The 9th European Congress on Computational Methods in Applied Sciences and Engineering
ECCOMAS Congress 2024
3 – 7 June 2024, Lisboa, Portugal

SEISMIC PERFORMANCE ASSESSMENT OF BOUÇÃ ARCH DAM. NON-LINEAR ANALYSIS CONSIDERING JOINT MOVEMENTS AND CONCRETE DAMAGE UNDER TENSION AND COMPRESSION

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Key words: Bouçã dam, Finite element model, Non-linear seismic analysis, Joint movements, Tensile and compressive concrete damage, Seismic performance assessment

1 INTRODUCTION

Large dams play a decisive role in the management and control of water resources, particularly when it comes to supplying drinking water to populations, renewable and non-polluting energy production, irrigation, and flood control. However, large dams are generally high potential risk infrastructures. Bearing in mind that many of these high-potential risk dams have been in operation for several decades, exhibiting signs of ageing and deterioration, it is essential to (re)evaluate their structural safety by conducting new studies that consider their current structural condition and deterioration state. Furthermore, these studies should be carried out using updated methods of analysis and modern performance criteria, as well as new methodologies and regulations for prescribing exceptional loads, such as seismic actions [1].

The development of certain pathologies in the body of dams requires special attention. In particular, the formation of cracks always calls for closer monitoring, with a view to control their growth and to ensure that they do not compromise the dam's structural integrity. In the Bouçã arch dam, the case study of this paper, a horizontal crack appeared on the downstream face, approximately at mid-height, extending to the right of the central section, apparently caused by temperature variations during the concrete cooling and the first reservoir filling [2]. The formation and growth of this crack raised some concerns about the structural continuity of the dam along its height, since water was passing through from upstream to downstream in certain zones of the crack, which could compromise its seismic performance [2].

For arch dams, during high intensity seismic events, the vertical contraction joints may open and close, leading to stress redistribution processes [3]. Simultaneously, significant stresses may develop, causing the formation of cracks, under tension, and/or concrete crushing, under compression [4]. As such, these are key factors to consider in seismic analyses of arch dams [5]. In the case of the Bouçã dam, under strong seismic motion the displacements of the structure may also originate opening/closing movements of the horizontal crack, altering its overall structural response. It was therefore considered of particular interest to analyse the seismic behaviour of the Bouçã dam, considering the existence of the horizontal crack. With that goal, a 3D finite element model was developed to simulate the non-linear seismic response of the dam, considering not only the movements of the vertical contraction joints but also of the horizontal crack, and the non-linear behaviour of concrete under tension and compression.

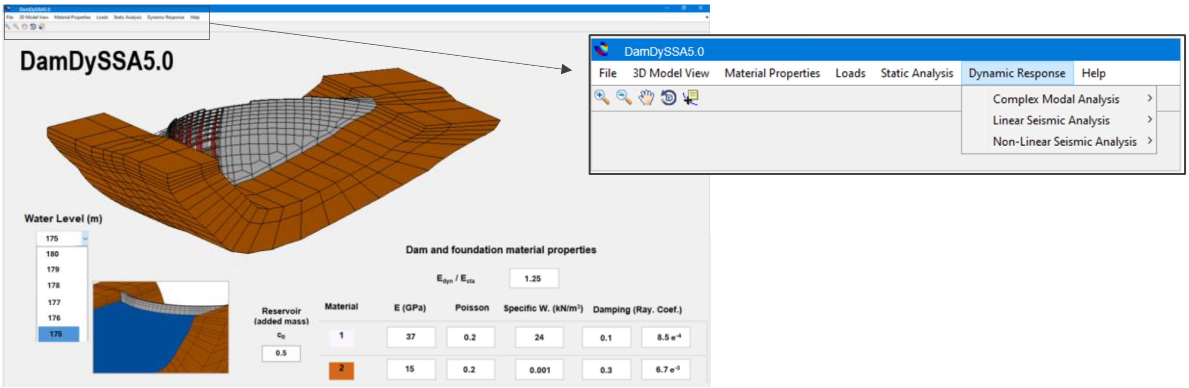
In this context, this paper presents a comprehensive study on the seismic response of the Bouçã arch dam, resorting to advanced finite element models for non-linear seismic response analysis and seismic safety assessment. The computational simulations are performed using the 3D finite element program DamDySSA, developed by some of the authors for dynamic analysis of dam-reservoir-foundation systems [6]. The results are obtained using a finite element model specifically developed for seismic analysis of Bouçã dam, incorporating the horizontal crack. First, geodetic observation data of the static response under the hydrostatic pressure is compared with the response predicted by the model, in order to calibrate the elastic properties of the materials (concrete and foundation rock) and the properties of the joints and of the horizontal crack. In addition, the main modal parameters of the dam, obtained from an ambient vibration test, are compared with the natural frequencies and mode shapes calculated using the model, to confirm the material properties and calibrate the model for dynamic analysis. Next, the seismic response of the dam is simulated under a strong seismic action, considering non-linear structural behaviour; the goal is to test the developed model and analyse the influence of the horizontal crack movements on the structural response. Finally, a method based on Endurance Time Analysis (ETA) [7] is used to carry out a seismic safety assessment of the Bouçã dam, considering the Operating Basis Earthquake (OBE) and the Safety Evaluation Earthquake (SEE); the seismic performance is evaluated by controlling the evolution of tensile and compressive damage under dynamic excitation of increasing intensity.

2 DAMDYSSA5.0: LINEAR AND NON-LINEAR DYNAMIC ANALYSIS OF DAMS

The numerical simulations for this work were carried out using DamDySSA5.0 (Figure 1). Under development for over a decade at the Concrete Dams Department of LNEC [8,9], DamDySSA is a 3D finite element program for static and dynamic analysis of concrete dams. The latest version of the program includes modules for linear and non-linear static analysis, modal analysis, and linear and non-linear seismic analysis [6].

