Analysis, interpretation and prediction of the structural behavior of Cahora Bassa dam (Mozambique), affected by concrete swelling

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Abstract

This paper presents the analysis, interpretation and prediction of the structural behavior of Cahora Bassa dam, which concrete is affected by a moderate ongoing swelling process, of the alkali-silica (ASR) type. To estimate the evolution of the dam's concrete swelling for a medium-term horizon, the performed analysis took into account the results of the dam's monitoring, of the concrete laboratory tests for diagnosis and prognosis of the concrete properties and of the visual inspections.

The interpretation of the dam's behavior over time and its prediction for the next decade was based on mathematical modeling, using a three-dimensional model of the dam and of the rock mass foundation, solved by the finite element method. All relevant actions on the structures were considered, namely the dead weight of the materials, the prestress connecting the mid-bottom spillway structures to the dam's body, the hydrostatic pressure, the temperature changes in the dam's body and the concrete expansions of internal origin. The structural model considered the concrete viscoelastic behaviour and the influence of the stress state on the development of the expansions.

The monitored values and the numerical results showed an excellent agreement until 2020, attesting the adequacy of the models used to simulate the dam's behaviour. The expansions will continue to have a central role in the dam's behavior. The stress fields, computed in the dam´s body and in the mid-bottom spillway structures, have a higher relevance in the abutment bearings, near the crest.

Keywords: *Cahora Bass dam; monitoring; concrete swelling (ASR); finite element method; structural analysis.*

1. INTRODUCTION

1.1 Main characteristics of the Cahora Bassa dam

The Cahora Bassa dam (Figure 1.1) is a part of a hydroelectric scheme located on the Zambezi river, close to Songo village, Tete province, Mozambique.

The structure is a double curvature arch dam with a 166 m maximum height, from the bottom level of the foundation. The crest is 303 m long, having a chord/height ratio of 1.54 and a thickness ranging, in the main cantilever, from 4 m at the crest to 23 m at the base [1]. The crest and the retention water level (RWL) are located at levels 331.00 m and 326.00 m, respectively. The dam is equipped with a small surface spillway, of the "volet" type, and a mid-bottom spillway with 8 orifices (Figure 1.2). The rock mass foundation is of very good quality and mainly consists of gneissic granite. The rocks are sound and the rock mass is poorly fragmented. The reservoir has a large volume of about 66000 hm^3.

The dam was built between September 1972 and March 1975. The first filling of the reservoir began on the 7th of December 1974, before its completion. Since then, the water level has been approximately constant and near the maximum (326.00 m).

Figure 1.1: Downstream view of Cahora Bassa dam

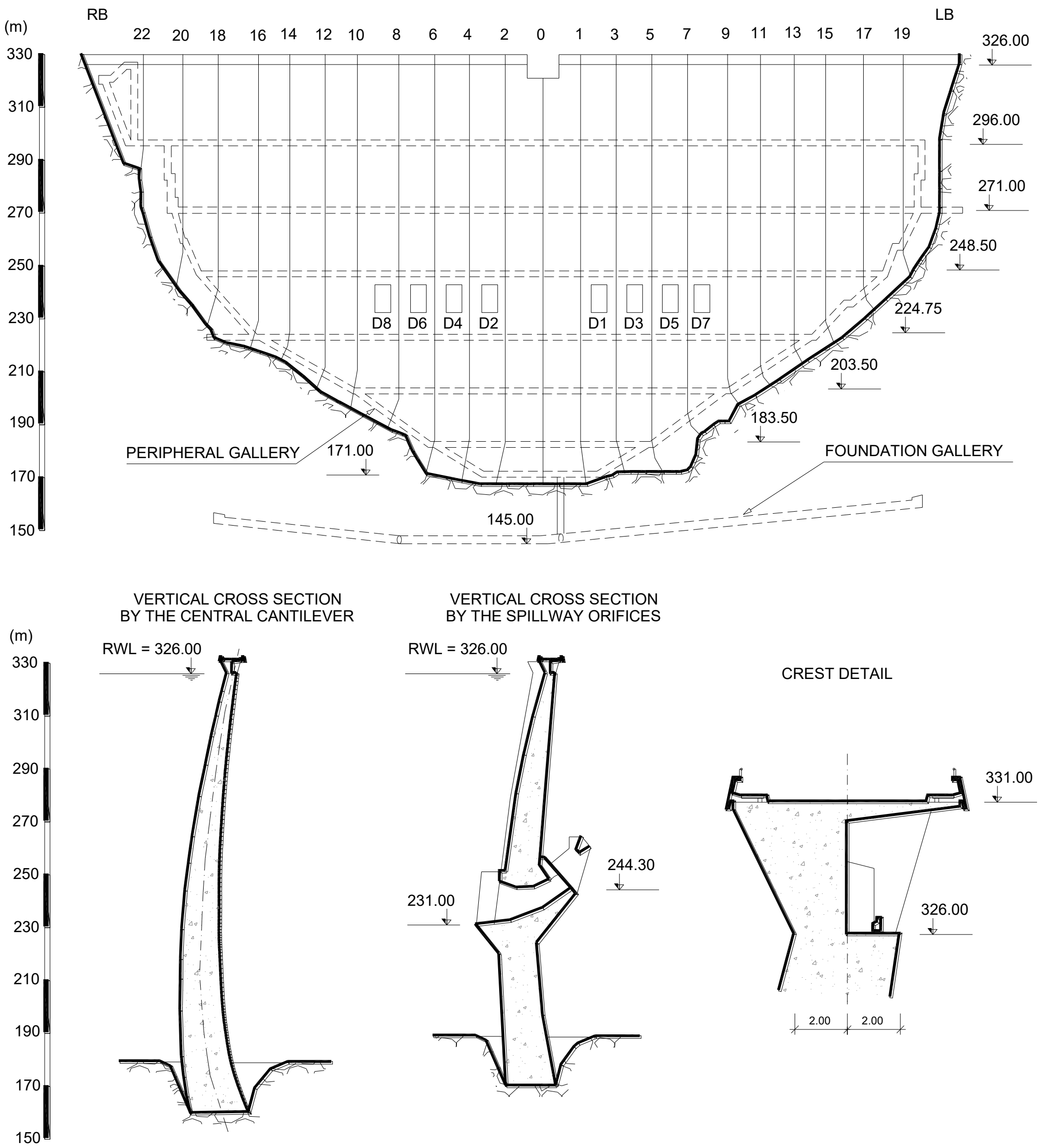

Figure 1.2: Cahora Bassa dam. Downstream elevation, vertical cross-sections and crest detail

