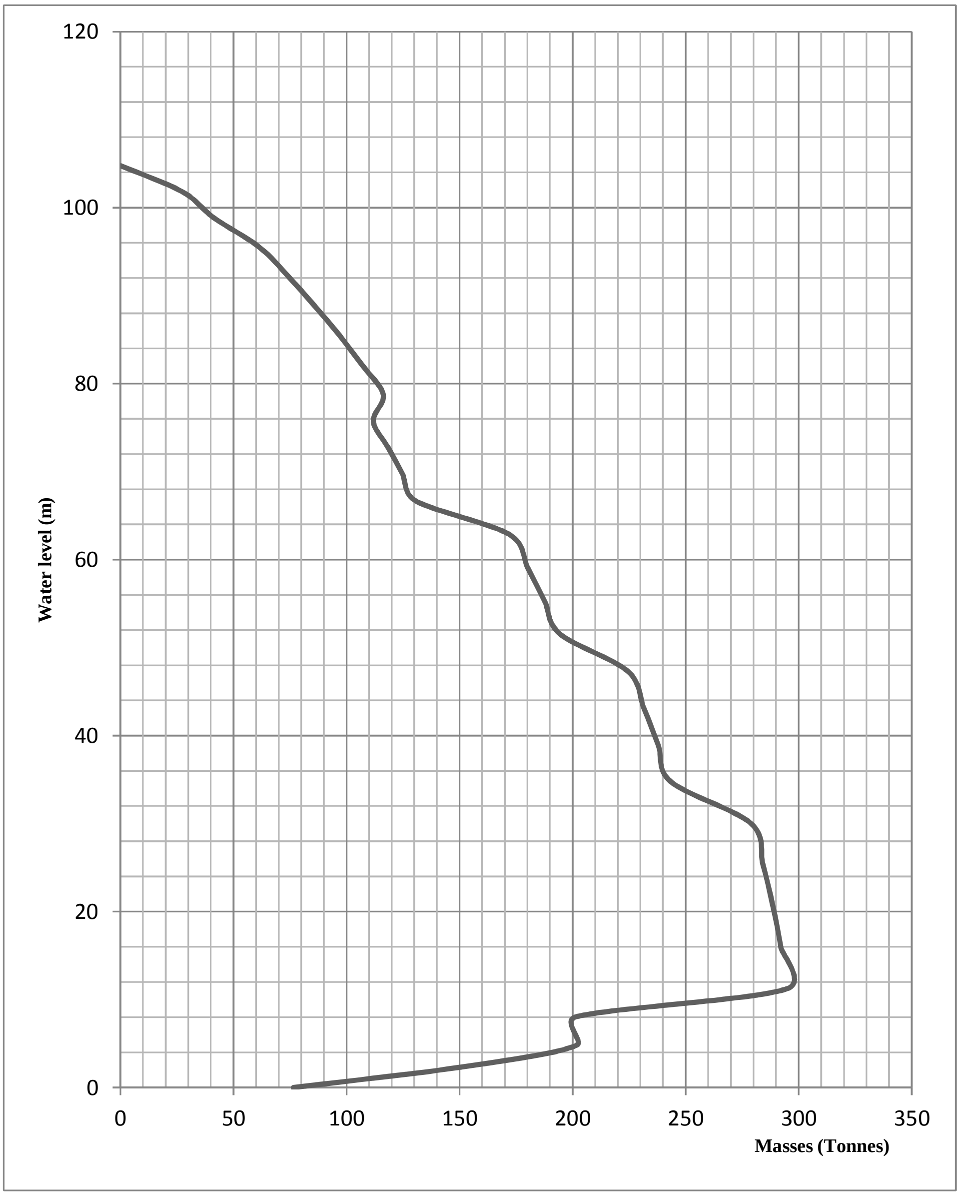
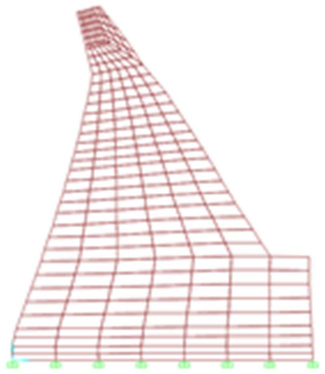


