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Research article

Dissipation tests with the BAT probe at the Sarapuí II soft clay

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Abstract: This paper presents dissipation tests performed at the Sarapuí II very soft clay test site in the metropolitan area of Rio de Janeiro, Brazil, with the BAT probe, a special type of piezometer. The tests performed indicated that the BAT probe is a useful tool for determining the coefficient of horizontal consolidation in situ. The obtained values of c_h in the very soft clay decreased from 10^{-5} m²/s at 1 m depth to 10^{-6} m²/s at 3 m depth, remaining constant to 6 m depth, consistently in the upper range of piezocone values. The quality of the dissipation curves, based on comparison with theoretical dissipation curves, was rated, in general, as fair, which agrees with evidence that the match quality between experimental and theoretical curves decreases as the distance from the cone mid-face increases. Dissipation tests and permeability tests conducted with the BAT probe were used to directly assess the coefficient of volume change in situ. Differences between in-situ and oedometer test results have been attributed to anisotropy, stress state differences, and influence of probe insertion on the coefficient of permeability values. The obtained data seemed to indicate that consolidation during dissipation takes place in recompression mode, as suggested by other studies.

Keywords: Dissipation test; Soft clay; In-situ coefficient of consolidation; Coefficient of volume change; BAT probe

1. Introduction

According to Lunne et al. [1], the coefficient of consolidation, c, and the coefficient of permeability (hydraulic conductivity), k, are some of the most difficult parameters to measure in geotechnical engineering. They are related through Equation 1:

$$c = kM/\gamma_w \tag{1}$$

where M is the constrained modulus and γ_w the water unit weight.

In the case of in-situ testing, the horizontal coefficient of consolidation, c_h, is often estimated from piezocone (CPTU) dissipation tests. Once c_h is obtained, the horizontal coefficient of permeability, k_h, may be assessed from the piezocone, and Equation 2, from Baligh and Levadoux [2], may be used for this purpose:

$$k_h = \frac{\gamma_w}{2.3\,\sigma'_{v0}} RR\, c_h \tag{2}$$

where RR is the recompression ratio (the strain per log cycle of effective stress), obtained in oedometer laboratory tests, and σ'_{v0} is the vertical effective stress before insertion of the piezocone penetrometer.

Several studies have reported the determination of the coefficient of permeability from piezocone tests either empirically (*e.g.,* [3,4]), by variations of the method described above (*e.g.,* [2,5]), or even on-the-fly, *i.e.,* during cone penetration ([6,7]). However, none of these methods directly assess the coefficient of permeability.

Dissipation tests are usually performed with the piezocone; however, piezometers and pore pressure probes may also be used for this purpose, provided the pore pressure during penetration and the subsequent dissipation can be properly recorded. In fact, before the development of the piezocone, those tools had already been used for this purpose ([8–10]). However, neither the piezometer used by Janbu and Senneset [8] nor the pore pressure probes developed by Wissa et al. [9] and Torstensson [10] were able to perform permeability tests due to a lack of the capacity of providing controlled injection (or extraction) of fluid into (or from) the soil mass. The BAT probe, named after its inventor Bengt-Arne Torstensson (Torstensson [11]), in addition to working as a regular piezometer, can perform permeability tests (variable head tests) and, if properly saturated (Vargas et al. [12]), also dissipation tests. Thus, from the assessment of both the coefficient of consolidation and the coefficient of permeability, the coefficient of volume change can be directly obtained in situ. Details of the BAT probe are included in Section 2.2. This study presents the results of dissipation tests carried out with the BAT probe at the Sarapuí II very soft clay reference test site [13,14]. The coefficient of volume change was assessed from these tests together with previous permeability tests [12] and then compared to oedometer laboratory tests, thus enabling to verifying the hypothesis of the dissipation tests carried out in the recompression mode.

2. Materials and methods

2.1. Test site

The Sarapuí test site is the first Brazilian geotechnical test site (Cavalcante et al. [15]), established on the left bank of the Sarapuí River, in the vicinity of the Guanabara Bay [16,17]. A number of up-to-date in-situ tests, undisturbed sampling, laboratory tests, and large joint research projects, Petrobras-UFRJ, have been carried out at the Sarapuí II test site [12,13,18–21]. The former Sarapuí I and the more recent Sarapuí II sites, distant 1.5 km from each other, are part of the same clay deposit and have essentially the same soil characteristics, except for the average soft clay thickness, which is slightly smaller in the Sarapuí II area.

The very soft clay deposit was formed in the Holocene, and a clayey-silt layer, formed in the Pleistocene, is found underneath the very soft clay. Roots, wood fragments, and shells are present in the very soft clay profile, as illustrated in Figure 1, in which the results of corrected cone resistance (q_t) from six piezocone tests carried out by Danziger et al. [14] in the area are also presented.

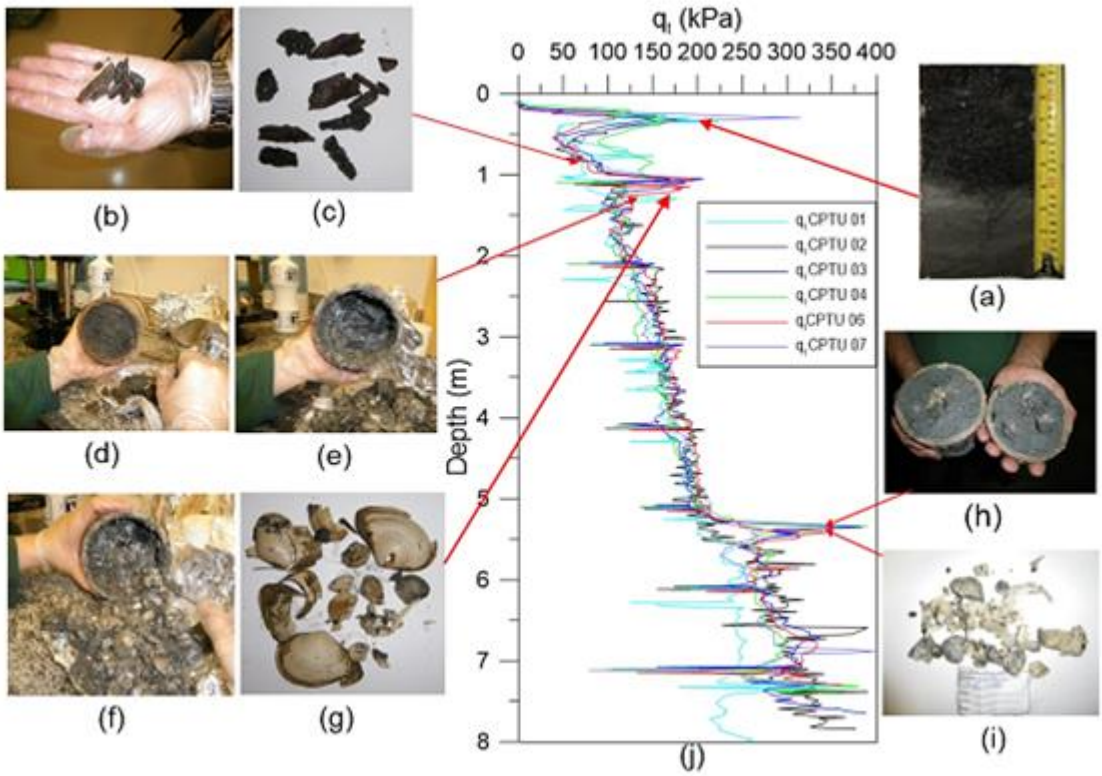


Figure 1. (a) Sample at the top of the profile, upper 15 cm of thin roots mixed with the topsoil; (b) and (c) wood fragments found between 1.38 m and 1.44 m depth; (d) top of slice 12 cm in height (1.38–1.50 m depth); (e) shells being removed; (f) bottom of slice, after removal of shells; (g) washed shells removed; (h) shells inside the sampler, sample slice 14 cm in height (5.86–6.00 m depth); (i) washed shells removed; and (j) corrected cone resistance from six piezocone tests (Danziger et al. [14]).

