Soils and Rocks
An International Journal of Geotechnical and Geoenvironmental Engineering
www.soilsandrocks.com
ISSN 1980-9743
ISSN-e 2675-5475

The relationship between geophysical and geotechnical data: a temporal analysis of an iron ore tailings dam

Isabela Vasconcelos Leite de Freitas[1], Hersilia Andrade e Santos[2#]

Case Study

Keywords
Electrical resistivity
Precipitation
Time analyses
Piezometry

Abstract

Iron ore tailings dams must be constantly monitored for safety purposes. Among the aspects traditionally monitored are geotechnical protocols, such as piezometric levels along the dam. Recently, geophysics, a science that studies, among other things, dynamic processes in the Earth, has contributed to non-invasive monitoring using electro-resistivity methods. Geophysical methods provide a large amount of data in relatively quick samples, but there is little information on the integration of traditional geotechnical and geophysical techniques. Therefore, this work aimed to evaluate the relationship between geophysical data, monitored every 15 days between May 2022 and March 2023, and geotechnical data from an iron ore tailings dam located in the Iron Quadrangle. The geophysical method used was two-dimensional electrical imaging with a Schlumberger array. Analysis of variance and multiple regression allowed us to evaluate the relationship between resistivity values, piezometer level, sampling time, and rainfall. Piezometry data explained the electro-resistivity significantly, while sampling time and rainfall did not significantly explain electro-resistivity. Therefore, the dam's electro-resistivity patterns have not changed significantly over the period, and local rainfall does not imply an immediate response in resistivity. These conclusions can support new directions in decisions about monitoring iron ore tailings dams and may contribute to advances in dam safety in the mining sector.

1. Introduction

The construction of dams has been frequent in the world for centuries, and their failure may cause life loss as well as severe environmental impacts (Mainali et al., 2015). Data on global hazards indicate a high probability of dam-break per year (Paiva et al., 2019). In Brazil, the failures of Fundão and Córrego do Feijão tailing dams are remarkable due to the killed people (more than 250 in these two failures) and disaster extension (Santamarina et al., 2019; Milanez et al., 2021)

Dam monitoring is essential to ensure the dam's safety throughout its lifetime. Instruments and visual inspections monitor these structures (Machado, 2007), such as surface markers, inclinometers, water level indicators (NA), and piezometers. These methods are efficient and quite traditional in the mining industry, but they offer specific information about the amount of dam water.

On the other hand, geophysical methods applications are more frequent now, and their non-destructive nature and cost-effectiveness stand out (Mainali et al., 2015). Geophysics works with physical phenomena, such as Earth's magnetic field, geothermal flow, seismic wave propagation, gravity, electric and electromagnetic fields, telluric currents, and radioactivity. The four main groups of Geophysics methods are: 1) gravimetric, 2) magnetometric, 3) geoelectric, and 4) seismic (Braga, 2006). Geoelectric methods include electro-resistivity (ERT), induced polarization, and spontaneous potential (SP) (Telford et al., 1990). Except for the SP method, which measures the natural potential in the subsurface, all the others depend on the electrical transmission of the current into the soil (Dentith & Mudge, 2014).

Geophysical methods have been used to study dam conditions (Mainali et al., 2015; Martini et al., 2016; Nikonow et al., 2019; Mollehuara-Canales et al., 2021). In such conditions, changes in natural potential in the subsurface occur due to water movement through the dam and changes in resistivity reflect changes in the electrical properties of the dam materials. Therefore, measuring the natural potential over time is a powerful method for detecting leaks, and time series resistivity measurements provide valuable information about changes in dam conditions over time. However, the time-lapse ERT is relatively uncommon in mining waste monitoring (Dimech et al., 2022).

Among the geophysical methods applied to dam monitoring, ETR and SP stand out. ETR is a method that uses an artificial current, introduced by two electrodes (called A and B) in a terrain, to measure the potential generated in two other electrodes (called M and N) in the vicinity of the

[#]Corresponding author. E-mail address: hsantos@cefetmg.br
[1]VALE S.A, Geotecnia Operacional, Belo Horizonte, MG, Brasil.
[2]Centro Federal de Educação Tecnológica de Minas Gerais, Departamento de Engenharia Civil, Belo Horizonte, MG, Brasil.

Submitted on December 10, 2023; Final Acceptance on July 9, 2024; Discussion open until February 28, 2025.
https://doi.org/10.28927/SR.2024.011923

