Cracking due to alkali-silica reaction in slab at the Jaguari hydroelectric power plant – a qualitative study

Estudio cualitativo sobre fisuración debida a la reacción álcali – sílice en el forjado de la represa hidráulica de Jaguari

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Abstract

The concrete structures of Jaguari Hydro Power Plant (HPP) display cracks due to the occurrence of Alkali-Silica Reaction (ASR). The qualitative analysis of the cracks that occur in the slab of the water intake structure was performed through in-loco visual mapping, and through results from the computational analysis, using the finite element method. The cracks were mapped using the plastic film technique with ink pens. The computational analysis was performed with a commercial program using bidimensional elastic elements, CSQ – Constant Strain Quad. The comparison of the results with the two techniques showed that the most intense cracking observed in certain regions of the slab coincides with the occurrence of the maximum tensions when an expansion in the walls of the intake is simulated, which can explain the origin of the cracks observed in the slab.

Keywords: Alkali-aggregate reaction, computational analysis of structures, dam monitoring, concrete, slab

Resumen

Las estructuras de hormigón de la Presa Hidráulica de Jaguari (PH) presentan una imagen de agrietamiento debido a la aparición de la Reacción Álcali-Sílice (RAS). En el presente trabajo se realizó un análisis cualitativo de las grietas que se producen en la losa por la entrada de agua con un estudio visual in situ, y los resultados de análisis por ordenador usando el método de elementos finitos. Para el estudio de las grietas se utilizó la técnica de registro con bolígrafos de plástico con tinta. El análisis computacional se realizó con el programa comercial de dos dimensiones de tipo elástico CSQ - Constant Strain Quad. Una comparación entre los resultados obtenidos con ambas técnicas mostró que el agrietamiento más intenso observado en ciertas regiones de la losa coincide con la aparición de los picos de tensión cuando se simula un taco de expansión en las paredes en contacto con el agua, lo que puede explicar el origen de fisuración observada en la losa.

Palabras Clave: Reacción álcali-agregado, análisis computacional de las estructuras, la vigilancia de las presas, hormigón, losa

1. Introduction

The UHE Jaguari plant is located in the Jaguari River, with the right margin belonging to the municipality of Jacareí and the left margin to São José dos Campos, State of São Paulo, Brazil. The last machinery equipment installed at the plant was in 1973. The power plant's electricity is generated by two Francis-type turbines with an installed capacity of 27.6 MW. The reservoir stretches over 56 km² and its main purpose is to regularize the flow of the River Paraíba do Sul, which supplies water to the cities in the Paraíba Valley in State of São Paulo and to the cities in the state of Rio de Janeiro. The power plant's water intake is a tower type structure with buttresses of 63m in height. The water reaches the power house through an abductor tunnel with drop reference value of 49.9 m (CESP, 2013). Figure 1 shows an aerial view of UHE Jaguari and its structures.

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Figura 1. Represa Hidráulica de Jaguari (PH). Fuente: CESP (2013)

Figure 1. UHE Jaguari. Source: CESP (2013)

Structural deterioration and damages were observed in the plant in 1980, which were related to Alkali-Aggregate Reaction (AAR) occurrences.

AAR is a chemical reaction in concrete between certain types of aggregates and hydroxyl and alkali ions, predominantly in the cement used in the reactive mixture and the result is the formation of products with hygroscopic and expansive characteristics located in the concrete mass. This product is popularly known as gel reaction.

The occurrence of ARR requires the simultaneous occurrence of three essential factors: reactive aggregate, cement with sufficiently high alkali content (K_2O , Na_2O), and moisture availability. The velocity and magnitude of expansions depend on temperature, specific surface area of the material, the confining stresses and the contribution of external alkalis (Priszkulnik, 2005).

According to Lu et al. (2006), in addition to the alkali content in cement, high alkali levels are provided by aggregates, especially those rich in feldspar, thus in concrete structures susceptible to the occurrence of AAR, the alkali contribution from the reactive aggregates should be taken into consideration.

According to Fournier et al. (2005), the chemical process of AAR can be classified into three types, depending on the type and mineralogy of the reactive aggregate, such as alkali-silica reaction, alkali-silicate reaction and alkali-carbonate reaction – with ASR as the most commonly recognized form of AAR worldwide.

The gel produced by the chemical reaction is responsible for the expansion and deterioration of concrete. The gel absorbs water and swells, and when it exceeds the concrete void content it causes interstitial pressures that induce tensile stresses when in contact with the pore walls. Therefore, micro fractures occur in the aggregates and around the cement paste, leading to the deterioration of concrete.

The main occurrences of AAR, regarded as characteristic reaction symptoms, are: deformations and displacements, cracking, concrete surface discoloration and gel exudations. According to Mehta and Monteiro (2008), in unreinforced concrete the cracks caused by ARR resemble a “map” pattern, and in reinforced concrete the cracks occur parallel to the reinforcement direction.

