COMPREHENSIVE ASSESSMENT OF THE CAHORA BASSA DAM´S CONCRETE SWELLING PROCESS

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Abstract

Cahora Bassa dam is a 171 m high arch dam, of the double curvature type, built in the 1970s on the Zambezi River, in Mozambique. The dam's concrete is affected by a moderate swelling process, due to alkali-aggregate reactions (AAR) of the alkali-silica (ASR) type, identified in the eighties of the last century, a few years after the construction (1970 to 1975).

The owner, the Hidroeléctrica de Cahora Bassa (HCB), in the scope of the general activities of monitoring and safety control, has been increasing the monitoring system and additional testing, to allow a proper characterization of that pathology. The results of laboratorial accelerated expansion tests in samples extracted from the dam´s body, of periodic analysis and the interpretation of the dam´s structural behaviour, based on numerical models of the dam and on the monitoring results, and of regular visual inspections, completed the framework of engineering activities to catch the core knowledge about the swelling phenomenon and its main effects.

The paper presents some relevant monitoring results and describes the main procedures related with the safety control activities, in order to allow a comprehensive phenomenon assessment and the correct timely decision making.

Keywords: Cahora Bassa dam, alkali-silica reaction (ASR), monitoring data, swelling comprehensive assessment

1 INTRODUCTION

Cahora Bassa dam, a thin arch dam 171 m high, is integrated in a large hydroelectric scheme on the Zambezi River, in Mozambique. The structures of the scheme were built between 1970 and 1975. The first filling of the reservoir began in December 1974, even before the dam completion.

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 directed upwards, measured by precision geometric levelling, and increasing strains, monitored by means of stress-free Carlson strain-meters. Specific studies then performed 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 [1,2,3]. These studies were developed by the National Laboratory for Civil Engineering (LNEC), in Lisbon (Portugal), which has been providing technical support to HCB over the years.

In fact, the international technical and scientific knowledge about the concrete swelling processes, when the project was 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 [4].

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 and low abortion (0.2%). The structural concrete of the dam also has a good quality, with a uniaxial compressive strength of about 36 MPa, evaluated on cubic specimens, 20 cm side, of wet-screened concrete by the 38 mm sieve, at the age of 28 days [4].

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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 on the dam concrete (Na_2O%+0.658K_2O%) was an average of 0.32% and 0.52%, this range was below the allowable values according to the 2011 Swedish recommendation of 0.6%.

However, further specific studies of the dam´s concrete confirmed the existence of the swelling phenomenon [5,6,7], which has been developing in a slow process, reaching nowadays values that can be considered moderate.

The paper describes the procedures used in Cahora Bassa dam for the proper treatment of the data selected from the monitoring system and its comparison with results obtained from tests, structural analysis, inspections and other measurements, to control the swelling process development and the related effects, in order to allow a comprehensive phenomenon assessment and correct timely decision making.

2 BRIEF DESCRIPTION OF THE HYDROELECTRIC SCHEME

2.1 Main structures and rock mass foundation

The Cahora Bassa hydroelectric scheme, in which the dam is integrated, is located on the Zambezi River, close to Songo, Tete province, Mozambique.

The scheme mainly consists of the dam, the underground powerhouse cavern, two large surge tanks and the underground power conduit, excavated in the rock mass of the right bank, which includes the water intakes, the penstocks and the tailrace tunnels. The installed capacity is 2075 MW, divided by 5 ground power units of 415 MW / 480 MVA each. During the project development a second powerhouse was contemplated, on the left bank (North), also underground, which was intended to be built in a 2nd stage.

The rock mass, on which the scheme is built, is of very good quality and mainly consists of gneissic granite. The rock masses are sound and poorly fractured. There are a few lamprophyre and gabbric veins, some of which were subject to specific treatment during construction.

