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Analysis of Peti dam swelling process

A. Tavares de Castro (1); J. Piteira Gomes (1); A. Bettencourt Ribeiro (1); P. Luciana Divino (2); A. Vaz Melo (2); A. Linhares de Carvalho Carim (2)

(1) Civil Engineering, Research Officer, Laboratório Nacional de Engenharia Civil (LNEC)
Av. Brasil, 101, 1900-064 LISBOA CODEX, PORTUGAL
(2) Civil Engineering, Companhia Energética de Minas Gerais (CEMIG)
Av. Barcarena, 1200, Santo Agostinho - Belo Horizonte/MG, BRASIL

E-Mail: *tcastro@lnec.pt*

Abstract

Several large concrete dams built during the first half of the 20th century, when the knowledge about the deterioration processes on the concrete was limited, are yet in service, although presenting, in some cases, signs of severe deterioration due to chemical internal reactions. When these structures have significant economic importance and its replacement is not easy or is very expensive, studies carried out in order to understand and characterize the deterioration processes are of utmost importance to extend the life of these structures with adequate safety conditions.
In this paper an overall view of the studies performed to a Brazilian arch dam, Peti dam, are presented. This dam, whose construction was finished in 1945, is submitted to a swelling process due to alkali-aggregate reactions (AAR). Since the detection of its abnormal behaviour, in the 60s of the last century, mainly through the observation of the development of significant cracks, several studies had been carried out involving the experimental evaluation of the concrete properties. A monitoring system was implemented in 1997 allowing the analysis and interpretation of the observed structural behaviour of dam.
In the last year, CEMIG and LNEC have been cooperating in order to analyse the safety conditions of Peti dam through experimental and numerical studies. This paper presents a methodology to determine the free swelling history in the concrete covering the 66 years life of the dam with base on the environmental conditions. These results will be used as prescribed deformations in a chemo-viscoelastic-damage model in order to predict the long term behaviour of the dam. The characterization of the swelling action was based on the data collected from the monitoring system and on laboratorial tests results.
keyword: Concrete dam; Concrete Swelling; Alkali-Silica reaction

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1 Introduction

The early detection of deterioration process on Peti dam led to the realization of several studies in order to evaluate the swelling characteristics and the mechanical properties of the concrete, allowing a proper management of the hydroelectric scheme by CEMIG. The concrete used on the dam's construction was made with gneissic aggregates. With these aggregates, the final swelling magnitude, as the chemical reaction kinetics, strongly depends on the quartz crystal lattice, the presence of micaceous and feldspathic minerals and, of course, the alkalis content. While all the necessary reagents remain, the chemical reaction proceeds, with the consequent increase in damage.

After performing several studies some years ago, CEMIG had made an agreement with LNEC to develop new studies to reassess the current safety conditions and examine eventual rehabilitation measures aimed to mitigate the swelling development and its structural effects. These studies will involve laboratory testing in order to obtain a better swelling characterization, establish its time evolution as well as a more reliable prognosis, and numerical analysis to simulate the deterioration process.

2 Peti Dam Characteristics

Peti dam, owned by CEMIG, is located in the State of Minas Gerais, Brazil, about 100 km east of Belo Horizonte, on Santa Barbara River, near S. Gonçalo do Rio Abaixo. It was built between May 1944 and November 1945 (EBASCO (1973)), pounds a reservoir with a surface area of about 4.25 km^2 and a volume of about 35 million m^3, for the normal water level (NWL), and its main purpose is the electricity generation.

The dam is 38 m high and 54 m long, endowed by a gated spillway located on the upper part of the dam, which is controlled by six 5.5 m high by 6 m wide vertical lift gates and a small span to evacuate solid residuals. It is possible to identify three different structural elements in the dam: 1) a cylindrical arch, 32 m high, with three zones of different thickness, a lower one, thicker, with 6.7 m at the bottom, an intermediate one with thickness varying from 4.5 m to 3.1 m, and an upper zone pending to the spillway edge with 4.0 m thickness; 2) thrust blocks at each embankment and a cut-off wing wall at the left bank; and 3) seven piers with 6 m high, inserted in the arch, to support the vertical lift gates and a pedestrian bridge constituted by eight simply supported beams which forms the crest of the dam, at elevation 713 m (Fig. 1).

2.1 Dam Foundation Properties

The foundation rock mass consists of a dense gneiss-granite (migmatite) rock, little cracked, with grains sizes from medium to thick, with biotite lined up in a quartz-feldspathic matrix. In the stream bed valley and in the left bank, the foundation rock mass presents good characteristics and very few discontinuities, offering good support conditions for the dam. However, in the higher elevations of the right bank several faults, fractures and altered rock had been detected, which had advised the execution of overburden excavations in order to improve the foundation conditions. A keyed addition was driven to

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a depth of 9 m long the decomposed zone, between elevations 702.5 m and 703.5m, and filled with concrete to reinforce.

