Damage-Chemo-Viscoelastic Model on the Analysis of Concrete Dams under Swelling Processes

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Abstract

The analysis of the observed behaviour and the structural safety control of concrete dams under swelling processes, namely due to alkali-silica reactions (ASR), require the use of appropriate mathematical models, generally supported by the finite element method. These models must take into account the factors that influence the development of swelling processes, namely the concrete properties, the environmental conditions (temperature and humidity) and the stress field in the structure, as well as the over-time changes in the rheologic properties of materials and the damage induced by swelling.

This purpose was achieved by a damage-chemo-viscoelastic model, based on a constitutive isotropic damage law, which consider that the evolution of the damage variables (both tensile and compressive) depends exclusively on elastic strains. The concrete time behaviour was taken into account by an incremental constitutive relation corresponding to a Kelvin chain. The hypothesis of isotropic material with a time variable elasticity modulus and a constant Poisson ratio was admitted. The free-stress swelling process is assumed to be isotropic and the influence of the stress field was also considered. This model makes it possible to compute displacements, strains, stresses and damage over time.

This paper is to present the main features of the mathematical models developed and the results of its application to the analysis of the observed behaviour of an approximately 60-years old Portuguese buttress dam, the Pracana dam, which has been subject to a concrete swelling process due to ASR.

Introduction

The damage-chemo-viscoelastic model considered is a non-linear structural model that includes a module to simulate the macroscopic effect of the swelling reactions by means of an imposed deformation history. The evaluation throughout the time of these imposed deformations, designated as the swelling action model, considers intrinsic factors to the concrete (aggregate type and size, cement and alkali content) and the ambient conditions of temperature and moisture, and resorts to Fourier's equation for solving the thermal and hydrometric problems, the differential equation that governs the kinetic of chemical reactions being solved by the Euler's method.

The structural model was implemented by the finite element method using a displacements formulation, establishing a separation between instantaneous and delayed responses. In instantaneous calculations, the imposed deformations due to the swelling process, the applied loads (hydrostatic pressure and uplifts) and the thermal variations are considered; and an iterative procedure is used to take into account the dependency of the swelling action on the stress field. In the delayed calculation the concrete time behaviour is considered using nodal forces equivalent to the effect of the load history. In both situations, the possible development of cracking, due to the swelling process, is evaluated using an iterative stress-transfer technique.

Some simplifying hypotheses have been admitted, namely the non-depreciation of the concrete strength and the constant hydrometric properties throughout the time. The model considers the main phenomena involved in this deterioration process, in an uncoupled form.

Models and Methods

Swelling action model

The main purpose of the modelling of swelling reactions, for solving engineering problems, consists of integrating in a macroscopic model, the data about the physical and chemical phenomena developed at a microscopic level.

It is considered that the development of alkali-silica reactions depends mainly on the variables as follows [1]: Q, which represents, in overall terms, the chemistry of the process and which depends on the concrete composition (type of cement and reactive aggregates, their size, shape and space distribution, existence and nature of admixtures, W/C ratio, porosity, water content, etc.); temperature T; relative humidity Hr; stress field σ ; and time t. This dependency can be written in a generic equation,

$$\varepsilon^{ASR}(t) = f\ (Q, T, H_r, \sigma, t) \qquad (1)$$

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 [2]. This makes it possible to analyse the behaviour of a closed system, in which a chemical reaction in the interstitial solution is produced and a differential equation can be obtained to evaluate the free swelling increment at the time interval dt [3],

$$t_c(T,\xi)\frac{d\xi}{dt}+\xi=1 \qquad (2)$$

where,

$$t_c=\tau_c(T)\,\frac{1+\exp[-\tau_L(T)/\tau_c(T)]}{\xi+\exp[-\tau_L(T)/\tau_C(T)]} \qquad (3)$$

where τ_L is the latency time, τ_C is the characteristic time and $\xi=\varepsilon_{Free}^{ASR}\,/\,\varepsilon_{Free}^{ASR}(\infty)$, being $\varepsilon_{Free}^{ASR}(\infty)$ the maximum value that the swelling process is likely to generate.

