Characterization of gold mine tailings variability and its influence in the study of drainage conditions in the CPTu test

Letícia Perini[1], Natália Ziesmann[1], Gracieli Dienstmann[1]

[1]Dept. of Civil Engineering, Federal University of Santa Catarina
Rua João Pio Duarte da Silva, 205, 88040-900, Santa Catarina/Florianópolis, Brazil
leticia.perini@hotmail.com; nziesmann@gmail.com; g.dienstmann@ufsc.br

Abstract. The effect of drainage conditions on piezocone test (CPTu) measurements is a critical factor in the assessment of mine tailings properties, as the material is in the intermediate permeability range. Studies of drainage conditions have been carried out by identifying a characteristic drainage curve. However, accurately identifying the range of drainage variation is a challenge due to high variability of the material. In this sense, this paper provides tools to assist the understanding of the effects of data dispersion over the definition of a drainage characteristic curve. A reference analysis is presented herein in where a characteristic profile of a CPTu test in gold tailings is used to quantify the statistics and its application. A numerical analysis of cavity expansion is used to obtain theoretical drainage curves. The variability characterized was applied to the numerical simulations, using the Monte Carlo method, to define in a rational way the range of possible theoretical drainage curves.

Keywords: cavity expansion, finite element, Monte Carlo.

Introduction

The piezocone test (CPTu) is a widely used in situ test that provides continuous measurements with depth of tip resistance (q_c), lateral friction (f_s) and excess pore pressure (u_2). This set of direct readings can be used to derive mechanical properties of strength, such as friction angle (ϕ) or undrained shear resistance (Su); stress history and elastic modulus as Young Modulus (E) or Shear Modulus (G).

Theoretical solution for obtaining geomechanical properties from CPTu are generally associated with a clear definition of the degree of drainage. In this sense, the test is generally interpreted under the assumption of undrained (total parameters) or completely drained condition (effective parameters). The problem relies in the execution and test interpretation on transient permeability materials, silty materials, such as mine tailings. A partial drainage condition may occur, that affects the reliability of results and can lead to errors of interpretation (DeJong and Randolph[1]; Salgado and Prezzi,[2] ; Schnaid [3]; Dienstmann et al.[4]; Schnaid et al. [5]).

Recent studies with intermediate permeability materials are based on the execution of a set of CPTu performed with different (nonstandard) execution rates, which are interpreted in a space relating a normalized velocity V, Eq. 1, and a degree of drainage U, Eq. 2 (House et al. [6]; Schnaid et al. [7]; Randolph and Hope [8]; Chung et al. [9]; Schneider et al. [10]; DeJong et al. [11]).

$$V = v.d / c_h \tag{1}$$

$$U = 1 - u / u_{\max} \tag{2}$$

where d is the probe diameter, v is the loading rate, c_h is the coefficient of consolidation, u is the measured pore pressure and u_{max} is the maximum value of pore pressure.

The normalized space of V x U allows the construction of characteristic drainage curves that can be used to define transition limits of undrained to partially drained behavior, and partially drained to drained behavior. The identified curves, however, in some cases, present considerable data dispersion due to high variability of the material that makes it difficult to accurately identify the range of drainage variation. In view of the described difficulty, this paper presents tools to deal with the dispersion of results in materials with high variability, aiming to improve the existing methods for assessing drainage conditions.

1 Gold mine tailings

The present paper describes the variability characterization of experimental data from a gold tailing storage facility located in northeast Brazil, the Fazenda Brasileiro Mine. The site is a subject of study for the past two decades (Bedin et al. [12], Schnaid et al. [13], Schnaid et al [14], Dienstmann et al. [4], Schnaid et al. [5]), with a research project including site evaluation, field and laboratory tests.

A total of eleven (11) different islands of investigation were defined and executed in Fazenda Brasileiro Mine, with sample collecting and in situ tests such as piezocone (conventional CPTu, and with seismic measurements SCPTu), seismic dilatometer (SDMT) and vane tests. The analysis of the variability of piezocone soundings is the object of the study Perini [15] and some aspects observed by the author are presented in sequence.

