Seismic and Structural Health Monitoring of Cabril dam

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Abstract. *This paper is focused on the Portuguese experience regarding the development and operation of continuous vibrations monitoring systems in large concrete dams. The goal is to emphasize the importance of the combined use of monitoring data and numerical models for Seismic and Structural Health Monitoring (SSHM) of Dams. The case study is Cabril arch dam (132 m high), the highest dam in Portugal, in which a pioneer SSHM system has been in operation since 2008. This system, installed by LNEC, was designed for measuring accelerations in the dam body and near the base (dam-foundation interface), using 16 uniaxial and 3 triaxial accelerometers. Appropriate software has been developed to integrate and complement the monitoring system, aiming to automatically process and analyse the recorded data, including tools for simplified study of monitoring results and for automatic comparison with numerical results from 3DFE models. The main experimental results obtained for Cabril dam are presented, namely the evolution of natural frequencies over time, mode shapes and the measured seismic response to an earthquake event. A comparison with results from numerical modelling is presented, using a coupled 3DFE model based on a formulation in displacements and pressures, considering a state space approach to simulate the dynamic behaviour of the dam-reservoir-foundation system and the Newmark method to compute the seismic response.*

1 INTRODUCTION

Nowadays, the installation of monitoring systems for continuously measuring vibrations is being proposed for most of the new large dams and for some of the older dams, given that these are civil engineering structures of great relevance and that are associated with high potential risk in case of collapse [1]. Thus, the safety control of large concrete dams tends to rely on Seismic and Structural Health Monitoring (SSHM) systems, aiming to study the dynamic response of dams both under seismic events and ambient or operational excitations (usually sampling frequencies of about 50 Hz are used, however, for seismic monitoring it may be useful to adopt higher sampling frequencies, e.g. up to 1000 Hz). In Portugal [2] (Fig. 1), the structural health monitoring of large concrete dams using systems for continuously measuring vibration started in 2008, when LNEC and Electricidade de Portugal (EDP) decided to install a pioneer SSHM system for monitoring the

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dynamic behaviour of Cabril dam over time, under ambient/operation excitations and/or seismic events [3]. This system was designed and implemented in the scope of a LNEC research program, supported by EDP and the Portuguese Foundation for Science and Technology (FCT). Following the success achieved with the system installed in Cabril dam, considering the important results obtained in several studies [4,5,6,7] EDP made the decision to install similar complete monitoring systems in other dams, namely in Baixo Sabor dam (2015) and Foz Tua dam. Other systems for measuring seismic vibrations in dams are installed in Alqueva dam, Alto Ceira II dam and Ribeiradio dam.

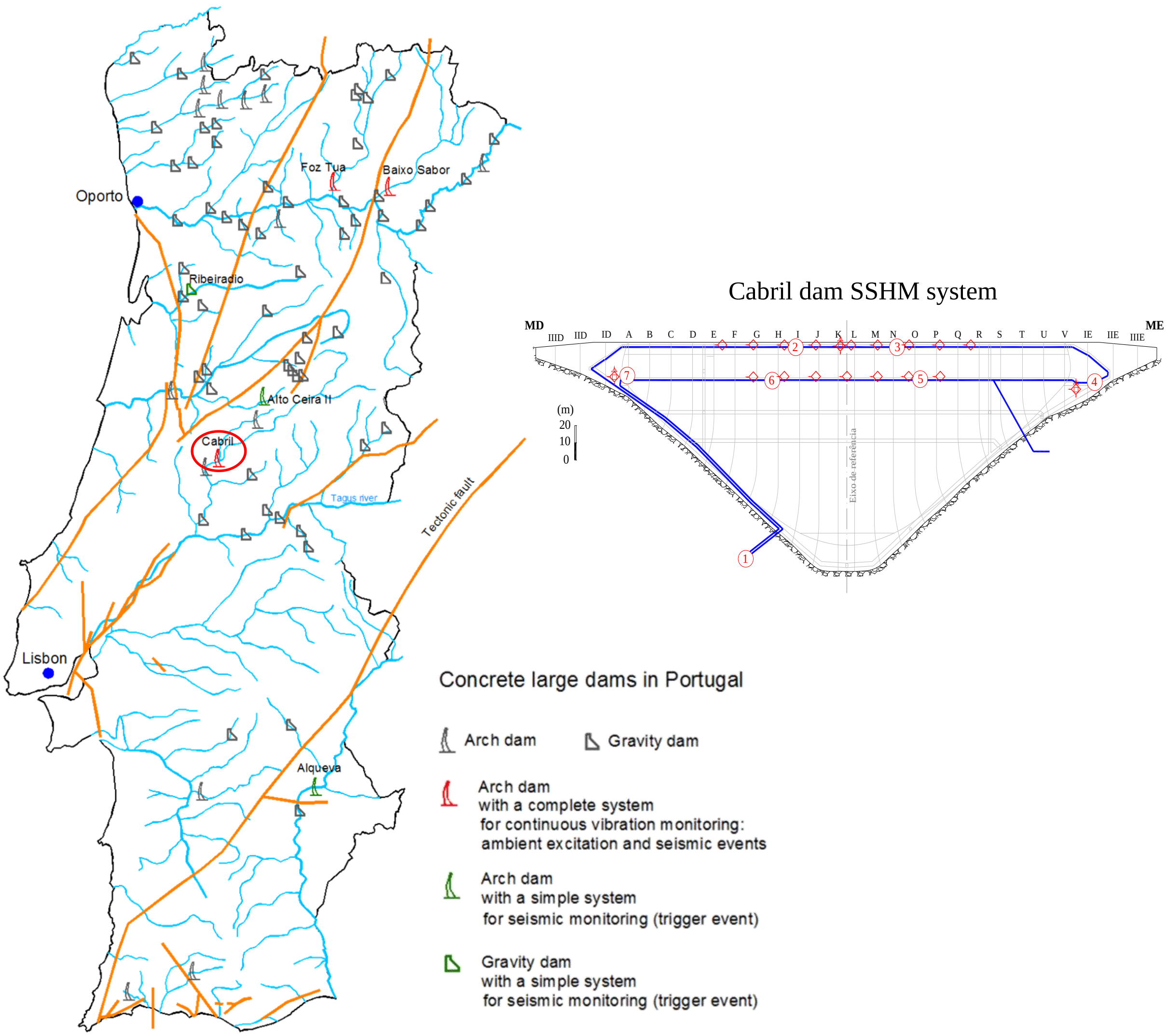

Figure 1: Concrete dams in Portugal and seismic faults. Indication of dams with monitoring systems installed for measuring vibrations under ambient/operation excitations and/or seismic events.

