STRUCTURAL EFFECTS OF AAR ON THE JAGUARI HYDROPOWERPLANT WATER INTAKE

Haroldo M. Bernardes[1]*, Rogério O. Rodrigues[1], Renato Bertolino Jr.[1]

[1]UNESP Universidade Estadual Paulista, Ilha Solteira, SP, BRAZIL

Abstract
The Jaguari hydro power plant (HPP) water intake is been affected by a swelling process, due to alkali-aggregate reaction (AAR) as proved by cores extracted for petrographic analysis. A system composed of rod extensometers, crack meters, tri-orthogonal meters and an innovative optical displacements meter was installed to monitor the behavior of the structure. It is a concrete tower-like structure 63 m tall with buttresses. Relative humidity is measured and thermometers allow knowing temperature inside and outside the structure. This paper describes a computational model of the water intake structure and compare its results with the ones obtained from the monitoring system. The aim is to estimate future strains and displacements taking into account concrete isotropic properties, environmental and confinement conditions, creep effect and damage.

Keywords: Alkali Aggregate Reaction, Finite Element Method, Structural Monitoring

1 INTRODUCTION

The structural aspects involved in the alkali-aggregate reaction are crucial to the complete understand the nature of the several effects that may appear. Although the local damages in concrete may be a serious and irreversible problem, the "structural effect" may turn it even worst by amplifying and transmitting their effects. The Jaguari HPP water intake structure presents cracking in concrete, loss of impermeability and alteration of the mechanical properties, common in structures exposed to moisture, like dams, when subjected to this chemical reaction. So serious like these may be some reflexes like the distortion and misalignment of turbines and, mainly, of equipment like gates and protection grids, that can lead to operational or safety problems.

This paper describes a computational model of the structure used to help understand its behavior and a system to monitor the structure, including instrumentation for the observation of the displacements due to the expansion developed in the concrete as result of the AAR.

The computational analysis was performed with a commercial program using bidimensional elastic elements, CSQ – Constant Strain Quad.

The monitoring techniques used for this particular application are the surveying methods and instrumentation, involving the instrument installation and monitoring of its readings. In addition to conventional instruments, an unconventional one is being used for a specific application.

Measurements provided by the monitoring system enable to value the vertical lifting and movement in the horizontal plane of the whole structure, expansions that cause fissures, the rate of concrete vertical expansion that is developing and the displacements of the walls and guide-walls that support the protection grids. Such monitoring is essential to evaluate the structural behavior of the construction and ensure that any interventions are made as early as possible.

Besides the computational model, calibrated by the results of monitoring, the entire system permits to evaluate the expansion rate of concrete, in order to estimate the continuity of the process and the extent of damage.

2 LITERATURE SURVEY

2.1 The thermo-chemo-mechanical models of AAR

The thermo-chemo-mechanical constitutive models to describe AAR expansions got impulse after 1988, with the publication of the Larive model [1] of the reactive process kinetics:

$$\varepsilon_{F,vol}^{AAR}(t) = \xi(t).\varepsilon(\infty) \qquad (1)$$

* Correspondence to: haroldom@dec.feis.unesp.br

where:

$$\xi(t,T) = \frac{1-e^{-\frac{t}{\tau_C(T)}}}{1+e^{-\frac{(t-\tau_l(T))}{\tau_C(T)}}} \qquad (2)$$

being τ_l the latency time and τ_C the characteristic time, parameters that determine the inflexion point in the normalized curve of the expansions and the intersection of the tangent at τ_l with the asymptotic unit value of ξ. Applying the Arrhenius Law, Ulm proposed in 2000 expressions to determine latency and characteristic times in function of the activation energies required to trigger the reaction for latency and characteristic times [2].

Assuming a volumetric expansion of the gel and redistribution on the basis of weights related to the stress tensor with an induced anisotropy, Saouma and Peroti proposed the following thermo-chemo-mechanical model of AAR expansion rate [3]:

$$\dot{\varepsilon}_{vol}^{AAR}(t,T) = \Gamma_t[(f'_t|w_c),(\sigma_I|COD_{max})]\Gamma_c(\bar{\sigma},f'_c).g(h).\dot{\xi}(t,T).\varepsilon(\infty) \qquad (3)$$

The model takes into account the Γ retardation tensile and compressive factors and the humidity h. Retardation depends on the concrete strength parameters and on the strain limits, including the crack opening displacement (COD), and kinetics depends on the Kelvin temperature (T).

