



Analysis of the Physical Integrity of Earth Dams from Electrical Resistivity Tomography (ERT) in Brazil

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Abstract—Dams are structures that barrier rivers and streams for a variety of purposes. The constant maintenance of these structures is essential, since a possible accident can lead to damage of catastrophic proportions. In November 2015 in the city of Mariana, Minas Gerais (MG), Brazil, a tailings dam burst and spilled 56 million cubic meters of tailings. In addition to victimize 19 people, the event caused material, economic and environmental damage—it is considered the largest environmental disaster of Brazil. This research presents a cheap and quickly applied alternative for investigation of seepage of water in earth dams, built with distinct embankment materials—one dam composed of predominantly silt and clay soil and the other predominantly composed of sandy soil. The research methods used were: geotechnical tests as gradation test, permeability test with the Guelph permeameter method and the application of the (DC) resistivity geophysical method from the electrical resistivity tomography (ERT) technique in Wenner array. Three ERT lines were positioned parallel to the longitudinal axis at each dam. The data are presented in 2D and 3D geophysical images with electrical resistivity values modeled. Based on the physical principle of electrolytic conduction, i.e., decrease in electrical resistance in materials or siliceous minerals in moisture conditions compared to the material in the dry state, the results revealed low-resistivity zones restricted to some points, associated with water infiltration in the transverse direction. The results indicate saturation restricted to some points and low permeability, at the present time, an installation of piping processes.

Key words: Internal erosion, geophysics, dams, electrical resistivity, tailings.

1. Introduction

A dam can be understood as a structure built across a river or thalweg aimed at damming and elevating the water level to create a reservoir of water. This reservoir can be used for several purposes: flood control, irrigation, power generation, navigation, flow regularization, urban and industrial supply, fish farming, recreation, tourism, industrial tailings, among other goals.

Water as a resource plays a key role in life in general and consequently in the world economy. The settlement of civilizations in different regions of the Earth was always closely dependent on the possibilities of water supply (Tanchev 2014). In this context, the dams had a great value in the development of civilizations. Its construction was motivated mainly by the shortage of water in the dry season and the consequent need for water storage in dams performed on empirical bases.

Unfortunately, problems with dams are frequent. Technological development has provided improvements over time, but there are still reports of problems associated with dams. Between 2000 and 2009, 140 incidents were reported only in Brazil. A large part of these incidents is associated with problems of infiltration and internal erosion (piping). The largest cause of accidents in earth dams is associated to erosion (Bonelli 2013).

On November 5th, 2015, there was an accident in a tailings dam owned by a mining company called Samarco, in the city of Mariana—Brazil. One of the three company's dams broke while passing by a heightening process. According to IBAMA—Brazilian Institute of the Environment and Renewable Natural Resources, there were an overflow of more

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than 56 million cubic meters of tailings from mining. The main damage caused by the accident was 19 fatal victims, as well as severe damage to the local community and to more 40 counties. The episode is rated as the largest environmental disaster in the country. The tailings caused an almost complete extermination of the Doce river's fauna and reached the coast of Espírito Santo State, affecting all local biome (IBAMA 2015).

After a careful investigation of federal prosecutors, it was proved that the main reason for the rupture of the structure was the internal pore pressure excess—what triggered soil liquefaction process of the structure. The structure was saturated and could not stand the high hydrostatic load, then it collapsed from the inside out. Monitoring of the structure through geotechnical instrumentation presented operational failures. It was discovered that the frequency of the readings of the instruments was incompatible with the daily volume of waste. Many instruments suggested by the designer were damaged or have not even been installed.

The accident in Mariana proved the importance of maintenance and constant monitoring of the tailings dams. The federal Government has increased supervision on companies, since then. However, for many smaller companies, the costs of constant monitoring through geotechnical instruments may be relatively high. In this context, the geophysics methods are noninvasive and important tools for the investigation, with relatively lower cost and that can be used in conjunction with geotechnical instruments.

Geophysics methods have been used to detect geological structures such as fault zones (Gélis et al. 2010, 2015) and cases of characterization of the hydrogeology (Khalil et al. 2018). But also several case studies of dams inspected by geophysical methods have been reported (Medina and Domínguez 1989; Loh and Wu 1996; Assumpção et al. 2002; Karastathis et al. 2002; Osazuwa and Chinedu 2008), but the electric resistivity method is little exploited for inspections of dams (Malagutti Filho et al. 1999; Sjö Dahl et al. 2005; Oh and Sun 2007; Asfahani et al. 2010; Al-Fares 2011; Minsley et al. 2011; Bedrosian et al. 2012; Yilmaz and Koksoy 2017); and there are reports of case studies to improve its storage capacity of tailing dams (Ozcan et al. 2013; Wei et al. 2016).

This paper presents the results of the application and comparison of electric resistivity tomography for investigation of two small earth dams, with the purpose of identifying areas of water percolation. The research's innovation consists of interpreting the qualitative data, represented by geophysics, in conjunction with the quantitative data, represented by geotechnical methods such as the Guelph permeameter technique, associating data from low resistivity zones to zones of greater permeability in the body of the dams.

The ERT technique represents an important tool for monitoring dams because it is a non-invasive method, since it is not necessary to install instruments inside the dam body. In addition, the acquisition of data in the field is relatively simple and inexpensive. Thus, the method presents valuable results regarding investigation and monitoring of possible infiltration evolution or points of weakness in the structure, together with conventional techniques of geotechnical instrumentation and other geophysical methods.

2. Area of Study and Geological Context

The first dam is located at the rural municipality of Cordeirópolis in the São Paulo State. The area can be accessed by the Washington Luis Highway (SP 310) (Fig. 1). The other dam is located at the rural municipality of Ipeúna in the State of São Paulo. The area can be accessed by the Irineu Penteadó Highway (SP 191).

The geological context of both dams is the Paraná sedimentary basin, a large intracratonic basin in South America, located in parts of Brazil, Paraguai, Uruguay and Argentina. Developed on continental crust and filled with sedimentary and volcanic rocks between Neo-Ordovician and Neo-Cretaceous (Milani and Ramos 1998). The stratigraphic framework is consist by six major depositional sequences (Silurian, Devonian, Permo-Carboniferous, Triassic, Juro-Cretaceous). The structural setting of Paraná Basin it consists of a several cratonic nuclei bounded by orogenic mobile belts which are composed of thrustsedimentary rocks intruded by granites (Eyles et al. 1993).

