Analysis of the Safety Monitoring of Earth Dams at the Belo Monte Hydroelectric Plant: Case Study of Dikes in the Filling and Operation Scenario

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Abstract: The present work seeks to understand the dam safety monitoring procedures in the filling and operation scenario using the 01- A, 01-B and 01-C dikes of the Belo Monte HPP intermediate reservoir, through the study of the different processes used to ensure the safety of that structure. The methodological path adopted was succeeded through the collection of technical information related to the dikes mentioned, in addition to the analysis of the construction projects and verification of all check lists involving field inspections and readings of auscultation instruments located in the body of the buses during the period filling and operation during the years 2015 to 2018. The work refers to a case study of a documentary nature, since data from safety monitoring are analyzed in addition to the performance of the structures. The results reveal that the Brazilian inspection agencies do not have a clear and specific methodology for the first filling of the reservoir as practiced internationally, and that in general, the monitoring mechanisms are not necessarily associated, and consequently, a non-conformity in the inspections visuals does not oblige the instrumental to have a reading outside the reference adopted as safety.

Keywords: Earth dikes; Belo Monte HPP; Dam Monitoring; Dam Safety.

1.0 Introduction

In hydroelectric use there are several risk factors that must be considered, such as: environmental factors, safety factors, technological factors, factors arising from the behavior of the structures, as well as piping. Bowles *et al.* (1999) reports that for the elaboration of an efficient analysis of dam safety risk, it is necessary to begin with the identification of potential critical points in a significant range of extremes such as periods of floods, periods with usual operation or in exceptional conditions. In this context, the scenario studied at HPP Belo Monte comprises the moment of transition between filling the reservoirs and starting operations.

The dam safety study increases the level of knowledge about the monitoring procedures and justifies items VI and VII of Art. 2 of Chapter I, items I, II, III, IV, V and VII of Art. 3 of chapter II, item I of Article 4 of chapter III of the Brazilian Federal Law No. 12,334 / 2010, which is responsible for establishing the National Dam Safety Policy for the accumulation of water for any use, at the final or temporary disposal of tailings and the accumulation of industrial waste.

According to Medeiros (2013), the Brazilian Committee on Dams (CBDB), the International Commission on Large Dams (ICOLD), the World Bank and the World Commission on Dams, says that a dam rated safe first, it needs to have acceptable structural performance, not present evidence of threat and have reduced environmental risks. These parameters are achieved by several and distinct criteria, and this increases the complexity of the analysis and contributes to the lack of explanation for most accidents resulting from dams in Brazil, in addition to

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delaying the advance of knowledge in the area.

One of the most critical periods of a bus is filling the reservoir. This moment is crucial for the verification of the structural calculations of the designer, besides being the best occasion to check the behavior of the structure; therefore, it is at this time that the saturation of the layers and the appearance of anomalies begins. Belo Monte HPP is the second largest hydroelectric plant in Brazil in terms of installed power, where it reached the 11,233 at the end of 2019 (Figure 1).

2.0 Characterization of the Belo Monte Complex

Brazil has its energy matrix with greater concentration in hydroelectric plants and the Belo Monte Hydroelectric Plant, installed on the Xingu River, in the state of Pará, contributes to this system with an installed capacity of 11,233.1 MW and an average amount of power generation of 4,571 MW , Belo Monte (Figure 2) will establish itself at the end of 2019 as the largest hydroelectric plant 100% Brazilian.

The Belo Monte HPP project is built on the Xingu River, in the municipalities of Altamira and Vitória do Xingu, in the state of Pará, as shown in Figure 3. Belo Monte HPP is characterized by presenting distinct and distant construction sites, from the main bus of the natural gutters of the Xingu River, at the Pimental site, to Sítio Belo Monte, where the main powerhouse of the enterprise is located. The distance between these two sites in a straight line is approximately 40 km. Between the sites, an addiction system to the main powerhouse was built, consisting of the bypass channel and the intermediate reservoir, the latter being formed by dikes and transposition channels, as shown in Figure 4.

The intermediate reservoir is formed by 28 containment dikes and is located, in its entirety, in the municipality of Vitória do Xingu and is limited by the Vertente do Santo Antônio dams, Left Lateral Closure, Right Lateral Closure and Water Intake, as shown in Figure 5. Dikes 01-A, 01-B and 01-C are intended to allow the creation of the intermediate reservoir, closing natural drainage valleys and water leakage points located in topographic saddles and are located on the left side of the intermediate reservoir , located in the thalweg of the drainage area of the Santo Antônio stream. The distance between dikes 1A, 1B, 1C and the Xingu River varies from 8.8 km to 10.9 km, passing through the Transamazônica highway (Figure 6). Constructive characteristics such as crest elevation, volume of the landfill, length, period of completion of the landfill and completion of dikes 01-A, 01-B and 01-C are represented, respectively, in Figures 7a, 7b and 7c.

3.0 Inspection and installed instrumentation

3.1 Auscultation of dikes 01-A, 01-B and 01-C - By visual inspection

In the field inspections, the safety conditions of the dikes are evaluated, using verification questionnaires, grouped into 7 modalities (check lists), which are:

(1) Operating conditions
(2) Amount slope
(3) Crest
(4) Downstream slope
(5) Shoulder pads
(6) Auscultation instrumentation
(7) Downstream strip

The safety check tables were developed by the Belo Monte HPP and include a color chart that indicates how to proceed and assists an appropriate communication action.

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3.2 Auscultation of dikes 01-A, 01-B and 01-C - By instrumentation

The instruments allow monitoring and detecting the occurrence of eventual anomalies, during the reservoir filling phase and the plant's operational period. The design of the dyke monitoring system by instrumentation does not consider an automated data collection system. The data acquisition process provides for direct readings of the instruments, the data of which must be stored in electronic files, usually in electronic spreadsheets of the type Excel, from Microsoft, with immediate update of values and graphs with the relation *readings x time*. The routine records must include: date, time and reading of the instrument, water levels upstream. The auscultation by geotechnical instrumentation of the dikes included open tube piezometers (Casagrande), superficial landmarks, triangular flow meters, magnetic discharge meter and level reference.

3.2.1 Open tube piezo meter (Casagrande)

The observation of underpressures in the foundation is of paramount importance for the supervision of its safety conditions, considering that the stability of these structures is directly affected by the level of piezometric pressures downstream of the vertical filter. Table 1 shows the identification of the instrument, stake, spacing of the shaft, dimension of installation and the material to be instrumented, respectively, of dikes 01-A, 01-B and 01-C.

3.2.2 Superficial Landmarks

The horizontal displacements of the superficial landmarks were measured through geodetic collimations, while the vertical displacements (settlements) consisted of measurements through precision leveling. The readings can be taken through a total station as long as the device has an accuracy of approximately 3 mm for distances of the order of 400 m. Table 2 presents the identification of the instrument, pile, spacing of the axis, and installation dimension, respectively, of the dikes 01-A, 01-B and 01-C.

3.2.3 Triangular Flow Meters

The measurement of infiltration flows by the foundation and the dyke mass constitutes one of the most important quantities to be supervised in the reservoir filling phase and in the operation period. Observations of a greater amount of infiltrated water and the carrying of fine material reflect some of the problems that can happen with this type of structure. Table 3 presents the identification of the instrument, pile, spacing of the axis, and installation dimension of dikes 01-A, 01-B and 01-C, respectively.

3.2.4 Level Reference

The level references, located on the jambs of the dikes 01-A, 01-B and 01-C, are the points of support in the reading of the superficial landmarks. They were installed in order to ensure that its metal rod reaches the surface of healthy rock making them indescribable points. The positions of the level references of each dike are shown in table 4.

3.3 Reading Frequencies of the Dyke 01-A, 01-B and 01-C instruments

The frequencies for reading the dyke auscultation instruments are shown in table 5, for the construction periods, reservoir filling, first year of operation and operation. The reading frequencies presented were understood to be minimal and always intensified when observed readings that exceed the attention value, or other exceptional occurrences, which resulted in marked variations in readings such as, rapid lowering of the reservoir, exceptional floods, sensitive earthquake in the dike area , anomalous or suspicious behavior of the structure or of any instrument, events that imply abnormal loading or unloading of the bus structures.

4.0 Monitoring of filling of reservoirs

The filling of the bypass channel and the intermediate reservoir of the Belo Monte HPP represented one of the fundamental milestones of the project. Initially it was predicted that the 95.00m quota in the water intake would be reached in 50 days and 1 h, but this process happened after 60 days and 9 h. The filling process advanced until the water level near the water intake reached an elevation of 97.0 m, but after the water level of 95.0 m, it was already possible to start the commissioning activities of the generating units.

For the formation of the intermediate reservoir, 28 containment dikes were built, which bar the saddles and slopes of the streams. The dikes have a homogeneous section on land and are built with soil originating from localized loan areas, almost entirely, within the flooded area, in order to cause minimal environmental impact or even taking advantage of the excavations carried out for the transposition channels.

The intermediate reservoir consists of eight hydrographic basins connected by seven transposition channels, three filling channels and two water dividers (natural transposition between basins). In a schematic way, the system of basins and channels that make up the intermediate reservoir is shown in Figure 8. It was through the control of the gates of the filling spillway that maintained the defined flow for each of the filling stages of the system. The spillway was designed for a maximum flow of 1000 m³ / s, considering the water level in the Pimental reservoir, at an elevation of 97.0 m.

As a condition to reduce the erosive effects due to the filling process, it was determined that the initial stage of filling the valleys was carried out with gradually increasing flows up to a flow of 200 m³ / s. The effluent flow from the filling spillway only increased to 500 m³ / s when the water level in the intermediate reservoir valleys reached an elevation of 71.0 m. This flow was maintained until the water level in these basins reached an elevation of 75.0 m. From then on, the filling proceeded with the two spillway gates fully open (with a flow of up to 1,000 m³ / s).

In order to guarantee an adequate system filling process, it was important to pay special attention to the continuous monitoring of water levels in the different millimeter rulers installed along the bypass channel and the intermediate reservoir in order to allow a correct operation of the spillway gates. In addition to reading rulers and instruments, it was necessary that during the filling process, visual inspections of the various structures that make up the adduction circuit were carried out in order to ascertain whether these structures were behaving properly during this process.

