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STATIC AND CONTINUOUS DYNAMIC MONITORING OF BAIXO SABOR ARCH DAM

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Abstract: *The failure of dams with large reservoirs can be the cause of catastrophic accidents with very important losses of human lives, material and environmental assets. For these reasons, the safety control of these constructions is regulated and followed by national authorities, considering the structural, hydraulic-operational and environmental aspects. In Portugal, the national authority is technically assisted, for dams that involve major risks, by the National Laboratory for Civil Engineering (LNEC). The structural safety control of dams is based on regular inspection and on the interpretation of data collected from the monitoring system, obtained from different measurement instruments installed according to the dam safety monitoring plan, and taking into account the results of numerical models, considering the material properties and the loads.*

Baixo Sabor dam, which is owned and was engineered and constructed by EDP-Energias de Portugal, is a good example of the technology and experience in the field of monitoring and instrumentation available in LNEC and in the Faculty of Engineering of the University of Porto (FEUP), able to analyze the behavior of the structure in all phases, namely during the first filling of the reservoir and exploitation period. Some results collected from different measurement instruments are presented, showing the proper functioning of the monitoring system.

1 DESCRIPTION OF THE BAIXO SABOR DAM

Baixo Sabor dam is in the lower section of Sabor River, one of the right-side tributaries of the Douro River, in the North of Portugal. It is a double curvature concrete arch dam 123m high, the crest is 505m long and has a theoretical width of 6m (Figure 1). The structure is divided into 32 blocks whose width vary from 15.4m on the left bank to 17,0m in the valley bottom and 15.7m on the right bank, having a total concrete volume of 670,000m^3. It was engineered and constructed by “EDP Produção” a company of “EDP-Energias de Portugal” Group. The first filling of the reservoir took place between February 2014 and April 2016.

There are six horizontal inspection galleries and a drainage gallery that is divided in two in the bottom of the valley, i.e., one upstream and another downstream. The inspection galleries

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have geodetic observation systems installed and allow the data collection of several dam monitoring devices. Drainage and piezometric systems were installed along the drainage gallery.

The spillway, which is controlled by four radial gates, is in the central part of the dam and comprises four 16m long bays with spillway gates separated by 5.83m wide piers. The spillway has a maximum discharge capacity of 5,000m³/s at maximum flood level. A downstream stilling basin dissipates the energy produced by the discharge.

The reservoir has a capacity of 1,095Mm³ and a surface area of 2,819ha at normal water level (NWL=234) being the crest elevation at 236. At the maximum flood water level, the reservoir capacity rises to 1,124Mm³ and the surface area increases to 3,100ha.

a) b)

Figure 1: Baixo Sabor dam, a) aerial view after the first filling of the reservoir, b) cross section through the bottom outlet

The bottom outlet is in the mid-section of the dam below the central pier of the spillway and it is equipped with an upstream fixed wheel gate and a downstream radial gate.

In the powerhouse, an underground structure located on the right bank, there are two turbines, each with a capacity of 81MW. The low-pressure headrace tunnels, located on the right bank, have a diameter of 6.7m and are 238m and 338m long respectively, and the tailrace tunnel serving both units is 34m long.

2 GENERAL REQUIREMENTS OF THE PORTUGUESE DAM REGULATIONS

The Dam Safety Monitoring Plan, according to the regulations dealing with dam safety in Portugal, namely the Dam Safety Regulation[1] and the Guidelines for the Observation and Inspection of Dams[2], define the physical quantities to be monitored and its reading frequencies, taking into account the risks involved, the size of the dam and its reservoir, the safety factors considered in the project itself, the characteristics of the dam foundation, the population downstream and the strategic importance of any downstream infrastructure. Those Guidelines establish the general rules for dams, monitoring systems, underground works, foundation rock mass and reservoir.

