# INPUT-OUTPUT vs OUTPUT-ONLY MODAL IDENTIFICATION OF BAIXO SABOR CONCRETE ARCH DAM

# IDENTIFICAÇÃO MODAL DA BARRAGEM DO BAIXO SABOR COM BASE EM ENSAIOS DE VIBRAÇÃO FORÇADA E AMBIENTAL

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## *ABSTRACT*

*The Baixo Sabor dam, whose construction ended in 2014, is a double curvature concrete arch dam 123 m high, built and owned by EDP Produção (a company of EDP-Energias de Portugal Group) in Sabor river, one of the right side tributaries of the river Douro in the North of Portugal. This structure creates a large reservoir whose first filling took place between 2015 and 2016. The estimate of the modal properties of this structure has been developed on the basis of two alternative procedures: (1) the performance of forced vibration tests based on the use of an eccentric mass vibrator and (2) the implementation of a vibration based structural health monitoring system, involving 20 uniaxial accelerometers, used to observe the dam behaviour during the first filling of the reservoir and the two first years of operation. This paper, apart from making a brief description of the dynamic tests performed, as well as, of the main characteristics of the monitoring system and results obtained during the first months of operation, presents a comparative analysis between the modal estimates achieved by the input-output and output-only modal identification techniques employed using the data associated to the performance of the forced vibration tests.*

## *RESUMO*

*A barragem do Baixo Sabor, cuja construção terminou em 2014, é uma barragem abóbada de dupla curvatura com 123 m de altura, construída pela EDP Produção (uma empresa do Grupo EDP-Energias de Portugal) no rio Sabor, afluente da margem direita do rio Douro no Norte de Portugal. Esta estrutura gerou uma grande albufeira, cujo primeiro enchimento ocorreu entre 2015 e 2016. A estimativa dos parâmetros modais desta estrutura foi efetuada com base em dois procedimentos alternativos: (1) a realização de ensaios de vibração forçada assentes na utilização de um vibrador de massa excêntrica e (2) a implementação de sistema de monitorização da condição estrutural baseado na medição de vibrações, envolvendo 20 acelerómetros uniaxiais, utilizado para observar o comportamento da barragem durante o primeiro enchimento da albufeira e os dois primeiros anos de exploração. Este artigo, para além de efetuar uma breve descrição dos ensaios dinâmicos realizados, bem como das principais caraterísticas do sistema de monitorização e resultados obtidos durante os primeiros meses de operação, apresenta uma análise comparativa entre as estimativas modais alcançadas através da aplicação de técnicas de identificação assentes em ensaios de vibração forçada e ambiental.*

Keywords: *Identificação modal, Barragens, Vibração forçada, Vibração ambiental*

## 1. INTRODUCTION

Experimental modal analysis has been used to identify the most relevant dynamic parameters of large civil structures with the main purpose of establishing correlations with numerical predictions or in some cases developing the updating of finite element models [1]. Such tests could characterize the baseline condition of the structural behaviour, thus allowing subsequent detection of structural changes. After the remarkable technological progress that occurred in the field of data acquisition systems during the past few decades, ambient vibration tests became gradually also more common before and after rehabilitation works. Additionally, the possibility of transmitting information through the internet made it feasible to continuously monitor the dynamic behaviour of structures.

In Portugal, hydroelectricity plays a crucial role within the development of renewable energies, covering over 30% of the national installed capacity of electricity production [2]. Therefore, the safety control of concrete dams is an issue of major importance due to the large number of existing 30-70 years old dams that may be affected by significant deterioration processes induced by dams ageing. Besides a new group of dams that were built in the last 5 years should now be evaluated so that their safety may be assessed in the future.

In this context, both experimental and operational modal analysis have been performed in Baixo Sabor arch dam, through the conduction of two forced vibration tests and the installation of a continuous dynamic monitoring system. The Baixo Sabor hydroelectric scheme, designed and owned by EDP, is located in Torre de Moncorvo, Bragança district, in the north of Portugal, over the lower stretch of river Sabor, a right bank tributary of river Douro [3]. The project includes an arch dam, upstream, and a gravity dam, downstream, to create the pool required for pumping. The upstream dam is located at about 12.6 km of the confluence of rivers Sabor and Douro. It includes the arch dam, the hydraulic circuits and the underground powerhouse, on the right bank (Figure 1).

