Geophysical investigation of earth dam using the electrical tomography resistivity technique

http://dx.doi.org/10.1590/0370-44672016700099

Pedro Lemos Camarero
Mestre
Universidade Estadual Paulista - UNESP
Departamento de Geologia Aplicada
Rio Claro – São Paulo - Brasil
camarero@folha.com.br

Cesar Augusto Moreira
Professor Assistente Doutor
Universidade Estadual Paulista - UNESP
Departamento de Geologia Aplicada
Rio Claro – São Paulo - Brasil
moreirac@rc.unesp.br

Abstract

Dams are structures that dam rivers and streams for a variety of purposes. These structures often need to be sturdy to withstand the force of the impoundment and the high values of accumulated water load. The constant maintenance of these structures is essential, since a possible accident can lead to damage of catastrophic proportions. This research presents an alternative cheap and quick application for investigating water seepage in earth dams, through the application of the DC resistivity geophysical method from the electrical resistivity tomography (ERT) technique in Wenner array. Three ERT lines were placed parallel to the longitudinal axis of a dam formed by clay soil from the decomposition of diabase. The data are presented in 2D and pseudo-3D geophysical images with electrical resistivity values modeled. Based on the physical principle of electrolytic conduction, that is, decrease in electrical resistance in materials or siliceous minerals in moisture conditions as 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 of the dam. The absence of evidence as water upwelling on the front of the dam together with geophysical evidence indicate saturation restricted to some points and low probability at the present time, for installation of piping processes.

Keywords: internal erosion, geophysics, dams, electrical resistivity.

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 key role 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 (Perini, 2009). 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 with erosion (Boneli, 2013).

On November 5, 2015, there occurred an accident in a tailings dam of the mining company Samarco in the city of Bento Rodrigues – MG. One of the three dams of the company broke while undergoing heightening works. According to IBAMA, there was an overflow of at least 34 million cubic meters of tailings from mining, causing severe damage to the local community. The episode is rated as the largest environmental disaster in the country, since the tailings caused the extermination of much of the fauna of Rio Doce and reached the coast of Espírito Santo, including all local biome (IBAMA, 2015).

Geophysics is an important tool for the investigation of structures like dams. Several case studies of dams inspected by geophysical methods have been reported (Medina and Domínguez, 1989; Loh and Wu, 1996; 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; Al-Fares, 2011; Minsley *et al*, 2011; Bedrosian *et al*, 2012; Case, 2012).

The present work has as its theme the application of the electric resistivity method for investigations within the body of a small earth dam, with the purpose of identifying areas of water percolation.

2. Area of study and geological context

The study area is located in the rural municipality of Cordeirópolis in the State of São Paulo. The area can be accessed by the Washington Luis Highway (SP 310) (Figure 1).

The geological context of the area of study is the Paraná sedimentary basin. The local geology is composed primarily of basic volcanic rocks of the Serra Geral Formation, which consists of a sequence of basaltic continental lava flows with about 1,500 m of thickness along the center of the basin, with coverage up to 1,200,000 km² (CPRM, 2003). According to Sousa (2002), the form of occurrence of the Serra Geral Formation in the eastern region of the São Paulo State are dikes and sills of basalts, plus a few narrow spills. The decomposition of the rocks generates a clay soil of the Latosol type. This soil amendment is the main material of loan used in the body of the dam.