5.0 Presentation and Analysis of Results

For the study of the dam safety monitoring procedures in the transition scenario between the implementation and the start of the Belo Monte hydroelectric operation, the period was delimited starting from the first inspection, carried out in 2015 before filling the reservoirs, and following in the assessment of inspections carried out after filling in the years 2016 to 2018, of dikes 01-A, 01-B and 01-C. The classification of dikes according to their risk category and DPA, has a final classification B, a low risk category, but with a high potential damage associated, that is, in line with ANEEL Normative Resolution 696/2015, for structures classified as B in the Dams Risk Classification Matrix, a Safety Inspection Report must be prepared on an annual basis. For dikes 01-A, 01-B and 01-C these actions are two, namely, visual inspections, together with the analysis of readings of the dam's instrumentation, and represent essential activities for the assessment of the safety status of the dike , since they allow the detection of previous signals through evidence of what may become an emergency. Emergency management applied to dams consists of a set of coordinated actions that aim to minimize the magnitude of possible damage due to incidents and accidents, ensuring the most appropriate response during and after the occurrence of an anomalous event to the operation of the dam.

5.1 Auscultation of Dikes 01-A, 01-B and 01-C by means of visual inspections

For auscultation of dikes through visual inspections, 12 checklists from each dike were analyzed, with 7 verification modalities grouped, so the analyzes within the defined period total 252 safety checks. The field inspections consisted of covering the crest of the structure, the intermediate shoulders and the downstream foot. It is important to note that the checklists analyzed are all existing between the period 2015 to 218 of the Belo Monte HPP, and include the filling and post-filling of the reservoirs. Table 6 shows the inspection period for each dike.

5.1.1 Visual inspections modality operating conditions

The occurrences of dikes identified through field inspections and recorded in the checklists in the operating conditions modality are recorded in Table 7. In the operational conditions, among the items analyzed the lack or deficiency of signposts and lack of available strategic stock were present in all checklists of dikes 01-A, 01-B and 01-C, however, it is worth noting that the period defined for the application of the present research, the work was still in progress, that is, the existing crushing plant supplied the need for materials for possible interventions. The lack or deficiency of signposts was considered at the end of the intervention downstream of dikes 01-A and 01-B.

Dike 01-C, despite not having undergone any intervention after filling the reservoir, the non-compliance remained due to its simplicity, since despite being a mandatory item to be inspected under operational conditions, the deficiency of signage and stock for any intervention did not affect the safety of the structure. However, these items were mandatorily remedied in the commissioning of the buses. Dike 01-B, on the other hand, was the only one that presented non-conformities in the items of conditions of access to the structure and inspections, registered, respectively, five and twice in different check lists in the aforementioned period, but only in 2016. of maintenance solved the pending issues.

5.1.2 Upstream slope visual inspections

The occurrences of dikes identified through field inspections and recorded in the check lists in the upstream slope modality are recorded in Table 8. There was a record of depressions or sinking of blocks in the check lists of September 2016 and the presence of a tree or shrub in two 2018 checklists on dikes 01-A and 01-C. Dike 01-B in the entire period studied showed non-conformity in only one item, that of surface erosion, the same being registered in the first two check lists of 2018 and resolved in the third and last check list formalized in October of the same year. Although the presence of a tree or shrub is an adverse situation to the harmony of the structure and found in four checklists, the most relevant points of non-conformity in the verification of embankment upstream are those related to depression and sinking in addition to surface erosion, therefore, they directly imply the relationship with the filling of the reservoir itself, since the upstream slope face undergoes the immediate actions of the reservoir load.

5.1.3 Visual modality inspections

The occurrences of the dikes identified through field inspections and recorded in the check lists in the crest mode are described in Table 9. Items about the absence of staking along the structure was present in all check lists, it is recommended to insert the definitive staking in the crest of the structure, in order to facilitate the location of the instruments as well as any anomalies.

However, it is worth mentioning that the dikes had not yet been commissioned in the period defined for this article. Dike 01-C was the only structure among those studied that suffered localized depression and longitudinal cracks, both in 2016 and quickly corrected by the maintenance sector. After correction of the abnormality, these two items did not reappear again until the end of 2018.

5.1.4 Visual inspections downstream slope modality

The items inspected on the downstream slope had critical points delimited in the years between 2015 and 2016 right after filling the reservoir. In the body of the embankment of dikes 01-A, 01-B and 01-C there was the presence of surface erosion, poor conditions in the drainage channels, occurrences of superficial cracks, evidence of water emergencies, bad shoulders and inadequate plant protection. In the foot drain and drainage channels, superficial contamination of the foot drain (Solo), deficiency in the lateral protection of the channels and occurrences of channel silting, shown in Table 10, were detected.

In dike 01-A, in 2015, the presence of cracks in the slopes that were not hydrosemed was recorded, as well as cracks due to dryness, among the EL. 90 m to 100 m. Between 2015 and 2016 in the vicinity of the abutments, the dams 01- A, 01-B and 01-C were found to have clear water and lagoon formation, close to the PZ-D01A-06, PZ-D01B-04 and PZ respectively -D01C-14, however, it was later certified that the lagoon downstream of dike 01-C already existed before the reservoir was filled. The item on plant protection in the downstream slope also appeared in all dikes between the years 2015 to 2016, however it was expected, since the structures were ready in less than a year and the plant protection was still in the growth phase.

In 2016, surface erosion, bad shoulders, superficial contamination of the foot drain, poor conditions and protection in the drainage channels associated with the occurrence of silting via channels in dikes 01-A, 01-B and 01-C were recorded. These non-conformities were the result of the lack of plant protection described in the previous paragraph, that is, due to the lack of plant protection that was under development.

5.1.5 Visual inspection of shoulder pads

The occurrences of the dikes identified through field inspections and recorded in the check lists in the jamb mode are shown in Table 11. Dike 01-A, in the check list dated 11/28/2015, presented the first record of evidence of emergencies d'agua, the report of that period formalized that in the vicinity of the left jamb of the dike it was verified the appearance of clean water and formation of lagoon, close to PZ-D01A-06. The maintenance team immediately intervened, and this anomaly did not appear again in the following reports.

After the reservoir filling period, from the last check list in 2016, superficial erosion (ravianning) was detected in the jambs of the dike 01-A in seven check lists between the years 2016 to 2018, the same non-compliance reached the dikes 01 -B and 01-C, however, in smaller incidences being, respectively, a check list in 2016 and two check lists in 2018. The lack of trees in the vicinity of the jambs were also occurrences against the harmony of the structure for the dikes 01-B and 01-C, however, it should be noted that the period registered for this event was precisely in the first year after the construction of the dam and filling of the reservoir, trees were planted and non-compliance did not appear again in the check lists of the years 2017 and 2018 Occurrences such as poor surface drainage conditions were recorded in dikes 01-A and 01-C, between the years 2016 to 2018. All of them originated from the drainage deficiency. These anomalies mainly caused erosion in the shoulders of the two dikes, however, as of the third check list dated in October 2018, these non-conformities had been resolved.

5.1.6 Visual inspections of auscultation instrumentation

The occurrences of dikes identified through field inspections and recorded in the checklists in the auscultation instrumentation modality are described in Table 12. Among the occurrences, the most frequent was the deficiency in the protection of piezometers, flow meters and surface landmarks, in addition to level reference equipment. This non-compliance was recurrent among the three dikes studied and were recorded in the years 2015, 2016, 2017 and 2018. The major factor that motivated the excess of this record was the reason for the interventions downstream that the dikes 01-A and 01-B they submitted themselves in addition to the non-commissioning of the structures until the end of 2018. Regarding the deficiency in the conditions of access to instrumentation equipment, which is very present in the check lists of dike 01-A, it reflected the stairs being temporary in wood.

All definitive accesses were scheduled to be implemented close to the commissioning of the buses, at the beginning of the year 2019. The need for cleaning around the instruments were occurrences recorded in the years between 2016 and 2018 exclusively in dikes 01-A and 01-C, this non-compliance occurs sporadically and can be easily resolved by maintenance teams. The failure to identify the equipment occurred mainly in the first months after filling the reservoir in all the dikes, even in 2016 all instruments had been provisionally identified; however, it was necessary to intervene because of weather conditions.

5.1.7 Visual inspections downstream lane modality

The main occurrences of the dikes identified through field inspections and recorded in the check lists in the downstream strip modality and are recorded in Table 13. The occurrences in the downstream strip were present since the first check list, dated in November 2015, where surface erosion was recorded, poor conditions in the drainage channels, evidence of water emergence, occurrence of humidity, presence of trees or shrubs, deficiency in cleaning the downstream strip and formation of the downstream pond in dikes 01-A, 01- B e 01- C formation of a lagoon in the downstream strip is an occurrence that is quite relevant after filling the reservoir, and was recorded in all check lists of 2015 and 2016 of dike 01-A, however, in 2017 it was verified that the existing lagoon and registered in the previous checklists already existed before filling the reservoir, therefore, this event did not appear in the inspections of 2017 and 2018. The same occurrence of lagoon formation Downstream rate was also found in the check lists of dikes 01-B and 01-C in the entire study period that includes the years 2015 and 2018. And they were being monitored to adopt the best form of intervention.

The signs of water emergence, humidity and the presence of a tree or shrub were recorded in practically all visual inspections of dikes 01-A, 01-B and 01-C, between 2015 and 2018, and it was the justification for the decision to subject dikes 01-A and 01-B to intervention downstream of the structure. Inverted drains were made in both dikes.

5.2 Auscultation of Dikes 01-A, 01-B and 01-C by means of instrumentation

For auscultation of dikes by means of instrumentation, all instruments located in the body of the busbars were analyzed, and the analysis of the available information is delimited between the years 2015 to 2018. Table 14 shows the summary of these instruments for each structure.

The control values of the readings of the instruments of the dikes 01-A, 01-B and 01-C are divided, whenever applicable, into two categories: attention values and alert values. The readings of the instruments that result in values below the attention values show that the behavior of the structures must be normal and according to the design criteria, according to which they were designed. The alert values, on the other hand, indicate the maximum acceptable values for each instrument, from which more detailed design analyzes should be carried out, since the minimum acceptable safety conditions may be being compromised.

5.2.1 Open tube piezometer instrumentation (Casagrande)

The attention and alert values of the piezometers were defined through numerical modeling, from simulations performed for scaling with the SLOPE / W computational software. For the definition of the attention value using these models, the phreatic line obtained in the percolation studies in operation regime (N.A. of the reservoir in the Maximum Normal quota, EL. 97.00) is imposed. Downstream of the vertical filter, the continuity of the phreatic line coincides with a hypothetical saturation line of the massif above the draining mat, which leads the structure to present a safety factor equal to 1.50 (FS = 1.5). In this condition, the piezometric loads that define the attention values are obtained by the difference between the water table considered and the installation dimensions of the instruments. Similarly, for the definition of alert values, the same methodology is applied, adjusting the phreatic line, in the section downstream of the vertical filter, in order to obtain a safety factor FS = 1.3.