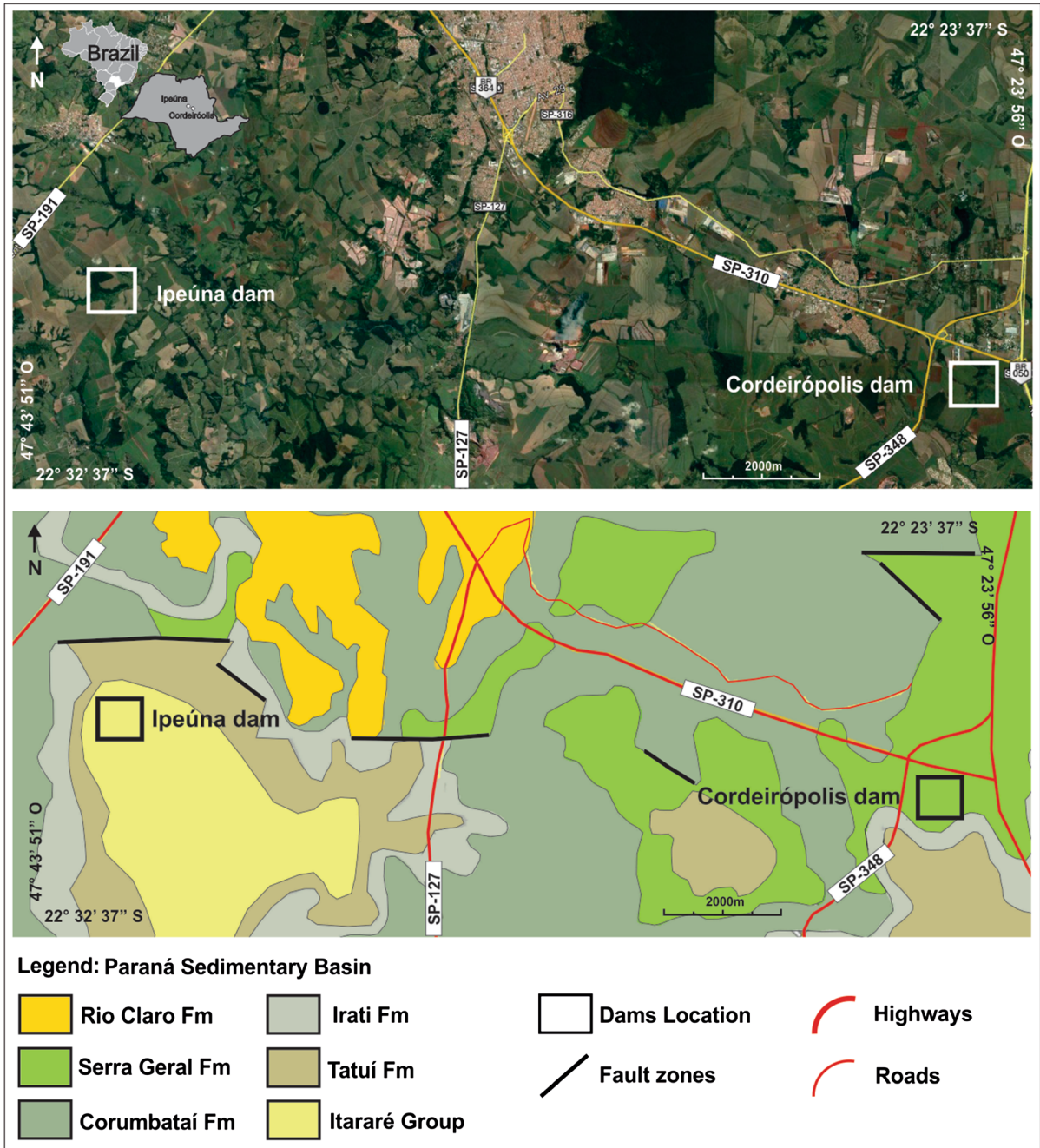


Figure 1
Location area at Cordeirópolis and Ipeúna dams and geologic context

The local geology of Cordeirópolis dam is composed primarily of basic volcanic rocks of the Serra Geral Formation, which consists of a sequence of basaltic continental lava flows with about 1500 m of

thickness along the center of the basin, covering up to 1,200,000 km² (CPRM 2003). According to Machado et al. (2005), the Serra Geral formation, in the eastern region of the São Paulo State, occurs in the forms of

dikes and sills of basalts. The decomposition of the rocks generates a clay soil of the Latosol type (Fig. 2a). This soil amendment is the main material used in the embankment of the Cordeirópolis dam. The local geology of Ipeúna dam is composed of sedimentary rocks of Itararé Group, which consists the Late Carboniferous sedimentary sequence of sandstones, siltite and diamictite; that remains a glacial condition of sedimentation (Schneider et al. 1974). The main soil material used in the embankment of the Ipeúna dam is a sandy-silt soil, product of decomposition of the rocks of the Itararé Group (Fig. 2b). Both dams were constructed to catch surface runoff for irrigating plantations.

3. Methodology

In DC resistivity method, electrical currents artificially generated are introduced into the soil, through a pair of electrodes called A and B, and potential resulting differences are measured on the surface through another pair of electrodes, called C and D, in the area of influence of the electric field. The deviations from the standard expected of the homogeneous soil potential differences provide information about the shape and the electrical properties of surface heterogeneities (Kearey et al. 2002). From the intensity of current that runs through the basement (I), the geometry of the arrangement of electrodes (K)

and the potential difference measured by electrodes receivers (ΔV), it is possible to calculate the apparent resistivity value due to heterogeneity following the equation:

$$\rho_a = \frac{K \cdot \Delta V}{I} \Omega \text{ m}$$

The unity of the apparent resistivity is measured in ohm m, the potential difference is measured in millivolt (mV), the current intensity is measured in miliampère (mA) and the geometric coefficient K in meters. In the case of earth dams, the contrast of physical properties of materials such as water and soil, may indicate abnormalities in the structure.

At each dam of the study, three electrical resistivity tomography—ERT were performed. The array used was Wenner. The ERT-1 was placed closed to the downstream and ERT-3 was placed closed to upstream (Fig. 3), and the ERT-2 in the middle. The equipment used for this study was ABEM Terrameter LS of 84 channels and power of 250 W (ABEM 2012).

At Cordeirópolis dam, 53 electrodes were placed, one every 2 m. Each ERT had 104 m long, which allowed cover the entire length of the dam and provided a resolution of approximately 17 m of depth (Fig. 4). At Ipeúna dam, 32 electrodes were placed, one every 2 m. Each ERT had 62 m long, which allowed cover the entire length of the dam and provided a resolution of approximately 10 m of depth.

