Seismic Studies of Foz Tua and Fridão Dams

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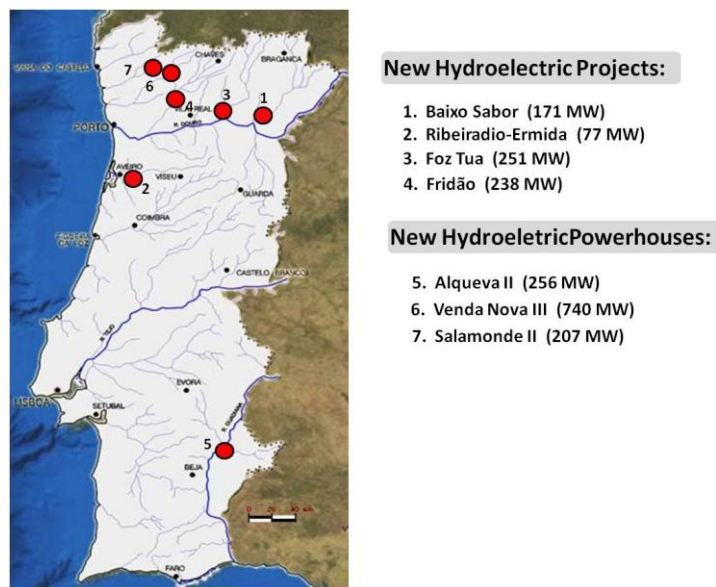*Laboratório Nacional de Engenharia Civil, Lisboa*

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SUMMARY:
A set of large concrete dams is currently under design or construction in Portugal. Earthquake loading is one of the important aspects to be considered in the design of these structures. A variety of numerical methods have been developed over the years by various researchers and are presently available for seismic analysis of concrete dams. In this paper, the models applied in the study of Foz Tua and Fridão arch dams, 108 m and 98 m high respectively, are presented, and their fundamental assumptions discussed, within the context of Portuguese regulations. In particular, the analysis of the response to the Maximum Design Earthquake is examined, considering the non-elastic behavior of the contraction joints and the dam foundation, and the safety assessment criteria employed.

Keywords: Concrete dam, Design criteria, Earthquake analysis

1. BRIEF DESCRIPTION OF FOZ TUA AND FRIDÃO HYDROELECTRIC PROJECTS

At present, EDP, Energias de Portugal S.A., has under construction three new hydroelectric projects - namely Baixo Sabor, Ribeiradio-Ermida and Foz Tua Projects. EDP has also under construction three new powerhouses – Venda Nova III, Salamonde II and Alqueva II. All these projects, with a total power of about 2.000 MW, will increase the renewable production of electricity in Portugal, and the last ones will also contribute to a more flexible exploitation of EDP electric generation.
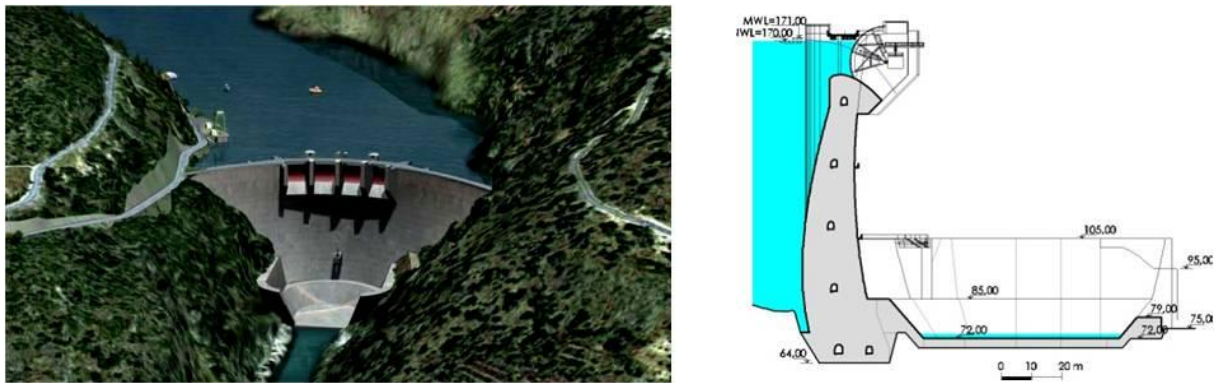

New Hydroelectric Projects:

1. Baixo Sabor (171 MW)
2. Ribeiradio-Ermida (77 MW)
3. Foz Tua (251 MW)
4. Fridão (238 MW)

New HydroeletricPowerhouses:

5. Alqueva II (256 MW)
6. Venda Nova III (740 MW)
7. Salamonde II (207 MW)

Figure 1. New hydroelectric projects of EDP, Energias de Portugal S.A.

