Bulletin of Earthquake Engineering (2022) 20:4483–4512
https://doi.org/10.1007/s10518-022-01392-1

ORIGINAL ARTICLE

Seismic and structural health monitoring systems for large dams: theoretical, computational and practical innovations

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Received: 7 June 2021 / Accepted: 19 March 2022 / Published online: 2 April 2022

Abstract

This paper is focused on the study of the dynamic behaviour of two large arch dams, and it presents some innovations for the improvement of Seismic and Structural Health Monitoring (SSHM) systems for dams. The work describes a methodology based on the integrated use of software for automatic monitoring data analysis and of computational 3D finite element (3DFE) models for dam dynamic behaviour simulation. The monitoring data analysis software was developed for automatic modal identification, in order to obtain natural frequencies and mode shapes, for automatic detection of vibrations induced by seismic events, to be distinguished from those caused by other operational sources, and for comparison between results retrieved from measured vibrations and numerical results from 3DFE modelling. The numerical simulations are carried out using a 3DFE program developed for dynamic analysis of dam-reservoir-foundation systems, based on a solid–fluid coupled formulation and considering the dam-water dynamic interaction, including calculation modules for complex modal analysis and for linear and non-linear seismic analysis. The case studies are two large arch dams that have been under continuous dynamic monitoring over the last ten years: Cabril dam (132 m high), the highest dam in Portugal, and Cahora Bassa dam (170 m high), in Mozambique, one of the highest dams in Africa. The SSHM systems installed in both dams have similar schemes and were designed to continuously record accelerations in several locations at the upper part of the dam body and near the dam-foundation interface, using uniaxial and triaxial accelerometers. The most significant experimental results from continuous dynamic monitoring are presented and compared with numerical results for both dams, with emphasis on the evolution of natural frequencies over time, including the vibration mode shapes for various water levels, and on the measured accelerations during low-intensity seismic events. Furthermore, the main results of non-linear seismic response simulations are provided, considering the effects due to joint movements and tensile and compressive concrete damage, aiming to assess the seismic performance of both dams based on the Endurance Time Analysis method.

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Keywords Dynamic behaviour of large concrete dams · Finite element numerical modelling · Seismic and structural health monitoring · Safety control · Dam-reservoir-foundation systems · Evolution of natural frequencies · Vibration modes · Seismic response

1 Introduction

Large concrete dams play a major role in the management of water resources, by making a decisive contribution to water supply, flood control, irrigation, and electrical energy production. In general, these are structures of high potential risk, since incidents or accidents involving this type of dams can result in significant losses for populations and the environment (Wieland 2016). According to the International Commission on Large Dams (ICOLD) it is therefore fundamental to evaluate their performance in normal operating conditions and during seismic events (ICOLD 2018, 2019), particularly in the case of dams subjected to concrete deterioration phenomena and/or those located in areas of medium to high seismicity. Furthermore, aiming to ensure the best operating and safety conditions, the structural safety of large concrete dams must be evaluated for common operational service scenarios and failure scenarios, under both static and dynamic loads, namely under strong earthquakes.

The importance of the observation and analysis of the behaviour of large concrete dams has been widely recognized for decades (Pedro 1999; Ramos 1994), especially when experimental data is used in combination with numerical modelling results. Regarding dynamic behaviour monitoring for structural safety control of large concrete dams, the popularity of continuous dynamic monitoring systems has grown significantly over the last decade (Oliveira and Alegre 2019) due to the recognition of the advantages of continuous ambient vibrations monitoring for increasing knowledge on the dynamic behaviour of dam-reservoir-foundation systems (Alegre et al. 2019; Bukenya, et al. 2014a, b; Bukenya & Moyo, 2017; Oliveira et al. 2012), as well as for detecting and controlling concrete deterioration (Oliveira and Alegre 2020), which can be induced by phenomena like concrete swelling or occur due to exceptional events such as floods or major earthquakes.

For these reasons, continuous vibrations monitoring systems started to be developed and installed in large concrete dams worldwide, in order to assess structural health, based on measured vibrations under ambient/operational excitation, and to monitor the response during seismic events. These are known today as Seismic and Structural Health Monitoring (SSHM) systems, and their implementation has been proposed for new large dams, to evaluate their performance since the first filling of the reservoir, and for some older dams, built decades ago and possibly suffering from deterioration problems, in order to (re-)assess their structural health. Furthermore, considering the lack of available data worldwide, this type of systems can also be extremely useful to obtain additional data for characterizing the seismic actions and for studying the seismic response of large concrete dams under low/medium/high intensity earthquakes.

The SSHM concept has emerged and asserted itself on a global level in the past years, not only due to the needs of owners, managers, and users, but also to the inherent advantages of SSHM and the useful data that can be provided to engineers and researchers, for dynamic behaviour monitoring and structural safety control (Limongelli 2020). Thus, this type of monitoring systems have been installed and used in large structures all over the world, such as tall buildings, long-span bridges, large dams, and other important structures (Li et al. 2016; Limongelli & Çelebi 2019).

In Portugal, the continuous dynamic monitoring of large concrete dams started in 2008, with the development and installation of an SSHM system to continuously measure vibrations under normal operating conditions and during seismic events in Cabril dam (Mendes 2010). This was achieved in the scope of a pioneer project (Oliveira 2002), funded by the Portuguese Foundation for Science and Technology (FCT) and supported by Energias de Portugal (EDP). In light of the success achieved with Cabril dam and of the valuable results obtained in various studies (Alegre et al. 2019; Alegre, Robbe, et al., 2020; Oliveira et al. 2012, 2014; Oliveira & Alegre 2018), the decision was made to invest in the installation of similar SSHM systems at Baixo Sabor dam 2015 (Gomes et al. 2018; Pereira 2019; Pereira et al. 2017, 2018) and at Foz Tua dam (Pereira et al. 2021; Silva Matos, Tavares de Castro, Gomes, and Figueiredo, 2019; Silva Matos, Tavares de Castro, Gomes, Faria, et al. 2019), as well as of trigger-event type systems for measuring seismic vibrations in Alqueva, Alto Ceira II and Ribeiradio dams.

In Africa, the Hidroelétrica de Cahora Bassa (HCB) decided to install a SSHM system in Cahora Bassa dam (Carvalho et al. 2014; Carvalho & Matsinhe 2014), which has been in operation since 2010 to enable the continuous evaluation of its behaviour in normal operating conditions and to measure the response during seismic events (Alegre et al. 2019, 2021; Alegre, Oliveira, et al. 2020). Later, in 2013, a continuous dynamic monitoring system was also installed for structural health monitoring of Roode Elsberg dam, located in Worcester, Western Cape, South Africa, after ambient vibration tests had been carried out for several years (Bukenya 2020; Bukenya, Moyo, & Oosthuizen, 2014; Bukenya & Moyo 2017).

Examples of large concrete dams currently under continuous dynamic monitoring worldwide include Enguri arch dam, 271.5 m high, in Georgia, Beli Iskar gravity dam, 51 m high, in Bulgaria, Xiangjiaba gravity dam, 161 m high, in China, as well as other 23 dams in South Korea (www.geosig.com/Dams-pg38).

SSHM systems for large concrete dams should ideally be designed to measure vibrations in as many locations of the dam body as possible, in several positions along the dam base, and, eventually, in the rock mass foundation (free field), aiming to continuously evaluate the dynamic performance and structural condition of dams and to monitor the response in terms of accelerations when earthquakes hit the dam site. With that goal, the measurement devices should be configured with a high dynamic range, enabling an accurate measurement of low amplitude vibrations, induced by ambient or operational sources or by low intensity earthquakes, and of high amplitude vibrations, caused by strong earthquakes or other exceptional occurrences (Mendes 2010). Moreover, these monitoring systems should include cutting-edge and high-quality equipment for automatic data measurement, acquisition, and transmission, including digitizers, recorders, transducers, accelerometers, data concentrators, etc., which are usually provided by specialized companies. Nevertheless, it is vital to complement the hardware component of the SSHM systems by developing suitable software, which must be adapted and optimized to each dam. This software should include computational tools to automatically process, manage and analyse the continuously recorded data, as well as to enable a simple and intuitive comparison between experimental and numerical results, in order to obtain useful data for dynamic behaviour analysis and for supporting seismic response monitoring and structural health monitoring (Oliveira & Alegre 2020).

Based on the experience gathered over the past decade in this field, particularly from studies on the dynamic behaviour of Cabril dam and Cahora Bassa dam, the combined use of experimental results extracted from continuous dynamic monitoring data and of numerical results obtained with advanced FE models can be extremely useful, namely:

(i) to study the evolution of modal parameters (natural frequencies, mode shapes and damping ratios) over time, enabling (a) to evaluate the influence of water level variations (Alegre et al. 2019; Darbre & Proulx 2002; Sevim et al. 2012) or thermal variations (Okuma et al. 2012; Ueshima et al. 2017) in the dynamic response of dam-reservoir-foundation systems, and b) to investigate the effects due to ageing of dams, evolutive deterioration phenomena, or damage due to strong earthquakes, by comparing the observed behaviour at a certain point in time with a specific reference state (Alegre, Oliveira, et al. 2020; Oliveira and Alegre 2020); (ii) to automatically identify vibrations induced by low, medium, or high intensity seismic events, and then study the seismic response based on recorded accelerations, allowing to analyse the base-to-top acceleration amplification factors and to investigate the damping ratios used in numerical models (Chopra and Wang 2010; Proulx and Darbre 2008; Robbe et al. 2017); and (iii) to calibrate and validate existing models, and support the development of new ones, to be used as reference models in future behaviour prediction studies (Oliveira et al. 2014; Sevim et al. 2011).

This work is dedicated to the study of the dynamic behaviour of two large arch dams, by providing valuable experimental and numerical results, in order to show some of the main theoretical, computational, and practical innovations achieved in recent years for the improvement of continuous dynamic monitoring systems for large concrete dams. Therefore, the programs that have been used in this study are presented. First, the software designed to integrate and complement the SSHM systems installed in large concrete dams is described, including the computational tools: (i) for automatic analysis and management of continuous dynamic monitoring data, aiming to assess data quality, to automatically detect vibrations induced by seismic events, and to perform the maintenance of the database; and (ii) for automatic modal identification, based on the frequency domain decomposition method, in order to obtain experimental natural frequency values and mode shapes. After that, the 3D finite element program developed for dynamic analysis of concrete dams is presented. The program is based on a coupled formulation in displacements and pressures to simulate the dynamic behaviour of the dam-reservoir-foundation system, and it includes three calculation modules, namely for: (i) complex modal analysis, using a state-space formulation that allows to consider generalized damping; (ii) linear seismic analysis, using a coupled time-stepping formulation based on the Newmark method; and (iii) non-linear seismic analysis, considering the opening/closing and sliding movements of joints in the dam body and the non-linear behaviour of concrete up to failure under tension and compression.

