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Procedia Structural Integrity 64 (2024) 749–756

Structural Integrity Procedia

www.elsevier.com/locate/procedia

SMAR 2024 – 7th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures

Monitoring internal swelling reactions in concrete dams

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Abstract

Alkali-silica reaction (ASR) and delayed ettringite formation (DEF) are the most common internal swelling reactions (ISR) in concrete dams. The swelling effects and concrete deterioration caused by ISR can be observed in several forms at the structural level, including relative movements between blocks, displacements and deformations, cracking, surface discoloration around the cracks, scaling or spalling as well as surface “pop-outs”.

The detection and the assessment of these structural symptoms in large concrete dams is usually made through visual inspection and interpretation of the monitoring data, such as stress free strainmeters embedded in concrete, geodedic levelling, pendulums, rod extensometers and internal or external jointmeters. The strainmeters and the levelling data are also used for providing estimations of the dam concrete expansion.

The Portuguese information system, designed to serve as a national database, has its own data structure and includes the monitoring systems data for large concrete dams of all structural types, including dams with over 60 years old. This information system is used by both the dam owners and the National Laboratory for Civil Engineering (LNEC) for dam safety assessment over the years.

This work discusses the importance of the dam observed behaviour data provided by the monitoring system as a tool for ISR assessment. The progression of concrete expansion for several dams located in Portugal is presented. The presented observed results were based on data from stress free strainmeters, while others were calculated from geodetic levelling.

Keywords: ASR; DEF; Concrete dams; Monitoring instruments; Expansion estimation

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2452-3216
10.1016/j.prostr.2024.09.340

1. Introduction

Internal swelling reactions (ISR), which comprises alkali-silica reaction (ASR) and delayed ettringite formation (DEF), is a term used to refer to the chemical reactions that lead to expansion, generation of tensile stresses, and, eventually, damage of the concrete elements in which they occur. Moreover, the surface cracking can leave the concrete exposed to other deterioration mechanisms such as corrosion and frost action.

ASR and DEF damage is largely associated with hydraulic structures, such as large dams and spillways, although it has been increasingly identified as a concern in other types of infrastructure. The above-mentioned expansion can result in cracking, misalignment of structural elements, closing of contraction joints and/or surface “pop outs”. Although research has yielded considerable success in understanding the mechanism of the reaction and how to minimize the risk of ISR in new constructions, knowledge of their structural effects and how to best assess the extent of damage to existing structures is still scarce and remains a major topic of ongoing research. When comparing both reactions, DEF typically develops faster and results in higher expansions than ASR (Fournier and Bérubé, 2000; Blight and Alexander, 2011; Martin et al., 2012; Saouma, 2020).

ASR, a chemical reaction between the alkali hydroxides dissolved in the concrete pore solution and the reactive silica from the concrete aggregates, stands as one of the most common deleterious mechanisms identified in concrete structures worldwide. The ASR reaction generates hydrophilic gel, which swells in the presence of moisture. This induces expansive pressures within the surrounding concrete, causing concrete swelling and cracking (Fournier and Bérubé, 2000; Blight and Alexander, 2011).

DEF, also known as internal sulfate attack (ISA), is a phenomenon that occurs within concrete due to high temperatures. This can be caused by thermal curing or by the heat of hydration produced during cement hydration reactions, particularly when the concrete reaches temperatures above 60 °C. At these elevated temperatures, the formation of primary ettringite, which is expected to occur during the early stages of concrete development, becomes unstable. Consequently, the formation of ettringite takes place later. When there is moisture present, the unreacted sulfate ions responsible for ettringite formation will belatedly react within the hardened cement paste, resulting in concrete expansion and cracking (Kuperman and Hasparyk, 2023; Martin et al., 2012).