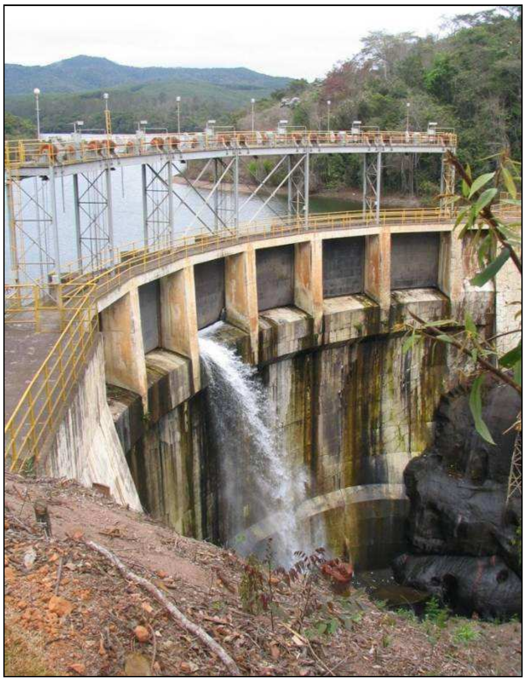

Figure 1 – Peti dam. Right abutment downstream view in June 2011

After this works, the quality of the foundation obviated the necessity for other works than the normal barring and wedging required removing shot loosened materials and providing a sound undisturbed bedrock foundation for the dam. Foundation grouting, either in a consolidation pattern or as a grout curtain, was not performed. The extremely small amount of seepage water presently visible in the gorge downstream of the dam supports the no necessity for such works (MAGALHÃES et al. (2000)).

2.2 Concrete Properties

The concrete was made with gneissic aggregates, obtained from the excavations performed for the different components of the hydroelectric scheme, in particular from the two intake tunnels and the surge chamber. A cement dosage of about 350 kg/m^3 was used, which had proceeded from the Itaú cement plant (BRITO et al. (1973)), but there are no information about the cement type used in the concretes of Dam (CEMIG (1996)).

3 Swelling Detection

The first cracks on the dam were detected at the gravity block and cut-off wing wall on the left bank in 1966. Since then CEMIG had promoted several studies in order to characterize the anomalies and evaluate the safety conditions of the structure.

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The first studies, carried out between 1972 and 1976, intended to characterize the anomalous behaviour and to find the causes of these anomalies. One of these studies admitted that the origin of the anomalies was related with the development of “secondary reactions in the concrete that have originated its deterioration throughout the time” and not with movements of the foundation (BRITO et al. (1973)). An ambitious program of laboratorial analysis was implemented by CEMIG in 1973, using concrete specimens extracted from 3 vertical core borings drilled in the dam’s body. In late 1974, the existence of products compatible with sulphating and carbonation processes had been detected, indicating that the chemical composition of the aggregates could originate swelling reactions of the concrete (BASÍLIO et al. (1973)). Additional tests performed in 1977, namely petrographic and x-ray diffraction analysis of specimens, had finally detected the existence of alkali-silica reaction (ASR).
In order to investigate the swelling evolution, further tests were performed in 1997 and 2004, which confirmed the presence of ASR, without mention to internal sulphatic reactions. New studies for the reassessment of the dam safety are now in progress, after the agreement between CEMIG and LNEC (LNEC (2011)).

4 Interpretation and Analysis of the Observed Behaviour

4.1 Monitoring System

Peti dam has a small monitoring system, which was only implemented in 1997. It includes two multi rod extensometers crossing the dam body, three 3D joint meters and four levelling targets (Fig. 2).

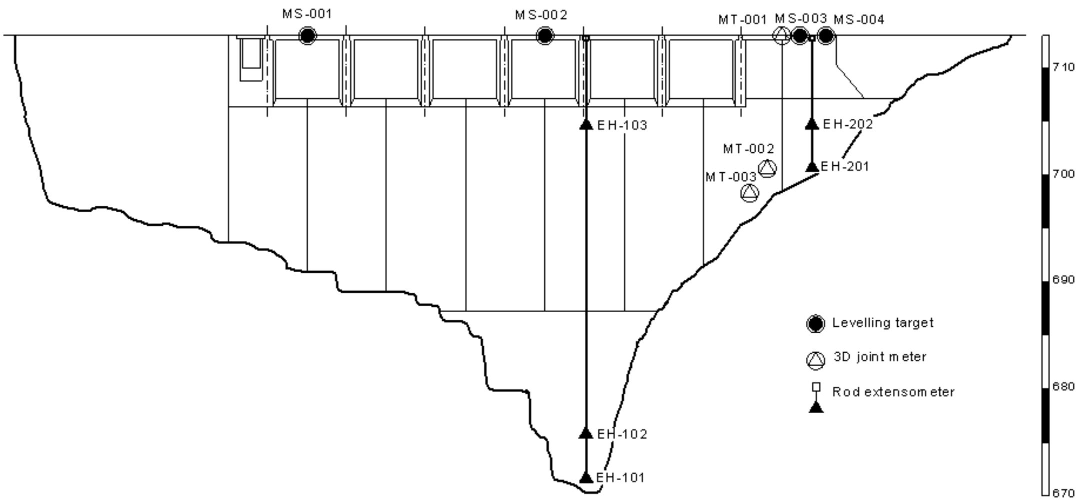

Figure 2 – Peti dam monitoring system

The first rod extensometer, located in the arch zone of the dam, has three rods, the deeper one sealed in the foundation, immediately below the dam, the intermediate one sealed in the concrete, close to the dam/foundation interface and the last one sealed in the upper zone of the arch. The second rod extensometer, placed in the gravity block of the left