In this program, the reservoir can be simulated based on two different approaches: (i) using the classic added water mass model, based on Westergaard's hydrodynamic pressure solution [10] to simulate the water mass and adopting an added water mass reduction factor for arch dams [5]; or (ii) using pressure-based fluid finite elements in the discretized reservoir domain, enabling to simulate the dam-water dynamic interaction effects and the pressure wave propagation in water [11]. The foundation is computed using a massless model, considering a condensed stiffness matrix and a proportional damping matrix applied at the dam-rock interface nodes. The seismic load is applied directly at the dam base, assuming uniform ground motion.

For seismic analysis, a time integration algorithm based on the Newmark method is employed to solve the dynamic equation of the dam-reservoir-foundation system [6,9]. Non-linear structural behaviour is simulated by combining the time integration algorithm with an iterative stress-transfer method [6,9], considering: (i) a constitutive joint model, based on the Mohr-Coulomb failure criterion and using normal and shear stress-displacement laws, to simulate opening/closing and sliding joint movements; and (ii) an isotropic constitutive damage model with softening, based on two independent damage variables to simulate the behaviour of concrete up to failure under tension and compression [12,13].



Water Level (m): 175

Dam and foundation material properties

E_{dyn} / E_{sta}: 1.25

Reservoir (added mass) c_R: 0.5

Material	E (GPa)	Poisson	Specific W. (kN/m³)	Damping (Ray. Coef.)	
1	37	0.2	24	0.1	8.5 e^{-4}
2	15	0.2	0.001	0.3	6.7 e^{-3}

Figure 1: DamDySSA5.0: user interface.

3 CASE STUDY: BOUÇÃ DAM

3.1 Dam description and observation system

The Bouçã dam (Figure 2) is located on the Zêzere River, in the Pedrógão Grande area, downstream from Cabril dam. In operating since 1955, this is a thin double curvature arch dam, with a maximum height of 70 m above the foundation level and a crest length of 175 m (Figure 2b). The thickness of the dam varies in height, from a maximum of 7 m at the base to a minimum of 2 m at the crest [14]. The dam is divided into 17 blocks by vertical contraction joints. The crest was designed with a Creager profile spillway (uncontrolled spillway), with a nominal load of 3 m, enabling the water to flow from the reservoir over the crest, away from the downstream surface [2]. The crest is divided into three sections; the central section, at el. 175 m (corresponding to the full reservoir level), is about 45 m long.

The structural response of the dam is monitored through a comprehensive observation system (Figure 2c and 2d). The horizontal and vertical displacements are measured based on geodetic methods. Additionally, the appearance of cracks on the downstream face (some exhibiting water flow), specifically the horizontal crack located approximately at mid-height, which extends to the right of the central section [2], motivated the installation of devices to measure crack movements and control their evolution of time. The observation system was upgraded over time, particularly with the installation of drains, piezometers and rod extensometers in the foundation. The dam is not equipped with a vibration monitoring system.

