Dynamic behavior of high arch dams under recorded seismic accelerograms Study on the influence of reservoir water level

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Abstract. *In this paper the seismic response of a large arch dam (290 m high), located in a high seismicity region, is analysed. The goal is to study the influence of the reservoir water level in the dam's dynamic response under recorded seismic accelerograms. The numerical calculations are carried out using a 3D finite element program (DamDySSA3.0), developed in MATLAB, for linear dynamic analysis of arch dams. The 3DFEM model is based on a formulation in pressures and displacements, considering a state space approach to solve the coupled eigenproblem with damping, while the seismic response is computed by means of direct integration in time domain using the Newmark method. The dam-reservoir-foundation system is discretized using cubic 3D finite elements with 20 nodal points. The seismic analysis of the dam is performed for the Jiashi earthquake (April5, 1997), using the recorded seismic accelerogram as input, and considering two different reservoir water levels, a massless foundation and a global damping of about 5%. The main numerical results are presented, including displacement and acceleration time histories, as well as the hoop and cantilever stresses envelopes.*

1 INTRODUCTION

Most of the major arch dams currently in operation, under construction or in the design phase, are located in seismic regions, as is the case of several of the new large dams under construction in China. Due to the high potential risk associated with large dams, it is fundamental to develop adequate methodologies to evaluate their behaviour under seismic events [1] and to support safety control activities [2]. With this aim, Seismic and Structural Health Monitoring (SSHM) systems have been installed in several large dams, allowing to control the evolution of the modal parameters over time [3] and to characterize the structural effects due to seismic events, provided that they include appropriate software to manage and analyse monitoring data and to perform the comparison between experimental and numerical results [3, 4, 5]. Nonetheless, important challenges still arise in the seismic analysis of arch dams in both monitoring and modelling, given that the structural response of the dam is

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strongly influenced by the water-structure dynamic interaction, by damping effects related with reservoir pressure waves radiation, by movements of contraction joints and cracks and, of course, by the seismic vibrations at the foundation and at the dam body. Regarding the influence of the reservoir water level in the dynamic response of dams, which is to be studied in this paper, it is important to remind that the full reservoir condition is generally assumed in seismic calculations. However, the oscillatory movements of greater amplitude can occur for non-full reservoir conditions, as shown in recent works [6].

In this context, the importance of performing reliable numerical simulations (Fig. 1) in order to predict the seismic behaviour of arch dams should be highlighted. These studies are off great use in the scope of SSHM of dams, namely for the comparison between the measured response during earthquake events and the corresponding seismic response computed with 3DFEM models, considering the real reservoir water level and the measured accelerogramas at the rock mass foundation during the seismic event as inputs to the numerical models.

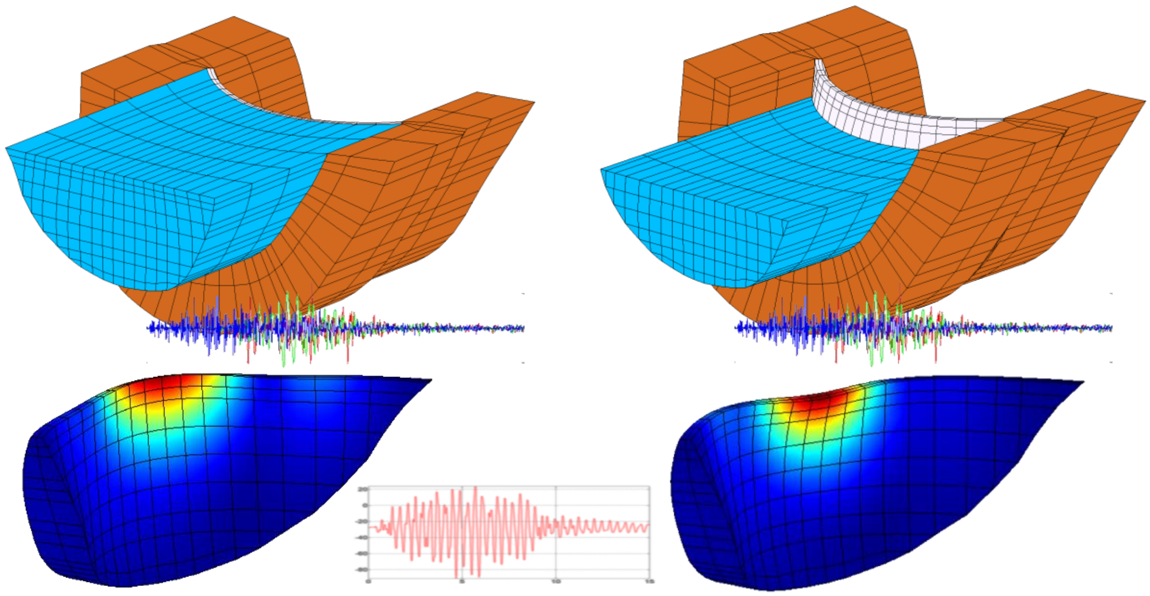

Figure 1: Numerical analysis of the seismic response of an arch dam for different reservoir water levels.

2 MODELING THE SEISMIC BEHAVIOR OF ARCH DAMS

For the simulation of the dynamic response of dams under seismic loading it is essential to use reliable numerical models, based on robust mathematical formulations and using adequate simplifying hypotheses. Here we present some considerations regarding the numerical modelling of dam-foundation-reservoir systems and the 3DFEM model implemented in the program DamDySSA3.0, used to carry out the seismic calculations.

2.1 Dam-foundation-reservoir systems. Water-structure dynamic interaction

For simulating the dynamic behaviour of dam-reservoir-foundation systems and the solid-fluid dynamic interaction, several formulations and models can be used, aiming at reproducing the measured response of dams under real seismic events as accurately as possible. In the numerical models, different hypothesis can be assumed, namely in what concerns the water-structure motion coupling [7, 8], the geometry of the dam and reservoir [9], the coupled system's global damping [4] and other hydrodynamic and foundation effects [10, 11].

