

GEOPHYSICAL METHODS FOR BR TAILINGS DAM RESEARCH AND MONITORING IN THE MINERAL COMPLEX OF TAPIRA – MINAS GERAIS, BRAZIL

Demetrius Cunha Gonçalves da Rocha¹, Marco Antonio da Silva Braga¹ and Camilla Tavares Rodrigues²

ABSTRACT. The use of geophysical methods in the BR dam at Tapira mining complex in Minas Gerais state, Brazil, had as main objective to develop a research geophysical methodology complementary to the existing conventional monitoring system. Electrical resistivity and GPR (ground penetrating radar) methods were used. Ten geophysical sections were acquired parallel to the main axis of the BR dam. The water table level delineated by geophysics was later compared to five type-sections data, which comprised the readings of 9 water level indicators (INA). The electrical resistivity results delineated the level of the water table and showed the moisture areas in the BR dam. Low resistivity zones (LRZ) were correlated with regions saturated or with a high moisture content with resistivity responses below 250 ohm-m. The GPR responses, saturated zones presented strong attenuation in the reflectors, being this effect smaller with the decrease in the water content. In some sections it was possible to correlate, patterns of reflectors to different resistive zones. Geophysics results showed great efficiency in the BR dam investigation and monitoring, through the generation of continuous indirect indicator data. Which after processing resulted in a complete 2D and 3D view of the interior of the studied dam.

Keywords: electrical resistivity, geotechnics, applied geophysics.

RESUMO. A utilização de métodos geofísicos na barragem BR do complexo de mineração de Tapira no estado de Minas Gerais, Brasil, teve como principal objetivo desenvolver uma metodologia geofísica investigativa complementar ao monitoramento hoje existente. Foram utilizados os métodos geofísicos de eletrorresistividade e GPR (ground penetrating radar). Durante a aquisição de dados foram levantadas 10 linhas paralelas ao eixo principal do barramento. O nível freático delineado pela geofísica foi posteriormente comparado com o nível freático de 5 seções-tipo mapeado pelas leituras de 9 indicadores de nível d'água (INA). Os resultados da eletrorresistividade delimitaram de forma precisa o nível freático, diferenciando áreas secas das úmidas ao longo do barramento. Zonas de baixa resistividade (ZBR), foram correlacionadas com regiões do maciço possivelmente saturadas ou com alto teor de umidade (< 250 ohm-m). Em resposta ao GPR, zonas saturadas apresentaram forte atenuação nos refletos, sendo esta atenuação menor com a diminuição no teor de água. Em algumas seções foram correlacionados padrões dos refletos a diferentes zonas resistivas. A geofísica mostrou ter uma grande eficácia na investigação e no monitoramento dessas estruturas, através da geração de indicadores indiretos contínuos, que após processamento resultaram em um imageamento completo em 2D e 3D do interior da barragem estudada.

Palavras-chave: resistividade elétrica, geotecnia, geofísica aplicada.

¹Universidade Federal do Rio de Janeiro, Centro de Pesquisa em Geofísica Aplicada (CPGA) Av. Athos da Silveira Ramos, 274, sala G-058, Cidade Universitária, Ilha do Fundão, 21941-916, Rio de Janeiro, RJ, Brazil – E-mails: demetrius@geologia.ufrj.br, marcobraga@geologia.ufrj.br

²Tetra Tech, Rio de Janeiro, RJ, Brazil – E-mail: milla_tavares1@hotmail.com

INTRODUCTION

Due to the increase of serious accidents with failure of tailings dams in Brazil, it is expected that the search for the development of new alternatives of investigation and monitoring technologies will contribute to predict geotechnical issues. The rupture of a dam is usually catastrophic, with life, social and financial losses and often generate an incalculable environmental impact, with consequences that can last for a long time.

In some countries, the use of near surface geophysical methods has already been largely used for the investigation and monitoring of different dam types. Nwokebuihe et al. (2016), for example, applied near surface methods in an earthfill dam located in Warren County in the state of Missouri - USA. The induced polarization (IP), self-potential (SP) and electrical resistivity methods were used to investigate a downstream leakage and internal seepage pathways and observe the central drainage pipe position verifying the appropriate operation with the initial design. All results were satisfactory for the research objective. In the earth dam located in Zaria, northwest of Nigeria, the use of electrical resistivity was chosen to investigate possible seepage in the low-velocity seismic waves areas located at the abutments. From these results, it was possible to identify three well defined layers in these regions and to identify low resistivity zones, which were interpreted as being less consolidated or fractured zones, suggesting moisture areas and possible presence of internal seepages (Chinedu & Ogah, 2013).

In Brazil, there are some published research papers on the use of geophysical investigation in these structures, with excellent results. For example, the use of the electrical resistivity method in the concrete dam UHE Governador José Richa, in the Paraná state, showed showed great efficiency for identifying moisture regions near the previously mapped cracks in the concrete structure, complementing the data of SP (self-potential) in the preferential seepage pathways identify along this structure (Zorzi & Rigoti, 2011). The use of electrical resistivity in the Earth dam located in Cordeirópolis, in the São Paulo state, also showed excellent results for the identification of moisture areas and the preferential seepage pathways through the dam (Camarero & Moreira, 2017).

Most tailings dams accidents occur due to a slow anomalous seepage process through discontinuities inside the center of the dam or at the ends of the abutments. This flow will initiate a progressive erosive process with the occurrence of internal cavities and piping process which may cause a

considerable structural alteration to the dam and lead to its total rupture (Abdel et al., 2004).

Another known mechanism that can generate the rupture of a tailings dam is static liquefaction. Inefficient drainage may raise the level of the water table, increasing the pore pressure and significantly reducing the effective stresses of the dam. This increase in internal pressure will result in loss of contact between the solid particles, leading the tailings to a total state of fluidity (Ishihara, 1977).

Geophysical methods are non-invasive and have a great potential of detecting internal erosion and anomalous seepages at an early stage before the safety and integrity of the dam is at stake (Abdel et al., 2004). Electrical resistivity and ground penetrating radar (GPR) were the methods used at the geophysical campaign in the BR dam. After acquisition and processing, subsurface images were generated. Once calibrated, based on direct investigations data, the geophysical data allowed a complete internal spatial evaluation through 2D sections generated along the structure. Subsequently, a complete 3D view was built with electrical resistivity data, where it was possible to separate regions with high moisture content classified as LRZ (low resistivity zone) from dry regions denominated as HRZ (high resistivity zone) and IRZ (intermediary resistivity zone) with low moisture content. Geophysics has also been able to identify bedrock using information from drill holes previously made at the BR dam.

In response to the GPR, saturated zones presented strong attenuation in the reflectors. Therefore, a decrease in the water content represents a low attenuation of the reflectors. Besides, it was possible to correlate patterns of reflectors to different resistive zones in some sections.

BR dam description

The BR dam reservoir, owned by Mosaic Fertilizantes, is located at the Tapira Mining Complex, considered to be the largest phosphate mine in Latin America. Its crest center is located at the coordinates: 308,045E / 7,805,260N, (UTM zone 23S, WGS-84 datum), at 400 km west of the Minas Gerais state, Brazil. Currently it bilks to 98,000,000 m³, and it has a total project capacity of 190,000,000 m³. The dam is 570 m long and its maximum height is 61 m, reached 1200 m quota after the latest heightening (Fig. 1). All heightenings were done by the centre line method, using magnetite in the downstream zone, with mechanical scattering and compaction. The tailings launched upstream from the crest of

BR dam, formed a beach with more than 100 m of length (Mosaic Fertilizantes, 2016) (Fig. 2).

