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VIBRATION MONITORING OF CAHORA-BASSA DAM

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ABSTRACT

This paper focuses on the experience gathered from the continuous dynamic monitoring of Cahora Bassa dam, a 170 m high arch dam in Mozambique, over the past decade. The installed Seismic and Structural Health Monitoring system was designed to continuously record acceleration time series in several locations in the dam body (crest gallery) and near the dam-rock interface, under ambient/operational vibrations and during seismic events, using uniaxial and triaxial accelerometers. The system was complemented with the development of software for automatic modal identification and automatic detection of seismic vibrations. The numerical simulations are carried out using a 3D finite element program, based on a solid-fluid coupled formulation to simulate the dam-reservoir-foundation system, considering dam-water dynamic interaction and propagation of pressure waves throughout the reservoir. The main experimental outputs are presented and compared with results from 3D finite element analysis, including the evolution of identified natural frequencies over time, vibration mode shapes for specific water levels, and the dynamic response in accelerations under seismic ground motion.

Keywords: Cahora-Bassa dam, Seismic and Structural Health Monitoring, Modal identification, Natural Frequencies, Seismic response, Finite element analysis.

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1. INTRODUCTION

The safety control and health monitoring of important structures like long span bridges and large dams (Fig.1), is nowadays supported by automatic monitoring to continuously control their performance for static and dynamic loads, using the so-called Seismic and Structural Health Monitoring (SSHM) systems for measuring vibrations. The concept of SSHM is a quite recent one, referring to the implementation of procedures and strategies to characterize the dynamic behavior of these structures under operation conditions and during seismic events, based on continuous monitoring data [1]. The main goals of implementing a monitoring system of the type SSHM are: (i) to characterize the global dynamic behavior; (ii) to study the evolution of modal parameters over time; (iii) to analyze the seismic response; (iv) to investigate the evolution of material deterioration for structural integrity assessment; (v) to provide useful information for stakeholders and technicians/engineers responsible for safety control and health monitoring, to fulfill regular maintenance needs and/or to support decision making in face of exceptional emergency situations.

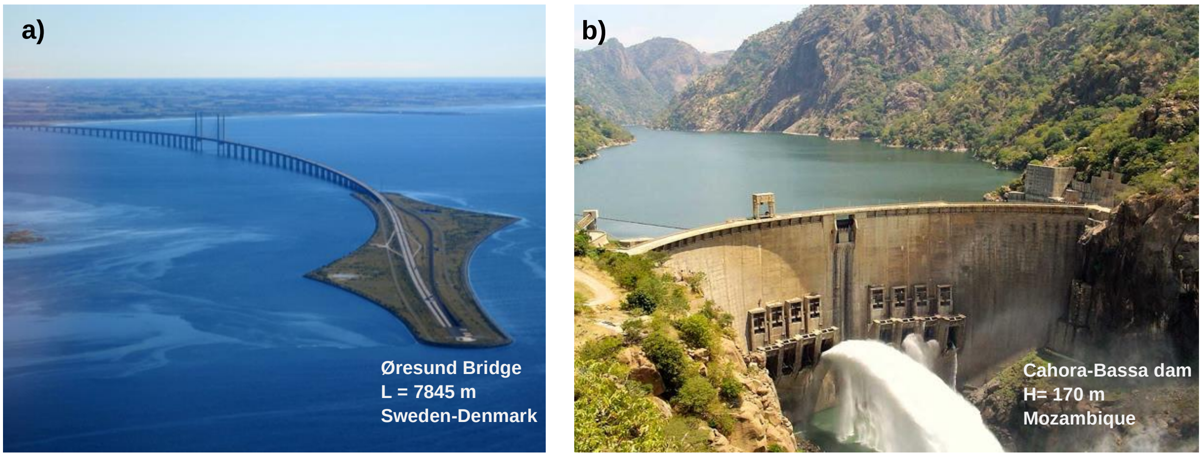

Fig. 1 – Examples of large structures under Seismic and Structural Health Monitoring

2. SEISMIC AND STRUCTURAL HEALTH MONITORING SYSTEMS FOR LARGE DAMS

In accordance with the general guidelines of the International Commission on Large Dams (ICOLD) on dam safety and health monitoring, the behavior of dams under operational/ambient vibrations and during earthquake events must be evaluated. This is particularly relevant considering the importance of dams for populations and the high potential risk they entail. Within this scope, the application of SSHM methodologies for dam safety control has suffered an important growth over the past decade, because of the undeniable advantages of continuous vibrations monitoring [2] and due to the increasing demands of owners, stakeholders and engineers. There-fore, the installation of monitoring systems for continuously measuring vibrations has been proposed for most of the new large dams, to evaluate their behavior since the early stages of their service life, and for older dams, some built several decades ago, with possible deterioration problems (e.g. swelling reactions) [2-4].