The Dam Safety Monitoring Plan also includes the definition of the different visual inspections required and their frequencies, the definition of the monitoring system, the placement of the measuring instruments, the observation frequency of the monitoring system instruments, the gathering and processing of the monitoring data, the reporting and communication scheme in the event of exceptional occurrences or the detection of abnormal behaviors, the installation and operation reports of the monitoring system, the qualifications of the staff responsible for the installation and operation of the monitoring system, the analysis of the behavior, and the assessment of the structure's safety.

3 MONITORING SYSTEM

3.1 Static monitoring system

Due to its large dimensions and consequent importance of the dam, the structure has a complex monitoring system[3]. The quantities monitored, by regulatory imposition, are: i) displacements; ii) joint and crack movements; iii) drainage flows; iv) uplift pressures; v) air temperature and air moisture; vi) concrete temperatures; vii) strains; viii) stresses; and ix) seismic induced vibrations. The different loads acting on the structure, such as the hydrostatic pressure on the upstream and downstream faces, air and water temperatures and seismic loads either at the dam site or on the perimeter of the reservoir are also monitored. Table 1 lists all the measurement instruments of the static monitoring system.

The monitoring system implemented satisfies the requirements of the Portuguese Dam Safety Regulations, monitoring all the required physical quantities, some of them redundantly. In addition to regulatory impositions, geodetic methods are used to measure slopes movements upstream and downstream of the dam and a dynamic response monitoring system was implemented.

The horizontal displacements are monitored at 27 points by five plumb lines, 32 points by precise traversing inside three inspection galleries, and three object points at crest, near the upper coordimeter bases of the three central plumb lines, by Global Navigation Satellite System (GNSS) (Figure 2). The vertical displacements are monitored at 25 points by levelling at crest, 69 points inside three inspection galleries and six points on horizontal drainage galleries at the bottom of the valley. Vertical and horizontal displacements at the dam insertion surface are measured by 16 rod extensometers also installed in the drainage gallery, six of which, the three closest to each bank, are single rod and the remaining 10, in the central part of the dam, are double rod extensometers.

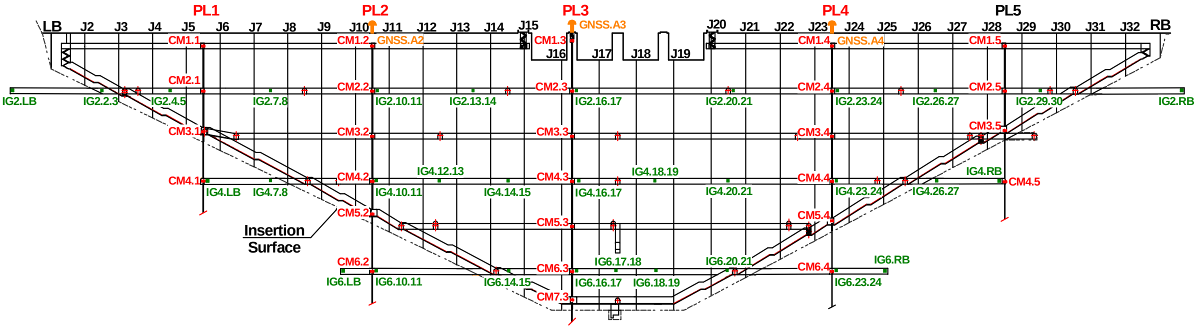


Figure 2 Horizontal displacements measuring instruments in Baixo Sabor dam. Five plumb lines (PL1 to PL5), three galleries with precise traverse (IG2, IG4 and IG6) and three GNSS antennas.

The relative movements of the contraction joints are measured manually by electrical resistance jointmeters at 152 points and by three-dimensional baselines placed in four galleries and in the drainage gallery in a total of 103 monitored points.

The state of strain in the dam's body's is monitored in 40 points, covering the zones of maximum stresses, by groups of Carlson strainmeters, being eight one-dimensional, 26 two-dimensional and six tri-dimensional, placed in 17 radial sections. The stress state is evaluated by the knowledge of the state of strain considering the creep function. Additionally, there are 10 stressmeters placed in 5 radial sections, near the strainmeters groups to get an acceptable calibration of the concrete stress-strain relationships.

