RELIABILITY OF ARCH DAMS SUBJECT TO CONCRETE SWELLING

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RELIABILITY OF ARCH DAMS SUBJECT TO CONCRETE SWELLING
Three cases histories

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SUMMARY

In the last few years reports have been made on many cases of concrete dams and appurtenant works subject to swelling processes due to alkali-aggregate reactions in concrete, justifying thus the increasing interest in the phenomenon and in its effect on the reliability of the structures affected.

In view of the consequencies of volume variations of concrete that the shapes of the arch dams impose, the development of swelling processes in concrete may put into jeopardy, eventualy in a more serious way than in dams of other types, their serviceability and even their safety. In fact, swelling can cause important alterations in the state of stress in the body of those structures, and therefore can lead to significant fissuration, namely when the swelling process is markedly heterogeneous. The effective knowledge of the state of stress in the body of the dams is, thus, an indispensable condition for assessing their serviceability and safety. In many dams however, as is frequently the case of old works without monitoring systems set up for the direct determination of variations in the concrete volume, the available information is scarce, this assessment being therefore difficult to be carried out.

In this report, results of several studies are presented. The main aim of those studies was to assess the reliability of the three arch dams, in which swelling occurred due to alkali-aggregate reactions in various stages of development and having different effects on their reliability: the Cahora-Bassa dam, in Mozambique, where swelling accumulated up to the moment are very moderate and their development is apparently homogeneous; Santa-Luzia dam, in Portugal, where accumulated swelling have already considerable magnitude, nevertheless, important fissuration has not been observed up to the moment due to the homogeneous development of the swelling process; Alto-Ceira dam, also in Portugal, where accumulated swelling have also considerable magnitude but with a heterogeneous development, causing in conjunction with thermal variations important fissuration.

Mention is made of mineralogical, chemical and petrographic analyses carried out for identification of the nature of reactions developed in each case and the back-analysis and other technics used in the assessment of the magnitude and distribution of swelling. Results are presented of measurement tests of the ultrasonic pulse velocity, used both in the assessment of alterations in the physical properties of concretes and in the determination of the depth of fissuration. Results are also presented of tests for characterisation of the rheology of integral concrete. Lastly, considerations are made about the reliability of the works on the basis of studies and the results of analyses of the state of stress, performed by means of the finite element method, by assuming for either visco-elastic or visco-elastic-plastic behaviour.

barragem de betão
barragem abóbada
reacções de agregados
expansão do betão

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INTRODUCTION

1. The awareness of the existence of an increasingly significant number of concrete structures in which deterioration processes are taking place due to alkali-aggregate reactions (alkali-silica and alkali-carbonate) has led, in the last decade to the increment of studies in various fields: the chemical mechanisms of alkali-aggregate reactions, the physical effect of swelling resulting from these reactions, their structural effects, namely in terms of servicebility and safety of structures, the need to undertake repairs in the affected works and the techniques used for the purpose.

Alkali-aggregate reactions have been known as a possible cause of concrete deterioration since the 40's and, at the time, they were the source of thorough studies. Nevertheless, recommendations resulting from these studies have proved to be insufficient at the present time. In fact, important fissuration due to swelling resulting from alkali-silica reactions have been observed in the concrete of many structures that have been built since the 50's and in which those recommendations have been followed (Coutinho, A. S., 1974). The fact that the development of the swelling is usually very slow, in conjunction with the inexistence of monitoring systems for its early detection and with the generalised absence of a practice of continuous and long term survey of the structural behaviour led to a late detection of the phenomenon. In many cases, that detection only occurred when stresses induced by swelling caused significant surface fissuration.

There are two major causes for deterioration of structural properties resulting from alkali-aggregate reactions: alteration of mechanical properties of concrete essentially due to micro-cracking and production of structural fissuration due to development of adverse states of stress in the body of the works. Reactions may however occur in the concrete of many structures without having a significant importance. It is only above a certain magnitude of the resulting swelling that important alterations are produced in the mechanical properties of concrete. Pressure exerted by swelling of gel during the water absorption process, causes, locally, tensile stresses in the concrete wrapping the swelling zone, which can cause micro-cracking. This micro-cracking may originate, in turn, a decrease in the compressive and tensile strength and an increase in the deformability. Results of several tests on unconfined concretes analysed by the ISE (ISE, 1992), show that, concerning mechanical properties determined for 28 days of age and for swelling of about 1000×10^{-6}, reductions are produced of about 15 to 20% in the compressive strength, 25% in the tensile strength and 30% in the elasticity modulus. On the other hand, in terms of the structure as a whole the development of adverse states of stress will depend on the shapes, on the magnitude of swelling and on their distribution in the body of the works. In many cases, swelling are essentially represented by a general increase in the compression, this increase being well supported by the structures.

2. The magnitude of swelling, i.e., the intensity of reactions varies both in terms of distribution in the body of a certain structure and in terms of its time evolution, as a result of numerous factors, such as: existence of reactive silica and alkalis in appropriate proportions, as it seems that there is a certain proportion of reactive material as regards the total amount of aggregate (varying according to the reactivity of the aggregate), designated as "very bad" percentage, which determines a maximum peak value of swelling (ICOLD, 1989); the time evolution in the quantities of the materials potentially reactive, as a result of "consumptions" of the very reaction; variations in the permeability of concrete, resulting from variations in the mixture, compaction, existence of discontinuities, fissuration and formation and penetration of gel into pores; the contents of relative humidity, which should be at least from 75 to 80% for the reaction to take place, which is always the case of dams; variations in the humidity contents in the body of the works, certain dams showing evidences of a more marked development of reactions in the upstream zone of variation of the level (ICOLD, 1989); existence of a sufficiently high pH, usually higher than 12, for providing the means adequate for producing a reaction (Silva, H. S., 1993); variations in the state of stress in the body of the structures, with higher swelling developing in the direction of tensions and smaller compressions, a limit compressive stress seeming to exist for the occurrence of swelling in the direction of this compression.

In the presence of water, alkali-aggregate reactions can continue, according to eventually variable rates, as long as potentially reactive materials exist in the body of the works. In some dams, the process stopped after about 30 years of development of reactions, in other dams the process continues for more than 50 years after its beginning (Charlwood, R.G.; Slymar, Z.V., 1992). On the other hand, the possible repair works in dams, such as impermeabilisation of the upstream face and, occasionally of the crest, even if they will certainly contribute to reduce the rate of expansions at long term, they are not effective at short term in view of the amount of water available for reactions that is always present in the body of the dams.

3. The effect of development of swelling can be particularly serious in arch dams. Apart from the aspects that are common to every type of dam, as is the case of the possible alteration in the servicebility of the hydraulic equipments, or the upstream/downstream heterogeneity in the development of swelling, or, also, the alteration of the mechanical characteristics of concrete, the type of restrictions to the increase in concrete volume imposed by their shapes may cause particularly adverse stress fields. In an arch dam, the homogeneous development of swelling is essentially represented by a general increase in compressions and by the development of tensile stresses downstream, along and normally to the insertion, only partially compensated by compressions resulting from the hydrostatic pressure. The existence of compressive stresses in the arches higher than those verified in the cantilevers may lead to an orthotropic development of swelling, with more significant values in the vertical direction. In the same manner, higher compressions usually existing in the central zone of the arch and along the downstream insertion can cause a smaller development of swelling in these zones. In addition to this heterogeneity there are those resulting from the different moisture conditions through the thickness or from different sunshine expositions of several zones.