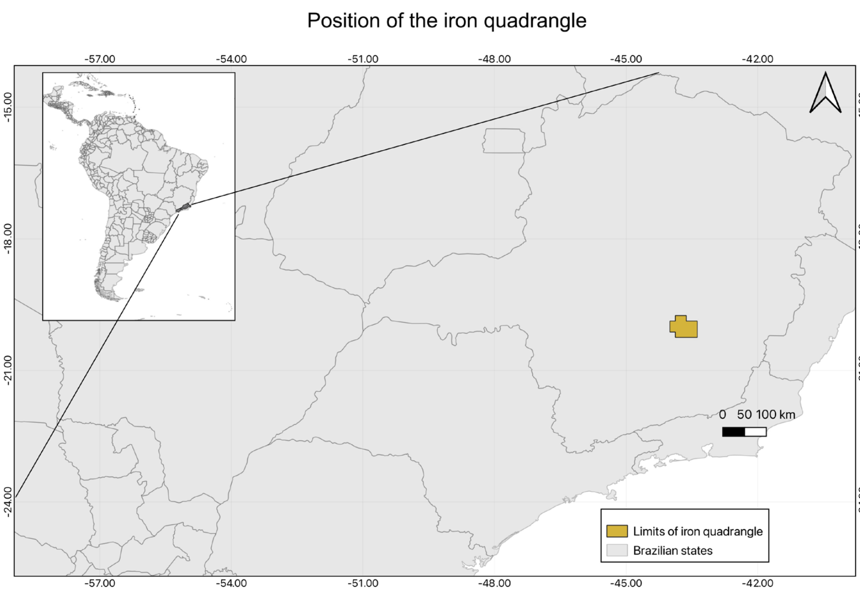
current flows, thus allowing the real or apparent resistivity in the subsurface to be determined (Lago et al., 2006). SP is a passive geophysical method that measures natural variations in electrical potential due to the spontaneous polarization of the earth, the causes of which are diverse (Telford et al., 1990).

Despite the increasing use of geophysical methods in tailings dams, few studies have presented an integrated analysis between data collected by traditional monitoring methods and geotechnical information on these structures. Besides that, the role of geophysical testing with geotechnical monitoring has been discussed for a long time (Jamiolkowski, 2012). Therefore, we aimed to investigate the relationships between data obtained by geophysical methods and those obtained by traditional dam safety monitoring methods. Thus, we compared the monitoring of an iron mining tailings dam, which applied the ERT method between May 2022 and March 2023, to the monitoring of traditional techniques such as piezometers, water indicators, and meteorological stations. The ERT method arrangement was Schlumberger, and the data was analyzed using statistical techniques of variance analysis and multiple regression, evaluating resistivity values, piezometer level, sampling time, and precipitation.

2. Materials and methods

2.1 Study area

The dam is in Nova Lima municipality (Brazil), which is the Belo Horizonte metropolitan region (Figure 1a). It is also in the north-central portion of the Iron Quadrangle, which is in the Brazilian Precambrian area with large mineral reserves and great structural complexity (Alkmim & Marshak, 1998). The stratigraphy of the Iron Quadrangle



a)

b)

Figure 1. (a) Study area in Minas Gerais (Brazil) map; (b) dam overview.

encompasses the gneissic complexes of the basement, the volcano-sedimentary sequence of the Rio das Velhas Supergroup, and the metasedimentary sequences of the Minas Supergroup and Itacolomi Group (Dorr, 1969; Machado et al., 1996; Almeida et al., 2005).

The water dam flows in the Rio das Velhas watershed, which runs through 51 municipalities, and its tributary is called the Taquaras stream. The dam is 24 meters high and 95 meters long. Its crest is 5.25 meters wide, and its intermediate berm is 3.00 meters wide. The downstream slopes have a slope between berms of 1V: 2H and the upstream slope has a shape of 1V: 1.7H (Figure 1b). The dam was built in a single stage and made of fine sandy silt to clayey silt soil. The foundation contains colluvial soil, residual phyllite soil, altered phyllite rock, and phyllite material.

2.2 Geotechnical monitoring

The dam has ten piezometers and seven water level indicators to measure the water and piezometric levels of the structure (Figure 2 and Table 1).

Table 1. Name and type of geotechnical monitoring instrument.

Instrument ID	Instrument type
PZ-01	piezometer
PZ-02	piezometer
PZ-03	piezometer
PZ-04	piezometer
PZ-05	piezometer
PZ-06	piezometer
PZ-07	piezometer
PZ-08	piezometer
PZ-09	piezometer
PZ-10	piezometer
NA-01	water level indicator
NA-02	water level indicator
NA-03	water level indicator
NA-04	water level indicator
NA-05	water level indicator
NA-06	water level indicator
NA-07	water level indicator