The case studies are Cabril dam, 132 m high, in Portugal, and Cahora Bassa dam, 170 m high, in Mozambique, two double curvature arch dams that have been under continuous dynamic monitoring since 2008 and 2010, respectively. The most important results from studies carried out in recent years are provided, with focus on: (i) the analysis of the evolution of the identified natural frequencies over time and the comparison with the corresponding numerical values, aiming to evaluate the influence of the reservoir water level variations and to perform vibration-based detection of evolutive damage; (ii) the study of the measured response during seismic events, based on the comparison between recorded and computed accelerations in various positions of the dam body, in order to investigate the base-to-top amplification factors and the damping ratios required in the numerical models; and (iii) the seismic safety assessment of arch dams, using a method based on Time of Endurance Analysis (ETA), in which dam performance is evaluated considering the evolution of tensile and compressive damage under intensifying seismic accelerations.

2 Used software: monitoring data analysis and finite element dynamic analysis

This work presents some of the most important experimental and numerical results from recent application studies on the dynamic behaviour of two large concrete arch dams. In order to conduct those studies, it was necessary to use software for monitoring data analysis, namely automatic modal identification (*DamModalID*) and automatic detection of vibrations due to seismic events (*DamSeismicVibID*), and for 3DFE dynamic analysis of concrete dams *(DamDySSA*), including modal analysis and linear and non-linear seismic analysis. The developed programs are described next, with emphasis on the innovations considered for the improvement of the software component of SSHM systems for dams.

2.1 Software for automatic analysis of monitoring data from SSHM systems

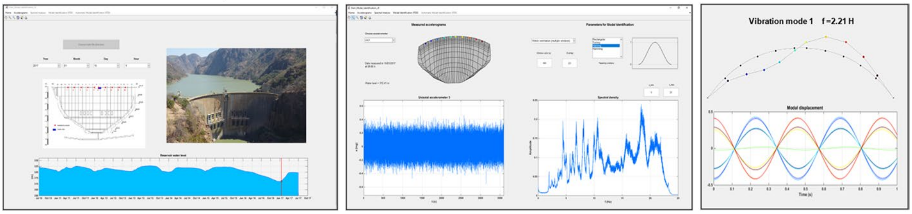
The software component of an SSHM system is fundamental not only to ensure that the system is operating normally and to support maintenance needs, but also to provide useful data for dynamic behaviour analysis and intuitive data for informed decision making (Oliveira and Alegre 2020).

The software specifically developed to integrate and improve the operation of SSHM systems installed in large concrete dams includes essentially two modules that automatically analyse dynamic monitoring data (Fig. 1). Both modules are available on the computer server of the system at the dam site, or they can be accessed remotely using remote access software.

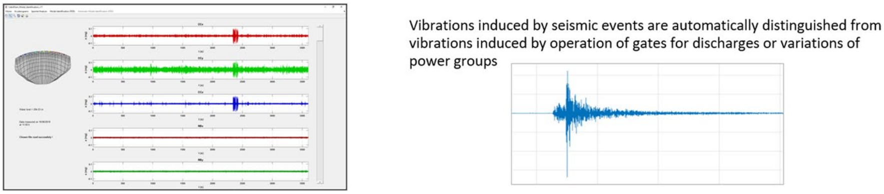
The first module, *DamModalID*, was designed for automated modal identification of dams, based on the Frequency Domain Decomposition method with Singular Value Decomposition (FDD-SVD) (Brincker et al. 2000; Brincker and Ventura 2015). The natural frequencies and mode shapes are estimated from the singular values and singular vectors of

SOFTWARE FOR MONITORING DATA ANALYSIS

***DamModalID**. Modal identification. Interactive and automatic modules*



***DamSeismicVibID**. Automatic identification of seismic vibrations*



Vibrations induced by seismic events are automatically distinguished from vibrations induced by operation of gates for discharges or variations of power groups

Fig. 1 Software for automatic analysis of monitoring data analysis from SSHM systems on large concrete dams the power spectral density matrix, which in turn is calculated from measured vibrations in the dam body. The original version of *DamModalID* performs the automatic modal parameter estimation using, as inputs, the data files containing the signals recorded continuously over time. In addition, an interactive version of the program was also implemented, with its own graphical user interface, to enable occasional data analysis to be conducted based on files collected on specific dates and hours. This interactive version can be useful to conduct parametric modal analysis studies and also to check the quality of recorded data at specific times.

The second module, *DamSeismicVibID*, was prepared to automatically detect vibrations induced on dams by seismic events, and simultaneously to distinguish them from vibrations caused by other operational sources, such as the operation of spillway gates or the operation of the turbines for electric power generation. This is done based on simplified pattern analysis of the recorded acceleration time series, considering the previous experience regarding the patterns usually observed in seismic accelerograms. Ideally, accelerations recorded in the dam body and near the dam-rock interface should be analysed. In case a seismic event is detected, this module automatically sends an email containing relevant information and figures of the recorded acceleration time histories in specific locations. *DamSeismicVIbID* also includes a graphical user interface that allows the user to see the acceleration records and analyse them carefully after an earthquake has been detected.

Both modules contain graphical tools that enable the automatic generation of useful and intuitive figures, showing, e.g., the evolution of natural frequencies over time, the mode shapes, and the recorded acceleration time histories. With these graphical tools, the studies based on the comparison between experimental data and numerical results can be improved, and valuable information can be provided to owners or engineers responsible for dam safety control, and thus help informed management in face of regular maintenance needs or possible emergency situations (Oliveira & Alegre 2020).

2.2 DamDySSA, a program for dynamic analysis of dam-reservoir-foundation systems

Large concrete dams are structures of considerable dimensions, usually with unique and complex geometry. Furthermore, their behaviour under static and dynamic loads is considerably influenced by the interaction with the reservoir and the foundation (Câmara 1989; Pedro and Câmara 1986). The dynamic properties of the dam-reservoir-foundation system can also change significantly over time due to reservoir water level and/or thermal variations and due to structural changes in the dam body, caused by evolutive concrete deterioration (Oliveira 2000) and/or concrete cracking (Cervera et al. 1995; Valliappan et al. 1999) and irreversible joint movements (Clough 1980; Fenves et al. 1992) under strong earthquakes. Therefore, it is essential to develop advanced models for the analysis of dam-reservoir-foundation systems, considering the various scenarios that can occur over the lifetime of dams, involving the variation of the dynamic properties and of the main static and dynamic loads, structural changes due to deterioration processes, and non-linear behaviour (joint movements and concrete damage).

The numerical simulations are carried out in this work using *DamDySSA4.0*, the latest version of a 3D FE program developed for dynamic analysis of concrete dams and optimized for studying arch dams (Fig. 2). The dynamic behaviour of dam-reservoir-foundation systems is simulated based on a coupled model for the dam-reservoir-foundation

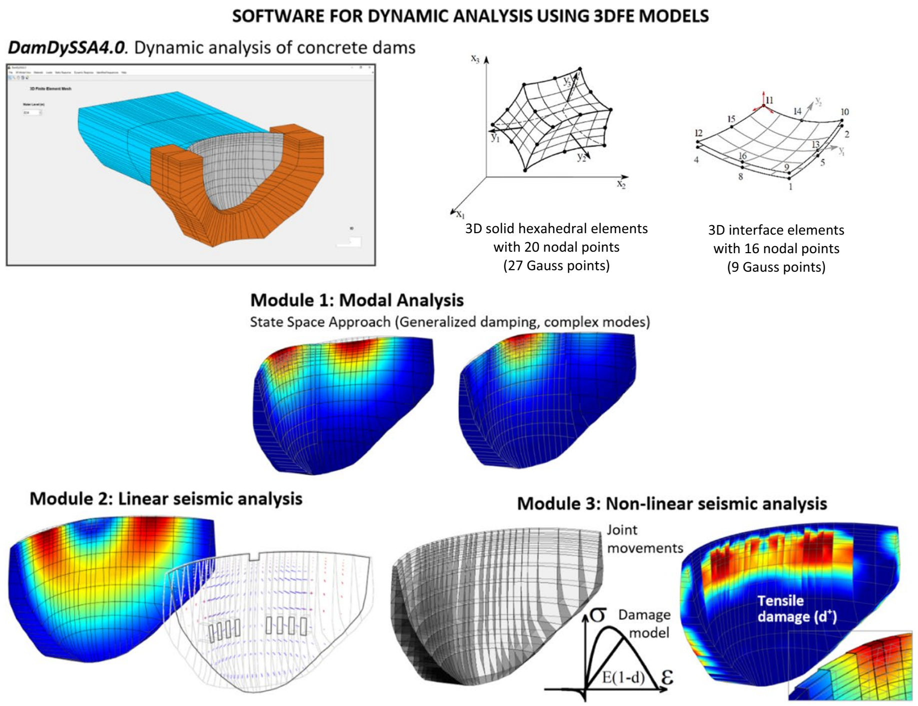


Fig. 2 Software for FE analysis of concrete dam-reservoir-foundation systems

system (Zienkiewicz et al. 2013), using a FE-based formulation in displacements $\underset{\sim}{u}$ (dam and foundation) and pressures $\underset{\sim}{p}$ (reservoir)

$$\begin{bmatrix} \underline{m} & \underline{0} \\ \rho_w \underline{Q}^T & \underline{S} \end{bmatrix} \begin{bmatrix} \ddot{\underset{\sim}{u}} \\ \ddot{\underset{\sim}{p}} \end{bmatrix} + \begin{bmatrix} \underline{c} & \underline{0} \\ \underline{0} & \underline{R} \end{bmatrix} \begin{bmatrix} \dot{\underset{\sim}{u}} \\ \dot{\underset{\sim}{p}} \end{bmatrix} + \begin{bmatrix} \underline{k} & -\underline{Q} \\ \underline{0} & \underline{H} \end{bmatrix} \begin{bmatrix} \underset{\sim}{u} \\ \underset{\sim}{p} \end{bmatrix} = \begin{bmatrix} \underset{\sim}{F}_s \\ \underset{\sim}{F}_w \end{bmatrix} \tag{1}$$

where $\underline{\mathrm{m}}$, $\underline{\mathrm{c}}$ and $\underline{\mathrm{k}}$ are the mass, damping and stiffness matrices for the solid domain, while the terms for the reservoir are $\underline{\mathrm{S}}$, $\underline{\mathrm{R}}$ and $\underline{\mathrm{H}}$. The coupling matrix associated with water-structure motion coupling is $\underline{\mathrm{Q}}$. The nodal force vectors are given by $\underset{\sim}{F}_s = \underset{\sim}{F}_s(t)$ and $\underset{\sim}{F}_w = \underset{\sim}{F}_w(t)$: the forces in solid domain may include those due to static loads, such as the dam self-weight and the hydrostatic pressure on the upstream face, and those induced by dynamic loads; for seismic analysis the force vectors become $\underset{\sim}{F}_s = -\underline{\mathrm{m}}\ \underline{s}\ \underset{\sim}{a}_S$ and $\underset{\sim}{F}_w = -\rho_w\ \underline{\mathrm{Q}}^{\mathrm{T}}\ \underline{s}\ \underset{\sim}{a}_S$, where $\underset{\sim}{a}_S = \underset{\sim}{a}_S(t)$ is the seismic input, which includes three acceleration time histories in the upstream–downstream, cross-valley and vertical directions, and $\underline{s}$ is a matrix to uniformly distribute the seismic accelerations by all degrees of freedom.

Boundary conditions are prescribed at the main interfaces in order to consider the dam-reservoir dynamic interaction, the propagation of pressure waves, the effect of radiation damping in the reservoir, and the reservoir free surface condition (Zienkiewicz et al. 2013). Furthermore, generalized damping is considered, with natural viscous damping in the solid domain and energy dissipation due to radiation in the fluid domain. The substructure method is used to calculate the foundation block as an elastic and massless substructure, considering equivalent stiffness and damping components incorporated in the dam-rock interface, while the seismic input is uniform and applied directly at the dam base.