This is an uncoupled model, except the interdependency between the mechanical and the chemical parts through the kinetics of the reaction. AAR strains can be computed separated from linear or nonlinear stress-strain relations. The use of weights controls the AAR volumetric expansion distribution with respect to the *l*, *m* and *n* principal directions.

2.2 The model used in this paper

As the water intake structure under study has a 3D complex geometry, in the present paper was preferable to perform a linear model adopting weights to take into account de effects of the hydrostatic stress, temperature, the reaction kinetics and the time (creep) [4].

2.3 Monitoring the water intake structure

The Jaguari HPP is located in the right edge of Jaguari River in the municipality of Jacareí and leading the San Jose dos Campos, São Paulo, Brazil. The power generation plant is performed by two Francis turbines with installed capacity of 27.6 MW. The reservoir has 56 square km in length and their main purpose is to regulate the flow of the Paraiba do Sul River, which is used for water supply of cities of the Paraíba Valley in the state of São Paulo and the city of Rio de Janeiro.

The water intake is a tower-like structure 63 m tall with buttresses. Water reaches the power house through a tunnel with a gap of 49.9 m downstream. Figure 1 illustrates the water intake at the time of construction and Figure 2,3 and 4 show the front view and longitudinal sections of the project. A cut view going below the deck (slab) is presented in Figure 7, showing the location of the monitoring instruments [5].

The swelling process may cause functionality problems to Jaguari HPP due to its structural configuration. It is a tower-like structure with buttresses, internally divided between walls and ceilings and exterior walls, between which the expansions may cause differential displacements and cracks.

The two lateral walls support the guides, the metal pieces where the gate move by the central caisson and where the trashrack moves by outside of the front wall. It is very important to catch possible displacements of these parts of the plant.

Based on the observations of the effects of expansions and major manifestations of the AAR and considering the aspects needed to monitor the behavior of structures affected by the problem, the main parameters to the monitoring system that were highlighted were:

- displacement of cracks in three orthogonal directions;
- relative horizontal displacements between a point in the slab on the water intake and a point in the foundation, in two orthogonal directions;
- absolute horizontal displacements measured on the slab of water intake;
- relative vertical displacements between two different layers of the structure with expandability and between the slab and a point of the foundation;
- characterization of the vertical rate of expansion of concrete;
- Absolute vertical displacements measured on the slab of water intake;
- relative displacement between the walls of the grid and guides
- relative displacement between the walls of storage compartment panels of the gate caisson (stop-log).

The choice of monitoring techniques must take into consideration, in addition to deployment on site conditions, the order of magnitude expected for the measurements. With the information on the main parameters of observation and considering displacements from the AAR with magnitude of 0.01 mm, at least, it was possible to determine the desirable characteristics and techniques used for monitoring, enabling the use of geodetic instruments and techniques measurement for the structural observations.

3 STRUCTURAL MONITORING

3.1 Methods for assessment and analysis

Monitoring the movements of cracks

To carry out the monitoring of the cracks movements there are 24 base pairs in 7 tri-orthogonal meters (MT) installed over the slab, the guide walls of the trashracks, the chamber of the servomotor, the loading gantry, in pillars and beams. The instrument named MT-3 allows to measure the open/closing movement at the main crack, close to pillar P3.

Monitoring of horizontal and vertical relative displacements

Given the expansive behavior developed by the AAR concrete, it is imperative to observe and quantify these shifts and to determine the rate of expansion developed. Sometimes affected structures develop vertical growth rates over hundred times 10^{6} by year, but the order of magnitude of this value depends on a number of factors, as seen in section 2. The specific equipment for monitoring the vertical and the rate of expansion of concrete is a multiple rods extensometer.