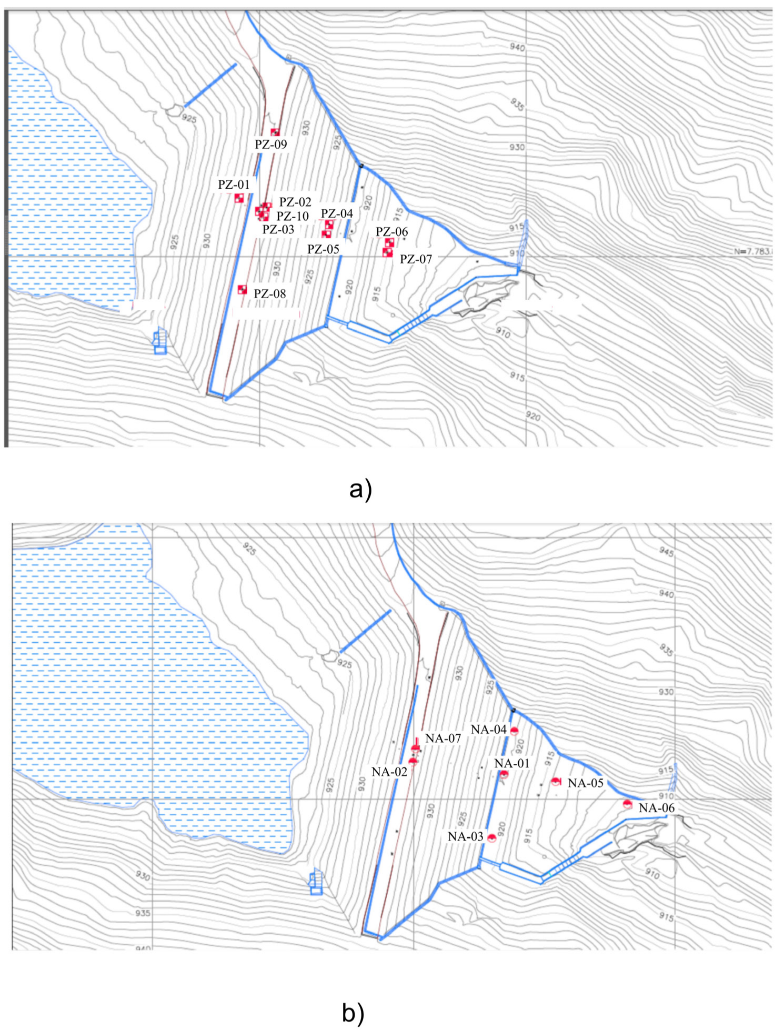


Figure 2. The location of ten piezometers (a) and seven water level indicators (b) in the dam.

2.3 Geophysical monitoring

The ERT method applied the two-dimensional electrical imaging technique (also known as two-dimensional Electrical Tomography) in the Schlumberger array. The spacing between the electrodes was 5 m. The survey comprised four electro-resistivity sections parallel to the dam axis, which is 320 meters long (Figure 3a). Interpolations allowed to creation of the three-dimensional model of ERT data (Figure 3b). Periodic surveys were carried out on the same sections as the initial survey, e.g. four sections parallel to the dam axis every 15 days, starting on 17th May 2023 and ending on 31st March 2023, totaling 22 surveys (Table 2).

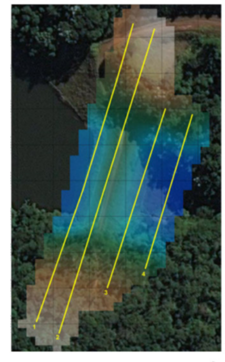
2.4 Database

The Leapfrog software (Version 2022.1.0) performed the analyses of periodic electro-resistivity surveys (in grid format) and the dimensional solids of electro-resistivity measurements. The instruments (piezometers and water level indicators) also had geographical coordinates (North/East coordinate and elevation), and so the data importation had the respective date readings equal to the days of the geophysical surveys (Figure 4a).

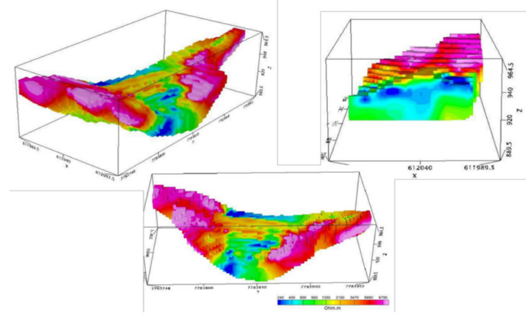
After the model creation, we defined data pairs (electro-resistivity and water level/piezometric level data) for each instrument and that date. It is important to note that if the instrument is dry, we selected the instrument base as the survey point (Figure 4b).

Table 2. Date of ERT surveys in the dam.

Monitoring number	Monitoring date
1	17-May-22
2	30-May-22
3	9-Jun-2022
4	17-Jun-2022
5	27-Jun-2022
6	8-Jul-2022
7	30-Jul-2022
8	8-Aug-2022
9	29-Aug-2022
10	5-Sep-2022
11	30-Sep-2022
12	17-Oct-2022
13	28-Oct-2022
14	9-Nov-2022
15	29-Nov-2022
16	8-Dec-2022
17	23-Jan-2023
18	10-Feb-2023
19	27-Feb-2023
20	10-Mar-2023
21	20-Mar-2023
22	31/03/2023

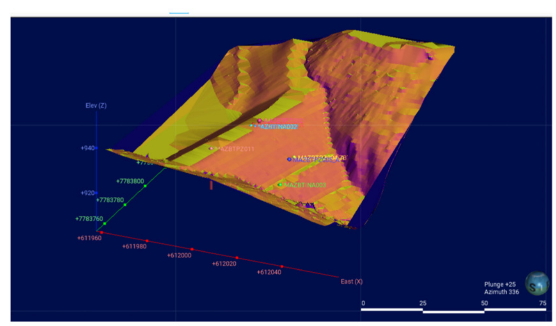


a)

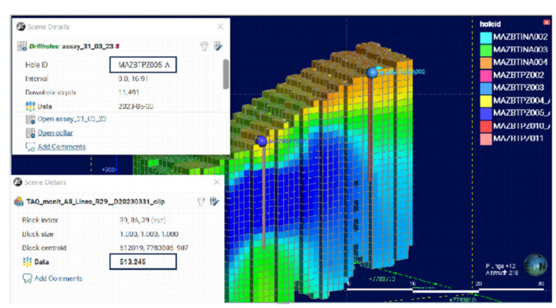


b)

Figure 3. (a) the ERT sections parallel the dam axis; (b) the dam three-dimensional model with electro-resistivity data.



a)



b)

Figure 4. (a) The dam three-dimensional model with electro-resistivity data and location of the geotechnical instrument on 30th March 2023; (b) the instrument position concerning the elevation level.

