Obtaining geotechnical parameters from correlations between geophysics and CPT tests in tailings dams

http://dx.doi.org/10.1590/0370-44672019730114

Gustavo Marçal Sousa[1,2]
https://orcid.org/0000-0002-0423-1442
Romero César Gomes[1,3]
https://orcid.org/0000-0002-2841-9597

[1]Universidade Federal de Ouro Preto - UFOP,
Escola de Minas, Departamento de Engenharia
Urbana, Núcleo de Geotecnia - NUGEO,
Ouro Preto - Minas Gerais - Brasil.

E-mails: [2]gustavo.marcal.eng@gmail.com,
[3]romero@ufop.edu.br

Abstract

This article introduces a hassle-free methodology for geotechnical parameters to be obtained from correlations between geophysics and CPT field tests in tailings dams undergoing the decommissioning process, which are reasonably representative of site conditions, from the very early project stages, with extensive coverage of all impoundment parts, without the requirement for large-size drilling programs. The development methodology consists of running direct (CPT) and indirect (geophysics) tests within the same area of the tailings dam to be decommissioned, with information crosschecking, thus allowing for results to be presented as adjustment equations, capable of describing tailings undrained shear strength based on geophysical survey data. A dam within the region known as Iron Quadrangle, in the state of Minas Gerais, Brazil, was selected to pilot the tests. The results obtained showed consistent adjustments, thus validating the proposed methodology as a complementary geotechnical investigation tool, and also enabling an optimized investigation plan to be proposed for similar tailings dams undergoing a mining process, so as to provide better assessment of the safety conditions of the proposals for deactivation with reduced schedule and resource savings.

Keywords: tailings dams; geophysics survey; penetration test; electrical resistivity correlation.

1. Introduction

Obtaining geotechnical parameters to develop stability analyses in tailings dams undergoing a deactivation process has evolved towards the deployment of site tests with direct strength measurement, whereby the Cone Penetration Test (CPT) stands out due to the array of existing correlations between cone penetration strength and undrained shear strength of saturated tailings, with references in literature including recent articles published by Olson and Stark (2003), Robertson (2010), and Jefferies and Been (2015).

Although the CPT performance methodology is simple and quick, and the interpretation of results is directly obtained by its own driving equipment software, when we talk about tailings dam deactivation projects, it is almost impossible to use driving spots to cover the whole impoundment area, either due to high costs associated with the large number of tests, or due to the impracticability of moving equipment over the impoundment that most of the times is partially filled with water or low-consistency slime and as such does not allow for equipment traffic and support. Therefore, test performance is rendered impossible in crucial spots set up by the investigative plan.

Specifically speaking, dam decommissioning projects require knowledge of the geotechnical behavior of tailings at all points of the reservoir where the tailings mass is to be excavated and removed due to the variability created by the hydraulic segregation process, which is quite usual in tailings storage facilities. Nevertheless, the risk of bogging due to the weight of the equipment in areas off the tailings beach restrict investigations to areas where driving equipment may safely operate, information collection being usually restricted to tailings beaches. Information collected from such locations is then randomly extrapolated to the remaining portions of the dam, which brings about great uncertainty whenever the necessary actions for deactivation and stability analysis are carried out.

Considering the constraints described herein for performing CPT direct investigation programs and the challenge to carry out consistent geotechnical investigations for deactivation/decommissioning projects involving over 80 tailings dams in Brazil, this article proposes complementary direct investigation programs with geophysical methods, specifically geoelectric imaging by means of Electrical Resistivity (ER) profiles. The combined use of direct and indirect investigation techniques allows for large reservoir areas to be covered for geophysical layouts that are manually arranged making walking possible within areas where CPT driving equipment would hardly have access to.

Geophysical methods are non-invasive, non-destructive, relatively rapid and cost effective. Therefore, they are more and more frequently used as a supplementary survey tool for sub-surface soil investigation, and also as a control survey during an object implementation and exploitation stage (Michaels, 1995; Sudha *et al.*, 2009; Martínez and Mendoza, 2011). Electrical Resistivity measurements provide a potentially powerful tool to estimate physical parameters of soils and materials used in earthworks and construction works, such as embankments and dams (Kowalczyk *et al.*, 2014). A site investigation using SPT tests was carried out in China to evaluate the influence of basic geotechnical properties on the electrical resistivity of marine clay, as per for Zhang *et al* (2018).

Using geophysical tests in studies related to tailings dams is a reality and their application has been widely spread over the last years as an auxiliary geotechnical investigation tool. Jamiolkowski (2012) highlights the role of geophysical methods for the geotechnical characterization of tailings dams, with an emphasis on the field and laboratory assessment of parameters describing soil conditions and its rigidity. The author draws attention to cross (S) and longitudinal (P) seismic waves and he compares the results obtained from downhole and crosshole seismic geophysical tests to seismic cone tests (S-CPT), showing correlations for the rigidity, saturation, porosity, void ratio and susceptibility to cyclic liquefaction modulus. Likewise, Shahrabi, *et al.* (2016) introduce a comparative study for liquefaction to be assessed based on SPT (Standard Penetration Test) and geophysical (downhole and crosshole seismic methods) tests, where the authors set forth relationships between the cyclic shear strength obtained from SPT and geophysical tests at the Mahabad tailings dam (located in Northwestern Iran) embankment and foundation. The cyclic shear strength values obtained using the geophysical method are slightly higher than the ones obtained from the SPT test.

Usually, using the geophysical method by applying the Electrical Resistivity technique to dams is restricted to foundation portions, where major subsurface characteristics can be identied that may affect stability, as presented by Zarroca *et al.* (2015) in regards to a tailings dam to be built in Ecuador. Given the progress of the Electrical Resistivity method, it is possible to collect robust sets of geophysical data covering long stretches and depths at reasonable costs. Such data may also be used for other purposes, e.g. tailings dam monitoring, as per Mainali (2006), to detect piping and anomalous seepage at an early stages through electric methods. Electrical Resistivity and spontaneous potential geophysical methods have already been successfully used towards that end.