The material composition is summarized in Figure 2a, where it can be observed that the material is a silty clay, with some sand, and that the clay content is roughly 60% on average. The organic content (Figure 2b) decreases with depth to 3 m, from a range of 11–18% to roughly 5–6%, is constant to 5.5–6.0 m depth, and also constant around 7–9% in the depth interval 6.0–8.0 m. The predominance of NaCl with respect to the other soluble salts can be observed in Figure 2c. The variation of NaCl is almost linear with depth. Regarding mineralogy (Figure 2d), kaolinite is predominant throughout the profile and increases almost linearly with depth. Smectite has, however, almost the same percentage in the upper layer (until approximately 3.5 m depth) [13,14].

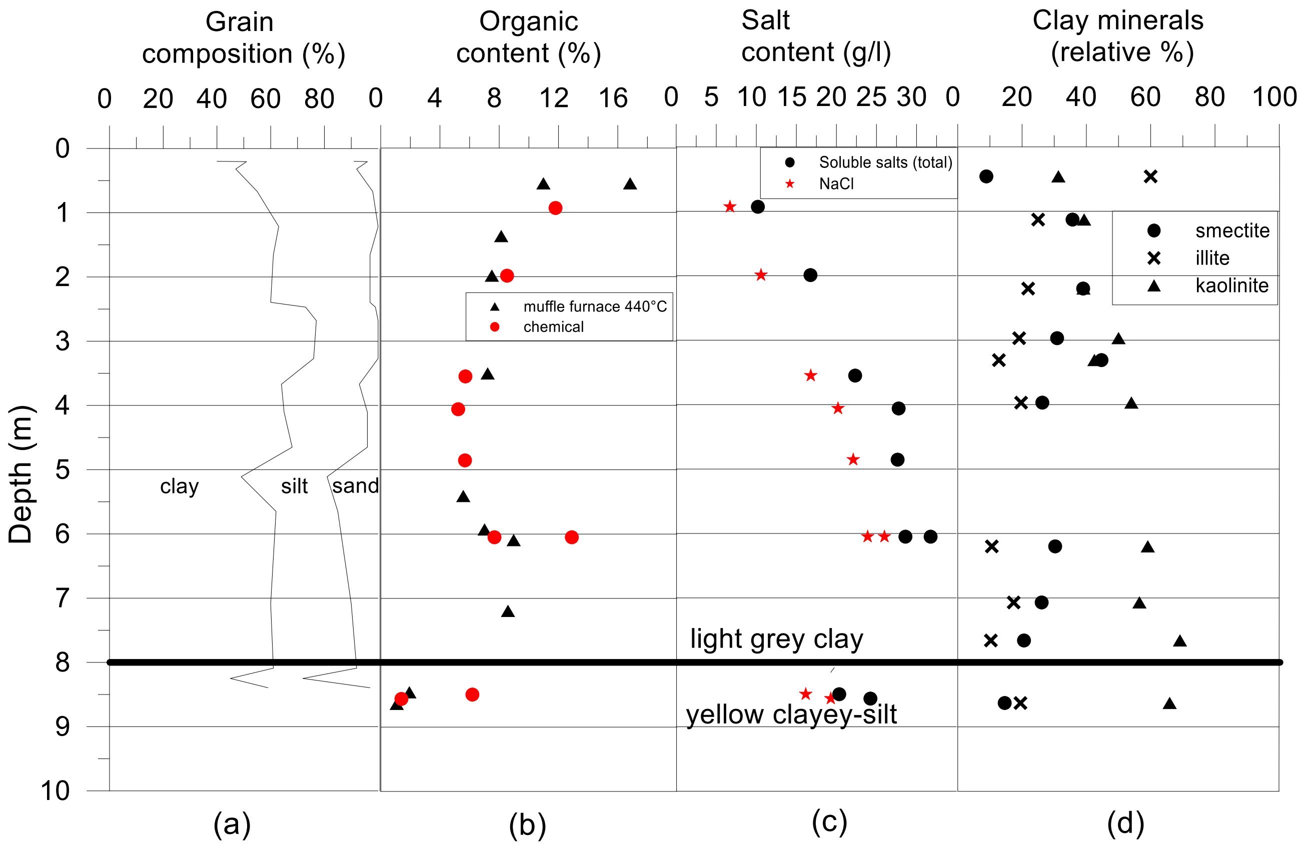


Figure 2. (a) Grain size distribution; (b) organic content; (c) total salt content and NaCl content; and (d) relative percentage of clay minerals versus depth (adapted from Jannuzzi et al. [13]).

State and index parameters are summarized in Figure 3. From the liquid limit and plastic limit (Figure 3a), it can be observed that the plasticity index (*PI*) is very high, increasing from 60–70% at the surface to 160–170% at 2.5–3.0 m depth, then decreasing with depth to around 90% at the bottom of the very soft material. The specific gravity (*G*) values (Figure 3b) show a trend of linear increase with depth, except for the upper soil, affected by the roots. Total unit weight (γ_n) values (Figure 3c) are reasonably constant to approximately 4.5 m depth, with an average value of 12.9 kN/m³, increasing linearly with depth to the bottom of the clay layer, reaching 14.8 kN/m³ at 8 m depth. The natural void ratio (e_0) values (Figure 3d) have a corresponding behavior with respect to γ_n values. They are reasonably constant to approximately 4.5 m depth, with an average value of 4.5, then they have a trend of decreasing linearly with depth, reaching 2.4 at 8 m depth. The activity (*PI*/clay percentage) values (Figure 3e) indicate that the soft clay is classified as active, according to the classification of Skempton [22], in the whole profile. Mineralogy of the material can explain the observed trend [13].

The overconsolidation profile, obtained from 24-h incremental loading (IL) testing, is shown in Figure 4, where it can be observed a significant decrease of the overconsolidation ratio (OCR) from 1 m depth (OCR = 8) to 3 m depth (OCR = 2), and constant values until the bottom of the layer. The constant values of OCR = 2 were attributed by Danziger et al. [14] to secondary consolidation; however, the OCR profile from the soil surface to 3 m depth cannot be attributed to water level drawdown or water level fluctuation according to those authors. It is a subject that deserves further investigations, and possible causes raised by Danziger et al. [14] are desiccation/suction caused by the vegetation and bacterial action. The groundwater is characterized by hydrostatic conditions with the water table at the ground level being subjected to small variations due to rainfall and tide [12,13]. Further information regarding properties of the deposit can be obtained in, *e.g.,* [12–14]. Permeability tests from Vargas et al. [12] are used in the study presented herein.

