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# Rate effect of piezocone testing in two soft clays

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ABSTRACT: The Onsøy and Sarapuí II soft clays have been studied for a number of years. In particular, piezocone tests with different rates have been conducted at both sites. Since the plasticity index and the coefficient of consolidation—which play important roles in the rate effect—are different in Onsøy and SarapuÍ II clays, an interesting comparison is possible. A bowl shaped curve was obtained for the normalized cone resistance versus penetration rate in the case of Sarapuí II clay. The cone resistance versus rate curve can be explained by the pore pressure trends, especially from the $u_1$ trend. Since only three rates have been used for Onsøy clay, a more complete picture cannot be obtained. However, the use of the normalized rate (or velocity), even using $c_h$ from piezocone dissipation data, was not capable to unify the resistance-rate data for the two clays tested. Adaptations in regular rigs, allowing much smaller penetration rates, and small diameter cones, are necessary if drained conditions are to be achieved when conducting piezocone tests in deposits like Sarapuí II or Onsøy clays. No rate effect was found for penetration rates greater than the standard rate, unlike expected, due to the high $I_p$ values in both deposits. Tests with higher rates are necessary to properly evaluate the role of $I_p$ on rate effect on cone resistance.

## 1 INTRODUCTION

The piezocone test is performed with the standard rate of 20 mm/s. With this rate tests in sands are considered to be performed in drained conditions and tests in clay in undrained conditions (e.g., Lunne et al. 1997). Partially drained conditions are generally obtained in silts, and the case of tailings dams is of particular interest to be studied. Moreover, the use of penetrometers with smaller diameters than the standard 10 $cm^2$ base area penetrometer are becoming more frequent, especially in offshore case, and the drainage conditions are strongly dependent on the cone diameter. Therefore, the interest of properly understanding the rate effect of piezocone testing is also important for that case.

It has been recognized that the rate effect is influenced by a number of factors, and the plasticity index, $I_p$, is one of the most important factors when tests are carried out in undrained condition, whereas it seems that the coefficient of consolidation is very significant when the drainage condition is to be analyzed. The present study makes a comparison between rate effect in piezocone testing in two soft clays, one from Norway, Onsøy clay, and the other from Brazil, Sarapuí II clay. The Sarapuí II clay (Jannuzzi et al. 2015) is a very plastic clay ($I_p$ in the range 60%–170%), whereas $I_p$ values in Onsøy clay are in the range 20%–50% (Lacasse & Lunne 1982; Lunne et al. 2003). The horizontal coefficient of consolidation, $c_h$, obtained from piezocone dissipation data is on average $10 \times 10^{-7}$ $m^2/s$ in the case of Onsøy clay (Lunne et al. 2003) and $4 \times 10^{-7}$ $m^2/s$ in the case of Sarapuí clay (Danziger et al. 1997b).

## 2 THE TEST SITES

### 2.1 *The onsøy clay*

The Onsøy test site has been used by NGI since 1969, and several areas have been developed. Prior to 2000 all of the test areas were grouped closely together within an area of about 140 m × 120 m. However due to development of this area a new test site was established some 200 m to 300 m to the northwest. The nature of the clay deposit in both areas is essentially identical. A number of in situ and laboratory tests, as well as other studies, have been performed at the test site. Some characteristics of the clay deposit are summarized in Figs. 1 and 2, from area 2 (Lunne et al. 2003).

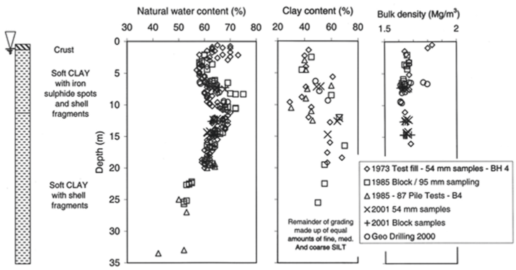


Figure 1. Natural water content, clay content and bulk density from Onsøy clay (Lunne et al. 2003).