The quotas for the installation of the rod extensometer (EH) are determined in order to check along the vertical extent of the structure local with different expansions. For this, the first step is to identify the influence of the confinement stresses and humidity in expansions, plotting the rods in quotas that could provide this representation. To install the extensometer rod, two boreholes were used in the span of a concrete wall of water intake with diameters of 4"and 6". The 4" diameter is sufficient to install the rod extensometer, but the 6" diameter hole was used for taking profit of a pre-existing hole, initially intended to install an inverted pendulum, what was not possible.

Table 1 shows a short description of the characteristics of the holes and the installed rods, and Figures 6 shows the EH-1 and EH-2 installation process. In this work, only EH-1 is considered.

4 COMPUTATIONAL MODELING

The concrete structures of Jaguari HPP present cracks (Figures 5,6) 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 2D elastic elements, CSQ – Constant Strain Quad.

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. In the computer program used, the geometry data input of the structure coincides with the finite element discretization.

Figure 7a provides a view of the water intake with the tower, buttresses and slab, modelled using finite elements, and Figures 7b, 8a,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.

First, a 63 m 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 modelled, located at the top of the tower, measuring 10.5 m x 11.5 m.

Modeling of expansions and processing

The simulation of the expansions due to AAR was done taking into consideration the effects of temperature, stress state due to self weight and hydraulic pressure and cracks. The creep has no effect for comparison to results from instruments, since they were installed more than 30 years after the construction. The imposed expansions vary from 0 to 500×10^{-6} along the height.

5 RESULTS

Results from monitoring

Readings from EH-1 are presented in the Figure 15 and, according to the numbers, the values shown to the displacements have increasing from 2009 to 2015, but with a decreasing rate.

The corresponding cumulated expansion to each one of the rods H1, H2 and H3 are 93×10^{-6}, 248×10^{-6} and 877×10^{-6} , respectively, from the longer (64.48 m) to the shorter (13.68 m). The readings show the biggest expansion rate reaches 4mm/year or about 300×10^{-6}/year for the H3 rod.

Figure 16 presents the readings of the tri-orthogonal meter MT-3, for the open/closing movement. From 2009 to 2015 the readings had increased about 0.05 mm.

Results from modelling

Figure 13 shows the results obtained in terms of maximum stress in the slab of the water intake. 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.

According to Figure 11, the region with the most intense cracking is aligned with the buttresses, located in the lower region. This result shows that 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 on the slab itself occurs somewhat more discretely, in the traditional way, with random map-type distribution, without a preferential direction, and sometimes with the presence of exudative material.

The displacements presented in the Figure 14 show the influence of the geometry on the structural effects of AAR, amplifying the influence of the material expansion. This a significant example of the importance of the structural geometry conjugated with the structural material, or the physical aspect.

6 DISCUSSION

Comparison of the results

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.

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.

7 CONCLUSIONS

• As the measures are shown, the expansion rate seems to trend to a reduction, what may indicate a stabilization in the AAR process at the Jaguari water intake;
• The opening of the cracks in the top slab are result from AAR expansion not only in the slab, but mainly from the buttress too.
• Results of the crack openings monitoring agreed with the rod extensometers results in the sense that the expansion rate is decreasing.
• The stresses calculated with the model present coincidence with the place of the cracks more open.
• Analysis of the displacements obtained with the model show the trend to the water intake to move from upstream to downstream because of the slope in the geometry.
• Monitoring system in conjunction to computational modeling can provide an excellent tool to owners to the management of the AAR problem.
• Full implementation of the Saouma model may provide results more quantitative in future studies.

8 AKNOWLEDGEMENTS

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TABLE 1: Characteristics of the Multiple Rod Extensometer EH-1.

