Seismic and Structural Health Monitoring of Cahora Bassa Dam

Sérgio Oliveira[1(✉)], Ezequiel Carvalho[2], Bruno Matsinhe[2], Paulo Mendes[3], André Alegre[1,4], and Jorge Proença[4]

[1] Laboratório Nacional de Engenharia Civil, Av. Brasil 101, Lisbon, Portugal
soliveira@lnec.pt
[2] Hidroeléctrica de Cahora Bassa, Songo, Maputo, Mozambique
[3] Instituto Superior de Engenharia de Lisboa, R. Cons, Emídio Navarro 1, Lisbon, Portugal
[4] Instituto Superior Técnico, Av. Rovisco Pais 1, Lisbon, Portugal

Abstract. This paper focuses on presenting a complete study on the dynamic behavior of Cahora Bassa dam (Mozambique), a 170 m high double curvature arch dam which has been under continuous vibrations monitoring since 2010. 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, and the seismic response in accelerations. Finally the non-linear seismic behavior of Cahora Bassa dam is studied for an input accelerogram with a 0.6 g peak acceleration, considering the joints movements and a damage model for concrete.

Keywords: Cahora-Bassa dam · Seismic and structural health monitoring · Natural frequencies · Finite element analysis · Linear and non-linear seismic response · Damage model · Joints' movements

1 Introduction

The safety control and health monitoring of large dams, is nowadays supported by automatic monitoring systems 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,

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based on continuous monitoring data [1]. The main goals of implementing a monitoring system for SSHM are: i) the characterization of the global dynamic behavior; ii) to study the evolution of modal parameters over time; iii) to study 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.

2 Seismic and Structural Health Monitoring Systems for Dams

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. Therefore, 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. 1). 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.

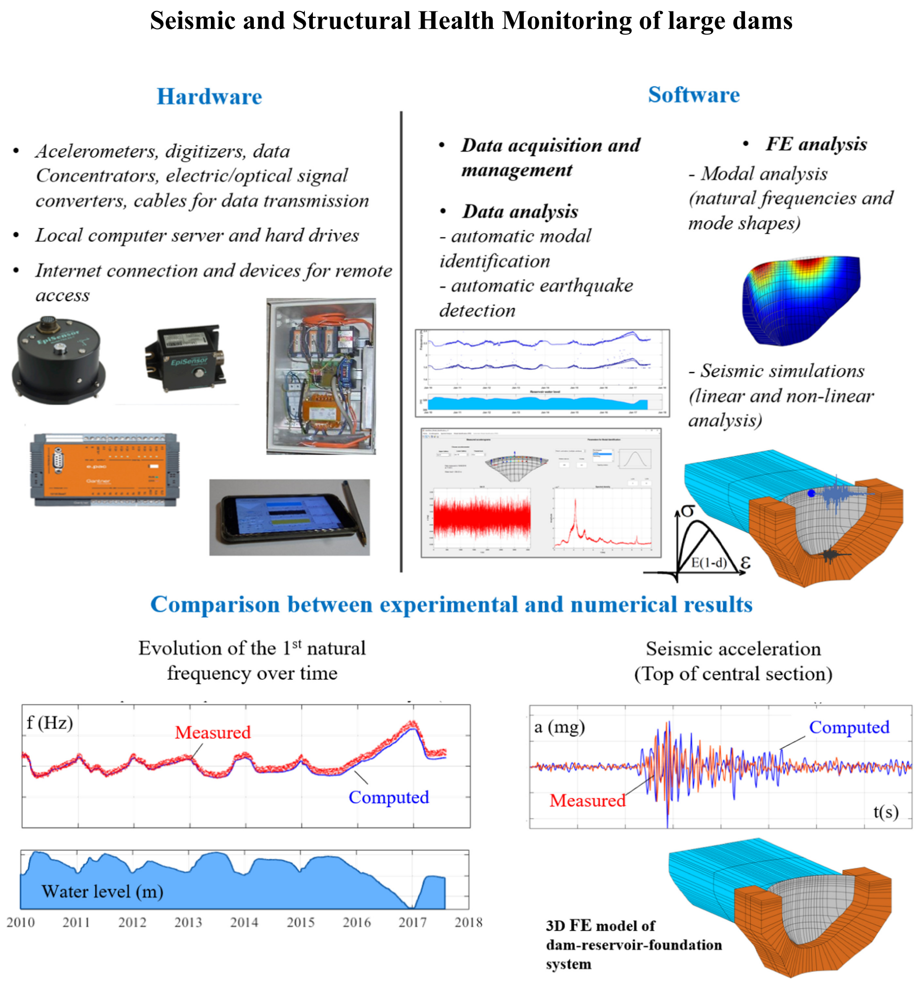

Fig. 1. Seismic and structural health monitoring for large dams. Main components and results.