This equation originates free swelling curves with an S configuration, which are characterised by an initial period of latency, in which the gel produced by chemical reactions fills the pores in concrete causing neither stresses nor swelling (Figure 1).

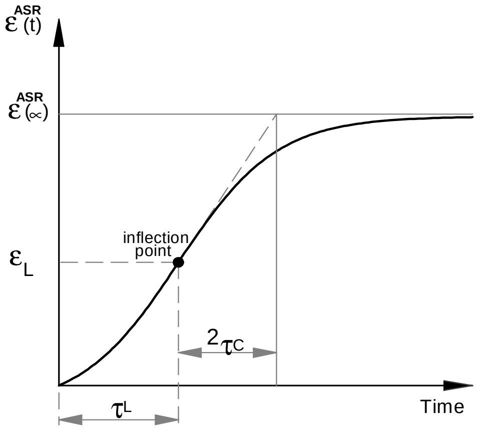

Fig. 1. Free swelling curve obtained in isothermal tests.

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.

To evaluate the influence of the temperature variation during the swelling process, the following equations are used,

$$\tau_C(T)=\tau_C(T_0)\,e^{[U_C(1/T\,-\,1/T_0)]} \qquad (4)$$

$$\tau_L(T)=\tau_L(T_0)\,e^{[U_L(1/T\,-\,1/T_0)]} \qquad (5)$$

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 temperature of the reference 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, being a function of environmental conditions resulting from their exposure and, in the case of dams, of their operation regimen. The thermal analysis is a problem of heat conduction, of which the solution implies the knowledge of the thermal conductibility of 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 variations in the reservoir water level. These two independent computations make it possible to know the temperature and the relative humidity histories, on each point of the structure, in each time interval Δt of the period considered.

The influence of the stress field on the swelling process was based on the experimental data performed in France, at the LCPC [4], and the following equation was implemented:

$$\psi_x(\sigma,t)=\frac{\varepsilon_x^{ASR}(\sigma,t)}{\varepsilon_{x,\,free}^{ASR}(t)}=e^{-(a\sigma(t))^b} \qquad (5)$$

where $\psi(\sigma,t)$ is the ratio between restrained swelling by the effect of unidirectional stress σ and the free swelling in a certain time interval. The free swelling was assumed as isotropic.

Structural model

The solution of the time dependent structural problem, considering the swelling and cracking development, was implemented by the finite element method, taking into account an incremental procedure in the application of loads and in the evaluation of the delayed behaviour of the concrete and the effects of the non-linearity due to possible damage occurrence.

A displacement formulation is adopted. Using the principle of virtual works, the following equilibrium equation is obtained,

$$\underline{K}(t)\,\Delta\underline{u}=\Delta\underline{f}^{a}+\Delta\underline{f}^{0}+\Delta\underline{f}^{*} \qquad (6)$$

where $\underline{K}(t)$ is the global stiffness matrix, $\Delta\underline{u}$ the increment in displacements, $\Delta\underline{f}^{a}$ the incremental forces due to the applied loads, $\Delta\underline{f}^{0}$ the incremental forces due to the imposed deformations and $\Delta\underline{f}^{*}$ the incremental forces due to the load history.

For each time step this equation is solved in order to evaluate the incremental displacements, the stiffness matrix being updated in each time step [4]. The cracking progress is computed using a scalar damage model with two independent variables, d^+ for the tension damage, and d^- for compressive damage. The effective stress tensor $\tilde{\sigma}$ is decomposed into the stress tensors $\tilde{\sigma}^+$ and $\tilde{\sigma}^-$, in order to obtain the following constitutive equation [5],

$$\sigma = \left(1 - d^{+}\right)\tilde{\sigma}^{+} + \left(1 - d^{-}\right)\tilde{\sigma}^{-} \qquad (7)$$