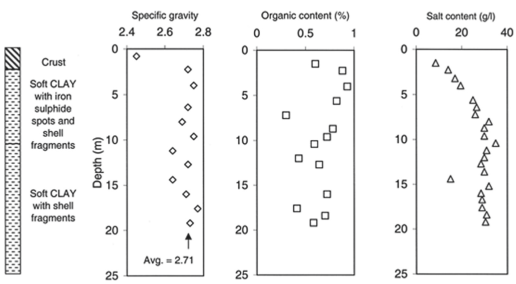


Figure 2. Specific gravity, organic and salt content from Onsøy clay (Lunne et al. 2003).

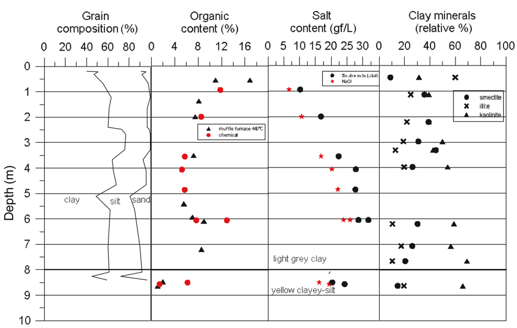


Figure 3. Grain size distribution; organic content; total salt content and NaCl content (data from Onsøy clay also included); relative percentage of clay minerals versus depth from Sarapuí II clay (adapted from Jannuzzi et al. 2015).

## 2.2 *The sarapuí II clay*

The Sarapuí test site has been used since mid 1970s, being the oldest test site in Brazil (e.g., Lacerda et al. 1977). As in the case of Onsøy, two areas have been used, the first one from mid 1970s until approximately 2000, and the second one, named Sarapuí II, from 2000 until today.

Comprehensive studies about Sarapuí I and Sarapuí II test sites have been provided by Almeida & Marques (2003) and Jannuzzi et al. (2015), respec-

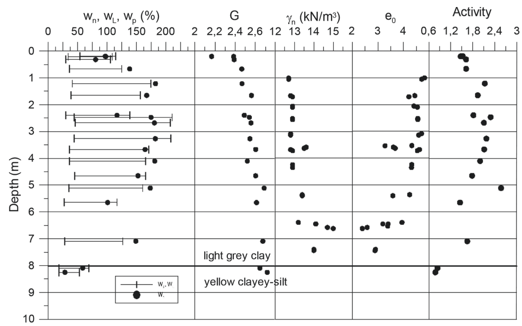


Figure 4. Liquid limit, plastic limit and natural water content; specific gravity; total unit weight; initial void ratio; activity versus depth from Sarapuí II clay (adapted from Jannuzzi et al. 2015).

Table 1. Tests performed at Sarapuí II test site.

| Rate of penetration (mm/s) | Number of tests |
|---|---|
| 2.5 | 2 |
| 5 | 2 |
| 10 | 2 |
| 20 | 4 |
| 40 | 3 |

tively. Some characteristics of the Sarapuí II clay deposit are summarized in Figs. 3 and 4.

It is interesting to note that the salt content in both deposits, Onsøy and Sarapuí II, is nearly the same, for unknown reasons. Moreover, the Onsøy clay is classified (by Norwegian experience) as having a high to very high plasticity. However, the Sarapuí II clay presents much higher values of liquidity limit and plasticity index, although also classified in the same way. It should be useful to define a new category in cases like Sarapuí II clay, maybe extremely high plastic clays.

# 3 TESTS PERFORMED

## 3.1 *At onsøy test site*

The tests performed at Onsøy test site have been reported by Lacasse & Lunne (1982). The piezocone used consisted of a modified 10 cm² Fugro cone with a 20 kN load cell capacity, and where the sleeve friction was not measured. The pore pressure measurement corresponded to the position $u_2$. Three rates have been used, 2 mm/s, 20 mm/s and 100 mm/s.

