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Technical Paper

Penetration and retrieval forces during sampling in a very soft clay

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Abstract

Three series of sampling with thin-walled samplers, with and without inside clearance and without a piston, have been performed in a very soft organic clay deposit. The penetration and retrieval forces were measured throughout the operation, thus contributing to a clearer understanding of the sampling process. The measured forces show the importance of proper borehole cleaning conditions, and also identify when samples were lost during retrieval. This occurs when the underpressure at the sampler bottom does not appear in the retrieval force versus time chart. The obtained values have been compared to the sleeve friction measured by piezocone tests. Direct simple shear (DSS) tests and vane shear tests have been used as references to back-calculate the dimensionless skin friction factor from both sample penetration and retrieval. The measurement of force during sampling proved useful for controlling sampling operation, also providing further information with respect to the regular procedure.

Keywords: Sampling; Soft clay; Penetration force; Retrieval force; Clearance; Skin friction

1. Introduction

It is well known that the quality of the sample plays an important role in the laboratory test results. Several types of samplers are available to collect soft clay samples from both onshore and offshore. The Sherbrooke sampler (Lefebvre and Poulin, 1979) is generally considered the best onshore sampler (e.g., Lacasse et al., 1985; Hight et al., 1992; Pineda et al., 2016; Amundsen et al., 2017), since a block sample with a large diameter (250 mm) is carved out in the bottom of a borehole.

Thin-walled piston samplers are generally considered good for providing good quality samples (e.g., Tanaka et al., 1996; Lunne et al., 1997; Tanaka and Nishida, 2007), both when displacement method and pre-augering are used. The use of a piston will reduce plugging tendency and enable retrieval of longer samples. During penetration, when the soil enters the sampler, the underpressure beneath the piston overcomes the inside friction, thus preventing plugging (Lunne et al., 2008). Thin-walled samplers without a piston, generally with a sampler head and a one-way ball valve to prevent sample loss during retrieval, are also very commonly used, and are standardised in different countries (e.g., ISO, 2006; ASTM, 2015). The wide use of this type of sampler is due to its low cost, robustness and simplicity of operation (Horng et al., 2010). However, sample retrievability may be a problem in very soft soils, in the case of inefficiency of the sampler head, as illustrated herein.

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A number of authors (e.g., Hvorslev, 1949; Kallstenius, 1963; Lefebvre and Poulin, 1979; La Rochelle et al., 1981; Baligh et al., 1987; Hight et al., 1992; Shogaki and Kaneko, 1994; Tanaka and Tanaka, 1999; DeGroot et al., 2008; Tanaka, 2000, 2008; Chung et al., 2004; Long et al., 2009; Horng et al., 2010) have studied the factors that affect the quality of the sample. Lunne and Long (2006) have reviewed and analysed the role of the sampler characteristics, in terms of effects on the sample quality: sample diameter, wall thickness, cutting edge angle, inside clearance, inside friction, outside friction, and effect of piston. In short, the larger the sample diameter, the smaller the wall thickness, and the sharper the cutting edge angle, the better the quality of the sample. Horng et al. (2010) showed that the cutting edge angle plays a more important role than the wall thickness on the sample quality. In fact, these authors found that in the case of very small edge angle, a large area ratio can still provide good quality samples. However, a small area ratio is required in case of not so small cutting edge angles.

Inside friction is one of the main causes of disturbance, and the smaller the inside friction the better the quality of the sample. Outside friction must also be reduced, since it is able to generate shear stresses in the soil below the cutting edge (Eide and Andresen, 1977). A number of papers have indicated that inside clearance must be avoided or kept to a minimum. A sample may expand laterally due to the inside clearance, thereby possibly causing some disturbance. Numerical analyses have also indicated (e.g., Baligh et al., 1987; Clayton et al., 1998) that inside clearance may cause sample disturbance. Some well-known samplers do not have inside clearance, namely the Laval sampler (La Rochelle et al., 1981) and the Japanese thin wall standard piston sampler (Tanaka et al., 1996; Tanaka and Tanaka, 1999). However, since the main purpose of inside clearance is to reduce inside friction, a number of samplers do have inside clearance, especially when long samples are to be retrieved, as in the case of some offshore samplers (Lunne and Long, 2006). The ISO (2006) and ASTM (2015) standards allow the use of inside clearance, although limiting to 0.5% the inside clearance ratio, C_r in ASTM (2015) or C_i in ISO (2006). Consequently, it was interesting in the present study to test not only samplers without inside clearance, but also with inside clearance.

A recent comprehensive research (Pineda et al., 2016) employed a microstructural approach to compare the quality of samples from piston samplers and Shelby tube samplers (without piston), using the Sherbrooke sampler as a reference. It also showed the better quality of samples from piston samplers compared to Shelby tubes. However, 75 mm Shelby samples were also shown to produce good quality samples in their central part. Also, the wall thickness to diameter ratio and cutting edge angle play an important role on the sample disturbance, because the disturbance is more significant near the sampler wall.

In order to contribute to a better understanding of the sampling process, the forces during penetration and retrieval of thin-walled tube samplers, 100 mm in diameter, with and without inside clearance have been measured. These measurements presented herein resulted in better understanding of the entire sampling process, including cleaning of the borehole and sample retrievability. Moreover, sampler penetration can be regarded as the penetration of an open-ended pile, and retrieval as an uplift test on a pile. Therefore, the measurement of force during sampler penetration and retrieval is able to provide an estimation of the sampler skin friction to be used in a preliminary design of piles, as shown in the paper. In other words, the measurement of force during sampling is a simple procedure that can control the sampling operation and provide further information with respect to the regular procedure.

2. The test site

Close to the city of Rio de Janeiro, in the Guanabara Bay area, the Sarapuí II test site was established in the early 2000s as an alternative to Sarapuí I test site for security reasons. The latter is the oldest test site area in Brazil, having been studied since the 1950s (Pacheco Silva, 1953), and then regularly from 1970s to 2000. Soil characteristics of Sarapuí I test site have been addressed in a number of papers (e.g., Lacerda et al., 1977; Werneck et al., 1977; Ortigão et al., 1983; Almeida and Marques, 2003).

The Sarapuí II test site has been extensively investigated recently, and a comprehensive description of soil properties has been presented (Jannuzzi et al., 2015). The soil is a very soft high plasticity (plasticity index in the range 60–170%) silty clay, some properties of which are summarised in Fig. 1. The material is slightly overconsolidated (overconsolidation ratio, OCR, of 2.0 from 24-hr incremental loading, IL, oedometer tests) from around 3 m in depth. Sensitivity from vane shear tests ranges from 4 to 8 in most of the data. Further details about the soil deposit can be found in Jannuzzi et al. (2015) and Danziger et al. (2019).

3. The samplers, sampling procedure and sample quality

Commercial brass tubes with a 101.5 mm outside diameter (OD), 1.65 mm wall thickness, corresponding to an area ratio (A_r from ASTM, 2015 or C_a from ISO, 2006) of 6.8%, were used to produce two types of samplers: (i) without clearance, cutting edge angle of 8.5°; (ii) with inside clearance ratio (C_r from ASTM, 2015 or C_i from ISO, 2006) of 1.0% and the same edge angle as in the sampler without clearance. In both cases the outside clearance ratio (C_o from ISO, 2006) is equal to 0%. The roughness of the brass tube was measured using a Form Talysurf Intra 112/2564–4339 roughness tester, and an average value of 1.26 μm was obtained for the surface of the sampler. Brass was chosen because the procedure adopted for trimming the specimen was that recommended by Ladd and DeGroot (2003), in which the sampler is sliced; in fact, brass facilitates this procedure with less damage risk to the specimen than stainless steel. The sampler length is

