The paper was published in the proceedings of XVI Pan-American Conference on Soil Mechanics and Geotechnical Engineering (XVI PCSMGE) and was edited by Dr. Norma Patricia López Acosta, Eduardo Martínez Hernández and Alejandra L. Espinosa Santiago. The conference was held in Cancun, Mexico, on November 17-20, 2019.

N.P. López-Acosta et al. (Eds.)

doi:10.3233/STAL190233

Geological-Geotechnical Investigation of an Old Tailings Dam from a Mine in the Peruvian Highlands

Christ Jesus BARRIGA Paria[a,1], Eleonardo Lucas PEREIRA[a], Jorge Pantaleon BARRIGA Gamarra[b] and María Isabel MARTÍNEZ López[a]
[a] *Federal University of Ouro Preto*
[b] *National University Jorge Basadre Grohmann*

Abstract. A tailings dam is geotechnical designed to operate in steady-state filtration conditions, an abnormal leak can be a threat to the integrity of the structure. Geological-geotechnical research becomes a constant need; geophysics has long played an important role in these investigations in situ, although the meaning and acceptance of the results have varied considerably, the acceptance and application in geotechnical engineering it has increased considerably years. This paper was carried out in the central highlands of Peru, in a mine of polymetallic ore of lead, zinc, silver and copper with a height of 4,700 meters above sea level, which has an old tailings dam in which the electrical method was used by electrical resistivity tomography with distribution of electrodes to obtain detailed information of the stratigraphy of the study area and delineate areas of possible filtration for the mine closure plan demanded by the competent authorities that ask to generate in the long term the lowest risk to the safety and health of the population and the least possible environmental impact. For the purposes of the case, an evaluation of the study area was carried out, with four profiles reaching the entire tailings dam, with a selected location, the cables were extended, the electrodes were fixed, the electrode conductivity test ordered from the injection equipment, record of the values obtained and an evaluation of each of the measures that the value of the equipment is stable.

Keywords. Tailings dam, geophysics, electrical tomography.

1. Introduction

Geophysical research for geotechnical purposes is necessary to obtain reliable results to be used in the mine closure plan. For this case study, the electrical method by electrical resistivity tomography (ERT) with a pole-dipole configuration was used. The mining company consists of a concentrator plant and amine, with a capacity of 2000 TPD, with the possibility of an increase of 3000 TPD for the treatment of minerals coming from the open-pit exploitation, and there are still plans for underground exploration and even the treatment of minerals from other neighboring mines. It has a polymetallic deposit, zinc, silver, and copper, and has an extension of approximately 2,100 hectares of concessions in an area with high geological potential. Currently, the ore obtained is transported from

[1] Mining engineer with a master's degree in Geotechnics, a doctoral student in Geotechnics, Nucleo de Geotecnia da Escola de Minas, Campus Universitário Morro do Cruzeiro, Ouro Preto, Minas Gerais, Brasil - 35.400-000; E-mail: christ.paria@aluno.ufop.edu.br

the stockpiles to the plant, with trucks of 40 TM capacities which allows a constant flow of power to the plant. Electrical scans were performed to obtain detailed information on the stratigraphy of the study area, identify the presence or absence of groundwater, the presence of fractures or some type of infiltration.

According to [1], problems of infiltration and internal erosion are generators of possible accidents. The greatest cause of accidents in earth dams is associated with erosion. For the purposes of the case, an evaluation of the study area was carried out, with four profiles reaching the entire tailings dam, with a selected location, the cables were extended, the electrodes were fixed, the electrode conductivity test ordered from the injection equipment, record of the values obtained and an evaluation of each of the measurements, to verify that the value of the equipment was stable.

2. Materials and Methods

2.1 Equipment

The procedures adopted in the investigation used the technique of electrical tomography, the equipment used was a Syscal Pro Resistivimeter of 10 Channels of French manufacture, reels with 100 m of cable for VES, Cable configuration for PDS (Pole-Dipole Sounding) with a spacing of 10 meters, 800 DC power supply, 30 electrodes of stainless steel (dipoles) and 04 of steel (AB).

2.2 Data Collection Procedures

After defining the research profiles, the cables were stretched and the electrodes positioned in the profile line (Figure 1). The conductivity of these electrodes was verified to the equipment that will transmit the electric current, verifying the stability of the readings measured.