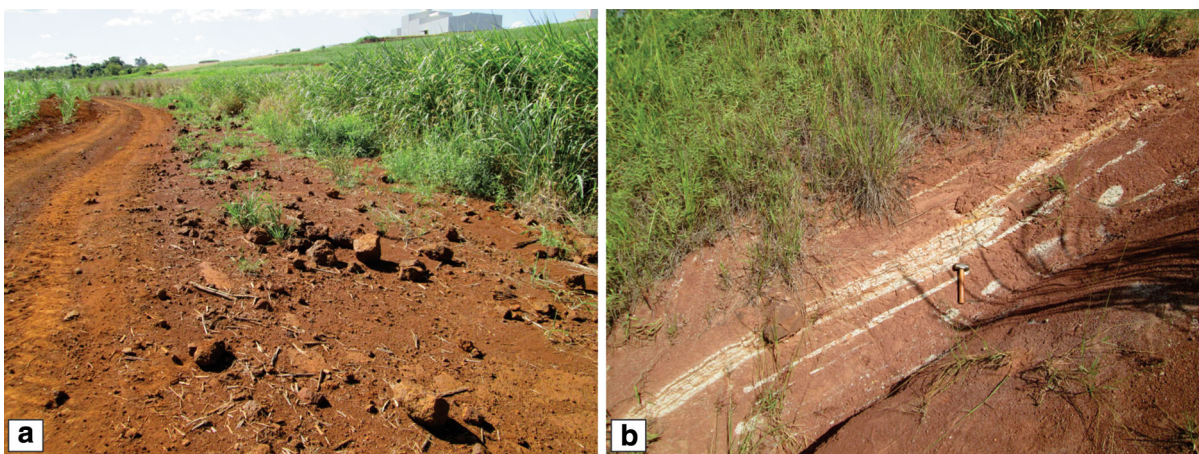


Figure 2

a The basalts rocks of Serra Geral Fm. at Cordeirópolis dam; **b** the siltite rocks of Itararé Group at Ipeúna dam

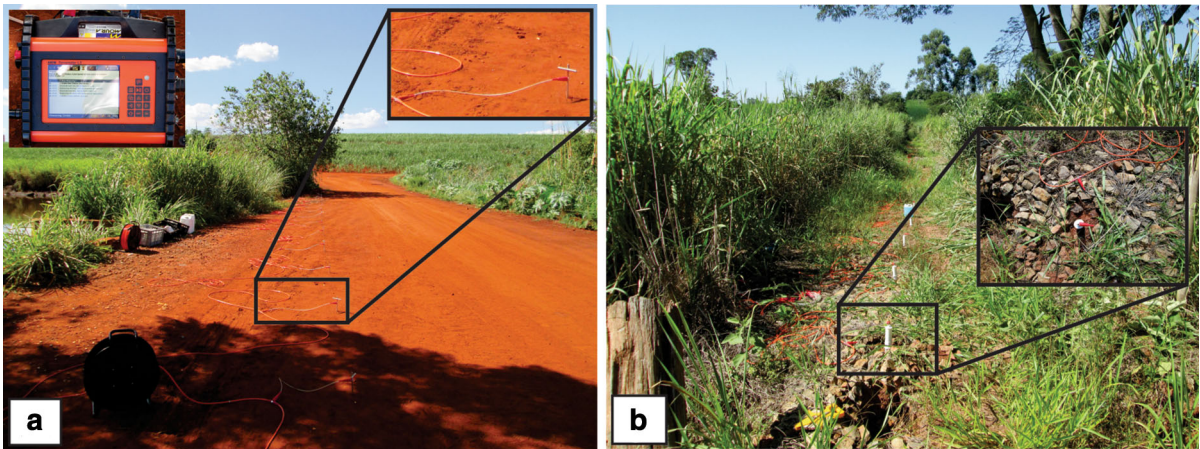


Figure 3

a Acquisition of ERT 3 at Cordeirópolis dam, with details of the electrodes and equipment; **b** acquisition of ERT2 at Ipeúna dam

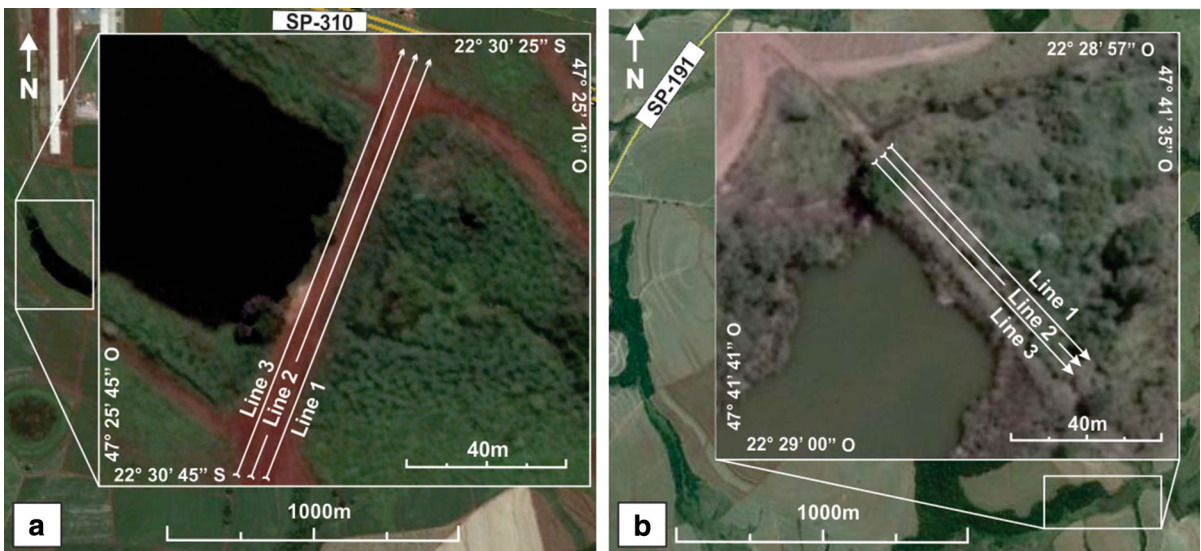


Figure 4

Location of ERTs at **a** Cordeirópolis dam; **b** Ipeúna dam

The instrument used for determination of the soil permeability is the Guelph permeameter. It is a field tool used to determinate values of the permeability coefficient of the sampled soil. This method has been applied in many researches to determine the soil *K* permeability factor (Höyng et al. 2013; Nasri et al. 2014). In general, the method presents results close to the results of laboratory tests of permeability, but with the advantage of field versatility. The basic

principle of the method is simple and somewhat analogous to Darcy’s experience.

4. Results

The data were processed on Res2dinv software, presented in the form of sections distance × depth, in the form of inversion model in terms of electrical resistivity (Loke and Baker 1996). This program is

designed for processing large data sets in two dimensions acquired by means of electrical imaging technique. The inversion process consists of a series of rectangular blocks. The layout of the blocks is linked to the distribution of data points on a pseudo-section, i.e., the section generated by in-depth theoretical field data. The distribution and the size of the blocks are generated automatically by the program according to the distribution of data points. The depth of the bottom row of blocks is set to be approximately equal to the equivalent depth of investigation of points with the largest gap between electrodes (Edwards 1977). The direct modeling technique is used to calculate the values of apparent resistivity, while the model of inversion is the technique of nonlinear optimization for least squares used in an inversion routine (Degroot-Hedlin and Constable 1990; Loke and Baker 1996).

The sample geophysical data mesh was planned with the aim of lateral line interpolation from the values of resistivity measurement and models of 2D inversion, through the method of minimum curvature, with the aid of the Oasis Montaj, Geosoft platform program. From the lateral interpolation, patterned lines generated images in three dimensions—pseudo 3D.

According to Moreira et al. (2018), geophysical 3D pseudo-models generated from 2D sections provide a very wide comprehension of the complexity of geological and hydrogeological structures, especially at short distance between the acquisition lines and data (Chambers et al. 2006; Mastrocicco et al. 2010; Aizebeokhai et al. 2011; Hamdan et al. 2014; Moreira et al. 2016; Vieira et al. 2016; Côrtes et al. 2016; Attwa and El-Shinawi 2017).