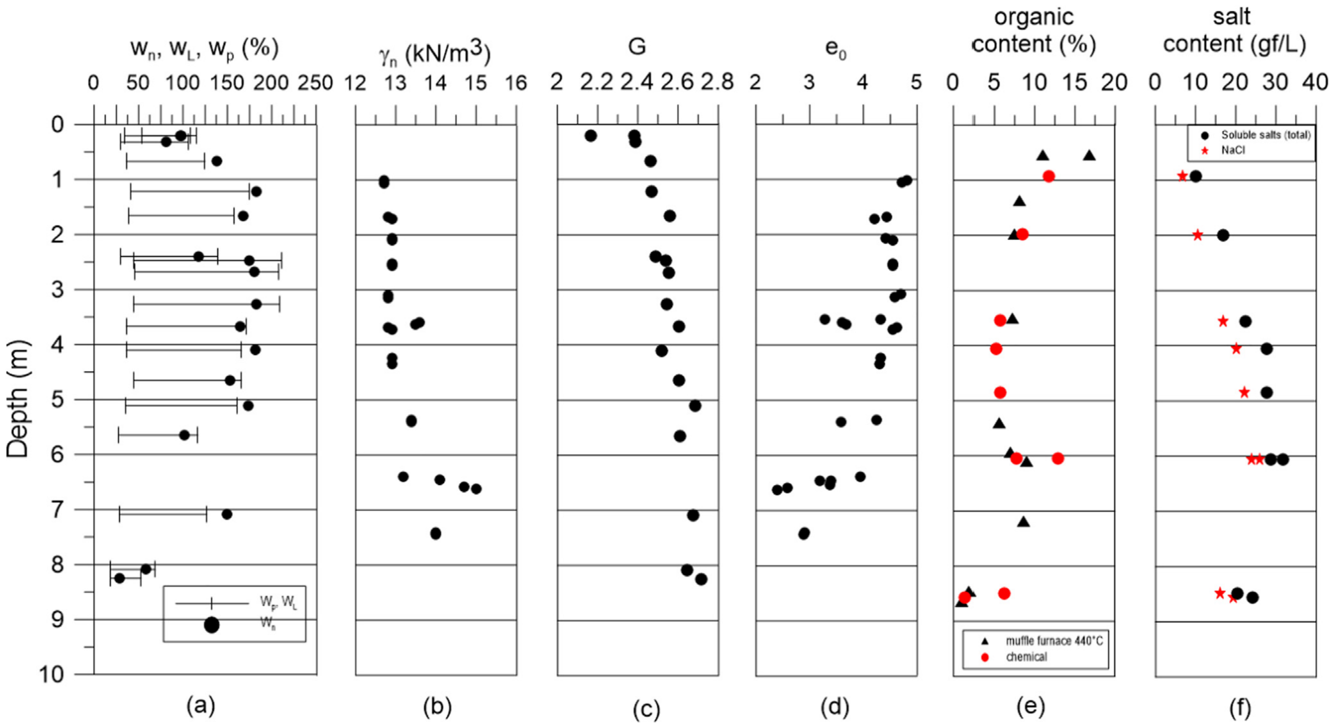


Fig. 1. (a) Liquid limit, plastic limit and natural water content; (b) total unit weight; (c) particle density; (d) initial void ratio; (e) organic content; (f) salt content versus depth, Sarapuí II deposit (adapted from Jannuzzi et al., 2015).

700 mm, providing a 650 mm long sample, due to the sampler head, schematically shown in Fig. 2, which is similar to the one illustrated in ASTM (2015). A piston was not used in the research reported herein for the following reasons: (i) Shelby tubes are most commonly used in practice (e.g., Andresen, 1981; Pineda et al., 2016); (ii) to check which conditions would cause sample loss when there is not enough underpressure at the top of the sample.

Three series of sampling, in which force was measured, have been performed for different purposes adopting slightly different procedures. Sampling operations were carried out at nominal depths of 1 m, 3 m and 6 m. Table 1 summarises the main variables of the series of sampling performed, to be detailed below. In the first series, only one out of four samples has been included in Table 1, because the load cell presented mal-functioning due to improper mounting in the case of the three other samples. The designation of the samples follow the series of the sample, related to their purpose, the number of the borehole in the series and number of the sample taken in each borehole.

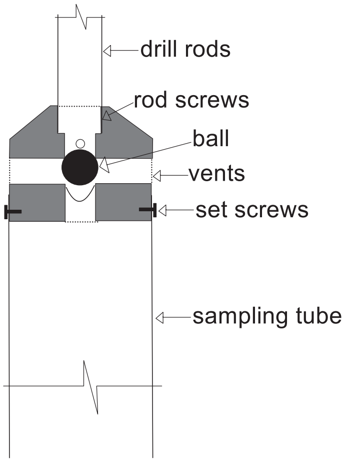


Fig. 2. Sampler head with a one-way ball valve.

The following sampling procedure was used:

(i) Drilling, casing and cleaning the borehole – The drilling process using a jet bit was alternated with the insertion of the casing with an inside diameter of 150 mm. In the third series of sampling, a flat bottom auger similar to the one used with the Sherbrooke block sampler (Lefebvre and Poulin, 1979) was also used for final cleaning of the borehole (Fig. 3a). This procedure was followed after observations that, although proper cleaning was tentatively done with the jet bit, it was not possible to guarantee an efficient process. It will be shown later that the efficiency of the cleaning process could be observed by measuring the penetration force.

(ii) Assembling and penetrating the sampler – The sampler was assembled to the sampler head, then connected to the rods, the same used in piezocone, dilatometer and T-bar testing, with 35.6 mm in diameter. A rig, 7.5 kN in weight, able to keep constant rates both during penetration and retrieval when conducting piezocone tests, was used to drive the samplers, and then centring the sampler as much as possible with respect to the casing (Fig. 3b). The sampler

Table 1
Series of sampling performed.

Sample designation	Nominal depth (m)	Inside Clearance Ratio (%)	Use of flat bottom auger	Sample retrieval (%)
S1B1S4	6	0	No	100
S2B1S1	3	0	No	0
S2B2S1	3	0	No	69
S2B4S1	3	0	No	100
S2B5S1	3	0	No	0
S2B6S1	3	0	No	100
S2B7S1	3	0	No	100
S2B8S1	3	0	No	100
S2B9S1	3	0	No	100
S3B1S1	1	0	Yes	0
S3B1S2	3	0	Yes	77
S3B1S3	6	0	Yes	69
S3B2S1	1	1.0	Yes	0
S3B2S2	3	1.0	Yes	75
S3B2S3	6	1.0	Yes	100
S3B3S1	1	0	Yes	0
S3B3S2	6	1.0	Yes	75

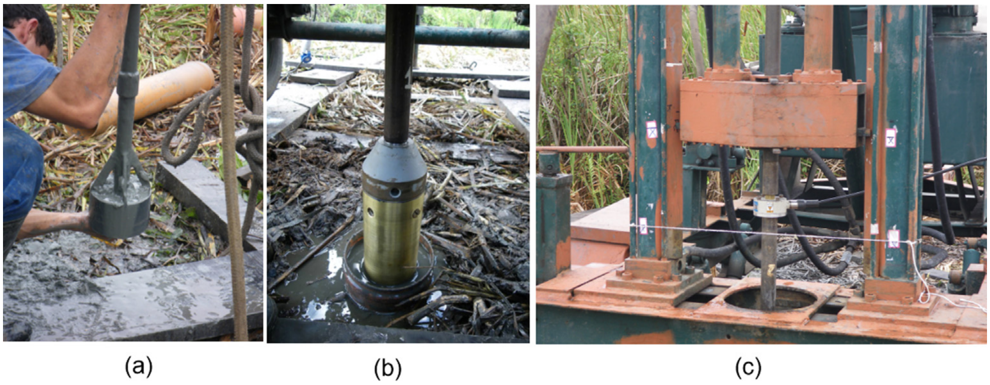


Fig. 3. (a) Flat bottom auger used for final cleaning of the borehole; (b) Positioning of the rig to centre the sampler with the casing; (c) Load cell in the rod stem, used to measure both penetration and retrieval forces during sampling.

was then carefully and slowly lowered to the sampling depth in order to release the air inside the sampler through the valve. A LUK-A Kyowa load cell, with 10 kN capacity, was then assembled in the rod stem (Fig. 3c). The sampler was penetrated at a constant rate of approximately 10 mm/s. This rate was chosen in order to guarantee undrained conditions, to avoid any excess pressure on the top of the sample due to the presence of the one-way ball (vent) valve (e.g., Hvorslev, 1949), and also for practical reasons, since it is easy to halt penetration to avoid overdriving the sampler. A Kyowa PCD-300B data acquisition system was used to record the loads. Ceasing penetration was controlled by marks on the rig.

iii) Resting period and sampler rotation – After penetrating the sampler a minimum resting period of one hour was allowed in order for the excess pore pressure generated during driving to dissipate and the soil adjacent to the sampler wall to regain strength. In order to separate the sample from the soil, 10 rotations were applied to the rod stem.

(iv) Retrieval of the sampler – The sampler was then retrieved and a constant rate was adopted. Since the same regulation of the valve that controls the oil flow results in slightly different rates in pushing and pulling the rods, a rate of approximately 7.3 mm/s was used during the retrieval of the sampler. The loads during retrieval were recorded in the same way as described above for sample penetration. As shown below, the results indicated in real time for retrieval or not of the sample. In the first sampling, the whole process was recorded, i.e., not only retrieving the sampler completely from the hole made by the sampler insertion, but also whenever a rod was removed from the rod stem.