The most important aspects for the assessment of the reliability of the works and for the decision making process about possible repair works are as follows: determination of the state of stress installed in the structures due to swelling; knowledge of the mechanical characteristics of the concrete, their evolution in time and in the body of the works and, finally, knowledge of the existing state of fissuration. It must be pointed out that some cases may exist of dams where the alkali-aggregate reactions causing swelling of considerable magnitude may cease without having significantly affected the safety and the sevicebility of the works.

The execution of tests for characterisation of the rheologic properties of concrete (compressive and tensile strengths, elasticity modulus and creep) on samples extracted from several zones of the works and the inter-connection between the results of these tests with predictions established from values previously obtained, namely during construction, may give some indications about the alteration existing in those properties, as a result of alkali-aggregate reactions. The performance of tests for determination of the ultra-sonic pulse velocity in the body of the dams will contribute to the zoning of the variation of the mechanical properties and, in conjunction with visual inspections, to the accurate survey of the state of fissuration.

ASSESSMENT OF THE MAGNITUDE OF SWELLING

1. Since in dams, independently from the existence of water upstream and for workability purposes, the water/cement ratio is always higher than the necessary for hydration of cement, the alkali-aggregate reactions and the resulting swelling may start long before the first filling, being subsequently fed by the slow percolation through concrete of water from the reservoir. The structural effects of variations in the concrete volume, namely the effects on displacements, joint contraction, stress-strain fields and states of fissuration, can be usefully recognised since the early life of those structures, providing that the necessary observation equipment will be available.

In local terms, the embedded equipment intended for measuring the variations in the concrete volume, namely the no-stress strain meters, makes it possible to carry out a rough characterisation of the evolution of swelling. The alterations caused by those devices in the seepage conditions in the body of the dams, may exert influence on the development of swelling. On the other hand, in most cases, their wrapping is made in wet-screened concrete of the integral dam concrete, the proportions of possibly reactive materials being therefore different. Nevertheless, those apparatuses apart from making it possible to carry out a very early detection of the existence of swelling, may give some indications about their distribution in the structure.

The results of mineralogical and morphometric analyses may also play an important part in the local assessment of the magnitude of swelling. In fact, from those analyses and from the volume of gels existing in the concrete, a magnitude of swelling associated with their formation can be deduced (Silva, H.S.; Delgado, J., 1991).

However, expansibility tests intended for predicting swelling resulting from future reactions among the remaining reactive materials in a certain period of the life of the structures will be of greatest and irreplaceable interest.

Also the apparatuses set up in the contraction joints, for measurement of displacements between the blocks of dams, will make it possible an early detection of swelling in the concrete, by indicating relative displacements, which cannot be related with the variation of the main actions.

In overall terms, the measurement and interpretation of displacements of the structure allow the assessment of the magnitude, evolution and distribution of swelling. In order to carry out this interpretation it is necessary to separate the components of displacements resulting from the main actions. In the case of arch dams, in which swelling cause horizontal displacements towards upstream, it is also necessary to differentiate these displacements from those towards downstream, which result from creep of concrete. However, for doing that one has to know, in principle, the concrete creep function. This diferentiation is easy when vertical displacements are concerned because the components resulting from hydrostatic pressure, both instantaneous and delayed are usually of small importance in view of the thermal components or those resulting from swelling. On the contrary, in the case of the orthotropy referred to above, which is frequently recognised in the development of the horizontal and vertical components of swelling and when the degree of that orthotropy is unknown, an integrated analysis of those components must be carried out.

2. Back-analysis techniques intended for solving "problems of characterisation" may play an important part in the assessment of the magnitude, evolution and zoning of swelling, based on the displacements observed. Back-analysis or characterisation problems can be stated as follows (Cividini, A., et al, 1981): find the values of unknown quantities, related with the geometry of the system, the zones formed by different materials, the parameters that define the laws concerning the behaviour of those materials, or the distribution of actions, which when introduced in the solution of the equations that govern the problem in analysis, lead to results as close as possible to the corresponding observed values.

Back-analysis techniques can be used in concrete dams engineering for the following purposes: for supporting the interpretation of tests carried out in the scale of the structures, e.g. forced vibration tests, for supporting the interpretation of techniques of characterisation of the foundation deformability, for identification of rheologic, thermal and hydraulic parameters of materials and, particularly, for supporting the analysis of the behaviour of old dams. The latter are sometimes subject to deterioration processes and little information is often available about the structural characteristics, namely material properties. It is possible, in principle, resorting to back-analysis techniques, to estimate from the observed displacements, the swelling magnitude, evolution, zoning in the structure and their orthotropy, by using the same mathematical models, which subsequently be used to calculate the state of stress.

RELIABILITY STUDIES

1. In reliability studies it is essential the determination of the state of stress installed which can be made, in principle, by conjugating results of direct measurement of stresses, for instance, by means of SFJ - Small Flat Jack, with results of studies on mathematical models. These studies, which must be based on surveys on the state of fissuration and its evolution, require the knowledge of the magnitude and the possible orthotropy of swelling, if possible from the beginning of their development and their distribution in the body of the structure, and the knowledge of the rheologic characteristics of the concrete. In the case of dams where the state of fissuration does not present structural characteristics, the calculation of stresses resulting from swelling (stresses due to imposed deformations) may be carried out by assuming a linear maturing viscoelastic behaviour for concrete (Mora Ramos, J., et al, 1992). (Mention must be made of that fact that, as in the case of other mechanical properties, due to micro-cracking and from a certain magnitude of swelling, the creep function of a concrete subjected to a swelling process may be altered, in comparison with the one expected for a undamaged concrete.) In the case of dams in which the state of fissuration assumes structural characteristics (fissures with significant continuity and depth), the calculation of stresses should be made by assuming a visco-elastic-plastic behaviour for the concrete and by simultaneously considering, in this case, all the main actions (Pedro, J. O., et al, 1990).

2. Ascertainment of the structural reliability should be made, in principle, by previously defining control variables for limit states of servicebility and for limit states of failure, and by determining which are the factors of amplification of the actions or of reduction of the mechanical properties of concrete, which lead to those states. In the case of arch dams, one can consider that the servicebility will be affected when cracks develop through all the thickness of the dam, defining then as a control variable, for instance, the tensile failure strain in the upstream face. Concerning collapse, the control variable can be the compressive failure strain at the downstream face.

CAHORA-BASSA DAM

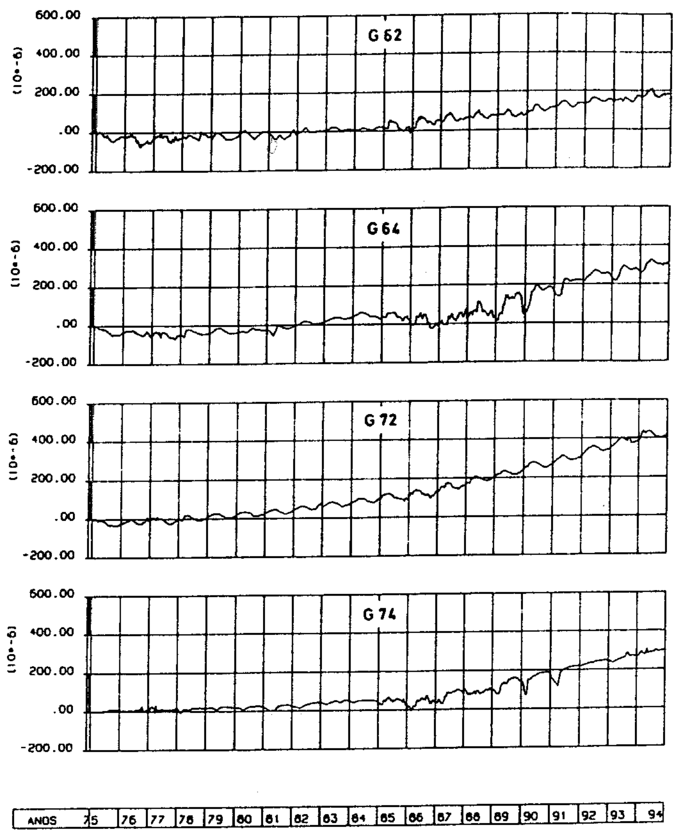
Cahora-Bassa dam is located in the river Zambeze, in Mozambique. The concretings of the dam were carried out between November 1971 and December 1974. The first filling started in January 1975. It is a double curvature thin arch dam, with the following main dimensions: maximum height above the foundation - 170 m; crest length - 300 m; base thickness of the central cantilever - 23 m. The rock mass is essentially constituted by granitic porphyroblastic gneisse.