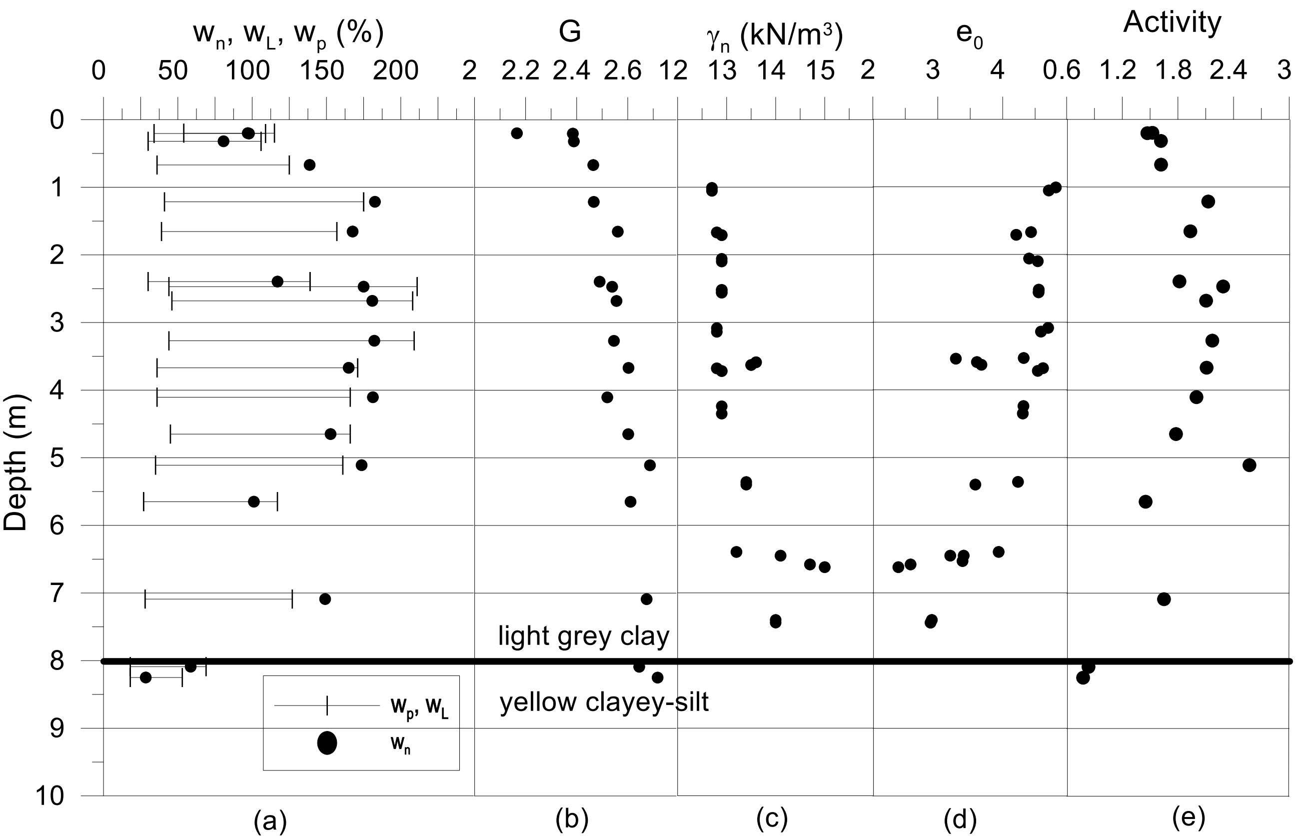


Figure 3. (a) Liquid limit, w_L, plastic limit, w_P, and natural water content, w_n; (b) specific gravity, G; (c) total unit weight, γ_n; (d) initial void ratio, e_0; and (e) activity versus depth ([13]).

2.2. Instruments and test procedure

The tests described herein have been performed with the BAT probe. The BAT probe, introduced by Torstensson [11], is essentially a piezometer that can be used for several applications in addition to pore pressure measurement. Among such applications are direct measurement of soil permeability (both inflow and outflow), hydraulic fracturing and K_0 (lateral stress ratio) determination, and ground water and gas sampling [11,12,23–27]. The BAT probe can also be used for dissipation tests, although very few tests of this type have been reported to date [23,28]. The key element of the BAT probe is its filter tip (Figure 5), which enables the detachment and re-attachment of the pressure transducer at any point of the test. Such a feature enables the operator to perform different tests in succession (*e.g.,* a dissipation test followed by a permeability test).

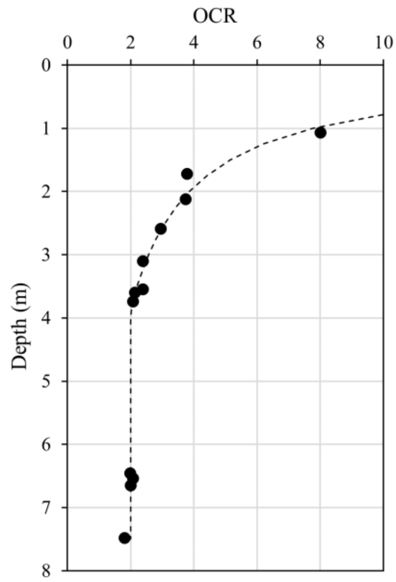


Figure 4. OCR versus depth from IL 24-h consolidation tests (modified from Jannuzzi et al. [13]).

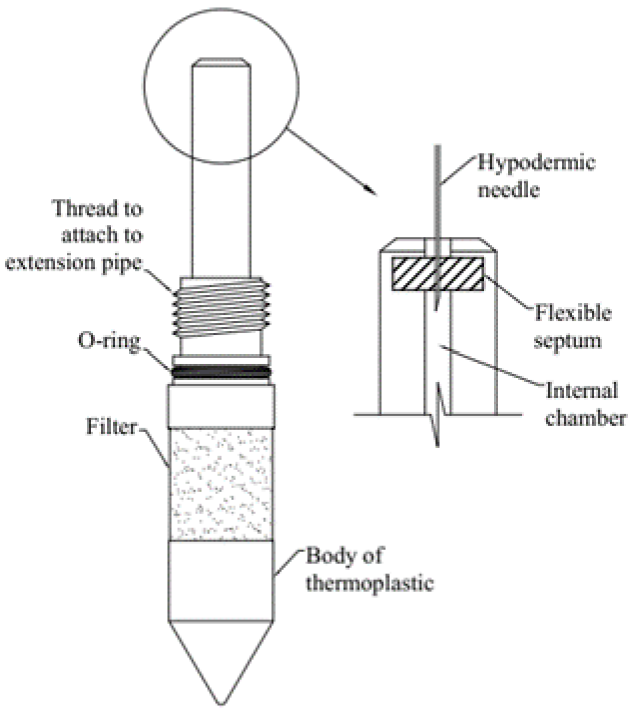


Figure 5. BAT probe filter tip (modified from Torstensson [11]).

The test procedure adopted in this study consisted of installing the probe to the desired depth and conducting a dissipation test. The dissipation process has been monitored for some time (see Table 1) with an automatic logging system. The transducer was then retrieved. To enable the complete dissipation of the pore pressures generated during installation, the permeability tests are conducted typically 3 days after installation [12]. To perform the permeability test, the permeability apparatus was lowered into the probe and connected to the filter tip. Such apparatus is comprised of a pressurized test container (usually a glass vial) that is connected both to a pressure transducer on its upper end and to the filter tip on its lower end by means of hypodermic needles. After the permeability test was completed, the permeability apparatus was detached and retrieved, and the probe was either left in place or pushed to a greater depth for another round of dissipation and permeability tests. In the latter case, the pore pressure measurement was resumed by reconnecting the pressure transducer to the filter tip. The aforementioned procedure enables the determination of both the coefficient of consolidation and the coefficient of permeability on the same portion of soil mass. The permeability results used in this study have been published by Vargas et al. [12]. Further details on the BAT probe testing can be obtained from, *e.g.,* Torstensson [11] and Vargas et al. [12].

Table 1. Data from BAT dissipation tests on Sarapuí II clay.

Test n.	Depth (m)	Duration (s)	Match quality	c_h (10^{-7} m²/s)
V7	9.09	2555	Good	175
V8	9.19	3150	Good	547
V9	8.12	2055	Fair	88
V10–1	0.99	275	Fair	70
V10–2	1.98	600	Fair	20
V10–3	3.00	875	Fair	9
V10–4	4.02	920	Poor	9
V10–5	5.02	1035	Poor	9
V10–6	6.02	1140	Poor	9
V10–7	7.01	2215	Poor	25
V11–1	1.01	330	Good	103
V11–2	1.99	3690	Good	25
V11–3	2.99	570	Fair	12
V14	6.19	2160	Poor	7
V15	5.15	1530	Good	10
V16	4.15	4565	Fair	7
V20	3.03	11815	Poor	4
V21	6.05	62600	Fair	7

2.3. Test interpretation

Usually, the coefficient of consolidation, c_h, is calculated following a monotonic pore pressure decay (*e.g.,* [2,29,30]), which relates a dimensionless time factor from a certain theory to the normalized excess pore pressure. The interpretation herein presented uses the theory proposed by Teh [30] and Teh and Houlsby [31], which employs a modified time factor, T_{mod}, Equation 3, to take into account the rigidity index, $I_r = G/s_u$ (where G is the shear modulus and s_u the shear strength) of the soil. The coefficient of consolidation, c_h, can be calculated by substituting the time to achieve a certain percentage (usually 50%) of excess pore pressure dissipation, t_{50}, and its corresponding time factor, T_{mod}, in Equation 3. Such interpretation relies on the assumption that the experimental dissipation curve matches the theoretical solution.

$$c_h = \frac{T_{mod}\sqrt{I_r}{r_0}^2}{t} \tag{3}$$

where r_0 is the radius of the penetrometer.

A more rational approach, following Thomas [32], Sills et al. [33], Danziger [34], and Danziger et al. [35], was adopted in the interpretation of the tests herein reported. It consists of equalizing the number of logarithm cycles of the experimental and the theoretical dissipation curves and overlaying them to find the best match. Once this is done, c_h can be calculated at any point on the x-axis. For simplicity, $T_{mod} = 1$ was selected to calculate c_h; thus, Equation 3 becomes Equation 4.

$$c_h = \frac{\sqrt{I_r}{r_0}^2}{t} \tag{4}$$

The aforementioned method of interpretation has the advantage of also working as a quality control of the test. By overlaying the experimental and theoretical curves, it is possible to evaluate how similar to the expected dissipation behavior the test is and, in turn, assess its quality.