Obtaining geotechnical parameters from correlations between geophysics and direct investigation methods, especially regarding downhole and crosshole seismic methods, has been widely spread in geotechnical engineering, with applications in dams as presented by Jamiolkowski (2012) and Shahrabi *et al.* (2016). Nonetheless, unlike existing papers, which are not specific for iron ore, the methodology introduced herein intends to set forth correlations using geoelectrical imaging through Electrical Resistivity profiles in a regional approach for iron ore tailings from a direct comparison to CPT test results and replicable to dams whose tailings bear similar density, porosity and saturation characteristics.

The development to be presented below has been carried out on actual site scale in a tailings dam selected as "pilot" and having very similar characteristics to most iron ore tailings dams in the Iron Quadrangle area in the state of Minas Gerais. Direct and indirect investigation programs were carried out specifically on specific comparison purposes for results to be used in the future for the pilot dam decommissioning project, which plans for tailings to be mined pursuant to the method proposed by Sousa and Gomes (2018).

2. Methods

Due to the difficulty of obtaining deep undisturbed samples for laboratory tests on tailings, in addition to the impossibility of accessing low-consistency saturated portions using direct drilling equipment, the proposal herein is to obtain geotechnical parameters for stability analyses from correlations between geophysics and CPT tests in tailings dams. The method consists in running both Electrical Resistivity (ER) and CPT tests within the same area of the "pilot" dam. The results were later assessed and associated, and the correlations obtained were used to define strength parameters for stability analyses in preliminary design stages, specifically during technical feasibility study stages concerning the decommissioning methodology defined for the embankment. The test arrangement, created for the Pilot Dam reservoir surface (Figure 1), on the tailings beach, mixes geophysical survey layers (TRVGA) by using the Electrical Resistivity technique and driving points for CPT tests (F).

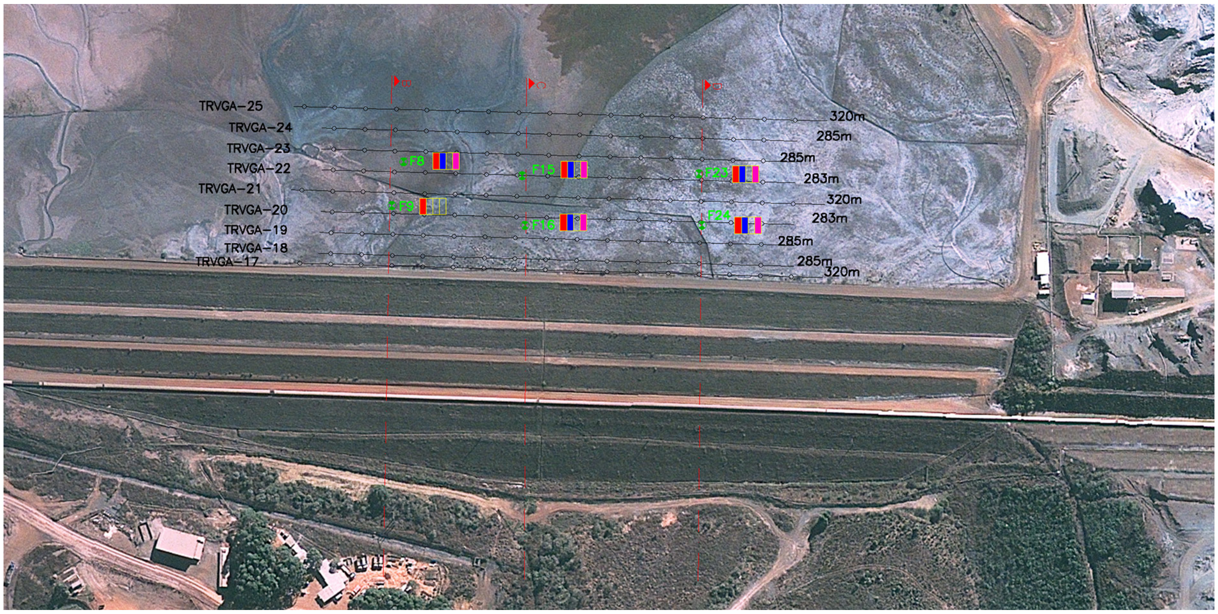

Figure 1 - Arrangement plan used to obtain Electrical Resistivity profiles through electrical routing (TRVGA) on the tailings beach along with CPT test location (F).

The proposed methodology includes using the averages obtained from two lengthwise sections (TRVGA_20 and TRVGA_22) for Electrical Resistivity geophysics (Ohm x m) and undrained shear strength (KPa) based on CPTu tests, with linear interpolation of average results according to the reservoir depth, as per the sequence under items 2.1 and 2.2. The geotechnical characteristics of the tailings within the test area varied as shown on Table 1 and characteristic ranges restrain the results.

Table 1 - Geotechnical characteristics of the tailings deposit.

Reference	Variance
Bulk specific weight (g/cm^3)	2.03 – 2.89
In situ moisture (%)	9.15 – 26.75
Grain density (g/cm^3)	4.30 – 4.55
Permeability (cm/s)	8.38E-06 – 2.08E-05
Void ratio	0.65 – 1.24

2.1 Electrical resistivity (ER)

Pacheco (2004) describes electrical resistivity as an inherent characteristic of materials. Its value in soil is affected by its three-phase composition of solids, liquid and air. Thus, it is possible to set forth different Electrical Resistivity profile standards for different material deposits, including tailings.

