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Main factors affecting the determination of the undrained strength of some Mexican soils by the field vane test

Principales factores que afectan la determinación de la resistencia no drenada de algunos suelos mexicanos mediante el ensayo de veleta in situ

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It is routine in geotechnical design practice to estimate the undrained strength of soils (s_u) using the CPTu test, based on correlations with laboratory tests. Correlations must be verified for each site with laboratory undrained triaxial tests on good quality undisturbed samples, which is a time-consuming and sometimes difficult activity. As an alternative approach, undrained strength can be determined more efficiently using the field vane shear test (VST). However, it should be noted that some adjustment to the standard rotation rate and/or correction to the μ factor may be required for particular soils. This paper presents experimental results on the influence of VST strain rate on the estimation of undrained shear strength. The test program was carried out on lacustrine soft clays from four sites in Mexico City (CDMX), where the water content varies from 100% to 500%, and experimental results from a tailings dam in northern Mexico are also presented. Undrained triaxial, VST and CPTu tests were performed on the CDMX soft clays. The rate of rotation $\dot{\theta}$ varied from 0.1°/s to 4°/s to evaluate the peak, residual and remolded shear strength with VST. For the soft clay, the results show that the curve $\dot{\theta}$ versus peak resistance has a minimum value in the range of 0.2 to 0.5, which is associated with the value of the undrained resistance of the soil without viscous phenomena. Therefore, for the clayey deposits of Mexico City, it is recommended to use this range of values to ensure that the correlations used in the piezocone are reliable. In terms of soil sensitivity, the results show that it decreases with increasing speed, with a smaller decrease at greater depths. For the tailings site, similar results to those found in Mexico City were observed, but VST tests using a rotation rate varying from 0.2 to 2°/s showed that the peak resistance has a minimum value at 1°/s.

Keywords: field vane test, undrained shear resistance, Mexico City, tailings, CPTu

Es rutinario en la práctica del diseño geotécnico estimar la resistencia no drenada de suelos (s_u) mediante el ensayo CPTu, con base en correlaciones con ensayos de laboratorio. Las correlaciones deben verificarse para cada sitio con ensayos triaxiales no drenados en muestras inalteradas de buena calidad, lo cual es una actividad que consume mucho tiempo y, en ocasiones, es difícil. Como enfoque alternativo, la resistencia no drenada puede determinarse de manera más eficiente utilizando el ensayo de veleta de corte in situ (VST). Sin embargo, debe tenerse en cuenta que puede requerirse algún ajuste a la velocidad de rotación estándar y/o corrección al factor μ para suelos particulares. Este documento presenta resultados experimentales sobre la influencia de la velocidad de deformación de VST en la estimación de la resistencia al corte no drenada. El programa de ensayos se llevó a cabo en arcillas blandas lacustres de cuatro sitios de la Ciudad de México (CDMX), donde el contenido de agua varía de 100% a 500%, y también se presentan resultados experimentales de una presa de relaves en el norte de México. Se realizaron ensayos triaxiales no drenados, VST y CPTu en arcillas blandas de la CDMX. La velocidad de rotación $\dot{\theta}$ varió de 0.1°/s a 4°/s para evaluar la resistencia al corte máxima, residual y remoldeada con VST. Para la arcilla blanda, los resultados muestran que la curva $\dot{\theta}$ versus resistencia máxima presenta un valor mínimo en el rango de 0.2 a 0.5, asociado con el valor de la resistencia no drenada del suelo sin fenómenos viscosos. Por lo tanto, para los depósitos arcillosos de la Ciudad de México, se recomienda utilizar este rango de valores para asegurar la fiabilidad de las correlaciones utilizadas en el piezocono. En cuanto a la sensibilidad del suelo, los resultados muestran que disminuye con el aumento de la velocidad, con una disminución menor a mayor profundidad. Para el depósito de relaves, se observaron resultados similares a los encontrados en la Ciudad de México, pero los ensayos VST con una velocidad de rotación de 0.2 a 2°/s mostraron que la resistencia máxima presenta un valor mínimo a 1°/s.

Palabras clave: ensayo de veleta in situ, resistencia al corte no drenada, Ciudad de México, relaves, CPTu

Introduction

Piezocone testing has the advantage of determining soil mechanical properties through correlations, specifically the undrained shear strength (equation (1)). The coefficients N_{kl} and $N_{\Delta u}$ may vary between 10 and 24 for N_{kl}, and 4 and 10 for $N_{\Delta u}$, as reported by Robertson and Cabal (2015) and Santoyo *et al*. (1989).

$$s_u = \frac{q_T - \sigma_v}{N_{kl}} \quad \text{or} \quad s_u = \frac{\Delta u}{N_{\Delta u}} \tag{1}$$

In large and/or high-risk projects, it is important to have reliable correlations by knowing the undrained strength values measured directly by field and laboratory tests. If good-quality undisturbed sampling is problematic, such as in very soft or very young soils like tailings deposits, the undrained shear strength in three conditions can be determined more efficiently by performing VST tests: maximum (s_{peak}), residual (s_{res}) and remolded (s_{rem}) shear strength.

