# Dynamic Behavior of Cabril Dam: Finite Element Model Calibration, Structural Health Monitoring (2008–2023) and Seismic Safety Assessment

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## ABSTRACT

This paper presents a complete study on the dynamic behavior of the 132 m high Cabril arch dam (Portugal). In operation for almost 70 years, horizontal cracks appeared on the downstream face after the first reservoir filling, and in the 1980s the dam started showing signs of concrete swelling. To address the concerns about its long-term safety, a pioneering continuous vibration monitoring system, designed for Seismic and Structural Health Monitoring, was installed in Cabril dam in 2008. In this work, the vibrations recorded under ambient/operational conditions for more than a decade are analyzed to estimate the modal parameters of the dam, which are then used to calibrate and validate a finite element model of the dam-reservoir-foundation system with the horizontal cracking. After that, the dynamic behavior of Cabril dam is simulated for the next decades, considering a computationally generated scenario of progressive damage due to concrete swelling. The results show that a) the dynamic behavior of Cabril dam is not being affected by the existing swelling phenomenon, and b) vibration-based analysis can be effective for detecting structural changes due to progressive damage. Lastly, the calibrated model is adapted for conducting non-linear seismic simulations, considering joint movements and tensile and compressive concrete damage. A method based on Endurance Time Analysis method is applied to assess the seismic safety of the dam with respect to the Operating Basis Earthquake and the Safety Evaluation Earthquake. The results confirm that Cabril dam can withstand accelerations several times greater than both earthquake levels, showing its adequate seismic capacity.


## 1. INTRODUCTION

Large concrete dams are high potential risk structures. Designed to be in operation for many decades, structural changes may occur over time due to evolutive deterioration

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phenomena. In addition, dams located in seismic zones can be hit by earthquakes, which may cause loss of service conditions or even compromise structural integrity. Therefore, a continuous dam behavior assessment based on continuous monitoring data and modelling results is essential to verify structural safety for current and failure scenarios and thus to ensure the best operating conditions. With that aim, it is recommended the investment in continuous vibration monitoring systems, designed for seismic and structural health monitoring (SSHM), since the analysis of vibrations measured under ambient/operational conditions and during seismic events can provide valuable results to dam engineers and actionable data to help dam owners make informed decisions [1]. For example, experimental modal parameters can be used for dam behavior analysis, considering, e.g., the influence of reservoir water level variations, and most importantly for structural condition assessment, by detecting structural changes due to progressive concrete deterioration or damages caused by earthquakes. In addition, experimental data can be applied for calibrating and validating computational models, which in turn are used to predict the dynamic response of dams, e.g., under seismic loads.

In this context, this paper presents valuable experimental and numerical results on the dynamic behavior of Cabril dam. First, the focus will be on the calibration and validation of the finite element (FE) model of the dam-reservoir-foundation system, based on modal parameters estimated from vibrations measured between 2008 and 2023 with the installed SSHM system. Then, the calibrated model is used in application studies for structural health monitoring, considering the swelling effects, and for seismic safety assessment. All numerical calculations were carried out using DamDySSA, a 3D FE program developed in LNEC for modal analysis and linear/non-linear seismic response simulation of dam-reservoir-foundation systems, using a formulation in displacements (dam-foundation) and hydrodynamic pressures (reservoir) [2].

## 2. CASE-STUDY: CABRIL DAM, PORTUGAL

Cabril dam is the highest dam and one of the most important infrastructures in Portugal, playing a key role for water supply and hydropower production (Figure 1). In operation since 1954, Cabril is a 132 m-high double curvature arch dam with a crest length of 290 m; the dam presents a unique geometry, with a thickness increase for the blocks at the crest. The hydropower plant was constructed on the downstream base and the intake tower is located on the upstream side the dam. In normal operating conditions, the reservoir level ranges from el. 265 m to the normal water level at el. 295 m.

Regarding the structural condition, during the first reservoir filling the deformation of the dam under the water pressure originated high vertical tensions at the upper zone of the downstream surface (around el. 285 m), which in turn caused horizontal cracking, a phenomenon that was conditioned by the crest geometry. Moreover, concrete swelling was first detected during the 1980s and has been progressing gradually over the years; nowadays, gel extrusions can be seen inside the dam galleries (Figure 1a).