Continuous monitoring of structures plays a key role in diagnosing and predicting distress observed in a structure. It also helps in making informed decisions regarding necessary repairs and strengthening measures. In situ monitoring instruments provide valuable data that serves as an initial indicator of potential issues related to ISR. Permanent monitoring devices and sensors are installed either during construction or at a later stage to monitor various phenomena, including structural displacements, concrete strains and temperature changes. Many of the swelling-related structural responses are straightforwardly detectable through a reliable dam permanent monitoring system following the best practices and recommendations (in some cases long before cracks become visible), which provide important information about the progression of ISR (Amberg, 2011; ICOLD, 2018; Saouma, 2020; Batista, 2022).

Results from concrete dams of all types, such as double curvature arch and gravity structures, are available in the Portuguese information system Gestbarragens (Castro et al., 2012). This includes dams with over fifty years old and recently built structures. The database has been expanded in recent years to incorporate monitoring information for certain concrete bridges and embankment dams. In addition to the current dam performance and safety assessment, the observed behavior data obtained from this information system has been extremely helpful in detecting and estimating the ISR symptoms in concrete dams. This work intends to emphasize the importance of the monitoring and corresponding updated information systems in the evaluation of expanding dams.

2. ISR concrete deterioration mechanisms

The consequences of ASR and DEF depend on various factors, including the type of aggregate (for ASR), structural geometry, reinforcement and exposure conditions to thermal and moisture conditions. The most significant concrete mechanical properties affected by these ISR are stiffness and tensile strength, both being considerably reduced due to the microcracking caused by the concrete expansion, which generally does not compromise the load bearing capacity of the structure. At the structural level, the ASR and DEF impact on the structural behaviour of dams is similar and the manifestations can be observed in several forms, the most common ones being relative movements, displacements and deformations, cracking, surface discoloration around the cracks, scaling or spalling and surface pop-outs, all of which are due to concrete swelling (Saouma, 2020; Larbi et al., 2004; Noël et al., 2017; Amberg, 2011).

Two types of ISR cracking may be distinguished: cracks directly caused by differential swelling and cracks induced indirectly by the structural response to the concrete expansion, i.e. structural cracks due to the new equilibrium induced by permanent displacements. The latter appear typically along structural discontinuities, as for example at the transition between a straight gravity and a curved part or along the foundation as peripheral cracks on the downstream face of arch dams. On the other hand, the differential swelling cracking type is caused by the higher expansion in the wetter subsurface layer compared to the surface layer. As a result, the expanding concrete beneath the surface layer causes superficial cracking. The orientation and pattern of these cracks can be influenced by factors such as the presence of internal reinforcement, geometric discontinuities, stress states and pre-existing cracks. In plain concrete, ISR-induced superficial cracking typically exhibits a random pattern, also known as map cracking, which is very common in dam facings due to the absence of reinforcement. These cracks generally do not penetrate deeper than 25-50 mm from the exposed surface. In restrained concrete (e.g., reinforced concrete), ISR-induced cracks often align parallel to the main restraint, such as the primary reinforcement, due to the confinement provided in that direction. Moreover, these cracks rarely extend below the level of the reinforcement. Initially, surface cracks start to appear when the tensile strain at the surface exceeds a threshold of 100 to 150 $\times 10^{-6}$. These cracks then widen, often seasonally, and new cracks form when the local surface tensile strain surpasses the cracking limit. Initially, the extent of pre-existing cracking (when present) increases before reaching a level where the strains from ISR exceed those from other causes of cracking (e.g. free expansion of 0.5-1 mm/m). It is at this point that the characteristic patterns of ISR cracking become clearly visible. (Saouma, 2020; Godart et al., 2013; Godart and Wood, 2016; ACI, 1998; Fournier et al., 2010; Fernandes and Broekmans, 2013; Blight and Alexander, 2011; Amberg, 2011).