In 1973, Bjerrum (1973) suggested applying a correction factor (μ) to the undrained resistance determined by the field vane test to account for the speed of load application. The speed of load application depends on the plasticity index of the soil, as shown in equation (2):

$$s_u = \mu \ s_{VST} \tag{2}$$

It is worth noting that determining the value of μ can be challenging due to the diverse nature of soft soils. As Kayabali and Tufenkci (2010) suggest, estimating s_u is appropriate when the soil's natural water content is near its plastic limit, but not when it is close to the liquid limit. This is particularly relevant for the very soft clays of CDMX.

Several authors have studied the factors that influence the determination of shear strength using the field vane test (s_{VST}). Larsson (1980), Jamiolkowski *et al*. (1985), Watson *et al*. (2000) and Hirabayashi *et al*. (2017) have identified the main factors: the overconsolidation ratio (*OCR*), the overconsolidation pressure (p'_L), the plasticity index (*IP*), rate vane rotation ($\dot{\theta}$), anisotropy of soil, progressive failure, reduction of shear strength due to disturbance, change of pore water caused by insertion of vane, and gain of shear strength during waiting time following the insertion.

In 1974, Bjerrum (1974) demonstrated that the strength of soft clay depends on the rate at which the clay is brought to failure. Subsequent research has confirmed this finding (*e.g*. Peuchen and Mayne, 2007; Wilson *et al*., 2016). Current codes, such as ASTM D2573 (2008), recognize this aspect and require that the rates of vane rotation fall within the range of 0.05 to 0.2°/s. However, it has been observed that in some soil deposits, a higher rotation rate than 0.2°/s is required for undrained behavior to occur and determine short-term shear resistance. This rate cannot be too high, as viscous phenomena may occur, increasing undrained resistance (Quinn and Brown, 2011; Wilson *et al*., 2016).

The aim of this study is to examine the influence of various factors on the outcomes of vane field tests, specifically the undrained resistance (peak and residual), sensitivity, remolded resistance, and the correction factor proposed by Bjerrum, μ. The analysis considers the rate of load application (time taken to reach soil failure), driving process (induced disturbance), and depth (level of geostatic stresses). An exploration and laboratory campaign were conducted in various sites in Mexico City, which are characterized by the presence of very soft soils with high water content. Furthermore, geotechnical surveys were carried out in tailings deposits located in the North of Mexico.

Equipment and procedure

The VST tests were conducted following the ASTM D2573 (2008) guidelines, utilizing an instrumented vane and hydraulic equipment mounted on a truck (Figure 1). The vane geometry varied depending on the soil's shear strength. Initially, the vane was driven with protection up to 50 cm before the test point. Subsequently, the protection was removed to drive the vane into the soil until reaching the test depth (conventional driving). At one of the sites studied in CDMX, the vane was driven using a drill rig. Subsequently, the vane was driven into the soil to the test depth using the drill driving method. In order to assess the impact of the vane driving process on different outcomes, such as stress relaxation, vane insertion, and an increase in confining pressure, a hole was drilled up to 50 cm prior to reaching the test depth.

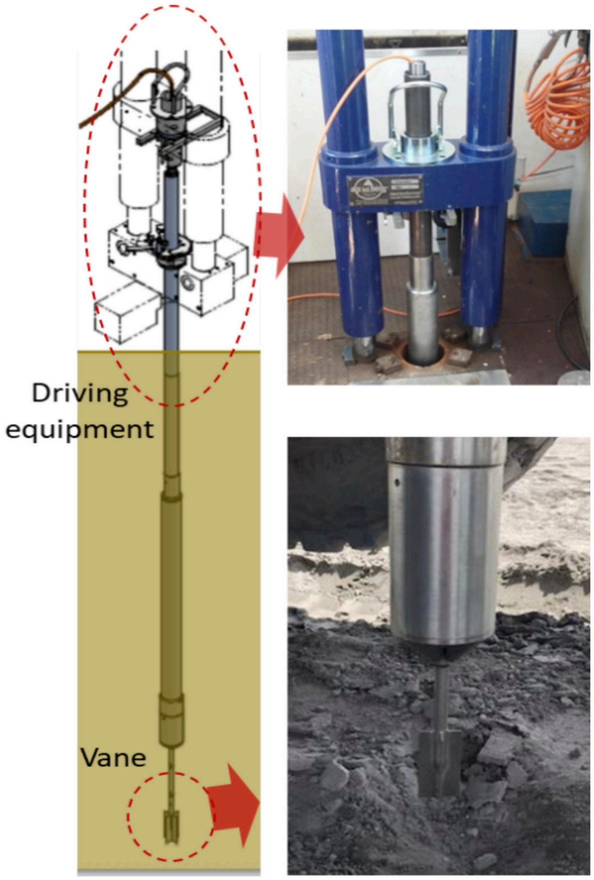

Figure 1: Shear vane testing equipment

Findings

The study presents results on the variation of peak, residual, and remolded shear strengths concerning rotation rate, depth, and driving process. Additionally, the study examines the soil sensitivity S_t, the correction factor of the resistance obtained with vane tests μ, and the time of soil failure.