## 3.2 *At sarapuí II test site*

A 10 cm² penetrometer was used in Sarapauí II test site, produced by COPPE/UFRJ and Grom Eng., in a partnership which started in 1984. The cone and friction load capacities are 50 kN and 7.5 kN, respectively. Since the last version of this penetrometer was produced, in 1996, pore pressures $u_1$ and $u_2$ have been measured (Danziger et al. 1997a). Water is always used as the saturation fluid, thus a previous hole with casing is necessary when the water table is below ground level. This is not necessary in Sarapuí II test site, since that the water table is roughly at ground level. All transducers are calibrated before and after each test series, in the range expected to occur in the field. Thirteen tests have been performed, with the rates included in Table 1.

## 4 TEST RESULTS

The piezocone test results for Sarapuí II clay are presented in Fig. 5 for the standard rate of 20 mm/s, in a magnified scale, to illustrate the upper 5 m of the profile. Tests with no proper saturation, although not considered in the analysis, have also been included in the figure. For the analysis herein performed, the measured values for each quantity have been averaged in the 0.5 m interval in every meter for all penetration rates. In other words, the values indicated as corresponding to 2.5 m depth represent an average of values in the interval 2.25 m–2.75 m. Data points corresponding to change of rods have been removed. The cone resistance, $q_{tn}$, the friction sleeve $f_{sn}$ and the pore pressures $u_{1n}$ and $u_{2n}$ for each penetration rate, n, have been normalized with respect to the average values corresponding to the standard rate of 20 mm/s, $q_{t\,20}$, $f_{s\,20}$, $u_{1\,20}$ and $u_{2\,20}$, respectively.

The normalized values $q_{tn}/q_{t\,20}$, $f_{sn}/f_{s\,20}$, $u_{1n}/u_{1\,20}$ and $u_{2n}/u_{2\,20}$ versus penetration rate are presented in Figs. 6, 7, 8 and 9, respectively, for 2.5 m depth, which presented the most consistent results and is also the region in the soil profile with the highest values of liquidity limit and plasticity index (see Fig. 4). The cone resistance in two tests performed with 40 mm/s penetration rate have not been presented due to mal-functioning of the load cell.

It can be observed in Fig. 6 that there is a reduction in the normalized $q_{tn}/q_{t\,20}$ values when the rate increases from 2 mm/s to 5 mm/s, and another reduction, although smaller, when it increases again to 10 mm/s. Then $q_{tn}/q_{t\,20}$ increases when the rate increases to 20 mm/s, and is roughly the same when the rate further increases to 40 mm/s. Other depths presented a similar behavior, however with almost the same $q_{tn}$ values for the rates 5 and 10 mm/s.

The observed behavior is similar to the results obtained by Bemben & Myers (1974), Fig. 10, in a research which is considered by Danziger & Lunne (1997) the first paper where a complete picture on this subject was obtained. In fact, for very slow rates the behavior is predominantly drained, and

