Undrained strength from free falling penetrometer tests

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Keywords: clay, penetration, undrained strength, rate effects

ABSTRACT

To determine the penetration depth of objects into the seafloor large penetrometers that fall freely through seawater and penetrate into the seabed are used. The deceleration of the penetrometer is used to infer the strength of the seabed sediments. To reliably interpret the data a significant correction for the initially high rate of penetration is required. For ease of use it is desirable for the penetrometer diameter to be only about 20 mm, but as diameter reduces, the rate correction increases significantly. To improve the understanding and reliability of these penetrometers a series of experiments have been conducted.

Results of tests are presented in which penetrometers with tips of different diameters (10 – 40 mm) have been dropped into uniform deposits of clay with undrained strengths from 2 kPa to 18 kPa, and with a range of impact velocities. In the majority of the tests an accelerometer has been attached to the penetrometer allowing the bearing pressure to be determined.

Current methods of interpretation of these types of test make use of a range of empirical relations to account for the rate effects. Data from the current investigation will be compared with existing methods and a new empirical relation proposed.

1 INTRODUCTION

Early studies of penetration of objects into the ground were often associated with the design of underground installations to provide passive resistance against bombing and shelling (Dayal and Allen, 1973). In the 1970s the potential for rapid penetration tests to provide information on the in-situ strength of inaccessible sites, lunar soils, and ocean sediments was first investigated (Dayal and Allen, 1973). Unfortunately the sensors and data logging equipment at the time were insufficiently reliable and little further research was conducted until recently. For the past decade or so many defence departments and organisations have been involved in research associated with the penetration of projectiles into the seafloor. This research is in particular aimed at finding out the penetration depth that mines will bury themselves into the seafloor when being deployed from a vessel on the surface of the ocean. Mines that have been left behind from past wars and security operations that are buried below the seafloor pose a problem for many countries with ensuing financial and economic difficulties. The desire to have tools that can predict regions of the seafloor where mine burial is likely has led to renewed interest in penetrometers that can be deployed underwater. Other applications where the properties of the sea floor are of interest include cable and pipeline route surveys, dredging and shallow foundations.

Pictures of three such penetrometers are shown in Figure 1. These penetrometers, which are 1.5 to 2 m long, are designed to freefall through the water and penetrate up to 1 m into the seafloor. They have varying shaft and tip diameter sizes. The penetrometers illustrated in Figure 1 are the Seabed Terminal Impact Naval Gauge (STING), the Electronic Sediment Strength Probe (ESP probe), and the Australian Sediment Strength Instrument (AUSSI probe). The STING penetrometer allows for tips of different diameters and shapes to be connected to it, which consequently enables a vast variety of data to be tested and collected (e.g. Mulhearn, 2003). All three penetrometers contain an accelerometer and on-board data aquisition and storage facilities. This is used to obtain a record of deceleration versus time for each penetration. This data is used to infer the soil strength as follows. The forces applied to the penetrometer upon entry into the sea floor can be calculated using the

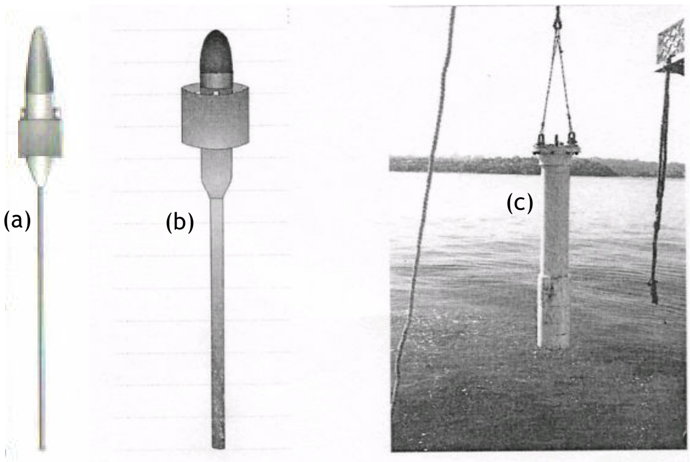

Figure 1: Underwater penetrometers (a) STING, (b) ESP probe, (c) AUSSI

formula below, which takes into account the weight of the penetrometer and the resistance to penetration offered by the soil.

