Detection of seepage paths in small earth dams using the self-potential method (SP)

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Abstract

The application of geoelectric methods, such as induced polarization (IP), the electrical resistivity and the self-potential (SP), presents an important indirect study methodology in several areas of geology, such as mining, geotechnics and environmental geology. The present study deals with the results of the application of the self-potential method (SP) in small earth dams in the cities of Cordeirópolis and Ipeúna, both in the state of São Paulo. Studies of the Engineering of Dams intensified at the end of century XX, due to alarming number of dam disruptions. In Brazil, small dams are still the majority, around 90% of the total. This article presents results of surveys of the self-potential in two small dams, analyzing the flow of fluids, heat or ions inside the dams, as well as possible areas of percolation or water saturation. Three lines of 78 meters each were made with a spacing of 2 meters between the electrodes in the Cordeirópolis dam, and three lines of 122 meters each, spaced 2 meters between the electrodes in the Ipeúna dam. In both collections, the potential technique (or fixed base) was used. The collected data was worked on 2D maps of self-potential, which allowed to identify the zones with greater and smaller values of potential difference, preferential flow of the subsurface fluids in the areas, and possible problems in the structure of the dam (seepage paths), which could affect the physical integrity of the structure.

Keywords: geophysics in dams, self-potential, subsurface flow, dam inspection.

1. Introduction

Dams are characterized as structural elements constructed transversely to the flow direction of a watercourse, creating an artificial reservoir for water accumulation. Utilization of this type of structure has increased over the years and currently dams accumulate waste materials too. They can be divided into three types depending on the material used: earth-fill, concrete and rock-fill.

According to Souza (2013), dams play a crucial role in the development of civilizations, mainly due to the need to store water. Currently, earth dams are the most common construction to accumulate water and, even with technological advances, still have structural problems (ICOLD, 1995). Data from the National Water Agency (ANA, 2015) shows that between the years 2002 and 2010, there was 800 incidents with dams, mostly due to problems of infiltration and internal erosion. In Brazil, still according to data from the National Water Agency, the great majority of resources (researches and investments, for example) are geotechnical research and technical projects for medium to large dams; in other words, the focus of investments is not on small dams, even though they are the majority.

Applied geophysics investigates structures, materials and elements in the subsurface through indirect measurements of the properties of the subsoil. Therefore, in the study of dams, the geophysical methods can assist the construction and monitoring phases. Several studies have already been carried out with this purpose, using geophysical methods in dams, such as; Bogoslovsky, 1970; Sirles, 1997; Panthulu, 2001; Aal *et al*., 2004; and Nwokebuihe, 2017.

In the present study, the subsurface flow of two small earth dams was analyzed through the self-potential method, to find areas of weakness, which in the case of the application of geophysical methods in dams, would be areas with potential for water flow or possible areas of saturation of the dam structure. Therefore, the present study did not relate the weakness zones with the self-potential method measurements and the shear strength of the landfill material, but with the identification of the zone with higher water contents.

It is important to mention that the construction project of the dams was not available, so the dams size values (crest height to base, for example) were unknown. However, the geophysical methods performed associated with the self-potential method during the project were able to provide bedrock depth values to the crest, with values of 6 meters for the dam located in Cordeirópolis and approximately 10 meters to the dam located in Ipeúna.

There is a clear need for investments in techniques that help in the management of dam safety levels and, more than that, seek methods that may help in the investigation of dam conditions in the absence of previous information, as many water reservoirs for irrigation are abandoned in Brazil (National Water Agency – ANA, 2015). Geophysical methods can be an interesting noninvasive investigation technique, as they provide data quickly at crucial points of the dams, such as the crest region, downstream slopes and contact areas between the dam body and the relief.

The present project focuses on the physical integrity of small earth dams located in Ipeúna and Cordeirópolis, both in the state of São Paulo. Therefore, the main objective of the project was to apply the self-potential method to two small earth dams to evaluate the flow potential; that is, identify the flow of fluids inside the dams through the interpretation of these data and detect the seepage paths or zones of water saturation, if they occur.

