Cyclic T-Bar Tests to Evaluate the Remoulded Undrained Shear Strength of the Sarapuí II Soft Clay

G.M.F. Jannuzzi, F.A.B. Danziger, I.S.M. Martins

Abstract. The undrained remoulded shear strength of a clay, s_{ur}, is an important parameter in the design of a number of geotechnical applications. In the case of onshore tests the value of s_{ur} is generally obtained from vane tests. Recently, cyclic T-bar tests have been used to obtain the s_{ur} value, especially for offshore applications. Seventeen T-bar cyclic tests in two deployments have been performed at Sarapuí II soft clay test site. In a third deployment only penetration was recorded. The presence of roots has influenced the values of the initial penetration in one of the deployments, as observed in another test site, which is a consequence of the shape of the penetrometer and may be considered a shortcoming of the test. Therefore, to know whether roots have influenced the test results in a site at least two repeatable tests must be performed. If cyclic tests are performed, their results can provide a good indication of the influence of the roots. Considering the vane shear test as reference for obtaining s_u and s_{ur}, $N_{T\text{-}bar}$ obtained from tests not affected by the roots ranged from 8.8 to 10.9, with an average of 9.8, while $N_{rem,\ T\text{-}bar}$ ranged from 14.1 to 19.5, with an average of 16.3. Therefore $N_{T\text{-}bar}$ values (related to the natural condition) were smaller than $N_{rem,\ T\text{-}bar}$ (related to the remoulded condition). The equations suggested by Yafrate *et al.* (2009) to evaluate the remoulded penetration resistance, the whole degradation curve and the sensitivity, based only on the initial penetration and extraction resistances have provided good results for the Sarapuí II soft clay, except in the case of very shallow depths.

Keywords: *in situ* testing, soft clay, T-bar, undrained shear strength, remoulded undrained shear strength, sensitivity.

1. Introduction

The remoulded undrained shear strength, s_{ur}, is an important parameter in the design of suction anchors and for offshore slope stability analyses. For suction anchors, the remoulded undrained shear strength is a key parameter for calculation of the penetration resistance and the under pressure required for installation. The remoulded undrained shear strength also influences the side shear resistance after penetration is completed (*i.e.*, "set-up") and thereby the holding capacity of an anchor. For offshore slope stability analyses, the remoulded undrained shear strength will influence the failure mechanism and the progressive failure of a potential slide (DeGroot & Lunne, 2007).

In the design of offshore piles the s_{ur} value (or the sensitivity, S_T, the ratio between the undisturbed shear strength, s_u and s_{ur}), is used to estimate the friction load during penetration (API, 2004). The s_{ur} value is also used in the design of torpedo piles (Medeiros Jr., 2010).

In the case of onshore tests the value of s_{ur} is generally obtained from vane tests. Recently, cyclic T-bar tests have been used to obtain the s_{ur} value, especially for offshore applications.

This paper analyses cyclic T-bar tests performed at Sarapuí II soft clay test site. Comparisons are made with values obtained from electrical vane tests.

2. T-bar tests

2.1. Historical

T-bar tests have been originally developed to be used in centrifuge testing at the University of Western Australia (UWA) by Stewart & Randolph (1991), aiming at the determination of a continuous profile of the undrained shear strength of soft clays. The test consisted of the penetration of a cylindrical horizontal bar, as shown in Fig. 1, at a rate of 3 mm/s.

This new test would combine the advantages of the CPT or CPTU (which gives a continuous profile of "strength"), and the vane test (which gives an "exact" or direct measure of shear strength) (Stewart & Randolph, 1991).

The T-bar was firstly used in the field in 1994 (Stewart & Randolph, 1994), in Burswood, Australia, and comprised a 50 mm in diameter and 200 mm long aluminium bar. The same rate of penetration used in the piezocone test, 20 mm/s, was also used in the T-bar test. Later the T-bar was used offshore, also in Australia, and changed its dimensions to a 40 mm in diameter and 250 mm long bar (Randolph *et al.*, 1998). These dimensions are included in the only standard that covers T-bar penetration testing, the NORSOK G-001 (Standards Norway, 2004) (Lunne *et al.*, 2011).

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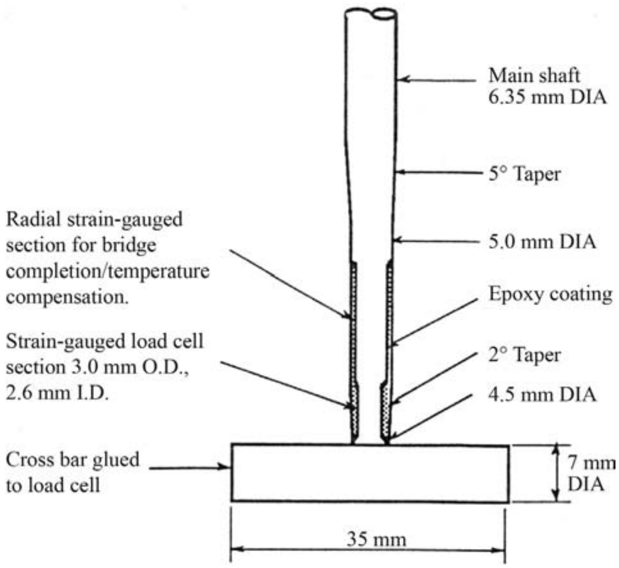

Figure 1 - Schematic diagram of the T-bar (Stewart & Randolph, 1991).

The resistance during penetration, q_m, is obtained from the load measured at the load cell divided by the projected area of the T-bar, *i.e.* 100 cm^2 in the case of *in situ* tests.

The main advantage of the T-bar test with respect to the CPTU test was thought to be that the interpretation of the T-bar test is based on the analytical solution of Randolph & Houlsby (1984), which shows that the penetration resistance does not depend on the rigidity index I_r (= G/s_u, where G is the shear modulus), as in the case of the piezocone (*e.g.*, Levadoux, 1980, Teh, 1987, Teh & Houlsby, 1991).

Other advantages of the T-bar are (i) improved accuracy in soft soils due to a larger penetrometer projected area and (ii) minimal correction for overburden stress (*e.g.*, Yafrate *et al.*, 2009).

Cyclic tests have been performed by Hefer & Neubecker (1999), aiming at the evaluation of the undrained remoulded shear strength. Cycles of penetration and extraction over a fixed 0.5 m depth interval were performed until it was apparent that a true residual (as mentioned by Hefer & Neubecker, 1999) or remoulded soil strength had been achieved.

T-bar cyclic tests were initially performed during extraction. Then this procedure was changed, and the cyclic tests were recommended to be performed during penetration phase, because partial consolidation of the soil around the push rod would result in higher extraction and remoulded resistances being measured if the cyclic penetration test is carried out during the extraction phase of the test (*e.g.*, Lunne *et al.*, 2011). According to those authors it is recommended that ten cycles of penetration and extraction through a minimum stroke of 0.15 m should be undertaken. Yafrate *et al.* (2009) mentioned that full strength degradation occurs within five to ten cycles. The penetration and extraction rate for the cyclic test should be the same as for the penetration phase, *i.e.* 20 mm/s should be used.

To the authors' knowledge, the first T-bar tests in Brazil were carried out in a soft clay deposit at the site where the 2007 Pan American Games Athletes' Village was to be built, at Barra da Tijuca, Rio de Janeiro (Macedo, 2004, Almeida *et al.*, 2006, Danziger, 2007). Two series of tests were performed with a T-bar penetrometer built from a COPPE piezocone penetrometer. Penetration and extraction resistance have been measured in the first series, where four tests were performed. Cyclic tests - during extraction phase - were conducted in the second series, where two tests have been carried out. Five cycles of penetration have been performed through a 1 m stroke, in the intervals 3-4 m, 5-6 m, 6-7 m, 7-8 m. The tests were part of a joint research project between NGI (the Norwegian Geotechnical Institute) and COPPE/Federal University of Rio de Janeiro. The penetration resistance of the first series of tests is shown in Fig. 2. Cyclic tests are shown in Fig. 3. Penetration values are plotted as positive values while negative values are used in the case of extraction.

2.2. Interpretation

As mentioned before, the interpretation of the T-bar test was based on the analytical solution of Randolph & Houlsby (1984). Classical plasticity theory was used to de-

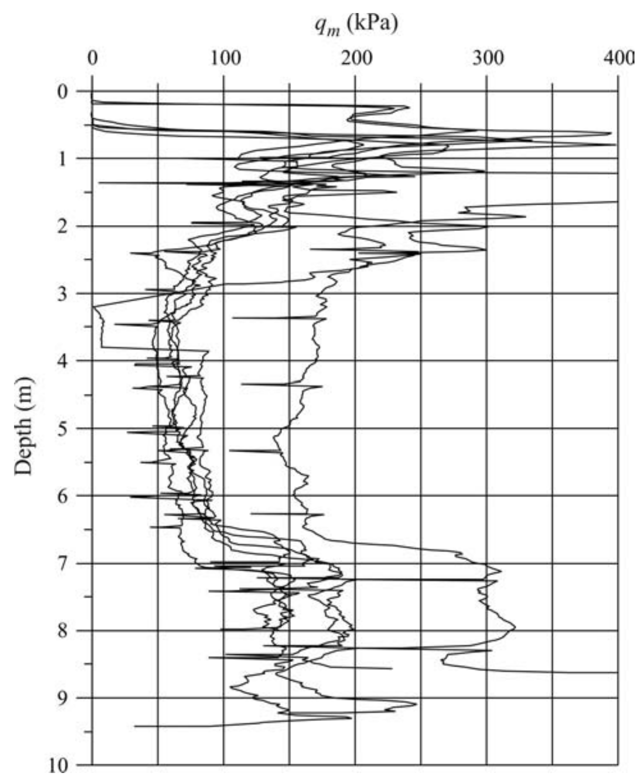

Figure 2 - Penetration resistance from T-bar tests at Pan American Games Athletes' Village test site (adapted from Macedo, 2004).

