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SPATIAL ANALYSIS OF PIEZOMETRIC DATA – ITAIPU DAM

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Abstract. *The evaluation of the structural performance of Itaipu Dam involves, among other activities, the analysis of data from instruments installed at different points of the structures and their foundations. A widely used instrument is the piezometer, which allows monitoring of uplift pressures and pore water pressure occurring in the foundation of the structures and in the body of the earthfill and rockfill dams. The piezometers provide information regarding the pressures caused by water infiltration via discontinuities in the rock mass, as well as via the pores of the earthfill. The variable supplied by the piezometers is called piezometric head, which can be converted into pressure. Monitoring is carried out in several features over large areas, which in many cases include the whole foundation of Itaipu. The main features are the contacts between structure and foundation (concrete and rock or soil and earthfill) and discontinuity or porous zones (geological faults, basaltic breccias and fractured zones, in addition to strategic points in the embankment dams). In general, the analysis of these data is performed in a timely manner, using the time series obtained by the instruments, where current values are compared with historical highs and with theoretical values obtained via mathematical models that simulate critical load situations. However, spatial evaluation allows a greater understanding of the hydrogeological phenomena, since these do not occur locally, being instead results of features' characteristics, of the drainage and waterproofing systems, and of treatments given to the foundation, as well as of the loads imposed by the presence of the reservoir and the rainfall patterns. Thus, this work aims to present the development of piezometric head and uplift pressure maps to modernize and improve the analysis of the performance of Itaipu's structures, based on mathematical interpolation and the use of Geographical Information Systems.*

1 INTRODUCTION

The work of auscultation of a dam has as its main activities the analysis of the data coming from instruments and the visual inspection of the structures and foundations. The instruments monitor different phenomena in strategic locations as defined in the project.

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The data obtained by this set of sensors permits the characterization of the actual behavior of the structures and the comparison of this with the behavior predicted in the theoretical models defined in the design phase.

This set of instruments, although extensive and installed in places most susceptible to problems, identifies possible anomalies at specific locations. This being the case, the continuous work of visual inspection of the structures is of paramount importance, in order to also evaluate the behavior of locations without monitoring instrumentation.

In the present work specifically the data of piezometers installed in the foundations of the Right Wing Dam (RWD) will be treated.

Thus, this article has the objective of analyzing the data from piezometers that monitor a geological feature within the mass of the foundations of the Right Wing Dam (RWD). The geological feature in question is known as Discontinuity D or Joint D, which is characterized by being a permeable feature of the rocky mass of the foundation.

For this work in particular, piezometric head values and uplift pressure maps will be spatially evaluated by means of mathematical interpolation methods.

The maps will be compared considering the summer period, related to the years 2015 and 2016. These in turn will be compared with the map of maximum values obtained for the piezometers since their installation to the present date, also called historical maximums.

2 LITERATURE REVIEW

2.1 Geological and geotechnical characteristics of the area under study

The Itaipu Dam was built on the basalts of the Serra Geral Formation. This formation has an approximate area of 1,200,000 km², and is inserted in the Paraná Sedimentary Basin. The Serra Geral Formation covers approximately 75% of the basin, occurring through a succession of basaltic lava flows, forming packages with variable total thickness, reaching up to 1700m. Each flow is distributed over large areas of the basin with thicknesses varying from 10 to 80m[12].

The thick flows of this Formation are typically characterized by an internal structure consisting of three distinct parts: superior vesicular and/or amygdaloidal layer, dense nucleus and a lower layer also known as basaltic breccia[3]

Studies regarding the basaltic flows located in the central-western region of the state of Paraná have verified that such flows also have the internal structure characteristic of this type of occurrence[4].

In general there are identified discontinuities associated with these flows, which can be contact between flows, internal joints, originating in the cooling of the magma, and faults, originating from the movement between layers, among others.

In order to implement the Itaipu Hydroelectric Power Plant, five different basaltic flows were intensively investigated, in ascending order, using the letters A, B, C, D and E, as shown in Figure 1.

The basaltic massifs are classified as fractured. When it comes to this type of mass, the hydrogeological behavior is governed by the discontinuity zones that have a much larger connection along the horizontal direction, having little or no vertical connection, developing in a spatial and sub-horizontal manner. These characteristics allow the passage and accumulation of water in these features, which cause pressures that, if not monitored, can destabilize the dam.

