Piezoball application on a Brazilian soft soil deposit

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ABSTRACT

Research has already demonstrated advantages in performing piezoball tests when compared to piezocone in estimating the soil undrained shear strength (S_u) along the stratigraphy and remolded strength (S_{ur}) through cyclic tests, showing a shorter range of strength correction factors (N) and lower dependence on the soil stiffness index (I_r). Another possible application is estimating the remolded shear strength directly from penetration (q_{in}) and extraction (q_{ext}) measurements without requiring cyclic tests. This research performed piezocone, vane, and piezoball tests (standard and cyclic) in a soft soil deposit in southern Brazil. Additionally, undisturbed samples were collected for characterization. The in situ investigation resulted in cone and ball factors in accordance with the international practice recommendation, resulting in similar profiles of undrained strength S_u which increases with depth from 3 to 14 kPa and constant values of remolded undrained strength S_{ur}. Regarding estimating the S_{ur} through direct measurements of penetration and extraction of the piezoball, it was necessary to carefully evaluate the time laps between probe insertion and extraction to avoid overestimating the remolded strength.

Keywords: cyclic test; piezocone; piezoball; undrained shear strength.

1. Introduction

Traditional geotechnical field tests such as piezocone and vane tests have long been instrumental in estimating consolidation parameters and undrained shear strength within clayey soils. Vane tests provide a direct assessment of undrained shear strength (S_u) at specified depths, while the piezocone test necessitates the use of proportion coefficients or cone factors, denoted as N_{kt}, to derive undrained shear strength values. Extensive literature exists to establish the suitable ranges of N_{kt} that ensure accurate adjustments between test-derived estimates and in-situ field measurements (Schnaid 2009). Complementary to the piezocone test with a conical tip, a variant uses the same pushing system but with a spherical tip. This variant primarily targets the determination of undrained shear strength (S_u) in the field (Stewart and Randolph 1991), using an equivalent ball factor denoted as N_B. Compared to the piezocone, ball tests demonstrate a narrower range of the strength factor in the literature (Colreavy et al. 2012), signifying improved test accuracy when compared directly.

The incorporation of pore pressure transducers at various positions within a spherical penetrometer (Piezoball) serves as an adaptation that enables the measurement of excess pore pressure generated during penetration. This application also facilitates the execution of dissipation tests and the determination of consolidation coefficients and permeability parameters (DeJong et al. 2008).

In addition to estimating the undrained shear strength along the stratigraphy, a remolded strength through cyclic tests can be considered for clay sensitivity analysis (e.g., Yafrate and DeJong 2007). Also, complementing the cyclic measurements that allow the estimation of remolded parameters and sensitivity, monitoring the probe's resistance to extraction can be used for analysis of soil disturbance. Consequently, Yafrate et al. (2009) propose a method to predict remolded strength without conducting cyclic tests, potentially reducing testing time and costs in practice.

In the present study, complementing the analysis of undrained shear strength and degradation trough cycling, Yafrate et al. (2009) proposal for determining remolded strength is verified by conducting two piezoball tests, labeled as tests A and B. Standard cyclic tests were performed in test A, while extraction measurements were recorded after the dissipation test in test B.

1.1. Piezoball test

The piezoball test is commonly used for offshore testing, where extremely soft soils that require equipment capable of performing measurements with high accuracy are found (DeJong et al. 2010).