In the framework of the Portuguese "National Program of Dams with High Hydroelectric Potential" (dated of December 2007) the Foz Tua Project was the first one to be launched and its construction started in April 2011.

The Foz Tua Hydroelectric Project (EDP 2010) is located in the north region of Portugal, in the Tua River, an important right bank tributary of Douro River, close to its confluence into Douro River. The project includes a double curvature arch dam, which is 108 m high and is provided with a controlled surface spillway over its crest designed for a 5500 m^3/s flood, an hydraulic circuit in the right bank, about 700 m long, composed of two independent tunnels, and a downstream powerhouse equipped with two reversible units with a rated output of 131 MW each one.

The designed arch dam has a total crest length of 275 m, at elevation 172 m. a.s.l., and a total concrete volume of 317000 m^3. In the dam site, the valley is quite narrow and the rock foundation is sound granite. Downstream, close to the confluence with the Douro River, the valley becomes wider and schistous rocks are present. For the full storage level, located at elevation 170 m. a.s.l., the reservoir capacity is 106 million cubic meters. The surface spillway is provided with four 15.7 m wide spans, controlled by radial gates, and a downstream plunge pool. The dam is also provided with a bottom outlet with a maximum discharge flow of 200 m^3/s. A diversion tunnel located in the left bank and two concrete gravity cofferdams allow the dam construction in the river bed zone.
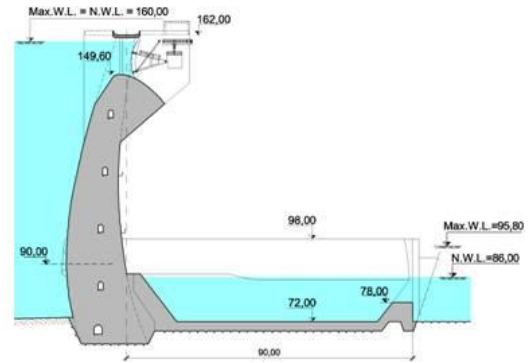

Figure 3. Foz Tua Hydroelectric Project. Preview and cross section of the dam.

The concession of the Fridão Hydroelectric Project (EDP 2011) was also awarded by EDP-Energias de Portugal S.A. in the frame of the Portuguese "National Program of Dams with High Hydroelectric Potential" and its construction will start in the second half of 2012. It is located in the northwest region of Portugal, in the middle reach of Tâmega River, one of the most important right bank tributaries of Douro River. The main dam is a concrete arch type with a maximum height of 98 m, a crest length of 300 m and a total concrete volume of 251500 m^3. The rock foundation is mainly composed of hornefels and aplite-pegmatites. A gated surface free fall spillway is incorporated over the central part of the dam body, with a design discharge capacity of 4000 m^3/s, as well as a bottom outlet designed for a 250 m^3/s flow. The dam reservoir has a total storage capacity of 196 million cubic meters.

The underground hydraulic circuit, in the right bank is completely independent of the main dam, has a total length of about 380 m and a current concrete lined cross section with 10.5 m diameter. The shaft powerhouse is equipped with one non-reversible Francis turbine designed for a nominal 350 m^3/s flow. The erection and command building and the compact switchyard are located in the access powerhouse surface platform, excavated in the hillside. The project also includes a downstream concrete gravity dam about 30 m high, located 4.2 km from the main dam.

As it can be seen in figures 2 and 3, Foz Tua dam and of the main dam of Fridão Project, are very similar structures. Fridão dam has a lower height dam Foz Tua (98 m against 108 m), but lies in a wider valley, so its crest length is larger (300 m against 275 m).

Figure 3. Fridão Hydroelectric Project. Preview and cross section of the dam.

2. DAM DESIGN SCENARIOS AND SEISMIC ACTIONS

According to the Portuguese Regulations for Safety of Dams (2007), and namely to the Portuguese Dam Design Recommendations (PDDR, 1993), two types of scenarios have to be considered when checking the dam structural safety: the exploitation and the failure scenarios.

The most frequent actions that can load the dam structure have to be considered in the exploitation scenarios, as are the case of the concrete weight, hydrostatic pressure, thermal variations, foundation uplifts and others. The dam must be able to support these actions without (or with minor) damages. On the other hand, the failures scenarios deal with extreme actions that can cause important damages in the dam. As example of failures scenarios, ruptures along the dam foundation surface or along discontinuities in the dam foundation can be pointed out. For failure scenarios overall dam stability has to be assured and uncontrolled reservoir water release cannot occur.