The dam is a concrete double-curvature arch dam, 123 m high, whose crest develops along 505 m, that is fully operating since early 2016. The reservoir has a capacity of 1,095 $Mm^3$ and a surface area of 2,819 ha at normal water level (NWL=234) being the crest elevation at 236 m. Two perspectives of the structure, located in the northeast of Portugal, are presented in Figure 2.

This work presents a comparison between the results obtained during the first six months of operation of the continuous dynamic monitoring system installed in Baixo Sabor arch dam [4], and the two forced vibration tests performed on the structure, first when the reservoir was empty, and then when it reached full capacity.

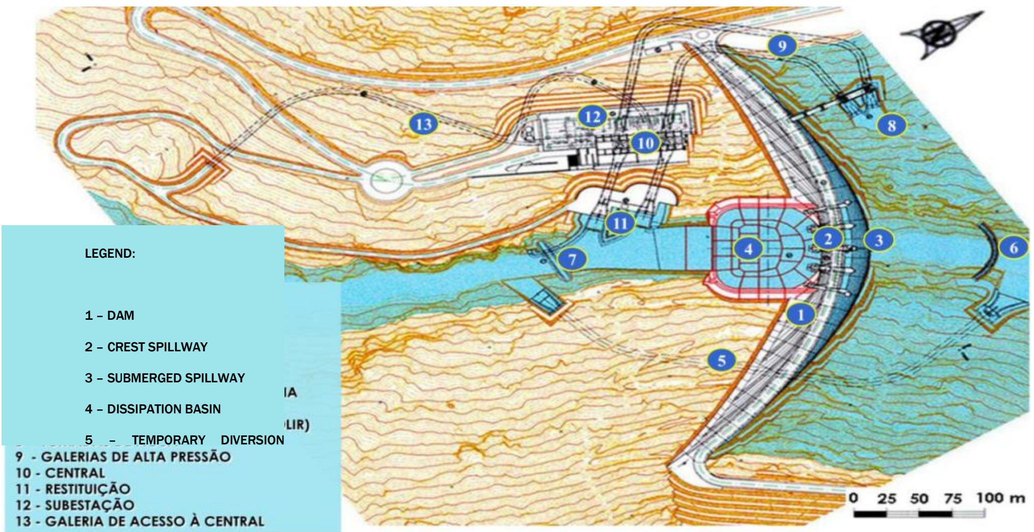


**Fig 1** - General layout of the Baixo Sabor arch dam


**Fig 2** - Baixo Sabor arch dam with full reservoir [5] and cross-section through the central cantilever

## 2. FORCED VIBRATION TESTS

Two forced vibration tests were performed in Baixo Sabor arch dam to assess the dynamic characteristics of the structure. The first test was conducted in January 2015 [6], when the water level in the reservoir was 195.5m, which was considered as representing an empty reservoir, and the second test was executed in May 2016 when the reservoir was completely full, with the water level reaching 234 m.

### 2.1. Introduction

Forced vibration tests consist of applying to a structure a force with a perfectly known sinusoidal time variation. Such action will cause a forced vibration in the structure with the same frequency of time variation of the applied force (although out of phase) and with amplitudes that, besides the intensity of the force, depend on its frequency and on the natural frequencies of the structure. Since an excitation is applied to the structure the measured values of the dynamic response are amplified (guaranteeing a greater reliability of the results) and most sources of noise are overlapped, forcing the structure to respond solely to the imposed excitation.

Natural frequencies are associated with well-defined vibratory movements of structures, so a good characterization of their movement during a forced vibration test, through an adequate arrangement of the measuring devices, coupled with the use of a suitable mathematical model, may allow the identification of areas of the structure where material deterioration processes may be taking place.

The test methodology developed in LNEC, which has been constantly improved by the implementation of automatic means of control and application of force, measurement of response and subsequent treatment of data, is based on a discrete frequency scan. For each frequency value imposed, the structure response is measured at representative points of its behaviour, and the maximum amplitude and phase values are subsequently determined. With these values, the frequency response functions of the structure are obtained and its natural frequencies are thus easily determined, since the amplitude of the response increases in its vicinity. A new methodology is being developed to apply force by continuous sweep (sine sweep).

