

## Seismic Monitoring System of Baixo Sabor and Feiticeiro Dams

Gilberto Silva Monteiro <sup>a\*</sup>, Jorge Pacheco Neves <sup>a</sup>, Jorge Pereira Gomes <sup>b</sup>

<sup>a</sup> EDP, Gestão da Produção de Energia S.A., R. Ofélia Diogo Costa n° 39, 4149-022 Porto, Portugal.

<sup>b</sup> LNEC, Laboratório Nacional de Engenharia Civil, Avenida do Brasil, 101, 1700-066 Lisboa, Portugal.

Received 29 November 2019; Accepted 03 October 2020

### Abstract

In the last decade Portugal made a significant set of investments in new hydroelectric projects. According the Portuguese Dam Safety Regulation and Supporting Technical Documents, and the seismic risk for the regions where the dams were built, several seismic monitoring systems were implemented. One of the most important projects was the Baixo Sabor hydroelectric scheme which includes two large dams, namely the Baixo Sabor and Feiticeiro dams. These dams are located at northeast of Portugal and are very close to a major geological fault that crosses the Portuguese territory. Considering the seismic risk of the dam's construction area, a seismic monitoring system was provided. That system incorporates stations in the dam's galleries and remote stations along the reservoirs to detect eventual induced reservoir seismicity. This system has been in continuous operation and the data of the recorded earthquakes records has been analyzed and processed. This paper presents some aspects of the Portuguese legislation, refers the main studies that were used, presents a brief description of the regional Baixo Sabor geological and tectonic settings, describes the main features of the seismic monitoring system and presents some of the main results obtained during the first period of operation of the dams.

*Keywords:* Dam; Safety Regulation; Risk; Seismic Monitoring System; Dynamic Behaviour.

### 1. Introduction

The Baixo Sabor Hydropower Scheme is situated in the north-eastern of Portugal in the lower part of the Sabor river, that is a tributary of the right bank of the Douro river (Figure 1). This global area has a moderate seismic risk, but the presence of the Vilarica fault near the scheme had to be considered. So, an exhaustive seismological study was developed in order to predict the characteristics of the seismic actions. These actions were considered in the dam's design to assure adequate safety conditions.

According to the current Portuguese legislation and considering the seismic risk of the dam's construction area, a Seismic Monitoring System (SMS) was provided, incorporating instrumentation to characterize the seismic action induced in the dams and the corresponding structural response. In this context, and for all new large dams, the implementation of an SMS is mandatory. In their most extensive configuration, these systems may incorporate remote stations along the reservoir for studying the propagation of seismic actions and to evaluate the induced reservoir seismicity.

The hydropower scheme of Baixo Sabor is composed of two dams, namely the upstream Baixo Sabor dam and the downstream Feiticeiro dam (Figure 2), located about 12.6 km and 3.3 km far from the confluence of the Sabor with the Douro River, respectively. Reversible units were installed in the powerhouses associated to each dam to enable the

\* Corresponding author: [gilberto.monteiro@edp.com](mailto:gilberto.monteiro@edp.com)

 <http://dx.doi.org/10.28991/cej-2020-03091603>



© 2020 by the authors. Licensee C.E.J, Tehran, Iran. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC-BY) license (<http://creativecommons.org/licenses/by/4.0/>).

water pumping from the upper zone of the Douro River to the large reservoir of the upstream dam. Both dams were studied and designed by EDP Produção.



**Figure 1. Location Baixo Sabor and Feiticeiro dam's in the Iberian Peninsula**

The Baixo Sabor arch dam is a 123 m high structure, with a total crest length of 505 m and a total concrete volume of 670 000 m<sup>3</sup>. For the full storage water level located at elevation (234.0), the reservoir capacity is of 1 095 million cubic meters. A controlled surface spillway is located at the central part of the dam crest with a discharge capacity of 5 000 m<sup>3</sup>/s, including four spans controlled by radial gates and provided of a downstream plunge pool. The underground power house, located in the right bank, has two reversible units of 81 MW each.



**Figure 2. Views of Baixo Sabor and Feiticeiro dams**

The Feiticeiro dam is a concrete gravity structure, with a rectilinear layout, a maximum height of 45 m, and a total crest length of 315m. The controlled spillway is located in the central part of the dam also designed for a maximum flood of 5 000 m<sup>3</sup>/s. It is provided of four spans controlled by radial gates and a downstream roller bucket for the water energy dissipation. Two independent tunnels connect the reservoir to the two reversible power units which, are installed into two shafts situated in the right bank, downstream the dam. The reservoir has a capacity of 30 million cubic meters of for the full storage level located at elevation 138 m.

For continuous dynamic monitoring behaviour of the two dams, when subjected to seismic action, a Seismic Monitoring System (SMS) was installed in the Baixo Sabor Scheme. This system has been developed as an active system, operating permanently and guaranteeing the recording of the dams and their soundings vibrations when earthquakes occur.

Characterization of the dynamic response is essential for structures located in seismic regions. Furthermore, the monitoring of the dynamic behaviour of concrete arch dams is increasingly viewed as an important component of safety assessment procedures to envisaging the risk associated to the prediction of dam's behaviour. The evolution of the dynamic characteristics may also help to detect the initiation or the development of damage phenomena throughout the structure lifetime. Ambient vibration monitoring is nowadays often used for these purposes. In this context, a

continuous dynamic monitoring system was also installed in the Baixo Sabor dam with sophisticated automatic tools based on operational modal analysis to continuously evaluate the dynamic parameters of the dam along the time.

This article is structured in a set of points where they are presented the geological and tectonic settings of Baixo Sabor site, the seismic studies and design scenarios adopted, the description of the seismic monitoring system, the first results obtained during the first period of operation of Baixo Sabor dam and finally the main conclusions.

## 2. Geological and Tectonic Setting

The Baixo Sabor and Feiticeiro dams are located in the northeast of Portugal in a region that is dominated by the important geological Vilarica fault (Figures 3 and 4), which is located 6.5 km and 0.5 km, in a straight line, to the west of the Baixo Sabor (BSD) and Feiticeiro dam (FD) sites, respectively. It is a late Hercynian NNE-SSW strike slip fault, with an accumulated horizontal sinistral displacement of approximately 6.5 km and a length of more than 200 km, extending from Sanabria region (Spain) to Serra da Estrela region, in the center of Portugal.

This fault was reactivated several times since the end of the Hercynian orogeny and presently is classified as active [1]. A distensive phase, with a vertical component of movement developed in the secondary subparallel faults, initiated in the Miocenic, and contributed to the formation of an *en echelon* graben [2] with an elevation difference of more than 300 m between the upper and the lower blocks, preserving the Quaternary torrential piedmont deposits (*rañas*) and the posterior fluvial deposits inside this tectonic basin.