It was then possible to generate the database for evaluating the relationship between the structure's geotechnical and geophysical data. In addition, the rainfall database from a rain gauge, which is near the structure, was also used. In addition to the daily spot reading, we evaluated the accumulated rainfall between geophysical surveys.

2.5 Statistical analysis

The analysis of variance, Pearson's correlation, multiple regression without interaction, multiple regression without interaction, and linear regression allowed to investigation of the relationship between geophysical data and geotechnical data, statistical analyses of the data were carried out using. The R program (version 4.2.1) ran the analyses, and the probability of 95% rejects the null hypothesis (*p-value* < 0.05).

The ANOVA analysis evaluated if the electro-resistivity data may be explained by the occurrence of precipitation (in mm) and the time (number of days that sampling). Pearson's correlation aimed to identify the relationship between electro-resistivity and piezometer reading, as well as electro-resistivity and precipitation survey. We used multiple regressions to explain electro-resistivity data by the number of days of rain, as well as the linear regression.

3. Results

3.1 Database

The PZ-04 instrument showed the greatest variation in geotechnical data compared to the other piezometers (Figure 5a). The others were dry or had low variation over

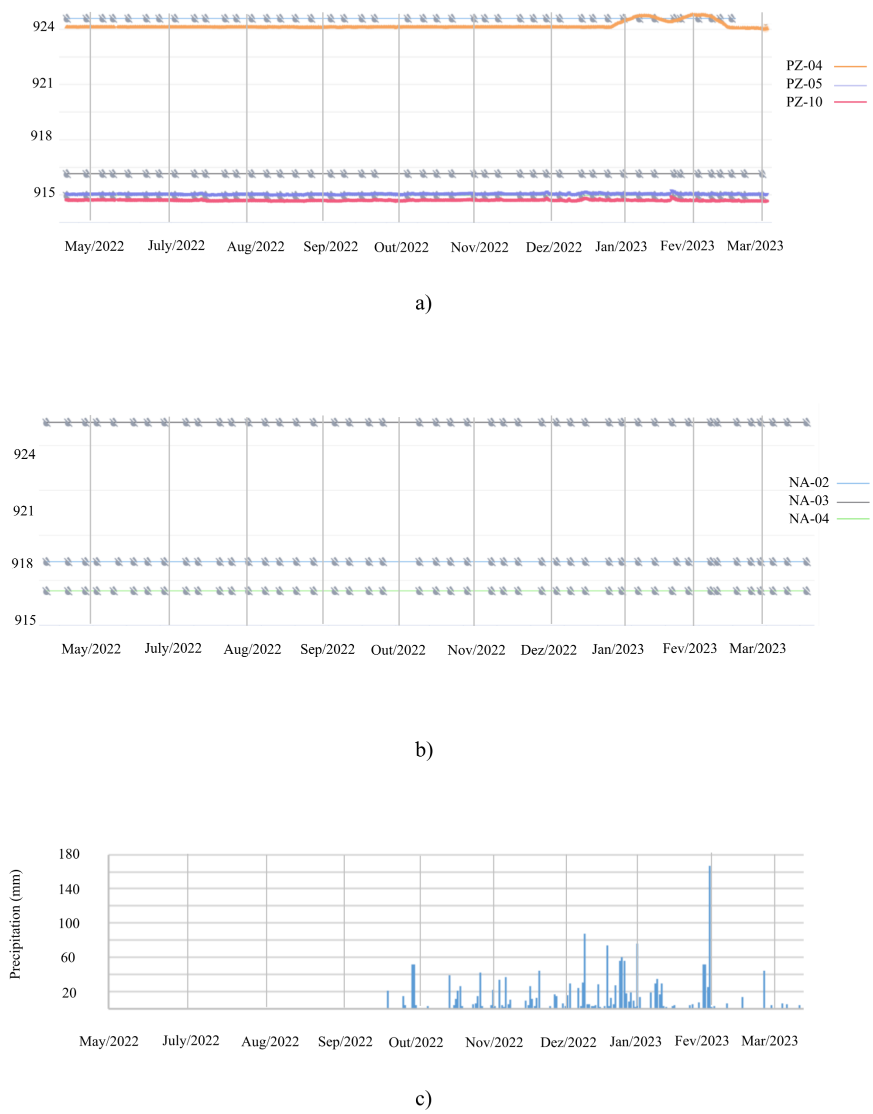


Figure 5. (a) Data by main piezometers (m); (b) data by water level indicator (m); (c) precipitation (mm) along the 11 monitoring months.

time. The water level gauges installed in the structure remained dry throughout the survey period (Figure 5b). During the sampling period, the highest rainfall occurred in February, around 160 mm (Figure 5c).