### 2.2. Forced vibration tests performed at Baixo Sabor dam

Two identical forced vibration tests were performed at Baixo Sabor dam. The first test (FVT 1) was performed in January 2015, when the reservoir water level was at 195.5 m, corresponding to 70% of the maximum level and the second test (FVT 2) was performed in May 2016, when the reservoir reached its full capacity (234 m).

The eccentric mass vibrator presented in Figure 3 a), which has been developed at LNEC, was used to apply horizontal forces with different amplitudes and frequencies. This vibrator was designed to apply a maximum force of 160 kN in a range of frequencies between 1 and 30 Hz.

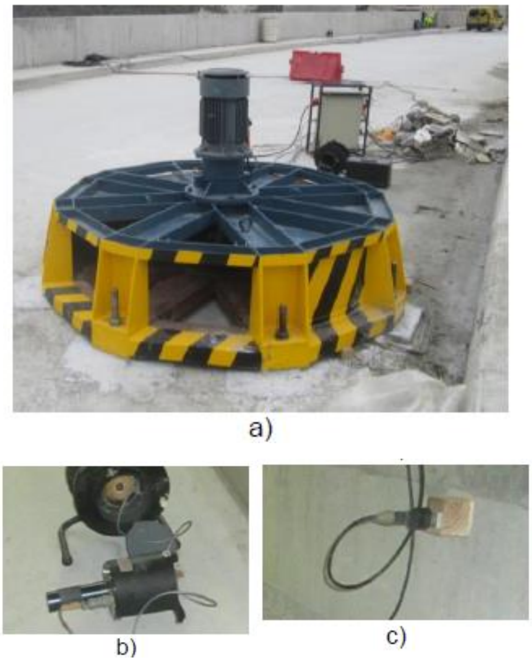


**Fig 3** - Field equipment: a) eccentric mass vibrator, b) velocity transducer, c) accelerometer

Both tests were performed by discrete scanning, in which excitation frequencies between 2.0 and 9.8 Hz were applied. The discrete frequency scanning was performed with a step of approximately 0.1 Hz. In order to ensure a better excitation of the dam, and consequently more reliable results, various mass configurations placed on the vibrator were used, concretely large masses for lower excitation frequencies, and small masses that allow higher frequencies to be applied. Figure 4presents the position of the vibrator (yellow dot) and the accelerometers (red dots) during the performed tests.

Based on the response functions determined from the experimental results, the modal parameters of the dam were identified, namely the natural frequencies, modal configurations and modal damping ratios. The structure natural frequencies and damping values obtained for the two tests can be compared by analysing Table 1.

**Fig 4** - Vibrator and accelerometers position during forced vibration tests

**Table 1** - Modal properties obtained with FVT 1 and FVT 2

| | FVT 1 (water level 195.5) | | FVT 2 (water level 234) | |
|---|---|---|---|---|
| Mode | Frequency [Hz] | Damping Ratio [%] | Frequency [Hz] | Damping Ratio [%] |
| 1 | 2.75 | 1.0 | 2.44 | 1.23 |
| 2 | 2.95 | 1.0 | 2.57 | 1.02 |
| 3 | 3.87 | 1.1 | 3.34 | 1.18 |
| 4 | 4.46 | 0.6 | 3.93 | 0.40 |
| 5 | 5.26 | 0.6 | 4.78 | 1.20 |
| 6 | 6.22 | 1.4 | 5.37 | 1.15 |

Comparing the results from FVT 1 and FVT 2, the values of natural frequencies decreased considerably for all the identified vibration modes, while the values of damping rations have both decreased and increased, depending on the mode. The decrease of frequency values is related with the higher water level in the FVT 2.

The identified mode shapes of the first six vibration modes are presented in Figure 5. The representation of mode shapes corresponding to the two upper visit galleries is achieved in red, while the original shape of the dam is represented in blue and grey.