2 DYNAMIC MONITORING OF LARGE DAMS. HARDWARE AND SOFTWARE.

For large concrete dams, the installation and operation of SSHM systems for continuous dynamic monitoring aims to measure physical quantities (e.g. accelerations) in the dam body and in the foundation, using the latest technology for automatic data acquisition. Nevertheless, besides the need for the installation of quality hardware (transducers, data acquisition and transmission, etc.), the efficiency and accuracy of these systems depend heavily on the use of sophisticated software to process, manage and analyse the recorded data. Currently, this is one of the main issues regarding the successful operation of monitoring systems, given that the equipment suppliers only deliver the specific software for data acquisition. Therefore, in order to improve the efficacy of the new SSHM systems, it has become necessary to develop appropriate software adapted and optimized to each dam thus enabling to carry out interactive and/or automatic analysis of monitoring data and to perform the comparison with numerical results from 3DFEM models [4], as has been done in LNEC in recent years [2]. In this way, important results can be provided for engineers/technicians responsible for dam safety control and health monitoring [4,5,6,7], to study the dynamic behaviour for ambient and operational excitations (e.g. to study the evolution of natural frequencies and mode shapes over time in order to characterize the effects of water level and/or seasonal variations, and in order to detect structural changes due to material deterioration), and to evaluate the structural response under seismic loading (for earthquakes with different peak accelerations and different frequency content). This data is also of great use to calibrate and validate the developed numerical FE models used to predict the seismic response of dams.

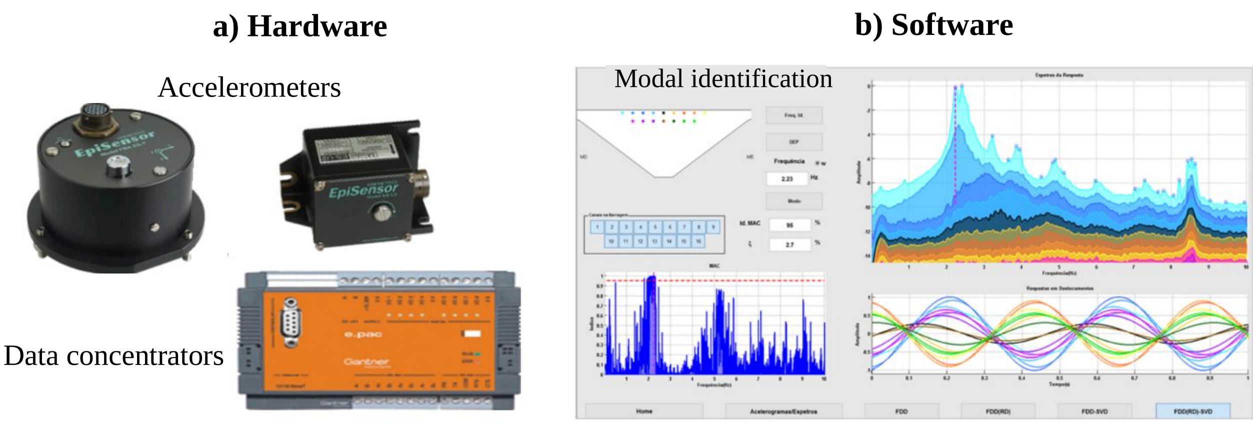

Figure 2: SSHM monitoring. Hardware components and software for modal identification.

3 CABRIL DAM. SEISMIC AND STRUCTURAL HEALTH MONITORING:

Cabril dam (Fig. 3a), the highest dam in Portugal, is located on the Zêzere river and has been in operation since 1954. This is a double curvature arch dam, founded on a granite mass rock foundation, with the particularity of presenting a greater thickness in the crest. The dam has a maximum height of 132 m above the foundation and the crest, which reaches an elevation of 297m, is about 290 m long. The central cantilever has a maximum width of 20 m at the base and a minimum width of 4.5 m below the crest. In this dam, a significant horizontal cracking phenomenon occurred near the crest (at the height 280-290 m) during the first filling of the reservoir. Also, a concrete swelling process has been detected in the late 90’s. As for the reservoir, the water surface level usually ranges from a minimum of about 265 m to the maximum storage level of 294 m (the maximum flood level is 296.3 m) throughout the year.

As mentioned previously, in the framework of LNEC research activities regarding monitoring and modelling the dynamic behaviour of dams, a pioneer SSHM system was installed in Cabril dam in 2008 [3] (Fig. 3b). The installation of the hardware components was carried out by the Scientific Instrumentation Centre, while the software presented in this work was developed in the Concrete Dams Department. The goal was to implement a system with high dynamic range, capable of a continuous and accurate measurement of the dam's response for ambient/operation excitations or earthquakes of various magnitudes. The system was designed to continuously measure accelerations in the upper zone of the dam body and near the base, thus including 16 uniaxial and 3 triaxial accelerometers. The outlined configuration was based on experience gathered in LNEC over the years, from both monitoring data and numerical results. The uniaxial accelerometers (measure vibrations in a radial direction) are distributed in the upper part of the dam by two galleries, above and below the cracked zone. As for the triaxial accelerometers, one is positioned in the central cantilever (upper gallery), while the other two are installed near the insertion of the dam base, in both banks. The accelerometers are connected to a modular system composed by acquisition/digitalization units, which in turn are controlled by 4 data concentrators that receive the recorded data. This data is sent through a local optical fibre network (intranet) to a computer in the observation and control station (OCS), located at the dam power station. In total, 25 accelerograms are recorded and stored every hour, continuously, at a sampling rate of 1000 Hz. Storage and management of the collected data is carried out at the server located in the OCS using appropriate software developed in LNEC. The data can be accessed remotely via internet (a smartphone can be used to explore the collected data with the referred software).