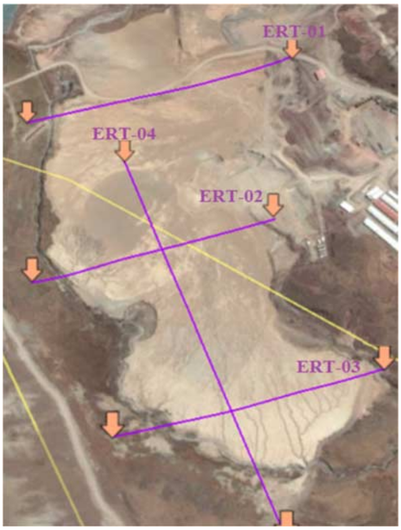

Figure 1. Location of tomographic profiles.

Subsequently, an evaluation algorithm was executed, considering that, in adjacent points, the resistivity variation cannot exceed 25% for more or less. In the case of larger variations, it is necessary to repeat the points in question and a new data collection must be performed.

2.3 Geophysical Prospecting for Resistivity through the Electrical Tomography Technique

According to [2], it is a friendly method and facilitates satisfactory results, which can use different types of array, and depending on the need these can be more detailed to obtain a better resolution. On the other hand, [3], mentions that the resistivity method can be used for the identification of soil stratigraphy variations and is applicable to different studies of soil electrical resistivity. [4], geophysical techniques are routinely used as part of geological investigations to provide information such as dimensions and depths of the subsoil and therefore perform a geological mapping.

Soil and rocks are good conductors of electric current, depending on the content of metallic minerals, moisture content and mineralization of the water that occupies the interstitial spaces and sedimentary formations. There are no fixed limits for values of electrical resistivity of sediments and sedimentary rocks, meanwhile, mean values can be established through statistics [5].

Temperature also influences the electrical conductivity of rocks. These are the most important characteristics that define the resistivity of the physical environment. In geological formations such as those observed in the area investigated in this investigation, resistivity values vary from units of Ωm for soils and rocks with different levels of mineralization and moisture [6].

According to [7], the difficulty that a body presents in letting itself be traversed by an electric current is given the name of electrical resistivity or electrosensitivity, as is more commonly referred to in the literature. This property is based on the Ohm's law, by which, having knowledge of the injected current (I), of the potential difference (ΔV) and of the positions of the injection points and current collection (current electrodes and potential respectively).

According to [8], carried out after having conducted tests and analyzing the advantages and limitations of the electrode arrays according to the effects of the anomalies, the authors recommend a distribution of pole-dipole (PDS) type electrodes, being the geology of the area under study that categorically determines the array. This probing, also called tripole, consists of three mobile electrodes along the motion profile, one of the current (A) and two of potential (MN) whose spacing ($a = MN$) remains constant.

2.4 Pole-dipole survey

According to [9], the pole-dipole arrangement has been widely used in surveys of electric roads oriented to the exploration of groundwater and mining. This happens depending on some of its positive features, such as the ease of operation in the field and its symmetry that is peculiar to it. The array and distribution of the electrodes used according to the pole-dipole method in the field work are shown in Figure 2A. The measurements performed provided the lateral and vertical resistivity changes of the subsoil. These changes made possible the construction and presentation of a 2D model, in order to graphically represent the so-called "pseudosection", as shown in Figure 2B.

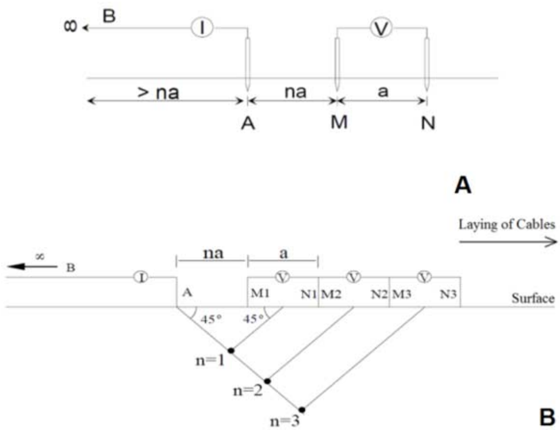

Figure 2. PD configuration (A) and representation of pseudosections through the PD technique (B).

To perform the readings, the current electrodes were initially positioned at points 1-2 of the graph (Figure 3), while the potential electrodes occupied positions 3-4, so that the separation factor of the device dipoles was n=1 (I) and potential (ΔV), which fed Eq. (1).

$$\rho_a = \pi * n(n+1)(n+2) * a\frac{\Delta V}{I} \quad (1)$$

where ρ_a: Electrical resistivity; a: spacing between electrodes.