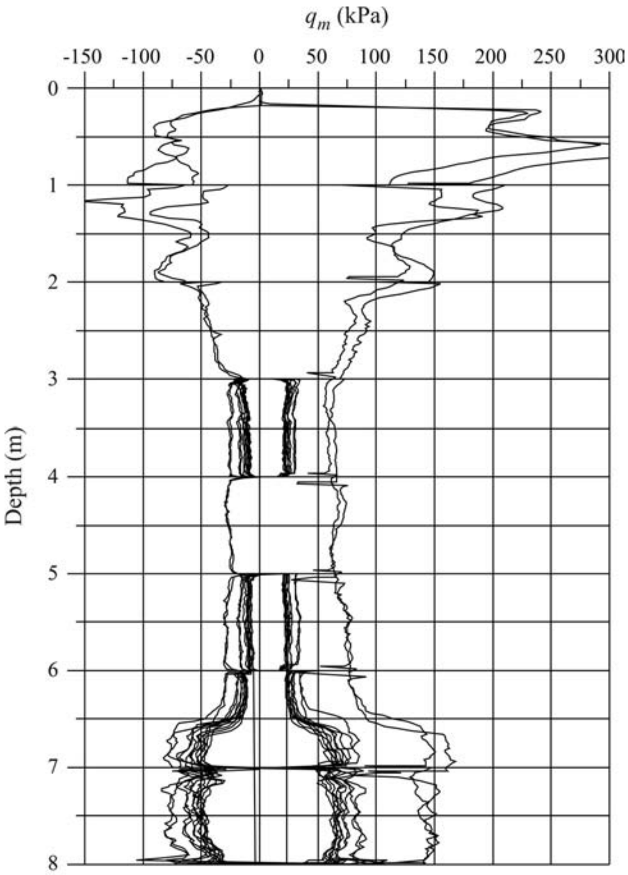

Figure 3 - Cyclic tests at Pan American Games Athletes' Village test site (adapted from Macedo, 2004).

rive exact solutions for the limiting lateral resistance of a circular pile (with infinite length) embedded in a saturated clay. Lower bound and upper bound approaches were used, and the final failure load per unit length of pile, P , normalized by the pile diameter, d , and s_u was obtained. The corresponding ratio is the $N_{T\text{-}bar}$ factor, Eq. 1. The solution obtained by Randolph & Houlsby (1984), amended by Murff *et al.* (1989), has been presented by Stewart & Randolph (1991), as shown in Fig. 4.

$$\frac{P}{s_u d} = N_{T-bar} \tag{1}$$

The resistance during penetration, q_m, is obtained from Eq. 2

$$q_m = \frac{P}{d} \tag{2}$$

The analytical factor $N_{T\text{-}bar}$ depends on the surface roughness of the cylinder, described by its adhesion factor, α. According to Randolph & Houlsby (1984) and Stewart & Randolph (1991), the adhesion factor very difficultly would reach 0 (perfectly smooth bar) or 1 (perfectly rough), thus a value of 10.5 was suggested for $N_{T\text{-}bar}$. According to

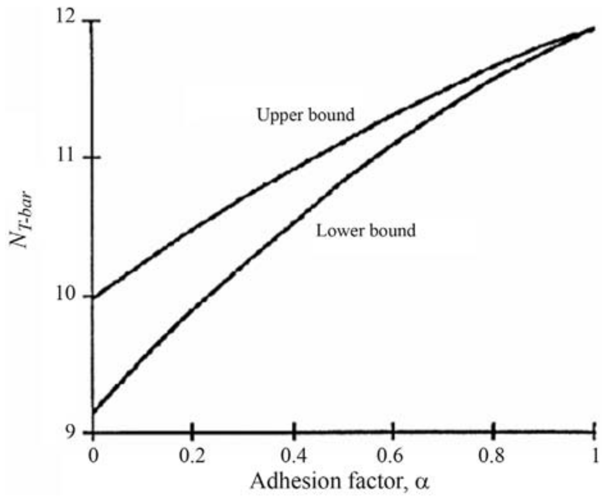

Figure 4 - Variation of $N_{T\text{-}bar}$ with surface roughness (Stewart & Randolph, 1991).

Stewart & Randolph (1991), the use of $N_{T\text{-}bar}$ = 10.5, associated to the very narrow range of possible factors for $N_{T\text{-}bar}$ (9.14 to 11.94), implies in a maximum error of 13%.

The initial papers about the T-bar mentioned that the *in situ* vertical stress is equilibrated across the T-bar, and thus there is no requirement to include a correction for the ambient stress level, unlike the CPT (Stewart & Randolph, 1994). Thus, the $N_{T\text{-}bar}$ factor was defined in terms of the total value of the T-bar penetration, or q_m (Eq. 2), as shown above. Watson *et al.* (1998) did mention a net value of penetration resistance, but also that there is no need to correct for overburden stress, and the measured penetration resistance is equal to the net penetration resistance.

Later, Chung & Randolph (2004) and Randolph (2004) suggested the correction shown in Eq. 3 to obtain q_{net}.

$$q_{net} = q_m - \left[\sigma_{vo} - u_o(1 - a_r)\right]\frac{A_s}{A_p} \tag{3}$$

where σ_{vo} = total vertical stress; u_o = hydrostatic pore pressure; a_r = load cell area ratio; A_p = the projected cross-sectional area of the T-bar and A_s = the cross-sectional area of the connection shaft (or push rods). Equation 3 must be used to correct both penetration and extraction resistances, inclusively during cyclic tests (Lunne *et al.*, 2011).

It follows that the $N_{T\text{-}bar}$ factor must be defined as in Eq. 4

$$N_{T-bar} = \frac{q_{net}}{s_u} \tag{4}$$

It must be pointed out that the value of q_{net} for the T-bar test is similar to the q_{net} obtained from the piezocone test, Eq. 5

$$q_{net} = q_t - \sigma_{vo} \tag{5}$$

where q_t is the cone resistance corrected for unequal end area, Eq. 6, from Campanella *et al.* (1982).

$$q_t = q_c + (1-a)u_2 \quad (6)$$

where q_c is the measured cone resistance, a the cone area ratio and u_2 the pore pressure measured at the cone shoulder.

Chung & Randolph (2004) verified that the correction for the T-bar is far less significant than that for the piezocone. This was largely due to the very small A_s/A_p ratio, typically 0.1 to 0.2 (Randolph, 2004).

Yafrate *et al.* (2009) mentioned that u_o in Eq. 3 should be replaced by the value of u_2 when it is available, which may occur when the T-bar is just the replacement of the cone tip from a piezocone penetrometer.

It must be pointed out that the theoretical analysis previously shown was based on plasticity solutions for simple rate independent, perfectly plastic soil models with isotropic strength (Randolph & Andersen, 2006). Recent numerical analysis performed by those authors, where anisotropy, rate dependency of shear strength and strain softening have been considered, have shown that all these factors do affect $N_{T\text{-}bar}$.

Data from ten sites, both onshore and offshore have been used by Low *et al.* (2010, 2011) to evaluate the effect of soil characteristics on piezocone, T-bar and ball penetration tests, as well as the corresponding *N* factors. *In situ* vane tests and laboratory tests (triaxial compression, triaxial extension and direct simple shear tests, providing respectively s_{uc}, s_{ue}, s_{uDSS}) have been used as references for the analysis. It was overall found (Low *et al.*, 2010) that the only significant trend to emerge from the database is the effect of the rigidity index on the cone factor N_{KT}, which increases with increasing I_r, as theoretically predicted (*e.g.*, Teh & Houlsby, 1991). Low *et al.* (2010) mentioned that, at least for the soils with S_T less than 6 that dominate the database, T-bar and ball penetration tests may potentially prove more reliable than CPTU in estimating s_{uave} (the average of s_{uc}, s_{ue} and s_{uDSS}) or s_{uvane} but the reverse is probably true for estimation of s_{uc}. Low *et al.* (2011) concluded that although theoretical solutions for penetrometers in isotropic, rate-independent and non-softening soils generally predict the trends of the field data, there are still discrepancies between the theoretical predictions and measured values. Further study is required to improve the theoretical solutions.

2.3. Other full-flow penetrometers

The T-bar is named a "full-flow" penetrometer because soil flows around the penetrometer during the penetration process, with soil occupying much of the same volume it did initially. This contrasts the cone penetrometer, where all soil is permanently displaced (Yafrate *et al.*, 2009). Other full-flow penetrometers are the ball penetrometer and the plate penetrometer. Figure 5 shows a schematic view of the "full-flow" penetrometers together with a regular 10 cm^2 piezocone.

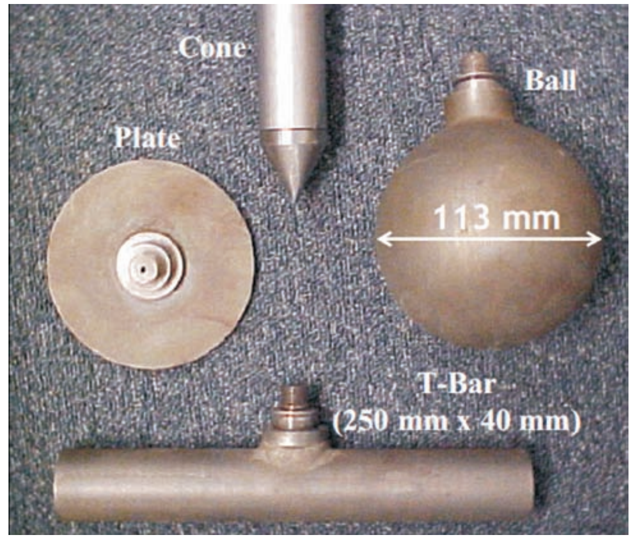

Figure 5 - T-bar, ball, plate and 10 cm^2 cone penetrometers (Randolph, 2004).