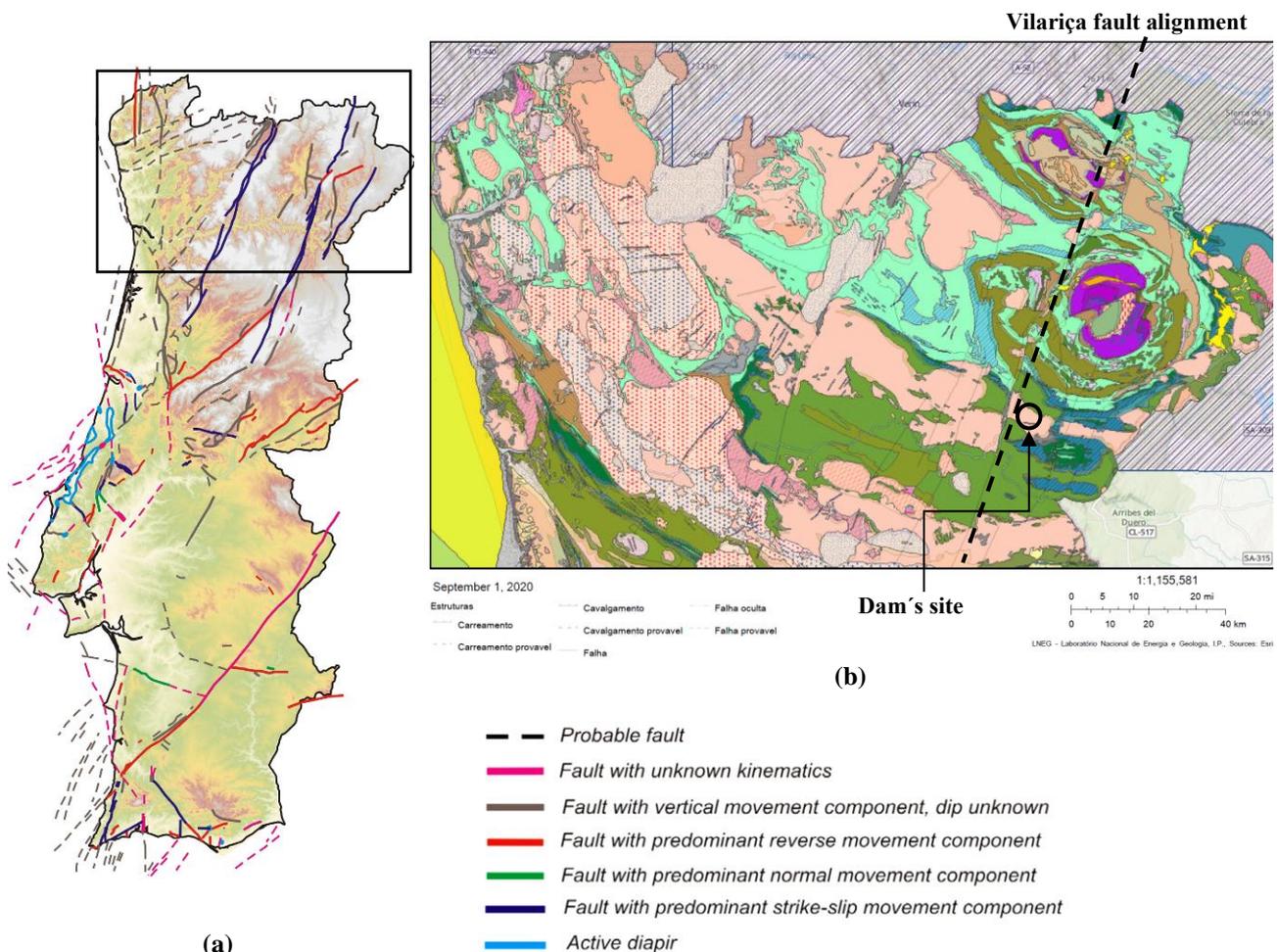
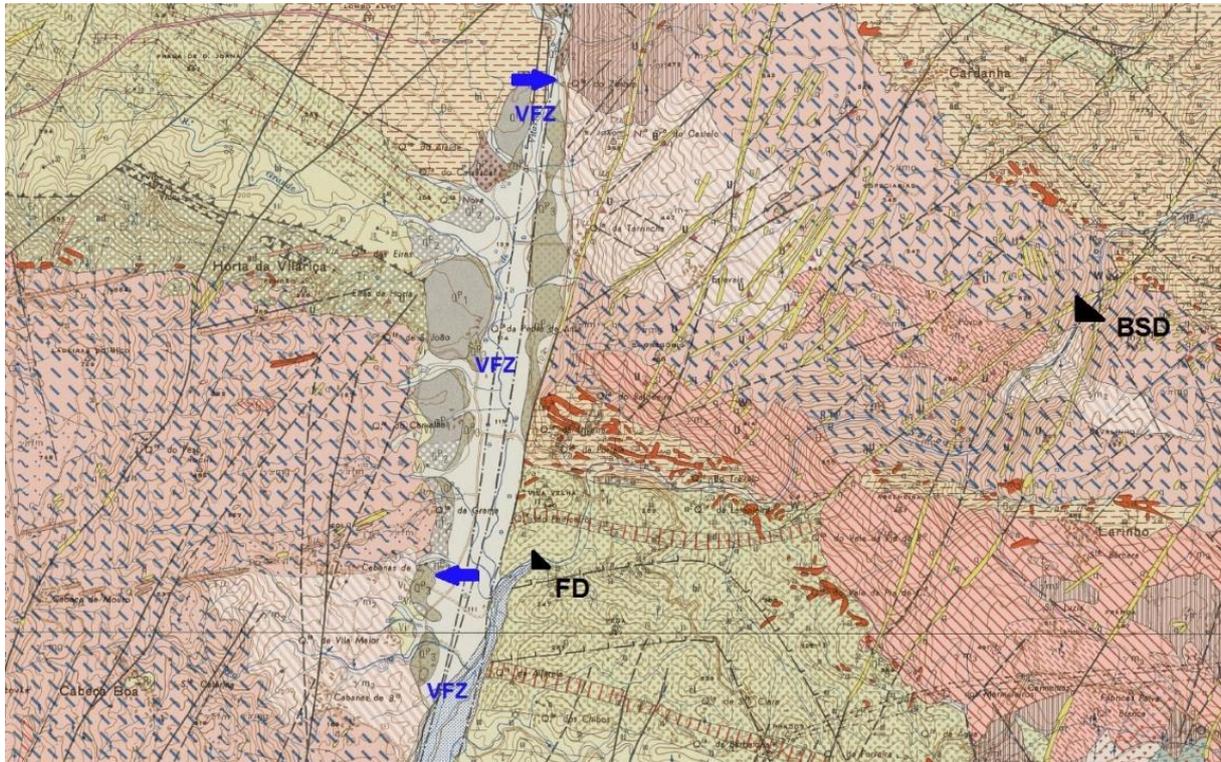


Figure 3. Localization of the main Portuguese geological faults (a) [3] and Northern Portugal geological map (b) [4]

The Baixo Sabor dam is located in a 1 km long, NE-SW orientated valley segment (Figure 4), with a deep, narrow and slightly asymmetrical transversal profile, 25 m wide at the base and 440 m at the crest level. The dam is founded in a granitic rock mass that intruded the phyllite-greywacke metasediments of the Douro-Beiras Group during the 3<sup>rd</sup> phase of the Hercynian orogeny, approximately 300 m.yr. ago (K/Ar dating) [2]. From a petrographic point of view, this rock corresponds to a medium to coarse grained, biotitic-muscovitic, porphyroid granite.

The oldest rocks in this region originated from a thick Cambrian turbiditic sequence of marine sandy-argillaceous sediments (greenish background colors in Figure 4) that were deformed during the Caledonian orogeny (~490-390

m.yr.) by epyrogenic movements and a compression phase with formation of large open folds and NW-SE to WNW-ESE sin-sedimentary thrust faults. The posterior Ordovician sandy-quartzitic and argillaceous sediments were deposited during this orogeny in costal to distal marine and, in some cases, euxinic environments [2].