The determination of penetration strength, denoted as q_m, in the piezoball test is mainly a result of soil flow around the ball and is influenced by geostatic stress acting above and below the probe. The difference in acting stresses at the top and bottom of the ball depends on the ratio of the cross-sectional area of the probe (A_p) and from the pushing section immediately above (A_s). Following this matter, Randolph (2004) suggests that the stress difference due to the pushing rod above the penetrometer should be considered through a correction similar to that applied for the piezocone test to determine a net strength (q_{net}), using Eq. (1):

$$q_{net} = q_m - [\sigma_{v0} - u(1-a)]\frac{A_s}{A_p} \quad (1)$$

where σ_{v0} is the total stress, u is the hydrostatic pore pressure, and a is the ratio of equipment load cell areas. Considering a ratio between the pushing system and ball projection area ($A_R=A_p/A_s$), a 10:1 ratio is usually indicated (Yafrate et al. 2009; Lunne et al. 2011). However, experimental results report that ratios greater than 5:1 are adequate and enough to minimize the effect of the pushing rod on the soil flow mechanism around the probe and, consequently, on the measurements of q_m.

Piezoball test with cyclic tests can be performed at specific depths in search of soil strength degradation (DeJong et al. 2010). It is recommended that for such tests, the minimum range of cyclic loading be set at 150 mm or three times the diameter of the ball. Additionally, to stabilize the strength degradation adequately, approximately ten cycles are advised (Chung and Randolph 2004; Yafrate and DeJong 2005; Lunne et al. 2011; Yubin et al. 2019). Furthermore, numerical simulations indicate that employing three penetrometer diameters ensures that the soil at the midpoint of the cycle amplitude undergoes complete passage through the flow mechanism (Zhou and Randolph 2009).

When performing the cyclic test, the remolded penetration strength (q_{rem}) is defined as the average of the penetration (q_{in}) and extraction (q_{ext}) measurements after the 10th cycle or stabilization. This number must be informed if the stabilization occurs in more than ten cycles (DeJong et al. 2010)

DeJong et al. (2010) recommend that cycles be performed immediately after penetration of the probe at a depth of interest since the time between penetration and extraction may be crucial due to the possibility of partial consolidation after initial ball penetration. Yafrate et al. (2007) observed an increase in q_{ext} in the Gloucester field, attributing it to an extended delay time between penetration and extraction.

Einav and Randolph (2005) delved into the decay of strength mobilized throughout penetration cycles and formulated a theoretical model to depict a strain-softening behavior during cycles. Building upon the work of Einav and Randolph (2005), Yafrate et al. (2009) revised their expression, incorporating parameters such as the number of cycles (n) and the number of cycles necessary for degradation to achieve 95% (N_{95}), as outlined in Eq. (2):

$$\frac{q(n)}{q_{in}} = \frac{q_{rem}}{q_{in}} + \left(1 - \frac{q_{rem}}{q_{in}}\right) e^{-3(n-0.5)/N_{95}} \quad (2)$$

where q_n is the strength of a given cycle, q_{in} is the strength for the initial penetration, and q_{rem} is the remolded strength. The number of cycles to define N_{95}, ninety-five percent degradation, must be defined based on the measured initial and remolded penetration resistance.

In the same research, Yafrate et al. (2009) proposed relation to predicting the remolded strength (q_{rem}) considering extraction measurements when no cycles are performed, Eq. (3). Moreover, the authors proposed that the estimation of N_{95} could be directly derived from Eq. (4), which was formulated based on Eq. (3), leading to Eq. (5). These equations proposed by Yafrate et al. (2009) were developed through the analysis of 20 piezoball tests carried out across five distinct sites.

$$\frac{q_{rem}}{q_{in}} = \left(\frac{q_{ext}}{q_{in}}\right)^{2.8} \quad (3)$$

$$N_{95} = 9.6\left(\frac{q_{ext}}{q_{in}}\right) \quad (4)$$

$$\frac{q(n)}{q_{in}} = \left(\frac{q_{ext}}{q_{in}}\right)^{2.8} + \left(\frac{q_{ext}}{q_{in}} - \left(\frac{q_{ext}}{q_{in}}\right)^{2.8}\right) e^{-\frac{3(n-1)}{9.6\left(\frac{q_{ext}}{q_{in}}\right)}} \quad (5)$$

The undrained shear strength (S_u) can be estimated by the ratio q_{net} and a ball factor (N_B), according to Eq. (6):

$$S_u = \frac{q_{net}}{N_B} \quad (6)$$

where N_B is a strength factor, which depends on the roughness of the sphere described by a roughness factor (α).