1.2 Study area

The study area includes two earth dams at the countryside of the state of São Paulo. The first is located in the rural area of the municipality of Ipeúna - SP, 195 km from the capital, located more precisely in the "Quilombo" fishing region, while the second is located in the municipality of Cordeirópolis - SP, 160 km from the state capital, accessed by Washington Luís Highway SP-310, near Km 156 in the South direction (Fig. 1).

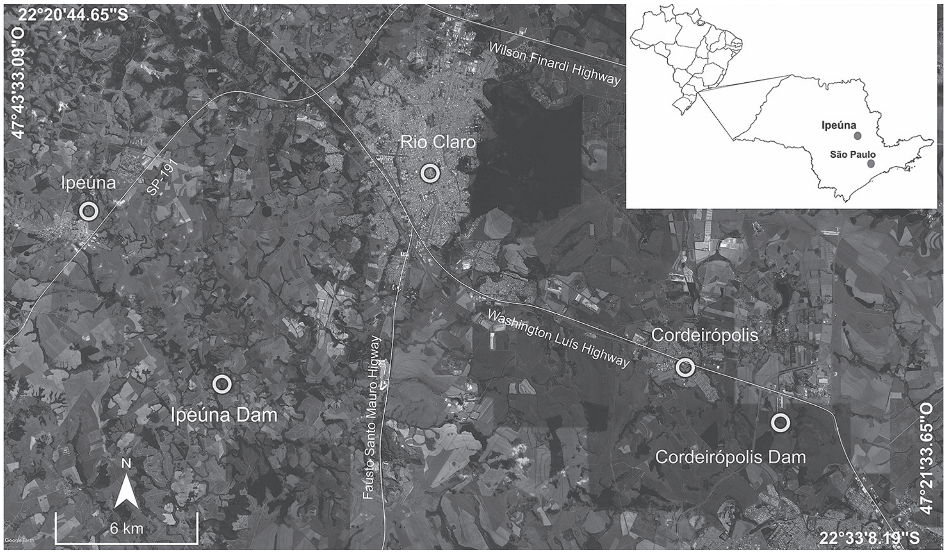

Figure 1 - Location of the study area, near Rio Claro, in the state of São Paulo, Brazil.

The choice of dams took into consideration the size of the dams (small size), the difference between the lithology that composes the dam structure - to compare a possible influence of the material on the obtained values - and the absence of dam construction projects (the age of the dams is not known, the oldest satellite images are from the year 2000; however, it is believed that the dams are older than that), so it is believed that both dams were built using very simple techniques that compacted the soil present in the areas, without drains or installation of any monitoring equipment, such as piezometers.

1.3 Regional and local geology

The study area is located in the Paraná Sedimentary Basin, which is located in the center-east of South America, covering about 1,700,000 km^2. In Brazil, it is located largely in the southern portion of the country, occupying approximately 1,000,000 km^2, with 160,000 km^2 in the state of São Paulo, and extending to Argentina, Uruguay and Paraguay (Zaine, 1994). It is classified as an extensive intracratonic basin established on the South American Plate.

Geologic Formations from Paraná Sedimentary Basin occur in the region of study: Group Itararé, Formations of Tatuí, Irati, Corumbataí, Pirambóia, Serra Geral and Botucatu. However, this article will only address the Itararé Group and Serra Geral Formation.

The sediments of the Itararé Group constitute the basal unit of the permo-carboniferous sequence of the Paraná Basin, appearing at the base of the column in the bottom areas of the Rio Claro and Ipeúna rivers, for example (Zaine, 1994). The dam located in Ipeúna is in a typical outcrop of the Itararé Group, with the presence of clayey diamictites having granules of approximately 4 centimeters around the dam (Fig. 2).

