CHARACTERISTIC BEHAVIOUR OF THE PORTUGUESE LARGE CONCRETE DAMS BUILT WITH GRANITE AGGREGATES AND AFFECTED BY ASR

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Abstract

In a universe of about sixty large concrete dams monitored in Portugal, there are 19 dams affected by swelling processes already identified. From these, there are 13, where coarse granite aggregates were used in the concrete composition, built between about 1940 and 1980, affected by alkali-silica reactions (ASR), which exhibit a behaviour characterized by very low expansion rates during the first 20 to 30 years, but showing since then increasing rates.

Some dams in which this characteristic behaviour occurs are described in the paper, as well as the related structural effects in each one.

The monitoring results of the 13 concrete dams, where granite aggregates were used, were obtained with specific devices. They show accumulated expansions of about $200x10^{-6}$ and current average free swelling rates of about $10x10^{-6}$ per year in most of them. However, there is one case in which the accumulated strain and the current swelling rate reach about $500x10^{-6}$ and $25x10^{-6}$ per year, respectively.

Since the swelling magnitude values are moderate, no problems related with serviceability and safety are expected in the near future. However, the standard tests of accelerated expansion performed on samples taken from the body of some of these dams showed a much lower growth potential than the one recorded on site. For this reason monitoring of these dams and careful analysis of the results should continue.

Keywords: Portuguese concrete dams, alkali-silica reaction (ASR), coarse granite aggregates, monitoring data, swelling estimation

1 INTRODUCTION

The existence of a significant number of concrete dams affected by swelling processes, particularly those due to alkali-aggregate reactions (AAR), has motivated, over the last three decades, the development of studies for a better understanding of these reactions and the related chemical and structural effects [1]. The swelling phenomenon can reduce the serviceability and the safety conditions of structures and, when it reaches certain levels of deterioration, can impose onerous repairing works or even their abandonment.

Among the various reactions that cause concrete swelling, the most common in Portugal are the alkali-silica reaction (ASR) and the internal sulphate reaction (ISR), which sometimes occur simultaneously. As it is very well known, the ASR in due to the alkalis presence in the interstitial solution and the active silica that exists inside the aggregates, and the ISR occurs due to time delayed ettringite formation.

These reactions require water, as a transport agent, to allow the migration of molecular or ionic species inside the concrete, as well as a reagent in the formation of the swelling reaction products. Since hydraulic structures have, in general, water to supply to the reactions, they are affected by this phenomenon. The temperature and the stress fields play also an important role in the swelling development [1].

The granites, which are quite abundant in the north of Portugal, and the granodiorites and gneisses, can be classified as slow reactive aggregates.

Small to moderate swelling strains (up to about $400x10^{-6}$) do not cause, in general, adverse consequences in concrete dams. However, higher strains can affect, initially, the serviceability conditions, namely related with gate operation, and after can introduce damage that compromises the concrete durability or even the structural safety. In concrete dams the structural evidences of AAR

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development can be dissimulated by the creep response, which causes some difficulties on the AAR phenomenon identification [2].

The significant signs of AAR development in concrete dams are the map cracking on surfaces, the linear cracking in specific zones, the contraction joints closure and sliding, and the increasing of certain physical quantities, like strains and displacements, highlighted in the records along the time.

Appropriate algorithms for effects separation, namely those based on statistical approaches [3,4], make a preliminary interpretation of the monitoring data possible and are very useful in the identification of the AAR effects, and, as a consequence, allow the quantification of some mechanical aspects due to AAR.

In a first approach, the concrete expansions can be evaluated from specific devices of the monitoring systems, namely from the stress-free strain-meters, which provide the concrete free strains, and from the geodetic levelling results, from which the vertical strains can be computed. The vertical strains are of the same magnitude of the free strains in the case of long gravity dams. However, in the case of arch dams, the differences between these strains are significant, namely for the dams built in narrow valleys, where the restriction to the vertical structural deflection is higher.

This paper presents some aspects of the Portuguese dams affected by AAR, namely those related with the dams that were built with granite aggregates in the concrete mix and show, after a long dormant period, moderate swelling rates but with a current tendency to increase, and thus require a more carefully follow up in the future. In the sequence of previous studies, this paper can be considered as an update and extension of a paper presented in 2012 [4], showing, in more detail, the cases of these dams where granite aggregates were used in their concrete composition.