The behavior of the data of the piezometers located in the body of the dikes 01-A, 01-B and 01-C between the period of filling and operation were presented without great variations. However, on dike 01-A, piezometers 02 and 04 were the instruments that came closest to the values of attention and alert, both concurrently in the same period between the months of March to May 2017. The PZ-D01A-02, has values of attention to a quota of 92.33m and alert of 94.35m and the values of the attention and alert load are respectively 24.36 mca and 26.38 mca The reading on March 6, 2017 recorded a quota of 89.01 and a load of 21.04, the closest to the attention values. The PZ-D01A-04, on the other hand, has attention values for a quota of 88.22 m and an alert of 88.70 m and the values for the attention and alert load are respectively 20.11 m.c.a and 20.59 m.c.a. The reading recorded on May 29, 2017 recorded a quota of 86.79 and load of 18.68, that is, values very similar to those established as a warning, as shown in Figures 9, 10, 11 and 12.

In dike 01-B, all piezometers are extracted only for reference readings, since the water table in the region does not affect the safety of the dike. And when the period of filling and operating period was evaluated, no reading came close to the established reference values of the instruments.

Dike 01-C, on the other hand, despite having thirteen piezometers, only the first six present data to verify the safety of the structure. The PZ-D01C-06 is the only one that presents its data close to the values of attention and alert. However, despite being readings very close to the levels of attention and alert, graph 34 shows stabilization of the values of quota and load obtained. Between the period studied, the reading on March 6, 2018 has values of 69.82 for quota and 4.55 for cargo, and its reference values are 71.20 for quota and 5.93 for cargo, as shown in the Figures 13 and 14.

In the piezometers not mentioned, the load line and elevation readings followed the movement of the level of the reservoir and the landfill line, in addition to behaviors that were absolutely below the attention and alert values established for the safety of these structures.

5.2.2 Surface mark instrumentation

In the superficial landmark instruments, the maximum crest settlement for dikes 01-A, 01-B and 01-C was adopted vertical deformation equivalent to 0.5% H, based on the safety simulations of this instrument, where H is the height of the dam. Thus, for landmarks installed in landfills with heights greater than 5.00 m, characteristic of dikes 01-A, 01-B and 01-C, the criterion used to determine the attention values was 50% of the maximum displacement defined for the crest of the Dyke, that is, 0.25% H. For alert values, 100% of the value was adopted, that is, 0.50% H. Table 15 presents the readings referring to the values of attention and alert of the superficial landmarks of the dikes.

Taking as a basis the monitoring of the surface landmarks readings performed after filling the reservoir and during the first year of operation, it is observed that the displacements measured by the surface landmarks were within the normal range. Although the data does not represent a static and / or stable behavior, all variations within the filling and operation period did not represent any risk to the levels of attention and alertness. Therefore, in the studied period, the structures of dikes 01-A, 01-B and 01-C had a good structural behavior, eliminating the need for intervention due to repression or displacement.

5.2.3 Instrumentation by triangular flow meters

The flow meters of dikes 01-A, 01-B and 01-C have the function of monitoring percolation through the foundation and the internal drainage system of the dyke. The effluent waters of the internal drainage system are of interest for the safety of the dam mainly in two aspects: incident flow and transport of solid particles. Observations of increasing flows over time and the presence of fine material in suspension may reflect some of the problems that can occur with this type of structure. However, the measured values were taken only as a reference to assist in the interpretation of the structure's behavior, together with the evaluation of the readings of other instruments and must be analyzed together with piezometric data to verify the efficiency of the internal drainage system.

After analyzing the graphs of the flow meters where the reference value corresponds to the flow obtained from the numerical modeling, under operation regime (El. 97.00), increased by five. This value represents 50% of the flow calculated for the design of the internal drainage system of the structures. Figure 15 referring to dikes 01-A also registered in 2016 a peak flow very close to the reference value considered for attention. In Figure 16 representing dike 01-B until the year 2017, at least three instrumental readings showed a flow above the allowable reference for the structure. Along with these readings there was distortion in the piezometric data of the same structures, in close periods. When the same anomaly, non-conformity and / or manifestation outside the desirable appear simultaneously in both monitoring methodologies. Therefore, the dam safety situation is the most unfavorable and requires immediate emergency action. The flow meters of dike 01-C showed readings well below the reference for attention during the entire period of filling and operation of the structure. The dike's piezometers also revealed no reading that could put safety at risk.

6.0 Conclusions and Final Considerations

The safety monitoring of the dikes 01-A, 01-B and 01-C of the Belo Monte complex was detailed, allowing to establish, based on the integration of the information, that despite the 364 adverse events, the harmony of the safety of the dikes and constants in check lists from filling to operation between the years 2015 to 2018, the majority that increased and that were repeated were inspected items of lesser safety and that fell in the absence of the commissioning process that meant the delivery of the executing consortium for the operation group. The occurrences most adverse to the safety of the structures were also subject to the commissioning hierarchy. However, when observing the checklists for the year 2018, most of the occurrences had been mitigated, as the delivery of the structures approached the operating company Norte Energia.

Although the filling of the reservoir immediately causes natural phenomena such as saturation and under pressures, the performance of dikes 01-A, 01-B and 01-C were adequate. However, through the analysis of the charts of the auscultation instruments, it was only possible to achieve stabilization in the readings from the first year after filling. Foster et al. (2000) presents statistics that about 50% of failures involving dams occur during the first filling and 64% of situations that contradict the safety of the structure occur in the first 5 years of operation. There are international recommendations that there is a project to monitor the first filling, and that this action should not be limited to the filling itself as happened at the Belo Monte HPP.

It is known that the dam safety inspection bodies in Brazil have the autonomy to legislate within their competences, obeying the PNSB guidelines. Hydroelectric Plants are directly supervised by ANEEL, the information is forwarded to ANA, which in turn issues the Annual Dam Safety Report, which is forwarded to the National Water Resources Council and to the National Congress. However, none of these Brazilian bodies requires a clear methodology or proposal for a plan on the first filling according to the methodologies already adopted at the international level. Based on the statistics of research and procedures practiced internationally, it is important that Brazil adopts a more specific plan that involves the speed of filling, monitoring with rapid response instruments and contingency plans.

Unlike dike 01-C, which did not undergo any intervention during the studied period, dikes 01-A and 01-B were subjected to corrective actions to ensure safety, based on occurrences recorded in the field with readings of the instruments that registered variations. And it was precisely the correlation between the instrumental data and the evidence of manifestations in the field check list that strengthened the need to intervene urgently. The existence of a connection between field inspection methodologies and the results of reading the instruments was a positive association and played an important role in decision making during the entire filling and operation period of the Belo Monte hydroelectric complex.

In general, the monitoring mechanisms are not necessarily associated, a non-conformity in the visual inspections does not oblige the instrumental to have a reading outside the reference. However, the analysis of these mechanisms in a combined way guarantees a conservation and greater safety of the structure. Therefore, it is observed that there is no methodology more important than the other, but that the use of both complement each other to provide more safety to the dam and allow the implementation of measures prior to the occurrence of any emergency in the structure, mitigating the possibility of a emergency situation and all the consequences associated with the scenario related to it.

7.0 References

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USINA HIDRELÉTRICA DE BELO MONTE (UHE BELO MONTE). **Relatório técnico do plano de ações emergências (PAE) – Dique 01-B**. Brasília: Norte Energia, 2016. 88 p.

USINA HIDRELÉTRICA DE BELO MONTE (UHE BELO MONTE). **Relatório técnico do plano de segurança de barragens (PSB) – Dique 01-B**. Brasília: Norte Energia, 2016. 42 p.

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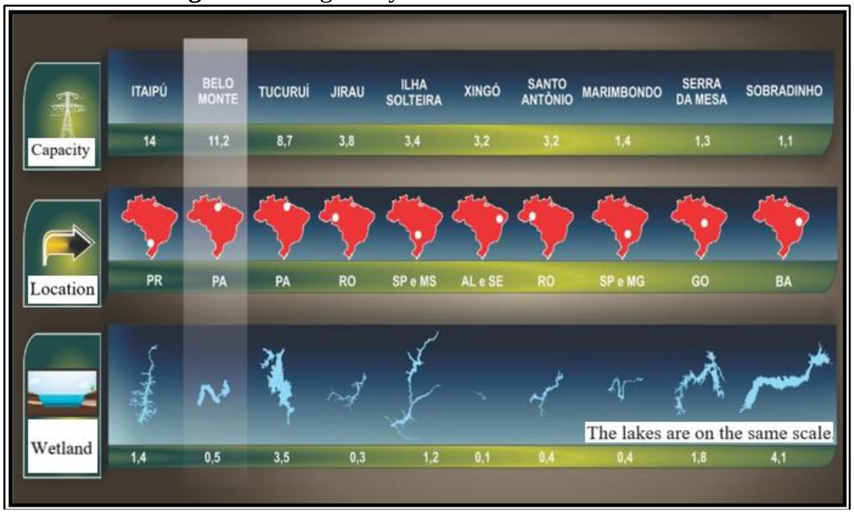
Figure 1 - Largest Hydroelectric Plants in Brazil

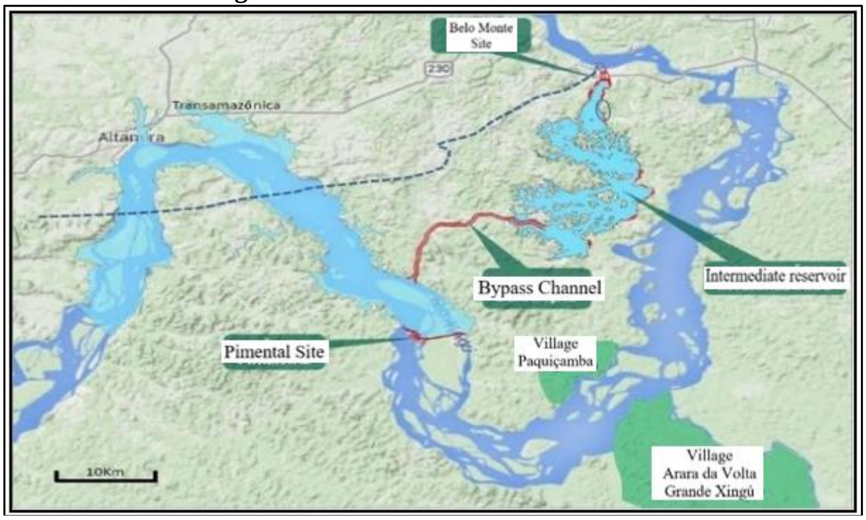


Source: New Employees Presentation Report (2018)