Inspection and monitoring of BR dam are done through direct measurements instruments, called auscultation methods. However, due to the local nature of their measurements, these traditional instruments do not have the capacity to continuously investigate the interior the structure, and can easily fail to show a weakness areas or regions of unexpected water saturation, being volumetrically un representative of the total mass of the dam.

BR dam foundation

The geology of the region of the Tapira Mining Complex is characterized by Canastra Group rock, represented by phyllites, with intercalations of quartzites and quartz-phyllites. The foundation of the abutments was constituted of clayey colluvium, superimposed to a residual soil of grayish silt-quartzite with presence of mica, whose resistance was considered adequate for the dam structure support. The central region of the massif was characterized by the presence of clayey alluvium of low consistency, that was removed reaching the horizon of residual soil of the silt quartzite (Mosaic Fertilizantes, 2016).

Composition of BR dam

According to 35 drill holes logs, it was possible to observe the presence of four (4) main types of materials in the central BR dam region (Fig. 3), from the base to the top, as follow:

- Residual Soil (SR): Residual horizon of silvery gray to greenish quartzite with presence of mica;
- Colluvium (CO): Clay of reddish-brown color, sometimes with gravel presence, of consistency ranging from soft to rigid in the most upstream sectors;
- Magnetite Tailings (MT): Fine sand to medium magnetite of dark color, from little to medium compact;
- Flotation Tailings (FT): Medium-compact, gray-colored sand-silt flotation tailings.

Auscultation instruments

Currently the monitoring at the BR dam are doing by the conventional instruments installed in the structure. This monitoring is constituted of 1 piezometer, 11 water level indicators (INA), 3 drains indicators of flow, 14 slope drains (in the right and left abutments), 11 superficial marks, 1 ruler in the reservoir, 1 pluviometer and 1 evaporimeter.

Five representative type-sections (B, C, D, E, F), transversal to the BR dam were used as a basic and reference for the interpretation. The sections were distributed as follows: C, D, E in the central region of the dam, F in the right abutment and B in the left abutment. The sections were arranged so that they represented well the main structures of the dam (starting dike, blanket drain and foundations) and crossed most of the INA (Fig. 4). The water level measurements used in the interpretative process correspond to the readings closest to the period of acquisition of the geophysical data (11/13/2017). Table 1 shows the location and respective levels of the readings.

METHODOLOGY EMPLOYED

In this paper, the integration of the two geophysical methods employed was proposed. Both methods provided results through different physical parameters in order to construct a set of data necessary to complement the existing direct auscultation methods.

Data acquisition

According to the objective of this paper, ten (10) parallel and longitudinal geophysical survey lines were made on the main axis of the BR dam (Fig. 5), among which two lines (L01 and L02) were acquired in the tailings beach region, seven lines (L03 to L09) located in the zone of the magnetite massif and abutments and one (L10) complementary line on the left abutment. In total, 4594 m of electrical resistivity sections and 4321 m of ground penetrating radar (GPR) were collected (Tab. 2). The spacing between these lines was variable, 15 m in the region of the massif, executed on the berms, and 25 m in the region of the beach. The ground penetrating radar (GPR) data were collected along the same lines as the electrical resistivity sections, however, some lines did not extend to the abutments due to the topographic difficulty. The L10 section was also collected parallel to the main axis of the BR dam but displaced to the left abutment and with partial overlap to section L07, in this region.

Electrical resistivity

The equipment used in this acquisition was the R8 resistivimeter manufactured by AGI with a 64 channels configuration and 3.0 meters spacing between electrodes, maximum current of 2A and cycle of 2s, reached 49.0 meters depth of investigation.

During the field work, a total of 4594 m of electrical resistivity section were acquired, with the electrodes arranged is Dipole-Dipole array. This arrangement was chosen because it



Figure 1 – Overview of the BR dam.



Contact between the flotation tailings and the magnetite sand.



Beach Material – Flotation tailings, fine sandy.



Dam Body Material – Magnetite sand.

Figure 2 – Main constituents of the BR dam.

generated better signal-to-noise ratio during the initial tests, as well as a satisfactory depth of investigation with a good lateral resolution.

As in practice, most of the geological scenarios cannot be considered as homogeneous, the measured amount of ΔV (potential difference) represents a weighted average of all true resistivities in a subsurface material volume. For the Dipole-Dipole arrangement the apparent resistivity (ρ_a) can be expressed by the equation shown in Figure 6. The Dipole-Dipole array commonly used for detailed work with the dipole spacing parameter (n) (Dentith & Mudge, 2014).

In this arrangement, several receiving dipoles (MN) arranged along the line can be used simultaneously. Each dipole MN corresponds to a level of investigation Z , as illustrate in the Figure 7.

The theoretical depth at each investigated level is taken as $Z = X_{MN}(n + 1)/2$ in meters (Dentith & Mudge, 2014).

The depth of penetration of the electric current in the soil is directly correlated to the length of the electrical resistivity section used, and the resolution will decrease with increasing survey depth and different conductive properties of the studied substrate. The Figure 8 illustrates electrical acquisition on the beach region.

Ground Penetrating Radar (GPR)

Initially several tests were performed, with variations of antenna frequencies, in order to determine the best methodology for the acquisition. Tests were performed on lines L01 and L03 (Fig. 9) with an antenna varying the center frequency of 100, 40 and 80 MHz, all in static mode, using the SIR3000 equipment manufactured by GSSI. The 100 MHz antenna achieved a better

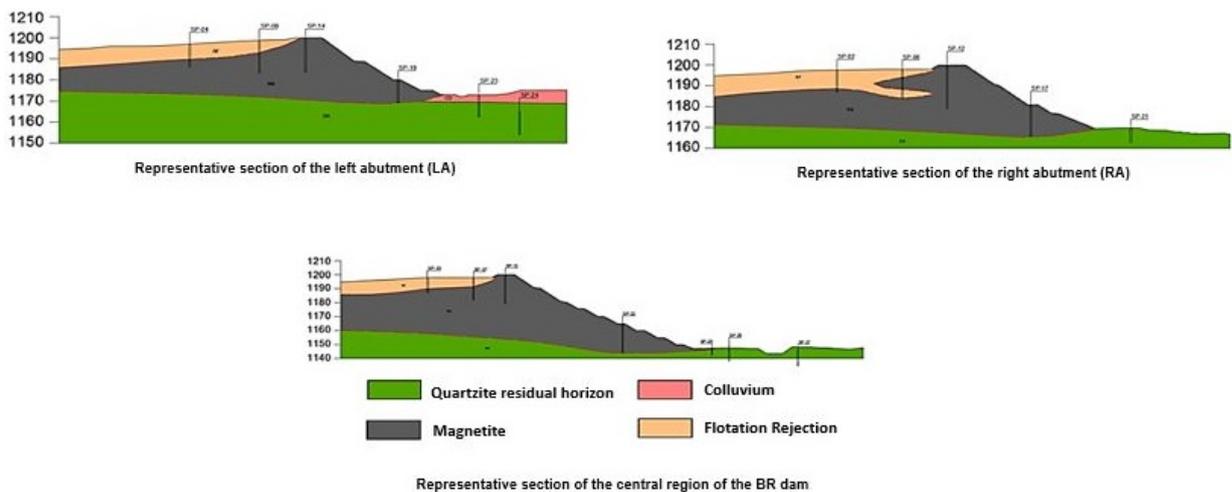


Figure 3 – Main constituents of the BR dam, according to 35 drilling holes.