For dynamic analysis of arch dams using Finite Element Method (FEM) based formulations [12] (Fig. 2)., it is common to use classic added water mass models based on Westergaard's solution [7] to simulate the hydrodynamic pressures in a simplified way. These models, although very useful and easy to implement, present limitations in the simulation of the dam-reservoir dynamic interaction. Therefore, more sophisticated models can be used, namely coupled models [8, 12], based on FEM formulations in displacements and pressures that enable to simulate the propagation of the pressure waves in the water by means of a FE discretization of the reservoir. As regards the calculation of the seismic response in time domain, the coupled problem can solved using a state space approach, in complex modal coordinates, or by direct time integration, in general coordinates.

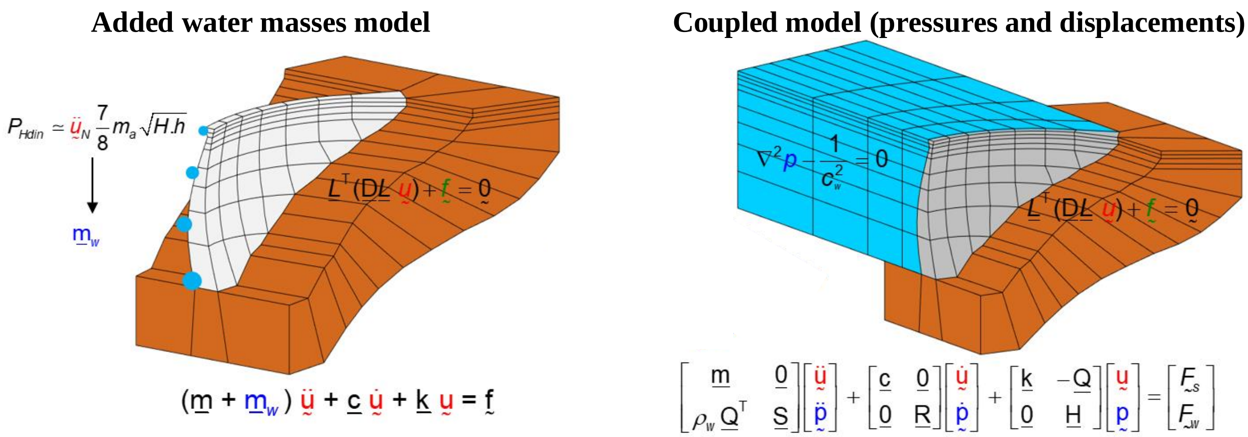

Figure 2: FEM based numerical models to simulate the water-structure dynamic interaction.

2.2 Developed MATLAB code: DamDySSA3.0

The numerical calculations were performed with DamDySSA3.0, a program developed in LNEC, using MATLAB, for linear dynamic analysis of arch dams. The dam-reservoir-foundation system is modelled using a coupled model [8], based on a FEM formulation in displacements and pressures [12]. The implemented coupled formulation enables to simulate the solid-fluid dynamic interaction, considering the propagation of pressure waves along the reservoir. For the solid domain the hypothesis of proportional or non-proportional damping can be assumed, while in the fluid domain the damping effect is associated with the energy loss by radiation of the hydrodynamic pressure waves. The foundation is simulated as an elastic, massless substructure. Also, the contraction joints are assumed to have linear behaviour. The dynamic calculations are performed for the coupled dam-reservoir system: the seismic response in displacements (dam) and pressures (reservoir) is computed by direct time integration using the Newmark Method.

DamDySSA3.0 includes an interactive and versatile graphical interface, developed in MATLAB (Fig. 3), which presents high quality graphical representations to facilitate the analysis and interpretation of the results obtained in the numerical calculations. As outputs, the program provides 3D representations of the dam-foundation-reservoir model, the natural frequencies and modal configurations of the main vibration modes, and the main results of the seismic analysis, including acceleration and displacement histories in certain nodes, as well as the displacement and stress fields in the dam body for specific time instants when the maximum displacements occur.

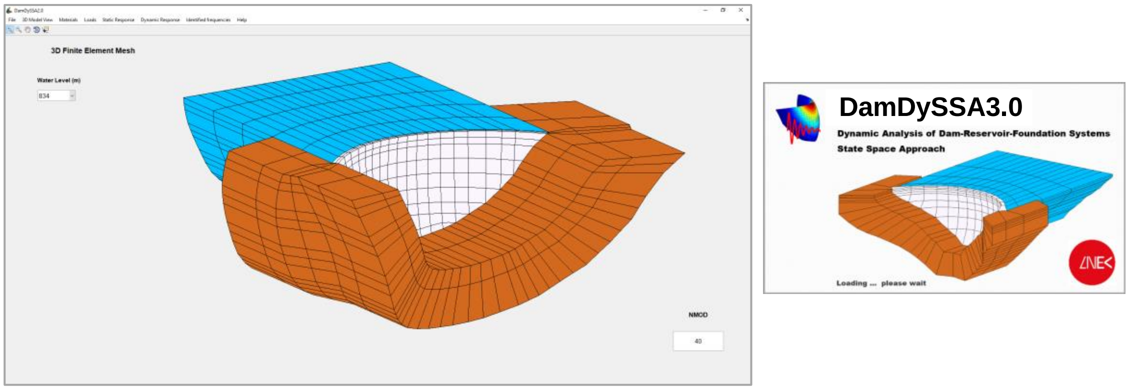

Figure 3: DamDySSA3.0. A 3DFE program for dynamic analysis of arch dams.