The sample quality was evaluated according to the criterion of Lunne et al. (1997) (based on the ratio $\Delta e/e_o$, where $\Delta e = e_o\text{-}e$ is the difference between the initial void ratio, e_o, and the void ratio when the specimen is consolidated to the best estimate of the vertical effective stress in the field, e), from incremental loading (IL) 24-h consolidation tests, and the results have been presented in Fig. 4. Those results are related not only to the tests in which the force was measured but also to previous tests, with the same procedure used in the second series of sampling. In most cases the

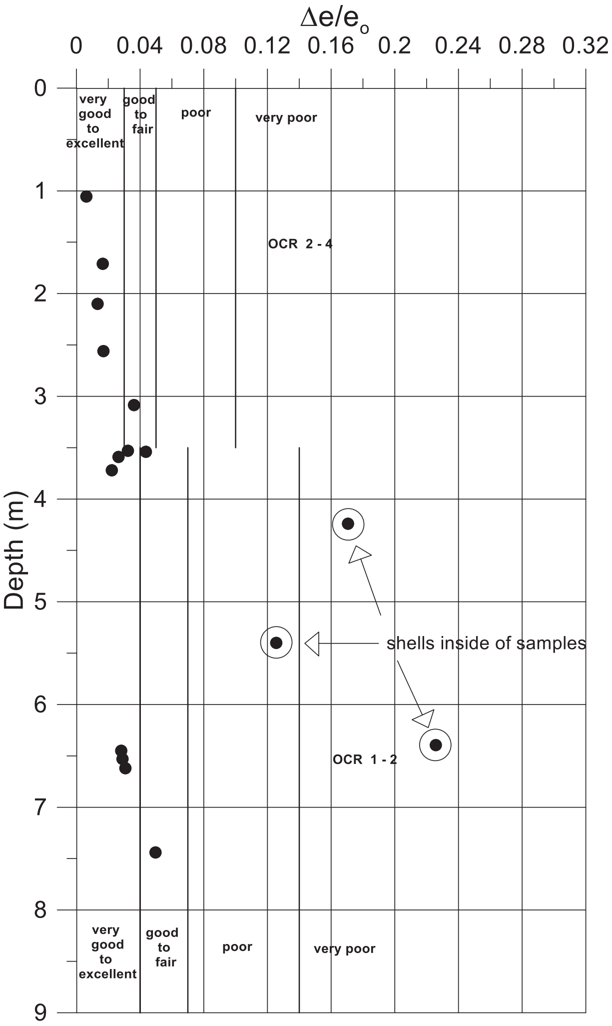


Fig. 4. $\Delta e/e_o$ versus depth, Sarapuí II clay.

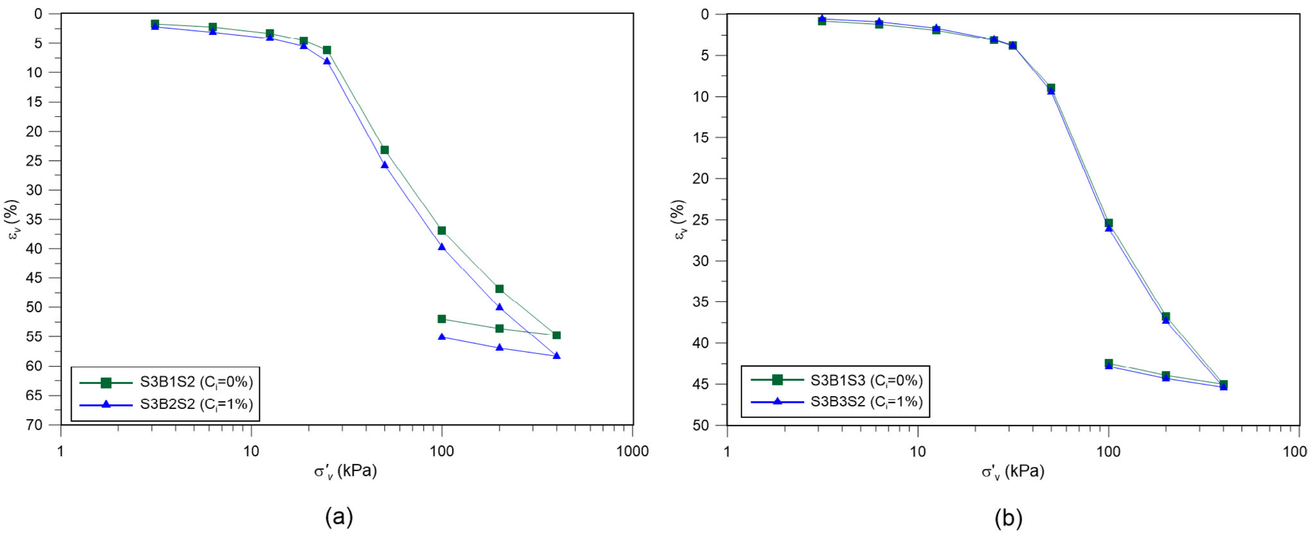
samples have been classified as very good to excellent. The sample quality in the case of the 1 m depth must be regarded with caution, because the Lunne et al. (1997) criterion is only valid for OCR of less than 4, and at this depth OCR is around 8. Poor quality samples were obtained in those cases where a significant amount of shells were present (see also Jannuzzi et al., 2015; Danziger et al., 2019). It must be clarified that it is almost impossible to obtain samples without shells in the 4–6 m depth interval.

When the samples from the samplers with and without clearance are directly compared, the difference is small for samples at 3 m nominal depth, as can be seen in Fig. 5a. The vertical strain has been used rather than the void ratio because the initial void ratio was not the same, but the ratio $\Delta e/e_o$ was 0.03 and 0.04 for $C_i = 0\%$ and $C_i = 1.0\%$, respectively. In the case of 6 m depth the difference is negligible (Fig. 5b), with $\Delta e/e_o = 0.03$ in both cases. It can be concluded that the adopted sampling procedures were able to produce high quality samples, even in the case of the sampler with clearance.

4. Forces measured

The force measured during penetration in the first sampling is illustrated in Fig. 6. Due to a malfunction, the clamping device that holds the rods laterally slipped twice (see also Fig. 3c), as shown in the figure. However, the increase of force with time (or penetration) can be seen followed by a sudden drop when the penetration ceases. Then the force reduces with time, i.e. a relaxation occurs. The slight oscillations in this period have been attributed to the crew walking around the rig, as shown later.

Fig. 7 illustrates the force measured during retrieval, where the whole process has been monitored. Negative values have been adopted to represent retrieval forces. The maximum force is measured immediately after starting



(a)

(b)

Fig. 5. Vertical strain versus vertical effective stress, samples from samplers without inside clearance and with inside clearance ratio of 1.0%; (a) 3 m depth; (b) 6 m depth.

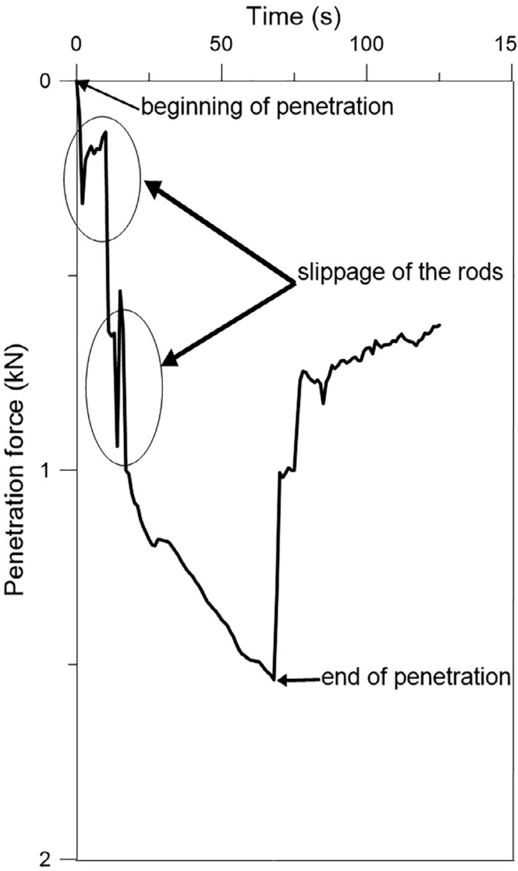


Fig. 6. Penetration force in the first sample (S1B1S4) where force has been measured.

the retrieval process, which represents the sum of (i) the weight of rods, sampler and soil inside the sampler (sample); (ii) the force equivalent to the underpressure at the base of the sampler; (iii) the soil resistance mobilised in the outer surface of the sampler, i.e. outside skin friction. After reaching the maximum value, the force starts to reduce due to the reduced length of the sampler in contact with the soil. When the sampler leaves the hole created during penetration the water enters the hole and the underpressure at the sampler base (represented by the nearly vertical line) disappears. The force is then due only to the weight of rods, sampler and sample. The continuous removal of each one-metre rod is also illustrated in the figure. The whole process was measured only in the first sample to analyse and check the obtained values. However, this is a cumbersome process, since the load cell must be removed and reassembled in a new rod when the previous rod has been removed. The nearly horizontal straight-line segments, with reducing loads, represent the progressive removal of one-metre rods.