Earthquake loading, due to seismic activity, is one of the important actions that have to be considered in the design of dams. In addition to a set of complete geological and geotechnical studies, seismic studies are essential in order to estimate the dynamic loadings that can load the dam. For these issues the statements of PDDR are very similar to the ICOLD (International Commission on Large Dams) standards.

The seismic studies are based mainly in the local and regional geological settings, and in the area seismic history. In this frame, the seismotectonic studies, which include the identification of the possible active faults, are a major issue.

The seismic action, which represents the level of the earthquake motion at the dam site, depends on the geological and tectonic conditions in the dam region, the localization of the earthquake source and, consequently, on the released energy, source mechanism, length of transmission path and related attenuation, and surface geology of the dam site.

In accordance with PDDR, the seismic studies should define the seismic actions in terms of intensity, frequency content and duration of the seismic vibrations in the dam site. The following design earthquakes types should be considered:
- The maximum credible earthquake (MCE) which must be evaluated using a deterministic procedure or a probabilistic approach, and should have a long return period;
- The maximum design earthquake (MDE) which for dams with high potential risk hazard should be considered as the MCE;
- The operating basis earthquake (OBE), less intensive than the MDE, and with an assumed return period related to the involved estimated risks, and that is determined by probabilistic approaches.

According to ICOLD (1989), the OBE is an earthquake with significant probability of occurrence

during the dam life, and it only can cause minor damage in the dam. So a 50% probability of not being exceeded in 100 years is usually adopted for OBE estimation. In this frame, and for dam design and for dam safety analysis, the OBE must be considered as an action included in the exploitation scenarios. In addition, a more severe earthquake with a return period of about 1000 years (BDE – Base Design Eartquake) is also used to check structural dam behaviour in these scenarios.

The MDE must be estimated rather by deterministic procedures taking into account local and regional seismotectonics conditions. Probabilistic approaches, considering long return periods, can also be applied for MDE estimation, and are often used for comparison purposes. So the MDE should be considered a failure scenario, concerning dam design or structural safety assessment purposes.

In addition, Reservoir-Induced-Earthquake (RIE) that represents the ground motions capable of being triggered at the dam site by the presence of the reservoir should be taken into account, and so, the effects of faults susceptible to give rise to induced seismicity should be properly evaluated. Depending on the dam location and on seismotectonics conditions the RIE may represent motions less than, equal to, or greater than the OBE, but should in no case be greater than the MDE (ICOLD, 1989)

Regarding the definition of the seismic actions in Foz Tua and Fridão dam sites (EDP, 2010 and 2011), the following studies have been performed:
- A geological and geotechnical study of the dam site and surround zone, based in site investigations and in "in-situ" and laboratorial tests, that have been performed by EDP;
- The geological mapping of the project site and of the reservoir area executed by FCUP - Faculdade de Ciências da Universidade do Porto (Sciences School of Oporto University);
- Seismological studies and definition of design earthquakes performed by LNEC – Laboratório Nacional de Engenharia Civil (Portuguese Laboratory of Civil Engineering).

In these seismological studies, LNEC made the estimation of the OBE and of the MDE using deterministic methods, but performed also a complementary estimation of the OBE by a probabilistic approach.

In the deterministic approaches, credible seismic scenarios have been previously defined using two parameters: the magnitude (M) and distance (R) between the earthquake focus and the dam site. For the defined scenarios the ground motion at the dam site have been evaluated both by the conventional empirical method, based on attenuation laws appropriate to the tectonics environment, and by a numerical method based on a stochastic model of fault rupture and seismic radiation (LNEC, 2009, 2010a).

3. ARCH DAMS DESIGN

The adopted shapes of the Foz Tua and Fridão arch dams have been defined by the Department of Dams of EDP (Energias de Portugal, S.A.), based on the experience developed for some decades in the design of this type of structures and continuously updated (EDP, 2010 and 2011).

Preliminary design is usually based on the acquired experience and on the comparison with similar projects. In a second stage, shape definition is refined using finite element models and taking into account the main static and dynamic actions. Subsequently, a shape optimization process is usually carried out, in order to reduce the concrete dam volume enforcing an appropriate structural behavior.

The limit values of 5.5 and 1.0 MPa for the compression and tensile stresses, respectively, were considered in the following loading scenarios: construction phase and reservoir filled up to the normal water level, with and without winter thermal action. The corresponding values for the scenario of empty reservoir in the summer period were 7.0 and 1.5 MPa. The limit values of 0.80 and 0.95 were adopted for the ratio between the tangential and normal forces at the base of each dam block for the scenario of reservoir filled up to the normal water level, respectively with and without winter thermal

action, and taking into account the uplift pressures. Afterwards, a final checking of the structural behaviour of the dam for all the mandatory scenarios according to Portuguese regulations on dams was performed.