1.1 Variability Characterization

The characterization of gold tailings variability was done for each vertical sounding. A total of eleven (11) vertical soundings were evaluated, each sounding having a number of available measurements ranged from 370 to 1051. Mean values, coefficient of variation (COV) and scale of fluctuation of the parameters q_c, f_s and u_2 and their residual values were characterized.

Table 1 presents the general result of mean and COV. It is important to highlight, that the values obtained after the removal of trends – residual values (COVres) – characterized statistics similar to the pure parameters of the deposit. The fluctuation were also characterized and showed similar behavior regarding trend removal. As the scale of fluctuation was not used in the applications described in this work, it was not presented.

Table 1. Statistics of q_c, f_s and u for different soundings

	q_c			f_s			u_2		
Sounding	mean (Kpa)	*COV*	*COV* res	mean (Kpa)	*COV*	*COV* res	mean (Kpa)	*COV*	*COV* res
I1K	392,50	0,76	0,81	3,52	0,83	0,83	101,74	0,77	0,36
I1S	553,99	0,90	0,93	6,27	0,61	0,60	132,88	0,50	0,33
I2K	879,61	1,20	1,04	15,59	2,71	2,54	69,69	0,87	0,70
PZC 01	863,60	0,87	0,85	7,34	0,78	0,82	111,05	0,54	0,32
PZC 02	3145,89	0,37	0,41/0,69	22,93	0,50	0,43/0,69	93,97	0,28	0,64/0,33
PZC 03	3852,24	0,67	0,67	34,40	0,67	0,73	93,20	0,34	0,62
PZC 04	738,44	0,92	0,83	6,49	0,81	0,80	106,42	0,52	0,26
PZC 05	4467,74	0,30	4,63	31,61	0,26	0,33	57,34	0,53	1,07
PZC 06	174,56	0,46	0,47	3,13	0,69	0,49	86,72	0,51	0,18
PZC 07	1785,63	1,23	0,86/0,56	8,39	0,91	1,47/0,43	36,52	0,91	0,60/0,42
PZC 08	373,13	1,21	0,71/0,71	6,08	0,46	0,37/0,45	74,13	0,72	5,27/0,33

In the sequence, the available data of the parameters q_c, f_s and u_2 were explored in the *Easyfit* software to obtain an overview of the best fit distribution. Figure 1 shows the histogram for the q_c parameter in KPa obtained in the I1K test, with three distributions that best fit the sample data according to the Kolmogorov Smirnov (KS) test. The Burr distribution was considered representative for the subsequent analysis.

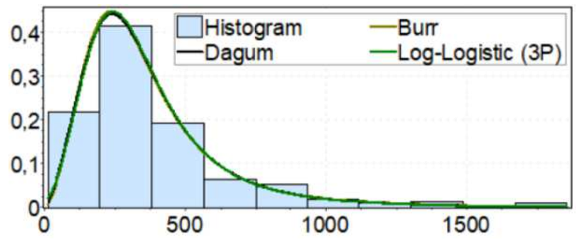

Figure 1. IK01 sounding: histogram and theoretical distribution for q_c measurements

In addition to the analysis of each complete profile, for Klahold [16] Island 1, IK1, the profile was separated into characteristic layers and the statistics of these layers were also evaluated. In summary, the statistics results separating layers showed lower dispersions, as expected. And, in some cases with different PDF curves from that characterized when the complete data of the profile is considered. The full analysis appears in Perini [15].

2 Numerical analysis

Cavity expansion solutions are often used in geomechanics to study the bearing capacity of piles or to interpret cone and pressuremeter tests. A cylindrical cavity expansion solution provides stresses (σ), strains (ε) and pore pressure (u) fields, that can be used to derive an approximated cone resistance (q_c) using an approach similar to that proposed by Rohani and Baladi [17] and used by Silva [18] and LeBlanc and Randolph [19]:

$$q_c = \sigma_r'(1+\tan\delta/\tan\alpha)/(1-\tan\delta\ \tan\alpha)+u \qquad (3)$$

where δ is the soil-surface resistance and α is the angle between the face of the conical tip and the vertical line, and σ_r' is the radial effective stress