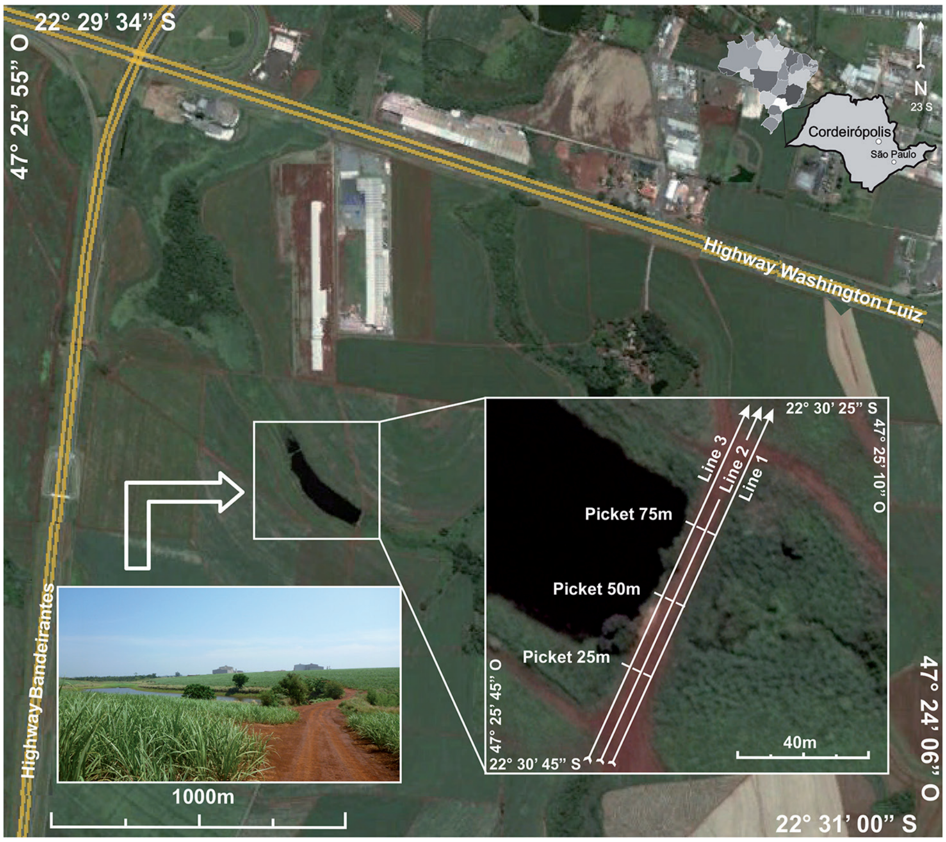

Figure 1
Location of the studied area and positions of the geophysical lines in the dam.

3. Methodology

In the Direct Current (DC) resistivity method, electrical currents artificially generated are introduced into the soil through a pair of electrodes, and potential resulting differences are measured on the surface through another pair of electrodes, in the area of influence of the electric field. Any existing heterogeneities in soils and rocks as bedding, foliation, fractures, as well as elements such as mineralogy, moisture content, porosity and permeability, can result in significant changes in the propagation of an electric field and provide definitions of contrasts structures to the local pattern (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. Equation:

$$\rho a = K.\Delta V / I \ \Omega.m.$$

The unity of the apparent resistivity is measured in Ohm.m, the potential difference is measured in milivolt (mV), while 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 the place of study, three electrical resistivity tomography (ERT) were carried out from southwest to northeast. The array used was Wenner with 53 electrodes spaced every 2m. Each ETR was 104m long, which allowed to cover the entire length of the dam and provided a resolution of approximately 17m of depth. The ETR-1 was leased closest downstream; ETR-3, closest to the upstream (Figure 1). The equipment used for this study was an ABEM Terrameter LS of 84 channels and power of 250W (ABEM, 2012).

In one day, 312m of geophysical data were acquired distributed in three ETRs arranged parallel to the ridge and in the direction of greater elongation of the body of the dam (Figure 2). Each line was run 104 meters long, with 53 electrodes spaced every 2m, with the space between ERTs was of 3m.

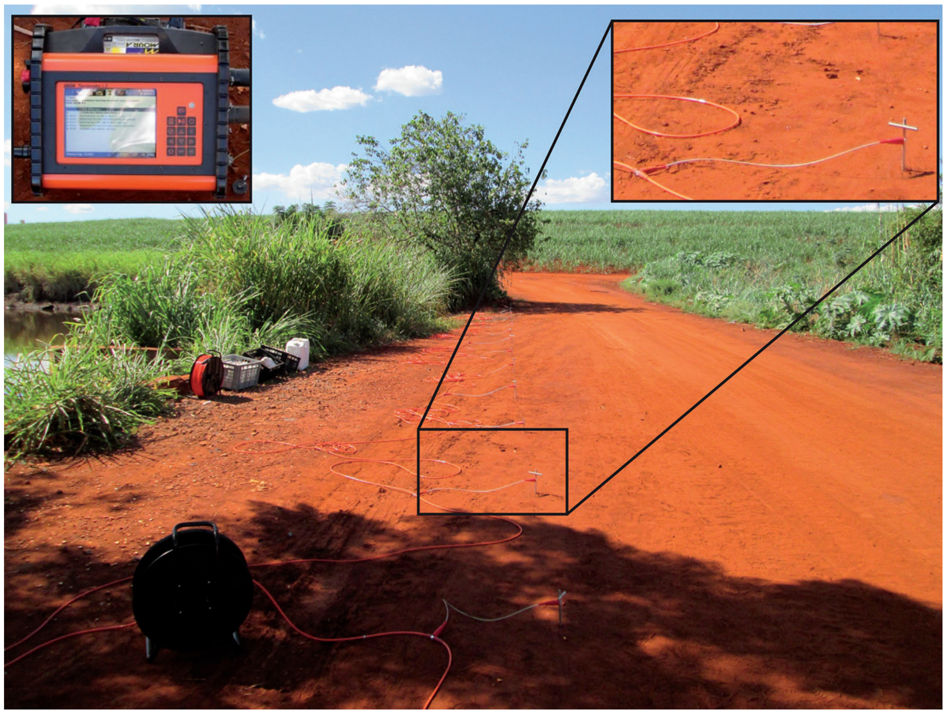

Figure 2
Acquisition of ERT 1, with
details of the electrodes and equipment.