The aggregates for the concrete were obtained by crushing of the rock from the excavation of the foundation and the large underground works. It is a rock with a high mechanical strength, which in compression tests of samples with a 10 cm edge showed strengths of about 150 MPa (LNEC, 1978). The main minerals in the agregates are feldspar and quartz. Rare there are occurences of gabro and granulite. Modified normal Portland cement was used in the construction of the dam. The mean composition of that cement until the end of 1973 was as follows: tricalcium silicate - 45%; bicalcium silicate - 20%; tricalcium aluminate - 6%; tricalcium ferric aluminate - 15%. From 1973 and due to the difficulty in maintaining the stability of this composition the percentage of tricalcium aluminate became first 9% and then 13%, the total sum of the percentages of silicates being kept constant at 65%.

1. Detection of the swelling

The detection of the existence of swelling in the concrete of the dam was carried out by means of the analysis on the evolution of the strains (Fig. 1a), observed in the no-stress strain meters (embedded in screened concrete) of the about 50 groups of extensometers installed, this detection being subsequently confirmed by the analysis of the precision levelling (Fig. 1b) and by results of some preliminary mineralogical and petrographic analysis. Petrographic analyses of thin sheets showed the existence of micro-cracking in the aggregates and in the paste, filled with isotropic gel, and the existence of rings of reaction in and out of the aggregates. Mineralogical analysis showed the existence of alkali-silica reactions that could have its beginning between the cement alkalis and the quartz, but that could have its developmet by auto-reaction of the aggregates, promoted by the high pH of the environment.

a)



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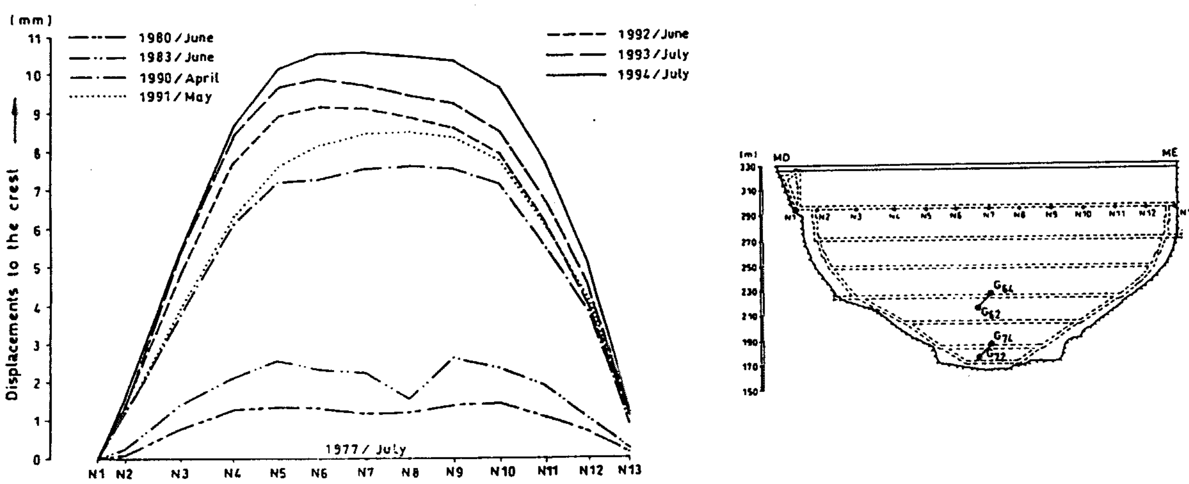


Fig.1 - Cahora-Bassa dam. Detection of swelling in the concrete. Evolution and values accumulated: a) no-stress strain meters; b) precision levellings.

2. Magnitude and zoning of swelling

Swelling developed up to the moment are rather moderate. They have progressed at constant rates, and they seem to have a symmetric distribution in the structure (Fig. 1b), even though with some heterogeneity, namely in the upstream-downstream direction and in the vertical direction. The permanent existence of high temperatures and degrees of relative humidity is likely to contribute to the development of reactions. However, the great thermo-hygrometric homogeneity and stability (the amplitude of the annual thermal wave in the site of the dam is about 8°C, the variations of the level have been small) are likely to contribute to the distribution apparently symmetric of swelling and to the restriction of heterogeneities.

Swelling accumulated between 1977 and 1994 caused a maximum bulking of about 11 mm in the gallery at the level 296m (Fig. 1b). These swelling did not cause any detectable structural fissuration though. The results of the no-stress strain meters and precision levellings made it possible to predict the zoning and evolution of swelling (Fig. 2). In view of the results of the minitoring of displacements it was admitted that isotropy existed in swelling developed up to the moment.

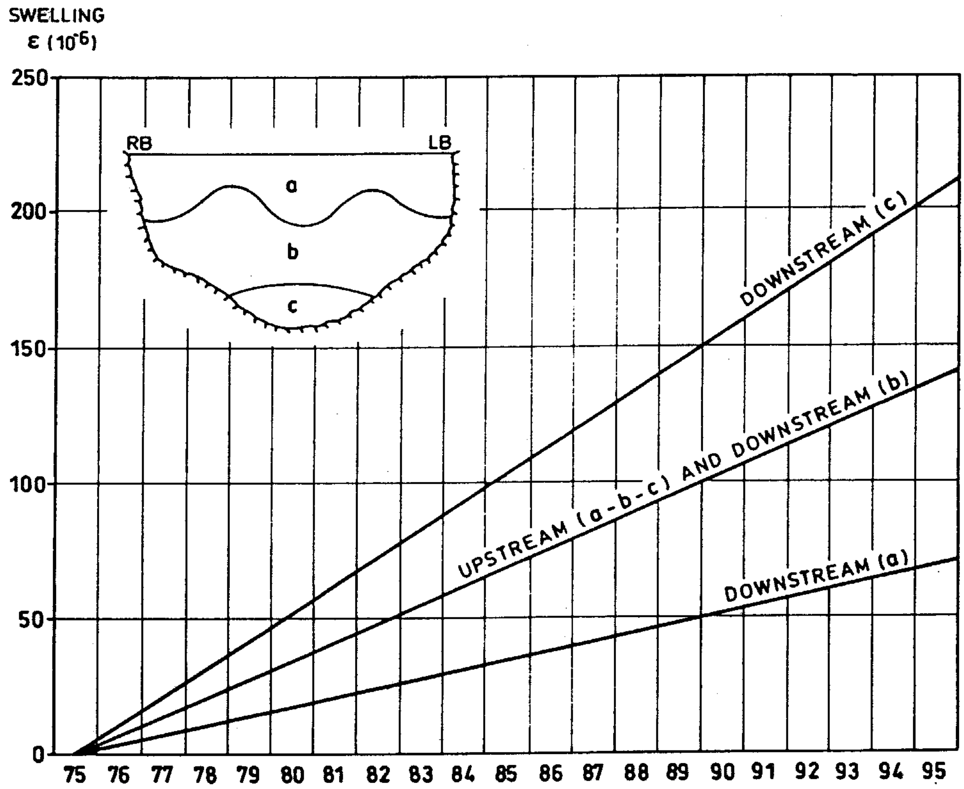


Fig.2 - Cahora-Bassa dam. Evolution and distribution of swelling.