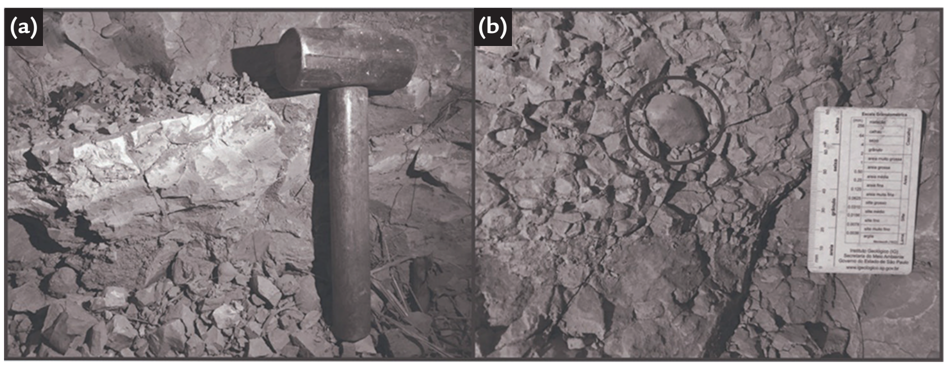

Figure 2 - a) Outcrop of roadside showing a clayey diamictite; b) Diamictite granule marked.

The Serra Geral Formation consists of basic toletic volcanic rocks, from black to grayish white, with thin layers of rocks formed by sandstones between spills (Zaine, 1994). In the Paraná Basin, the occurrence of the unit is generalized, reaching thicknesses of approximately 1530 meters.

The dam located in Cordeirópolis is in the classical lithology of the Serra Geral Formation. The structure of the dam presents a clayey lateritic soil with a characteristic yellowish-brown coloration originating from the alteration of basic rocks (basalts). It is important to mention that basalt blocks of various sizes occur in large quantities all over the area, near the dam crest and around the reservoir (Fig. 3).

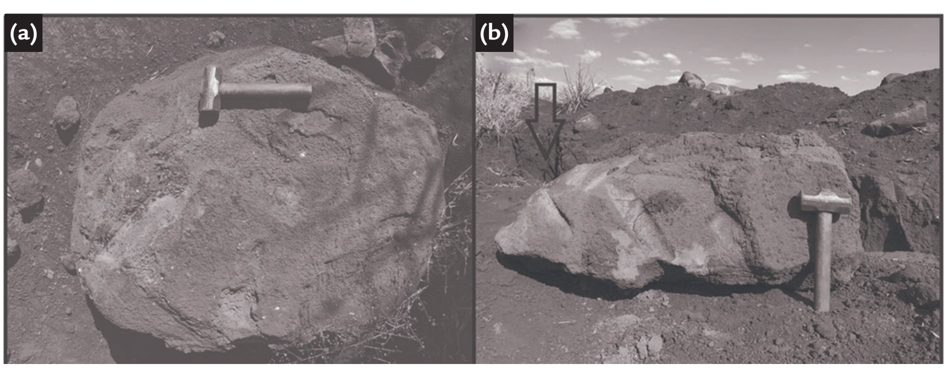

Figure 3 - a) Basalt block under a heavy alteration process around the dam; b) Basalt block altered next to a ditch (pointed by the arrow).

2. Material and methods

The self-potential method - also known as SP method - defines that it is possible to measure the natural electric potential difference between two electrodes located on the ground. In other words, it is a natural method, since there is no need to induce an electrical current in the subsurface, capable of reading the potential difference through the use of a millivoltmeter (Corwin, 1990; Minsley *et al*., 2007).

The self-potential itself, as its name implies, is nothing more than any potential that originates spontaneously in the ground, being generated, in most cases, by electrochemical or electrokinetic activity, through the flow of fluids, heat or ions that is also capable of generating self-potential (Sato and Mooney, 1960; Minsley *et al*., 2008).

The employment of the self-potential method in dams is based on the attempt to identify possible water percolation zones in the subsurface and the sources that generated them. The flow of water inside an earth dam, for example, if not controlled, can develop to an erosion process (piping) and result in the breakage of the structure (Gallas, 2000).