2.4. Degradation during cyclic testing

Cyclic tests have been presented in Fig. 3, where penetration and extraction resistances were plotted *vs.* depth. Another way of representing cyclic test results is to average the central part of each cycle stroke - to avoid the influence of conditions at the extreme of the cyclic zone - and plot both penetration and the modulus of the extraction values *vs.* number of cycle, which consists the so-called degradation curve (*e.g.*, Lunne *et al.*, 2011). It has been initially suggested that the cycle number for the initial penetration should be taken as 0.25 and initial extraction taken as 0.75 and so forth (Randolph *et al.*, 2007, Lunne *et al.*, 2011). Yafrate *et al.* (2009) mentioned that conventional practice is to present the initial penetration as cycle 0.5 and initial extraction as cycle 1. The degradation curves for Onsøy and Gloucester clays and the ball penetrometer using this representation are shown in Fig. 6. Both measured (q_m) and cor-

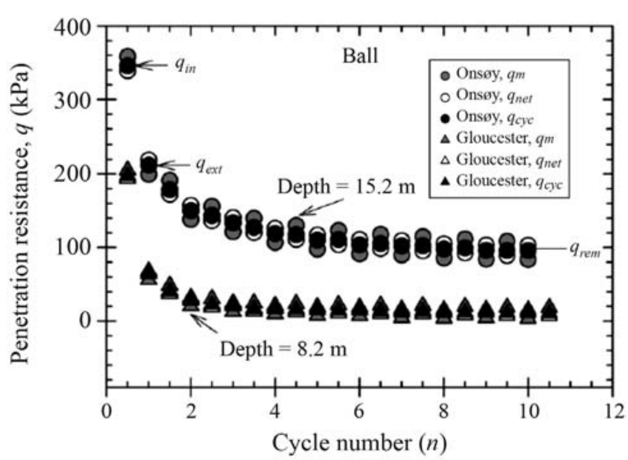

Figure 6 - Cyclic ball penetrometer degradation curves from Onsøy and Gloucester test sites (DeJong *et al.*, 2010a).

rected (q_{net}) values are shown in the figure. The values corresponding to the initial penetration are named q_{in} and those corresponding to the initial extraction q_{ext}.

As pointed out by Yafrate *et al.* (2009), during cyclic testing the magnitude of penetration and extraction resistance (both q_m and q_{net}) is not generally equal under remoulded conditions. To create a smooth degradation curve one-half of the difference between penetration and extraction resistance in the remoulded condition (termed the cyclic offset) is added to (or subtracted from) each value of net penetration resistance, resulting in q_{cyc} values in Fig. 6. According to those authors, the reason for this offset is not yet clear, and a number of factors can contribute to it.

To compare test results from different depths and locations, Yafrate *et al.* (2009) have normalized the penetration resistance values in the cycles, $q(n)$, with respect to the initial values, q_{in}. Test results from different test sites are presented in Fig. 7, which shows that the shape of the curve is affected by the soil sensitivity, the higher the sensitivity the faster the resistance degradation.

The normalized cyclic degradation curve inherently contains information regarding the soil sensitivity and the rate at which the soil strength reduces (strain softening), Yafrate *et al.* (2009). The soil sensitivity is related to the ratio q_{rem}/q_{in}, while the rate of softening is related to the ratio q_{ext}/q_{in}. It can be seen from Fig. 7 that the penetration resistance degrades more rapidly at the Gloucester test site (3 cycles to q_{rem}) than at the Onsøy test site (8 to 10 cycles to q_{rem}) due to the higher sensitivity at Gloucester. The rate of strain softening and sensitivity are interrelated.

Yafrate *et al.* (2009) suggested Eq. 7 to estimate the remoulded shear strength based only on initial penetration q_{in} and extraction q_{ext} values, *i.e.*, without the need of performing the cyclic test, aiming at initial estimates.

$$\frac{q_{rem}}{q_{in}} = \left(\frac{q_{ext}}{q_{in}}\right)^{2.8} \tag{7}$$

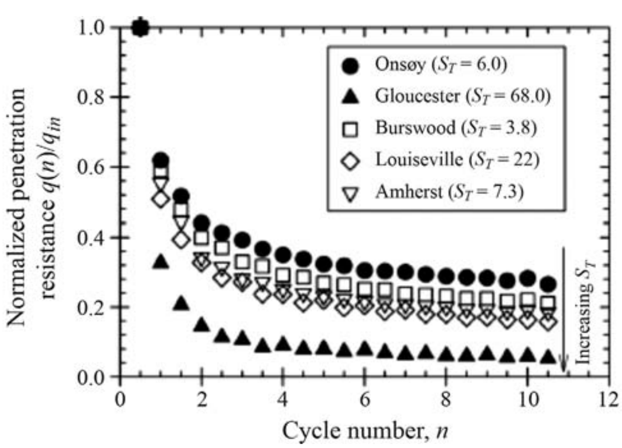

Figure 7 - Normalized cyclic degradation curves for various sites (Yafrate *et al.*, 2009).

The whole degradation curve can also be estimated based only on q_{in} and q_{ext} values, according to Eq. 8 below, valid for n ≥ 1 (Yafrate *et al.*, 2009).

$$\frac{q(n)}{q_{in}} = \left(\frac{q_{ext}}{q_{in}}\right)^{2.8} + \left(\frac{q_{ext}}{q_{in}} - \left(\frac{q_{ext}}{q_{in}}\right)^{2.8}\right) e^{-3(n-1)/(9.6(q_{ext}/q_{in}))} \tag{8}$$

2.5. Estimation of soil sensitivity

The soil sensitivity is not equal to the ratio q_{in}/q_{rem}, as one would expect to be, but rather can be estimated according to Eq. 9 (Yafrate *et al.*, 2009). Equation 9 was based on experimental values (Fig. 8), where the reference sensitivity was obtained from field vane tests. Equation 9 indicates that even with a significant number of cycles the T-bar is not able to completely remould the soil in the same way as the vane test does. Actually, *e.g.*, Randolph & Andersen (2006) and Lunne & Andersen (2007) have shown that different methods provide different values of the remoulded shear strength. Rate dependency of the remoulded shear strength in a similar way as intact shear strength may at least partly explain the mentioned differences (Lunne & Andersen, 2007).

$$S_T = \left(\frac{q_{in}}{q_{rem}}\right)^{1.4} \tag{9}$$

Due to the interrelationship between the rate of initial strain softening and the soil sensitivity, the soil sensitivity can also be estimated from the q_{in}/q_{ext} ratio, *i.e.* without the need of performing the cyclic test, according to Eq. 10, also based on field vane tests to obtain the sensitivity values.

$$S_T = \left(\frac{q_{in}}{q_{ext}}\right)^{3.7} \tag{10}$$

2.6. Estimation of remoulded bar factor

The $N_{T\text{-}bar}$ factor for the remoulded condition, $N_{rem,\,T\text{-}bar}$ is defined as

$$N_{rem,\,T-bar} = \frac{q_{rem}}{s_{ur}} \tag{11}$$

Yafrate *et al.* (2009) verified a trend of $N_{rem,\,T\text{-}bar}$ to increase with the increase of sensitivity, according to Eq. 12.

$$N_{rem,\,T-bar} = 12 + \frac{5.5}{1 + \left(\frac{S_T}{6}\right)^{-3}} \tag{12}$$

As a consequence of considering the reference shear strength both in undisturbed and remoulded condition from the vane test, and Eq. 9, it follows that $N_{T\text{-}bar}$ and $N_{rem,\,T\text{-}bar}$ are not equal.

3. The Test Site

The Sarapuí soft clay test site has been used since the 70's as a research site, and a number of *in situ* and laboratory tests have already been performed (*e.g.*, Lacerda *et al.*,

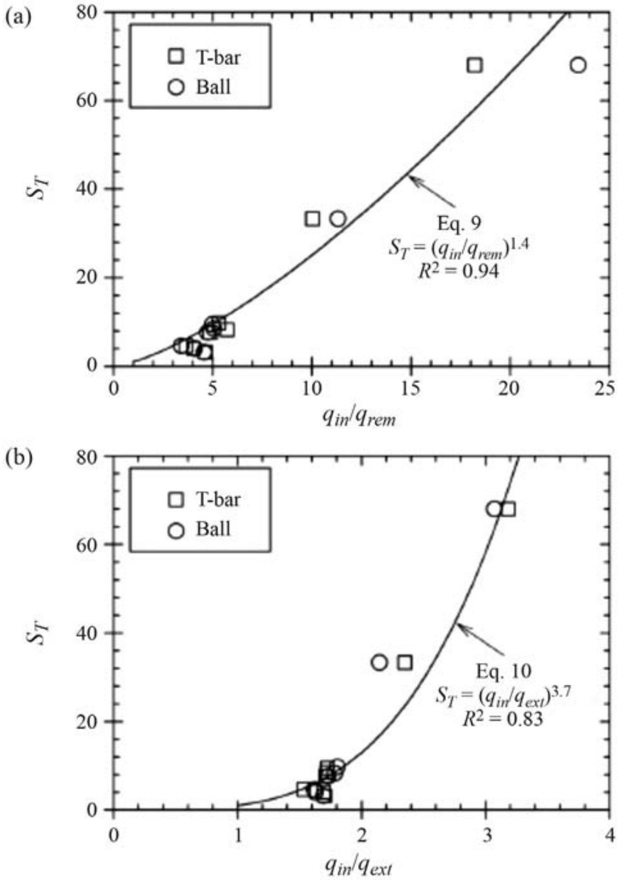

Figure 8 - Sensitivity as a function of (a) q_{in}/q_{rem} and (b) q_{in}/q_{ext} (Yafrate *et al.*, 2009).