Table 1 – Location and descriptive aspects of the INA (water level indicators) installed in the BR dam.

Instruments identification	Coordinates		Elevation of the instruments (m)		Length (m)
	North	East	Top	Water level (13/11/17)	
INA 1	7,805,177.755	308,011.379	1,201.238	Dry	36.49
INA 2	7,805,269.943	308,051.092	1,201.162	Dry	41.22
INA 3	7,805,288.220	308,019.059	1,180.280	1,150.32	32.43
INA 4	7,805,293.979	307,995.503	1,170.020	1,149.50	26.92
INA 5	7,805,345.732	308,082.883	1,201.681	1,158.75	43.76
INA 6	7,805,352.500	308,048.448	1,181.680	1,150.36	36.22
INA 7	7,805,367.834	308,026.489	1,170.680	1,149.41	27.37
INA 8	7,805,434.944	308,120.412	1,201.913	Dry	39.76
INA 9	7,805,074.869	307,972.062	1,201.042	1,182.07	20.96

signal-to-noise ratio, thus it was utilized for all GPR surveys. The sampling frequency used was 1000 MHz with 512 samples and intervals of 0.2 meters between traces and dynamic acquisition mode. A 4321 m GPR survey was carried out, parallel to the principal axis of the structure, comprising lines L01 to L10.

During the scanning, the control unit produces and regulates the energy pulses of the radar, which is amplified and transmitted to the subsurface by the antenna. The frequency of the antenna is inversely proportional to the depth reached, which makes the antenna selection the most important step in the survey planning (Desai et al., 2016).

GEOPHYSICAL RESULTS

Electrical resistivity

After processing of the data measured in the field, it was possible to identify zones of high resistivity (HRZ), whose values are above 1,116 ohm-m. Low resistivity zones (LRZ), whose values are below 250 ohm-m and intermediate resistivity zones (IRZ), where the values are between approximately 250 and 1,116 ohm-m (Fig. 10).

In general, in all electrical resistivity sections, the low resistivity zones (LRZ) were delimited to values below 250

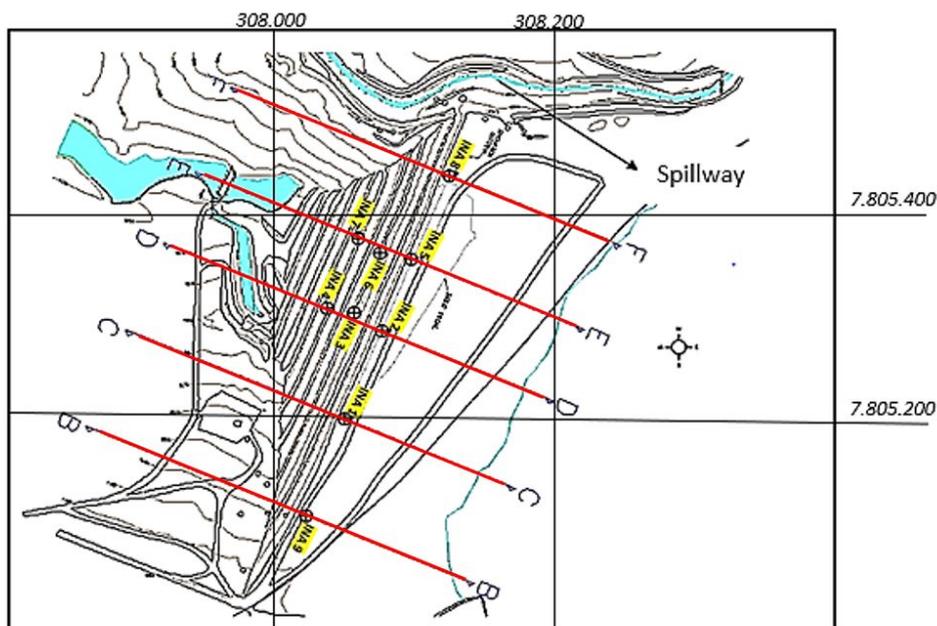


Figure 4 – The five type-sections of the BR dam. The sections positioned so that they crossed as many dam structures and INA (water level indicators) as possible.

Table 2 – Length, in meters, of the geophysical acquisition lines executed at the BR dam.

Lines ID	Electrical Resistivity length (m)	GPR length (m)
L01	585.00	585.00
L02	583.00	583.00
L03	691.00	578.00
L04	479.00	479.00
L05	475.00	475.00
L06	447.00	409.00
L07	516.00	394.00
L08	365.00	365.00
L09	265.00	265.00
L10	188.00	188.00
Total	4594.00	4321.00

ohm-m, can be correlated with regions possibly saturated, or even with a certain moisture content.

For a better understanding of the results, three distinct zones of the BR dam are described separately: central region (massif), left abutment and right abutment.

Central Region

This region is covered by the sections L03 to L09, which showed some common patterns in the responses of resistivity values. After analyzing these sections, it was possible to delimit a surficial