Mexico City's soft clay deposits

Undrained triaxial tests, VST, and CPTu tests were conducted at four sites in CDMX, where clayey deposits are normally consolidated soils with varying water contents ranging from 150% to 500%. The peak, residual, and remolded strengths were evaluated for rotation rates ranging from 0.1 to 0.2°/s. At one site, the rotation rate was extended up to 4°/s.

Peak, residual, and remolded resistances

Figure 2 shows the variation of induced shear stress in the soil at the Texcoco site in CDMX with respect to rotation angle ($0 \leq \theta \leq 180°$), rotation rate ($\dot{\theta} = 0.1$ and $0.2°/s$), and depth ($1.5\text{ m} \leq z \leq 26\text{ m}$) during conventional driving (with a protected vane). It is observed that:

- Both, shear stress and strength, increase with depth.
- The shear stress increases as the angle of rotation increases until it reaches its maximum value, also known as peak strength (s_{peak}), at approximately $\theta = 10°$, and then decreases to its residual value, also known as residual strength (s_{res}).
- The shapes of the s_{VST} vs θ curves obtained for the two rotational rates, $\dot{\theta} = 0.1$ and $0.2°/s$, are similar. However, for depths $z \leq 20$ m ($\sigma'_v \sim 50$ kPa), the induced shear stress is higher for the highest rotation rate used, $\dot{\theta} = 0.2°/s$. For greater depths $z > 20$ m, this trend is reversed.

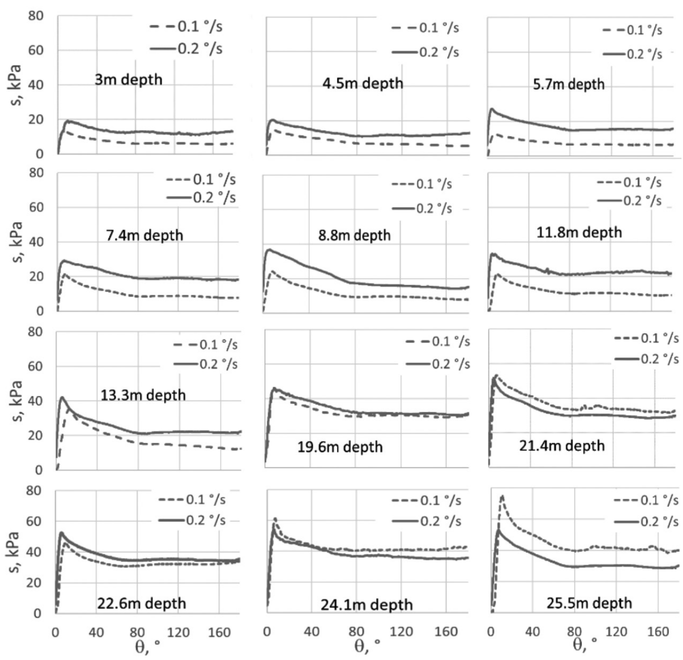

Figure 2: Variation of the vane resistance s_{VST} with rotation angle θ, rotation rate $\dot{\theta}$ and depth, at the Texcoco site.

Figures 3(a) and 3(b) show similar results for the Soho site, with additional values for vane rotation rates ($\dot{\theta} = 0.1$, 0.2, 0.5, 1 and 4°/s) following the conventional driving process. Shear stress and strength increase with depth, with peak strength observed at $\theta = 10°$. At a depth of 20 m, a change in the trend of the curves s_{VST} vs θ for different rotation rates is also observed. Similarly, upon comparing the peak and residual strengths with the strength determined through the UU laboratory triaxial test (unconsolidated and undrained), it is evident that the latter is almost identical to the residual strength, $s_{u\_TX\text{-}UU} \sim s_{res}$. This suggests soil disturbance during soil sampling.

Figures 3(c) and 3(d) present the results for the Soho site but using the drill rig driving process. The s_{VST} *vs* θ curves indicate that soil disturbance is induced during the driving process, resulting in poor quality results. Therefore, the drill driving process is inadequate for clayey deposits in Mexico City.