Tension softening is simulated using an exponential law [6],

$$d^{+} = 1 - \frac{r_0^{+}}{\tilde{\tau}^{+}}\, e^{A^{+}\left(1 - \frac{\tilde{\tau}^{+}}{r_0^{+}}\right)}, \qquad \tilde{\tau}^{+} \geq r_0^{+} \qquad (8)$$

where $\tilde{\tau}^{+}$ is an equivalent stress for tension, r_0^{+} is a damage threshold for tension and

$$A^{+} = \left(\frac{G_f\ E}{w^{*}\left(f_0^{+}\right)^{2}} - \frac{1}{2}\right)^{-1} \qquad (9)$$

G_f being the fracture energy, w^{*} a characteristic dimension associated to the spatial discretisation so as to guarantee the objectivity of numerical solutions [7].

For each time step, the damage is evaluated using an iterative stress-transfer procedure, in order to pursuit the global equilibrium, by updating damage, stresses, strains and displacements. After achieving the equilibrium, the analysis proceeds to the next step [8].

Case Study – Pracana Dam

Pracana dam characteristics

Pracana dam is located in the centre of Portugal, on Ocreza river, a tributary of Tagus river, and mainly consists of a concrete gravity buttress dam, 60 m high and 245 m long at the crest elevation (115.00), with 12 buttresses 13.0m wide (diamond shaped head type) and 3 massive blocks at each abutment. The dam was built between 1948 and 1951, with a shaft spillway on the right bank having a discharge capacity of 1 650 m^3/s and a bottom outlet with a maximum discharge capacity of 52 m^3/s. The total concrete volume of the dam is 129 000 m^3.

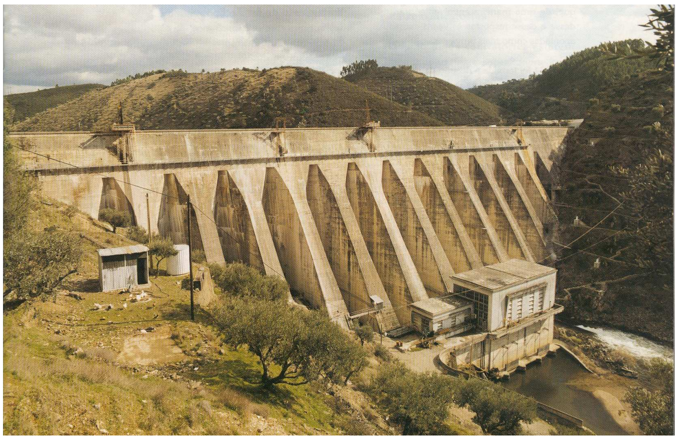

Figure 2 – Pracana Dam in 1986. Downstream view.

The progressive deterioration of the dam, as well as the insufficient discharge capacity of the shaft spillway for the new design flood, led to the decision of emptying the reservoir in 1980.

Dam foundations properties

The foundation bulk consists of silica shale and greywacke of the lower cambric, with shale planes approximately transverse to the river; the rock mass is not homogeneous, and therefore, presents alternating massive benches with fine soft and decomposed shale’s layers [9]. Geologic and geotechnical surveys carried out between 1978 and 1980 made it possible to conclude that the foundation bulk is heterogeneous and anisotropic, with a stratified structure, where the formations are folded, the thicker decomposed zone being located in the right bank and being variable in depth from the valley to the upper part of the hillsides [10].

Properties of the concrete

The concrete used in the construction of Pracana dam resulted from an aggregate mixture originating from the gravel bed of Barca da Amieira, of which the thick rolled aggregates can be broken down into four main petrograhic types: quartzite, milk quartz, granite and shale-greywacke. The fine aggregates mainly constituted of angular quartz and feldspar grains. Portland cement from two factories, Tejo and Liz, were used, due to the difficulty, at the time, in ensuring the supply from only one manufacturer. Cement dosages of 280 kgm^{-3} were used in the upstream zone of the buttresses heads and of 250 kgm^{-3} in the remaining parts of the dam [11].