The dam monitoring system allows the evaluation of the actions and the determination of the thermal, structural and hydraulic responses, by measuring: i) the upstream and downstream levels, by staff gauges and water level recorders; ii) air temperatures, by both thermometers and thermograph; iii) uplifts, by simple piezometers and by piezometer fans; iv) horizontal displacements, by coordimeter bases installed at the intersection of the five plumb lines with the inspection galleries; v) horizontal displacements by geodetic methods; vi) vertical displacements, by precision geometric leveling in some galleries, and by rod extensometers installed at the central cantilever of the dam and at the foundation, from the peripheral gallery; vii) convergences, by convergence meters installed close to the spillway orifices; viii) joint movements, using devices for measuring the movement of joints and deformeters; ix) temperatures in the concrete, by thermometers, by devices for measuring the movement of joints, by strain meters and stress meters; x) strains, by groups of two, five or nine Carlson strain meters; xi) stress, by stress meters; and xii) discharged and infiltrated flows, by drains and seepage measuring weirs. The dam is also equipped with a rain gauge, for measuring rainfall, as well as with an earthquake monitoring system and a dynamic response monitoring system, formed by a seismometer network.

1.2 Previous studies about the dam´s concrete swelling and its structural effects

The swelling process of internal origin in the concrete of the dam was identified in the late 1980s, about 15 years after the first filling of the reservoir. Its characterization, from the monitoring results and through physical and chemical tests, was carried out in three stages, the first in the early 1990s, the second at the end of that decade and the third between 2017 and 2021 [2]. In parallel with these studies, the modeling of the structural behavior of the dam was carried out, in order to know the evolution of the swelling effects. The structural analysis was performed in 1991, 2002, 2009, 2017 and 2021, considering the knowledge about the swelling phenomenon itself and the development of the numerical capabilities to its simulation [3, 4, 5, 6, 7, 8, 9, 10]. The upgraded model developed in 2021 was also used to forecast the behavior of the dam in the next decade.

In fact, a few years after the beginning of the dam operation, signs of an unusual structural behaviour were identified, related with the existence of progressive vertical displacements upwards, measured by precision geometric levelling, and increasing strains, monitored by means of stress-free Carlson strain-meters. From the set of studies then performed, it was concluded that a swelling process was on going in the dam’s concrete, due to alkali-aggregate reactions (AAR) of the alkali-silica (ASR) type. These studies were mainly developed by the National Laboratory for Civil Engineering (LNEC), in Lisbon (Portugal), which has been providing technical support to HCB over the years.

The technical and scientific knowledge about the concrete swelling processes, when the design and the construction were developed, was still in a rudimentary state. Following the knowledge of that time, testing of the materials (cement, aggregates, water and additives) of the concrete placed at Cahora Bassa dam and appurtenant works was properly done to determine their chemical composition and the ideal dosage of each material in order to avoid or limit the development of ASR in the concrete.

The sand and coarse aggregates used for the dam’s concrete came from crushing the rock blocks of the excavations for the foundations, tunnels and caverns. The maximum size of the aggregates was 150 mm in almost the entire dam´s body, with 215 to 265 kg of cement content per cubic meter of concrete. The aggregates are mainly gneiss of good physical and mechanical proprieties, with uniaxial compressive strength that reached of 135 to 150 MPa. The structural concrete of the dam also has a good quality, with a long term uniaxial compressive strength of about 50 MPa.

The large percentage of the free calcium oxide on the cement, identified during the works between 1971 and 1972, required a strict control of the expansibility of the concrete. From 1972 to 1975 the amount of alkalis of the cement used in the dam concrete (Na_2O %+0.658 K_2O %) has annual average values ranging from 0.32% to 0.52%. However, further specific studies of the dam´s concrete confirmed the existence of the swelling phenomenon, which has been developing in a slow process, reaching nowadays values of about 600×10^{-6} to 900×10^{-6}, that can be considered moderate. From the results of recent tests, long term maximum values of about 1400×10^{-6} are expected [10, 11].

1.3 Scope of the paper

The paper presents the relevant results of the analysis, interpretation and prediction of the dam's structural behavior. To estimate the evolution of the dam's concrete swelling for a medium-term horizon, the performed analysis considered the results of the dam's monitoring, of the concrete laboratory tests for diagnosis and prognosis of the concrete properties and of the visual inspections.

The interpretation of the dam's behavior over time and its prediction for the next decade was based on mathematical modeling, using a three-dimensional model of the dam and of the rock mass foundation, based on the finite element method. All relevant actions on the structures were considered, namely the dead weight of the materials, the prestress connecting the mid-bottom spillway structures to the dam's body, the hydrostatic pressure on the upstream face, the temperature changes in the dam's body and the concrete expansions of internal origin. The structural model considered the concrete viscoelastic behaviour and the influence of the stress state on the development of the structural expansions.

2. STRUCTURAL MODELING

2.1 Finite element model

A homogeneous continuous structural finite element model was used to support the analysis, interpretation and prediction of the dam behaviour. The continuous model is suitable for the analysis because of the very small movements occurring at the contraction joints since the first filling of the reservoir, which in turn are related to the small variations of the main loads (water level and thermal effects) and also to the concrete swelling, that contributes for closing the dam joints.