Figure 2 – Belo Monte HPP

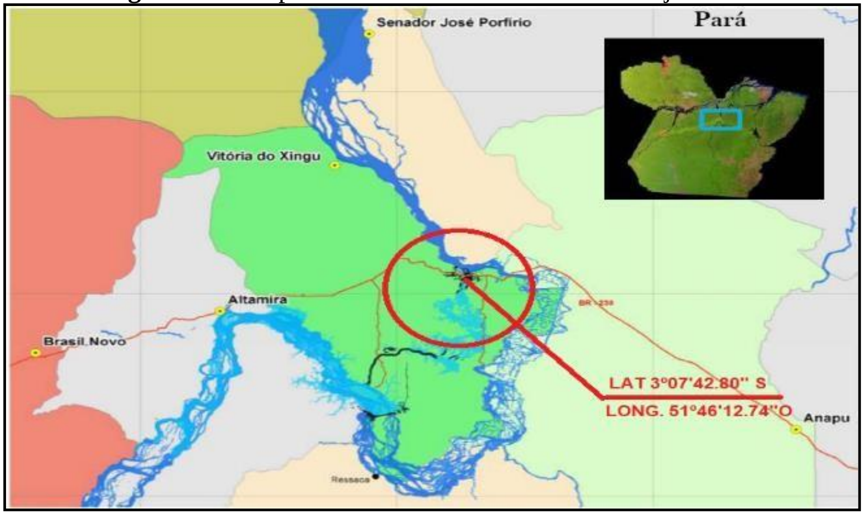
Source: Norte Energia (2019)

Figure 3 – Belo Monte HPP location



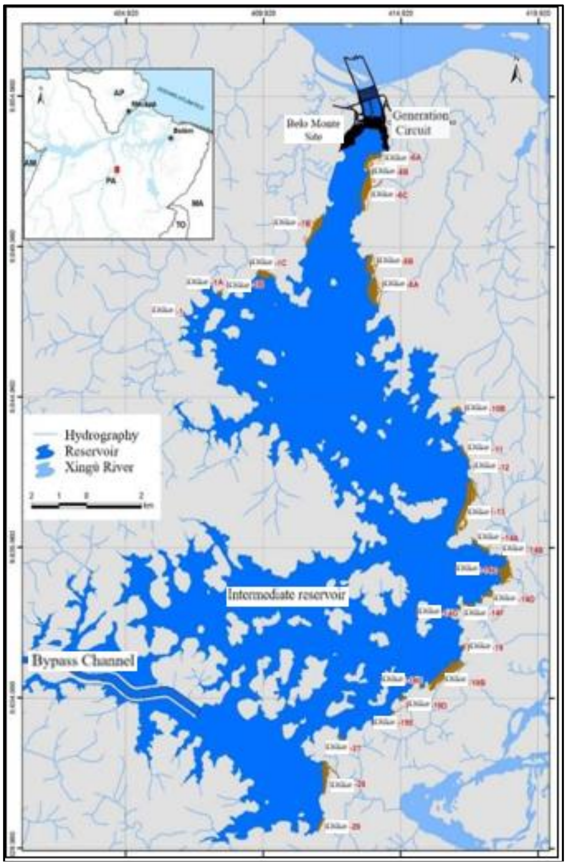
Source: Emergency Action Plan – BELO MONTE (2016)

Figure 4 – Composition of the Belo Monte HPP Project



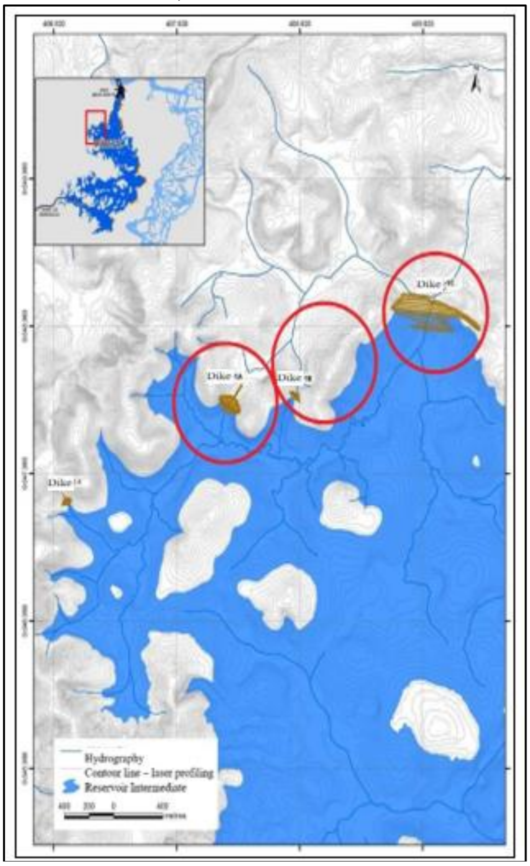
Source: Emergency Action Plan – BELO MONTE (2016)

Figure 5 – Intermediate reservoir and its containment dams at HPP BELO MONTE



Source: Emergency Action Plan – BELO MONTE (2016)

Figure 6 – Location of Dikes 01-A, 01-B and 01-C - Belo Monte Site - Belo Monte HPP



Source: Emergency Action Plan – BELO MONTE (2016)

Figure 7 – Constructive characteristics of dikes

Crest Elevation	100 m	Length	185 m
Landfill Volume	140.822 m³	Landfill Completation	21/08/2015
		End of the Dike	01/11/2018

Crest Elevation	100 m	Lenght	100 m
Landfill Volume	5.972 m³	Landfill Completation	19/01/2015
		End of the Dike	21/07/2018

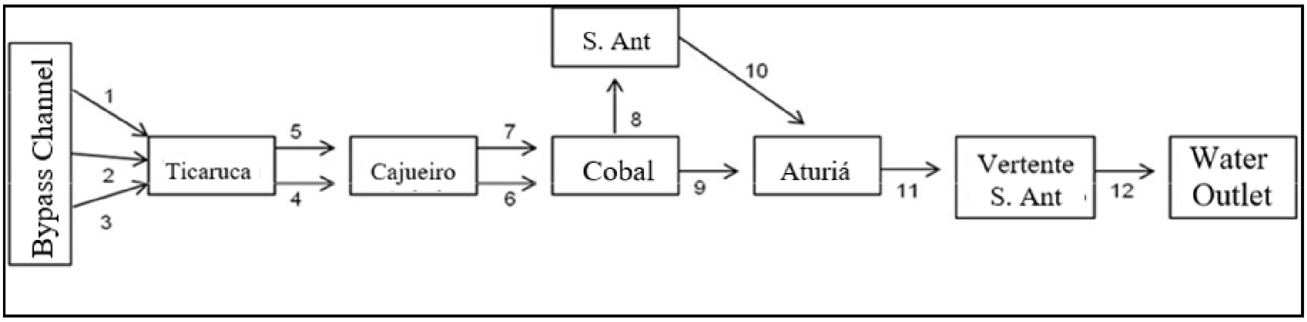
Crest Elevation	100 m	Lenght	740 m
Landfill Volume	844.466 m³	Landfill Completation	05/11/2015
		End of the Dike	11/11/2018

Source: Emergency Action Plan – BELO MONTE (2016)

LEGEND:

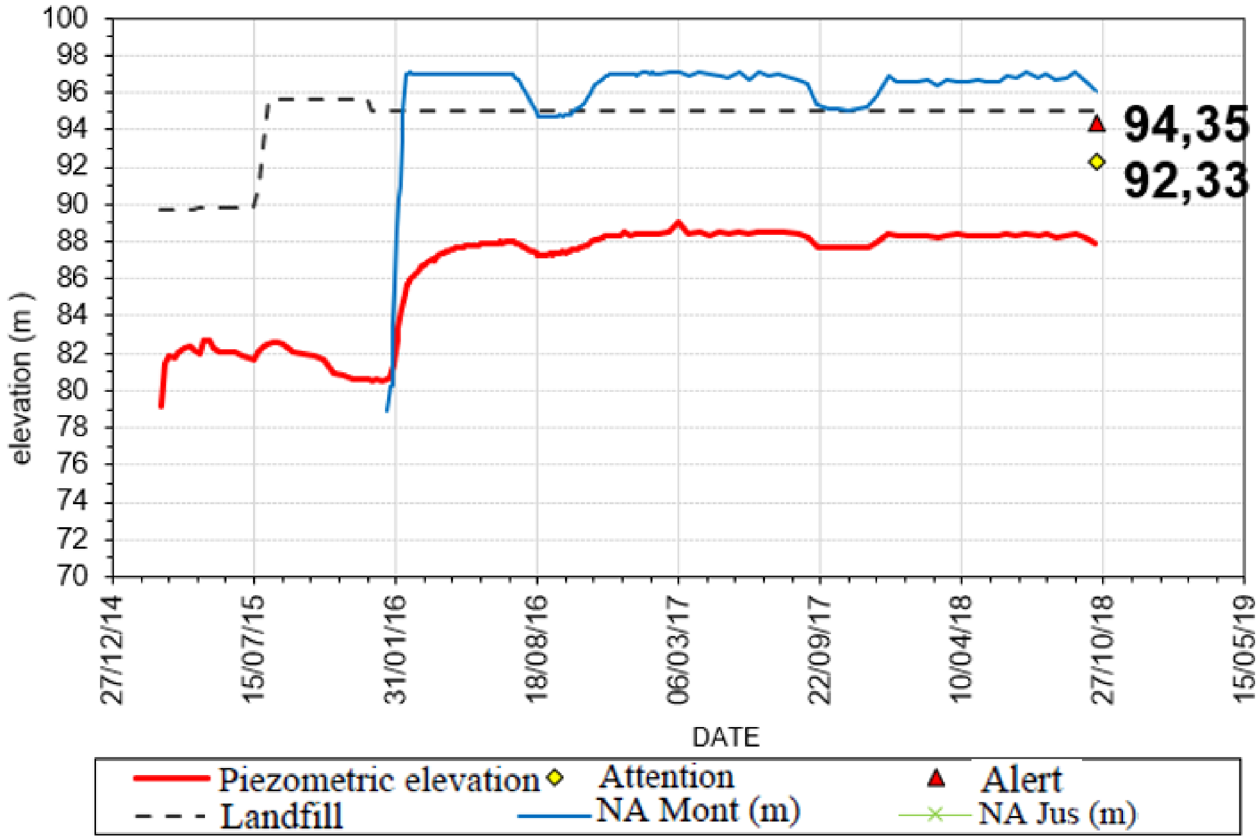
- Anomaly Requires Monitoring
- Anomaly Requires Repair
- Anomaly Requires Short-Term Corrective Action
- Anomaly Requires Emergency Action, Immediate Repair