In dams, ISR is manifested according to the above mentioned with some particularities, many of which are part of the structural response to the concrete swelling. These include irreversible vertical displacements, such as rising of dam height, and irreversible horizontal displacements (often upstream drift, except in buttress dams; in arch dams, this upstream drift is governed by the expansion of the arches, whereas in gravity dams is due to non-uniform expansion within the wall thickness), relative movements between blocks, i.e. vertical misalignment (for hypothetical uniform swelling across the dam, taller blocks rise more than shorter ones) and contraction joints closure (which may result in crushed joint edges). Other typical ISR signs in dams are a greater expansion in the upper part of the dam (due to the ISR mitigating effect of compressive stress in the lower layers and, in some situations, to the fact that in the upper, thinner part, the concrete can reach higher temperatures during the operation stage, accelerating the swelling reaction over time), non-uniform expansion within the dam body causing cracks in galleries which are less visible at both dam faces, ovalisation and/or misalignment of the conducts, openings and structural voids and jamming of dam gates (Amberg, 2011; Batista, 2022).

To date, ISR remedial works have generally a temporary character and need to be repeated after a certain period. The historically most effective interventions on expanded dams are installation of an impervious membrane on the upstream face for mitigating the evolution of the reaction, reinforcement with anchorages to assure the dam stability, injection of cracks with cement and/or resins for improving the dam continuity and reducing the leakage, slot cutting to alleviate compressive stresses and improvement of drainage system and upstream curtain efficiency (Amberg, 2011; Silva and Serra, 2022a; Silva and Serra, 2022b).

3. Monitoring of swelling structural effects in dams

3.1. Monitoring systems for ISR detection and assessment

Techniques such as geodetic levelling, pendulums (direct and inverted), concrete strain or jointmeters (either embedded or surface ones) and laser scanning are commonly used to measure displacements in concrete dams, which are typically installed during construction (Saouma, 2020; Amberg, 2011).

Vibrating wire and electrical resistance strain gauges are popular devices for measuring internal concrete strains in dams. To isolate the gauges from the structure's stress field and obtain strains related to imposed deformations (e.g. temperature, ISR swelling), they can be embedded in concrete placed inside a stress-free incasement. Fiber-optic sensors can also be installed for strain measurement and crack detection. Manual and automated crack meters, such as inductive-type or LVDT-type meters, are commonly used to measure the evolution of crack widths with good accuracy (ca. 0.1 mm). These devices provide valuable information along with displacement data, contributing to a better understanding of the structural response to ISR (Saouma, 2020; Batista, 2022).

Temperature monitoring is essential in ISR-affected structures due to its impact on the reaction rate as well as due to the thermal expansion/contraction of the structure (if not considered, the thermal expansion/contraction could obscure ISR expansion trends). Additionally, concrete temperature history, especially during the early stages after placement, is valuable for diagnosis in DEF-affected structures. Resistance temperature detectors (RTD) or thermocouples can be embedded in the structure to measure internal temperature (Amberg, 2011; Saouma, 2020; Kuperman, 2023).

The estimation of the concrete expansion is a common practice for appraising the progression of the expansive phenomena. The total and rate of expansion are usually estimated based on the displacements data provided by the geodetic levelling (crest elevation) and stress free strainmeters embedded in concrete. Even though the rod extensometers are typically used to monitor the behaviour of dam foundations, these instruments can also be valuable in assessing expansion development within the concrete. In Pracana dam, for example, multiple rod extensometers were installed across the dam body for monitoring the progression of swelling over the dam height. The evaluation of the superficial cracking also serves as an indicator of degradation and expansion progression, which is the reason why semi-quantitative methods (e.g. 'expansion index to date' and the 'LCPC-cracking index') have been established for estimating the expansion due to ISR (Amberg, 2011; Saouma, 2020; Batista, 2022).

3.2. Portuguese experience

An estimation of the accumulated and rate of strain as function of both reaction types (ASR or/and DEF) and the aggregate nature are presented in Table 1. Each line of this table compiles information from one or more of the most expanded Portuguese large dams that simultaneously have been affected by the same expansive reaction(s) (ASR, DEF or both) and used the same combination of concrete aggregates (fine and coarse). This information was essentially obtained from stress free strainmeters and geodetic levelling data. From this table, one may infer that quartzite is the aggregate causing the highest magnitudes and rates of ISR expansion. No conclusions can be drawn regarding the aggregate effect for dams affected by DEF, as this reaction is independent of the aggregate type.