The lines of electrical tomography were performed by means of the Wenner arrangement, due to its excellent signal/noise ratio and trend of horizontal spread of the electric field. In general, the red/yellow present values of higher resistivity; the tones of cold colors, such as blue, feature lower resistivity values.

At the Cordeirópolis dam, all ERTs registered the spillway of the dam. In this case, the spillway was made of concrete. Due to the large physical properties contrast between the embankment material of the dam and the spillway, these structures were well visible and easily identified. The spillway is characterized by a large zone of high resistivity, which

occurs approximately between 39 and 43 m. The contact region between the embankment and the rocky top was easily identified (Fig. 5).

Besides the high resistivity of the spillway area, there is another area of high resistivity in the lower portion of the images, interpreted as the contact of the soil with rocks of the Serra Geral Formation.

The ERT-1 nearest downstream, features a low resistivity one, with less than 100 Ω m horizontally between 19 and 45 m and vertically between 4 and 8 m from the surface. This zone was named LRZ-1 (low resistivity zone). The LRZ-1 is visible on ERT-2 between the same ranges but with a slightly lower resistivity in the center of the anomaly. This also occurs on ERT-3, but greater than in ERT-1 and 2; resistivity focus is smaller, with less than 60 Ω m. In ERT-3, the anomaly is distributed horizontally between 18 and 45 m and between 2 and 8 m of depth.

The ETRs can also identify additional zones of low resistivity, as the LRZ-2 between 46 and 52 m, next to the spillway. The location near to the spillway might cause the generation of this zone by means of infiltration of water next to the upper portion of the dam. This infiltration generates an electrical conductor contrasting with the nearby dry soil and concrete characterized as an electrical insulator.

Between 10 and 32 m, it is also possible to identify the third zone of low resistivity, denominated LRZ-3. This zone is shallower with a maximum depth of 2 m below the surface, and may be related to a point of weakness caused by a layer of soil with insufficient compression, and consequently lower permeability.

The results of the measures with the Guelph permeameter show that the average of permeability at Cordeirópolis dam is relatively low, with values in the order of 10^{-5} cm/s. The results of the granulometry data of the material of the dam embankment show that the soil is predominantly clay-silt ($\sim 70\%$) and only 30% consists of sand.

The Ipeúna dam has the spillway at the corner of the dam, therefore, in this case, it was possible to place the ERTs outside the area of influence of the spillway. The contact region between the embankment and the rocky top was hard to identify because the sandstone was saturated. Thus the contact was inflected based on field observations. The ERTs could also identify two zones of low resistivity.

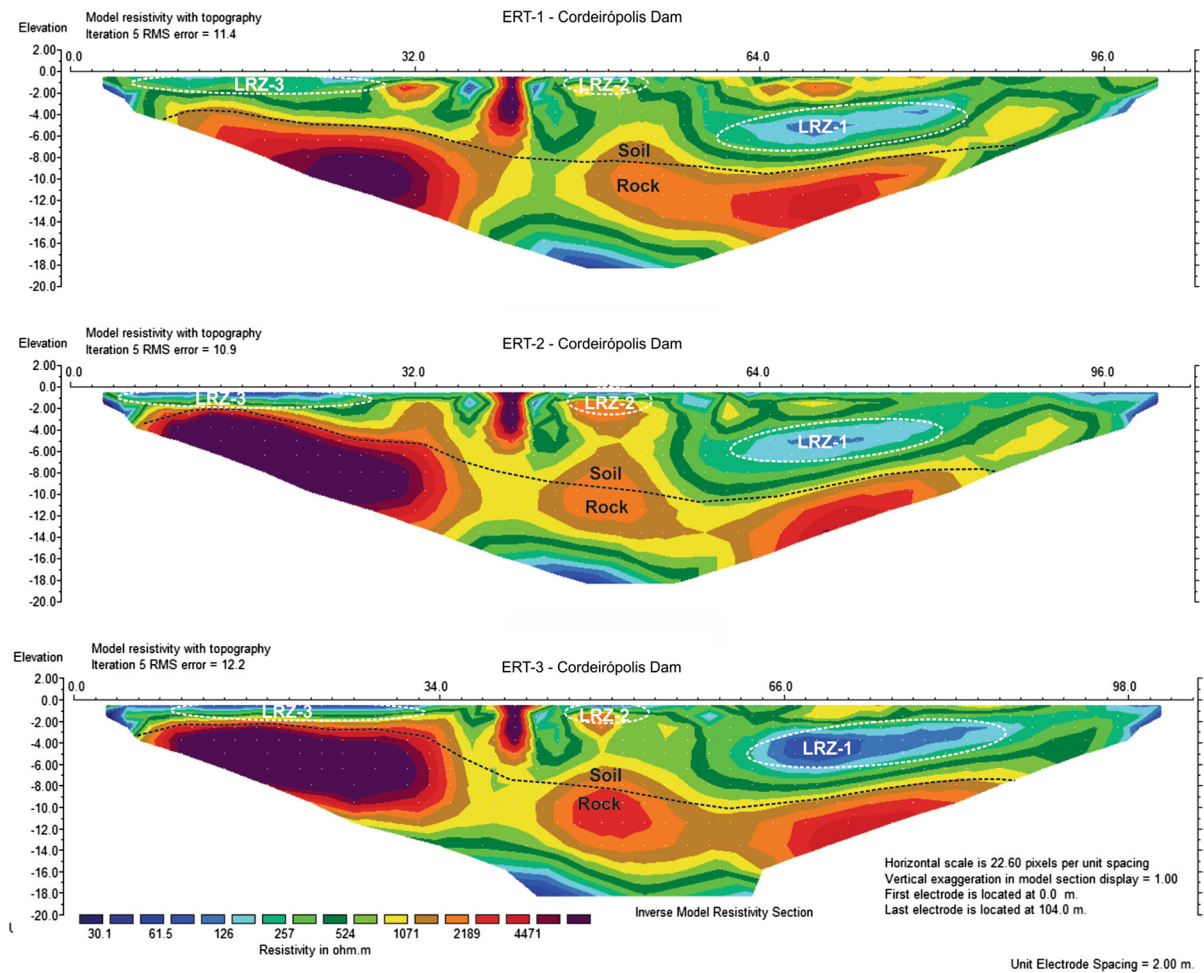


Figure 5
ERT-1, 2 and 3—Cordeirópolis dam. The LRZ zones are indicated in white marks

The ERT-1 nearest downstream, features a low resistivity one, with less than $100 \Omega \text{ m}$ horizontally between 4 and 16 m and vertically between 2 and 5 m from the surface. This zone was named LRZ-1 (low resistivity zone). The LRZ-1 is visible on ERT-2 between the same ranges. This also occurs on ERT-3 (Fig. 6). The ERTs can also identify additional zone of low resistivity. There is between 21 and 40 m and vertically between 6 and 10 m from the surface, another low resistivity zone, called LRZ-2. This zone also occurs in ERT-2 and ERT-3 but in smaller sizes and intensity.