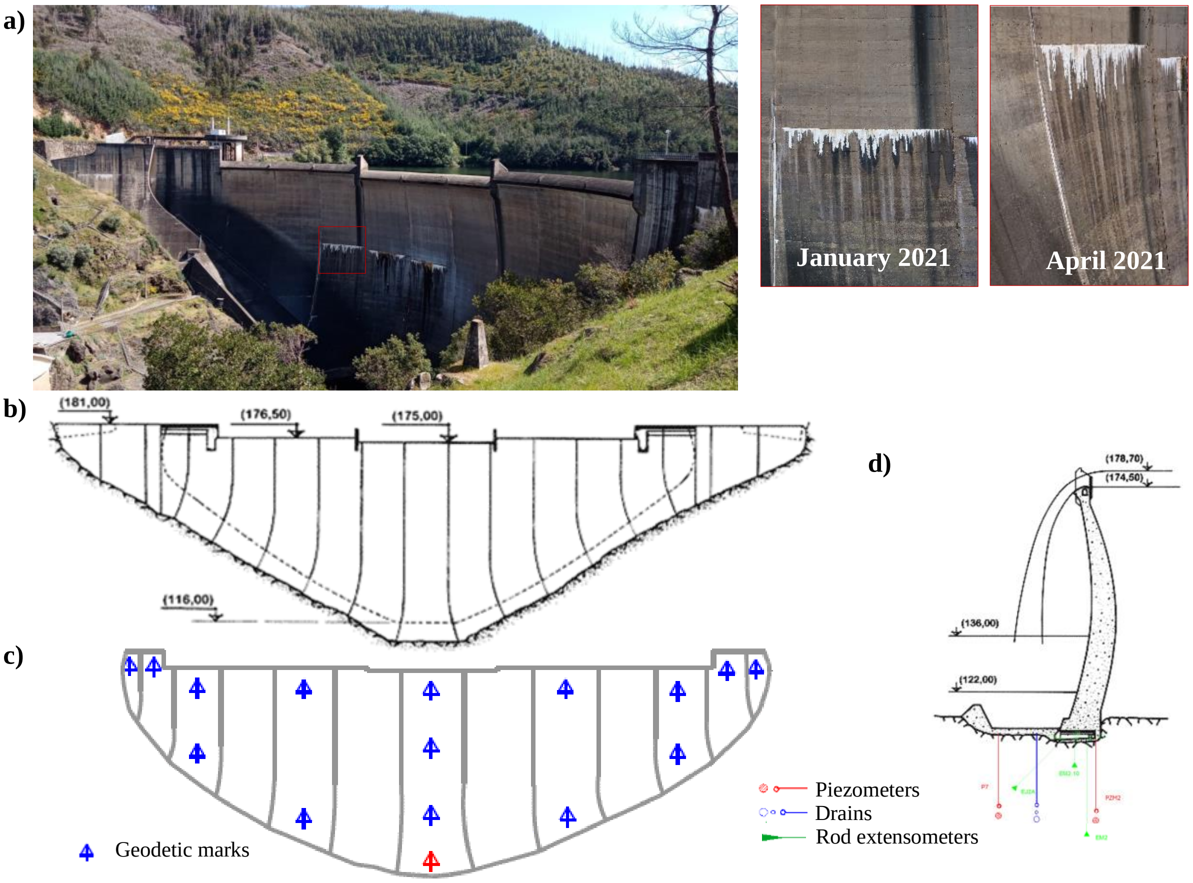


Figure 2: Bouçã dam: a) downstream view and detail of the horizontal crack evolution [2]; b) downstream elevation; c) observation system - geodetic marks on the downstream face (from the geodetic triangulation network) and, d) cross section with location of drains, piezometers and rod-type extensometers.

3.2 3D finite element model of Bouçã dam: mesh and material properties

The 3D finite element mesh of the Bouçã dam model was created based on the design equations and drawings published in old LNEC reports [14,15]. First, the elevation drawings were represented in CAD, and from these a 2D mesh was created. Then, the design equations were implemented into a MATLAB code, enabling to draw the arches for the upstream and downstream faces of the dam at various heights. Finally, using the 2D mesh data and the arches' equations, the program DamMesh3.0, developed by some of the authors, automatically generated the 3D finite element mesh of the dam and foundation (Figure 3). Then, the program introduced interface elements to represent all vertical contraction joints, the horizontal crack, and a discontinuity surface along the base (dam-rock interface) of the 5 central cantilevers. DamMesh3.0 and DamDySSA5.0 resort to hexahedral elements with 20 nodal points and 27 Gauss points and interface elements with 16 nodes and 9 Gauss points. Overall, the mesh has 960 elements in the dam (3 elements along the cross section) and 378 in the foundation.

With regard to the main properties of the model, for the dam concrete it was decided to use the current value (t = 70 years of age) of the elasticity modulus, E = E (t) = 37 GPa. This value was calculated based on the concrete creep function [16], considering its maturity process [2]. The foundation is assumed to be uniform; thus, the same rock material is adopted for all elements, with elasticity modulus E_f = 15 GPa e Poissont coefficient $\nu = 0.2$ [2]. In order to simulate non-linear structural behavior, it was necessary to define the joint properties (normal and shear stiffness K_N and K_T, cohesion c, and friction angle ϕ), and the concrete parameters for the damage model, namely the tensile and compressive strength, f_t and f_c, fracture energy, G_f, and ultimate compressive strain, ε_u. All properties and parameters are shown in Figure 3.

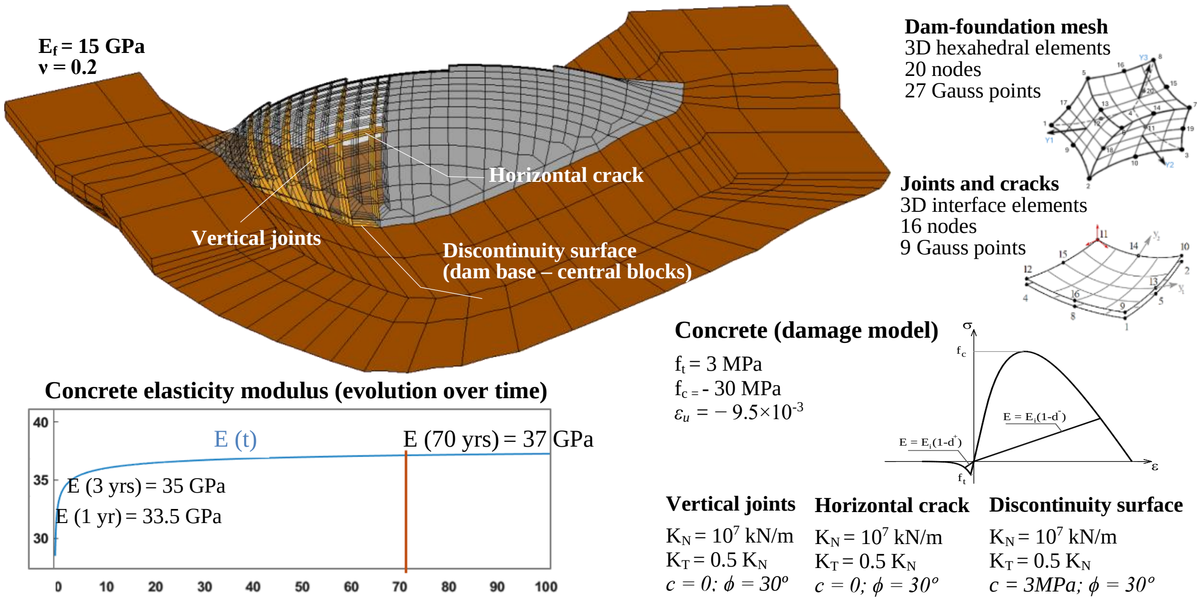


Figure 3: 3D finite element model of the Bouçã dam. Finite element mesh of the dam-foundation system (with joints in the dam body), used solid and interface elements, and main material and joint properties.