The concrete dam is a double curvature arch dam with a 171 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 bottom. The crest and the retention water level (RWL) are located at elevations 331.00 m and 326.00 m, respectively. The dam is equipped with a central surface spillway, of the "volet" type, and with 8 spillway orifices (Figure 1).

The reservoir has a volume of about 66000 hm^3. The maximum discharge capacities of the surface spillway and of each spillway orifice are 600 m^3/s and 1600 m^3/s, respectively, amounting to a total discharge capacity of 13400 m^3/s.

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).

2.2 Monitoring system

The dam monitoring system that is now installed allows the evaluation of the actions and 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) uplift pressures 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 levelling in some galleries and by rod extensometers installed at the central cantilever of the dam; 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, as well as 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 [8].

3 MONITORING RESULTS DIRECTLY RELATED WITH SWELLING

3.1 Selected monitoring devices and results

For the underground powerhouse excavation, a set of access galleries was previously excavated. The upper section of one of those galleries (South attack gallery) was reinforced with 3 concrete buttresses, on one of its sides, where the rock mass was much more fractured. This zone is permanently subjected to elevated temperatures (more than 30º C) and humidity (near 100% of relative humidity). Some years after the construction, some cracks appeared on specific zones of the concrete buttresses surfaces. Due to this situation, HCB took the decision to monitor these buttresses with horizontal rod extensometers. The results provided by these instruments are very important, since they are, in fact, the results of local tests of accelerated expansion that can anticipate what might happen in the dam's structural concrete.

The concrete deformations field in the dam´s body is monitored by small-base Carlson strain-meter groups, embedded in the concrete. Each group has a stress-free strain-meter that measures the free strain, which is independent of the stress field.

The vertical displacements of the dam’s body have been observed by precision geometric levelling in galleries at elevations 296.0 m and 224.8 m, since 1977, and at elevation 326.0 m, since 1995. In 2005 and 2006, vertical rod extensometers were installed between the galleries of the dam, at the central cantilever. The results obtained made it possible to perform a complementary evaluation of the vertical displacements. The analysis of the results provided by these sub-systems is relevant for the swelling quantification.

Figure 2 presents the dam´s monitoring system for the observation of vertical displacements and concrete strains.

3.2 Free strains and vertical strains computed from the rod extensometers data

Figure 3 represents the time evolution of the strains computed from the horizontal displacements measured on the rod extensometers of the South attack gallery buttresses, from 2007 to 2015, which can be considered as free strains. The evolution is almost linear in all the cases. The average strain value is about $400\text{x}10^{-6}$ after 8 years of monitoring that corresponds to an annual average value of $50\text{x}10^{-6}$. This value can be considered as an envelope of the swelling development.

Figure 4 presents the vertical strains computed from the displacements monitored by rod extensometers installed in 2006 and 2007 at the central cantilever of the dam. The strain pattern evolution is similar for all the devices, except on the lower extensometer EB203 that recorded unusual displacements. At the intermediate zone (extensometers EB224, EB248 and EB271), the strains follow an almost linear evolution, with peak accumulated values ranging from $100\text{x}10^{-6}$ to $180\text{x}10^{-6}$. At the upper section, where extensometers EB296 and EB326 are installed, the strains also have a linear evolution, if the thermal portion is disregarded, but the accumulated values in about 9 years rise up to about $170\text{x}10^{-6}$ and $280\text{x}10^{-6}$, respectively. These vertical strains average values are about $15\text{x}10^{-6}$/year and $30\text{x}10^{-6}$/year at the large intermediate zone and for the upper device, respectively.

Figure 5 represents the time evolution of the free strains measured by the stress-free Carlson strain-meters of the embedded strain-meter groups located at the middle surface of the bottom arches of the dam, from 1975 to 2015. The typical sigmoid shape of the curves must be pointed out. The currently free strain values are between $400\text{x}10^{-6}$ and $750\text{x}10^{-6}$. The strain average value in the last 10 years is about $200\text{x}10^{-6}$, which corresponds to a value of $20\text{x}10^{-6}$/year. These monitored swelling strains are of the wet-screened concrete that involves the strain-meter groups, and may have a magnitude different from swelling corresponding to the full-mixed concrete of the dam.