2 PORTUGUESE DAMS AFFECTED BY SWELLING REACTIONS

In a universe of about 60 large concrete dams monitored, there are in Portugal 19 dams where the concrete swelling phenomenon has already been identified from the visual inspections and the monitoring results. In most of them, complementary studies to allow a better characterization of the expansive reactions and their effects were also made, namely by means of physical and chemical tests and structural modelling and analysis. The dams affected by AAR are (Figure 1): i) Penide, Alto Rabagão, Caniçada, Miranda, Picote and Bemposta, in the north part; ii) Fagilde, Aguieira, Raiva, Coimbra, Covão do Meio, Alto Ceira I, Santa Luzia, Cabril, Fratel and Pracana, in the centre-north part; and iii) Caia and Monte Novo, in the centre-south part.

It should be noted that the Portuguese dams that are most affected are the Santa Luzia, Alto Ceira I, Pracana and Fagilde, the first three ones built with quartzite aggregates and the last one submitted to an intense ISR. It seems that the remaining expansion potential is nowadays very small in the Santa Luzia dam, and the dam shows very smooth structural effects [5]. The Alto Ceira I dam, which was severely damaged and considered without possible rehabilitation, was replaced by the Alto Ceira II dam in 2014, built about two hundred meters downstream [6]. The Pracana dam was submitted to large rehabilitation works in the 1990s [7], being considered, in the international technical and scientific community, as a successful case of an extensive and complete structural intervention. The Fagilde dam is seriously damaged and is the case that causes more concerns to the Portuguese dam engineering.

Table 1 presents a synthesis of the studies already developed to characterize the AAR phenomenon of the 13 dams affected by ASR that were built with coarse granite aggregates (marked with yellow colour in the table of Figure 1), between about 1940 and 1980. These dams exhibit a behaviour characterized by very low expansion rates during the first 20 to 30 years, but show since then considerably higher rates. The Miranda, Covão do Meio and Cabril dams were selected to show this characteristic behaviour; their cases are presented in this paper. A comparative analysis of the expansion strains evaluated from the monitoring results of the 13 mentioned dams is presented.

3 THREE TYPICAL CASES: MIRANDA, COVÃO DO MEIO AND CABRIL DAMS

3.1 Miranda dam

The Miranda dam is a buttress structure, 80 m high, located in the beginning of the international stretch of the Douro River (which is shared by Spain and Portugal), that is founded on a granite and schist rock mass (Figure 2). It was completed in 1961. Coarse and fine granite aggregates were used in the concrete mix. Evidences of the swelling phenomenon were identified in the eighties of the last century, about 20 years after the construction, by the detection of progressive vertical displacements upwards (Figure 3), as well as vertical sliding on the central contraction joints, near the top, and the increase of strains measured in the stress-free strain-meters. Linear and mapping cracking was detected on specific zones of the galleries and of the downstream surface. The ASR was confirmed, some years ago, by the chemical analysis of gels removed from the galleries' sidewalls. Mechanical and chemical tests (modulus of elasticity, compressive and tensile strengths, stiffness damage test, mineralogical analysis, petrographic characterization, cement, sulphate, alkali and silica contents and residual expansion) are ongoing on samples taken from the dam's body at the end of 2012 [8].

3.2 Covão do Meio dam

The Covão do Meio dam, located in the Estrela Mountains, at an altitude of about 1650 m, is a thin arch dam, 28 m high, founded on a granite rock mass. The spillway is formed by a gravity structure, located on the left side (Figure 4). It was completed in 1953. Coarse granite aggregates were used in the concrete composition. The first signs of the swelling phenomenon were identified in the nineties, about 40 years after the construction, by the observation of progressive displacements, vertical upwards (Figure 5) and radial upstream, obtained by the geodetic monitoring system installed in 1984. Linear cracking on the downstream surface, parallel to the foundation, was detected in the last years (Figure 4). Mechanical and chemical tests (modulus of elasticity, compressive and tensile strengths, stiffness damage test, mineralogical analysis, petrographic characterization, cement, sulphate, alkali and silica contents and residual expansion), performed on samples taken from the dam's body at the end of 2011, were concluded recently [9].