## 3. BAIXO SABOR VIBRATION BASED HEALTH MONITORING SYSTEM

The continuous dynamic monitoring of civil structures, conjugated with the implementation of automated methods of operational modal analysis, provides a suitable approach for the accurate tracking of the most relevant dynamic properties, just based on the use of natural excitation. Therefore, a vibration-based health monitoring system has been installed at Baixo Sabor arch dam, which has been working almost uninterruptedly since December 2015, when it was installed.

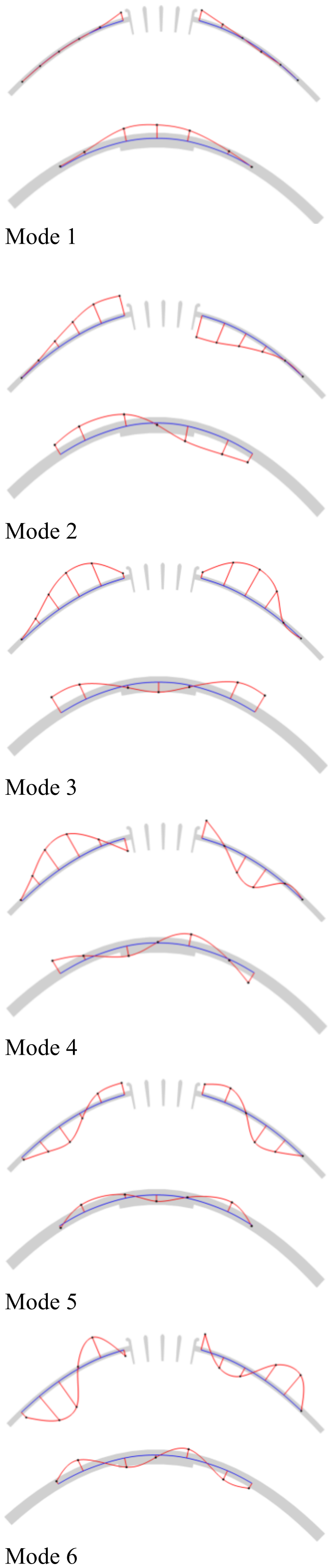


**Fig 5** - Modal configurations of the first six modes of Baixo Sabor arch dam obtained with forced vibration tests

### 3.1. Description of the monitoring system

The number of measuring points is very important when characterizing the dynamic behavior of a structure, since the mode shapes of higher order vibration modes will only be differentiated if there is enough information to accurately identify such modes. In that sense, the Baixo Sabor arch dam was equipped with 20 uniaxial accelerometers that were radially disposed along its three upper galleries, as illustrated in Figure 6. All the installed accelerometers are force balance and were configured to measure in the range ± 0.25 g, in order to allow the accurate characterization of very low acceleration signals. The position of the measuring points is illustrated in Figure 6, where the red dots represent the actual location of the installed accelerometers on the dam.

Since the spillway gates of the dam are located in the central part of the structure, the monitoring system had to be installed around them. Therefore, there are 12 accelerometers in the upper visit gallery (visit gallery 1 - GV1) divided in two groups of 6, located on each side of the spillway. The other eight accelerometers were disposed in the central part of the dam, along the second and third upper visit galleries (GV2 and GV3). In order to reduce cable length and electrical interferences, the accelerometers are connected to four digitizers, which in turn are linked to a field computer where the data is stored. All the equipment is connected by optic fiber and the synchronization of the data recorded by each digitizer is assured with GPS antennas. Additionally, the system is connected to the fiber optic network between the dam and the plant, thus allowing remote access.

The dynamic monitoring system is configured to continuously record acceleration time series with a sampling rate of 50 Hz and a duration of 30 minutes at all instrumented points, thus producing 48 groups of time series per day.

### 3.2. Output-only identification

Independent processing of the continuously collected data has been carried out by the two institutions involved in this project

**Fig 6** - Accelerometers position on the vibration-based monitoring system (marked with red dots)

(ViBest/FEUP and LNEC). In this paper, the processing developed by ViBest/FEUP is presented, which is accomplished with a monitoring software developed at ViBest/FEUP called DynaMo [7].