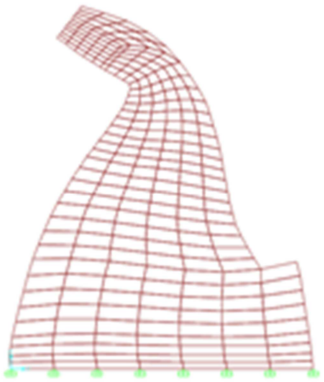
Figure 4. Mass distribution on the upstream face of the dam

Two dimensional models

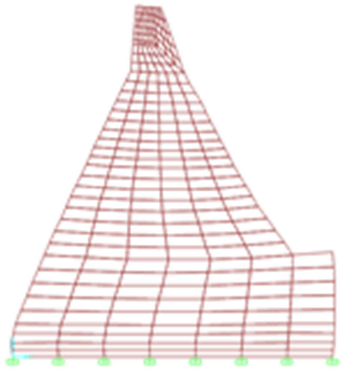
Two dimensional models with 4 nodes plain strain elements are used. The frequencies of the empty reservoir are first computed. The main vibration modes are plotted below.



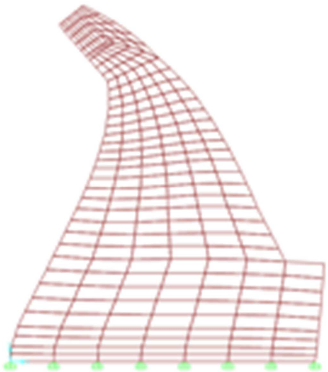
Mode shape n°1. F = 4. 64 Hz



Mode shape n°2. F =9.27 Hz



Mode shape n°3. F = 10.72Hz



Mode shape n°4. F = 15 Hz

Figure 5. Different mode shapes for empty dam

The frequencies computed using the 2D plane strain are close to those obtained with the simplified approach with a difference of 7%.

The same model is used to compute the modal characteristics of a full reservoir by adding nodal equivalent masses to simulate the hydrodynamic effect of water pressure on the upstream dam face. The obtained results for the first modes are shown in the Table1 below.

Table 1. Frequencies of the model with attached masses

Mode shapes	Frequencies (Hz)
Mode n° 1	2.59
Mode n° 2	5.44
Mode n° 3	7.76
Mode n° 4	9.43

The calculated frequency for the first mode is about 22.7 % lower than the frequency predicted by the simplified approach.

In the following section a three dimensional model will be elaborated and the results will be compared to those obtained from the ambient vibration testing.

Three dimensional model

The three dimensional model of the dam is generated using 8 nodes solid elements. Both the walkway over the spillway and the eleven supporting piers are modeled using shell elements. The foundation is also assumed to be rigid.
To take into account the hydrodynamic effect of the actual water pressure nodal equivalent masses are added on the upstream face of the dam. These attached masses correspond to 304 NGA water level reached in March 2014, which represents about 100 m water high.