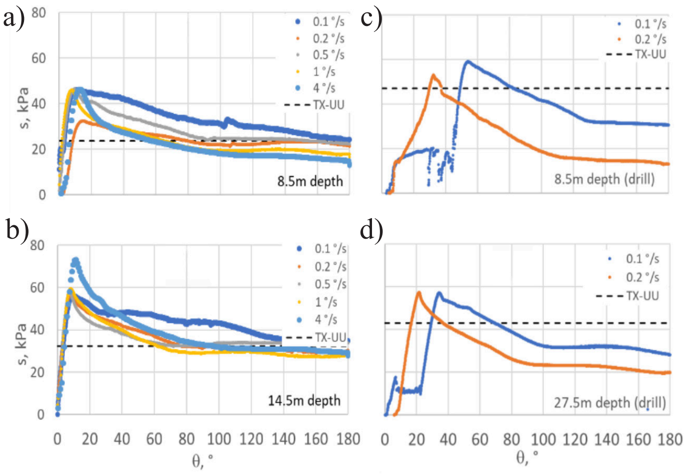

Figure 3: Variation of shear stress s_{VST} with the angle of rotation θ, rotational rate $\dot{\theta}$, and depth for the Soho site using both driving processes, a) and b) conventional and c) and d) drill rig

As shown in Figure 4, the summary results indicate the strengths of s_{peak}, s_{res}, and s_{rem} in relation to rotation rate, depth, and type of driving, and compare them with the undrained strength obtained from the triaxial test ($s_{u\_TX\text{-}UU}$).

It has been found that the peak resistance increases with depth and rotational rate. However, for the 8.5 m depth curve, a minimum value is presented at a rotational speed of $\dot{\theta}$ = 0.2°/s, after which the peak resistance increases and remains constant for $\dot{\theta}$ > 0.5°/s. However, it has been observed that the peak resistance exceeds the undrained shear resistance determined in the TX-UU test. The residual strength increases with depth, but rotational speed has no effect on it, and its value is similar to the strength determined in TX-UU test. Variations in the remolded resistance are observed at rotation speeds lower than $\dot{\theta}$ < 0.5°/s, after which its value remains almost constant.

Figure 4 also illustrates that the resistance value decreases at the minimum of the curve $\dot{\theta}$ *vs* s_{peak}, which occurs within the range of 0.2°/s < $\dot{\theta}$ < 0.5°/s, which corresponds to the undrained state of the soil. This interval exceeds the rate specified in the standards (0.05 and 0.2°/s). Therefore, for the Soho soft clays, the recommended vane rotation rate is 0.2°/s ≤ $\dot{\theta}$ ≤ 2°/s. It is important to note that a higher rotation rate could cause viscous phenomena, which would increase undrained resistance (Quinn and Brown, 2011). Additionally, these rotation rates result in shorter test times.

Figure 5 illustrates the relationship between peak, residual, and remolded resistances and vane rotational speed and depth test at the Antiguo Frontón, Barrio Letrán, and Texcoco sites. Overall, increasing the rotation speed from 0.1°/s to 0.2°/s results in a decrease in resistances. However, in some cases, such as the Texcoco site and when

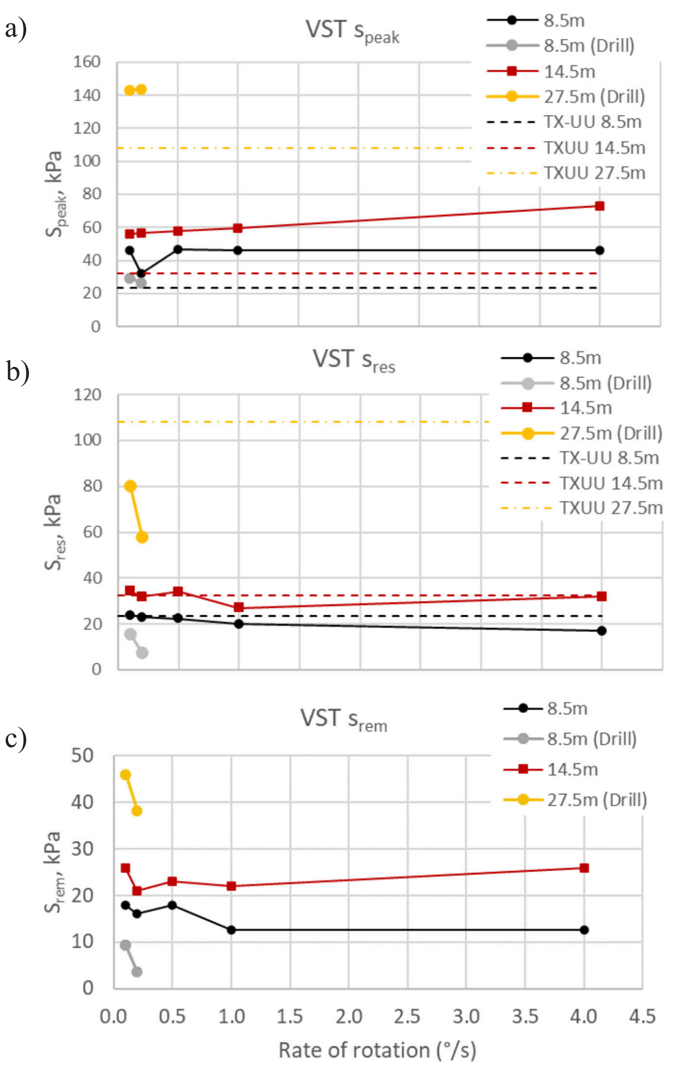

Figure 4: Variation of a) peak, b) residual and c) remolded resistances with respect to vane rotational speed and depth for the Soho site.