The temperature of the concrete is measured by 52 electric resistance thermometers, 26 of them on the upstream and downstream dam surfaces, but also by the jointmeters, strainmeters and stressmeters, which makes a total of 480 electric instruments measuring the temperature.

The percolation through the foundation is monitored by 216 foundation drains, five drains per block, measuring the drainage flows in the drainage gallery and the infiltrated flows in the unsupported adits which extend three of the inspection galleries to the banks interior. There are 18 flow measuring weirs to control the partial flows by structural areas and the total flow.

The creep of the concrete is evaluated by sets of three cells, in three different blocks, several meters apart. Each set has one full-mixed creep cell and one full-mixed non-stress cell, one wet-screened #76 mm creep cell and one wet-screened #76 mm non-stress cell; one wet-screened #38 mm creep cell and one wet-screened #38 mm non-stress cell. The creep law was determined through the results obtained from the creep cells installed in the dam[4].

	Values	**Monitoring devices**	**Number of Instruments**	**Automatic Monitoring System**
1	Air parameters	Meteorological station		
		Air temperature sensor	1	Yes
		Air humidity sensor	1	Yes
		Solar radiation sensor	1	Yes
		Rain gauge	1	Yes
2	Water level	Upstream water level indicator	1	Yes
		Downstream water level indicator	1	Yes
3	Water pressure in the concrete	Pressure cells	6	-
4	Uplift pressure	Piezometers	41	25
5	Displacements	Coordimeter bases at 5 plumb lines	27	9
		Geodetic survey points at crest with GNSS	3	3
		Levelling at crest	1	-
		Levelling inside inspection galleries	4	-
		Precise traversing inside inspection galleries	3	-
		Rod extensometers	15	12
		Electrical resistance jointmeters	152	16
		Three-dimensional baselines	103	24
6	Drainage	Foundation drains	216	-
		Flow measuring weirs	18	6
7	Concrete temperatures	Electric resistance thermometers	52	30
8	Strains	Carlson strain meters	265	14
9	Stresses	Stress meters	10	8

Table 1 Static and automatic monitoring systems of the Baixo Sabor dam

The implemented automatic data acquisition system (ADAS) covers all the physical quantities contemplated by the dam monitoring system, reading in automatic mode about 300 different values. It is a system of significant size involving the automation of about 27% of the readings performed in manual mode. This system is under test, with good results already being obtained in the readings of some measurement instruments, namely the displacements measured by plumb lines[5].

An Emergency Plan and a Warning and Alert System, enabling the population immediately downstream of the dam to be warned in case of an incident or accident, were also implemented.

3.2 Dynamic monitoring system

To ensure a good characterization of the dynamic behavior of the Baixo Sabor dam, 20 uniaxial accelerometers were radially installed along the three upper galleries. Figure 3 characterizes the position of the accelerometers, marked in red.

In the GV1 gallery, 12 accelerometers are divided in two groups of six, disposed on each side of the spillway. Each of these groups of six is connected to a digitizer, which is linked to a field computer. In turn, the eight accelerometers on the two lower galleries are connected to a different set of two digitizers. All the equipment is connected by optic fibre and the synchronization of the data recorded by each digitizer is assured with GPS antennas.

The main field computer is connected to the fiber optic network between the dam and the plant, allowing remote access to the acquired data. All the installed accelerometers are uniaxial and force balance, which were configured to measure in the range -0.25g and 0.25g, in order to allow the accurate characterization of very low acceleration signals.

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.