The cavity expansion model displayed on Fig. 2 was created in the finite element software Abaqus and was used to assess theoretical drainage and resistance characteristic curves. The cavity expansion simulated in Abaqus was defined according an axisymmetric model, with unit weight and infinite extend (classical approach). In this approach an initial cavity of radius R is expanded by the application of a radial controlled displacement (ζ_r). Mechanical boundary conditions are defined as: restriction of vertical displacement in the upper and lower boundary; restriction of horizontal displacement in the right face. An initial field of stress and pore pressure (σ_0; p_0) is also considered. The radial extension is set to r=100R, which proved sufficient to not affect the displacement field at r>>R. Elements used are 8-node axisymmetric quadrilateral, biquadratic displacement, bilinear pore pressure and reduced integration (CAX8RP). For the constitutive model the Clay Plasticity model was considered. The Clay Plasticity model is a Cam Clay type of model computing deformation by the compressibility index λ, recompression index κ, initial void ratio e_0, and elastic shear modulus G. Failure criteria is defined by friction coefficient M. Permeability k, and fluid density complement the necessary parameters for flow characterization.

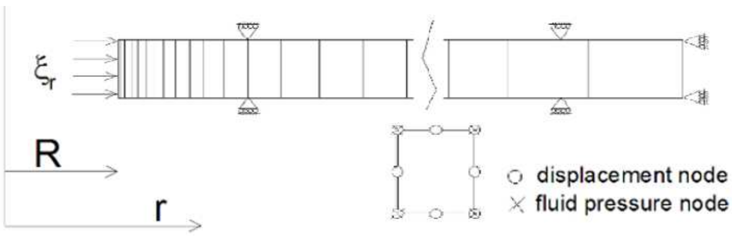

Figure 2. Finite-element mesh detail (not in scale)

2.1 Sensibility analysis

Before applying the material variability to a numerical analysis with Monte Carlo approach, a sensibility analysis was performed. This analysis sought to characterize the influence of the compression index, friction coefficient, shear elastic modulus and permeability parameters on the characterization of drainage curves in V x

U space and Q x U space. In the V x Q spacediagram, derived q_c values are displayed relating the evolution of strength with the degree of drainage. Q quantity represents the ratio between the minimum predicted value of $q_{c,min}$ and the q_c for the evaluated analysis. The variation range for the listed parameters is presented in Tab. 2, results are display on Fig. 3 and 4.

Table 2 Sensibility analysis

Parameter	**Value**
λ	0,060; 0,045; 0,036
κ	0,05λ
M	1,0; 1,2; 1,4
G_0	10 GPa; 30GPa; 50GPa
σ'_0	50 kPa
u_0	110 kPa
k	1E-6; 1E-7; 1E-8 (m/s)
e_0	1,2

The compression index variation [λ=Cc/(1+e_0)] with results illustrated on Fig. 3a and 3b indicates that low values of λ, which are associated with more rigid materials, developed higher values of maximum mobilized resistance and lower values of transitional velocities (a shift on V x U curve to the left can be observed when more rigid material is characterized). When permeability is evaluated, no influence on the drainage curves was observed on Fig 3c and 3d.

Figures 4a and 4b illustrate the evaluation of friction coefficient variation indicating, as expected, that higher values of M developed higher values of maximum mobilized resistance. No influence on the space of V x U was observed. When shear modulus is evaluated, Fig. 4c and 4d, higher values of modulus are also associated with an increase on maximum mobilized strength and no significant influence on the V x U drainage curves was observed.

Based on the results it was verified that the influence of the evaluated parameters is better visualized in the space of normalized velocity versus resistance (V x Q). This space was used as reference in the next analyses.