Randolph's theoretical solution (2004) suggests that the roughness factor can range from 0 (indicating a perfectly smooth surface) to 1 (representing a rough surface), resulting in corresponding values of N_B between 10.97 and 15.31, respectively. Despite this significant variability in N_B values, Chung and Randolph (2004) advocate for a specific value of 10.5 for flow penetrometers. This value has shown consistency in estimating S_u (undrained shear strength) during field tests when compared to results obtained from the standard vane test.

The sensitivity of clays can be directly determined from the data obtained from the field vane test (FVT), as represented by Eq. (7). Yafrate et al. (2009), drawing on data collected from five distinct sites, propose empirical ratios between qin/qrem (Eq. (8)) and q_{in}/q_{ext} (Eq. (9)) to estimate soil sensitivity utilizing information obtained from flow penetrometers:

$$S_T = \frac{S_u}{S_{ur}} \quad (7)$$

$$S_T = \left(\frac{q_{in}}{q_{rem}}\right)^{1.4} \quad (8)$$

$$S_T = \left(\frac{q_{in}}{q_{ext}}\right)^{3.7} \quad (9)$$

According DeJong et al. (2011) the primary soil property that influences values of N_B is sensitivity (S_T), presented in Eq. (7), suggesting that the estimation of the strength factor could follow this parameter according to Eq. (10). Building upon the proposal by Yafrate et al. (2009), they also suggest an equation based on q_{in}/q_{ext} (Eq. (11)) for estimating sensitivity.

$$N_B = 13.2 - \frac{7.5}{1+\left(\frac{S_T}{10}\right)^{-3}} \quad (10)$$

$$N_B = 13.2 - \frac{7.5}{1+\left(\frac{q_{in}/q_{ext}}{1.9}\right)^{-20}} \quad (11)$$

For undrained remolded strength S_{ur}, an appropriate factor N_{rem}, other than N_B must be considered (Eq. (12)). A solution for estimating N_{rem} from S_T was proposed by Yafrate et al. (2009), (Eq. (13)). If the sensitivity is not directly measured, the remolded strength factor can also be estimated using the extraction ratio due to the relationship between soil sensitivity and the extraction ratio (Eq. (14)).

$$S_{ur} = \frac{q_{rem}}{N_{rem}} \tag{12}$$

$$N_{rem} = 13.2 + \frac{7.5}{1+\left(\frac{S_T}{8}\right)^{-3}} \tag{13}$$

$$N_{rem} = 13.2 + \frac{7.5}{1+\left(\frac{q_{in}/q_{ext}}{1.8}\right)^{-20}} \tag{14}$$

In a more practical approach, the ball factors can be directly obtained from calibration against FVT or undrained shear strength from laboratory triaxial tests (DeJong et al. 2010).

2. Methods

2.1. Characterization Campaign

The experimental program was conducted in the municipality of Tubarão, in Santa Catarina, in the southern region of Brazil. The soft soil deposit is situated in the delta of the Tubarão River, bordered to the North and West by Precambrian crystalline rocks of the Atlantic Shield, and to the South and East by lagoon and aeolian deposition systems.