As for seismic risk, Cabril Dam is located in the center of Portugal, integrated in a national region of high seismic risk, close to some active intraplate faults (Figure 1b). Thus, peak ground accelerations of 0.1 g (OBE) and 0.2 g (SEE) have been assumed as reference for seismic safety assessment studies [3].

With a view to address the concerns about long-term safety, Cabril dam was instrumented in 2008 with a pioneering SSHM system, developed to monitor dam behavior under ambient/operational conditions and to measure the response during seismic events [4-6]. The system was designed to continuously measure vibrations on the dam, using a) 16 uniaxial accelerometers to record accelerations along the upper part of the dam, 9 in the upper gallery, at el. 294 m, and 7 in the gallery below the cracked zone, at el. 275 m, and b) 3 triaxial accelerometers, 1 positioned in the upper gallery, at the central section of the dam, and the other 2 inside the foundation gallery, close to the dam-rock surface, both at el. 274 m (Figure 1c).

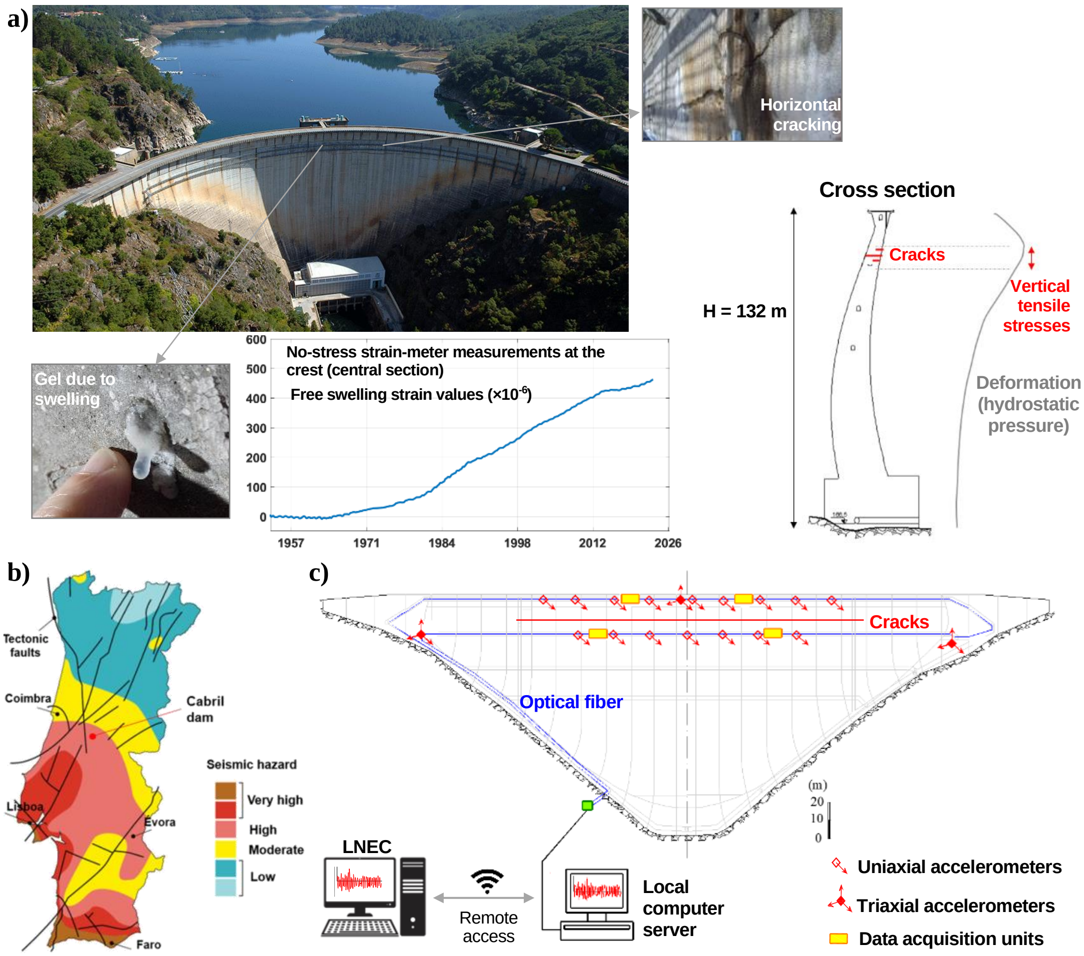


Figure 1. Cabril dam: a) aerial view and details of concrete swelling and horizontal cracking; b) location in the seismic hazard map of Portugal; c) SSHM system installed in 2008.