The methodology used in the data collection of the self-potential method was the potential technique, the most recommended and practiced because it reduces the cumulative error (the use of one pair of electrodes perform the work). Non-polarizable electrodes, filled with a solution of copper sulphate and a porous base, usually a ceramic, facilitated the slow and controlled contact of the solution of the electrode with the soil; conductive cables and millivoltmeter were used also. The latter requires high input impedance (preferably greater than 108 Ω), accuracy of at least 1 mV in the readings and capable of measuring contact resistances.

The location of the fixed electrode (or base) was chosen at the point that presented better contact resistance and lower external noises, therefore, stabilizing the values more quickly. At the beginning and at the end of the acquisition data, the values obtained in the base electrode (fixed) were measured to divide the difference between the initial and final values among all the other data collected, amortizing the error. There wasn´t vegetation in large quantity in both areas, which facilitated the study. Another important factor is that both data acquisitions were performed during the period of little rain in the area (between the months of July and September), so the level of the reservoir was low (approximately 1.5 - 2 meters from the water level to the crest), a factor that influences the values of the self-potential.

The spacing between the acquisition lines was established according to the width of the crest of the dam. Performing 3 lines with a spacing of 2 meters between them would be enough to cover practically the entire crest of the dam. The spacing between the electrodes (2 meters) was defined according to the electric tomography previously performed on the dams, which used this spacing and reached satisfactory results in depth. In addition, data could be integrated later.

The study presented here is only part of a large project for the use of geophysical methods in small-scale dams, so that other methods have already been performed in dams, such as electroresistivity (Camarero, 2016). There is a clear need for investments in techniques that help in the management of dam safety levels and, more than that, to look for methods that can help in the investigation of the dam conditions in the absence of previous information.

All data collection was performed with the millivoltmeter BISON 2390. The map of the self-potential was generated with the help of the SURFER 9 program, using the kriging method (default values were used), since this type of interpolation emphasized the extreme values, while other interpolation techniques softened the values and, in some cases, created anomalies that were not compatible with observed in the data acquisition.

The first data collection was performed in the dam localized in Cordeirópolis, 234 meters of self-potential data were collected, divided into three lines parallel to the crest of the dam and its region of greatest elongation (Fig.4). Therefore, each line was 78 meters long, containing in total of 39 electrodes distributed to each other every 2 meters, which generated the map showed in Fig. 4.

Figure 4 - Location of data collection lines in the Cordeirópolis dam.

The second data collection occurred in the Ipeúna dam, 366 meters of self-potential data were collected, divided into three parallel lines in the crest of the dam (Fig. 5). Each line was 122 meters long, containing a total of

61 electrodes spaced 2 meters apart. The processed data generated the self-potential map.

The spacing between the electrodes was defined according to the length of the dams to achieve a good level of detail. If the spacing between the electrodes was greater, the quality of the acquisition would be lower, since the sources of generation of subsurface potential difference are very sensitive and difficult to locate, so an arrangement with widely spaced electrodes would make it difficult to understand the method.