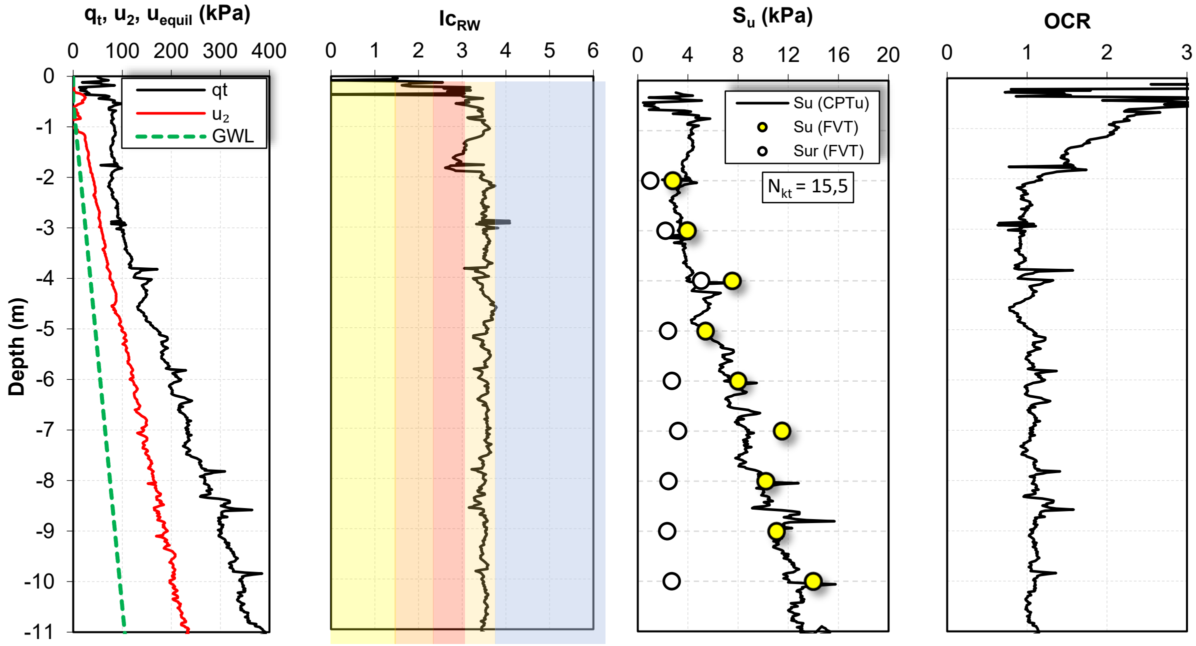
Sedimentary soil deposits in the region are predominantly found in the deltaic plain covering approximately 250 km^2 (Nascimento Jr 2011). The environmental conditions of the site have led to the formation of typical geological soft soils, typically ranging from normally consolidated to slightly pre-consolidated, characterized by the presence of organic matter, high compressibility, and low values of shear strength parameters (Odebrecht and Schnaid 2018)

The region has been investigated with piezocone-type field tests, vane tests, Marchetti dilatometers, and laboratory tests for characterization (Mantaras et al. 2014; Schnaid et al. 2016; Odebrecht and Schnaid 2018).

The conventional test campaign in the present research complies with standard piezocone tests, vane tests, and sample collection for characterization. Piezocone dissipation tests were performed at three depths (4.8, 6.8, and 7.8 m).

Laboratory characterization has revealed that the site primarily consists of silt (43% silt, 24% clay, and 33% sand) with a specific gravity of 2.71 g/cm^3 and exhibits high plasticity (Plasticity Index - IP approximately 18%), classifying it as MH according to USCS. These soil characteristics are consistent with Brazilian clay soils (Jannuzzi 2009; Schnaid 2009; Baroni 2010; Dienstmann et al. 2021).

In terms of field test results, Figure 1 displays standard piezocone test outcomes, including tip penetration resistance (q_t), pore pressure (u_2), Soil Index behavior (Ic_{RW}) from Robertson and Wride (1998), undrained (S_u), and remolded (S_{ur}) shear strength values with depth, as well as the interpretation of over consolidated ratio (*OCR*). These results indicate that the site is predominantly composed of clay soils exhibiting low values of tip strength (q_t ranging from 10 to 400 kPa) and excess pore pressure generation (u_2 ranging from 0 to 230 kPa). Moreover, the values of Ic_{RW} fall within the range of 3.6, corresponding to clay and organic clays as proposed by Robertson and Wride (1998). The undrained shear strength (S_u) obtained from vane tests increases with depth from 3 to 12 kPa, and these values were utilized to define a N_{kt} cone factor of 15.5, which is depicted in Figure 1c to delineate the S_u profile. Additionally, Figure 1c illustrates the remolded shear strength obtained through vane tests, which can be used to establish a sensitivity (S_T) ranging from 1.5 to 5.2 with depth. Furthermore, Figure 1d illustrates the *OCR* interpretation based on Konrad and Law (1987), indicating that the soil below 2 m depth exhibits *OCR* values close to unity, suggesting a normally consolidated behavior of the material.