## 3. EXPERIMENTAL RESULTS AND FE MODEL CALIBRATION

This section presents the main results obtained from dynamic monitoring data gathered on Cabril dam from December 2008 to January 2023, and then focuses on the calibration and validation process of the dam-reservoir-foundation system FE model.

The modal parameters of Cabril dam were retrieved by performing automatic modal identification on the vibrations recorded on all measurement points under environmental and operational excitation. This was done using the program DamModalID, based on the frequency domain decomposition method and on techniques for automatic selection of spectral peaks [2]. As an example, Figure 2 presents the frequency spectra of the acceleration time histories measured hourly with an accelerometer located about 30 m the right of the central section, over the course of the entire monitoring period; for the highlighted spectrum, on July 18, 2021 (water level at el. 283 m), the identified frequencies for the first, second and third modes are, respectively, 2.46 Hz, 2.6 Hz, and 3.54 Hz. Moreover, these results show that there is a clear correlation between the natural frequency values (spectral peak positions) and the reservoir water level variations, which evidences the influence of the water mass on the dynamic behavior of the dam. As for the vibration mode shapes, the first mode is antisymmetric, while the second and third modes are symmetric.

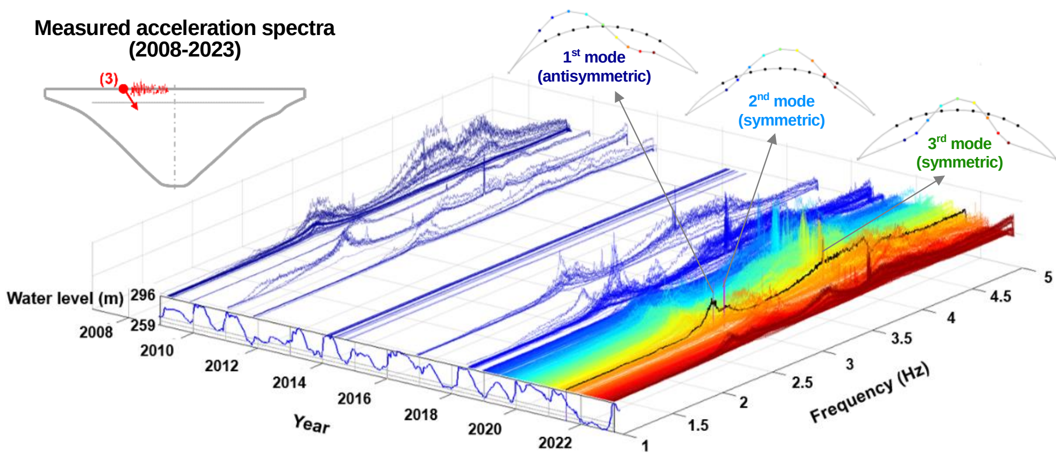


Figure 2. Frequency spectra obtained from acceleration time histories measured on Cabril dam (2008-2023) and identified mode shapes for the first three vibration modes.

The FE model of the Cabril dam-reservoir-foundation system is presented in Figure 3. The dam mesh, developed with 3 elements along the cross section, properly represents Cabril dam's geometry. Also, interface elements (with duplicate nodes) were introduced at el. 280 m to simulate the horizontal cracking in the dam body. Regarding the material properties, the dam concrete and foundation rock are assumed as isotropic materials with linear-elastic behavior, considering Young's modulus E = 25 GPa and Poisson ratio $\nu = 0.2$; the concrete specific weight is $\gamma = 24$ kN/m$^3$, while the rock mass is neglected, since the substructure method is adopted to compute the foundation block. The water in the reservoir is a compressible fluid with specific weight $\gamma = 10$ kN/m$^3$.

The calibration of the FE model was conducted based on the modal parameters estimated from vibrations measured in the first monitoring years [7], from December 2008 to April 2009, in late 2012, and during 2014; this enabled to consider a set of data measured under normal operating conditions, with reservoir levels from el. 265 m to 295 m. The aim of the calibration process was to adjust the material properties in order to obtain the best possible agreement with the experimental results for the first three vibration modes, namely: (i) the coefficient applied to the elasticity modulus of the dam concrete and foundation rock for dynamic analysis; (ii) the value of the pressure wave propagation velocity in water ($c_w$); and (iii) the normal ($K_N$) and shear ($K_T$) stiffness of the horizontal crack elements, assuming opening movements restricted at the upstream elements and enabled for the middle and downstream elements. The results validate the calibrated model, since it enabled to adequately simulate the mode shapes and reproduce the evolution of the natural frequencies according to the reservoir level variations, not only during the period considered for calibration, but also for recent years.