Fig. 8 presents the forces measured during penetration of the second series of sampling. At the onset of penetration it can be seen that there is an almost immediate increase in load, albeit very small. This initial force increase was attributed to forcing the water inside the sampler, through the holes inside the valve in the sampler head. The load then starts to increase with time (Fig. 8a, or with penetrated length, Fig. 8b, since the rate is constant) almost linearly, until 30–50 s (300–500 mm penetrated length), depending on the sample. A non-linear behaviour is then observed, with a higher gradient of force versus time (or penetrated length). The deviation from the linear behaviour was attributed to the borehole not being properly cleaned, especially at the bottom (i.e. at the top of the sample), implying that dirty water (not clean water) passes through the valve head. As will be seen later, when the borehole is properly cleaned, the force is almost linear with penetrated length. A maximum value is then reached at the end of penetration. When penetration ceases, there is an immediate reduction in load, which can be attributed to the deactivation of the viscous parcel of force, i.e., the one depending on the rate. This is the same phenomenon observed in both cone resistance, q_c, and sleeve friction, f_s, when changing rods during piezocone testing in clays. Then a load relaxation with time occurs, which can be seen in Fig. 8a.

Fig. 9a shows the retrieval force versus time in those cases with no sample loss, i.e. where samples have been retrieved. The corresponding behaviour has been previously explained when addressing the whole retrieval process. However, the data is now more illustrative. In some cases the reduction of force with time is found not to be smooth, indicating that the underpressure on top of the sample was not properly maintained. It is worth noting that the underpressure on top of the sample can only be assured if the one-way ball valve (illustrated in Fig. 2) works properly, preventing air (or water) from entering the top of the sample through vents or drill rods. As a measure to contribute to the efficiency of the valve, the top of the drill rod stem was closed during sampling retrieval. The case of sample S2B4S1 (Fig. 9b) illustrates that this procedure is indeed useful. In that case, closure of the top of the drill rod stem had been forgotten. However, the problem was detected at the very beginning, the retrieval procedure stopped and the cover installed. An immediate restoration of the underpressure can then be observed, with no sample loss, i.e. proper retrieval of the sample. Some oscillations in the curve (indicated in the figure) were the result of the crew walking around the rig.

The force versus time curves of the cases with sample loss in this series of sampling are shown in Fig. 9c. The vertical segment corresponding to the end of sampler retrieval inside the hole does not appear. This means that the head valve was not efficient enough to keep the underpressure on top of the sample, which is the reason for the sample loss. It is interesting to note that this information is useful when following the process in the field, because all precautions when handling the sampler in the final part of the operation, already inside the rig, could be avoided and another sampling could go ahead. If a piston is used, this also could be achieved.

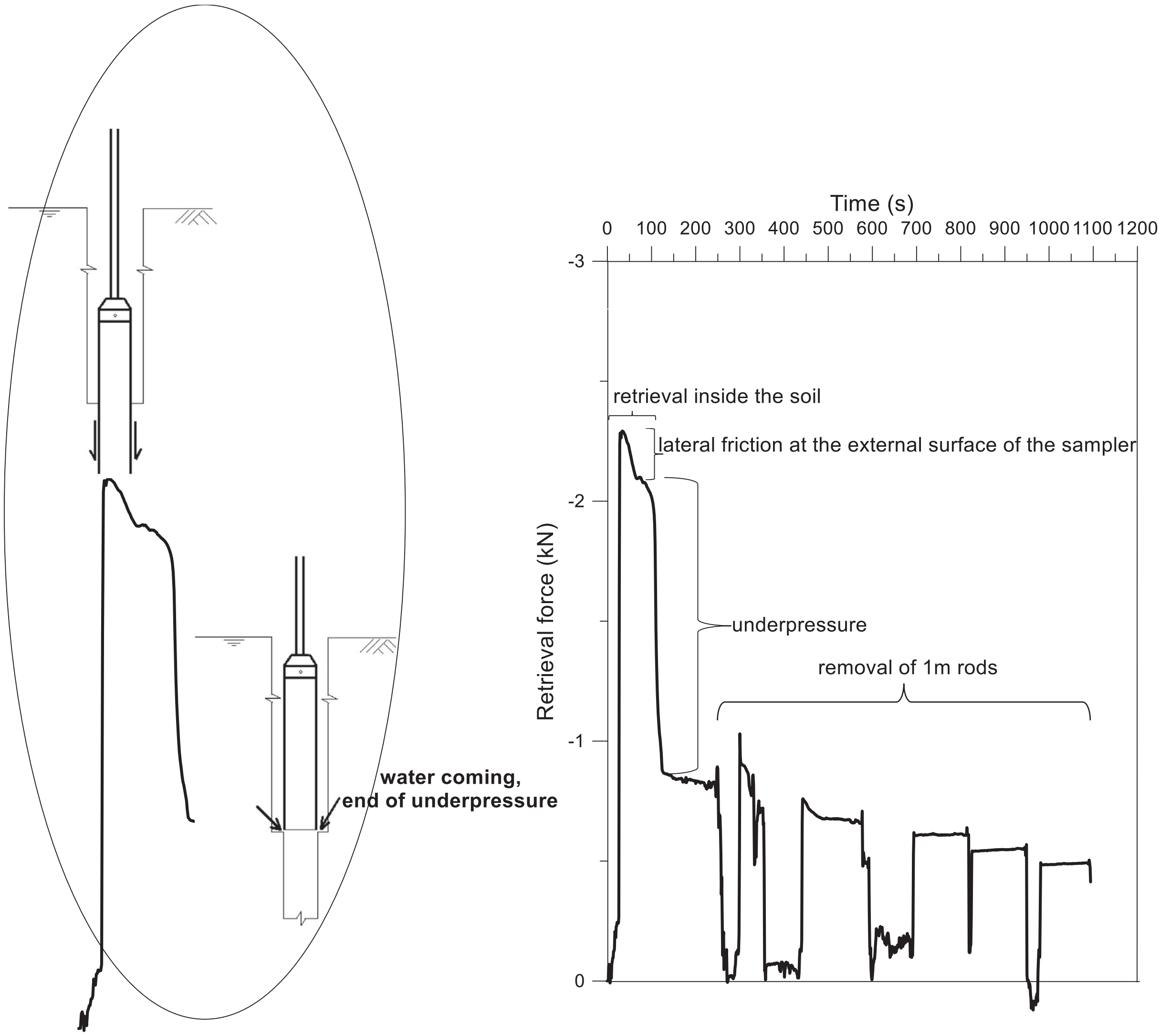


Fig. 7. Retrieval force in the first sample (S1B1S4) where force has been measured.

It should be pointed out that the penetration force curve is similar to the case where the samples have been retrieved. As in the case of sample S2B4S1, some oscillations can be observed due to the crew walking around the rig.

The purpose of the third series of sampling was to compare the forces measured in samplers with and without inside clearance. The results for the penetration in the case of 1 m nominal depth are shown in the lower part of Fig. 10. Since there has been a slight difference in the rate of penetration, the force versus time curve was replaced (and magnified) by force versus penetrated length in a better comparison, shown in Fig. 11. A higher resistance, characterised by the higher inclination of the curve force versus penetrated length, can be observed in the case of the sampler without clearance, albeit small. Neither the sample from the sampler with clearance nor those from the sampler without clearance were retrieved at 1 m depth in that series of sampling, which is noticeable by the absence of underpressure at the bottom of the sample (upper part of Fig. 10).

The same qualitative results for sampler penetration as in the previous case are illustrated in Figs. 12 and 13, where samples at nominal depth of 3 m are compared. A sudden increase at the end of penetration can be observed in the case of the sampler with clearance, due to the presence of shells in the sample.

With regard to retrieval, part of the sample inside the sampler with clearance slipped (16 cm were lost), which can be observed by the sharp variations in force indicated in the figure.

Similar results have been obtained in the case of 6 m nominal depth, i.e. the penetration force of the sampler without clearance was greater than with clearance. The corresponding values are analysed below.