The monitoring system organizes the continuously collected acceleration time series in files with 30 minutes which are regularly downloaded through a FTP connection to the main field computer. These files are then handled by DynaMo software that was configured to perform the following tasks:

- backup the original data file in a database;
- pre-process of the acceleration time series, which includes trend elimination, filtering with an eighth-order low-pass Butterworth filter and re-sampling with a frequency of 25 Hz;
- characterize the acceleration amplitude by maxima and root mean squares values (RMS);
- construct colour maps in the frequency domain, which characterize the energy distribution along the analysed frequency range over time;
- identify the dam modal parameters (natural frequencies, mode shapes and modal damping ratios), based on its response under normal operation, using state of the art output-only modal identification algorithms;
- store all the obtained results in a database;

The continuous automated identification of the modal parameters is the most important and challenging task. After testing alternative output-only algorithms [8], it was concluded that good results could be obtained combining the Covariance Driven Stochastic Subspace Identification method (SSI-COV) with a routine based on clusters analysis to automate its application. This approach and its theoretical background are described in reference [9].

The evolution of natural frequencies during the first six months of monitoring are presented in Figure 7, for the first six vibration modes. In this figure each colour represents a different mode and the period when the second forced vibration test (FVT 2) was performed is indicated.

On the other hand, Figure 8 presents the values of the natural frequencies identified during only three days, from the day before the FVT 2 until the end of the next day.

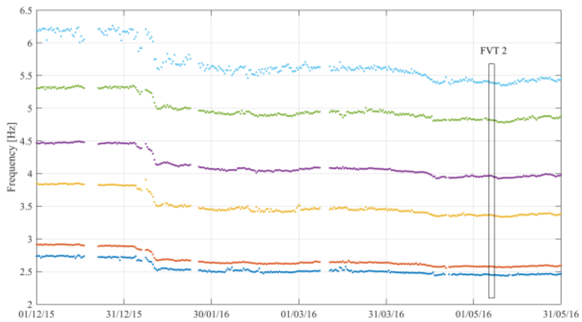


**Fig 7** - Time evolution of natural frequencies' 12-hour averages

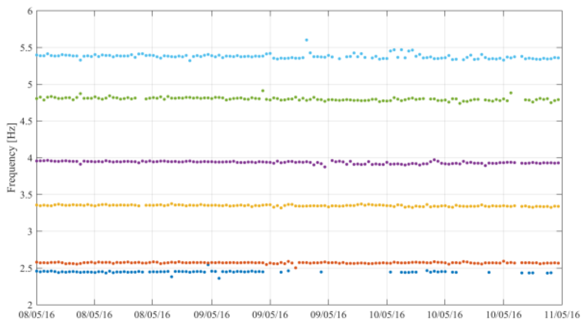


**Fig 8** - Identified natural frequencies before, during and after the second forced vibration test

Modal properties, including a description of the mode shape as well as frequency and damping values, are presented in Table 2. Since the performance of the forced vibration test induced in the structure an input that is much different from a white noise, which may disturb the identification process, the values presented in Table 2 were achieved calculating the average of the frequencies and damping values identified during the day before the test (8th of May). Even if Figure 8suggests that no major shifts occurred between the frequencies identified on the 8th and on the 9th of May.

The modal shapes identified for the tracked vibration modes, presented in Figure 9, are clear and well defined. The part of the modal shapes corresponding to measuring points located in the upper visit gallery (GV1) are represented in blue, while the points measured in the second and third galleries (GV2 and GV3) are represented in red and black. The first, third and fifth modes are approximately symmetric, whereas the second, fourth and sixth modes are antisymmetric.

**Table 2** - Modal properties obtained with operational modal analysis

| Mode | Frequency [Hz] | Damping Ratio [%] | Description |
|---|---|---|---|
| 1 | 2.45 | 1.54 | Symmetric |
| 2 | 2.57 | 1.39 | Antisymmetric |
| 3 | 3.35 | 1.63 | Symmetric |
| 4 | 3.94 | 1.45 | Antisymmetric |
| 5 | 4.80 | 2.02 | Symmetric |
| 6 | 5.38 | 1.49 | Antisymmetric |

## 4. RESULTS COMPARISON

Since the first forced vibration test was performed much before the continuous monitoring system was installed, only the results from the second forced vibration test can be directly compared. Table 3 summarizes the modal properties obtained with input-output and output-only analyses when the reservoir reached full capacity and so the second forced vibration test was performed. In the case of frequency, the values obtained with both approaches are identical, while the values obtained for damping are slightly lower in the case of input-output analysis. The differences verified between the two approaches are acceptable attending to the variability associated with damping estimates and to the fact that different identification methods have been used.