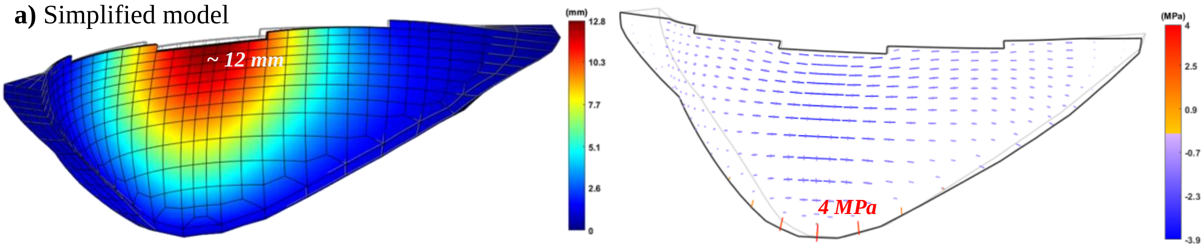
3.3 Model calibration: static response analysis and comparison with observation results

In order to calibrate and test the developed 3D finite element model of the Bouçã dam, the static response (Figure 4) was simulated for a load combination including the self-weight (W) and the hydrostatic pressure (HP_{175}) for a full reservoir scenario (water at the level of the crest central section, el. 175 m), and the results are compared with observation data, namely with the displacements measured based on the geodetic methods.

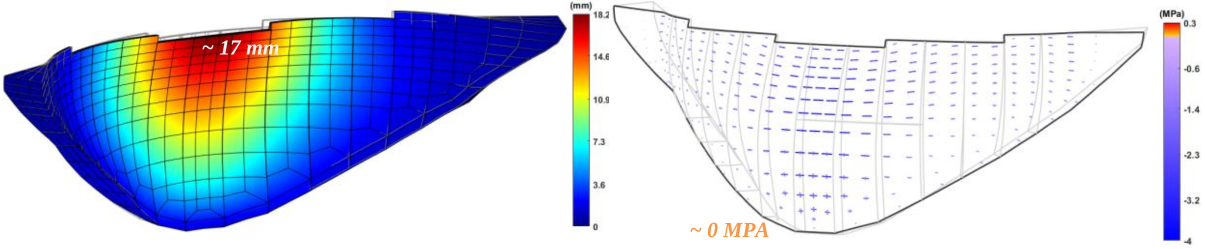
First, the static analysis was carried out using a simplified model, without vertical joints nor discontinuities (Figure 4a). The radial displacements at the top of the central section are around 12 mm, which is lower than the measured radial displacement (17 mm) at the geodetic mark located at el. 170 m. The displacements calculated in the positions corresponding to the other geodetic marks are also lower than the measured values. Furthermore, the principal stresses field shows that high vertical tensions (around 4 MPa, more than the concrete tensile strength) arise at the base of the central cantilevers. It is therefore assumed that cracking may occur in this area. These results show that the structural response of Bouçã dam should be analysed using a computational model that incorporates not only the vertical joints, but also the horizontal crack and a discontinuity at the base of the central cantilevers (as shown above in Figure 3).

Accordingly, a new static analysis was carried out using the model in Figure 3, with the vertical joints, the horizontal crack and the discontinuity at the base. The achieved results show an overall increase in the computed displacements, which are now very similar to the measured values in the displayed geodetic observation marks: for example, the displacement computed at the central section, around el. 170 m, is now of 17 mm. The opening of the base discontinuity also resulted in the release of the vertical tensions along the base of the central cantilevers, as intended. In conclusion, this process allowed to properly calibrate the Bouçã dam model and to confirm the adopted material properties and the joints' and discontinuities' parameters.

a) Simplified model



b) Model with vertical joints, horizontal crack and base discontinuity



c) Geodetic observation values

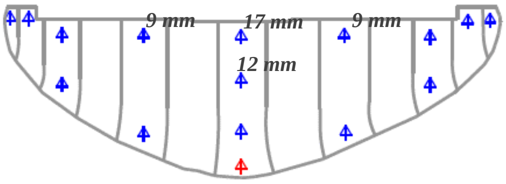


Figure 4. Static response analysis (W+HP$_{175}$): a) simplified model, without joints and discontinuities; b) model with vertical joints, horizontal crack, and base discontinuity; c) geodetic observation values.

3.4 Properties for dynamic analysis: comparison with ambient vibration test results

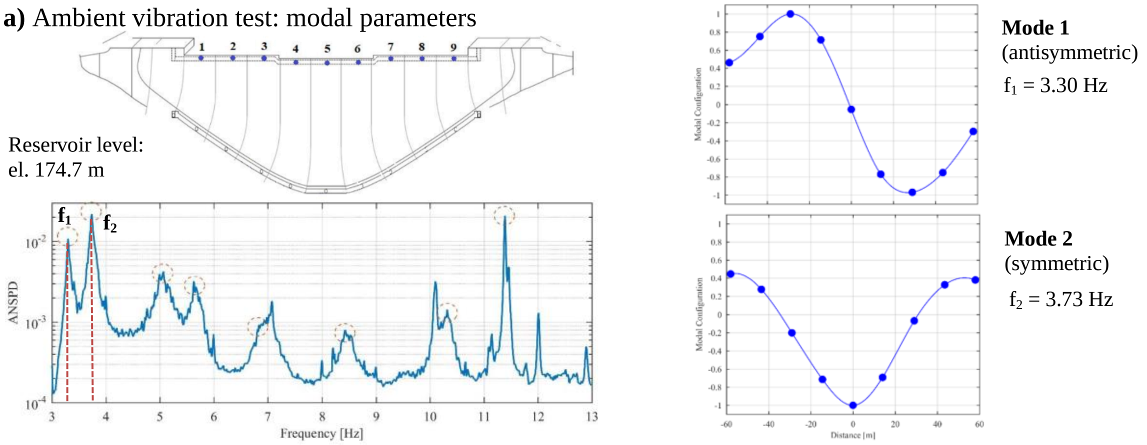
In a second step in the model calibration process, the goal was to calibrate the material properties for dynamic analysis and adjust the reservoir parameters. With that goal, the computed modal parameters were compared with experimental natural frequencies and mode shapes extracted from ambient vibrations measured on the dam (Figure 5).

