Proceedings of the 7th International Conference on Geotechnical and Geophysical Site Characterization
Barcelona, 18 - 21 June 2024

3D Resistivity Survey of a Weathering Profile of Metamorphic Rocks in State of Pernambuco, Brazil

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ABSTRACT

This paper aims to study a weathering profile of crystalline rocks in the City of Camaragibe, State of Pernambuco, Brazil. For this purpose, a survey using electroresistivity was conducted. A regular mesh was performed aiming at 3D acquisition. The target area of the survey has 3 meters of depth (the Data Collection Platform, abbreviated as PCD) responsible for recording soil moisture information. An auger soil sampler was also made reaching a depth of 3 meters to describe and identify the substrate. The main objectives of the paper are to determine the geoelectrical characteristics of the materials and relate them to the strata previously identified and the soil moisture profiles. A goal was also to calculate moisture from the resistivity model and compare the results with those obtained by the PCD. The results allowed the creation of 3D geo-electric models, extending to a depth of 8 meters. It was also possible to create a 3D soil moisture model. It was possible to make a correlation between the geoelectric horizons and the layers of the rock alteration profile. The humidity results obtained by PCD and the resistivity model were examined, indicating favorable prospects for applying the method.

Keywords: 3d resistivity; soil weathering; soil moisture

1. Introduction

The rock alteration profiles result from the interaction between the original rocks and weathering processes, leading to the formation of soil. Soil is a superficial layer of the Earth's crust, composed of mineral particles, organic matter, water, and air. In alteration profiles, different horizons or layers can be observed, reflecting the transformations undergone by the original rock. The application of methods for more accurate characterization is becoming increasingly important. In this context, the use of geophysics stands out as a non- destructive method of obtaining subsurface information. The applications of this tool can contribute to geological and geotechnical knowledge in the context of both sedimentary and crystalline rocks. In the case of crystalline rocks in humid tropical climates, there is generally, the formation of complex, variable, and difficult-to-predict alteration profiles.

Civil engineering, faced with the aforementioned difficulty, resorts to a series of tests and instrumentation to achieve the highest possible accuracy. However, such study methodologies may have higher costs, be more destructive, and involve mobilization of larger materials or equipment. Geophysics stands out as the possible contributions to research related to geological characteristics and also in associations with geotechnical parameters.

The use of the geophysical method of electrical resistivity is emphasized here. Electrical resistivity is a technique employed in engineering to estimate the properties of the subsurface or other materials. It involves measuring the electrical resistance of a material when an electric current is passed through it.

Examples of common applications of electrical resistivity is the determination of the hydraulic conductivity of formations (Huntley, 1986; Lima and Niwas, 2000), detection of the presence of salts (Borner et al., 1993; Zhang et al., 2014), Geophysical prospection (Archie, 1942; Waxman and Smits, 1968; Kibria and Hossain, 2012; Foti, 2013), compaction control (Abu-Hassanein et al., 1996; Gingine et al., 2016) and monitoring the evolution of the degree of saturation in soils (Khalil and Santos, 2009; Gunn et al., 2014; Kibria and Hossain, 2016).

The geological context of the current paper focuses on a region belonging to the crystalline basement. Gneisses, migmatites, and granites prevail. The humid tropical climate has contributed to the formation of alteration profiles, exposing residual soil horizons.

Field tests were conducted to obtain soil electrical resistivity values. These data will be correlated with descriptions of samples collected from a borehole and with the recording of the soil moisture. The aim is also to calculate soil moisture from the electrical resistivity model. Bibliographic Review

2.1. Electrical resistivity

An electrical resistivity, also known as the electrical resistivity method, is a widely used technique in engineering to estimate the geo-electric distribution of the subsurface. This process involves measuring the potential difference ΔV on the soil surface through electrodes. The electric current travels through the subsurface and interacts with the electrical characteristics of the material present, such as resistivity.

Electric current is applied to the surface through immediate galvanic contact with the soil. The method is known for its direct impact, enabling the measurement of the potential difference in values. This way, it becomes possible to make accurate estimates of the resistivity distribution of materials in depth (Gandolfo; Gallas, 2007; Santos, 2005).