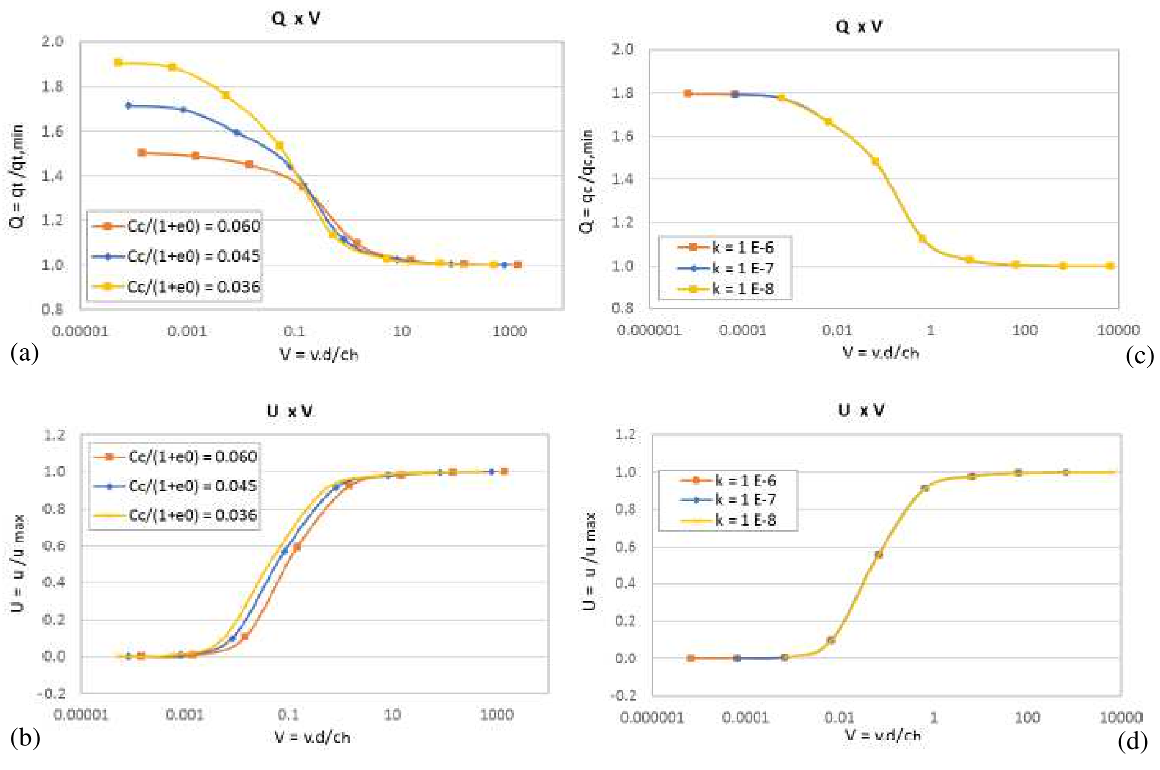

Figure 3. Sensibility analysis results on V x U and V x Q: (a) and (b) compression index; (c) and (d) permeability