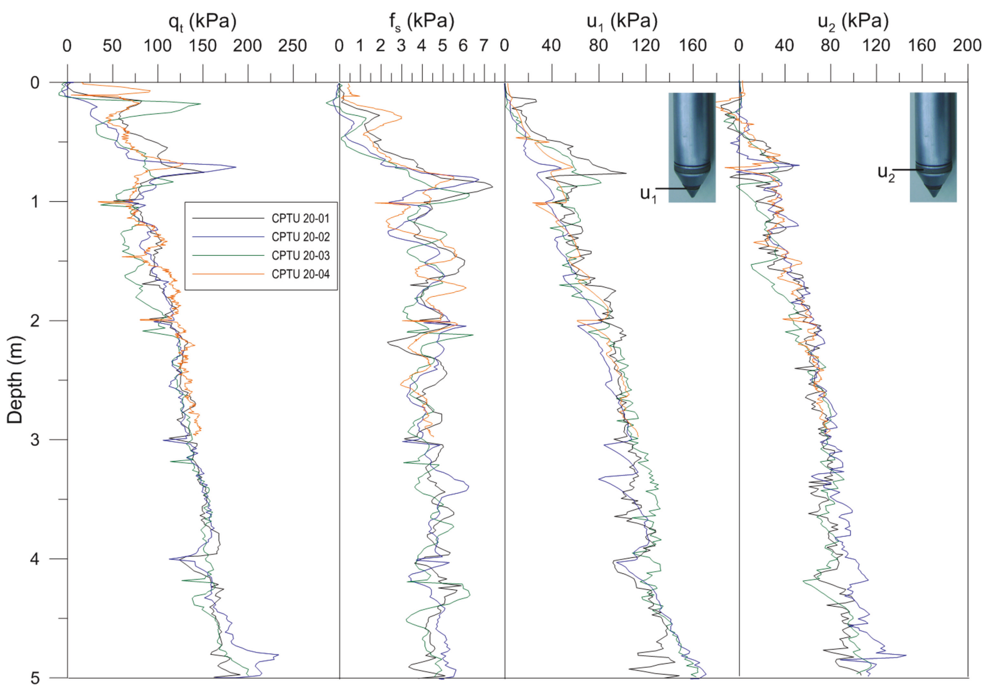


Figure 5. Piezocone test results for Sarapuí II clay, penetration rate of 20 mm/s.

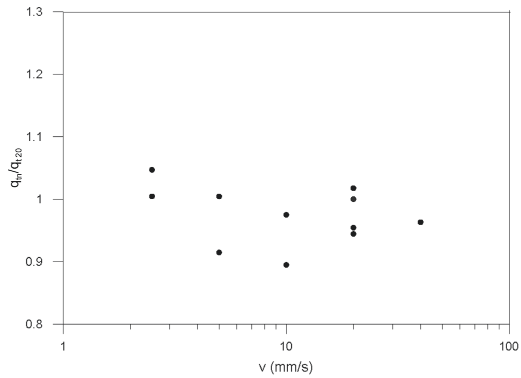


Figure 6. Normalised $q_{tn}/q_{t\ 20}$ versus penetration rate, Sarapuí II clay.

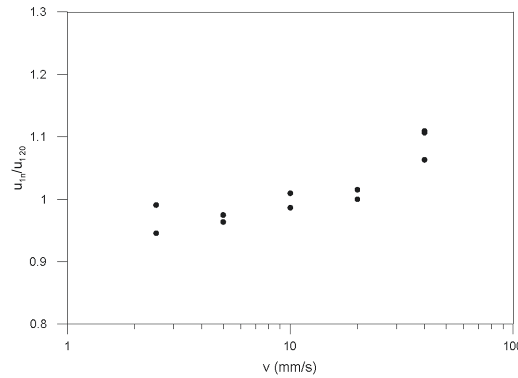


Figure 8. Normalised $u_{1n}/\ u_{120}$ versus penetration rate, Sarapuí II clay.

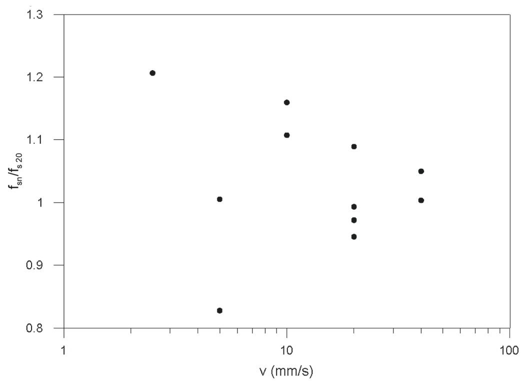


Figure 7. Normalised $f_{sn}/f_{s\ 20}$ versus penetration rate, Sarapuí II clay.

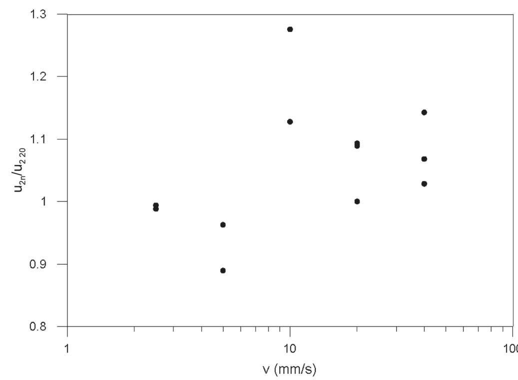


Figure 9. Normalised $u_{2n}/u_{2\ 20}$ versus penetration rate, Sarapuí II clay.

as the rate increases, the cone resistance decreases due to the pore pressure generation and there is a decrease in effective stress. As the penetration rate increases furthermore, the viscous forces offset the strength reduction and the curve will pass through a minimum. Then the viscous forces will dominate the process, now in an undrained behavior (see also Roy et al. 1982; Campanella et al. 1982).