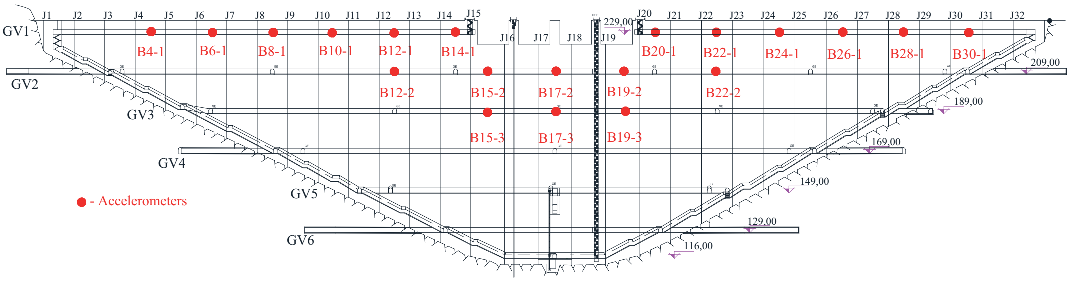


Figure 3: Position of measuring points on Baixo Sabor monitoring system[6].

4 SOME RESULTS FROM THE MONITORING SYSTEM

4.1 Static monitoring system

The monitoring system is in full operation, with very few exceptions, since the beginning of the first filling of the reservoir in February 2014 and almost all the measuring instruments are in very good working condition, ensuring the safety of the dam.

In Figure 4 a comparison between the horizontal displacements monitored by the central GNSS antenna, located in block 16-17 at elevation 239.66 m, and the displacements measured at the upper coordimeter base of the central plumb-line, placed in the same block at elevation 233.06 m, are presented, showing an excellent agreement since GNSS started operating, in May 2016. The comparison took into account the different elevations of the two instruments, the measurements in the coordimeter base had been extrapolated to the antenna elevation, through an algorithm that considers the dam structural deformation[7].

Figure 5 shows the horizontal displacements monitored by precise traversing inside GV2 inspection gallery at elevation 210.23 m, block 16-17, and the displacements measured at the nearest coordimeter base of the central plumb-line, placed in the same block and same elevation. Although only 9 geodesic campaigns have been carried out, an excellent agreement is showed since July 2014 until late July 2017.

Figure 6 shows the displacements measured on the double subvertical rod extensometer EF9, located downstream on the bottom of the central block 17-18 at 116.3 m elevation, from July 2014 to January 2018. The global shape of the displacements evolution over time is similar on both rods and compatible to the main action, the hydrostatic pressure.

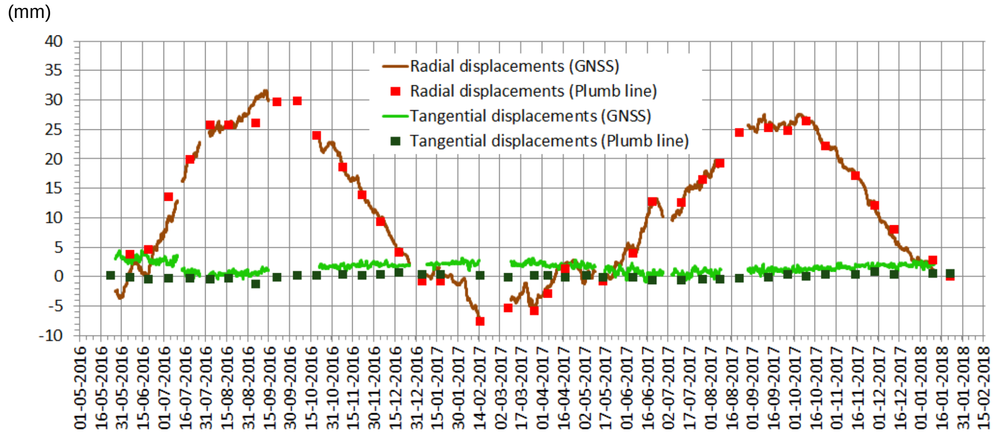


Figure 4: Comparison of the horizontal displacements monitored by the central GNSS antenna, with the displacements measured in the upper coordimeter base of the central plumb line at 16-17 block (displacements extrapolated for the central GNSS antenna elevation)