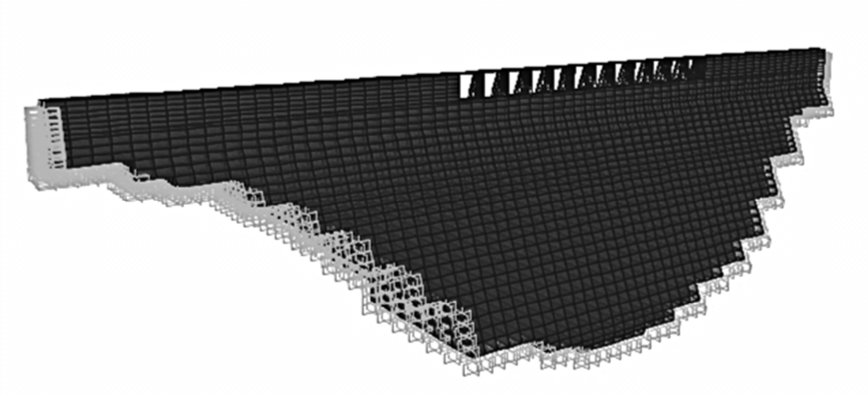


Figure 6. Three dimensional model view

AMBIENT VIBRATION TESTING

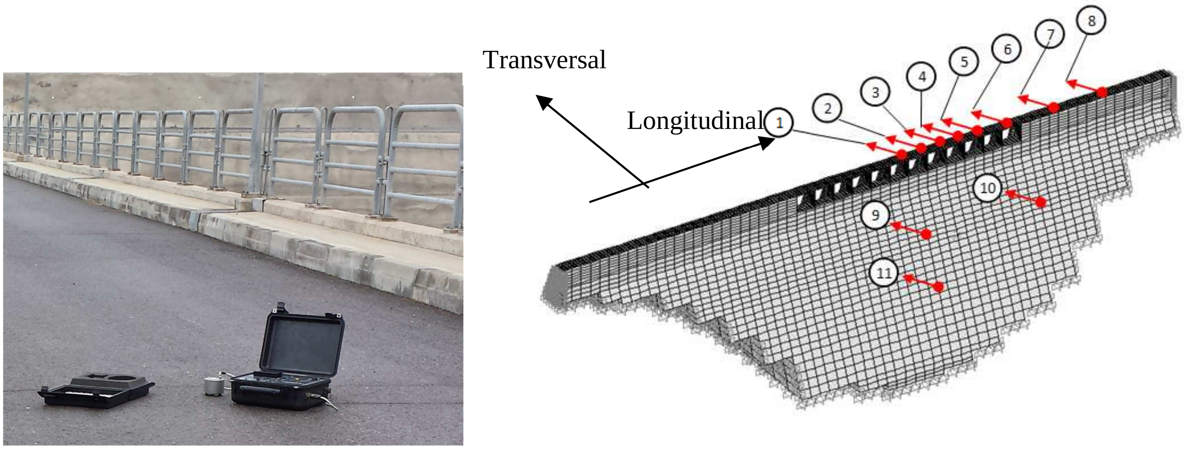
In addition to the standard instrumentation on the Koudiat Acerdoune dam intended to monitor the dam evolution and its response to the seismic activity of the region, an ambient vibration survey is carried out for further detailed characterisation of its dynamic response to wind and microtremor excitation. This method which was fully developed in early 1970's, now is becoming even more advantageous and convenient to use, due to the increased capabilities of personal computer (PC) and commercially available recorders. In this paper we present briefly the main issues pertaining to this particular modal testing; frequency response function (FRF) measurement techniques, testing procedure, and modal parameter estimation method.

Test setup and procedure

The tests were performed using three degrees of freedom seismometer type Lennartz electronic (Le3Dlite) and a data acquisition system type City Shark II. The measured signals were processed using the GEOPSY program (Wathelet 2005) capable to perform most of the signal processing operations for the analysis of ambient vibration data.

The sensors were located along the east side of the dam crest. The first five measures were centered on the walkway above the spillways and two other points were positioned directly on the crest at mid-way from the walkway end and the dam east edge as shown on Figure 7 Four measuring points were taken inside the upper and lower galleries.

The recording time for each sequence was set to 5 mn and found to be largely sufficient to obtain smooth FRF curves. Measurement locations were chosen to capture most of the lateral (upstream/downstream) direction modes. Moreover, both perpendicular horizontal and vertical responses were measured for each point.