Table 1. Estimated accumulated and rate of strain (based on stress free strainmeters and geodetic levelling) in Portuguese large dams as function of the type of reaction (ASR or DEF) and aggregates (adapted from Batista, 2022)

Reaction	Coarse aggregate	Fine aggregate	Maximum accumulated strain (με)	Maximum strain rate (με/decade)
ASR	Quartzite	Quartzite	600-4000	5-50
ASR	Granite	Granite	20-100	5
ASR	Granite	n.a.	80-250	5-30
ASR	Granite	Siliceous	70-250	10
ASR + DEF	Quartzite	Quartzite	1400	50
ASR + DEF	Granite	n.a.	80	5
ASR + DEF	Granite	Siliceous	400	15
DEF	Limestone	Siliceous	2400	50

The strains obtained from stress free strainmeters installed in some Portuguese large dams affected with ASR were plotted against their measured temperature (Figure 1) and the dam age (Figure 2). For sound concrete, the strains and temperatures for each strainmeter are expected to display a direct proportion in sound (non-expanded) concrete, as per the Figure 1 left chart. The subsequent charts, i.e. central and right charts, illustrate moderately and highly expanded concrete, respectively. The Figure 2 is similarly arranged according to the strains magnitude, from the non-expanded (top chart) to the highly expanded (bottom chart) concrete. The calculated strains obtained from the geodetic levelling data of Portuguese large dams affected with ISR (ASR and/or DEF) is presented in Figure 3. This figure is organized in a similar way to the Figure 2, i.e. slightly expanded concrete at the top, moderately expanded concrete in the middle and highly expanded concrete at the bottom. These records provide valuable information regarding aspects that should be taken into consideration by engineers when conducting diagnosis and prognosis, which are discussed below.

More than one concrete strain (expansion) magnitude was observed for each dam, which is due to the dams' heterogeneity in terms of concrete composition, hence different regions of a dam may have concrete with distinct ISR (ASR and/or DEF) reactivity. Different dam zones (e.g. dam core, dam facing and highly reinforced zones) require distinct concrete formulations (for example, Figures 1 and 2 show Dam #01 with no signs of swelling in certain areas and highly reactive concrete in other areas, measured with stress free strainmeters). Also, it is a common procedure to use more than one concrete formulation in each zone, due to adjustments in the concrete composition during a dam construction, namely modifications in the dosages as well as changes of aggregates, of addition or of admixture. On top of that, the distinct expansion magnitudes within the same dam may also be attributed to the concrete exposure, namely to humidity (e.g. upstream facings are exposed to water, which feeds the reaction) and temperature (e.g. zones facing south are warmer, potentiating these reactions). Finally, the anisotropic development of swelling (e.g. due to dissimilar confinements for different directions) is another factor to take into consideration.