3.3 Vertical displacements from geodetic levelling

Figure 6 presents the evolution of vertical deformations of the gallery at elevation 296.0 m, observed between July 1977 and July 2015. It is noticed that, for identical time intervals between observation periods, there are progressive and approximately constant swellings since 1983 (the vertical displacements rate is almost constant over time), which is in agreement with the previous considerations regarding the swelling rate.

4 RESULTS OF TESTS, STRUCTURAL ANALYSIS AND INSPECTIONS

4.1 Laboratorial accelerated expansion tests

LNEC performed for HCB laboratory tests on concrete samples extracted from the dam´s body in 1991, 1994 and 1999 [5,6,7]. In 1991, 8 samples were extracted from 4 boreholes at the galleries at elevations 326 m, 296 m, 271m and 203.50 m, for petrography analyses. In 1994 some exudation samples were collected from the gallery at elevation 296 m, from the blocks 15-17 and 17-19, and on the peripheral gallery, from block 7-9, for mineralogical analysis.

The results obtained from those tests indicated the existence of alkali-aggregates reactions of the alkali–silica–silicate type, due to the concrete components and the environmental conditions [5,6].

At the end of 1999 a set of 37 samples of concrete was taken from 9 boreholes done at different elevations and blocks of the dam. Those samples were tested to determine the residual reactivity of the concrete to the alkalis, minerals identification, chemical composition and petrography analyses. The samples were submerged in 3 types of alkaline solutions at a standard temperature of 38ºC: sodium hydroxide ($NaOH$), potassium hydroxide (KOH) and calcium hydroxide ($Ca(OH)_2$). These ultra-accelerated tests, done according to the NBRI and the ASTM C 1260 standards, revealed, after one year of extreme aggressively, moderate strains of about 500×10^{-6} on the samples submerged into the sodium solution and of about 750×10^{-6} on those placed in the potassium solution [7]. This suggested that similar values could be registered on the dam concrete in the future.

4.2 Dam´s behaviour analysis and interpretation

The analysis and the interpretation of the dam´s structural behaviour, based on numerical models of the dam and on the monitoring results, since the first filling of the reservoir, were performed by LNEC at different times [1,9,10,11].

In these studies 3D finite element meshes of the dam and its foundation were used for structural simulation. The construction sequence of the dam's body, the water level variation in the reservoir, the thermal variations in the air and in the water, the viscoelastic behaviour of the concrete and the swelling due to the ASR were taken into account. These models require a reasonable prediction of the concrete creep function, a proper swelling zoning and evolution over time, as well as the consideration of the dependence between the swelling evolution and the stress field, to represent the phenomenon anisotropy.

Good agreements between the results obtained numerically and those measured by the monitoring system were achieved in all the analyses, and a great influence of creep and swelling effects on the dam´s behaviour was noticed.

The behaviour analysis of the dam over time carried out until the end of 2008 showed that the swelling has led to an increase in compressive stresses on a large part of the structure, and to a decrease in these stresses along the insertion downstream, and on the upper central zone upstream. Due only to swelling, the compressive stresses reach values of about 12 MPa at the bearings of the upper arches, both upstream and downstream, whereas the highest tensions, near the insertion surface downstream, reach values of about 3 MPa. At the end of 2008 all the tensile stresses were largely compensated by compressive stresses due to dead weight and hydrostatic pressure. By considering the set of all loads, a generalized compression field was computed for the dam's body, with peak values of about 12 MPa at the bearings of the upper arches, upstream and downstream, and of about 8 MPa at the closure of the arches above the spillway orifices (Figure 7).

At the end of 2008 it was concluded that serviceability and safety conditions of the dam remained good [10,11].