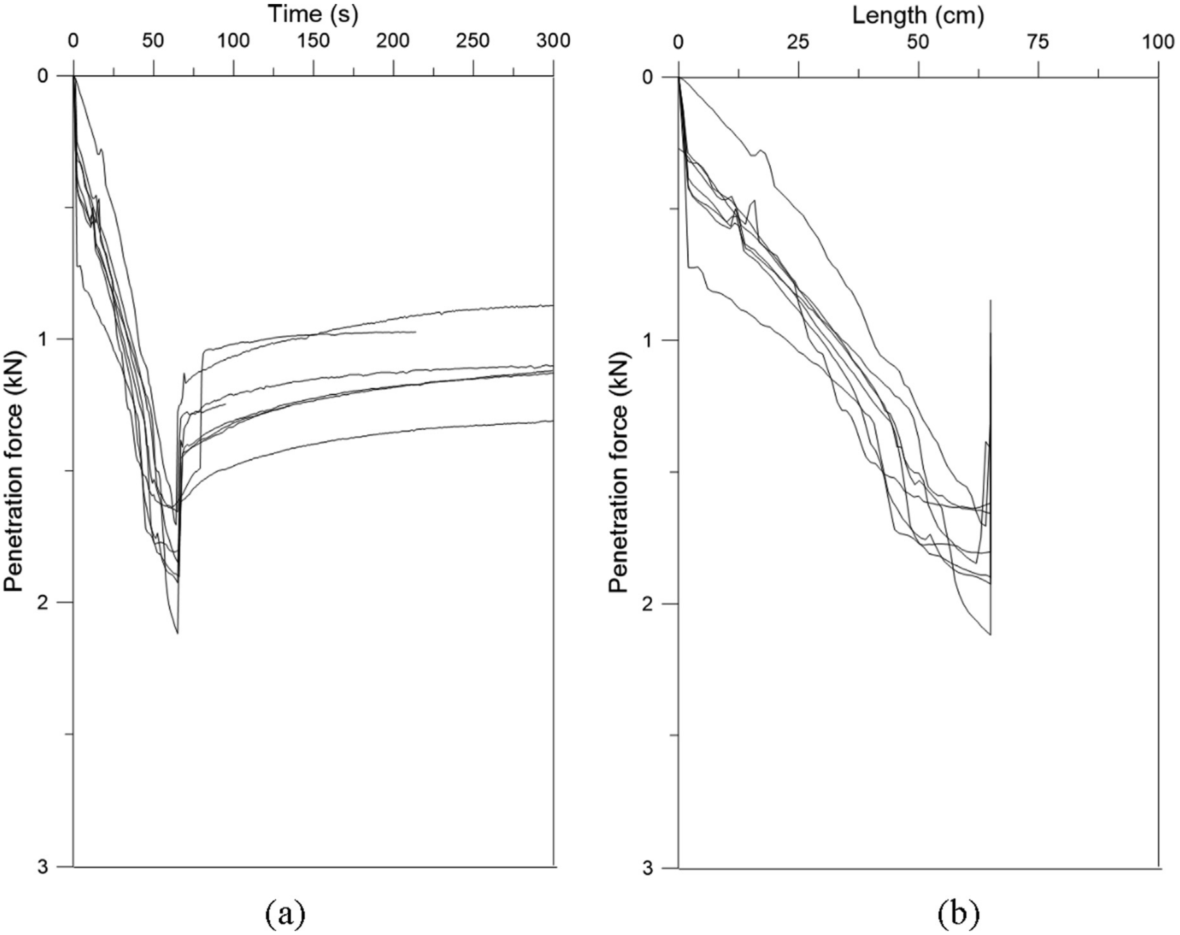


Fig. 8. Penetration force versus: (a) time, (b) penetrated length, second series of sampling, 3 m nominal depth.

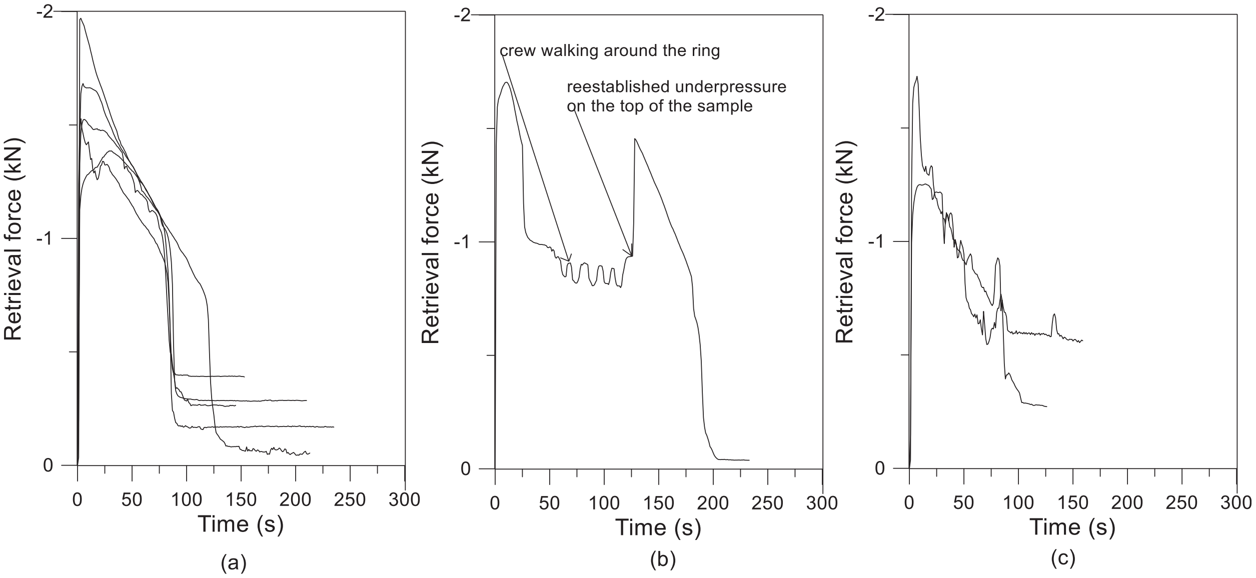


Fig. 9. (a) Retrieval force versus time, samples retrieved in the second series of sampling, 3 m nominal depth; (b) Retrieval force versus time, sample S2B4S1; (c) Retrieval force versus time, samples not retrieved (S2B1S1 and S2B5S1) in the second series of sampling, 3 m nominal depth.

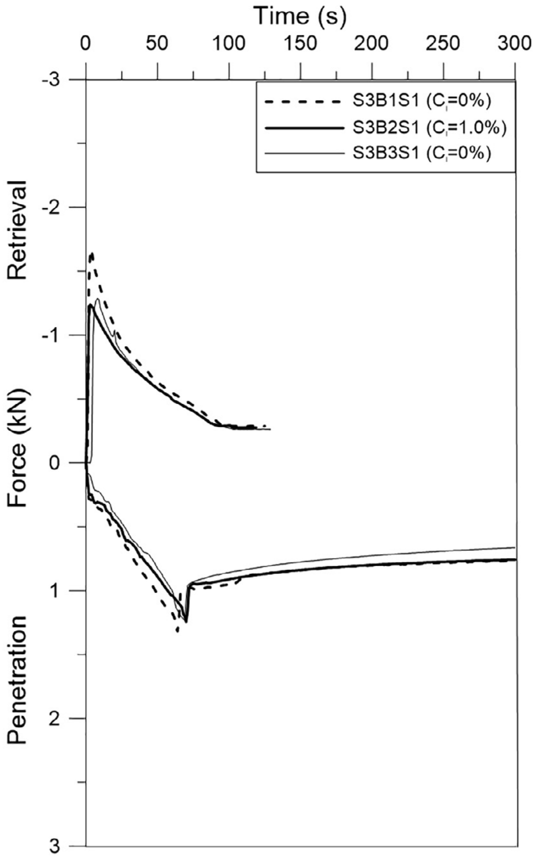


Fig. 10. Penetration and retrieval forces for 1 m nominal depth, third series of sampling.

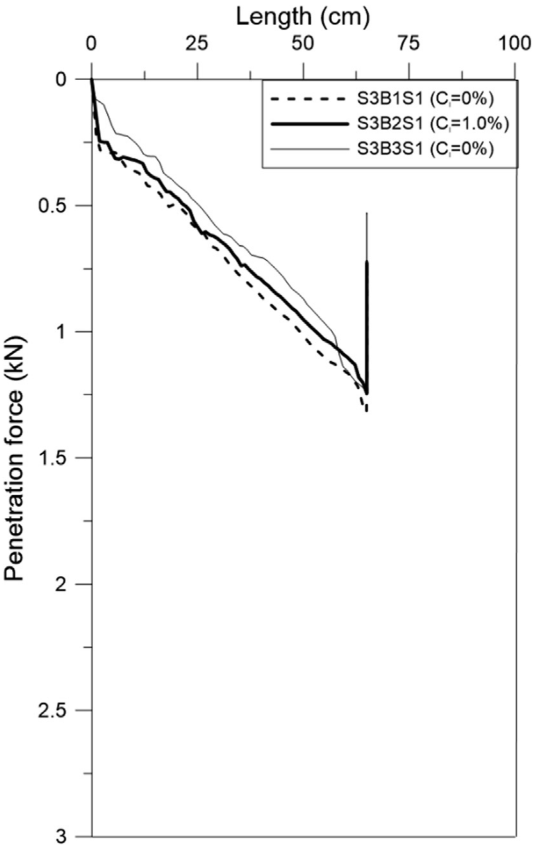


Fig. 11. Penetration force versus penetrated length for 1 m nominal depth, third series of sampling.

5. Discussion

5.1. On cleaning the borehole

Fig. 14 provides all results for 3 m nominal depth, thus including the second and the third series of sampling. Some conclusions can be drawn from the figure. In the penetration case it is noticeable that in the third series of sampling (S3), where the boreholes were cleaned using the flat bottom auger, the force versus penetration curve is linear after the initial low force, whereas there is an increase of force with time beyond the linear trend in the case of the second series of sampling (S2).

Cleaning the borehole also resulted in lower values in the retrieval force, which is 1.2–1.5 kN in the case of the third series of sampling, and 1.5–2.0 kN in the case of the second series.