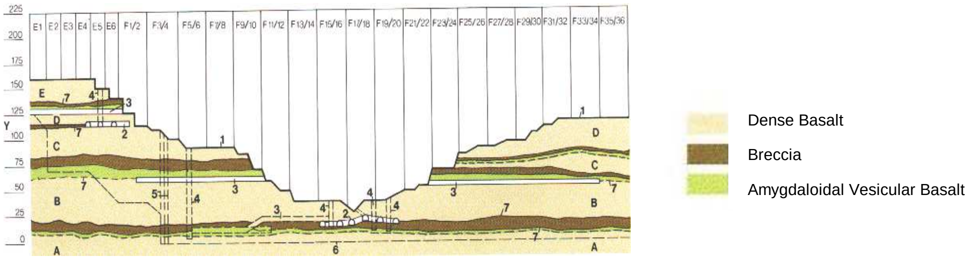


Figure 1: Location of study area

2.2 Geological and geotechnical characteristics of the area under study

Piezometers are instruments capable of providing pressure data relative to the water present inside a medium. For geotechnical purposes this pressure is generally referred to as uplift pressure for fractured media (eg: basaltic massifs) and neutral pressure for porous media (eg: earthy massifs).

These instruments are of paramount importance for the monitoring of the stability of a dam, since this type of structure is subject to these pressures, both in the contact between structure and foundation as well as inside the rocky and earthy massifs. Therefore, such loads contribute to dam instability, which can occur through a phenomenon of slipping, tipping or floating.

The most commonly used piezometers are of the standpipe type, as can be seen in Figure 2, which are made up of open tubes, whereas in the area where the pressure is be measured there is a perforated bulb, which is isolated by injection of cement grouting above the bulb. The bulbs, in general, have a length of 2 to 3 m and diameter of ¾”.

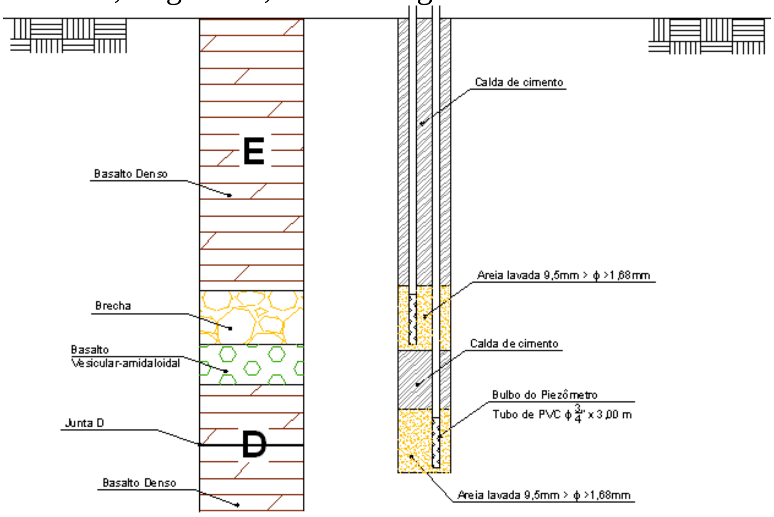


Figure 2: Schematic for installation of standpipe type piezometers at Itaipu.

These instruments provide information on the hydrogeotechnical behavior of the massifs, which is conditioned to the zones of greater hydraulic conductivity. In the case of basaltic massifs these zones are associated with regions of contact between flows, joints and groups of fractures within the flow.

In order to determine these regions of discontinuity, the profiles of rotating probes (rock drills with extraction of cores) are used. However, in some cases well and trench investigations and water loss pressure tests inside the rotary drill holes are required in order to determine the most permeable part, which would identify the position of the discontinuity zone which must be monitored.

2.3 Characteristics of variables

The piezometers basically provide two types of variables, the piezometric head (z P /γ) and uplift pressure (P /γ), as can be seen in Figure 3, where z (cm) is the position as related to the reference plane, P is the pressure (kgf / cm²) and γ is the specific weight of the fluid (kgf / cm³).

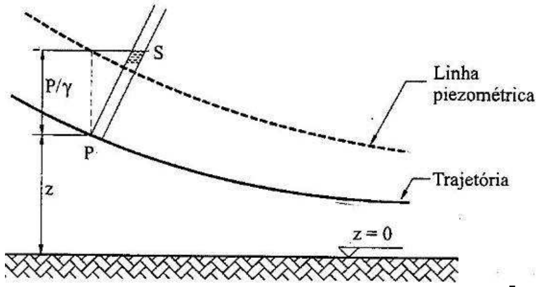


Figure 3: Piezometric head and uplift pressure[5].