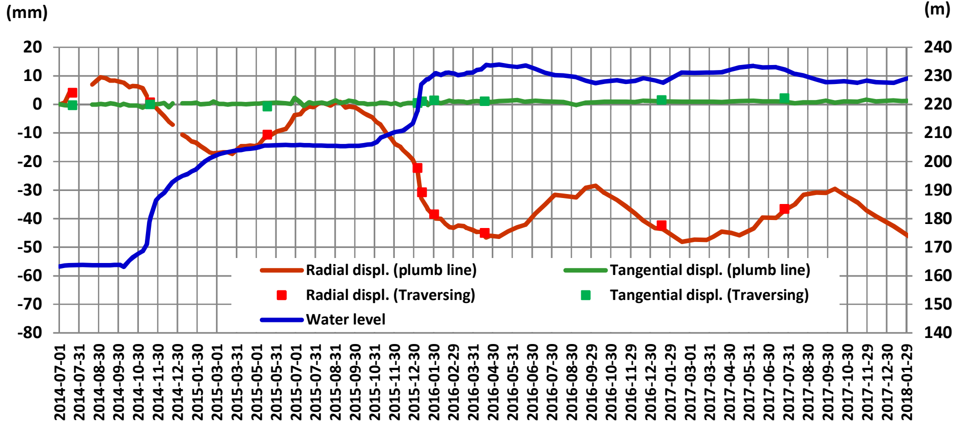


Figure 5: Comparison of the horizontal displacements monitored by precise traversing inside GV2 inspection gallery at elevation 210.23 m, block 16-17, and the displacements measured at the nearest coordimeter base of the central plumb-line, placed in the same block and same elevation.

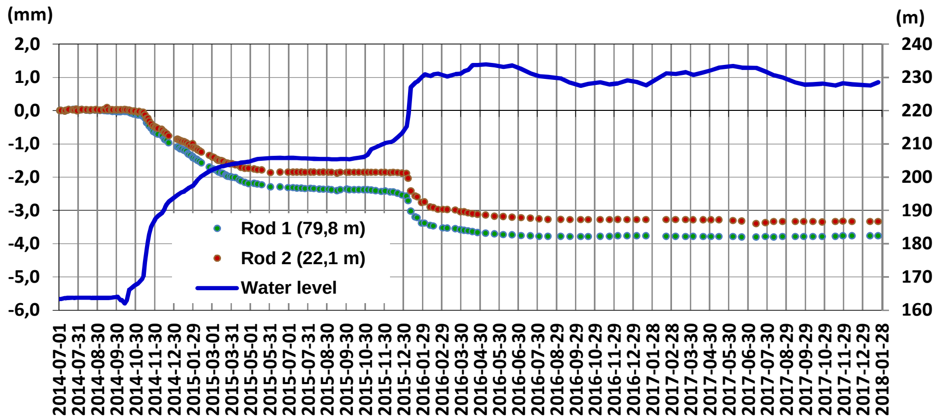


Figure 6: Displacements measured on the subvertical rod extensometer EF9, located downstream on the bottom of the central block 17-18 at 116.3 m elevation, from July 2014 to January 2018.

Figure 7 shows the temperatures measured in thermometers and jointmeters of central cantilever and the temperatures interpolated on nodal points of the finite element mesh, in two different phases, one at the beginning and another at the end of the first filling of the reservoir, July 2014 and January 2016 respectively. Using an interpolation method and a numerical technique to spread the temperatures from discrete samples to a finite continuum domain represented by a finite element mesh, it was possible, from the data collected by electric measurement instruments embedded in the concrete to reproduce the thermal field evolution during the first filling of the reservoir[8]. An excellent agreement between the computed and observed displacements was achieved[9].