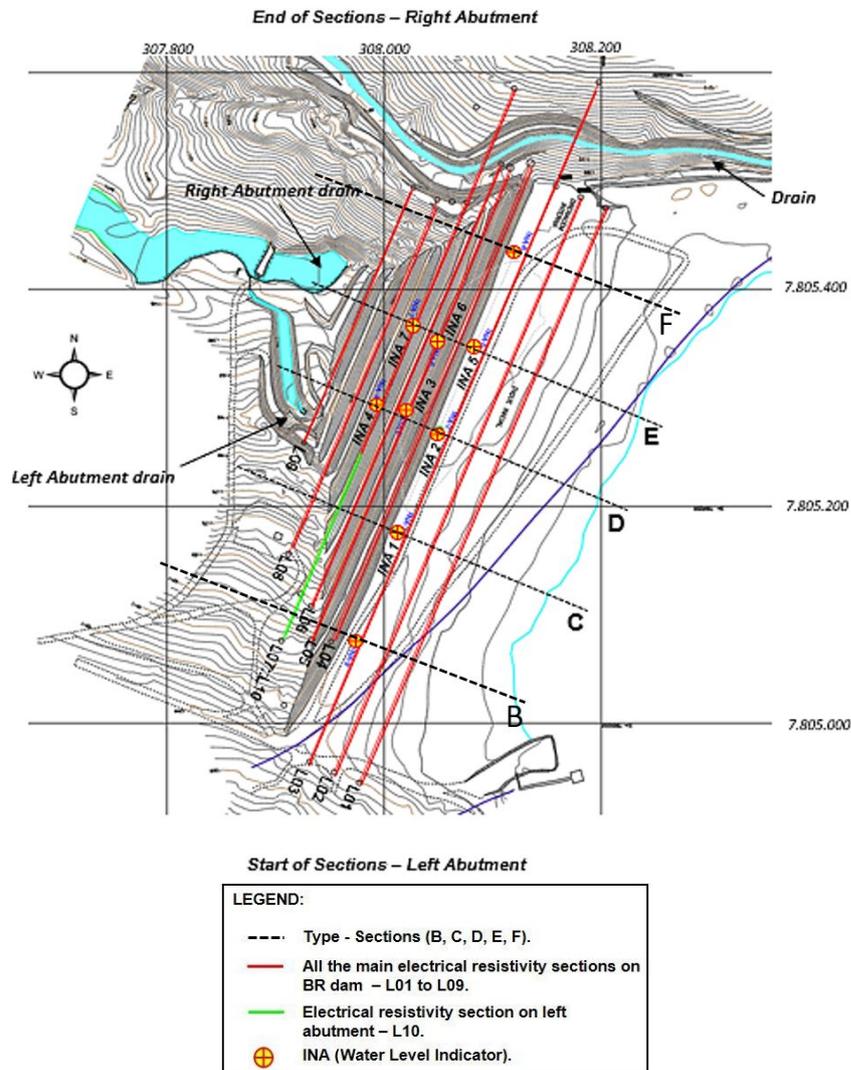


Figure 5 – The ten geophysical acquisition sections surveyed along the BR dam.

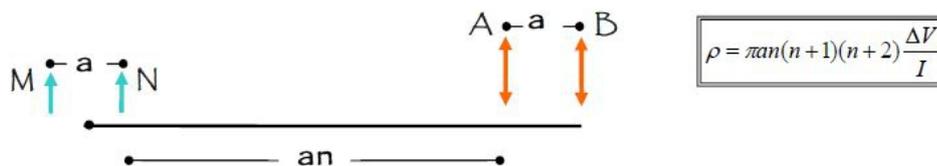


Figure 6 – Formula to calculate the apparent resistivity using the Dipole-Dipole method.

region approximately 3 m thick with intermediate resistivity (IRZ) values (250 to 773 ohm-m). It can be suggested that this horizon is composed of a more sand layer of magnetite where the voids were filled by air and, in smaller amount, by water. This zone is more susceptible to weather effects (precipitation and evaporation).

Below this layer, there is a second zone approximately 6.0 to 7.0 m thick, well delimited, in continuous to moderately continuous form with high resistivity (HRZ) values of 1195 to 3430 ohm-m. Considering that heightening were always made with the same material composed of magnetite, and that according to the data of the SP-09 drill hole, that showed that there

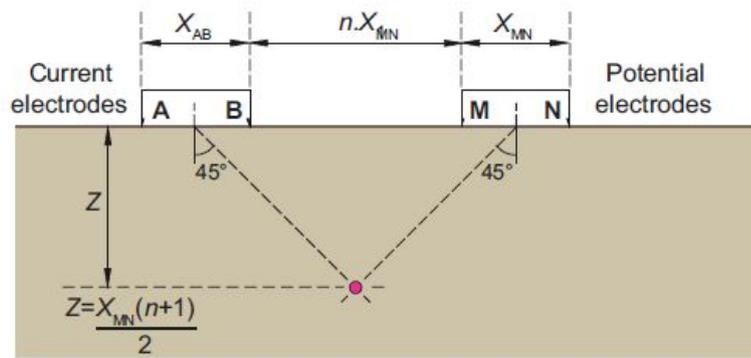


Figure 7 – Electrode configuration in the Dipole-Dipole array arrangement (DDP) (Dentith & Mudge, 2014).

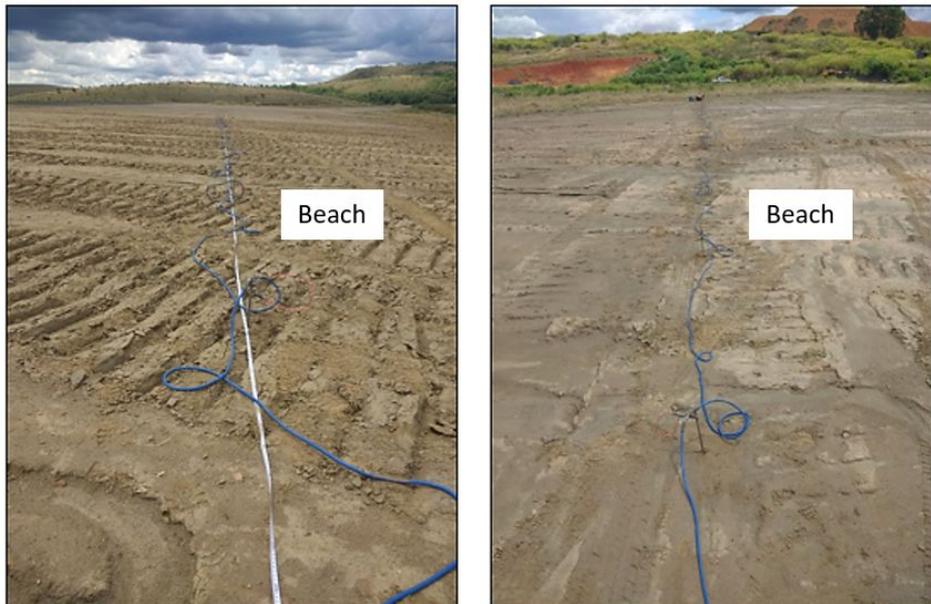


Figure 8 – Electrical survey on the beach region, line L01.



Figure 9 – Acquisition of GPR data at the crest of the BR dam, line L03.

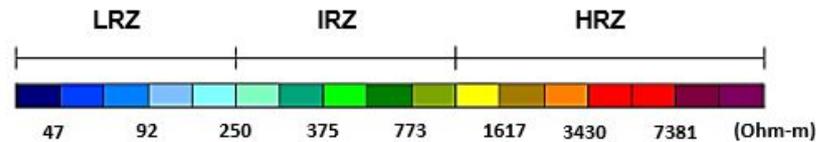


Figure 10 – Scale used for the results of electrical resistivity in ohm-m.

were no changes in this composition, we can interpret that this increase in resistivity values may be related to granulometric differences or different degrees of compaction. Its reflecting directly on the decrease or increase of porosity and permeability and consequently on storage capacity or percolation of water. Lower, there is a transition zone with intermediate (IRZ) of 375 to 1195 ohm-m resistivity values that may be related to a small increase in moisture in the pores, due to its proximity to the zone of low resistivity. Underneath this zone, there is a low resistivity zone (LRZ), marked with values below 250 ohm-m, being associated with high moisture contents (Fig. 11). The top of this anomaly (LRZ) was interpreted as being equivalent to the top of the water table (W.T) and later compared to the INA data and plotted for comparative effect in the type-sections previously used for geotechnical monitoring.

By the positioning of the water table level on L05 in the D type-section, it was possible to observe that the blanket drain was below the top of the conductive anomaly (LRZ). The top of the blanket drain was located at 35 m depth and the top of the water table identified by the electrical resistivity data in this section was 29 m deep, so this draining structure at the time of the geophysical survey showed to be positioned 6 meters below the top of the ZLR. Therefore, this drain structure was drowned in relation to the level of the water table identified by geophysics (Fig. 11).

