

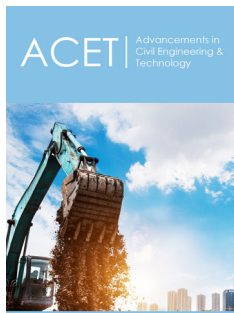
A Statistical Model for Estimating Shear Undrained Strength in Bauxite Mining Tailings Based on *in situ* Tests

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Abstract

Mining tailings' undrained strength (S_u) is a relevant design parameter for tailings storage dams. One way to obtain S_u , independent of sample extraction and along the depth, is to carry out field tests, such as the CPTu test. Given some uncertainties related to the estimation of S_u from the CPTu test, this paper aims to evaluate the variation of this parameter statistically, comparing it with vane test results and understanding the main variables involved in correctly obtaining the parameter in bauxite mining tailings. The database includes results of CPTu and vane tests carried out at specific depths in two Brazilian bauxite tailings deposits. The results demonstrate that it is possible to establish a statistical model to estimate S_u as a function of data obtained by the CPTu test (q_t and f_s), with an r^2 of 0.95.

Keywords: Undrained resistance; Mining tailings; Vane tests; CPTu tests; Statistical analysis

Introduction

The undrained strength of soils (S_u), as postulated by Classical Soil Mechanics [1], concerns the material's operational resistance under loading conditions that do not dissipate excess pore pressure. In the specific case of mining tailings, which are mostly available in deposits under conditions of total saturation, the value of S_u gains importance in evaluating the stability of these structures when subjected to rapid loading without time for the excess pore pressure generated to dissipate. Morgenstern et al. [2] and Robertson et al. [3] evaluated rupture mechanisms in Brazilian mining tailings deposits that would have mobilized the material's resistance in undrained conditions.

S_u values can be determined through field and laboratory tests. According to Nierwinski [4], there are difficulties in obtaining a representative and good-quality sample for laboratory tests on these materials. In this way, field trials become attractive for the evaluation of design parameters in mining tailings. Schnaid and Odebrecht [5] highlight that the test traditionally used in the field to obtain S_u is the vane test. This test allows an analytical interpretation based on the hypothesis of a cylindrical surface of soil rupture obtained by the rotation of a cruciform element inserted at a certain depth. Despite this attractiveness, the vane test is carried out punctually, and the complete characterization of a profile can become costly and economically unviable. Alternatively, the possibility is presented of obtaining S_u from piezocone tests (CPTu) in a semi-empirical way, as presented by Equation 1.

$$S_u = \frac{q_t - \sigma_{v0}}{N_{kt}} \quad 1$$

Where q_t is the cone tip resistance, σ_{v0} is the total vertical stress, and N_{kt} is a load capacity factor, whose value is generally calibrated from results of vane tests carried out at the same location or estimated based on results provided in the literature. Although S_u 's estimate from CPTu allows obtaining the parameter along the profile, it is guided by empiricism related to the correct definition of the N_{kt} value [5]. On the other hand, statistical tools have increasingly

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covered more areas of knowledge. In geotechnics, these tools allow the evaluation of databases in a deterministic way based on concepts of reliability and probability, which supports risk management in design development [6]. Statistical analysis allows a regression of parameters, considering the variability of the studied database. For example, Mayne [7] and Mayne et al. [8] used statistical regressions to define equations to estimate the weight soil specificity from cone test results. More recently, Collico et al. [9] used statistical tools to delineate different soil layers along the geotechnical profile based on material behavior index (I_c) values.

In this context, the present work aims to apply statistical tools to study S_u values obtained through field tests (CPTu and vane), seeking to evaluate a possible statistical equation between S_u and results obtained in the cone test, such as q_t and f_s .

Methodology

The database studied consists of results from CPTu and vane tests carried out in two bauxite mining tailings deposits in Brazilian territory. From the first deposit, six vertical CPTu and 19 vane tests are distributed at different depths at the same points as in the CPTu tests. For the second deposit, 15 CPTu verticals and 36

vane tests are distributed at different depths at the same points as in the CPTu tests. The statistical analyses carried out in this work were performed using available tools to the R® software. For the development of the multiple linear regression model, the following tools were used: ggpairs from the Ggally package to compare the variables and identify their correlations; aov to perform analysis of variance; and lm to perform the regressions linearly.