1977, Werneck *et al.*, 1977, Ortigão *et al.*, 1983). A comprehensive report about the deposit has been provided by Almeida & Marques (2002). Geotechnical characteristics of the soil are included in Figs. 9 and 10, based on investigations carried out near the trial embankments sites. The very soft organic clay layer is about 11 m thick, and overlyes sand layers. The plasticity index (IP) of the Sarapuí clay decreases with depth, from around 100% to 50%. Stress history and compressibility characteristics of the deposit are shown in Fig. 10.

In the last fifteen years, however, security reasons have prevented the use of the test site. A new area (named Sarapuí II) in the same deposit, 1.5 km from the previous area and inside of a Navy Facility, has been used since then (Fig. 11). Two researches on pile behaviour have been carried out at Sarapuí II site (Alves, 2004, Francisco, 2004, Alves *et al.*, 2009). The initial tests with the torpedo-piezocone (Porto *et al.*, 2010, Jannuzzi *et al.*, 2010, Henriques Jr. *et al.*, 2010) have already been performed at Sarapuí II test site.

Although the whole deposit can be considered fairly homogeneous in horizontal directions, a number of *in situ* tests have been performed in this new area. In fact, 6 deployments of SPT's (performed at each meter in Brazil), 7 CPTU's, 51 vane tests (in 5 deployments) and 4 T-bar tests have been performed (Jannuzzi, 2009). The very soft clay layer in this particular area varies from 6.5 m to 10 m. This new area is been used by the Research Center of the Brazilian Oil Company (CENPES/PETROBRAS) and Federal

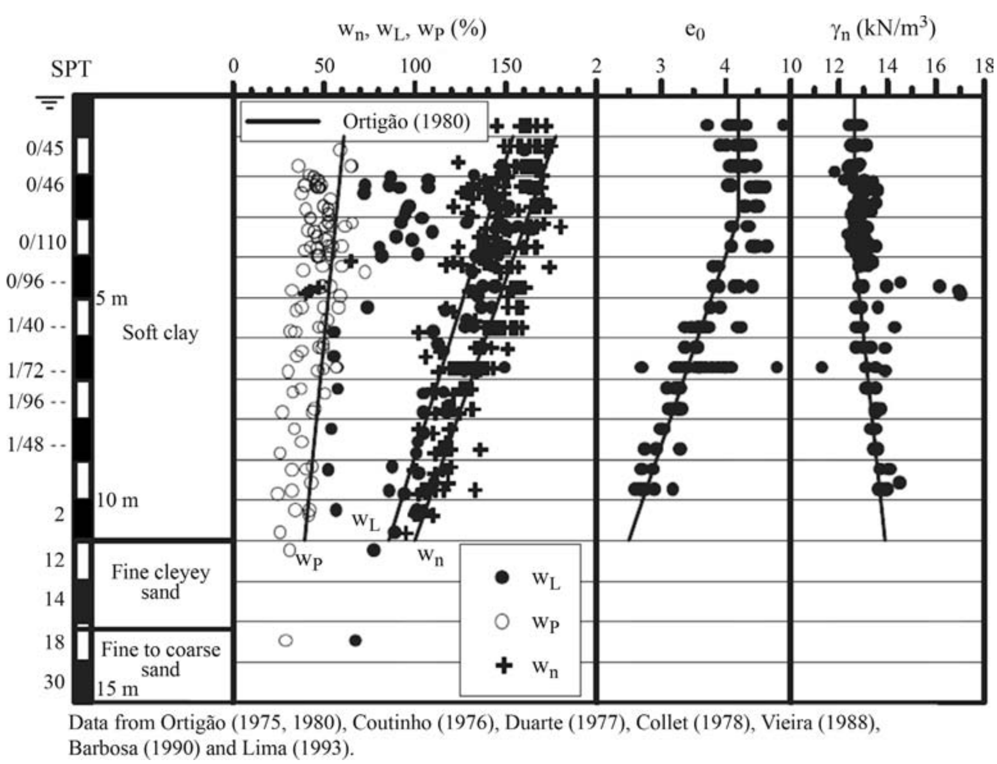

Figure 9 - Characteristics of Sarapuí soft clay deposit (Almeida & Marques, 2002).

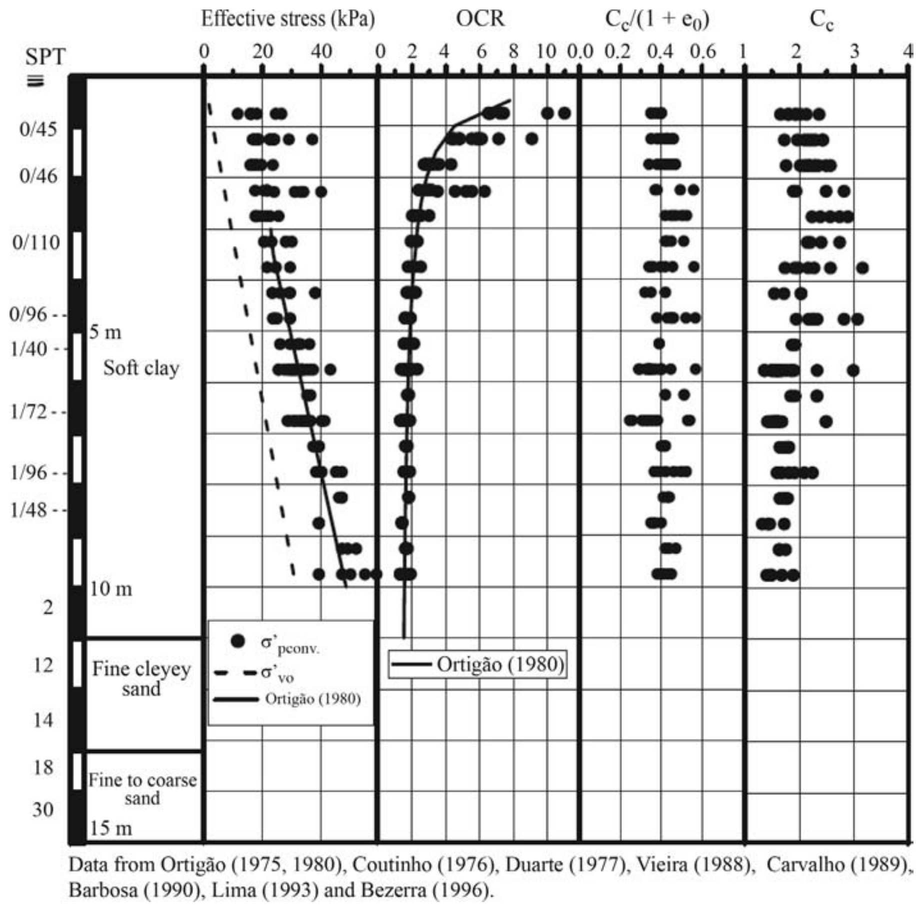

Figure 10 - Stresses and compressibility parameter profiles (Almeida & Marques, 2002).

Figure 11 - Sarapuí II test site with respect to the early Sarapuí I test site.

University of Rio de Janeiro as a state-of-the-art test site on very soft organic clay. Laboratory tests (triaxial and direct simple shear) on very high quality samples will be performed in 2013. Instrumented model torpedo-anchors will be tested in the same area. Fig. 12a shows corrected cone resistance q_t, pore-pressures at the cone shoulder u_2 and cone face u_1 *vs.* depth from a typical piezocone test. It can be seen that the very soft clay layer is around 8 m deep, and