With the values replaced, the resistivity value corresponding to the pair of electrodes in positions 1-2 and 3-4 was obtained. The method suggests the construction of lines inclined at 45°, so that, at the point where they are cut, the measured apparent resistivity value is assigned. The continuity of the procedure was therefore followed by the measure corresponding to the pair of positions 1-2 and 4-5 and so on.

It should be noted that this pseudosection tracing procedure is only a graphical convention, and does not imply that the depth of investigation of the device is given by the intersection of the two 45° lines. The pseudosection provides an image very close to the distribution of resistivity in the subsoil. However, the image provided is distorted.

3. Processing of Data

Initially, we set out to organize the information obtained by all pairs and to calculate the apparent resistivity value, making a layered arrangement. For a separation of the electrodes, "A" was designated the first layer, for "NA" the second layer and so, successively, until layer "N". This information was converted into a one-dimensional file, to be processed and obtained a two-dimensional image, which allowed analyzing, in a simple way, the geological information, the information of the subsoil material and the electric and stratigraphic characteristics.

The software used to visualize the data was with the Prosys II, and for the interpretation of inversion data, the Res2Dinv [10], using the finite element method and the least squares solution. The topography was then inverted (Figure 3).

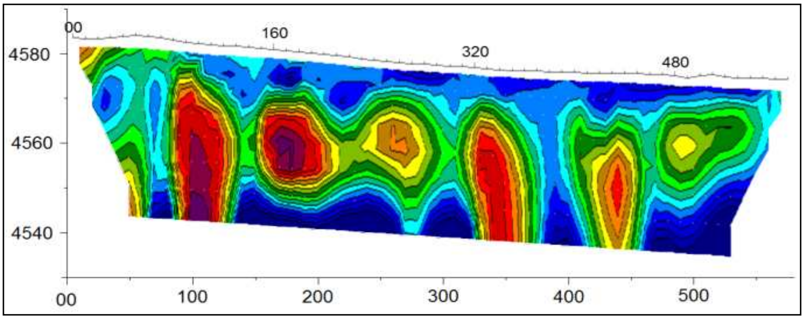

Figure 3. Investment model by topography.

4. Results and Analysis

4.1 Resistivities Range for Lithology

During resistivity processing, the software assigned a color to each resistivity contrast, progressively varying the color tone, as shown in Figure 3, which shows the topographic inversion model. The range of color variation is shown in Table 1, where they were separated into three groups according to the geological formations in the area under investigation, this table shows the relationship between soil type and resistivities.

Table 1. Range of Resistivities Generated by ERT and corresponding Lithology.

Resistivity (Ω-m)		
20 35 62	107 187 327	572 1000
Probable geological lithology		
Fine sand and wet to saturated silty of the tailings dam. Lacustrine clay with sands and / or fragments of rocks.	Glaciofluvial deposit and / or morass deposit with clays and lightly compacted stones.	Glaciofluvial deposit and/or moraines with clays and compact stones.

4.2 Description of electric resistivity tomographic

The results of the electrical scans were contrasted with the lithology found in the PTS Wash Boring perforations, observing a good correlation between the resistivities and the geological formations. The results are important for geological interpretation.

The ERT-01 profile is located at the head of the tailings dam, as shown in Figure 4A. The profile has a length of 400 m from northeast to southwest. The ERT-02 profile was performed in parallel with the ERT-01, located 260 m downstream. It has a length of 330 m, as shown in Figure 4B.

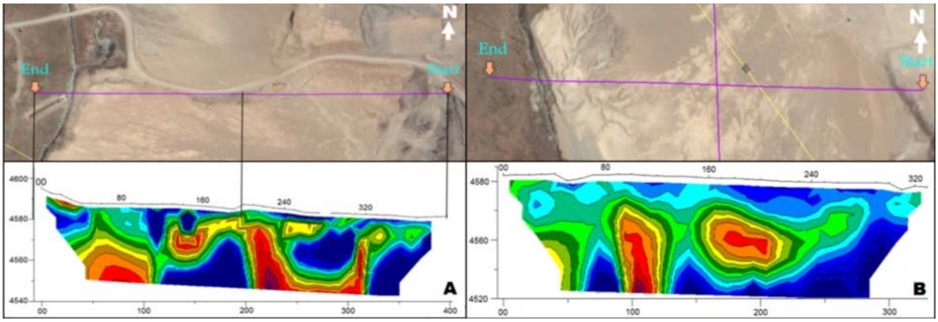

Figure 4. Satellite image of the ERT-01(A) ERT-01 (B) and location and its profile.