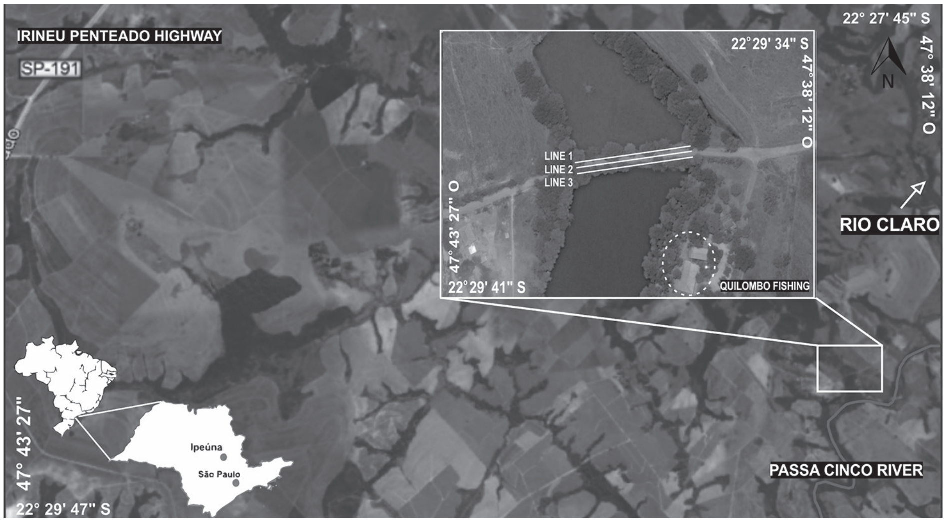

Figure 5 - Location of data collection lines in the Ipeúna dam.

3. Results and discussion

3.1 Cordeirópolis dam

The results are presented in a self-potential map which will be interpreted below identifying possible causes of the observed anomalies. Areas with the main positive and negative SP anomalies were marked (A, B and C) on the map.

It is possible to notice a region, between the points 58 and 60 meters away from the beginning of the line (point a in Figure 6), which presents the highest positive values of potential difference. It is worth mentioning that this region coincides with the presence of a concrete spillway in the dam structure (Fig. 6).

The spillway was dry. Due to the low rainfall season in the region, the reservoir was below the spillway height. However, the spillway structure crossed the dam crest

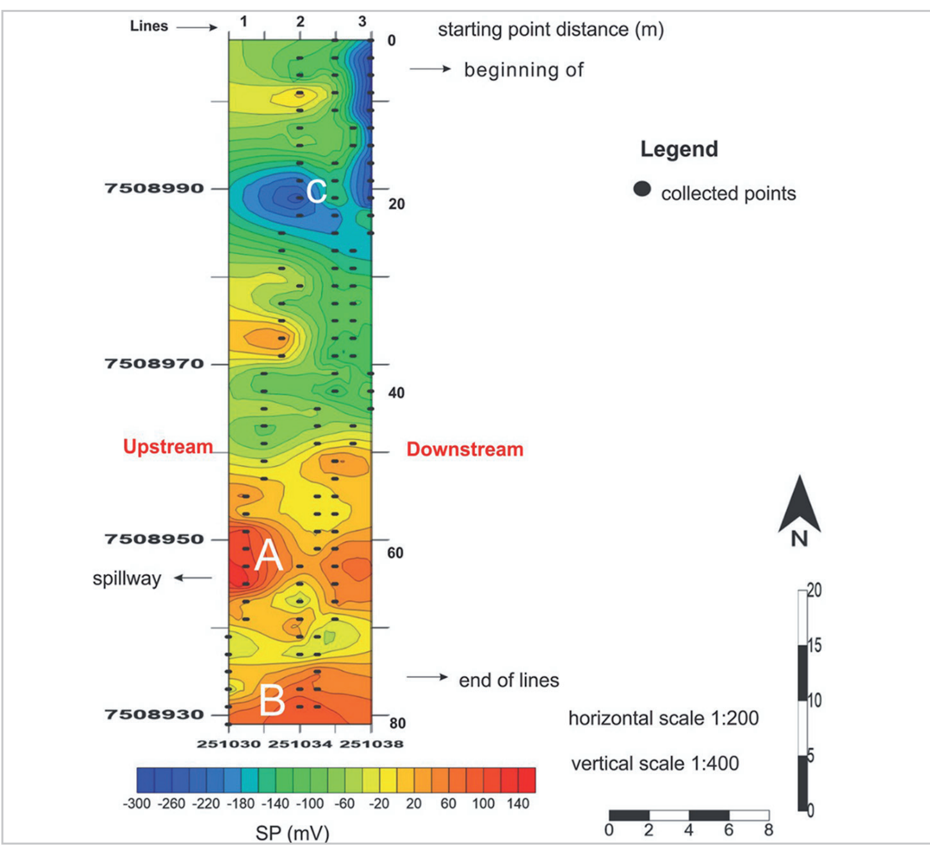

Figure 6 - Map of the self-potential of the dam located in Cordeirópolis. Black circles show electrode placement during collection.

perpendicularly, reaching the downstream slope. In this case, due to the construction material (concrete), the spillway structure itself can serve as a barrier, making it difficult to pass perpendicular flow in the structure, resulting in high SP values.