3.3 Cabril dam

The Cabril dam, the highest in Portugal, is a thin arch structure, 132 m high, located in the Zêzere River, in a narrow V-shaped valley (Figure 5). The foundation is a granite rock mass. It was completed in 1954. Coarse granite aggregates were used in the concrete mix. Abnormal behaviour was observed during the first filling of the reservoir, characterized by horizontal cracking formation close to the top, on the downstream surface, due to the high stiffness (thickness) of the crest arch. Large scale rehabilitation works were done in the eighties, in an attempt to solve these problems. Since then, progressive displacements have been reported, vertical upwards (Figure 6) and radial upstream, as well as an increase in the strains measured by the stress-free strain-meters. Linear and mapping cracking was detected on specific zones of the galleries and on the downstream surface. The ISR and ASR were firstly confirmed by the chemical analysis of gels removed from the galleries' sidewalls. Laboratory testing for AAR evaluation, including petrographic, chemical and expansion tests, were also made [10], for better characterization of the swelling reactions.

4 SYNTHESIS OF RESULTS FOR THE 13 AFFECTED DAMS

The continuous monitoring and long term behaviour analysis of the concrete dams affected by AAR has been adequately performed in Portugal, in order to follow up the phenomenon development and the structural assessment in each one, and to understand, in an integrated way, the relations between the different actions and causes, and the major effects.

Table 2 and Figure 8 summarise the main results of the comparative analysis carried out about the concrete swelling of the 13 dams built with granite aggregates and affected by AAR. Table 2 shows the average values of the monitored free strains by the stress-free strain-meters and the strains computed from the crest geodetic levelling results. Figure 8 represents the same values in function of the dam age. In this figure are only represented the results of the 9 dams in which the monitoring results are available since the construction stage, and the results of the Covão do Meio dam monitoring in the last 30 years.

In the case of Aguieira dam (a multiple-arch structure) the results of the geodetic levelling of the crest cannot be directly related with the expansion strains because the complex shape of the dam does not allow it. For this reason the results were not considered in the analysis.

As a first comment, it can be said that the free strains measured by the stress-free strain-meters are about twice the vertical strains obtained from the geodetic levelling results. This difference is higher in the arch dams, due to the structural restriction that exists in the vertical direction, namely in the case of Picote dam, built in a very narrow U shape valley, in which that relation reaches nearly 4. On the other hand, the swelling strains monitored by the stress-free strain-meters are of the wet-screened concrete that involves the strain-meter groups, and may have a higher magnitude than the swelling corresponding to the full-mixed concrete of the dam.

The accumulated free expansion strains and the current average free swelling rate are about $200x10^{-6}$ and $10x10^{-6}$ per year, respectively, in most of the dams. The Covão do Meio dam is a single case, in which the estimated vertical strain and the current vertical swelling rate reach about $500x10^{-6}$ (only in the last 30 years) and $25x10^{-6}$ per year, respectively. Unexpectedly, the laboratorial standard tests of accelerated expansion performed on samples taken from the dam's body in 2011, which were concluded recently, show a much lower growth potential then the one recorded on site [9]. A similar tendency was achieved in the first results of the ongoing tests performed on samples taken from the body of the Miranda dam [8].

The band limits of the free and vertical expansion, represented in Figure 8, show that swelling strains greater than $500x10^{-6}$ may occur in the future, in most of these affected dams.

5 CONCLUSIONS

The 19 Portuguese concrete dams affected by AAR correspond to about 30% of the total number of the large concrete dams that are monitored. In France, EDF has identified at least 20% of concrete dams with an important rate of swelling [11].

The dams affected by AAR were built between 1940 and 1980, when there wasn't enough knowledge about this phenomenon. In Portugal there are still no signs of this phenomenon in dams built in the last 30 years.

The 13 Portuguese concrete dams built with granite aggregate exhibit a typical behaviour characterized by very low expansion rates during the first 20 to 30 years, that were partially masked by the creep effects, but showing from that age onwards considerably higher rates. However, as the swelling magnitude is still moderate in all of them, no problems related with serviceability and safety are expected in the near future. However, swellings greater than $500x10^{-6}$ may occur in the future in most of these affected dams. As mentioned before, the standard tests of accelerated expansion performed on samples taken from the body of some of these dams, showed a much lower growth potential then the one recorded on site. Continuation of monitoring is, therefore, essential.