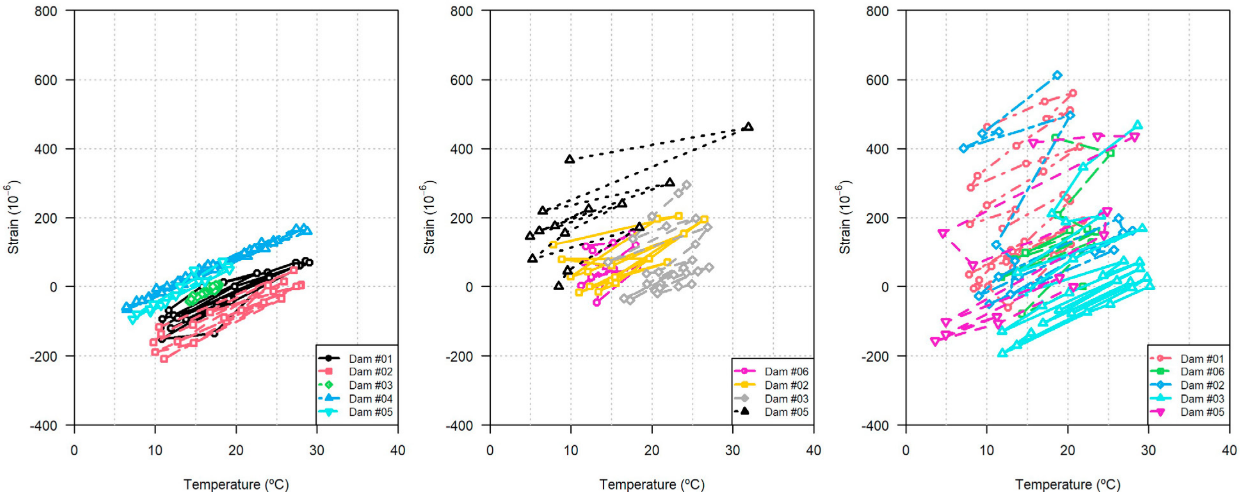

Fig. 1. Strains and temperatures obtained from stress free strainmeters installed in Portuguese large dams affected by ASR, arranged according to the concrete expansion magnitude. Left chart: non-expanded; Central chart: moderately expanded; Right chart: highly expanded (points correspond to the strainmeters readings and the line segments unite them chronologically)

The Figures 2 and 3 provide rather consistent data, indicating a relatively high reliability of the estimations provided by both methodologies. In both figures, one can distinguish between swelling that develops in an earlier stage and expansions that emerge later. These findings seem to be in agreement with what is already fairly well established, i.e. DEF is expected to develop earlier than ASR and to cause higher expansions, as well as with the literature, which distinguishes between early-expansive and late expansive ASR (Amberg, 2011; Saouma, 2020).

For example, in the bottom chart of Figures 2 (highly expanded concrete), where only dams exclusively affected by ASR are represented, one can distinguish between concrete with the first expansive signs within the dams' early age (e.g. at 10-15 years old) and concrete revealing the initial swelling symptoms considerably later (e.g. 20-30 years old). These discrepancies in the start of the expansive phenomena for different dams (or even for different zones of the same dam) might be attributed to aspects such as distinct quality and/or availability of reactants, concrete porosity (the gel resulting from ASR might initially fill the voids before starting the expansion) and the influence of the temperature on the kinetics of the chemical reaction (reaction at the areas that are mostly exposed to solar radiation is accelerated due to the higher temperatures).