The ERT-03 profile (Figure 5A) was defined in parallel to the previous ERT. It is located downstream, distant at 250 m from the ERT-02 profile. Its route has a total length of 340 m, from northeast to southwest. The tomographic profile ERT-04 is configured transversely to the previous lines. It passes approximately through the middle of the dam, with a length of 500 m; the profile is shown in Figure 5B.

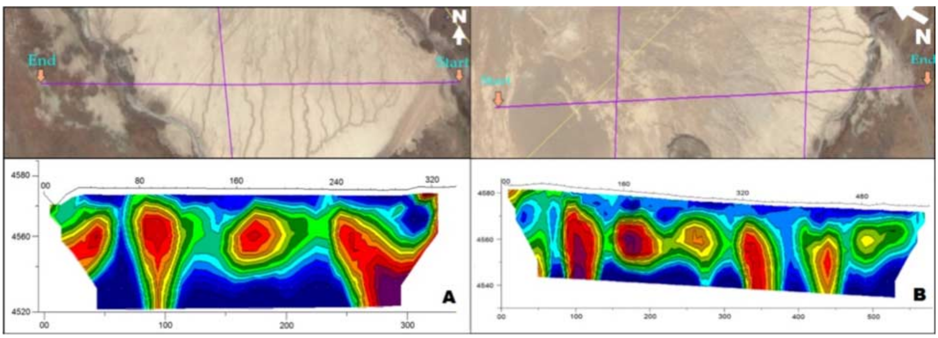

Figure 5. Satellite image of the ERT-03(A) ERT-04 (B) and location and its profile.

It was observed that the present study provided the possibility of including technical knowledge regarding risk management to the technical staff of the mining company. The presented gain corroborates with the understanding of the behavior of the soil that constitutes a tailings dam of relevance, the lines of electric resistivity tomographic scans used to investigate it allowed to define 3 types of georesistivity strata that are detailed below, depending on the resistivity:

- Resistivities less than 80 Ω-m are represented by colors ranging from light blue to dark blue. In the tomographies, they are presented in the superficial part that would correspond to the fine sands with silts, wet to saturated, coming from the tailings dam, with a thickness ranging from zero to 10 m, on average. When these colors are below the stratum defined by the green to red colors, they would correspond to sedimentary formations, such as very wet to saturated shales, located between 15 and 20 m depth, as seen in the 4 ERT's.
- Resistivities between 80 and 300 Ω-m are represented by colors ranging from green to yellow. Geologically, these resistivities would correspond to a transition between the silty sands for the brown formations (deposits produced by the glaciers when moving) and/or glacial-fluvial with fine to coarse sands.

As the resistive values increase, it is an indicator that the sediment granulometry is coarser and/or more compact. It has an average thickness of 3 to 8 m.

- Resistivities between 300 and 1000 Ω-m are represented by brown to purple colors. Geologically, these representations correspond to very compact formations or bedrock. In the study, they would be associated with the more compact glacial and/or even glacial-fluvial deposits, as presented in the 4 tomographies made in the tailings dam area. Descriptions of ERT's are presented in Table 2 that demonstrates that the resistivity results are adjusted to the actual soil conditions.

Table 2. Results (description) of the ERTs performed in the dam.