The pore pressure $u_1$ may be considered the most representative to analyze the cone resistance behavior, due to the position where it is measured, and the normalized $u_{1n}/u_{1\ 20}$ values versus rate are shown in Fig. 8. Despite not very clear, there is a trend of $u_1$ increasing with increasing rate, and the region of 10 mm/s – 20 mm/s may be considered to be in undrained condition. However, the higher increase in the case of 40 mm/s has no explanation except for data scatter, since results for other materials show no pore pressure increase in the undrained condition. Further research is still needed on this subject.

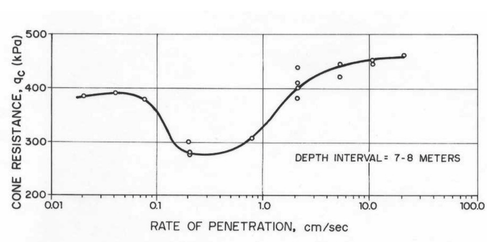


Figure 10. Influence of rate of penetration on cone resistance (adapted from Bemben & Myers 1974).

Normalized $u_{2n}/u_{2\ 20}$ values (Fig. 9) present more scatter than $u_{1n}/u_{1\ 20}$ values, although with the same general trend, except for 10 mm/s.

Despite the data scatter, the $f_{sn}/f_{s\ 20}$ values (Fig. 7) seem to be more influenced by the rate effect than $q_{tn}/q_{t\ 20}$, which has also been reported elsewhere (e.g., Campanella et al. 1982).

## 5 DISCUSSION

Despite the trends described above on the four piezocone quantities, the differences in the measured values are not very significant. In other words, although the measured data seem to indicate that the undrained behaviour initiates at the rate 10 mm/s, the differences with respect to the "partially drained" behaviour is not significant. It must be noted that $u_1$ and $u_2$ corresponding to the smallest penetration rate used, 2.5 mm/s, i.e. $u_{1\ 2.5}$ and $u_{2\ 2.5}$ are still much higher than the hydrostatic values ($u_0$), approximately 3.0–4.5 times greater than $u_0$ in the case of $u_1$ and 2.1–2.6 greater in the case of $u_2$. As far as excess pore pressure is concerned, $u_1$-$u_0$ is in the range 50–90 kPa (increasing with depth) and $u_2$-$u_0$ in the range 20–50 kPa. Therefore it is clear that in the case of soft clays with very low consolidation coefficients, like Sarapuí clay, it is virtually impossible to reach drained conditions in the field when using regular 10 $cm^2$ penetrometers.

As a consequence of this small difference in drainage conditions, there is a small difference also in the case of cone resistance and sleeve friction. If a drained condition is to be achieved, adaptations in regular rigs, allowing much smaller rates, and small diameter cones, are necessary.

In order to compare the Onsøy data with the Sarapuí II data, a normalization of the rate of penetration, v, to take into account the diameter of the penetrometer, d, and the coefficient of consolidation, c (Eq. 1) was done.

$$V = \underline{v\ a} \quad (1)$$

where V = normalized rate

Finnie & Randolph (1994) firstly proposed the use of the normalized rate (or velocity), where the coefficient of consolidation c was $c_v$, i.e., the vertical coefficient of consolidation, however no reference was made to the stress level considered in the analysis performed by these authors.

Other suggestions regarding the use of the proper $c_v$ value followed (e.g., $c_v$ at a representative stress level, House et al. 2001, at the same overconsolidation ratio, Suzuki & Lehane 2015), however this issue is outside the scope of the present paper. When the horizontal coefficient of consolidation from piezocone dissipation tests are available, they seem to be the best choice, thus those values have been used herein.