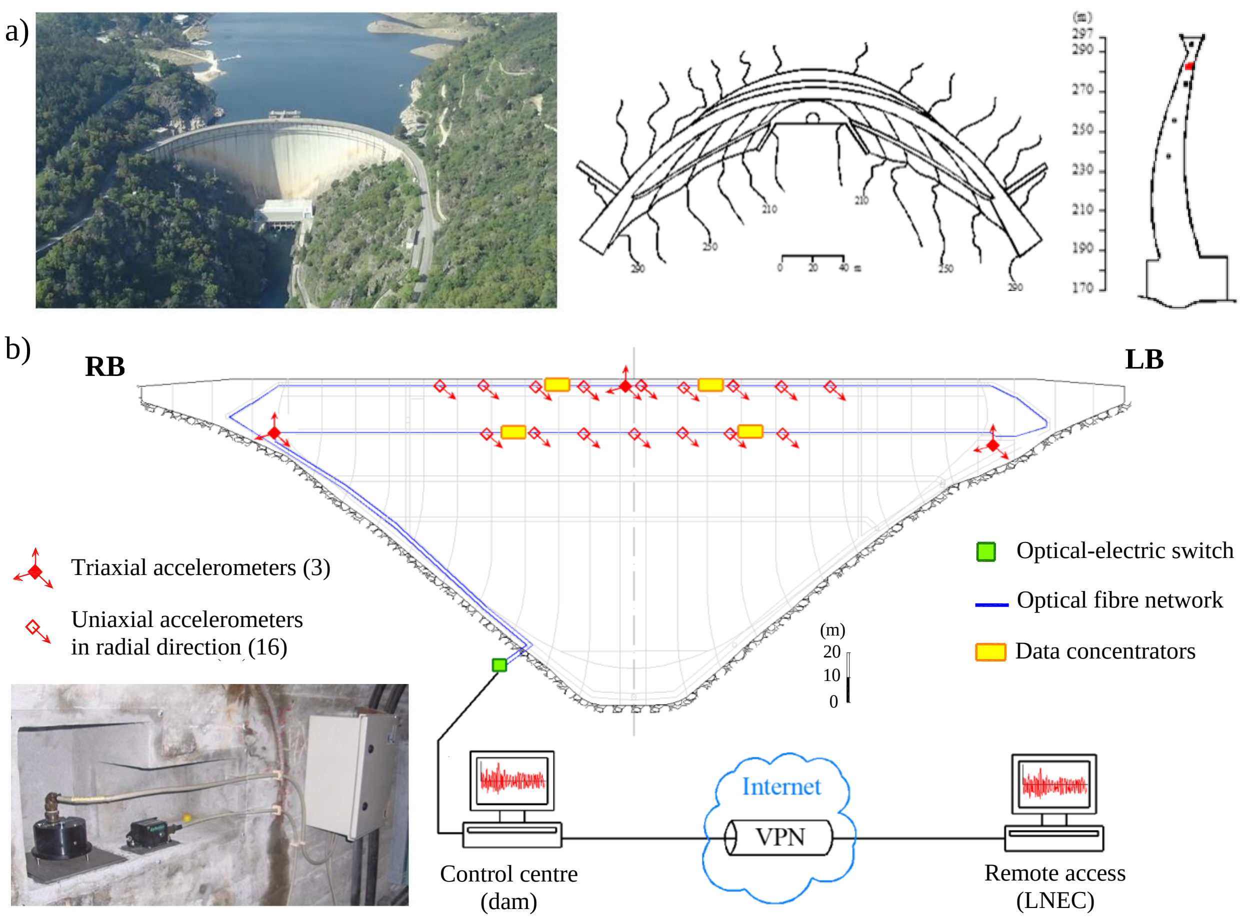

Figure 3: Cabril dam: a) aerial view, plan view and central cantilever cross section; b) front view and SSHM system (main hardware components)

The SSHM system installed in Cabril dam integrates two computational modules (developed using MATLAB): i) **DamModalID1.0**, for interactive monitoring data analysis; and

ii) **DamModalID_Auto1.0**, for automatic analysis of data measured over time. The natural frequencies and mode shapes are estimated from acceleration records measured on site, using the Frequency Domain Decomposition (FDD) method for modal identification [8], which is based on the Singular Value Decomposition (SVD) of the Power Spectral Density (PSD) Matrix, using a technique for automatic identification of spectral peaks specifically developed in LNEC.

Regarding **DamModalID_Auto1.0**, this software performs automatic signal processing and modal identification of natural frequencies and mode shapes from large datasets of acceleration time series measured continuously over time, based on parameters defined in advance by the user. With the goal of facilitating the analysis and interpretation of several months or even years of experimental data, the program generates files with a synthesis of the most important results as well as graphical representations that show the evolution of the natural frequencies over time (Fig. 4). This type of results is very important for engineers/technicians responsible for structural health monitoring, namely, to analyse the influence of the water level and/or seasonal thermal variations in the dynamic response of dams and to detect eventual structural changes due to concrete deterioration or seismic loading.

With **DamModalID1.0** (Fig. 5), the user can chose a data file, with measured accelerations, for any 'hour-day-month-year'. The measured water level is showed and an interactive graphical user interface allow the visualization of all the acceleration records. A modal identification can be easily performed for several parameter sets. The developed user interface includes several menus, where the following outputs are presented: a) the acceleration records for each accelerometer installed in the dam and the corresponding auto-spectral density functions; b) graphical representations of the singular values spectra; and c) the estimated natural frequencies and the respective mode shapes (2D configurations and harmonic waves that represent the oscillatory movement in each measured point). The modal identification results are presented in order to be immediately available for a simple comparison with results from numerical models.