Swelling detection

In 1962, several cracks were detected in some buttresses and, in 1964, the seepage through the dam increased suddenly. The development of these cracks occurred with a progressive upward movement of the crest and a downstream movement of the dam.

To detect the phenomena, several tests were carried out in 1978 on cores drilled from the body of the dam, namely:

- chemical analysis of deposits in cracks and of aggregates;
- mineralogical analysis of aggregates;
- standard and non-standard expansion tests.

These tests made it possible to detect some ettringite on the concrete. The increase in sulphate content in the infiltrated water and the type of cracking has led to the research on alkali-silica reactions (ASR). Furthermore, the mineralogical identification of alkaline efflorescences, namely sodic, at the downstream face, as well as the existence of typical margins of reaction in siliceous aggregates and the silicate nature of the filling material of some voids indicated that ASR were probably the cause for the swelling phenomenon.

The petrographic analyses of thin layers of concrete samples and the identification of the zones of alteration with an electronic microscope and with an electronic micro sounder showed that the aggregates used were highly susceptible to this type of reactions.

Swelling action model

The environmental conditions of the dam, namely the thermal and hygrometric actions, were considered in the modelling of the swelling action. The evolution of the vertical crest displacements, recorded by geodetic levelling done between 1951 and 1980, was taken into account.

The swelling action was characterized by the same swelling properties for all buttresses, by a sigmoid function, in which the maximum expansion that can be reached in the concrete is $\varepsilon_{free}^{ASR}(\infty) = 700 \times 10^{-6}$. Furthermore the chemical reaction kinetics, defined by a latency time $\tau_L = 98{,}0\, dias$, a characteristic time $\tau_C = 64{,}0\, dias$, an energy of latency U_L = 18500 K and a characteristic energy U_C = 17500 K, were obtained from the data collected by the monitoring system of the dam, namely from the vertical displacements of the crest. An isotropic free swelling was assumed.

The results obtained for the free swelling have shown, considering the same swelling properties for all the concrete, the influence of the buttress geometry, its exposure to the environment, namely to temperature and moisture, the influence of the wetting/drying cycles, introducing an important differentiation in the development of the swelling process, as shown in figure 3.

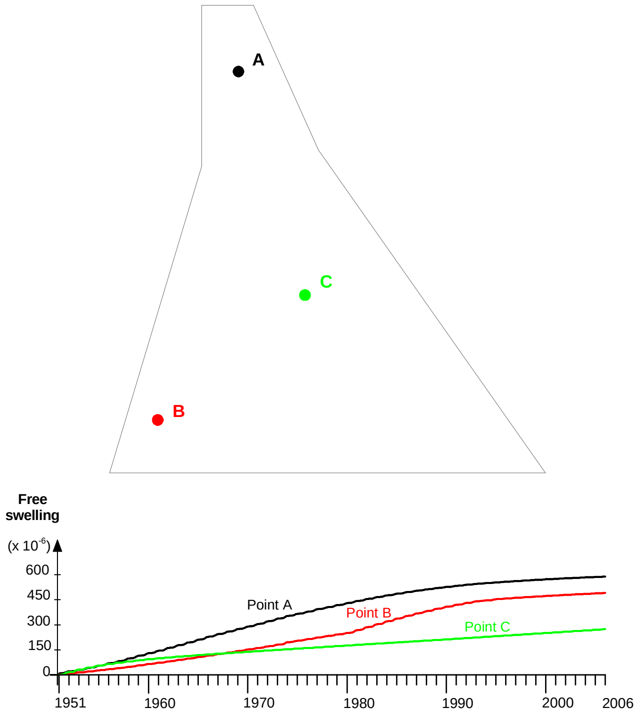

Figure 3 – Evolution of the free swelling in three points

This example has made possible to assess the importance of the discretisation adopted and the relevance of the water movements inside the concrete for the development of the swelling process, as has been experimentally demonstrated, namely the water supply to the concrete and also the effect of wetting/drying cycles.