The PZ04 piezometer is 8.34 m deep, and its top level is on the downstream slope (Figure 6). The electrical resistivity values for the reading points of this instrument ranged from 39 ohms to 57 ohms, without much variation over the rainy/dry period. The instrument's reading of the piezometric level varied over the period, and it was possible to observe that a lower piezometric load is associated with lower electro-resistivity.

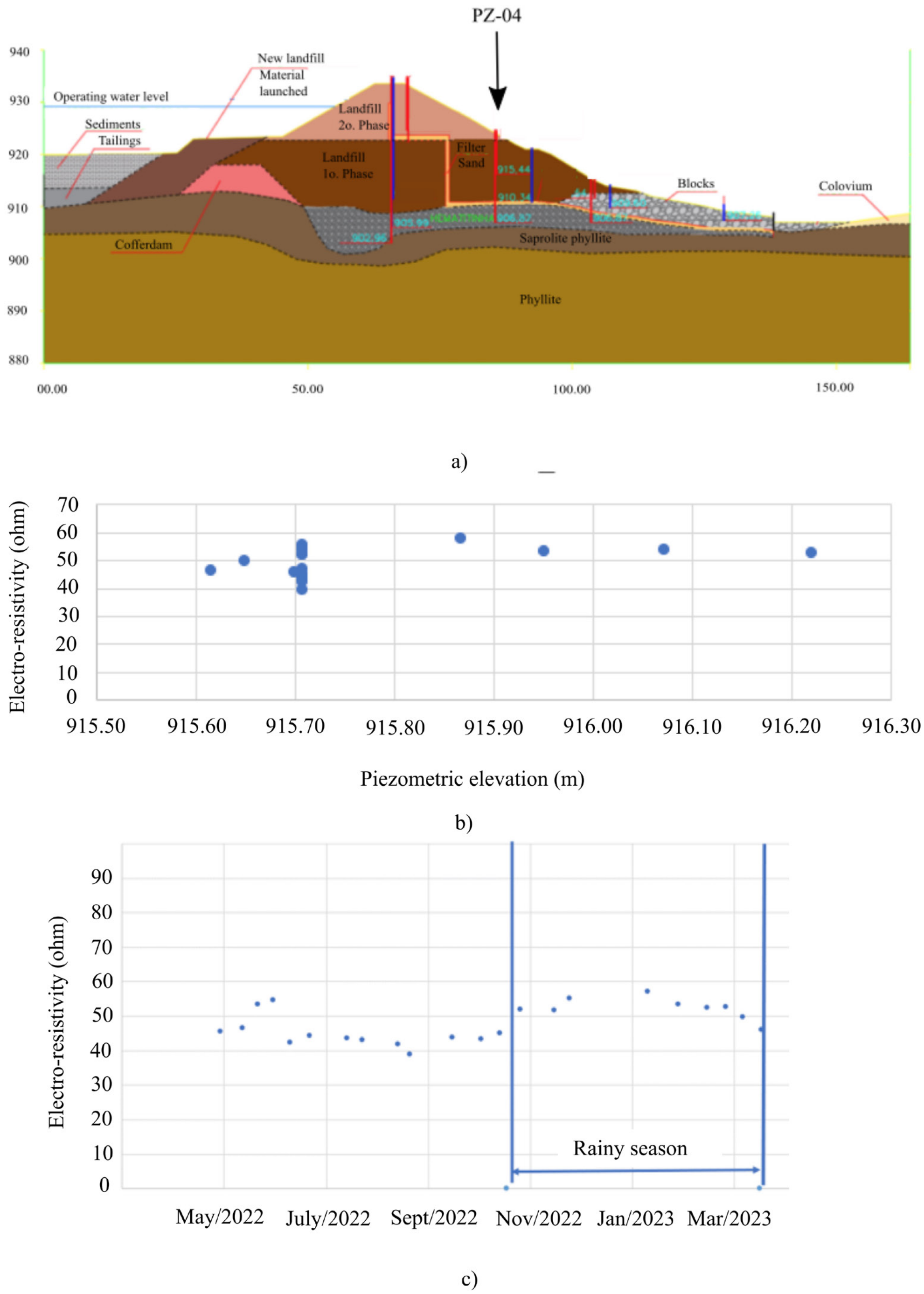


Figure 6. (a) Location of PZ-04 in the dam; (b) electro-resistivity versus piezometric elevation in PZ-04; (c) electro-resistivity versus date in PZ-04.

The NA-03 water level indicator is 6.34m deep, and its top level is located on the middle berm downstream (Figure 7). The electro-resistivity values for the reading points of this instrument ranged from 286 ohms to 442 ohms, with the lowest measurements at the end of the rainy season. The instrument had no variation in water level readings during the period.