Continuing the analysis of the high positive values that stand out, close to the landmarks of 74 and 76 meters distance from the starting point of the lines (point b in Figure 6), it is possible to identify values of approximately 100mV, possibly due to the presence of the basalt found right there (Fig. 6).

Basalt is a well-studied basic rock and several studies show a resistive character (high electrical resistivity values) for the material. In this case, the presence of resistive blocks makes it difficult for fluids to pass through the area, since more conductive conditions make the electric charge easier to carry.

Another factor that stands out in the obtained map is a great concentration of negative values between -200mV and -250mV north of the dam, precisely because it presents higher negative values downstream with a regression of the upstream values (point C in Figure 5); a piping process may have been installed in the dam structure. This erosive process is the most recurrent in earth dams, and is classified as an internal erosion that starts downstream and walks upstream due to the infiltration of water into the structure of the dam (Fig. 6).

Negative SP values appear in the region of the downstream slope and develop upstream, as shown in the scheme of Figure 7. It is not the focus of this research, but electrical resistivity surveys in this same dam showed high values of electrical conductivity at this point, identifying a possible water saturation zone (Camarero, 2017).

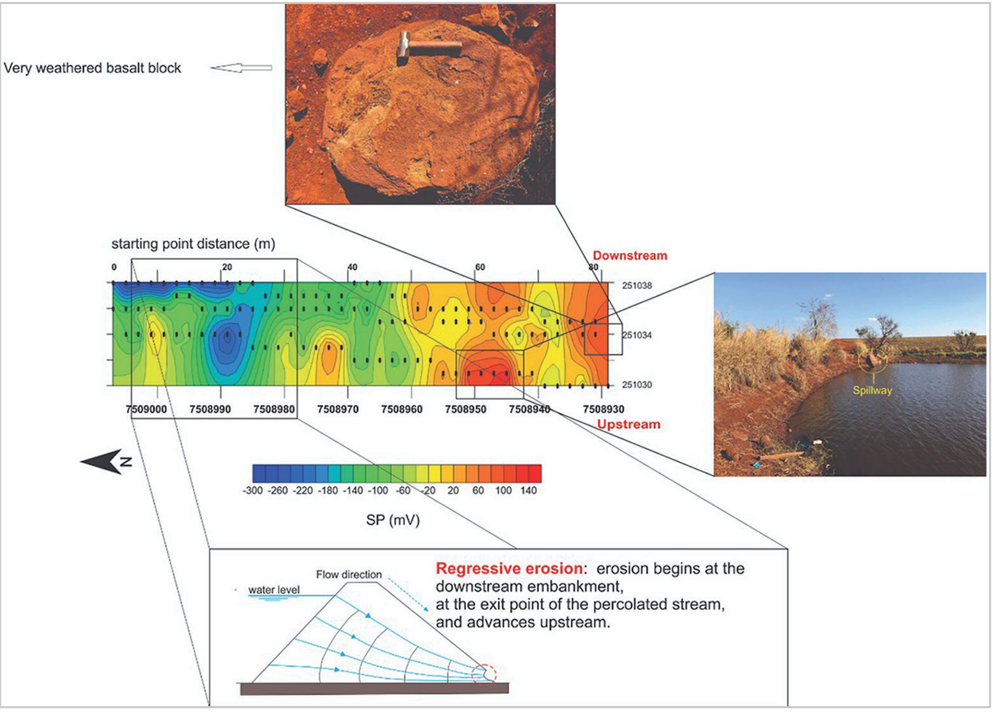

Figure 7 - Map of the self-potential of the dam of Cordeirópolis with an explanation of the anomalies.