(a) (b) (c) (d)

Figure 1. Typical soil profile from CPTu and vane test measurements.

2.2. Equipment

The equipment used for the piezoball test has a diameter of 80 mm, resulting in a cross-section of 50 cm². The ratio between this area and the cross-section of the pushing rod just above the ball (A_s/A_p) is 7:1. The piezoball test also featured pore pressure measurements via three pressure transducers installed at the tip (u_1), middle face (u_2 = 45º), and on the equator line of the sphere (u_3 = 90º). A load cell is positioned immediately behind the probe, consisting of four strain gauges protected by a sealing system through O-rings, to record the penetration or extraction resistances. All equipment was calibrated in the laboratory and met the minimum requirements indicated in ASTM D5778 (2020) before conducting field tests.

2.3. Procedures

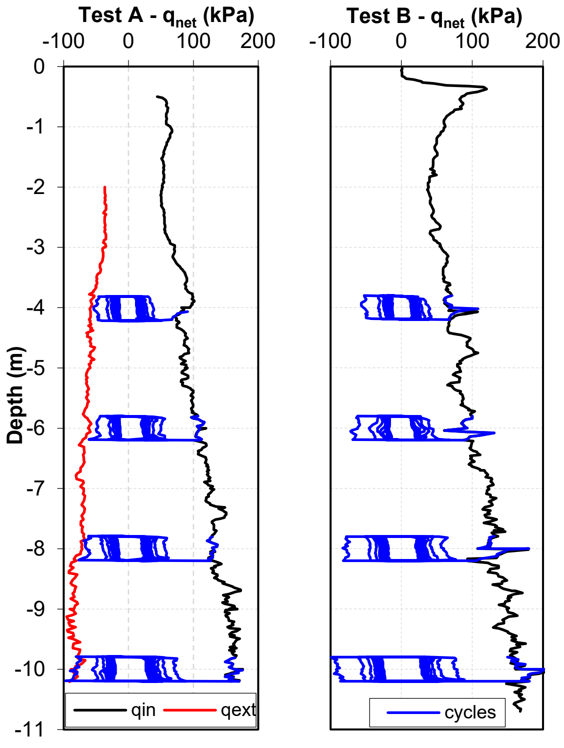
Two piezoball tests were performed with a standard penetration rate of 20 mm/s called A and B tests. Cyclic tests were performed in both tests at depths of 4, 6, 8, and 10 meters, with a cycle range of 40 cm (5 diameters). A minimum number of ten cycles was adopted as a reference. However, the tests were taken more cycles to ensure stabilization. The differences between tests A and B are as follows: in test A, the cycles were performed at the established depth, and the probe was extracted after performing the cycle at a depth of 10 m. Then, the extraction resistance was recorded, providing a continuous profile during the removal of the penetrometer; in test B, a dissipation test was conducted before the cycles were performed at the established depths. The dissipations of test B were performed at the reference depths of the cyclic test, i.e., at depths of 4, 6, 8, and 10 m. Once the excess pore pressure at the reference depth was dissipated, cycling was performed at that depth.

3. Results and interpretation

Figure 2 (a) and (b) shows the results of q_{net} for penetration and for cycles in tests A and B, respectively. The values of q_{net} are results of Eq. (1), and all analyses from strength measurements (e.g., S_u and S_{ur}) were performed using net penetration values, considering the hydrostatic pore pressure according to Randolph's (2004) recommendation.