The geophysics profile arrangements have been defined for the Electrical Resistivity (ER) through the Electrical Routing (on-site data collection) method to be used. Arrangements are usually positioned in parallel to the dam axis, on the tailings beach. The Electrical Resistivity (ER) method as per Telford *et al.* (1990) is based on the electrical potential study, both of natural electrical fields, associated with the geological substrate, and of artificially formed fields. Thus, by measuring the electrical potential on the surface, ore bodies can be identified, and geological structures can be recognized underground. The Electrical Routing (CE) field survey technique was used to assess the Electrical Resistivity. This enables studying the side variation of the Electrical Resistivity physical parameter at several depth levels, obtaining horizontal and vertical subsurface material characterization as per Gallas (2000). The Dipole-Dipole Data collection arrangement was used following *in situ* tests with 4-meter spacing between electrodes and eight (8) 280-meter long investigation sections.

High Resistivity zones and horizons (HRZ) and low Resistivity zones and horizons were defined by means of Electrical Resistivity, as shown in Figure 2. Within the reservoir area, HRZs appear quite below and off the saturated clay and ferrous material that characterize the tailings. Within these areas, they would represent the natural lithological substrate of the deposit, probably consisting of cohesive or dense phyllites. Between those materials is the medium resistivity zone, possibly with most of it associated to residual soils of such phyllites. LRZs would set the boundaries to higher moisture zones or to water seepage locations, predominantly associated to pelitical lithotypes (clay and silt fills), in addition to clay tailings strata and saturated sandy and granular materials.

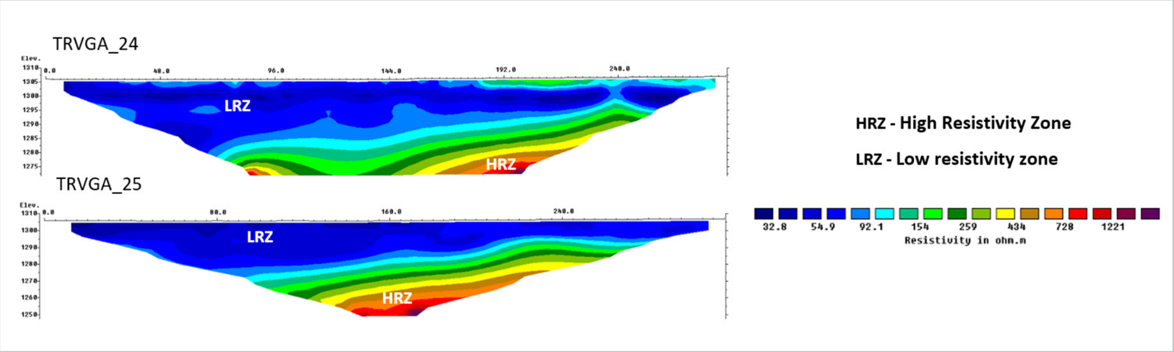

Figure 2 - Example of sections obtained from ER surveys within the Pilot Dam tailings reservoir area.

Electrical Resistivity values ranging from 32 Ohm x m to 154 Ohm x m on Figure 2 comprise extracts of tailings disposed in the pilot dam reservoir. They were confirmed based on primary surveys. The low Electrical Resistivity values in this case may be attributed to granular, saturated and soft tailings, and also the resistivity three-phase solid, liquid and air conditioning factor varies according to depth; a characteristic that is usually noticed during the execution of driving tests for iron ore tailings disposed in dams.

In addition to defining the stratigraphy between matters or physical characteristic changes to materials of the same type, this method has allowed for potential water seepage points to be pointed at in the dam structure, which are associated to the proximity between rather contrasting electrical Resistivity zones.

2.2 Cone penetration test (CPT)

Cone penetration tests with pore pressure measurement are used for stratigraphic determination of soil profiles and prospected material properties, especially in unconsolidated deposits. The test provides tip strength, side friction and pore pressure data. As reference to perform CPT (Cone Penetration Test), CPTu (Piezocone Penetration Test) and pore pressure dissipation tests, procedures described in NBR 12069 – Ensaio de penetração de cone in situ (CPT) (ABNT, 1991) and ASTM D5778 – Standard test method for performing electronic friction cone and piezocone testing of soils (ASTM, 2012) have been used.

The CPT test consists of statically driving a rod into the soil (penetrometer), which has a cone-shaped tip (vertex angle of 60°) on its lower end and cross area of 10 cm². A static cone piece of equipment with a 200 kN reaction capacity, model TG 73-200 manufactured by Pagani Geotechnical Equipment was used (Figure 3). The penetrometer hydraulic system is driven by a diesel fuel engine, the reaction being achieved by helical anchorage. For pore pressure measurements, all routine saturation maintenance procedures were complied with. Driving velocity was maintained constant at approximately 2 cm/s.

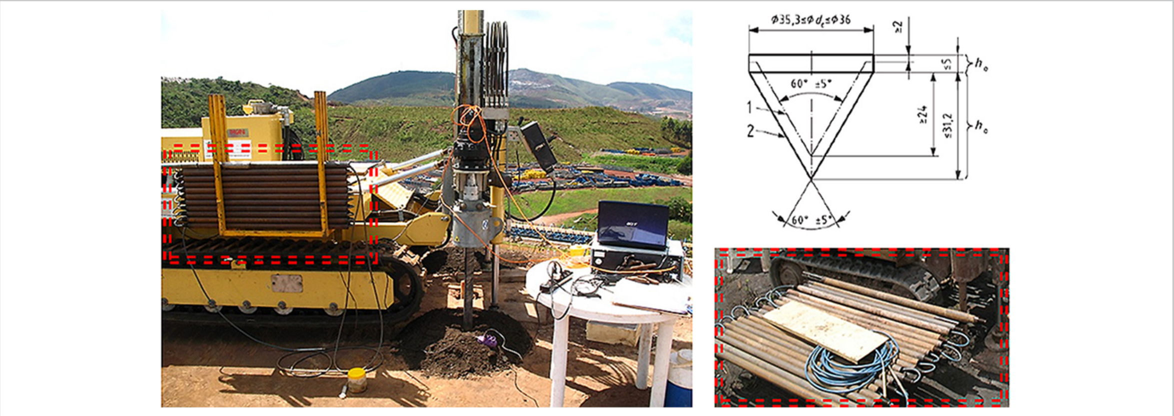

Figure 3 - Detail of penetrometer and TG 73-200 driving equipment during CPT tests at Vargem Grande Dam (dimensions in mm), selected as "pilot".