Thus, uplift pressure is the pressure that the fluid exerts at the monitoring point, which can be read via the installation of a piezometer, in m.w.c.

The piezometric head is the sum of the position head (m) and the uplift pressure (m.w.c.). In the case of the installation of two or more piezometers, it is possible to identify the spatial dynamics of the water as well as the loss of head between one point and another.

In the case of dam safety evaluation, both variables are important, since one is related to the structural behavior and the other to the hydrogeotechnical behavior of the foundation, which may reveal changes in drainage and injection systems and even in the natural behavior of the mass, such as the form and direction of refilling of the aquifers.

Each of the piezometers is linked to the positioning data, such as: coordinates and elevation. Thus, each value obtained through the reading is accompanied by spatial positioning data, which can be georeferenced via a local or global reference system.

2.4 Spatial processing and representation of data

A spatially distributed variable is associated with spatial variables, which are: coordinates and elevations. The data from piezometers have this characteristic and when they are distributed spatially they can show regional phenomena originated by natural processes and, in the case of dams, also by variations or changes in the different types of demands or treatments in the structures and foundations.

In this way, these variables can reflect the variability of the medium in which the instrument is inserted, with the possibility of being interpolated to identify regional behavior trends.

2.4.1 Interpolation Methods

In order to evaluate the spatial behavior of the variables and to identify regional phenomena from data associated with spatial characteristics, such as data from piezometers, spatial data interpolation methods are used to obtain trend surfaces. Such methods can be classified as deterministic or stochastic.

The main methods classified as deterministic are those that use polynomial regression to obtain a trend surface, these methods were extensively used to treat geological data in the sixties. Another deterministic method is the one that uses multi-quadratic equations, as proposed by Hardy[6], such method proved to be more accurate than polynomial regression, especially with respect to engineering variables[7].

Other examples of interpolation methods classified as deterministic are: linear interpolation with triangles, inverse distance weighting, radial basis functions (using splines as basic function, for example), and minimum curvature.

Stochastic methods, defined by geostatistics, deal with regionalized variables, which have spatial correlation.

Geostatistics is capable of treating the genesis and the natural laws that govern regional phenomena. In addition, it allows estimating regional variables and spatial characteristics of these variables, according to data from a discrete set of samples. Geostatistics also makes it possible to evaluate the errors made in the estimates, allowing a certain degree of safety in optimum forecasts and sampling patterns according to a maximum error[8].

In order to study the behavior of regionalized variables, two tools of geostatistics stand out: Semivariogram and Kriging.

Another method of data interpolation, which can be used for the spatial interpretation of variables, is based on radial basis functions, with emphasis on multi-quadric equations. This method can be compared to the traditional estimators used for interpolation of geological-geotechnical data, as are the cases of inverse square of distance and ordinary kriging (as demonstrated in work developed by Hardy[9]; Myers[10]and Yamamoto[11], Patias[12]).

2.4.2 Piezometric Map

A piezometric map can be defined as a cartographic document representative of the distribution of the hydraulic potential (water level) of an aquifer[13]. These maps can also be called zoning and are represented by means of piezometric or equipotential lines or by distribution of a predefined color scale.

The documents generated allow the acquisition of information such as the potential difference between two points, the direction of underground flow, the possibility of communication between isolated aquifers, or the very identification of their existence and position, as well as the aquifers' recharge and discharge zones.

The aim of the analyzes of these maps is the study of the hydrogeological behavior of the massifs and inform preventive or corrective actions related to the underground flow.

2.4.3 Map of uplift pressures

The uplift pressure maps are also cartographic documents that make possible the spatial visualization of the uplift pressure values in different monitored locations. With this type of document it is possible to spatially identify the distribution of this type of request at the base of each structure, identifying the most loaded points.

This analysis together with information from other instruments may show behaviors that would be difficult to identify with a specific comparative analysis.

It is also possible to identify behavior trends in the area, which can help in the identification of new monitoring sites (instrument installation) or more detailed studies, with sampling and laboratory tests or in situ and mathematical modeling.