4. Results

The data were processed on Res2dinv software, presented in the form of sections distance x 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 the 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, procedure adopted in some scientific articles (Moreira & Ilha, 2011; Moreira *et al*, 2012; Moreira *et al*., 2016a; Moreira *et al*., 2016b; Vieira *et al*., 2016 & Côrtes *et al*., 2016).

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 presents values of higher resistivity; the tones of cold colors, such as blue, feature lower resistivity values. All ETRs picked up the spillway of the dam. In the investigated case this spillway is made of concrete. Due to the large physical properties contrast with the body material of the dam, on all images this structure is well visible and easily identified. The spillway is characterized by a large zone of high resistivity, which occurs approximately between 39m and 43m (Figure 3).

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

The ETRs can also identify additional zones of low resistivity, as the LRZ-2 between 46m to 52m, 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 10m and 32m, 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 high permeability. Both the LRZ-2 and the LRZ-3 are most notable in Figure 4, which shows the block diagram of 3D visualization.

In the pseudo-3D images, it is possible to identify the shape of the LRZs, modeled in isosurfaces of 60Ω.m. 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 horizontals anomalies. It is still possible to identify trends of major low resistivity streams and locate the areas of greatest intensity of these zones (Figure 4).

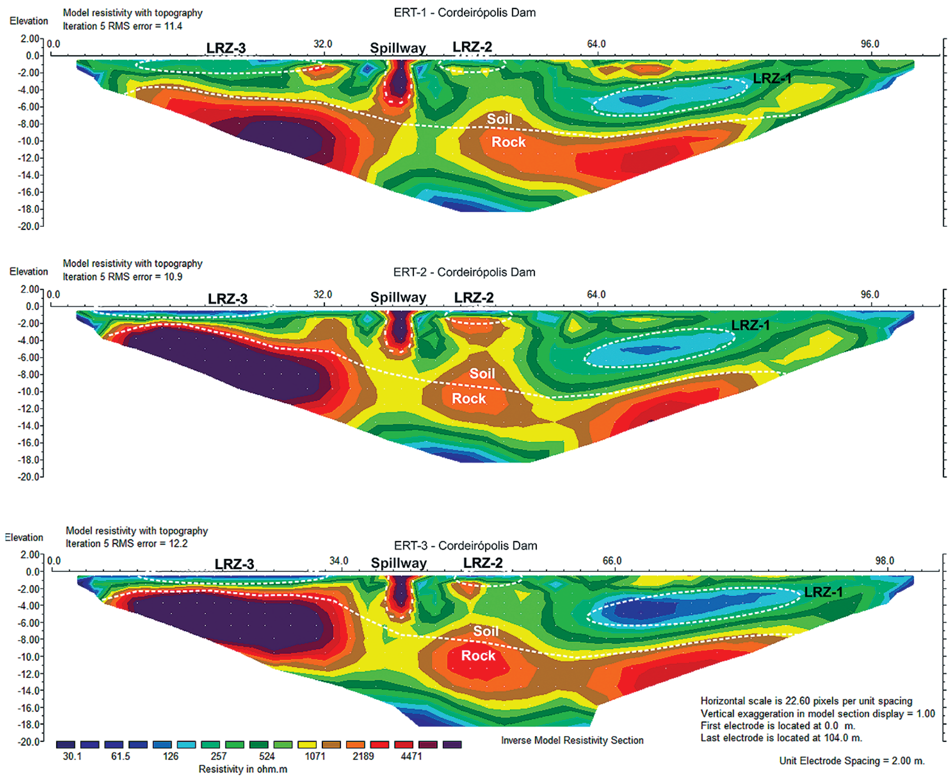

Figure 3
Inversion models of the electric resistivity, with soil/rock contact, spillway and LRZs (Low Resistivity Zone).