As rods are driven into the soil, the following components are automatically acquired at every 2 cm progress: Tip strength (q_c); Side or local friction strength (f_s), measured in a sleeve with side area of 150 cm² (h_s); Pore pressure, by using a porous element located at the cone base (position u_2). Maximum depths reached during drilling are shown in Table 2.

Table 2 - CPT Test Data.

CPTu Borehole	Expected depth (m)	Actual depth (m)	Tested stretch (m)	Water level depth
F8	20.00	20.5	16.57	3.90
F9	20.00	20.92	9.41	11.50
F15	15.45	20.89	16.4	4.40
F16	10.45	20.46	17.41	3.00
F24	10.00	10.10	7.53	2.50

CPT test results are jointly shown on the graphs on Figure 4, which indicate variation with depth, q_t and u_2 respectively as follows:

✓Total corrected tip strength (q_t), due to pore pressure effect given by $q_t = q_c + (1-a_n)\ u_2$, with $a_n = 0.75$ (value obtained by calibration);

✓Pore pressure (u_2).

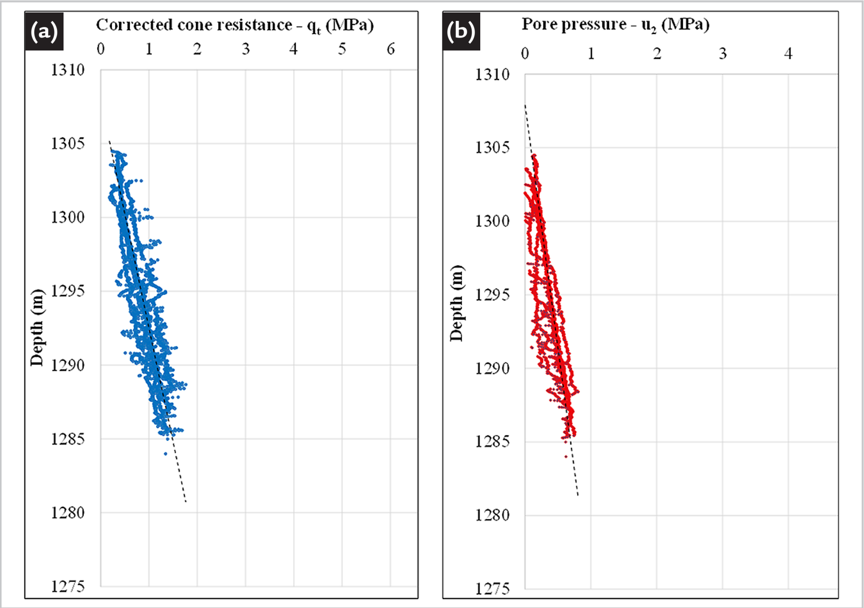

Figure 4 - Variation of CPT test results with reservoir depth (F8, F9, F15, F16 and F24): (a) corrected tip strength - q_t and (b) pore pressure measured obtained during cone driving – u_2.

Through linear adjustment, corrected tip strength (q_t) and pore pressure measured during cone driving (u_2) can be observed to vary respectively as shown by Equations 1 and 2.

$$q_t = 84.480 - 0.0646 \times depth\ (MPa) \qquad (1)$$

$$u_2 = 39.495 - 0.0302 \times depth\ (MPa) \qquad (2)$$

Fear and Robertson (1995), when proposing a methodology to estimate undrained shear strength for sands based on SPT and CPT tests, highlighted the need to know such parameter in stability analyses under an undrained loading condition, with an emphasis on the difficulty to decide which S_u value would better represent particular conditions of each case on site, especially after liquefaction is triggered, for saturated and "soft" sands.

Thus, a thoughtful parametric analysis is essential for geotechnical safety assessment of dam mining, whose disposed tailings almost always bear undrained behavior characteristics when subject to shear stresses, which is the case of the Pilot Dam.

Undrained peak and liquefied strength can be approached based on CPT tests, which herein has been respectively based on the formulations proposed by Olson and Stark (2002) and Olson and Stark (2003), as per Equations 3 and 4, valid for sandy granular soils, as it is the case of the pilot dam.

$$\frac{S_u(PIC)}{\sigma'_{v0}} = 0.205 + 0.143\ (q_{c1}) \mp 0.04\ for\ q_{c1} \leq 6.5\ \text{Mpa} \qquad (3)$$

$$\frac{S_u(LIQ)}{\sigma'_{v0}} = 0.03 + 0.143\ (q_{c1}) \mp 0.03\ for\ q_{c1} \leq 6.5\ \text{Mpa} \qquad (4)$$

Where q_{c1} stands for normalized tip strength for an effective vertical stress of 100 kPa. Thus, undrained peak strength $((S_u(PIC))/\sigma'_{v0})$ and liquefied $((S_u(LIQ))/\sigma'_{v0})$ ratios, obtained based on Equations 3 and 4, have been plotted as shown in Figure 5.