3.2 Ipeúna dam

The dam located in Ipeúna was built to separate two water storage reservoirs. Reservoir 1 is located topographically above reservoir 2 and its main purpose is to supply the reservoir located at lower levels during drought periods. This detail is important since it was expected to find saturation responses in the central region of the dam body near reservoir 1, as water would tend to infiltrate the structure due to topographic variation (Figure 8).

Analyzing the map of the self-potential of the dam located in Ipeúna, it is possible to notice that the large range of constant negative values (between -2 to -8mV) of self-potential found between points 42 and 90 of line 1 are the result of the proximity of the water level of the reservoir 1 located in the northern portion of the dam prove, which was already expected.

This theory gains support when analyzing the southern portion of the dam, in line 3, where no negative values were found and the water level is approximately 2 meters from the data collection surface, while in line 1 this distance is only 1 meter. Therefore, the negative values found in line 1 justify a possible infiltration of reservoir water into the dam structure.

The linear feature with negative values of north-south direction, which crosses the dam well in the central portion, more precisely at the point of a distance of 56 meters from the beginning of data collection, coincidentally where the spillway is installed in reservoir 1.

The connection between the two reservoirs, in order to the reservoir 1, located higher up topographically, to supply the reservoir 2 generates a flow of water which explains those values (Figure 9).

This point in the structure is important, since the results for the spillway (which was dry) in the dam located in Cordeirópolis were the opposite (high SP anomaly values). It clarifies the influence of water flow on the spillway structure and the method response. However, in both cases, the presence of the spillway was marked by the method, which is positive.

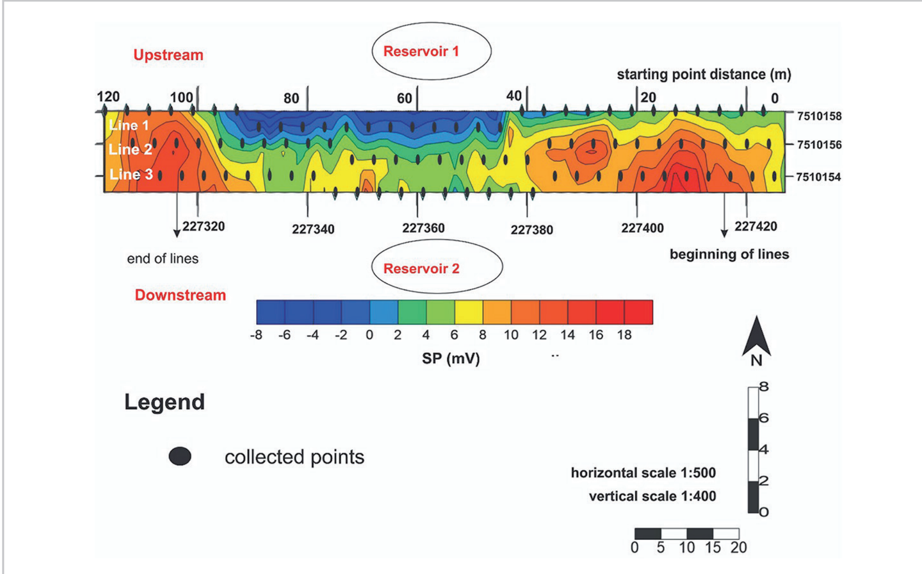

Figure 8 - Map of the self-potential of the dam located in Ipeúna. Black circles show electrode placement during collection