The discrete dynamic equation of the dam-reservoir-foundation system with generalized damping can be simply written as

$$\underline{M}\ddot{\underset{\sim}{q}} + \underline{C}\dot{\underset{\sim}{q}} + \underline{K}\underset{\sim}{q} = \underset{\sim}{F}, \; \underset{\sim}{q} = \underset{\sim}{q}(t) = \begin{bmatrix} \underset{\sim}{u} \\ \underset{\sim}{p} \end{bmatrix} \tag{2}$$

and a coupled approach is adopted for solving the problem without splitting for displacements and pressures (Alegre 2021).

The discretisation of the dam-foundation-reservoir system, resorts to solid hexahedral finite elements, with 20 nodes (isoparametric elements with interpolation functions of the 2nd degree, which are integrated using 27 Gauss points). The main discontinuities (dam-foundation interface, vertical contraction joints, and possible cracks) are discretized using the corresponding interface elements with 16 nodes and 9 integration Gauss points. The referred solid and interface elements are represented in Fig. 2.

In the latest version of the program *DamDySSA*, the numerical analysis of Eq. 2 is carried out using three calculation modules, namely for: (i) complex modal analysis (module 1), using a coupled state-space approach that enables the consideration of generalized damping, and the computation of natural frequencies, non-stationary modes, and damping ratios of the whole dam-reservoir-foundation system; (ii) linear seismic analysis (module 2), using a coupled time-stepping procedure based on the Newmark method for numerical integration in displacements and pressures, assuming linear elastic behaviour for concrete and joints; and (iii) for non-linear seismic analysis, by combining the time-stepping method with the stress-transfer method, to account for the redistribution of unbalanced stresses, and considering the concrete behaviour up to failure, based on an isotropic damage model (Oliveira and Faria 2006) with softening and two independent scalar damage variables (d^+ for tension and d^- for compression), and the opening, closing, and sliding joint movements, using a simple constitutive model based on the Mohr–Coulomb failure criterion and on normal and shear relative displacement-stress laws (Fenves et al. 1992; Lau et al. 1998).

The main outputs of *DamDySSA4.0* include 3D graphic representations of mode shapes, deformed shapes with joint movements, stress fields at both upstream and downstream faces, acceleration time histories, and tensile and compressive damage distributions.

3 CABRIL DAM

3.1 Dam characteristics and installed SSHM system

Cabril dam, the highest dam in Portugal (Fig. 3), has ben in operation since 1954. Located on the Zêzere river, it is a 132 m high double curvature arch dam, with a 290 m long crest, at the elevation 297 m. The central section maximum thickness is of about 20 m at the dam base, and the minimum thickness is 4.5 m, about 10 m below the crest. Regarding the foundation, Cabril dam was constructed on a good quality granite rock mass. The reservoir water level usually ranges from a minimum at el. 265 m to the maximum storage level at el. 295 m. Regarding the appurtenant works, there is a reinforced concrete intake tower upstream of the dam, which is connected to the crest of central cantilever through a concrete walkway, with a joint in the dam-tower contact. In what concerns the dam's structural

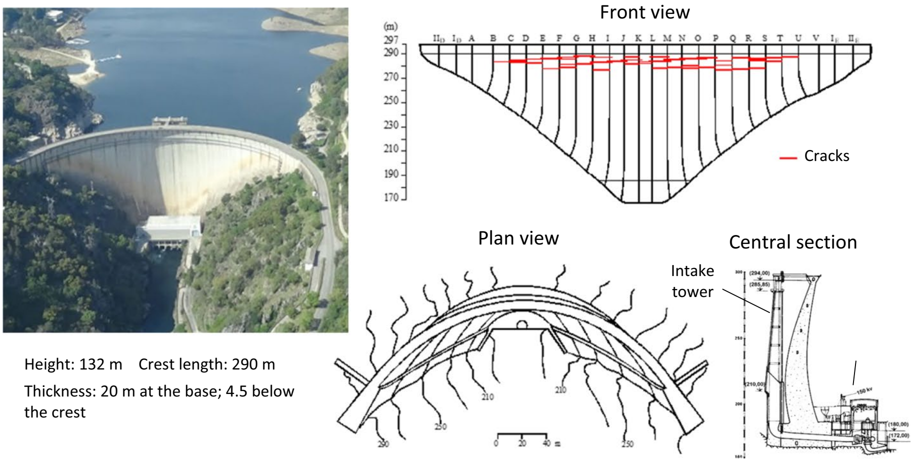


Fig. 3 Cabril dam. Aerial view and technical drawings

health, it is worth mentioning that horizontal cracking was observed at upper part of the downstream face, around el. 280 m to 290 m, during the first filling of the reservoir. Also, a concrete swelling process was detected in the late 1990s.

The continuous dynamic monitoring system of the Cabril dam was conceived and implemented as part of a research project (Oliveira 2002), financed by the FCT and supported by EDP, carried out in collaboration with the Department of Concrete Dams and the Scientific Instrumentation Centre of Laboratório Nacional de Engenharia Civil (LNEC). The development of this system (Mendes 2010) involved the design of the monitoring scheme, the assembling and installation of all equipment (optical fibre networks, data concentrators, accelerometers, etc.), and finally the development of software for automatic data processing, management, and analysis. The goal of this SSHM system was to continuously monitor the dam's dynamic behaviour over time in normal operating conditions and to measure the dam response during seismic events.

Therefore, the monitoring scheme (Fig. 4) was outlined to record accelerations at the upper part of the dam structure and near the dam-rock interface, using 16 uniaxial (EpiSensor ES-U2) and 3 triaxial (EpiSensor ES-T) force balance accelerometers from Kinemetrics, Inc. (https://kinemetrics.com/). The uniaxial sensors measure accelerations in the

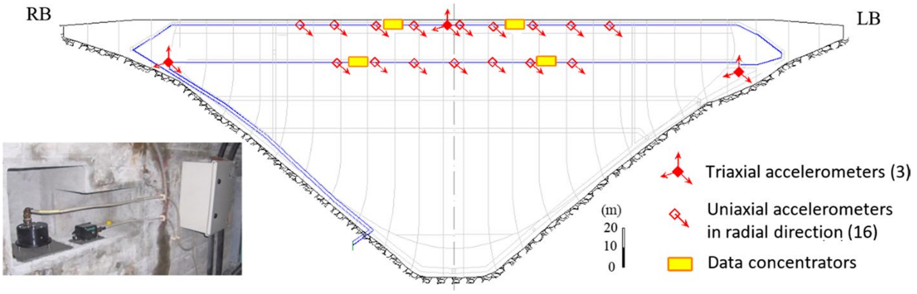


Fig. 4 Seismic and Structural Health Monitoring system installed in Cabril dam in 2008

radial direction: 9 are located in the upper gallery, at el. 294 m, below the crest, and 7 are positioned in the second gallery, at el. 274 m, below the cracked zone. As for the triaxial sensors, one is installed in the upper gallery, in the central section, while the other two are located inside the dam base gallery, in both banks, around el. 274 m. Aiming to achieve a high dynamic range (Mendes 2010), to enable the accurate measurement of low amplitude vibrations, due to ambient/operational sources or lower intensity earthquakes, and high amplitude vibrations, cause by strong earthquakes, full-scale recording ranges of ±0.25 g and of ±1 g were prescribed for uniaxial and triaxial sensors, respectively. In what concerns data acquisition and transmission, all 25 channels are connected to a modular system, composed by an optical fibre network and four data acquisition units that gather all recorded data, which is then sent to the central computer server installed in the office at the dam's power plant. Basically, 25 acceleration time histories are recorded, in 24 bit and at a sampling rate of 1000 Hz, collected, and stored in the central server, every hour. The system was not active during some periods over the first decade of monitoring, due to either malfunctions or damages in sensors and/or data acquisition units. However, the several visits for maintenance and repairs, the system has been fully operational since June 2008.

In order to ensure a proper operation of the system and to provide useful information on Cabril dam's behaviour, the SSHM system was complemented with the installation of specific software, namely for collecting and processing measured data, automatic data management and analysis, including the module for detection of vibrations induced by seismic events (*DamSeismicVibID*), and for automatic modal identification of dams (*DamModalID*).

3.2 Numerical model of Cabril dam

The linear and non-linear dynamic behaviour of Cabril dam is simulated with the program *DamDySSA4.0,* considering the 3DFE model discretization of the dam-reservoir-foundation system presented in Fig. 5 (Alegre 2021) and using the aforementioned hexahedral finite elements with 20 nodes and the corresponding interface elements. Regarding the key mesh metrics, the percentage of FE with acceptable aspect ratio is 98.4% and that of FE acceptable skewness index is 97.3%; these are usual values for 3D dam meshes as is the case, e.g., of the mesh provided by ICOLD for the 13th Benchmark Workshop on the Numerical Analysis of Dams (Gunn et al. 2016).

The dam concrete and the foundation rock are isotropic materials, considering Young's modulus $E = 25$ GPa and Poisson's ratio $\nu = 0.2$, assuming a factor of 1.3 applied to E for dynamic calculations. The water in the reservoir is a compressible fluid with a pressure wave propagation velocity of $c_w = 1440$ m/s (mean temperature of around 15 °C). The existing cracking band is simulated in a simplified way as a single horizontal crack, incorporated by introducing duplicate notes and interface elements at el. 285 m. However, the current model does not include the intake tower.

For linear dynamic analysis, the concrete has linear behaviour (no damage) and a version of the model without any joints is used. As for non-linear seismic analysis, the non-linear behaviour of concrete up to failure is simulated using a strain-softening constitutive damage model, considering tensile strength $f_t = 3\ MPa$ and compressive strength $f_t = -30\ MPa$; moreover, all vertical contraction joints and the surface along the dam-foundation interface are incorporated into the model, considering appropriate normal and shear stiffness values and stress-displacement laws to simulate opening/closing and sliding movements.