4.3 Visual inspections

As part of the visual inspection of the dam, HCB controls, in a systematic way, the evolution of cracking on the apparent surfaces of the dam. Such control is performed by means of records on inspection sheets taking into account the main characteristics of cracks. In order to make this activity impersonal and more objective, in 1999, visual inspection aided by georeferenced photograph records was introduced and, since 2007, three-dimensional surveys by laser scanning have been used [12,13].

Although there are some diagonal cracks on the left bank concrete structure, on the access to the open gallery under the crest, at elevation 326.00 m, which were formed due to localized restriction of this weak structure to the dam body expansions in the vertical direction, mention must be made to the fact that the dam concrete does not present any significant cracking. There are only a few older cracks, at the top and at the sidewalls of some galleries, and diffusive cracking, which is more relevant close to the abutments at the sidewall of the mentioned open gallery near the crest. That cracking has had no significant evolution over time [1,9,10]. In Figure 8 are represented the reduced calcium carbonate deposits on the downstream face, at concreting and contraction joints, identified in LNEC´s 2008 inspection [10].

5 FINAL REMARKS

5.1 Brief analysis of results

The analysis of the evolution of the free strains and of the vertical displacements, monitored along a period of about 40 years, since the dam construction, as well as the main results obtained in tests, structural analyses and visual inspections, allows the following main considerations:

i) The swelling process of the dam´s concrete is still under way, with constant rates in the last 20 years (there are a small number of stress-free strain-meters that show a slight decreasing trend in recent years);

ii) The free strains computed from the horizontal displacements measured in the last years on the South attack gallery buttresses, in very aggressive conditions of temperature and humidity, show an annual average value of $50x10^{-6}$, that can be considered as an envelope of the swelling rate development;

iii) The free strains monitored on the stress-free Carlson strain-meters of the embedded strain-meter groups of the dam, from 1975 to 2015, show the typical sigmoid shape for the time evolution, with maximum accumulated values of about $800x10^{-6}$ and an average value of about $20x10^{-6}$/year in the last years;

iv) The vertical strains computed from the displacements monitored by the rod extensometers of the central cantilever of the dam, show, in the last years, an average value of about $15x10^{-6}$/year;

v) A coherent swelling estimation was achieved from different sources (continuous monitoring, tests and structural analyses), but it seems that the structural concrete swelling rates are smaller than the ones given by the monitoring data;

vi) The swelling process of dam's concrete has been developing in a slow process, reaching nowadays values that can be considered moderate;

vii) The structural analysis carried out in 2008 showed a generalized compression field in the dam's body, with peak values of about 12 MPa at the bearings of the upper arches, on the upstream and downstream surfaces, and of about 8 MPa at the closure of the arches above the spillway orifices; and

viii) The dam surfaces are nearly free of cracks.

5.2 Benefits of the concrete swelling process assessment

There are already significant benefits of the adopted approach to the comprehensive assessment of the Cahora Bassa dam concrete swelling process.

The first one, and perhaps the most important, is that the current good knowledge about the swelling phenomenon of the dam´s concrete allows the scheme operation with no worries related with serviceability and safety conditions of the dam.

The values of the global closures of the spillway openings computed in the last structural analysis performed by LNEC [10], anticipated problems related with the gates operability that would be expected in medium term. In fact, during the ongoing general rehabilitation of the 8 spillway gates, closures and distortions of the openings sidewalls were measured, with distortions towards the banks on the top, with increasing values from the centre of the dam to the sides [14]. These trends were taking into account in the definition of the rehabilitation options and techniques of the gates and its seals, to avoid future malfunction, due to loss of the gates clearance, or even the gates jamming.