3 SSHM System Installed at the Cahora Bassa Dam

Cahora Bassa dam (Fig. 2), is located near Songo, in western Mozambique, and was 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 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 hydrostatic pressures and/or thermal loading.

An SSHM system (Fig. 2) 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. Therefore, 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 ± 1 g. 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.

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 Dam-DySSA4.0, 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.

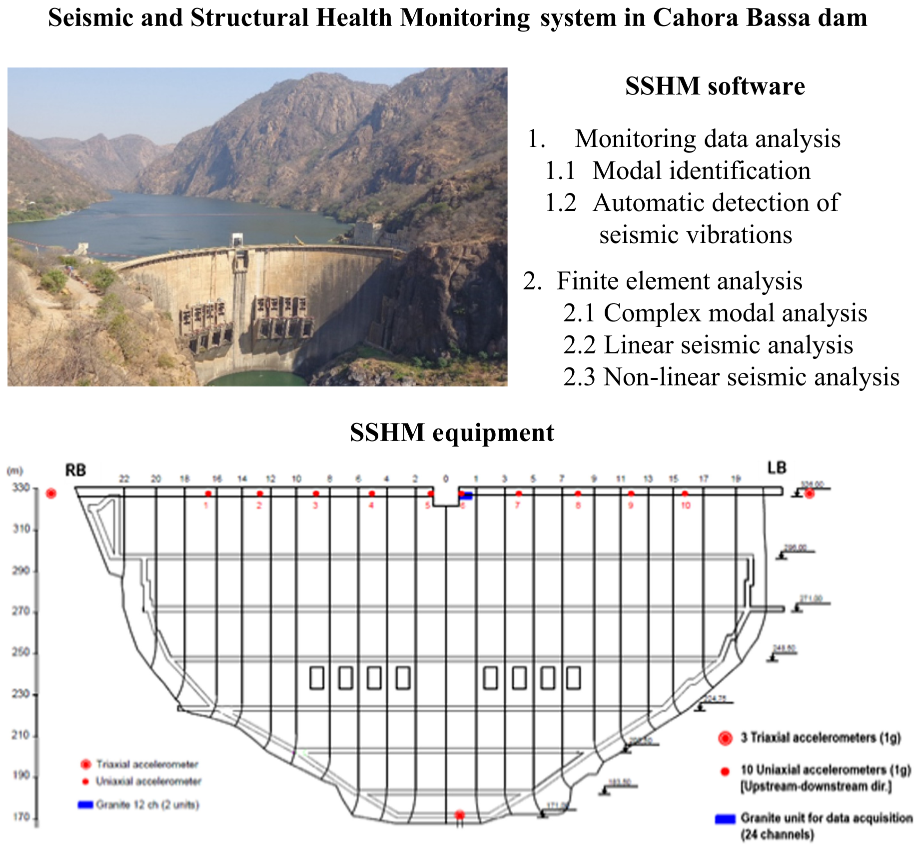

Fig. 2. Seismic and structural health monitoring system installed Cahora Bassa dam.

4 Vibrations Monitoring over Time

The dynamic behavior of Cahora Bassa dam under ambient/operational excitation 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 five dam vibration modes is presented (Fig. 3). 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.

Figure 3 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 antisymmetric, 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.