5.2. On sample retrievability

In order to more clearly understand the causes of sample loss during sampling, and also the magnitudes of the forces measured during retrieval, an analysis is carried out on the forces acting on the sample when there is no underpressure at the top of the sample. Those forces are: (i) sample weight; (ii) atmospheric pressure multiplied by the sample area; (iii) water pressure multiplied by the sample area. These forces are illustrated in Fig. 15 for samplers with an inside diameter of 75 mm and 100 mm, in both cases for 650 mm sample length. The soil unit weight was taken as 13 kN/m^3. The atmospheric pressure at sea level was assumed to be equal to 101.3 kN/m^2.

The figure shows that: (a) the force acting on top of the sample is greater for the higher sample diameter; (b) the deeper the sample, the greater the force; (c) the weight of the sample is very low compared to the other forces.

The onset of pulling the sampler is the critical moment for sample retrieval. In fact, if a sample is to be retrieved, and disregarding any force due to bottom failure, the forces shown above must be resisted by the adhesion between the inside sampler wall and the sample. Adhesion values (e.g., for piles) are generally obtained by multiplying the undrained shear strength by a constant. In fact, the penetration of the sampler can be regarded as the penetration of an open-ended pile, therefore the adhesion value, or unit skin friction (ISO, 2016), can be obtained based on the so-called α-values, where α is referred to as the dimensionless skin friction factor (ISO, 2016), or dimensionless shaft friction factor (API, 2014, as similarly suggested in ISO, 2016) and defined as in Eq. (1).

$$f(z) = \alpha\, s_u(z) \tag{1}$$

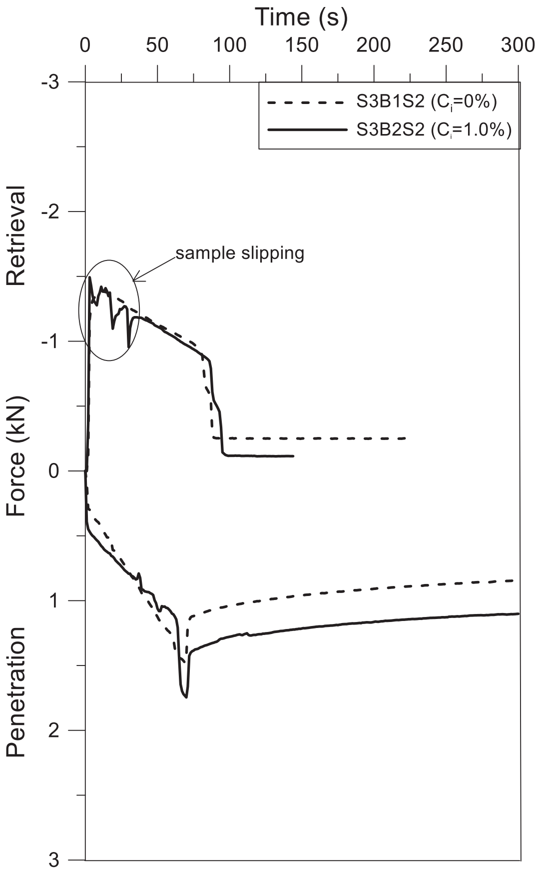


Fig. 12. Penetration and retrieval forces for 3 m nominal depth, third series of sampling.

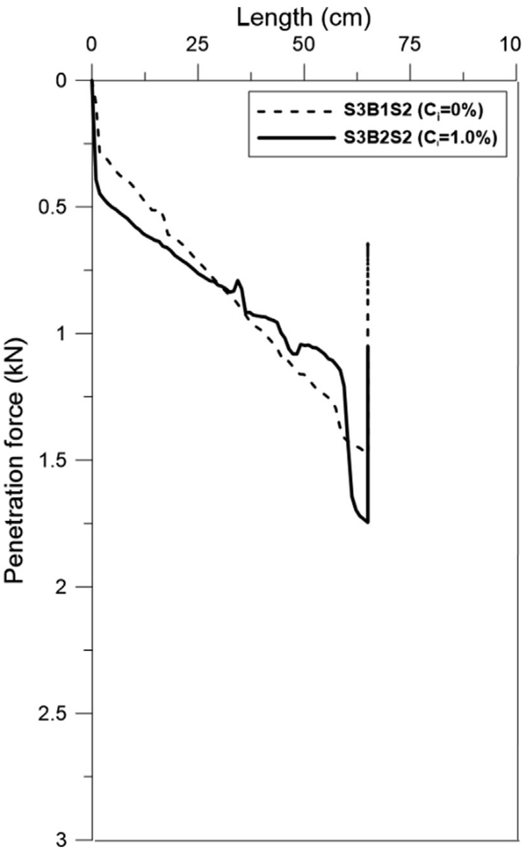


Fig. 13. Penetration force versus penetrated length for 3 m nominal depth, third series of sampling.

where *f*(z) and s_u (z) are the unit skin friction and the undrained shear strength at depth z, respectively. Factor α can be computed by Eqs. (2) or (3), depending on the value of Ψ, which is defined in Eq. (4), for a depth (z) with the constraint that $\alpha \leq 1.0$.

$$\alpha = 0.5\ \Psi^{-0.5} \quad \text{for} \quad \Psi \leq 1.0 \tag{2}$$

$$\alpha = 0.5\ \Psi^{-0.25} \quad \text{for} \quad \Psi > 1.0 \tag{3}$$

$$\Psi = \frac{s_u(z)}{\sigma'_{vo}(z)} \tag{4}$$

where $\sigma'_{vo}(z)$ is the vertical effective stress at depth z.

API (2014) states that for s_u/σ'_{vo} values greater than 3, equation (3) must be applied with care, due to shortage of pile tests. Also, Karlsrud (2012) presented a chart of α versus s_u/σ'_{vo} where the maximum value of s_u/σ'_{vo} is 5, corresponding to α equal to 0.33. Thus, since smaller values of α are on the safe side as far as retrievability is concerned, the following analysis has considered α-values of 0.3 and 0.5.

Fig. 16 shows the minimum value of undrained shear strength required for sample retrieval, assuming that the valve in the sampler head is inefficient. It was assumed that the sample recovered its original undrained shear strength after sampler penetration, i.e., a time was required to allow regain in strength, as mentioned before. As an example to better clarify how the values included in Fig. 16 were obtained, if a sample is considered with 100 mm in diameter, 0.65 m in length, and 5 m of water column on its top, the force on its top at the onset of retrieval is 1255 N (see Fig. 15). When the lateral area of the sample multiplied by α s_u is equalled to this force, the minimum value of s_u is obtained, which corresponds in the example to 20.5 kN/m^2 for $\alpha = 0.3$ and 12.3 kN/m^2 for $\alpha = 0.5$.

The undrained shear strength for Sarapuí II clay, from average values of vane shear tests (used as reference), has also been included in the figure. It can be concluded that samples with 100 mm in diameter are irretrievable in the case of 1 m and 3 m depth if there is not enough underpressure due to inefficiency of the ball valve head, which has happened in a number of cases.

When the skin friction is unable to withstand the forces acting on top of the sample, the sample will fall out, i.e., there is no underpressure at its base, therefore the nearly vertical line segment in the retrieval force versus time chart, indicated in Fig. 7, does not appear in the diagram.

In order to illustrate how general the chart (Fig. 16) is, i.e. whether it may be considered applicable to other soils, a unit weight of 18 kN/m^3 was also plotted. It is noticeable that there is almost no difference with respect to the unit weight of 13 kN/m^3, which is due to the very small influence of the sample weight, as mentioned before and can be observed from Fig. 15. The undrained shear strength

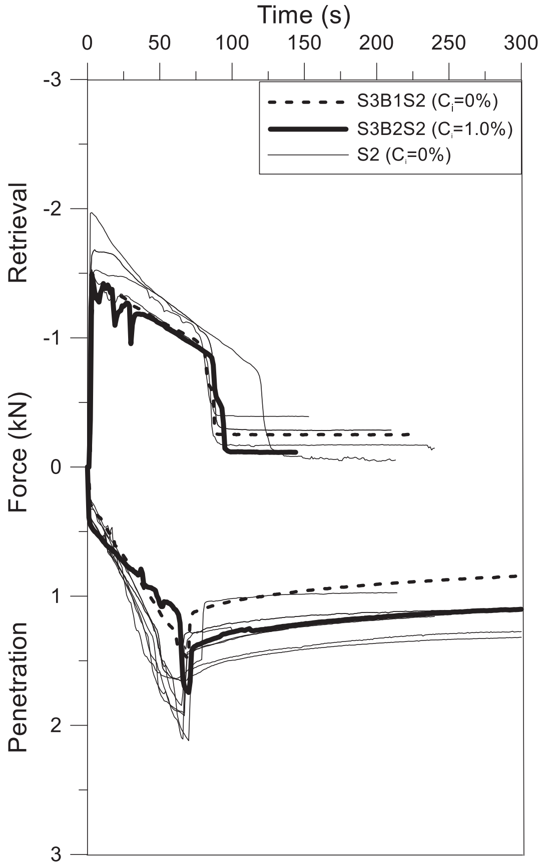


Fig. 14. Penetration and retrieval forces for 3 m nominal depth, second (S2, cleaning without flat bottom auger), and third (S3, cleaning with flat bottom auger) series of sampling.

of Bothkennar clay, obtained from vane shear tests (Hight et al., 2003) is also plotted in the figure. It can be observed that, regardless of the efficiency of the ball valve, a sample with 65 cm in length would always be retrieved, even in the case of 100 mm diameter samples.