3 MATERIALS AND METHODS

3.1 Definition and characterization of the study area

The study presented in this paper is limited to the foundation of the Right Wing Dam (BLD), highlighted in Figure 4, specifically the geological feature denominated in the research phase as Discontinuity D or Joint D. It is emphasized that these analyzes are being extended to all geological features and contact between structure and foundation of all the dams.

The RWD (Right Wing Dam - Sections E and D) is composed of 64 blocks of buttresses arranged in a curve, located between the Main Dam and the Spillway.

Joint D, in this section, is located in the RWD approximately between elevations 120 and 160 and is characterized by being the discontinuity of greatest extension in the foundation of the Itaipu Dam, running from the Spillway to the Rockfill Dam.

The detection of this feature initially happened through rotary exploratory drilling, and the detailing of its characteristics was possible via the digging of tunnels and trenches, and during the procedures of preparation of the abutments for concreting the blocks, as well as mechanical and hydraulic tests performed in the field and laboratory.

Figure 4: Location of study area

According to the studies carried out in the identification of this feature, the following characteristics stand out for the area under study:

- Section D - Blocks D15 to D42: in the foundation zone of these blocks all the probes revealed markedly unfavorable characteristics, with the presence of open and oxidized fractures being a constant, at some points clay filling or the presence of altered rock was observed;
- Section D - Blocks D43 to D52: in the area of foundation of these blocks observations revealed that the feature is semi-open with little absorption of grouting;
- For the foundation of the other blocks of Section D the discontinuity is apparently closed;
- Section E - Blocks E1 to E2: for most of the investigations this feature is closed, however, in the zone downstream of the blocks it was observed that the rock is little altered throughout this feature;

- Section E - Blocks E4 to E6: in the zone of foundation of these blocks the feature in question registered average to low permeabilities and vestiges of clay.

3.2 Points monitored by piezometers

Joint D throughout the foundation of the RWD is monitored by 56 standpipe piezometers. The readings of these instruments are taken manually by means of electric wire and, in cases where the water surpasses the top of the tube, by means of manometer. The frequency of readings is biweekly.

The piezometers of section D and E are identified as PS-D-000 and PS-E-000, where PS stands for standpipe piezometers, D and E referring to the section, and followed by a sequential number.

In Figure 5 a section of Block D7 (Section D) is presented, where the instrumented features, including the Joint D, can be seen, it can also be seen that for this block this feature is monitored in different places, namely: upstream of the grout curtain (PS-D-14), between the grout and drainage curtains (PS-D-16) and downstream of the drainage curtain (PS-D18).

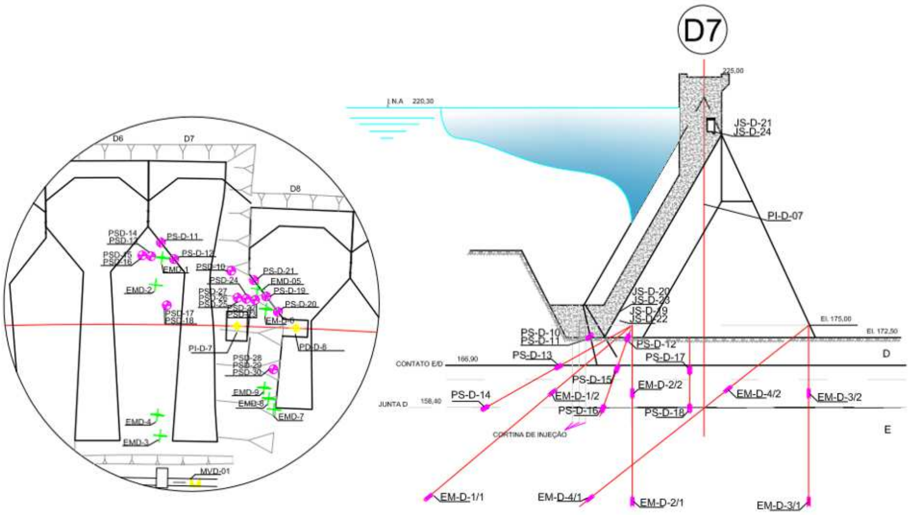


Figure 5: Instrumented section of Block D7

3.3 Characteristics of the data

In the phase prior to the process of data interpolation, it was necessary to put together a database with the values that would be mapped. For this purpose, the coordinates N and E were determined and / or consulted in reference documents, as well as the installation head of each piezometer.