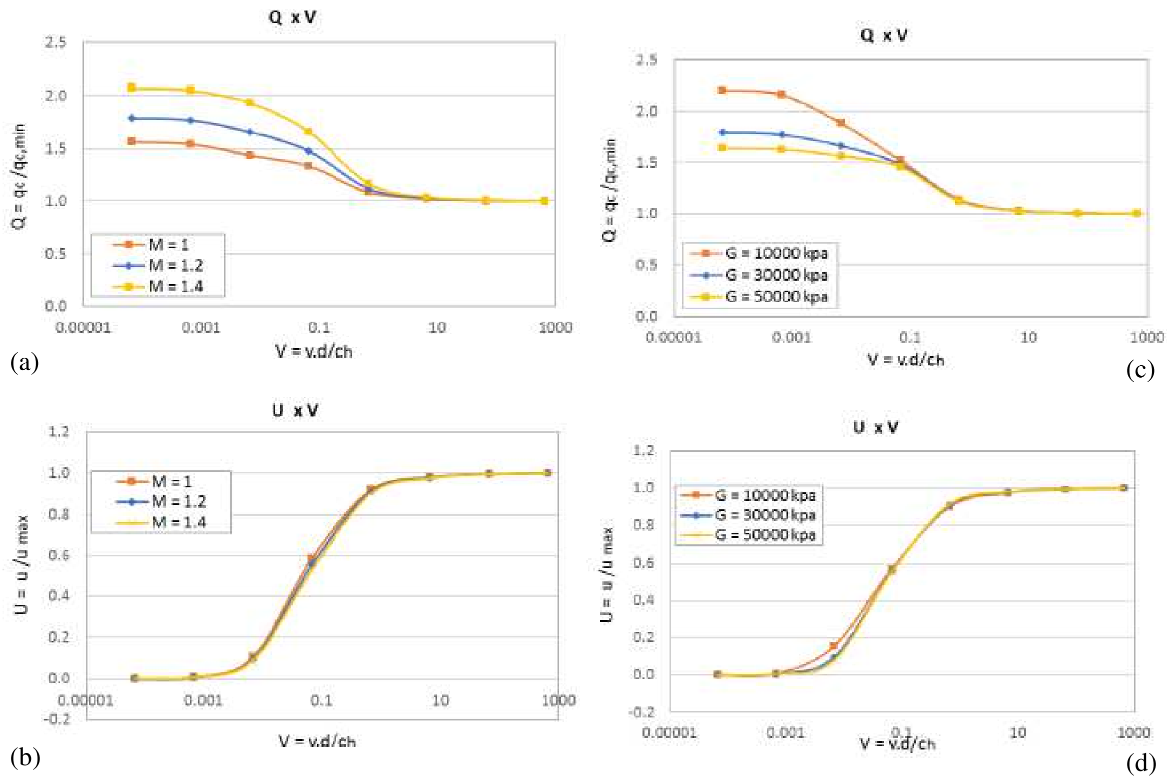

Figure 4. Sensibility analysis results on V x U and V x Q: (a) and (b) friction coefficient; (c) and (d) elastic shear modulus

2.2 Monte Carlo

The uncertainty in the estimation of parameter M was incorporated in a numerical analyses using the Monte Carlo Method. The results presented in herein refer to the sounding region designated as IK1 (Island 01 of Klahold [16]) and are evaluated in the space of normalized velocities and resistance (V x Q).

To perform this evaluation a set of random values respecting the PDFs characterized in item 1.1 was generated and incorporated in the numerical model. A total of 1000 random values of M were initially generated and the convergence of the mean values of q_c was set as the stopping criteria (error of 0,5%). For each value of M, five velocities of expansion are modeled to represent the spectrum of data in the V x Q. In this evaluation, a direct comparison was made between field and numerical prediction results. As the field results comprise measurements only from 3 to 5m, an analysis of the variability of this layer was also performed. Results are displayed on Fig. 5 and Fig. 6 and Tab 3.

Figure 5 shows the spectrum of predictions in the normalized velocity space with a direct comparison of field data points. The variability adopted for the complete profile resulted in numerical data with a greater amplitude of resistances than that characterized by the field points (Fig. 5a and 5b). When the variability of the specific layer from 3 to 5 m of the profile was considered in the analysis, the amplitude range of predicted resistance is substantially more closed to the field data.

The PDF's of the maximum strength predictions obtained considering the complete profile and different layers are displayed of Fig. 6 and are used to derive the probability of occurrence of certain ratios between drained and undrained resistance presented on Tab. 3. An example of use of the related data can be highlighted considering the statistics of the complete profile compared to the statistics of a reference layer, layer 9: the probability of a $q_{c,max}/q_{c,min}$ greater than 2 is 16,3% when the complete profile is considered and reduces to 0,4% for layer 9.