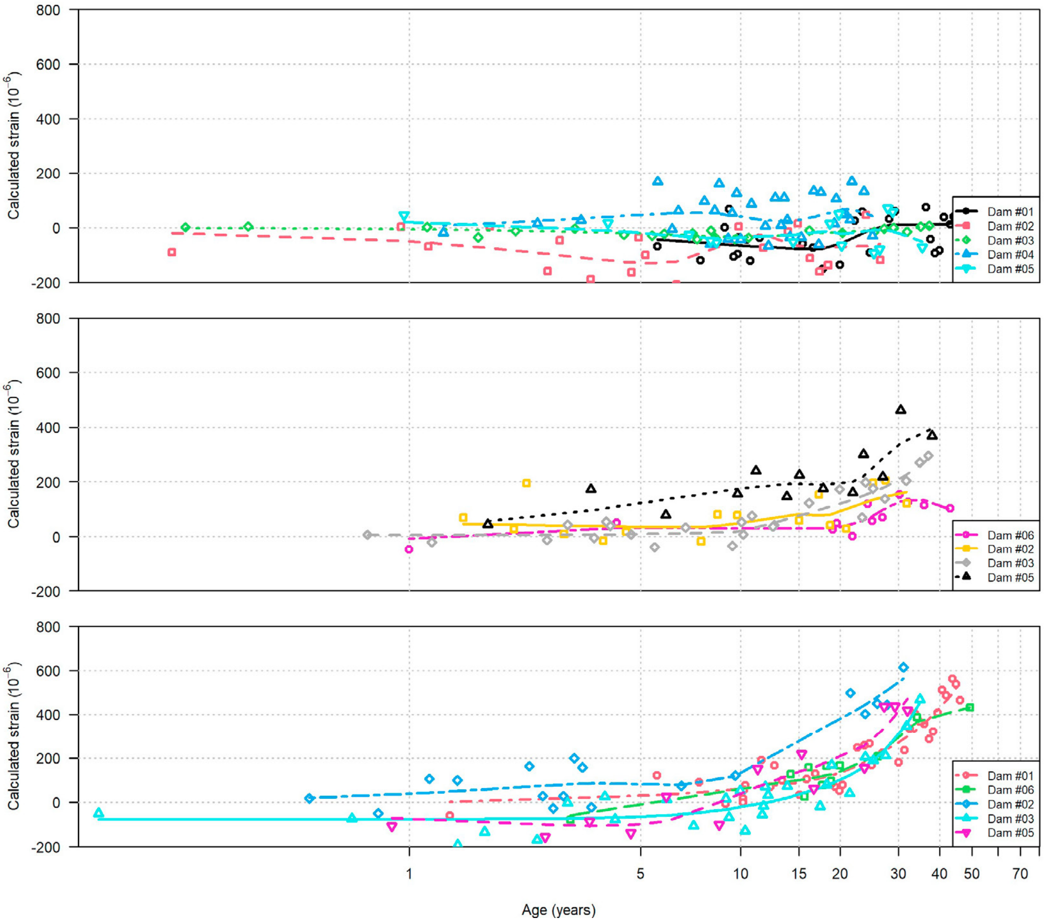

Fig. 2. Strains time series obtained from stress free strainmeters installed in Portuguese large dams affected by ASR, arranged according to the concrete expansion magnitude. Top chart: non-expanded; Middle chart: moderately expanded; Bottom chart: highly expanded (points correspond to the strainmeters readings and the curves are their respective interpolations)

The last line of Table 1 refers to a dam in Portugal affected solely by DEF that exhibits significant expansions. The swelling estimation for this dam is represented in the Figure 3 bottom chart. The first expansions in this dam were first noticed at ca. 10 years of age, i.e. comparatively early. This dam was built with ready-mix concrete with a relatively high cement dosage, which may have caused relatively high hydration temperatures, resulting in the development of this ISR (Batista, 2022). Also in Figure 3 bottom chart, one plot represents a dam that combines the effects of DEF and ASR. Even though ASR is much more common than DEF, these two dams affected by DEF (one solely and the other combined with ASR) are the ones with most estimated expansions (estimated from the levelling data), which suggests that DEF is the main reason for relatively high expansion levels.