Then the date for which the maps were to be generated was determined, this choice was based on the analysis method already established by the Itaipu Dam Safety team, which considers two periods throughout the year, the winter period and the summer period. According to a study developed by Porto et al.[14], it can be seen that the structure responds to the summer temperatures in the period that includes the months of March to September, and winter from October to April.

For this article the maps of maximum values relative to the summer period of the years of 2015 and 2016 will be considered, as well as the historical maximum values.

3.4 Methods of interpolation and piezometric elevations map generation and uplift pressure maps

The developed database was interpolated using the inverse square distance method. This method was adopted because it proved to be very reliable for the data in question, as shown by Altíssimo[15]. The software used for this paper is the *Sistema de Informações Geográficas* (SIG) Arc.GIS®.

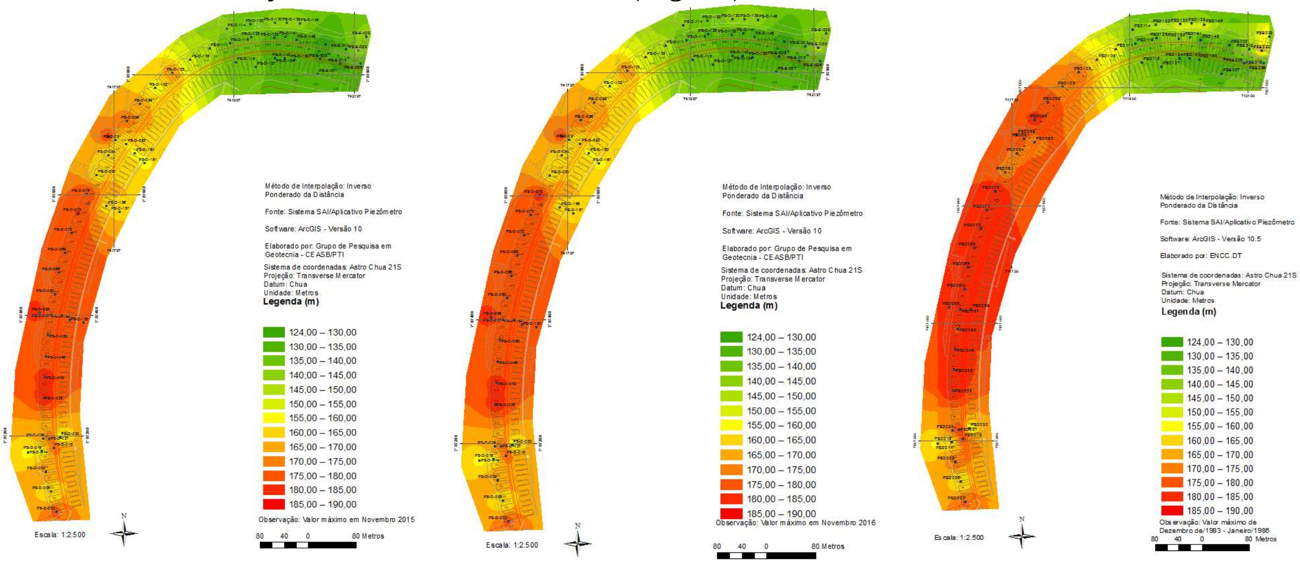
3.5 Manner of analysis of piezometric head maps and uplift pressure maps

The analysis of the maps is done in a comparative way, observing changes in the hydrogeological behavior of the feature between the summer and winter periods, and between the current year and the previous one, as well as with the map of historical values.

4 RESULTS

4.1 Methods of interpolation and mapping of piezometric elevations

Figure 6 shows piezometric maps of Joint D for the summer period between the years 2015-2016 and 2016-2017 (Figures 6a and 6b, respectively), as well as the map with the values of maximum piezometric elevations reached by the piezometers throughout the working life of the dam which, in general, happened during the filling of the reservoir and immediately after, from 1982 to 1986 (Fig. 6c).



(a) (b) (c)

Figure 6: Piezometric maps of Joint D (RWD), summer period. (a) October 2015 to March 2016. (b) October 2016 to March 2017. (c) Historical maximum.

In Figure 7, the suppression maps of Joint D for the summer period between the years 2015-2016 and 2016-2017 (Figures 7a and 7b, respectively) are presented, as well as the map with the maximum suppression values reached throughout the working life of the dam (Figure 7c).