3 SEISMIC RESPONSE OF A 290 m HIGH ARCH DAM

The numerical results are presented in this section for the chosen case study, a large arch dam (Fig. 4) located on a tributary of the Yangtze River in Southwest China. The dam has been under construction since 2008 and is expected to go into operation in 2021. It is a double-curvature arch dam with a maximum height of 290 m above the foundation. The arch at the crest presents a development of 710 m between banks. The minimum thickness is of 14 m at the crest and the maximum of about 64 m at the insertion.

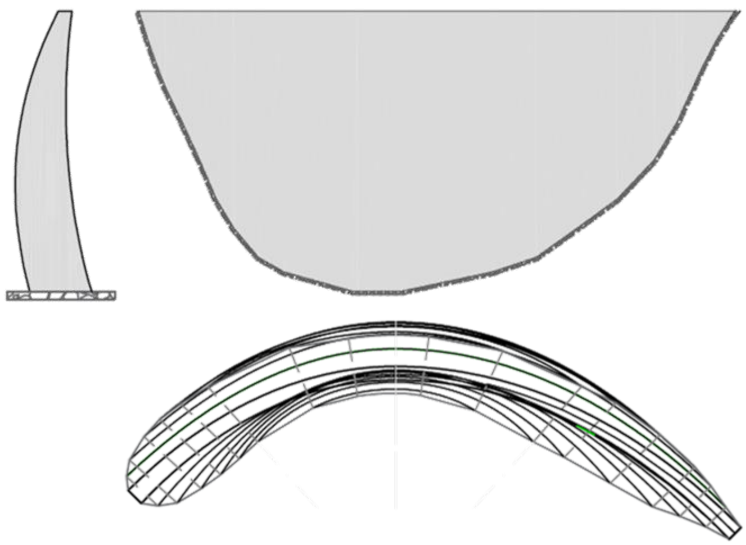

Figure 4: Arch dam, 290 m high. Cross section, front view and plan view.

The main results of the present work, regarding the study of the seismic behaviour of the abovementioned arch dam, which were computed with DamDySSA3.0, are presented herein. The aim is to evaluate the influence of the reservoir water level variations in the dam's response under earthquake motion, namely for a real accelerogram with a peak acceleration of about 0.23g, recorded during the Jiashi earthquake, China, on April 5, 1997, The numerical calculations are performed for two water levels: full reservoir (H_w=834 m) and a non-full reservoir, considering the water level at 34 m below the crest (H_w=800 m).

3.1 Seismic response for full reservoir

First, the numerical study of the dam's seismic response was carried out considering a full reservoir (Fig. 6) and using the referred Jiashi earthquake accelerogram as input to the numerical model In this case, despite the asymmetry of the dam, the modal configurations are symmetric for modes 1, 3 and 4, and antisymmetric for mode 2 (Fig.7). For a seismic analysis, it is important to know the natural frequencies in order to evaluate the frequency content of the seismic load.

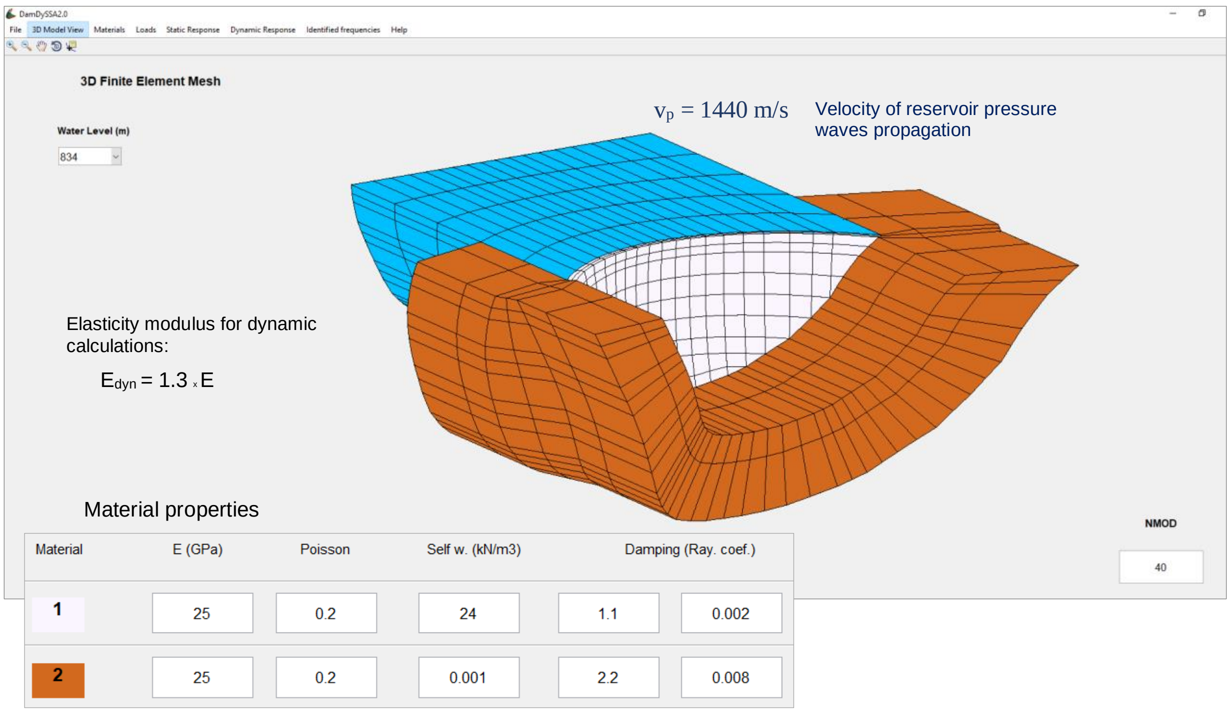

Figure 6: Dam-reservoir-foundation system with full reservoir. 3DFE discretization (cubic FE, 20 nodes), and material properties