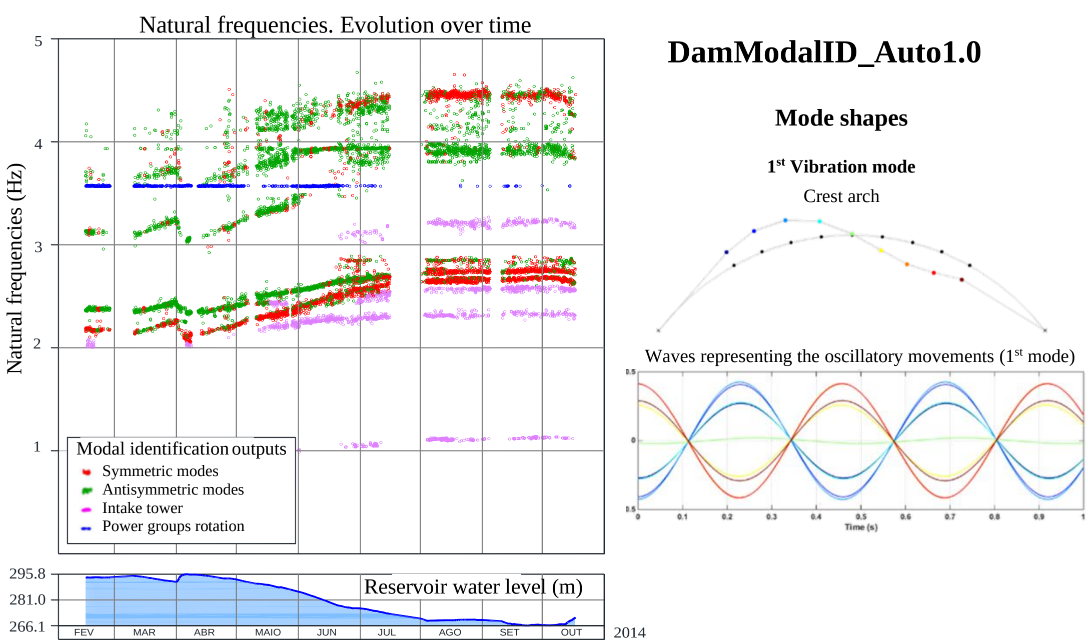

Figure 4: Modal identification software developed for Cabril dam's SSHM system. Results from **DamModalID_Auto1.0**, for automatic monitoring data analysis.

DamModalID1.0

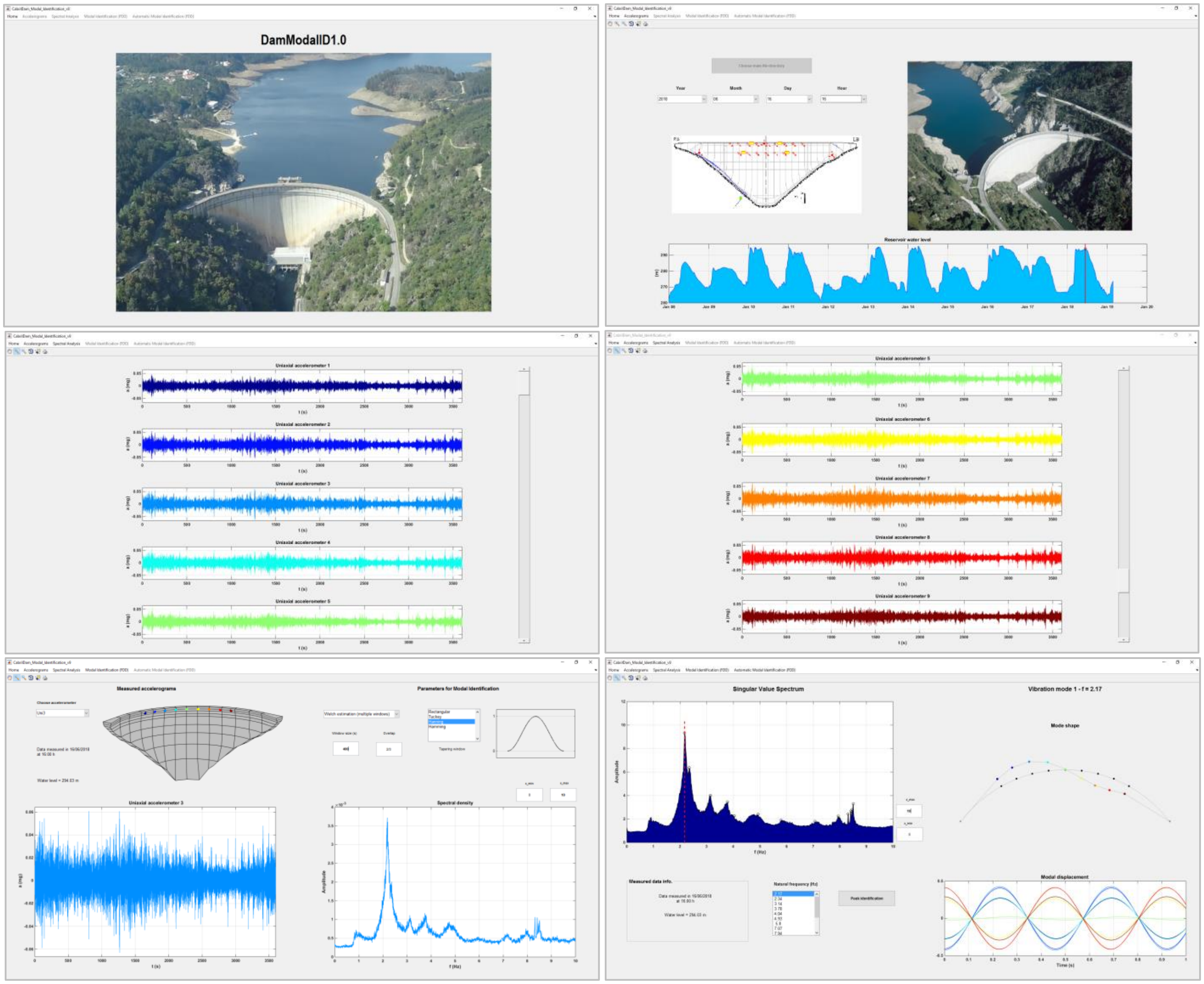

Figure 5: Modal identification software developed for Cabril dam's SSHM system. Results from **DamModalID1.0**: interactive monitoring data analysis, including modal identification using FDD-SVD.

