MODAL IDENTIFICATION OF CONCRETE DAMS WITH DIFFERENT TYPOLOGIES UNDER NATURAL EXCITATION

IDENTIFICAÇÃO MODAL DE BARRAGENS DE BETÃO COM DIFERENTES TIPOLOGIAS SOB EXCITAÇÃO AMBIENTAL

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ABSTRACT

The Laboratory of Vibrations and Structural Monitoring (ViBest) of FEUP is presently responsible by the development of the research project DAM_AGE (Advanced Online Dynamic Structural Health Monitoring of Concrete Dams). One of the first tasks of this project consists on the performance of ambient vibration tests on concrete dams with different typologies and stiffness characteristics and on the application of state of art output-only modal identification methods, getting better sensitivity to the problems raised by the very low collected signals (of the order of micro g) when dealing with such massive structures. In this context, this paper describes a set of ambient vibration tests performed on different Portuguese concrete dams and presents the most relevant modal estimates obtained with the application of modern output-only modal identification techniques, stressing the good level of accuracy in general achieved, despite the very unfavourable signal-to-noise ratio in comparison with other civil engineering applications.

RESUMO

O Laboratório de Vibrações e Monitorização de Estruturas (ViBest) da FEUP é presentemente responsável pelo desenvolvimento do Projeto de investigação DAM_AGE (Monitorização Avançada da Condição Estrutural de Barragens de Betão). Uma das primeiras tarefas deste projeto consistiu na realização de ensaios de vibração ambiental de barragens de betão com diferentes tipologias e caraterísticas de rigidez e na aplicação de métodos recentes de identificação modal exclusivamente baseados na medição da resposta a excitações naturais, por forma a obter melhor sensibilidade em relação aos problemas colocados pelo nível muito baixo dos sinais colhidos (da ordem de micro g) em estruturas massivas de betão desta natureza. Neste contexto, este artigo descreve um conjunto de ensaios de vibração ambiental realizados em diferentes barragens de betão portuguesas, apresentando as estimativas modais mais relevantes obtidas, mediante a aplicação de modernas técnicas de identificação modal output-only, e realçando o bom nível de precisão em geral alcançado, apesar da muito desfavorável relação sinal-ruído, em comparação com aplicações noutros tipos de estruturas de Engenharia Civil.

Keywords: *Ensaios de vibração ambiental, Identificação modal, Barragens de betão*

1. INTRODUCTION

The modal identification of dams is historically associated to experimental modal analysis, which has been widely 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]. In this sense, many forced vibration tests have been performed on dams in the past and continue to be performed nowadays [2] [3].

However, the technological progress that occurred in the field of data acquisition systems during the past few decades promoted the emergence of operational modal analysis as a reliable alternative that gradually became more frequent. Even though operational modal analysis today is more common in bridges, wind turbines, towers and other lighter structures, there are already some successful examples of the application of such modal identification techniques to dams, both through the performance of ambient vibration tests [4] [5] and through the installation of vibration-based health monitoring systems [6] [7]. Nevertheless, when compared to forced vibration tests, much lower levels of vibration and much lower signal to noise ratios should be expected under natural excitation [8], thus very sensitive sensors and high-resolution digitizers are required to obtain good results.

In this context, this work refers a set of ambient vibration tests performed on six Portuguese concrete dams with different typologies and stiffness characteristics, with the aim of getting better sensitivity to the problems raised by such very unfavourable signal-to-noise ratios, as well as to better understand the level of accuracy that can be achieved in such applications. More specifically, the results from the application of operational modal analysis to three of the tested arch dams, which vary from 39 to 110 meters of height, are presented and analysed.

1.1. Overview on performed tests

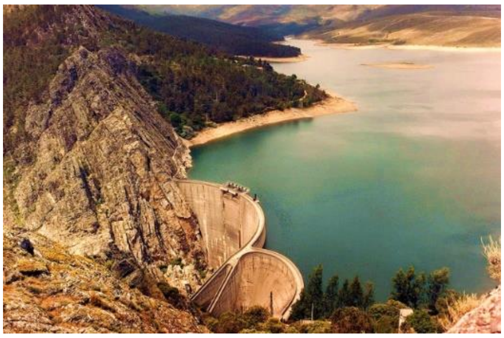
The Laboratory of Vibrations and Monitoring (ViBest) of FEUP has tested a set of six concrete dams with different characteristics during the last couple of years. This group is composed by four arch dams with very different heights (Alto Lindoso dam, Santa Luzia dam, Bouçã dam and Caldeirão dam), an arch-gravity dam (Castelo do Bode dam) and a multiple arch dam (Aguieira dam). Pictures of the six dams are presented in figure 1.