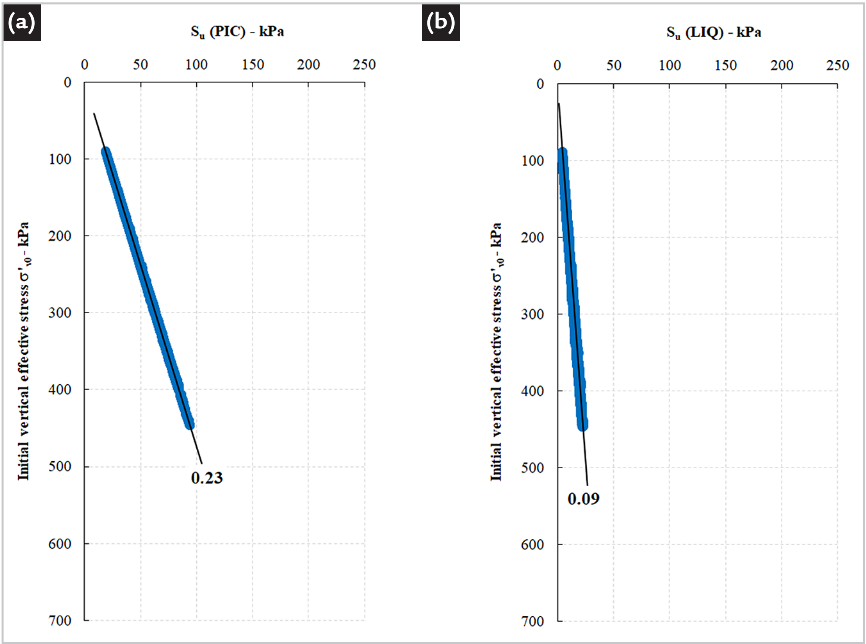

Figure 5 - Undrained shear strength ratios obtained based on CPT tests (CPTu-F8, CPTu-9, CPTu-F15, CPTu-F16 and CPTu-F24): (a) peak strength; (b) liquefied strength.

Relationships between undrained shear strength (S_u) and initial vertical stress (σ'_{v0}) shown in Figure 5 are only valid for conditions in which the material is normally consolidated, considering $\sigma'_{v0} = \sigma'_{1c} \approx \sigma' \approx \sigma'_p$. For, as highlighted by Terzaghi *et al.* (1996), the S_u/σ'_p ratio represents a constant for FVT (Field Vane Test) field tests and triaxial lab tests with CT (Compression Test), ET (Extension Test), DSS (Direct Simple Shear) shearing modes, regardless of the σ'_p/σ'_{v0} ratio, with S_u/σ'_p ratio being potentially used for S_u estimation. As for deposits where $\sigma'_p/\sigma'_{v0} > 1$, S_u/σ'_{v0} ratio has no physical representation, this is not a usual engineering parameter.

3. Results and discussion

3.1 Relationship between Electrical Resistivity and undrained shear strength

Electrical Resistivity measured from the Pilot Dam reservoir surface (Figure 1) suggests a gradual increase throughout the tailings deposit that is also seen in foundation substrates (Figure 6). In these sections, tailings strata depth variations range from 10 to 30 m, from right to left, with contact between tailings and foundation soil being defined by Resistivity values higher than 154 Ohm x m.

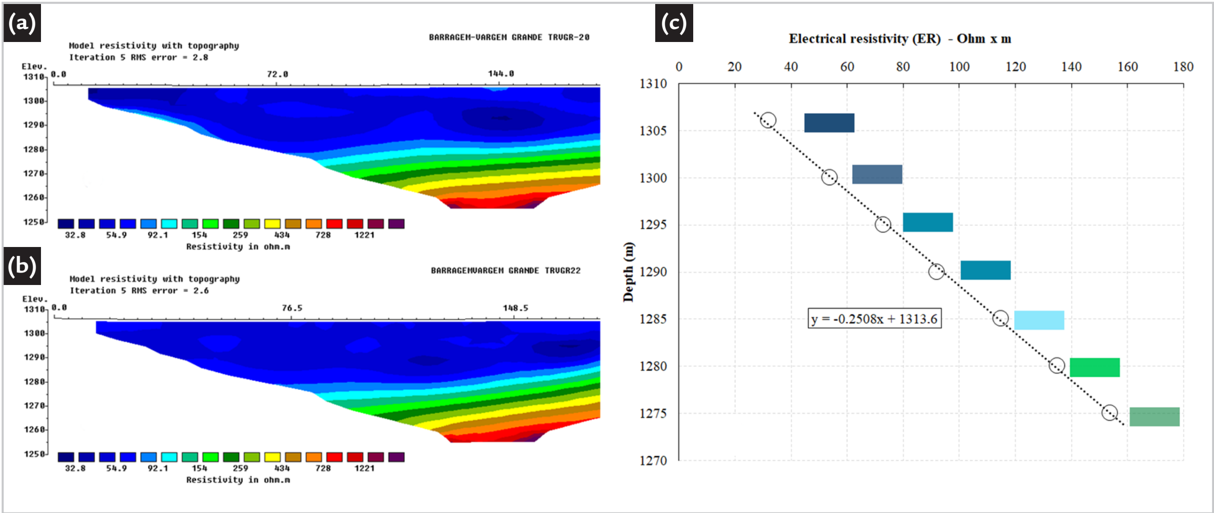

Figure 6 - Lengthwise profiles showing gradual Resistivity increases associated to depth: (a) TRVGR 20 coinciding with boreholes F09, F16 and F24; (b) TRVGR 22 coinciding with boreholes F08, F15 and F23, according to Figure 1; (c) weighted average for Electrical Resistivity measured in sections TRVGR 20 and TRVGR 25.

Low penetration strength and pore pressures seen in cone tests plotted on Figure 4 and used to obtain the undrained shear strength ratios shown on Figure 5 are characteristic of saturated soft tailings, which has also conditioned the low Electrical Resistivity values (Figure 6). Both tailings characteristics had their values linearly increased with depth and, as for the specific tailings deposits, such increases may be associated to the initial effective stress σ'_{v0} at any given point.