6 ACKNOWLEDGMENT

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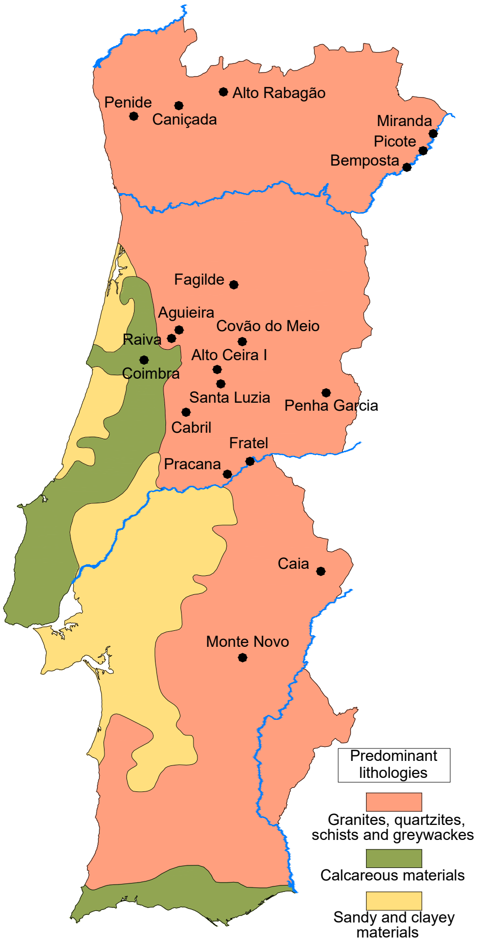

Dams affected by AAR	Structural type	Year of completion
Santa Luzia	Arch	1942
Alto Ceira I (1)	Arch	1949
Penide (2)	Gate	1949
Pracana (3)	Buttress	1951
Covão do Meio	Arch	1953
Cabril	Arch	1954
Caniçada	Arch	1955
Picote	Arch	1958
Miranda	Buttress	1961
Alto Rabagão	Arch	1964
Bemposta	Arch-gravity	1964
Caia	Buttress	1967
Fratel	Gate	1973
Penha Garcia	Gravity	1980
Coimbra	Gate	1981
Aguieira	Multiple-arch	1981
Raiva	Gravity	1981
Monte Novo	Gravity	1982
Fagilde	Gravity	1984

(1) Replaced and demolished in 2014
(2) Surfaces with a stone masonry lining
(3) Rehabilitated in the 1990s
Yellow rows – Dams built with granite aggregates

FIGURE 1: Map of Portugal with the location of the 19 large concrete dams affected by AAR.

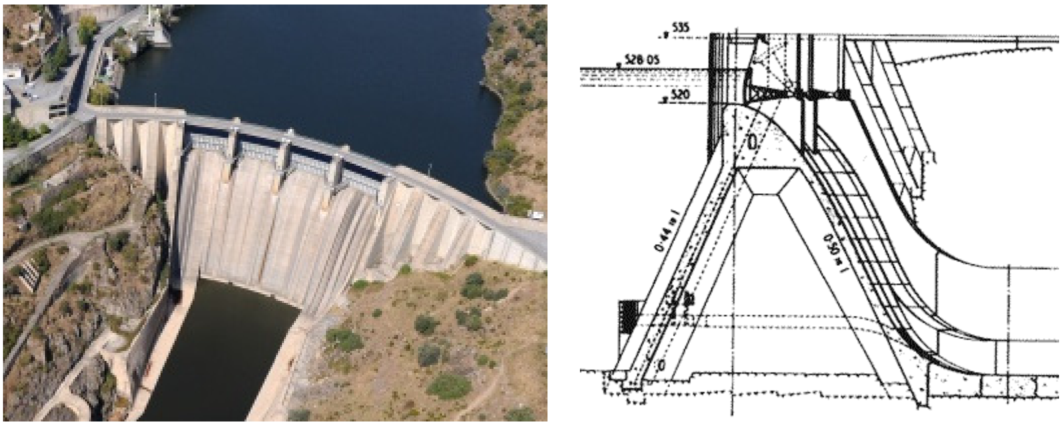

FIGURE 2: Miranda dam. Downstream view and buttress profile.