The installation of an SSHM system in large concrete dams aims at continuously measuring accelerations in as many locations in the dam as possible, in various positions along the dam-foundation interface, and, if possible, in the free field, to enable ongoing evaluation of the response under operational/ambient vibrations and under earthquake ground motion. For SSHM, it is essential to design a system with high dynamic range, capable of an accurate measurement of the dam's response for reduced amplitude motions, i.e. ambient/operational vibrations and low intensity earthquakes, and for movements of greater amplitude, e.g. caused by high intensity earthquakes. Therefore, the systems should be implemented [2-4] using cutting-edge equipment for automatic data measurement, acquisition and transmission, including, e.g., digitizers, recorders, transducers and accelerometers. They should also be complemented with the development of software, adapted and optimized to each dam, to automatically process and analyze the measured vibrations, e.g. for modal identification and earthquake detection (Fig. 2). In addition, reference 3D finite element (FE) models are required, to enable the comparison between measured and computed response, in order to support structural health evaluations and dam safety control studies, while also providing useful data to calibrate/validate new models in development.

Taking into consideration the experience accumulated over the years with Cahora Bassa dam vibrations measurement [2 4], the combined use of complete monitoring systems, appropriate data analysis software and 3DFE models can provide important results for engineers/technicians responsible for dam safety and health monitoring, namely: i) to study the evolution of modal parameters over time, enabling to assess the effects of reservoir water level and thermal variations on the measured response; ii) detect structural changes due to material deterioration, given that its evolution over time will affect the global stiffness of the dam and cause changes in the natural frequencies; iii) to automatically detect earthquake events and hence analyze the seismic response due to seismic ground motion based on recorded acceleration time histories; and iv) to evaluate the structural effects caused during significant seismic events (e.g. cracking phenomena), by analyzing the dynamic performance in normal operation conditions before and after said events. In resume, based on the comparison between measured and computed response, structural health assessments can be made, and thus immediate actions can be proposed for both regular maintenance and eventual emergency cases.

