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Dynamic monitoring of a concrete arch dam during the first filling of the reservoir

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ABSTRACT

The Baixo Sabor dam is a concrete double-curvature arch dam, 123 m high, located in the north-east of Portugal, which is being monitored by a dynamic monitoring system that comprises 20 uniaxial accelerometers. The paper starts with the description of the structure and of the installed monitoring equipment, as well as the monitoring software used to process the data that is continuously retrieved from site through an internet connection. Then, the results obtained during the system's first six months of operation are presented, which include the characterization of acceleration levels for major events, such as the opening of spillway gates after intense rain, and the evolution of the dam modal properties (natural frequencies, modal damping ratios and mode shapes) during the reservoir first filling. In particular, the continuous characterization of the dam modal properties during important variations of the water level is a very unique experimental result (up to the authors knowledge, this is the first journal paper describing the continuous tracking of the modal parameters of a dam during its first filling), which is particularly interesting for the calibration of numerical models that take into account water-structure interaction. Additionally, it should be noted that the accurate tracking of the modal properties, in quite demanding conditions motivated by the very low vibration levels, associated to the massive nature of the structure, and by the presence of harmonics induced by the turbines of the hydroelectric power plant, was only possible thanks to the use of a carefully designed installation and advanced processing methodologies. At the end of the paper, it is presented a comparison between the results estimated with ambient excitation and the ones obtained with a forced vibration test and also predicted by a numerical model that includes the water effect with the added mass technique.

1. Introduction

In order to confidently maintain large civil infrastructures, such as dams, with high levels of performance and safety, decisions should be supported by integrated monitoring systems considering real continuous data, directly obtained from the structures. The Portuguese regulations for dams safety [1] actually imposes the implementation of equipment to characterize seismic actions and the performance of in situ dynamic tests in structures with high risks (class I).

Health monitoring systems are historically associated with static data. This is the case of dams, which are classically equipped with systems capable of measuring displacements, stresses, relative movements between joints or temperatures, with the aim of studying the structural static behaviour. However, vibration-based health monitoring systems have also already been successfully implemented in many different large civil structures such as bridges [2], wind turbines [3], stadia roofs [4] or bell-towers [5].

In the case of dams, forced vibration tests [6,7] are historically the most common tests performed with the aim of identifying the structure dynamic properties, and the dynamic monitoring systems are generally just concerned with the characterization of the structure response during earthquakes [8,9]. Dynamic tests using ambient vibration have already been conducted in the past [10–14], often as an addition to forced vibration campaigns. In recent years, the performance of these tests on dams with the aim of calibrating numerical models became more common [15–18]. On the other hand, the installation of vibration-based health monitoring systems on dams is still very uncommon. A continuous ambient vibration programme was carried out in Mauvoisin dam [19], recording twice a day during 180 days, with the main purpose of studying the effect of the reservoir water level on the structure natural frequencies. Similar works were later developed in Hitotsuse dam [20] in Japan, and in Cabril dam [21] in Portugal. The main goal

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of both applications was to follow the evolution of natural frequencies over time and for this the first three or four vibration modes of these structures were tracked for about one year, respectively in the Japanese and in the Portuguese case.

It should be noted that the measurement of the dynamic response of such massive structures usually located in quite remote places with low background excitation is very demanding. One of the main objectives of the present paper is to show that nowadays, due to the recent advances in the monitoring hardware and software, it is possible to perform vibration-based monitoring of dams in an accurate way. This will be demonstrated with an implementation on a recently built infrastructure, the "Baixo Sabor" arch dam.