Some considerations were tested for analyzing the q_{ext}/q_{in} ratio proposed by Yafrate et al. (2009) (Eq. (3)) to estimate the remolded penetration resistance with results displayed in Figure 3. The considerations are listed below:

1. Values of q_{ext}/q_{in} were taken directly from the first penetration and extraction of each cycle in tests A, and B. Values considering this approach were analyzed and are indicated on the graph with a Δt of 30 s, which refers to the time between recording the values of q_{in} and q_{ext};
2. Values of q_{ext}/q_{in} were calculated after concluding test A, taking q_{ext} from the total extracting measurements. In this condition, Δt – time gap between measurements - varies depending on the depth (e.g., the time between q_{ext}/q_{in} was 1410 s at 10 m depth, while the time was over 4700 s for the depth of 4 m);
3. Values of q_{ext}/q_{in} calculated considering the resistance q_{in} before the dissipation test was performed in test B, while q_{ext} was taken after the dissipation, considering the first cycle. In these hypotheses, time also varies according to the required consolidation times.



(a) (b)

Figure 2. Profiles of (a) net penetration, extraction resistance, and cycles-Test A; (b) net penetration resistance, and cycles-Test B.

Based on Figure 3, it is possible to see that the proposed relation between q_{ext}/q_{in} and q_{rem}/q_{in} is better suited to the results with the shortest times between the q_{in} and q_{ext} readings (best results were obtained considering Δt of 30s – tests A and B hypothesis *1* – measurements of the cycle). The time between q_{in} and q_{ext} measurements seems to be substantial for the analyses involving the proposed ratio since the results of test A deviate from the regression when Δt increases in hypothesis *2*, which derives q_{ext} from the total extraction values: observing results indicate that for 10m depth, the extraction reading fall into the proposed relation since the time lap is the shortest evaluated (Δt of 1410s). The same observation can be extended considering results of test "*B – Before diss*" (hypothesis *3*), where a lower q_{ext}/q_{in} ratio was obtained at a depth of 10m due to the lower Δt compared to other dissipation tests.

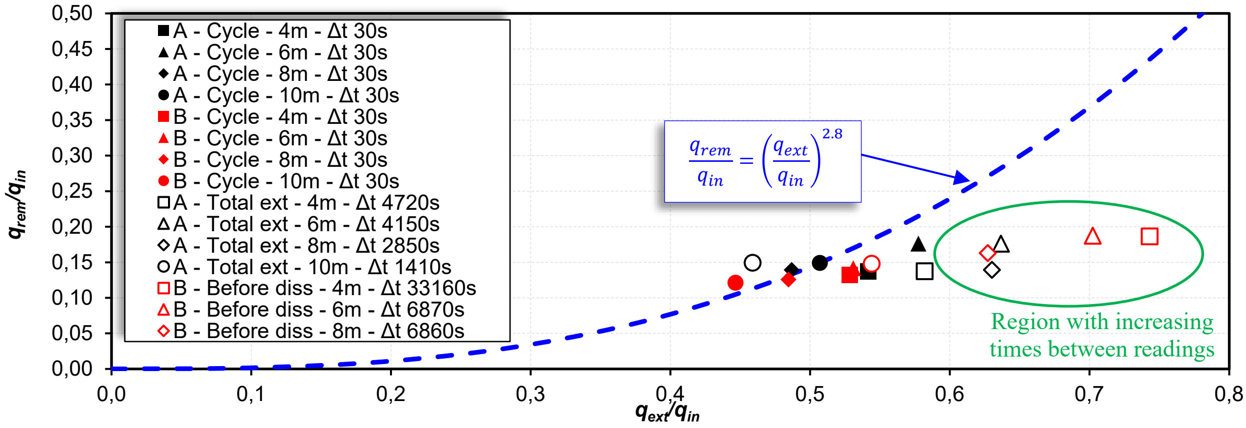


Figure 3. Relationship between extraction ratio q_{ext}/q_{in}) and normalized remolded resistance (q_{rem}/q_{in}) (Δt is defined as the time delay between q_{in} and q_{ext} measurements.