As mentioned previously, the Bouçã dam still has not been equipped with a continuous vibration monitoring system. However, on June 12, 2018, an ambient vibration test was carried out to characterise the dynamic behaviour of the structure [17]. Nine uniaxial accelerometers, distributed along the crest, were used to measure accelerations in the radial direction. During the ambient vibration test, the reservoir level was at el. 174.7 m, right below the central section of the crest. The recorded ambient vibration data was analysed to obtain the natural frequencies and modal configurations of the main vibration modes (Figure 5a): the first identified natural frequency is 3.30 Hz (antisymmetric mode) and the second is 3.73 Hz (symmetric mode).

The modal response of Bouçã dam was computed using the developed finite element model of the dam-foundation and considering the added water mass model to simulate the reservoir (Figure 5b). To achieve the best agreement with the experimental results, the calibrated material properties were the concrete and rock dynamic elasticity moduli, E_{dyn} = 46.25 GPa, which were adjusted by applying a multiplicative factor of $C_E = 1.25$ to the corresponding static values E. In addition, a reduction factor $C_R = 0.5$ was applied to the reservoir added water masses, accounting for the curvature and flexibility of the Bouçã dam structure (double-curvature arch).

The modal analysis of the Bouçã dam-reservoir-foundation system was carried out by setting the reservoir level at el.175 m, to reflect the conditions observed on the day of the ambient vibration test. The calculated natural frequencies are 3.24 Hz for the first vibration mode (antisymmetric) and 3.63 Hz for the second vibration mode (symmetric). The results show that it was possible to achieve a very good agreement with the identified frequencies and the modal shapes of the vibration modes. To conclude, the developed model was able to successfully reproduce the modal response of the Bouçã dam, further confirming the calibration process.

a) Ambient vibration test: modal parameters



b) Finite element model: modal analysis results

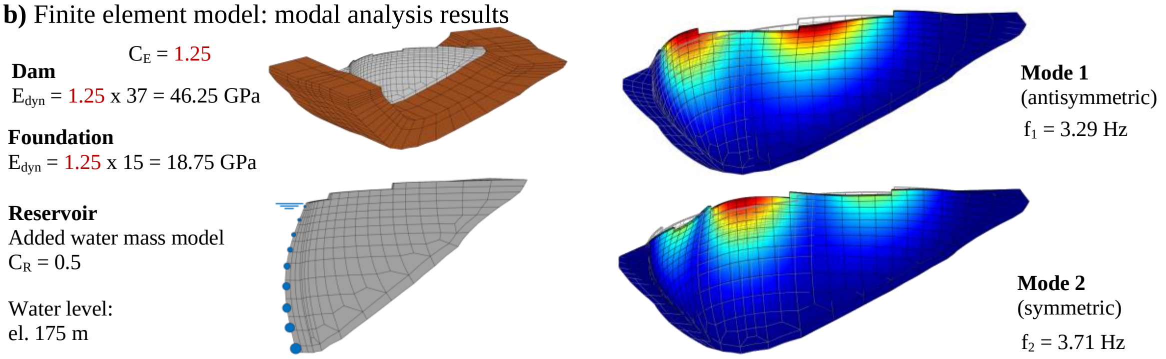


Figure 5. Dynamic behavior of Bouçã dam (modal response): a) Identified natural frequencies and mode shapes (water level, el. 174.7 m); b) calibrated model for dynamic analysis and computed vibration modes.

4 NON-LINEAR SEISMIC RESPONSE ANALYSIS

This section presents a study on the seismic behavior of Bouçã dam. The non-linear seismic response is computed using the developed model with vertical joints, the horizontal crack, and the discontinuity at the dam base, and considering concrete tensile and compressive damage. The results are compared with the response simulated in a linear seismic analysis, using a model without interface elements and assuming linear elastic concrete behavior. The goal is to test the model and analyse the influence of the horizontal crack movements on the structural response.

The load combination for this study includes the dam self-weight (W), the hydrostatic pressure for full reservoir (HP_{175}), and the seismic load (S); in this case the seismic input consists of uniform ground motion, applied at the dam base, given by a computer-generated acceleration time history (10 s) with a peak acceleration of 0.5g (Figure 6).

The results are presented in Figure 7 for two instants of interest, namely the instants of maximum displacements in both upstream and downstream directions.

For the linear seismic response (Figure 7a), the maximum upstream (≈ 23 mm) and downstream (≈ 62 mm) displacements were computed at the top of the central cantilevers; it is interesting to note that the central section and the lateral sections move in opposite directions. For the instant of maximum upstream displacement, high arch tensions occur at the upper blocks of the central section of the dam (3.7 MPa), on the upstream face, and at the upper blocks of the lateral sections (3.6 MPa), on the downstream face. When the dam moves towards downstream, even higher tensions arise at the top of the central cantilevers (downstream face), in the arch direction (8.8 MPa), and to the side of the central blocks (≈ 6 MPa), on the upstream face; high vertical tensions also develop at the base of the dam (6.2 MPa). Joint movements and concrete damage are expected in these zones, as the stresses exceed concrete tensile strength.

As for the non-linear seismic analysis (Figure 7b), the results show that the dam's structural response is no longer symmetrical, which is essentially due to the presence of the horizontal crack. In comparison to the linear response, the maximum upstream (≈ 58 mm) and downstream (≈ 66 mm) movements continue to occur at the top of the dam's central section. However, the maximum upstream displacements increase significantly, and the movements at the top of the right section of the dam, i.e., on the side of the horizontal crack, are greater than those on the left section. This effect is particularly important when the seismic forces push the dam upstream, causing the horizontal crack to open (≈ 5 mm) and amplifying the motion of the upper blocks. When the dam moves in the downstream direction, the vertical joints and horizontal crack close, and thus the structural response becomes very similar to that of the linear model.