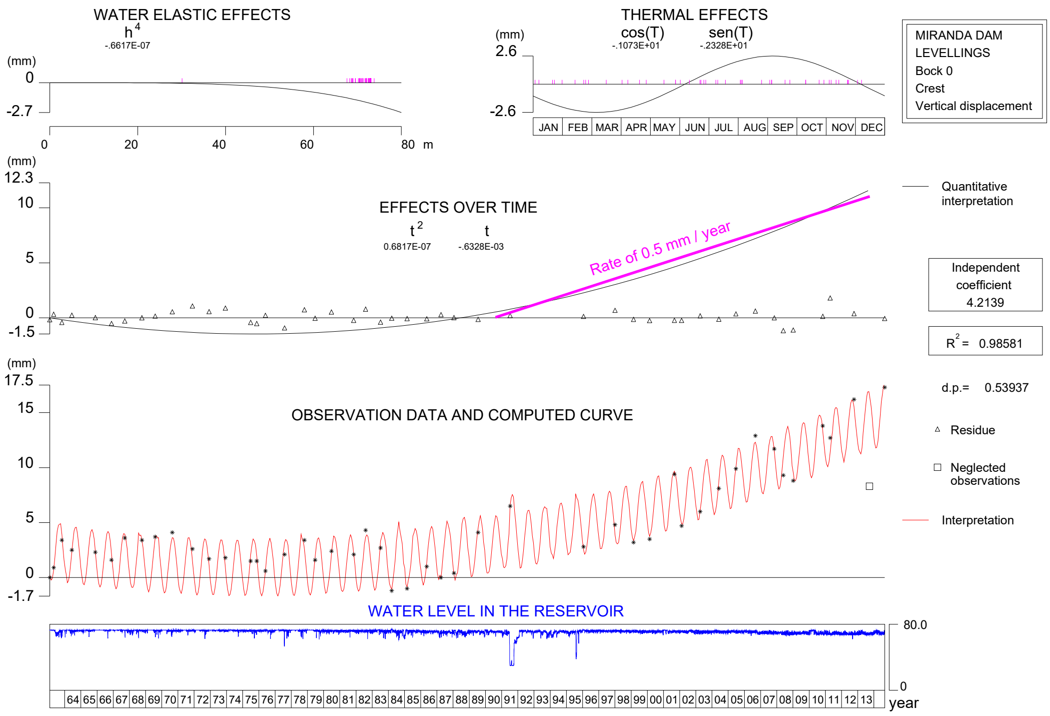

FIGURE 3: Miranda dam. Results of quantitative analysis of vertical displacements at the top of the central buttress, obtained from geodetic levelling, between 1963 and 2014.