The electric current injected into the soil, conceptually considered as a means of uniform resistivity, adopts different behaviors depending on the use of one or two injection electrodes. The current transmission reaches a capture electrode located at a horizontal distance from the injection electrode. The current transmission circuit takes on a radial shape between the electrodes and it is responsible for a uniform distribution, forming equipotential lines. (Kearey; Brooks; Hill, 2009). There are two main data acquisition techniques. Vertical Electrical Sounding considers a distribution of vertical resistivity, while Horizontal Profiling considers a distribution of lateral electrical resistivity. While one method focuses on lateral variations, the other aims to investigate vertical points in the subsurface (Madrucci, 2000).

In addition to the basic data acquisition techniques, there are also arrays in the distribution of electrodes. The main arrays are: Wenner- Schlumberger, pole-pole, inline dipole-dipole, pole- dipole and equatorial dipole-dipole (Milson, 2003).

2.2. Soil Resistivity

2.2.1. Mineralogical content

Research on the resistivity of highly plastic clay has revealed that the ionic composition and specific surface are important in studies of the electrical resistivity of soils (Kibria and Hossain, 2012).

The interaction between physico-chemical attributes and electrical conductivity is intricately connected to the crystalline structures and elemental composition of soils. Electrical resistivity of sodium kaolinite is notably affected by soluble salts and their concentrations. However, there has been insufficient attention given to understanding the impact of clay mineral types and their physico-chemical characteristics on electrical properties (Mitchell and Arulanandan, 1968).

In a study conducted by Kibria and Hossain (2014), the investigation centered on the impact of bentonite content on the electrical resistivity of artificially mixed soils. The experimental setup involved tests on ten artificial soils created by combining bentonite and sand. The results clearly demonstrated significant variations in resistivity corresponding to varying bentonite contents. The impact of electrically charged clay minerals depends on their specific surface, and that is determined by the type of minerals (McCarter, 1984; Kibria and Hossain, 2012, for example). Surface electrical conductivity fluctuates notably in accordance with the cation exchange capacity of particles, representing the quantity of exchangeable cations offered by a specific clay mineral type. This dependency becomes more evident at very low water contents, where the influence of the free liquid phase is absent. In such cases, water exists adsorbed to the mineral surfaces, establishing a connection between the minerals through which electrical current can flow (Wildenschild et al., 2000; Kibria and Hossain, 2012).

2.2.2. Degree of saturation

The empirical evidence presented underscores the importance of taking into account the presence of water in both liberated and adsorbed states when evaluating the electrical resistivity of clays. The distinction between these two pathways of electrical flow within the soil requires more comprehensive data, challenging the conventional approach of solely considering the degree of saturation (volume of water) (Dias and Cardoso, 2016).

2.3. Geological Context

The geological context points to rocks of the crystalline basement. In the broader context, these lithotypes belong to the Borborema Province. This province occupies an area of approximately 450,000 km2 and is geographically located in the Northeast of Brazil. According to Jardim de Sá (1994), metamorphic rocks, migmatites, and various granitoids make up the overall geological panorama.

3. Methodological procedures

This section presents the materials used in the research, as well as the methods applied to obtain the results. Initially, an area (11m × 35m) was delimited for the acquisition of electrical resistivity data. There is a probe for recording soil moisture. A handmade auger hole was made for reconnaissance and sample collection.

3.2. Soil Sample Description

An auger hole was made in the central portion of the studied area. The profile is 3 meters deep with sample collection at every 0.5 meters. A visual-tactile analysis of the samples was performed.

3.3. Electroresistivity

The method uses pairs of electrodes to inject direct current and pairs of electrodes to measure potential differences between two points at the surface.

The area is 11 meters × 35 meters, as previously mentioned. Profiles were created along the longest axis of the area with position spacing of 0.5 meters. The electrode spacing was 1 meter. The arrangement used was multgrad.

The measurement results allow the creation of 2D profiles. As a regular grid was performed, 3D image acquisition was possible.

The Syscal PRO resistivity meter was used. The necessary programs for data processing and geoelectric inversion were Res2DInv and Res3DInv software, both developed by Aarhus GeoSoftware.

3.4. Soil moisture PCD GEO

Soil moisture was obtained from a device known as PCD GEO. PCD (the acronym in Brazilian Portuguese stands for Data Collection Platform) GEO refers to geotechnical equipment that integrates rain gauges with probes equipped with moisture sensors every 0.5 meters, totaling 3 meters in depth. CEMADEN (National Center for Monitoring and Alerts of Natural Disasters) is responsible for the installation and maintenance of these devices. Currently, there are 107 operating PCDs in Brazilian territory.