The concrete rheological behaviour was simulated by using a viscoelastic model, characterized by the creep function (1) and a Poisson ratio ν_c = 0.2. For the rock mass foundation, also considered homogeneous and continuous, the time effects were not considered, being used a Young's modulus E_f = 50.0 GPa and a Poisson ratio ν_f = 0.2.

From the results of creep tests performed at LNEC, data about the concrete composition, results of continuous monitoring, swelling quantification and structural modeling, the following Bazant e Panula creep function J was adjusted for the dam concrete,

$$J(t,t_0) = \frac{1}{50.0}\left(1 + 3.0(t_0^{-0.34} + 0.042)(t - t_0)^{0.18}\right) \qquad (\text{GPa}^{-1}) \qquad (1)$$

which is represented in Figure 2.1 for three ages of loading, as well as the corresponding relaxation curves R, obtained through numerical inversion. Mention must be made for the fact that the concrete presents considerable creep rates for high load ages, which also corresponds to a good stress relaxation capacity for prescribed strains.

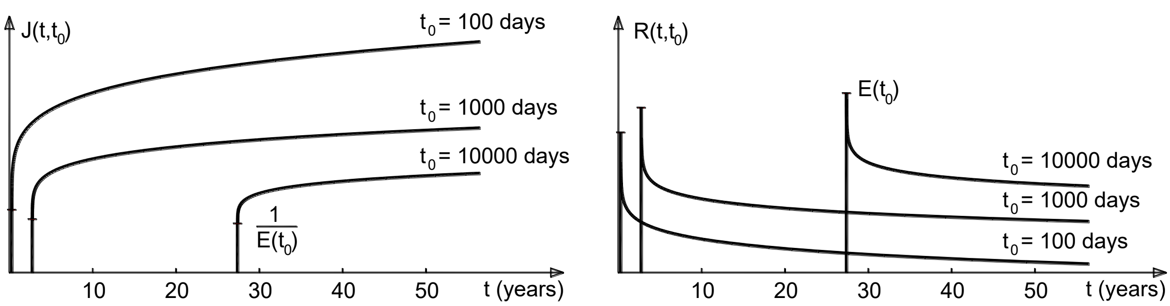

Figure 2.1: Creep and relaxation curves of Cahora Bassa dam's concrete

Since the expansive process in the dam concrete is of moderate magnitude, it was assumed that the mechanical properties of the concrete are still not effected by internal damages due to swelling. The concrete non-linear behaviour, due to tensile cracking, was also not considered in this study, because structural cracking occurs only in some localized zones of the dam, not affecting its global behaviour.

The upgraded finite element mesh includes the rock mass foundation and the mid-bottom spillway structures. Two elements were considered through the dam's thickness, which allows a better representation of the crest geometry (Figures 2.2 and 2.3). The mesh has a total of 20775 nodal points for 4962 volumetric finite elements (1320 of the 20-node hexahedral type, from which 586 corresponding to the dam's body and 734 to the rock mass foundation, and 3622 of the 10-node tetrahedral type, representing the mid-bottom spillway structures).

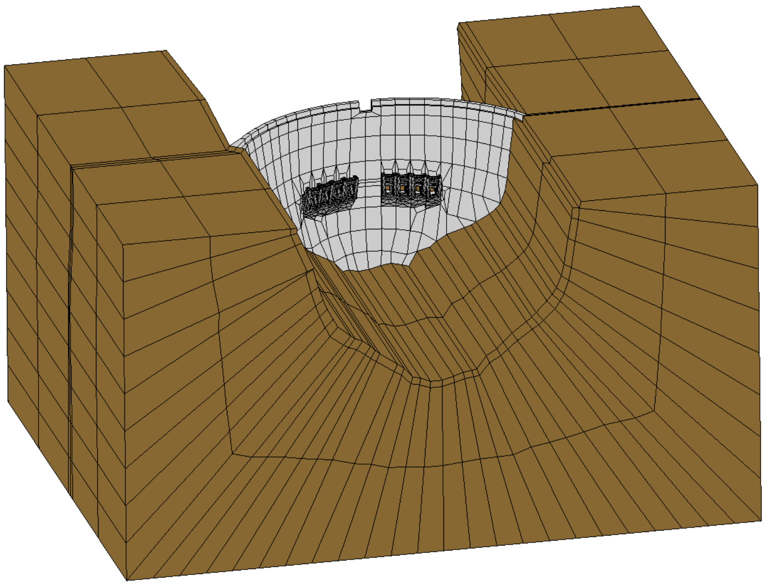

Figure 2.2: Downstream view of the finite element mesh of the dam and its rock mass foundation

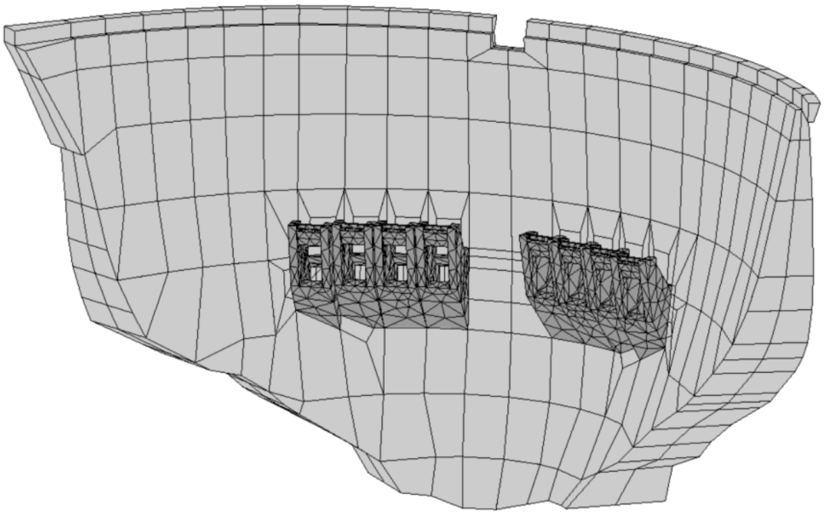

Figure 2.3: Downstream view of the finite element mesh of the dam and the mid-bottom spillway structures

2.2 Loads

For analysing the dam behaviour, since the beginning of the first filling of the reservoir to the end of 2030, the following loads were considered: i) the concrete dead weight; ii) the prestressing forces in the spillway structures; iii) the hydrostatic pressure; iv) the temperature variations due to the annual waves in the air and in the reservoir water; and v) the concrete swelling due to alkali-aggregate reactions.