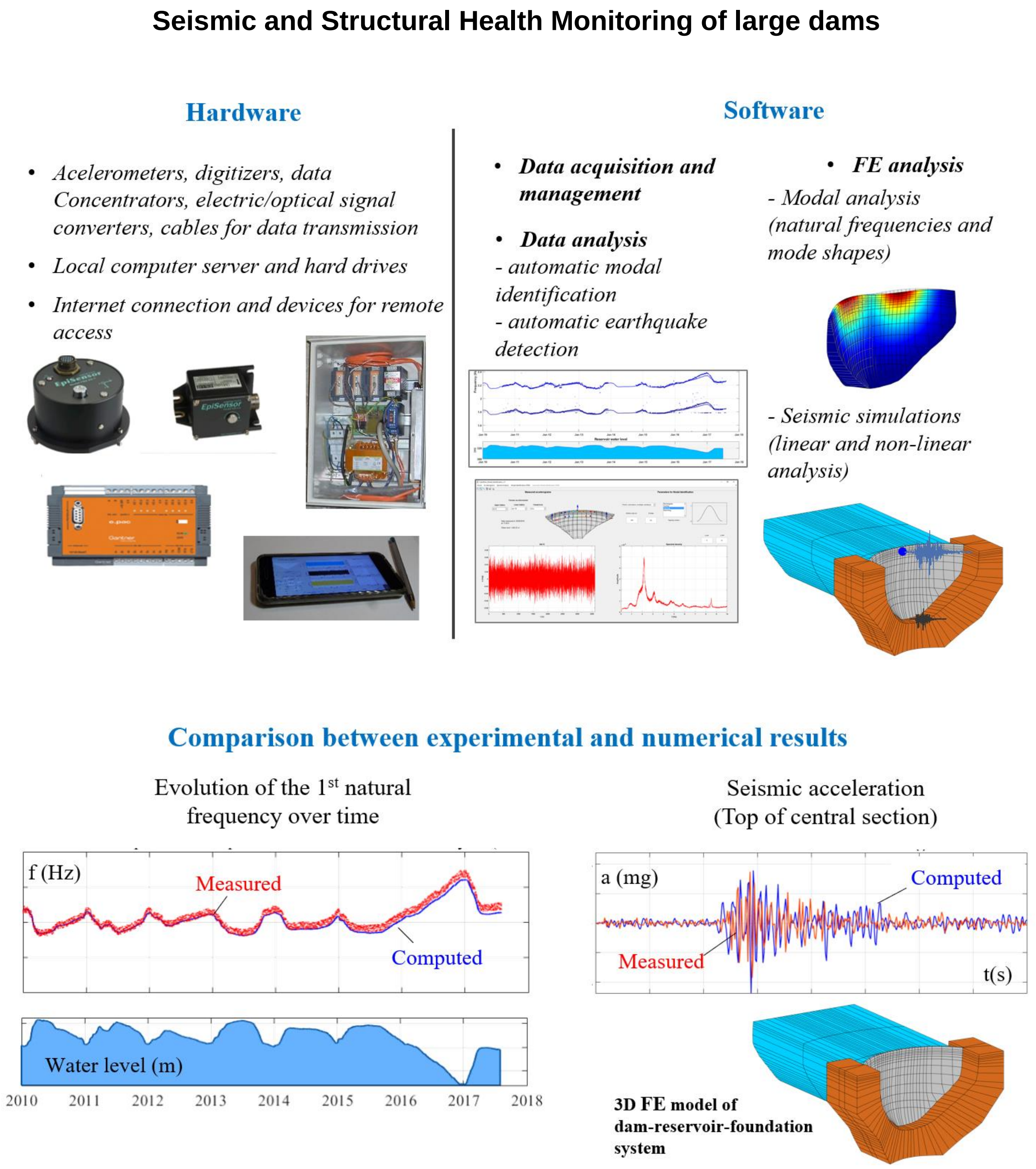

Fig. 2 – Seismic and Structural Health Monitoring of large dams. Main components and results

In Africa, continuous dynamic monitoring of dams for safety control and health monitoring purposes started in 2010, when HCB made the decision to invest in the installation of a SSHM system in Cahora Bassa dam for continuously measuring accelerations over time [5-7]. In 2013, after several years of ambient vibration testes, a dynamic monitoring system was installed for health monitoring of Roode Eslberg dam, in Worcester, Western Cape, South Africa [8].

3. CAHORA-BASSA DAM AND THE INSTALLED SSHM SYSTEM

Cahora Bassa dam (Fig. 1b), one of the largest dams in Africa, is located near Songo in the province of Tete, in western Mozambique. Built in late 1974 on the Zambezi river, it impounds Lake Cahora Bassa, a 270 km long lake that extends to the Mozambique Zimbabwe/Zambia border. Cahora Bassa dam is a thin 170 m high double curvature arch dam, founded on a gneissic granite mass rock foundation of very good quality. The crest, at el.331 m, has a 303 m long arch. The central cantilever is 23 m wide at the base and 4 m wide at the crest. Concerning structural integrity, a concrete swelling process was detected in the 1980’s, a few years after the dam’s construction (a cracking pattern can be observed at the top of the crest, which is common on dams with internal swelling processes); also, small horizontal cracks appeared at the upstream face due to the high tensile stresses induced by the hydro-static pressures and/or thermal loading.

An SSHM system (Fig. 3) was installed in Cahora Bassa dam in 2010, aiming to characterize its dynamic behavior under ambient/operational vibrations and to measure the response during seismic events for health monitoring over time. There-fore, the system was designed to continuously record acceleration time histories using extremely low noise sensors, at a sampling rate of 50 Hz and considering one-hour series, with a full-scale recording range of ± 1g. Thus, the implemented monitoring scheme includes 10 uniaxial accelerometers (EpiSensor ES-U2), located in the upper gallery below the crest, to measure accelerations in radial direction, and 3 triaxial sensors (EpiSensor ES-T), one positioned near at the base (dam-foundation interface) and two in the right and left banks. All sensors (19 channels) are connected to a 24 channel Granite unit from Kinemetrics for data acquisition/digitalization, in 24 bits. In total, 19 accelerograms are continuously recorded, every hour, and then sent and stored to the computer server located in the offices at the dam’s control center.