3.5. Results of Moisture derived from 3D Electrical Resistivity

The indirect soil moisture content was obtained from electrical resistivity data. The "Guara" software was used, which is capable of calculating geotechnical parameters from a geo-electric model using databases from the works of Siddiqui and Osman (2013) and Braga (2016). In this study, the mentioned software was used to calculate the regular moisture along the depth profile of the PCD. It was also possible to model the soil moisture information in three dimensions.

4. Results and Discussions

4.1 Electrical resistivity

The results allowed the creation of 2D sections and 3D geo-electric models (Figure 1). The modeled information depth reached a depth of 8 meters. The distinction of three layers with various resistive characteristics was evident. The upper geo-electric horizon has predominant resistivity values ranging from 1200 to 670 Ohm.m in depth from 0 to 1 meter. A middle geo-electric layer has predominant resistivity values ranging from 670 to 520 Ohm.m in depth from 1 to 2 meters. The lower geo-electric layer has predominant resistivity values ranging from 520 to 100 Ohm.m in depth from 2 to 8 meters. The geo-electric horizon with a depth of 0 to 1 meter may be related to the superficial organic-rich soil layer. The geo-electric layer from a depth of 1 to 2 meters may correlate to a saprolitic soil horizon, where clay minerals are identified following a relic rock structure. The geo-electric layer with a depth of 2 to 8 meters may correlate to another saprolitic soil horizon, where a higher quantity of clay minerals is found.

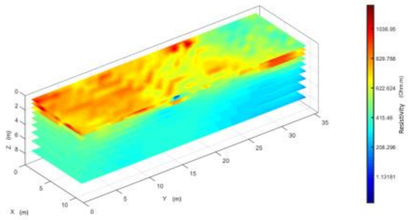


Figure 1. 3D resistivity model

4.2 Integration of Resistivity and Moisture Results

The soil moisture content measured by the Data Collection Platform (PCD) were consulted on the Interactive Map of the Cemaden's Observational Network for Monitoring the Risk of Natural Disasters on the day and time of the geophysical survey. The calculation of indirect moisture from the 3D resistivity model was also carried out. The results of moisture obtained by the PCD and the resistivity model were analyzed and, in general, they show convergence. The most divergent value occurs at a depth of 1 meter, reaching a difference of about 30%. A correlation graph of PCD vs. indirect moisture shows a linear regression (Figure 2). The correlation coefficient results (0.903) and determination (0.816) indicate very strong correlations in both coefficients.

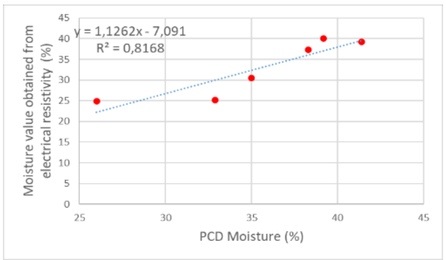
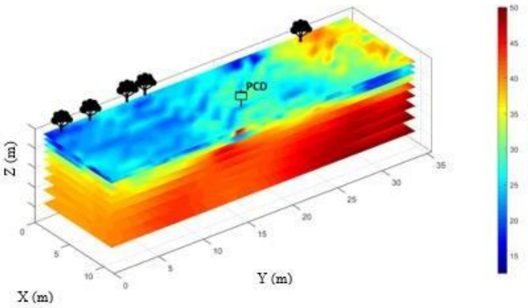


Figure 2. Graph of Correlation. PCD Moisture vs Moisture content obtained from electrical resistivity

Figure 3 shows the Moisture cube calculated from the electrical resistivity model. The 3D moisture model allows for observing predominant values between 15% and 30% up to a depth of 1 meter. Between a depth of 1 to 2 meters, resistivities between 30% and 35% prevail. From 2 meters to 8 meters, moistures between 35% and 50% predominate. The higher moisture content may be related to saprolitic soil horizons, where clay minerals are found following a relic rock structure.



. **Figure 3**. 3D Moisture model

4.3 Integration of Resistivity, Moisture, and Material Description

A sampling collected through the hand auger allowed the recognition of a typical alteration profile originating from crystalline rocks. Through tactile-visual analysis, it was observed that up to 1 meter, prevails more organic material and a more brownish color. From the first meter to the second, there is a reddish material with the presence of white clay minerals aligned according to the old rock structure. From the second to the third meter of depth, the same reddish clayey material is observed with a greater presence of white clay minerals (Figure 4). According to the classification by Chiossi (2013), the material corresponding to a depth of 1 meter can be classified as the Organic Soil Horizon. The material corresponding to a depth from 1 to 3 meters can be understood as a Saprolitic Soil Horizon.