**Figure 4. Baixo Sabor dam geological setting (adapted from [2]); BSD – Baixo Sabor dam; FD – Feiteiceiro dam; VFZ – Vilarica fault zone (the space between arrows corresponds to the horizontal accumulated displacement)**

During the Hercynian orogeny (~370-270 m.yr.) these lithologies were intensely folded, metamorphized and intruded by large granitic batholiths (pinkish background colors in Figure 4). There were 3 Hercynian deformation phases, the 1<sup>st</sup> one being the responsible for the main NW-SE mega and meso-scale folds with formation of an axial plane schistosity. The 2<sup>nd</sup> phase originated overthrust and thrust faults and a crenulation (microfolds) cleavage [2].

Several granitic batholiths were implanted during and immediately after the 3<sup>rd</sup> phase of this orogeny. Isoclinal folds and an axial plane schistosity were also formed, transposing the 1<sup>st</sup> phase schistose cleavage.

A brittle fracture regime was established in final Hercynian times and later, with formation of large NNE-SSE to NE-SW sinistral strike-slip faults and 2<sup>nd</sup> order WSW-ESE dextral conjugated faults. Many of these faults were intruded by thick quartz or aplitic-pegmatitic veins and sometimes micro-gabbros, during the post-tectonic distensive phase.

The region where the Baixo Sabor Hydropower Scheme is located presents diffuse seismicity of moderate to low intensity, which is characteristic of an intra-plate zone.

The proximity of the Vilarica fault zone to the Baixo Sabor and Feiteiceiro dams led to the development of a geomorphologic and paleoseismological study [2] during the design phase. This study included the detailed mapping geological (Figure 5) of trenches located on the Vilarica fault trace, sediment sampling and dating using Optical Stimulated Luminescence technics and allowed the estimation of a slip rate of 0.2-0.3 mm/yr. The long return period (~9000 years) obtained for the Maximum Credible Earthquake (MCE) on Vilarica fault, with an estimated magnitude of 7.25, reflects the above mentioned intraplate seismotectonic setting of this region.

The most striking feature visible in Figure 5 is the one related with the fault N15°E, 85°SE, that puts in contact the Cambrian phyllites (Pi) and the Quaternary alluvium (Qoa) and, also affects the Quaternary colluvium (Col2), proving the activity of the Vilarica fault in this geological period (< 1.6 m.yr.).

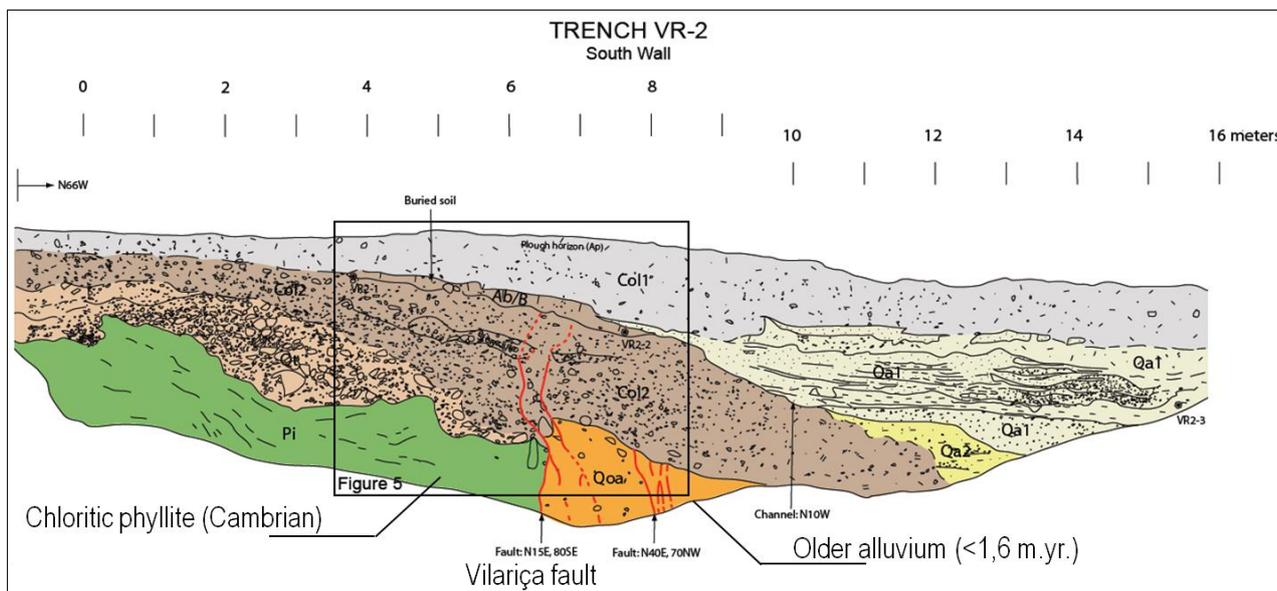


Figure 5. Detailed geological mapping of the south wall of trench VR2 (adapted from [5]); Pi – Chloritic phyllite (Cambrian); Qoa – Older alluvium; Qt – river terrace; Col2 – Older colluvium; Qa2 – Intermediate alluvium; Qa1 – Younger alluvium; Col1 – Younger colluvium.

Other nearby faults also considered active in Cabral and Ribeiro (1988) study [1], are the Ribeira de Zacarias fault, a 20 km long, N-S reverse fault that crosses the dam reservoir approximately 8.5 km upstream and a 4 km long, NNE-SSW fault, near the village of Felgar.

The current Alpine orogeny, with a NW-SE to NNW-SSE maximum compressive stress orientation [6] in the NE region of Portugal, is the responsible for stress accumulation and the reactivation of ancient faults like the Vilarica and other faults, that have implications in the Baixo Sabor area seismicity. So, considering the tectonic setting in the Baixo Sabor area, the dam height (123 m) and the reservoir dimensions, the tectonic and the reservoir induced seismicity had to be monitored. The selection of locations for the seismic monitoring remote stations (Table 1 and Figure 6) was performed during the design phase, taking into account this seismotectonic framework.

Table 1. Remote seismic monitoring stations

Remote Station		Foundation	Nearby fault
Designation	Localization		
SR 1	Adeganha	Coarse grained granite (W3-4)	Vilarica
SR 2	Felgar	Coarse grained granite (W3)	Felgar
SR 3	Meirinhos	Phyllite (W3)	Ribeira de Zacarias
SR 4	Sendim	Greenish phyllite (W3-4)	Ribeira de Zacarias
SR 5	Baixo Sabor dam	Fine to medium grained granite (W4)	Vilarica
SR 6	Feiteiro dam	Greyish phyllite (W3)	Vilarica

In the construction phase, these locations were slightly adjusted, also considering the foundation geotechnical characteristics.

### 3. Seismic Studies and Design Scenarios

According to Portuguese Dams Safety Regulations (PDSR) [7] and to the Technical Documents Support for Portuguese Dam Safety Regulations (TDS\_PDSR) [8], two types of scenarios must be considered when checking the dam structural safety, namely the exploitation and the failure scenarios.