	Length (m)	**Installation quota (m)**	**Installation date**
H1	64.48	563.20	20/8/2009
H2	40.18	587.50	21/8/2009
H3	13.68	614.00	22/8/2009
Top/Reading	-	627.68	23/8/2009
Diameter of the hole	**Depth of the hole (m)**		
	Concrete	**Rock**	**Total**
4"	62.70	1.60	64.30

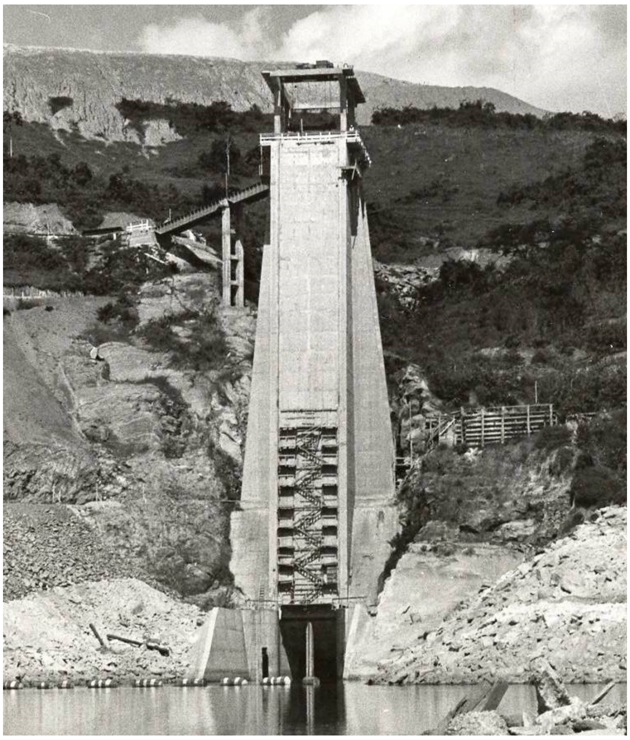

FIGURE 1: Water intake during the construction period (1960's).

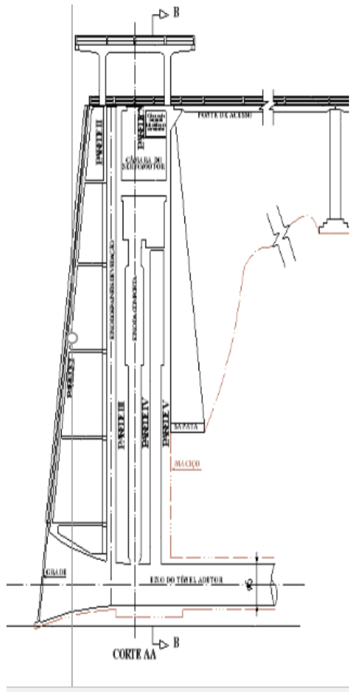

FIGURE 2: Water intake Section AA.

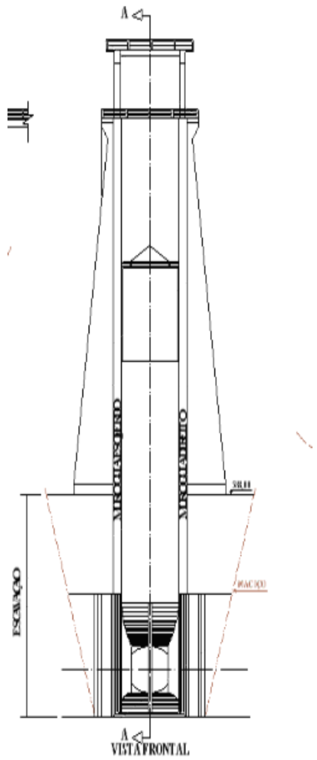

FIGURE 3: Frontal view.

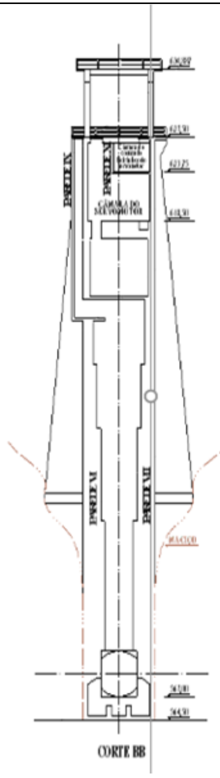

FIGURE 4: Water intake Section BB.

FIGURE 5: View of the water intake with the normal reservoir level.

FIGURE 6: Perfuration for installing the extensometers.