Alto Lindoso dam (heigth: 110m; crown length: 297m)

Bouçã dam (heigth: 110m; crown length: 175m)

Caldeirão dam (heigth: 39m; crown length: 122m)

Santa Luzia dam (heigth: 76m; crown length: 178m)



Castelo do Bode dam (heigth: 115m; crown length: 402m)

Aguieira dam (heigth: 89m; crown length: 400m)

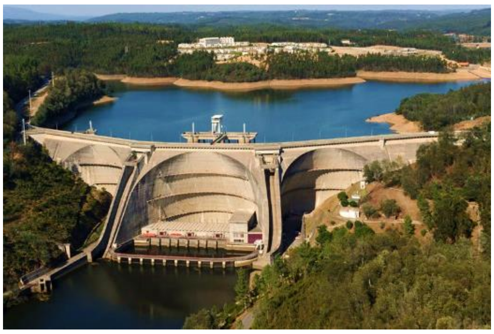


Fig 1 - Pictures of the six tested dams [9]

The tests performed consisted of ambient vibration tests executed during the day with normal operational conditions, which periodically included the rotation of electricity production turbines since all the dams are part of hydroelectric developments. Even though a few measurements have been conducted in visit galleries, the bulk of the tests were performed in the dam crowns, which are generally accessible and mostly consist of road connections between the two river margins. The exception was Bouçã dam, whose crown constitutes the dam main spillway, in which the test was performed inside the upper visit gallery. A sampling frequency of 100 Hz was used in every test.

1.2. Equipment used during ambient vibration tests

Two different sets of equipment have been used, depending on the dam's dimensions and characteristics. The first system consisted of uniaxial force balance accelerometers connected to a central acquisition unit with electric cables. Cables with different lengths were used, the longest one being just 75 m long, in order to guarantee good quality signals. Therefore, this equipment was used to test just three dams (Bouçã, Caldeirão and Santa Luzia) since it can only cover a maximum length of roughly 150 m.

The second system consisted of a set of tri-axial force balance accelerometers with internal acquisition units and batteries, whose synchronization is achieved through GPS. This system was used to test the larger dams (Alto Lindoso, Castelo do Bode and Aguieira) and it was used simultaneously with the first system in Caldeirão dam and Santa Luzia dam, so that the results from both systems could be compared. Bouçã dam is the only one where the second system could not be used, since the test had to be performed inside the upper visit gallery where there is no GPS signal, so the sensors would not be synchronized.

Figure 2 presents pictures of both the uniaxial (on the left) and the tri-axial (on the right) accelerometers used. The first one is connected to the acquisition system through an orange cable, while the second is connected to a GPS antenna.

Fig 2 - Sensors positioned during tests: uniaxial accelerometer with cable (top); tri-axial recorder with GPS antenna (bottom)

2. GENERAL RESULTS

Even though different test layouts and durations had to be considered for each case, all the tests were successfully executed and time series of accelerations were collected for the whole set of dams.

The intensity of the recorded accelerations mainly varies according to the operation conditions, namely the rotation of turbines in power plants whose operation may increase vibration levels by a factor of 100 to 1000, depending on the proximity of the plant to the dam. Apart from Santa Luzia dam, whose respective power plant is not located in its vicinity, the effect of the production complex operation on vibration levels was felt in every dam during the entire test or just part of it, depending on the case.