3. State of stress and reliability

A thick shell model was used in the analysis of the state of stress resulting from swelling. This model was elastically supported in the foundation and it was analysed by the finite element method (Batista, A. L., et al, 1992). Structural continuity was considered and maturing linear viscoelastic behaviour was assumed for concrete. The characterisation of creep and relaxation of the concrete of the dam was carried out from results of an "in-situ" creep test, in conjunction with results of back-analysis (Castro, A. T., et al, 1990), results of deformability tests for rapid loads, results of failure tests, and by taking into account the concrete composition. The calibration of the model was carried out by considering the evolution of displacements, involving the elastic and delayed effects of the hydrostatic load and the thermal and swelling effects. Stresses due to swelling calculated in the upstream and downstream faces, being essentially characterised by generalised compressions and by tensions along the downstream insertion (Fig. 3a), these ones largely compensated, at the moment, by compressions resulting from hydrostatic pressure (Fig. 3c).

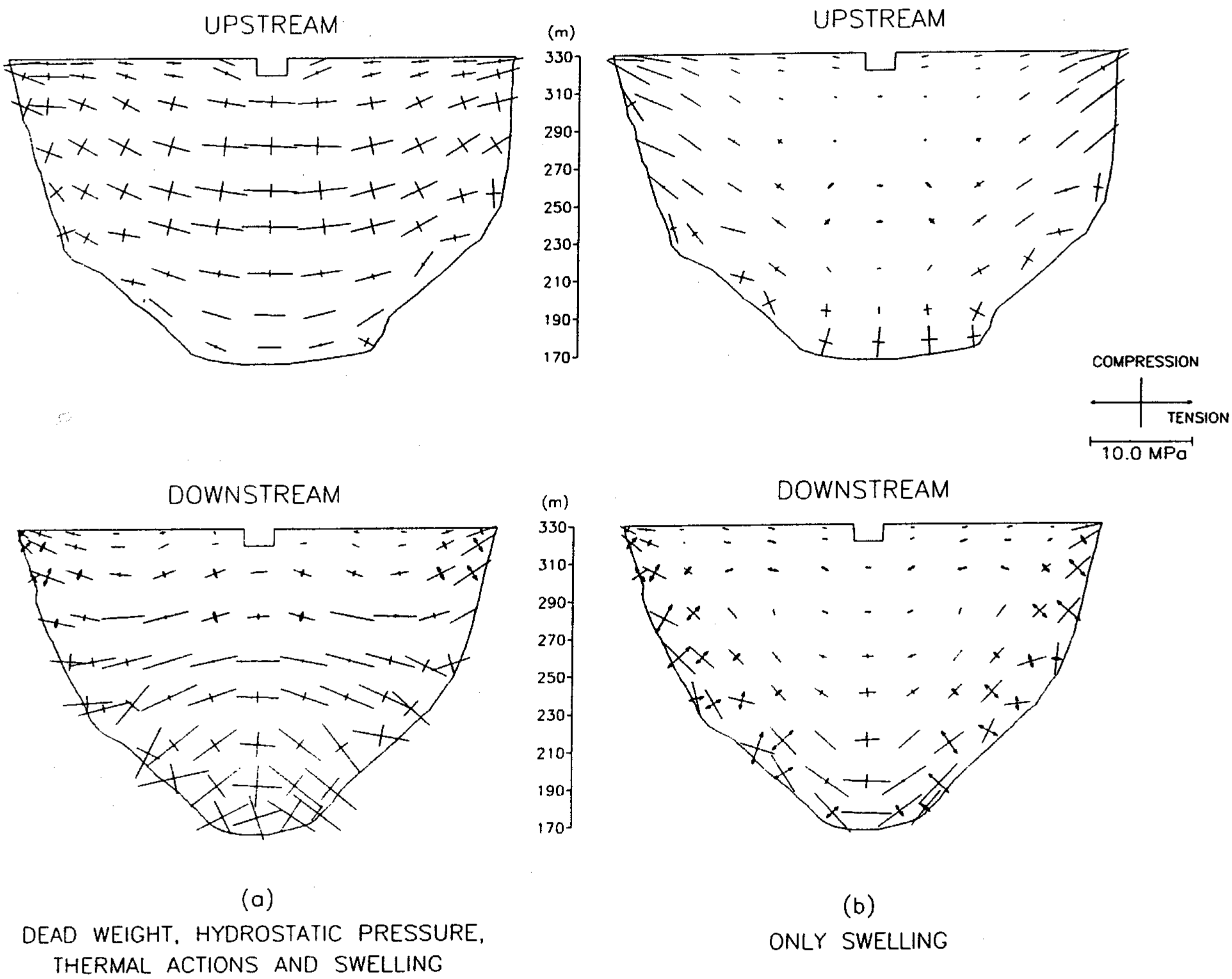


Fig.3 - Cahora-Bassa dam. Principal stresses on dam surfaces: a) resulting from swelling, hydrostatic pressure, dead weight and thermal actions; b) resulting from swelling.

Simulation studies are under way, by assuming that the actual rate of swelling will be maintained. It is the aim of those studies to predict the evolution of the state of stress and, consequently the time that it will take for the servicebility conditions to be affected, if that is the case.

4. Continuation of the studies

At present a large program of tests and analyses is under way for better characterisation of swelling namely with the aim of collecting information about the remaning potential reactivity. Expansibility tests are also being performed. Simultaneousely, works for reinforcement of the monitoring systems of the scheme are underway. As far as the dam is concerned, the main objective of those reinforcement is the better knowledge of the vertical displacements along the insertion, of the vertical displacements of the arch and of displacements concerning the supports of the hydraulic equipments.

SANTA LUZIA DAM

Santa Luzia dam, in Portugal, is a thin cylindrical arch dam. It has 76 m of maximum height above the foundation and 115 m of crest length. The asymmetric arch was completed in 1943 and its foundation is on a quartzitic rock mass.

1. Detection fo swelling

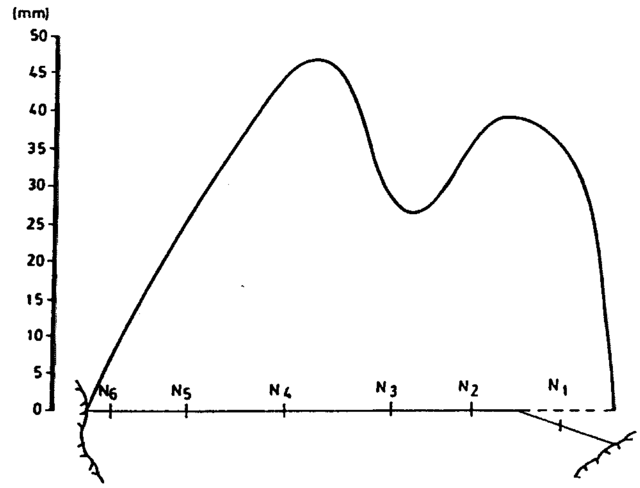
The detection of swelling resulted from measurement of horizontal displacements (in the downstream face) by means of geodetic methods and vertical displacements (in the crest) by means of precision levelling. Since the beginning of the first filling those measurements have been showing the development of horizontal components towards upstream and vertical components upwards, not related with the main actions.