Figure 8 - Intermediate Reservoir - Transposition scheme between basins - Belo Monte HPP



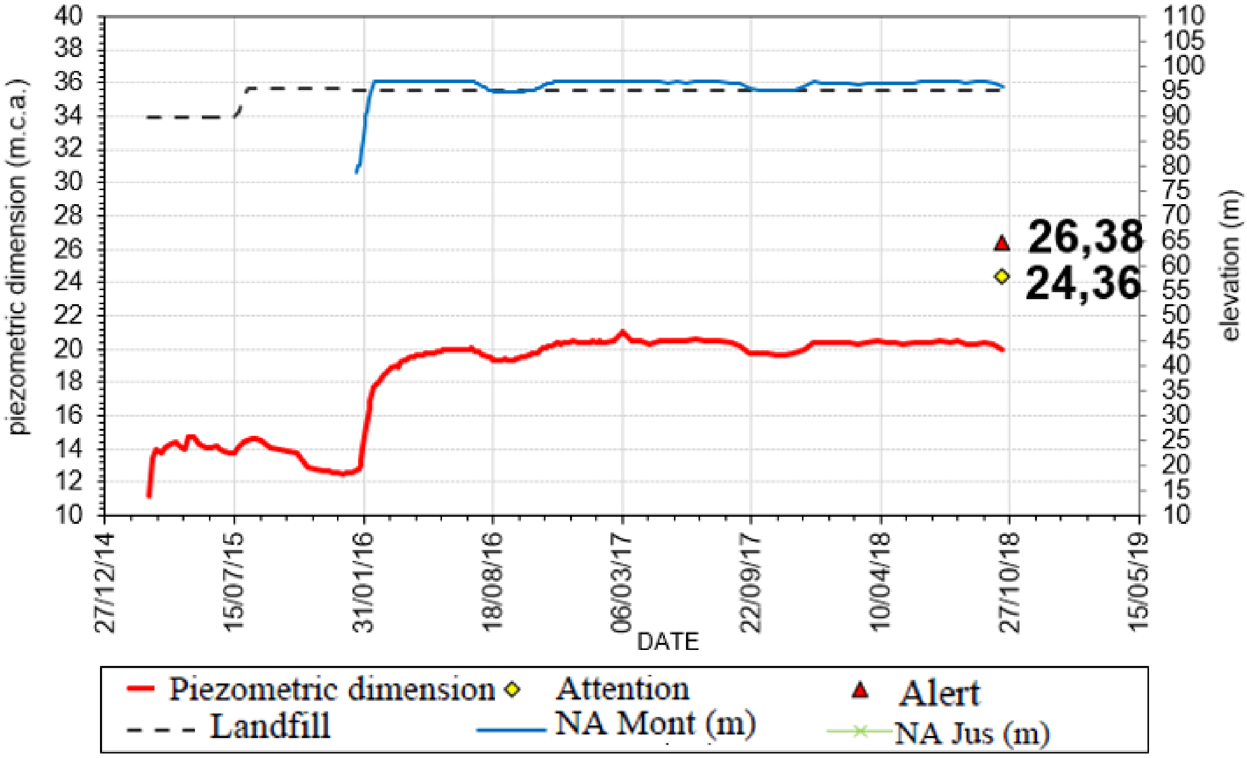
Source: Filling Procedure - Intermediate Reservoir. CA3-CV00-ITT-CHH-RT-0001 (2015, p. 6).

Figure 9 – Reading the piezometric dimension (m) of the piezometer (PZ-D01A-02) of the dike 01-A



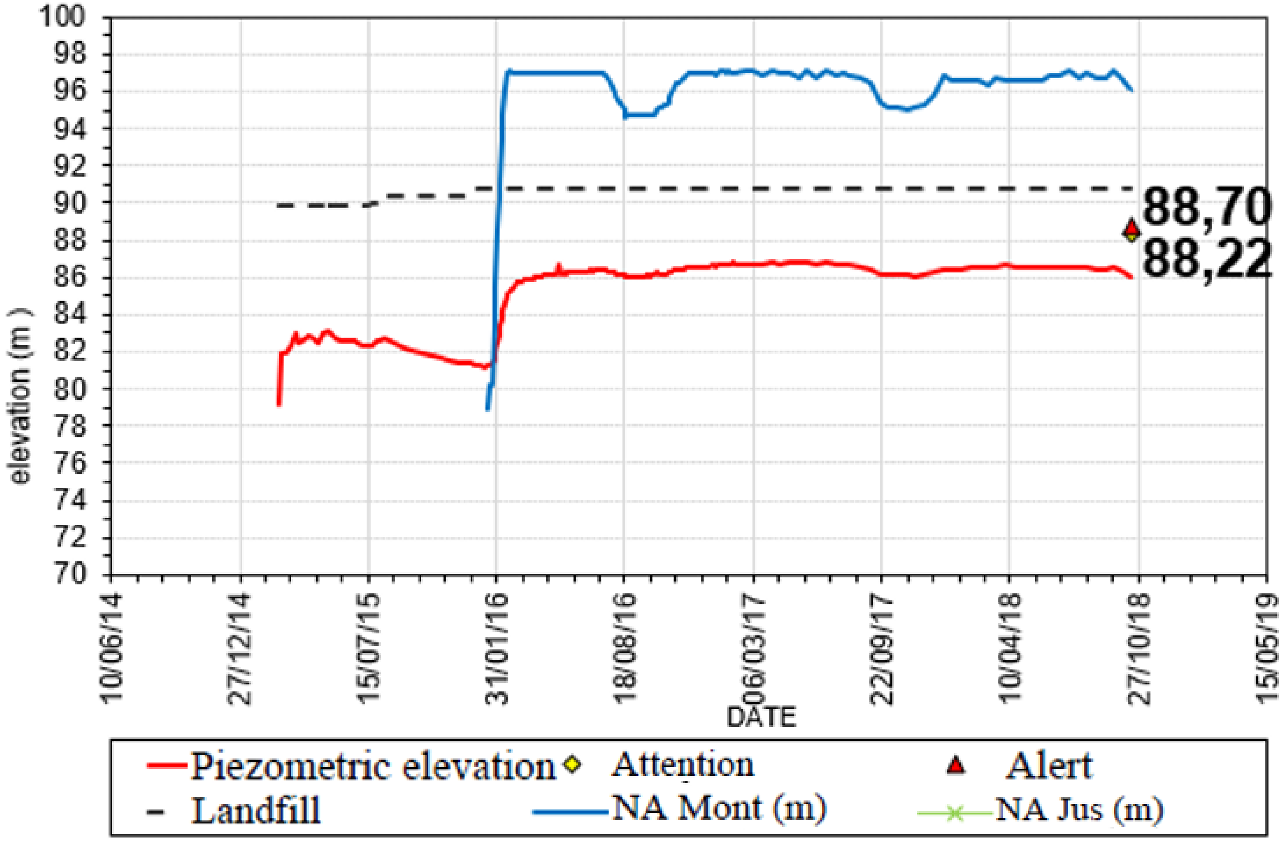
Source: Report on auscultation instruments, Norte Energia S.A (2018)

Figure 10 - Piezometer load reading (m.c.a) of the piezometer (PZ-D01A-02) of dike 01-A



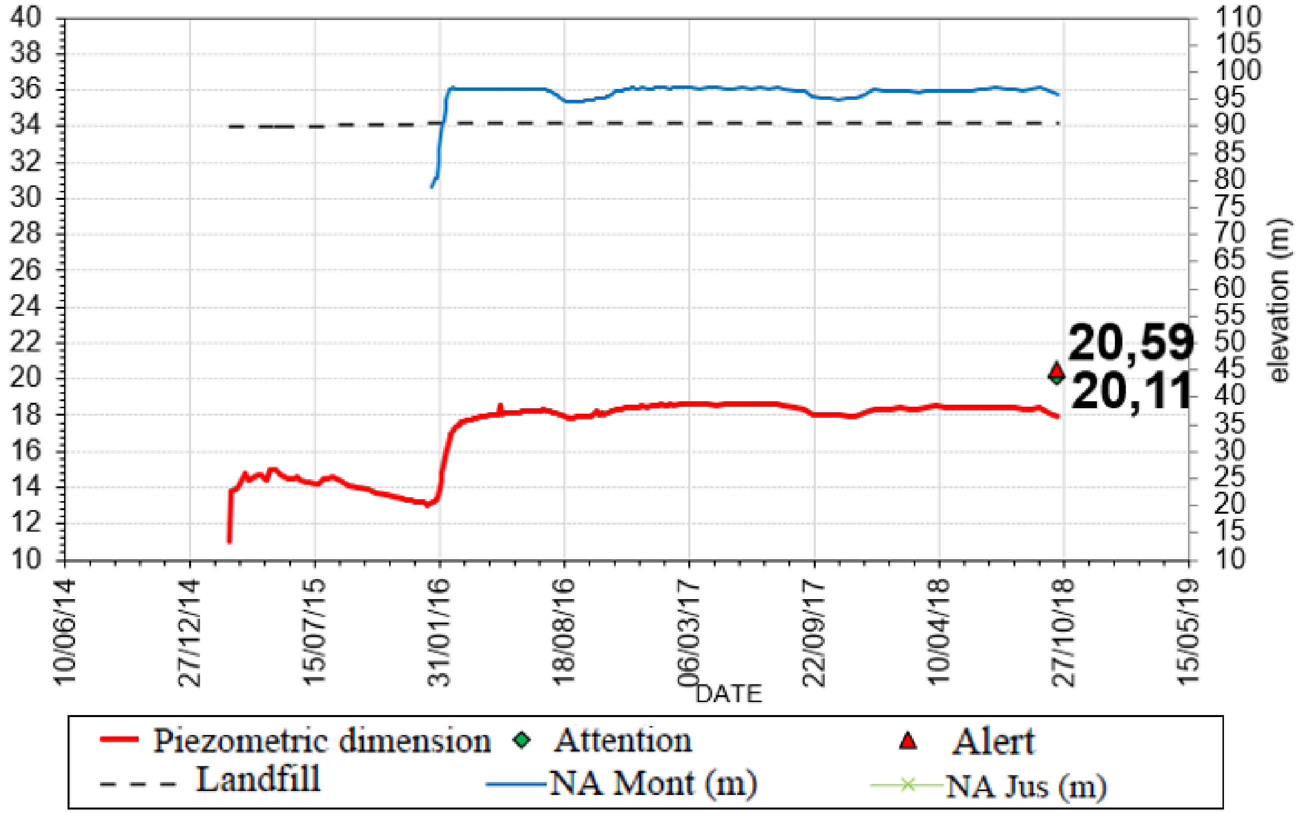
Source: Report on auscultation instruments, Norte Energia S.A (2018)