For the most frequent scenarios that can occur to be considered in the exploitation scenarios, the dam must be able to support these actions without, or with minor damages. On the other hand, the failure scenarios deal with extreme actions that can cause important damages to the dam, and failure scenarios like ruptures in the dam foundation or in the dam structure must be considered. For failure scenarios, overall dam stability must be assured, and uncontrolled reservoir water release can't occur.

Earthquake loading, due to seismic activity is one of the important actions that have to be considered in the design of dams. In addition to a set of complete geological and geotechnical studies, seismic studies are essential to estimate

the dynamic loadings that can appear. For these issues, the statements of TDS\_PDDR are very similar to the ICOLD (International Commission on Large Dams) standards.

The seismic studies are based mainly in the local and regional geological settings, and in the area seismic history. In this context, the seismotectonic studies, which include the identification of the possible active faults, are a major issue.

In accordance with TDS\_PDDR, the seismic studies should define the seismic actions in terms of intensity, frequency content and duration of the seismic vibrations in the dam site. During the design phase, the following design earthquakes types were considered:

- The maximum credible earthquake (MCE), which must be evaluated using a deterministic procedure or a probabilistic approach, and should have a long return period;
- The maximum design earthquake (MDE), which for dams with high potential risk hazard should be considered as the MCE;
- The operating basis earthquake (OBE), less intense than the MDE, and with an assumed return period related to the involved estimated risks, and that is determined by probabilistic approaches.

According to ICOLD [9], the OBE is an earthquake with significant probability of occurrence during the dam life, and it only can cause minor damage in the dam. So, a 50% probability of not being exceeded in 100 years is usually adopted for OBE estimation. In this context, for dam design and for dam safety analysis, the OBE must be considered as an action included in the exploitation scenarios. In addition, a more severe earthquake with a return period of about 1000 years Base Design Earthquake (BDE) is also used to check structural dam behaviour in these scenarios.

The MDE must be estimated rather by deterministic procedures, considering local and regional seismotectonics conditions. Probabilistic approaches, considering long return periods, can also be applied for MDE estimation, and are often used for comparison purposes. So, the MDE should be considered a failure scenario, concerning dam design or structural safety assessment purposes.

In addition, Reservoir-Induced-Earthquake (RIE), that represents the ground motions capable of being triggered at the dam site by the presence of the reservoir, should be take into account, and so, the effects of faults susceptible to give rise to induced seismicity should be properly evaluated. Depending on the dam location and on seismotectonics conditions the RIE may represent motions less than, equal to, or greater than the OBE, but should in no case be greater than the MDE [9].

Given the importance and the potential risks associated to the Baixo Sabor dam, and in line with the adopted in the design of other EDP dams, a 50% probability of not being exceeded in 100 years was adopted for the Operating Basis Earthquake. According to the studies carried out [5] this seismic action has a peak ground acceleration of 0,084 g.

Relying on the same seismological study, which takes in account the importance of the Vilariça geologic fault near to the dam's, the peak ground acceleration of 0,522 g (corresponding to a return period of about 10 000 years) was estimated as maximum design earthquake (MDE). The seismological studies also gave information about intensity, frequency content and duration of the seismic vibrations loads that are probable to occur in the dam site, which have supported the dynamic dam behaviour analysis for this extreme scenario. The faults classified as active in the Neotectonic Map of Portugal [1] that cross the Baixo Sabor reservoir (Ribeira de Zacarias and Felgar faults) have a maximum length of approximately 20 km, thus it is estimated that these faults may not produce an induced earthquake with an acceleration greater than the OBE value at the dam site.

#### 4. Description of the Seismic Monitoring System

The structural response analysis requires a correct characterization of the seismic action induced to the dam, so, the SMS allows the characterization of the seismic action, but also its propagation along the rock mass from different directions and the characterization of the induced seismicity associated to the large reservoir. According to these objectives the SMS of the Baixo Sabor scheme was defined with the following composition layout (Figure 6):

*Baixo Sabor dam:*

- 1 Station placed near the Vilariça fault;
- 3 Stations located around the Baixo Sabor dam reservoir;
- 1 Station placed next to the Baixo Sabor dam (upstream the dam);
- 6 Stations installed inside the galleries of Baixo Sabor dam;

*Feiticeiro dam:*

- 1 Station next to the Feiticeiro dam;
- 2 Stations installed inside the galleries of Feiticeiro dam.

A computer unit was installed to manage the data transmission process and to collect, organize and process the data from all stations. Each station consists of a triaxial accelerometer (GeoSIG, Model: GMSplus, full scale:  $\pm 2g$ ) equipped with the associated equipment for data acquisition and data transmission to the central unit. All the stations have local memory for long term autonomous work. Since real time data transmission is not required, because the data segments of interest may be sent with some time delay. The 3G/GPRS service was considered adequate for the communication process with remote stations, while an Ethernet network with TCP/IP protocol was installed for connecting the central unit to the stations inside each dam.

Each station is permanently measuring and when an earthquake event occurs, identified by acceleration(s) higher than a pre-defined trigger value, a call to the central unit (alert) is issued and data is automatically stored in local memory, within an interval from a pre-event to a post-event time, at a given sampling frequency [10]. After receiving an alert, the central unit initiates a process of gathering the data stored in all stations sequentially.

If any remote station is temporarily unavailable, the central unit will contact it later, repeatedly. Whenever ordered by the central system, each data acquisition unit should be able to retrieve the registered data of specified intervals from pre-trigger to post-trigger limits. The time synchronization is essential to achieve the objectives of this system, because it is necessary that all stations are constantly collecting data in accurate and same instants of acquisition, with GPS time synchronization facility used for that purpose [11].