(a) Seismometer Lennartz (b) Sensor locations

Figure 7. Location of performed tests on dam using seismometer

Frequencies identification

The natural frequencies of the Koudiat Acerdoune dam were identified using a “peak cursor” on the frequency response functions. The first curve in Figure 8 shows the FRF of the transversal vibrations measured on the centre of the top of the walkway (point 1 on Figure 7). Several peaks can be easily identified. The clearly distinct first peak at 3.20 Hz corresponds to the fundamental transversal mode (figure 8).

The other peaks, as shown on the same figure, correspond to the higher modes which have an antinode on the middle where sensor 1 is located. It should be noted that the frequency of the second mode is missing on this FRF curve because this mode has a node at the measuring point 1. However, the frequency of the second mode appears on the FRF curve of point 3 as shown on Figure 9. The FRF curves shown on Figure 10 were recorded on point 6 along the longitudinal, transversal and vertical directions.

The main peak at 13.68 Hz corresponds to the vertical direction which goes with the fact that the sensor 6 is positioned at the middle of the first span. The recorded responses (Figure 11) inside the upper and middle galleries exhibit a different trend with very closely peaks around the frequency of 0.71 Hz and 2.41 Hz. No analytical frequencies were found to match these frequencies and the recorded time histories were very uniform along all axes (directions).