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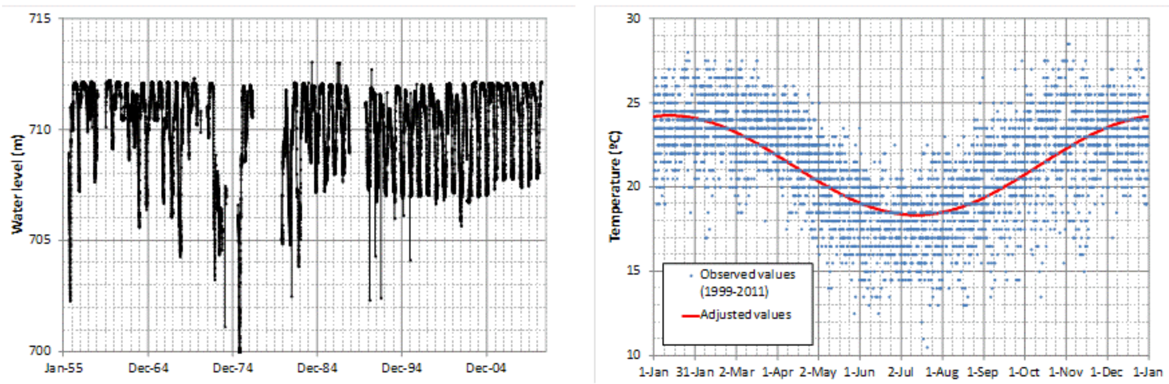
bank, presents two rods sealed in the concrete, the deeper one close to the dam/foundation interface and the other sealed 4 m above. One of the 3D joint meters is installed in the downstream zone of the structural joint between the arch and the gravity block and the others two were installed in one crack in the downstream face of the dam. Along the dam crest were placed four targets integrating a precision levelling network.
Although the dam has an age of about 67 years, there are only monitoring data concerning the last 15 years. Nevertheless, the quantitative interpretation of the vertical displacements measured in the levelling targets and in the rod extensometers present interesting results about the evolution of the swelling effects during the last years, as is described in the following paragraphs.

4.2 Actions Definition

The interpretation and analysis of the observed behaviour is based on the comparison between the observed results and the correspondent predicted values, which requires data about the evolution of the main actions and of the structural response (absolute and relative displacements). In the case of Peti dam, the main actions to be considered are the hydrostatic load and environmental temperature variations, and the observed structural response corresponds to the displacements measured with the rod extensometers and with the crest levelling.
Unfortunately there aren't records of the water level during the first filling of the reservoir. The existing records show high water levels in the reservoir during the winter, close to the spillway crest, and low water levels during the summer (Fig. 3a). There are records of an important emptying during the summer of 1974. The daily mean air temperature presents an annual average of 20ºC and varies between 15ºC, during the coldest season, and 30ºC, during the hot season (Fig. 3b).



(a) Water level variation in the reservoir

(b) Observed and adjusted values of average daily air temperatures

Figure 3 – Actions definition

4.3 Statistical Interpretation of the Monitored Data

In the interpretation of the structural response, a quantitative interpretation method was used. The applications of this method is based in the following hypotheses: i) The observed response is due to a combination of three main factors: the hydrostatic pressure due to the water level in the reservoir, the concrete temperature variations due to the air and water temperatures and all the non-reversible effects considered as time related factors; ii) In normal conditions, the structure presents an elastic behaviour, thus the total responses correspond to the sum of the responses due to each one of the referred factors; iii) The structural response to each one of the factors is represented by an empirical function, previously defined, which parameters are determined through statistical methods. In this case, the response to the hydrostatic load, $E_h(H)$ is characterized by a polynomial on the water height in the reservoir, (H-H_0),

$$E_h(H) = a(H - H_0)^4 \qquad \text{(Equation 1)}$$

The response to the environmental temperature variations can be represented by a periodic function with annual period, that assumes that the temperature and the correspondent response depend on the number of day since the beginning of the year, s:

$$E_\theta(s) = b_1 \cos\frac{2\pi s}{365} + b_2 \sin\frac{2\pi s}{365} \qquad \text{(Equation 2)}$$

Time factor represent time dependent phenomena, such as time evolution of the concrete deformability, and other time dependent actions, like concrete swelling. The qualitative analyses of the monitoring data of Peti dam suggest the consideration of a parabolic function of the time elapsed since the date representative of the beginning of the dam construction (1st July 1945):

$$E_t(t) = c_1\, t + c_2\, t^2 \qquad \text{(Equation 3)}$$

Thus, the response of the structure can be represented by the following expression, whose parameters are determined by the least square method.

$$E = E_h(H) + E_\theta(s) + E_t(t) =$$

$$= a(H - H_0)^4 + b_1 \cos\frac{2\pi s}{365} + b_2 \sin\frac{2\pi s}{365} + c_1\, t + c_2\, t^2 + K \qquad \text{(Equation 4)}$$

This methodology has been applied to the interpretation of the displacements measured at the rod extensometers and at the levelling targets placed at the dam crest.

4.4 Vertical Displacements Observed on Rod Extensometers

In all the instruments, the results from the interpretation of 352 campaigns performed since 1997 show a good agreement between observed and predicted value, as can be seen in figure 4 for the case of EH101 and EH201, and is confirmed by the very high determined coefficients that were obtained. While the hydrostatic load and temperature effects present small values, the time effect presents important values. As the elastic responses to the hydrostatic load are very small, the effect of concrete creep can be neglected and all the time effect can be attributed to the concrete swelling.