Some mineralogical and petrographic analyses carried out on samples extracted from the dam showed the existence of alkali-silica swelling reactions, among aggregates, with formation of gel: the reactive silica results, essentially, from cataclastic quartz; the alkalis, namely potassium, result from feldspars. Apart from providing the necessary alkaline environment, the cement has little importance in the reaction, due to its low alkali content (Silva, H. S., 1992).

2. Magnitude and zoning of swelling

The maximum vertical displacements, observed in the crest, accumulated during 40 years, are about 50 mm (equivalent to mean extensions of about 700×10^{-6}) the maximum horizontal displacements towards upstream accumulated during the same period are about 30 mm (Fig. 4). Mention must be made of the fact that the M shape of vertical displacements is frequent in arches subject to swelling processes. In view of the small vertical component of displacements resulting from hydrostatic pressure it is possible to consider that the vertical displacements observed are essentially due to swelling. Concerning horizontal displacements it is necessary to take into account horizontal displacements towards dawnstream resulting from creep, the displacements towards upstream resulting from swelling and accumulated along the years, will be therefore significantly higher than the 30 mm observed.

a)



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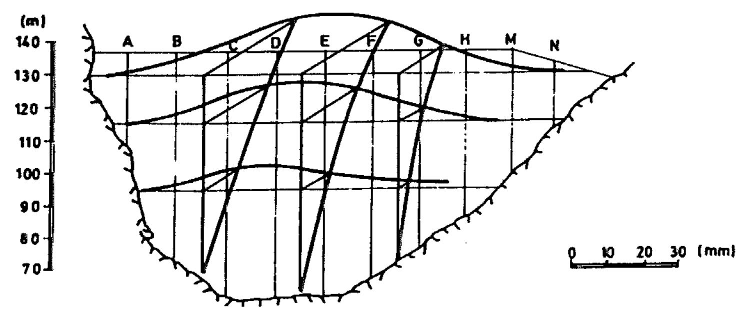

Fig.4 - Santa Luzia dam. Vertical displacements (a) and horizontal displacements (b) accumulated during 40 years.

3. Reliability studies

Several studies are presently underway aiming at achieving the following objectives: better characterisation of the alkali-silica reactions; more accurate quantification of the magnitude of swelling, their possible orthotropy and heterogeneities of distribution and remaning potential reactivity; the present rheologic behaviour of the concrete of the dam; structural effects of swelling. It is also being considered the possibility of carrying out periodically tests for measurement of the ultrasound pulse velocity to obtain a better characterisation of the existing fissuration and its evolution, and forced vibration tests for obtaining indicators on the global response of the structure and its evolution. In the mathematical models developed structural continuity was admitted and a linear viscoelastic behaviour with maturation was considered for the concrete, this behaviour having been estimated based on deformability tests for rapid and slow loads.

Both the reformulation of the monitoring system and the revision of the hydraulic, operational and environmental safety conditions of the scheme will be carried out simultaneously.

Apart from the improvement of the monitoring of the structure, it is the aim of those studies to predict the evolution of the swelling process and its impact on the servicebility and safety conditions of the dam, in order to evaluate the advantages and the effective time of execution of a possible impermeabilisation of the upstream face.

ALTO-CEIRA DAM

Alto-Ceira dam (Fig. 5), in Portugal, completed in 1949, is a thin arch dam defined by circular arches with a constant thickness. The dam has 37 m maximum height above the foundation, 120 m crest length and a thickness of 1.20 m at the crest and 4.5 m at the base.

The foundation rock mass is composed of schist and greywacke. The dam is supported in the higher levels by concrete abutments, the left bank abutment being continued by a masonry spillway.

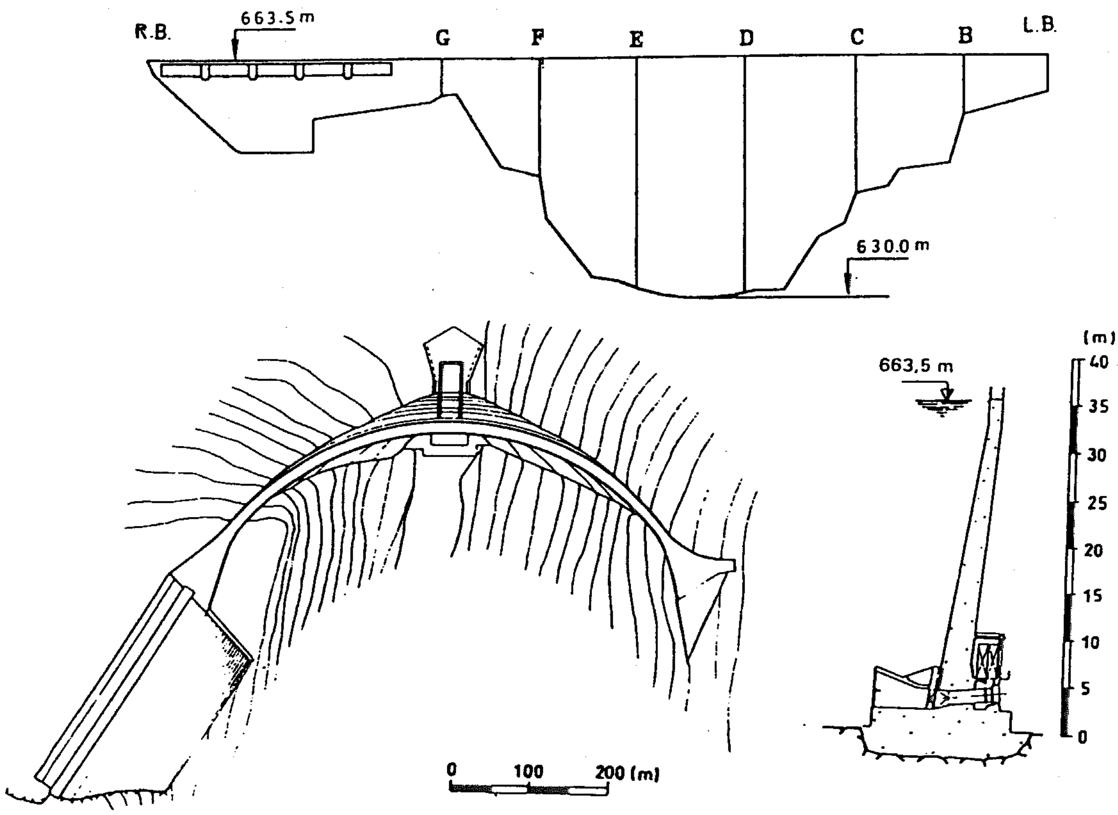

Fig.5 - Alto-Ceira dam.

1. **Detection of swelling**

The monitoring of the dam has been showing, ever since the first filling of the reservoir, an anomalous behaviour, mainly characterised by the existence of horizontal upstream displacements and vertical upwards displacements, progressive in time (Fig. 6), the latter corresponding, in a certain zone of the work and assuming structural continuity, to a strain of about 1600×10^{-6}. Simultaneously, progressive fissuration has developed, this playing a structural character and having a very significant importance presently.