Based on such observations and being aware of the potential association between Electrical Resistivity and geological structures due to the chemical, physical and saturation characteristics, association of that electrical property to undrained shear strength of saturated and non-compacted iron ore tailings is proposed as shown in Figure 7, where initial effective stresses σ'_{v0} were calculated according to depth and specific weight of tailings, and values vertically associated to the linear adjustment that represents the weighted average for the Electrical Resistivity measured in sections TRVGR 20 and TRVGR 22, as shown on Figure 6 (c). Subsequently, peak and liquefied undrained shear strength ratios were graphically associated to σ'_{v0} = ER (Electrical Resistivity) on Figure 7.

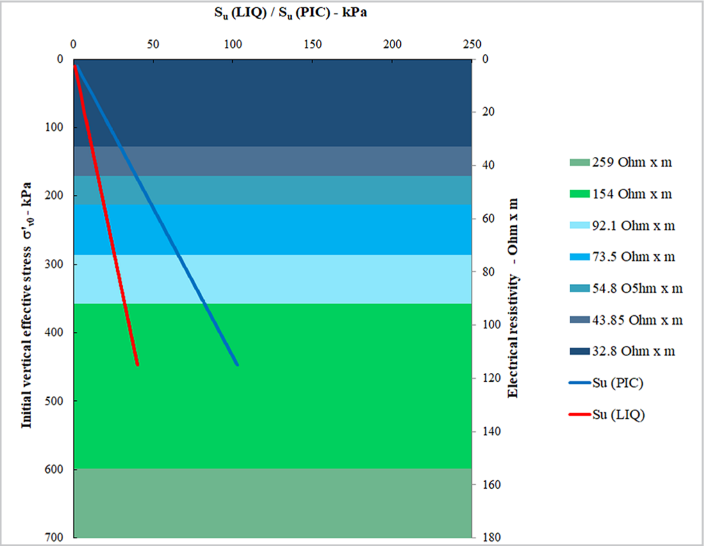

Figure 7 - Association of peak and liquefied undrained shear strengths to Electrical Resistivity, according to the Pilot Dam reservoir depth.

Based on such proposition, peak and liquefied undrained shear strengths have been plotted according to the average Electrical Resistivity in sections TRVGR-20 and 25 (Figure 1), as shown in Figure 8. Undrained shear strength values were calculated according to the adjustments in Figure 8, valid for predominantly saturated and soft tailings, with physical characteristics within the variation ranges defined in Table 1.

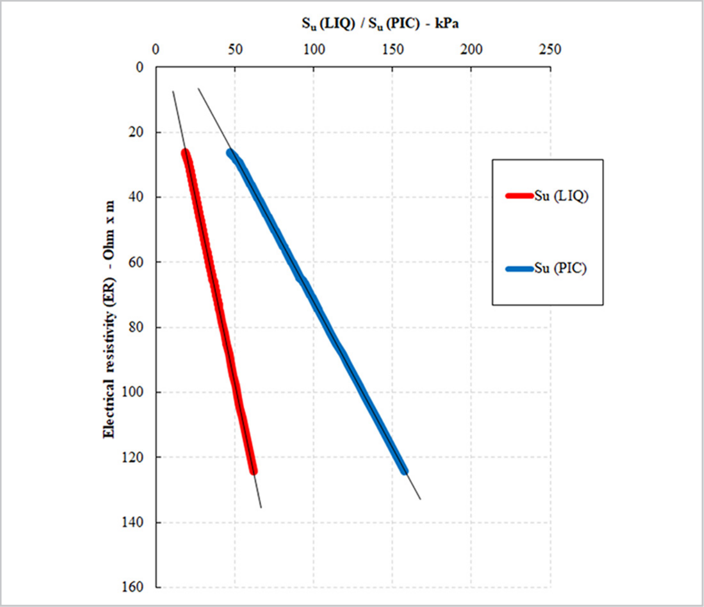

Figure 8 - Estimation of peak and liquefied undrained shear strengths according to Electrical Resistivity (ER): $S_u(PIC) = 1.11(ER) + 19.62$; $S_u(LIQ) = 0.44(ER) + 7.68$, with Electrical Resistivity being obtained using the electrical routing technique.

Such association might be used to obtain preliminary parameters during conceptual and basic design for dam mining, thus allowing for most of the dam reservoirs to be mapped out in order to access and assemble electric routing lines, which would probably be inaccessible for direct drilling equipment. Results must be validated later on using direct drilling at key points upon completion of basic and detailed design with a relevant potential for direct drilling grid decrease.

3.2 Optimized investigation plan – similar dams

Based on the results and experiences obtained during the execution of the geological-geotechnical investigation plan for the Pilot Dam, the drilling results of SPT (Standard Penetration Test) performed at the Pilot Dam stand out because in most of the boreholes drilled, the slide hammer went down due to its own weight. This rendered it impossible to discretize variable strength layers in the reservoir from such information. Such assessment could only be performed as of information obtained from CPT tests run within the tailings beach area, as well as from indirect investigation data (geophysics). Another relevant point is that it is difficult to collect undisturbed deep samples given material consistency, which seldom allows for representative samples to be recovered in depths over 10 m.