$$ma = mg - F_D - F_{BC} \tag{1}$$

Where m is the submerged mass, F_D is the hydrodynamic drag, and F_{BC} is the force due to the resistance of the soil. It has been reported that the shaft resistance of the penetrometer is negligible (Mulhearn, 2003) and can be reasonably ignored. With this assumption the resistance of the soil can be derived from the end bearing resistance which can be calculated from:

$$F_{BC} = q_u AR \tag{2}$$

Where q_u is the static end bearing capacity of the soil, A is the area of the penetrometer tip, and R is a rate dependent factor. There are a number of approaches that can be used to estimate the static bearing capacity. In this study the general bearing capacity formulae of Vesic (1975) have been used. These have the advantage for penetrometers that do not penetrate large distances of allowing for penetration to diameter ratio, and this approach is used in mine penetration studies (e.g. Mulhearn, 2003). For rapid undrained penetration of a circular footing into a uniform soil deposit the general bearing capacity equation reduces to:

When $z < B$
$$q_u = 5.14 S_u \left(1 + \frac{1}{5.14}\right)\left(1 + \frac{0.4z}{B}\right) + \gamma' z \tag{3}$$

When $z > B$
$$q_u = 5.14 S_u \left(1 + \frac{1}{5.14}\right)\left(1 + \frac{1.6}{\pi}\tan^{-1}\left(\frac{z}{B}\right)\right) + \gamma' z \tag{4}$$

Where q_u is bearing capacity, B is penetrometer diameter, z is penetration, S_u is undrained strength, and γ' is effective unit weight. Several formulae have been proposed for the rate dependent factor, R, given in equation 2 (e.g. Dayal and Allen, 1975, True, 1975, Hurst & Murdoch, 1991). Mulhearn (2003) has shown that good strength predictions are obtained using an empirical rate correction factor, derived from experiments reported by Hurst (1992), which depends on penetrometer impact velocity, v, and diameter, B, given by.

$$R = \left(\frac{0.5v}{B}\right)^{0.15} \tag{5}$$

However, Mulhearn et al. (1999) also show that this equation does not correctly allow for the penetrometer diameter as the rate factor increases very significantly as diameter reduces. A combination of the empirical nature of the rate factor, its derivation from soil specimens with variable strength, and the lack of detailed analysis leads to a low level of confidence in the estimated soil strengths. The objectives of the tests described in this paper are to provide further data on the diameter dependence of rate effect, and to understand the underlying mechanics.

2 APPARATUS AND PROCEDURE

2.1 Penetrometer

The penetrometer consisted of a shaft 5 mm diameter, 200 mm long. Cylindrical tips 5 mm thick with diameters of between 10 mm and 40 mm were attached to one end of the shaft. The mass of the penetrometer was varied from 70 g to 470 g by adding a series of brass discs to the other end of the shaft. An accelerometer was connected to the top of the shaft and in some tests fins were added to improve aerodynamic stability. The penetrometer was released from a locator that ensured it fell vertically through air into the clay specimen. Fall heights of up to 2 m were used giving a maximum impact velocity of approximately 6 m/s.

2.2 Soil and Confining Vessel

Uniform clay specimens were prepared by one-dimensionally consolidating slurried Kaolin, Q145, in two cylindrical tanks. One 150 mm thick with diameter 450 mm and the other 370 mm thick with diameter 300 mm. The properties of the Q145 kaolin are LL = 44, PL = 27, Gs = 2.60, $\phi' = 26^{o}$, $c_v \approx 5$ m^2/yr.

Nine tubs of clay were produced in the current test series. A range of confining pressures was used to give undrained strengths that varied from 2 kPa to 18 kPa.