Figure 5 displays the studied soil profile, moisture content obtained by the Data Collection Platform (PCD), moisture calculated by the resistivity model, and resistivity values. Through the resistivity and moisture models, at that depth some values were identified at the PCD location for information analysis.

The organic soil, located up to the first meter, presents the highest resistivity values (830 and 750 Ohm.m). The moisture calculated by the resistivity model ranges from 24.9% to 25.2%, and the moisture obtained by the PCD ranges from 26% to 32.9%.

The saprolitic soil, located from the first meter to the second, has resistivity values between 600 and 620 Ohm.m. The moisture calculated by the resistivity model ranges from 30.5% to 37.3%, and the moisture obtained by the PCD ranges from 35% to 38.2%.

The saprolitic soil, located from the second meter to the third, has resistivity values between 480 and 500 Ohm.m. The moisture calculated by the resistivity model ranges from 39.2% to 40.0%, and the moisture obtained by the PCD ranges from 39.2% to 41.4%.

Figura 4. Alignment in clay minerals

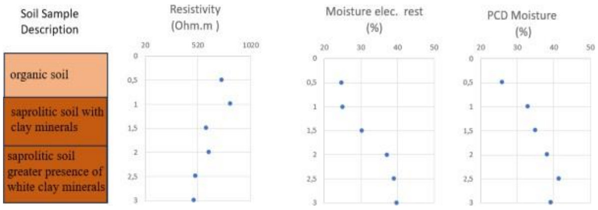


Figura 5. Comparison between soil profile, moisture content obtained by the PCD, moisture calculated by the resistivity model, and resistivity values

5. Conclusions

This study demonstrated the variation of electrical resistivity in a weathering profile of crystalline rocks. Through tactile-visual analysis, it was possible to identify an organic soil horizon (0 to 1 meter depth) and another saprolitic soil horizon (1 to 3 meters depth). The saprolitic soil exhibits white clay minerals aligned according to the relic rock structure. At a depth of 2 to 3 meters, a higher quantity of clay minerals is found. The presence of clay minerals along the weathering profile had a direct influence on the resistivity and moisture content. The organic soil layer presents the highest electrical resistivity values and the lowest PCD moisture content (26% to 32.9%). The saprolitic soil horizon (1 to 2 meters depth) exhibits resistivities of 600 and 620 Ohm.m and PCD moisture content ranging from 35% to 38.2%. The saprolitic soil horizon (2 to 3 meters depth) shows the lowest resistivity values between (480 and 500 Ohm.m) and the highest PCD moisture content ranging from 39.2% to 41.4%. Electrical resistivity proved to be an applicable method for recognizing weathering profiles of crystalline rocks, including the definition of distinct alteration horizons.

The moisture calculations from the electrical resistivity model converged with the values measured by the Data Collection Platform. This observation suggests that the methodology can be applied in studies that require information on moisture variation in a specific area.

Acknowledgements

The authors are grateful for the financial support provided by FACEPE (Fundação de Amparo a Ciência e Tecnologia de PE)

References

Abu-Hassanein, Z., Benson, C., Boltz, L. 1996. Electrical resistivity of compacted clays. J. Geotech. Eng. 122 (5), 397– 406.

Archie, G.E. 1942. The electrical resistivity log as an aid in determining some reservoir characteristics. Pet. Trans. AIME 146 (1), 54–62.

Borner, F., Gruhne, M., Schon, J. 1993. Contamination indications derived from electrical properties in the low frequency range. Geophys. Prospect.

Foti, S. 2013. In: Coutinho, Mayne (Eds.), Combined use of Geophysical Methods in Site Caracterization. Geotechnical and Geophysical Site Characterization, Vol 4. Taylor and Francis Group, pp. 43–61.

Gandolfo, O. C. B.; Gallas, J. D. F. 2007. O arranjo pólo- dipolo como alternativa ao dipolo-dipolo em levantamentos 2d de eletrorresistividade. Revista Brasileira de Geofísica, v. 25, n. 3, p. 227–235.