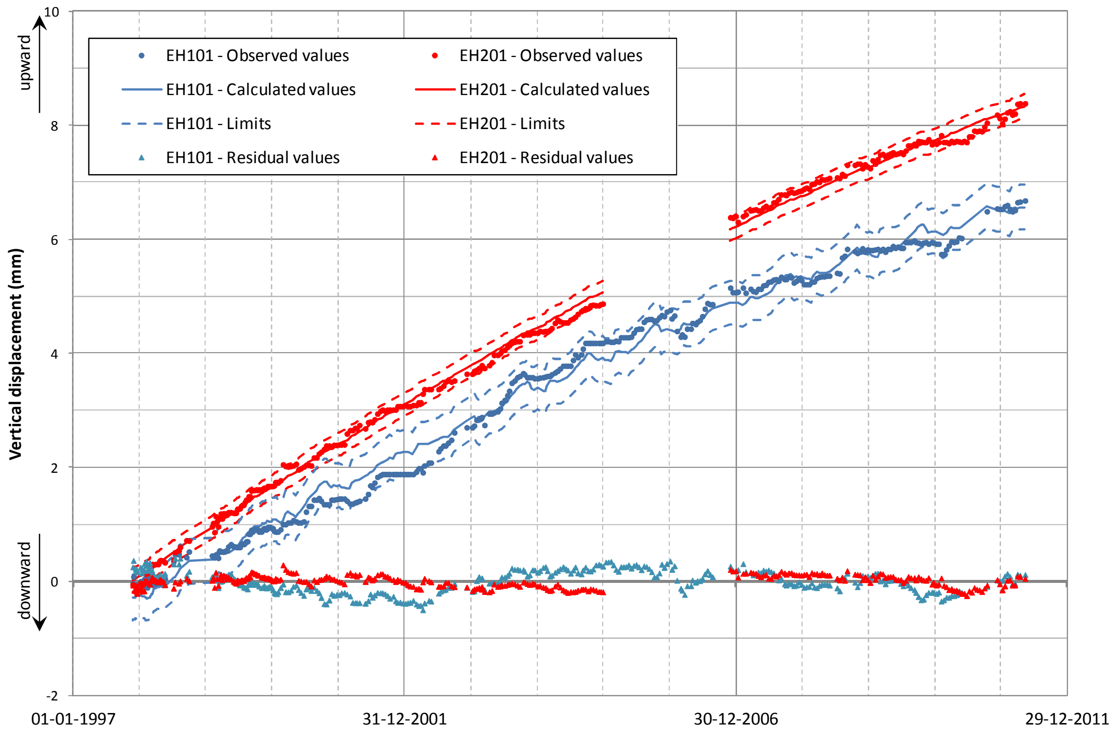


Figure 4 – Quantitative interpretation of displacement measured in rod extensometers EH101 and EH201

While in the rod extensometer located in the arch (EH101) it is estimated an annual expansion rate of 13×10^{-6}/year, in the other rod extensometer, located in the left bank gravity block (EH201), an annual expansion rate of 49×10^{-6} /year was estimated (Fig. 4). This difference can be partially justified by the difference between the structural restrictions in the two zones, but can also be related with the probable use of concrete with different cements.

4.5 Vertical Displacements Observed by Levelling at Crest

Concerning the monitoring data of the crest levelling, there are results of 31 campaigns, performed between March 1998 and March 2010. Although the obtained results are not of so good quality, due to the more important measuring errors associated with this methodology, the interpretation results show a similar structural response: small value of the hydrostatic load and an important time effect related with the concrete swelling. The results show upward irreversible displacements of about 1 mm/year, compatible with the expansion rates estimated with the rod extensometers.

5 Current Studies

The analysis of the observed structural behaviour and the assessment to the actual safety conditions of the dam will be supported by a mathematical model, which requires an

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accurate characterization of the mechanical properties and of their evolution over time, as well as an accurate estimate of the free swelling evolution due to ASR. Table 1 shows the list of recommended tests and its objectives.

As regards the free swelling definition, the proposed tests are intended to help the definition of the curve used by the mathematical model, a sigmoid curve with an S shape. For old dams with no monitoring data for long periods, as is the case of Peti dam between 1945 and 1997, the definition of this curve requires the evaluation of several swelling components: an estimation of the swelling that has occurred up to 1997, before the installation of the monitoring system; a calculation of the swelling between 1997 up to now and an evaluation the potential for future additional swelling. Tests numbers 1 to 6 are intended to give an estimation of the first two components of the expansion and the purpose of tests numbers 7 to 16 is the evaluation of the potential for remaining expansion.

Both current and remaining expansions are difficult to estimate and only by indirect methods. To increase the accuracy of the estimation different methods are used, all of them based on the principle that there is increased degradation with increasing expansion.

For example, the determination of the modulus of elasticity (test number 5) allows estimating the current degree of expansion knowing the initial elasticity modulus and its variation with the value of expansion. The initial modulus of elasticity can be estimated from the tests performed at different periods after construction (ABCP (1974); CEMIG (1997); GEOTECH&FAL (2001)). The function expressing the variation of elastic modulus with the expansion can be estimated from literature, for example using the values given by the Institution of Structural Engineers (ISE (1992)).

Similar estimates can be obtained with the other tests, leading to a mean value and standard deviation of estimates which can be considered in the model.