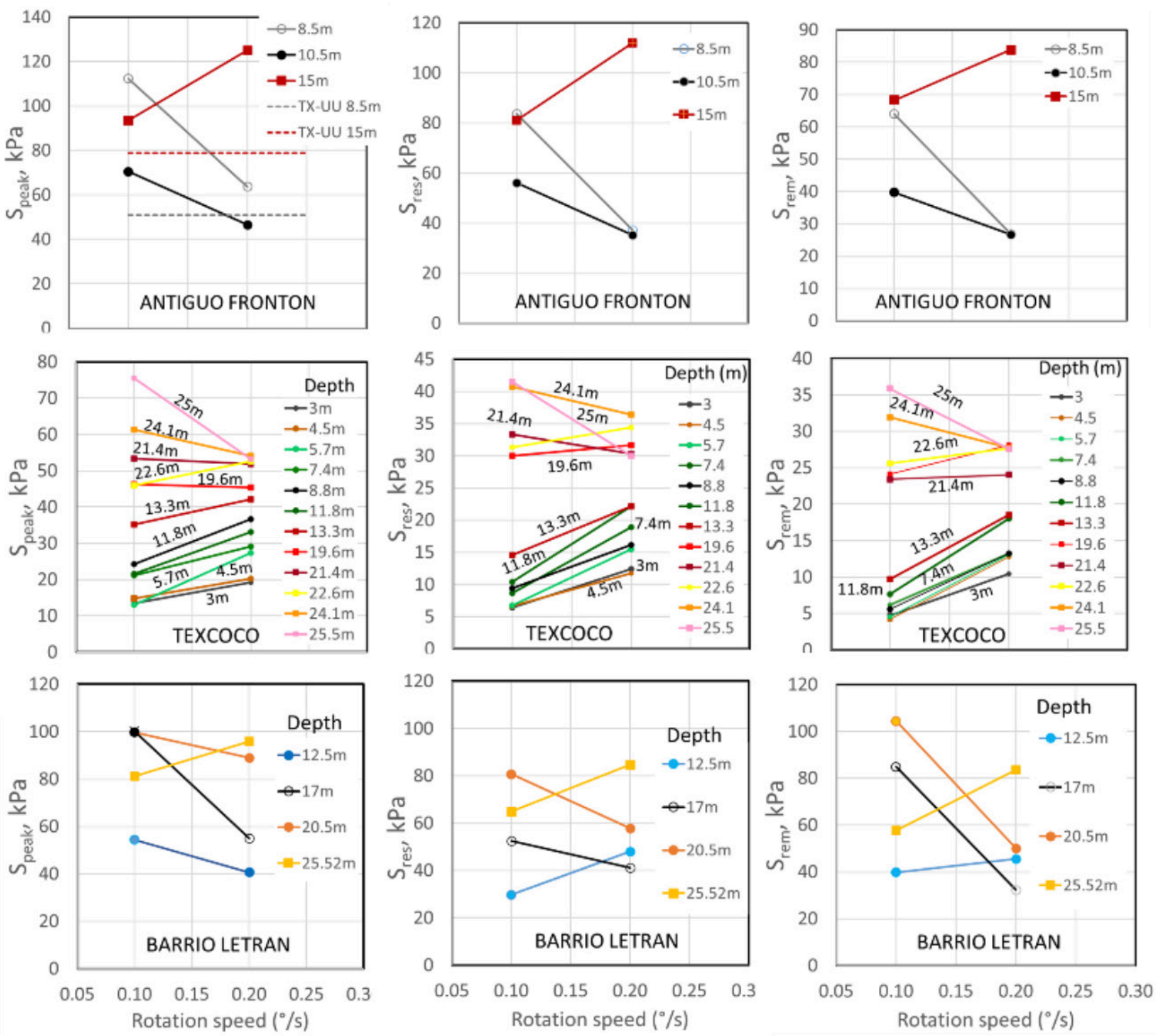

Figure 5: Variation of peak, residual, and remolded resistances in relation to vane rotation speed and depth for the following sites: Antiguo Frontón, Texcoco, and Barrio Letrán.

the depth test exceeds 20 m, the resistances may increase slightly. In these cases, there is no clear minimum in the peak resistance *versus* vane speed curve. This is probably due to the lack of data obtained at speeds greater than 0.2°/s, as was the case for the Soho site. In general, as the resistance increases with speed rotation, a minimum value could be identified at speeds greater than 0.2°/s.