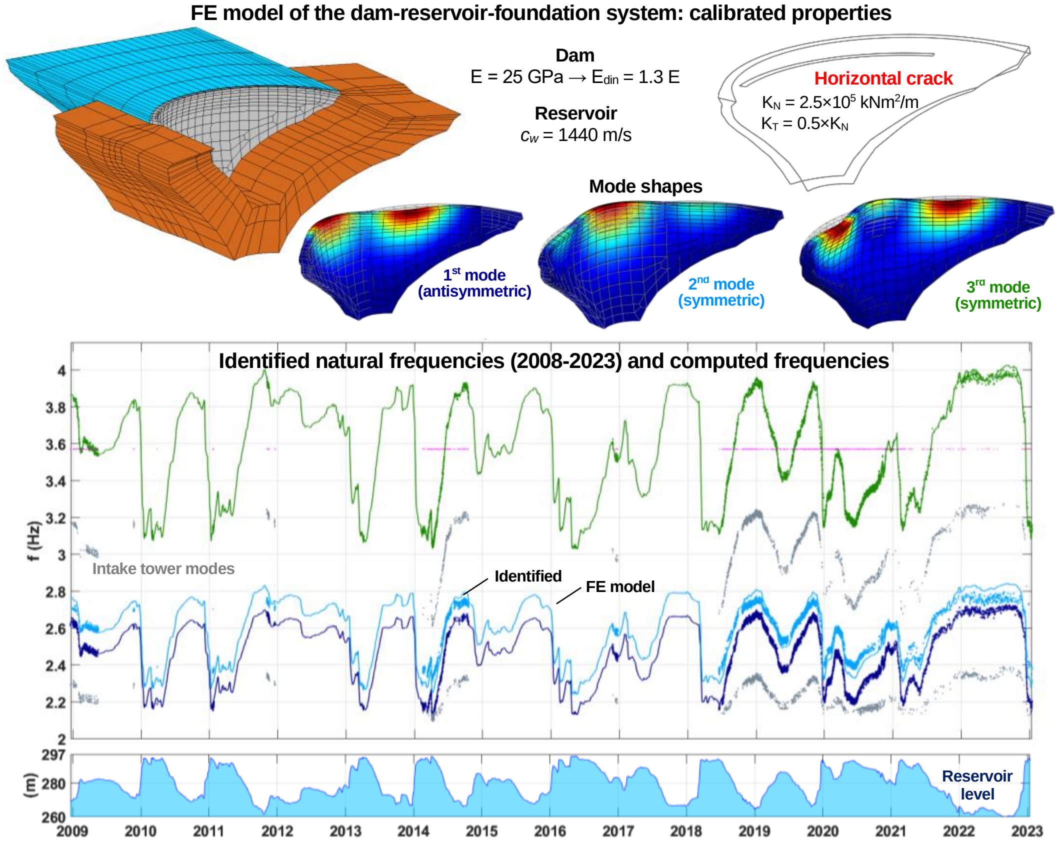


Figure 3. FE model of Cabril the dam-reservoir-foundation system. Numerical mode shapes for three vibration modes and comparison between identified natural frequencies and computed frequencies.

## 4. STRUCTURAL CONDITION ASSESSMENT

Next, the work focuses on structural condition assessment of Cabril dam, based on natural frequency analysis. Specifically, experimental and numerical results are compared for the monitoring period between 2008 and 2023, and then the dynamic response of the dam is simulated until 2054, considering a computationally generated progressive deterioration scenario due to concrete swelling (Figure 4).

For this study, damage to the dam body was simulated considering a variation over time given by a sigmoid-type function (Figure 4a) and assuming non-uniform deterioration in height (Figure 4b), in order to achieve a deterioration state in the model consistent with observation data on the evolution of the swelling process. The model with progressive deterioration was developed by adapting the calibrated model of the dam-reservoir-foundation system, considering a decrease in dam stiffness. This was accomplished by reducing the elasticity modulus of concrete, according to the damage variation throughout the dam body and to its progression over time; essentially, at each material point, the elasticity modulus of concrete becomes $E(t) = E_0(1-d(t))$, where $E_0$ is the initial value and d is the damage [8].