The detailed structural behavior of the dam-foundation structure was foreseen by 3D finite element analyses (performed with the Ansys software). The relevant load combinations for exploitation scenarios, considered according to the Portuguese Regulation requirements, comprise the dead weight of the independent dam blocks along construction ($\gamma = 24$ kN/m3), the hydrostatic pressure ($\gamma = 10$ kN/m3) at the upstream face for characteristic water table levels of the exploration of the reservoir, the extremes of the seasonal variations of temperature occurring in the structure, with respect to the reference thermal field occurring at the date of the grouting of the contraction joints, and the basis design earthquake (BDE). The concrete and foundation mass were considered as isotropic, linear elastic materials with the values $E = 20$ GPa, $\nu = 0.2$ and $\alpha = 10^{-5}$ °C^{-1} for the mechanical proprieties.

Considering as example the Foz Tua dam, the structural behaviour of dam agrees in general terms with the above limits prescribed in the optimization phase. It is pointed out that, as a result of this phase, for several load combinations the extreme values of the prescribed stresses occur in vast zones, showing a good exploitation of the structural material. The evaluated behaviour for the several scenarios comprising the BDE seismic action, which was defined by a response spectra based in the Portuguese Regulation and a 0.084g peak ground acceleration (return period of 949 years), is completely suitable presenting 1.7 MPa tensile stresses (close to the concrete cracking level) and 7.0 MPa compression stresses.

4. DAM ANALYSIS FOR THE MAXIMUM DESIGN EARTHQUAKE

4.1 Description of the numerical models

The analysis of the dynamic behaviour of the two arch dams was performed with the code 3DEC (Itasca, 2006), a discrete element program employed not only in rock mechanics, but also in the study of various types of structures with discontinuities. In the present models, the rock mass was assumed elastic, thus the nonlinear behaviour of the foundation was restricted to the dam-rock interface. The concrete arch was represented by a set of elastic cantilever blocks separated by the contraction joints. The seismic analysis of problems involving foundations with nonlinear behaviour may be approached with the type of numerical model shown in Fig. 4, in which the seismic action is represented by plane waves, propagating upwards from a model base with non-reflecting behaviour. The dynamic boundary conditions of the 4 lateral boundaries of the model are obtained by performing independent free-field calculations, subject to the same base motion. For each side of the model, a 2D free-field mesh is created, each one having its own 1D free-field meshes at the sides (Lemos, 1999). In the present studies, the only discontinuities are the dam-rock interface and the contraction joints, but this scheme can also handle models with rock mass joints.

The model in Fig. 4 shows the case of Foz Tua dam. The mesh of dam and foundation rock mass is composed of 20-node brick finite elements. The nonlinear behaviour of the discontinuities was assumed to follow a Mohr-Coulomb criterion. The dam-rock interface was assigned a tensile strength of 3 MPa, a cohesion of 4.7 MPa and a friction angle of 55°. The contraction joints were assumed to have only frictional strength, with an angle of 45°, therefore not considering the effect of the shear keys. Mass-proportional Rayleigh damping was used, with a value of 5% at the fundamental frequency of each dam. The hydrodynamic interaction effects were represented by Westergaard added-masses.
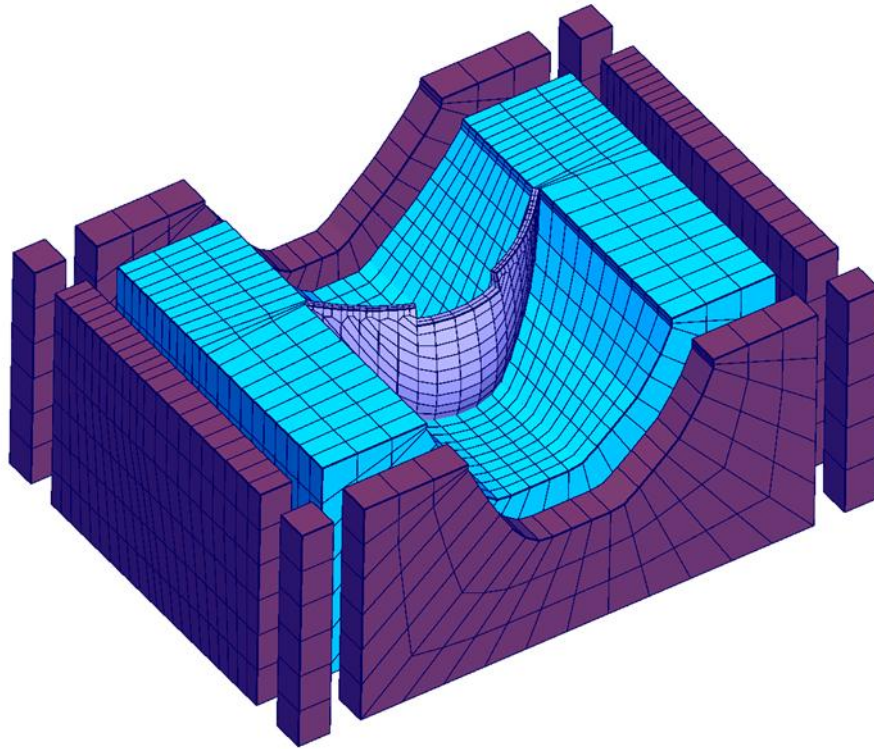
Figure 4. Numerical model for seismic analysis of Foz Tua dam. Main model and free-field meshes.