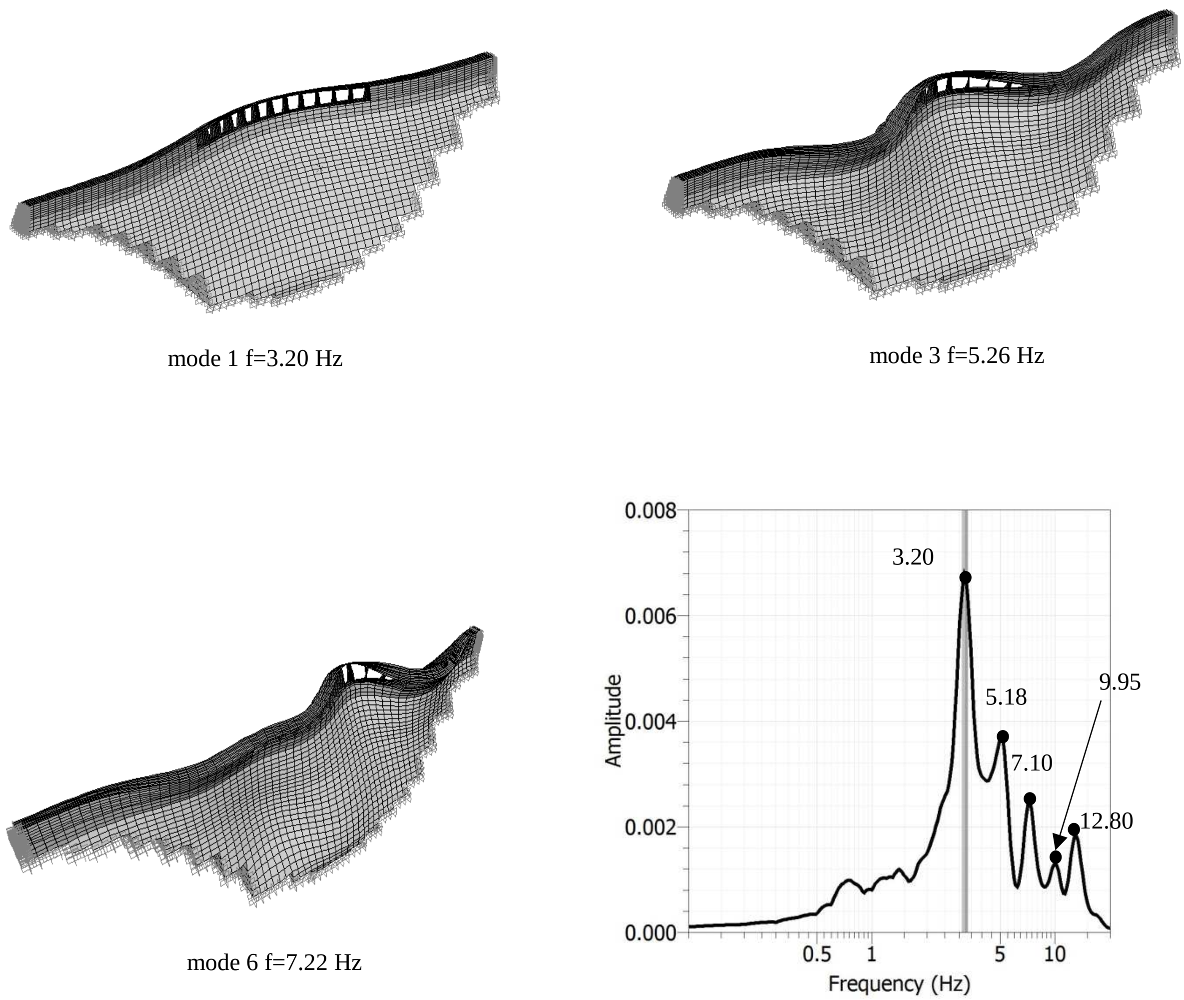


Figure 8. Calculated vibration modes and the corresponding measured frequencies at mid walkway (sensor 1)

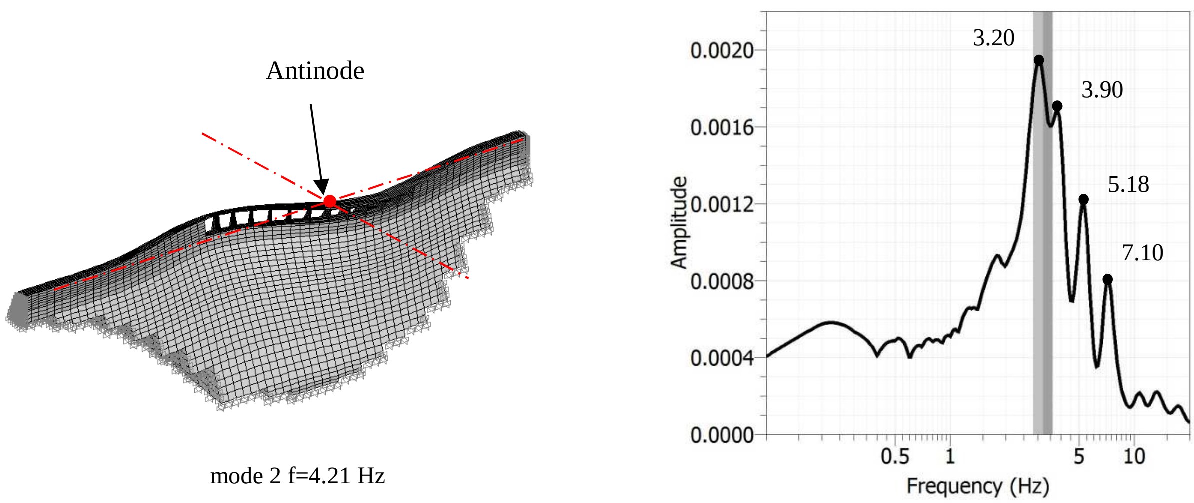


Figure 9. Second vibration mode with the corresponding measured frequency at the right side of the walkway (Sensor 3)