The potential additional free expansion that may occur until the reaction is exhausted is estimated from free expansion test (test number 9). However, this test has some limitations in predicting the remaining expansion, namely due to sample representativeness (e.g. small size) and alkalis leaching, among others. Tests number 7, 8 and 10 to 16, provide information regarding the quantities of alkali and reactive silica which are available in the concrete. This information together with the proportions of the mixture, allows estimation of the expansion, as defined by some authors (MULTON et al. (2010)).

The expansion models obtained with this approach have a strong empirical component since they are based on results from tests made with concrete specimens collected from different zones of the structure at different times and are not based on pure physical-chemical phenomena. However, using estimates from distinct sources, and knowing the dispersion of the results, it is possible to consider a range of scenarios and compare them with the observed degradation process on the dam. In addition, monitoring will allow the comparison of the values of the model with those actually measured for possible correction of long-term estimates.

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Table 1 – List of recommended tests

Test	Description	Purpose
1	On-site measurements such as length, widths and frequency of cracks	Estimate current expansion, and monitoring for long term expansion
2	Compressive concrete strength	Swelling indicator and strength evaluation
3	Determination of aggregate and cement contents in concrete	Evaluation of mixture proportioning
4	Splitting tensile strength	Swelling indicator and strength evaluation
5	Elastic modulus	Swelling indicator and evaluation of elastic response
6	SDT – Stiffness Damage Test	Swelling and crack formation indicator
7	Total alkali concentration in concrete	Assess alkali content
8	Water-soluble alkali content of concrete	Assess alkali content
9	Potential additional expansion, estimated from cores	Evaluation of the potential maximum additional free swelling that may occur in the structure
10	Accelerated Mortar Bar Test using coarse aggregate	Evaluation of potential additional alkali-reactivity of coarse aggregate
11	Accelerated Mortar Bar Test using fine aggregate	Evaluation of potential additional alkali-reactivity of fine aggregate
12	Accelerated Mortar Bar Test using a mixture of coarse and fine aggregates	Evaluation of potential additional alkali-reactivity of the mixture of coarse and fine aggregates
13	Accelerated Mortar Bar Test using coarse aggregate with enhanced alkali level	Evaluation of potential additional alkali-reactivity of coarse aggregate
14	Accelerated Mortar Bar Test using fine aggregate with enhanced alkali level	Evaluation of potential additional alkali-reactivity of fine aggregate
15	Accelerated Mortar Bar Test using a mixture of coarse and fine aggregates with enhanced alkali level	Evaluation of potential additional alkali-reactivity of the mixture of coarse and fine aggregates
16	Soluble silica of the aggregate	Assess silica content

6 Swelling Action

6.1 Model Definition

The characterization of the swelling action and its modelling is a key problem in order to predict the long term behaviour of dams affected ASR. The main challenge of modelling swelling reactions is the integration of the data associated with the physical and chemical phenomena developed at the microscopic level in a macroscopic model to assess the structural safety conditions. It can be considered that ASR mainly depends on the following variables (CAPRA (1997)): Q, which represents, in overall terms, the chemistry of the process, and depends on the concrete composition (type of cement and reactive aggregates, their size, shape and distribution, existence and nature of admixtures, W/C ratio, porosity, water content, etc.), temperature T, relative humidity H_r; stress field σ, and time t. This dependency can be written in a generic equation,

$$\varepsilon^{ASR}(t) = f(Q, T, H_r, \sigma, t) \qquad \text{(Equation 5)}$$

By assuming the hypothesis that the chemical reactions occur on an isotropic material with elastic behaviour, a relation between chemistry and mechanics can be established using the reactive porous media theory (COUSSY (1995)). This makes it possible to analyse the behaviour of a closed system, in which a chemical reaction is produced and a differential equation can be obtained to evaluate the free swelling increment at the time interval (LARIVE (1998)),

$$t_c(T,\xi)\,\frac{d\xi}{dt} + \xi = 1 \qquad \text{(Equation 6)}$$

where

$$t_c = \tau_c(T)\,\frac{1+e^{[-\tau_L(T)/\tau_C(T)]}}{\xi+e^{[-\tau_L(T)/\tau_C(T)]}} \qquad \text{(Equation 7)}$$

being τ_L the latency time, τ_C the characteristic time and $\xi = \varepsilon_{Free}^{ASR} / \varepsilon_{Free}^{ASR}(\infty)$ a parameter that expresses the reaction progress, in which ε_{Free}^{ASR} is the free strain at instant t and $\varepsilon_{Free}^{ASR}(\infty)$ the maximum strain that the swelling process is likely to generate.
This equation makes the free swelling curves have an S configuration, characterized by an initial period of latency, in which the gel produced by chemical reactions causes smaller swelling and stresses because one portion will fill the pores in concrete (Fig. 5).