In order to compare the extremely low vibration levels recorded in the different dams, time series of accelerations recorded by the sensors positioned in the central part of each of the tested structures are presented in figure 3. Time series were chosen taking into account operation conditions, so that electricity production turbines were stopped, and only ambient vibration was exciting the dams during these periods. In the case of Castelo do Bode dam, the power plant was operating during the entire test, thus it was not possible to record any period during which the dam was being excited solely by ambient vibration. Generally, the vibration levels recorded go from a few micro g in quiet conditions to many tens of micro g when traffic crosses the dam or human activities with machinery occur nearby. In the case of Castelo do Bode, which had the power plant fully operating, vibration levels are constantly close to milli g.

To complement this analysis, the time series presented in figure 3 were used to obtain auto-spectra, which are represented in figure 4 with the same colour codes. Figure 4 is very interesting in the sense that it exposes the minimum signal amplitude needed to assure adequate characterization of the auto-spectra from the whole set of tested dams, which is between 10^{-13} and 10^{-14} g^2/Hz.

It is also interesting to notice that the auto-spectra from the time-series measured in Castelo do Bode, though being the ones with more energy associated, present poorly defined peaks, suggesting higher vibration intensities do not necessarily imply better results. Even though it is not represented in figure 4, the same was observed at Aguieira dam (whose power plant is also very close), with time series measured when the turbines were operating.

Additionally, it may be concluded that the frequency of the first vibration mode of dams can vary significantly in the range 3-12 Hz, depending on the structure's geometry.

3. AMBIENT VIBRATION TEST OF ALTO LINDOSO DAM

Alto Lindoso dam is an arch dam embedded in a narrow valley zone in the Lima River, in the north of Portugal. The dam is 110 meters high and its 297 meters long crest constitutes a road link between the two banks of the river. A hydroelectric power plant was built close to the dam left abutment, where two vertical Francis turbines operate at 214.3 rpm.

The ambient vibration test of Alto Lindoso dam was performed on the 22nd of February 2017 and it was based on the use of ten GSR-24 recorders from Geosig equipped with internal tri-axial force-balance accelerometers. With the purpose of identifying as many vibration modes as possible, and taking into account the large dimensions of the structure, a test grid was prepared considering 21 measuring points, corresponding to the dam's 21 concrete blocks. To assure the measuring of accelerations in every point of the defined grid, four setups were considered, during which 6 recorders acted as references, and the other 4 recorders as mobile sensors. The six points marked with red dots in figure 5 were used as references, while the other 15

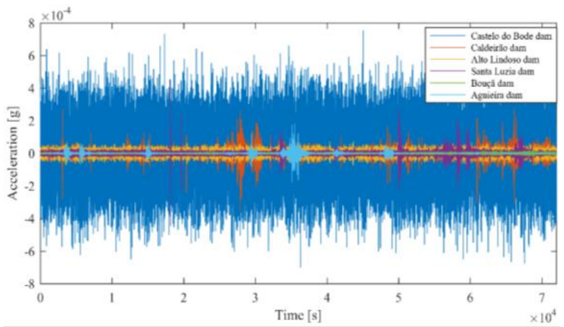


Fig 3 - Time series of accelerations collected in the whole set of tested dams

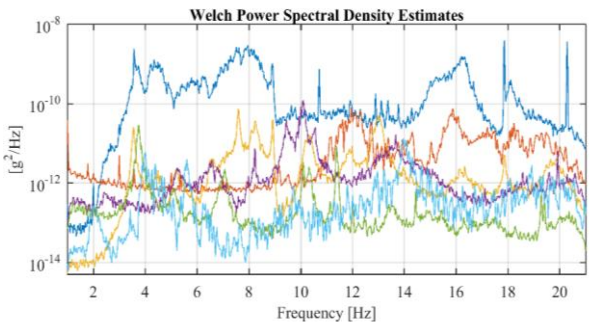


Fig 4 - Auto-spectra obtained from each of the time series presented in Figure 3

points (blue dots) were measured by the mobile recorders. The water level in the reservoir during the test was 322 m (elevation above sea level).

The SSI-cov method was applied to obtain accurate estimates of natural frequencies, modal damping ratios and mode shapes. This method was applied to each setup, and model orders between 20 and 80 were considered. The first 7 vibration modes were identified, and their modal properties are presented in Table 1. The results presented correspond to the average of each of the values identified across the several setups. In the case of the first symmetric mode (mode 2), two different frequencies that are associated with the same mode shape were identified, depending on the structure vibration level.