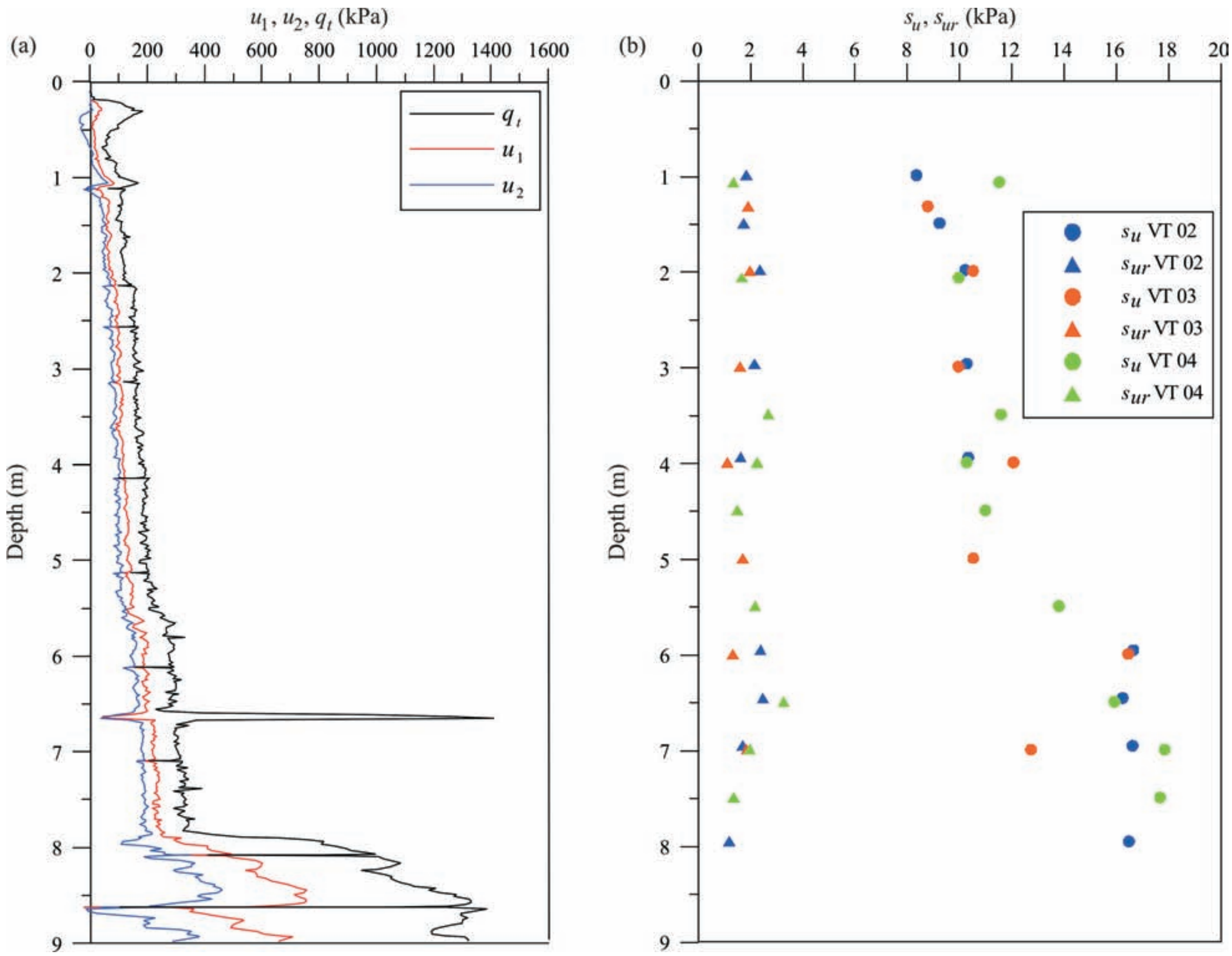

Figure 12 - (a) Cone resistance and pore pressure from typical piezocone test; (b) undrained shear strength and remoulded undrained shear strength from vane tests in 3 deployments; Sarapuí II soft clay test site (Jannuzzi, 2009).

a clayey-silt layer underlies the very soft clay. Fig. 12b shows s_u and s_{ur} values obtained from 3 vane test deployments. The equipment used is able to measure the torque close to the blade, aiming at minimizing the rod friction, which was developed in a joint research project among the Federal University of Rio de Janeiro, the Federal University of Pernambuco and Grom Eng. (*e.g.*, Nascimento, 1998, Oliveira, 2000, Coutinho *et al.*, 2000, Crespo Neto, 2004). Further details of the *in situ* tests can be obtained in Jannuzzi (2009).

4. Tests Performed

Four T-bar tests have been performed, three of them in the natural soil and one under an existing embankment, in order to verify the ability of the T-bar to identify the influence of the embankment on the soft material (Jannuzzi *et al.*, 2012). Values of the measured penetration resistance, q_m, for the three tests performed in the natural soil are presented in Fig. 13. It can be seen that the values of q_m corresponding to T-bar 3 are greater than the other tests, which was attributed to the shape of the T-bar allowing the existing roots of the vegetation to be pushed together with the penetrometer, increasing the corresponding resistance (see Fig. 14). It must be pointed out that the roots layer is roughly 30 cm thick, where the upper half is composed by thick roots (few millimeters, reaching in some cases 3 cm in diameter) and the lower half typically 1 mm in diameter. Similar phenomenon was verified by Macedo (2004), see also Almeida *et al.* (2006) and Danziger (2007). This means that when performing T-bar tests in places where there is an intense presence of roots, at least two tests with good repeatability must be performed in order to be sure that the results are not affected by the roots. Another way of checking whether roots are influencing the penetration resistance is through cyclic test results, as shown later.

Seventeen cyclic tests were conducted during extraction phase in T-bar 2 and 3, which are plotted *vs.* depth in Figs. 15 and 16, and summarized in Table 1. Each cyclic test consisted in 5 or 6 cycles. Due to localized mal-functioning of the device that holds the rods during penetration and extraction - allowing them to have some sliding, thus preventing an accurate control of the depth -, test T-bar 2-7

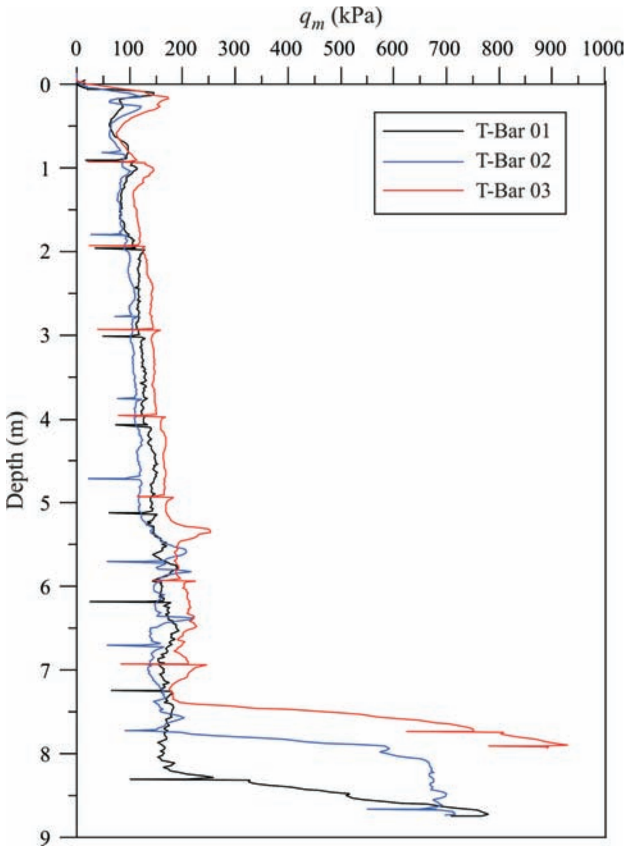

Figure 13 - Measured penetration resistance, q_m, *vs.* depth.

Table 1 - Cyclic tests performed.

Test	Nominal interval cycled (m)	Average depth (m)	Number of cycles
T-bar 2-1	0.00-0.73	0.36	6
T-bar 2-2	0.73-1.73	1.23	6
T-bar 2-3	1.73-2.73	2.23	6
T-bar 2-4	2.73-3.73	3.23	6
T-bar 2-5	3.73-4.73	4.23	6
T-bar 2-6	4.73-5.73	5.23	6
T-bar 2-7	5.73-6.73	6.23	6
T-bar 2-8	6.73-7.73	7.23	5
T-bar 2-9	7.73-8.73	8.23	5
T-bar 3-1	0.00-0.92	0.46	6
T-bar 3-2	0.92-1.92	1.42	6
T-bar 3-3	1.92-2.92	2.42	6
T-bar 3-4	2.92-3.92	3.42	6
T-bar 3-5	3.92-4.92	4.42	6
T-bar 3-6	4.92-5.92	5.42	6
T-bar 3-7	5.92-6.92	6.42	6
T-bar 3-8	6.92-7.92	7.42	6

Figure 14 - T-bar in the beginning of a test at Sarapuí II test site, where the intense presence of roots can be noted.

was not cycled in the same interval, *i.e.* did not have the same initial and final depths in each cycle. Besides, the procedure used to end up each test was not accurate enough to guarantee the exact same depth, thus few centimeters in difference may be found in the initial and final depths from one cycle to another. This problem has not, however, produced errors in the test results, since the 10 cm in the middle of the penetration interval of 1 m were considered to obtain the average value. It must be emphasized that the lack of accuracy in the beginning-end of each cyclic test is a regular occurrence, *i.e.* it is not a particular occurrence of the tests performed at Sarapuí II.

It can be observed from Figs. 15 and 16 that the deepest test was performed entirely in the clayey-silt layer in the case of T-bar 2, while the corresponding test in the case of T-bar 3 involved both the very soft clay and the clayey-silt material. The magnification of two cyclic tests is presented in Figs. 17 and 18.

5. Analysis and Discussion

The values of q_m and q_{net} in two degradation curves are shown in Figs. 19 and 20, where the initial penetration was assigned cycle number 0.5, initial extraction cycle number 1, second penetration cycle number 1.5 and so forth. In both cases, the trend of q_m being greater in the penetration than in extraction was found. This behaviour was found in all tests performed. As far as q_{net} is concerned, in most cases the same trend found for q_m was found, *i.e.*, q_{net} was greater in the penetration than in extraction. However, few cases have shown a different trend, with q_{net} being smaller in the penetration than in extraction, which is shown in Fig. 20. The reason for this behaviour still deserves investigation.