The seismic action was represented by 2 components, in the upstream-downstream and vertical directions, both applied as stress records at the non-reflecting bases of the model and the free-field meshes. Several combinations of records obtained by the numerical fault rupture calculations were used, with the vertical component scaled by a factor of 2/3. The seismological studies of Foz Tua led to a MDE of 0.27g (LNEC, 2010a). One of the records employed in the analyses is shown in Fig. 5. For Fridão dam, a lower value of PGA, 0.14g, was prescribed in the seismological studies, which also provided a set of records for the structural analysis (LNEC 2009).
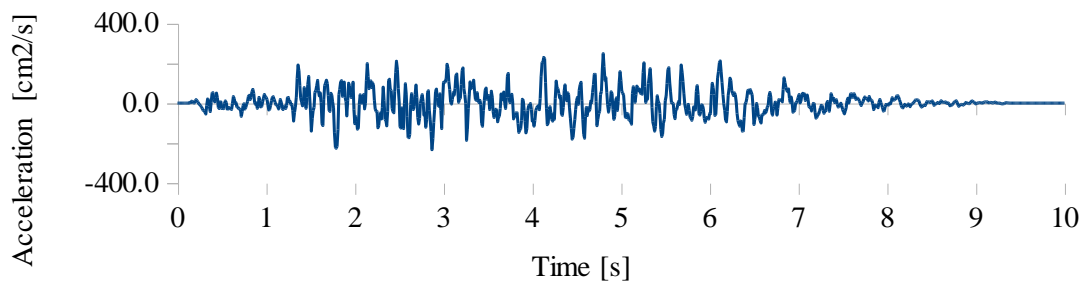

**Figure 5.** Accelerogram for MDE analysis of Foz Tua dam (PGA=0.269g).

4.2 Analysis of results

Modal analysis of Foz Tua dam indicated, for the full reservoir situation, a fundamental frequency of 2.7 Hz, an asymmetric mode, and a second frequency of 3.2 Hz, for the symmetric mode. For the MDE, four seismic actions were considered, with different input records for horizontal (upstream-downstream) and vertical motions. For each case, elastic and non-elastic analyses were conducted, but only the latter results, for full reservoir conditions, will be presented.

Fig. 6 shows the history of upstream-downstream displacement at the dam crest in one of the nonlinear runs, displaying a peak of about 50 mm. The peak stresses obtained for the various records were in the same range. In the nonlinear analyses, the peak compression in the arches, developing in the central sections of the upper arches, ranged from 7 to 8.6 MPa. Fig. 7 shows an envelope of peak compressive stresses in the arches, in the upstream and downstream faces. Arch tensile stresses were not significant in the nonlinear runs due to the opening of the contraction joints. In the cantilevers, maximum compressive stresses reached 6 MPa, and tensile stress peaks ranged from 2.2 to 2.7 MPa, as shown in Fig. 8. Compressive stresses are well within the admissible range for the dam concrete, while tensile stress results indicate that significant cracking in the dam body is not to be expected. Therefore the assumption of elastic cantilevers is acceptable.
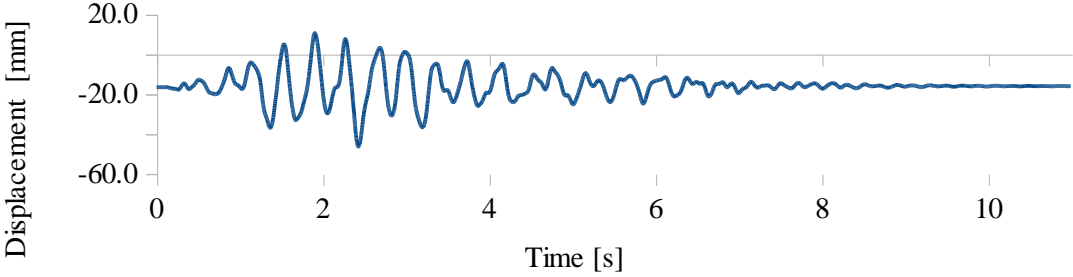
Figure 6. Horizontal displacement at crest, Foz Tua dam.