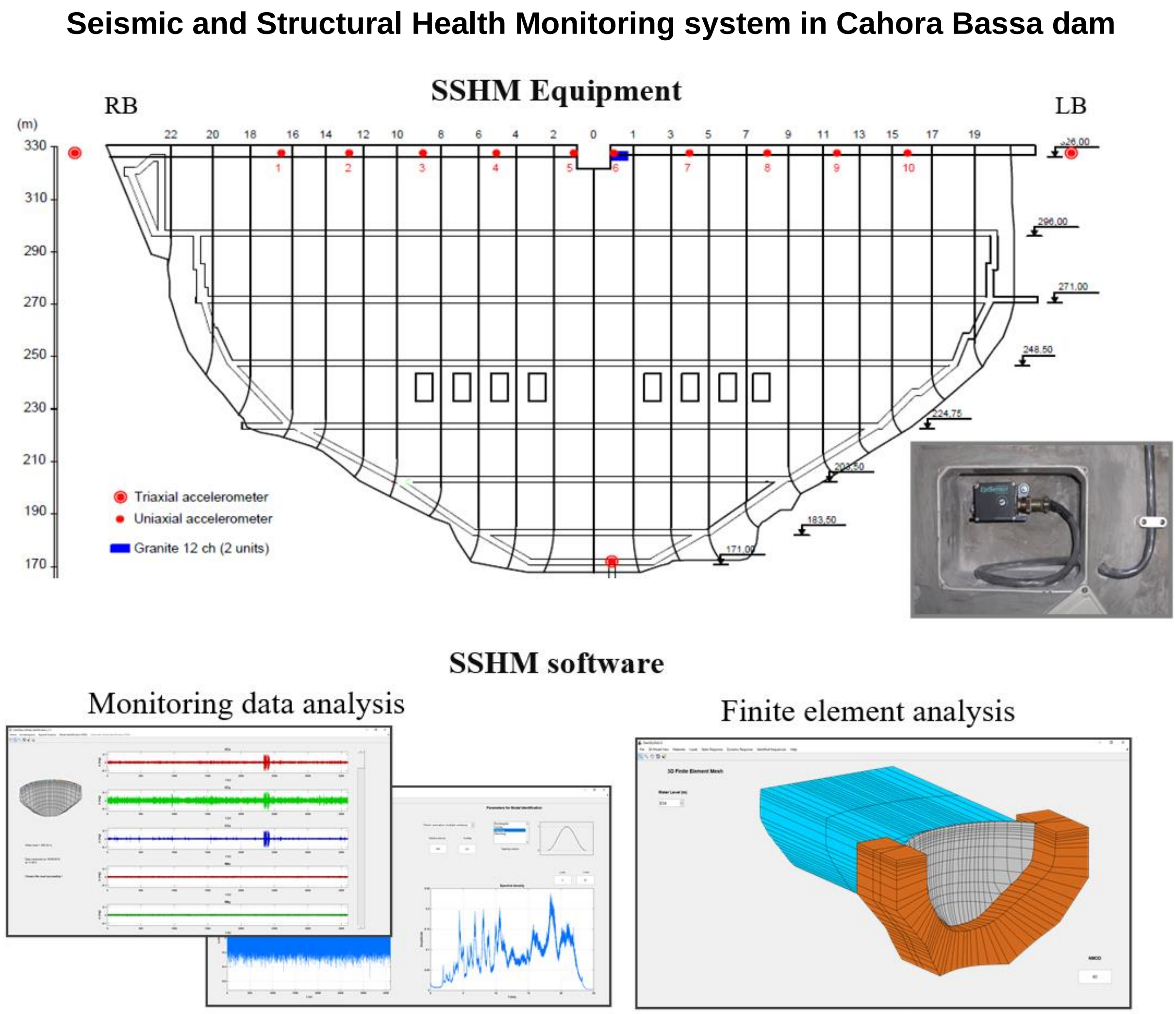

Fig. 3 – Seismic and Structural Health Monitoring system installed Cahora Bassa dam.

Specific software has been developed to analyze data collected with continuous monitoring systems, including the one installed in Cahora Bassa dam. This software comprises various tools, namely for: i) interactive (with user interface) and automatic modal identification, using the Frequency Domain Decomposition (FDD) method [9] with Singular Value Decomposition (SVD), a novel technique for automatic peak selection based on a threshold line procedure, and an optimized clustering technique for distinguishing the different modal frequencies; and ii) for automatic earthquake detection, based on maxima analysis, enabling alert emails to be sent to owners and/or engineers responsible for the safety control. Based on the experimental results obtained with this software, it is possible to evaluate the evolution of the dynamic behavior of dams over time and to carry out comparative studies with the predicted response from FE analysis. The numerical simulations for this paper were conducted using DamDySSA4.0, a 3D FE program developed for linear and non-linear dynamic analysis of concrete dams. The dam-reservoir-foundation system is simulated using a coupled model [10] with massless foundation, based on a formulation in displacements and pressures to simulate the pressure waves' propagation throughout the reservoir [11]. For modal analysis, a state space formulation with two state matrices and complex modal coordinates is used to solve the eigen problem of the whole system and calculate natural frequencies (eigenvalues) and mode shapes (eigenvectors). For seismic analysis, the response is computed by an algorithm for numerical integration in time domain based on the Newmark method, with the seismic accelerograms applied at the base and uniformly distributed along the dam-rock interface.

4. DYNAMIC MONITORING OVER TIME (2010-2019)

The dynamic behavior of Cahora Bassa dam under ambient/operational excitations is analyzed for the monitoring period between August 2010 and June 2019, with a reservoir level variation from 312 to 326 m: the evolution of the automatically estimated natural frequencies for ten dam vibration modes is presented (Fig. 4). The frequency value of the first mode ranges between 1.95 Hz to 1.78 Hz, considering a water level variation from 312 m to 326 m, respectively; for the second mode, the values vary from 2.4 Hz to 2.16 Hz. As expected, the influence of the water level in the dynamic response of the dam is clearly noted, which can be seen by the variations in natural frequencies (especially for modes with higher frequencies).