Figure 11 - Reading the piezometric dimension (m) of the piezometer (PZ-D01A-04) of the dike 01-A



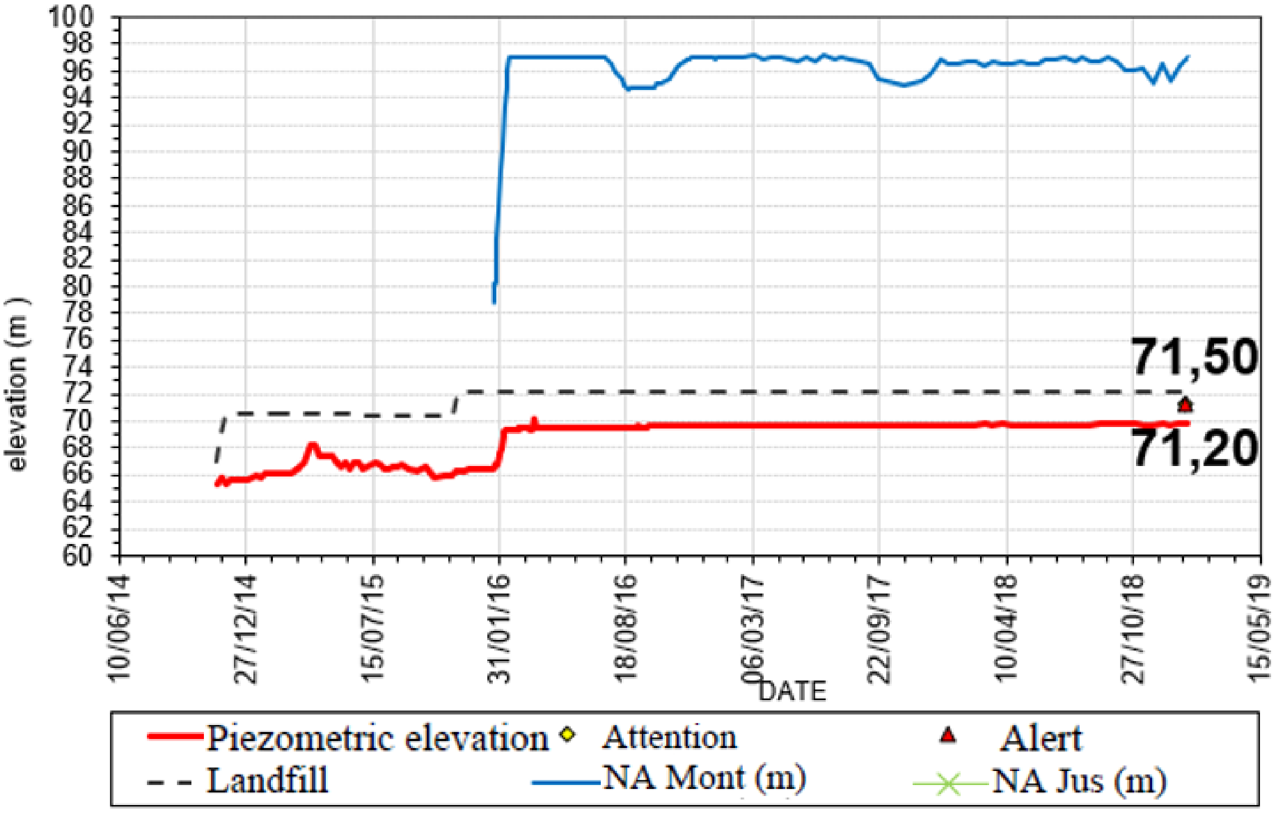
Source: Report on auscultation instruments, Norte Energia S.A (2018)

Figure 12 - Read the piezometric load (m.c.a) of the piezometer (PZ-D01A-04) of the dike 01-A



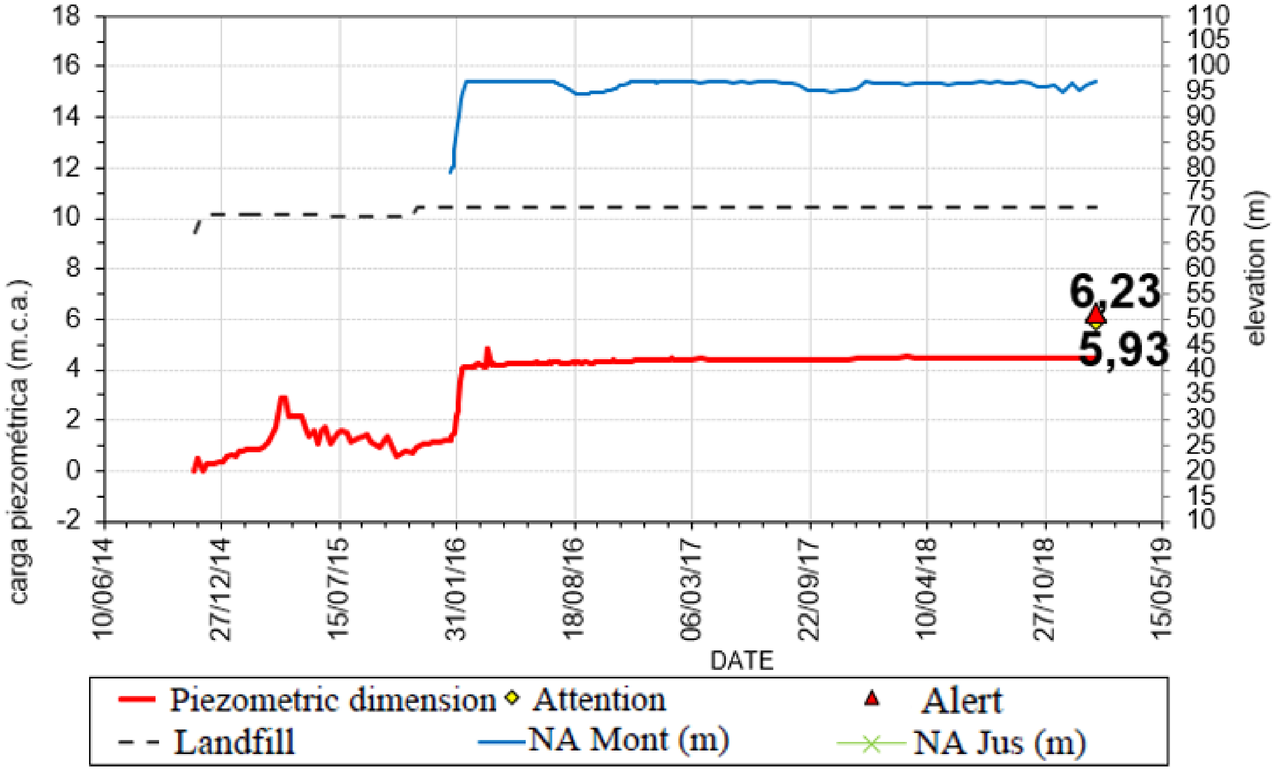
Source: Report on auscultation instruments, Norte Energia S.A (2018)

Figura 13 - Reading the piezometric dimension (m) of the piezometer (PZ-D01C-06) of the dike 01-C



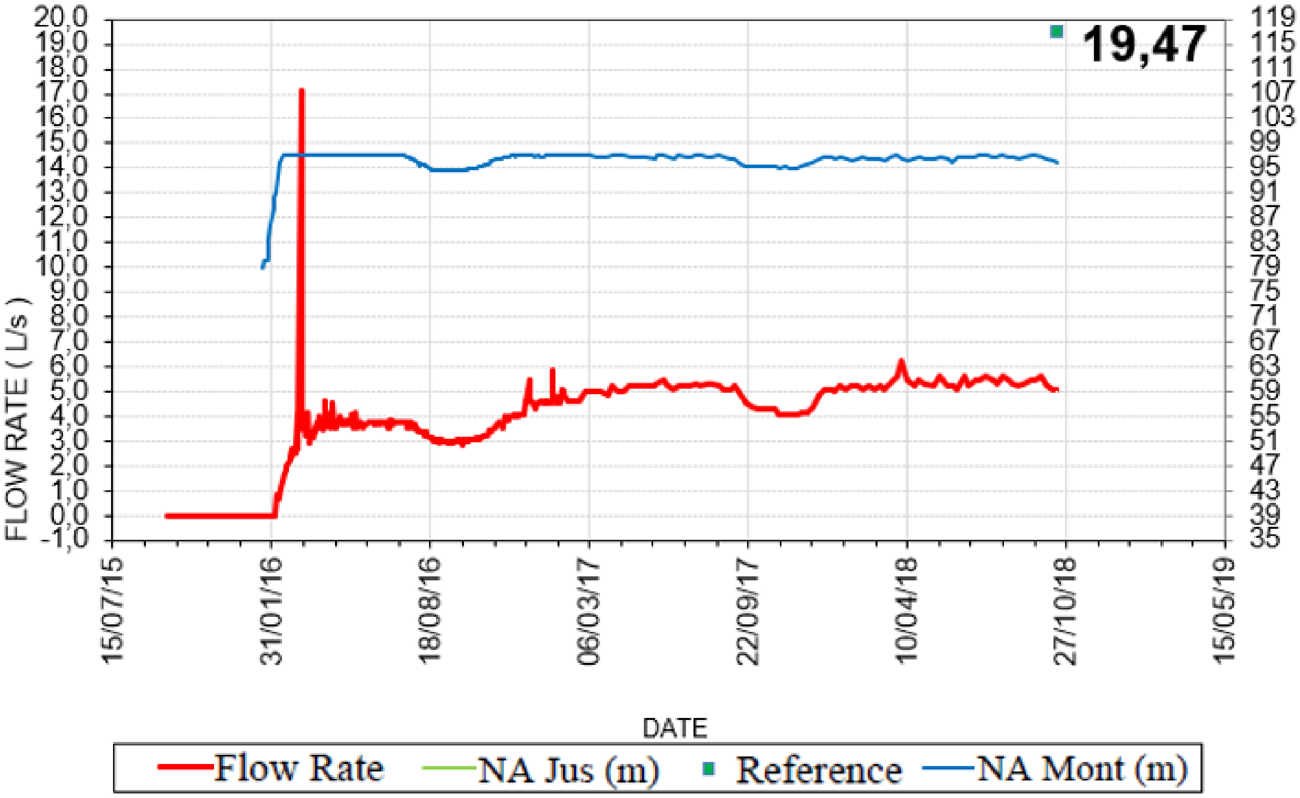
Source: Report on auscultation instruments, Norte Energia S.A (2018)