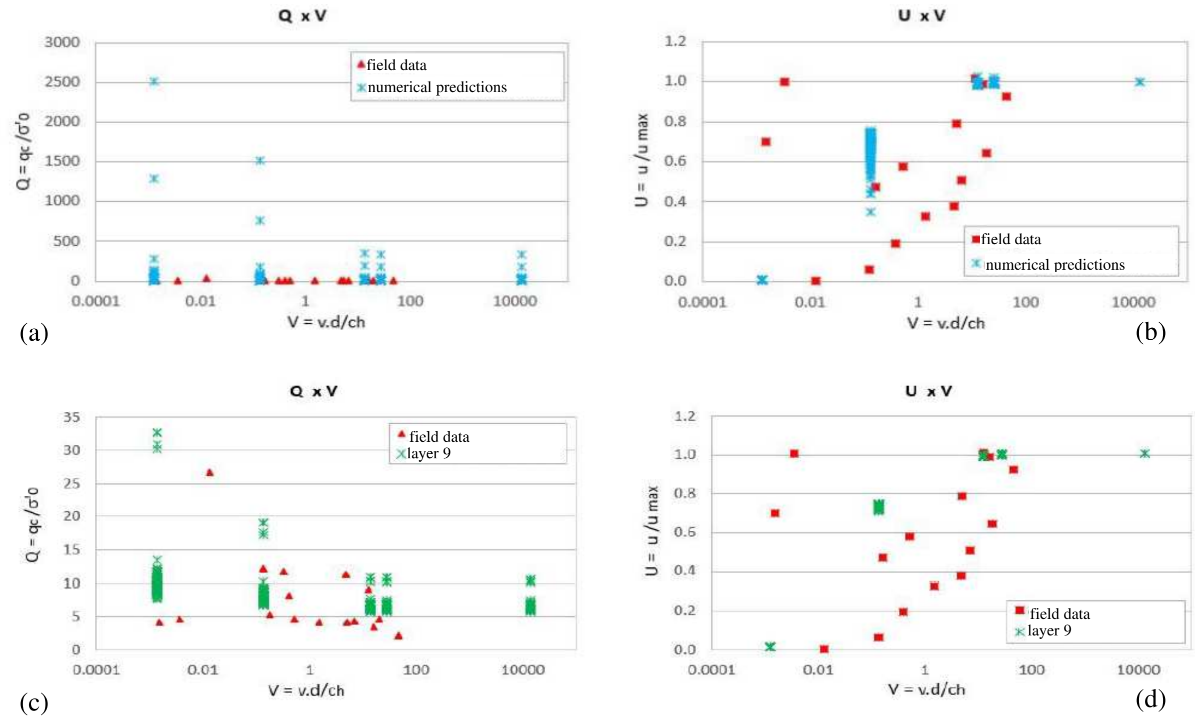

Figure 5. Variability analysis results on V x U and V x Q: (a) and (b) IK1 complete profile; (c) and (d) layer 9 from IK1 profile

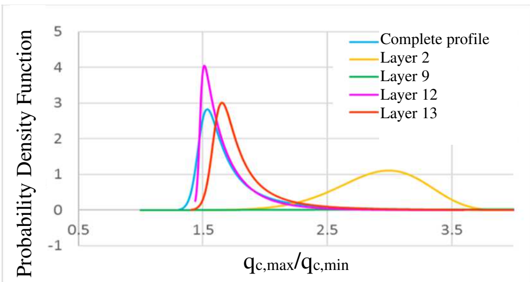

Figure 6. Variability analysis results of PDF distribution of $q_{c,max}/q_{c,min}$

Table 3. Probability of occurrence of certain ratios between drained and undrained resistance

$q_{c,max}/q_{c,min}$	1	1.25	1.5	1.75	2	2.25	2.5
Complete profile	100.0%	100.0%	83.9%	33.2%	16.3%	8.7%	5.8%
Layer 2	100.0%	100.0%	100.0%	99.8%	98.8%	95.5%	87.1%
Layer 9	100.0%	100.0%	65.5%	0.5%	0.4%	0.4%	0.4%
Layer 12	100.0%	100.0%	87.8%	26.9%	7.4%	2.8%	1.7%
Layer 13	100.0%	100.0%	99.1%	45.8%	17.3%	8.6%	5.7%

3 Conclusions

A sample analysis of data variation considering a representative piezocone sounding (IK1) of a gold tailing was presented. The statistics of mean, COV and characteristic PDF curves were presented and used to asses a numerical analysis of variation. This variability analysis covered the statistics of the complete vertical profile and the statistics of the layer corresponding to the depths of 3 to 5 m, depth in which field data was available.

The variability adopted for the complete profile resulted in numerical data with a greater amplitude of resistances than that characterized by the field points, as expected. When the variability of the specific layer from 3 to 5 m of the profile was considered the amplitude range of predicted resistance is substantially closer to the field data. Results of this analysis can also be used to verify the probability of occurrence of maximum values of q_c.

The methodology applied in the analysis demonstrated that considering uncertainties in the probabilistic analysis produces better results when statistics data is related to the same depths of field results. This observation validates the practice of pre-selecting layers with less variability to intensify the research campaign through complementary field and/or laboratory tests. Finally, in case of working with materials with high variability, it is more appropriate to characterize amplitude ranges, especially if the mobilized resistance is evaluated, rather than the search for a single characteristic drainage curve.