The consequences of ARR occurrences can change the mechanical properties of concrete and the functionality conditions of various structures that are affected by the damage, such as bridges, buildings, dams, decks, among others, provided all the conditions to develop the reaction are in place.

According to Fournier and Bérubé (2000), large concrete structures affected by ASR are rarely demolished and/or reconstructed but there are reports of structures and structural parts that are replaced due to functionality and security reasons.

CESP has always been attentive to the occurrence of ARR in the construction of its projects since the 1960s, when detailed studies of the reaction and mitigation methods, with international consultants, were undertaken for the construction of the UHE of Jupiá, and for UHE of Ilha Solteira and also for later works. It is believed that the reaction developed in UHE Jaguari was due to failure in the research methods regarding the potentially reactive aggregates.

The visual inspections carried out at the water intake structure of UHE Jaguari, together with the plant operators’ reports on operational problems and also the observation of case studies of other structures, resulted in implementing a broad monitoring system at the UHE water intake. This included observing the relative motion of walls and retaining walls, and also parameters to indicate the potential rate of concrete expansion and the gradual progress of the phenomenon and anomalies appearing as a result.

There are numerous factors that influence the development of ARR and the magnitude of the expansions. Given the unfamiliarity with the real behavior exhibited by AAR affected structures, detailed information on structural movements are crucial for monitoring programs, namely: periodic visual inspections, additional instrumentation to quantify the displacements of cracks, joints and the structure as a whole, determine the concrete expansion rate and develop three-dimensional mathematical models of structural expansions to estimate the main and potential damage, hence ensuring that early interventions are performed. Interpreting the results of instrumentation can be done by establishing models and criteria to explain the structural behavior of the dam. Understanding the development of expansions allows issuing a feedback on the safety conditions of the structure, and also how to verify the need for mitigation repair works or prevention measures.

There are numerous mathematical models that attempt to represent the expansions caused by AAR. To validate the model, field monitoring techniques should be used for comparison and calibration.

Establishing mathematical models for the behavior of structures can assist to diagnose ARR, facilitate the structural assessment, anticipate future expansions and structural integrity and enable to observe the effects of the remedial actions implemented (Bérubé et al., 2002).

A typical modeling, in finite elements, in which the customary actions are introduced, with the proper precautions, can predict safety levels of the dam prior to the onset of any changes. Thus, the present study examined the origin of apparently symmetrical cracks observed in certain water intake locations, by means of three-dimensional mathematical modeling and by simulating ARR expansions on the walls of the structure.

1.1 Current dam situation

Signs of deterioration

Currently, the UHE Jaguari water intake structure shows signs of concrete deterioration caused by ARR. The main superficial deteriorations found in the plant's water intake are cracks, which in turn are responsible for the loss of concrete permeability and exposure of the reinforced concrete to weather conditions, there are some cracks exuding white gel, discoloration points of the concrete, among other signs.

Intense cracking

Virtually all of the concrete structures of UHE Jaguari display intense cracking. The object of this work is the slab in the water intake, which has map-type cracks, characteristic of ARR and cracks with larger openings. Figure 2 shows the overall cracking signs and also the discoloration points in the concrete. Figure 3 shows 10 mm crack openings, also located in the slab of the water intake, where the reinforced concrete is exposed and which exhibits reduced thickness due to its direct contact with weather conditions. The reinforced concrete usually ruptures due to the tensile stress induced by the opening of the cracks, but in this case, there was a loss of adhesion between the concrete and reinforcement.

Figura 2. Agrietamiento en la losa de la entrada de agua de la PH de Jaguari
(a) Agrietamiento aleatorio, (b) Grietas centrales con fisuras aleatorias alrededor
Figure 2. Cracking in the slab at the water intake of UHE Jaguari
(a) Random Cracking; (b) Oriented cracks with random cracks around it

Figura 3. Grietas con el refuerzo expuesto
Figure 3. Cracks with exposed reinforcement

Possible presence of gel from AAR

Apart from the map-type cracking, the concrete exudes a white colored material from some of the cracks in the slab, believed to be the product of AAR. This material is under study. Figure 4 shows the exudation.

Figura 4. Presencia de material blanco en las grietas
Figure 4. Presence of white material in the cracks

Cracks on the walls of the water intake plant

There are completely cracked walls and buttresses at the water intake plant. All faces show the same type of cracking. As shown in figure 5, even the internal walls of the servomotor chamber show signs of cracking. This demonstrates that cracking due to AAR occurs throughout the thickness of the walls.

Figura 5. Grietas aleatorias en las fachadas interiores y exteriores de los muros y muros de contención, en la entrada de agua. (a) Muro exterior, (b) muro de contención y (c) muro interior

Figure 5. Random cracks on internal, external walls and buttresses of the water intake.
(a) External wall; (b) Buttress; (c) Internal wall

2. Materials and methods

2.1 Mapping of cracks in the slab

Visual inspection of the slab at the water intake revealed the existence of apparently symmetrical cracks around the pillars of the loading gantry. Tri-orthogonal meters were installed on the cracks to monitor the displacements. These cracks may have been caused directly or indirectly by ARR, which is what this study intends to verify, using a three-dimensional mathematical modeling of the structure. Figure 6 shows the location of these cracks and images of the tri-orthogonal meters installed in the slab.