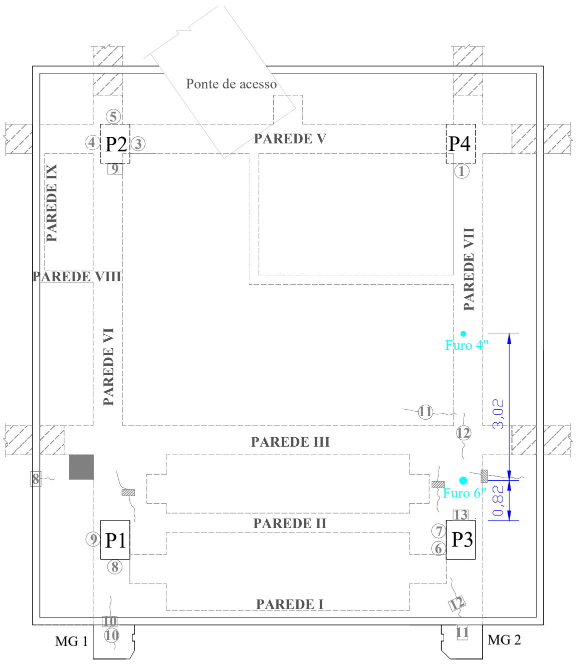

FIGURE 7: Location of the (a) EH-1 and (b) MT-3.

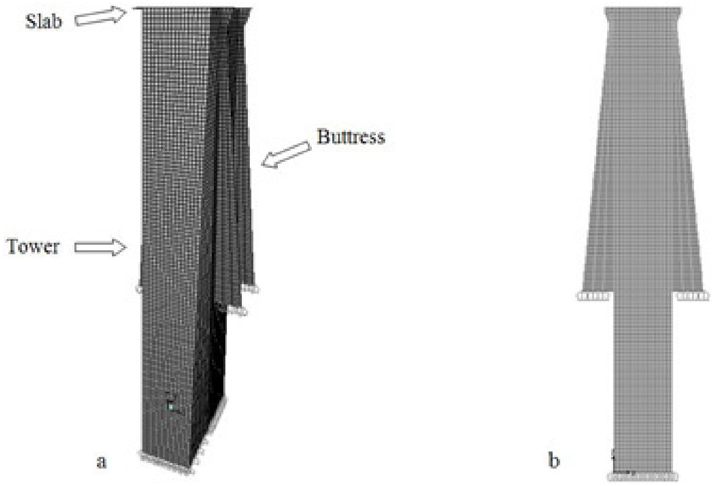

FIGURE 8: (a) Side view of the finite element model; (b) Front view.

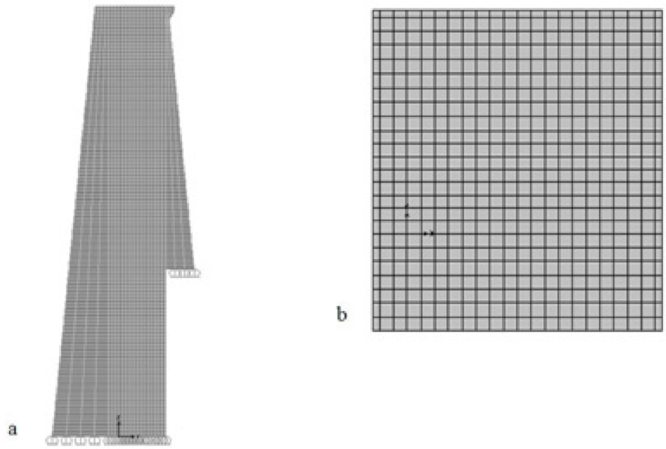

FIGURE 9: (a) Right Side view of the finite element model; (b) Top view of the slab model.

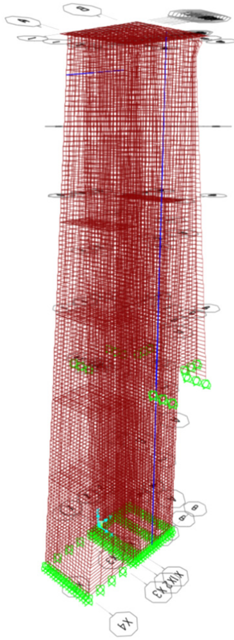

FIGURE 10: Bar finite elements (in blue) simulating the extensometer rods.