Figure 4c) shows the identified natural frequencies for the first vibration mode (2008-2023), as well as the first frequency values computed using the calibrated model and the model with progressive damage, for the entire monitoring period (2008-2023) and for future years (2023-2054); the modal analyses were performed using the real water levels until January 2023, and, from then on, considering a generated reservoir level variation. The results show an excellent agreement between the identified natural frequencies and the frequencies computed using the calibrated model, without damage. However, the model with progressive deterioration gives frequency values that decrease over time as the global dam stiffness decreases, gradually diverging from the values of the calibrated model. Also, even with the simulated damage between 2008 (2%) and 2023 (5%), the differences in relation to the experimental frequencies are not significant.

The outcomes of this study suggest that the detected concrete swelling phenomenon is not affecting the structural integrity of Cabril dam. In addition, if dam behavior remains unaffected by concrete swelling, the identified natural frequencies are expected to follow the frequency values predicted by the calibrated model over time.

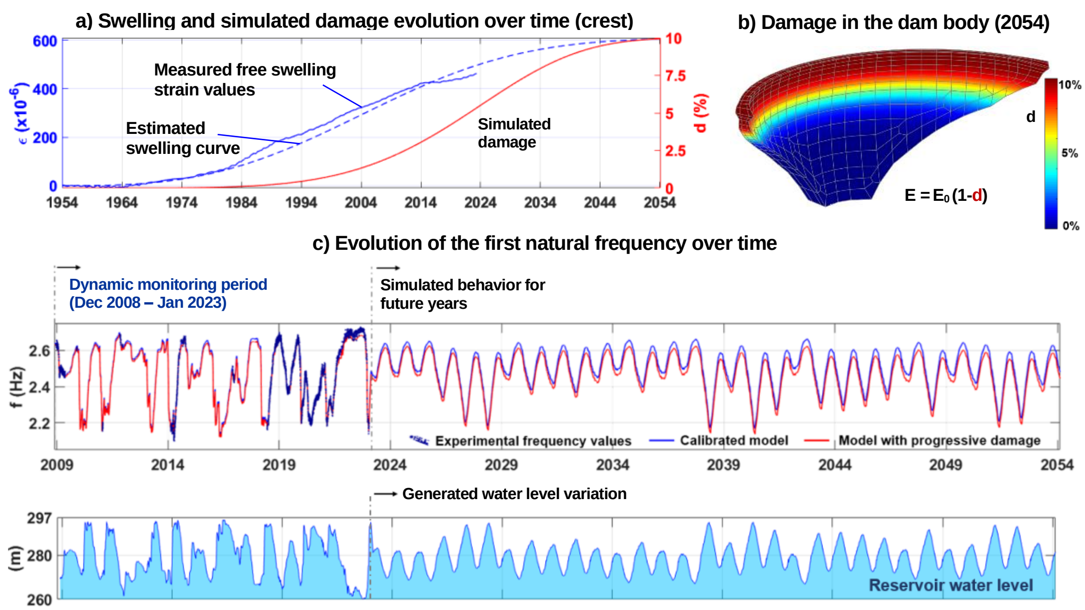


Figure 4. Structural condition assessment of Cabril dam: a) Simulated progressive deterioration scenario (evolution over time) and comparison with measured swelling values at the crest, b) simulated damage variation in the dam body, and c) analysis of the first natural frequency over time until 2054 (experimental and numerical frequencies).

## 5. SEISMIC SAFETY ASSESSMENT

Finally, a study for seismic safety assessment of Cabril dam is presented, using an efficient method [3] based on Endurance Time Analysis (ETA) [11] . Specifically, the seismic performance is evaluated by controlling the evolution of the tensile and compressive damage state of the dam, under accelerations of increasing intensity. With this method, the aim is to estimate endurance limits, which give the maximum accelerations the dam can withstand without presenting unacceptable damage. To verify the seismic safety, the endurance limits associated with tensile and compressive damage are compared, respectively, with the peak ground accelerations prescribed for the Operating Basis Earthquake (OBE) and the Safety Evaluation Earthquake (SEE).