Regarding the non-linear stress fields, the results show that the arch tensions that develop in the upper part of the dam disappear as concrete damage progresses. However, there was no significant opening of the vertical contraction joints and the consequent release of the arch tensions along the top of the dam (hence the damage caused to the crest blocks), as is usual for arch dams [9,18]; this is due to the fact that the Bouçã dam is divided into sections with different heights, which results in a break to the arch effect along the crest, thus preventing the typical arch opening when the dam moves towards upstream. On the other hand, the opening of the horizontal crack results in the release of the tensions in the surrounding blocks, and the opening of the base discontinuity releases the vertical tensions along the central section base.

In conclusion, this study has shown that the horizontal crack and the base discontinuity may influence the overall structural behaviour of the Bouçã dam when subjected to strong earthquakes, emphasizing the importance of considering these elements when carrying out seismic behaviour analyses and safety verification studies.

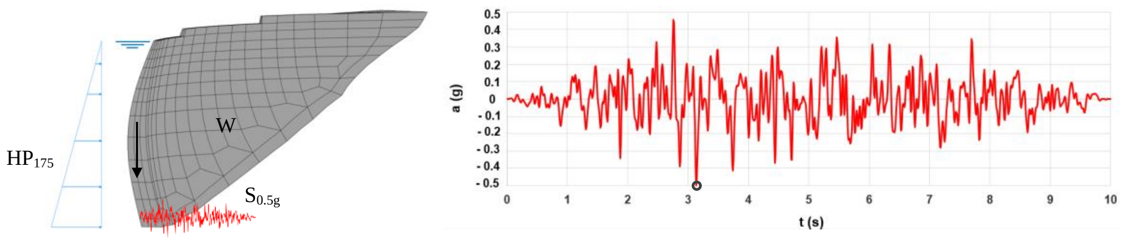
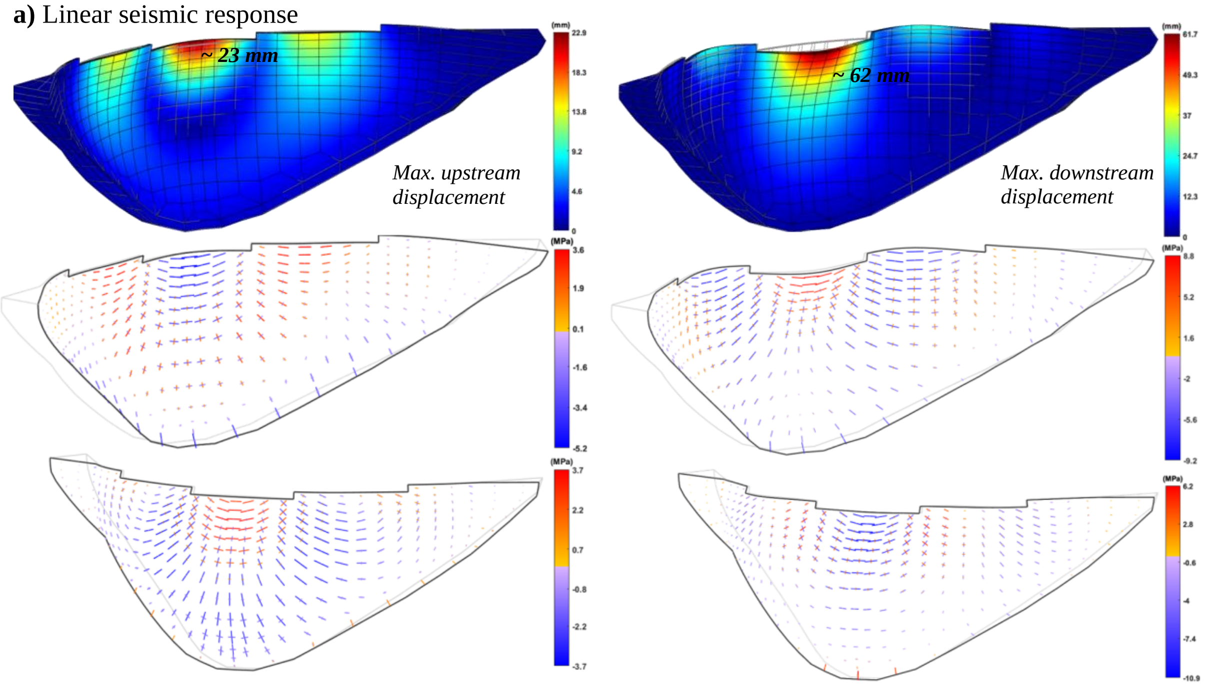


Figure 6. Seismic analysis of Bouçã dam: load combination (W+HP_{175}+$S_{0.5g}$) and seismic input.