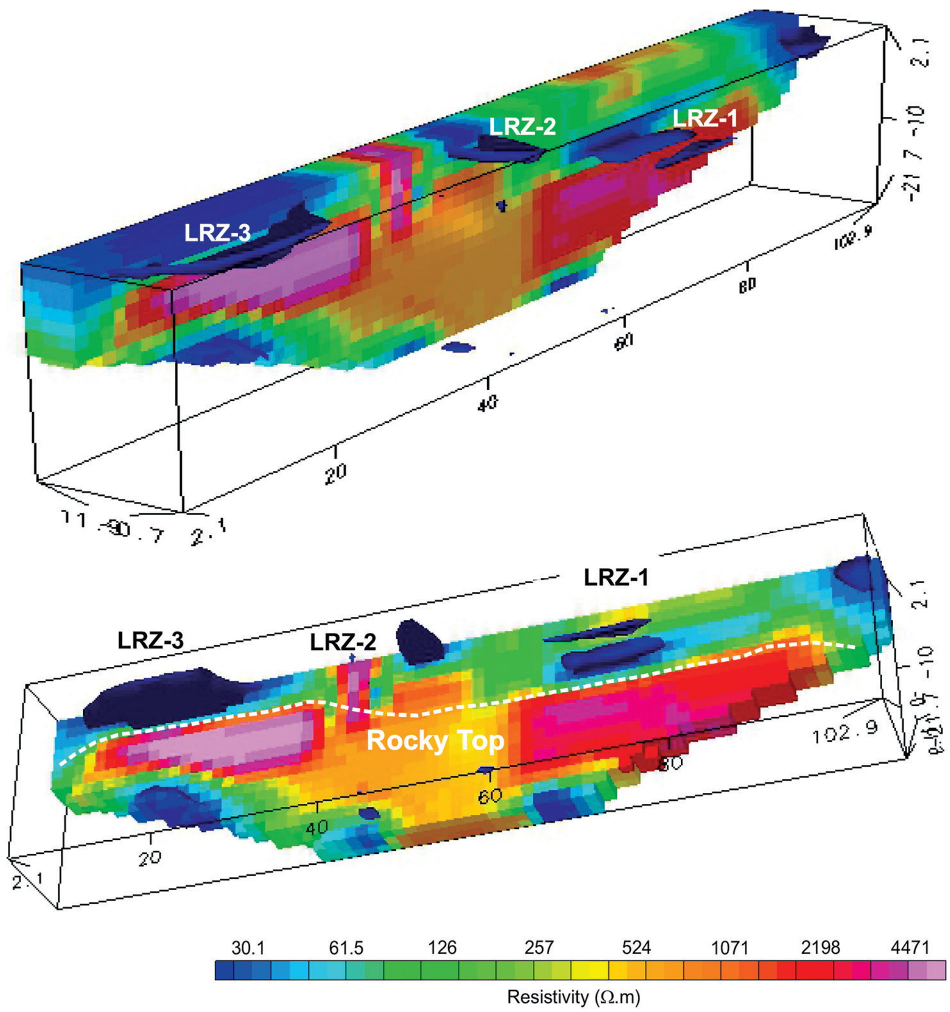

Figure 4
Pseudo-3D model of electric resistivity, with rocky top contact and isosurface modelling of the low resistivity (60Ω.m).

5. Conclusions

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.

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 LRZ-3 occurs in a shallow area and has its origin associated with the origin of the LRZ-1. The LRZ-2 has a lesser extent and points out a zone of weakness at the dam. This zone is interpreted as a location prone to internal erosion, and in fact, the data of pseudo-3D modeling, presents this area as the area that most closely resembles the piping.

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. The images indicate possible areas of structural weakness of the dam. These problems can lead to serious economic and environmental damage.

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.

Referências

ABEM. Instruction Manual Terrameter LS, Suécia, 122f. 2012.

Al-Fares, W. Contribution of the geophysical methods in characterizing the water leakage in Afamia B dam, Syria. ***Journal of Applied Geophysics,*** v. 75, p. 464–471, 2011.

BEDROSIAN, P. A., BURTON, B. L., POWERS, M. H., MINSLEY, B. J. Geophysical investigations of geology and structure at the Mathis Creek Dam, Truckee, California. ***Journal of Applied Geophysics,*** v. 77, p.7-20, 2012.

CPRM. Geologia, tectônica e recursos minerais do Brasil: texto, mapas & SIG – Brasília: CPRM – Serviço Geológico do Brasil, 2003. 692 p.

BONELI, S. ***Erosion in geomechanics applied to dams and levees.*** London: Wiley, 2013. 416p.

CASE, J. S. ***Inspection of earthen embankment dams using time lapse electrical resistivity tomography.*** Mississippi: University of Mississipi, Department of Civil Engineering, 2012. 123p. (Thesis Master in sciences).