5.3 Short-term actions and studies

From the available data, it is expected that the swelling rates will continue unchanged for the next 10 or 15 years. However, HCB is committed to obtaining reliable information about the long term development of the swelling process itself and of its structural effects. In order to do this, some short-term actions and studies are planned, with LNEC´s support, namely:

i) Development and exploitation of a new refined finite element model of the dam and its foundation, with explicit representation of the salient structures of the spillways, for behaviour interpretation and prediction, including the stress fields evolution over time;

ii) "In situ" overcoring tests for stress evaluation in significant sections of the dam´s body, to confirm some numerical results already available [10];

iii) Installation of specific instrumentation in the holes drilled for the overcoring tests, to follow up the future strain and stress evolution; and

iv) Additional laboratory tests on samples to be collected, in order to evaluate the concrete properties (strength, deformability and damage) and the remaining potential expansibility.

5.4 General conclusions

It can be said that HCB has appropriate engineering resources to face properly the dam´s follow up in terms of its structural behaviour. A right attitude towards maintaining updated knowledge about the dam´s concrete swelling process and the related structural consequences is also present. Additionally, and when required, namely for sensitive matters and studies, HCB also mobilizes the help of international expertise.

The procedures currently adopted at Cahora Bassa dam, related to monitoring and maintenance, guarantee the assessment to the dam´s serviceability and safety conditions and a correct timely decision making process to face new situations. The major goal is, of course, the extension of the dam's life time in good safety conditions.

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FIGURE 1: Downstream view of Cahora Bassa dam

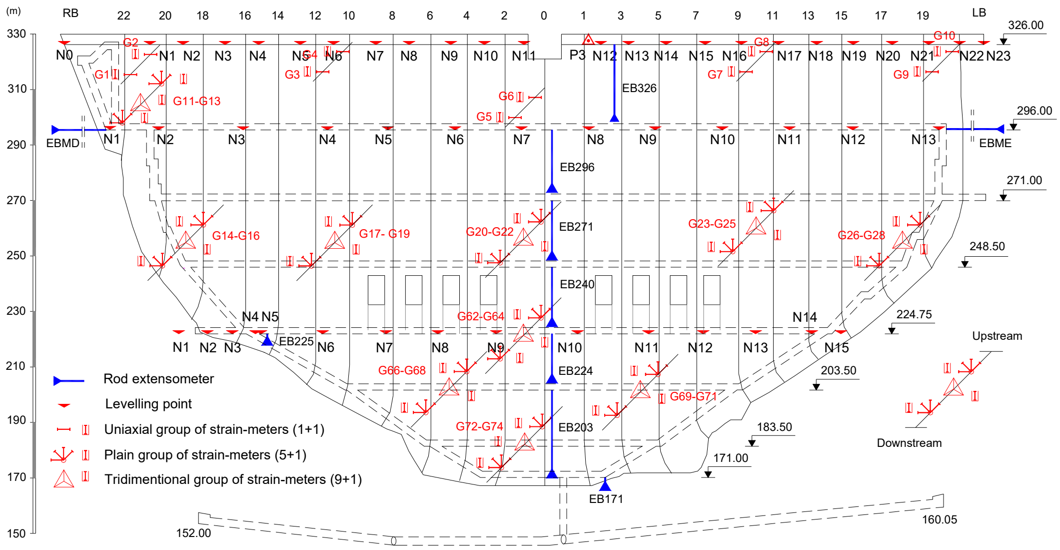

FIGURE 2: Dam´s monitoring system for the observation of vertical displacements and concrete strains