According to DeJong et al. (2010), this can occur due to a partial reconsolidation of the material after an initial penetration or thixotropic hardening effect. This effect must be considered for deeper tests to measure in the first meters of depth and needs further evaluation. In this sense, in the case of the Tubarão soft soil, the values of q_{ext}/q_{in} with high times between recording the measures move away from the Yafrate et al. (2009) proposal, creating a warning criterion for future applications. Additionally, it is recommended that the analysis considering extraction be carried out on a monotonic test, where only penetration and extraction are carried out. The estimate considering a profile after consolidation (hypothesis *3*) proves the effect of drainage, sample restructuring, and its influence on the remolded resistance, which can lead to interpretation errors.

For undrained resistance determination using the piezoball test, it is necessary to define the ball factors N_B and N_{rem}, the first for the natural condition of the test and the second for the remolded condition. The following possibilities were tested: determination of N_B and N_{rem} through direct measurements of undrained resistance obtained by FVT; and determination of strength factor coefficients considering the proposals of DeJong et al. (2011) (Eq. (10) and (11)) and Yafrate et al. (2009) (Eq. (13) and (14)). Equations (10) and (13) consider the sensitivity of the soil, which was obtained directly from the FVT, while Eq. (11) and (14) consider the extraction ratio (q_{in}/q_{ext}), which was analyzed for hypotheses *1* and *2* of Test A.

Figure 4 shows the values of strength factor (N_B – Figure 4a; and N_{rem} - Figure 4b) along the depth and the respective undrained shear strength results (S_u – Figure 4c; and S_{ur} – Figure 4d) for the FVT and CPTu, as well as the values from hypotheses *1* (cycle) and *2* (total extraction) for the A test. Concerning the N_B results, values obtained directly from vane tests FVT (Eq. (6)) range from 10 to 19, while the application of Eq. (10) resulted in almost constant values along the depth (≈ 12.8). The same tendency was observed considering Eq. (11) and q_{in}/q_{ext} measurements for hypothesis *2*, using extration values, an exception was observer for the 10 m depth. For N_{rem} determination (Figure 4b) values derived from the FVT S_{ur} measurements (Eq. (12)) were lower than the proposed estimates in Eq. (13) and (14), and the analyses are similar to the N_B reviews: a tendency of constant value around 13 was obtained from test A (Eq. (13)).