The numerical simulations were carried out using a reference 3D FE model of the dam-reservoir-foundation system, considering a Young's modulus E = 40 GPa and a Poisson's ratio ν = 0.2 for the dam and the foundation materials and a pressure waves propagation velocity c_w = 1500 m/s in water. For dynamic calculations the relation $E_{dyn} = 1.3 \times E$ was used.

Fig. 5 presents the comparison between the identified natural frequencies over time and the frequency curves from 3D FE analysis, considering the real water level variations as inputs to the FE model, as well as the mode shapes computed for a water level at el. 319 m. Focusing on the first five vibration modes, modes 1 and 5 are anti-symmetric, while modes 2, 3 and 4 present symmetric shapes. The comparative analysis shows an excellent agreement between identified and computed natural frequencies for the first five modes, with differences of less than 0.1 Hz noted for the third and fourth modes.

To exemplify how the development of software for monitoring data analysis and FE analysis is useful to complement SSHM systems for safety control and health monitoring of large dams, an additional study was conducted for the first vibration mode. Fig. 6 shows the evolution of the first mode's frequency over time and its comparison with the curves computed using the reference FE model, both without damage (intact material) and considering evolutive damage from 0 to 4% (material deterioration over time). A good correspondence is achieved between the identified frequencies and the curve computed with the undamaged model, which means the dam has not suffered significant deterioration during the last decade; as shown, if that wasn't true, the changes in the evolution of the first natural frequencies could be noted.