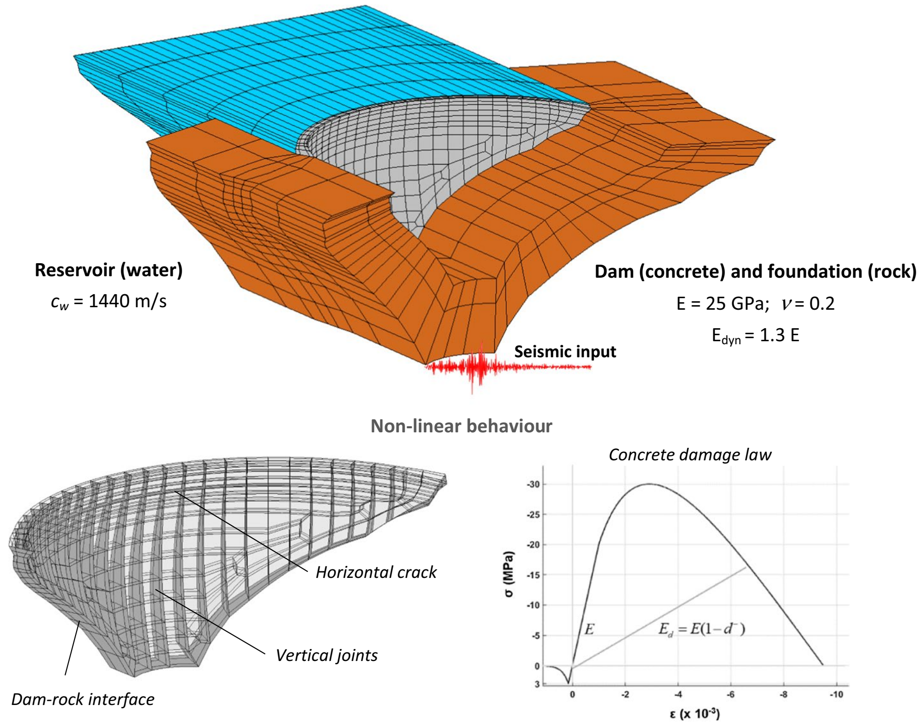


Fig. 5 Cabril dam: 3DFE model of the dam-reservoir-foundation system. Material properties, joint elements, and constitutive damage law for concrete

3.3 Modal analysis. Evolution of natural frequencies over time

This section presents results on the dynamic behaviour of Cabril dam in normal operating conditions, under ambient/operational vibrations, for the monitoring period between December 2008 and December 2020. The natural frequencies and mode shapes identified using *DamModalID* are presented and then compared with numerical results obtained with *DamDySSA*. The aim is, on the one hand, to evaluate the influence of reservoir level variations on the dynamic behaviour of the dam-reservoir-foundation system, and, on the other hand, to show how this study can be of value for vibration-based damage detection.

Figure 6 shows the evolution of the identified natural frequencies for the first five vibration modes of Cabril dam, for the whole monitoring period (2008–2020), with a reservoir level variation from el. 261.5 m, 31.5 m below the crest, to el. 295 m, 2 m below the top, representing a maximum 33.5 m variation. Based on these results it is possible to see that the dynamic properties of the dam-reservoir-foundation system and thus the dynamic behaviour the dam are clearly influenced by the water level in the reservoir, given that the frequency values follow the water level variations over time: the higher the water level, the higher the global mass of the system, the lower the frequency values. This effect is more noticeable for the modes with higher natural frequencies. As for thermal variations, the air temperature amplitude of only around ± 8° over the year, and thus its influence in the dynamic response of the dam is not considered here.

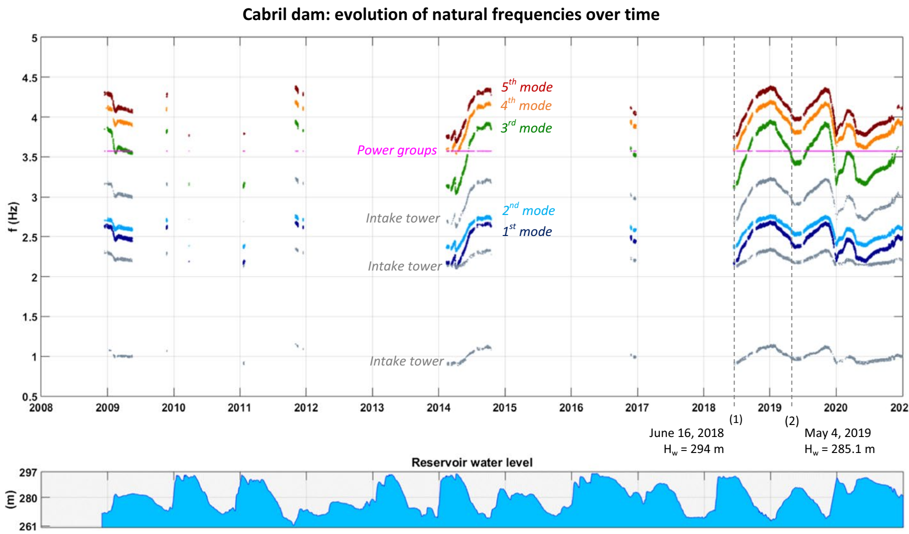


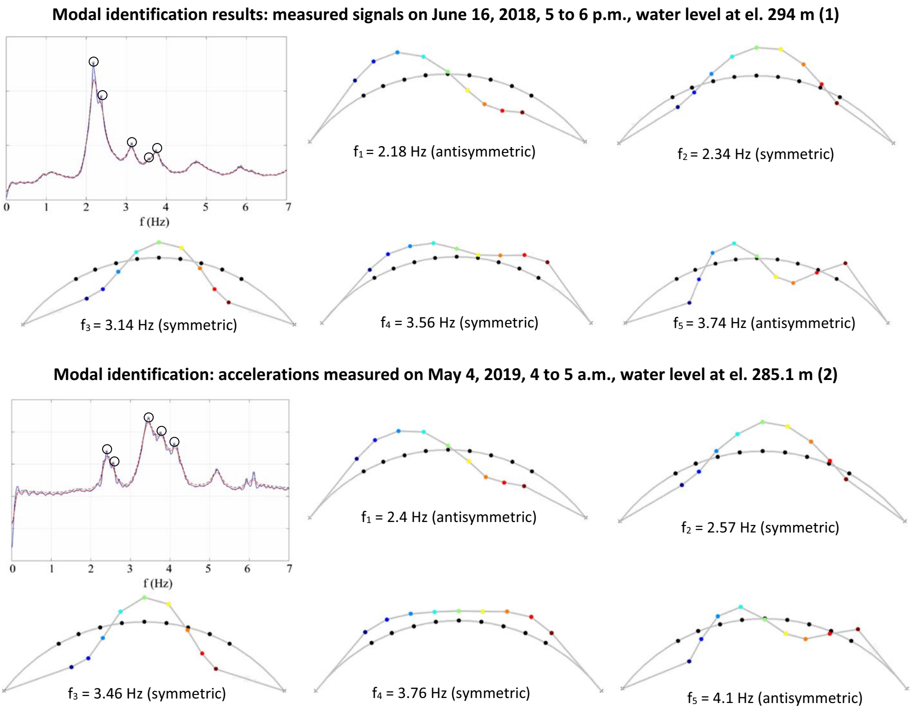
Fig. 6 Results from continuous dynamic monitoring of Cabril dam: evolution of identified natural frequencies over time (2008 to 2020)

Furthermore, modes that are most likely associated with the vibrations of the intake tower are also detected: for lower water levels, the tower leans against the dam, inducing a certain dam-tower dynamic interaction (Mendes and Oliveira 2009), while for higher water levels the joint opens and tower and dam are separated. The modal identification results also display the frequencies associated with the operation of the energy production groups, with rotation frequency of 3.57 Hz.

The frequencies and mode shapes of the first five modes, estimated from the accelerations measured on June 16, 2018 (17 h-18 h), corresponding to a reservoir level at el. 294 m, and on May 4, 2019 (4 h–5 h), for the water level at el. 285.1 m, are presented in Fig. 7. These dates are identified as (1) and (2), respectively. The first and fifth modes are antisymmetric, while the second and third modes are symmetric. Also, it is worth noting that the configuration of the fourth mode is clearly influenced by the existing horizontal cracking in the downstream face, resulting in the oscillation of the upper blocks of the dam body.

The comparison between the identified (circles) and computed (lines) natural frequencies over time is provided in Fig. 8. Overall, a good agreement was achieved between experimental and numerical natural frequencies for the first five vibration modes, especially for higher water levels, given that the dam-tower interaction is not as significant. Afterwards, Fig. 9 presents the numerical frequency values and mode shapes calculated considering the reservoir water level in the model at both el. 285 m and el. 293.5 m. The shapes of modes 1 (antisymmetric), 2 (symmetric), and 3 (symmetric) are well reproduced by the model, while for modes 4 and 5 the mode shapes are swapped.

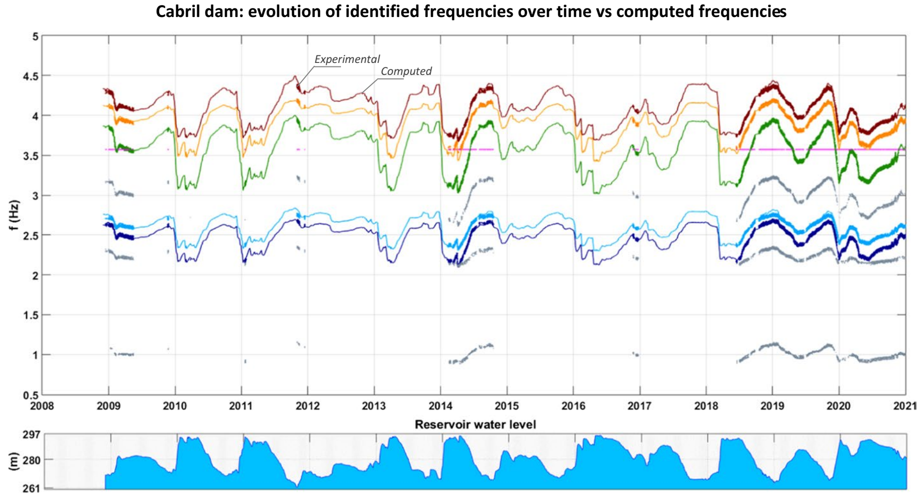
The results achieved in this application study allowed to show the usefulness of the SSHM installed in Cabril dam and of the program *DamModalID*, as well as the potential of the 3DFE program *DamDySSA* for simulating the dynamic response of dam-reservoir-foundation systems. Nevertheless, additional studies are proposed in the future to



Modal identification results: measured signals on June 16, 2018, 5 to 6 p.m., water level at el. 294 m (1)

Modal identification: accelerations measured on May 4, 2019, 4 to 5 a.m., water level at el. 285.1 m (2)

Fig. 7 Results from continuous dynamic monitoring of Cabril dam. Singular value spectra and estimated frequencies and mode shapes for two specific dates and reservoir water levels



Cabril dam: evolution of identified frequencies over time vs computed frequencies

Fig. 8 Comparison between identified natural frequencies over time and computed frequencies for Cabril dam

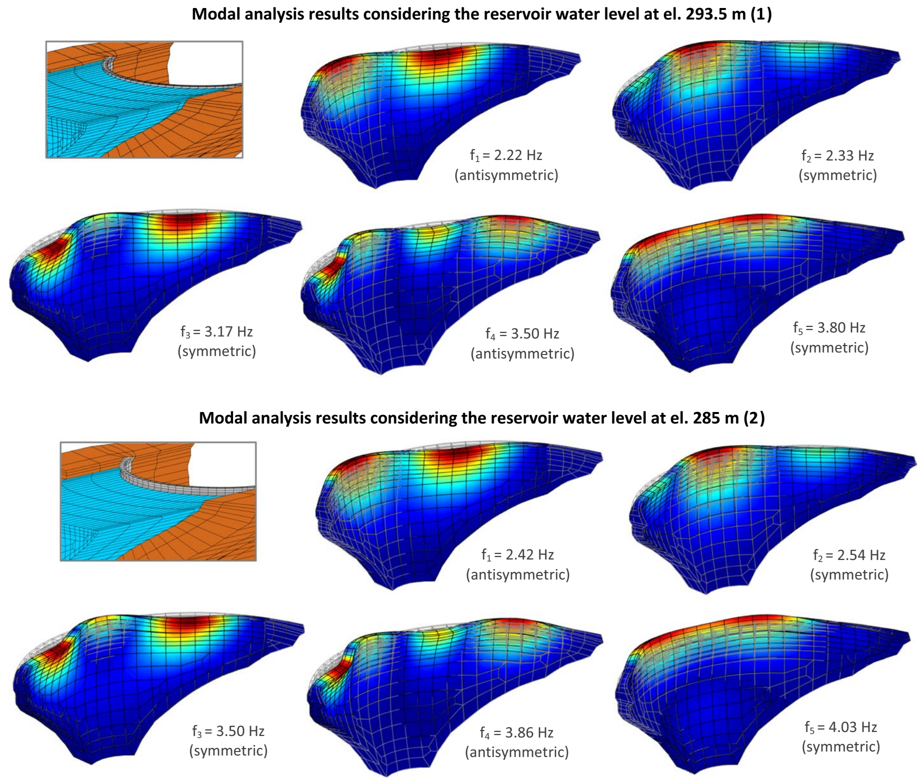


Fig. 9 Finite element modal analysis of Cabril dam: frequencies and mode shapes for two reservoir water levels

better understand the phenomena associated with the intake tower and with the horizontal cracking.