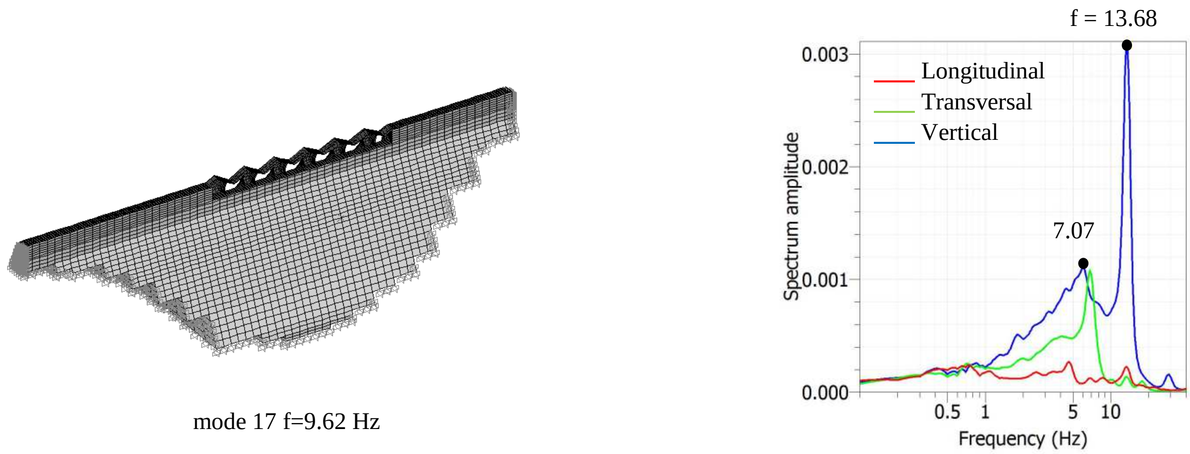


Figure 10. Mid-span vibration mode of the walkway and the corresponding measured FRF at the middle of the first span (sensor 6)

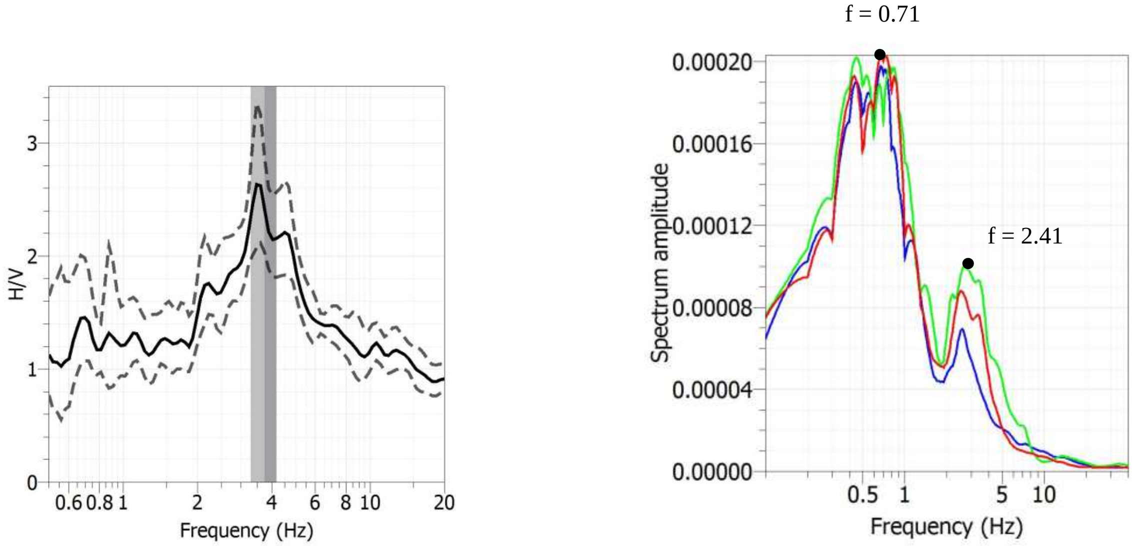


Figure 11. Typical FRF curves and H/V spectrum recorded inside the upper and middle galleries of the dam (Sensor 10)

Identification of the modal damping ratios

The ambient vibration output-only data is commonly used to estimate the damping ratios of structures at low amplitudes of vibration. For each identified frequency, a damping ratio has been determined using the random decrement technique. Figure 12 shows typical free decay fitting using Geopsy software. The values of the damping ratios corresponding to the walkway structure in reinforced concrete (longitudinal and vertical modes) are lower compared to those of the overall dam modes (Table 2).