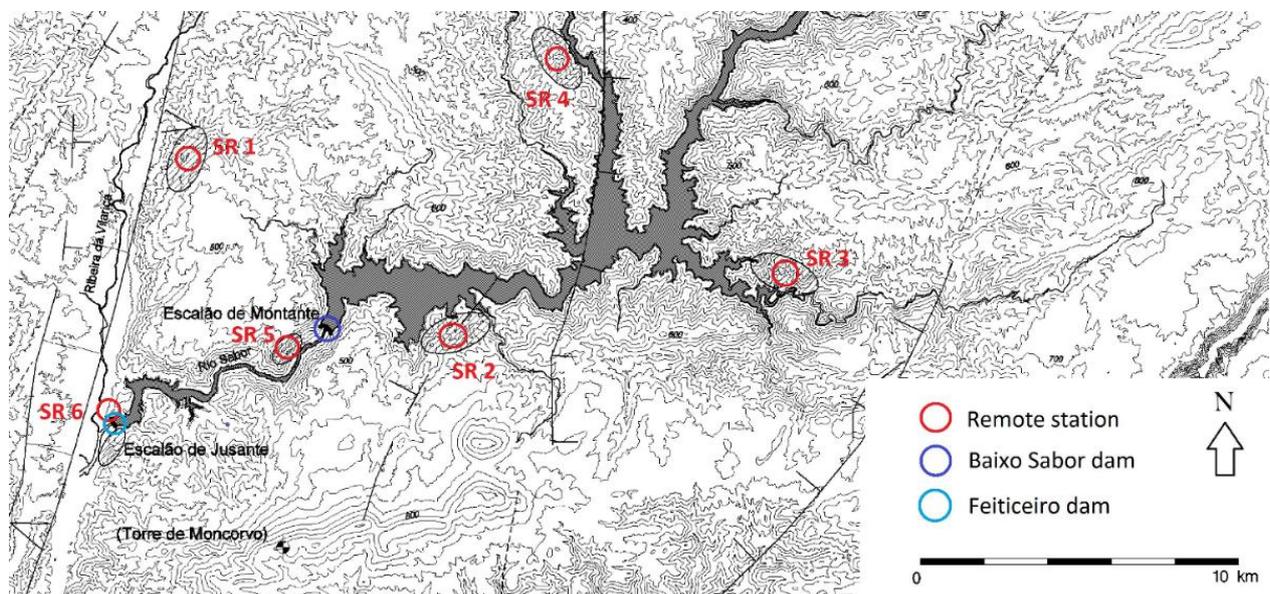


Figure 6. Location of remote stations on Baixo Sabor scheme

The remote stations are normally implanted in locals without mains power supply, so it is necessary to provide a system with a photovoltaic panel and accumulators for energy storage. The remote stations are implanted in a  $15 \times 5 \text{ m}^2$  area (Figure 7a). This area is protected with a metal net fence, and has two small masonry cabinets, for protection of equipment from aggressive environmental actions (solar radiation, wind, heat, rain, atmospheric discharges). One cabinet contains the measurement equipment and the other the components of power supply, data transmission and GPS time synchronization (Figures 7b and 6c). The proximity of masts or poles to the measurement units should be totally avoided in order to preserve measurements from artificially induced background noise.



(a)



Figure 7. Remote station of Baixo Sabor scheme: a) global view; b) inside view of one cabinet showing a seismometer installed on a concrete block; and c) a view of the other cabinet with a photovoltaic pannel on the rooftop and the location of accumulators.

In the Baixo Sabor dam, 6 remote stations were installed, consisting of triaxial accelerometers, distributed through the galleries of the dam. In the drainage gallery was installed a station in the bottom of the valley, and a station in the upper part of the left and right banks. Other 3 stations were installed in the galleries of the dam structure near the crest (Figure 8).

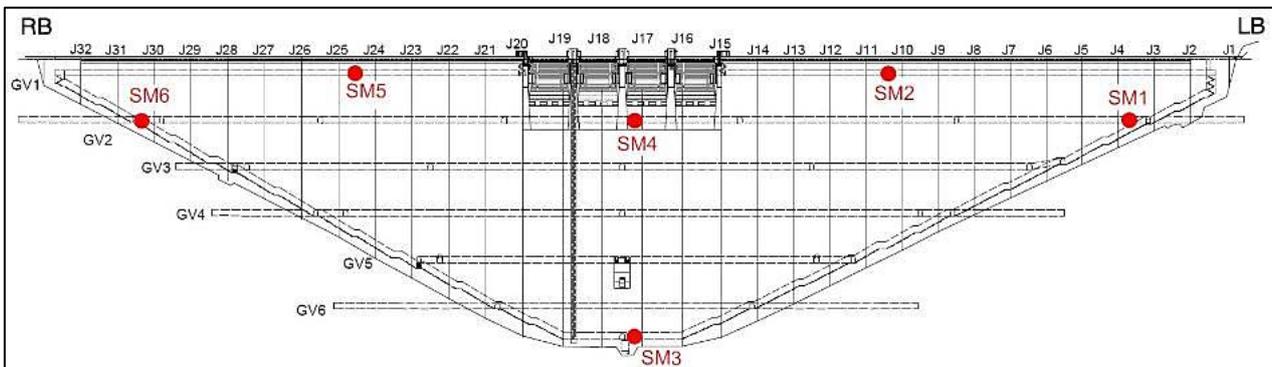


Figure 8. Location of the seismic stations inside Baixo Sabor dam

In the Feiticeiro dam two seismic stations were installed, one at the top and other at the foundation of the central block (Figure 9). Figure 10 presented a view of the seismic stations inside the dams.

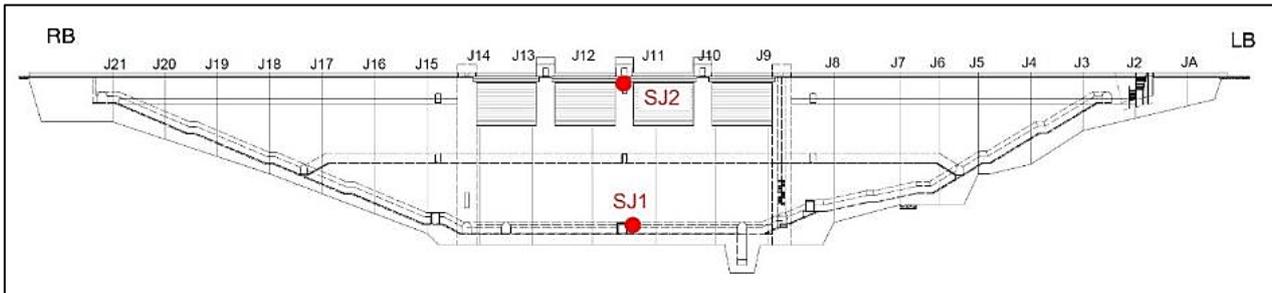


Figure 9. Location of the seismic stations in Feiticeiro dam



Figure 10. Seismic station in a dam gallery and operational center in Baixo Sabor power station

Figure 11 shows the general layout scheme of the entire seismic network.

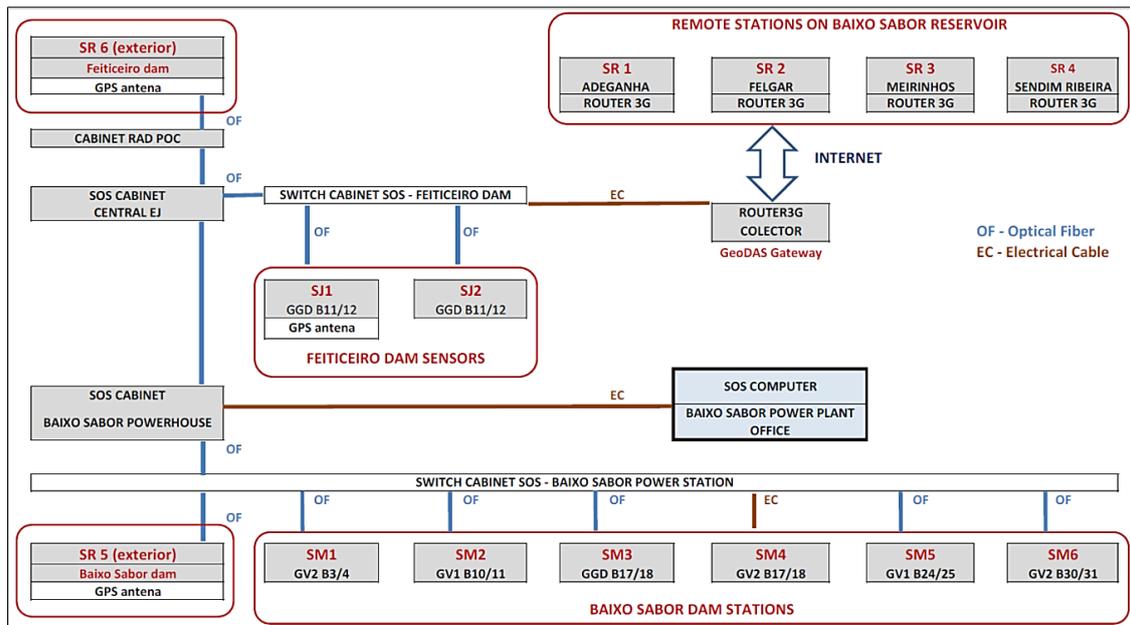


Figure 11. Baixo Sabor seismic monitoring system layout

The time series from the remote stations are used in the Seisan software to determine the event characteristics [12] and in the future these records will be integrated in the Portuguese seismic network. The installation of this system was finalized in June of 2017 and is now fully operational.