2.3 Test Procedure

After consolidation was complete, which took from 2 to 8 weeks, the vertical stress was removed and the upper surface of the clay exposed. For each tub of clay several penetrometer drops were performed while varying mass, fall height and tip diameter. For each penetrometer fall, the acceleration versus time was recorded using a data acquistion rate of 10 kHz to ensure reasonable definition of the deceleration event. Integration of the acceleration, time record allowed velocity and displacement to be determined. The undrained strength was assessed by performing T-bar tests (Stewart & Randolph, 1991). In each case three widely spaced T-bar tests were performed to determine the undrained strength. The T-bar used in these tests had a diameter of 8 mm and a length of 40 mm. This was attached to a 5 mm diameter shaft that was driven into the clay at a nominal rate of 20 mm/sec. The load was measured by a transducer at the top of the shaft.

3 RESULTS AND DISCUSSION

Figures 2 and 3 show some typical results. Figure 2 shows a typical acceleration, time history and indicates the period of free fall where the acceleration is very close to the acceleration due to gravity, and then a dramatic deceleration as the penetrometer impacts the clay. It is believed that the fluctuations in acceleration after impact are related to waves, set-up by the initial impact, passing up and down the penetrometer shaft. It may also be noticed that the deceleration is approximately constant for some time before dropping rapidly followed by the penetrometer rebounding slightly before finally coming to rest. The soil resistance calculated using equation 1, versus penetration is shown in Figure 3. The pattern of an approximately constant stress before a rapid drop as the penetrometer comes to rest was observed in all tests. A check on the data reduction was provided by the measured values of the fall heights and penetrations into the clay. Generally very good agreement (within 10%) was found between the measured and calculated penetrations. To estimate the rate correction factor the static bearing capacity was calculated using equations 3 and 4. This required an estimate of undrained strength, which was obtained from the T-bar tests. In each tub of clay 3 T-bar tests were performed. A typical set of results is shown in Figure 4. This Figure shows a plot of estimated undrained strength versus penetration where the undrained strength has been calculated from

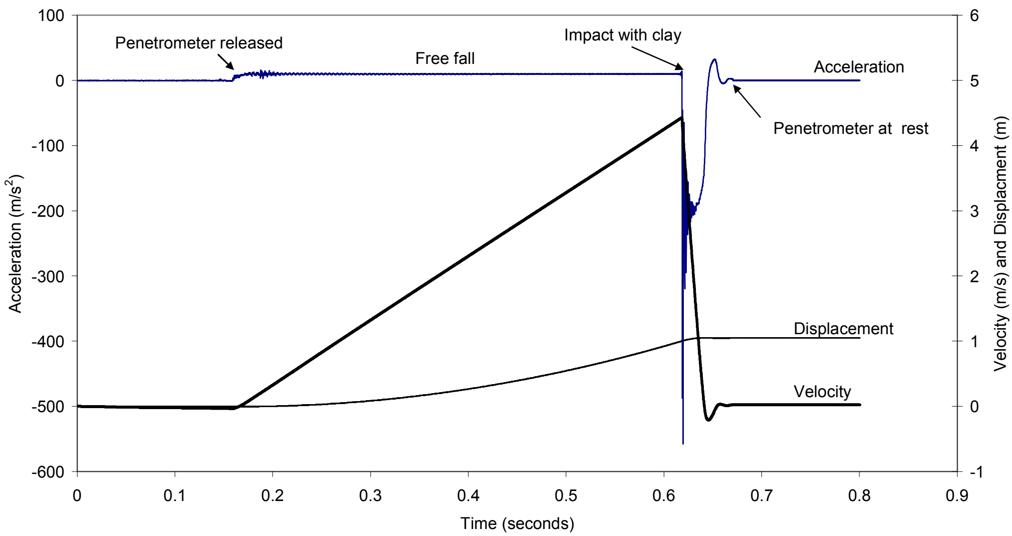

Figure 2: Acceleration, velocity and displacement for a typical penetration event