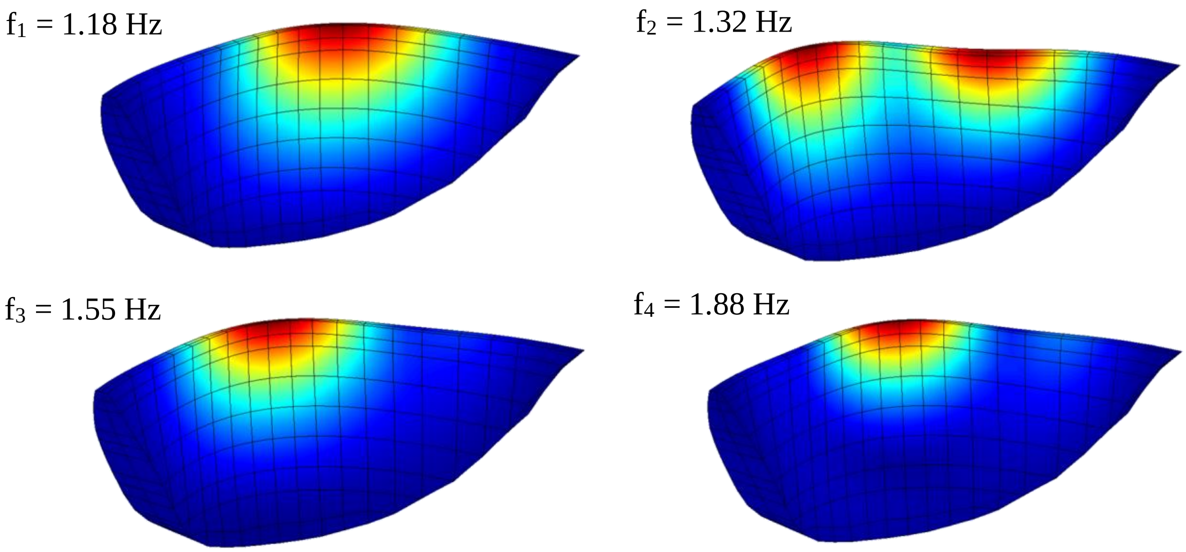

Figure 7: Vibration modes and natural frequencies for full reservoir.

The dam's seismic response is shown in Fig. 8, considering only the application of the seismic load. For full reservoir, it should be noted that the main natural frequencies do not coincide with the largest peaks of the seismic acceleration Fourier spectrum. Concerning the accelerations at the control node, located at the top of the central cantilever, a peak acceleration of about 16 m/s^2 was calculated in the upstream-downstream direction, which represents an amplification of about 7 times in relation to the seismic acceleration applied at the base. The maximum radial displacement due to the seismic load occurs in the upper central zone, to the left of the central cantilever, and corresponds to an oscillatory movement with a half-amplitude of about 100 mm. The principal stresses, computed at the time instant when the maximum downstream displacement occurs, are also presented: high tensile ($\sigma \approx$ 3.3 MPa) and compressive hoop stresses ($\sigma \approx$ - 4.6 MPa) occur in the upper central zone at the upstream face).