The results of the measures with the Guelph permeameter show that the average of permeability at Ipeúna dam is relatively low, with values in the order

of 10^{-4} cm/s . The results of the granulometry data of the material of the dam embankment show that the soil is predominantly clay-silt ($\sim 55\%$) and only 45% consists of sand.

At Cordeirópolis dam, all low resistivity zones are easily identified and the trends of hydric flow are also notable, especially at LRZ-2 and 3, which are highlighted in the geophysical 3D pseudo-models (Fig. 7). According to Foster et al. (2000), the main locations where piping initiates are in trenches and conduits over the embankment. However, there are other uncommon locations where piping can be initiated: the contact between the embankment and concrete structures such as spillways and over irregularities in the foundation. The LRZ-2 is an example

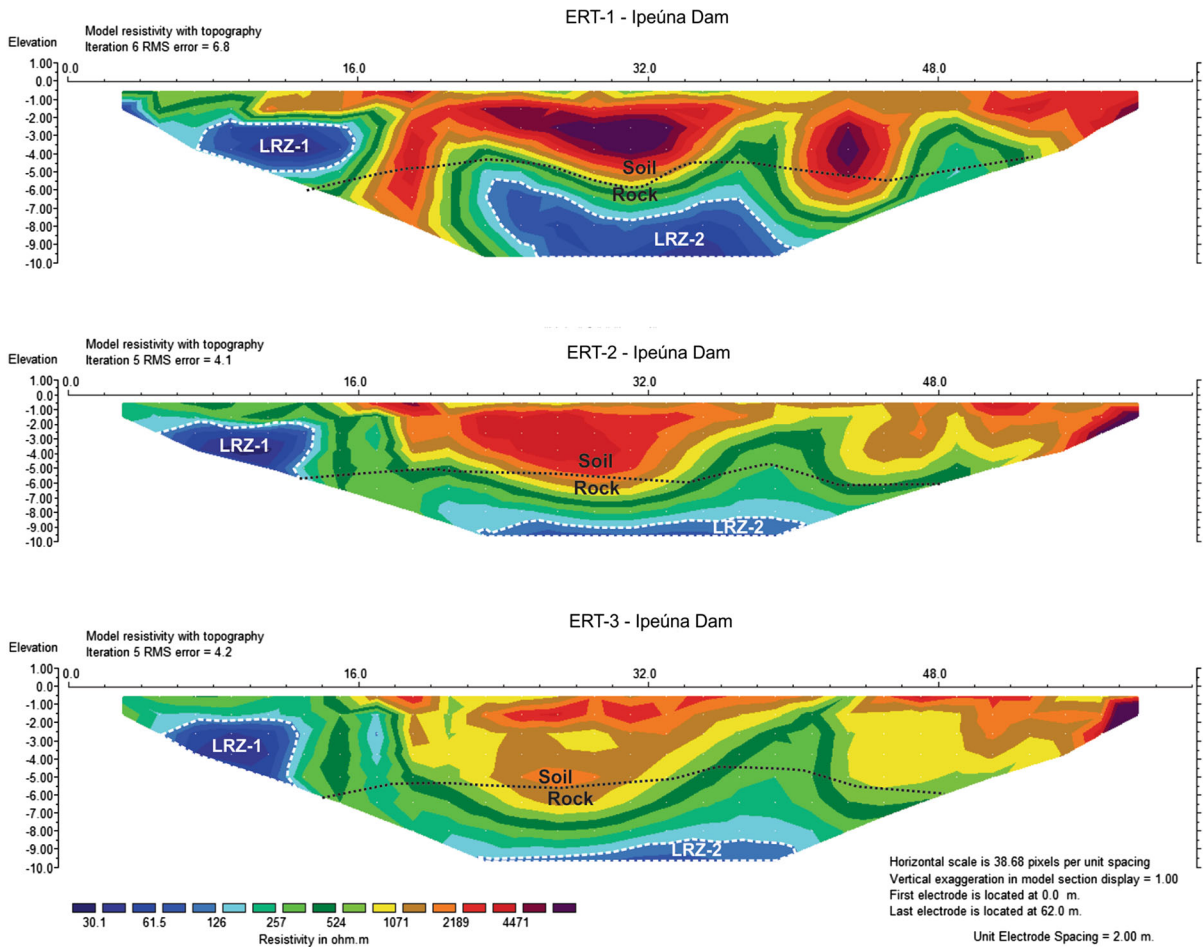


Figure 6
ERT-1, 2 and 3—Ipeúna dam. The LRZ zones are indicated in white marks

of these types of piping occurrence, and in fact, the data of pseudo-3D modeling presents this area as the area that most closely resembles the piping. Analogous to these contact zones, the LRZ-1 occurs in the contact area between embankment and rocky top. These locations are particularly susceptible to hydraulic fracturing and differential settlement.

One of the mechanisms that may have led to the formation of such area could be a layer of soil that has not reached the desired compression level. This can give rise to a stratum where the horizontal permeability is greater than the vertical permeability— $kh > kv$, which would justify such infiltration.

The low resistivity zone LRZ-1 in the dam of Cordeirópolis is the most visible in electrical resistivity tomography. The intensity and the size of the

zone are higher upstream than downstream. This feature is interpreted as a saturation zone due to a probable preferential flow of water accumulation in the direction perpendicular to the axis of the dam.

Some evidences of the damage caused by LRZ-1 infiltration were observed in the dam structure and are illustrated in Fig. 8a. There is a destabilization of the downstream slope caused by the association of the superficial and the internal erosion of LRZ-1 infiltration. The oscillation of the reservoir water level is conditioned by the regional precipitation regime. In times of higher water level, there is a greater supply and infiltration in the LRZ-1 area, causing issues, such as piping. On the other hand, when there is lower water level, the damage remains evident, even if there are no wet areas in front of the downstream