The values of natural frequencies provided by the two forced vibration tests are

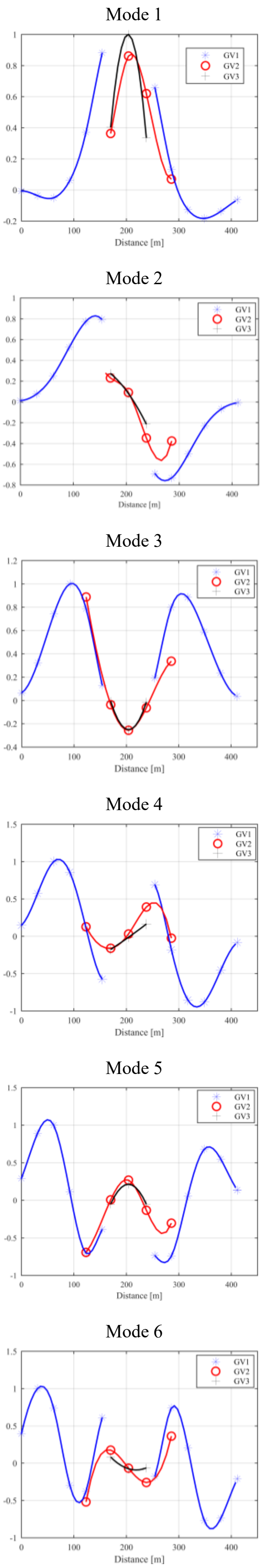


**Fig 9** - Modal configuration of the first six modes of Baixo Sabor arch dam obtained with operational modal analysis

**Table 3** - Comparison between modal properties

| Mode | Input-Output | | Output-only | |
|---|---|---|---|---|
| | Frequency [Hz] | Damping Ratio [%] | Frequency [Hz] | Damping Ratio [%] |
| 1 | 2.44 | 1.23 | 2.45 | 1.54 |
| 2 | 2.57 | 1.02 | 2.57 | 1.39 |
| 3 | 3.34 | 1.18 | 3.35 | 1.63 |
| 4 | 3.93 | 0.40 | 3.94 | 1.45 |
| 5 | 4.78 | 1.20 | 4.80 | 2.02 |
| 6 | 5.37 | 1.15 | 5.38 | 1.49 |

represented in Figure 10 together with the ones from the continuous monitoring. In this representation over time, the results from the forced vibration tests are clearly defined by larger symbols, and the axis of time was interrupted for the purpose of a better perception of the results, since the first forced vibration test had been performed almost one year before the continuous monitoring system was installed.

Even though many variables contribute to the variation of natural frequencies values over time, this evolution being mainly due to the variation of the reservoir water level [4], represented in upper part of Figure 10. During the first six months of continuous monitoring, a major part of the reservoir first filling occurred, so the water level rose about 24 m, and the frequency values decreased between 10 and 15 %. On the other hand, between the day the first forced vibration test was performed and the

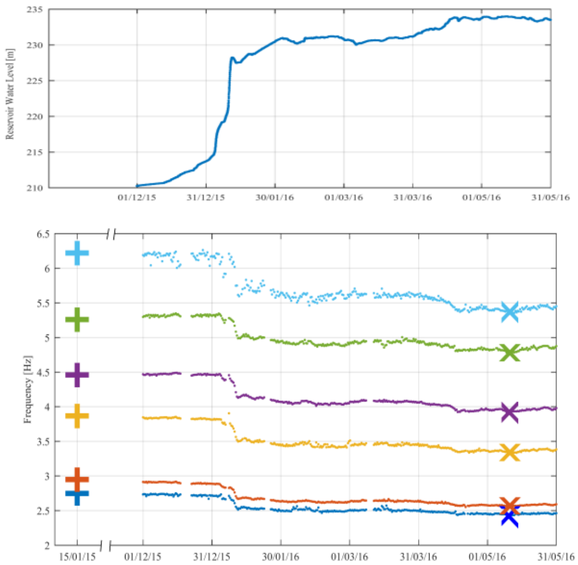


**Fig 10 -** Reservoir water level evolution over time; natural frequencies evolution over time with results from forced vibration tests

day the continuous dynamic monitoring began, the water level also rose about 15 m, but the frequency values remained almost unchanged, indicating that the effect of water level on natural frequencies attenuates for lower levels.