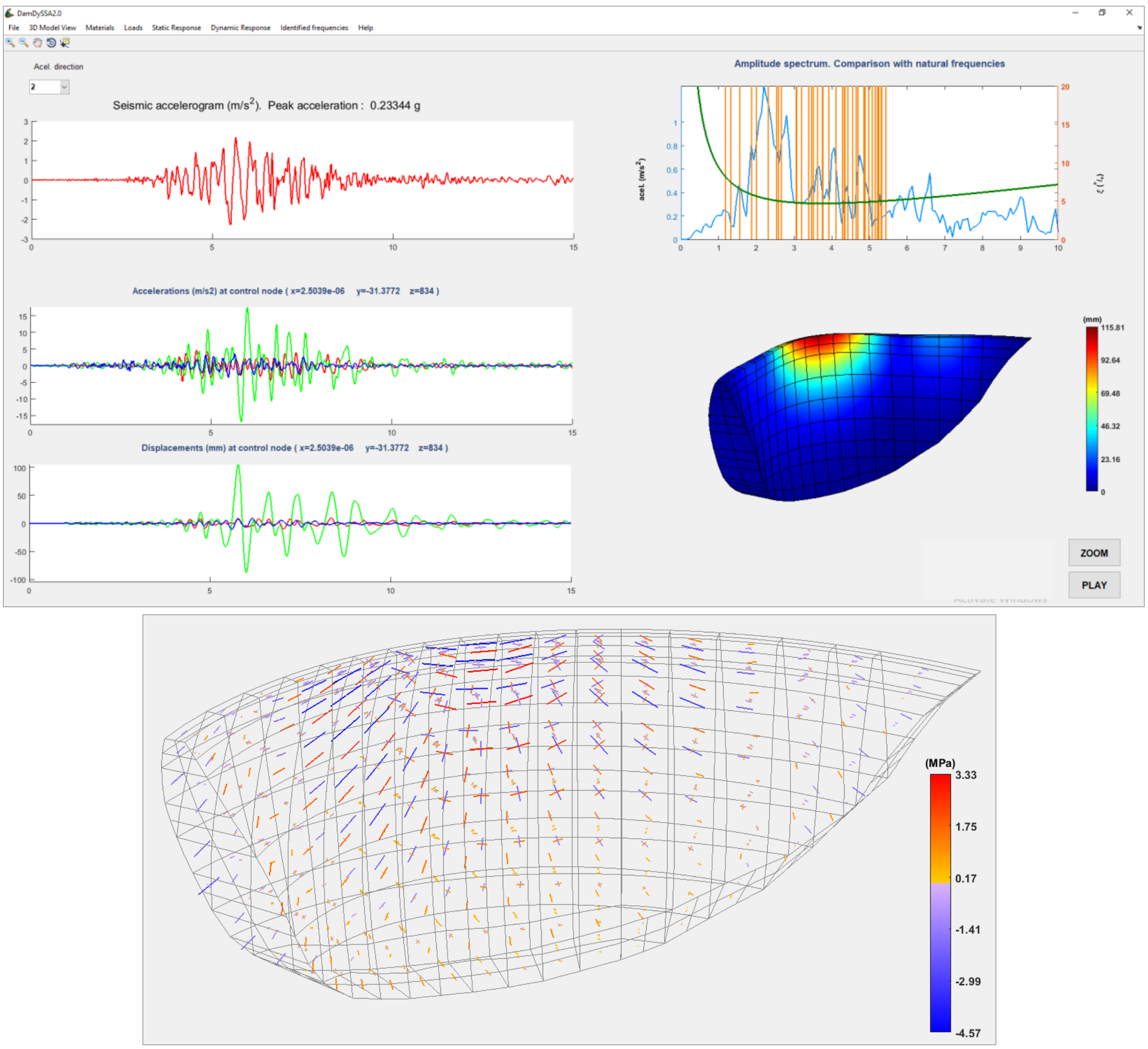

Figure 8: Seismic response for full reservoir. Accelerogram in the upstream-downstream direction and Fourier spectrum (with Rayleigh damping law and the main dam natural frequencies); history of accelerations and displacements at the top of the central cantilever; and displacement field and principal stresses at the instant the maximum downstream displacement occurs.

Fig. 9 shows the hoop and cantilever stress envelopes at the central cantilever for a dynamic load combination involving the self-weight (SW), the hydrostatic pressure for full reservoir (HP290) and the seismic acceleration (applied at the base): SW+HP290+Earthquake. The highest hoop compressions are of σ ≈ - 11 MPa (in both faces, upstream and downstream), in the upper zone; tensions in the hoop direction do not arise and the minimum hoop stresses are inferior to - 1 MPa, near the insertion. Regarding the cantilever compressions, the maximum values are around σ ≈ - 5 MPa at the downstream face, close to the base. For this earthquake, even when the largest seismic upstream displacements occur, which might result in significant hoop tensions (or, alternatively, cause the contraction joints to open), the dam remains generally under compression due to the static compressive stresses. In summary, no tensions occur for full reservoir, which means that the opening of the contraction joints is not expected.

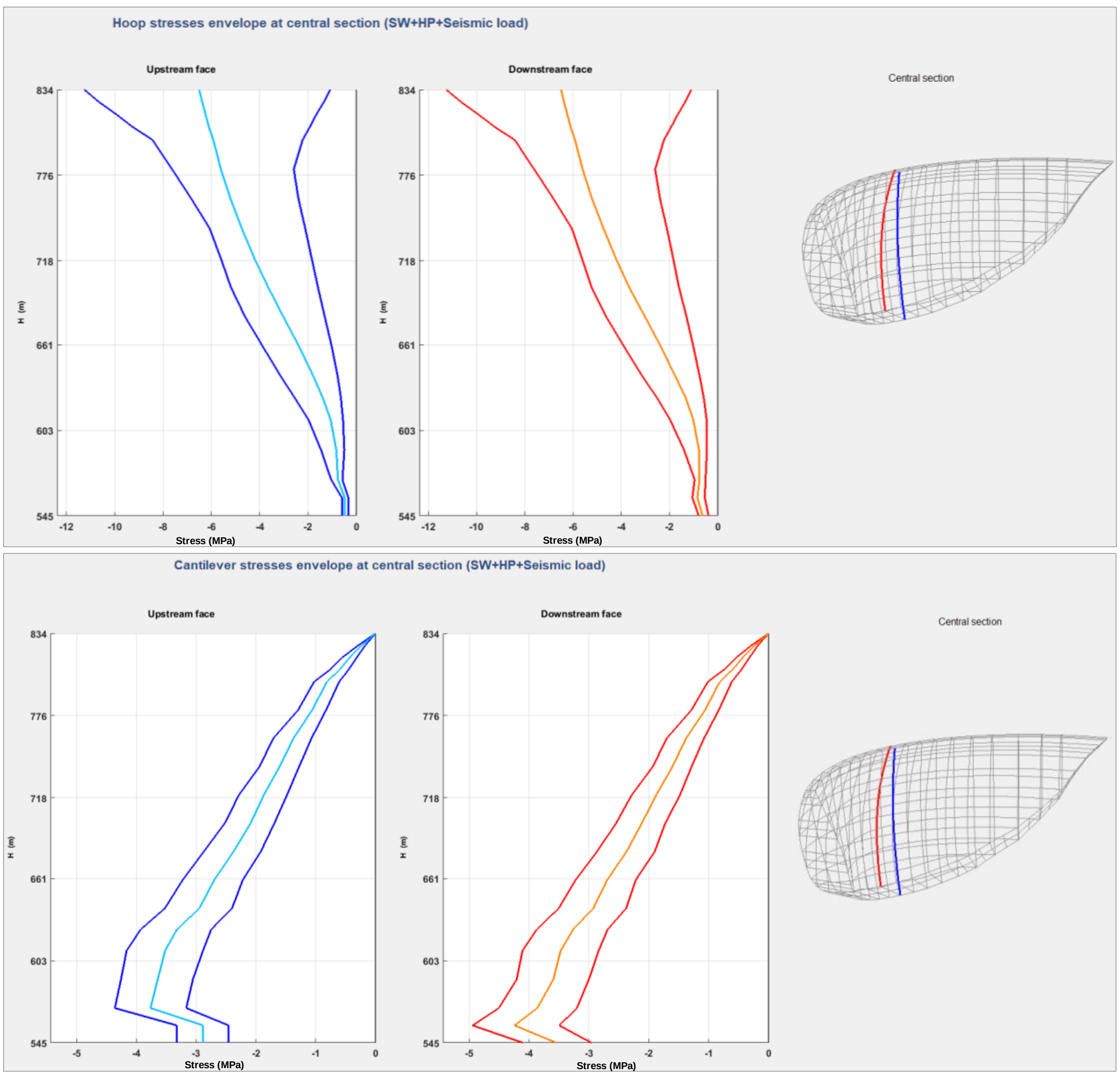

Figure 9: Seismic response for full reservoir. Results for the combination SW + HP290 + Earthquake. Hoop and cantilever stresses envelopes in the central section.