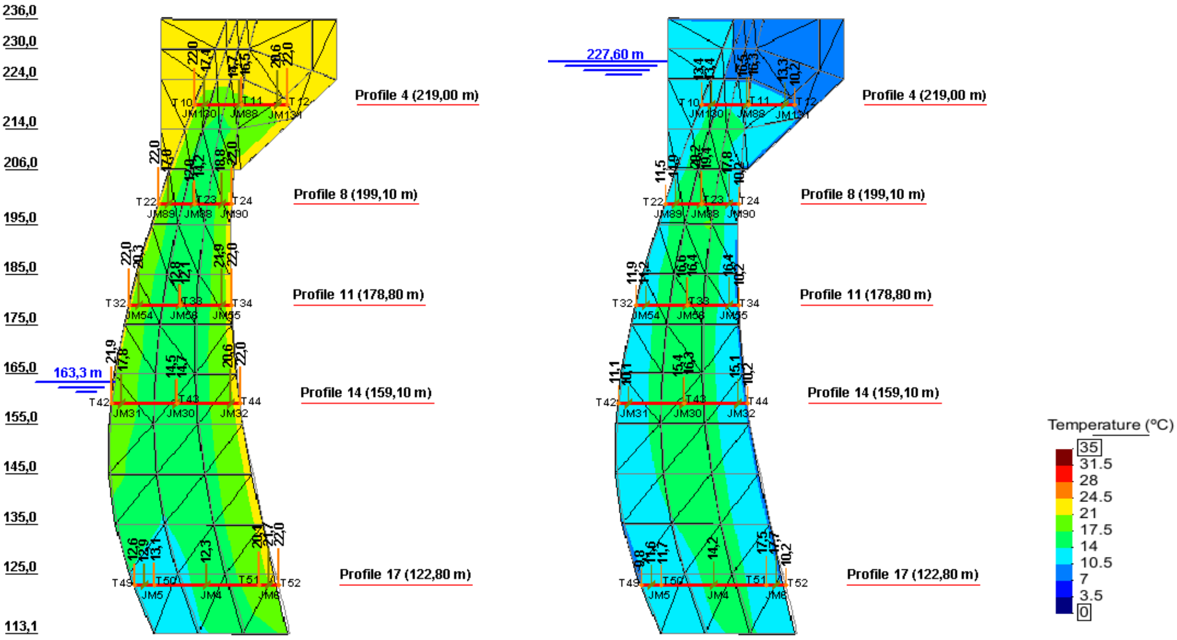


Figure 7: Temperatures measured in thermometers and jointmeters in the central cantilever instruments and interpolated temperatures on the nodal points of the finite element mesh, in July 2014 (left) and January 2016 (right).

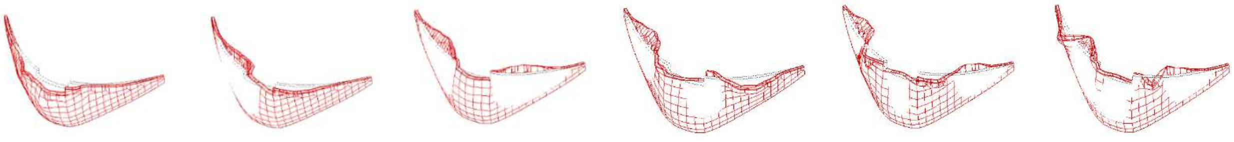
4.2 Dynamic monitoring system

The data continuously collected by the dynamic monitoring system is independently processed by ViBest/FEUP and LNEC, this paper presents the processing developed by ViBest/FEUP, which is accomplished with a monitoring software developed at ViBest/FEUP called DynaMo, initially designed for continuous dynamic monitoring of bridges and now adapted for the monitoring of dams[10].

The monitoring system organizes the continuously collected acceleration time series in files with 30 minutes which are regularly downloaded through an FTP connection to the main field computer. These files are then handled by the DynaMo software.

The most important and challenging task is the continuous automated identification of the modal parameters. In the present application, after testing alternative output only algorithms[11], 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. A description of this approach and of its theoretical background can be found in reference[12].

The section presents results obtained during the first six months of operation of the system, from December 2015 to May 2016. The first six modes of vibration were identified and natural frequencies, modal damping values and modal configurations were obtained. The three-dimensional representations of the modal configurations are presented in Figure 8, in which the dashed line represents the dam original geometry and the modal configuration is represented in red. The first, third and fifth modes are approximately symmetric and the second, fourth, and sixth are antisymmetric.



Mode 1 Mode 2 Mode 3 Mode 4 Mode 5 Mode 6

Figure 8: Modal configuration of the first six modes of Baixo Sabor arch dam.