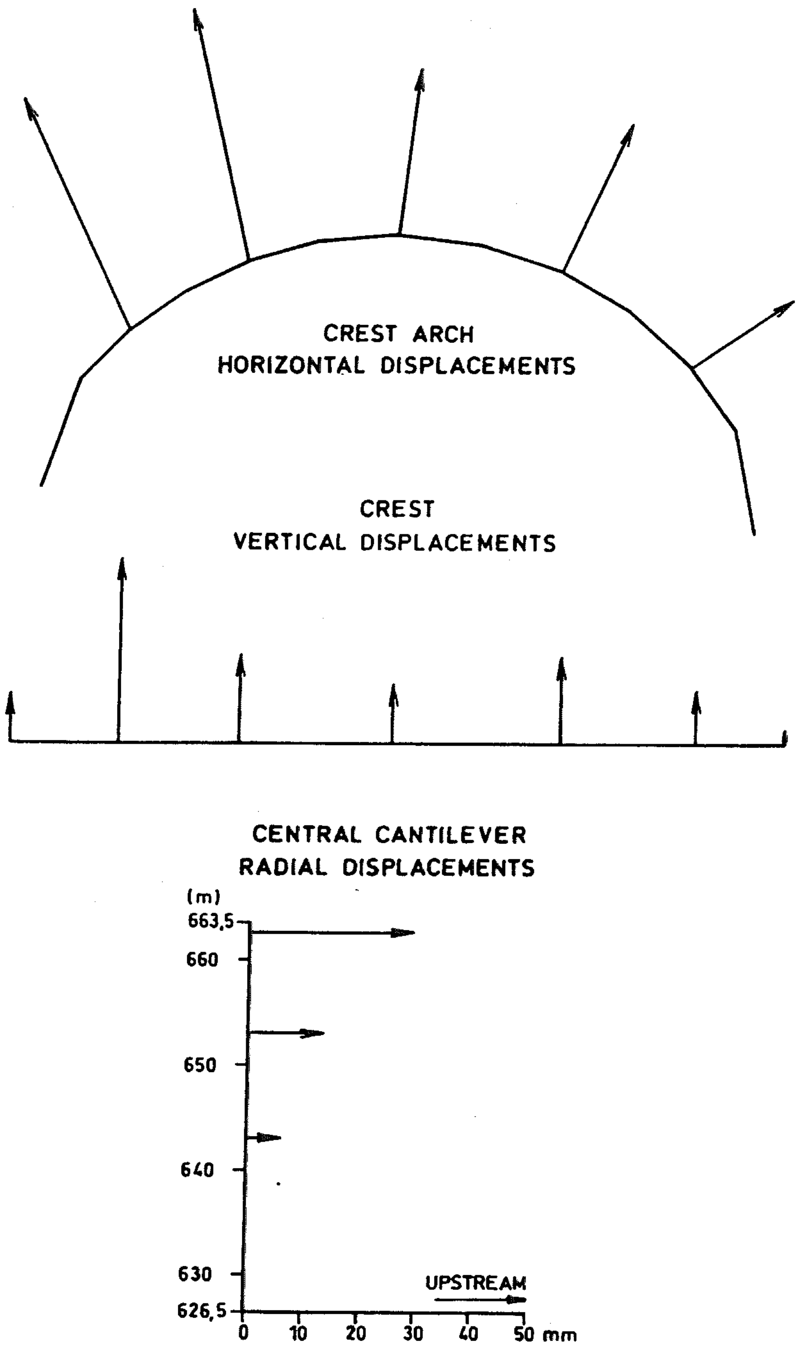

Fig.6 - Alto-Ceira dam. Horizontal and vertical displacements accumulated along the years.

This anomalous behaviour was the object of numerous studies, aiming at identifying its source and its effect on the servicebility and safety of the dam. Within the scope of those studies several emptyings of the reservoir, (1950, 1963, 1986) and numerous tests, visual inspections, etc.. were conducted. Simultaneously, the observation systems were the object of successive improvements. Among the studies carried out, mention must be made of the survey of fissuration, characterisation of mechanical properties of the concrete of the dam and the execution of petrographic and mineralogical analysis on concrete samples.

It was possible to conclude from those studies that very significant swelling exist in the concrete of the dam, resulting from alkali-silica reactions which are essencially similar to those observed in the Santa Luzia dam: the reactions occur among quartz and metapelite aggregates, which are the source of reactive silica, and feldspar aggregates, the source of alkalis. The contribution of the cement is to provide the alkaline environment necessary for the reaction (Silva, H. S., 1992). Presently, swelling develop according to approximately constant rates, the loss of servicebility or even of safety of the dam being inevitable in the future, if those rates are not significantly reduced.

2. Magnitude and zoning of swelling

The evolution and zoning of swelling (Fig.7) was determined from horizontal and vertical displacements observed between 1950 and 1993, based on a back-analysis algorithm that incorporated a 3D finite element model of the dam, spillway and foundation and in which a visco- -elastic-plastic behaviour, with limitation of the tensile strength, was assumed for concrete.

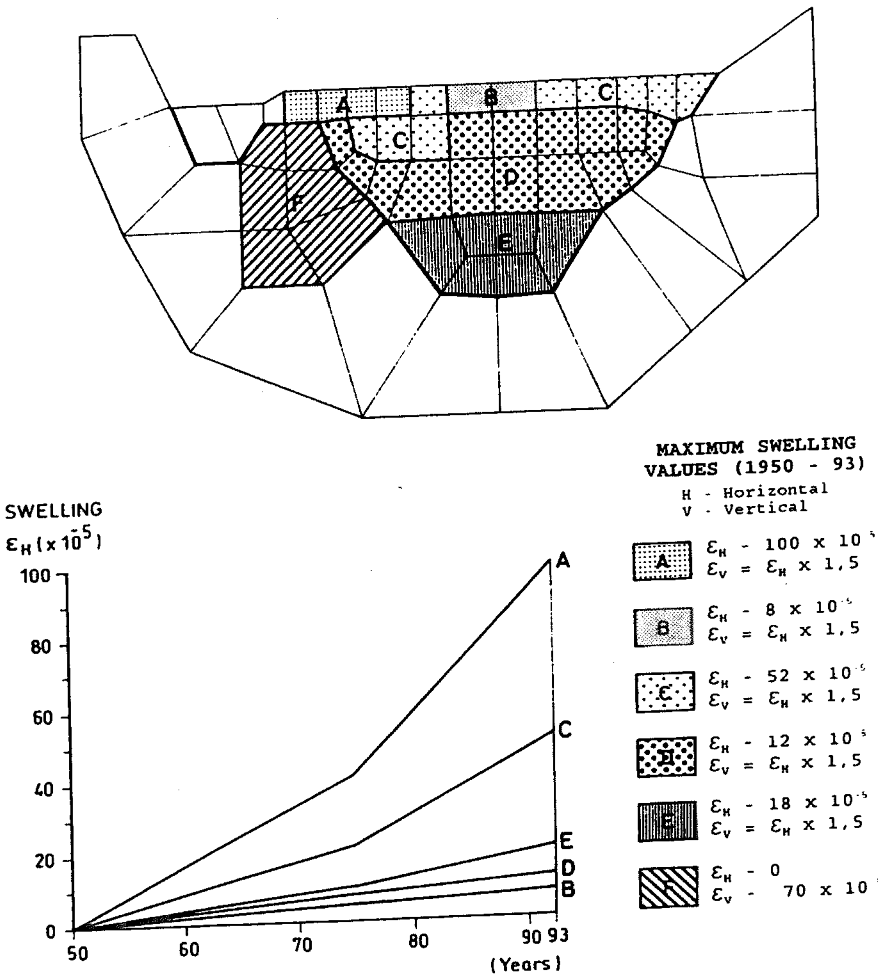

Fig.7 - Alto-Ceira dam. Evolution and zoning of swelling.