(a)

(b)
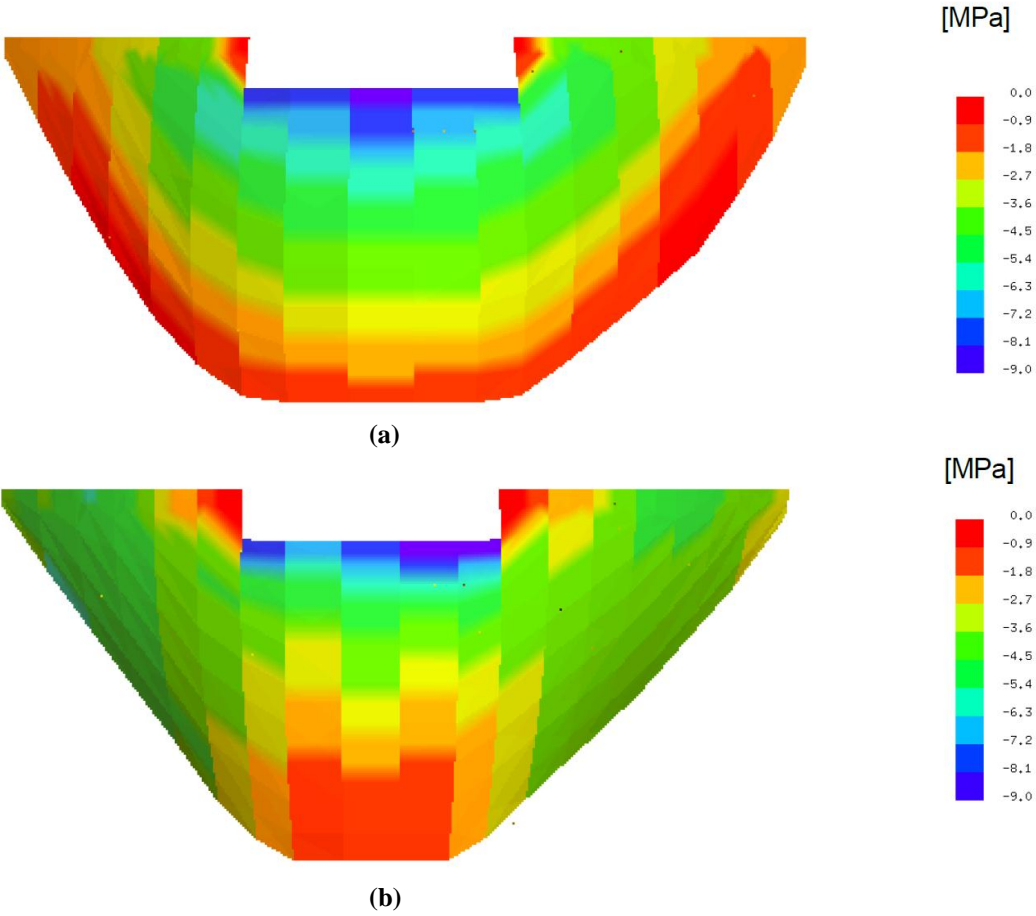
Figure 7. Envelope of peak arch compressive stresses, Foz Tua dam: (a) upstream face; (b) downstream face.
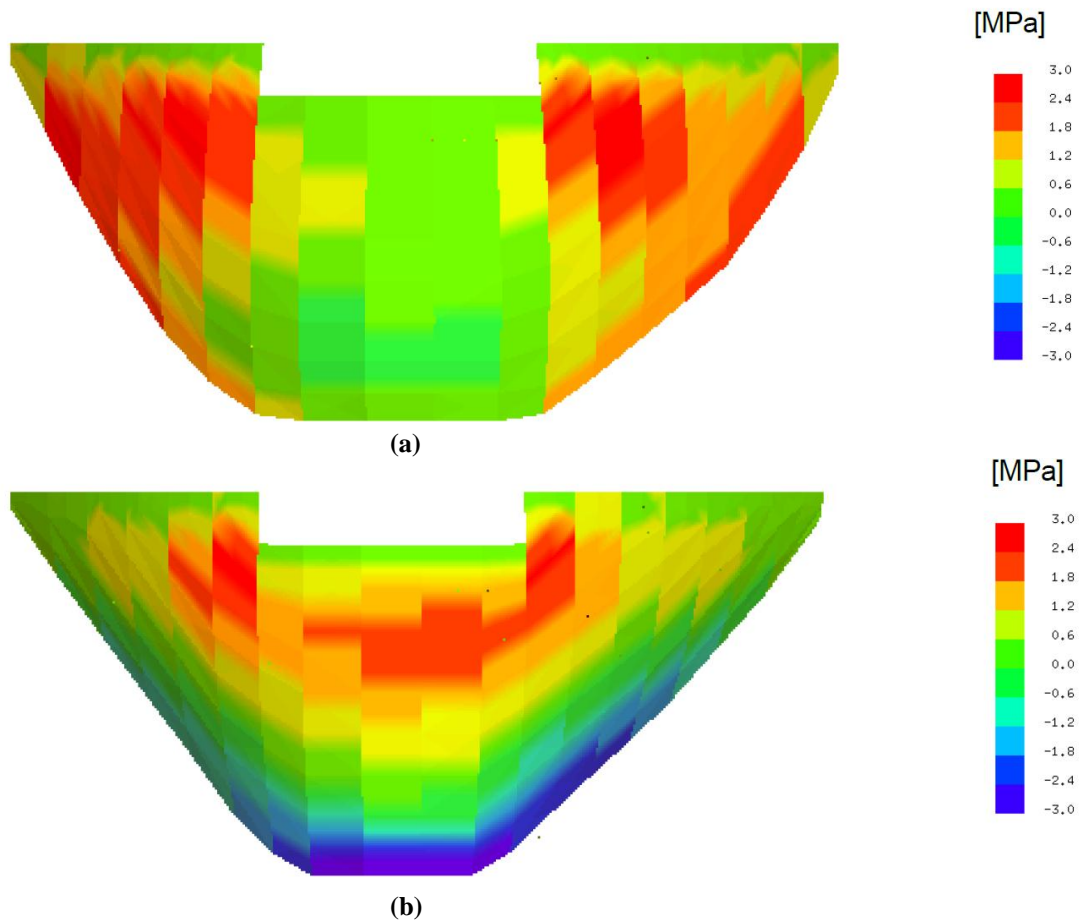
Figure 8. Envelope of peak cantilever tensile stresses, Foz Tua dam: (a) upstream face; (b) downstream face.