Figure 14 - Read the piezometric load (m.c.a) of the piezometer (PZ-D01C-06) of the dike 01-C



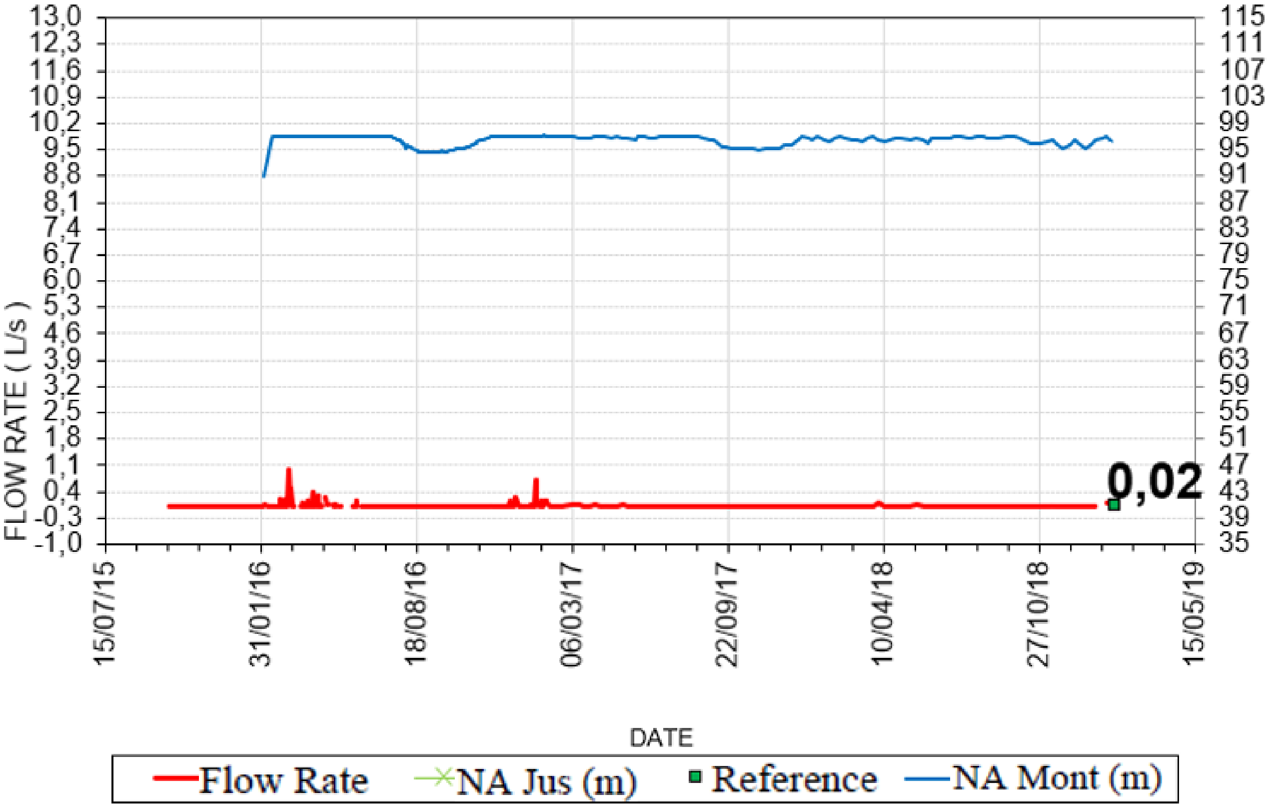
Source: Report on auscultation instruments, Norte Energia S.A (2018)

Figure 15 - Flow reading in L / s of the flow meter (MV-D01A-01) of dike 01-A



Source: Report on auscultation instruments, Norte Energia S.A (2018)

Figure 16 - Flow reading in L / s of the flow meter (MV-D01B-01) of dike 01-B



Source: Report on auscultation instruments, Norte Energia S.A (2018)

Table 1 - Location of Casagrande type Piezometers of dikes 01-A, 01-B and 01-C

Instrument	Stake	Dyke Axis Spacing	Installation Quota	Material to be instrumented
DIKE 01-A				
PZ-D01A-01	5+8,70	12,72(J)	74,04	Horizontal filter
PZ-D01A-02	5+8,70	12,72(J)	67,97	Foundation
PZ-D01A-03	5+8,46	24,11(J)	74,03	Horizontal filter
PZ-D01A-04	5+8,46	24,11(J)	68,11	Foundation
PZ-D01A-05	3+7,50	71,34(J)	74,46	Downstream
PZ-D01A-06	7+4,44	70,65(J)	73,44	Downstream
DIKE 01-B				
PZ-D01B-01	3+10,00	6,50(J)	96,18	Horizontal filter
PZ-D01B-02	3+10,00	6,50(J)	93,17	Foundation
PZ-D01B-03	3+10,00	28,00(J)	86,86	Downstream
PZ-D01B-04	3+10,00	36,90(J)	85,41	Downstream
DIKE 01-C				
PZ-D01C-01	18+18,00	21,50(J)	71,94	Horizontal filter
PZ-D01C-02	18+18,00	21,50(J)	66,95	Foundation
PZ-D01C-03	25+0,00	21,50(J)	65,9	Horizontal filter
PZ-D01C-04	32+13,00	21,50(J)	73,23	Horizontal filter
PZ-D01C-05	32+13,00	21,50(J)	65,19	Foundation
PZ-D01C-06	25+0,00	66,50(J)	65,27	Horizontal filter
PZ-D01C-07	6+1,31	36,70(J)	79,64	Downstream
PZ-D01C-08	6+0,75	108,55(J)	75,79	Downstream
PZ-D01C-09	9+5,39	23,45(J)	86,97	Downstream
PZ-D01C-10	18+19,48	89,16(J)	67,34	Downstream
PZ-D01C-11	22+4,26	96,80(J)	67,28	Downstream
PZ-D01C-12	34+8,80	83,50(J)	65,63	Downstream
PZ-D01C-13	36+18,00	48,00(J)	77,72	Downstream

Source: BELO MONTE Instrumentation Manual - RI3-D01A-ITT-CIO- MA-0001 p.5 (2017).

Table 2 - Surface Landmarks Location of Dikes 01-A, 01-B and 01-C

Instrument	Stake	Dyke Axis Spacing (m)	Installation Quota
DIKE 01-A			
MS-D01A-01	2+12,17	2,53(J)	100,32
MS-D01A-02	5+8,74	2,86(J)	100,27
MS-D01A-03	8+4,17	2,56 (J)	100,31
MS-D01A-04	5+11,29	22,07(J)	91,21
DIKE 01-B			
MS-D01B-01	2+5,09	3,55(J)	100,44
MS-D01B-02	3+10,04	3,497(J)	100,326
MS-D01B-03	4+15,04	3,51(J)	100,37
MS-D01B-04	2+8,52	8,54(J)	99,26
MS-D01B-05	4+5,57	8,35(J)	99,40
DIKE 01-C			
MS-D01C-01	5+19,93	2,98(J)	100,09
MS-D01C-02	12+2,98	2,44(J)	100,21
MS-D01C-03	18+18,33	3,02(J)	100,26
MS-D01C-04	24+19,94	2,68(J)	100,31
MS-D01C-05	32+12,74	2,79(J)	100,36
MS-D01C-06	18+17,62	44,16(J)	80,73
MS-D01C-07	24+19,97	45,08(J)	80,11
MS-D01C-08	32+13,75	45,03(J)	80,06

Source: BELO MONTE Instrumentation Manual - RI3-D01A-ITT-CIO- MA-0001 p.5 (2017).

Table 3 - Flowmeter location of dikes 01-A, 01-B and 01-C

Instrument	Stake	Dyke Axis Spacing	Installation Quote
DIKE 01-A			
MV-D01A-01	5+6,91	49,52(J)	82,78
DIKE 01-B			
MV-D01B-01	3+4,40	22,93(J)	91,00
DIKE 01-C			
MV-D01C-01	24+10,95	81,45(J)	69,45
MV-D01C-02	27+15,15	80,50(J)	69,10
MV-D01C-03	34+2,70	82,50(J)	69,70

Source: BELO MONTE Instrumentation Manual - RI3-D01A-ITT-CIO- MA-0001 p.5 (2017).

Table 4 - Location of Level References for dikes 01-A, 01-B and 01-C

Instrument	Stake	Dyke Axis Spacing	Installation Quote
DIKE 01-A			
RN-D01A-01	0+7,30	21,98(J)	103,9
RN-D01A-02	10+14,68	22,27(J)	107,91
DIKE 01-B			
RN-D01B-01	0+8,31	20,81(J)	103,15
RN-D01B-02	5+18,82	17,40(J)	102,02
DIKE 01-C			
RN-D01C-01	00 -8,19	11,30(M)	104,08
RN-D01C-02	38+9,34	29,79 (J)	101,14

Source: BELO MONTE Instrumentation Manual - RI3-D01A-ITT-CIO- MA-0001 p.5 (2017).

Table 5 - Reading frequencies of the dikes 01-A, 01-B and 01-C instruments

PERIOD				
INSTRUMENT	**CONSTRUCTIVE**	**FILLING THE RESERVOIR**	**FIRST YEAR OF OPERATION**	**OPERATION**
Open tube piezometers	1 fortnightly reading	1 Reading every 2 days	2 weekly readings	1 fortnightly reading
Meter Flow Triangular	-	1 Reading every 2 days	Daily readings	1 weekly reading
Superficial and Reference Landmarks	1weekly reading	1 weekly reading	1 monthly reading	1 half-yearly reading

Source: Instrumentation Manual - Dikes. RI3-D01A-ITT-CIO-MA-0001 p.16 (2017)

Table 6 – Period of Check Lists for Visual Inspections of Dikes 01-A, 01-B and 01-C of Belo Monte HPP

DIKE 01-A					
YEAR	**2015**	**2016**	**2017**	**2018**	**TOTAL**
PERIOD	28/11/2015	30/04/2016	30/01/2017	03/01/2018	12
		01/06/2016	05/04/2017	21/05/2018	
		29/09/2016	12/06/2017	26/10/2018	
		21/112016	04/10/2017		
DIKE 01-B					
YEAR	**2015**	**2016**	**2017**	**2018**	**TOTAL**
PERIOD	28/11/2015	30/04/2016	02/02/2017	09/01/2018	12
		01/06/2016	04/04/2017	22/05/2018	
		30/09/2016	06/06/2017	29/10/2018	
		23/11/2016	14/09/2017		
DIKE 01-C					
YEAR	**2015**	**2016**	**2017**	**2018**	**TOTAL**
PERIOD	27/11/2015	18/01/2016	02/02/2017	04/01/2018	12
		01/06/2016	11/04/2017	18/06/2018	
		30/09/2016	22/06/2017	01/11/2018	
		29/11/2016	06/10/2017		

Source: Norte Energia S.A (2018).