The dead weight of concrete was represented by means of vertical body forces ($\gamma_c = 24$ kN/m^3).

The water pressure was simulated by surface loads, applied on the upstream face of the dam and on the spillway gates ($\gamma_w = 10$ kN/m^3). To forecast the behavior of the dam until 2030, the level of the reservoir was considered equal to the average water level in the period between mid-2003 and October 2015, approximately 323 m (Figure 2.4).

The prestressing forces were considered as punctual loads in the mesh nodes corresponding to tendons anchorages and deviations (Figure 2.5). For each tendon, during the construction, a long-term prestressing of about 3500 kN was predicted, that corresponds to a service stress of about 1000 MPa. The used steel has a rupture stress of 1780 MPa.

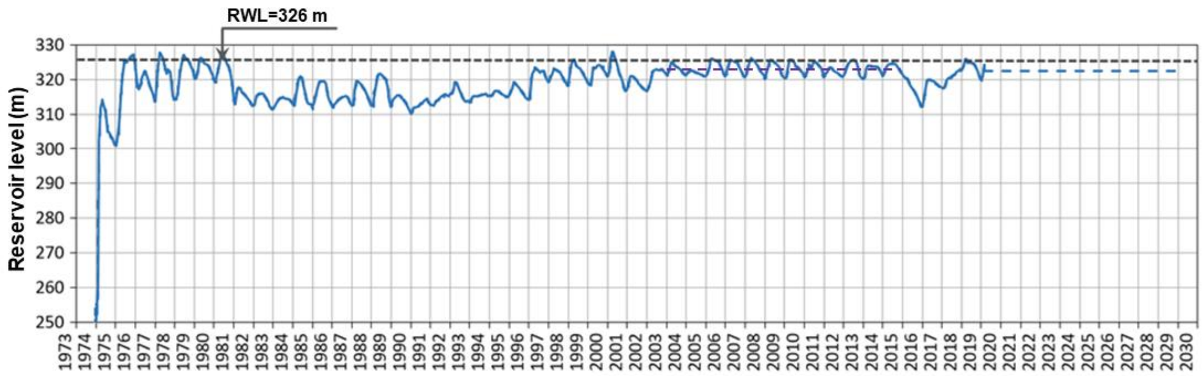

Figure 2.4: Monthly discretization of the reservoir level since 1975 until 2030

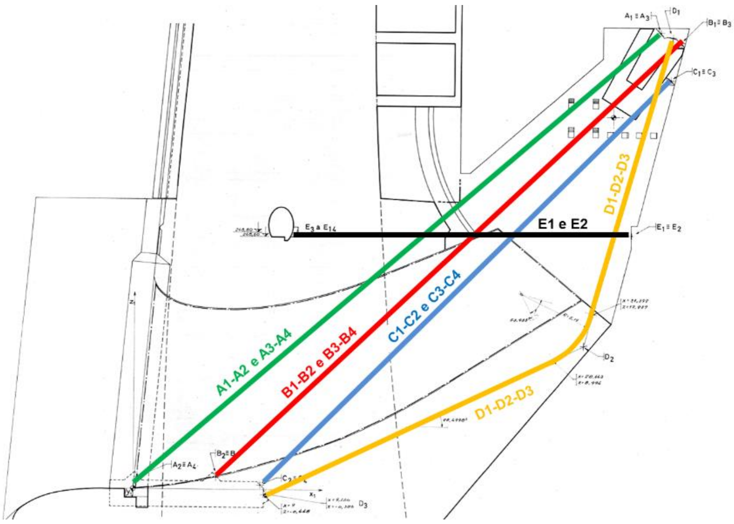

Figure 2.5: Elevation of the prestressing tendons connecting the spillway structures to the dam's body

The thermal actions on the dam surfaces were represented by sinusoidal waves of annual period for the air and water. The wave parameters were numerically determined by the least square method based on the temperatures observed on air and water thermometers (Figure 2.6). For the concrete thermal dilation coefficient was considered a value of $\alpha = 1.0\text{x}10^{-5}$ /ºC.

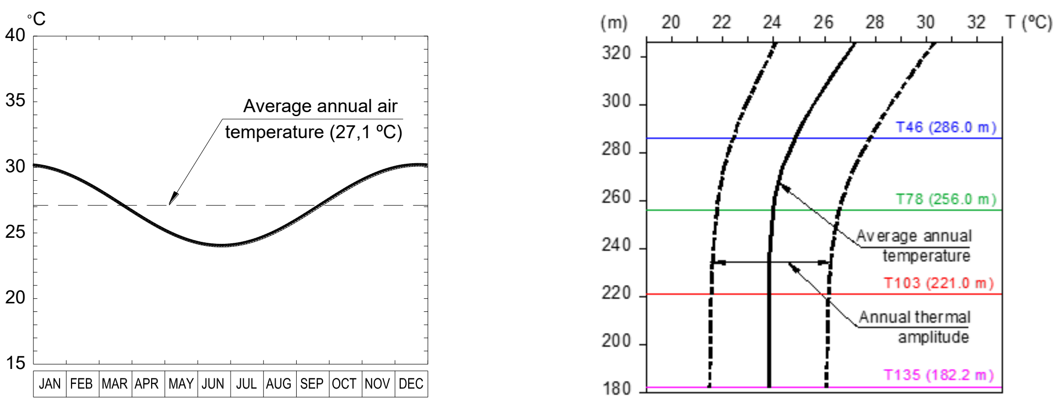

Figure 2.6: Average annual thermal wave on air and variation with depth of the average annual thermal wave amplitude of the reservoir water, evaluated from the monitoring data

The action of the concrete expansion was represented in the model by means of imposed free-swelling deformations. The evolution of the concrete free-swelling in four different zones (Figure 2.7) was estimated on the basis of the information about the concrete composition (in particular the quantity of cement and alkali), the results from chemical tests, observations at stress free strain meters and geometric levelling, and also from results obtained with the numerical modelling. The estimated free expansions have long-term maximum values of about 1400x10^{-6}.