Modal estimates corresponding to the first six modes are resumed in Table 2, where minimum, maximum, mean and standard deviation frequencies and damping values are presented. It is important to notice the significant difference between minimum and maximum frequencies for each vibration mode (even after the elimination of outliers), which is reflected in the standard deviation values as well, indicating significant oscillations during the evaluation period. Additionally, it is interesting to observe that the damping values present slightly higher mean values for the symmetric modes.

Mode	$f_{[Min\ ;\ Max]}$ [Hz]	f_{mean} [Hz]	f_{std} [Hz]	$\xi_{[Min\ ;\ Max]}$ [%]	ξ_{mean} [%]	ξ_{std} [%]	Description
1	[2.43 ; 2.75]	2.53	0.10	[1.16 ; 3.16]	1.50	0.23	Symmetric
2	[2.57 ; 2.92]	2.68	0.11	[0.85 ; 2.11]	1.42	0.15	Antisymmetric
3	[3.33 ; 3.85]	3.51	0.17	[0.55 ; 3.00]	1.67	0.25	Symmetric
4	[3.92 ; 4.50]	4.12	0.19	[0.92 ; 1.82]	1.36	0.16	Antisymmetric
5	[4.78 ; 5.34]	4.99	0.18	[0.75 ; 2.66]	1.88	0.30	Symmetric
6	[5.32 ; 5.95]	5.58	0.16	[0.50 ; 2.29]	1.44	0.26	Antisymmetric

Table 2 Modal Parameters

However, the evolution of the modal parameters is easier to understand when graphically depicted. Therefore, the temporal evolution of the natural frequencies of the first six modes of vibration of the structure is characterized in Figure 9 – a), where each point corresponds to a 12-hour average. The small blank spaces correspond to periods of system failure or maintenance, for which no data is available. As 12-hour averages were calculated, two values are presented per day. This process leads to a visually clean figure without losing accuracy in the characterization of the modal parameters fluctuations, since modal parameters variations are quite slow in such massif structure.

At the same time, Figure 9 – b) shows the temporal evolution of the reservoir water level. Observing these two figures (Figure 9 a and b), it is possible to observe that the values of the natural frequencies of the structure have decreased considerably and continuously since the beginning of the monitoring. Moreover, this decrease accompanies the increase of the water level of the reservoir, thus suggesting an inverse proportionality between these two variables. This phenomenon is clearer observed during January 2016, when intense rains occurred, motivating the sudden rise in the reservoir water level and a sudden drop in the frequency values. Furthermore, it is interesting to observe the sensitivity of the natural frequencies to the relatively low variations of the water level occurred between February and May, thus, confirming the accuracy achieved in the natural frequencies estimates.

These experimental results obtained during the first filling of a dam reservoir are quite unique and very relevant for the tuning of numerical models that consider the influence of the water level in the dynamic behaviour of dams.

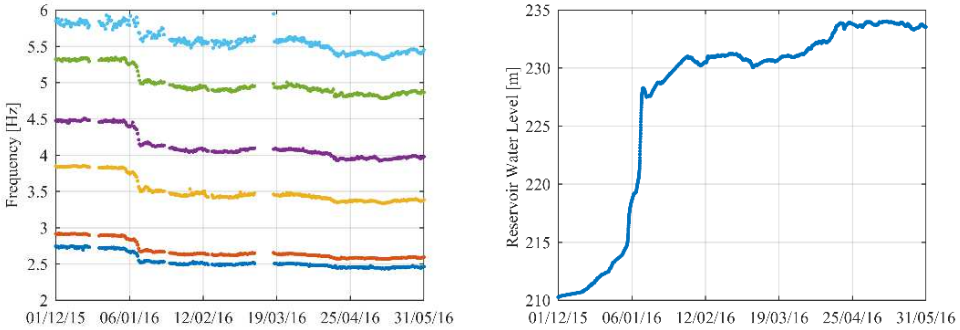


Figure 9: a) Time evolution of natural frequencies 12-hour average; b) Time evolution of reservoir water level.