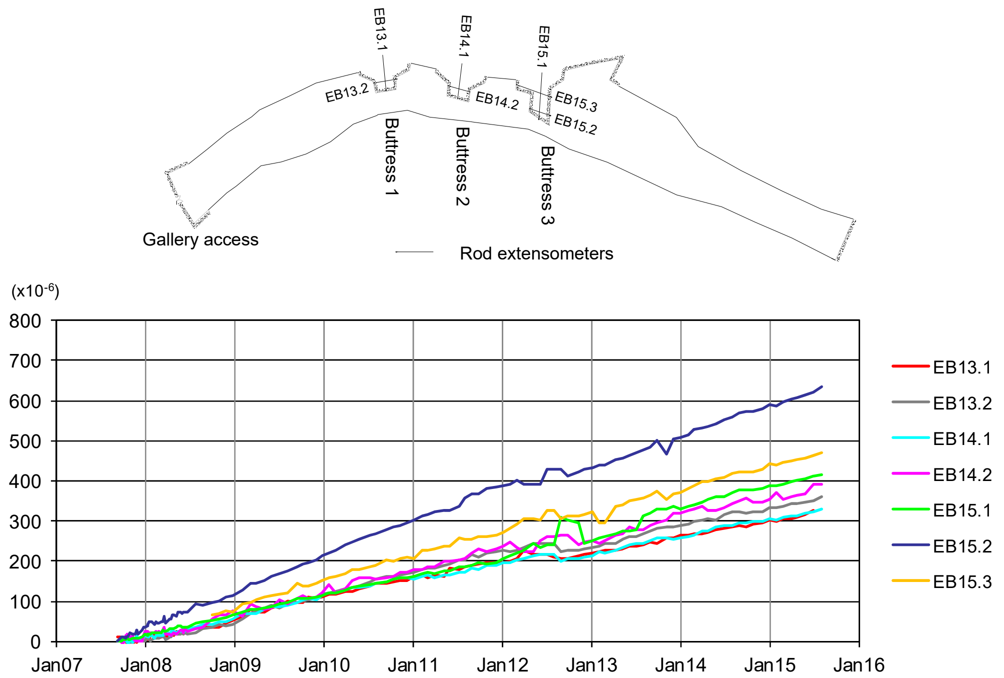

FIGURE 3: Time evolution of strains computed from the horizontal displacements measured by the rod extensometers of the South attack gallery buttresses, from 2007 to 2015

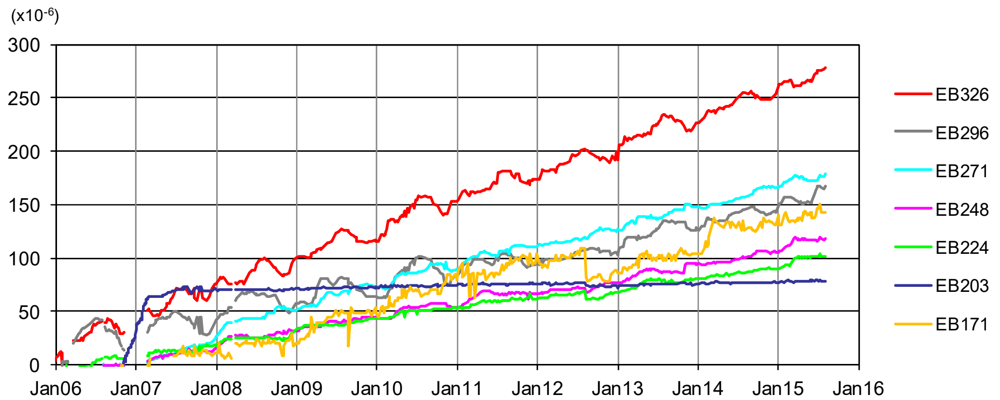

FIGURE 4: Time evolution of strains computed from the vertical displacements measured by the rod extensometers of the dam´s central cantilever, from 2006 to 2015