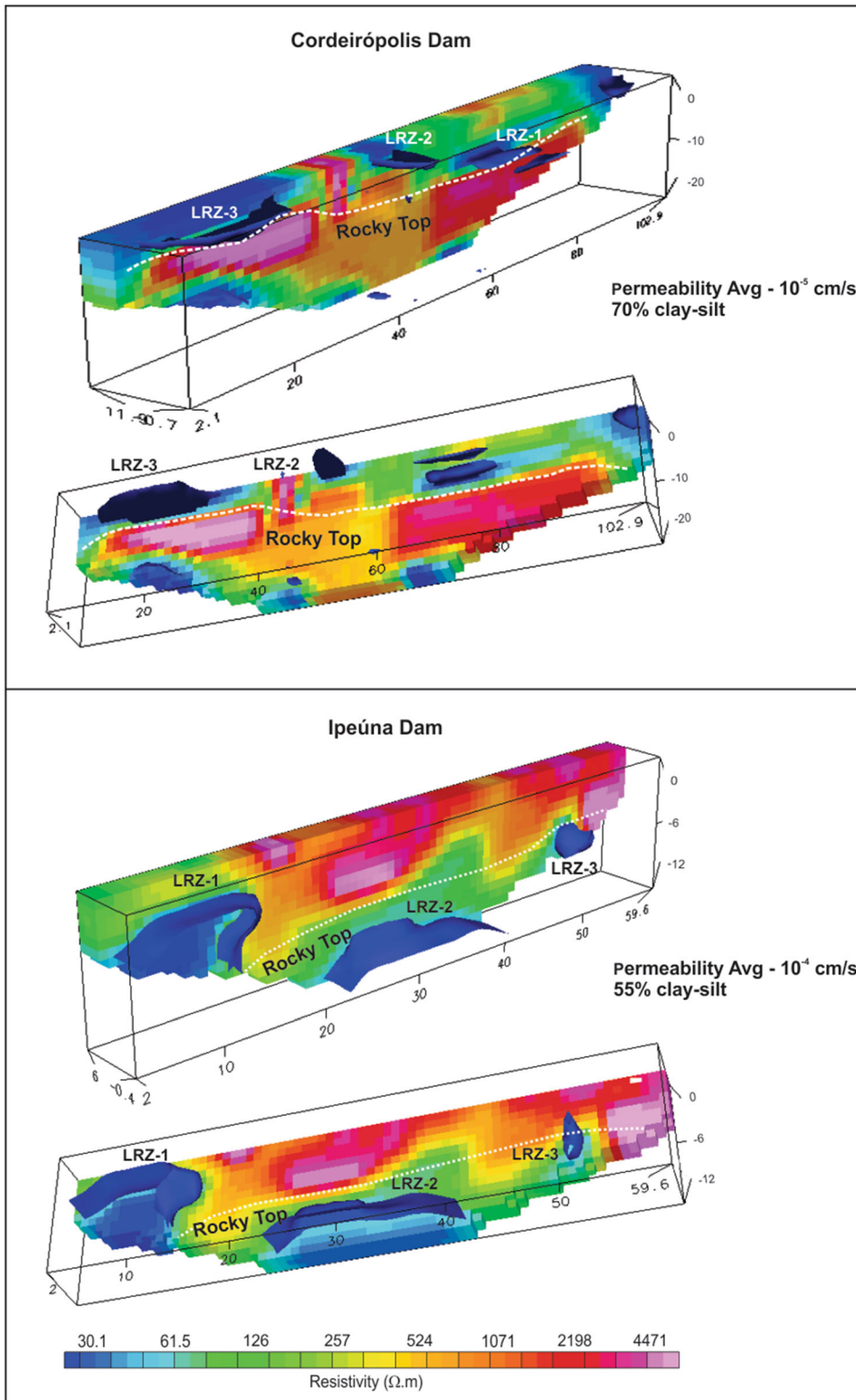


Figure 7
3D block viewed with direction following the groundwater flow

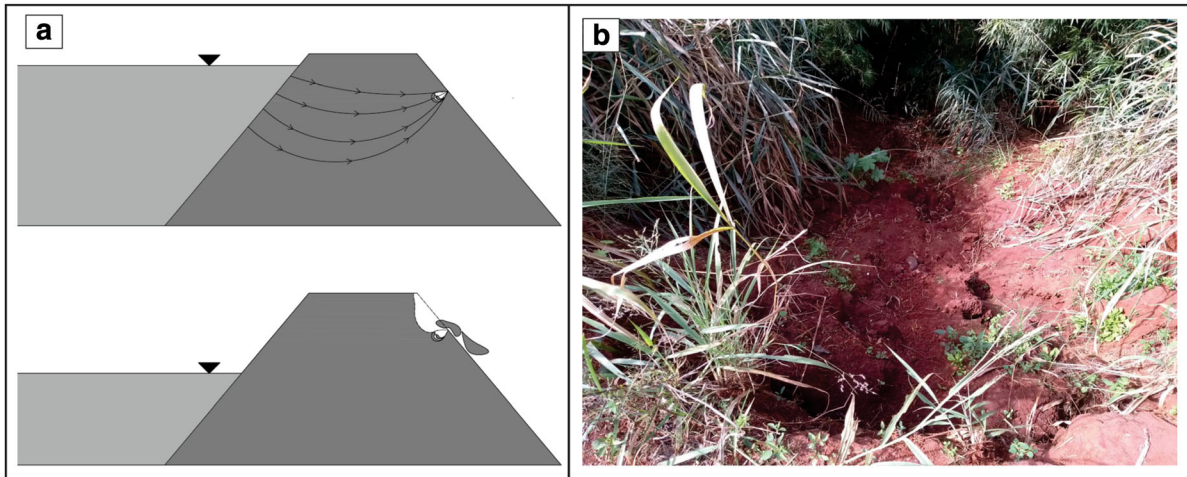


Figure 8

a The oscillation of the reservoir water level. **b** A upper view of the damages at the downstream slope

slope, as shown in Fig. 8b, where the damage is observed despite the absence of wet spots.

At Ipeúna dam, the LRZ-1 and 2 were also highlighted by the treatment of the data in 3D, but it was also possible to identify another zone of low resistivity, called LRZ-3 (Fig. 7). In the 2D inversion model, some smaller zones of low resistivity can be obscured if they occur close to areas with high resistivity. This can occur due to the processing of the least squares model. In the case of Ipeúna's block diagram 3D model, this contrast was minimized by the lateral lines interpolation, through the method of minimum curvature, and therefore it was possible to identify the LRZ-3 occurring between 50 and 53 m and vertically between 5 and 7 m from the surface.

In addition, it is possible to identify the shape of the LRZs. In general, the areas have a greater lateral distribution. The use of the Wenner array favors the prominence of structures with greater horizontal distribution and it helps to identify the horizontal anomalies. It is still possible to identify trends of major low resistivity streams and locate the areas of greatest intensity of these zones.

At Ipeúna dam the LRZ-1 and 2 are larger in size and lateral distribution. In compliance with the geological characteristics of the embankment dam, where only 55% of the soil consists of clay-silt and presents relatively higher permeability, the structure may be more susceptible to suffosion process than piping.

According to Richards and Reddy (2007), the term "suffosion" is used to describe the gradual migration of fine materials through a coarse matrix leading to failure. Researchers from Eastern Europe (Galarowski 1976; Burenkova 1993) reported this process, which is a slower process if compared to piping.

The LRZ-3, which occurs punctually, can be an area more susceptible to piping. Focally at the embankment dam, there may be various degrees of soil compaction and, consequently, higher permeability. This permeability contrast can act as an embankment zoning. As stated by Foster et al. (2000), the embankment zoning has an important influence on the frequency of initiation of piping. Dams with poor control of pore pressures in the embankment have generally experienced more problems associated with piping and slope instability compared with other dam types.

5. Conclusions

Accidents involving dams are not rare. There are several reports of these events. Phenomena such as piping, internal erosion, seepage and leakage can cause serious damage to structures of dams, especially earth dams. It is important that every dam receive proper care, monitoring and technical support.

The dam of Ipeúna presented areas of relatively lower resistivity than Cordeirópolis dam due to the higher permeability average values, as evidenced by the permeability data. The results of electric resistivity inversion models revealed zones of infiltration related to internal erosion and initiation of piping process, which is characterized by low resistivity values.