3.2 Statistical results

According to the analysis of variance, neither the precipitation factor nor the time factor significantly explained the variation in the average electro-resistivity values (*p-value*<0.05) (Table 3).The result of the regression

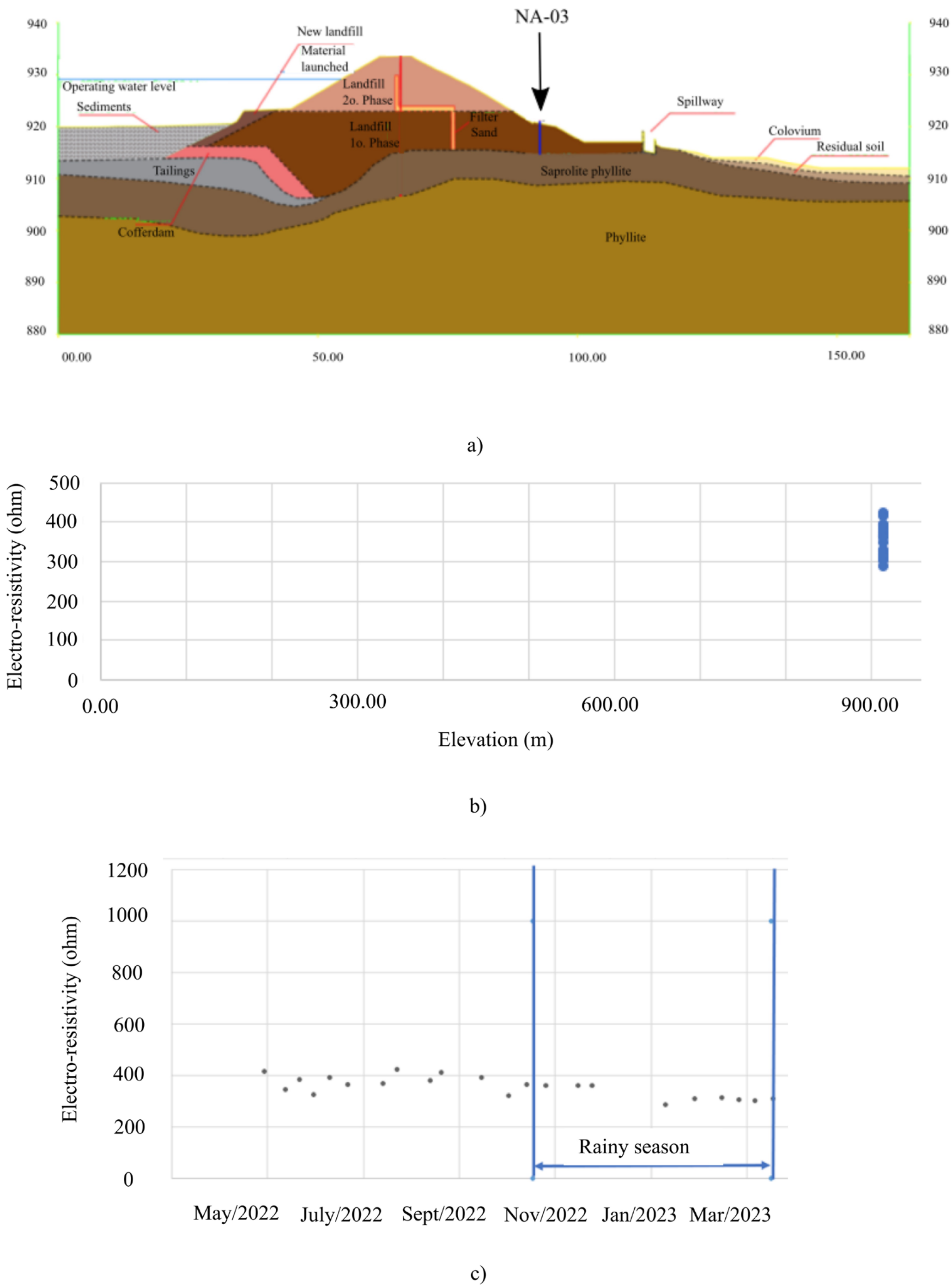


Figure 7. (a) Location of INA-03 in the dam; (b) electro-resistivity versus piezometric elevation in PZ-04; (c) electro-resistivity versus date in PZ-04.

indicated that electro-resistivity is significantly explained by piezometric variation (Table 4). The multiple linear regression with interaction aimed to check whether the variables had a combined influence on the final result of the analysis. The interaction between the variables was unable to explain (p-value > 0.05) the electro-resistivity values found (Table 5).

4. Discussion

The use of indirect methods applied to direct methods is of paramount importance since there is a significant gain in the laterality of the information and the possibility of extrapolating it. Oliveira (2018) states that geophysical data generates continuous subsurface images, making it possible to identify possible irregularities in the dam structure. The methods are highly capable of detecting failure modes such as internal erosion (Mainali et al., 2015). It clearly shows the potential of using geophysical data integrated with geotechnical data to gain confidence in the information on structures.

By analyzing the data collected over the eleven-month monitoring period, it was possible to obtain the following results: 1) electro-resistivity was significantly explained by piezometric variation; 2) precipitation had no significant relationship with electro-resistivity and 3) electro-resistivity showed no variation concerning time in the sampling collected.