2.3.1. Corrections to the experimental curves

Some dissipation tests present a slight increase in pore pressure at the beginning of the dissipation process. This increase in pore pressure has been reported by several authors (*e.g.,* [36–38]) and is commonly referred to as non-standard behavior of the dissipation curve, or as non-monotonic dissipation. Some factors can be responsible for such behavior, the more common being the poor saturation of the filter, but also dilatory behavior due to overconsolidation, the so-called Mandel-Cryer effect, and even redistribution of pore pressures due to drainage patterns [2,36,38].

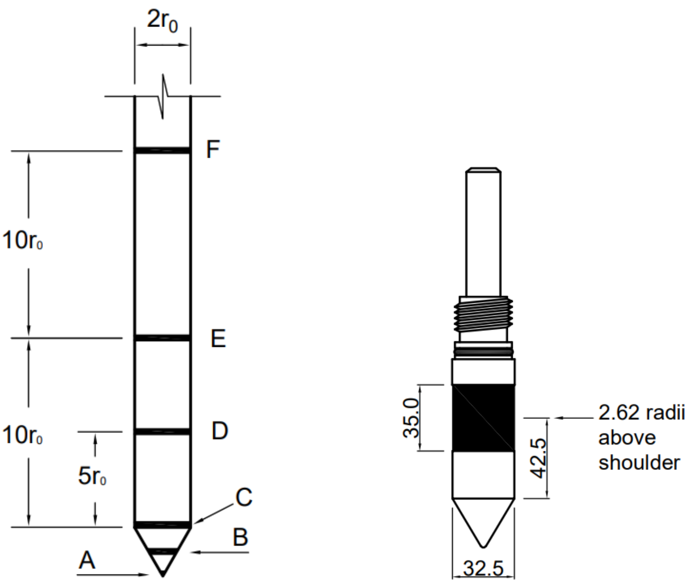
Although some authors have developed solutions for the non-monotonic behavior of the pore pressure dissipation curve (*e.g.,* [38]), others have suggested simple corrections (*e.g.,* [4,36,37,39]). Nonetheless, since the observed increase in pore pressures in some dissipation tests presented herein were very small and, more importantly, lasted no longer than a few seconds, no correction of the curves were used. The dissipation curves were dealt with in the simplest way, considering Equation 5 for the normalized pore pressure, U:

$$U = \frac{u - u_0}{u_{max} - u_0} \tag{5}$$

where u is the pore pressure at any instant, u_0 is the equilibrium pore pressure, and u_{max} is the maximum pore pressure value.

2.3.2. Position of the BAT filter

Figure 6 compares the possible positions of the filter on the piezocone and on the BAT filter tip. Teh [30] and Teh and Houlsby [31] presented theoretical solutions for all positions indicated in Figure 6a from a 60° cone angle penetrometer of radius r_0: at the cone tip (A), mid-face (B), shoulder (C), at 5 radii above the shoulder (D), at 10 radii above the shoulder (E), and at 20 radii above the shoulder (F). The BAT filter tip, however, possesses only one filter whose dimensions are shown in Figure 6b. The position of the mid-height of the BAT filter is not similar to any of the positions given by the theory and, therefore, an adjusted curve for such a position needed to be obtained. To do that, initially, a generalization of the Teh´s [30] curves for I_r = 100 was obtained, simply transforming T to T_{mod}, as presented in Figure 7. These curves must be seen with caution for positions A, E, and F, for which a narrow range is not obtained when T is transformed to T_{mod} [30]. Nevertheless, due to the position of the BAT filter, which is approximately halfway between positions C and D, the assumption used was considered valid. The curve for the BAT filter was obtained from graphical interpolation from the data provided by Teh [30] and included in Figure 7.



(a) (b)

Figure 6. Positions of the filter: a) Piezocone (modified from Teh [30]) and b) BAT filter tip (dimensions in mm, drawings not to scale).

2.4. Description of tests

Information from the dissipation tests performed with the BAT probe at the Sarapuí II deposit is included in Table 1. Test numbers are the same presented by Vargas et al. [12], although only dissipation tests performed in adequately saturated probes are shown in Table 1. Tests were performed between September 2020 and June 2023. Tested depths ranged from 1.0 m to 9.2 m, covering the Holocene soft soil deposit, the Pleistocene clayey-silt layer, and the underlying sandy layer. The duration of the tests was limited by the field activities of each installation day and varied from 275 to 62600 seconds (approximately 5 to 1043 minutes, respectively). The values of c_h included in Table 1 were obtained according to the method described in Section 2.3. I_r = 44 was adopted for the calculation of c_h following Danziger et al. [35]. This value agrees reasonably with I_r values obtained by Jannuzzi [40] for the Sarapuí II clay, which is in the range 50-60. Since the calculation of c_h uses the square root of I_r, the difference in the values of c_h using I_r = 44 and I_r = 50-60 is only 7% (for I_r = 50) - 17% (for I_r = 60), which are very small compared with the scatter of the test results.