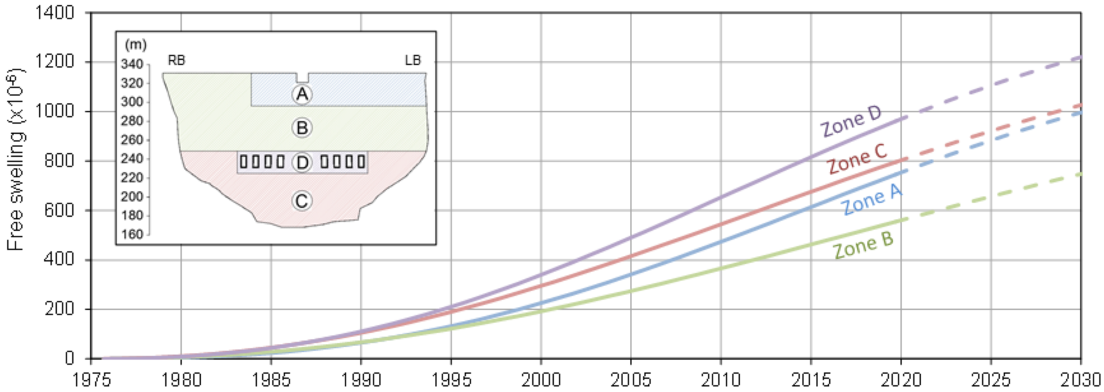

Figure 2.7: Zoning and evolution over time of free swelling strains in dam's body

The water level and the free swelling strains time discretization were done monthly.

The influence of stress field on swelling evolution was considered according to the relation proposed by Larive [12], based on experimental studies (Figure 2.8). Changes on the concrete rheological behaviour were not considered since the swelling magnitude is still moderate.

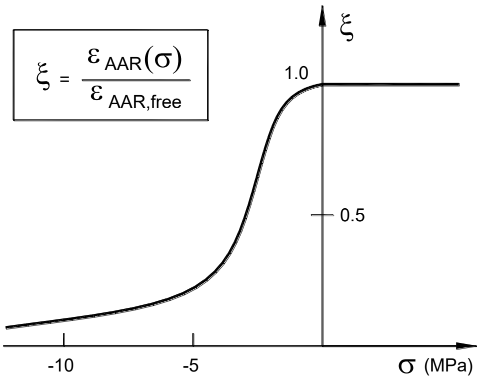

Figure 2.8: Relationship considered for taking into account the influence of the stress field on the swelling development

3. ANALYSIS AND PREDICTION OF THE STRUCTURAL BEHAVIOR

The results computed by the structural model, together with the data provided by the dam monitoring system, support the analysis and interpretation of the dam behaviour until 2020.

The second plot of Figure 3.1 shows the evolution of the radial displacements since the first filling of the reservoir until 2020, monitored in the central plumb line I1 at elevation 296.0 m, along with the values computed with the numerical model until 2030, considering the combined loads of the dead weight, water pressure, swelling and their delayed effects. The good agreement between the computed and observed results, until 2020, is remarkable. The computed response is also depicted in the third plot of the same figure, but there the effects are separately represented, so the relative influence of each effect can be appreciated. The delayed response is higher than the elastic response while the swelling effects starts assuming relevant values. The elastic response is consistent with the evolution of the reservoir level, shown in the first plot of the figure.