Structural model

The numerical model adopted for the analysis and interpretation of the Pracana dam behaviour represents the structure of a buttress and its foundation. A central buttress and the respective foundation block were considered, with a discretisation of 5112 hexahedral elements, each having 20 nodal points. Due to the extent of the problem, and to the need of carrying out several non-linear analyses throughout the time, a substructuring technique was adopted, which made it possible to consider only the 2832 elements of the buttress (13793 x 3 degrees of freedom) supported on a foundation block, of which the rigidity was previously calculated, and thus reduce the extent of the problem. The refinement adopted in the buttress discretisation is intended to solve some problems related with the local effect associated to the variations in temperature and moisture, and to evaluate more accurately the differential swelling from the external surfaces to the core of the concrete, through elements with low average volumes (of the 4.25 order of m^3) and with a relatively homogeneous distribution in all the buttress. Thus, using 27 sampling (Gauss) points, the dimension of the volume associated with each point of integration is, on the entire buttress, of the order of magnitude of the width of the zone in process of fracture (ZPF) of the concrete.

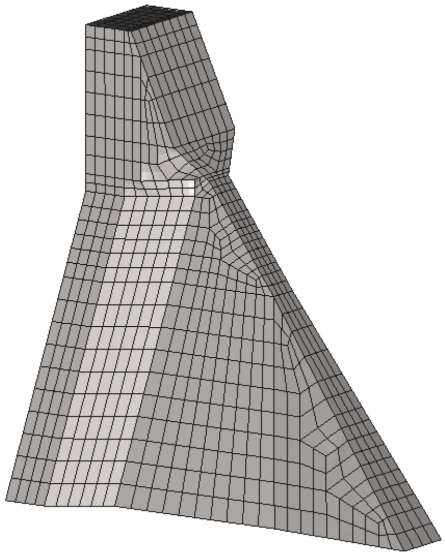

Figure 4 – Finite element mesh of the central Pracana dam buttress.

It was assumed that the concrete is homogeneous and isotropic with a rheologic behaviour defined by the following Bazant and Panula creep law:

$$J(t,t_0) = \frac{1}{40.0}\left(1 + 4.0\left(t_0^{-0.40} + 0.05\right)(t - t_0)^{0.120}\right) \quad GPa^{-1} \qquad (10)$$

As regards the foundation bulk the hypothesis of an elastic and isotropic medium was assumed, with a 20 GPa modulus of elasticity, a 0.2 Poisson ratio and with a non-time dependent behaviour.

The effects of the neighbouring buttresses on the studied buttress were taken into account, in a simplified mode, by the application of surface forces on the contact lateral faces. A sigmoid function was used to simulate the evolution of the lateral confinement forces due to swelling, with a maximum value of 3.75MPa, when the free swelling reached the maximum value of 700×10^{-6}. A trigonometric function was also used to represent the effect of the thermal variations of the annual period that introduces a maximum confinement of 2,0MPa.

An isotropic damage model was assumed to simulate the concrete behaviour, considering an exponential weakness in tension, as Figure 6 shows. Until the peak tension has been reached, ft = 2 MPa, the concrete presented a linear elastic behaviour with a modulus of elasticity of 20 GPa and a Poisson ratio of 0.2. Furthermore, for strains greater than the peak, the concrete is expected to enter a weakness phase that is characterised for a descending exponential damage, which corresponds to a fracture energy of 0.95 kNm/m^2.

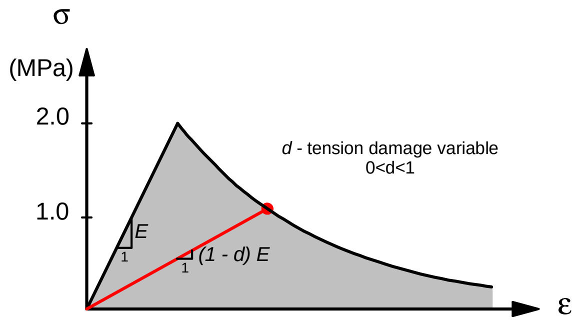

Figure 5 – Stress-strain law in tension with exponential damage.