Table 7 - Summary of occurrences recorded in the operating conditions modality between 2015 to 2018

INSPECTED STRUCTURES	D-01A	D-01B	D-01C	D-01A	D-01B	D-01C	D-01A	D-01B	D-01C	D-01A	D-01B	D-01C
ITEMS INSPECTED WITH ADVERSE OCCURRENCES THE HARMONY OF THE STRUCTURE	PERIOD OF OCCURRENCES											
	2015			2016			2017			2018		
	CHECK-LIST AMOUNT											
Lack of documentation on the dam												
Lack of maintenance of civil structures												
Lack of maintenance of instruments												
Attention or alert level piezometers												
Sudden increase or decrease in piezometric levels												
Flow meters with flow rates above attention or alert levels												
Lack of access road conditions		1			4							
Access conditions for inspection are lacking		1			1							
Lack or deficiency of signposts	1	1	1	4	4	4	4	4	4	3	3	3
Residences on the dam jambs												
Lack of strategic stock available	1	1	1	4	4	4	4	4	4	3	3	3

Source: Adapted from Norte Energia S.A (2018)

Table 8 - Summary of occurrences recorded in the amount of slope between 2015 and 2018

INSPECTED STRUCTURES	D-01A	D-01B	D-01C	D-01A	D-01B	D-01C	D-01A	D-01B	D-01C	D-01A	D-01B	D-01C
ITEMS INSPECTED WITH ADVERSE OCCURRENCES THE HARMONY OF THE STRUCTURE	PERIOD OF OCCURRENCES											
	2015			2016			2017			2018		
	CHECK-LIST AMOUNT											
Reservoir NA near El. 97.40 m												
Very cloudy water												
Surface erosion											2	
Slip indications												
Block displacement signs												
Depression or sinking				1		2						
Breakdown of rock blocks												
Poorly imbricated rock blocks												
Presence of trees or shrubs										2		2

Fonte: Adapted from Norte Energia S.A (2018)

Table 9 - Summary of occurrences registered in the Crest modality between 2015 to 2018

INSPECTED STRUCTURES	D-01A	D-01B	D-01C	D-01A	D-01B	D-01C	D-01A	D-01B	D-01C	D-01A	D-01B	D-01C
ITEMS INSPECTED WITH ADVERSE OCCURRENCES THE HARMONY OF THE STRUCTURE	PERIOD OF OCCURRENCES											
	2015			2016			2017			2018		
	CHECK-LIST AMOUNT											
Piling along the ridge	1	1	1	4	4	4	4	4	4	3	3	3
Localized depression						2						
Presence of sinkhole												
Transverse cracks												
Longitudinal cracks						1						
Evidence of erosion												
Good floor conditions												
Good drainage conditions												

Source: Adapted from Norte Energia S.A (2018)

Table 10 - Summary of occurrences recorded in the downstream slope modality between 2015 to 2018

INSPECTED STRUCTURES	D-01A	D-01B	D-01C	D-01A	D-01B	D-01C	D-01A	D-01B	D-01C	D-01A	D-01B	D-01C
ITEMS INSPECTED WITH ADVERSE OCCURRENCES THE HARMONY OF THE STRUCTURE	**PERIOD OF OCCURRENCES**											
	2015			**2016**			**2017**			**2018**		
	CHECK-LIST AMOUNT											
SLOPE												
Surface erosion				3		4						
Poor drainage channel conditions				1	4							
Slip indications												
Occurrence of superficial cracks	1											
Depression or sinking												
Evidence of water emergence	1	1				1						
Water emergence with particle carrier												
Occurrence of humidity												
Presence of trees or shrubs												
Presence of sinkhole												
Occurrence of sand boils (sand eruptions)												
Bad shoulders				3		2						
Inadequate plant protection	1	1		3		2						
Animal burrows / termites / anthills												
FOOT DRAIN AND DRAINAGE CHANNEL												
Poorly imbricated rock blocks												
Breakdown of rock blocks												
Surface contamination of the foot drain (soil)				3		3						
Water flow through the flow meter												
Deficiencies in the lateral protection of the channels				3	3	2						
Presence of trees or shrubs												
Occurrence of channel silting				3		3						

Source: Adapted from Norte Energia S.A (2018)

Table 11 - Summary of occurrences recorded in the jamb mode from 2015 to 2018

INSPECTED STRUCTURES	D-01A	D-01B	D-01C	D-01A	D-01B	D-01C	D-01A	D-01B	D-01C	D-01A	D-01B	D-01C
ITEMS INSPECTED WITH ADVERSE OCCURRENCES THE HARMONY OF THE STRUCTURE	PERIOD OF OCCURRENCES											
	2015			2016			2017			2018		
	CHECK-LIST AMOUNT											
Surface erosion (ravination)				1	1		4			2		2
Existence of depression												
Cracks occurrence												
Evidence of water emergence	1											
Water emergence with particle carrier												
No trees nearby		1				2						
Poor drainage conditions				1			4			2		2
Poor cleaning conditions												
Presence of sinkhole												

Fonte: Adapted from Norte Energia S.A (2018)

Table 12 - Summary of occurrences recorded in the downstream slope modality between 2015 to 2018

INSPECTED STRUCTURES	D-01A	D-01B	D-01C	D-01A	D-01B	D-01C	D-01A	D-01B	D-01C	D-01A	D-01B	D-01C
ITEMS INSPECTED WITH ADVERSE OCCURRENCES THE HARMONY OF THE STRUCTURE	PERIOD OF OCCURENCES											
	2015			2016			2017			2018		
	CHECKLIST AMOUNT											
NA PIEZOMETERS AND METERS												
Deficiency in protection	1	1	1	2		3				2		
Deficiency in access conditions	1	1	1	1	2	4				2	2	2
Inadequate cleaning							1			1		1
Inadequate identification	1	1	1			1				1		
Instruments in poor condition												
FLOW METERS												
Poor protection						4			2			1
Deficiency in access conditions												
Inadequate cleaning						2						
Inadequate identification	1	1	1	2	2	2						
Instruments in poor condition												
SURFACE MARKS AND RN's												
Poor protection				4		1					3	
Deficiency in access conditions												1
Inadequate cleaning												1
Inadequate identification	1	1	1			1						
Instruments in poor condition												

Fonte: Adapted from Norte Energia S.A (2018)

Table 13 - Summary of occurrences recorded in the downstream strip modality between 2015 to 2018

INSPECTED STRUCTURES	**D-01A**	**D-01B**	**D-01C**	**D-01A**	**D-01B**	**D-01C**	**D-01A**	**D-01B**	**D-01C**	**D-01A**	**D-01B**	**D-01C**
ITEMS INSPECTED WITH ADVERSE OCCURRENCES THE HARMONY OF THE STRUCTURE	**PERIOD OF OCCURENCES**											
	2015			**2016**			**2017**			**2018**		
	CHECK-LIST AMOUNT											
Surface erosion			1									
Poor drainage channel conditions	1											
Breakdown of rock blocks												
Poorly imbricated rock blocks												
Evidence of water emergence		1	1	4	1	4	4	4	4	2	2	3
Water emergence with particle carrier												
Occurrence of humidity	1			4		2	4	1	4	2	2	3
Presence of trees or shrubs	1			4	1	2	4	1	4	2	2	3
Presence of sinkhole												
Occurrence of sand boils (sand eruptions)												
Deficiency in cleaning the downstream strip	1											
Lagoon formation in the downstream strip	1	1	1	4		4		2			2	2

Source: Adapted from Norte Energia S.A (2018)

Table 14 - Summary of auscultation instruments for dams 01-A, 01-B and 01-C of Belo Monte HPP

DIKE 01-A		
INSTRUMENT	**UNITY**	**AMOUNT**
PIEZOMETER	UNITY	6
SUPERFICIAL LANDMARK	UNITY	4
FLOWMETER	UNITY	1
LEVEL REFERENCE	UNITY	2
DIKE 01-B		
PIEZOMETER	UNITY	4
SUPERFICIAL LANDMARK	UNITY	5
FLOWMETER	UNITY	1
LEVEL REFERENCE	UNITY	2
DIKE 01-C		
PIEZOMETER	UNITY	13
SUPERFICIAL LANDMARK	UNITY	8
FLOWMETER	UNITY	3
LEVEL REFERENCE	UNITY	2

Source: Adapted from Norte Energia S.A (2018)

Table 15 - Attention and alert values for surface landmarks installed on Dike 01-A, 01-B and 01C

DIKE 01-A					
Instrument	**Installation Quota**	**Vertical Offsets**		**Horizontal Offsets**	
		Attention Value (cm)	**Alert Value (cm)**	**Attention Value (cm)**	**Alert Value (cm)**
MS-D01A-01	100,32	2,6	5,2	2,6	5,2
MS-D01A-02	100,27	6,6	13,2	6,6	13,2
MS-D01A-03	100,31	3,1	6,2	3,1	6,2
MS-D01A-04	91,21	4,4	8,7	4,4	8,7
DIKE 01-B					
Instrument	**Installation Quota**	**Vertical Offsets**		**Horizontal Offsets**	
		Attention Value (cm)	**Alert Value (cm)**	**Attention Value (cm)**	**Attention Value (cm)**
MS-D01B-01	100,44	1,25	2,5	1,25	2,5
MS-D01B-02	100,33	1,25	2,5	1,25	2,5
MS-D01B-03	100,37	1,25	2,5	1,25	2,5
MS-D01B-04[1]	99,26	1,5	3	1,5	3
MS-D01B-05[1]	99,4	1,5	3	1,5	3
DIKE 01-C					
Instrument	**Installation Quota**	**Vertical Offsets**		**Horizontal Offsets**	
		Attention Value (cm)	**Alert Value (cm)**	**Attention Value (cm)**	**Attention Value (cm)**
MS-D01C-01	100,09	2	3	2	3
MS-D01C-02	100,21	3,1	3,7	3,1	3,7
MS-D01C-03	100,26	7,1	14,2	7,1	14,2
MS-D01C-04	100,31	8,6	17,2	8,6	17,2
MS-D01C-05	100,36	6,4	12,7	6,4	12,7
MS-D01C-06	80,73	3,7	7,4	3,7	7,4
MS-D01C-07	80,11	3,8	7,6	3,8	7,6
MS-D01C-08	80,06	3,6	7,1	3,6	7,1

Source: Instrumentation manual Dike 01-A, 01-B and 01-C, Norte Energia: S.A (2018).

* Levels revised according to the readings observed during the 1st year of operation.