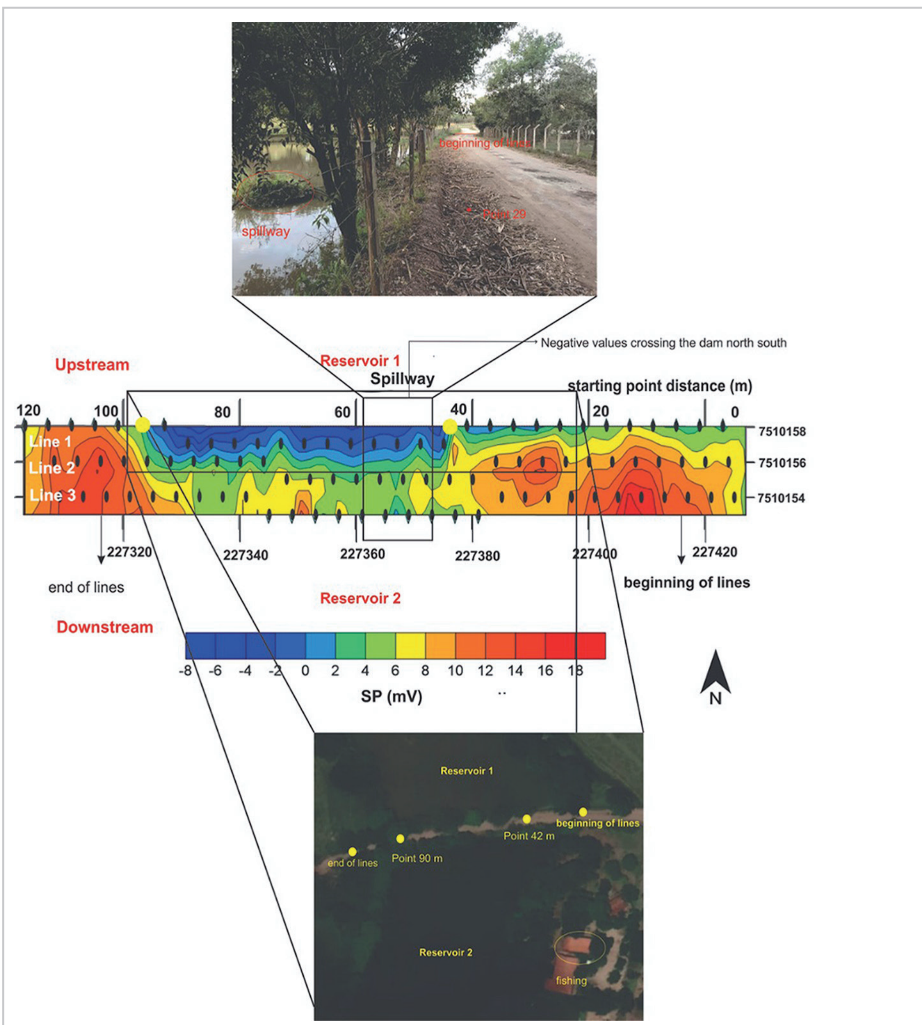

Figure 9 - Map of the self-potential of the Ipeúna dam with an explanation of the anomalies.

4. Conclusions

The results showed the applicability of the self-potential method in the area of engineering geology, such as dams. The application of the self-potential method in small dams resulted in satisfactory data, making it possible to identify a possible process of internal erosion (piping) in the dam located in Cordeirópolis and another possible infiltration process in the dam located in Ipeúna.

It is important to mention that some points drew attention, such as the presence of basalt blocks and the high values of SP anomalies in these areas. In this case, possibly the basalt blocks were acting as membranes, hindering the flow of fluids in the area, which resulted in this method response.

Precisely due to the lithology of each, dam the values obtained from SP in the two dams were quite different. In the dam located in Ipeúna, the values ranged from -8 to 20 mV, while in the dam located in Cordeirópolis, the values had greater variations, between -300 to 160 mV. This type of behavior was expected and was one of the reasons for choosing a dam built from the compaction of basic rock soils and another from sedimentary rocks.

Another information that could be collected with the application of the self-potential method is the preferential flow direction of the subsurface fluids in the area, being able to locate the undesired water flow, since water percolation in the structure of a dam is either earth or concrete and can compromise the physical integrity of the structure.

The application of the self-potential method was interesting because it is a traditional method in fluid flow investigations in dams and the analyzed data can be interpreted with other geophysical methods, such as the electroresistivity method, for example.

In addition to the method used being useful and effective in the study of dams, the method of self-potential has other advantages that must be taken into account: low operation cost and simple operation, since the millivoltmeter is very intuitive and practical.

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