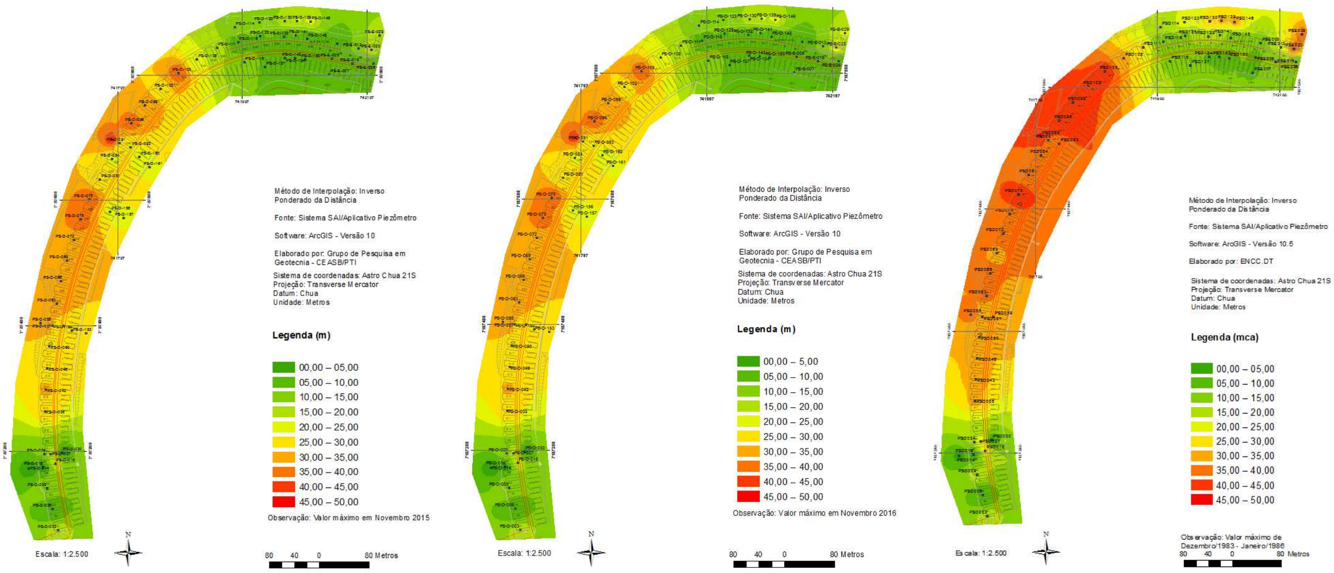


Figure 7: Uplift pressure maps of Joint D (RWD), summer period. (a) October 2015 to March 2016. (b) October 2016 to March 2017. (c) Historical maximum.

4.1 Analysis of results

It can be observed in Figure 6c (historical values map) that the region with the highest values of piezometric head is located in the foundation between blocks D11 and D47, presenting a reduction for the maps of the last two summers, being restricted to the section between D11 and D33

The zone with lower piezometric head is located in the foundation of the last blocks of Section D and the whole of Section E.

The hydrogeotechnical behavior of this feature was stable during the summer period between 2015 and 2016 (Figures 6a and 6b). The comparative analysis with the map of maximum values (Figure 6c) shows that there was a reduction of the pressures caused by the presence of water in this feature, which indicates a greater stability with respect to the action of the uplift pressures in Joint D.

In the case of uplift pressures, it can be observed in Figure 7c that these occur in the same way as in the piezometric heads of Figure 6c, with maximum historical uplift pressure areas between D20 and D47, presenting a general reduction for the maps of the last two summers.

The zones with lower uplift pressure are the first buttress blocks of section D and the last blocks of section D and most of section E.

The behavior of the uplift pressures was stable in the periods 2015 and 2016, figures 7a and 7b being smaller than the maximums in figure 7c, besides this analysis, comparing figures 7a and 7b with figure 7c it is possible to observe the reduction of the uplift pressures in the foundation of blocks D11 to D20 and D33 to D38.

5 CONCLUSION

It is concluded that the analysis done with the spatial distribution of the values of the piezometric head and the uplift pressures allows a behavioral analysis of Joint D, verifying the hydrogeotechnical condition of this feature and specifically no more, since the geological structures present regional behavior, which had already been mentioned in the geological-geotechnical research carried out for the construction of the dam.

In terms of structural safety of the RWD, it is verified that the current values are constant and below the historical highs, which indicates that, in general, the massif shows a regime of stable uplift pressures between the years 2015 and 2016.

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