5.3. Back-calculating α-values

The variation in the measured penetration force with sample length was divided by the outside and inside lateral surface areas of the sampler, producing an average skin friction. The values adopted for the calculations are taken from the third series of sampling, and are basically the same as the initial linear part of the second series. In other words, it has been assumed that the internal resistance is equal to the external resistance of the sampler, as generally assumed in the case of open-ended piles in clay (ISO, 2016). This was done not only in the case of the samplers without clearance but also in the case of samplers with clearance, due to the slight differences between both cases. The corresponding values were plotted in Fig. 17. A similar procedure was adopted for the measured retrieval force in those cases where samples have been retrieved. In such cases, the variation in the force was divided by the outside lateral surface area of the sampler. The corresponding average resistance is also plotted in Fig. 17 for 3 m and 6 m depths, since no samples were retrieved in the case of 1 m depth. The resistance in penetration and retrieval can be regarded as $\alpha\, s_u$ values, and will be referred to as $\alpha\, s_{u\ \mathrm{penetration}}$ and $\alpha\, s_{u\ \mathrm{retrieval}}$, as shown in Fig. 17.

In the case of penetration, it is noticeable that for 1 m and 6 m depth the differences between samplers with clearance and without clearance were small (4%, or 0.12 kPa and 0.18 kPa, for 1 m and 6 m depth, respectively), and was about 31% (or 0.9 kPa) in the case of 3 m depth. Thus, most data indicated that the clearance did not produce the amount of reduction in force that was to be expected.

The retrieval resistance was 5% (or 0.15 kPa) more than the penetration resistance in the case of 3 m depth, and 15% (or 0.7 kPa) in the case of 6 m depth. Although the differences in absolute values are very small, it was expected that the penetration resistance and retrieval resistance would be the same (e.g., ISO, 2016). One reason for the difference would be the assumption that internal and external resistances were the same in the case of penetration, which might not be true. Should the external friction be assumed to be higher than the internal one, a different result would have been obtained.

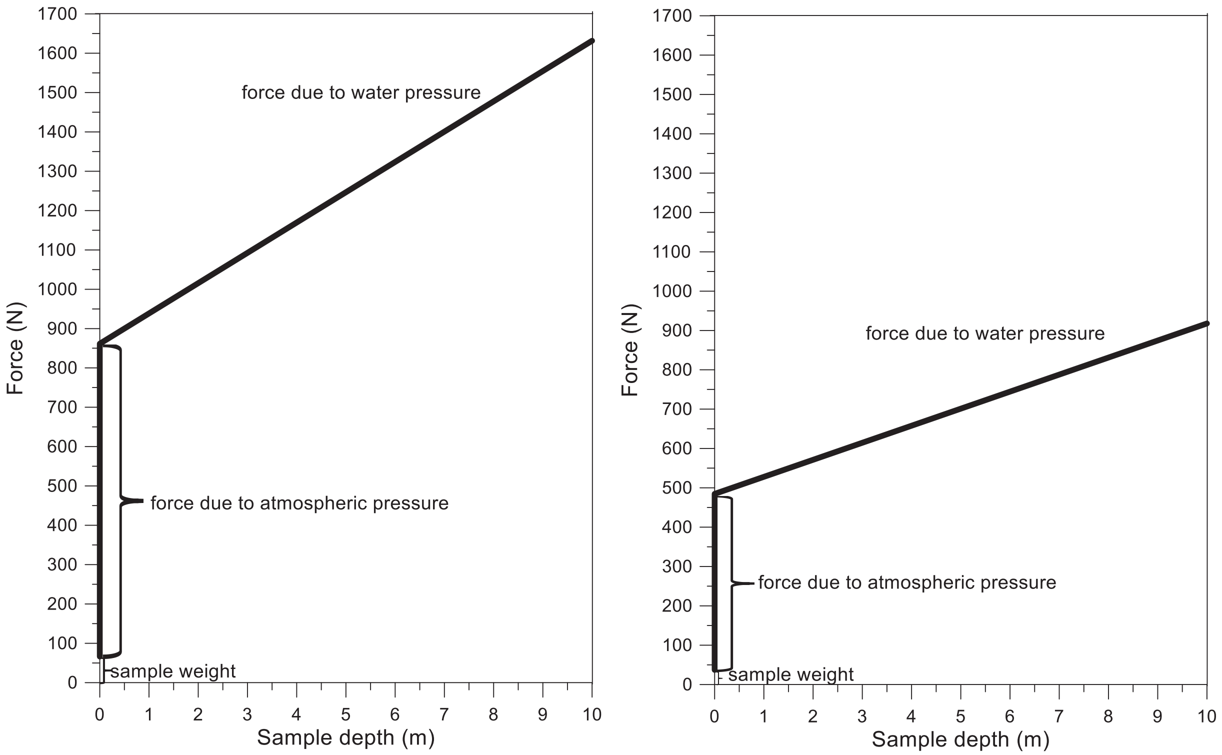
The resistance is compared to a friction sleeve from a typical (1000 mm^2, a and b values respectively 0.75 and 1) piezocone test, as well as other quantities also in Fig. 17. It should be pointed out that the increase in friction sleeve at approximately 1.2 m and 6.6 m depth is due to the presence of shells in the profile (see Danziger et al., 2019). As the figure shows, $\alpha\, s_{u\ \mathrm{penetration}}$, without clearance, and $\alpha\, s_{u\ \mathrm{retrieval}}$ are smaller than f_s values by around 1 kPa (25% less) in the case of 1 m and 3 m depth, and are basically the same in the case of 6 m depth.

The difference may be attributed to four main reasons: (i) rate of penetration; in fact, the piezocone tests have been performed at the standard rate of 20 mm/s, whereas the samplers have been penetrated at the rate of 10 mm/s; (ii) differences in the state of stresses and shearing mode; (iii) differences in the surface roughness; (iv) factor b and pore pressures at both ends of the sleeve might also be important. Other factors are discussed by Lunne (2010).

The values of α have been assessed both for penetration and retrieval resistances, taking DSS tests and vane shear tests as references. The corresponding values are included in Table 2.

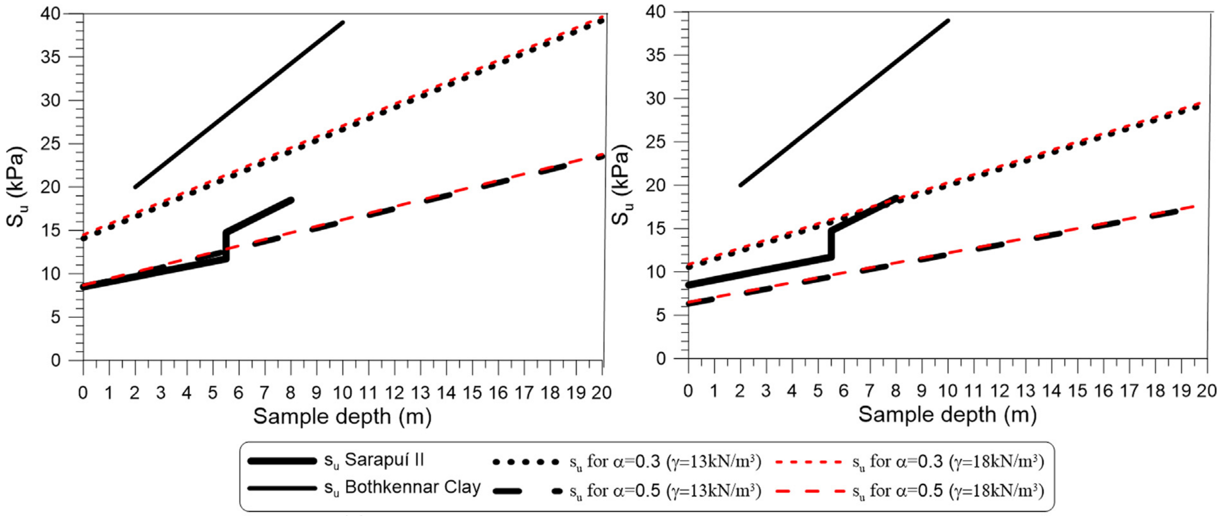
As can be seen from the table, α-values are in the range 0.36–0.48 for the case of DSS tests, except for 1 m depth, since the trend of s_u from DSS in that region is not clear and the s_u value used for the calculation of α was obtained at 1.8 m depth (see also Fig. 17). For vane shear tests, α-values are within the range 0.25–0.34.