4 DYNAMIC BEHAVIOUR OF CABRIL DAM. EXPERIMENTAL AND NUMERICAL RESULTS

The dynamic analysis of Cabril dam under ambient/operational excitations and under seismic events is presented in this section, based on the combined use of experimental and numerical modelling results. The goal is to contribute in improving knowledge regarding the dynamic response of Cabril dam, as well as to demonstrate the potential of the developed software to study the dynamic response of arch dams and support seismic and structural health monitoring.

The numerical calculations were carried out with **DamDySSA3.0**, a 3DFEM program developed in LNEC, using MATLAB, for linear dynamic analysis of arch dams with generalized (non-proportional) damping. The dam-reservoir-foundation system is simulated using a coupled model based on a Finite Element Method (FEM) formulation in displacements and pressures [10].

The dam-reservoir dynamic interaction is modelled considering the solid-fluid motion coupling at the dam-water interface and the pressure waves propagation throughout the reservoir, which is a semi-infinite domain terminated by a radiation boundary. The foundation is simulated as an elastic massless substructure: only its flexibility is computed and incorporated into the dam-foundation interface. A state space formulation with two state matrices and complex modal coordinates is used to solve the damped eigenproblem of the system and thus compute the natural frequencies (eigenvalues) and mode shapes (eigenvectors). The seismic response is calculated by direct time integration in global coordinates using the Newmark method, considering seismic accelerograms applied at the base.

A 3DFE model of the dam-reservoir-foundation system (Fig. 6), comprising 626 FE and 3914 nodes (106 elements in dam body), was used. For concrete, the Young's modulus is $E = 25\ GPa$ and Poisson's ratio $\nu = 0.2$. In the dynamic calculations it was used for concrete $E_{dyn} = 1.25 \times 25\ GPa$. For the reservoir it was considered a pressure waves propagation velocity of $c_w = 1440\ m/s$.

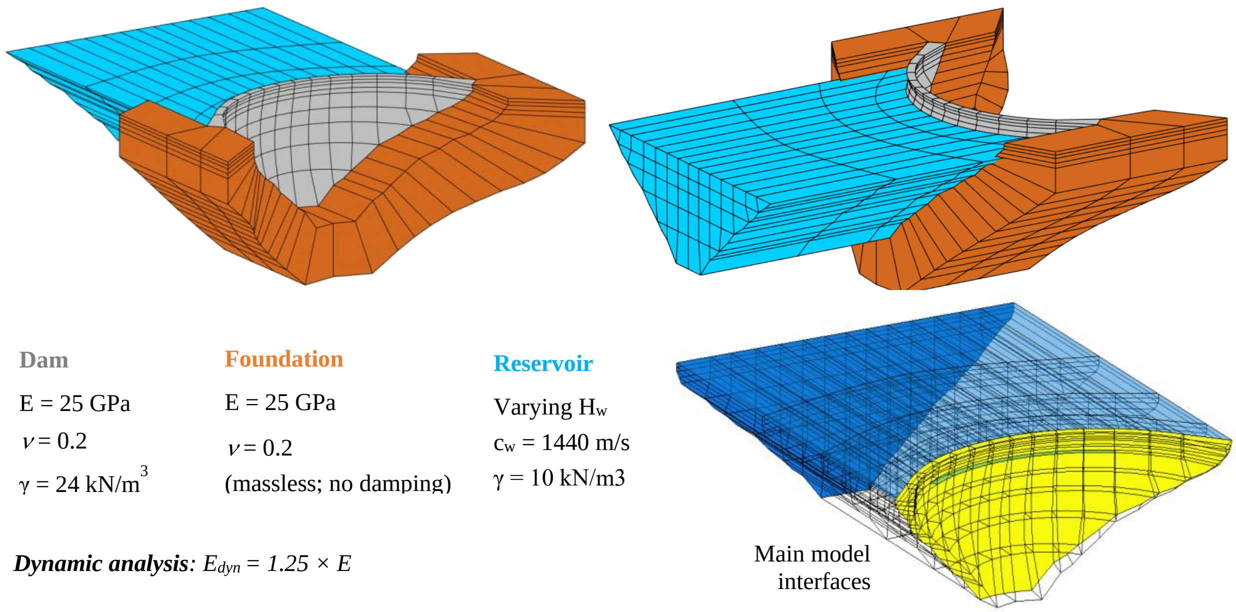

Figure 6: Cabril dam: 3DFE model and material properties.

4.1 Dynamic behaviour: natural frequencies and mode shapes

Initially the analysis is focused on the natural frequencies and mode shapes estimated from the measured acceleration records in the dam body, using interactive (**DamModalID1.0**) and automatic (**DamModalID_Auto1.0**) software. Modal identification is performed using the FDD-SVD method: the PSD matrix is computed using Welch method, considering 400 s long data segments (overlap: 2/3) and Hanning tapering windows. The natural frequencies are estimated from the PSD matrix first singular value spectrum, by automatically selecting the main spectral peaks. The corresponding mode shapes are obtained from the singular vectors of the PSD matrix. For Cabril dam, the identification of natural frequencies should take into account that some values of the dam natural frequencies could be near from the natural frequencies of the intake tower and from the power groups rotation frequencies. It is necessary to implement methodologies that allow to distinguish properly the frequencies of the dam, the tower and the power groups.

Fig.7 shows the evolution of the automatically estimated dam natural frequencies (green and red circles), using acceleration time series recorded from February to October 2014 (water level variation: from 296 to 266 m). The coloured lines represent the correspondent evolution of dam natural frequencies, numerically computed with DamDySSA3.0. In Fig.8, the natural frequencies and mode shapes identified in June 16, 2018 (acceleration records measured between 4 and 5 p.m.) are presented, as well as the correspondent modes and natural frequencies computed numerically. The water level was 294.03 m (3 m below the crest). The first mode is antisymmetric, the second and third modes are symmetric, and the fourth is also antisymmetric.

From the presented study, one can note that a very good agreement between modal identification outputs and 3DFE numerical results was achieved, for different reservoir water levels, regarding the evolution of natural frequencies and the modal configurations (particularly for the first three modes). It is also worth highlighting that the coupled model with generalized damping enables the computation of non-stationary vibration modes, as can be measured in situ. Finally, it is relevant to state that such promising results could not be achieved using classic added water mass models based on Westergaard's solution [5, 6].