At the dam-rock interface, however, where stress concentrations are anticipated, the assumed 3 MPa tensile limit was attained, so episodes of joint opening took place along the upstream edge of the joint, mainly in the central part of the valley. Most of the dam-rock interface remained elastic, not permitting the development of shear slip. In the vertical contraction joints, the episodes of joint separation were restricted to the uppermost arches, with a maximum opening under 2 mm. Fig. 9 depicts the joint normal displacement in one of the joints in the spillway section, where essentially three short episodes of opening are visible. It may be concluded that Foz Tua dam is capable of withstanding the action of the MDE with a substantial safety margin.
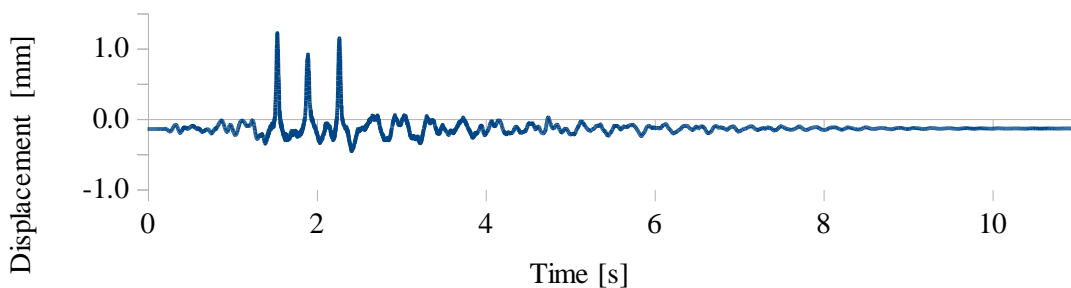

Figure 9. Normal displacement of contraction joint at the crest, Foz Tua dam.