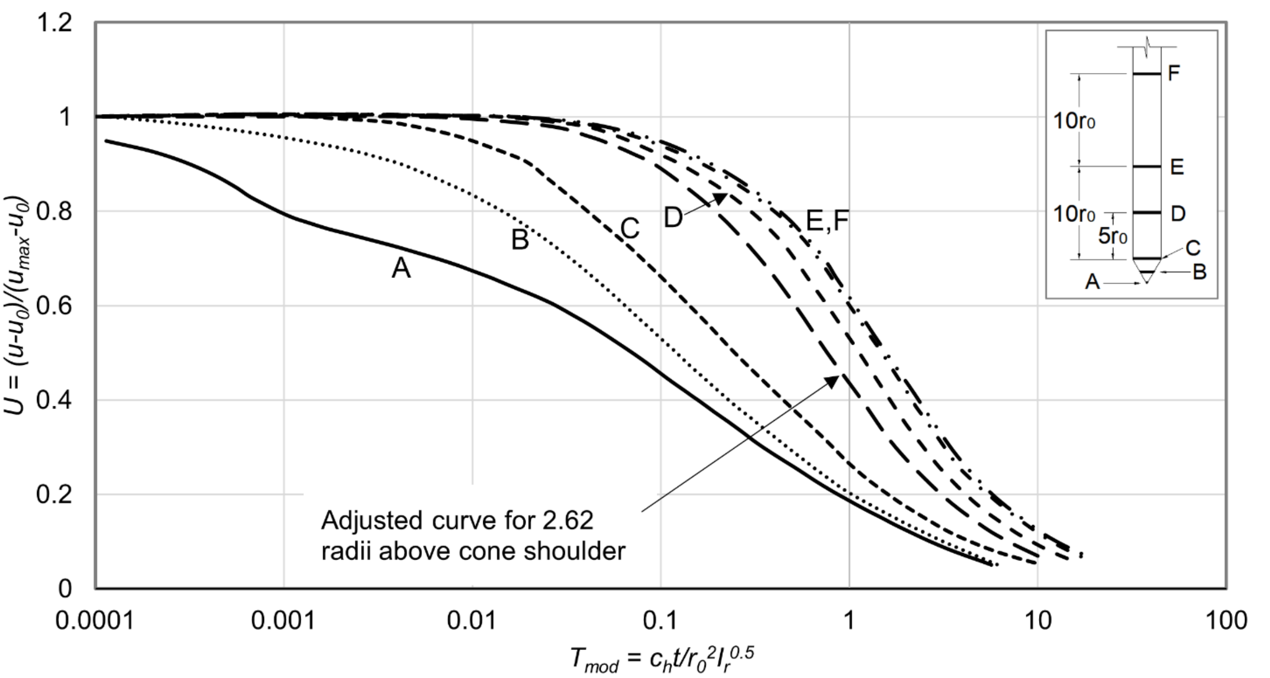


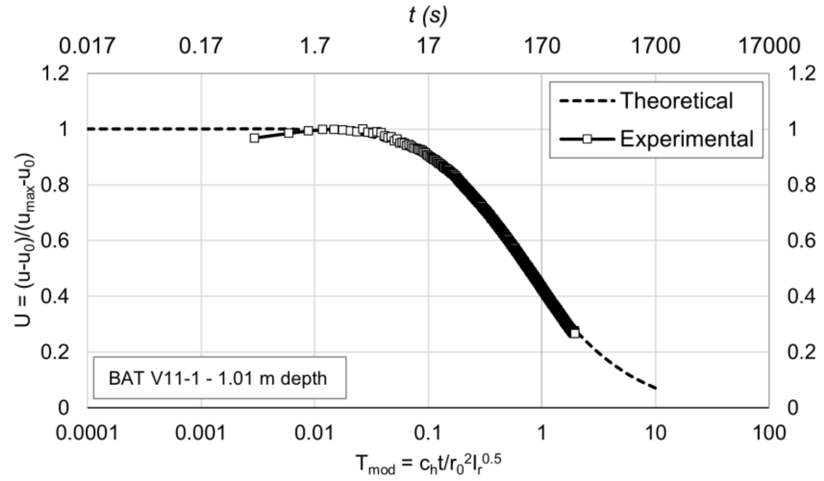
Figure 7. Adjusted dissipation curve for the mid-height of the BAT filter on the generalized Teh [30] chart.

A match quality score similar to the one used by Danziger et al. [35] was adopted to evaluate the quality of the tests. The match score can be either good, fair, or poor, and is based on qualitative evaluation. The basic criteria used were the following: a) Good match—the experimental curve agrees in most part or completely with the theoretical curve; b) fair match—the experimental curve agrees in part with the theoretical curve and does not show significant deviation in the rest; and c) poor match—the experimental curve agrees with the theoretical curve in a few points and/or shows relevant shape deviation from the theoretical curve.

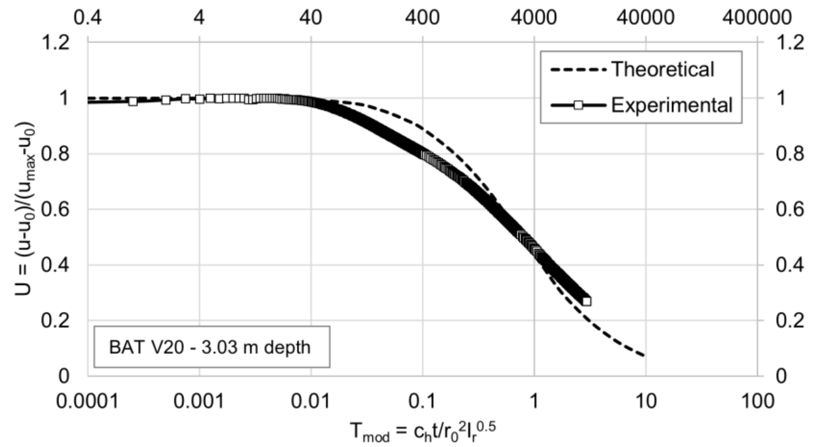
3. Test Results

Figure 8 shows examples of good (Figure 8a), fair (Figure 8b), and poor (Figure 8c) match qualities of dissipation tests with the BAT probe. The experimental dissipation curves have been overlaid with the adjusted theoretical dissipation curve for the BAT filter position (Figure 7).

The coefficient of consolidation calculated from the dissipation tests versus depth is shown in Figure 9 (see values in Table 1). It decreases approximately from 10^{-5} m²/s at the top of the deposit to 10^{-6} m²/s at 3 m depth, remaining constant between 3 m depth and the bottom of the very soft clay layer (6.5 m depth at the tested area in Sarapuí II). The values below this depth are not from the Holocene soft clay and will not be considered in the analysis. Dissipation tests reported by Danziger et al. [35] at the Sarapuí I clay (in a tested area with a larger thickness than Sarapuí II) and by Jannuzzi [40] at the Sarapuí II clay are also plotted in Figure 9. The results show good agreement between c_h obtained with the piezocone and the BAT probe, with BAT values consistently in the upper range of piezocone values. It is important to note that, apart from the filter position (Section 2.3.2), the drainage conditions of the piezocone and the BAT probe are the same during the dissipation test, *i.e.,* with water flowing predominantly in the radial direction away from the probe.



(a)



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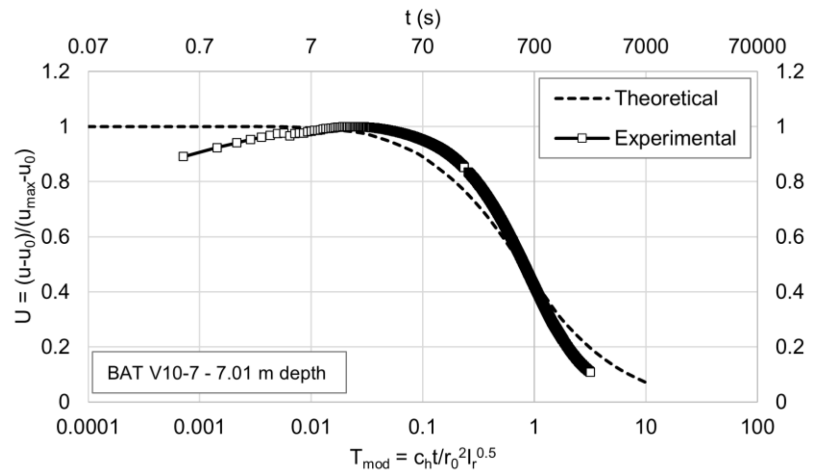

(c)

Figure 8. Examples of dissipation tests performed with the BAT probe and their respective match quality: a) good; b) fair; and c) poor.

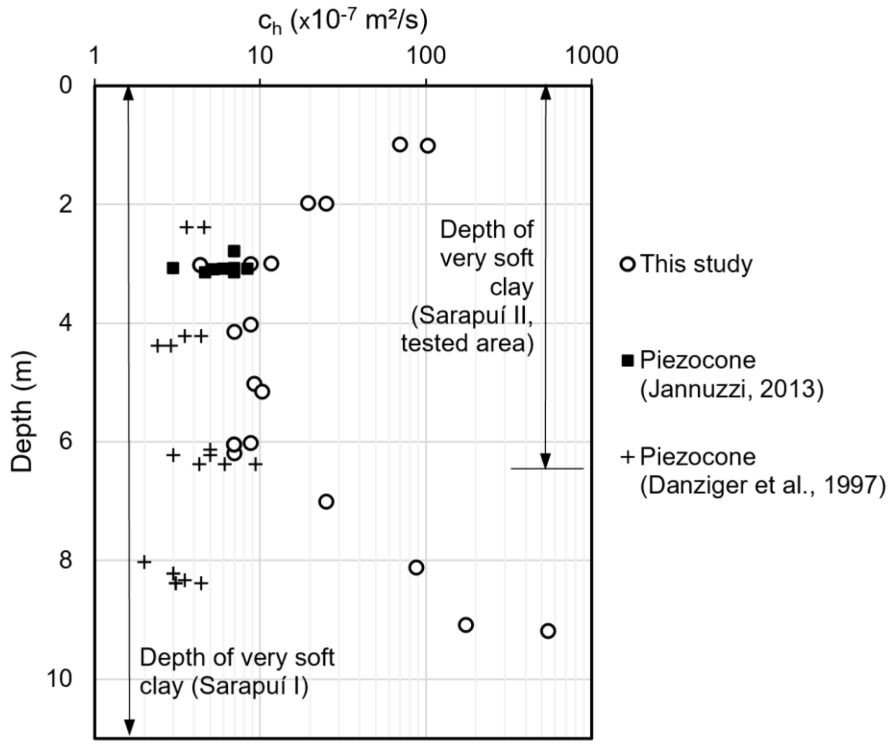

Figure 9. Horizontal coefficient of consolidation (c_h) calculated from dissipation data.