### 5. Main Results During the First Period of Operation of Baixo Sabor Dam

During the first months of operation the system registered three seismic events that are characterized in Figure 12 and Table 2. The maximum value record was 8.6 mg in the radial direction for the station SM5, located in the gallery GV1 in the right bank (Table 3). Figure 13 presents the records in radial direction for the event with the epicenter in Torre de Moncorvo, occurred in 2017/08/03 09:17. It is visible the amplification caused by the dam, of the accelerations recorded in the foundation when compared with the dynamic structural response in the crest.

With the seismic records of the six tridimensional points in the dam, the natural frequencies of the dam were calculated applying output only modal identification techniques. The length of these records is only about 60 s and the duration of the seismic event is near 5 seconds. This small duration may be a problem for the correct identification of the dynamic parameters, but it is compensated by the amplitude values of the accelerations. The values of the first 5 natural frequencies for the events occurred in Torre de Moncorvo are presented in the Table 4.

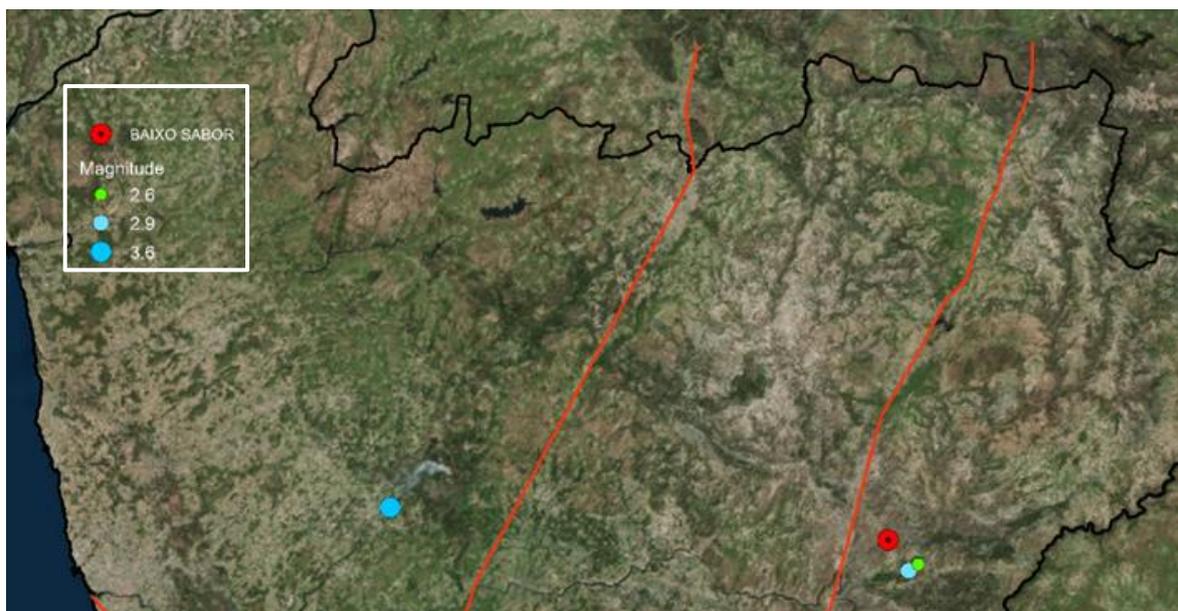


Figure 12. Seismic events registered with the SMS in relation to the principal Portuguese north faults

Table 2. Seismic event registered with the SMS

Date		Magnitude	Localization of the event	Distance to the Baixo Sabor dam
Day	Time			
2017/06/06	16:03	3.6	Amarante	≈ 115 km
2017/08/03	09:17	2.9	Torre de Moncorvo	≈ 8 km
2017/08/03	14:57	2.6	Torre de Moncorvo	≈ 10 km

Table 3. Maximus values of accelerations registered in the SMS (mg) in the Baixo Sabor dam stations

Stations	Events date			
	2017/06/06 16:03	2017/08/03 09:17	2017/08/03 14:57	
Dam	SM2r	2.72	7.51	5.35
	SM2t	1.61	4.36	2.64
	SM2z	0.76	5.77	2.48
	SM4r	1.66	3.79	3.33
	SM4t	1.15	4.20	2.61
	SM4z	1.22	4.37	2.80
	SM5r	3.08	8.60	6.01
	SM5t	1.12	8.14	6.01
	SM5z	0.99	5.69	3.58
Foundation	SM1r	0.38	4.74	2.86
	SM1t	0.79	2.85	1.93
	SM1z	0.52	2.84	1.88
	SM3r	0.66	6.42	3.15
	SM3t	0.69	2.83	1.87
	SM3z	0.50	2.69	1.48
	SM6r	0.61	3.04	1.50
	SM6t	0.62	5.12	3.70
	SM6z	0.52	3.04	2.20

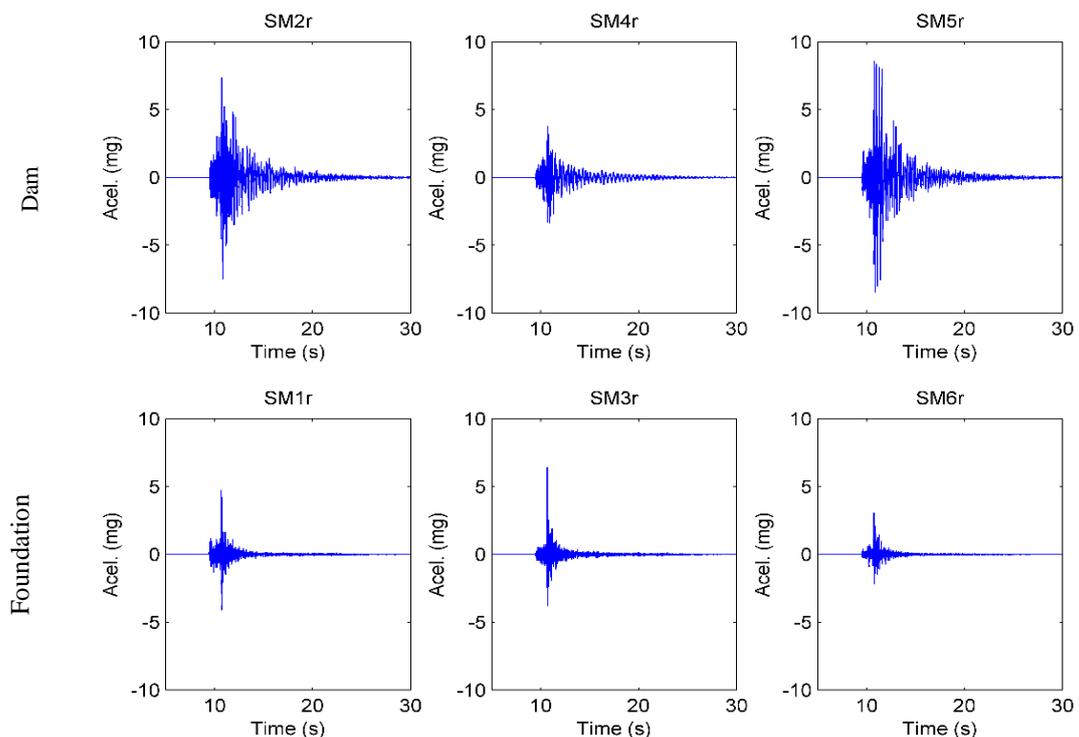


Figure 13. Radial seismic records (acceleration) in the Baixo Sabor dam for the event of 2017/08/03 09:17