FIGURE 11: Crack opening in the slab at the top and buttress below.

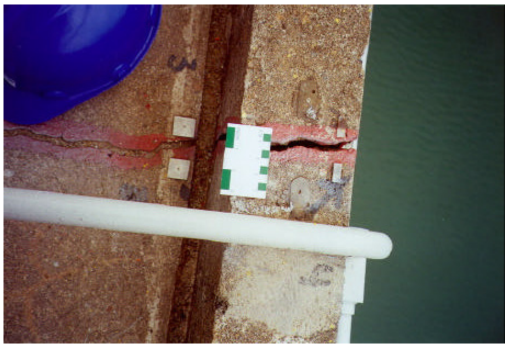

FIGURE 12: Crack opening in the slab.

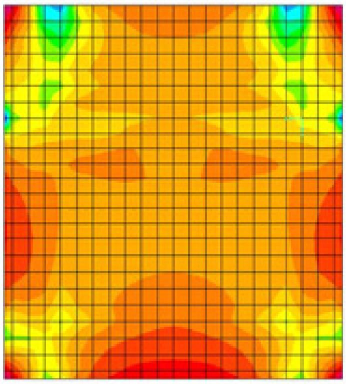

FIGURE 13: Absolute maximum stresses in the slab, from red (compression) to blue (tension).

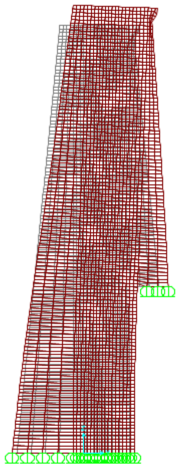

FIGURE 14: Influence of the slope of the buttress geometry on the horizontal efforts on the top slab.

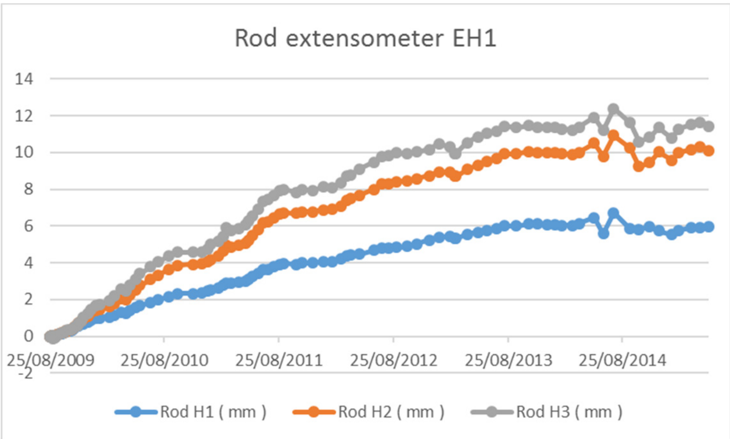

FIGURE 15: Evolution of the displacements (mm) in the 3 rods along 6 years.

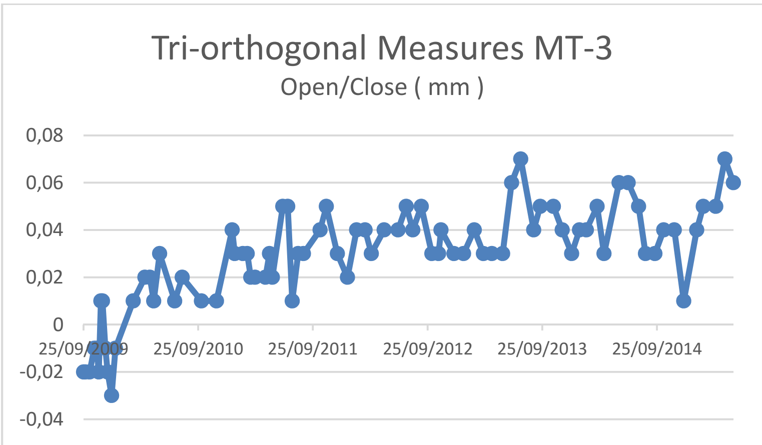

FIGURE 16: Evolution of the crack opening (mm) in the slab along 6 years.