Layer	Resistivity Ω-m	ERT-01	ERT-02	ERT-03	ERT-04
Blue to Sky Blue	20 a 80	Saturated silty fine sand. Corresponding to the tailings dam, it is between 00 and 13 m deep. They are also present between 15 and 20 m deep, which would correspond to clays of lacustrine origin with sands and/or fragments of rocks.	Saturated silty fine sand. Corresponding to the tailings dam, it is between 00 and 7 m deep. They are also present between 15 and 20 m deep, which would correspond to clays of lacustrine origin with sands and/or fragments of rocks.	Saturated silty fine sand. Corresponding to the tailings dam, it is between 00 and 14 m deep. They are also present between 14 and 18 m deep, which would correspond to clays of lacustrine origin with sands and/or fragments of rocks.	Saturated silty fine sand. Corresponding to the tailings dam, it is between 00 and 10 m deep. They are also present between 15 and 20 m deep, which would correspond to clays of lacustrine origin with sands and/or fragments of rocks.
Green to yellow	80 a 300	Fluvial reservoir glacier and/or moraines with slightly compact clays and gravels. Located between the progressions from 00 to 50 m and 295 to 315 m, the flower of the earth and/or very close to the surface. They are practically outside the tailings dam (Figure 4A).	Fluvial reservoir glacier and/or moraines with slightly compact clays and gravels. Located between the progressions from 00 to 50 m and 310 m at the end of the ERT, the flower of the earth and/or very close to the surface. They are practically outside the tailings dam (Figure 4B).	Fluvial reservoir glacier and/or moraines with slightly compact clays and gravels. Located between the progressions from 00 to 30 m and 310 m at the end of the ERT, the flower of the earth and/or very close to the surface. They are practically outside the tailings dam (Figure 5A).	Fluvial reservoir glacier and/or moraines with slightly compact clays and gravels. Located between the progressions from 00 to 30 m and 310 m at the end of the ERT, the flower of the earth and/or very close to the surface. They are practically outside the tailings dam (Figure 5B).
Brown to Purple	300 a 1000	Glaciofluvial deposit and/or moraines with clays and compact boulders.	Glaciofluvial deposit and/or moraines with clays and compact boulders.	Glaciofluvial deposit and/or moraines with clays and compact boulders.	Glaciofluvial deposit and/or moraines with clays and compact boulders.

5. Conclusions

The studies carried out in this research have shown that, in addition to the conventional instrumentation, oriented to the measurement of poropressions, horizontal displacements, repressions, etc., that geophysical studies can also contribute to the control mechanisms of a tailings dam. A periodic geophysical investigation, performed before, during and after the decommissioning of the structure, is fundamental to the knowledge of the behavior throughout its life period, also contributing to the risk management associated with the dam. This type of study contributes to reinforcing the observations coming from the two-dimensional model, as well as providing knowledge of some features in the subsoil, demonstrating that the resistivity results are adjusted to the actual soil conditions.

Finally, it is pointed out that for the proper evaluation of a structure, with respect to the geotechnical behavior of tailings and a dam, studies of this nature are relevant. The application of geophysics as a tool for the internal structural visualization of the structure allows interpreting its updated behavior since many structures are dimensioned from values obtained in laboratory tests. Often, the results of these differed when compared to the field condition.

Electrical resistivity tomography showed a particularly interesting and consistent tool for the evaluation of the tailings of the polymetallic ore, making it possible to know the thickness, the general grain size classification, the stratigraphy and even the humidity, in an approximate way. The project results in the sense of safety, since the structures are controlled periodically, avoiding risks of ruptures or even simpler anomalies, and reducing, therefore, possibilities of associated environmental impacts.

References

[1] Boneli, S., Erosion in geomechanics applied to dams and levees. London: Wiley, (2013), 416.

[2] Borges, W. R. Caracterização geofísica de alvos rasos com aplicações no planejamento urbano e meio ambiente: estudo sobre o sitio controlado do IAG/USP. Tese de Doutorado, Instituto de astronomia, geofísica e ciências atmosféricas, IAGUSP, (2007), 256.

[3] Berry, A. A.; Saad, A., Tropical clay sand soil's behavior analysis and its empirical correlations via geophysical electrical resistivity method and engineering soil characterizations. International Journal of Geosciences, v. 3, (2012), 11-116.

[4] Haile, T., & Atsbaha, S. Electrical Resistivity tomography, VES and magnetic surveys from dam site characterization, Wukro, Northern Ethiopia. Journal of African Earth Sciences, 97, (2014), 67-77.

[5] Todd, D. K. Groundwater Hydrology, New York, Jhon Wiley and Sons, second edition, (1980), 535.

[6] Gadallah M. R. and Fisher R., Exploration Geophysic An Introduction Springer-Verlag Berlin Heidelberg (2009), 257.

[7] Orellana, E.,Prospección geoeléctrica en corriente continua. Ed. Paraninfo, Madrid, (1972), 523.

[8] Dahlin, T., Zhou, B., A numerical comparison of 2D resistivity imaging with 10 electrode arrays. Geophysical Prospecting 52, (2004), 379–398.

[9] Keller, G. V. & Frischknecht, F. C. Electrical methods in geophysical prospecting. Oxford: Pergamon Press, (1966), 517.

[10] Loke, M.H. & Barker, R.D., Least-square inversion of apparent resistivity pseudosections, Geophysics, 60, (1995), 1682–1690.