4. Discussion

4.1. Saturation of the filter

Figure 10 presents examples of dissipation tests performed with the BAT probe at the Sarapuí II site at 6 m nominal depth. Tests V10–6, V14, and V21 were performed in adequately saturated probes and included in this study (Table 1). Test V6–4 was performed in a probe that was not properly saturated and was not presented in Table 1. As shown by Vargas et al. [12], some filter tips that had been saturated according to the usual procedure (submerging the filter tip and drawing de-aired water into it using a syringe) exhibited delayed pore pressure response during probe installation. A second group of filter tips was saturated by vacuum according to the procedure proposed by Lacasse [41], *i.e.,* applying vacuum during a minimum of 12 hours, then, additionally, a minimum of 12 hours of submerged vacuum. This group exhibited adequate pore pressure response during installation, showing spiky traces, and quicker stabilization of the measured coefficient of permeability during permeability tests, as shown by Vargas et al. [12].

In Figure 10, all three adequately saturated probes rapidly reached the peak pore pressure (in less than 10 s), whereas the inadequately saturated probe (V6–4) took approximately 500 seconds to reach peak pore pressure. In addition, the pore pressure measured by the inadequately saturated probe took more than 900 seconds to reach the same trend as the adequately saturated probes, indicating that the coefficient of consolidation could have been correctly determined only after this point. Any correction applied to the V6–4 curve would arguably affect the calculated coefficient of consolidation; thus, only dissipation tests from adequately saturated probes from Vargas et al. [12] were used in this study.

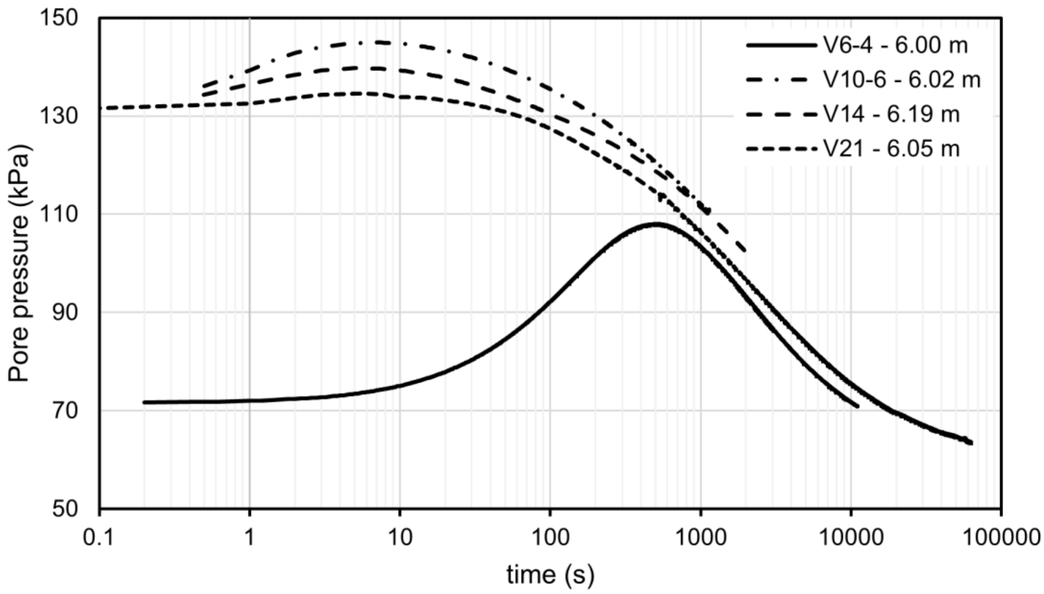

Figure 10. Examples of dissipation tests performed with the BAT probe at 6 m nominal depth.

4.2. Match quality of the experimental curves

The experimental curves were overlaid on the theoretical dissipation curves and revealed good, fair, and poor matching qualities, which are represented in Figure 11. The match scores obtained by Danziger et al. [35] for piezocone tests at Sarapuí I clay and Jannuzzi [40] at Sarapuí II are presented for the sake of comparison. Positions P1, P2, P3, and P4 correspond, respectively, to filter positions at cone face (B in Figure 6), cone shoulder (C), middle of the friction sleeve (D), and top of the friction sleeve (E), (D) and (E) obtained only from a 25 mm diameter cone penetrometer owned by Oxford University [35]. It can be seen that most of the P1 and P2 tests reported by Danziger et al. [35] yield good matching experimental curves, whereas positions P3 and P4 provided mostly poor match quality. In the case of the tests reported by Jannuzzi [40], P1 tests are rated as good matches, whereas P2 tests are either good (more cases) or fair. As a conclusion, there is a trend of reducing the match quality of the dissipation tests for filters positioned farther from the piezocone mid-face. The BAT tests fit properly in this trend, because the mid-height of the BAT filter is positioned approximately 2.6 radii from the cone shoulder, i.e., the matching quality is not as good as P1 and P2, though better than P3 and P4.

4.3. Coefficient of consolidation

Figure 12 presents a comparison of the coefficient of consolidation obtained from in-situ tests (BAT and piezocone), and IL oedometer tests with both vertical and radial drainage (with vertical compression) at Sarapuí clay. The coefficient of consolidation obtained in the normally consolidated and overconsolidated ranges from oedometer tests is included in the figure (Coutinho [42], Jannuzzi [40]). The values in the overconsolidated range correspond to the in-situ vertical stresses at the corresponding depths. The normally consolidated values correspond to the range of stresses above the yield stress. Only good-quality samples were selected.

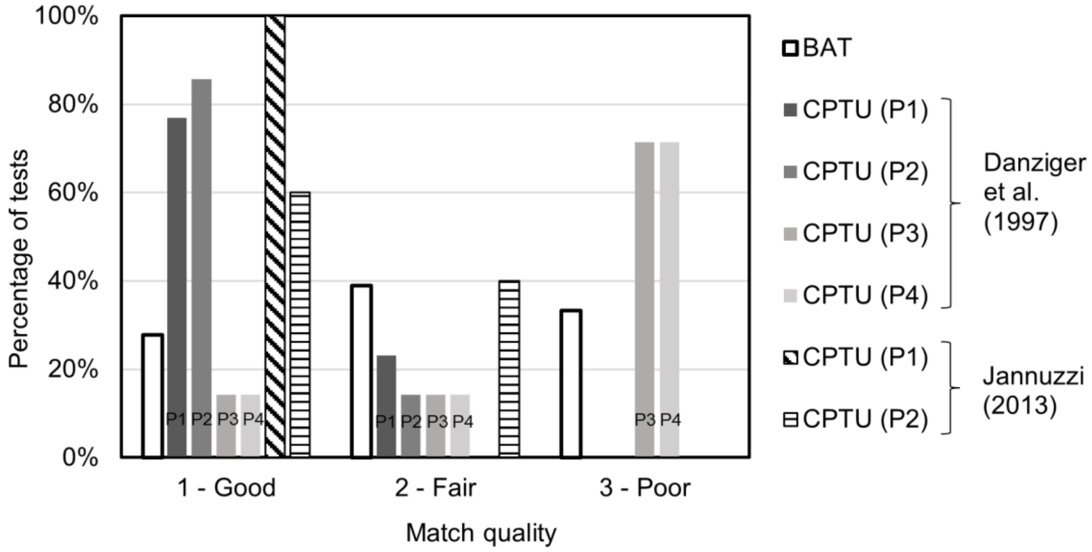

Figure 11. Comparison of matching scores for experimental dissipation curves obtained with the piezocone (Danziger et al. [35]; Jannuzzi [40]), and the BAT probe.