The normalized cyclic degradation curves (q_{cyc} *vs.* cycle number) of all tests are presented in Figs. 21 and 22, respectively for T-bar 2 and T-bar 3. It is interesting to note that the degradation is much faster and greater in the tests performed at the smallest depths (T-bar 2-1 and T-bar 3-1),

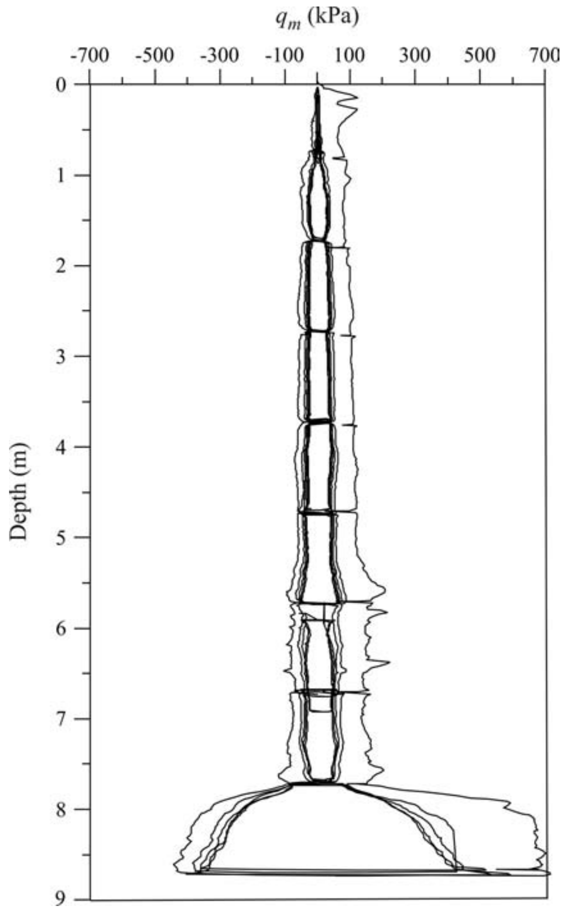

Figure 15 - T-bar 2 - cyclic tests.

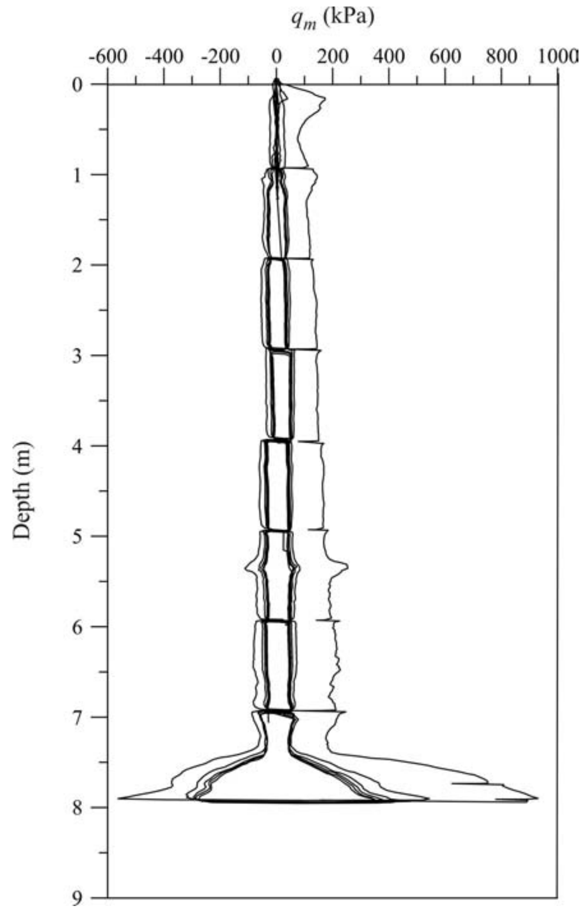

Figure 16 - T-bar 3 - cyclic tests.

while the tests performed at the greatest depths (T-bar 2-9 and T-bar 3-8) presented the smallest degradation. All other tests have presented a similar normalized behaviour.

The behaviour associated with the tests performed at the smallest depths may represent the real soil behaviour or not. The first case would correspond to soil sensitivity higher at those depths than at the other depths. To evaluate this hypothesis vane tests would have been performed. However, vane tests are not available at such small depths. Two explanations may be provided for the second case. The first one is related to the presence of the roots, *i.e.* the value of q_{in} (initial penetration value) is mostly due to the resistance offered by the roots, which is removed when the cyclic test is performed. Another possible explanation is related to the very low effective stresses at those test depths. In this case the full-flow mechanism may not occur (DeJong *et al.*, 2010). More research is needed to properly investigate this subject. This is indeed an issue, since T-bar tests are very often used as an investigation tool in the design of pipelines in very soft soils, where the remoulded shear strength is an important parameter.

As far as the deepest tests are concerned, they have indicated that this clayey-silt layer has a smaller sensitivity than the soft clay material. This hypothesis cannot be checked, since vane tests are not available due to the difficulties in penetrating the vane blade in the silty material. Another possible explanation is also related to the non occurrence of the full-flow mechanism, which might happen in stiff soils, where an open cavity or "slotting" may occur (DeJong *et al.*, 2010).

Although a similar trend was found in all cyclic tests for T-bar 2 and T-bar 3 with the exceptions mentioned above, the measured values are different from one test to another. In fact, the average value of q_{rem}/q_{in} is around 0.3 for the T-bar 2 cyclic tests while it is around 0.2 for T-bar 3. This comparison can be better illustrated when two tests performed at similar depths are plotted together, as in Fig. 23. Now, instead of plotting the normalized values, the absolute values for the same tests are compared in Fig. 24. It can be observed that there is a significant difference between the initial penetration values (cycle 0.5), 43 kPa or 27-37% of the initial penetration. However, the first extraction has reduced this difference to only 10 kPa (or 6-8%) of the initial value, and continued to reduce until the same values were found, at cycle 2.5. The values of q_{rem} of all tests (T-bar 2 and 3) are plotted *vs.* depth in Fig. 25, where it can be observed that except in two cases, all values are approxi-

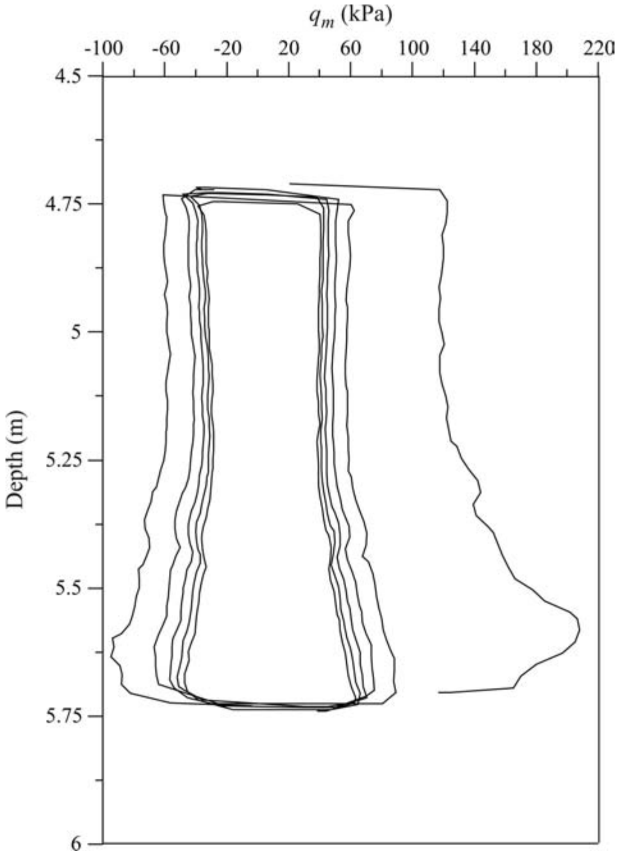

Figure 17 - T-bar 2-6 cyclic test.

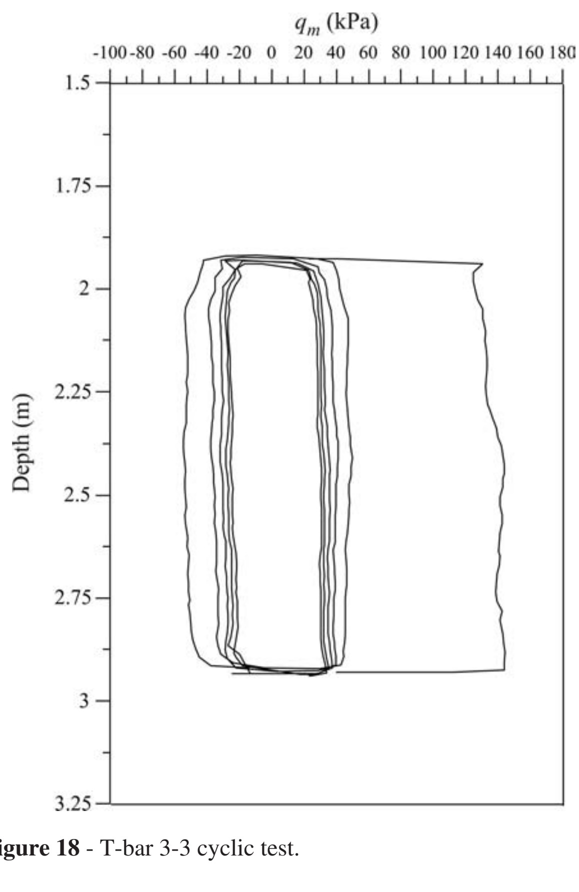

Figure 18 - T-bar 3-3 cyclic test.

mately the same, indicating that the influence of the roots have disappeared when the cycling procedure was applied.