Low resistivity zones in each dams indicate different problems. At the dam of Cordeirópolis, the zones are focal, meanwhile at Ipeúna's dam the structure presents a greater degree of damage. In Cordeirópolis there is a risk of accident and failure in the structure, but it is not possible to say that the entire structure is compromised. Unlike Ipeúna, where a failure may be a trigger for a dam burst, causing damage proportionately higher. All this confirms the need for maintenance in both dams.

The unification of 2D data results in 3D viewing models, allowing a comprehensive and integrated analysis. The methodological proposal for the interpolation of 2D sections for the generation of 3D visualization models is a routine used in the estimation of reserves in mineral exploration, from geochemical data obtained in drillings, whose 3D modeling is adopted in the economic viability of mining projects and justifies the investment of millions of dollars (Moreira et al. 2018). On the geotechnical context, the integrated analysis of electrical resistivity in 3D models helps to indicate areas susceptible to internal erosion and subject to piping.

At the Ipeúna dam, the LRZ-1 that occurs on the left side of the dam, can be interpreted as a saturated zone of the dam embankment. Such zone was possibly influenced by erosion from upstream to downstream. The LRZ-2, located in the central portion of the dam, can be considered a zone of water infiltration and increased saturation of the material on the site. The fact of LRZ-2 increase in downstream direction can indicate the process of piping installed in the embankment of the dam. It is important to emphasize the need for adequate data treatment, since certain low resistivity zones were only identified in the 3D diagrams blocks. The LRZ-3 was not visible in the treatment ERT data, but in the data of the 3D block diagram model it was possible to identify it. It can represent the first stage of piping process.

This study can be widely applied in dams of different nature, whether for the decanting of tailings in mining, storage of water for irrigation/supply or even power generation. The results of the work show that the electrical tomography technique is a great alternative. The contrast of the physical properties of the soil with the water is visible and striking.

Analyzing the occurrences and the disposition of these Low Resistivity Zones, which are presented in almost the entire structure of the embankment and around the foundation, it is possible to affirm that the dam needs urgent maintenance. These zones indicate that the dam is propitious to accidents similar to Mariana's dam burst. Despite of the Ipeúna's dam is smaller compared to the Samarco's dam, in Mariana, an accident in Ipeúna could bring serious damage to the local environment and economy.

Therefore, it is possible to affirm that the study presents satisfactory results, even if not the most used, and conclude that geophysics represents an inexpensive alternative and non-invasively for inspection of earth dams. In any case, the results of geophysical surveys are based on indirect analyses and must necessarily be measured with direct investigations of the area identified through sounding or excavations. However, the use of other geophysical methods, such as seismic or ground penetrating radar (GPR), can aid in the diagnosis of possible pathologies of structures and add greater credibility to the results.

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REFERENCES

- ABEM. (2012). *Terrameter LS-instruction manual* (p. 122). Sundbyberg: ABEM Instrument AB.
- Aizebeokhai, A. P., Olayinka, A. I., Singh, V. S., & Uhuegbu, C. C. (2011). Effectiveness of 3D geoelectrical resistivity imaging using parallel 2D profiles. *International Journal of the Physical Science*, 6, 5623–5647.
- Al-Fares, W. (2011). Contribution of the geophysical methods in characterizing the water leakage in Afamia B dam, Syria. *Journal of Applied Geophysics*, 75(3), 464–471.