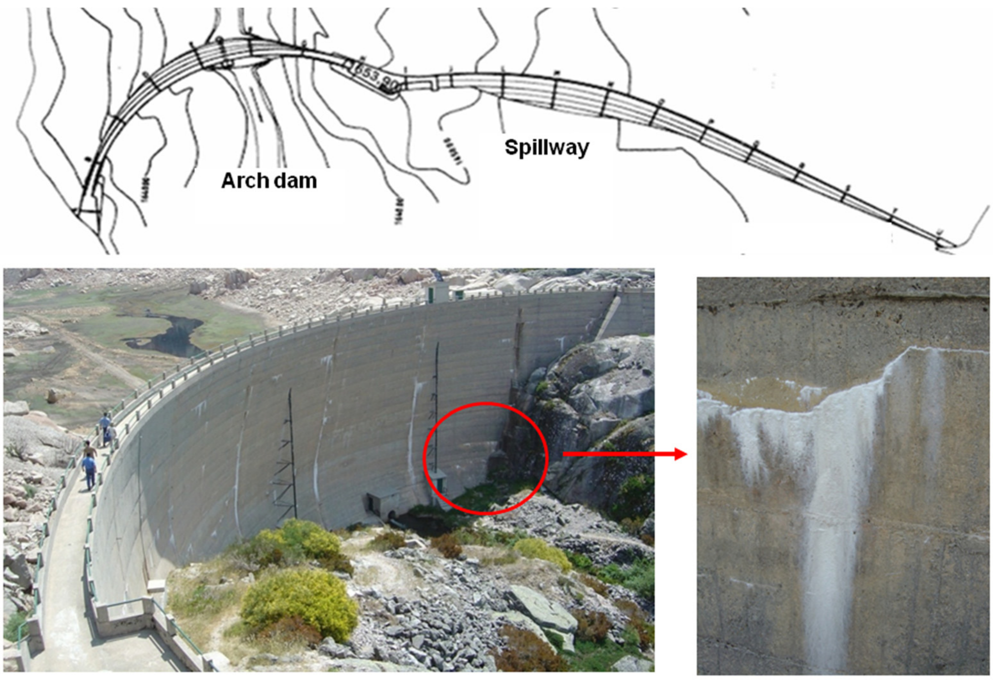

FIGURE 4: Covão do Meio dam. Plan, general downstream view of the arch dam and detailed view of the cracks on the downstream surface, parallel to the foundation insertion.

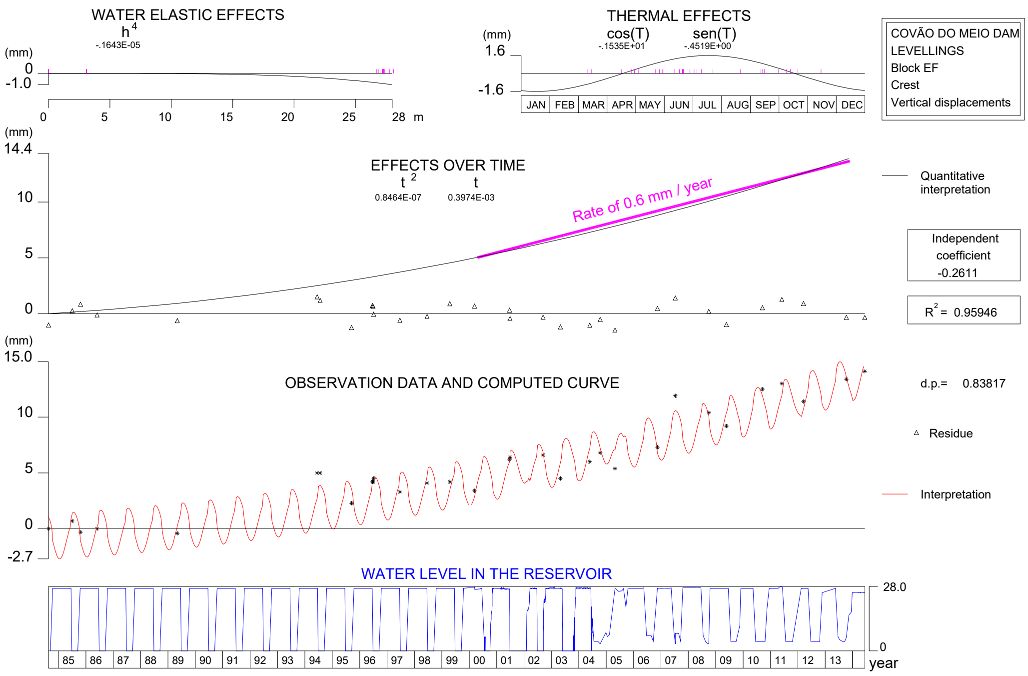

FIGURE 5: Covão do Meio dam. Results of quantitative analysis of vertical displacements at the top of the central cantilever, obtained from geodetic levelling between 1984 and 2014.