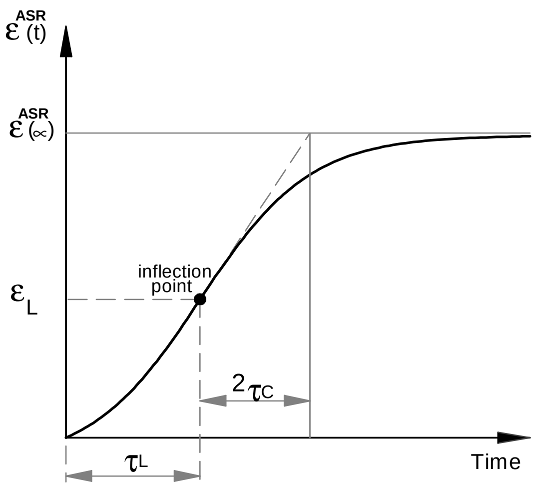

Figure 5 - Free swelling curve similar to those obtained in laboratorial tests

The swelling parameters τ_L, τ_C and $\varepsilon_{Free}^{ASR}(\infty)$ can be directly obtained from free swelling tests, carried out at standard humidity and temperature conditions, or estimated from the monitoring system data.
To evaluate the influence of the temperature variation during the swelling process, the following equations are used,

$$\tau_c(T) = \tau_c(T_0)\,e^{[U_c(1/T-1/T_0)]} \qquad \text{(Equation 8)}$$

$$\tau_L(T) = \tau_L(T_0)\,e^{[U_L(1/T-1/T_0)]} \qquad \text{(Equation 9)}$$

where U_C is the activation energy associated to the characteristic time, U_L the activation energy corresponding to the latency time, T_0 the reference temperature on the free swelling test and T is the temperature in the time interval Δt considered in the discretisation established for the analysis in the time domain.
Therefore, the free swelling in a structure depends on thermal and hygrometric fields, which are a function of environmental conditions resulting from the exposure of the structure and, in the case of dams, of their operation regimen. The thermal analysis is a heat conduction problem, which solution implies the knowledge of the thermal conductibility of the concrete and of the annual thermal waves of air and water, as well as of exposure conditions to solar radiation. The hygrometric computation is similarly done, on the basis of the representative curve of the average local humidity and of the water level variations in the reservoir. These two independent computations make it possible to evaluate the temperature and the relative humidity histories, on each point of the structure, in each time interval Δt of the period considered.

6.2 Parameterization of Swelling Action

The characterization of the swelling action on Peti dam took into account the vertical displacement obtained by the rods extensometers installed in the main arch and in the left abutment block, in November 1997, but also the results of laboratory tests, namely the residual expansion tests performed at Furnas Laboratory in 2004 (CEMIG (2004)). It was not possible to characterize the developed swelling exclusively on laboratory tests because no tests were performed to access the swelling developed between 1945 and 1997.
From the data collected from the monitoring system, mainly the vertical displacements measured with the rod extensometers, a statistical analysis was performed and it was possible to evaluate the swelling occurred between November 1997 and December 2011, as well as the swelling rates in this period. The results of the residual swelling tests were used to predict the development of future swelling. All this information was crucial to adjust a sigmoid function that represents the deformation observed on site, which was a starting point to define the parameters of equation (7). In this transformation from onsite conditions to laboratorial conditions the difference between the concrete average temperature on the dam and the standard temperature used in the laboratorial tests (38ºC) was taken into account, to obtain the maximum swelling that can be reached $\varepsilon_{free}^{ASR}(\infty) = 1200 \times 10^{-6}$, and the chemical reaction kinetics parameters, latency time $\tau_L = 98$ days, characteristic time $\tau_C = 78$ days, latency activation energy U_L= 30600 $J.mol^{-1}$ and the characteristic activation energy U_C = 26200 $J.mol^{-1}$.

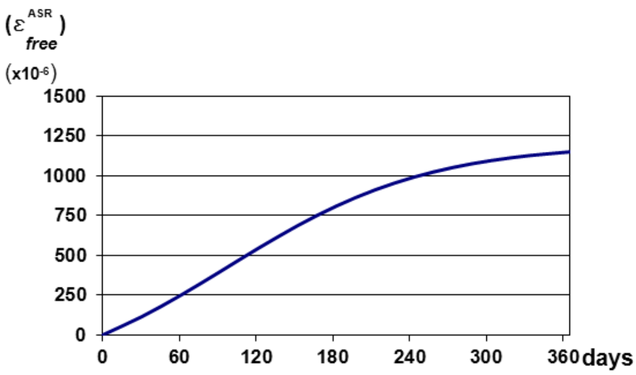

Figure 6 - Free swelling curve under laboratorial conditions (38ºC, 95 to 100 RH)

6.3 Swelling Results

The purpose of the swelling modelling is to determine the strain evolution, due to chemical reactions, which will be used in the structural analysis as prescribed deformations. The numerical model adopted is a relatively refined spatial discretization, with 2366 three-dimensional isoparametric elements, with 20 nodal points, to represent the structure and 2448 elements of the same type to represent the foundation. However, the study of the swelling process was done considering only the dam with appropriate boundary conditions (Fig. 7). This relatively tight discretization intends to ensure an adequate representation of the distribution of temperature and humidity through the thickness, in order to obtain a suitable swelling distribution, and also to catch the existing cracks in the arch and in the left abutment.