3.2 Seismic response for non-full reservoir (water level at 34 m below the crest)

In this section are presented the numerical results of the dam seismic response considering the reservoir water level 34 m below the crest (Fig. 10) and the same Jiashi earthquake accelerograms. As expected, with a lower water level, the mass of the global coupled system is reduced and thus the natural frequencies increase, while the modal configurations are similar to those obtained for a full reservoir model (Fig. 11).

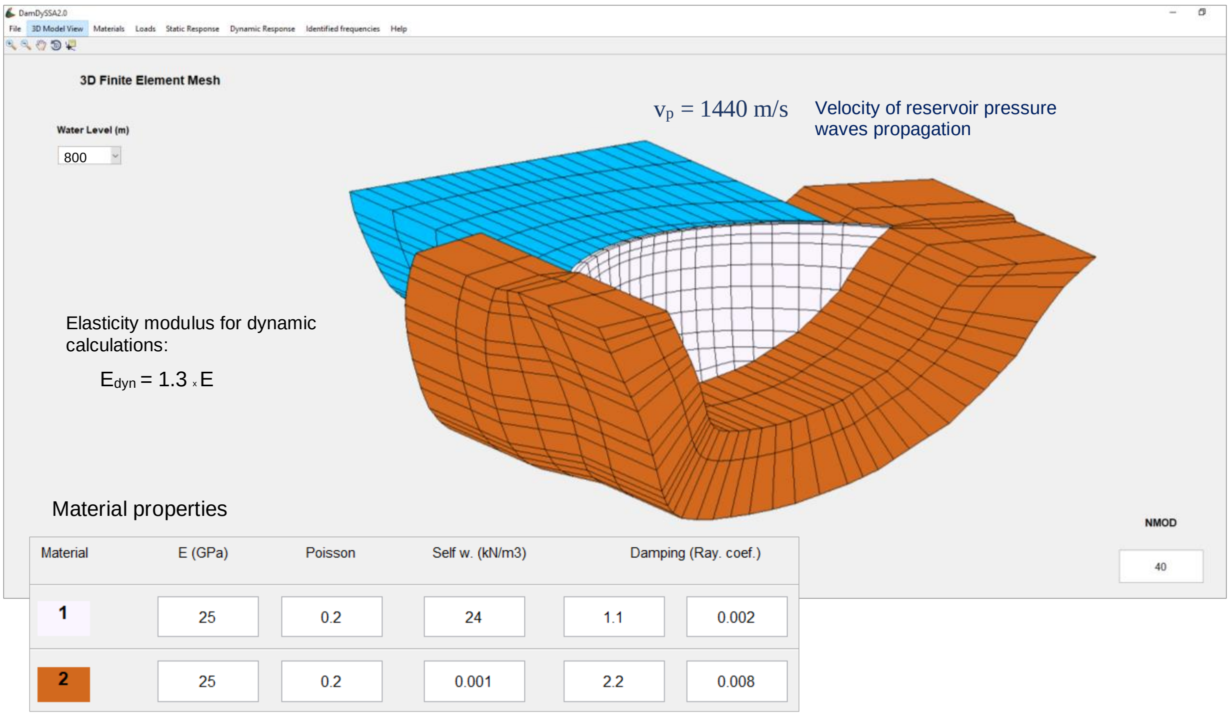

Figure 10: Dam-reservoir-foundation system with non-full reservoir: water level 34 m below the crest. 3DFE discretization (cubic FE, 20 nodes), and material properties.

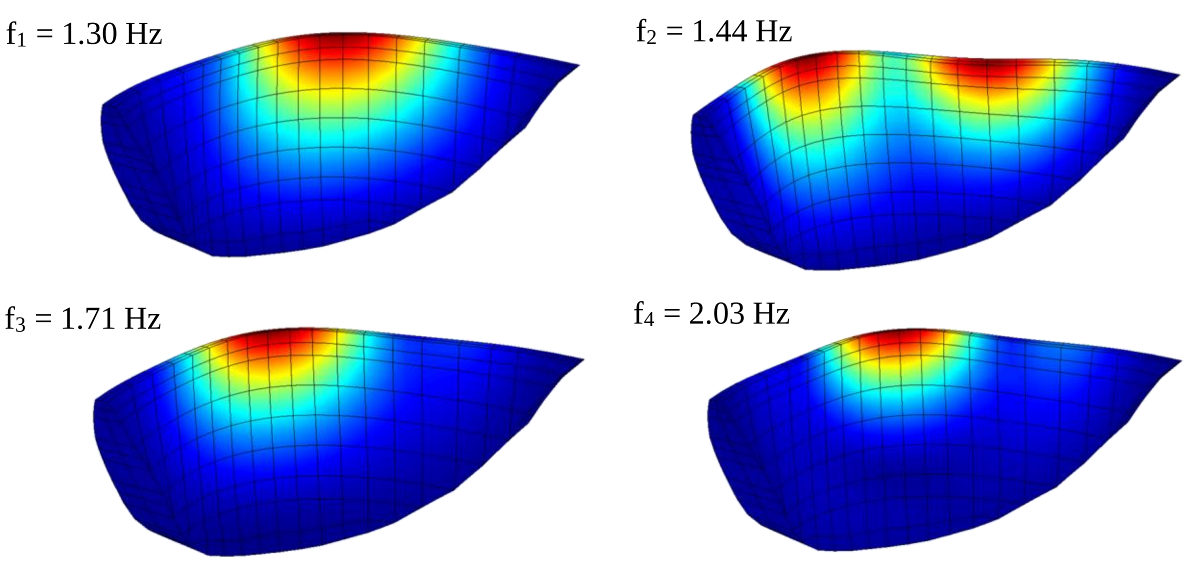

Figure 11: Vibration modes and natural frequencies for non-full reservoir: water level 34 m below the crest.