Results and discussion

The numerical results corresponding to the time-analysis, with a monthly discretisation of all actions (dead weight, hydrostatic pressure, temperature variations and swelling), since the first filling of the reservoir until the respective emptying in 1980, show that the considered swelling process introduces increasing axial displacements towards downstream and gradual vertical displacements upwards the crest.

However, the results obtained showed a progressive disagreement between the computed displacements and the values observed on the monitoring system, as a result of a swelling action less than the one that effectively occurs in the structure.

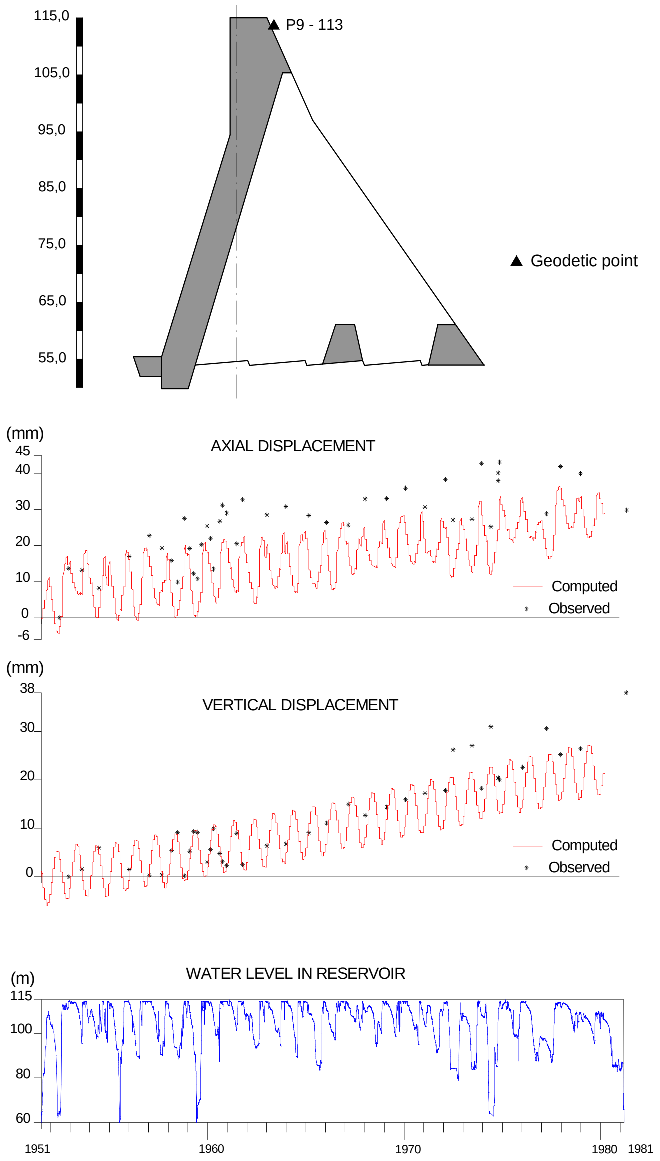

Figure 6 – Axial displacements computed and observed on point P9-113 and vertical displacements at the crest, between 1951 and 1980.

As regards the damage evolution, mention must be made of the fact that the numerical results have indicated that the cracking started on the upper part of the buttress head in 1965, 14 years after the first filling, and, subsequently, the affected zones have increased and superficial cracks on the downstream faces of the buttress head and also in the web, next to the downstream foot, have appeared. These results present a time lag, and therefore the information related with the cracking appearance is previous.

Figure 7 presents the damage computed in 1980.