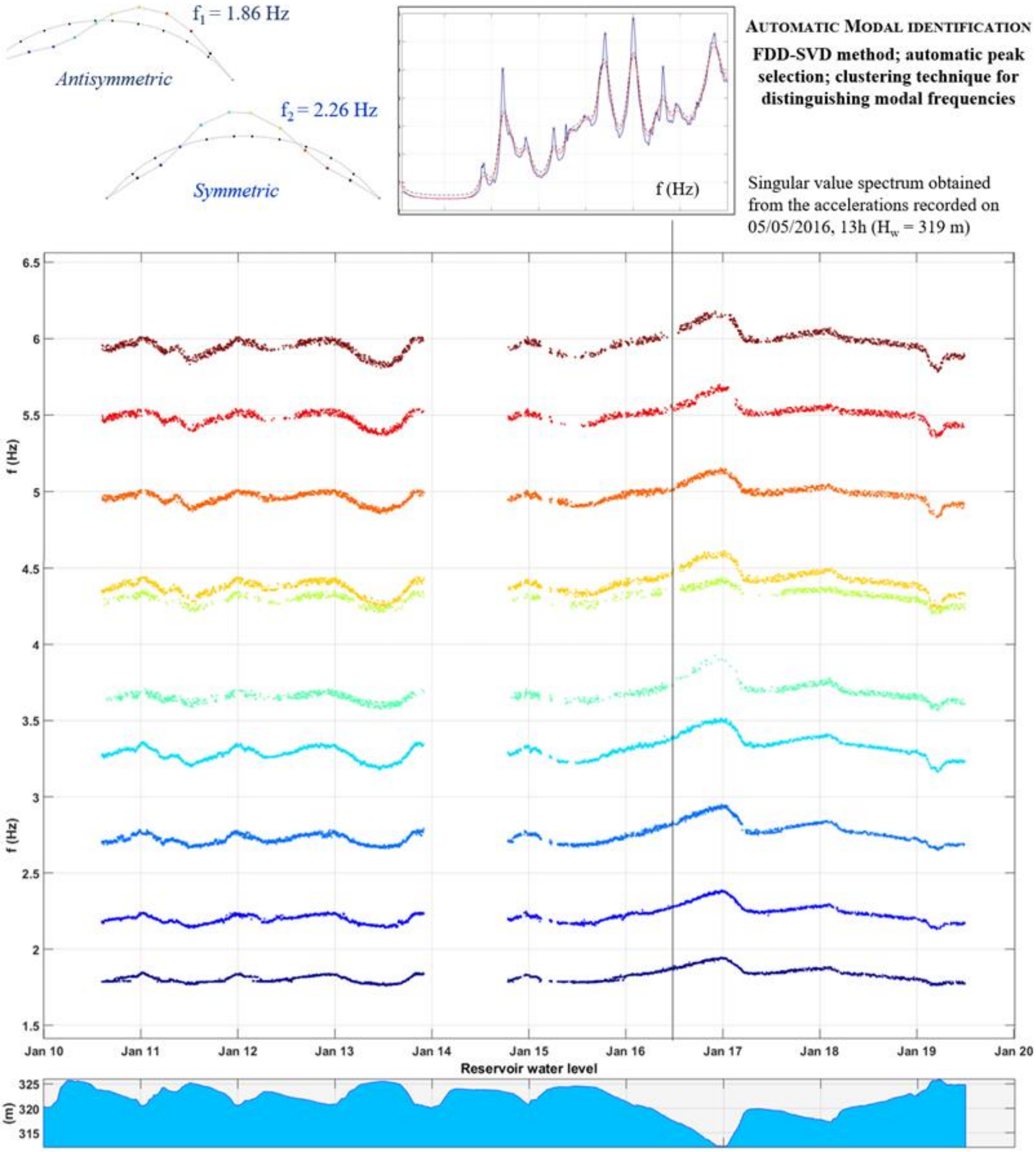

Fig. 4 – Cahora Bassa dam. Modal identification results. Mode shapes and evolution of natural frequencies over time (2010-2019)

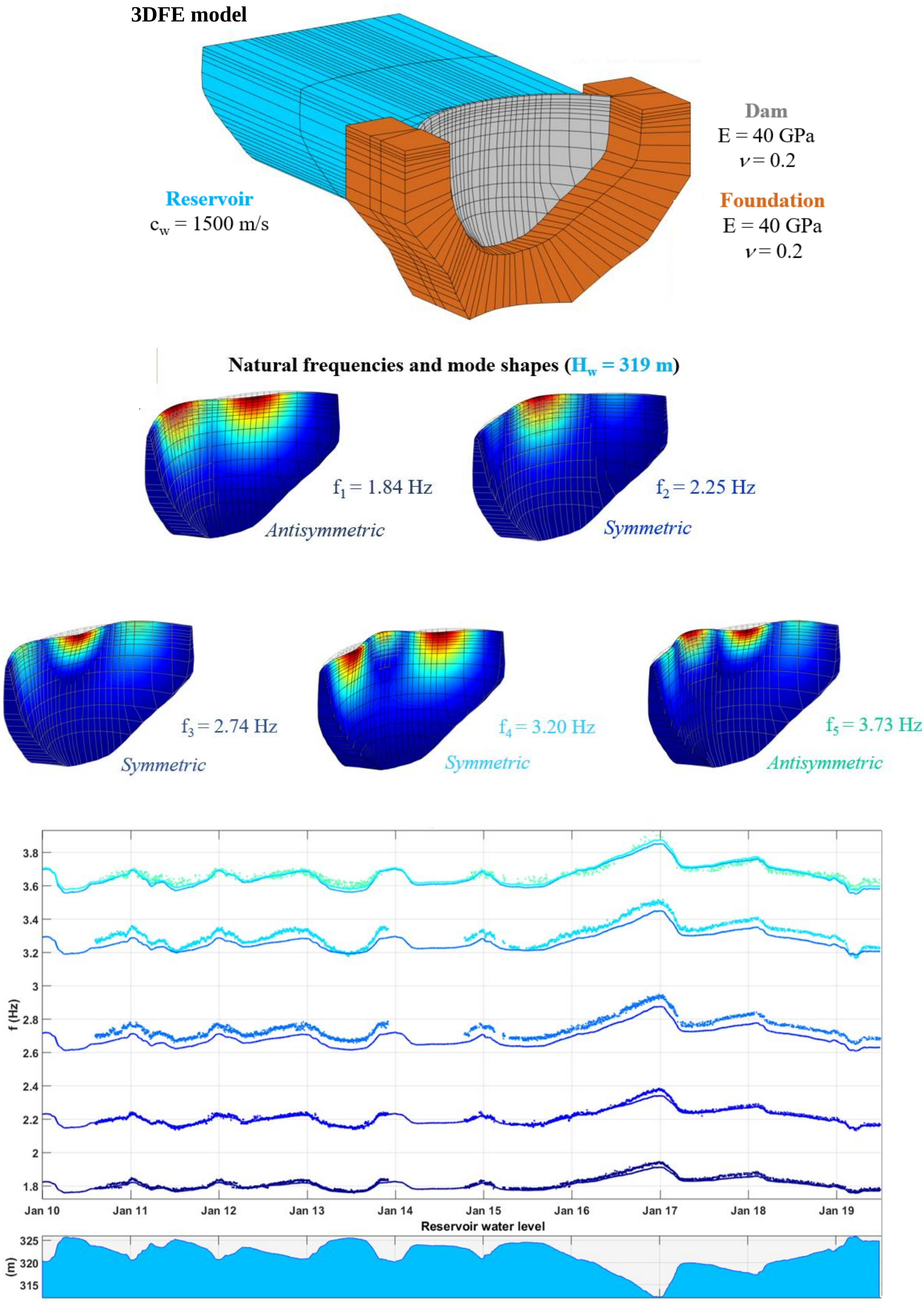

Fig. 5 – Cahora Bassa dam. Dynamic monitoring over time (2010-2019): evolution of natural frequencies. Comparison between identified and computed values (3DFE)