Results

The first step necessary to construct a statistical model based on linear regression involves checking the relationships between possible model parameters and data behavior when crossed with each other [10]. The graph in Figure 1 displays the relationships between f_s , u , q_t , and S_u . The analysis of these results allows us to draw two important conclusions: first, there is a strong correlation between S_u and q_t ; second, the behavior of f_s about S_u exhibits non-linear behavior, as can be observed by the highlighted blue line, indicating that a logarithmic function can transform f_s to represent S_u 's behavior. It is also noteworthy that the heteroscedastic relationships between the variable's f_s and u , f_s and q_t , and u and q_t are not relevant to the context of this work, which aims to estimate S_u as a function of other variables.

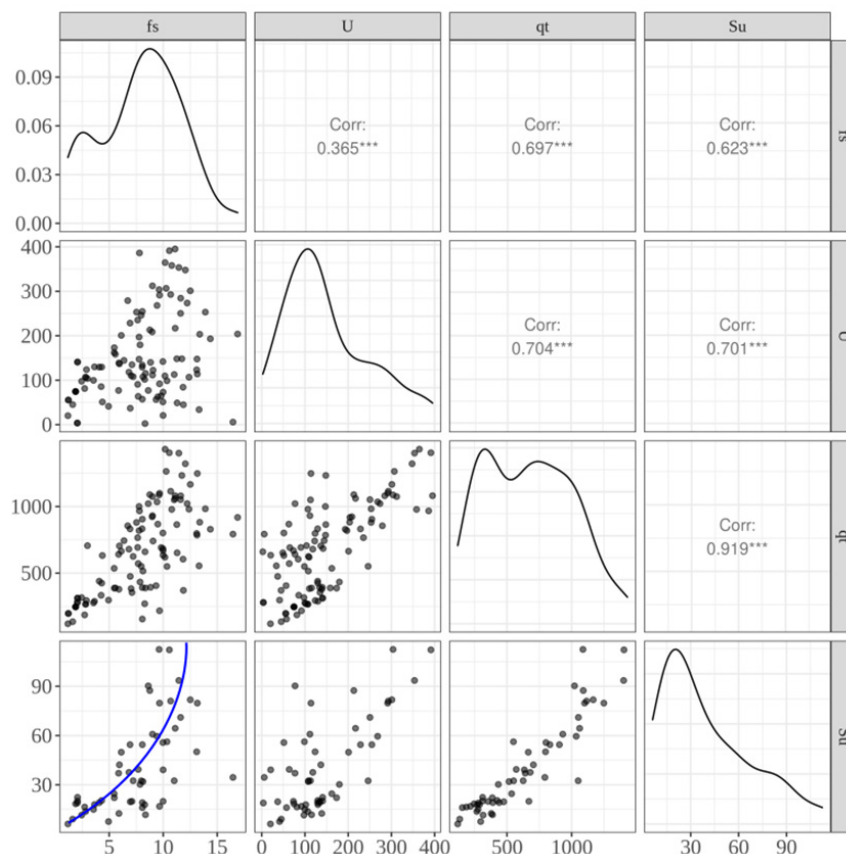


Figure 1: Statistical correlations between f_s , u , q_t e S_u .

Once the relationships between the variables and the transformation carried out for the values of f_s are understood, the second step to building a regression model involves analyzing the impact of each variable dependent and the relationships between them on the variations of S_u . In this article, this analysis was carried

out through the ANOVA technique [11], evaluating the impact of the factors q_t , $\log(f_s)$, and u individually and when combined. Table 1 shows the analysis of variance (ANOVA) results for selecting the factors relevant to constructing the linear model.

Table 1: Variance analysis (ANOVA).