Figura 6. Sensores tri-ortogonales (TM) instalados en las grietas centrales, en la losa de la entrada de agua. (a) TM - 2 and TM - 3; (b) TM - 1

Figure 6. Tri-orthogonal meters (TM) installed in oriented cracks, in the slab of the water intake. (a) TM - 2 and TM - 3; (b) TM - 1

Mapping was performed in order to catalog the cracks in some places of the slab in the water intake of UHE Jaguari, this consisted in affixing a plastic film to a previously determined location, an area of about 1m^2 , where the cracks located under the plastic were drawn on the concrete using a colored pen. In due time, the plastic will again be affixed in the same location, and using a different color pen, the changes that occurred in that specific area will be drawn from the first map, therefore the appearance of new cracks and the increase of the existing ones can be monitored. Figure 7 shows the place where this mapping was performed along the slab, and the location of the cracks around the pillars, which shows the sketch of the water intake plant. Figure 8 illustrates the mapping performed.

Figura 7. Vista superior del esquema de la losa, en la entrada de agua de la PH de Jaguari

Figure 7. Top view sketch of the slab at the UHE Jaguari water intake

Figura 8. Mapeo de las grietas en la losa

Figure 8. Mapping of cracks along the slab

2.2 Computational modeling of water intake

Modeling the geometry and external connection

The modeling of the water intake structure used constant geometry data for the executive project carried out by a designer company, contracted by the owner in the 1960s. Figure 9 shows the final stage of construction.

Figura 9. Entrada de agua en la PH de Jaguari (vista frontal), en la etapa final de la construcción

Figure 9. Water intake of UHE Jaguari (front view) at the final stage of construction

In the computer program used, the geometry data input of the structure coincides with the finite element discretization. First, a 63m tower was created, using finite element CSQ – Constant Strain Quad, in other words, quadrangular elements with four nodes and linear interpolation for displacements. The tower is composed of internal and external walls, according to the structural design. Next, the six buttresses were made, and last, the slab was modeled, located at the top of the tower, measuring 10.5m x 11.5m.

Figure 10a provides a view of the water intake with the tower, buttresses and slab, modeled using finite elements, and Figures 10b, 11a,b illustrate the front, right side and top views (of the slab) of the structure, respectively. The external connection of the structure rests on the rocky mass in the lower wall and buttress region.

Figura 10. (a) vista lateral, (b) Vista frontal

Figure 10. (a) Side view; (b) Front view

Figura 11. (a) Vista del lado derecho, (b) Losa

Figure 11. (a) Right Side View; (b) Slab

Modeling of expansions and processing

The simulation of the expansions due to ASR was done taking into consideration the thermal expansions caused by a hypothetical temperature of 10 degrees centigrade, corresponding to a deformation of 100×10^{-6} . The deformation was imposed on the tower walls, the region of the structure that is immersed in the water reservoir, therefore considered more susceptible to ASR expansions.

3. Results and discussion

Figure 12 shows the results obtained in terms of maximum stress in the slab of the water intake, with the respective color palette. As can be seen, the regions of the slab subject to the maximum stresses correspond to the regions adjacent to the pillars P1 and P3, in the upstream sections where the cracks are more open.

Figura 12. Esfuerzos absolutos máximos en las losas (10^3 kN/m²)
Figure 12. Absolute maximum stresses in the slabs (10^3 kN/m²)

According to Figure 13, the region with the most intense cracking is aligned with the buttresses, located in the lower region. This result shows that, possibly, the most pronounced opening of the cracks in the corners of the slab is due to the expansion of the walls of the tower and buttresses. However, the cracking of the slab due to expansion occurs somewhat more discretely, in the traditional way, with random map-type distribution, without a preferential direction, and with the presence of exudative material.

Figura 13. Agrietamiento de la losa, con refuerzo expuesto; mostrando el muro de contención al fondo
Figure 13. Cracking in the slab with exposed reinforcement, with buttress in the background

The comparison of the results, obtained with the slab's visual inspection and the mapping of cracks and with the processing of the computational model of the structure, shows evidence of the origin of cracking. It was observed that there are at least two types of cracking, one with more open and directed cracks and another with cracks more characteristic of ASR expansions.

4. Conclusion

The methodology used enabled to formulate a hypothesis so that some crack apertures are far bigger than others, in the same slab. Additional studies should be conducted to confirm the hypothesis presented herein, the opening of cracks in the slab, as a result of expansions in the walls and buttresses of the tower. If this hypothesis is confirmed, over the course of several years the information retrieved from the displacement meters installed in the slab may be used to quantitatively estimate the expansions that occur in the structure due to ASR. The results of these estimates may be measured later, within a few years, with the readings of the recently installed extensometers to directly measure the expansions of the water intake tower.

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