Fig. 11 presents the Sarapuí II data from Fig. 6 with the Onsøy data included. Unfortunately, only three rates have been used in Onsøy clay, thus a more complete picture cannot be obtained. However, it seems clear that the use of the normalized velocity, even using $c_h$ from piezocone dissipation

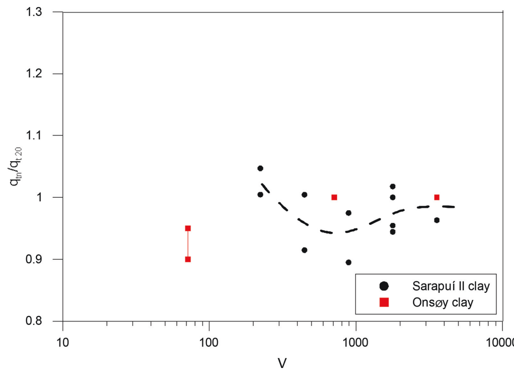


Figure 11. Normalised $q_{tn}/q_{t\ 20}$ versus normalized penetration rate, Sarapuí II and Onsøy clays.

data, was not capable to unify the resistance-rate data for the two clays tested. It must be noted that this conclusion was also obtained by Suzuki & Lehane (2015), for the case of laboratory $c_v$ values (at the same overconsolidation ratio) for kaolin and kaolin mixture in centrifuge.

In both deposits, rates greater than the standard rate, in the range 40–100 mm/s, did not result in increase in the normalized $q_{tn}/q_{t\ 20}$, as it could be expected from the high $I_p$ values in both cases. Tests with higher rates are necessary to properly evaluate the role of $I_p$ on rate effect on cone resistance.

As far as pore pressure is concerned, $u_{2\ 2}$ was approximately the same as $u_{2\ 20}$ for Onsøy clay, thus the same conclusion as Sarapuí II clay can be obtained, i.e. adaptations in regular rigs, allowing much smaller rates, and small diameter cones, are necessary if drained conditions are to be achieved for soft clays with low $c_h/c_v$ values.

## 6 CONCLUSIONS

A comparison was undertaken between piezocone tests with different penetration rates in two soft clay deposits, one from Norway, Onsøy clay, and the other from Brazil, Sarapuí II clay. The Sarapuí II clay is a very plastic clay ($I_p$ in the range 60%-170%), whereas $I_p$ values in Onsøy clay are in the range 20%-50%.

The horizontal coefficient of consolidation, $c_h$, obtained from piezocone dissipation data is on average $10 \times 10^{-7}$ $m^2/s$ in the case of Onsøy clay and $4 \times 10^{-7}$ $m^2/s$ in the case of Sarapuí II clay.

Within the range of penetration rates used, 2.5 mm/s – 100 mm/s, the following conclusions can be drawn: in the case of Sarapuí II clay, there is a reduction in the normalized cone resistance $q_{tn}/q_{t\ 20}$ when the rate increases from 2 mm/s to

5 mm/s, and another reduction, although smaller, when it increases again to 10 mm/s. Then $q_{tn}/q_{t\ 20}$ increases when the rate increases to 20 mm/s, and is roughly the same when the rate further increases to 40 mm/s.

The cone resistance versus penetration rate trend may be explained by the corresponding pore pressure trend (especially $u_1$, but also $u_2$).

The friction sleeve versus penetration rate trend, although similar to the cone resistance trend, showed a higher rate effect, i.e. rate effect is more pronounced in the case of sleeve friction than in the case of cone resistance, as found by other authors (e.g., Campanella et al. 1982).

The use of the normalized rate (velocity), even using $c_h$ from piezocone dissipation data, was not capable to unify the resistance-rate data for the two clays tested, Onsøy and Sarapuí II.

Despite the trends mentioned above, adaptations in regular rigs, allowing much lower penetration rates, and small diameter cones, are necessary if drained conditions are to be achieved when conducting piezocone tests in deposits like Sarapuí II or Onsøy clays.

No rate effect was found for penetration rates greater than the standard rate, unlike expected, due to the high $I_p$ values in both deposits, especially in Sarapuí II clay. Tests with higher rates are necessary to properly evaluate the role of $I_p$ on rate effect on cone resistance.

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