For the sake of comparison, α-values that would be obtained in accordance with ISO (2016), as aforementioned, are included in Table 3. It should be remembered that the values in Table 3 correspond to the assumption that the soil has recovered its original strength (i.e., related



(a) (b)

Fig. 15. Forces acting on top of samples when there is no underpressure: (a) sample diameter 100 mm; (b) sample diameter 75 mm.



(a) (b)

Fig. 16. Minimum undrained shear strength required for sample retrieval in case of inefficient valve head: (a) Sampler diameter 100 mm; (b) Sampler diameter 75 mm.

to peak strength) after pile installation, and the back-calculated values correspond to the soil after shearing.

When values of Table 2 are compared with those of Table 3, the back-calculated values are always smaller, as expected, than those suggested by ISO (2016), except in the case of DSS tests and 1 m depth (in this case, for the aforementioned reason). Taking average values of DSS tests and vane shear tests from Table 2, the ratio between back-calculated α-values and ISO values is in the range 0.69–0.70 for DSS tests and 0.54–0.59 (0.79 for 1 m depth) for vane shear tests. The obtained ratio is smaller than expected, because the values from Table 3 are considered to be high. In fact, the ISO (2016) recommendations are based on the test results from sea-floor samples with a

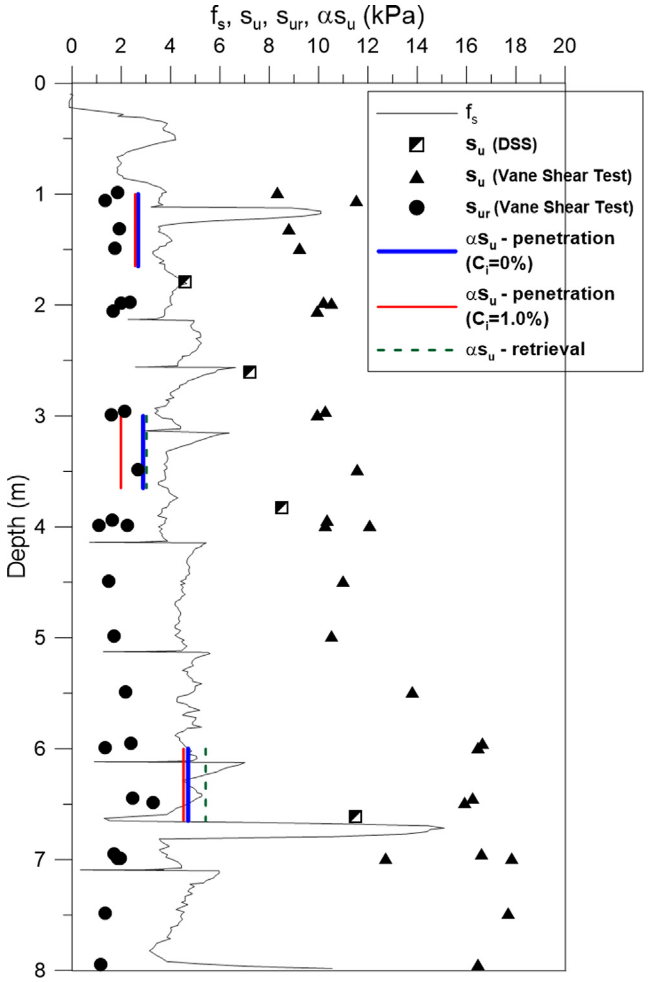


Fig. 17. s_u from vane shear tests and DSS tests, s_{ur} from vane shear tests, f_s from piezocone test, αs_u from sampling.

quality much lower than good onshore practice and unconsolidated undrained (UU) tests (Olsen et al., 1986). This subject is discussed in detail by Saye et al. (2016).

It should be pointed out that the obtained αs_u values are consistent with the s_{ur} and the f_s values, which are related to the after failure soil condition. In fact, it seems that the phenomenon of pushing and pulling a sampler in the soil is similar to pile penetration, hence the lateral resistance measured in those operations may provide useful information for the estimation of the forces during pile (and bucket) penetration.

Table 3
Values of α according to ISO (2016).

Depth (m)	α-values	
	From DSS	From vane
1	0.45	0.38
3	0.53	0.47
6	0.65	0.54

6. Recommendations

Although the use of a piston is always recommended, thin-walled samplers without a piston can still provide good quality samples, as addressed herein. In that particular case, some recommendations are listed below.

(1) The use of a sampler head and a one-way ball valve is recommended, because at least some underpressure is built up.

(2) Although not a conclusion of the present research, provided that the wall thickness to diameter ratio is the same, 100 mm samples are preferred to 75 mm samples whenever possible. Also, a very small cutting edge angle is strongly recommended (Horng et al., 2010).

(3) If there is a previous estimation of s_u, Fig. 16 can be used to evaluate the retrievability of the sample in case of doubts regarding the efficiency of the valve head. If it were shown that the sample is irretrievable in that case, a piston would therefore be mandatory. In some cases of extremely soft clays and muds, even a piston may be unable to retrieve the sample.

(4) The use of a flat bottom auger improves the quality of borehole cleaning and is, therefore, recommended. It must be pointed out that even in the case of piston samplers in pre-augering mode, cleaning the borehole is an important issue. In fact, when lowering the sampler into the borehole, if perfect depth control is not taken, the top of the sample may be contaminated by material from the drilling operation.

(5) The sampler must be lowered into the borehole slowly to allow air and water to flow through the valve.

(6) Sampler penetration should not be too slow (to guarantee undrained conditions) or too fast (to allow the water to flow through the valve and to better control the end of penetration). A penetration rate of 10–20 mm/s seems satisfactory for most soft clays.

(7) Measuring the forces on the sampler during both penetration and retrieval is recommended for the following reasons:

Table 2
Back-calculated values of α.

Depth (m)	Penetration (without clearance)		Retrieval	
	From DSS	From vane	From DSS	From vane
1	0.58	0.30	–	–
3	0.36	0.25	0.38	0.26
6	0.42	0.30	0.48	0.34

(i) It serves as a quality control of the cleaning of the borehole.
(ii) It is useful to show whether the sample will be retrieved or not, by measuring (or not) the underpressure at the sample bottom.
(iii) It can provide a measurement of α-value (or a direct measurement of the skin friction), to be used for the estimation of pile (or bucket) penetration.

7. Summary and conclusions

The force during both penetration and retrieval sampling operations has been measured in a very soft clay deposit. Thin-walled tube samplers, 101.5 mm OD, with a sampler head, with and without clearance, were used. All samplers were driven at a constant rate of approximately 10 mm/s and retrieved at 7.3 mm/s. The force measurement allowed the verification of the borehole cleaning conditions. It was found that cleaning with a jet bit, even carefully, was not enough to provide proper cleaning conditions. The use of a flat bottom auger, similar to the one used when sampling with the Sherbrooke block sampler, offered much better conditions for final cleaning of the borehole and is therefore recommended. The force measurement during penetration showed that there is an immediate increase in load (although very small) at the onset of penetration, followed by a linear increase of force with sampler penetrated length, when the borehole is properly cleaned. When it is not properly cleaned, there is an additional increase over time due to forcing the dirty water through the head valve. There is a sudden reduction in force when penetration is halted, comparable to what is observed on q_c and f_s when changing rods in piezocone testing. Then a relaxation over time occurs. The force measurement during retrieval revealed that at the onset of pulling the sampler there is an immediate increase in force, which is due to the sum of (i) the weight of rods, sampler and sample; (ii) the force equivalent to the underpressure at the base of the sampler; and (iii) the soil resistance mobilised in the outer surface of the sampler. After reaching the maximum value, the force starts to drop due to the reduced length of the sampler in contact with the soil. When the sampler leaves the hole created during penetration the water enters the hole and the underpressure at the base of the sampler (represented by a nearly vertical line segment) disappears. Then the force is due only to the weight of rods, sampler and sample. The force for penetrating the samplers with clearance was less than those without clearance, as expected. However, it was low (around 4%) in two cases and significant (31%) in only one case. Assuming equal internal and external resistances, the retrieval resistance was 5% (or 0.15 kPa) and 15% (or 0.7 kPa) more than the penetration resistance for 3 m and 6 m depth, respectively. The resistance from sampler penetration in the case of no clearance was 1 kPa (25%) less than the friction sleeve from a typical piezocone test in the case of 1 m and 3 m depth, and approximately the same in the case of 6 m depth. The back-calculation of α-values from the sampler resistance provided values in the range 0.36–0.48 and 0.25–0.34, respectively, when DSS tests and vane shear tests are considered as references. These values are lower than α-values suggested by ISO (2016), but with a lower difference than expected, which was attributed to the sample quality and laboratory tests adopted by ISO (2016) as references. Measuring force during sampling proved to have some advantages, including measurement of α-value (or a direct measurement of the skin friction) for the estimation of pile (and bucket) penetration, and it is therefore recommended. Recommendation procedures have been provided for sampling when a piston is not used, including the evaluation of sample retrievability when the sampler head is considered to be inefficient.

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