Having said this, an optimized preliminary investigation plan is proposed to generate data for the development of conceptual and basic designs for tailings dam mining, which should be complemented in case the information generated is not enough for detailed design development. Such proposition consists of CPT test programs and disturbed and undisturbed sample collection from the tailings beach through percussion drilling (SPT), and also, indirect investigation through the Electrical Resistivity using the Electrical Routing (ER) technique, as shown on Figure 9. From the definition of the section best representing the whole reservoir extension, four investigation standards would be applied due to their location along the dam extension:

⊗ **Standard 1:** Investigation points located within the central area towards reservoir bottom, 150 m one from another and depth corresponding to the tailings layer thickness. Performance of SPT (every meter) and CPT (continuous quick driving) tests; ⊗ **Standard 2:** Investigation points located on the tailings beach, 50 m one from another and depth corresponding to the tailings layer thickness. Performance of SPT (every meter) and CPT (continuous quick driving) tests and porepressure dissipation every 5 m; ⊗ **Standard 3:** Investigation points located on raise dikes and depth corresponding to the tailings layer thickness under the dike. Performance of SPT (every meter) and CPT (continuous quick driving) tests and porepressure dissipation every 5 m; - - - **Standard 4:** Electrode line coinciding with direct investigation points (standards 1 and 2), lengthwise to the embankment and extension twice as long as the tailings layer thickness at the investigation point.

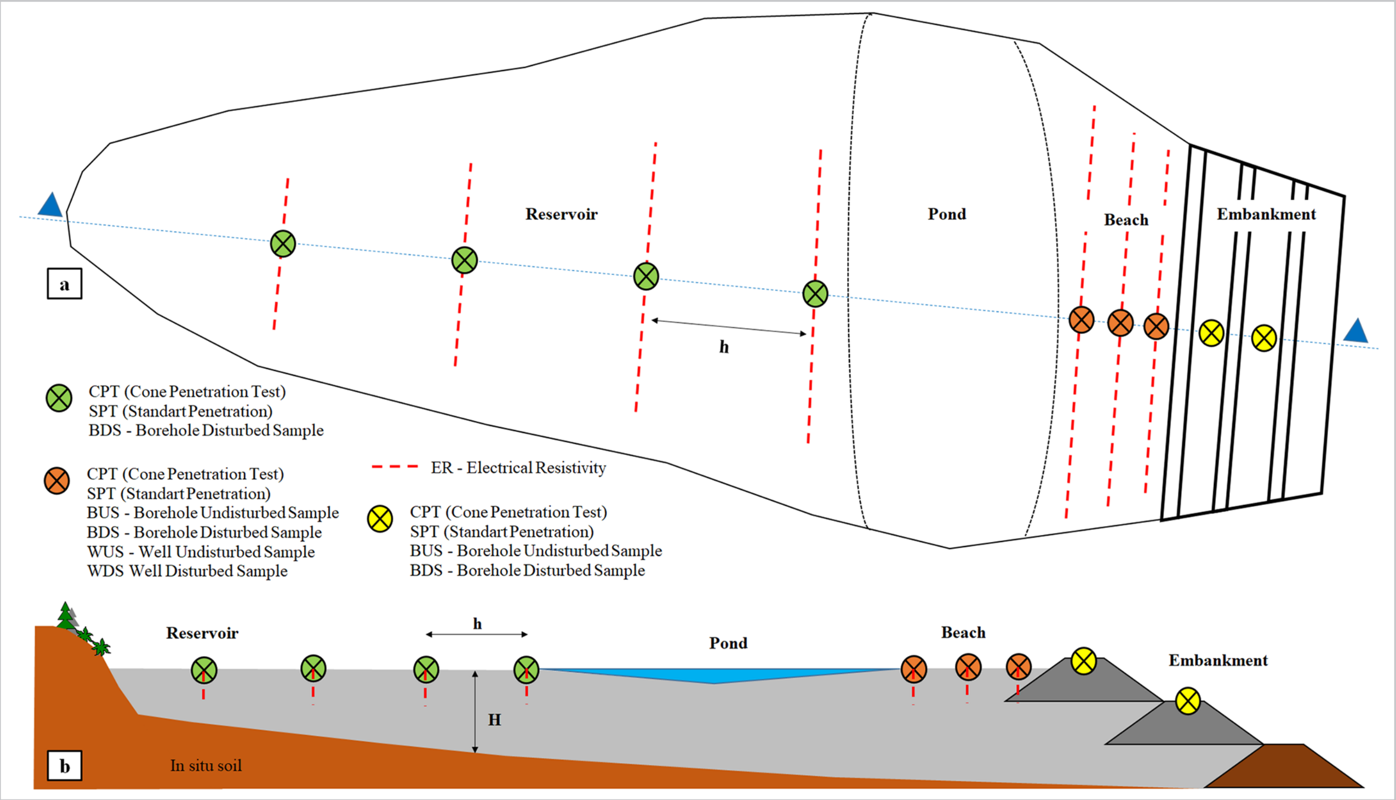

Figure 9 - Layout proposed for optimized investigation plan: (a) plan view; (b) section.

Optimized investigation plan execution as described herein can generate enough information to validate hypotheses and apply mining methodologies, techniques and interventions aiming at decommissioning. Electric routing Electrical Resistivity geophysics would be the major strength parameter generating source for stability analyses, with application of equations and adjustments described under item 3.1, whose methodology represents the very essence of this research.

4. Conclusions

The methodology presented has allowed for an appropriate interpretation of the strength characteristics of the tailings disposed in the Pilot Dam reservoir. This is achieved by obtaining the undrained shear strength parameter (S_u) resulting from the consistency of investigation programs. As such, hypotheses could be formulated and field database treatment methodologies could be applied, fostering a significant progress in terms of investigative methodology for decommissioning projects.

Indirect Electrical Resistivity (ER) investigation using the electric routing technique has shown a direct linear relationship when compared to the tailings undrained shear strength estimated from CPT tests. ER and CPT tests were combined to estimate undrained shear strength parameters, which stands for a quick and relatively inexpensive investigation alternative for direct investigation programs to be held on the spot during later stages.