**Table 4. Dynamic parameters calculated for the two Torre de Moncorvo events by modal identification (SSI)**

Mode	Mode type	Events			
		2017/08/03 09:17		2017/08/03 14:57	
		Freq (Hz)	$\xi$ (%)	Freq (Hz)	$\xi$ (%)
1	Symmetric	2.54	1.32	2.55	0.96
2	Antisymmetric	2.66	0.77	2.67	0.99
3	Symmetric	3.48	1.70	3.50	1.79
4	Antisymmetric	4.10	2.06	4.11	1.34
5	Symmetric	4.95	2.50	4.94	2.01

To ensure a good characterization of the dynamic behavior of the Baixo Sabor dam a continuous dynamic monitoring system (CMDS) was installed. 20 uniaxial accelerometers were radially installed along the three upper galleries of the dam. 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 fiber and the synchronization of the data recorded by each digitizer is assured with GPS antennas.

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 [13].

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 [14].

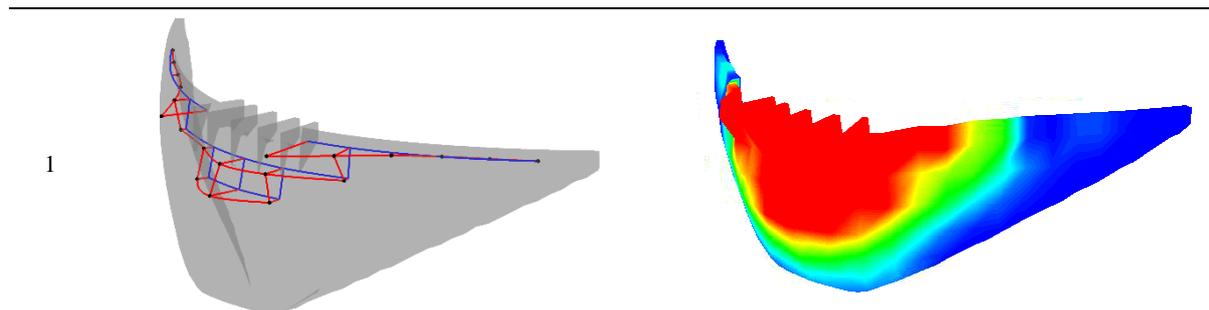
Estimations of the modal parameters by the CDMS system for the first five modes are resumed in Table 5, where minimum, maximum, mean, and standard deviation frequencies and damping values are presented. Notice the significant difference between minimum and maximum frequencies for each vibration mode, even after the elimination of outliers, which is reflected in the standard deviation values as well, indicating significant oscillations during the evaluation period. Additionally, the damping values present slightly higher mean values for the symmetric modes.

**Table 5. Modal Parameters obtained by SMC for Baixo Sabor dam**

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

The first six months of data were processed, and the first 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 14. The first, third and fifth modes are approximately symmetric and the second and fourth are antisymmetric.

These results are consistent in the results obtained by the seismic monitoring system and by the continuous dynamic monitoring system are reliable [15, 16].



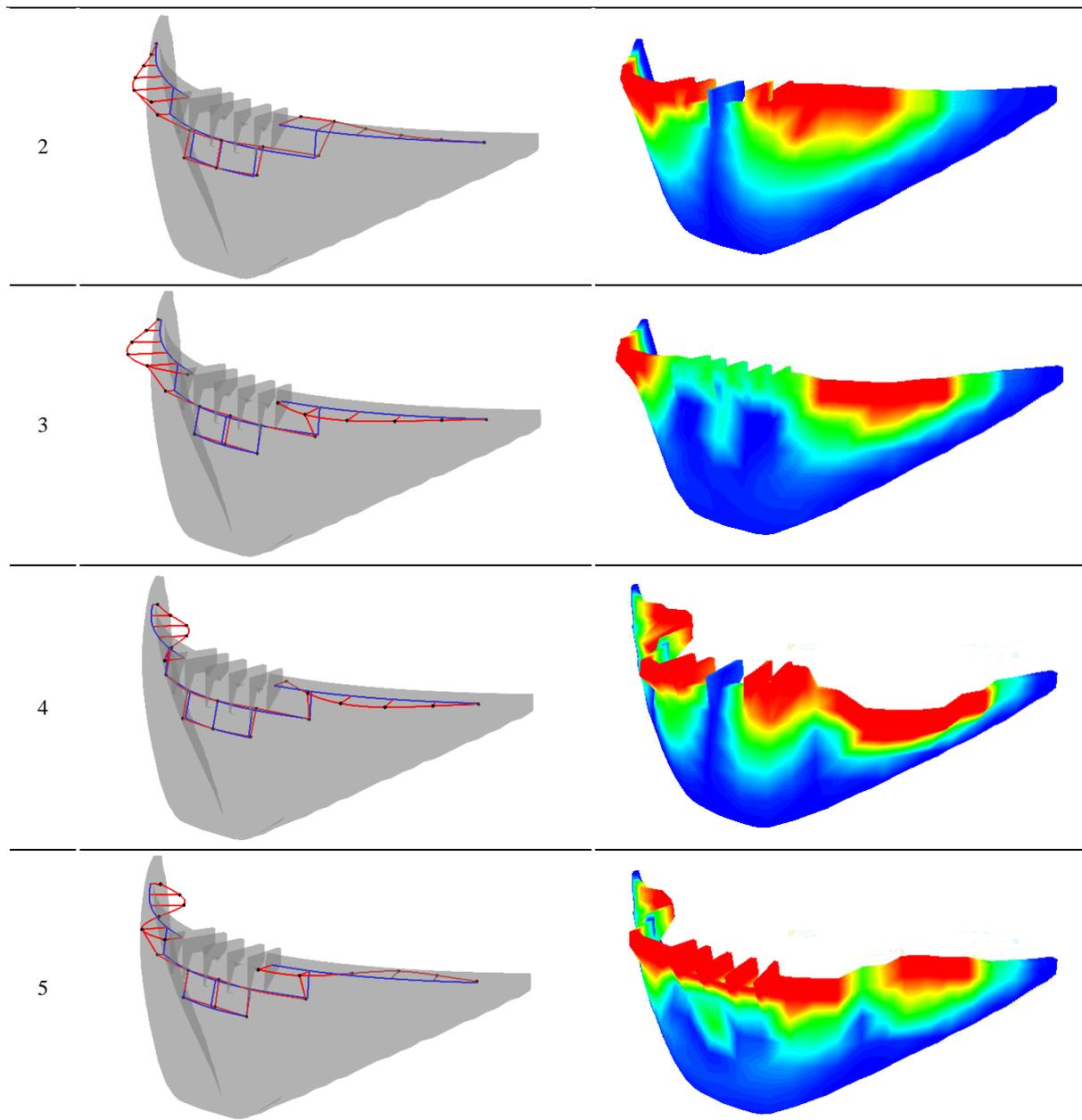


Figure 14. Modal configuration of the first five modes of Baixo Sabor arch dam [17]

## 6. Conclusion

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 dynamic monitoring.