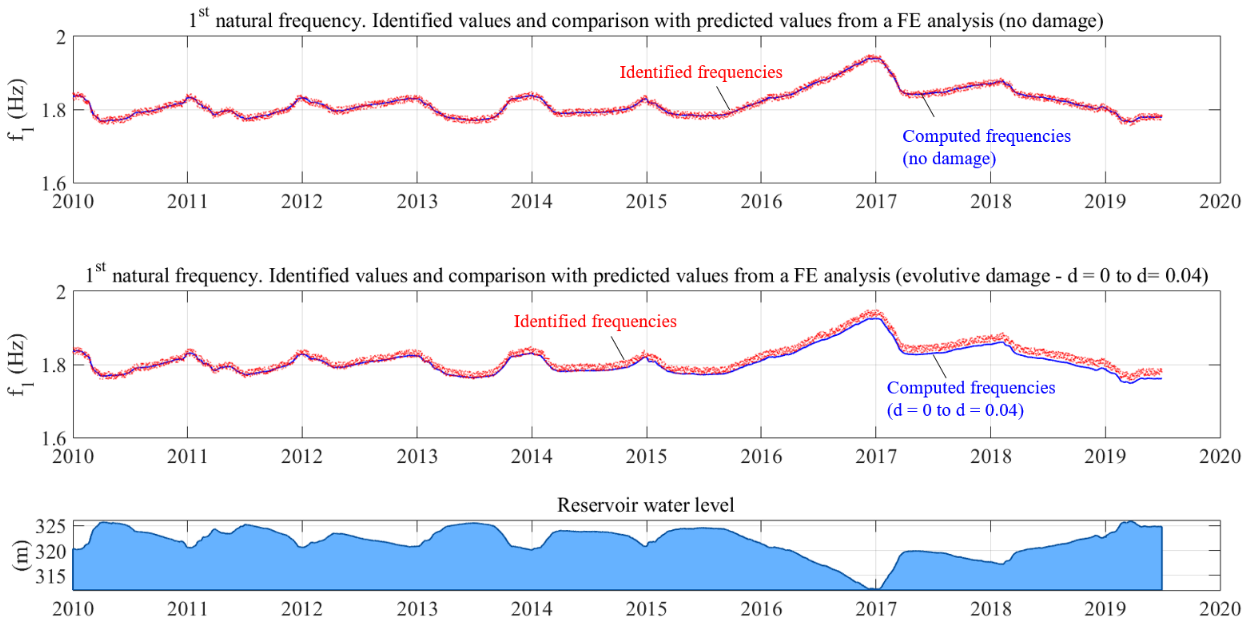

Fig. 6 – Cahora Bassa dam. Evolution of the 1st natural frequency over time (2010-2019). Comparison with results from 3DFE analysis: no damage and evolutive damage (from 0 to 4%)

5. SEISMIC RESPONSE ANALYSIS

With Cahora Bassa dam's SSHM system, several earthquakes have been automatically identified and recorded, allowing studies on the seismic response to be carried out based on measured accelerations. Some important issues to consider are the base to top amplification of the measured vibrations, the influence of reservoir water level and the damping of the dam-reservoir-foundation system under seismic loading, for different earthquake events.

In the present work, the seismic response of Cahora Bassa dam is analyzed for a low magnitude earthquake, near Songo, at about 30 km from the dam, which was measured at the dam site on June 21, 2017. The water level during the seismic event was at el. 319 m, i.e. 12 m below the crest, and the recorded peak acceleration near the dam base was 13.5 mg (0.1324 m/s2), in the upstream downstream direction. The comparison between measured and computed seismic accelerations of Cahora Bass dam is presented in Fig. 7.