3. Reliability studies

The observed behaviour, initially in association with difficulties in its interpretation, nowadays, partly owing to economic reasons (the costs of a new work are likely to be smaller than those resulting from repair works in the existing dam since they imply losses of production of energy during the execution of the repair works), led to the perspective of abandoning the work and constructing another dam downstream. During the construction of the new dam the old dam would serve as cofferdam. This solution was chosen also because it is difficult to predict the degree of reduction in the rate of swelling that a possible impermeabilisation of the upstream face would cause and therefore to estimate the possible evolution of the reliability of the dam.

Under these conditions, one of the main aim of both the monitoring and analyses, which will continue to be carried out, will be to follow the evolution of the servicebility and safety conditions of the work in order to determine in advance the time when it will be necessary to deactivate the dam.

Recently, (LNEC, 1995) another assessment was conducted on the present structural safety conditions (and the revision of the hydraulic, operational and environmental safety conditions is also underway). In this assessment, a visco-elastic-plastic behaviour was assumed for concrete. This hypothesis tries to be consistent with the existing fissurations. It conjugates the importance of release and redistribution of stresses resulting from fissurations, with the reduction through relaxation of stresses resulting from swelling. From this study, it was possible to conclude that in spite of the significant decrease in the safety conditions, in comparison with those existing after construction, the present safety conditions are still fairly satisfactory, because the dam was designed with a large safety margin.

The state of stress obtained (Fig.8) was compared with direct measurements of the stresses (SFJ). In the verification of safety, central coefficients of safety were calculated for a hypothesis of proportional decrease in the concrete strength, by considering an initial situation of deterioration corresponding to the state of stress previously calculated and to the corresponding fissuration observed.

In conjunction with those studies, a new survey on the fissuration was carried out aiming at assessing the evolution of the fissuration that has been taking place since 1986 (the date of the previous survey). Ultrasound pulse velocity tests were also performed in the most fissured blocks of the dam, aiming at estimating both possible heterogeneities in the mechanical characteristics of the concrete and the depth of the most relevant cracks. Those tests showed mean pulse velocities of about 4200 to 4300 ms^{-1} (Fig.9), however, in some zones values between 3500 and 4000 ms^{-1} were obtained, which correspond in laboratory tests of concretes of another type of structures (other grain sizes and dosages), to significant deterioration of the concrete (ISE, 1992).
Regarding the depth of the more relevant cracks, maximum values of about 60 cm were determined (Figs.10,11).

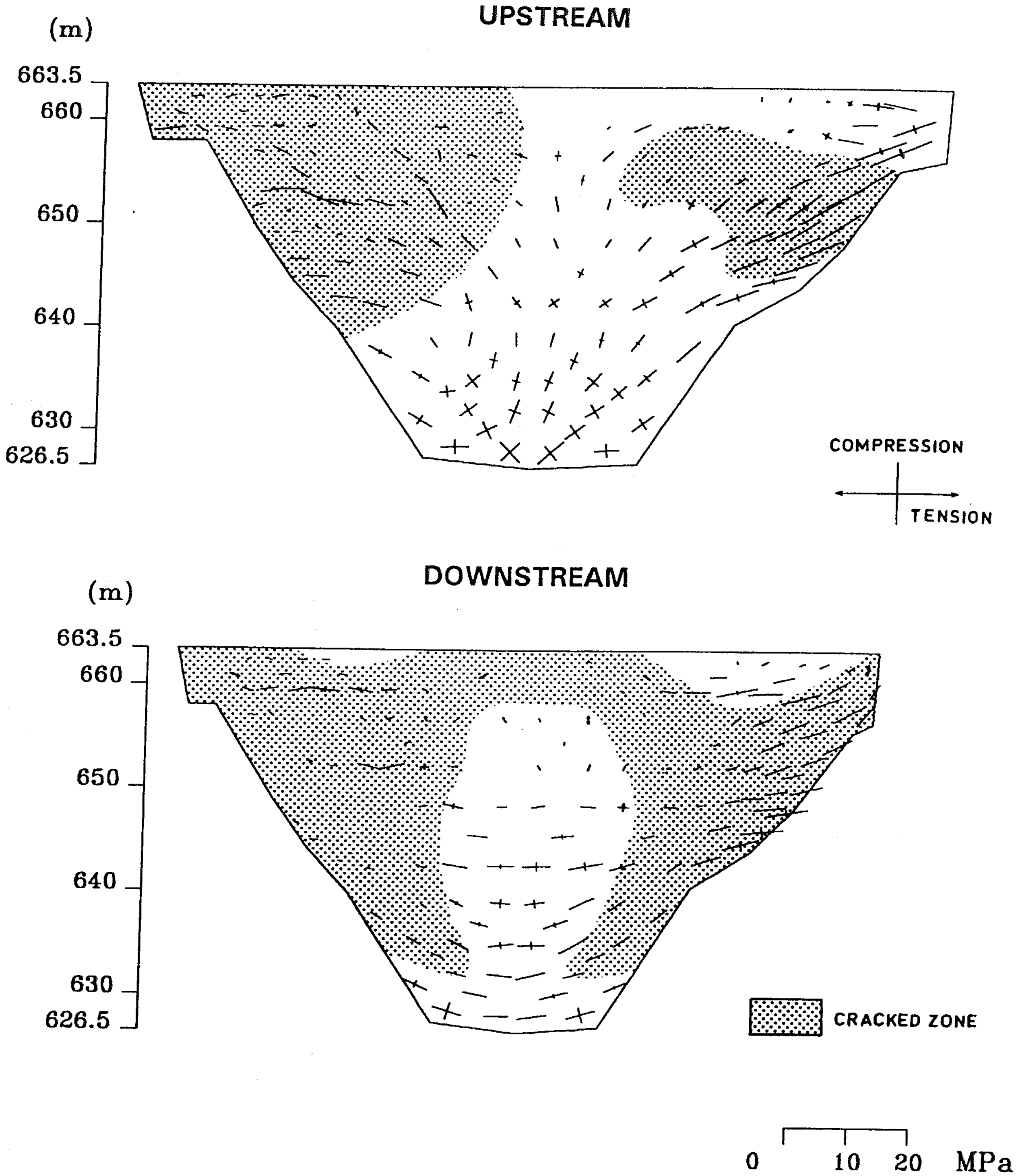

Fig.8 - Alto-Ceira dam. Principal stresses due to dead weight, hydrostatic pressure and swelling.

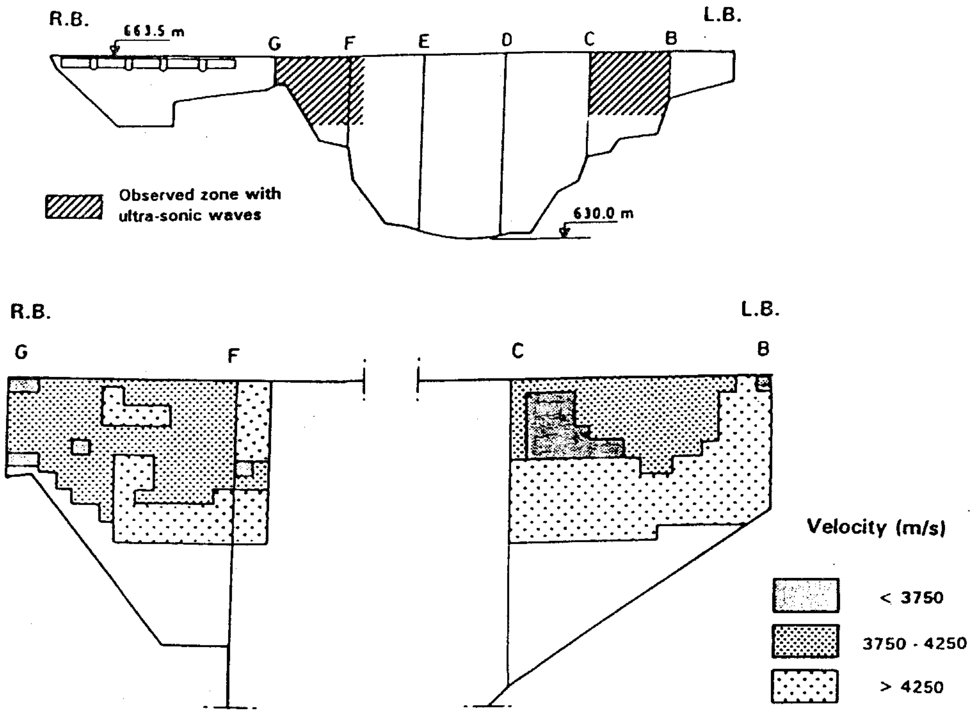

Fig.9 - Alto-Ceira dam. Ultrasonic pulse velocities in the most fissured blocks.