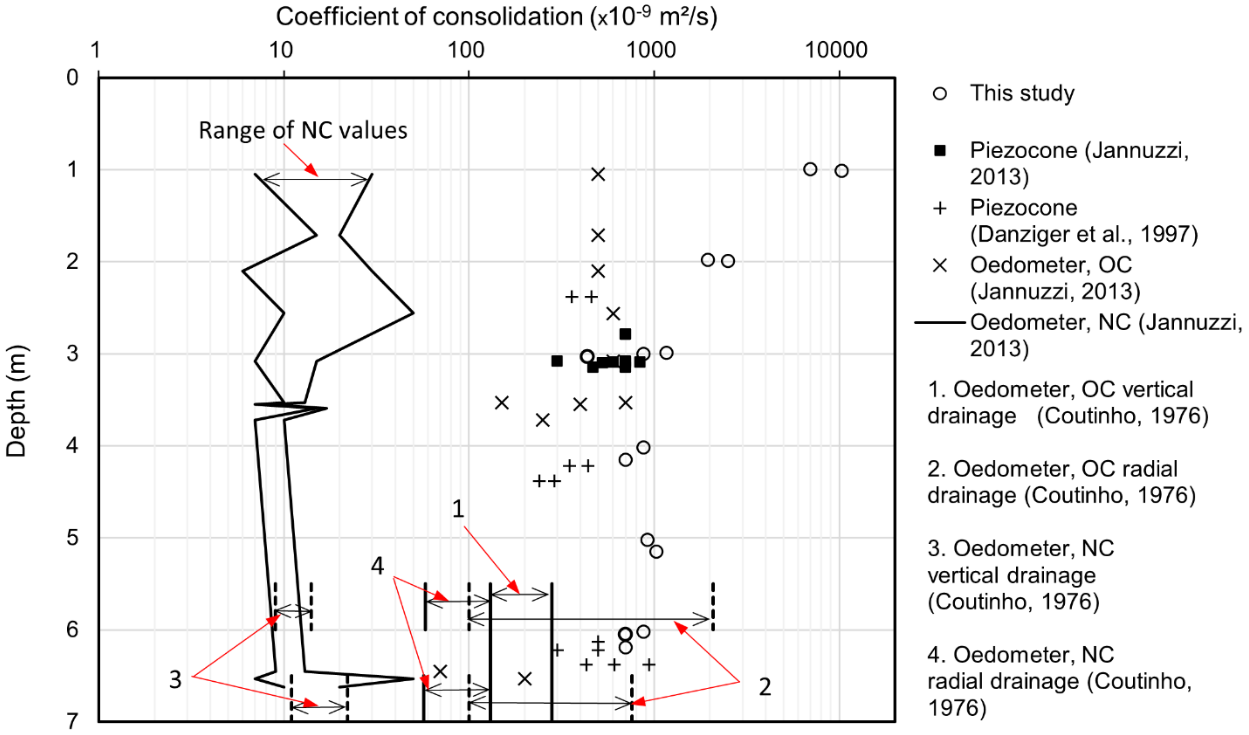

Figure 12. Comparison of the coefficient of consolidation data from Sarapuí clay.

From Figure 12, it can be seen that although with a large scatter, the OC oedometer results agree reasonably well with the in-situ data, which are much higher than the NC oedometer results. The BAT data are well above the oedometer results between 1 and 3 m depth. Unfortunately, there are no piezocone data in these depths. However, it must be reminded that the conditions for the in-situ tests (both the BAT and the piezocone) are different from the oedometer laboratory tests carried out. In fact, in the in-situ tests, both the drainage and the compression are in the horizontal direction; in the oedometer tests, the drainage is either in the horizontal or in the vertical direction, and the compression is always in the vertical direction. More tests are needed to properly quantify the role of anisotropy in such a comparison. Considerations on this issue are made in the following section.

4.4. Interpretation of the coefficient of volume change

Equation 6 relates the coefficient of consolidation to the coefficient of permeability (k_h) and the coefficient of volume change, m_v (Barron [43]). As pointed out by Leroueil and Hight [44], c_h is arguably not a basic soil parameter, but rather a function of the permeability and the volumetric compressibility of the soil. It must be reminded that Equation 6 corresponds to vertical compression, whereas the piezocone dissipation tests are related to horizontal compression; thus, m_v must be replaced by m_h.

$$c_h = \frac{k_h}{m_v \gamma_w} \tag{6}$$

From Equation 6, considering the values of k_h measured in Sarapuí II by Vargas et al. [12] and c_h obtained in the dissipation tests (Figure 13), the values of m_h can be obtained (Table 2). This assessment of the compressibility of the soil appears to be first proposed by Mitchell and Gardner [45]. Some permeability tests followed dissipation tests, *i.e.*, there is a direct correspondence between these two tests. In other cases (indicated in Table 2), because of the need to have data at the same depth, they were obtained from the trend of k_h versus depth, which is shown as a dashed line in Figure 13. The data analyzed are limited to 6.5 m depth, *i.e.*, to the depth that all BAT tests correspond to the very soft clay.

Figure 13 shows that k_h and c_h values present a similar trend with depth. Both parameters decrease from 1 m to 3 m depth following approximately a straight line in the logarithm scale, with the coefficient of consolidation exhibiting a more pronounced variation (one order of magnitude) compared to the permeability (4 to 7-fold). From 3 m to the bottom of the layer, both parameters assume approximately constant values, 10^{-9} m/s for k_h and 10^{-6} m²/s for c_h. In addition, both parameters present little scattering, with the only apparent exception being the c_h measurement at 3.03 m depth (dissipation test V20), which provides a smaller coefficient of consolidation than expected compared to the other two measurements at the same depth. The match quality of the dissipation curve V20 is deemed poor (see Table 1), which can explain such a value of c_h.

The values of m_h versus depth are plotted in Figure 14. The coefficient of volume change is seen to slightly increase from 1 m to 3 m depth, and then assumes a constant value of around 1.2×10^{-4} m²/kN. In fact, a constant value of 10^{-4} m²/kN would be, based on the BAT tests, a representative value of m_h across the deposit. In addition, taking out the m_h values calculated from the aforementioned dissipation test V20, the parameter lies in the $1–2 \times 10^{-4}$ m²/kN range from 2 m to 6 m depth.

Table 2. Values of c_h and k_h measured with the BAT probe, and m_h calculated from Equation 6.

Depth (m)	Dissipation test n.	c_h (10^{-7} m²/s)	k_h (10^{-10} m/s)	m_h (10^{-5} m²/kN)
0.99	V10–1	70	45*	7
1.98	V10–2	20	22*	12
3.00	V10–3	9	13*	15
4.02	V10–4	9	11*	12
5.02	V10–5	9	11*	12
6.02	V10–6	9	8*	9
1.01	V11–1	103	71	7
1.99	V11–2	25	26	11
2.99	V11–3	12	14	13
3.03	V20	4	15	36
			13	31
			13	31
			14	32
4.15	V16	7	14	21
			14	20
5.15	V15	10	12	12
			12	12
6.05	V21	7	8	12
			8	12
			9	12
			9	13
6.19	V14	7	7	10
			7	10

*k_h calculated from dashed line from Figure 13.

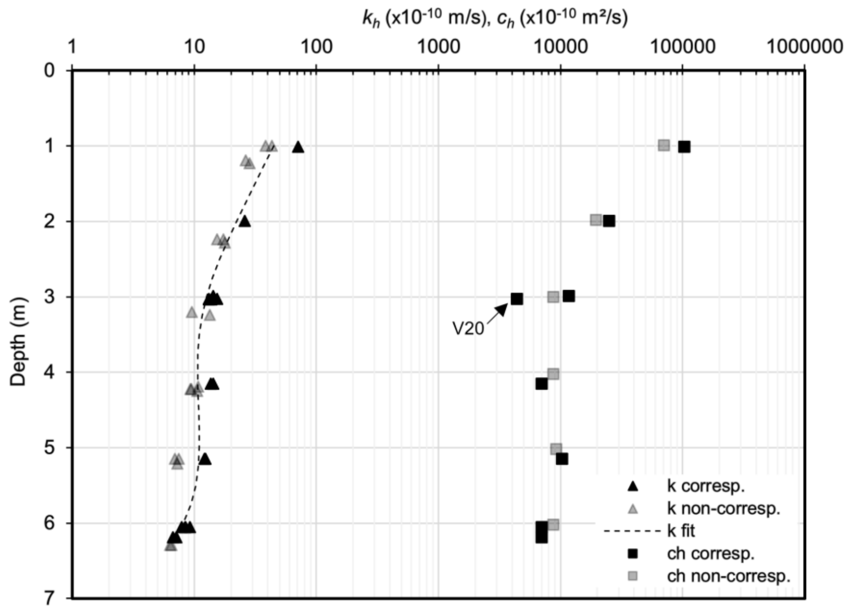

Figure 13. Coefficient of permeability [12] and coefficient of consolidation from BAT tests.