The non-linear seismic simulation was carried out for a load combination including the self-weight of the dam (SW), the hydrostatic pressure for full reservoir (HP), and a seismic action given by an acceleration time history with accelerations increasing to about 1.5g in 15 s (Figure 5a). For this study, the calibrated model of Cabril dam is adapted by a) introducing interface elements for all vertical contraction joints in the dam body, enabling to simulate the structural effects due to opening/closing joint movements [9], and b) considering an isotropic constitutive damage model with softening to simulate damage under tensile and compressive stresses [10] (Figure 5b).

The results showing the evolution of tensile and compressive damage are displayed in Figure 5c). Up to t = 5 s, there is a gradual progression of tensile damage, until tensile failure ultimately occurs in several blocks along the upper part of the downstream face, and near the dam base, on the upstream side. Nevertheless, concrete cracking is mostly superficial and thus this damage state is still considered acceptable. However, after that there is an important damage increase along both upstream and downstream faces, with concrete cracking propagating across several cantilevers. This scenario could affect the structural integrity of the dam, hence failing to meet the requirements for the OBE excitation level. Accordingly, the endurance limit for tensile damage corresponds to an acceleration of 0.5 g, which is five times the OBE peak ground acceleration (0.1 g). As for compressive damage, it is worth noting that deterioration began to occur only after t = 11 s, while the first areas under compressive failure occurred at the top of the central cantilever, after the dam was subjected to peak accelerations around 1.3 g. In order to meet the dam safety requirements, concrete compressive crushing with propagation across the blocks in key areas of the dam is not acceptable, as it may induce collapse and uncontrolled release of water from the reservoir. Therefore, the compressive endurance limit is 1.4 g, 7 times more than the SEE peak ground acceleration (0.2 g).

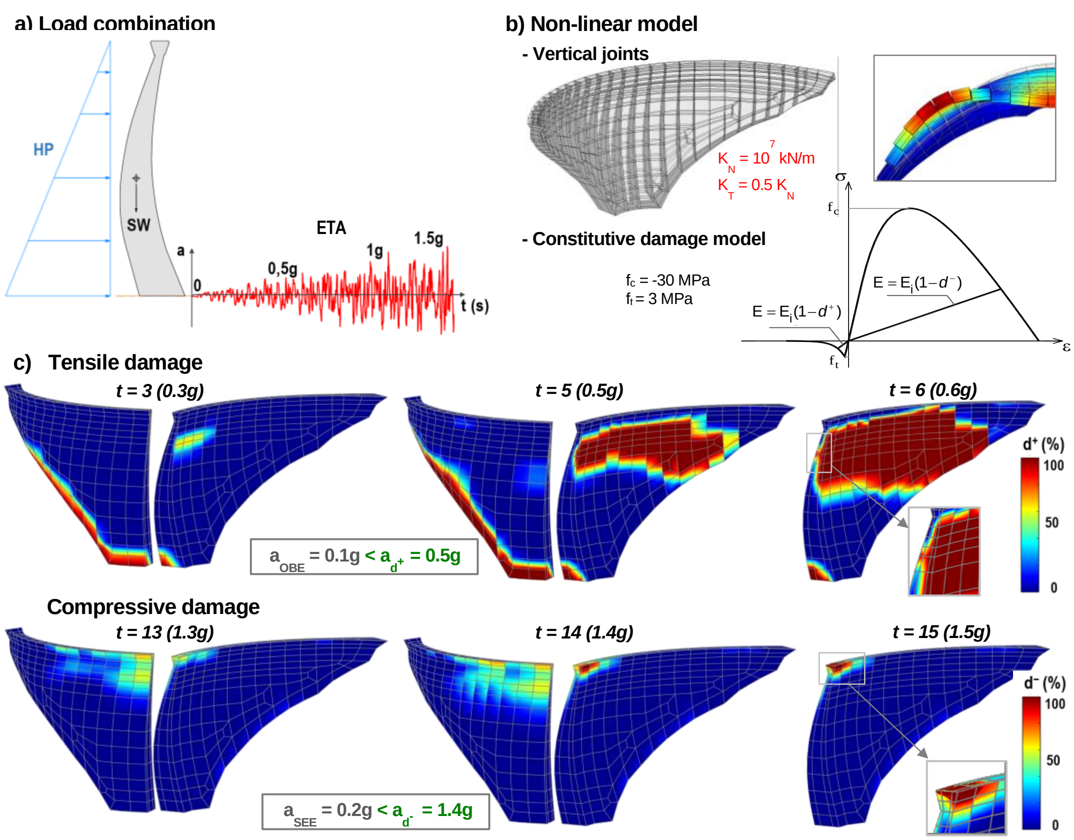


Figure 5. Seismic safety assessment of Cabril dam: a) load combination; b) vertical joints and constitutive damage model used for non-linear seismic analysis; c) evolution of tensile and compressive damage and comparison of endurance limits with the OBE and the SEE accelerations.