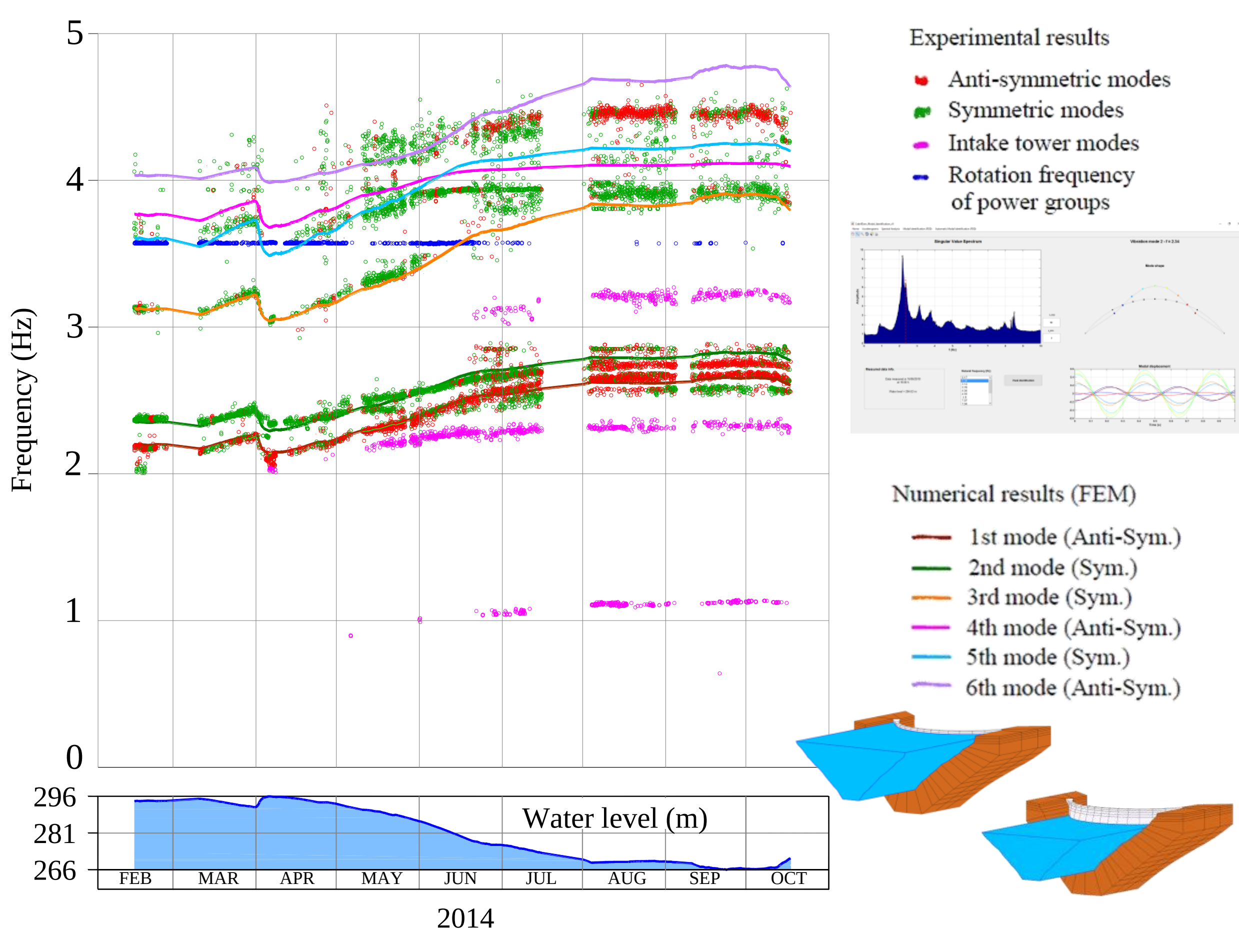

Figure 7: Cabril dam: evolution of natural frequencies over time. Comparison between automatic modal identification outputs (data from February to October 2014) and numerical results from **DamDySSA3.0**.