$$s_u = \frac{F}{Nld} \tag{6}$$

Where F is the force, d is the T-bar diameter, l is the length of the T-bar, and N is a resistance factor taken to be 10.5 (Stewart and Randolph, 1991). It can be seen that the T-bar needs to penetrate about 50 mm or 6 diameters before the inferred strength becomes constant. This is a limitation of equation 6 which assumes the T-bar is deeply buried. It is believed that the undrained strength is reasonably constant throughout the clay, and this has been assumed in interpretation of the data. It can be seen that the T-bar indicates some variability in undrained strength. A variability of +/- 10% of the mean was observed in most tests. An average of the three T-bar responses ignoring the upper 50 mm has been used to provide a representative undrained strength.

Using the average undrained strength the static bearing capacity has been calculated using equations 3 and 4, and this is shown on Figure 3. It was found that multiplication of the static capacity by a constant value gave reasonable agreement with the measured resistance, as shown in Figure 3. For the test shown in Figure 3 this factor was 2.1. Similar responses to Figure 3 were observed in all tests.

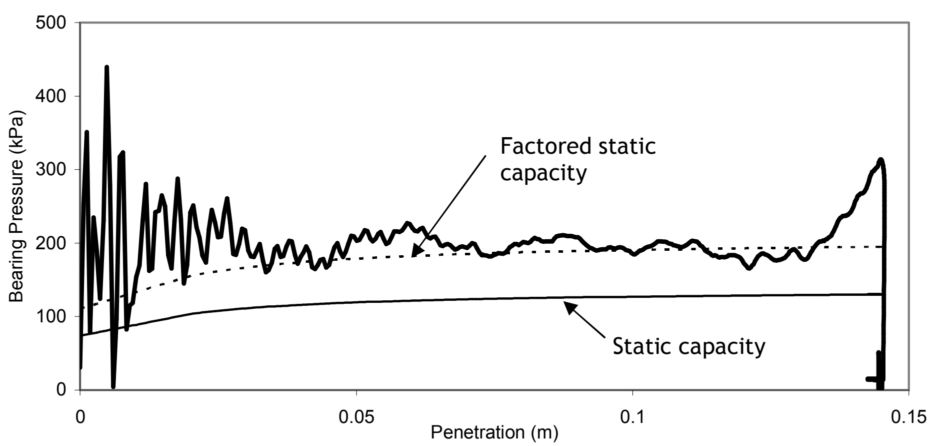

Figure 3: Comparison of dynamic and predicted static bearing pressures

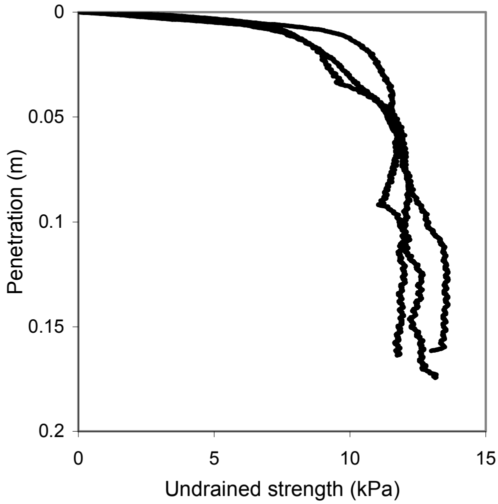

Figure 4: Typical set of T-bar results

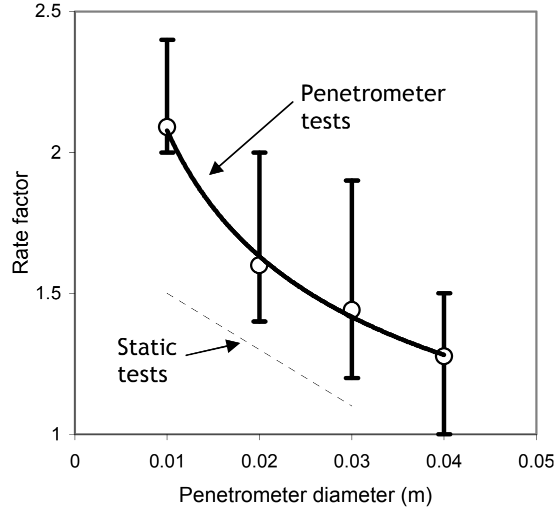

Figure 5: Effect of diameter on rate factor

A total of 73 penetrations were recorded in this study. For each diameter it was found that the calculated rate factors were independent of the undrained strength, which varied from 2 kPa to 18 kPa, and were independent of the penetrometer mass which varied from 70 to 470 g. Although these parameters did not influence the rate factor they nevertheless had a significant impact on the penetration. This and previous studies with the same apparatus, but without the accelerometer, (Leitner & Maco, 2003) suggested penetration could be estimated to sufficient accuracy from

$$penetration = \frac{0.025\, m v^2}{s_u B^2} = \frac{0.05\, m g H}{s_u B^2} \tag{7}$$

Where v is the impact velocity, and H is the fall height. It was also noted that the penetration resistance appeared to be independent of the (reducing) velocity from impact until just before coming to rest. However, only a limited range of impact velocities, between 4 m/s and 6 m/s have been investigated. In the current series of tests only one parameter, the penetrometer tip diameter appeared to have any significant effect on the rate factor. This is shown in Figure 5. The best fit line through the data relating rate factor, R, to diameter, B, is given by

$$R = 0.42 B^{-0.35} \tag{8}$$