Sensitivity

Figure 6 illustrates the sensitivity variation (S_t) concerning rotation, depth, and rate of rotation for the Texcoco site. The following observations can be made:

- Sensitivity increases as the angle of rotation increases, reaching its maximum value at approximately $\theta = 10°$, after which it decreases asymptotically.
- The maximum sensitivity value ranges from 2 to 8 for a rotational speed of 0.1°/s, and from 2 to 4 for speeds of 0.2°/s. Therefore, the lower the rotational speed, the higher the sensitivity value.
- Between depths $0 \leq z \leq 20$ m, sensitivity values for rotational velocities of 0.1°/s are higher than those for the 0.2°/s. At greater depths, sensitivity values tend to be consistent regardless of rotational velocity.

Figure 7 illustrates how sensitivity varies with rotation speed and depth for Texcoco and Antiguo Frontón cases. The results show that sensitivity decreases as rotation speed increases, as mentioned above, with a smaller decrease at greater depths. Considering the undrained condition for

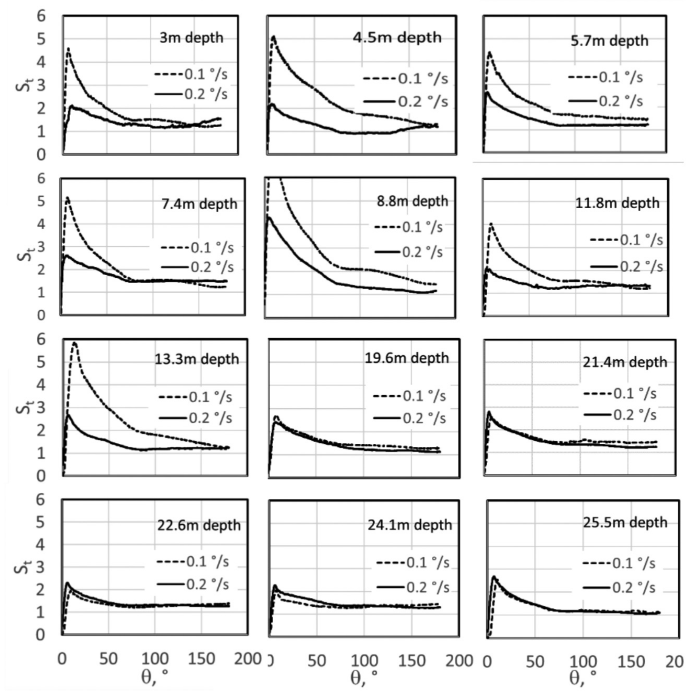

Figure 6: Variation of sensitivity S_t with respect to rotation angle θ, depth and driving speed, for Texcoco site.

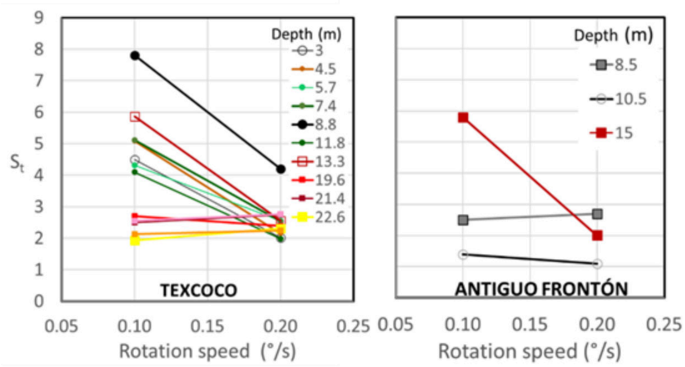

Figure 7: Variation of sensitivity S_t with rotation speed and depth at the Texcoco and Antiguo Frontón sites.

these two cases as having values above 0.2 and below 0.5, the sensitivity value would tend towards values near 2.

Failure time

Figure 8 illustrates the variation of soil shear strength in relation to the time of load application until soil failure for each of the cases studied. The values for times greater than 250 s correspond to the triaxial UU test. It is generally observed that resistance is higher for faster tests, such as the vane test, where the time to failure is shorter.

The general trend of the curve indicates that Bjerrum's proposed correction factor is appropriate for considering the speed of load application.