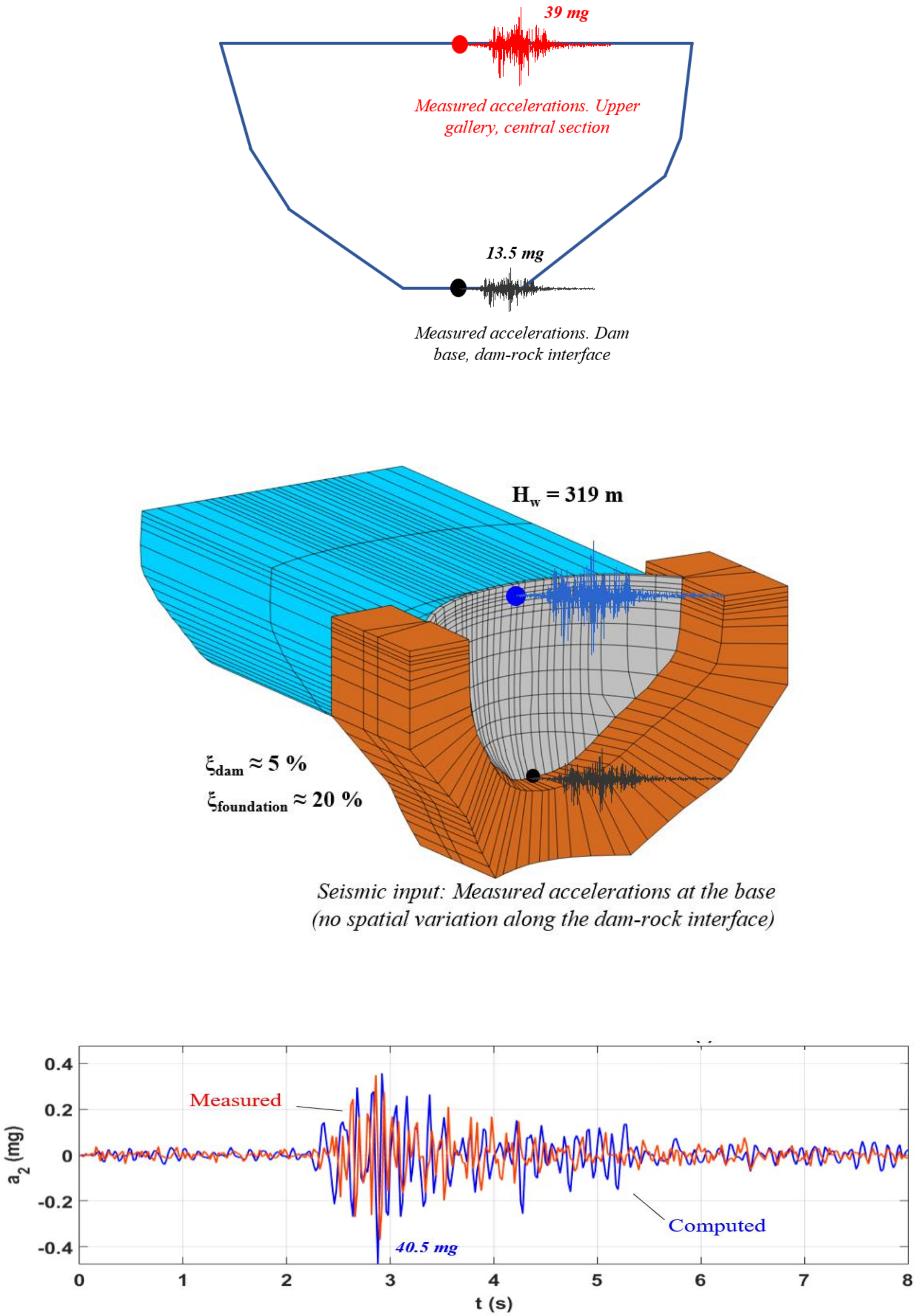

Fig. 7 – Cahora Bassa dam. Comparison between measured and computed seismic accelerations

The measured accelerations were recorded with the sensor located at the upper gallery (el. 326 m), about 5 m to the right of the centre of the dam: a peak acceleration of about 39 mg was measured (base to top amplification factor of 2.9 times). The seismic simulations were performed considering a reservoir level at el. 319 m and the seismic accelerograms measured at the dam base as inputs: a peak acceleration of 40.5 mg was computed (amplification factor of 3 times). In this study, it was possible to fit the computed accelerations to the measured response by using a damping ratio of about 5% in the dam and 20% in the foundation (although these values are high in comparison with standard ratios, analogous conclusions have been drawn by other researchers [12,13])

6. CONCLUSIONS

This paper presents important remarks based on the experience gathered from the continuous dynamic monitoring of Cahora Bassa dam (Mozambique) over the past decade, as well as some significant results on dynamic response over time and on seismic response analysis.

The recorded monitoring data from 2010 to 2019 was used in combination with results from 3D FE analysis, namely: i) to study the dynamic behavior of the dam under ambient/operational vibrations, enabling to evaluate the evolution of natural frequencies over time, considering the influence of the reservoir level - a very good agreement was obtained between identified natural frequencies and the computed frequency curves; ii) in the scope of health monitoring, to assess that the existing deterioration phenomena have not progressed significantly and therefore are not affecting the structural integrity of the dam; and iii) for analyzing the measured response during a seismic event, based on the accelerations recorded in the central section, at the upper gallery (it was possible to fit the computed accelerations to the measured response by using a damping ratio of about 5% in the dam and 20% in the foundation).

This work has demonstrated the usefulness of SSHM systems and the importance of developing appropriate software for monitoring data analysis and for 3D FE analysis, as well as the potential of their combined used to study the dynamic behavior of large dams over time for dam safety control and health monitoring of large dams.

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