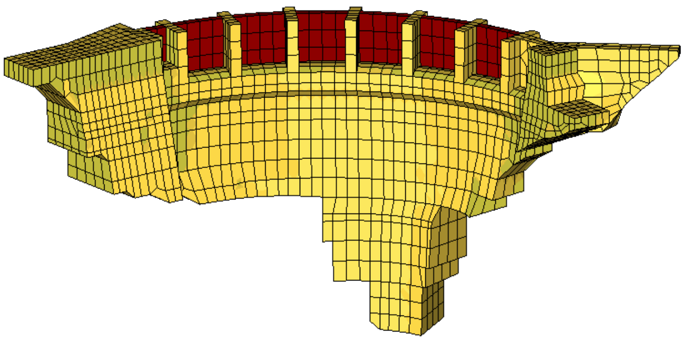

Figure 7 - Finite element mesh of Peti dam

A time discretization of the period between October 1945 and December 2011 in 15 days constant intervals was adopted in these calculations.
As formerly mentioned, the computational algorithm implemented to compute the swelling action requires the knowledge of swelling characteristics of the concrete, under normalized conditions, as well as the temperature and moisture fields on the structure due to operational and environmental conditions.

The temperature fields were obtained considering the thermal action in the dam surfaces due to the air and water temperatures, approximated by harmonic functions of annual period (Fig. 8).

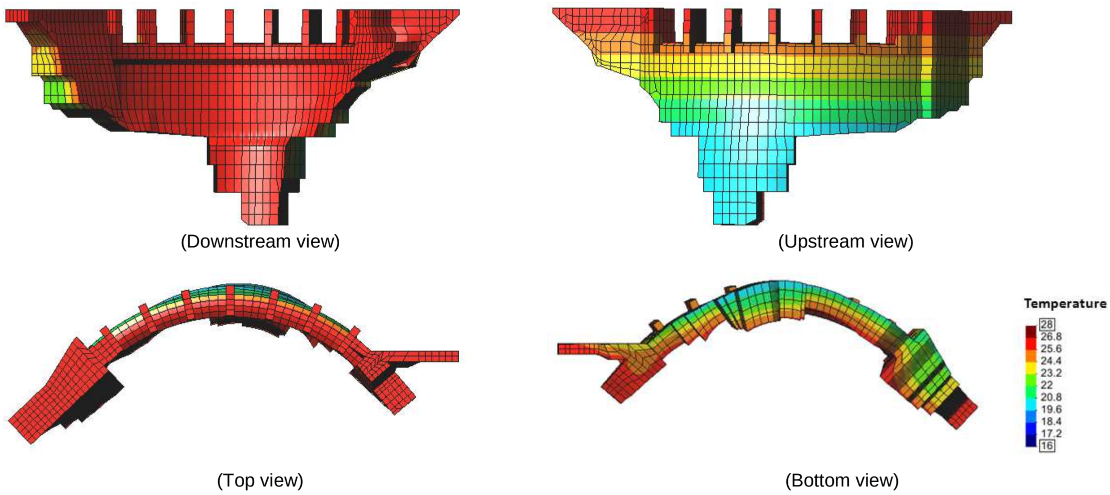

Figure 8 – Computed thermal field on Peti dam in a summer season (January 16, 1979).

The moisture fields were obtained considering the hygrometric action in the dam surfaces due to the air humidity and the presence of the water in the reservoir (Fig. 9).

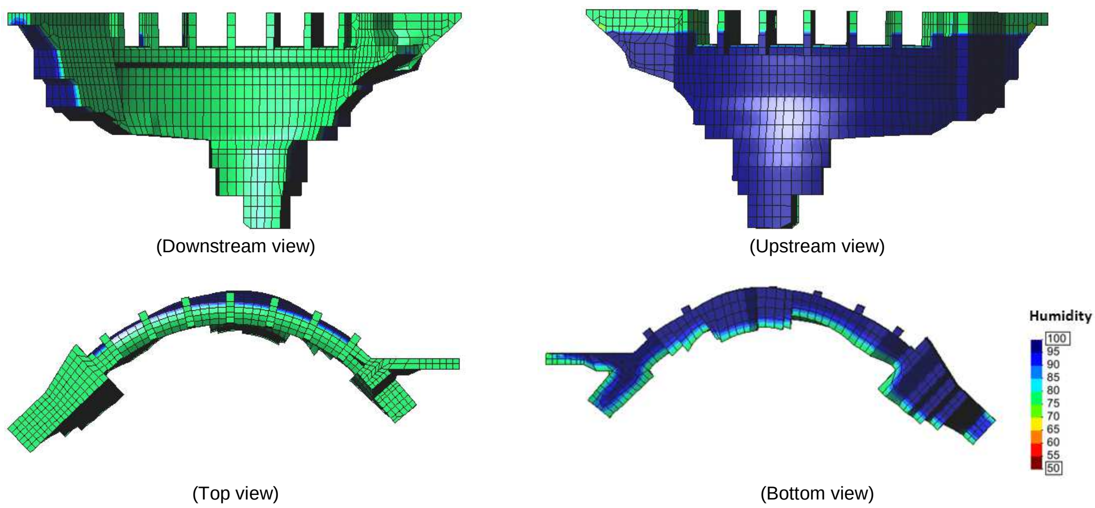

Figure 9 – Computed moisture field on Peti dam in a summer season (January 16, 1979).

Known the thermal and hygrometric actions and considering the concrete as homogeneous, identical swelling characteristics across the dam and abutments, it was possible to obtain free swelling histories in the structure, as prescribed deformations. Figure 10 shows the free swelling computed at March 1979 (at age of 35 years) and Figure 11 shows the free swelling computed at December 2011 (at age of 66 years).