Acknowledgements. The authors gratefully appreciated the financial support provided by the Research Councils CNPq and CAPES. We are particularly grateful to Geoforma and Yamana for the permission to assess data.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] J. T. Dejong and M. Randolph, Influence of partial consolidation during cone penetration on estimated soil behavior type and pore pressure dissipation measurements. *Journal of Geotechnical and Geoenvironmental Engineering*, v. 3, pp. 6–11, 2012.
[2] R. Salgado and M. Prezzi, Penetration rate effects on cone resistance: insights from calibration chamber and field testing. *Soils and Rocks*, v. 37, n. 3, pp. 233–242, 2015.
[3] F. Schnaid, Geo-characterization and properties of natural soils by in situ tests. *Proc. 16th International Conference on Soil Mechanics and Geotechnical Engineering*, Osaka, vol. 1, pp. 3–47, 2005.
[4] G. Dienstmann and S. Maghous and F. Schnaid, Assessment of rate effects in piezocone tests from poroelastic cavity expansion analysis. *Soils and Rocks*, v. 41, n. 3, pp. 319-332, 2018.
[5] F. Schnaid, G. Dienstmann, E. Odebrecht and S. Maghous, A simplified approach to normalization of piezocone penetration rate effects. *Geotechnique*, v. 1, pp. 1-25, 2019.
[6] A.R. House, J.R.M.S. Oliveira and M.F. Randolph, Evaluating the coefficient of consolidation using penetration tests. *International Journal of Physical Modelling in Geotechnics*, v. 1, n.3, pp. 17-25, 2001.
[7] F. Schnaid, B. M. Lehane and M. Fahey, In situ test characterization of unusual geomaterials. *Proc., 2nd International Conference on Site Characterization*, v. 1, 2004.
[8] M.F. Randolph and S.N. Hope, Effect of cone velocity on cone resistance and excess pore pressure. *Proc. of the International Symposium on Engineering Practice and Performance of Soft Deposits*, pp. 147–152, 2004.
[9] S.F. Chung, M. F. Randolph and J. A. Schneider, Effect of penetration rate on penetrometer resistance in clay. *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 132, n. 9, pp. 1188-1196, 2006.
[10] J. A. Schneider, B. M. Lehane and F. Schnaid, Velocity effects on piezocone measurements in normally an over consolidated clays. *International Journal of Physical Modelling in Geomechanics*, v. 7, n. 2, pp. 23–34, 2007.
[11] J. T. DeJong, R. A. Jaeger, R. W. Boulanger, M. Randolph and D. A. J. Wahl, Variable penetration rate cone testing for characterization of intermediate soils. *Proc., 4th International Conference on Site Characterization*, vol. 1, pp. 25-42. London, UK, 2013.
[12] J. Bedin, F. Scnhaid, A. J. P. V. Fonseca and L. M. Costa Filho, Gold tailings liquefaction under critical state soil mechanics. *Geotechnique*, v. 62, pp. 263-267, 2012.
[13] F. Schnaid, J. Bedin, A. J. P. V. Fonseca and L. M. Costa Filho, Stiffness and strength governing the static liquefaction of tailings. *Journal of Geotechnical and Geoenvironmental Engineering*, v. 139, pp. 2136-2144, 2013.
[14] F. Schnaid, E. Odebrecht, J. Sosnoski and P.K. Robertson, Effects of test procedure on flat dilatometer test (DMT) results in intermediate soils. *Canadian Geotechnical Journal*, v. 53, n. 8, 2016.
[15] L. Perini, Characterization of gold mining tailings variability and its influence on the velocity effect analysis in the CPTu. Federal University of Santa Catarina, Brazil (in portuguese), 2021.
[16] P.A. Klahold, Interpretation of field tests on soils with intermediate permeability. MSc Thesis, Federal University of Rio Grande do Sul, Brazil, (in Portuguese), 2013.
[17] B. Rohani and G. Y. Baladi, Correlation of mobility cone index with fundamental engineering properties of soil. *International Society for Terrain -Vehicle Systems*, vol 3, pp. 959-990, Alberta, Canada, 1981.
[18] M.F. Silva, D.J. White and M.D. Bolton, An analytical study of the effect of penetration rate on piezocone tests in clays. *International Journal for Analytical and Numerical Methods in Geoemechanics*, v. 30, n. 6, pp. 501-527, 2006.
[19] C. Le Blanc and M.F. Randolph, Interpretation of piezocones in silt, using cavity expansion and critical state methods. *Proc., 12th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG)*, pp. 822-829, 2008.