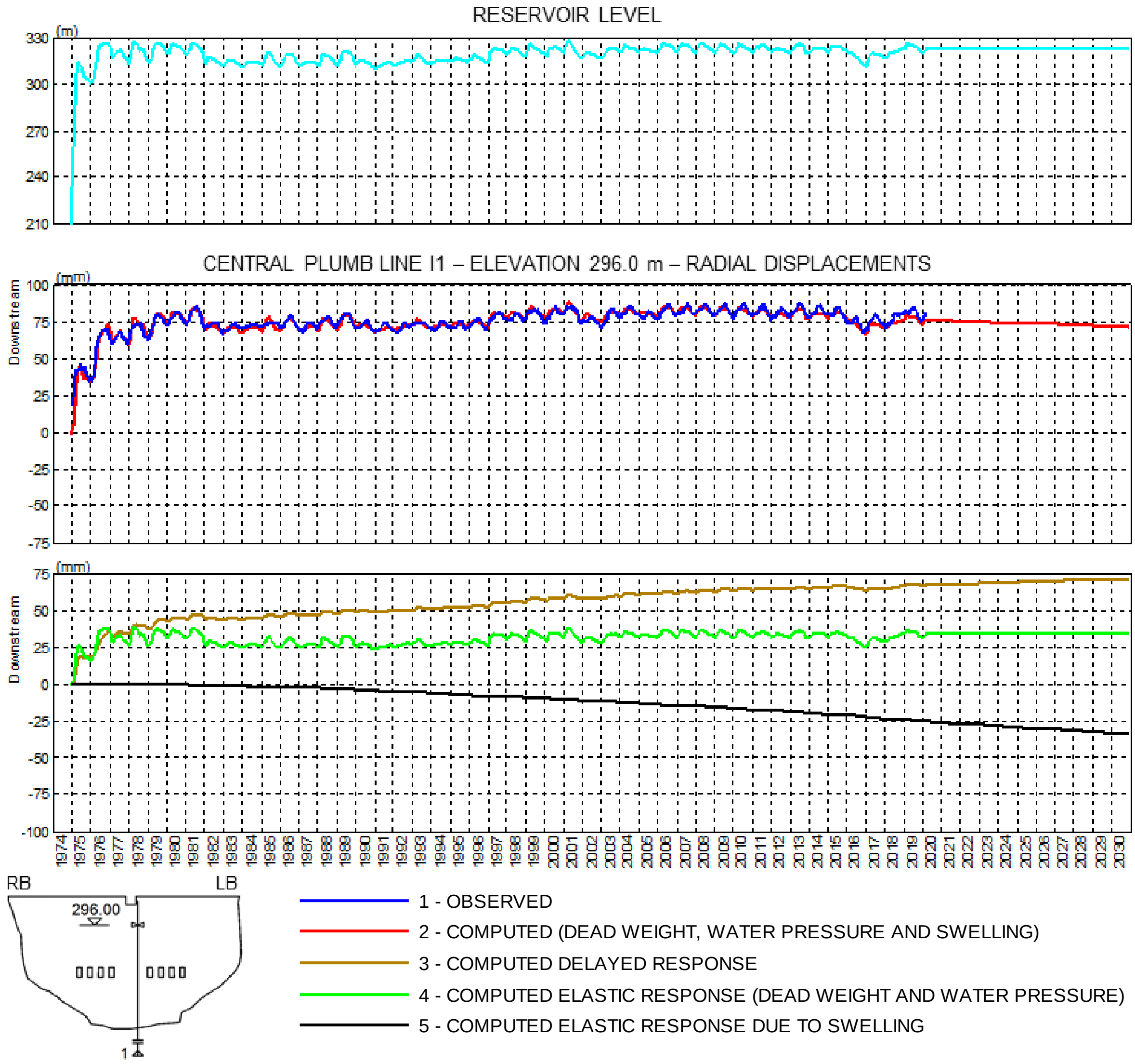

Figure 3.1: Central cantilever radial displacements at 296.0 m elevation, measured on the plumb line I1 until 2020 and computed since 1975 until 2030

Figure 3.2 presents the evolution of the vertical displacement at the point corresponding to the levelling mark N11 of the gallery at elevation 326.0 m. The plots have an organization similar of Figure 3.1, omitting the evolution of the reservoir water level. The first plot shows that the computed vertical displacements compare well with those observed by the geometric levelling, until 2020. The second plot, where the effects are separately represented, shows that the vertical displacements are almost entirely due to swelling effects.

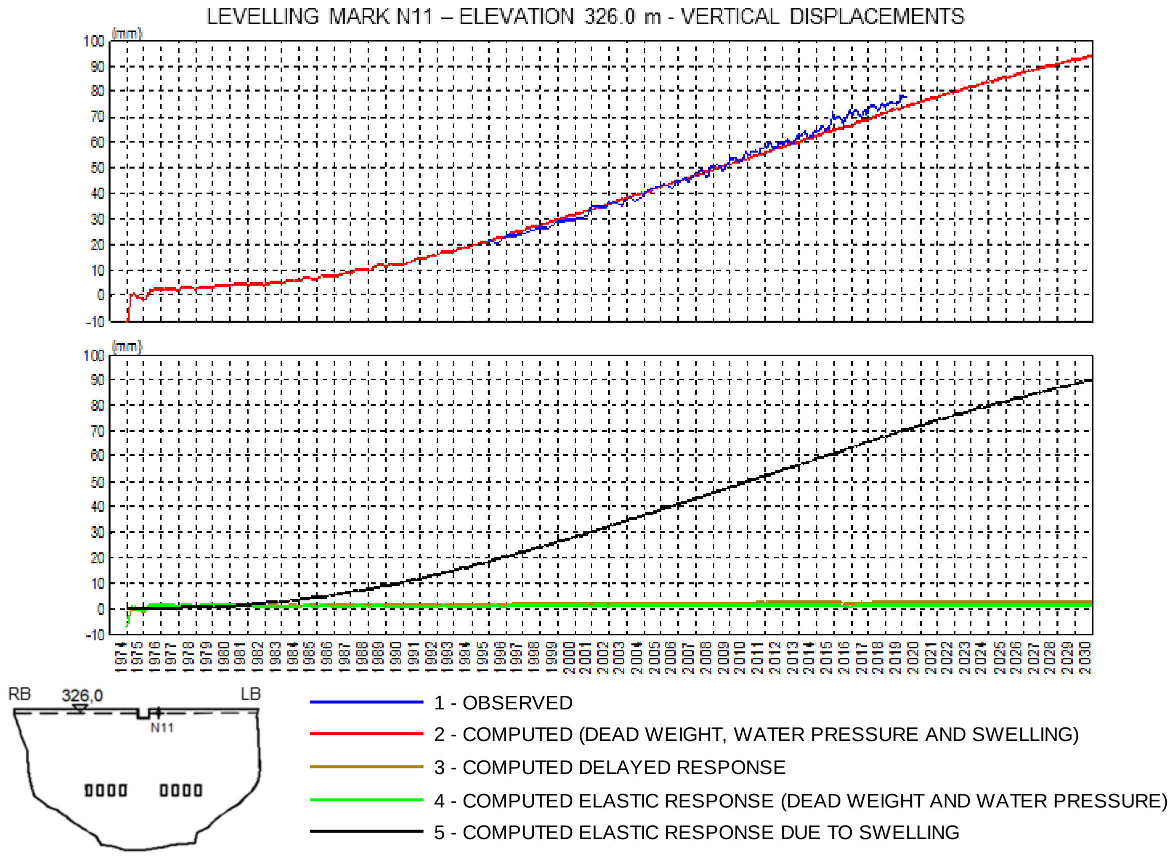

Figure 3.2: Vertical displacements at 326.0 m elevation, at the point corresponding to the levelling mark N11, measured until 2020 and computed since 1975 until 2030

