DETECTION, ASSESSMENT AND MONITORING OF COMMON ANOMALIES IN CONCRETE DAMS

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Abstract
The current document compiles some of the most relevant information concerning the symptoms and respective causes of common anomalies observed in concrete dam bodies. These include physical degradation phenomena, like abrasion, cavitation and freeze-thaw cycles, and chemical reactions, such as expansive reactions and leaching. The methodologies available to detect, assess and monitor these are addressed as well, with a special focus on cracking.

1. Introduction

Portland cement is an inherently durable material. Nonetheless, even the most well designed and built concrete structures have a life time limited by the cement itself. The degradation of a concrete structure is always a concern, with the situation becoming even more serious when the risk of failure jeopardizes people's lives and properties, which is the case of dams with populations downstream [1, 2]. Given the importance of this topic, some of the most frequently observed anomalies in concrete dam bodies, along with their respective causes as well as procedures developed to identify and evaluate them, are presented here.

2. Most common anomalies

Some of the most common symptoms of pathologies observed in concrete dams are cracking, unexpected displacements, water seepages and degradation of the exposed concrete, mainly in upstream and downstream faces as well as around spillways and outlets [2].
The causes of these anomaly signs can be divided into two main categories, the ones with origin in physical phenomena and the ones caused by chemical reactions. The first ones include abrasion, cavitation, shrinkage, mechanical and thermal loads and freeze-thaw cycles.

In what concerns to the chemical reactions, the most frequent ones in concrete dams are leaching of the cement matrix by seepage water, alkali silica reactions (ASR) and internal sulfate attack (ISA). The dam design, concrete manufacture and construction process are also within the main reasons for the appearance of anomalies in concrete dams [1, 3, 4].
Despite being a symptom, cracking is addressed separately due to its remarkable relevance.

2.1 Physical phenomena

2.1.1 Abrasion

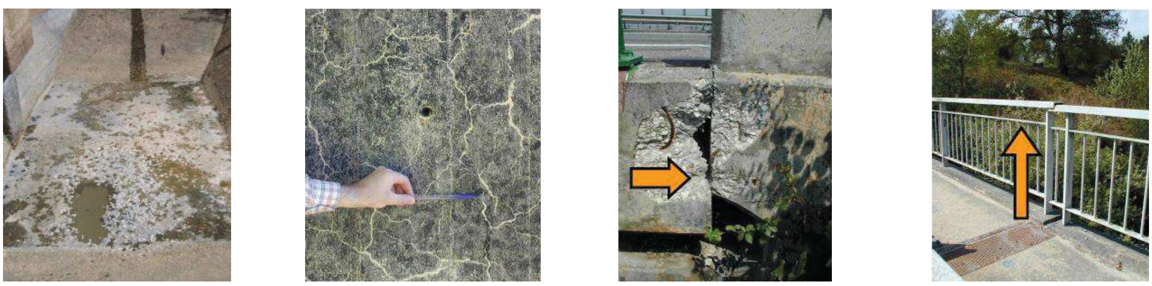
Mirza *et al.* [2] define abrasion in concrete dams as the wear of the concrete surface due to the flowing water carrying solid particles (e.g. sand, gravel and even larger particles), resulting in a smooth surface (smoother than the one produced by cavitation). The extension of the damage is dependent on the speed and turbulence of the water transporting the abrasive material, the hardness of this material as well as the quality of the surface submitted to the abrasion action. Stilling basins (Fig. 1a)) and bottom outlets are particularly susceptible to abrasion and the most effective way to detect it is through visual inspection [5].

2.1.2 Cavitation

The erosion by cavitation is one of the most common causes of deterioration in high head spillways and outlet works. It occurs due to a sharp reduction of water pressure during the flow, which may change the state of the water from liquid to vapor. When the pressure drops under a certain limit, the vapor cavities formed inside the liquid become unstable and blow up, which may produce damage to the concrete structure. The damaged surface is more likely to be eroded by cavitation, which often result in a snow ball effect. In hydraulic structures, with high-speed flows, this reduced pressure is typically due to irregularities in the flowing concrete surface, with the most vulnerable zone being the one where the water changes to free flow, e.g. the spillway surfaces, immediately downstream of a floodgate or a valve. The most efficient way to detect damage by cavitation is also through visual inspection [2, 5].