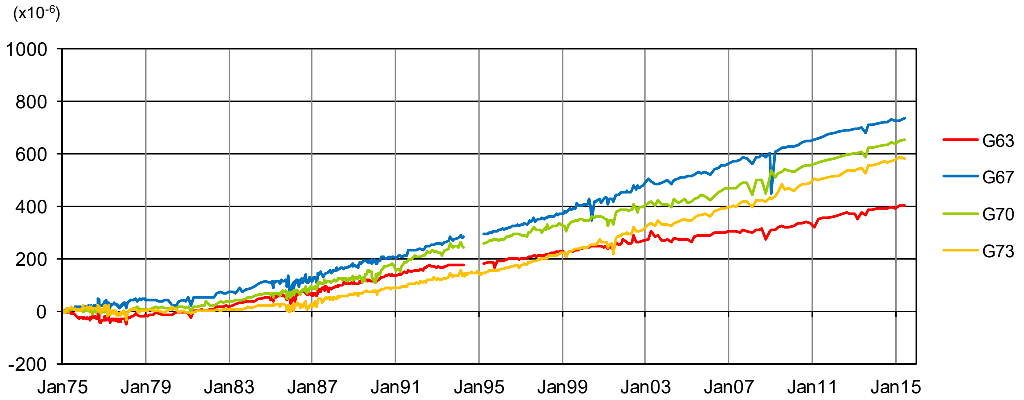

FIGURE 5: Time evolution of free strains measured on the stress-free Carlson strain-meters located at the middle surface of the bottom arches of the dam, from 1975 to 2015

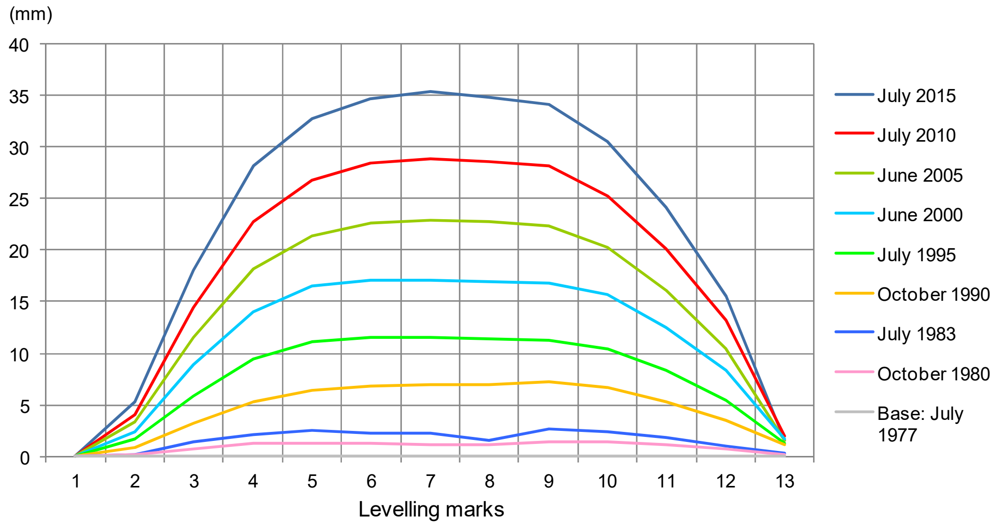

FIGURE 6: Vertical displacements at the 296.0 m elevation gallery, measured by geometric levelling between July 1977 and July 2015