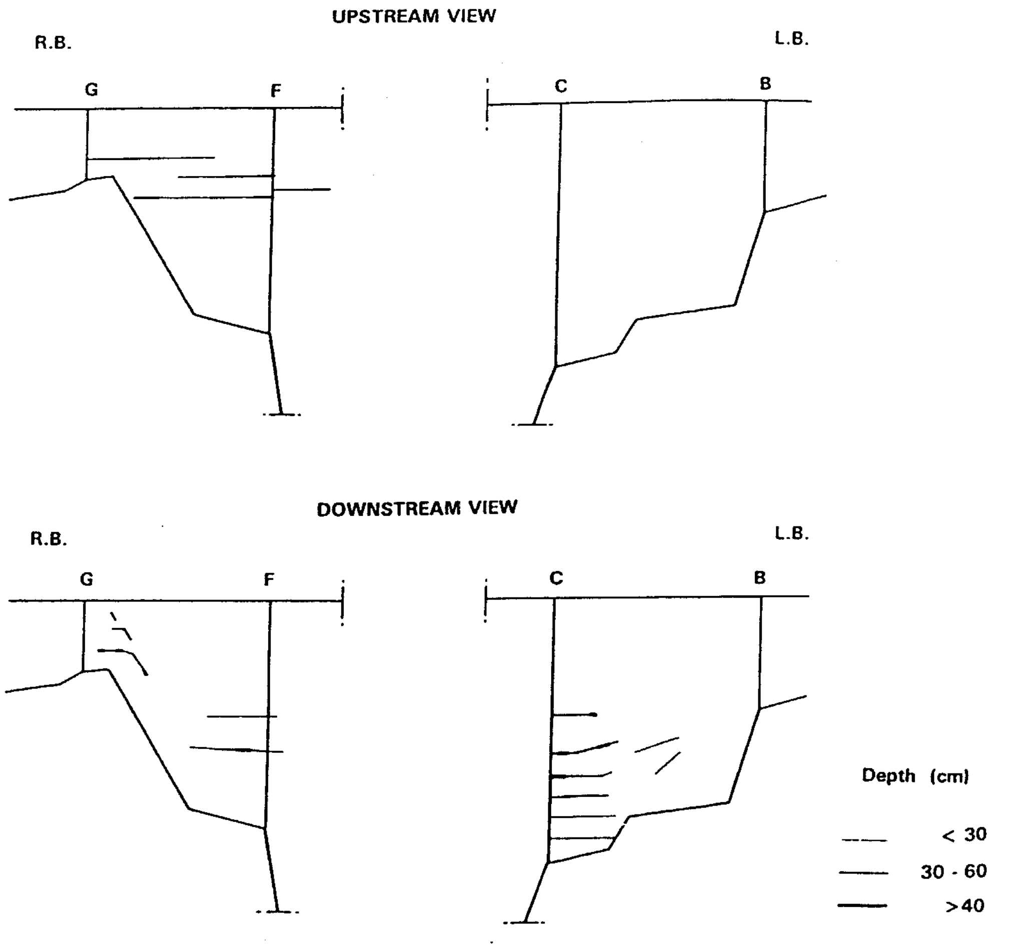

Fig.10 - Alto-Ceira dam. Localization and depth of the main structural cracks in the most fissured blocks.

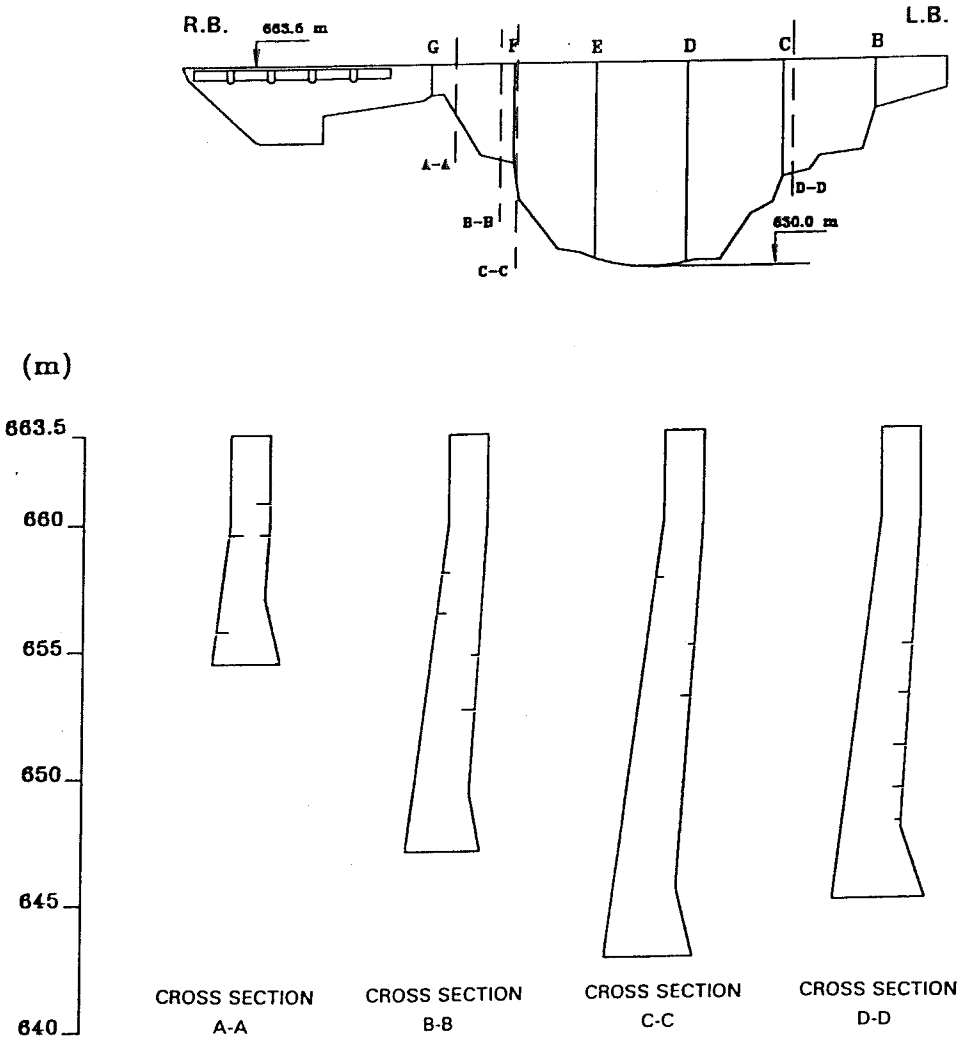

Fig.11 - Alto Ceira dam. Depth of the main structural cracks. Vertical sections in blocks BC, EF and FG.

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