In order to show how the combined use of information extracted from continuous vibrations monitoring and of numerical results can be applied for vibration-based damage detection and hence for evaluate the structural integrity of dams, an additional comparative analysis is provided in Fig. 10. The identified natural frequency values of the first mode (in red) are compared with the computed frequency values (in blue), using a) a linear reference model, without concrete damage, and b) a model that simulates the scenario of evolutive damage during the period under analysis (2008–2020), considering a gradual damage variation between 0 and 5% over the whole dam body (uniform reduction of the elasticity modulus).

First, it can be noted that the identified frequency values based on recent data are similar to the values in the early monitoring period. Furthermore, the differences between the identified frequencies and the values computed using the reference model without damage remain the same, for similar water levels, over the entire monitoring period. However, the frequency curves computed for a scenario of evolutive damage start to diverge from the identified frequencies. Therefore, this comparative analysis seems to indicate that the dynamic behaviour of Cabril dam has not changed over the

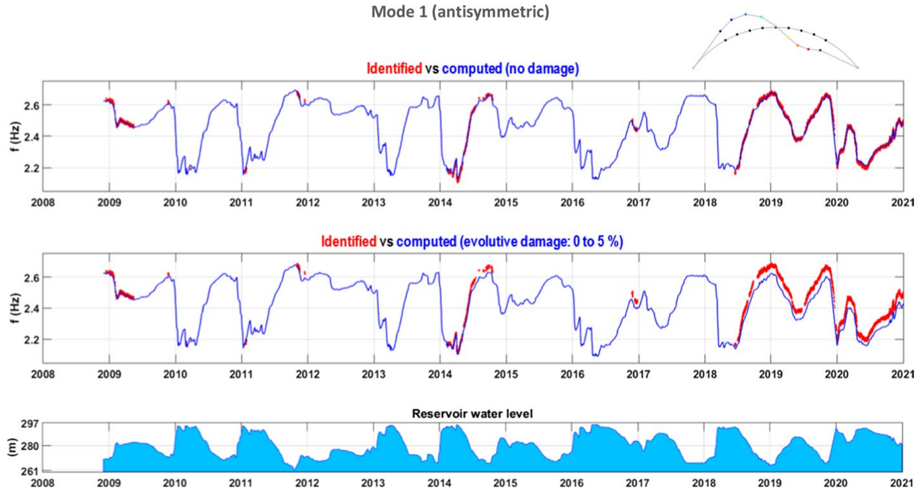


Fig. 10 Vibration-based analysis for damage detection. Evolution of the identified natural frequency of the first mode over time (2008–2020 and comparison with results from numerical simulations using a reference model and a model with evolutive damage (0 to 5%)

last decade, which means that the existing deterioration phenomena are not affecting the structural integrity of the dam in a significant way.

3.4 Measured seismic response

In this section the analysis of the dynamic response of Cabril dam during a seismic event is presented. The seismic acceleration time histories recorded with the SSHM system are compared with the numerical accelerations computed using *DamDySSA4.0* (Fig. 11), in order to analyse the accelerations amplification from the dam-rock surface to the crest centre point, and to investigate the required damping ratio to be used in the numerical model for simulating the measured dam response.

The seismic response of Cabril dam is analysed for an earthquake of magnitude 4.6 that occurred on September 4, 2018, with epicentre in the Peniche abyssal region (off the coast of Portugal), at 206 km from the dam. The seismic waves hit the dam from the west-northwest, approximately in the cross-valley direction. On that day, the water level was at 281.2 m, 15.8 m below the crest. This earthquake originated low amplitude vibrations in the dam, from 1 to 4 mg; as expected, the greater accelerations were recorded at the central upper part of the structure. The peak ground acceleration at the dam-rock interface (1.31 mg) was recorded with the triaxial sensor at the right bank, while the maximum acceleration in the dam body (3.62 mg) occurred at the top of central section, both in the upstream downstream direction. The acceleration amplification factor from the RB foundation to the crest centre was of around 2.8.

The FE seismic simulations were conducted using the numerical model shown previously in Fig. 5, assuming linear behaviour, and considering the reservoir level at el. 281 m and the accelerations recorded at the right bank as the uniform seismic input. Figure 11 shows the comparison between measured and computed accelerations at the upper gallery, in the central section of the dam, in the cross-valley, upstream–downstream, and vertical directions.

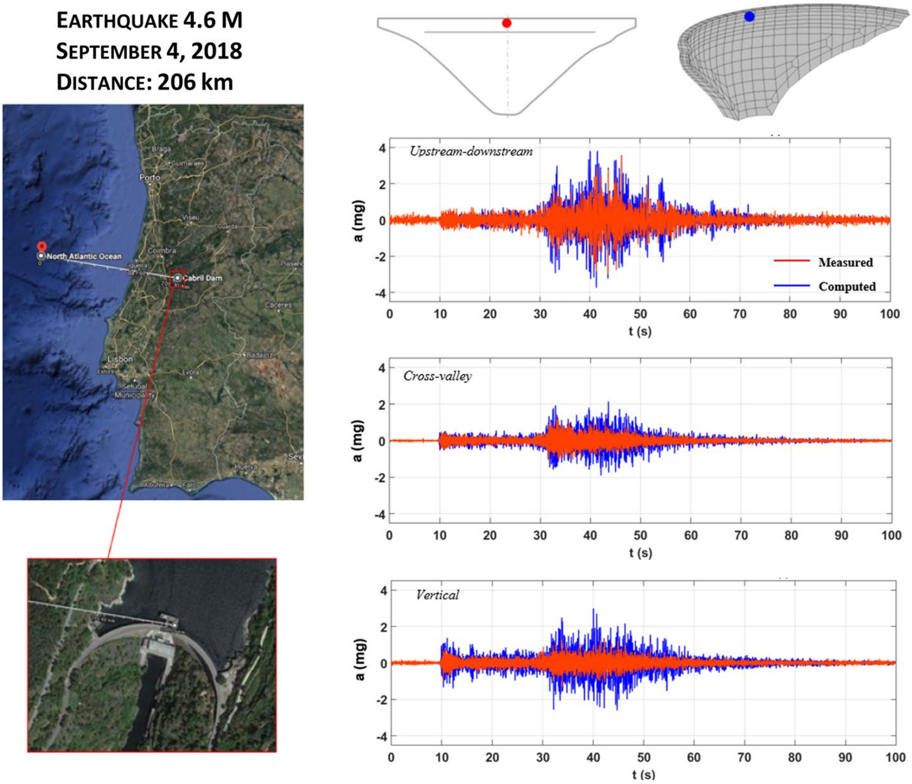


Fig. 11 Seismic response of Cabril dam: seismic event (4.6 M) on September 4, 2018. Comparison between measured and computed accelerations—upper gallery, central section

The provided result show that there is a good fit with the computed accelerations in the upstream–downstream direction, while in the cross-valley and vertical directions the response is overestimated. However, to achieve this agreement it was necessary consider use a damping ratio of about 10% around the frequency band 2–3 Hz (first vibration modes), which is an unusually high value for arch dams (Chopra and Wang 2012; Proulx and Darbre 2008; Robbe et al. 2017).

This comparative study enabled to show not only the reliability of Cabril dam's SSHM system to measure vibrations during seismic events, even those of lower amplitude induced by earthquakes with epicentres at a great distance from the dam site, but also the interest of seismic records measured on site to help in the validation and calibration of numerical models used for dam seismic behaviour simulation.

Nevertheless, important questions were also raised on numerical modelling of the linear seismic response of Cabril dam, particularly in what concerns the need to use such a high damping value in order to reproduce the measured response. In the case of this dam, this difficulty may be related to the use of an inadequate seismic input, namely of a seismic accelerogram measured in the RB upper dam-foundation interface, since an accelerometer has not yet been installed at the bottom of the valley. Therefore, with a view to improve the characterization of the seismic action and to allow a better understanding of the seismic behaviour of Cabril dam it is planned the installation of a new triaxial accelerometer at the dam downstream base.

3.5 Non-linear seismic response. Safety assessment based on endurance time analysis

This section presents the most important results from a study on the non-linear seismic behaviour of Cabril dam under intensifying seismic accelerations (Fig. 12). The goal is to assess the seismic safety of the dam based on an Endurance Time Analysis (Estekanchi et al. 2004). Therefore, the tensile and compressive damage distributions are analysed at increasing excitation levels in order to evaluate the performance of the dam (Fig. 13).

The numerical simulations were carried out using *DamDySSA* and the non-linear version of the model presented above in Fig. 5, considering both damage in concrete and joint movements. The seismic response was calculated for the dynamic load combination involving the self-weight of the dam (SW), the hydrostatic pressure for full reservoir (HP297), and an intensifying seismic load (SeismicL) applied in the upstream–downstream direction. The considered seismic input was an ETA acceleration time history provided in (Salamon et al. 2021), with increasing peak accelerations (a_p) from 0 to 1.5 g in 15 s (Fig. 12).

In what concerns the seismic safety assessment, a method for empirical evaluation of the seismic performance of the dam was adopted. Essentially, the seismic safety was verified at the end of each second of the seismic simulation based on the damage distributions, until an endurance limit was reached (Fig. 13). The criterion adopted here respects to the damage extension at both upstream and downstream faces, and particularly along the thickness of the main dam cantilevers: the occurrence of considerable areas in which damage propagates across the whole thickness is considered unacceptable.