The optimized investigation plan proposed can generate enough elements to comply with design criteria. This allows for a conceptual and basic design to be developed and used as a basis for decision making associated with the technical and economic feasibility of decommissioning actions. It can be used with complementary efforts, if required, during the detailed design phase.

Geotechnical parameters obtained from correlations for CPT tests for the Pilot Dam showed to be consistent when compared to results in literature, which evidenced the importance of that test as a tool for the development of projects during preliminary stages and allowing for the extraction of almost all the necessary parameters to evaluate and guarantee the geotechnical stability of a dam mining project.

Acknowledgments

The authors would specially like to thank Vale S.A for its financial support to the project and for allowing the use and dissemination of test results, as well as the Federal University of Ouro Preto – UFOP, represented by NUGEO, for its partnership in technological development focused on sustainable mining.

References

AMERICAN SOCIETY FOR TESTING AND MATERIALS. ***ASTM D5778:*** Standard test method for performing electronic friction cone and piezocone testing of soils. [*S. l.*]: ASTM, 2012.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. ***NBR 12069*** – Ensaio de penetração de cone in situ (CPT): Método de ensaio. Rio de Janeiro: ABNT, 1991.

FEAR, C. E.; ROBERTSON, P. K. Estimating the undrained shear strength of sand: a theoretical framework. ***Canadian Geotechnical Journal,*** v. 32, n. 5, p. 859-870, 1995.

GALLAS, J. D. F. ***Principais métodos geoelétricos e suas aplicações em prospecção mineral, hidrogeologia, geologia de engenharia e geologia ambiental.*** 2000. 174f. Tese (Doutorado em Geociências) – Instituto de Geociências e Ciências Exatas, Universidade Estadual Paulista, Rio Claro, 2000.

JAMIOLKOWSKI, M. Role of geophysical testing in geotechnical site characterization. ***Soils and Rocks,*** v. 35, n. 2, p. 117-137, 2012.

JEFFERIES, M.; BEEN, K. ***Soil liquefaction:*** a critical state approach. CRC press, 2015.

KOWALCZYK, S.; MAŚLAKOWSKI, M.; TUCHOLKA, P. Determination of the correlation between the electrical resistivity of non-cohesive soils and the degree of compaction. ***Journal of Applied Geophysics,*** v. 110, p. 43-50, 2014.

MAINALI, G. ***Monitoring of tailings dams with geophysical methods.*** 2006. 74 f. Thesis (Licentiate) - Department of Chemical Engineering and Geosciences, Luleå University of Technology, Luleå, Sweden, 2006.

MICHAELS, P. A geophysical site investigation for a bridge foundation in a narrow canyon. ***Environmental & Engineering Geoscience,*** v. 1, n. 2, p. 219-226, 1995.

OLSON, S. M.; STARK, T. D. Liquefied strength ratio from liquefaction flow failure case histories. ***Canadian Geotechnical Journal,*** v. 39, n. 3, p. 629-647, 2002.

OLSON, S. M.; STARK, T. D. Yield strength ratio and liquefaction analysis of slopes and embankments. ***Journal of Geotechnical and Geoenvironmental Engineering,*** v. 129, n. 8, 2003.

PACHECO, A. O. ***Ensaios com cone resistivo em solos saturados.*** 2004. 150 f. Dissertação (Mestrado em Engenharia Civil) - COPPE/UFRJ, Rio de Janeiro, RJ, 2004.

ROBERTSON, P. K. Evaluation of flow liquefaction and liquefied strength using the cone penetration test. ***Journal of Geotechnical and Geoenvironmental Engineering,*** v. 136, n. 6, p. 842-853, 2010.

SHAHRABI, M. M.; JAFARZADEH, F.; GARAKANI, A. A.; ESKANDARI, N.; BANIKHEIR, M.; JAHROMI, H. F. Comparison of liquefaction evaluation based on SPT and geophysical tests (case study: Mahabad dam, Iran). *In:* INTERNATIONAL CONFERENCE GEOTECHNICAL AND GEOPHYSICAL SITE CHARACTERISATION, 5., 2016, Queensland, Australia. ***Proceedings*** [...]. Queensland, Australia: ISC'5, 2016. p. 657-662.

SOUSA, G. M.; GOMES, R. S. Lavra de barragens de rejeito: uma alternativa para manejo e desativação de estruturas. In: CONGRESSO BRASILEIRO DE MECÂNICA DOS SOLOS E ENGENHARIA GEOTÉCNICA, 19., 2018, Salvador, Brasil. ***Anais*** **[...].** Salvador: Cobramseg, 2018.

SUDHA, K. *et al.* Soil characterization using electrical resistivity tomography and geotechnical investigations. ***Journal of Applied Geophysics,*** v. 67, n. 1, p. 74-79, 2009.

TELFORD, W. M.; GELDART, L P.; SHERIFF, R. E. ***Applied geophysics.*** 2. ed. Cambridge: Cambridge university press, 1990. 770 p.

TERZAGHI, K.; PECK, R. B.; MESRI, G. ***Soil mechanics in engineering practice.*** 3.ed. New York: John Wiley & Sons, 1996. 549 p.

ZARROCA, M.; LINARES, R.; VELÁSQUEZ-LÓPEZ, P. C.; ROQUÉ, C.; RODRÍGUEZ, R. Application of electrical Resistivity imaging (ERI) to a tailings dam project for artisanal and small-scale gold mining in Zaruma-Portovelo, Ecuador. ***Journal of Applied Geophysics,*** v. 113, p. 103-113, Feb. 2015.

ZHANG, T.; LIU, S.; CAI, G. Correlations between electrical Resistivity and basic engineering property parameters for marine clays in Jiangsu, China. ***Journal of Applied Geophysics,*** v. 159, p. 640-648, 2018.

Received: 13 August 2019 - Accepted: 30 May 2020.