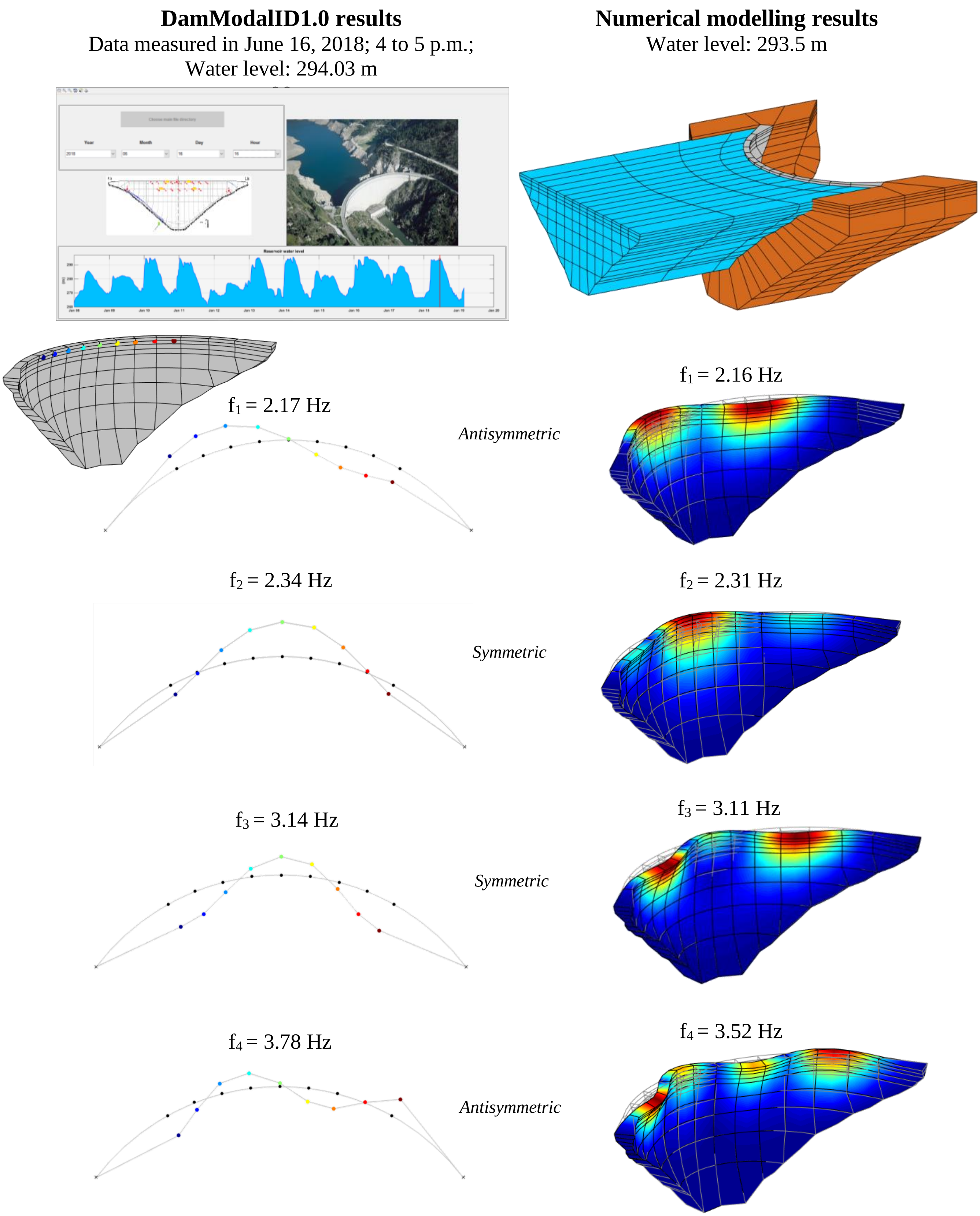

Figure 8: Cabril dam: Natural frequencies and mode shapes. Comparison between modal identification outputs (June 16, 2018, 4 to 5 p.m.) and 3DFE results (**DamDySSA3.0**).

4.2 Seismic response

Using Cabril dam's SSHM system, it has been possible to automatically identify earthquake events and to measure the accelerations close to the foundation and in the dam body, thus allowing to study the dynamic response of the dam under seismic loading. One of the main goals is to analyse the accelerations amplification factor between the base and the top of the dam, for different earthquakes measured on Cabril dam.

In this section, the seismic response of Cabril dam is studied for an earthquake of magnitude 4.6 on the Richter scale, measured on site on September 4, 2018 (Fig. 9). The epicentre was in Peniche abyssal region, at a distance of around 200 km from the dam and the reservoir water level at the time was 281.2 m (15.8 m below the crest). The acceleration time histories recorded with the triaxial accelerometer located in the right bank (RB_{xyz}) are shown: the peak accelerations near the base were of 2.16 mg in the cross-valley direction, 1.39 mg in the upstream-downstream direction and 1.23 mg in the vertical direction.

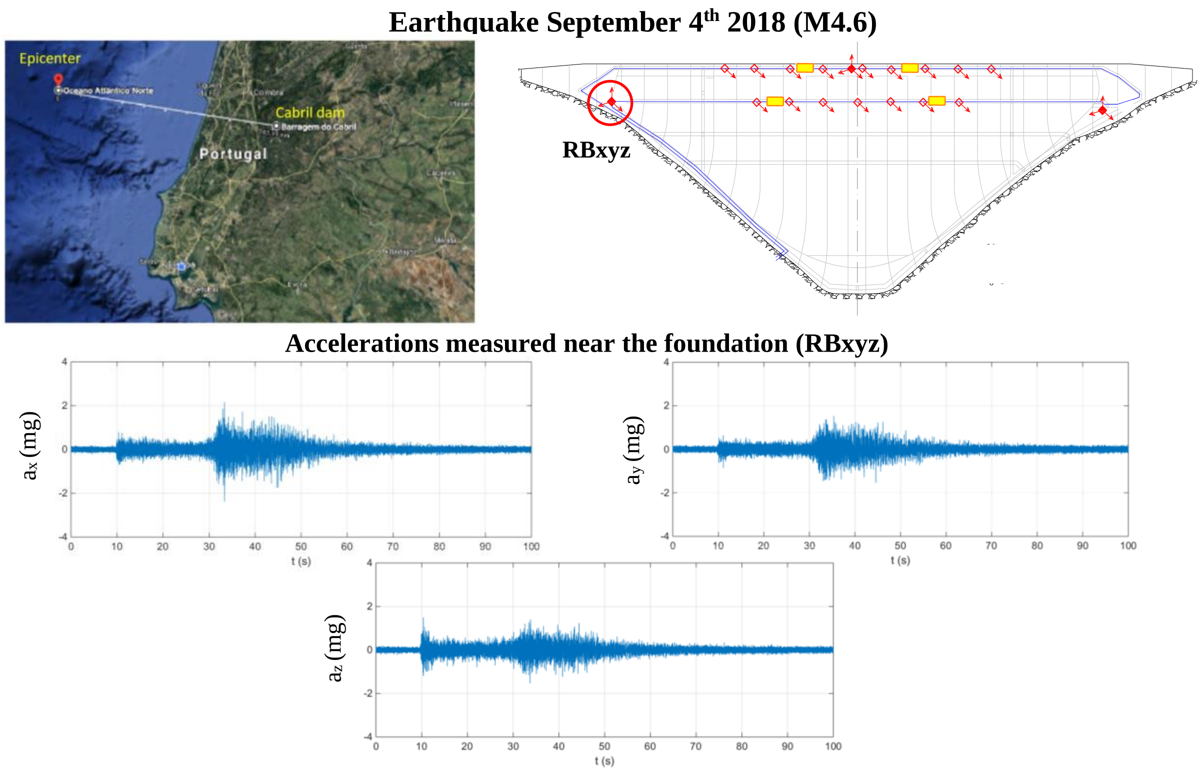

Figure 9: Cabril dam. Earthquake event on September 04, 2018: measured accelerations near the base.