Analyzing the downstream sections, it was observed an increase in LRZ thickness and a decrease in IRZ and HRZ. The LRZ top elevations become shallower when compared to the upstream sections (Fig. 12).

POSITIONING OF THE WATER TABLE

With the aim of investigating and comparing the direct data provided by the auscultation instruments, it is sought to delimit the level of the water table in the central region of the massif by identifying the top of the anomaly of low resistivity zones (LRZ) on the type-sections (C, D, E) (Fig. 13).

It is important to note that the readings of the water level indicators (INA) present in the type-sections for the central region

of the massif (Section C - INA 1; Section D - INA 2, INA 3 and INA 4; and Section E - INA 5, INA 6 and INA 7), are very close to the data obtained from the electrical resistivity responses on the same site. This fact is corroborated by the correlation of the conductive anomalies top with the water level readings measured by the INA, which are approximately coincident (Fig. 13).

Left Abutment (LA)

The response of the electrical resistivity method in this region are characterized by the presence of a deep gradation of horizons with intermediate to high values (IRZ to HRZ) of resistivity to low values (LRZ) lower. These values of IRZ and HRZ located in the basal part of the left abutment can be interpreted as the residual quartzite soil horizon (2523 to 7381 ohm-m). The low resistivity values (LRZ) underneath to the intermediate to high values may be related to the possible zones of accumulation of water or of sufficient moisture content to generate such conductive anomalies. Other hypothesis may be related to the presence of clayey materials identified in the SP-09 drill hole performed near the L02 section in its initial meters, where the presence of silt was observed at conductive levels (Fig. 14).

It can be observed that the conductive anomaly that appears in a localized form in the left abutment does not seem to have continuity with the central part of the massif, where the position of the water table was defined through the mapping of the LRZ top and confirmed by the geotechnical instruments, through the readings of the INA. Thus, it was not possible to delineate the water table because of the non-continuity of the conductive anomaly to the central part of the massif.

Right Abutment (RA)

In the regions of the geophysical sections near the F type-section, an arrangement of intermediate resistivity zones (IRZ) overlapping with HRZ of greater thickness is noted. The LRZ occur in a punctual way with no continuity to the central region of the

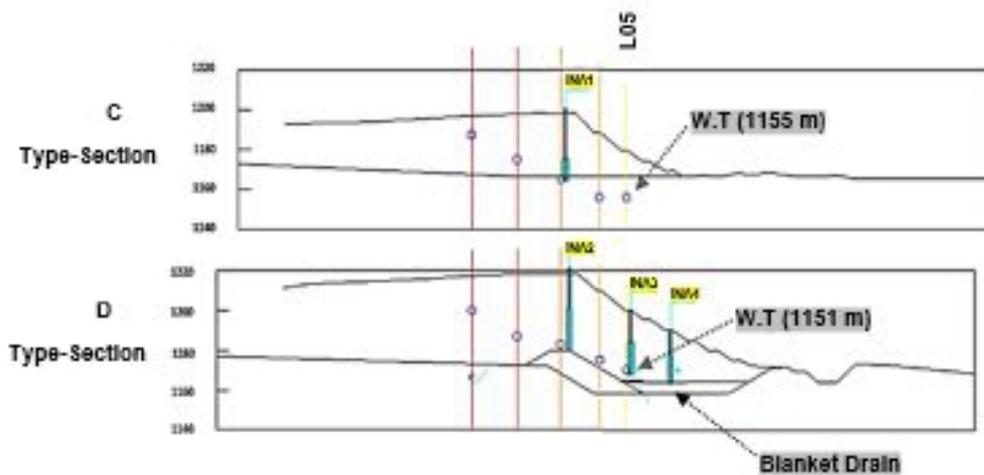
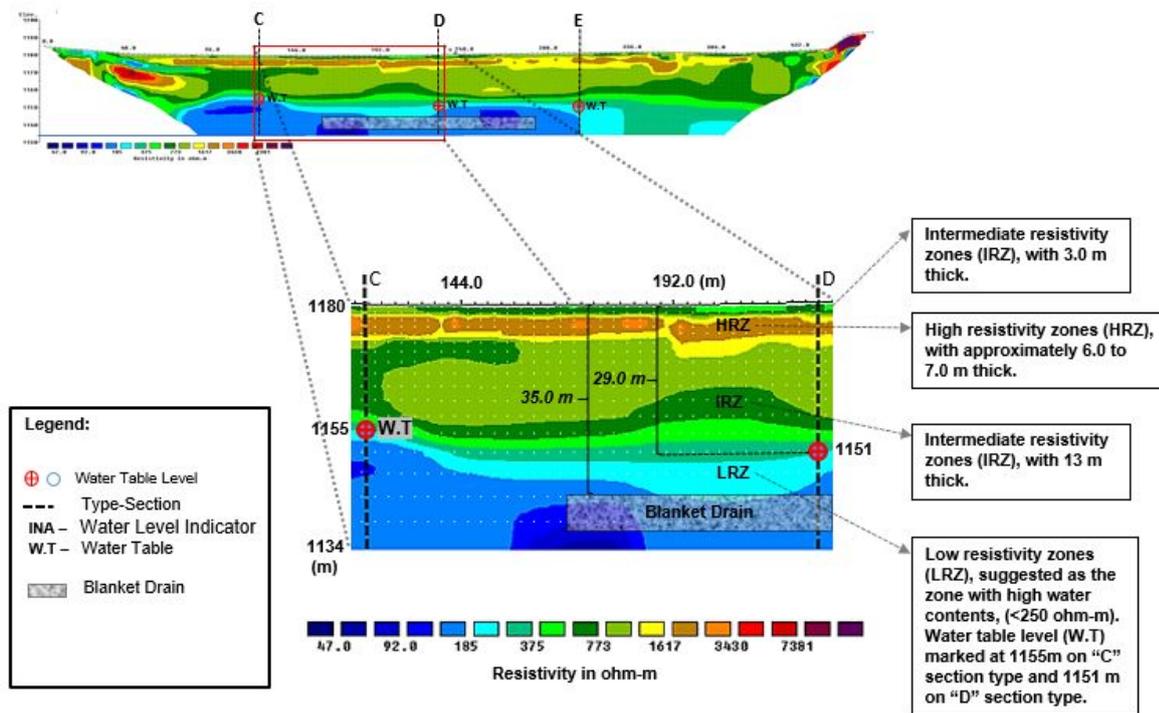


Figure 11 – The L05 section, used as being representative of the central part of the massif, showing the different resistive zones delimited through the results obtained from the electrical resistivity survey. The blanket drain appears to be drowned in 6 m depth in the central part of the massif in relation to the water level elevation in the D type-section. The top of the water table was marked as the top of the zone of low resistivity (< 250 ohm-m).