We expected the relationship between the electro-resistivity and piezometry data since low electrical resistivities are associated with the presence of water. Electro-resistivity, on the other hand, did not respond immediately to rainfall. According to Canatto (2021), in the study of a small dam located in Minas Gerais (Brazil), there was variability in the electro-resistivity values between the surveys, with the months with low rainfall (August, September, and October) showing higher electro-resistivity amplitudes, while the months with the highest rainfall (November, December, and January) showed low electro-resistivity values with little amplitude. The large influence of rainfall on the saturation patterns of dams may explain these results. It is important to note that the response time of the measurements and the variation in the electro-resistivity can lead to different results. In other words, for future work, the temporal correlation between the data and the variation in time could be related.

We also expected the correlation between the variation in electro-resistivity over time. However, we did not find any temporal correlation between the geophysical data. It was possible to observe that in the year of the surveys, there were no successive days with rainfall, but isolated peaks of rain, which did not generate a constant saturation of the soil with significant changes in electro-resistivity.

Table 3. Analysis of variance of the electro-resistivity data by precipitation and time factors.

Variable	Sum	Sum *SQ*	Sum *F*	*F*	*p*-value
Precipitation (mm)	1	31588	31588	0.81	0.37
Time (days)	20	73038	3652	0.09	1.00
Residues	176	69000817	39209		

Table 4. Result of the multiple linear regression of electro-resistivity by the dependent variables precipitation, piezometric variation, and time.

	Estimate	Std. Error	*t*-value	*p*-value
Intercept	-7307.49	2043.00	-3.58	<0.05
Precipitation (mm)	-0.65	1.39	-0.47	0.65
Piezometric variation (m)	8.42	2.38	3.76	< 0.05
Time (days)	-0.12	0.13	-0.93	0.35

Table 5. Results of the multiple linear regression of electro-resistivity considering the interaction between the independent variables precipitation, piezometric variation, and time.

	Estimate	Error	*t*-value	*p*-value
Intercept	-1567.00	3690.00	-0.43	0.67
Precipitation (mm)	335.00	1936.00	0.17	0.86
Piezometric variation (m)	2.13	4.04	0.53	0.60
Time (days)	-36.91	22.70	-1.63	0.11
Precipitation (mm) and Piezometric variation (m)	-36.59	2.12	-0.17	0.86
Precipitation (mm) and Time (days)	-1.82	9.57	-0.20	0.85
Piezometric variation (m) and Time (days)	0.04	284.60	1.62	0.11
Precipitation (mm), Piezometric variation (m) and Time (days)	<0.01	0.01	0.19	0.85

Geophysical monitoring proved to be important and could provide additional information for geotechnical structures. Further research could be carried out to verify the applicability of the correlations between electro-resistivity and piezometry in surveys of other dams, to identify whether the correlation applies to other structures, which have different boundary conditions, such as construction method, construction material, variations in internal piezometry, etc.

5. Conclusion

This study aimed to correlate geotechnical data with geophysical data from periodic surveys of a tailings dam in an ore mine. The main findings of this work are: 1) In terms of variations in water levels as well as piezometric heights, the survey points did not have significant variations, with many instruments having dry readings for a large part of the surveys. As a result, it was not possible to observe any great dispersion in the geotechnical data; 2) the electro-resistivity data is explained by the piezometric level; 3) the date of the survey does not produce significant variation in electro-resistivity data, and 4) the electro-resistivity data do not present direct relation with precipitation. These conclusions may contribute to advances in dam monitoring of the mining sector and, consequently, to improving dam savings policies.

Acknowledgements

The authors are grateful to the Centro Federal de Educação Tecnológica de Minas Gerais (CEFET-MG) for the infrastructure for student work and the VALE S.A for supporting the dam monitoring. This study was also partly funded by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Brazil (CAPES), Finance Code 001.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Isabela Vasconcelos Leite de Freitas: conceptualization, data curation, investigation, software, funding acquisition, writing – original draft. Hersilia Andrade e Santos: conceptualization, data curation, methodology, supervision, validation, writing – original draft, writing – review & editing.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

List of symbols and abbreviations

p-value	level of marginal significance within a statistical hypothesis test
t	value of student's t-test
ERT	electro-resistivity
F	value of F-test
H	horizontal increment
NA	water level indicators
PZ	piezometer
SP	spontaneous potential
SQ	square
V	vertical increment

References

Almeida, L.G., Castro, P.T., Endo, I., & Fonseca, M.A. (2005). O grupo sabará no sinclinal dom bosco, quadrilátero ferrífero: uma revisão estratigráfica. *Revista Brasileira de Geociencias*, 35(2), 177-186. http://doi.org/10.25249/0375-7536.2005352177186.

Alkmim, F.F., & Marshak, S. (1998). Transamazonian orogeny in the Southern Sao Francisco craton region, Minas Gerais, Brazil: evidence for Paleoproterozoic collision and collapse in the Quadrilátero Ferrıfero. *Precambrian Research*, 90(1-2), 29-58. http://doi.org/10.1016/S0301-9268(98)00032-1.