For the case of Cabril dam, the endurance limit for tensile damage was of 6 s ($a_p = 0.6$ g), since that at this excitation level significant tensile damage stars to cover an extensive area of the downstream face, which even propagates along the thickness of some of the shorter, lateral cantilevers. Moreover, there is an increase of tensile damage at the upstream face and concrete failure starts to cross from upstream to downstream in some areas of the upper part of the dam, even in the central cantilevers. However, it is worth emphasizing that compressive damages only appear after 10 s ($a_p = 1$ g), while the first occurrence of concrete

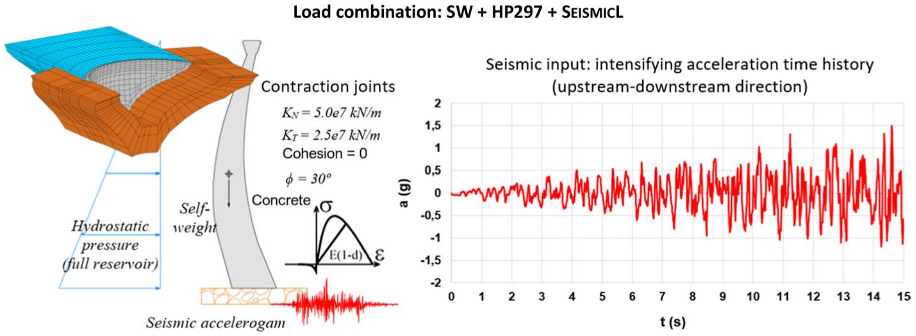


Fig. 12. 3DFE model of the dam-reservoir-foundation system used for non-linear seismic analysis of Cabril dam. Joint properties, concrete constitutive law, load combination, and intensifying seismic input used for ETA

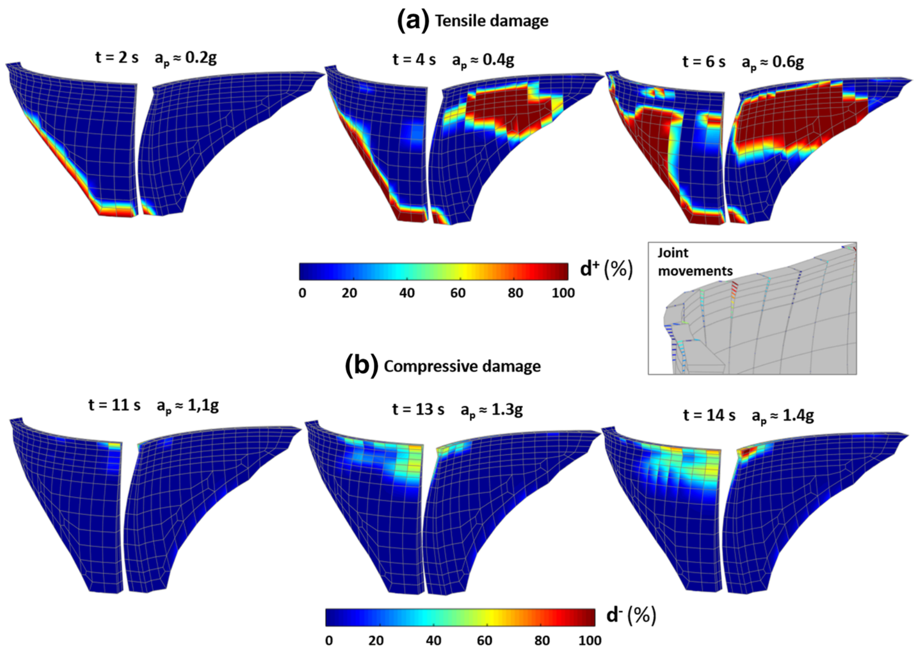


Fig. 13 Non-linear seismic behaviour of Cabril dam. Performance for increasing ETA excitation levels: evolution of tensile (**a**) and compressive damage distributions (**b**)

failure under compression is seen at the top of the central cantilevers, which increase progressively until 14 s ($a_p = 1.4$ g).

In synthesis, the results of the non-linear seismic response of Cabril dam obtained with the ETA allowed to conclude that Cabril dam presents a very good performance for high seismic excitation levels, corresponding to peak ground accelerations that could perfectly be prescribed for seismic safety verification studies. The Cabril dam is capable of withstanding seismic accelerations that are 3 times greater than those defined for the Maximum Design Earthquake (MDE: $a_p = 0.2$ g) without severe tension damage, and 7 times greater than that defined for the MDE without considerable compressive damage (no collapse).

4 Cahora Bassa Dam

4.1 Dam characteristics and installed SSHM system

Cahora Bassa dam, located on the Zambezi River in western Mozambique, near the village of Songo, came into operation in late 1974. This dam is a 170 m high thin double curvature arch dam with a 303 m long crest, which is at an elevation of 331 m (Fig. 14). The thickness of the central section varies from 23 at the base to 4 m at the crest, which presents a particular half hollow geometry. This large concrete dam has a surface spillway, in the middle of the crest, and eight half-height spillways, with a combined discharge capacity of 14 000 m^3. On the upstream face there are several concrete ribs, extending extend from the crest to the top of the half-height spillways, which are used to raise and lower the spillway

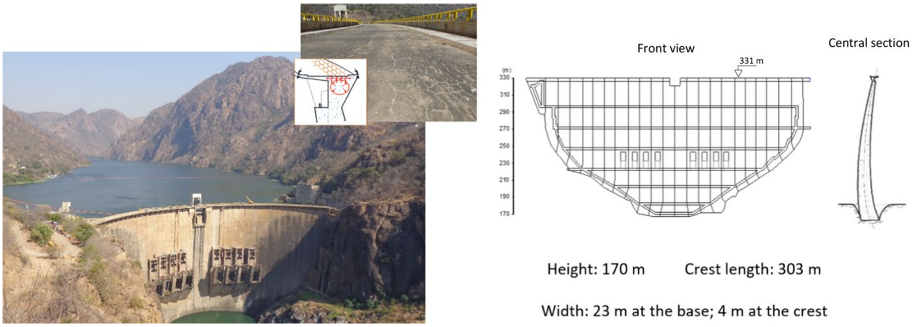


Fig. 14 Cahora Bassa dam. Downstream view, crest cracking view, and technical drawings

gates. The dam was built on a gneiss granite rock mass of very good quality. The Cahora Bassa hydroelectric plant, located on the south bank of the river, is the largest hydroelectric project in southern Africa.

Regarding known pathologies, a process of concrete swelling was detected in the 1980s, as evidenced by a typical hexagonal crack pattern on the crest surface. Also, upward and upstream evolutive displacements due to swelling have been measured over time.

The SSHM system of Cahora Bassa dam was installed in 2010 to allow the continuous evaluation of dam behaviour in normal operating conditions, under ambient/operational vibrations, and during seismic events. So, the system is prepared to provide useful experimental information for structural health monitoring and for seismic behaviour control. Acceleration records are recorded in various locations, namely in dam body, near the crest and near the base of the central section, and in the foundation, close to the dam-foundation interface, in both banks (Fig. 15). For that, the monitoring system comprises 10 uniaxial accelerometers (EpiSensor ES-U2) and 3 triaxial accelerometers (EpiSensor ES-T) from Kinemetrics. The uniaxial sensors, which measure accelerations in the radial direction, are installed in the upper gallery, at el. 326 m. As for the triaxial sensors, two are located in the right and left banks, in the rock, and the third one is position at the downstream base of the dam, in the central section. To achieve a system with a high dynamic range, extremely

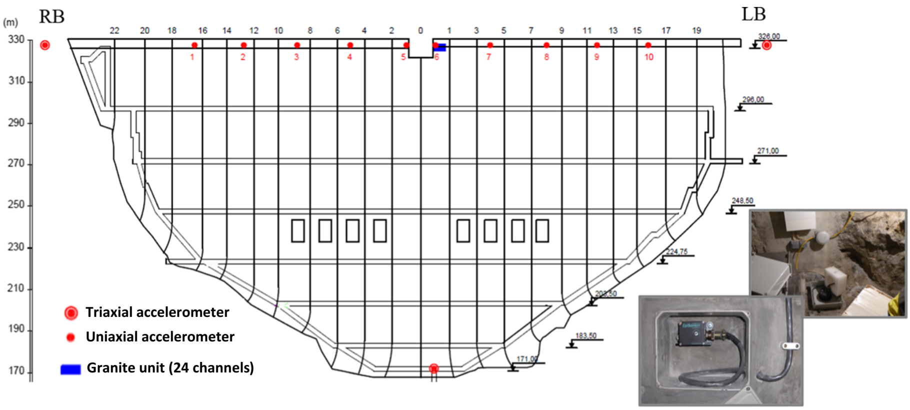


Fig. 15 Seismic and Structural Health Monitoring system installed in Cahora Bassa dam in 2010

low noise sensors with a full-scale recording range of ± 1 g were used. All sensors are connected through a local optical fibre network to a single 24-channel data acquisition Granite unit from Kinemetrics (24 bit). To summarize, 19 acceleration time histories are continuously recorded, every hour, at a sampling rate of 50 Hz, and then transmitted to the computer server in the dam's control centre.

4.2 Numerical model of Cahora-Bassa dam

The numerical simulations for Cahora Bassa dam are performed using the program *DamDySSA* and the model discretisation of the dam-reservoir-foundation system (Alegre 2021) shown in Fig. 16, considering hexahedral finite elements with 20 nodes and the corresponding interface elements (as in the previous example). In what concerns the mesh metrics, the percentage of elements with acceptable aspect ratio is 92.4% and that of elements with acceptable skewness index is 99.1%; as previously mentioned, these are suitable values for 3DFE meshes used in dam engineering numerical studies (Gunn et al. 2016).

The dam concrete and the foundation rock are isotropic materials, with the same values for Young's modulus E = 40 GPa and Poisson's ratio $\nu = 0.2$, and considering a 25% increase of E for dynamic analysis. The reservoir water is a compressible fluid, assuming

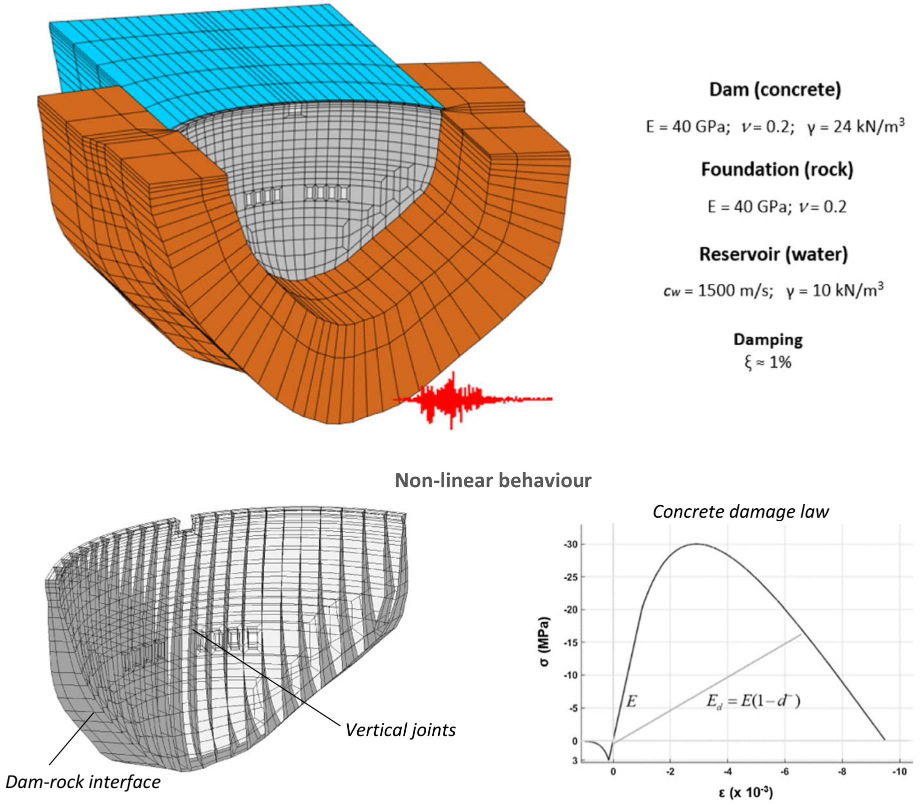


Fig. 16 Cahora Bassa dam: 3DFE model of the dam-reservoir-foundation system. Material properties, joint elements, and constitutive damage law for concrete

an average pressure wave propagation velocity $c_w = 1500$ m/s since the water temperature in the reservoir showed seasonal oscillations between 20 and 30 °C. The current model of Cahora Bassa dam does account for the concrete ribs at the upstream face, and it does not incorporate the surface and half-height spillways. The version of the model used for non-linear seismic calculations considers the non-linear behaviour of concrete up to failure, using a strain-softening constitutive damage law with tensile strength $f_t = 3$ MPa and compressive strength $f_c = -30$ MPa, and it incorporates all vertical contraction joints and the surface along the dam-foundation interface, assuming appropriate normal and shear stiffness values and stress-displacement laws to account for opening/closing and sliding movements.