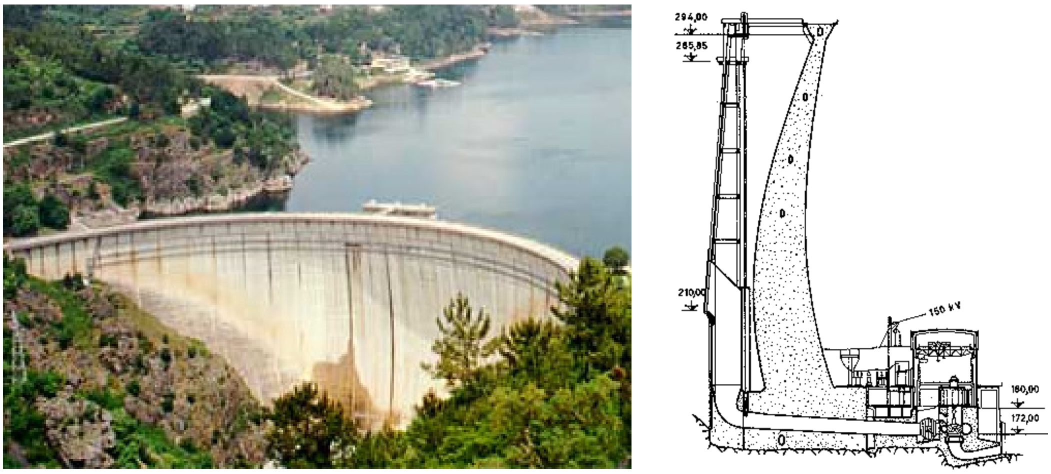

FIGURE 6: Cabril dam. Downstream view and cross section of the central cantilever.

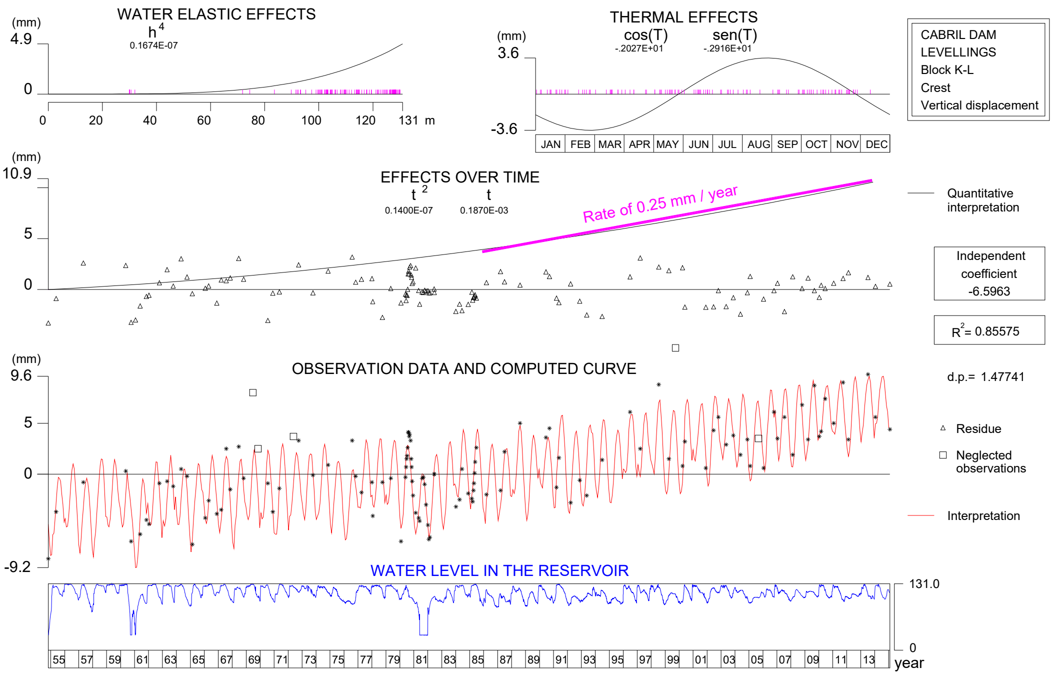

FIGURE 7: Cabril dam. Results of quantitative analysis of vertical displacements at the top of the central cantilever, obtained from geodetic levelling between 1954 and 2015.

