Investigation of Penetration Process of Three Full-flow Penetrometers in Marine Soft Clay

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Abstract. This study presents an experimental investigation of the penetration process in marine soft clay in the Shanghai coastal area using three types (non standard Ball (N), standard Ball(S) and T bar) of full-flow penetrometers. Three main factors (the penetration resistance, strength degradation, and strength factor) are evaluated and discussed in the comparative analysis of the penetration process. The results reveal that there is a model to predict the soil strength degradation in the range of low soil sensitivities (ST < 8). In particular, for the Ball(N) penetrometer, which is a non-standard penetrometer, the degradation process is more readily affected by the soil properties. For the Ball(S) and T bar penetrometers, the test results indicate a certain relationship between the soil sensitivity (ST) and the strength factors of undisturbed and remoulded soils with low sensitivity (ST < 8). However, this relationship is not observed with the Ball(N) penetrometer. These tests can enrich the application of conventional full-flow penetrometers in marine soft soils while facilitating the adaptation of non-standard penetrometers for in-situ tests in various soft soils.

1. Introduction

With the development of the social economy, an increasing number of engineering projects have begun to involve marine construction, especially for relatively developed coastal cities. Special attention should be paid to the marine soft soil during geotechnical engineering design for all types of marine construction. It is crucial to obtain the physical and mechanical properties of these soft soils accurately, as this can directly determine the success of the engineering construction [1]. Such marine sedimentary soft soils have high water content, a high plasticity index, and are easily disturbed. Rather than laboratory tests, in-situ testing is commonly used for accurate geotechnical parameter acquisition. The most common in-situ testing methods for obtaining the physical and mechanical properties of soft soils include field vane shear tests (FVT) and piezocone penetration tests (CPTu) [2-5]. The tests can accurately determine the characteristics of marine soft soils, such as the deformation, strength, and permeability.

An innovative in-situ testing method utilizing full-flow penetrometers (ball and T-bar) has been extensively studied and practiced in recent years [6-8]. Compared to FVT and CPTu, this testing method has the clear advantages of minimizing the effect of the overburden stress and pore pressure, intuitively defining the soil failure process, and accurately obtaining the strength characteristics. Low and Randolph (2010) used full-flow penetrometers to test seabed sediments in several places in Western Australia [8]. Combined with a theoretical analysis, the results verified that these tests could be used to obtain the
undrained shear strength of undisturbed and remolded soft soils. DeJong et al. (2011) integrated numerous theoretical and experimental results and established testing standards, requirements, and data processing techniques for full-flow penetrometers [9]. Yafrate et al. (2009) discussed the relationship between the strength factor and penetration resistance, soil sensitivity, plastic limit, and liquid limit of ball and T-bar tests [10]. With further research, influencing factors such as the strain softening, penetration rate, and soil anisotropy have been investigated through theoretical analyses, numerical simulations and field tests [11,12]. For example, Martin and Randolph (2006) proposed a solution for the strength factor based on plastic theory [13]. Einav and Randolph (2005) discussed the strain softening caused by different penetration shapes under various soil sensitivities [14]. In addition, numerous researchers have utilized numerical methods (e.g., UBSPM, LDFE, and SSFD) to explore the full-flow penetration process [15-17].

Although the penetration process of the ball and T-bar methods has been extensively studied, most studies have been based on the initial specifications: the projected area of the penetrometer was 100 cm². However, various shapes have been used in actual marine engineering construction, such as suction buckets, screw piles, and drag anchors. Therefore, it is worth exploring whether the shape can influence the penetration process in marine sedimentary soft soils. To address this issue, three full-flow penetrometers with different shapes were tested on marine sedimentary soft clay in the Shanghai coastal area. It is better if replaced with: The results in terms of penetration resistance, soil strength degradation, and strength factors of undisturbed and remolded soils were discussed and compared with those obtained with the CPTu and FVT. This study provides a supplement on the use of full-flow penetrometers with different shapes in marine sedimentary soft soils and attempts to adapt non-standard penetrometers for in-situ testing in various soft soils.

2. Experimental setup and test procedures

2.1. Full-flow penetrometers testing

Three types of full-flow penetrometers—T-bar, Ball(S), and Ball(N)—were used in the marine soft clay tests (Figure 1). The T-bar and Ball(S) penetrometers have a projected area of 100 cm² (T-bar with the length of 25cm, diameter of 4cm; Ball(S) with the diameter of 11.3cm), which is the same as those used by other researchers. The Ball(N) penetrometer has a diameter of 15cm, with a projected area of approximately 177 cm². Three penetrometers were crushed into soils by the same push rod with the projected area of 10 cm². Penetrometers with larger projection areas can effectively avoid the influence of pore pressure and overburden pressure on the penetration resistance compared with the conventional CPTu test.