Fridão dam has a lower height dam Foz Tua, 98 m against 108 m, but lies in a wider valley, so its crest length is larger, 300 m against 275 m. The lowest asymmetric mode has a frequency of 2.9 Hz, and the lowest symmetric mode of 3.1 Hz. The seismological studies prescribed a less severe action at this site, leading to a PGA for the MDE of 0.14g instead of 0.27g for Foz Tua dam. The design of both

dams being relatively similar, less important earthquake effects are to be expected. A 3DEC numerical model, similar to the one shown in Fig. 4, was built for the dynamic analysis of Fridão dam. The non-elastic behaviour was again concentrated at the discontinuity surfaces, the dam-rock interface and the vertical contraction joints. As in the previous case, several analyses were performed with seismic records generated by the fault rupture model.

Fig. 10 displays the history of upstream-downstream displacement at the dam crest in one of the nonlinear analyses, with a peak value of about 38 mm. The peak stresses obtained for the various records were lower than those of Foz Tua dam. In the nonlinear case, for full reservoir water level, the peak compression in the arches ranged from 5.2 to 6.4 MPa. In the cantilevers, maximum compressive stresses between 4.4 to 5 MPa were obtained, while the tensile stress peaks ranged from 0.9 to 1.5 MPa. The discontinuity placed at the dam-rock interface showed small regions of tensile failure, at the upstream edge, as shown by the peak opening contours of Fig. 11, where the maximum value is 1.4 mm. The contraction joints displayed few episodes of opening, the maximum value being 0.5 mm. In conclusion, the MDE analyses confirm the seismic safety conditions of the dam.
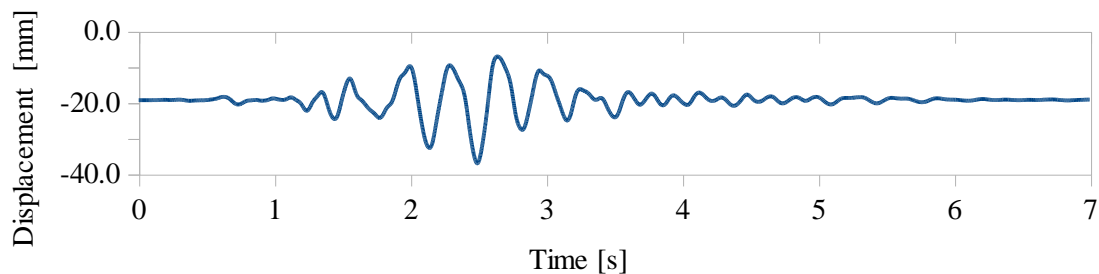
Figure 10. Horizontal displacement at crest, Fridão dam.
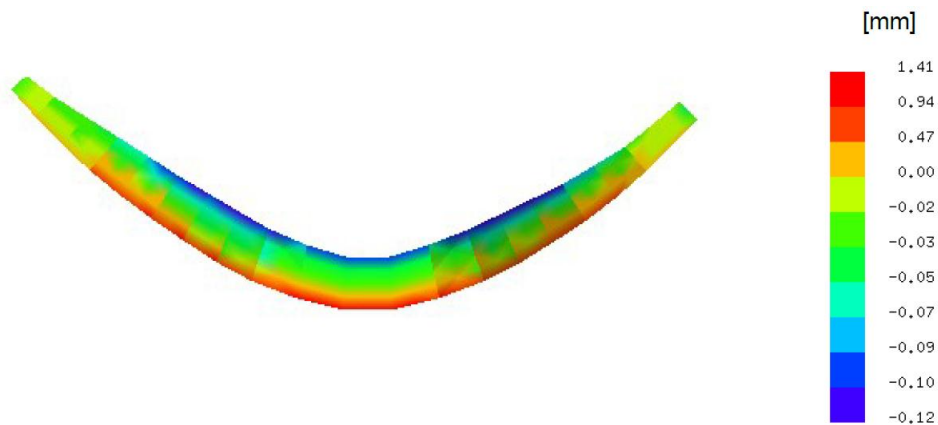
Figure 11. Contours of maximum opening at dam-rock interface, Fridão dam.

5. CONCLUDING REMARKS

The dynamic analysis of concrete dams located in seismic regions is an essential step in the verification of safety requirements. Design criteria, model assumptions and analysis results were presented for two case studies of new large arch dams, namely Foz Tua dam and Fridão dam, 108 m and 98 m high respectively, considering exploitation and failures scenarios. For the level of seismic action associated to the Maximum Design Earthquake, a numerical model considering the nonlinear behaviour at the contraction joints and the concrete-rock interface displayed an effective performance, providing the means for the prediction of the dynamic response and the safety verification. The application of these models to the above referred dams confirmed their adequate safety conditions.

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