Equation 7 was evaluated separately for cyclic tests performed at T-bar 2 and T-bar 3, and the corresponding results are found in Figs. 26 and 27, respectively. A significant difference can be observed from the results of the tests. Cyclic tests performed at T-bar 2 showed a trend very close to Eq. 7, except in the case of the tests performed at the smallest and greatest depths, due to the reasons previously discussed. The tests performed at T-bar 3 did not present the same results. In fact, the tests performed at similar depths at T-bar 3 are all apart from the curve representing Eq. 7, which is due to the q_{in} values being affected by the

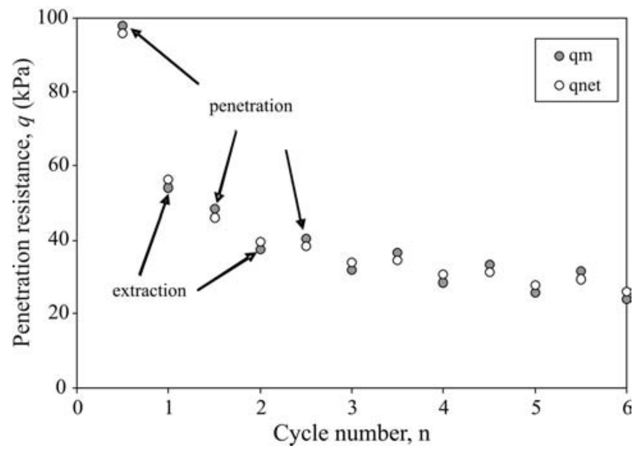

Figure 19 - Degradation curve, T-bar 2-3 cyclic test.

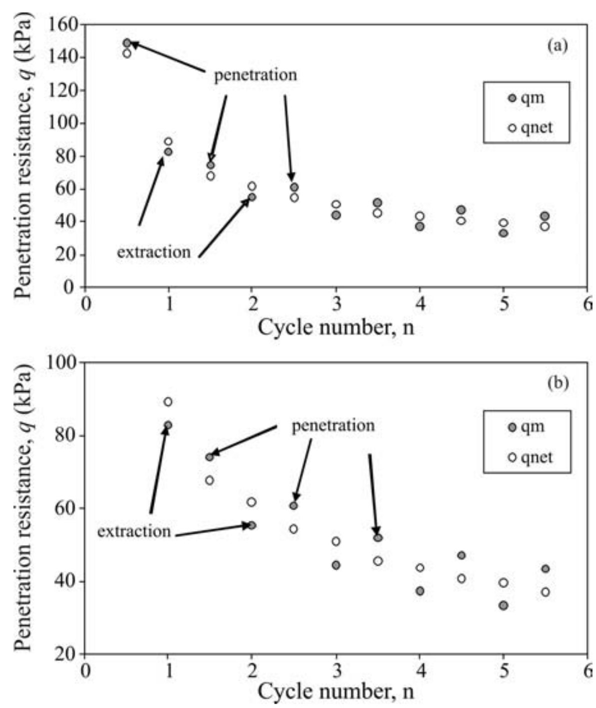

Figure 20 - Degradation curve, T-bar 2-7 cyclic test; (a) all data; (b) without initial penetration to allow magnification.

roots. Had this not occurred, similar results as for T-bar 2 would have been obtained, once q_{rem} values are about the same, as showed in Fig. 25. It can be concluded that Eq. 7 proved to be a useful tool to predict q_{rem} values based only in q_{in} and q_{ext} values in the case of Sarapuí II soft clay.

The whole degradation curve, predicted by Eq. 8, was compared with the data obtained from tests performed at T-bar 2 and 3, and are presented in Figs. 28 and 29, respectively. Cyclic test T-bar 2-3 is shown in Fig. 28, where a good matching between predicted and measured values has been obtained. All tests in T-bar 2 except T-bar 2-1 and 2-9, for the reasons discussed above, presented similar results.

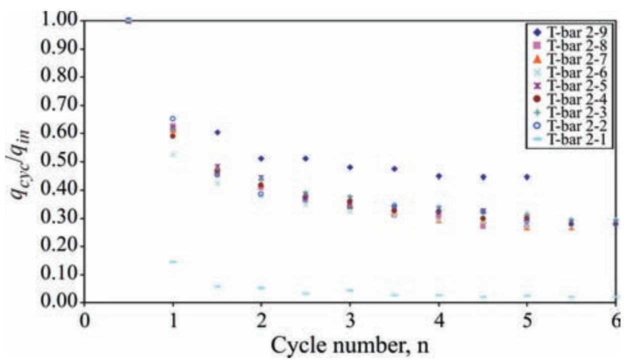

Figure 21 - Normalized cyclic degradation curves, T bar-2.

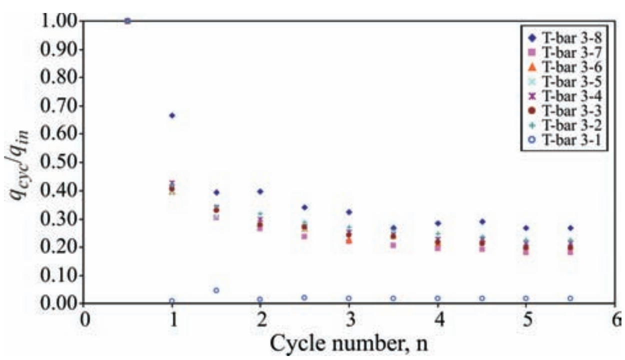

Figure 22 - Normalized cyclic degradation curves, T bar-3.

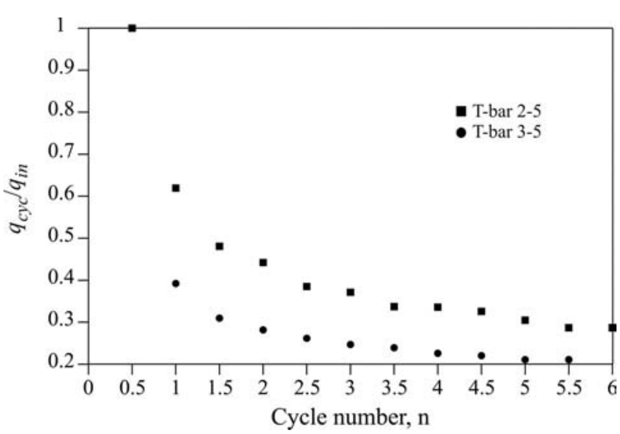

Figure 23 - Normalized degradation curves, T-bar 2-5 and T-bar 3-5 tests.

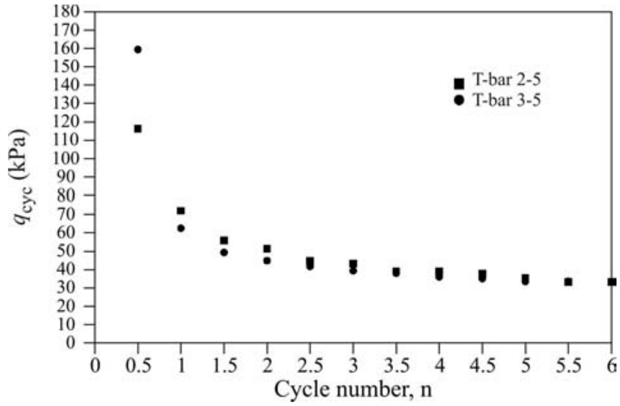

Figure 24 - Degradation curves, T-bar 2-5 and T-bar 3-5 tests.

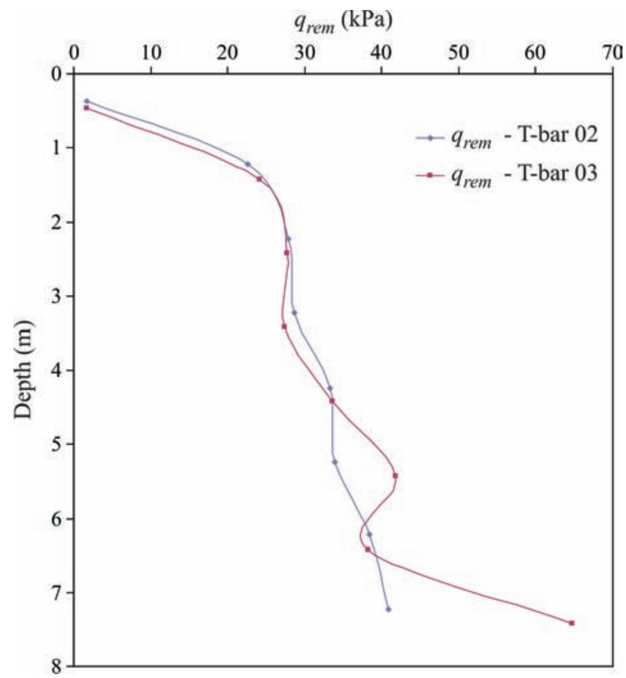

Figure 25 - Values of q_{rem} from all tests performed.

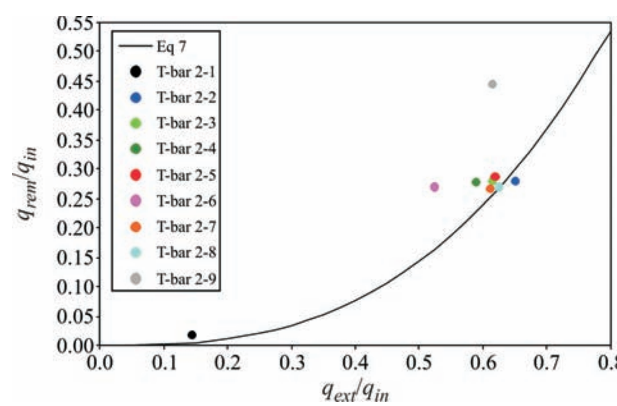

Figure 26 - Relationship between extraction ratio (q_{ext}/q_{in}) and normalized remoulded resistance (q_{rem}/q_{in}), data from T-bar 2 cyclic tests.