Very clear and well-defined modal sha-pes were achieved for the seven identified modes, which are presented in figure 6. In order to facilitate the observation of modal configurations of higher order modes, splines were adjusted to the identified modal ordinates. The first mode is anti- symmetric and the second one is symmetric. From the third to the seventh mode, the configurations are alternatively symmetric and antisymmetric.

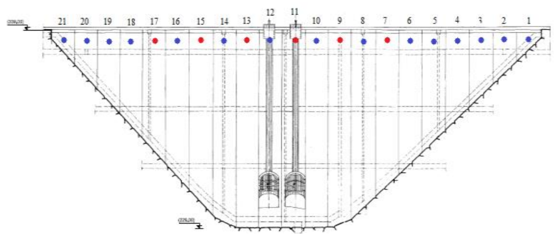


Fig 5 - Alto Lindoso dam: test layout.

Table 1 - Modal parameters for Alto Lindoso dam first 7 vibration modes

Mode	f_{mean} [Hz]	ξ_{mean} [%]	Description
1	3.547	1.259	Antisymmetric
2	3.752 / 3.963	2.850 /2.164	Symmetric
3	5.004	1.593	Symmetric
4	6.564	1.305	Antisymmetric
5	8.256	1.336	Symmetric
6	9.972	1.291	Antisymmetric
7	11.863	1.497	Symmetric

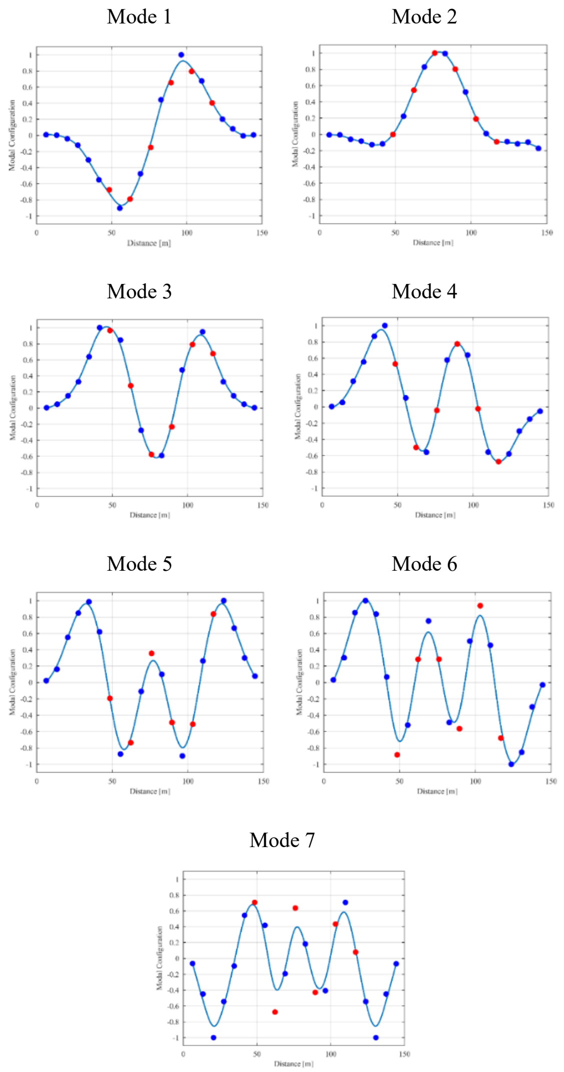


Fig 6 - Modal shapes of the first 7 modes of Alto Lindoso dam

4. AMBIENT VIBRATION TEST OF BOUÇÃ DAM

Bouçã dam is an arch dam located in Zêzere river, a tributary of Tagus river in central Portugal. The dam, which started operating in 1955, is 63 meters high and its 175 meters long crest mostly constitutes the structure spillway. The hydroelectric power plant that was built downstream is installed with a capacity of 44 MW, assured by two Francis turbines that operate at 214.3 rpm.