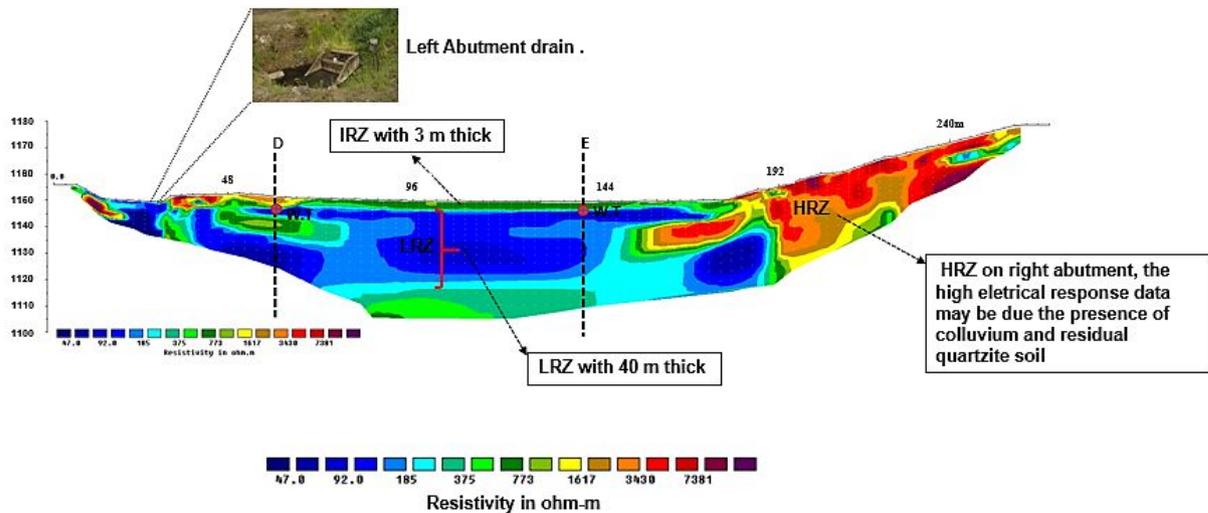


Figure 12 – The L09 section, further downstream, showing the increase of the conductivity anomaly thickness and the shallower dimension of the water table evidenced by the LRZ (<250 ohm-m). The water table levels plotted in sections C and D are 1148 m and 1145 m, respectively. It can be evidenced the increase of the LRZ in subsurface and the reduction of the overlapped IRZ.

massif. Below the LRZ, we again found regions of resistivity with intermediate (IRZ) to high (HRZ) values (Fig. 15).

The occurrence of horizons with high resistivity values suggests the possible presence of foundation materials composed of residual quartzite soil. Such association can be confirmed by drill hole data, which showed the presence of this material in the high resistivity regions (HRZ). Below the spillway region there is a very expressive conductive anomaly possibly resulting from an infiltration into this structure.

GROUND PENETRATING RADAR (GPR)

The GPR interpretation sought to track the patterns and terminations of the reflectors. As well as to map features that could indicate the beginning of internal erosive processes in the BR dam. The GPR geophysical sections reached up to 24 m depth and due to topographical difficulties, it was not possible in some profiles to extend the investigation to the abutments. In the first 2 lines (L01 and L02), a truncation pattern was observed between the reflectors near the abutment's regions (Fig. 16), suggesting a heterogeneity in the arrangement of the flotation tailings released from the crest to upstream. The L03 section, at the crest of the dam until the L09 section, suggested a decrease in the truncation pattern with an increase of the parallelism between the reflectors can be observed.

In these downstream sections a well-marked surface layer, approximately 3.0 m thick, was observed, with a pattern of continuous reflectors, which are generally not very attenuated and

with low amplitude. In addition to this layer, there is a second well-marked layer of approximately 6.0 to 7.0 m thick with a pattern of reflectors of strong contrasts and with larger amplitudes and undulating to wavy ones. Already close to the abutments the reflectors behave in parallel ways and with low amplitudes. An increase in the attenuation of the reflectors with punctual higher contrast passages was observed lower. This third layer may already be suffering from an increase intra-pores moisture due to the direct influence of the region mapped by the electrical resistivity data as the top of the water table of the BR dam.

The L05 section (Fig. 17) was used to exemplify the correlations obtained from GPR and electrical resistivity data. Taking into account that the BR dam massif is composed only of magnetite sand. The different patterns of reflectors that correlate with different distinct electrical zones can be interpreted as:

- Different compaction phases of the embankment;
- Different granulometry of materials of the same composition (magnetite);
- Areas with different moisture content.

CONCLUSION

Applied geophysics contributed significantly to the geotechnical knowledges of the dam, effectively complementing the pre-existing conventional instruments used for the monitoring of the BR dam. Geophysics generated continuous 2D and 3D

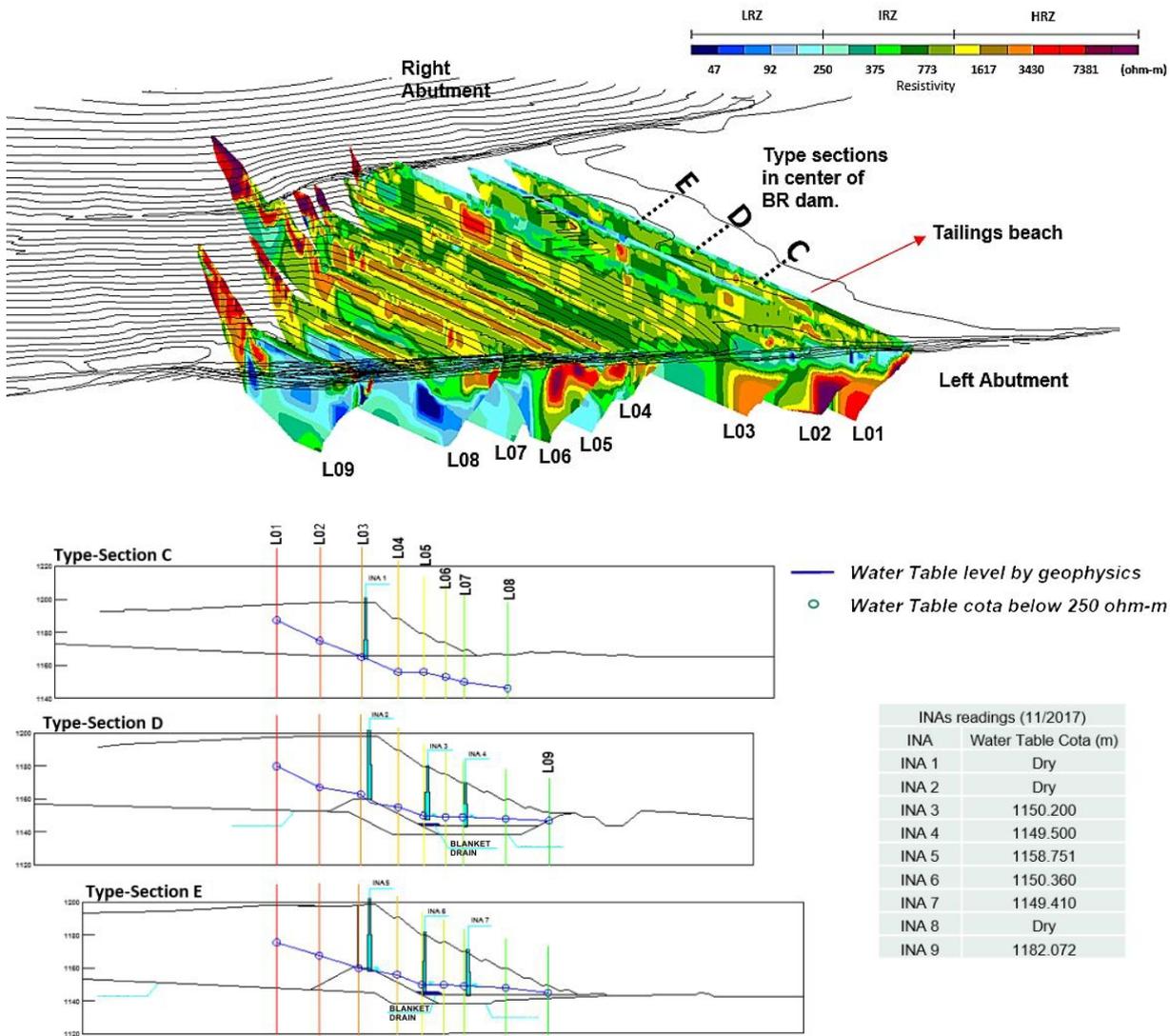


Figure 13 – Electrical survey in 3D (L01 to L09) showing that the position of the water table in the type-sections (C, D and E), inferred by the geophysics in the central region of the BR dam, approximates the position suggested by reading the indicators of the water level (INA).