Factor	Sum (SQ)	F-value PR (>F)	Significance
q_t	123648	1048685,00	<2e-16
$\log(f_s)$	666	5645,00	0,0215
u	389	3297,00	0,0757
$q_t \times \log(f_s)$	69	0,58	0,4496
$q_t \times u$	311	2638,00	0,1109
$\log(f_s) \times u$	21	0,18	0,6769
$q_t \times \log(f_s) \times u$	34	0,29	0,5917

Considering the results of the analysis of variance, the following were selected for the regression model: linear variables, whose significance factor and consequent impact on the variance of S_u was greater than 95%. Therefore, the linear regression model for estimating undrained strength for bauxite tailings is defined according to Equation 2.

$$S_u = w_1 \cdot q_t + w_2 \cdot \log(f_s) \quad 2$$

Where w_1 and w_2 are weights estimated through linear

regression, this regression was carried out using the 55 observations containing S_u values obtained through the vane test (joining the data referring to the two deposits evaluated).

The results of this estimate can be seen in Figure 2, which displays a scatter plot between the S_u value measured by the vane test (y-axis) and the S_u value estimated by the statistical model, with $w_1 = 0.0789$ and $w_2 = - 5.1$. As can be seen, this model estimates values with a coefficient of determination (r^2) equal to 0.95.

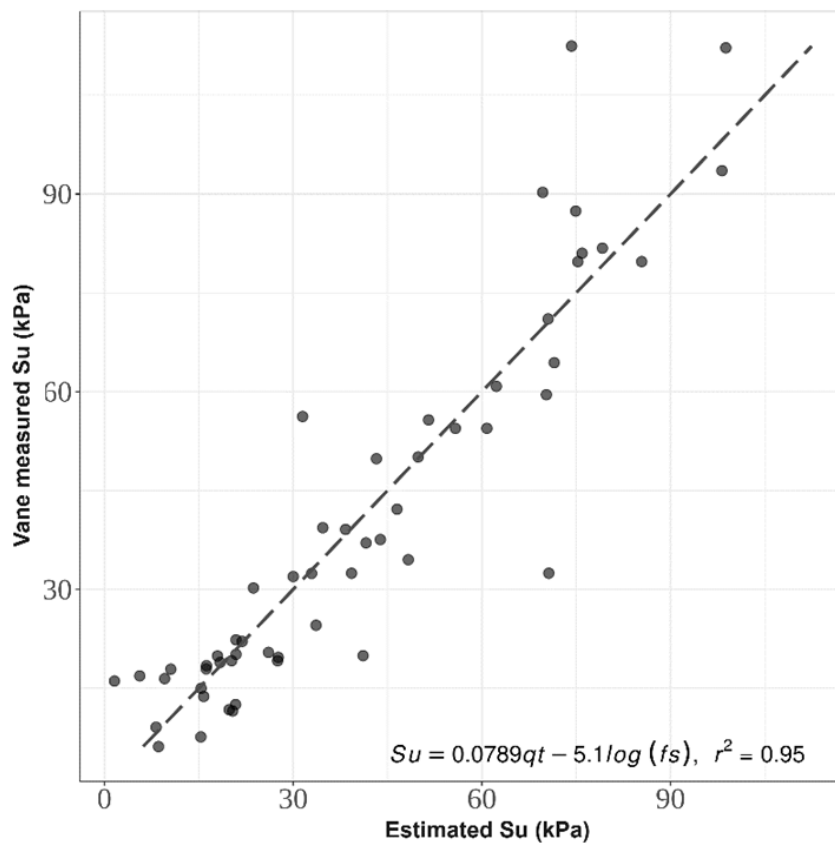


Figure 2: Scatter plot between S_u values measured in the vane test and estimated by statistical model.

Conclusion

The present work sought to conduct a statistical study of S_u based on a database composed of CPTu and vane tests conducted in two bauxite mining tailings deposits. Through linear regression, it was possible to define a statistical model to determine values

of S_u from q_t and $\log(f_s)$, assigning weights (w_1 and w_2) to each variable. The results showed that the statistical equation fits well ($r^2=0.95$) with the measured data. Thus, it would be possible, by statistical means, to calculate the undrained shear strength without necessarily carrying out the vane test several times, considering the evaluated database.

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