4.3 Modal analysis. Evolution of natural frequencies over time

This section is focused on analysing the dynamic behaviour of Cahora Bassa dam in normal operating conditions, under ambient/operational excitation, between August 2010 and June 2020. The modal parameters are extracted from monitoring data using *DamModalID*, and the dynamic calculations are performed using *DamDySSA*. As in the case of Cabril dam, the goal is to investigate the influence of water level variations on the dynamic response of the dam-reservoir-foundation system and to show how the combined use of experimental and numerical frequencies can be used for damage detection.

Figure 17 presents the comparison between the automatically identified natural frequencies over time (circles), based on vibrations measured during the entire monitoring period, with a reservoir level variation from el. 312 m to el. 326 m, and the numerical frequency curves, computed in various numerical simulations conducted considering with different reservoir levels, for the first three vibration modes. The calculated frequencies and 3D mode shapes are also displayed for two reservoir water levels (Fig. 18), at el. 326 m and el. 315 m: mode 1 is antisymmetric, while modes 2 and 3 are symmetric.

The provided modal analysis results show once again that the water level variations have a significant influence on the dynamic response of the dam, as indicated by the correlation between the water levels and the frequency values. For example, the natural frequencies vary from 1.95 to 1.78 Hz, for the first mode, and from 2.4 to 2.16 Hz,

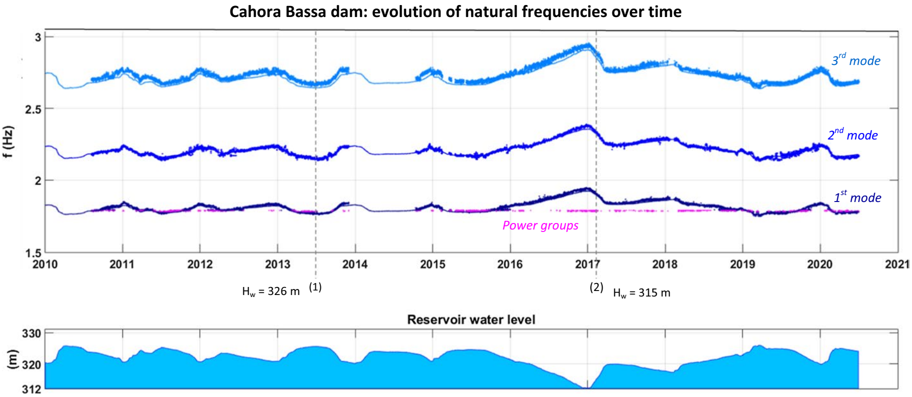


Fig. 17 Continuous dynamic monitoring of Cahora Bassa dam: evolution of identified natural frequencies over time (2010 to 2020) and comparison with computed frequency values

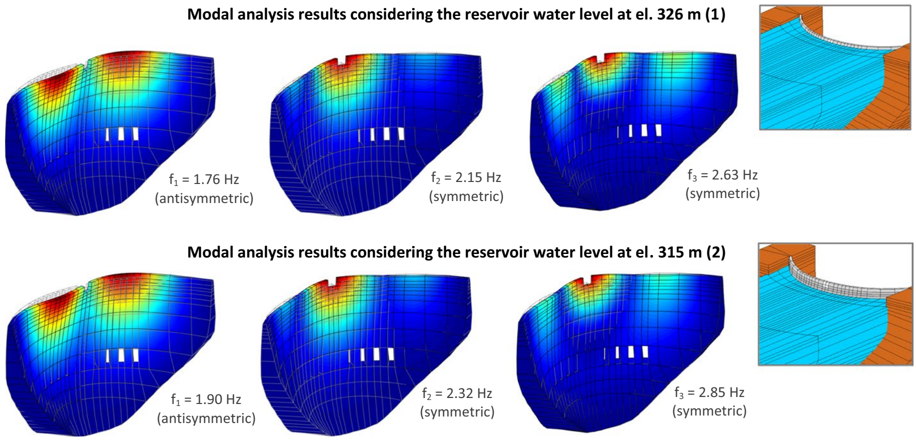


Fig. 18 Finite element modal analysis of Cahora Bassa dam: mode shapes and frequency values for two reservoir water levels

for the second mode. In comparison with Cabril dam, it is worth mentioning that for Cahora Bassa dam the variations in the frequency values for modes with similar frequencies are lower, given that the water level variations are not as significant. Moreover, in Cahora Bassa dam, the temperature semi-amplitude is around ± 4 °C throughout the year, and thus the influence of thermal variations was not considered. Furthermore, the figure displays the identified frequencies associated with the power groups, with rotation frequencies at 1.79 and at 3.57 Hz.

The comparative analysis presented here also shows that it was possible to reach a good agreement between experimental and numerical frequency values for Cahora Bassa dam, for the first three vibration modes. The comparison improves as the water level increases, but even for lower reservoir levels the observed differences are not greater than 0.1 Hz.

Despite the good results that have been obtained in recent studies for Cahora Bassa dam, further analyses are proposed in order to investigate vibration modes with higher frequencies, in terms of the frequency value evolution over time and of the mode shapes. if possible, the future calculations should be carried out using a more advanced FE model of the dam that incorporates new geometry details, particularly in what concerns the upstream face concrete ribs, the half-height spillways, and the half-hollow crest.

In the scope of structural health monitoring of Cahora Bassa dam, next is a comparison between the identified natural frequencies for the first and second modes (in red) and the computed frequency curves (in blue), considering a linear reference model without damage (Fig. 19). By analysing the presented results for a decade of continuous dynamic vibrations monitoring, it is possible to see that recent experimental frequencies are similar to those obtained in the first monitoring years, for the same water levels, and that the experimental/numerical relation for the natural frequencies is stable over the last decade. As such, it can be concluded that the concrete swelling process does not seem to be significantly affecting the dam's structural integrity, since its dynamic response has not changed in a noticeable way over the past ten years.

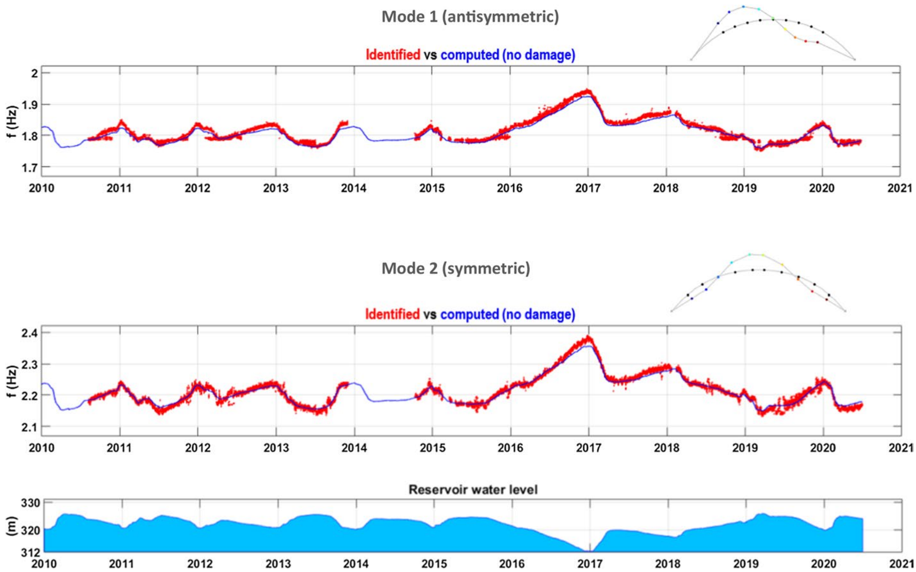


Fig. 19 Vibration-based analysis for damage detection. Evolution of the identified natural frequency of the first and second modes over time (2010–2020) and comparison with results from numerical simulations using a reference model without damage

4.4 Measured seismic response

This section presents an analysis of the seismic response of Cahora Bassa dam, measured during an earthquake that occurred on June 21, 2017 (Fig. 20). It was estimated that the distance to the epicenter would be approximately 32 km. The seismic waves reached the dam site from the west-northwest, between the upstream–downstream and cross-valley directions. The reservoir level was at el. 319.7 m (11.3 m below the crest) that day. This was a low intensity, near seismic event that caused low amplitude vibrations in the dam. The maximum ground accelerations recorded at the downstream base were 22 mg in the cross-valley direction, 9 mg in the upstream–downstream direction, and 6 mg in the vertical direction. The maximum acceleration recorded at the upper gallery was of 38 mg, resulting in a base to top acceleration amplification factor of about 4.2 in the upstream–downstream direction.

The linear seismic calculations were performed using the numerical model of the dam shown before (Fig. 16), considering the water level at el. 319 m in the model and using the acceleration records measured at the base of the central section as the seismic input. The comparison between recorded and computed accelerations in Fig. 20 shows the good agreement reached for the point located in the upper gallery. Unlike in the study for Cabril dam, where a high damping ratio of 10% was required since the seismic accelerations measured on the right bank were used as input, in the case of Cahora Bassa dam the good measured/calculated agreement was achieved considering a reasonable damping ratio of 1% (for the lower natural frequencies).