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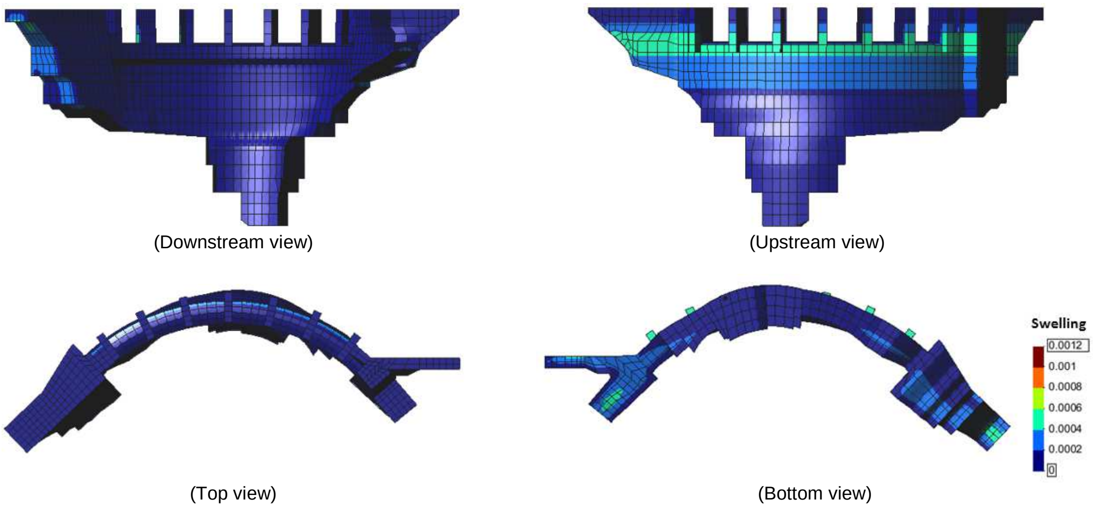

Figure 10 – Computed free swelling on Peti dam at age of 35 years (March 27, 1979)

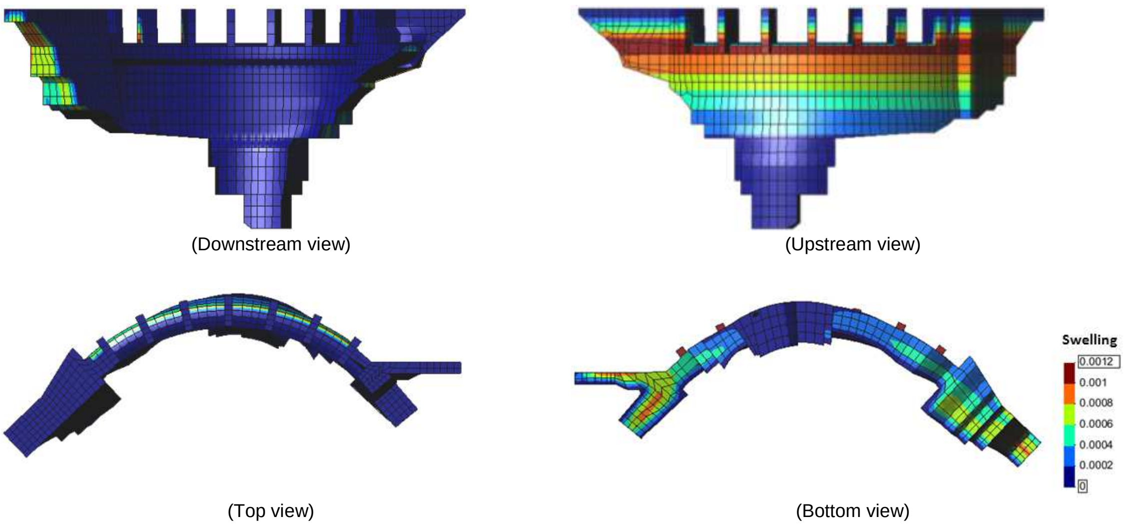

Figure 11 – Computed free swelling on Peti dam at age of 66 years (December 5, 2011).

The obtained strain fields reveal the heterogeneity due to environmental conditions to which the dam was submitted. As can be seen, under the considered conditions, the most important swellings are close the upstream face, in particular in the area of water level variation in the reservoir. There should be a reminder to the fact that these results do not yet incorporate the effects of structural constraints that can only be considered in the structural analysis computation.

7 Conclusions

Deterioration processes due to swelling reactions, common in old concrete dams, can affect seriously the safety conditions of the structures and may lead, in extreme cases, to its abandon. As these dams have an important economic value, scientific and technical studies should be done in order to assess their safety conditions and, when possible, propose structural or non-structural remedial measures. These studies shall include experimental tests to characterize the material properties and the expansions evolution, numerical modelling of the thermo-chemo-mechanical behaviour of the structure and, whenever available, the analysis of monitoring data.

In this work, the case of Peti dam, a 67 old Brazilian concrete dam with very expressive expansions in the concrete, is presented. After a brief reference to the studies developed during the last 45 years, a more detailed description of the actual studies is presented, including the proposal of a set of experimental tests of concrete specimens extracted from the dam body and the development of numerical models that simulate both the swelling process and the structural behaviour of the dam along all its life.

The final analysis of the results of all these studies shall enable us to assess the actual safety conditions of the dam, evaluate the more probable evolution of the degradation process and propose eventual structural or no-structural measures that can ensure the operation of the dam in adequate safety conditions.

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