The left side of Figure 3.3 presents the principal stresses on the upstream and downstream faces, calculated in 2020, due to the combined loads of the dead weight, hydrostatic pressure and swelling, as well as their delayed effects. The stress field is generally compressive except for the upper part of downstream face, where tensile stresses occur. In compression, the maximum values reach 23 MPa and 22 MPa on the upstream and downstream faces, respectively, near the left bank bearing. At the closure of the arches, above the spillway orifices, the maximum compressive stresses are about 11 MPa, upstream. The tensile stresses are vertical and lower than 2 MPa at the closure of the upper arches, and diagonal and superior to 2 MPa near the bearings, with values reaching 5 MPa in some localized zones.

The right side of Figure 3.3 presents the principal stresses on the upstream and downstream faces calculated in 2020, due only to swelling and corresponding delayed effects, in particular relaxation. Stresses with significant values appear along the dam insertion. The higher compressive stresses are located at the bearings of the upper arches, reaching values of about 22 MPa at the left bank, upstream, while the higher tensile stresses, of about 4 MPa, were computed downstream with orientation normal to the foundation surface.

In a similar way to the previous figure, Figure 3.4 shows the predicted stress fields for 2030. The maximum compressive stresses of 23 MPa will increase to 28 MPa. As the concrete strength is about 50 MPa, no safety problems are expected. The localized areas with relevant tensile stresses will have a very limited progression.

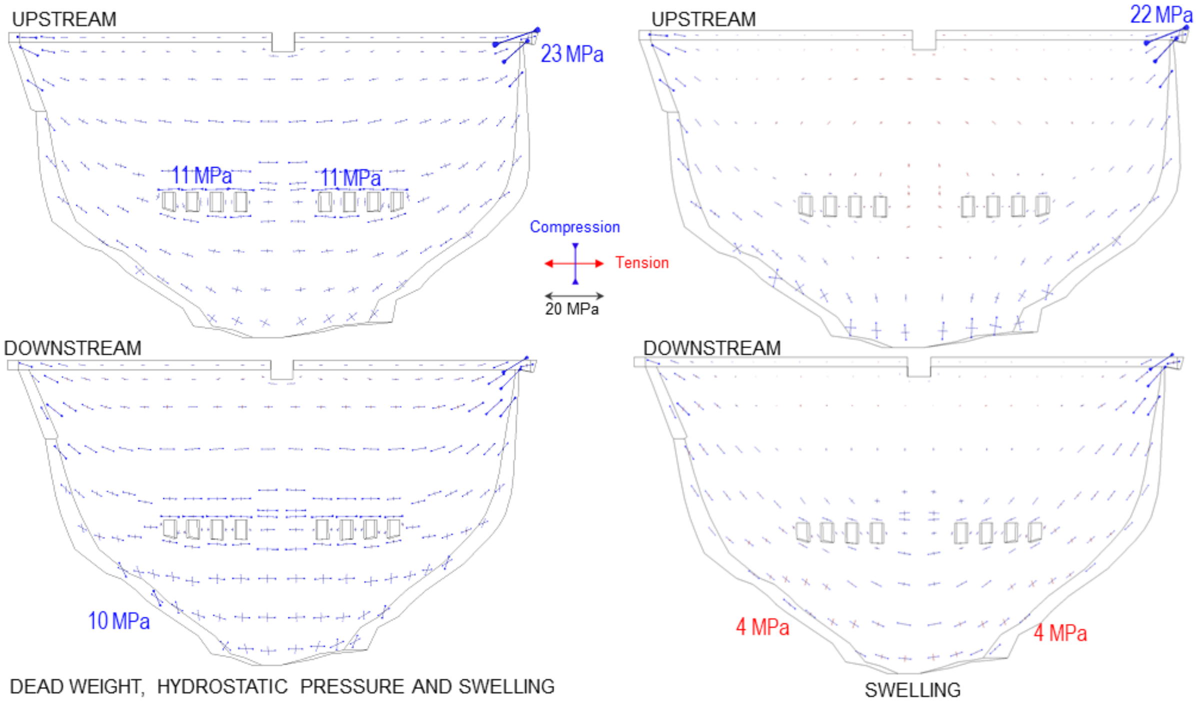

Figure 3.3: Principal stresses on dam faces computed in 2020, due to the combined loads of the dead weight, hydrostatic pressure and swelling (left side) and only due to swelling (right side)