a) Linear seismic response



b) Non-linear seismic response

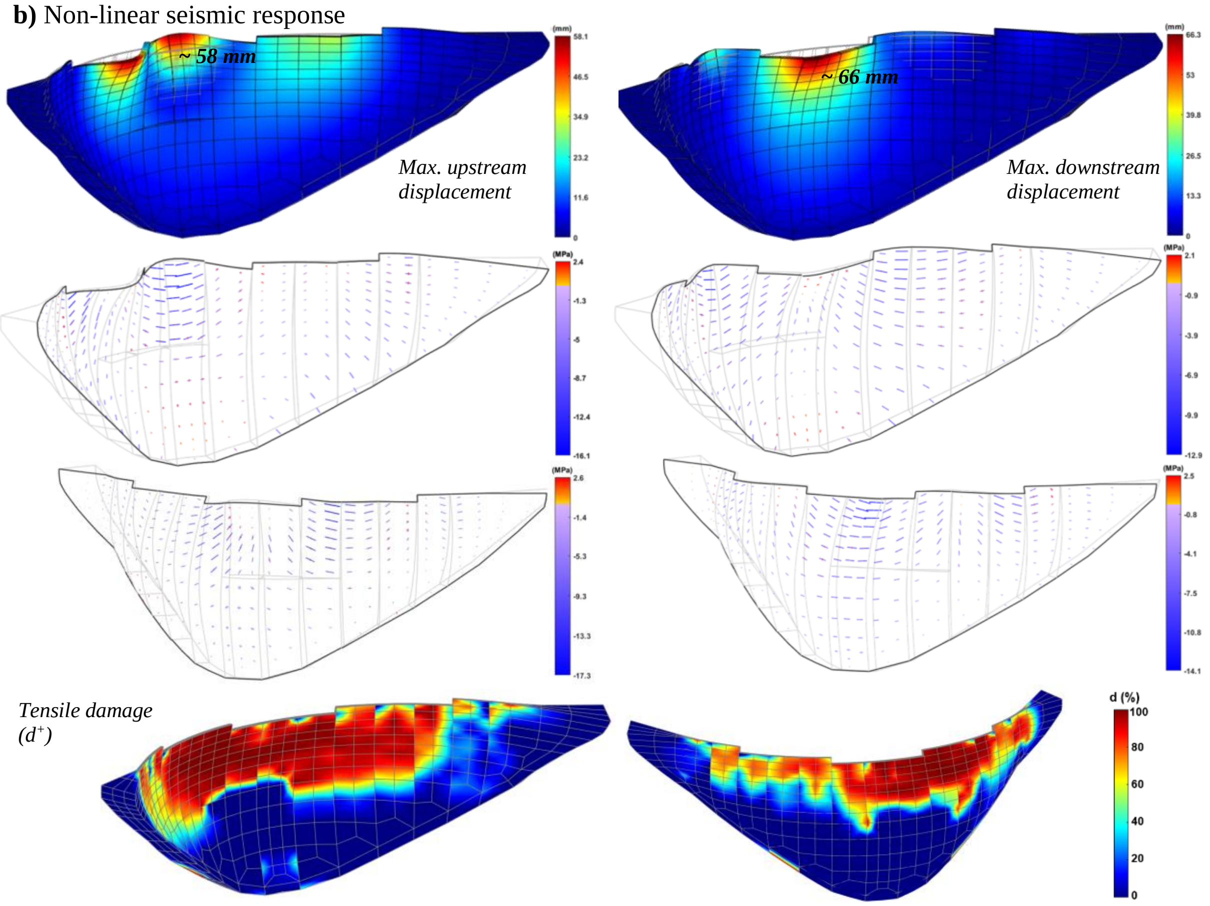


Figure 7. Seismic analysis of Bouçã dam (W+HP$_{175}$+S$_{0.5g}$): a) linear seismic response and b) non-linear seismic response (model with vertical joints, horizontal crack and base discontinuity).

5 SEISMIC SAFETY ASSESSMENT: ETA-BASED METHOD

This last section presents a study for seismic safety assessment of Bouçã dam, using a method based on ETA [7] and considering the OBE and the SEE (Figure 8). With this method, the seismic performance (or capacity) of the dam is evaluated by controlling the evolution of the deterioration state under dynamic excitation of increasing intensity. Specifically, the progression of both tensile and compressive damage is controlled [6,18], in order to determine the maximum accelerations that the dam can withstand without suffering unacceptable damage.

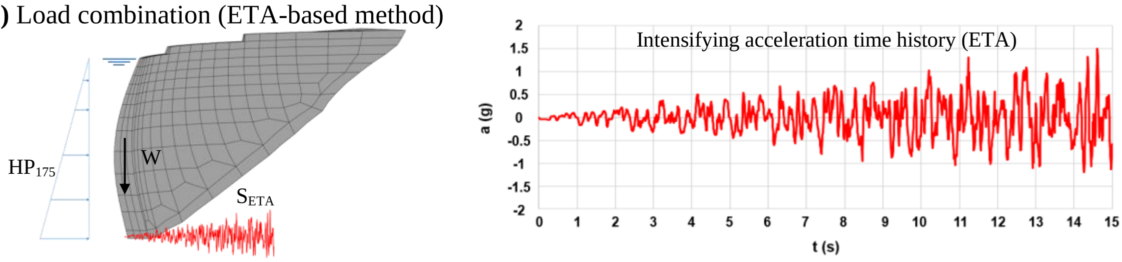
The adopted seismic performance criteria, associated with the damage level in the dam body, were established in order to meet the requirements defined for large concrete dams under the seismic excitation levels corresponding to the OBE and the SEE [19]. For the OBE, the operational conditions of the dam must not be affected by the earthquake. Therefore, it is considerable unacceptable for tensile failure (i.e., concrete cracking) to occur in significant areas of the dam faces, particularly if there is propagation of cracks along the entire cross section, as this may affect the integrity of the structure. For the SEE, the seismic performance criteria states that uncontrolled release of the reservoir should not occur; as such, an unacceptable scenario would involve the occurrence of failure under compression (i.e., concrete crushing) in key areas of the dam structure, e.g., at the top of the central section, as this could lead to a localized collapse situation, with uncontrolled release of water from the reservoir.

The non-linear simulations were performed using the calibrated finite element model with vertical joints, the horizontal crack, and the discontinuity at the dam base, and considering concrete tensile and compressive damage (recall Figure 3). For this safety assessment study, the load combination (Figure 8a) includes the self-weight of the dam (W), the hydrostatic pressure for full reservoir scenario (HP_{175}), and the seismic load applied at the dam base; specifically, the seismic input consists of an accelerogram of increasing intensity, generated for ETA, with acceleration levels that increase up to 1.5g in 15 s.