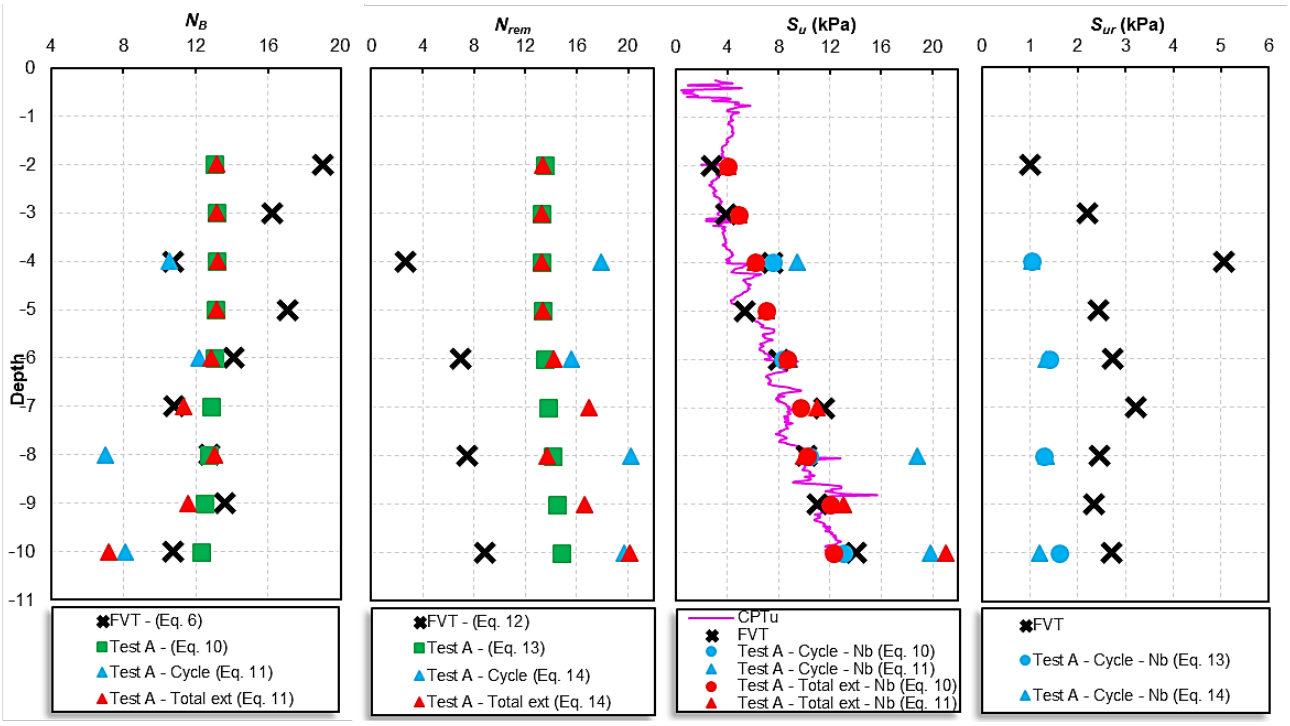
After the definition of strength factors N_B and N_{rem} the determination of undrained strength and remolded undrained strength was established, resulting in Figure 4c and 4d. The best approximation considering the determination of undrained strength by both the vane test and the piezoball test was obtained by considering the determination of N_B according to Eq. (10), whereas the results from Eq. (11) were the most divergent.

Finally, when considering the remolded strength, an apparent discrepancy was observed between the results obtained from the vane test and the piezoball test. However, such divergence occurs due to the low magnitude of the values (less than 3 kPa). Another possible explanation for the disparity in values is the different soil failure mechanism between the vane test and full flow penetrometers. In the vane test, failure occurs through a shear plane defined on a cylindrical surface; in other words, the failure surface and process remain constant during a degradation test. In contrast, in the piezoball penetrometers, the failure mechanism is more complex, involving compression and distortion (shear) stresses, resulting in distinct structural rearrangement (DeJong et al., 2011).

4. Conclusions

In this research, piezocone, vane test, and two piezoball tests were performed in a soft soil deposit in southern Brazil (Tubarão deposit), and undeformed samples were collected at three depths for characterization. Cyclic and dissipation tests were performed at four depths for two piezoball tests (A and B).

In general, the performed piezoball tests displayed a good repeatability. The effect of time between q_{in} and q_{ext}, insertion, and extraction readings was evaluated for the piezoball test using different methodologies: values obtained through penetration and total extraction (test A) and penetration and extraction readings before and after a dissipation test (test B). .



(a) (b) (c) (d)

Figure 4. Typical soil profile from CPTu and vane test measurements.

Regarding the estimation of undrained shear strength, good agreement was observed when applying the approach proposed by DeJong et al. (2011). However, the remolded strength was underestimated using the proposal by Yafrate et al. (2009), likely due to the different failure mechanisms between the vane test and the flow penetrometers.

Additionally, it was noted that the proposals for estimating degraded strength values should be cautiously adopted, especially with higher times between measurements. Therefore, a recommendation for flow penetrometer tests is to measure q_{in} and q_{ext} with the shortest possible time interval to avoid overestimating the values of q_{rem}.

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