Braga, A.C.O. (2006). *Métodos da eletrorresistividade e polarização Induzida aplicados nos estudos da captação e contaminação de águas subterrâneas: uma abordagem - metodológica e prática* [Doctoral thesis]. Universidade Estadual Paulista's repository. Retrieved in December 10, 2023, from http://hdl.handle.net/11449/116123

Canatto, B.F. (2021). *Geofísica eletrorresistiva aplicada ao monitoramento temporal da percolação de fluidos no interior de estruturas de barragens* [Master's dissertation]. Universidade Federal de Itajubá's repository. Retrieved in December 10, 2023, from https://repositorio.unifei.edu.br/jspui/handle/123456789/2511

Dentith, M., & Mudge, S.T. (2014). *Geophysics for the mineral exploration geoscientist*. Cambridge: Cambridge University Press. http://doi.org/10.1017/CBO9781139024358.

Dimech, A., Cheng, L., Chouteau, M., Chambers, J., Uhlemann, S., Wilkinson, P., Meldrum, P., Mary, B., Fabien-Ouellet, G., & Isabelle, A. (2022). A review on applications of time-lapse electrical resistivity tomography over the last 30 years: perspectives for mining waste monitoring. *Surveys in Geophysics*, 43(6), 1699-1759. http://doi.org/10.1007/s10712-022-09731-2.

Dorr, J.V.N. (1969). *Physiographic, stratigraphic, and structural development of the Quadrilatero Ferrifero, Minas Gerais, Brazil* (No. 641-A, pp. A1-A110). Washington, D.C.: U.S. Government Publishing Office.

Jamiolkowski, M. (2012). Role of geophysical testing in geotechnical site characterization. *Soils and Rocks*, 35(2), 117-137. http://doi.org/10.28927/SR.352117.

Lago, A.L., Elis, V.R., & Giacheti, H.L. (2006). Aplicação integrada de métodos geofísicos em uma área de disposição de resíduos sólidos urbanos em Bauru-SP. *Revista Brasileira de Geofísica*, 24(3), 357-374. http://doi.org/10.1590/S0102-261X2006000300005.

Machado, N., Schrank, A., Noce, C.M., & Gauthier, G. (1996). Ages of detrital zircon from Archean-Paleoproterozoic sequences: implications for Greenstone Belt setting and evolution of a Transamazonian foreland basin in Quadrilátero Ferrífero, Southeast Brazil. *Earth and Planetary Science Letters*, 141(1-4), 259-276. http://doi.org/10.1016/0012-821X(96)00054-4.

Machado, W.G.F. (2007). *Monitoramento de barragens de contenção de rejeito da mineração* [Master's dissertation]. Universidade de São Paulo's repository.

Mainali, G., Nordlund, E., Knutsson, S., & Thunehed, H. (2015). Tailings dams monitoring in Swedish mines using self-potential and electrical resistivity methods. *The Electronic Journal of Geotechnical Engineering*, 20(13), 5859-5875.

Martini, R.J., Caetano, T.R., Santos, H.A., & Aranha, P.R.A. (2016). Deposição de rejeitos de minério de ferro em reservatórios: uma aplicação do método GPR. *Revista Ambiente & Água*, 11(4), 878-890. http://doi.org/10.4136/ambi-agua.1831.

Milanez, B., Ali, S.H., & de Oliveira, J.A.P. (2021). Mapping industrial disaster recovery: lessons from mining dam failures in Brazil. *The Extractive Industries and Society*, 8(2), 100900. http://doi.org/10.1016/j.exis.2021.100900.

Mollehuara-Canales, R., Kozlovskaya, E., Lunkka, J.P., Moisio, K., & Pedretti, D. (2021). Non-invasive geophysical imaging and facies analysis in mining tailings. *Journal of Applied Geophysics*, 192, 104402. http://doi.org/10.1016/j.jappgeo.2021.104402.

Nikonow, W., Rammlmair, D., & Furche, M. (2019). A multidisciplinary approach considering geochemical reorganization and internal structure of tailings impoundments for metal exploration. *Applied Geochemistry*, 104, 51-59. http://doi.org/10.1016/j.apgeochem.2019.03.014.

Oliveira, L.A. (2018). *Caracterização de barragens de rejeito através de métodos geofísicos elétricos: estudo de caso na barragem b1 de Cajati, São Paulo* [Master's dissertation]. Universidade Federal do Rio de Janeiro's repository.

Paiva, R.C.D.D., Fan, F.M., Tassinari, L.C.D.S., & Tschiedel, A.D.F. (2019). Barragens e rompimentos: compilação histórica nacional e internacional. *Anais do 23º Simpósio Brasileiro de Recursos Hídricos*, Foz do Iguaçu. Porto Alegre: ABRH. Retrieved in December 10, 2023, from https://anais.abrhidro.org.br/job.php?Job=5724&Name=barragens_e_rompimentos_compilacao_historica_nacional_e_internacional

Santamarina, J.C., Torres-Cruz, L.A., & Bachus, R.C. (2019). Why coal ash and tailings dam disasters occur. *Science*, 364(6440), 526-528. http://doi.org/10.1126/science.aax1927.

Telford, W.M., Geldart, L.P., & Sheriff, R.E. (1990). *Applied geophysics*. Cambridge: Cambridge University Press.