2.1.3 Freeze-thaw cycles

Once saturated, the concrete cracks when exposed to freezing temperatures. The saturation degree is a function of its capillarity and amount of air in its pores. The water expands around 9% from the liquid to the solid state and this volume increase cannot be absorbed by the saturated concrete without damage, normally resulting in cracking or scaling. When there are dissolved salts in the water, the potential damage is even higher. The greater the difference between the thermal expansion coefficients between the aggregates and the cement paste, the higher is the chance of damage due to the freeze-thaw cycles. It can also be easily detected by visual inspection and is mostly observed in the downstream face and in the crest of dams [6].



a) Abrasion in stilling basin   b) Map cracking [8]   c) Crushed joints [8]   d) Relative displacements [8]

Figure 1 - Common anomalies in concrete dams.

2.2 Chemical reactions

The anomalies caused by chemical reactions are also very recurrent in concrete dams, with the expansive reactions (ASR and ISA, which may appear in a combined form) standing out. The ASR needs three ingredients to occur: reactive aggregates, alkalis and external water. The reaction product is a gel, which gradually absorbs external water, resulting in an expansion of concrete and, consequently, introducing internal stresses. Concerning the ISA, the sulfates, soluble in water or in the aggregate, may react with the aluminates in the cement paste. The product, ettringite, absorbs water, which may eventually cause expansion and cracking of the concrete. This reaction is relatively common in massive structures like dams, due to the high temperatures achieved at early ages (over 70^{o}C), which delay the formation of ettringite. This mineral also expands by water absorption, hence this late reaction results in swelling of concrete after hardening, with similar consequences as for the ASR [6, 7, 8].

The current state-of-the-art regarding these swelling reactions is already sufficient to avoid its occurrence in new dams, as long as appropriate measures are taken. The methods to prevent the manifestation of ASR and ISA in new constructions are mostly based on controlling and minimizing the variables that contribute to the development of these chemical reactions. Concerning the ASR, the reaction potential of the aggregates may be assessed by a petrologist, whereas the alkalis present in the cement can be controlled. Regarding the ISA, the recommended procedures are to limit the maximum temperature achieved during the hydration reaction of the binders (e.g. replacing part of the cement by pozzolanic materials) and limiting the amount of aluminates and sulfates in the binder (e.g. using high sulfate resistant cements). Accelerated tests are usually efficient in detecting the concrete potential for developing ISA. Keeping the concrete relatively dry is another relatively common solution to mitigate these expansive reactions (e.g. waterproofing the upstream face), although this solution is mostly used in existing dams [4, 6, 7, 9].

When dealing with operating dams, there are several ways to detect the symptoms resulting from ASR and ISA in concrete dams. The most direct one is through visual inspection, with cracking (Fig. 1b)) and ASR gel being among the most frequent manifestations. Further information on crack assessment can be found in 2.3.1. The other key signs are abnormally closed contraction joints (which may eventually start crushing against one another) (Fig. 1c)), relative displacements between adjacent blocks (Fig. 1d)), elevation of the dam height (crest rising) and horizontal permanent displacements (often upstream drift). The dam apertures may also be affected, e.g. ovalization of the ducts and warping of the floodgates. The most effective way for detecting most of these manifestations is through surveillance instrumentation installed in the structure, whose complexity depends on the dimension and safety risk of the dam [6, 8, 10].