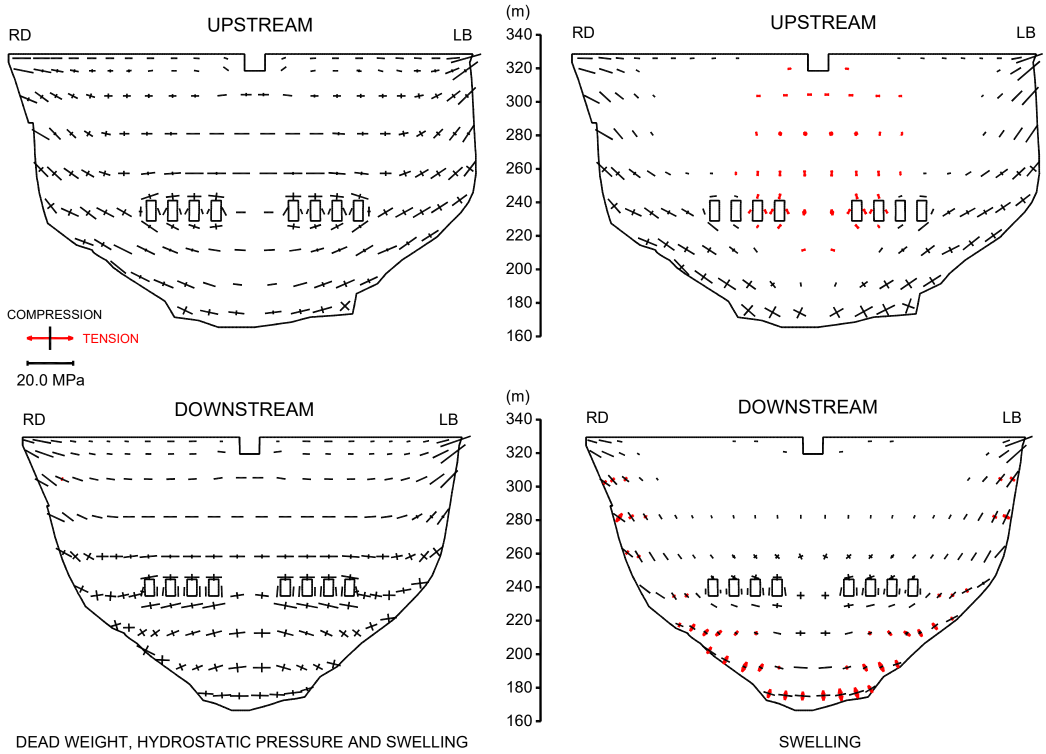

FIGURE 7: Principal stresses on the dam surfaces computed at the end of 2008 [10,11]

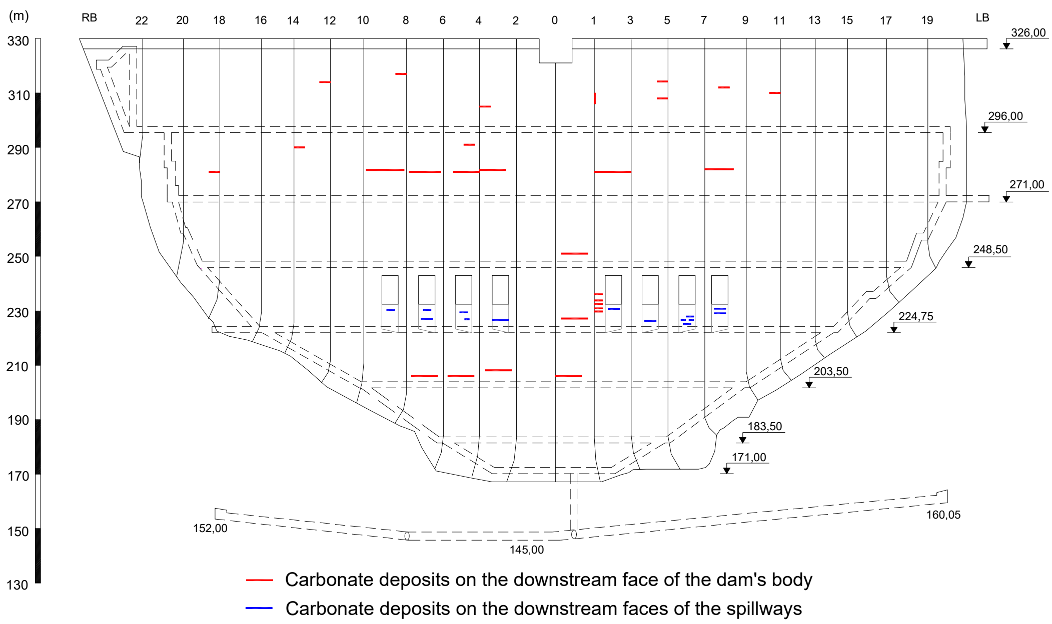

FIGURE 8: Downstream dam surface with the location of carbonate deposits in June 2008 [10,11]