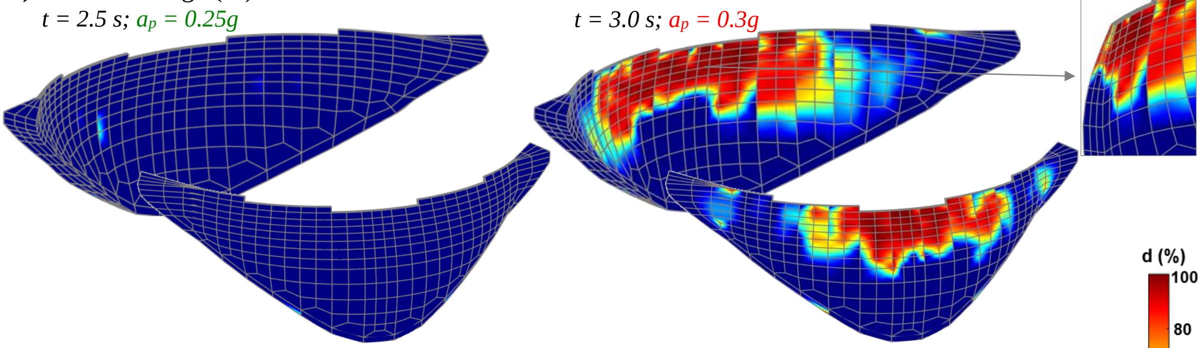
With regard to the seismic performance of the dam, the achieved results show that up to t = 2.5 s (0.25g), the dam presents acceptable tensile damage (Figure 8b). However, for excitation levels around 0.3g, there is maximum tensile damage (100%) across the entire thickness of the central upper blocks, i.e., the dam is already exhibiting deep cracks from upstream to downstream. Therefore, the acceleration threshold for maintaining normal operations (OBE safety) is assumed to be 0.25g. In the case of Bouçã dam, this value is 2.5 times higher than the peak ground acceleration (0.1g) prescribed for the OBE at the dam site, representing an important safety margin (of 2.5 times).

In this study, it is also worth highlighting that the first signs of compressive damage only occur at t = 10 s (accelerations around 1.0g), namely in the upper blocks of the central cantilevers (Figure 8c). Moreover, even at t = 15 s, which corresponds to the maximum excitation level of the applied accelerogram (1.5g), the dam still does not show substantial compressive damage throughout the dam body; there is no concrete crushing susceptible of causing localized collapse in key areas and the consequent release of the reservoir. As such, it is possible to conclude that the structural safety of Bouçã dam is verified for the SEE by a wide margin (more than 7.5 times), considering the peak ground acceleration prescribed for the SEE (0.2g).

a) Load combination (ETA-based method)



b) Tensile damage (d^+)



c) Compressive damage (d-)

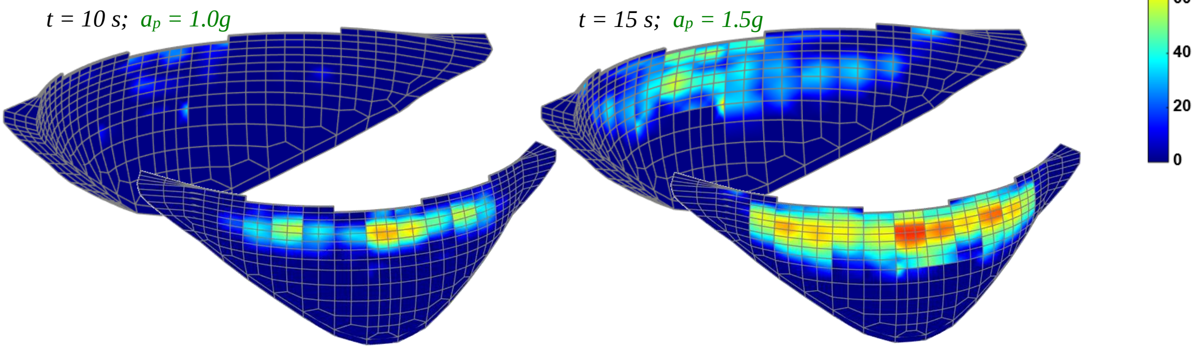


Figure 8. Seismic safety assessment of Bouçã dam using an ETA-based method: a) load combination and ETA acceleration time history, b) tensile damage evolution, and c) compressive damage evolution.

12 CONCLUSIONS

This paper presented a comprehensive study on the seismic behavior of the Bouçã dam. In operation since 1954, Bouçã is a thin double-curvature arch dam with a maximum height of 70 m and a crest length of 175 m. The structure has a horizontal crack, located about 25 m below the crest, which extends from the central section towards the right abutment. A 3D finite element model of the dam was developed and successfully calibrated, based on static observation and ambient vibration experimental data. A non-linear seismic analysis was then conducted, enabling to show how the dam geometry, the horizontal crack and the base discontinuity influence the overall seismic response of the dam under strong earthquakes. Finally, an ETA-based method was used for seismic safety assessment, considering specific performance for the OBE and SEE; the results showed that the structural safety of Bouçã dam is verified for both OBE and SEE by wide margins. All numerical simulations were performed using the finite element program DamDySSA, developed by the authors for linear and non-linear dynamic analysis of concrete dam-reservoir-foundation systems.

Acknowledgements

The authors thank the Portuguese Foundation for Science and Technology (FCT) for funding the research project SSHM4Dams (PTDC/ECI-EGC/5332/2020), the CERIS research unit (UIDB/04625/2020), and PhD fellowship of the second author (2023.00414.BD).

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