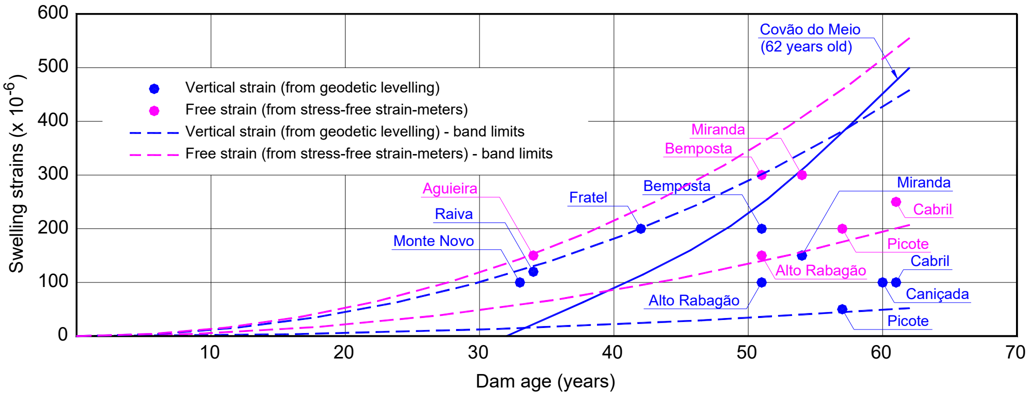

FIGURE 8: Portuguese dams built with granite aggregates and affected by AAR. Average values of the monitored free strains by the stress-free Carlson strain-meters and strains obtained from geodetic levelling, in function of the dam age.

TABLE 1: Portuguese dams built with granite aggregates and affected by AAR. Reaction type and phenomenon identification procedures.

Dam	Year of completion	Height (m)	Aggregate type		Reaction type	Phenomenon identification		
			Coarse	Fine		Visual inspections	Results from monitoring systems	Results from physical and chemical tests
Penide	1949	18	Granite	Quartz	ASR	V1	M2	-
Covão do	1953	28	Granite	?	ASR	V1+V2	M2	T1+T2+T3
Cabril	1954	132	Granite	?	ISR-ASR	V1+V2+V3	M1+M2	T1
Caniçada	1955	76	Granite	?	ASR	V1	M2+M3	-
Picote	1958	100	Granite	Granite	ASR	V3	M1+M2+M3	T1
Miranda	1961	80	Granite	Granite	ASR	V1+V2	M1+M2+M3	T1+T2+T3
Alto Rabagão	1964	94	Granite	Granite	ASR	V1+V3	M1+M2	-
Bemposta	1964	87	Granite	?	ASR	V3	M1+M2+M3	T1
Caia	1967	52	Granite	Quartzite	ISR-ASR	V1+V2	M2	-
Fratel	1973	43	Granite	Quartz	ISR-ASR	V1+V2	M2+M3	T1+T2+T3
Aguieira	1981	89	Granite	Quartz	ASR	-	M1+M2	-
Raiva	1981	36	Granite	Quartz	ASR	V1	M2	-
Monte Novo	1982	30	Granite	?	ASR	V1	M2+M3	T1

ASR – Alkali-silica reaction
ISR – Internal sulphate reaction

V1 – Diffuse (map) cracking
V2 – Linear cracking downstream
V3 – Gel exudation

M1 – Progressive strains
M2 – Progressive displacements
M3 – Differential movements of joints

T1 – Product identification
T2 – Strength and deformability
T3 – Expansibility

TABLE 2: Portuguese dams built with granite aggregates and affected by AAR.
Average values of the monitored free strains by the stress-free Carlson strain-meters and strains obtained from geodetic leveling.

Dam	Age in 2015 (years)	Stress-free Carlson strain-meters		Geodetic levelling at the crest	
		Average value of the accumulated free strain (x 10^{-6})	Average annual rate in the last 5 years (x 10^{-6})	Average value of the accumulated vertical strain (x 10^{-6})	Average annual rate in the last 5 years (x 10^{-6})
Penide	66	-	-	150 (last 16 years)	10
Covão do Meio	62	-	-	500 (last 30 years)	25
Cabril	61	250	10	100	5
Caniçada	60	200 (last 25 years)	10	100	5
Picote	57	200	5	50	< 5
Miranda	54	300	10	150	5
Alto Rabagão	51	150	10	100	5
Bemposta	51	300	15	200	10
Caia	48	-	-	50 (12 years, 1996-2008)	5 (2003-2008)
Fratel	42	-	-	200	10
Aguieira	34	150	5	(not directly related)	(not directly related)
Raiva	34	-	-	120	5
Monte Novo	33	-	-	100	10