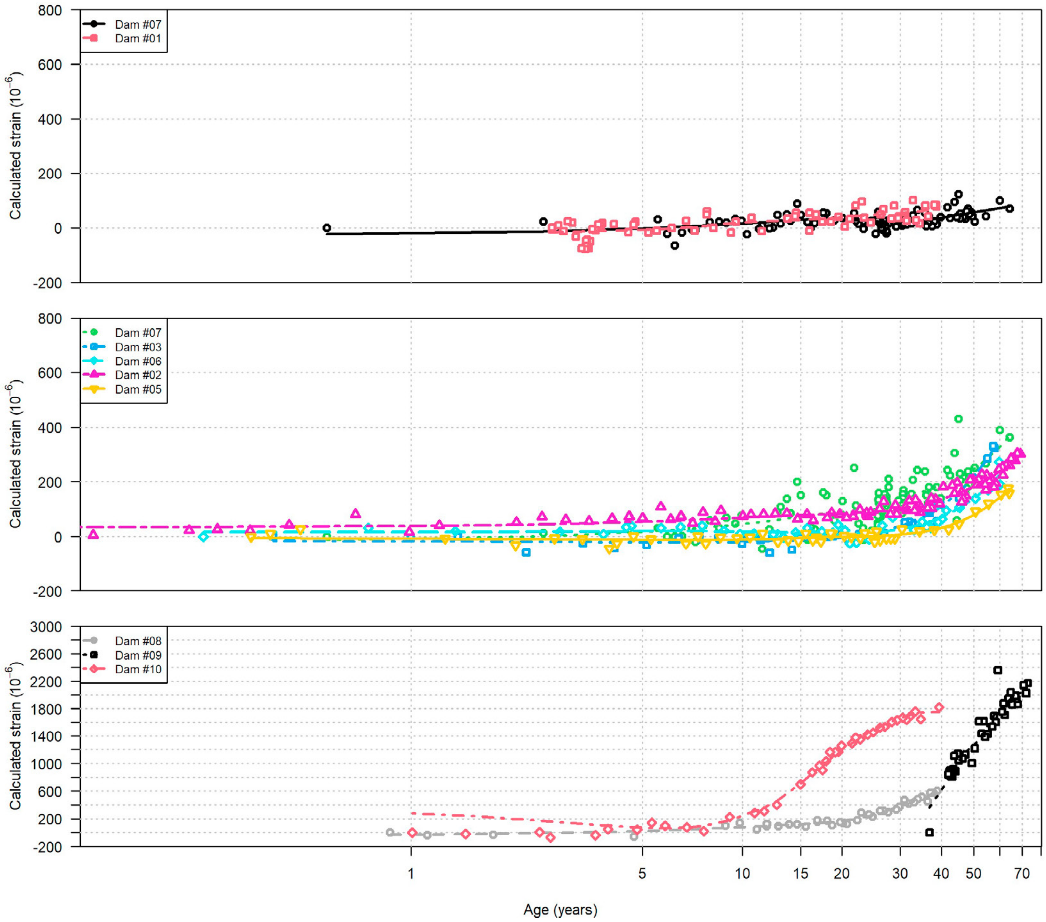

Fig. 3. Strains time series calculated from geodetic levelling of Portuguese large dams affected by ISR, arranged according to the concrete expansion magnitude. Top chart: slightly expanded; Middle chart: moderately expanded; Bottom chart: highly expanded (points correspond to the strainmeters readings and the curves are their respective interpolations)

4. Final remarks

ISR (namely ASR and DEF, which have similar structural symptoms), are a significant concern for dam engineers as, despite the advances in preventative measures for new concrete dams, the diagnosis and, especially, the prognosis and maintenance of affected structures is still a challenge. Furthermore, one should bear in mind that symptoms similar to the ISR ones may have distinct causes. For instance, the drying and plastic shrinkages often result in a similar map cracking pattern to the ISR one, although the latter takes much longer to develop (years or even decades).

In Portugal, the large dams monitoring systems have been crucial for the early detection and subsequent progress assessment of ISR in these structures. Nonetheless, the monitoring results alone are never sufficient for a correct diagnosis nor for a reliable prognosis. For diagnosing and prognosing these ISR and their structural consequences in concrete dams, one must combine several methodologies, which should include the analysis and interpretation of the monitoring data, complementary field assessment, such as crack evaluation techniques, and lab evaluation, including microscopical examination, mechanical and physico-chemical tests of the concrete, as well as numerical modelling.

In this context, the analysis and interpretation of observed behaviour given by the monitoring data implies the separation of the effects of the main solicitations, i.e. hydrostatic pressure and environmental temperature, from the so-called time effects. In ISR-affected dams, among the time effects, one should distinguish between the ISR and the creep effects. Bear in mind that the latter may be contrary to the displacements caused by ISR, which would result in creep hindering the ISR displacements.

As for the swelling appraisals, this work highlights the importance of cross-checking estimations based on data from distinct monitoring instruments data. The main estimation approaches, i.e. stress free strainmeters, geodetic levelling and cracking assessment techniques, only provide rough estimations of the concrete swelling. Ideally, for each dam zone, these should be compared in order to have redundant information for the same concrete (identical composition, similar environmental exposure, analogous confinement, etc.). If the estimations based on different instruments data do not differ significantly, the reliability of these will be higher.

Overall, there is a relatively good qualitative knowledge of the various aspects that influence the ISR expansion of a concrete dam. On the other hand, the way all these aspects combine and interact is still not fully comprehended, which results in rather inaccurate quantitative assessments.

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