The ambient vibration test of the Bouçã dam was performed on the 12th of June 2018 and it was based on the use of nine uniaxial force-balance accelerometers that were radially disposed along the dam's upper visit gallery. Since the dam crown is constituted by its main spillway, the test had to be performed inside the upper visit gallery, precluding the utilization of the GPS based system. Therefore, the acquisition system using cables was used and every measuring point had its own fixed sensor. The test grid prepared considered 9 measuring points on the dam's 9 central concrete blocks, which correspond to the group of blocks that are crowned by the spillway, and the farthest sensor was nearly 65 m away from the acquisition unit. To assure a good characterization of the structure's dynamic behaviour several similar setups were developed with a sampling rate of 100 Hz. The level in the reservoir during the test was 174.7 m (elevation above sea level).

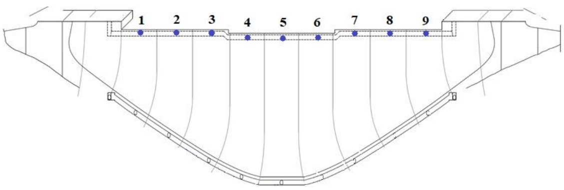


Fig 7 - Bouçã dam: test layout

Table 2 - Modal parameters for Bouçã dam first 8 vibration modes

Mode	f_{mean} [Hz]	ξ_{mean} [%]	Description
1	3.298	1.500	Antisymmetric
2	3.737	1.363	Symmetric
3	5.063	2.631	Symmetric
4	5.678	1.808	Antisymmetric
5	6.874	1.802	Symmetric
6	8.452	1.562	Antisymmetric
7	10.302	1.055	Symmetric
8	11.394	1.936	Antisymmetric

To assure accurate estimates of modal properties, the SSI-cov method was applied considering model orders between 20 and 80. The first 8 vibration modes were identified and their modal properties, including natural frequencies and damping values, as well as the description of mode shapes, are presented in Table 2. The results shown correspond to the average of each of the values identified across the several setups.

Very clear and well-defined modal shapes were achieved for the 8 identified modes, which are presented in figure 8. The first mode is antisymmetric and the second one is symmetric. From the third to the eighth mode, the configurations are alternatively symmetric and antisymmetric.

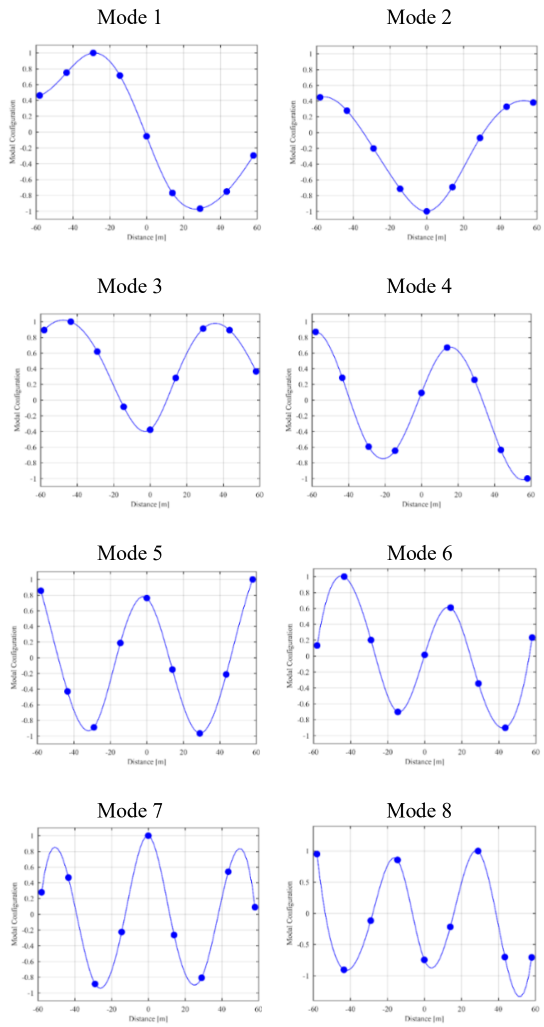


Fig 8 - Modal shapes of the first 8 modes of Bouçã dam

5. AMBIENT VIBRATION TEST OF CALDEIRÃO DAM

Caldeirão dam is a stiff double-curvature arch dam located in the interior of Portugal, just 50 km away from the border with Spain. The dam is just 39 meters high and its 122 meters long crest is mostly constituted by the dam spillway, even though there is a viaduct over the dam that allows to cross the Ribeira do Caldeirão river by car. The hydroelectric power plant associated with Caldeirão dam has a total installed capacity of 40 MW, assured by vertical Francis turbines that operate at 333.3 rpm.