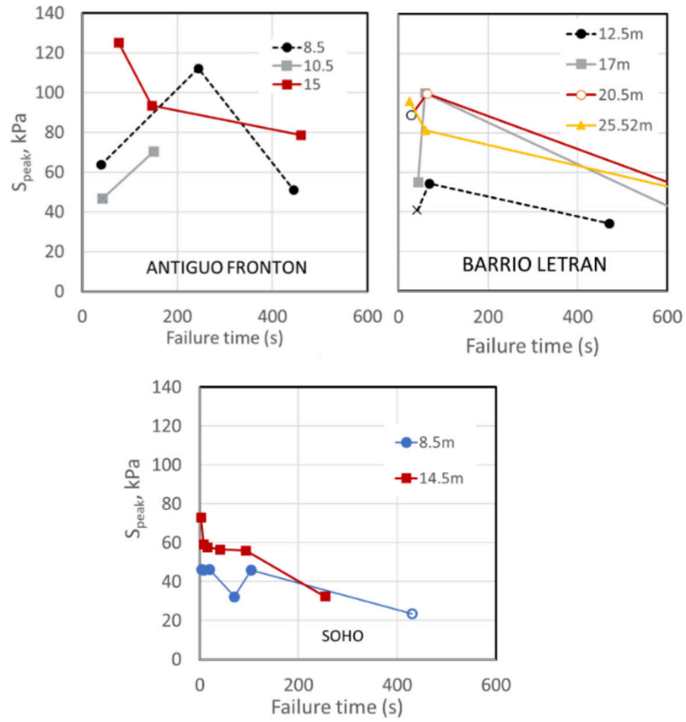

Figure 8: Variation of the shear strength peak s_{peak} in relation to the time required to reach failure and depth, for the Antiguo Frontón, Barrio Letrán and Soho sites.

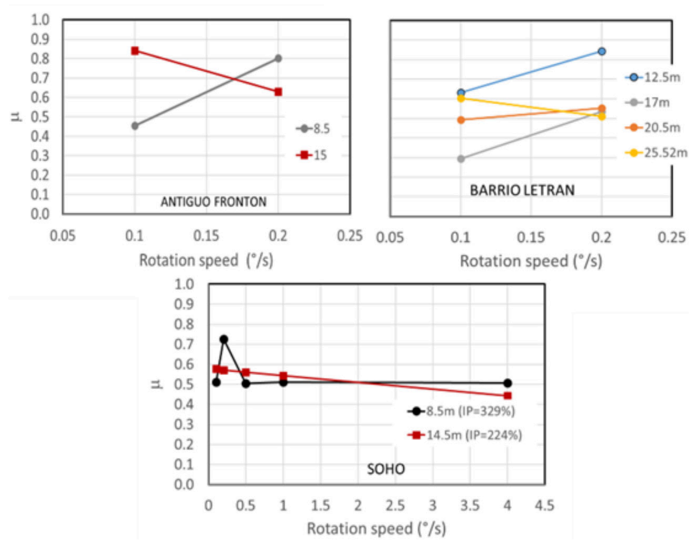

Figure 9: Correction factor μ with rotation speed and depth for the Antiguo Frontón, Barrio Letrán, and Soho sites.

***Correction factor* μ**

This factor is calculated by comparing the peak resistance to the undrained shear resistance value obtained from triaxial tests of the UU type, expressed as $\mu = s_{u\_TX\text{-}UU}/s_{peak}$. Figure 9 displays the values obtained for the cases studied, and no clear trend is observed regarding rotational speed. In some cases, the value decreases as the speed increases, while in others, the opposite occurs. However, the average value of $\mu = 0.55$ is obtained.

Tailings deposits

Vane tests were performed at different rotational speeds (0.2 to 2°/s) in a tailings deposit containing partially saturated deposits and intercalation between fine and granular soils (Figure 10). The layers of fine soils were tested.

Figure 11 illustrates how the peak, residual, and remolded resistances vary with rotational speed. As with previous cases, resistances increase with depth. The s_{VST} vs $\dot{\theta}$ curves show a minimum value at $\dot{\theta} = 1°/s$, indicating that this rotational speed is recommended for tailings deposits. Regarding sensitivity, there are varying magnitudes between 1 and 6. Generally, as the vane's speed increases, sensitivity decreases, as previously observed in the clayey deposits of Mexico City.