## 6. CONCLUSIONS

Overall, this paper provided valuable insight into the dynamic behavior analysis for the safe and efficient operation of Cabril dam, using vibration-based data from the SSHM system and results from a calibrated FE model. First, modal parameters obtained from vibrations measured on the dam between 2008 and 2023 were analyzed and used to calibrate a FE model of the Cabril dam-reservoir-foundation system, emphasizing the value of data gathered with continuous vibration monitoring systems on dams. Then, the results of a comparative study between identified natural frequencies and the frequencies computed using the calibrated model and a model that simulated a progressive deterioration scenario (due to concrete swelling) enabled to conclude that a) the performance of Cabril dam in normal operating conditions is not being affected by the existing swelling phenomenon, and b) vibration-based analysis can be effective for detecting structural changes in concrete dams due to progressive deterioration. Finally, the calibrated FE model was properly adapted to enable the simulation of joint movements and tensile and compressive concrete damage, in order to conduct non-linear seismic analyses, and an ETA-based methodology was applied with a view to assess the seismic safety of Cabril dam with respect to the OBE and the SEE. The results showed that Cabril dam can withstand accelerations several times greater than the OBE and SEE peak ground acceleration levels with acceptable damage, thus showing its adequate seismic capacity.

## REFERENCES


1. Oliveira, S., Alegre, A., Carvalho, E., Mendes, P. and Proença, J. 2022. "Seismic and structural health monitoring systems for large dams: theoretical, computational and practical innovations", *Bull. Earthq. Eng.*, 20(9):4483-4512.
2. Alegre, A. 2021. *Modelling and monitoring the dynamic behaviour of concrete dams. Modal analysis and seismic response*. PhD Thesis, Instituto Superior Técnico - University of Lisbon, Portugal.
3. Alegre, A., Oliveira, S., Mendes, P., Proença, J., Ramos, R. and Carvalho, E. (2022). "Seismic Safety Assessment of Arch Dams Using an ETA-Based Method with Control of Tensile and Compressive Damage", *Water*, 14(23):3835.
4. Mendes, P. 2010. *Observation and analysis of concrete dams dynamic behaviour*. PhD Thesis (in Portuguese), Faculdade de Engenharia da Universidade do Porto (FEUP), Portugal.
5. Oliveira, S., Ferreira, I., Berberan, A., Mendes, P., Boavida, J. and Batista, B. 2010. "Monitoring the structural integrity of large concrete dams: the case of Cabril dam, Portugal", presented at HYDRO 2010, Lisbon, Portugal.
6. Oliveira, S., Espada, M. and Câmara, R. 2012. "Long-term dynamic monitoring of arch dams. The case of Cabril dam, Portugal", presented at the 15th World Conference on Earthquake Engineering, Lisbon, Portugal.
7. Alegre, A., Carvalho, E., Matsinhe, B., Mendes, P., Oliveira, S. and Proença, J. 2019. "Monitoring vibrations in large dams", presented at HYDRO 2019, Porto, Portugal.
8. Alegre, A., Oliveira, S., Carvalho, E., Mendes, P., Proença, J. and Matsinhe, B. 2022. "Continuous dynamic monitoring of large arch dams and vibration-based damage detection", presented at HYDRO 2022, Strasbourg, France.
9. Fenves, G.L., Mojtahedi, S. and Reimer, R.B. 1992. "Effect of contraction joints on earthquake response of an arch dam", *J. Struct. Eng. (ASCE)*, 118:1039-1055.
10. Oliveira, S. 2000. *Models for the analysis of concrete dams behaviour considering cracking and time effects. Damage formulations*. PhD Thesis (in Portuguese), Faculdade de Engenharia da Universidade do Porto (FEUP), Portugal.
11. Estekanchi, H. E., Vafai, H. and Sadeghazar, M. 2004. "Endurance Time Method for Seismic Analysis and Design of Structures", *Scientia Iranica*, 11(4):361–370.