The ambient vibration test of Caldeirão dam was performed on the 2nd of June 2017 and it was based on the use of both the acquisition systems presented before, with the purpose of comparing the results obtained from the two procedures. Therefore, since GPS signal was needed for synchronization when using the seismographs, the test could not be performed on the dam gallery and thus seven uniaxial force-balance accelerometers and six GSR-24 recorders from Geosig (equipped with internal tri-axial force-balance accelerometers) were radially disposed, side by side, along the dam's top viaduct. The test grid prepared considered 7 measuring points corresponding to the position of the walls connecting the dam to the viaduct, which in the case of the tri-axial recorders were covered in two setups, and a sampling rate of 100 Hz was used during the acquisition with both the used systems. Additional measures were performed with two tri-axial recorders in the dam's upper visit gallery. The position of the 7 measuring points is marked with blue dots in the picture of the structure presented in figure 9. The level in the reservoir during the test was 655.08 m (elevation above sea level).

Fig 9 - Caldeirão dam: test layout

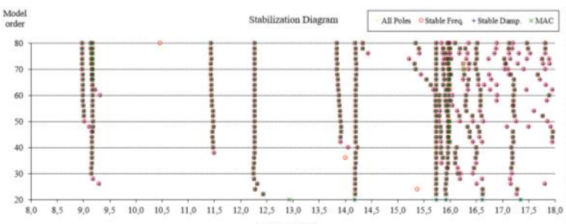


Fig 10 - Stabilization diagram obtained after the application of SSI-cov method to data from Caldeirão dam

Modal identification was developed using the measured time series of accelerations, through the application of the SSI-cov method. Model orders between 20 and 80 were used and the stabilization diagram presented in figure 10 was obtained. A few well-defined vertical alignments appear between 9 and 16 Hz, whereas from 16 to 20 Hz many disperse poles appear, creating a couple of poorly-defined vertical alignments.

However, this analysis suggested that besides the vibration modes of the dam, vibration modes of the viaduct are being identified as well, creating uncertainty in the identification process. In order to clarify which modes were really vibration modes of the dam, separating those of the viaduct, auto-spectra were calculated using time series measured by the two sensors that had been placed in the upper visit gallery, thus not suffering direct influence from the viaduct dynamic properties.

Two calculated auto-spectra, from measures in the gallery (on the left) and from measures in the viaduct (on the right), are represented in figure 11 for comparison. Even though not being entirely clear, the auto-spectra obtained from the data recorded in the visit gallery show a couple of distinct peaks around 12.2 and 15.7 Hz,

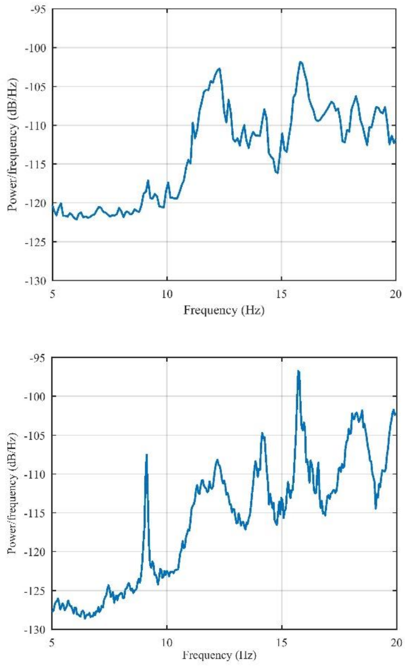


Fig 11 - Auto-spectra from time series recorded inside the upper visit gallery (top) and from time series recorded in the top viaduct (bottom)

frequencies that are present in the auto-spectra from the viaduct as well, and therefore must correspond to vibration modes of the dam. Also around 14.1 Hz, a smaller peak may correspond to a different vibration mode. Nevertheless, this can still be due to the influence of the viaduct, therefore this frequency ends up being discarded, along with all the other frequencies that had been previously identified, since neither of them may be assuredly associated to either the dam or the viaduct.