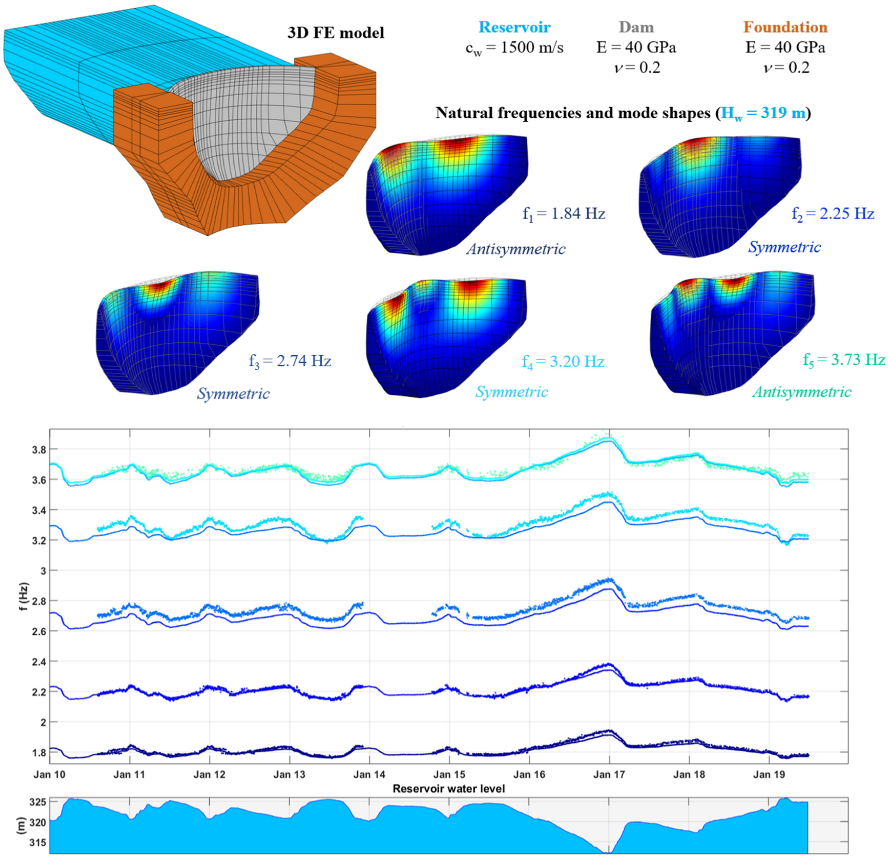

Fig. 3. Cahora Bassa dam. Evolution of the natural frequencies (2010–2019): comparison between identified and computed (FEM) natural frequencies.

5 Measured Seismic Response Under Low/Medium Earthquakes

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/s^2), in the upstream-downstream direction. The comparison between measured and computed seismic accelerations of Cahora Bass dam is presented in Fig. 4. The measured accelerations were recorded with the sensor located at the upper gallery (el. 326 m), about 5 m to the right of the center 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]).

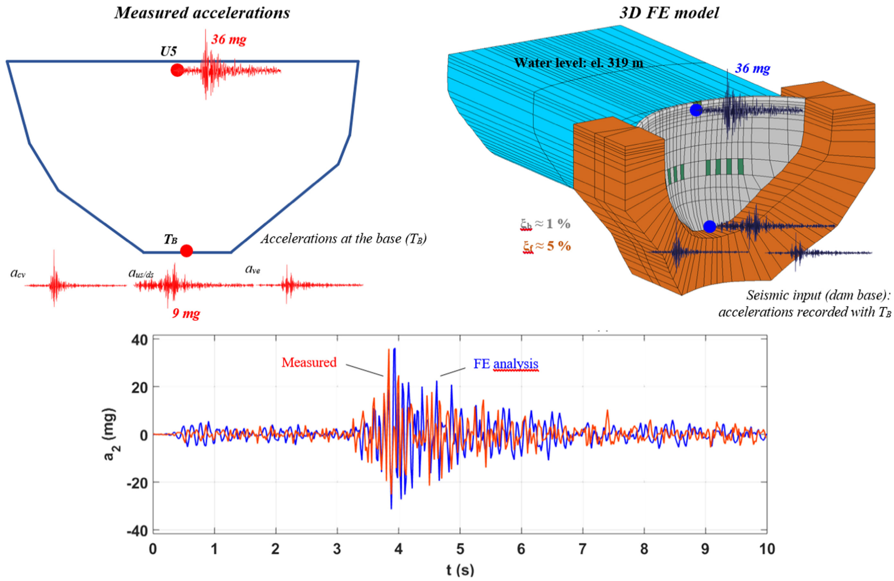

Fig. 4. Cahora Bassa dam. Seismic event detected on June 21, 2017. Measured and computed seismic response

6 Predicted Seismic Response for a Strong Earthquake

In this section is presented a study on the non-linear seismic response of Cahora Bassa dam for a load combination including the self-weight (SW), the hydrostatic pressure (HP) for full reservoir and a seismic accelerogram with peak acceleration of 0.6 g. The numerical simulations are carried out with **DamDySSA4.0**, using a FE model with joints and concrete non-linear behavior (Fig. 5). The dam concrete and the foundation rock are assumed as isotropic materials, considering the same properties as in the linear model. Damping ratios of about 10% in the dam and 15% in the foundation were assumed. The non-linear concrete behavior is simulated using a strain-softening constitutive law with tensile strength $f_t = 3$ MPa and compressive strength $f_c = 3$ MPa. For the vertical contraction joints, null cohesion is considered, to simulate the opening movements under tensions, and a 30° friction angle is used to consider the existing shear keys in the contraction joints of Cahora Bassa dam. For the dam-rock interface, high values of cohesion and friction angle are used to take into account the dam's insertion in the valley along the foundation. The seismic input is a 10 s computer generated seismic accelerogram, with a peak acceleration of 0.6 g, which is applied at the dam base in the upstream-downstream direction.