images of the interior of the dam, where it made a complete imaging along the massif and abutments. Electrical resistivity results showed a good ability to delineate the water table level, internal hydraulic dynamics, local saturations, seepages and was able to identify the main discontinuities of the materials used during the heightening stages. In general, the electrical resistivity method proved to be the one that best identifies dry zones (HRZ) of saturated zones (LRZ) or with some moisture content (IRZ). The resistivity sections showed that the conductive anomalies of the central part of the massif and the abutments do not have

continuity. Thus, it is suggested that there is no evidence on the contribution of flow from the abutments to the central region of the BR dam.

Through the GPR results, it was possible to map different horizons in the BR dam to investigate the appearance of potential internal voids and the different heightening stages. Based on the reflector responses, GPR was able to identify different levels of compaction and the type of materials used. The GPR reflector patterns showed strong attenuation in the moisture zones mapped by electrical resistivity.

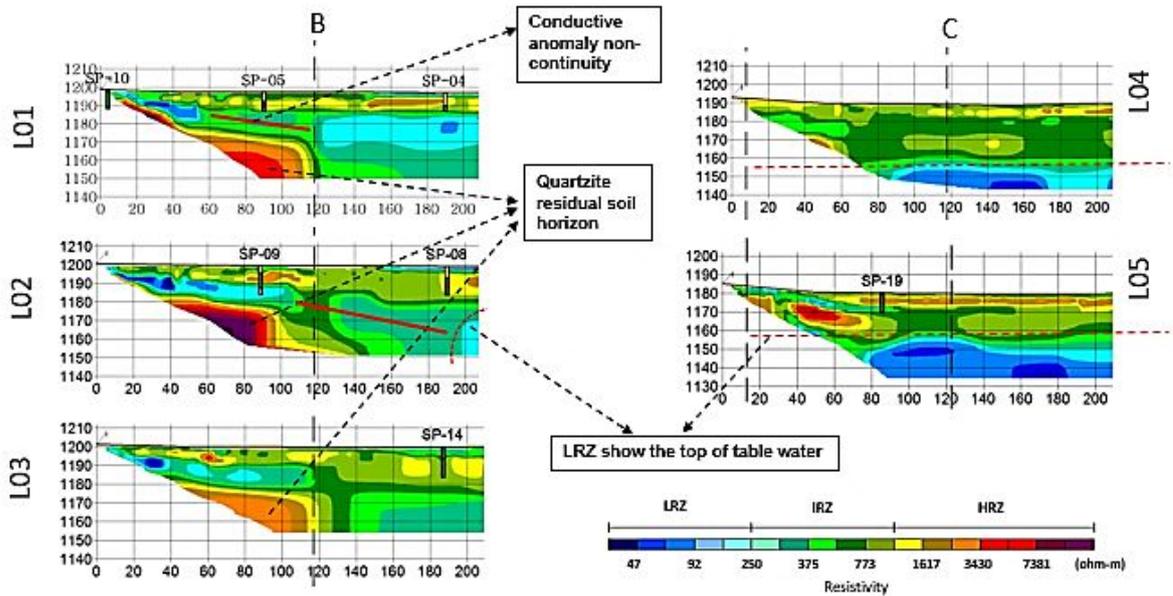
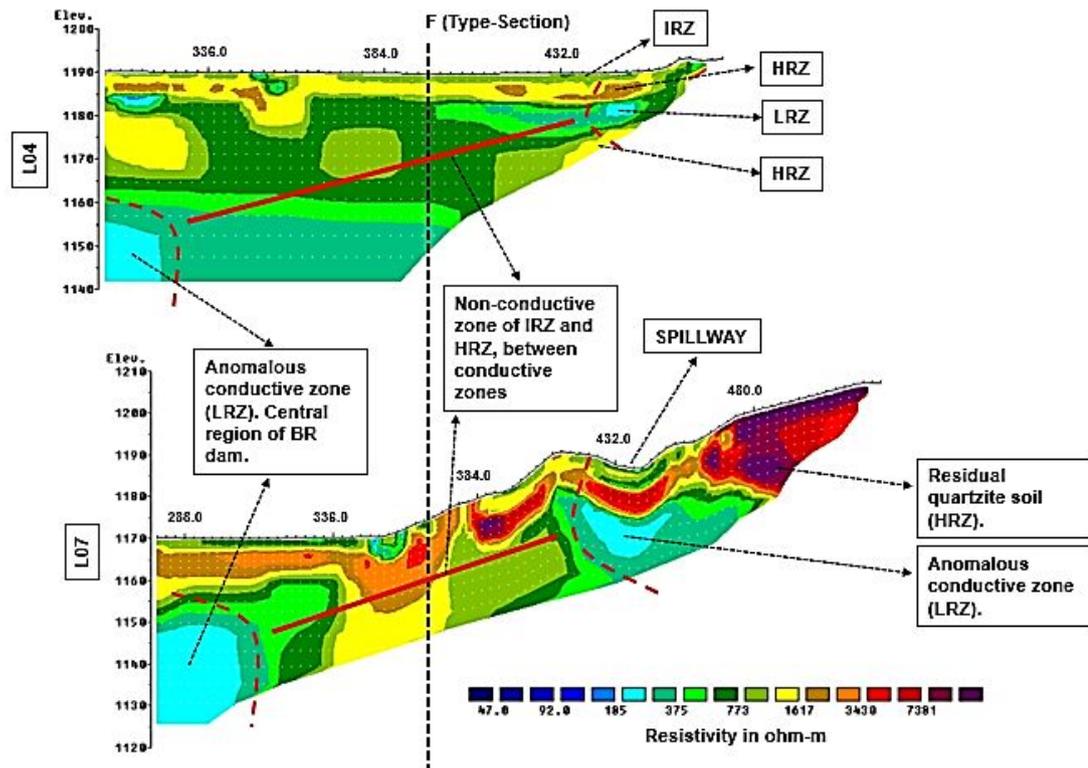


Figure 14 – L01 to L05 sections showing the different zones of resistivity in the left abutment.