To better understand the relation between natural frequencies and the reservoir water level, the two variables were represented together in Figure 11, showing that the rise of water in the dam reservoir provokes a decreasing in frequency values. For each vibration mode, the regression that better suited the relation between the two variables for the first six months of continuous monitoring corresponded to a quadratic curve (represented in blue). The natural frequencies obtained from both forced vibration tests were represented by red marks. Even though there is no data available for water levels from 195.5 m to 210 m, the analysis of Figure 11 induces the idea that for such interval of levels, frequency values would present a stable behaviour or, at least, very low variations, when compared to the ones verified for higher water levels.

## 5. CONCLUSIONS

A dynamic testing campaign has been carried out at Baixo Sabor arch dam, through the performance of two forced vibration tests and the installation of a continuous vibration-based monitoring system.

Natural frequencies, damping values and mode shapes were obtained from both input-output and output-only analysis. The results obtained for natural frequencies and mode shapes were identical with both approaches, whereas the damping values obtained with experimental modal analyses were generally lower than the ones obtained with operational modal analysis.

While operational modal analysis allowed the continuous characterization of the structure dynamic properties, the first forced vibration test provided results from a period when the installation of a continuous monitoring system was not possible. In that sense, the two approaches did not just validated each other's results but have also complemented each other.

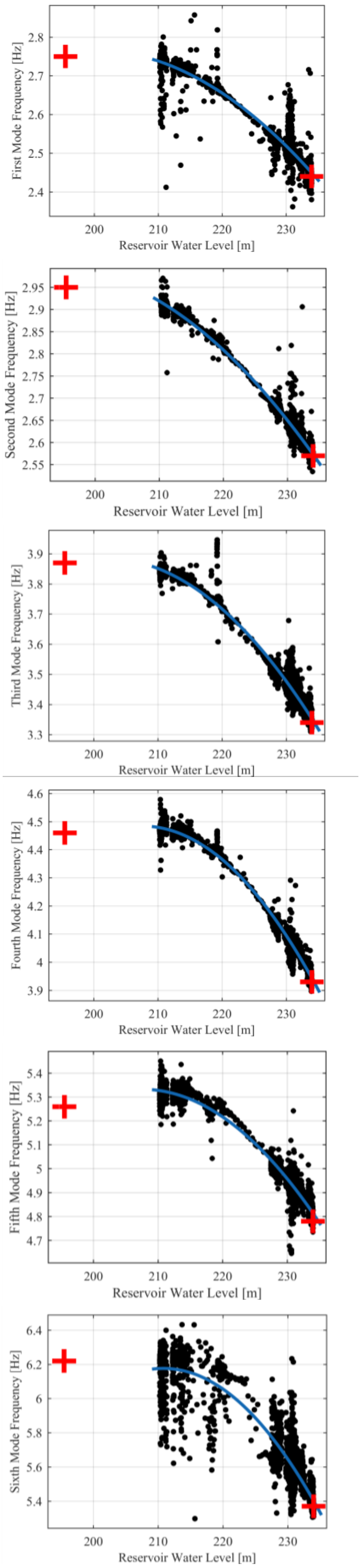


**Fig 11 -** Relation between the reservoir water level and the natural frequencies obtained by both the continuous dynamic monitoring (black points) and the two forced vibration tests (red marks)

Finally, the study of the relation between natural frequencies and reservoir water level suggested that for low levels of water in the reservoir its effect on natural frequencies is residual, when compared to the effects verified when the reservoir is full or close to full.

In the future, the authors expect to use the obtained results to calibrate a numerical model and thus be able to numerically reproduce such results.

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