The comparative study presented in this work clearly demonstrates the capacity of the SSHM system installed at the Cahora Bassa dam to measure vibrations induced by seismic events, as well as the interest of measured in-situ accelerations to validate

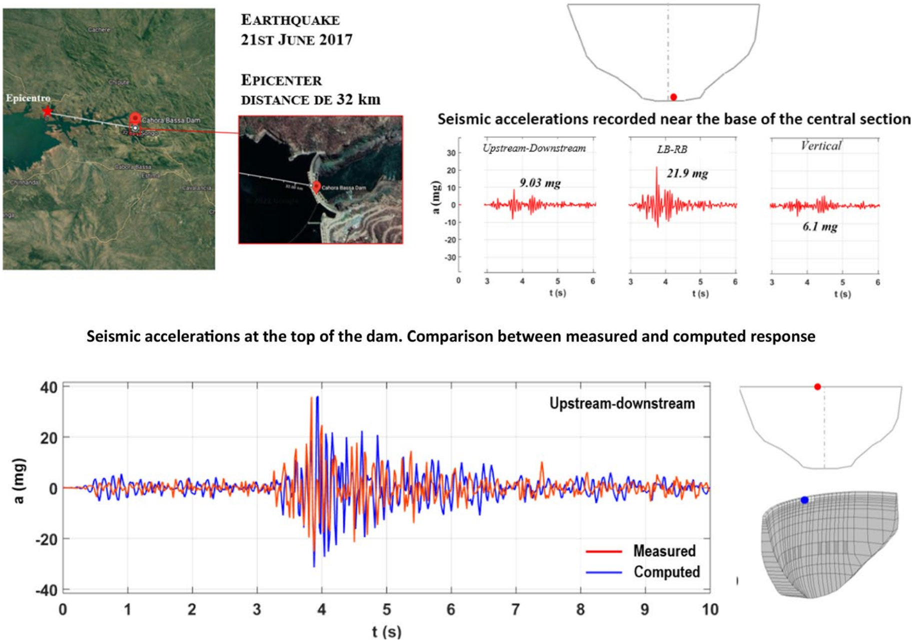


Fig. 20 Seismic response of Cahora Bassa dam: seismic event on June 21, 2017. Comparison between measured and computed accelerations—upper gallery, central section

and calibrate the numerical models, which are later used in seismic safety verification studies.

4.5 Non-linear seismic response. Safety assessment based on Endurance Time Analysis

In this section, the non-linear seismic response of the Cahora Bassa dam is analysed under seismic accelerations of increasing amplitude (Fig. 21), with the goal of evaluating the performance of the dam based the ETA method (Estekanchi et al. 2004). The seismic safety assessment is carried out based on the evaluation of the evolution of both tensile and compressive damage distributions (Fig. 22), considering the same performance criteria adopted before for the case of Cabril dam in order to define the endurance limits.

The non-linear calculations were performed using *DamDySSA4.0* and considering the non-linear model of Cahora Bassa dam (recall Fig. 16), considering concrete damage and the effects due to joint movements. The seismic response was computed for the load combination with the dam self-weight (SW), the hydrostatic pressure for full reservoir (HP331), and an intensifying seismic accelerogram (SEISMICL) applied in the upstream–downstream direction (Fig. 21).

For the case of the Cahora Bassa dam, the endurance limit is defined as 5 s ($a_p = 0.5$ g), as for this excitation level the tensile damage is mostly superficial, although it starts to occur in a significant area of the downstream surface (Fig. 22). However, for higher excitation levels, tensile damage extends over significant areas of the upstream and downstream faces and starts to propagate through the thickness of most cantilevers, which would not

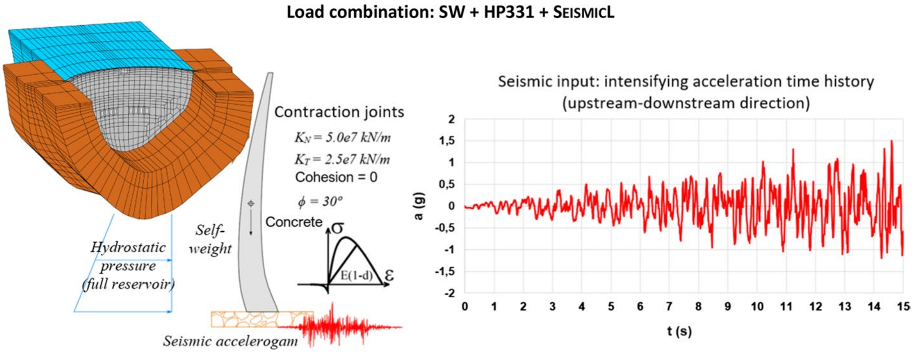
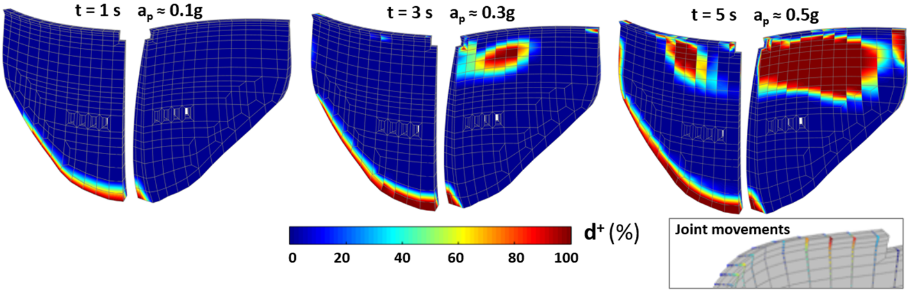


Fig. 21. 3DFE model of the dam-reservoir-foundation system used for non-linear seismic analysis of Cahora Bassa dam. Joints properties, concrete constitutive law, load combination, and intensifying seismic input used for ETA

(a) Tensile damage



(b) Compressive damage

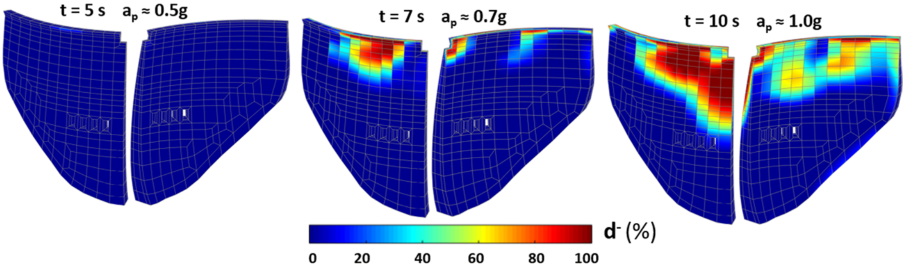


Fig. 22 Non-linear seismic behaviour of Cahora Bassa dam. Performance for increasing ETA excitation levels: evolution of tensile (**a**) and compressive damage distributions (**b**)

be acceptable. Also, until t = 5 s, there is no noteworthy compressive damage. However, high compressive damage starts to occur after 7 s, which progressively increases up to 10 s ($a_p = 1$ g), when the compressive failure of the concrete crosses the entire thickness in the upper blocks of the central cantilevers. In summary, the results achieved in the Endurance Time Analysis of Cahora Bassa Dam allow to conclude that this dam presents a very good seismic performance, even for excitation levels up to 5 times higher than the prescribed

Maximum Design Earthquake (MDE), which corresponds to a peak ground acceleration of 0.1 g (Li-EDF-KP 2001).

5 Conclusions

This work presented complete studies on the dynamic behaviour of two large arch dams that have been under continuous dynamic monitoring for over a decade, Cabril dam (Portugal) and Cahora Bassa dam (Mozambique), considering some of the most important innovations achieved for the improvement of SSHM systems for dams. Essentially, the adopted methodology considers the integrated use of computational tools for automatic monitoring data analysis, including the identification of modal parameters and the detection of seismic vibrations, and of a program for simulating the dynamic behaviour of dams, namely complex modal analysis, and linear/non-linear seismic analysis, as well as the development of graphical tools to enable a simple and intuitive comparison between experimental and numerical results. The presented results intended to show the value of this type of approach, particularly for increasing knowledge on the dynamic behaviour and to support the safety control of large concrete dams.

Experimental results, obtained from continuous dynamic monitoring data using the programs *DamModalID* and *DamSeismicVibID*, were compared with numerical results, computed using the FE program *DamDySSA*, for both dams. Regarding the evolution of the natural frequencies over time and the corresponding mode shapes, overall, a good agreement was achieved between experimental and numerical modal parameters when the linear reference models (without damage) are used. The conducted comparative studies allowed not only to calibrate the reference models, but also to demonstrate how the combination of results extracted from SSHM data and results from FE calculations can be useful to support structural health monitoring, by applying vibration-based damage detection methodologies—the obtained results seem to indicate that the existing deterioration phenomena have not significantly affected the dynamic performance of Cabril and Cahora Bassa dams in normal operating conditions over the last decade. Furthermore, the results showed that the dynamic behaviour of both dams is clearly influenced by the variations of the reservoir water level. In what concerns the seismic response during low-intensity earthquake events, the comparison between measured and computed accelerations was important to further investigate the seismic behaviour of both dams, as well as to calibrate the damping parameters required as inputs in the FE models. For Cahora Bassa dam, considering the accelerations recorded at the dam base as seismic input, a good agreement was achieved using a damping ratio around 1%. As for Cabril dam, since the seismic input consisted of accelerations recorded near the dam-rock interface, but at a much higher elevation than the dam base, a higher damping value was required to reproduce the measured response; as a result, the installation of a new triaxial accelerometer at the bottom of the valley (i.e., at the downstream base) of Cabril dam has been proposed, in order to improve the characterization of the seismic action and allow a better understanding of the seismic behaviour of the dam.

Furthermore, the non-linear seismic behaviour of both Cabril dam and Cahora Bassa dam was numerically simulated using *DamDySSA*, considering the effects due to joints movements and the concrete behaviour up to failure under tension and compression. The load combinations involved the dam self-weight, the hydrostatic pressure for full reservoir, and an intensifying seismic action. The seismic performance of both dams was evaluated using a safety assessment method based on ETA, considering the evolution of tensile and compressive damage over time. The presented results allowed to confirm that Cabril dam (medium seismicity zone, MDE: 0.2 g) and Cahora Bassa dam (low seismicity zone: MDE: 0.1 g) present a very good resistant capacity, being able to withstand peak ground accelerations of about 0.6 g and 0.5 g, respectively, without tensile damage occurring across the entire thickness of the main cantilevers. Moreover, both dams are also capable of supporting seismic accelerations of about 1.4 g and 1.0 g, respectively, without presenting severe compressive damage in key areas of the dam body.

The results obtained in the presented application studies emphasized the potential of the programs developed for automatic modal identification (*DamModalID*) and automatic detection of seismic vibrations (*DamSeismicVibID*), particularly to integrate and improve the software component of SSHM systems installed in large concrete dams and demonstrated the reliability of *DamDySSA* to simulate the linear and non-linear dynamic behaviour of arch dam-reservoir-foundation systems.

Finally, this paper showed the importance that SSHM systems can have for the safety control of large concrete dams, as long as the systems are complemented with appropriate software for the analysis of vibrations monitoring data and with numerical models for dynamic behaviour analysis, in addition to the installation of adequate equipment for data measurement, acquisition, transmission, and storage. In this way, it will be possible to provide important results for monitoring deterioration processes over time and seismic behaviour monitoring, which can be of great interest for dam owners and engineers responsible for dam safety control. Moreover, this type of approach can also be useful for investigating the dynamic behaviour of dam-reservoir-foundation systems, and thus help calibrate the current numerical models or support the development of new models, which are then used in behaviour prediction studies.

Acknowledgements The authors thank Eletricidade de Portugal (EDP) and Hidroeléctrica de Cahora Bassa (HCB) for their efforts in the installation and maintenance of the SSHM systems of the Cabril dam and Cahora Bassa dam, respectively.

Funding The authors thank the Portuguese Foundation for Science and Technology (FCT) for the initial funding for the acquisition of equipment for the Cabril Dam (REEQ / 815 / ECM / 2005), for the funding of the SFRH/BD/116417/2016 doctoral scholarship and for the funding of the Project “Seismic and Structural Health Monitoring for Large Concrete Dams (SSHM4Dams)”, PTDC / ECI-EGC / 5332/2020.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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