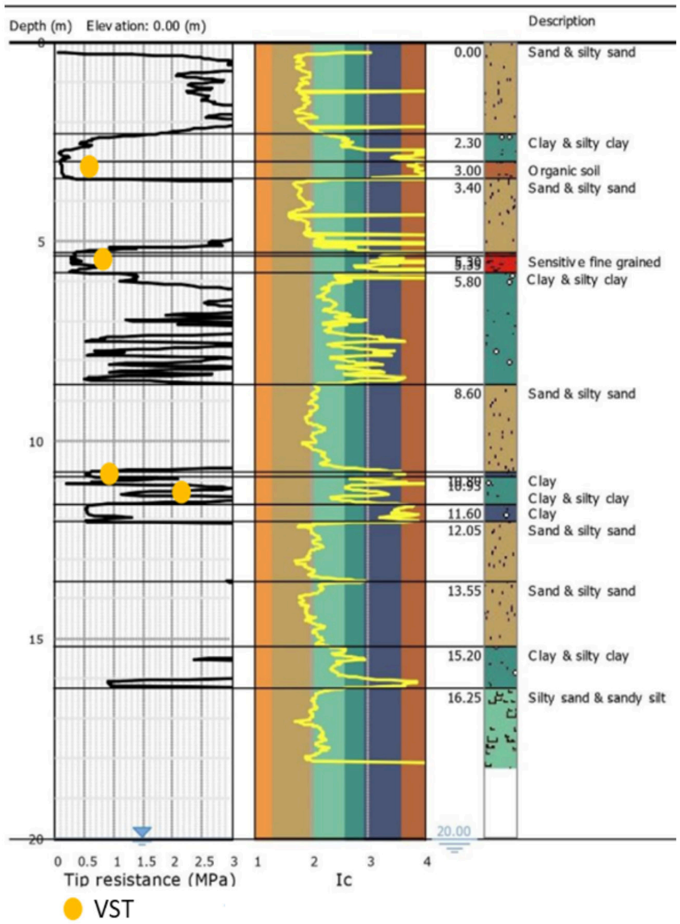

Figure 10: Stratigraphy of the tailings deposit where vane tests were conducted at various depths and rotational speeds on layers of fine soil.

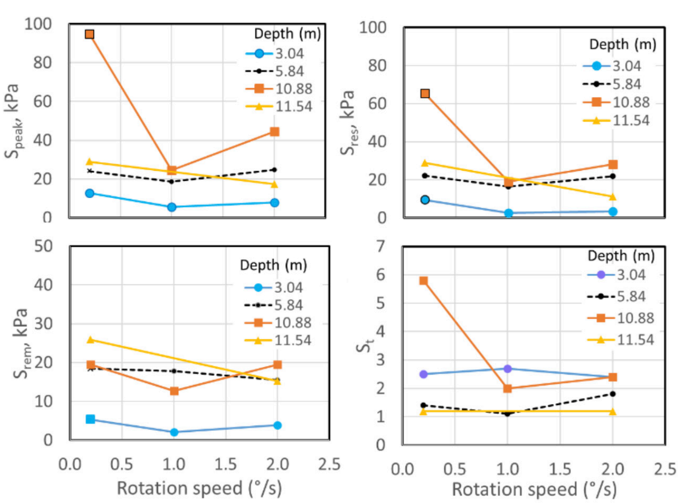

Figure 11: Variation of peak, residual, and remolded resistances (s_{peak}, s_{res} and s_{rem}) and sensitivity S_t concerning depth and rotation speed for the tailing deposit.

Conclusions

To enhance the reliability of correlations used to determine undrained soil resistance through the piezocone test CPTu, this article presents experimental results on the variation of shear resistance with respect to the rotation rate of the VST. The study was conducted on clayed deposits in four sites of Mexico City and a tailings deposit in northern Mexico, where obtaining undisturbed soil samples is difficult.

For the study of clay deposits, four sites were examined in Mexico City to determine the peak, residual, and remolded shear strength using VST. The rotation speed varied from 0.1 to 2°/s and in one case up to 4°/s. In general, the results show that the curve $\dot{\theta}$ *vs* s_{peak} has a minimum value in the range of 0.2 to 0.5°/s, which is associated with the value of the undrained resistance of the soil without viscous phenomena. Therefore, for the clayey deposits of Mexico City, it is recommended to use this range of values to ensure that the correlations used in the piezocone are reliable. A minimum value is also observed for the residual strength, but the changes are small. Two driving processes were studied: conventional and drill driving processes. It was observed that for clayey deposits in Mexico City, the drill driving process produces significant alterations in the test area, making it unsuitable. As for sensitivity, increasing the rotation speed results in a decrease in sensitivity, with a smaller decrease at greater depths. In the speed range where the undrained state of the soil occurs, and for the cases studied, the sensitivity tends to a value of 2.

In general, resistance is higher for faster tests such as the vane test, where time to failure is shorter. The curve's general trend suggests that Bjerrum's proposed correction factor is appropriate for accounting for load application speed relative to test speed. However, the value of the correction parameter μ does not show any trend as the rotation speed changes. The average value of $\mu = 0.55$ is obtained for the clayey deposits of Mexico City.
Similar results to those found in Mexico City were observed in the studied tailings deposits. Experiments were conducted using rotation speeds ranging from 0.2 to 2°/s, and it was observed that as the rotation speed increased, the peak resistance reached a minimum value at 1°/s rotation. The sensitivity varied between 1 and 6, and in general, as the vane speed increased, the sensitivity decreased.

Discussions

According to the standards ASTM D2573 (2008) and Eurocode 7 (2000), the vane rotation speed should be between 0.05 and 0.2°/s to determine the undrained strength of soils. However, for certain soils, such as those studied in this work, the undrained shear strength occurs at higher rates. Therefore, the usual correction factor, μ, used to determine the value of undrained strength through the VST test would be inadequate. Therefore, to obtain accurate correction factor values from the VST test, a research campaign with this specific purpose is necessary.

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