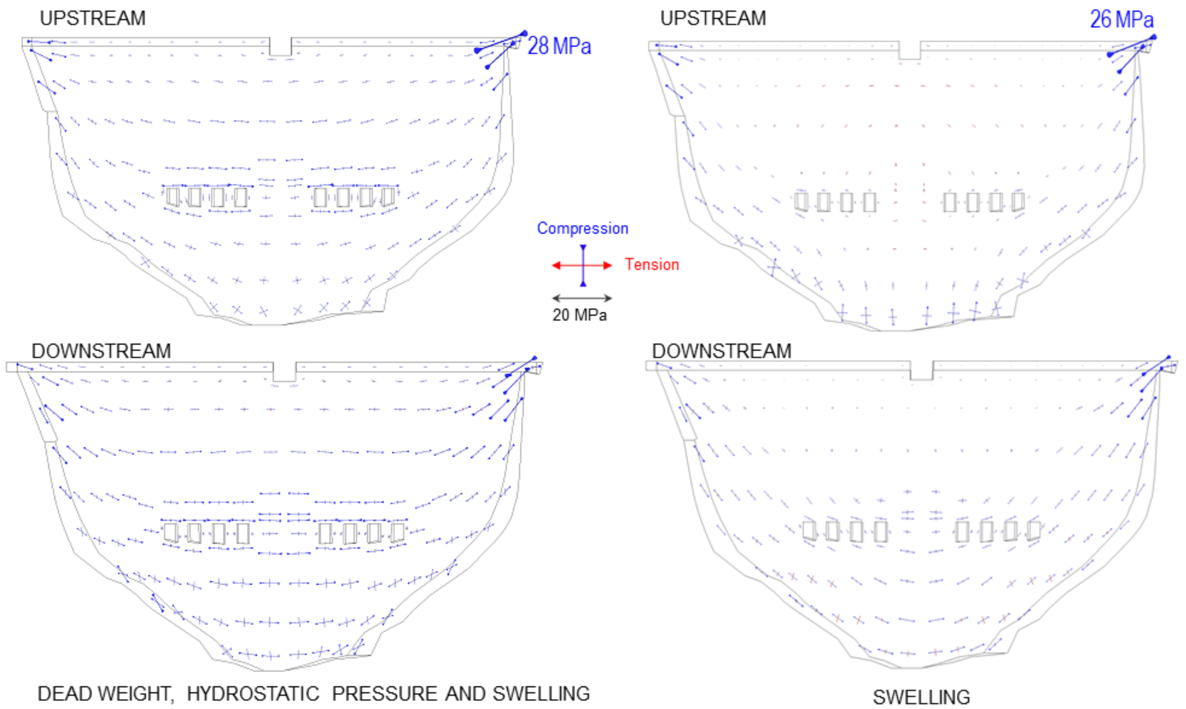

Figure 3.4: Principal stresses on dam faces predicted for 2030, due to the combined loads of the dead weight, hydrostatic pressure and swelling (left side) and only due to swelling (right side)

Figure 3.5 shows a detail of the stress fields on the downstream face, at the upper arches near the left bearing. In the zone connecting the open gallery, at the elevation 326 m, with the left bank access, diagonal tensile stresses of about 5.0 MPa take place in 2020, justifying the cracks in the dam faces and as well their dominant direction. In the right bank, there are also tensile stress of about 4.0 MPa in the zone corresponding to the beginning of the bearing enlargement, which also justify the small cracks identified in this zone.

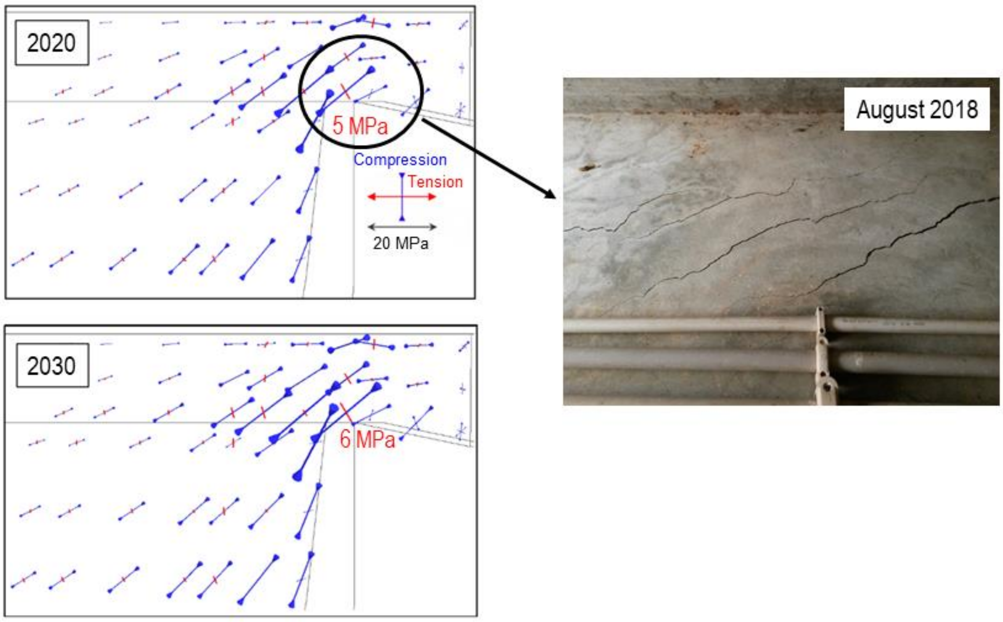

Figure 3.5: Detail of the stress fields on the downstream face of the upper arches near the left bearing, computed in 2020 and in 2030, due to the combined loads of the dead weight, hydrostatic pressure and swelling, and view of the main cracks of this zone in August 2018

The numerical results also show a progressive approximation of the lateral surfaces of the mid-bottom spillway orifices, due to the concrete swelling, that was confirmed by the monitoring results of relative displacements in those zones. In the last years some corrections have been done in the lateral steel linings of these orifices, to guarantee the operation of the radial gates.

Due to the swelling effects, it was estimated, in the long term, an increase of about 260 MPa in the tensile stresses of the prestressing tendons, whereby the maximum stresses will reach about 1260 MPa, which is about 70% of the rupture strength of steel (1780 MPa).

It should also be noted that, in 2017, the measurement of in situ stresses in the dam’s concrete was carried out by the overcoring technique, and the values of the high compressive stresses were confirmed [13].

4. FINAL REMARKS

The monitored values and the numerical results showed an excellent agreement until 2020, attesting the adequacy of the models used to simulate the dam’s behaviour. The expansions will continue to have a central role in the dam's behavior. The stress fields have a higher relevance at the abutment bearings, near the crest. In these zones, maximum stresses of about 23 MPa (compression) and 5 MPa (tension) were computed in 2020. The compressive stresses can reach of about 28 MPa in 2030, if the swelling development remains the same pattern. As the concrete strength is about 50 MPa, no safety problems are expected in the short term. Cracking of concrete can continue, but only in limited areas. Recent interventions in the mid-bottom spillways will avoid serviceability problems of the radial gates in the next years.

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