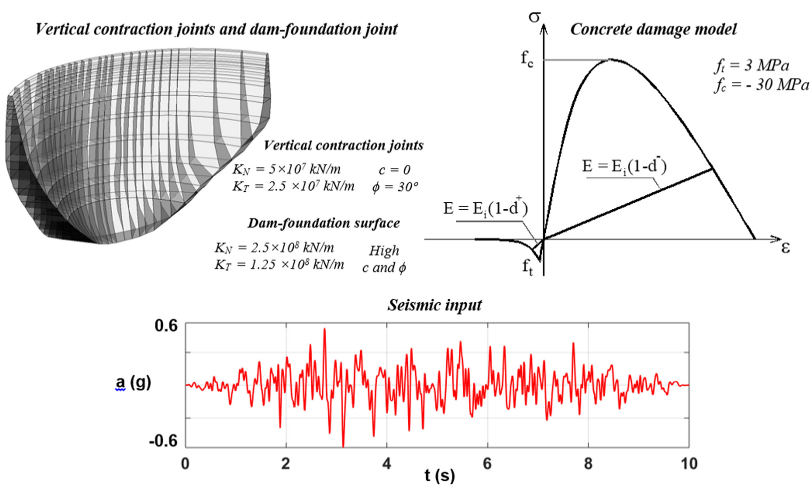

Fig. 5. Cahora Bassa dam. FE model, material properties, joints, concrete damage law and seismic input.

These results show that Cahora Bassa dam's seismic response under a strong earthquake is clearly influenced by the opening of the vertical contraction joints, for a full reservoir condition, and that significant concrete cracking under tension can occur in the upper part of the dam, at the downstream face, and close the dam base, at the upstream face. Nevertheless, concerning the structural safety for a collapse situation, it is possible to conclude that Cahora Bassa dam is capable of withstanding the strong earthquake applied (Fig. 6).

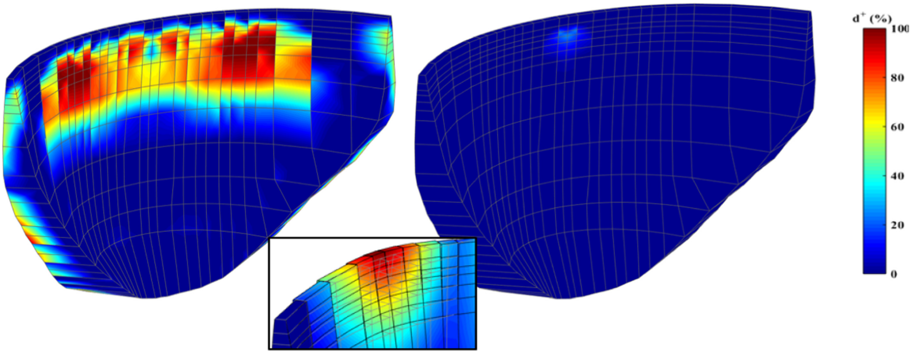

Fig. 6. Cahora Bassa. Non-linear seismic response. Tension and compressive damage, and joints movements at the crest.

7 Conclusions

The recorded monitoring data from the SSHM system of Cahora Bassa dam was used, in combination with results from 3DFE analysis, 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 water level: a good agreement was obtained between identified natural frequencies and the computed frequency curves. The measured vibrations data was also used 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).

A non-linear seismic analysis of Cahora Bassa dam was also carried out. It was considered a load combination involving the self-weight, the hydrostatic pressure for full reservoir and the seismic load, represented by a computer generated seismic accelerogram with a peak acceleration of 0.6 g. The seismic simulations were carried out considering the non-linear behavior of concrete and the joints movements. The comparison between linear and non-linear seismic response showed how taking the movements of the vertical contraction joints and the non-linear behavior of concrete in the model into account has influenced the dam’s structural response. Namely, the opening of the vertical contraction joints led to a significant decrease of the arch stresses at the top of the dam, and hence to an increase of the stresses along the height of the cantilevers (particularly to the right and left of the central section), at the downstream face, and near the base of the dam, at the upstream face. Significant tension damages were computed in these zones. Regarding the structural safety for a collapse situation, the presented results allowed to conclude that the Cahora Bassa dam is capable of withstanding the 0.6 g earthquake, despite the occurrence of important tensile damage.

Finally, with this paper it was possible (i) to emphasize the advantages of using SSHM systems, complemented with software for monitoring data analysis, and programs for FE analysis to study the dynamic behavior of arch dams over time and thus provide useful information for supporting safety control and health monitoring; and (ii) to demonstrate the potential of **DamDySSA4.0** for predicting the non-linear seismic behavior of concrete dams and to support seismic safety verifications.

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