- Asfahani, J., Radwan, Y., & Layyous, I. (2010). Integrated geophysical and morphotectonic survey of the impact of ghab extensional tectonics on the Qastoon Dam, Northwestern Syria. *Pure and Applied Geophysics*, *167*(3), 323–338.
- Assumpção, M., Marza, V., Barros, L., Chimpliganond, C., Soares, J., Carvalho, J., et al. (2002). Reservoir-induced seismicity in Brazil. *Pure and Applied Geophysics*, *159*(1–3), 597–617.
- Attwa, M., & El-Shinawi, A. (2017). An integrative approach for preliminary environmental engineering investigations amidst reclaiming desert-land: a case study at East Nile Delta, Egypt. *Environmental Earth Science*, *76*, 304–322.
- Bedrosian, P. A., Burton, B. L., Powers, M. H., & Minsley, B. J. (2012). Geophysical investigations of geology and structure at the Mathis Creek Dam, Truckee, California. *Journal of Applied Geophysics*, *77*(1–2), 7–20.
- Bonelli, S. (2013). *Erosion in geomechanics applied to dams and levees*. Hoboken: Wiley.
- Burenkova, V. V. (1993). Assessment of suffosion in non-cohesive and graded soils. In J. Brauns, M. Heibaum, & U. Schuler (Eds.), *Filters in geotechnical and hydraulic engineering* (pp. 357–360). Rotterdam: Balkema.
- Chambers, J. E., Kuras, O., Meldrum, P. I., Ogilvy, R. D., & Hollands, J. (2006). Electrical resistivity tomography applied to geologic, hydrogeologic, and engineering investigations at a former waste-disposal site. *Geophysics*, *71*(6), 231–239.
- Côrtes, A. R. P., Moreira, C. A., Veloso, D. I. K., Vieira, L. B., & Bergonzoni, F. A. (2016). Geoelectrical prospecting for a copper-sulfide mineralization in the Camaquã sedimentary basin, Southern Brazil. *Geofísica Internacional*, *55*(3), 107–117.
- CPRM. (2003). *Geologia, tectônica e recursos minerais do Brasil: texto, mapas and SIG*. Brasília: CPRM—Serviço Geológico do Brasil.
- Degroot-Hedlin, C., & Constable, S. (1990). Occam's inversion to generate smooth, two-dimensional models from magnetotelluric data. *Geophysics*, *55*(12), 1613–1624.
- Edwards, L. S. A. (1977). A modified pseudosection for resistivity and induced polarization. *Geophysics*, *42*(5), 1020–1036.
- Eyles, C. H., Eyles, N., & Franca, A. B. (1993). Glaciation and tectonics in an active intracratonic basin: the Late Paleozoic Itararé Group, Paraná Basin, Brazil. *Sedimentology*, *40*(1), 1–25.
- Foster, M., Fell, R., & Spanngle, M. (2000). The statistics of embankment dam failures and accidents. *Canadian Geotechnical Journal*, *37*(5), 1000–1024.
- Galarowski, T. (1976). New observations of the present-day suffosion(piping) processes in the Bereznicza catchment basin in the Bieszczady Mountains (The East Carpathians). *Studia Geomorphologica Carpatho-Balcanica (Krakow)*, *10*, 115–122.
- Gélis, C., Noble, M., Cabrera, J., Penz, S., Chauris, H., & Cushing, E. M. (2015). Ability of high-resolution resistivity tomography to detect fault and fracture zones: Application to the tournemire experimental platform of, France. *Pure and Applied Geophysics*, *173*, 573–589.
- Gélis, C., Revil, A., Cushing, E. M., Jougnot, D., Lemeille, F., Cabrera, J., et al. (2010). Potential of electrical resistivity tomography to detect fault zones in limestone and argillaceous formations in the experimental platform of Tournemire, France. *Pure and Applied Geophysics*, *167*, 1405–1418.
- Hamdan, H., Andronikidis, N., Kritikakis, G., Economou, N., Agioutanis, Z., Schilizzi, P., et al. (2014). Contribution of electrical tomography methods in geotechnical investigations at Mavropigi lignite open pit mine, Northern Greece. *Environmental Earth Sciences*, *72*(5), 1589–1598.
- Höyng, D., D’Affonseca, F. M., Bayer, P., Oliveira, E. G., Perinotto, J. A. J., Reis, F., et al. (2013). High-resolution aquifer analog of fluvial-aeolian sediments of the Guarani aquifer system. *Environmental Earth Sciences*, *71*(7), 3081–3094.
- IBAMA. (2015). Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais. <http://www.ibama.gov.br/publicadas/onda-de-rejeitos-da-samarco-atingiu-663-km-de-rios-e-devastou-1469-hectares-de-terras>. Accessed 21 Oct 2017.
- Karastathis, V. K., Karmis, P. N., Drakatos, G., & Stavrakakis, G. (2002). Geophysical methods contributing to the testing of concrete dams. Application at the Marathon Dam. *Journal of Applied Geophysics*, *50*(3), 247–260.
- Kearey, P., Brooks, M., & Hill, I. (2002). *An introduction to geophysical exploration*. Hoboken: Wiley.
- Khalil, M. A., Bobst, A., & Mosolof, J. (2018). Utilizing 2D electrical resistivity tomography and very low frequency electromagnetics to investigate the hydrogeology of natural cold springs near Virginia City, Southwest Montana. *Pure Applied Geophysics*. <https://doi.org/10.1007/s00024-018-1865-2>.
- Loh, C. H., & Wu, T. S. (1996). Identification of Fei-Tsui arch dam from both ambient and seismic response data. *Soil Dynamics and Earthquake Engineering*, *15*(7), 465–483.
- Loke, M. H., & Baker, R. D. (1996). Rapid least-squares inversion of apparent resistivity pseudosections by Quasi-Newton Method. *Geophysical Prospecting*, *44*(1), 131–152.
- Machado, F. B., Nardy, A. J. R., Melo, R. P., Oliveira, M. A. F., & Squisato, E. (2005). As rochas intrusivas da formação serra geral na porção leste da bacia do paraná no estado de são paulo: aspectos petrográficos e geoquímicos—resultados preliminares. *Geociências*, *24*(1), 5–17.
- Malagutti Filho, W., Braga, A. C. O., Elis, V. R., & Dourado, J. C. (1999). Estudos de minibarragens: exemplo de aplicação de técnicas geofísicas. *Geociências*, *18*(1), 53–67.
- Mastrocicco, M., Vignoli, G., Colombani, N., & Abu Zeid, N. (2010). Surface electrical resistivity tomography and hydrogeological characterization to constrain groundwater flow modeling in an agricultural field site near Ferrara (Italy). *Environmental Earth Sciences*, *61*(2), 311–322.
- Medina, F., & Domínguez, J. (1989). Boundary elements for the analysis of the seismic response of dams including dam water foundation interaction effects. *Engineering Analysis with Boundary Elements*, *6*(3), 152–157.
- Milani, E. J., & Ramos, V. A. (1998). Orogenias paleozóicas no domínio sul-ocidental do Gondwana e os ciclos de subsidência da Bacia do Paraná. *Geociências*, *28*(4), 473–484.
- Minsley, B.J., Burton, B.L., Ikard, S., Powers, M.H. (2011). Geophysical investigations at Hidden Dam, Raymond, California: Summary of fieldwork and data analysis. Open File Report 2010–2013. United States Geological Survey. <https://pubs.er.usgs.gov/publication/ofr20101013>. Accessed 22 Nov 2018.
- Moreira, C. A., Helene, L. P. I., Nogara, P., & Ilha, L. M. (2018). Analysis of leaks from geomembrane in a sanitary landfill through models of electrical resistivity tomography in South Brazil. *Environmental Earth Sciences*, *77*, 7. <https://doi.org/10.1007/s12665-017-7180-x>.
- Moreira, C. A., Lapola, M. M., & Carrara, A. (2016). Comparative analyzes among electrical resistivity tomography arrays in the characterization of flow structure in free aquifer. *Geofísica Internacional*, *55*(2), 119–129.

- Nasri, B., Fouché, O., & Ramier, D. (2014). Monitoring infiltration under a real on-site treatment system of domestic wastewater and evaluation of soil transfer function (Paris Baisn, France). *Environmental Earth Sciences*, 73(11), 7435–7444.
- Oh, S., & Sun, C. G. (2007). Combined analysis of electrical resistivity and geotechnical SPT blow counts for the safety assessment of fill dam. *Environmental Geology*, 54, 31–42.
- Osazuwa, I. B., & Chinedu, A. D. (2008). Seismic refraction tomography imaging of high-permeability zones beneath an earthen dam, in Zaria area, Nigeria. *Journal of Applied Geophysics*, 66(1–2), 44–58.
- Ozcan, N. T., Ulusay, R., & Isik, N. S. (2013). A study on a geotechnical characterization and stability of downstream slope of a tailings dam to improve its storage capacity (Turkey). *Environmental Earth Sciences*, 69(6), 1871–1890.
- Richards, K. S., & Reddy, K. R. (2007). Critical appraisal of piping phenomena in earth dams. *Bulletin of Engineering Geology and the Environment*, 66(4), 381–402.
- Schneider, R. L., Muhlmann, H., Tommasi, E., Medeiros, R. A., Daemon, R. F., & Nogueira, A. A. (1974). Revisão estratigráfica da Bacia do Paraná. *Brazilian Congress of Geology*, 1, 41–65.
- Sjödahl, P., Dahlin, T., & Johansson, S. (2005). Using resistivity measurements for dam safety evaluation at Enemossen tailings dam in southern Sweden. *Environmental Geology*, 49(2), 267–273.
- Tanchev, L. (2014). *Dams and appurtenant hydraulic structures*. Boca Raton: CRC Press.
- Vieira, L. B., Moreira, C. A., Côrtes, A. R. P., & Luvizotto, G. L. (2016). Geophysical modeling of the manganese deposit for Induced Polarization method in Itapira (Brazil). *Geofísica Internacional*, 55(2), 107–117.
- Wei, Z., Yin, G., Wan, L., & Li, G. (2016). A case study on a geotechnical investigation of drainage methods for hightening a tailing dam. *Environmental Earth Sciences*, 75, 106. <https://doi.org/10.1007/s12665-015-5029-8>.
- Yilmaz, S., & Koksoy, K. (2017). Electrical resistivity imaging and dye tracer test for the estimation of water leakage paths from reservoir of Akdegirmen Dam in Afyonkarahisar. *Turkey. Environmental Earth Sciences*, 76, 829. <https://doi.org/10.1007/s12665-017-7174-8>.

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