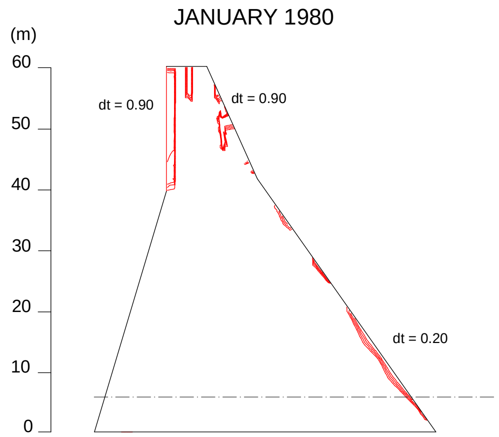

Figure 7 – Isolines of tension damage computed at January 1980.

Conclusion

The Pracana dam results presented, which were obtained with the damage chemo-viscoelastic model developed, have shown that this model gives the possibility of analysing the dam behaviour under a swelling process.

Considering the same swelling properties on the entire buttress studied, the numerical results show a progressive crest movement upwards and towards downstream, as observed. This particular behaviour corresponds to a non-homogeneous swelling distribution: higher on the buttress head. This can be explained by the temperature and moisture distribution over the buttress that induces an increasing swelling action on the head; on the web, where there is no water supply and a faster loss of moisture occurs, the swelling is less.

Although the presented results do not show a perfect agreement with the displacements and damage observed, it is possible to improve the numerical results with some adjustments in the swelling properties and in the strength parameters (for instance, a tensile strength of 2 MPa, was used, which can be considered as a high value for the concrete of this dam).

In this model, the porosity is not explicitly considered and the hydro diffusivity of the concrete was assumed as a constant throughout the time, rather than dependent on the evolution of the swelling process and the microcracking induced does not affect the permeability. However, this study showed the importance of simulating the water movement inside the dam body, by taking into account the evolution of the water level, in order to obtain an accurate swelling development.

This structural model considers the viscoelastic behaviour, on the basis of a Kelvin chain with maturation, and still considers the cracking development, using an uncoupled continuous isotropic damage model, with two independent damage variables, as well as a formulation to guarantee the objectivity of the numerical solutions in case of occurrence of ruptures in tension. In further developments, the numerical modelling should include the different interactions between the swelling process, the viscoelasticity and the cracking development.

Acknowledgements

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References

[1] Capra, B. (1997). *Modélisation des effects mécaniques induits par les reactions alcalis-granulats*. PhD Thesis, École Normale Superieure de Cachan, France.
[2] Coussy, O. (1995). *Mechanics of porous continua*. Ed. J Wiley and Sons.
[3] Larive, C. (1998). *Apports combines de l'expérimentation et de la modelisation à la comprehension de l'alcali-reaction et de ses effects mécaniques*. PhD Thesis. Laboratoire Central des Ponts et Chaussés, LCPC, Paris.
[4] Batista, A.L. (1998). *Análise do comportamento ao longo do tempo de barragens abóbada*. PhD Thesis, Technical University of Lisbon.
[5] Faria, R., Oliver, J., Cervera, M. (1998). *A strain-Based Plastic Visco-Damage Model for Massive Concrete Structures*. Int. Journal Solids Structures, Vol. 35, Nº.14, pp. 1533-1558.
[6] Oliver, J., Cervera, M., Oller, S., Lubliner, J. (1990). *Isotropic Damage Models and Smeared Crack Analysis of Concrete*. Journal of Engineering Materials and Technologies, Trans. of the ASME, Vol. 105, pp. 99-105.
[7] Oliveira, S.B., Faria, R. (2006). *Numerical simulation of collapse scenarios in reduced scale tests of arch dams*. Engineering Structures 28, Ed. Elsevier, pp. 1430-1439.
[8] Gomes, J.P. (2007). *Modelação do comportamento estrutural de barragens de betão sujeitas a reacções expansivas*. PhD Thesis, Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa.
[9] Gignoux, M. (1941). *Rapport sur les conditions geologiques du Barrage de Pracana sur le Rio Ocreza*. Ed. EDP.
[10] EDP (1985). *Barragem de Pracana. Projecto de remodelação – Vol. III – Estudos geológicos e geotécnicos*. EDP, Porto.
[11] EDP (1978). *Estudo das condições de segurança da Barragem de Pracana*. EDP, Porto.