The surveillance methods that can be used to monitor the dam behavior and consequently assess the above mentioned symptoms are: a) internally embedded and external joint meters (axial/radial, planar or 3D measurement) for measuring the joint displacements; b) mechanically isolated extensometers embedded in the concrete, to assess the stress-independent extensions, such as the ones resulting from ASR and ISA; c) geometric levelling, for measurement of vertical displacements of the dam crest; d) plumb lines, global navigation satellite systems (GNSS) or geodetic planar system, for measuring the horizontal displacements. However, the interpretation of the data obtained by most of the above mentioned surveillance methods should include a statistical analysis, in order to estimate the weight that distinct variables have on the dam behavior. Thus, statistical models to

quantitatively interpret the collected data are usually utilized. One of the most used methods is the separation of the effects caused by the variables hydrostatic pressure (which is proportional to the reservoir level), temperature (air and reservoir water) and ageing (such as creep or swelling caused by expansive reactions). The first two variables are usually known (by direct measurement) and their effects are assumed to be reversible, whereas ageing effect is presumed to be a non-elastic phenomenon solely time dependent [6, 10, 11, 12].
The other frequently occurring chemical reaction in concrete dams, i.e. leaching, consists on the dissolution of material from the cement matrix (calcium and magnesium hydroxide crystals) by reservoir water, with the dissolving potential being enhanced by the pureness of the water. This often leads to formation of crystalline salt deposits known as efflorescence (Fig. 2a)). This loss of solids from the cement matrix reduces the strength and the permeability, which will eventually facilitate the penetration of harmful substances into the concrete, namely water. Hydrochemical analyses of the reservoir water, such as temperature, pH, electrical conductivity, redox potential and total dissolved solids are undertaken to evaluate the water aggressiveness [1, 5].

2.3 Cracking

Cracking may have origin on loads (e.g. hydrostatic pressure, self-weight) or on volumetric changes (e.g. thermal, shrinkage, expansion, creep) and should be faced as a potential deficit which needs to be evaluated. The most common causes of cracking in concrete dams are drying shrinkage, temperature changes, expansive reactions (namely ASR and ISA), design or construction defects, ageing, freeze-thaw cycles, foundation settlement and occasional mechanical loads. Understanding the cause of cracking is indispensable for the repair to have effective and long lasting effects. For instance, if cracking is due to drying shrinkage, it will stabilize, so crack repair is more likely to be successful. On the other hand, for the progressive phenomena, such as differential foundation settlements, the treatment of the cracks have more limited effects. Cracking may be the first symptom indicating other issues in concrete. Thus, the structure evaluation, including a detailed crack assessment, should be undertaken when a crack is detected [1, 6, 13].

a) UAV (drone) visual inspection of dam with efflorescence ($CaCO_3$)

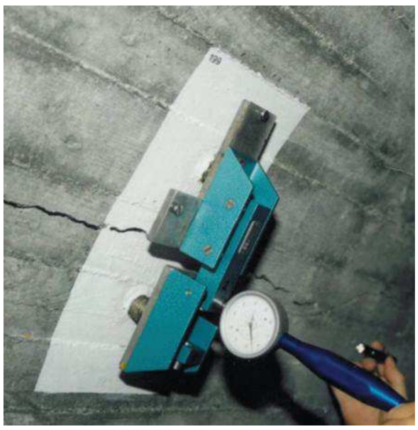

b) Crack meter in gallery [10]

Figure 2 - Crack assessment in concrete dams.

2.3.1 Assessment of cracking

The surveying of cracks is one of the main tasks involved in the monitoring plan of a concrete dam. It includes a general structure inspection, identifying and describing the cracks as well as, eventually, deducing their origin. Crack meters may also be used to monitor their movement (see Fig. 2b)). If, by chance, the reservoir is emptied, a detailed visual inspection should be undertaken in upstream face, even if no crack signs have been detected. Differential settlements, spalling, seepage and leaching deposits (see Fig. 2a)) are common consequences of cracking [6].

New technologies based on digital image processing are very useful for visual inspections (Aided Visual Inspections) of cracking and its consequences (see Fig. 3). Unmanned Aerial Vehicles (UAV) (see Fig. 2a)) are also extremely convenient for visual inspections [14].