CORTÊS, A. R. P., MOREIRA, C. A., VELOSO, D. I. K., VIEIRA, L. B., BERGONZONI, F. A. Geoelectrical prospecting for a copper-sulfide mineralization in the Camaquã sedimentary basin, Southern Brazil. ***Geofísica Internacional,*** v. 55, n°3, 165 – 174, 2016.

DEGROOT-HEDLIN, C., CONSTABLE, S. Occam`s Inversion to generate smooth, two-dimensional models from magnetotelluric data. ***Geophysics,*** v. 55, p.1613-1624, 1990.

EDWARDS, L. S. A modified pseudosection for resistivity and induced polarization. ***Geophysics,*** v. 42, p. 1020-1036, 1977.

IBAMA. Disponível em: <http://www.ibama.gov.br/publicadas/onda-de-rejeitos-da--samarco-atingiu-663-km-de-rios-e-devastou-1469-hectares-de-terras>. Access in 12/12/2015.

KARASTATHIS, V.K., KARMIS, P. N., DRAKATOS, G., STAVRAKAKIS, G. Geophysical methods contributing to the testing of concrete dams. Application at the Marathon Dam. ***Journal of Applied Geophysics,*** v. 50, Issue 3 p.247-260, 2002.

KEAREY P., BROOKS M., HILL, I. ***An introductionto geophysical exploration.*** (3° ed.) Oxford: Wiley-Blackwall Science Ltd, 2002. 281p.

LOH, C. H., WU, T. S. Identification of Fei-Tsui arch dam from both ambient and seismic response data. ***Soil Dynamics and Earthquake Engineering,*** v. 15, Issue 7, p.465-483, 1996.

LOKE, M. H., BAKER, R. D. Rapid least-squares inversion of apparent resistivity pseudosections by Quasi-Newton method. ***Geophysical Prospecting.*** v. 44, p.131-152, 1996.

MEDINA, F., DOMÍNGUEZ, J. Boundary elements for the analysis of the seismic response of dams including dam water foundation interaction effects. ***Engineering Analysis with Boundary Elements,*** v. 6, Issue 3, p.152-157, 1989.

MINSLEY, B. J., BURTON, B. L., IKARD, S., POWERS, M. H. Geophysical investigations at Hidden Dam, Raymond, California: summary of fieldwork and data analysis.2011. Open File Report 2010-2013. ***United States Geological Survey.*** 2011.

MOREIRA, C. A., ILHA, L. M. Prospecção geofísica em ocorrência de cobre localizada na bacia sedimentar do Camaquã (RS). REM: ***Revista da Escola de Minas,*** v. 64, n°3, 305-311, 2011.

MOREIRA, C.A., BORGES, M.R., VIEIRA, G.M.L., MALAGUTTI FILHO, W., Montanheiro, M.A.F. Geological and geophysical data integration for delimitation of mineralized areas in a supergene manganese deposits. ***Geofísica Internacional,*** v.53, n.2, p.201-212, 2012.

MOREIRA, C. A., BORSATTO, K., ILHA, L. M., SANTOS, S. F., ROSA, F. T. G. Geophysical modeling in gold deposit through DC Resistivity and Induced Polarization methods. ***REM: Revista da Escola de Minas,*** v. 64, n°3, p.305-311, 2016a.

MOREIRA, C. A., LAPOLA, M. M., CARRARA, A. Comparative analyzes among electrical resistivity tomography arrays in the characterization of flow structure in free aquifer. ***Geofísica Internacional,*** v.55, n.2, p. 119 – 129, 2016b.

OSAZUWA, I. B. & CHINEDU, A. D. Seismic refraction tomography imaging of high-permeability zones beneath an earthen dam, in Zaria area, Nigeria. ***Journal of Applied Geophysics,*** v. 66, issue 1-2, p.44-58, 2008.

PERINI, D. S. ***Estudo dos processos envolvidos na análise de riscos de barragens de terra.*** Brasília: Universidade de Brasília, 2009.

SOUSA, M.L. ***Evolução tectônica dos altos estruturais de Pitanga, Artemis, Pau d'Alho e Jibóia – centro do Estado de São Paulo.*** Rio Claro: Universidade Estadual Paulista, Instituto de Geociências, 2002. 227 p. (Tese de Doutorado em Geociências).

TANCHEV, L. ***Dams and appurtenant hydraulic structures.*** (2° ed.). London: Taylor & Francis Group, 1073. p., 2014.

VIEIRA, L. B., MOREIRA, C. A., CÔRTES, A. R. P., LUVIZOTTO, G. L. Geophysical modeling of the manganese deposit for Induced Polarization method in Itapira (Brazil). ***Geofísica Internacional,*** v. 55, n°2, p.107-117, 2016.

Received: 14 July 2016 - Accepted: 8 November 2016.