Next, the measured seismic response of Cabril dam (Fig. 10) is compared with the response computed numerically, considering a reservoir water level of 280 m and using the seismic acelerogramas measured at the dam-foundation interface (RB_{xyz}) as inputs to the reference 3DFE coupled model. In this study, in order to analyse the amplification of the accelerations from the insertion to the top of the central cantilever, the average peak accelerations, calculated as the mean value of the ten highest peaks of the acceleration time series, are considered.

Regarding the measured response, let us focus on the acceleration time series recorded with the accelerometer KL294, at a height of 294 m, in the upper gallery of the central cantilever (block KL). An average maximum acceleration of 2.69 mg was recorded, which corresponds to a base

(RBxyz) to top acceleration amplification of about 2.5 times. For comparison, the radial acceleration time histories are computed for nodal point 140 (in blue), at a height of 293.5 m, chosen to be located as near as possible to the real position of the sensor KL294. The average peak acceleration is of about 2.94 mg, resulting in a base to top amplification of about 2.7 times.

Finally, it can be noted that a very good agreement has been achieved between measured and calculated acceleration time histories, but only when a global (dam and foundation) damping ratio of about 20% was assumed in the model. Although this is a surprisingly high value, in comparison with standard values (1 to 5 % in the dam) used when studying the seismic behaviour of large dams, analogous conclusions have been drawn by other researchers in similar studies [10] (as mentioned, this might be related to the averaging of the input seismic accelerograms along the dam-foundation interface).

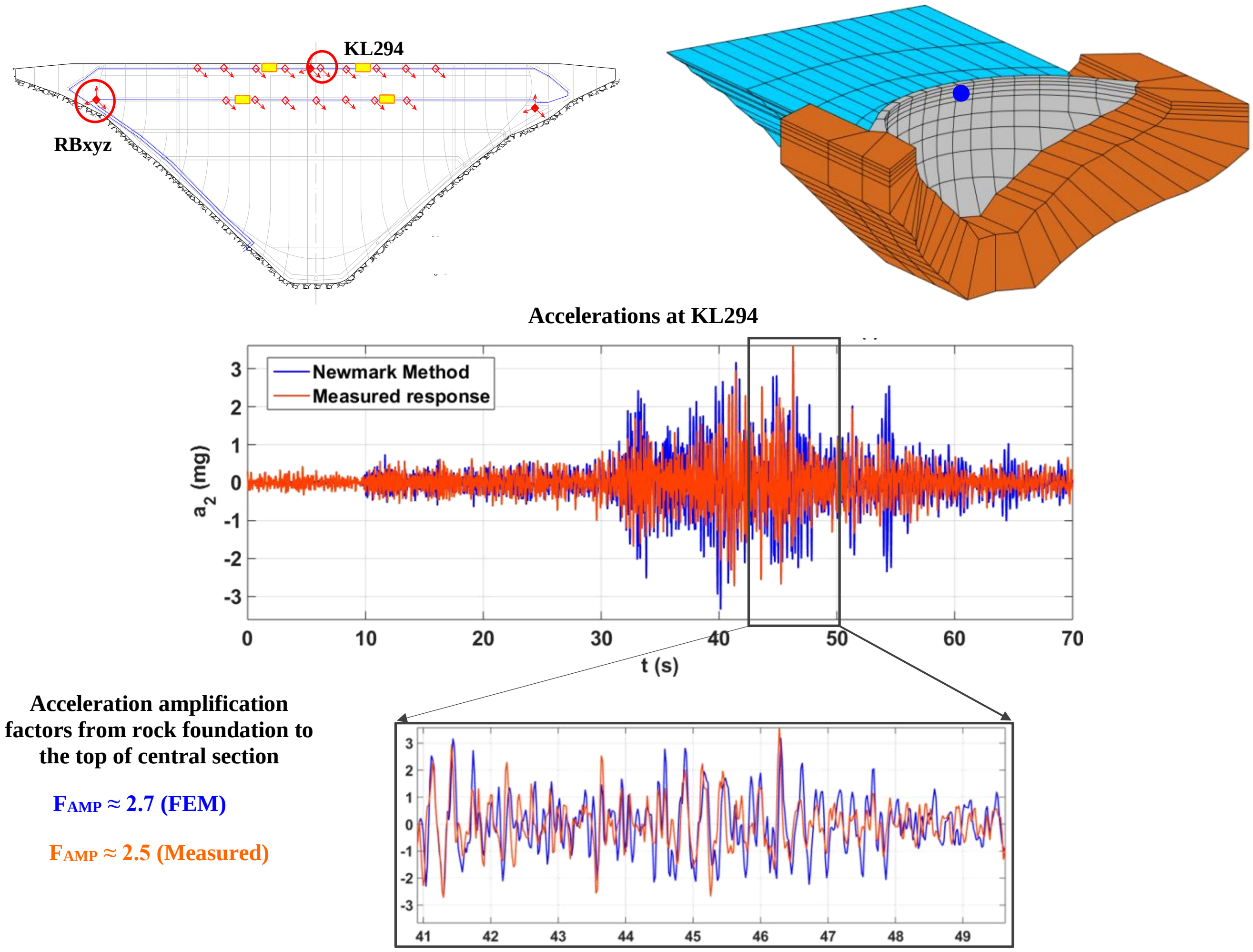

Figure 10: Cabril dam. Earthquake event on September 04, 2018. Measured and computed seismic response.

5 CONCLUSIONS

In this paper it was presented the software developed in LNEC to integrate the SSHM system installed in Cabril dam, namely the programs **DamModalID1.0** and **DamModalID_Auto1.0**, for interactive and automatic analysis of acceleration records. The obtained monitoring results were used to study the dam's dynamic behaviour under ambient/operational excitations, aiming to estimate the natural frequencies and mode shapes for several reservoir water levels, and the response under seismic loading, by analysing the accelerations at the top of the central section. The experimental outputs were compared with numerical results obtained with a 3DFE coupled model, considering generalized damping and a massless foundation. Based on the presented results, one can note that it was possible to achieve a good agreement between the measured dynamic response of Cabril dam and the response predicted in the numerical calculations.

This paper has shown the potential of the developed software for SSHM systems to study the dynamic behaviour of arch dams over time based on acceleration records (continuously acquired), as well as the importance of the combined use of experimental and numerical results for supporting seismic and structural health monitoring studies.

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