The surface cracking might be mapped using the detailed surveying, photos and pathology maps (see Fig. 3). If necessary, underwater inspections may be undertaken by divers. All the openings (such as tunnels) related to the structure should be inspected as well. When possible, the external signs of cracking should be correlated with internal cracks. The internal cracks may be detected through soft hammering, as a hollow sound usually indicates the presence unsound concrete, e.g. internal cracks. Several tests to identify the internal cracking degree are at one's disposal, such as lab tests on concrete core extracted from the dam. Non-destructive tests (NDT) are also available for this purpose, namely sonic and ultrasonic waves, geo-radar (based on the changes of magnetic permeability and dielectric constant), video cameras, optic fibers, permeability tests and controlled injection of fluids [6, 15].

Numerical damage models, such as finite element models (FEM) and discrete element models (DEM), are often used as a supplement to the above mentioned methods. These models are very helpful at predicting the locations where cracking is probably occurring. FEM and DEM may even indicate the directions in which cracks are most likely to develop.

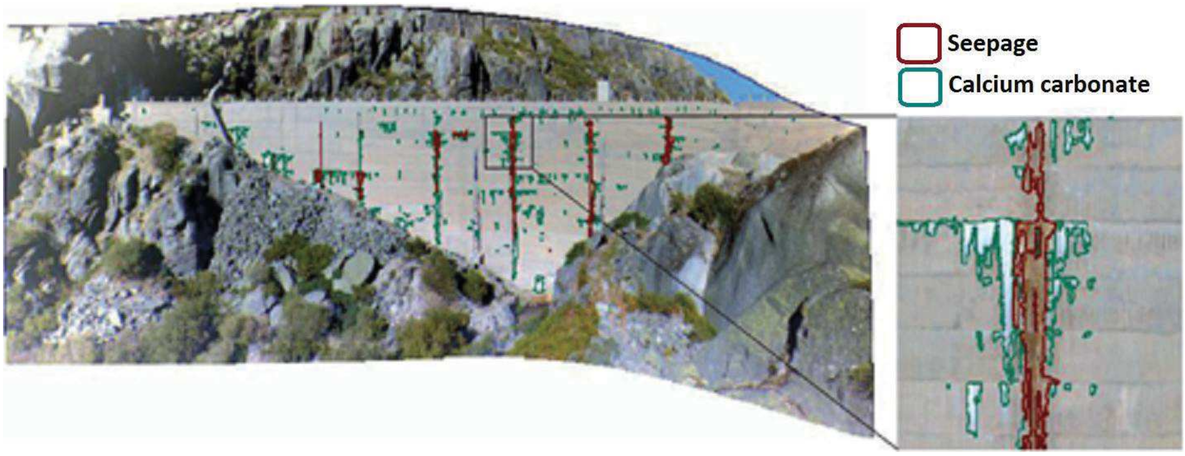


Figure 3 - Pathologies map obtained in the sequence of Aided Visual Inspection [14].

The methods utilized for surface mapping of cracks are relatively simple and relatively inexpensive. On the other hand, the methods to assess the internal cracking degree are usually sophisticated and need specialized workers with adequate training, namely for the processing and interpretation of data [6].

4. Final remarks

The most frequent anomalies in concrete dams may be divided in two main groups, as function of their origin: physical and chemical phenomena. The first ones include abrasion, cavitation and freeze-thaw cycles, and the most adequate way to detect these is through visual inspections. The most relevant chemical reactions are the expansive ones (ASR and ISA) and leaching of the cement matrix. The swelling due to the expansive reactions has numerous typical symptoms, such as abnormally closed contraction joints, distinct displacements and cracking. Instrumentation along with visual observation play a key role in providing early warnings for these unusual behaviors, hence contributing to avoid any subsequent incidents.

Cracking is a common symptom for different causes, so it should be thoroughly evaluated, as an accurate diagnosis is crucial for a successful repair. Several methods for assessing surface and internal cracking have been developed, with their own advantages and limitations.

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