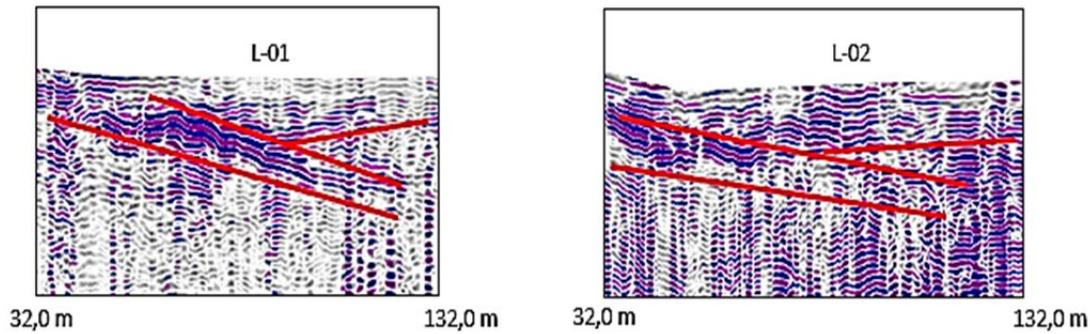


Figure 16 – L01 and L02 sections showing the truncation pattern of the reflectors near the left abutment (LA).

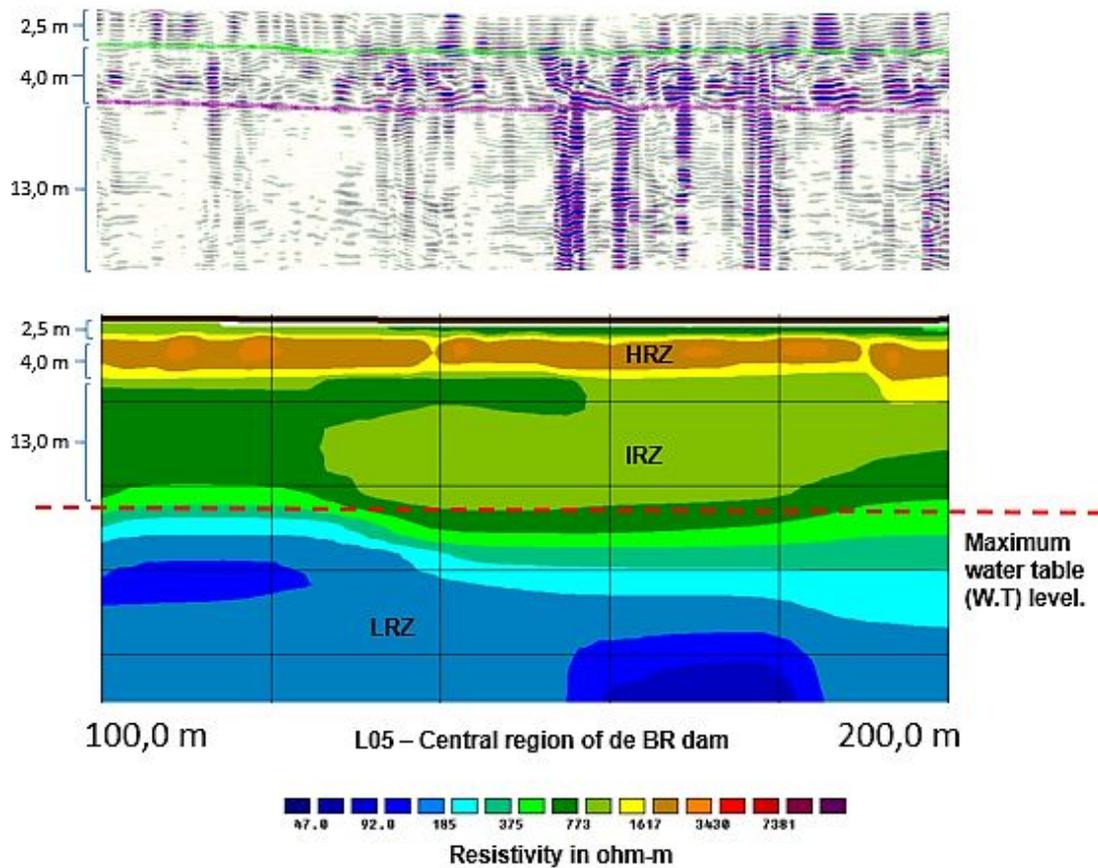


Figure 17 – Excerpt from L05 section showing the correlation between different resistivity zones and reflector patterns.

Finally, it is important to emphasize that the integration of the two geophysical methods is more effective, contributing to the reliability of the acquired results, through the consistency observed between them. Thus, the delimitation of the two groups of reflector patterns described above overlaps satisfactorily with the more superficial levels of the electrical resistivity sections,

demonstrating the importance of applying different methods to meet the objective of the present study.

Due to the high risk of accidents involving tailings dams, which could generate enormous social, economic and environmental losses, it is necessary to develop a correct and effective investigation and monitoring method to improve the

safety of the physical and operational integrity of dams in general. This paper shows the efficiency of near surface geophysics as an indispensable complementary tool to conventional geotechnical instruments in the investigation and systematic monitoring of dams.

REFERENCES

- ABDEL AAL GZ, ISMAIL AM, ANDERSON NL & ATEKWANA EA. 2003. Geophysical Investigation of Seepage from an Earth Fill Dam, Washington County, MO. In: 3rd International Conference on Infrastructure. Orlando, Florida, USA. 8 pp.
- CAMARERO PL & MOREIRA CA. 2017. Geophysical investigation of earth dam using the electrical tomography resistivity technique. *REM - International Engineering Journal*, 70(1): 47-52.
- CHINEDU AD & OGAH AJ. 2013. Electrical resistivity imaging of suspected seepage channels in an earthen dam in Zaria, north-western Nigeria. *Open Journal of Applied Sciences*, 3: 145-154.
- DENTITH M & MUDGE ST. 2014. *Geophysics for the Mineral Exploration Geoscientist*. Cambridge University Press, New York, (5): 438 pp.
- DESAI L, JADHA G, SHINDE V & PATIL S. 2016. Ground Penetrating Radar (GPR). *Imperial Journal of Interdisciplinary Researcher (IJIR)*, 13(5): 1508-1511.
- ISHIHARA K. 1977. Simple method of analysis for liquefaction of sand deposits during earthquakes. *Soils and Foundations*, 17(3): 1-17.
- MOSAIC FERTILIZANTES. 2016. VAFZ.AL-LT-FTP-103-01. Auditoria técnica de segurança da barragem BR. Relatório de inspeção de segurança regular. Relatório de auditoria técnica de segurança, Complexo de Mineração de Tapira, Brazil. p. 5-8.
- NWOKEBUIHE SC, ALOTAIBI AM, ELKRRY A, TORGASHOV EV & ANDERSON NL. 2016. Dam seepage investigation of an earthfill dam in warren County Missouri using geophysical methods. Missouri University of Science and Technology Rolla, Missouri. *AIMS Geosciences*, 3(1): 1-13.
- ZORZI RR & RIGOTI A. 2011. Aplicação de métodos geoelétricos para monitoramento da barragem de concreto da UHE Gov. José Richa. *Boletim Paranaense de Geociências*, 65: 1-11.

Recebido em 16 de Abril de 2019 / Aceito em 13 de Agosto de 2019

Received on April 16, 2019 / Accepted on August 13, 2019