Finally, natural frequencies and damping ratios associated to the two identified vibration modes are presented in Table 3. The mode shapes of the two identified modes are presented in figure 12. These modes are antisymmetric and symmetric, respectively.

Table 3 - Modal parameters for Caldeirão dam identified vibration modes

Mode	f_{mean} [Hz]	ξ_{mean} [%]	Description
1	12.265	2.074	Antisymmetric
2	15.759	0.336	Symmetric

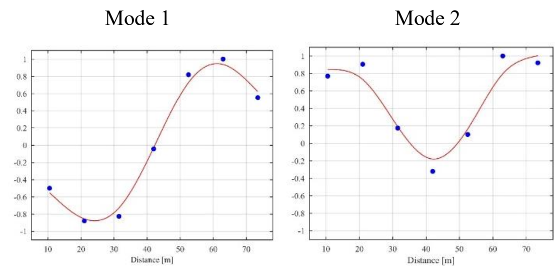


Fig 12 - Mode shapes of the identified modes of Caldeirão dam

6. CONCLUSIONS

Ambient vibration tests have been successfully performed in a group of six concrete dams located in Portugal, with distinct characteristics and typologies, which during the tests were submitted to different operational and ambient excitations, showing the suitability of operational modal analysis to concrete dams. The studied group of structures included four arch dams with very different heights (Alto Lindoso dam, Santa Luzia dam, Bouçã dam and Caldeirão dam), an arch-gravity dam (Castelo do Bode dam) and a multiple arch dam (Aguieira dam). Two distinct acquisition systems were available to perform the tests and each of them was used depending on the characteristics and geometry of the structure.

Different vibration levels were measured, which depending on the operational conditions could go from few micro g to few milli g. Nevertheless, despite the very low vibration levels, satisfactory results were obtained in all the applications.

The modal identification developed in the three double-curvature arch dams with different heights was achieved through the application of the SSI-cov method. Seven to eight vibration modes were identified with the analysis of the two highest structures, while just two modes were identified in the third example. In all the three cases, the first mode identified is antisymmetric while the second mode is symmetric, however the first natural frequency may vary from around 3 Hz to around 12 Hz.

The results obtained are being used to numerically test the accuracy that would be achieved in the modal identification if lower cost accelerometers had been used during the tests instead.

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REFERENCES

[1] Cunha, A., et al., *Recent perspectives in dynamic testing and monitoring of bridges.* Structural Control and Health Monitoring, 2013. **20**(6): p. 853-877.

[2] Gomes, J. and J.V. Lemos, *Characterization of the dynamic behavior of an arch dam by means of forced vibration tests*, in *1st Meeting of EWG Dams and Earthquakes*. 2016, Balkema: Saint Malo, France.

[3] Gauron, O., et al., *Forced-Vibration Tests and Numerical Modeling of the Daniel-Johnson Multiple-Arch Dam.* Journal of Performance of Constructed Facilities, 2018. **32**(2).

[4] Deinum, P.J., et al., *Vibration tests on emosson arch dam, Switzerland*. Earthquake Engineering & Structural Dynamics, 1982. **10**(3): p. 447-470.

[5] Proulx, J., et al., *An experimental investigation of water level effects on the dynamic behaviour of a large arch dam*. Earthquake Engineering and Structural Dynamics, 2001. **30**(8): p. 1147-1166.

[6] Darbre, G.R. and J. Proulx, *Continuos ambient-vibration monitoring of the arch dam of Mauvoisin*. Earthquake Engineering and Structural Dynamics, 2002. **31**(2): p. 475-480.

[7] Mendes, P., *Observação e Análise do Comportamento Dinâmico de Barragens de Betão*. 2010, Faculdade de Engenharia da Universidade do Porto.

[8] Pereira, S., et al., *Dynamic monitoring of a concrete arch dam during the first filling of the reservoir*. Engineering Structures, 2018. **174**: p. 548-560.

[9] EDP. *Energias de Portugal*. [cited 2018 21/09/2018]; Available from: http://www.a-nossa-energia.edp.pt/centros_produtores/.