The "Baixo Sabor" hydroelectric power plant is constituted by two dams located 12.6 km from each other in Sabor river, a tributary of Douro river, in "Torre de Moncorvo", north-east of Portugal. This work focuses on the upstream dam, a concrete double-curvature arch dam, embedded in a narrow valley zone, which is 123 m high and whose crest is 505 m long. Thirty-two concrete vertical blocks, separated by vertical contraction joints, compose the arch, which is crossed by six horizontal visit galleries. The dam is endowed with a spillway composed of four floodgates, 16 m long each. Fig. 1 shows an aerial view of the dam and the reservoir and a closer picture of the spillway. In the aerial photography, it is possible to observe that the powerhouse, which contains the turbines for electricity production, is quite close to the dam. The reservoir, which extends 60 km north along the Sabor river and allows a useful storage of 630 million m^3 of water [22], is strategically located since there are four other power plants located downstream that can be supplied by it in case of need.

Besides the more common static monitoring, which includes the measuring of water pressures, temperatures, movements of joints and concrete strains, among others [23], the dam is also equipped with a geodesic system to measure absolute and relative displacements, a seismic monitoring system to evaluate the behaviour of the structure when subjected to seismic actions and a dynamic monitoring system to continuously characterize its dynamic properties.

This work focuses on the dynamic monitoring equipment, the experimental processing tools and the numerical modelling adopted to assess the dynamic behaviour of Baixo Sabor arch dam during the first six months of operation, which includes the reservoir-filling phase. The results obtained are quite rare, not only because there are only a couple of similar applications, mentioned above, but especially because the dam's behaviour during the first reservoir-filling period was continuously monitored. These results are very important to better understand the effect of the water on the structure dynamic behaviour and will be extremely helpful in the updating of numerical models that take into account water-structure interaction. Moreover, it is important to notice that the dam presents very low vibration levels, which hinders the identification process, forcing the adoption of advanced processing techniques. In addition, due to the proximity of the powerhouse to the dam, the electricity production turbines rotation frequency and its harmonics pollute the recorded acceleration time series, which challenges, even more, the routines for automatic tracking of modal parameters.

When comparing this work to the set of previous similar applications it should be highlighted that the structure has been continuously monitored (48 sets of 30 min time series are being created per day) during the reservoir first filling and the data acquired was processed with recent and advanced algorithms which, despite the difficulties imposed by this specific application, provided excellent results, allowing the tracking of the structure first six vibration modes.

2. Dynamic monitoring system description

When monitoring large civil structures, it is advantageous to have digitizers distributed along the monitored structure in order to reduce cable length and thus electrical interferences that can corrupt the signals [24]. Therefore, the dynamic monitoring system installed in Baixo Sabor arch dam is divided in three subsystems connected by optical fiber. Subsystem 1 and subsystem 2 are composed by 6 uniaxial force balance accelerometers and a digitizer each, and both subsystems are connected to a field processor which is, in turn, linked to a computer (NUC). The two groups of accelerometers are radially installed along the upper gallery, disposed on each side of the spillway. Subsystem 3 is composed of 8 uniaxial force balance accelerometers, radially installed along the second and third upper galleries, and two digitizers that are connected to the computer, which is responsible for running the acquisition. To perform modal analysis a good synchronization of the data recorded by all digitizers must be assured, which required the installation of GPS antennas. In addition, the field computer is connected to the optical fiber network between the dam and the plant allowing remote access. A scheme representing the monitoring system main elements is presented in Fig. 2, while the position of the total 20 accelerometers is characterized in Fig. 3 by red marks.

The force balance accelerometers used (FBA ES-U and FBA ES-U2 from Kinemetrics) have a dynamic range of 140 dB and 155 dB, respectively, and a frequency bandwidth that goes from DC to 200 Hz. These accelerometers can measure up to 4 g, but in this application, they were configured to measure in the range $-0.25\,g/+0.25\,g$, 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 min at all instrumented points, thus producing 48 groups of time series per day. These data are automatically stored in the field computer and then transferred remotely both to FEUP and LNEC, with a FTP connection, where they are stored and processed.

Additionally, in order to better characterize eventual seismic actions acting on the dam, a seismic monitoring system has also been

Fig. 1. Baixo Sabor arch dam, aerial view of dam and reservoir and detail of the spillway from downstream [22].