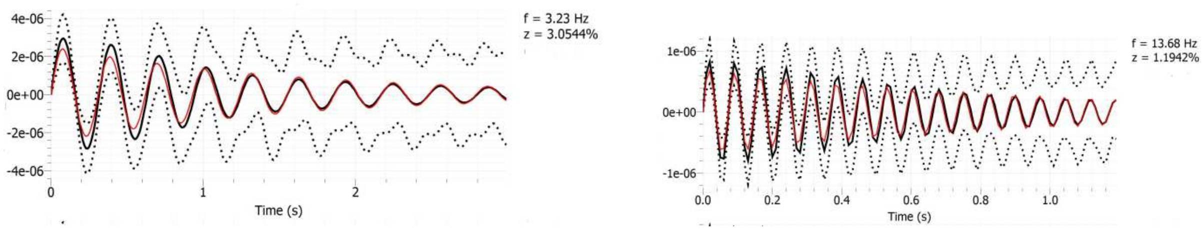


Figure 12. Typical free decay fitting of the fundamental and vertical walkway frequencies

Experimental and analytical modal correlation

Using the design average material properties, good correlation between experimental and analytical natural frequencies is achieved in most cases as can be seen from Table 2.
The 3-D model has a very large number of vibration modes. Because of the limited number of sensors and recording channels, only few modes were identified experimentally and correlated to the analytical modal data on the basis of mode shapes and sensor locations matching.

In first instance, an evident discrepancy (30%) between the experimental frequency of the vertical mode of the mid-span of the walkway and the corresponding analytical frequency can be attributed to the fact that the last support of the walkway is considered fixed in the model instead of an isolated support. For the same reason the lowest longitudinal frequency (4.62 Hz) is not predicted by the model.

The measured frequencies along the transversal direction, however, were in good agreement with analytical predictions and the errors were less than 12%.
Another important observation is the FRF curves along the three axes recorded inside the galleries have the same trend and the peaks do not correspond to any of the analytical frequencies. Nevertheless, the H/V spectrum shows a peak at 3.40 Hz which is roughly equal to the fundamental frequency.

Table 2: Analytical and experimental frequencies and the corresponding damping ratios

Mode	Type	Experimental (Hz)	Analytical (Hz)	Error (%)	Damp. %
1	Transversal	3.20	3.21	0.3	3.05
2	Transversal	3.90	4.26	9.2	5.12
3	Longitudinal	4.62	-	-	1.88
4	Transversal	5.18	5.26	1.5	3.62
5	Transversal	6.88	6.33	8.0	2.44
6	Transversal	7.10	7.22	1.7	2.97
7	Longitudinal	9.67	10.11	4.6	1.15
8	Transversal	9.95	8.79	11.7	3.20
9	Transversal	12.80	-	-	2.14
10	Vertical	13.68	9.62	30	1.94

CONCLUSIONS

This work is a contribution to generalise the use of ambient vibration method as a validation method of the as-built status of the Koudiat Acerdoune dam (Algeria). The correlation between experimental and analytical modal data is used to evaluate the accuracy of the analytical models used in the design phase. In the light of the obtained results, the following observations are noteworthy:

- For practical reasons a 3-D preliminary modal analysis is essential to optimize the sensor locations.
- The use of the design average material properties has led to a good correlation between experimental and analytical natural frequencies in most cases.
- In this particular case the 2-D model under-estimate the fundamental frequency for full reservoir.
- Simplified models are reasonably accurate but do not predict antinode modes.
- Support characteristics of the walkway are to be included in the 3-D model to reduce the discrepancy in the predicted vertical frequency.
- Relatively high damping values are obtained at very low amplitude excitations.

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