Gingine, V., Dias, A., Cardoso, R. 2016. Compaction control of clayey soils using electrical resistivity charts. Procedia Eng. 143C, 803–810.

Gunn, D.A., Chambers, J. E., Uhlemann, S., Wilkinson, P.B., Meldrum, P.I., Dijkstra, T.A., Haslam, E., Kirkham, M., Wragg, J., Holyoake, S., Hughes, P.N., Hen-Jones and R., Glendinning, S., 2014. Moisture monitoring in clay embankments using electrical resistivity tomography. Constr. Build. Mater. 92, 82–94

Holtz, R. D., Kovacs, W. D. 1981 An Introduction to Geotechnical Engineering. Prentice-Hall, Englewood Cliffs, NJ, US

Jardim de Sá, E. F. 1994. A Faixa Seridó (Província Borborema, Nordeste do Brasil) e o seu Significado Geodinâmica na Cadeia Brasiliano/pan Africana. brasília-df. Tese de Doutorado, n.3, Instituto de Geociências-Universidade de Brasília

Kearey, P., Brooks, M.; HILL, I. 2009. Geofísica de exploração. São Paulo: Oficina de Texto

Khalil, M.A., Santos, F.A.M., 2009. Influence of degree of saturation in the electric re sistivity-hydraulic conductivity relationship. Surv. Geophys. 30, 601–615

Kibria, G., Hossain, M. S. 2012. Investigation of geotechnical parameters affecting electrical resistivity of compacted clays. Journal of Geotechnical and Geoenvironmental Engineering 138(12): 1520–1529, http://dx.doi. org/10.1061/(ASCE)GT.1943-5606.0000722.

Kibria, G., Hossain, M. S. 2014. Effects of bentonite content on electrical resistivity of soils. In Geo-congress 2014 Technical Papers: Geocharacterization and Modeling for Sustainability (Abu-Farsakh M, Yu X and Hoyos LR (eds)). American Society of Civil Engineers, Reston, VA, USA, pp. 2404–2413.

Kibria, G., Hossain, M.S. 2016. Quantification of degree of saturation at shallow depths of earth slopes using resistivity imagining technique. J. Geotech. Geoenviron. Eng. 142 (7), 06016004.

Lima, O.A.L., Niwas, S. 2000. Estimation of hydraulic parameters of shaly sandstone aquifers from geoelectrical measurements. J. Hydrol. 235, 12–26.

Madrucci, V. 2000. Prospecção de água subterrânea em terreno cristalino utilizando-se análise integrada de dados de sensoriamento remoto, geofísicos e técnicas de geoprocessamento, região de Lindóia, São Paulo. 2000. 174 f. Tese (Doutorado) — USP, São Paulo.

McCarter, W.J., 1984. The electrical resistivity characteristics of compacted clays. Geotechnique 34 (2), 263–267.

Mitchell, J.K., Arulanandan, K. 1968. Electrical dispersion in relation to soil structure. Journal of Soil Mechanics and Foundation Division 94(2): 447–472.

Milson, J. 2003. Field geophysics: the geological field guide series. [S.l.]: Third edition. John Wiley & Sons.

Huntley, D., 1986. Relations between permeability and electrical resistivity in granular aquifers. Ground Water 24 (4), 466–474.

Revil, A., Darot, M., Pezard, P. A. 1996. From surface electrical properties to spontaneous potentials in porous media. Surveys in Geophysics 17(3): 331–346, https://doi.org/10.1007/ BF01904047.

Santos, F. M. 2005. Aplicação de métodos geofísicos no estudo da contaminação de águas subterrâneas no Lixão de Cuiabá - MT. 234 f. Dissertação (Mestrado em Física e Meio Ambiente) — Universidade Federal de Mato Grosso, Cuiabá - MT. 2005.

Waxman, M.H., Smits, L.J.M., 1968. Electrical conductivities in oil-bearing shaly sands. Soc. Pet. Eng. J. 107– 12

Wildenschild, D., Roberts, J.J., Carlberg, E.D., 2000. On the relationship between microstructure and electrical and hydraulic properties of sand-clay mixtures. Geophys. Res. Lett. 27 (19), 3085–3088.

Zhang, D., Cao, Z., Fan, L., Liu, S., Liu, W., 2014. Evaluation of the influence of salt concentration on cement stabilized clay by electrical resistivity measurement method. Eng. Geol. 170, 80–88