Both dynamic monitoring systems installed in the Baixo Sabor Hydroelectrical Scheme, SMS and CDMS, are operational and integrate automatic procedures that make them fully autonomous, providing useful outputs for the safety control of these important structures. The features implemented in both systems revealed excellent efficiency and demonstrated a perfect suitability. The results showed an expected and direct relation with the variation of seismic and dynamic loads.

The results of the observation systems are being compared with the ones obtained with numerical models that were calibrated with the results provided by the forced vibration tests that were performed in the dam, both for empty and full reservoir situations [18-21].

These systems proved already to be extremely useful to evaluate the behavior of these structures during seismic events and to provide relevant information for the development of numerical models including new behavior models. So, they demonstrate to be a very important tool concerning dam safety control and seismic risk management.

## 7. Funding

LNEC and FEUP work was partially supported by: PTDC/ECM-EST/0805/2014|16761 – DAM\_AGE - Advanced Online Dynamic Structural Health Monitoring of Concrete Dams, funded by FEDER funds through COMPETE2020 - Programa Operacional Competitividade e Internacionalização (POCI) – and by national funds through FCT - Fundação para a Ciência e a Tecnologia.

## 8. Conflicts of Interest

The authors declare no conflict of interest.

## 9. References

- [1] Cabral, J. and Ribeiro, A. “Neotectonic map of Portugal. Scale 1:1000000, Portugal Geological Services”. Lisboa, Portugal, 1988.
- [2] Ferreira da Silva, A., Rebelo, J.A. and Ribeiro, M.L. “Geological map of Portugal on the scale 1/50000”. Sheet 11-C (Torre de Moncorvo), Lisboa, Portugal, 1989.
- [3] Cabral, J. “Neotectonics of Mainland Portugal: State of the Art and Future Perspectives.” *Journal of Iberian Geology* 38, no. 1 (September 7, 2012). doi:10.5209/rev\_jige.2012.v38.n1.39206.
- [4] LNEG. “Laboratório Nacional de Energia e Geologia”, Available Online: <https://geoportal.lneg.pt/mapa/> (Accessed on 27 May 2020).
- [5] EDP. “Hydroelectric Power Scheme of Baixo Sabor”. Project, (in Portuguese), 2005.
- [6] Heidbach, Oliver; Custodio, Susana; Kingdon, Andrew; Mariucci, Maria Theresa; Montone, Paola; Müller, Birgit; Pierdominici, Simona; Rajabi, Mojtaba; Reinecker, John; Reiter, Karsten; Tingay, Mark; Williams, John; Ziegler, Moritz (2016): “Stress Map of the Mediterranean and Central Europe 2016”. GFZ Data Services. doi:10.5880/WSM.Europe2016.
- [7] PDSR. “Portuguese Dam Safety Regulation”, (in Portuguese), 2018.
- [8] TDS\_PDSR “Technical Documents Support for Portuguese Dam Safety Regulation”, 2018.
- [9] ICOLD. International Commission on Large Dams, “Bulletin 72: Selecting seismic parameters for large dams, Guidelines”, 1989.
- [10] GEOSIG. “GMS Measuring System: Features, Applications”, Electronics manufacturer in Schlieren, Switzerland (2012).
- [11] GEOSIG. “GMS – GPS Receiver”, Electronics manufacturer in Schlieren, Switzerland (2012).
- [12] Havskov and Ottemoller, SEISAN “Earthquake analysis software”, *Seis. Res. Lett.*, 70, 2012. Available Online: [http://www.seismosoc.org/publications/SRL/SRL\\_70/srl\\_70-5\\_es.html](http://www.seismosoc.org/publications/SRL/SRL_70/srl_70-5_es.html) (Accessed on 23 April 2020).
- [13] 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”, 2015.
- [14] Magalhães, F, S Amador, Á Cunha, and E Caetano. “DynaMo - Software for Vibration Based Structural Health Monitoring.” *Bridge Maintenance, Safety and Management* (June 21, 2012): 2160–2167. doi:10.1201/b12352-322.
- [15] LNEC, FEUP “Baixo Sabor dam. Characterization of the dynamic behavior of the dam by continuous monitoring from 2016 to 2019”, (Jul 2020).
- [16] Pereira, Sérgio, Filipe Magalhães, Jorge P. Gomes, Álvaro Cunha, and José V. Lemos. “Dynamic Monitoring of a Concrete Arch Dam during the First Filling of the Reservoir.” *Engineering Structures* 174 (November 2018): 548–560. doi:10.1016/j.engstruct.2018.07.076.
- [17] LNEC. “Baixo Sabor dam. Characterization of the dynamic behavior of the dam through the continuous monitoring system. Analysis of results between December 2015 and May 2017”. Report 331/2017. Lisbon, (October 2017).
- [18] LNEC, “Upstream dam of the Baixo Sabor hydroelectric scheme. Characterization of the dynamic behavior by performing a forced vibration test in January 2015”, Lisboa, 2016.
- [19] Gomes, J.P.; Lemos, J.V. “Characterization of the dynamic behavior of an arch dam by means of forced vibration tests”. 1st meeting of the EWG “Dams and Earthquakes”, Saint-Malo, France, (September 2016).
- [20] LNEC. “Baixo Sabor dam. Characterization of the dynamic behaviour by performing forced vibration tests in May 2016, with the reservoir water at 234,0 m elevation”, Lisboa, 2017.
- [21] Gomes, Jorge P., and José V. Lemos. “Characterization of the Dynamic Behavior of a Concrete Arch Dam by Means of Forced Vibration Tests and Numerical Models.” *Earthquake Engineering & Structural Dynamics* 49, no. 7 (February 3, 2020): 679–694. doi:10.1002/eqe.3259.

- [22] Wieland, M. "Features of Seismic Hazard in Large Dam Projects and Strong Motion Monitoring of Large Dams." *Frontiers of Architecture and Civil Engineering in China* 4, no. 1 (December 16, 2009): 56–64. doi:10.1007/s11709-010-0005-6.
- [23] ICOLD. International Commission on Large Dams, "Bulletin 46. Seismicity and dam design", 1983.
- [24] ICOLD. International Commission on Large Dams, "Bulletin 52. Earthquake analysis for dams", 1986.
- [25] ICOLD. International Commission on Large Dams, "Bulletin 137. Reservoirs and seismicity - State of knowledge", 2011.
- [26] SPANCOLD. "Technical guides on dam safety. Technical guide on operation of dams and reservoirs. Volume 1. Risk analysis applied to management of dam safety", 2012.
- [27] ICOLD. International Commission on Large Dams, "Bulletin 155. Guidelines for use of numerical models in dam engineering", 2013.
- [28] ICOLD. International Commission on Large Dams, "Bulletin 148. Selecting seismic parameters for large dams – Guidelines. Revision of Bulletin 72", 2016.
- [29] ICOLD. International Commission on Large Dams, "Bulletin 166 - Inspection of dams following earthquake – Guidelines. Revision of Bulletin 062A", 2016.
- [30] ICOLD. International Commission on Large Dams, "Bulletin 158. Dam surveillance guide", 2018.