One possible reason for the effect of diameter is that the static bearing capacity equations do not correctly allow for the diameter variations. This has been indicated by numerical analyses (e.g. Randolph et al. 2000). To assess this effect the penetrometer was pushed into the clay at speeds similar to the T-bar. Using a similar methodology to that used for the dynamic tests apparent rate factors of 1.1 and 1.5 were determined for diameters of 30 mm and 10 mm respectively. These are shown on Fig 5 for comparison. It can be seen that a significant part of the apparent dependence of the rate factor on diameter is due to inadequacies in the static bearing capacity estimation.

There are several uncertainties in the interpretation because the estimation of the T-bar strength and static bearing capacity are based on empirically derived equations. For the T-bar the rate of penetration must be sufficient to ensure undrained behaviour. However, as the rate is increased further rate effects can occur. Einav and Randolph (2005) present a model that suggests competing effects from rate and strength reductions due to soil sensitivity both contribute to the resistance factor. Alternatively the strength may be estimated from correlations with moisture content, and these suggest that errors in the T-bar strengths are relatively minor. It may be noted that any inaccuracy in resistance factor would affect all the data, changing the magnitude of the rate effect, but not the influence of diameter. The general bearing capacity equation is based on a particular mechanism of failure for a surface footing. Empirically based factors are then used to account for footing shape and embedment depth. Numerical analyses have indicated that these formulae do not correctly allow for diameter, especially as diameter reduces, and this is shown in the experiments. Numerical studies and experiments are in progress to better explain the mechanics.

4 CONCLUSIONS

Tests have been performed in which a small penetrometer has been allowed to free fall into clay. By recording the acceleration, the soil resistance and penetration can be simply determined. To estimate the soil undrained strength the static bearing capacity was multiplied by a rate factor. This rate factor was independent of the soil strength and penetrometer mass. The rate factor appears to be significantly affected by the penetrometer tip diameter; however, this effect is in part due to the failure of conventional bearing capacity formulae to correctly account for diameter. For the impact velocities considered the soil resistance is independent of velocity provided the velocity is above a critical value at which the penetrometer rapidly decelerates to a stop.

ACKNOWLEDGEMENT

This work was supported by the ARC through a discovery project grant investigating the mechanics of dynamic loading and rapid penetration of soils.

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