The dam's seismic response under the seismic load is shown in Fig. 12. In what concerns the accelerations at the top of the central cantilever, a peak acceleration of about 22 m/s^2 was computed in the upstream-downstream direction, representing an amplification of around 9 in comparison with the seismic peak accelerations at the base. Again, the maximum radial displacement solely under seismic loading were computed in the upper central zone, resulting in an oscillatory motion with a 100 mm half-amplitude. As in the calculation for full reservoir, the higher tensions and compressions arise in the hoop direction at the upper zone (upstream face). However, due to the lower water level a decrease in the maximum tensions and an increase in the maximum compressions is obtained.

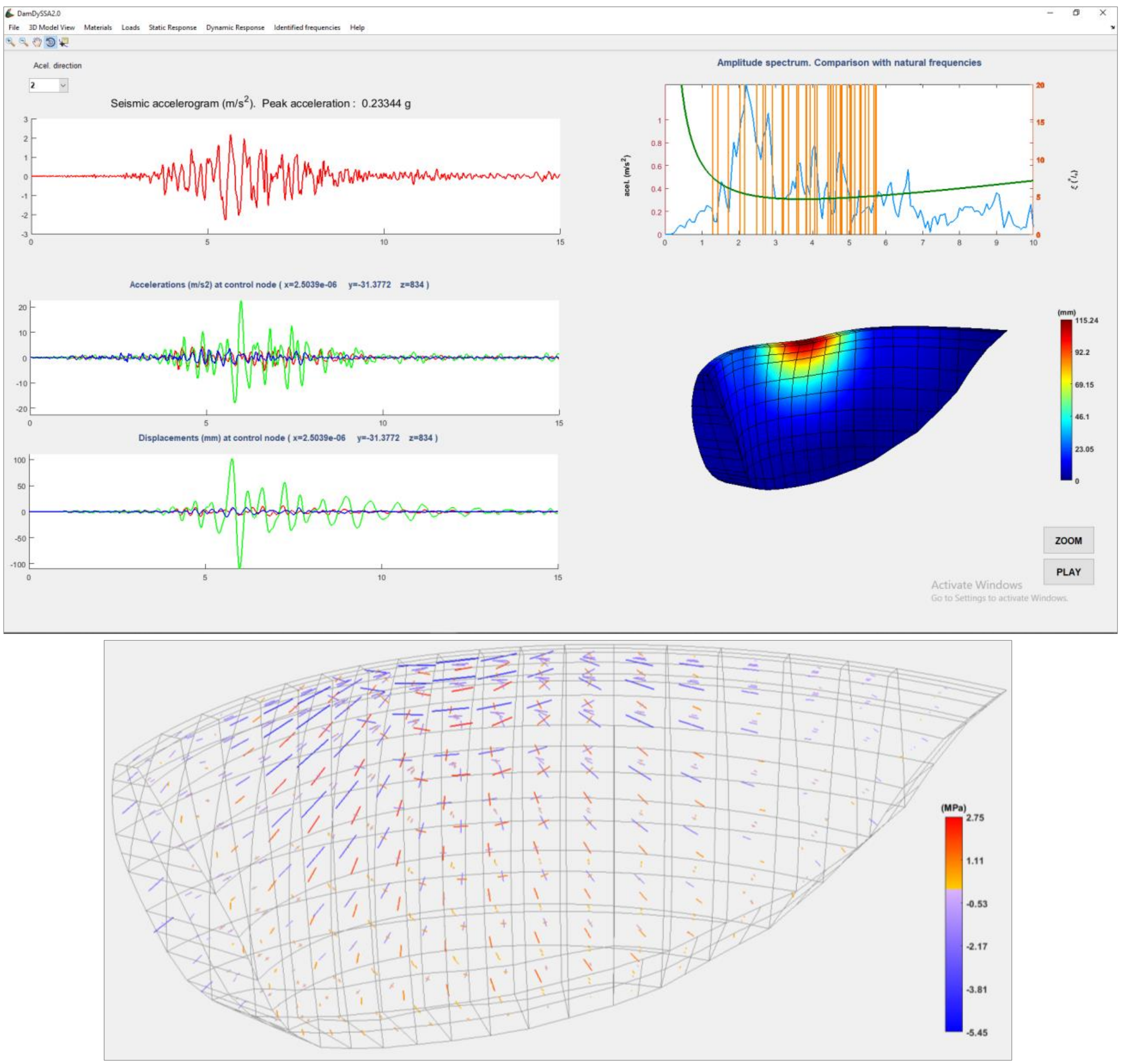

Figure 12: Seismic response with non-full reservoir: water level 34 m below the crest. Accelerogram in the upstream-downstream direction and Fourier spectrum (with Rayleigh damping law and the main dam natural frequencies); history of accelerations and displacements at the top of the central cantilever; and displacement field and principal stresses at the instant the maximum downstream displacement occurs.

The stress envelopes at the central section for the load combination SW+HP256+Earthquake are presented in Fig 13. The maximum hoop compressions, (σ ≈ - 7.5 MPa) are calculated in both upstream and upstream faces at the upper zone; once more, tensions in the arch direction do not arise. The minimum hoop stresses are inferior to - 1 MPa and are calculated near the dam base. In relation to the cantilever compressions, the higher stress values are around σ ≈ - 5 MPa at the downstream face, near the insertion. In comparison with the stress fields computed for the seismic calculations with full reservoir, one can note that the cantilever stresses envelopes are quite similar, while for the hoop stresses envelopes, a decrease in the maximum and minimum compressions at the upper zone of the central cantilever was obtained. In resume, no tensions arise for the combination with the water level at 34 m below the crest even when the largest seismic upstream displacements occur, hence the contractions joints are not expected to open, as for the previous load combination with full reservoir.