As far as T-bar 3 is concerned, a different trend was obtained. All tests presented a poor matching between predicted and measured values, as showed for test T-bar 3-3, which may be considered a typical test. This is an expected behaviour, since Eq. 8 is an empirical equation based on "well behaved" soils and regular conditions, *i.e.* the presence of roots influencing test results are not taken into account in the equation.

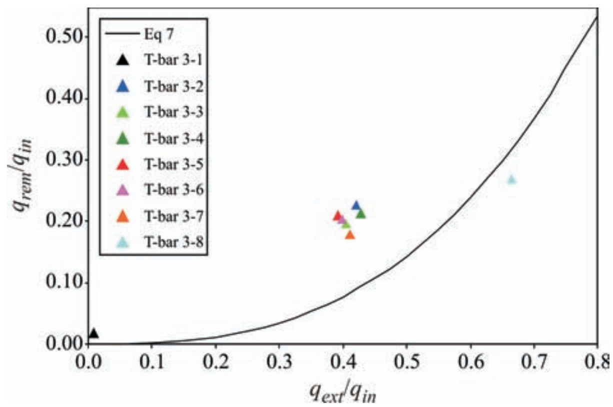

Figure 27 - Relationship between extraction ratio (q_{ext}/q_{in}) and normalized remoulded resistance (q_{rem}/q_{in}), data from T-bar 3 cyclic tests.

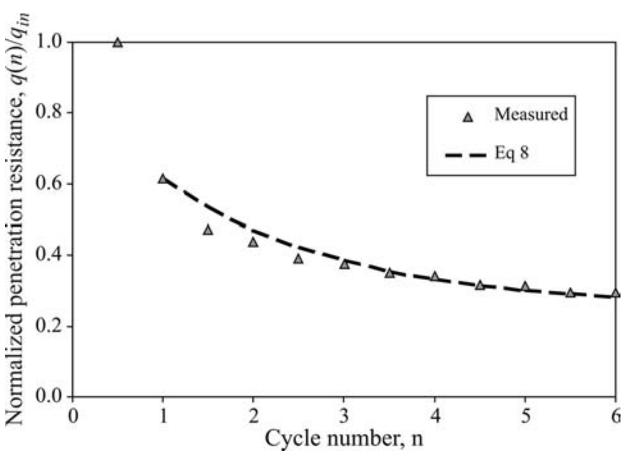

Figure 28 - Normalized cyclic degradation, T-bar 2-3.

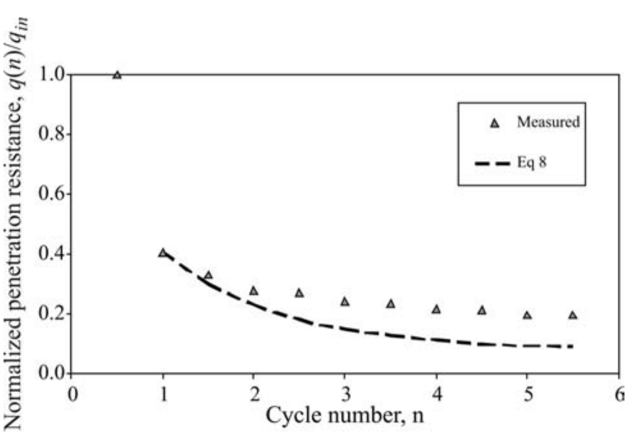

Figure 29 - Normalized cyclic degradation, T-bar 3-3.

Equations 9 and 10 are represented in Figs. 30 and 31, where the experimental values are also included. The reference S_T values were obtained from the vane test results showed in Fig. 12b.

As expected, the cyclic tests corresponding to T-bar 2 have provided good results, and the tests related to T-bar 3 (not showed) have provided poor matching, for the reasons previously discussed.

As far as $N_{T\text{-}bar}$ factors are concerned, $N_{T\text{-}bar}$ obtained from tests not affected by the roots ranged from 8.8 to 10.9, with an average of 9.8, while $N_{rem,\ T\text{-}bar}$ ranged from 14.1 to 19.5, with an average of 16.3. It must be pointed out that $N_{rem,\ T\text{-}bar}$ were evaluated based on all cyclic T-bar tests, since the roots have not influenced the remoulded values.

Therefore $N_{T\text{-}bar}$ values (related to the natural condition) were smaller than $N_{rem,\ T\text{-}bar}$ (related to the remoulded condition). A possible explanation for this behavior was provided by Low *et al.* (2010), attributing it to the soil being partially remoulded during the initial penetration of the T-bar, whereas the soil becomes fully remoulded locally at the end of a cyclic test. As a result, the strength enhancement owing to high strain rate around the T-bar is partly

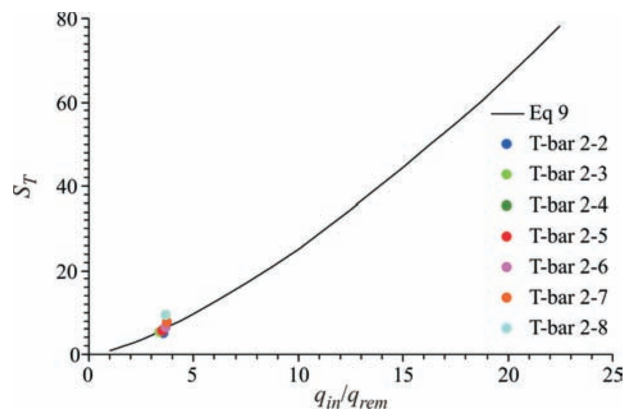

Figure 30 - Sensitivity against q_{in}/q_{rem}, T-bar 2 cyclic tests.

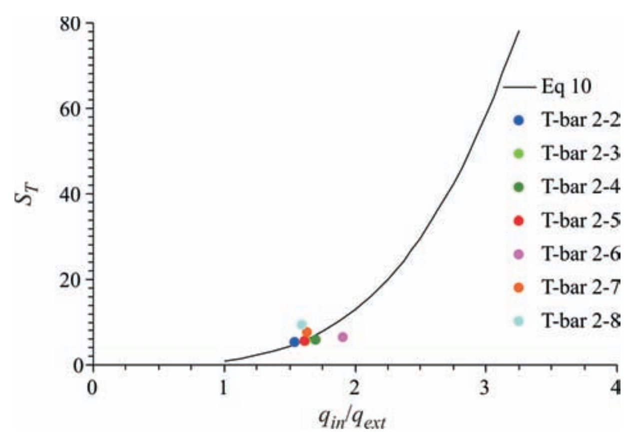

Figure 31 - Sensitivity against q_{in}/q_{ext}, T-bar 2 cyclic tests.

compensated by the strength reduction owing to partial remoulding during the initial penetration, but not after remoulding.

Moreover, there is a trend of of $N_{rem,\ T\text{-}bar}$ to increase with the increase of sensitivity, as showed in Fig. 32, as predicted from Eq. 12. It must be noted that all values - except those with different trends, previously discussed - were included, *i.e.* values from both T-bar 2 and 3 were included in the figure, since the remoulded values were not affected by the influence of the roots.

6. Additional Remarks and Conclusions

Seventeen T-bar cyclic tests in two deployments have been performed at Sarapuí II soft clay test site. In a third deployment only penetration was recorded.

The presence of roots has influenced the values of the initial penetration in one of the deployments, as observed in another test site, which is a consequence of the shape of the penetrometer and may be considered a shortcoming of the test. Therefore, to know whether roots have influenced the test results in a site at least two repeatable tests must be performed. If cyclic tests are performed, their results can provide a good indication of the influence of the roots.

The equations suggested by Yafrate *et al.* (2009) to evaluate the remoulded penetration resistance, the whole degradation curve and also the sensitivity, based only on the initial penetration and extraction resistances have provided good results for the Sarapuí II soft clay. The tests performed at very shallow depth (less than 1 m deep), however, did not provide good predictions in general, which was attributed to either: (i) the presence of roots, *i.e.* the value of q_{in} (initial penetration value) is mostly due to the resistance offered by the roots, which is not present when the cyclic test is performed; (ii) the very low effective stresses, which preclude the occurrence of the full-flow mechanism. More research is needed on this subject, since T-bar tests are very often used in the design of pipelines, where the values corresponding to very low depth are of paramount importance.

Considering the vane shear test as reference for obtaining s_u and s_{ur}, $N_{T\text{-}bar}$ obtained from tests not affected by the roots ranged from 8.8 to 10.9, with an average of 9.8, while $N_{rem,\ T\text{-}bar}$ ranged from 14.1 to 19.5, with an average of 16.3. Therefore $N_{T\text{-}bar}$ values (related to the natural condition) were smaller than $N_{rem,\ T\text{-}bar}$ (related to the remoulded condition).

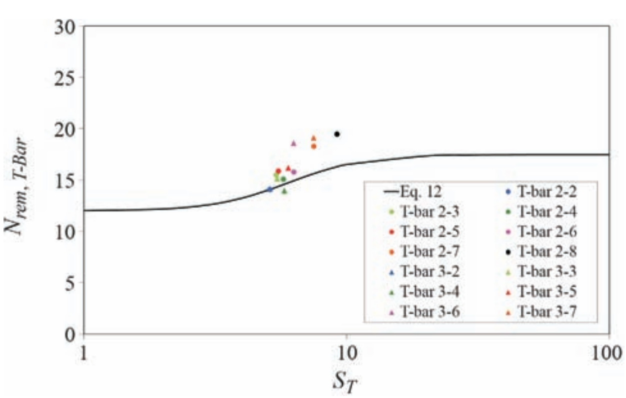

Figure 32 - $N_{rem,\ T\text{-}bar}$ *vs.* S_T.

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