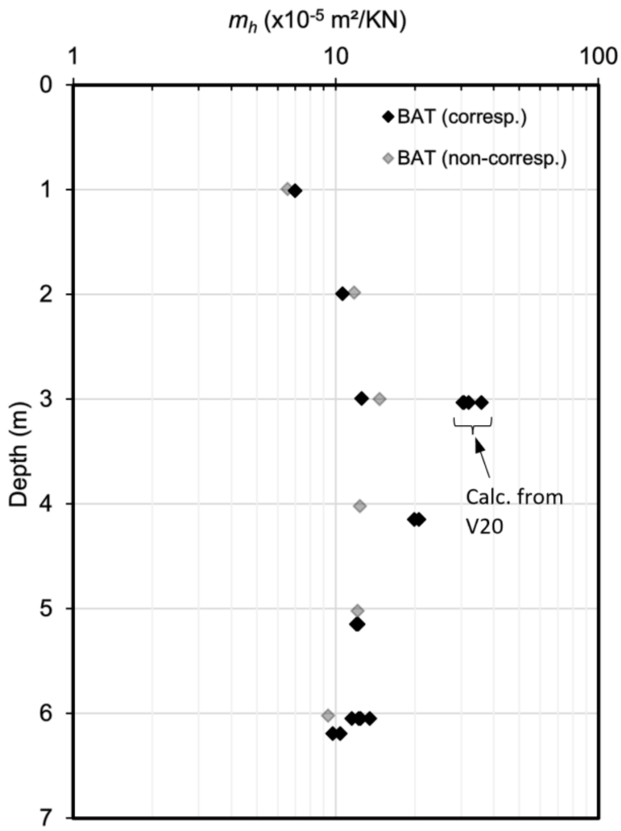

Figure 14. Coefficient of volume change, m_h, calculated from BAT tests.

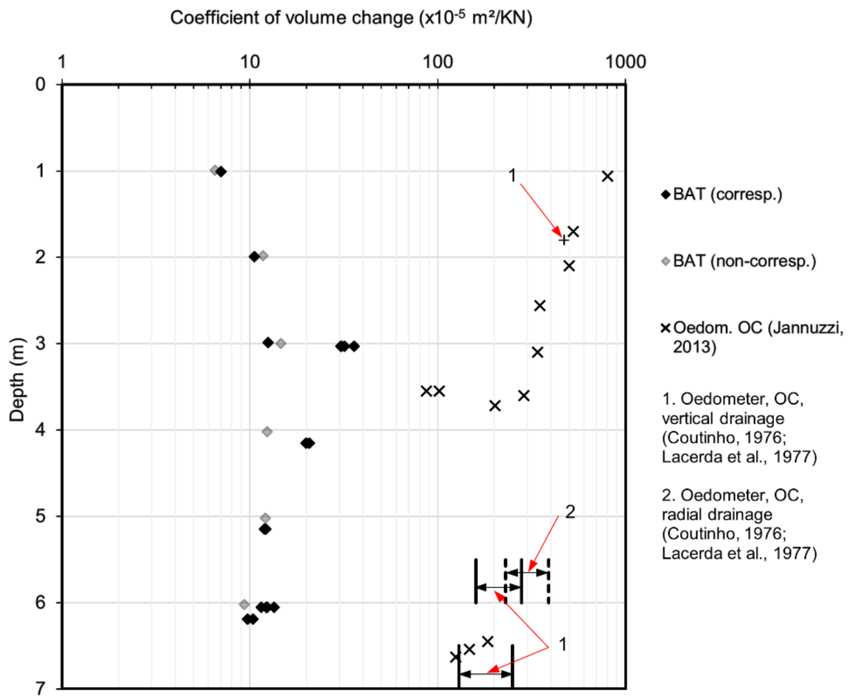

Figure 15. Coefficient of volume change from different tests at the Sarapuí clay.

Figure 15 compares values of the coefficient of volume change from BAT tests with oedometer tests. Values of m_v from oedometer tests were obtained considering the vertical effective stress at the sample depth. Since the soil is overconsolidated, the corresponding values are represented in this way. No values for the normally consolidated range are plotted in the figure due to the lack of a reference stress. However, those values should present an even larger difference with respect to the BAT values. As stated, in the case of the BAT probe, the coefficient of volume change refers to m_h, whereas in the oedometer tests, it refers to m_v.

From Figure 15, it can be seen that the values from the oedometer laboratory tests are very consistent from the Sarapuí I and Sarapuí II sites. Moreover, although from a limited number of oedometer tests, values from tests with radial drainage tend to be slightly higher than with vertical drainage. A quite significant difference was found between the BAT values and the oedometer values. From 3 m depth to the bottom of the clay layer, *m* values may be considered approximately constant with depth. In this case, m_v from oedometer laboratory tests is approximately 20–30 times higher than m_h from BAT tests. In the upper part of the deposit, there are different trends of m_v, decreasing with depth, and m_h, increasing with depth. The observed differences may be attributed to some factors: i) Anisotropy, because the compression is carried out in vertical and horizontal directions in the different tests, as mentioned. Further studies are required to confirm this hypothesis. ii) Stress state. The insertion of the BAT probe introduces stress changes, increasing the radial effective stress in the vicinity of the probe (e.g., Baligh and Levadoux [2] and Bjerrum et al. [46]); however, Tavenas et al. [47] suggested, from their observations on piezocone tests in Champlain clays, that the rate of pore pressure dissipation is mainly governed by the consolidation characteristics of the intact clay, which is distant from the piezocone, a portion of soil that is subjected to initial swelling then recompression. In the case of the oedometer tests, only the vertical stress is the in-situ stress; the horizontal stress is less than the horizontal in-situ stress in the case of overconsolidated soils, the difference increasing with the increase of OCR (see Figure 4). This means that the oedometer samples are less stiff than the in-situ soil due to the horizontal stresses not being properly applied. iii) Measured k_h. The permeability tests with the BAT probe are carried out after the dissipation tests, *i.e.,* after some permeability reduction due to soil consolidation. This value has been estimated to vary between 1.15 and 10 times for Canadian clays (Tavenas et al. [48]).

Regardless of the real reasons for such a complex analysis of this issue, the obtained values indicate that, as suggested, the dissipation around the probe takes place in recompression mode ([2,24,47]).

5. Conclusions

Dissipation tests were performed with the BAT probe at the Sarapuí II very soft clay test site. The dissipation tests were combined with permeability tests presented by Vargas et al. [12] to assess the compressibility of the soil around the probe during the dissipation process. This study has been possible due to the fact that the BAT probe enables dissipation and permeability tests to be performed in the same position.

- It has been shown that, provided the probe is properly saturated, i.e., with vacuum instead of the regular procedure, the obtained c_h values are reliable.
- The tests have been interpreted following the method suggested by Danziger et al. [35], in which a match is carried out between the measured curve and the theoretical one, from the

Teh [30] and Teh and Houlsby [31] theory. Since the relative position of the filter at the BAT probe does not coincide with any of the positions for which a curve was derived in the theory, an adjusted curve was constructed. The match quality of the tests was not as good as the piezocone dissipation tests carried out in the cone face and cone shoulder, but was fair in most cases and better than the piezocone dissipation tests carried out in positions in the middle of the friction sleeve and at the top of the friction sleeve. It was verified that the match quality decreases as the distance from the middle of the cone face increases.

- The results in the slightly overconsolidated soil (from 3 m in depth) show good agreement between the c_h obtained with the piezocone and the BAT probe, with BAT values consistently in the upper range of piezocone values. Although with a large scatter, the coefficient of consolidation from the IL oedometer tests, taken in the overconsolidated range, agree reasonably well with the in-situ data in the same soil region. The BAT data are well above the oedometer results between 1 and 3 m depth, the overconsolidated material.
- The coefficient of volume change was assessed directly from the BAT probe, from the coefficient of consolidation obtained in the dissipation tests, c_h, and the coefficient of permeability in the permeability tests, k_h. The significant differences between in-situ and oedometer laboratory values have been attributed to anisotropy, stress state, and the influence of probe insertion on the coefficient of permeability values. However, tests to properly explain the role of each factor in the case of Sarapuí II clay are needed. Data provided evidence that the consolidation during dissipation around the probe takes place in the recompression mode, as suggested by other studies.

Author contributions

J.W.S. de Vargas: data curation, investigation, methodology, visualization, writing–original draft, writing–review & editing; F.A.B. Danziger: conceptualization, funding acquisition, methodology, project administration, resources, supervision, validation, writing–review & editing; G.M.F. Jannuzzi: investigation, methodology, validation, writing–review & editing; T. Lunne: validation, writing–review & editing.

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Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of Interest

The authors declare no conflict of interest.

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