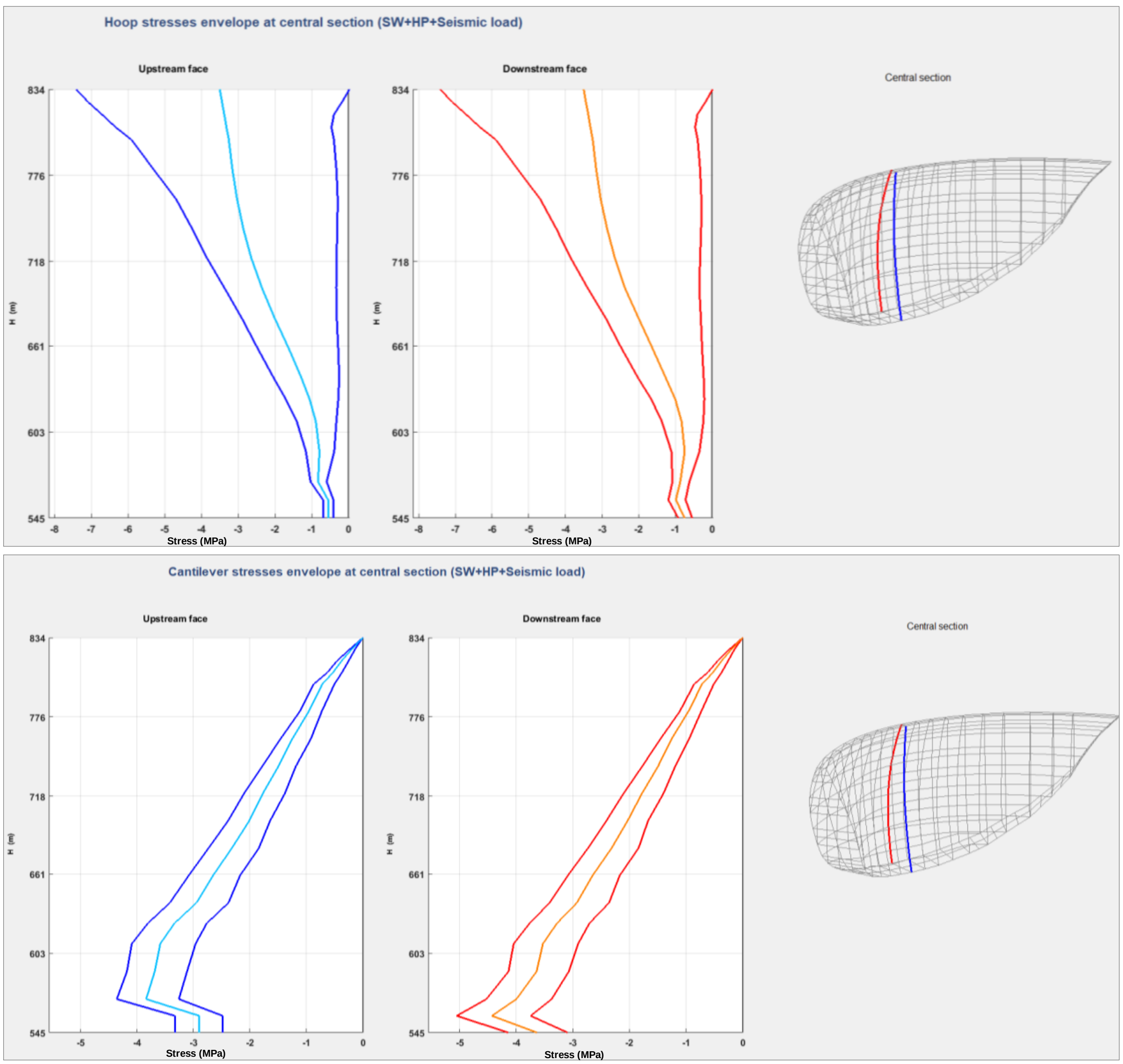

Figure 13: Seismic response for the reservoir water level at 34 m below the crest. Results for the combination SW+HP256+Earthquake. Hoop and cantilever stresses envelopes in the central section.

4 CONCLUSIONS

In this work the program DamDySSA3.0, developed at the Concrete Dams Department in LNEC for linear dynamic analysis of arch dams, was used to study the seismic behaviour of a 290 m high arch dam, considering two reservoir conditions: full reservoir and a reservoir water level at 34 m below the crest. The numerical calculations were carried out using a coupled formulation to simulate the dam-reservoir dynamic interaction, considering the propagation of pressure waves in the reservoir. The seismic analysis is performed for a recorded accelerogram from the Jiashi earthquake (April 5, 1997) with a peak acceleration of 0.23g and considering Rayleigh damping with a damping ratio of about 5% for the frequencies of the main dam vibration modes.

The presented results show that only compressive hoop stresses occur in the upper central zone for the full reservoir combination (SW+ HP290 + Earthquake), which indicates that there will be no opening of the contraction joints. For the combination with the reservoir water level at 34 m from the top (SW+PH256+Earthquake), if the same damping law is used, one can note that the greatest hoop compressions occur in the upper central zone, at the time instant when the maximum downstream displacements downstream; also, the maximum compression values are clearly inferior than those obtained for full reservoir. In both cases, even when the maximum displacements occur, the contraction joints are not expected to open, given that no tensile hoop stresses arise (if that were to be the case, tensile stresses would be computed at the locations of the contraction joints opening, given that the implemented model does not incorporate joints).

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