5 CONCLUSIONS

Baixo Sabor dam is the second highest dam in Portugal, its reservoir is the second in volume and its monitoring system is one of the most complexes implemented in Portugal, combining traditional measurements instruments with the most advanced technologies applied in this field. A monitoring campaign involves more than 900 reading in different measurement instruments, not considering the geodesic observation related to precise traversing and leveling, emphasizing the existence of redundant systems in the displacements observation.

The results obtained during the first filling of a dam reservoir are quite unique and very relevant for the tuning of numerical models that take into account the influence of the water level in the dynamic behaviour of dams.

The analysis performed since the beginning of the first filling reveals that almost all the instruments are working correctly, allowing for the analysis and interpretation of the monitoring results and assuring the safe and adequate structural behavior of the dam for static and dynamic actions.

Acknowledgements

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REFERENCES

[1] *RSB - Regulamento de Segurança de Barragens 2007* (*in Portuguese*). Decreto-Lei n.º 344/2007 de 15 de Outubro de 2007. Diário da República 1ª. Série–Nº 198, Portugal (2007).

[2] *NOIB - Normas de Observação e Inspecção de Barragens 1993 (in Portuguese*). Portaria 847/93 de 10 de Setembro de 1993. Diário da República, I Série–B–Nº 213. Portugal (1993).

[3] EDPP, *Aproveitamento Hidroeléctrico do Baixo Sabor. Projecto. Memória geral e Apêndices. Volume II – Apêndices do Escalão de Montante. Tomo 6 - Plano de Observação*. Dezembro de 2005 (*in Portuguese*). Porto, Portugal (2005).

[4] LNEC, *Barragem de montante do aproveitamento hidroelétrico do Baixo Sabor. Instalação de células de fluência e ensaios nas primeiras idades (in Portuguese).* Proc. 0403/121/17076. Relatório 311/2014 – DBB/NO, Lisbon, Portugal (2014).

[5] *João G. CUNHA, Juan T. MATA, Gonzalo L. Ortiz. Structural safety control of the Baixo Sabor dam based on an automated data acquisition system. ICOLD Vienna 2018*

[6] LNEC, FEUP, and Ambisig, *Upstream step dam of Baixo Sabor hydroelectric power plant. Characterization of the dam's dynamic behaviour through continuous monitoring. Installation Report*, (*in Portuguese*), Lisbon, Portugal (2015).

[7] LNEC, *Barragem do Baixo Sabor. Resultados preliminares da monitorização de deslocamentos com o GNSS (in Portuguese*). Proc. 0403/121/17076, 0404/121/1707602. Relatório 92/2017 – DBB/NGA. Lisbon, Portugal (2017).

[8] J. Piteira Gomes, A.L. Batista, J. Casaca, *Methodologie for spatial interpolation of continuum physical quantities in a finite domain based on discrete samples. Application to arch dams*. Third International Dam World Conference, Foz do Iguaçu, Brasil (2018).

[9] J. Piteira Gomes, A.L. Batista, D. Silva Matos, *Analysis and interpretation of the Baixo Sabor Dam's behaviour during the first filling of the reservoir*. Symposium of the 26th ICOLD World Congress, Vienna, Austria (2018).

[10] Magalhães, F., Amador, S., Cunha, A. and Caetano, E., *Dynamo - software for vibration based Structural Health Monitoring*, 6th Int. Conf. on Bridge Maintenance, Safety and Management, IABMAS 2012, Vila Erba, Lake Como, Italy, (2012).

[11] Magalhães, F. and Cunha, A., *Explaining Operational Modal Analysis with data from an arch bridge*, Mechanical Systems and Signal Processing, Invited Tutorial Paper, Volume 25, Issue 5, pp. 1431-1450, (2011).

[12] Magalhães, F., Cunha, A. and Caetano, E., *Online automatic identification of the modal parameters of a long span arch bridge*, Mechanical Systems and Signal Processing, Vol.23, Issue 2, pp. 316-329, (2009).