Figure 1. Test equipment (CPTu and three types of full-flow penetrometers).

Klar and Pinker (2010) presented a method to obtain the steady-state solution for full-flow penetrometers [18]. The factors of interface roughness, penetration rate, and strain softening effects affected the test results. To facilitate comparison of the test results, an interface roughness of 0.4 and a penetration rate of 20 mm/s were maintained during the tests. The other test conditions were in accordance with the conventional full-flow penetrometer test procedure proposed by Yafrate and DeJong (2009) [10]. Full-flow penetrometer testing was conducted at two sites located on land reclaimed from the sea (Figure 2), and the soil at each site was classified as marine deposit soft soil. Site 1 is
located on the sea, ~3 km from the coastline, and the seabed soil was in the initial stage of land formation. The full-flow penetrometers penetrated the seabed to a depth of ~2.5 m with a sea water depth of ~3 m. Site 2 is located in the preliminary land formation area, and the thickness of the soft clay varies from 2 to 9 m with poor soil conditions. The penetration depth was up to 8.5 m during the tests. The basic properties of the marine soft soils at the two sites are listed in Table 1. It can be noted that the soil located at Site 1 has a higher water content, void ratio, and liquidity index compared to the site 2. This indicates that soil at Site 1 is softer to a certain extent.

![Figure 2. Locations of test sites.](image)

### Table 1. Summary of the properties of the marine soft clays at each test site.

| Properties           | Site 1          | Site 2          |
|----------------------|-----------------|-----------------|
| Water content, W (%) | 58 – 90.1       | 42.8 – 63       |
| Specific gravity, Gs | 2.68 – 2.73     | 2.72 – 2.76     |
| Void ratio, e        | 1.576 – 2.603   | 1.192 – 1.765   |
| Liquid limit, LL     | 42.4 – 59       | 30.4 – 51.3     |
| Plastic limit, PL    | 26.5 – 35.1     | 18.0 – 27.1     |
| Plasticity index, IP | 15 – 23.9       | 12.3 – 26.2     |
| Liquidity index, IL  | 1.45 – 3.21     | 1.04 – 1.76     |

#### 2.2. Main components of the tests

Three main aspects were considered and discussed in a comparative analysis of the penetration process for the three full flow penetrometers. First, the penetration resistance of the three full-flow penetrometers was compared at each test site, and the relationship between the projected area and penetration resistance was analysed. Second, cyclic penetration tests were carried out at five depth intervals (Site 1: 0.5–0.8 m and 1.3–1.6 m; Site 2: 2.0–2.5 m, 5.0–5.5 m, and 8.0–8.5 m). The change of penetration resistance was studied in detail considering the number of cycles and soil sensitivity. A degradation model of the soil strength at each depth interval was proposed. Third, combined with FVT, a detailed analysis of the strength factor (the ratio of penetration resistance with shear strength) was summarized and compared. The main aim of this study was to analyse the variation in the test results caused by different penetrometer shapes. In addition, this study aimed to elucidate the interlinks among the three full-flow penetrometers in marine soft clay tests.

### 3. Results and discussion

#### 3.1. Comparison of penetration resistance

The test results for the two test sites are shown in Figures 3 and 4. The cyclic penetration test was implemented at five depth intervals (Site 1: 0.5–0.8 m and 1.3–1.6 m; Site 2: 2.0–2.5 m, 5.0–5.5 m, and 8.0–8.5 m). The obtained results show that the average penetration resistance of Ball(S) at Sites 1 and
2 was 108% and 124%, respectively, greater than that of the T-bar penetrometer. These different values indicate that the shape of the penetrometer and the difference in soil influence the initial penetration resistance. Ultimately, the different shear strain rate on the surrounding soils led to the difference of penetration resistance with the same projected area, surface roughness, and penetration rate.

Approximately equal ratios of 146% and 147% were obtained when comparing the results of Ball(N) and Ball(S) at sites 1 and 2 respectively. In other words, for the spherical penetrometer (more symmetrical), differences in the soil had little effect on the penetration resistance, and the size of the projected area determined the difficulty of initial penetration instead. We should also note that the penetration resistance does not increase by the same multiple as the increase of 1.77 times in the projected area.

Figures 3 and 4 also show the results of the cyclic penetration tests conducted at the two test sites. Owing to limitations in the sensor installation, the analysis focused on the penetration process, while the extraction resistance measurements are ignored. According to the obtained curves, the penetration resistance gradually decreases with an increasing number of penetration cycles and eventually tends to be stable. The decrease of penetration resistance is discussed below.
3.2. Strength degradation

3.2.1. Relationship between strength degradation and the number of cycles. The soil sensitivity ($S_T$) was used to measure the influence of clay structure on strength ($S_T$) was obtained by calculating the undrained shear strength ratio of undisturbed soil to remolded soil using FVT at each test point. Figure 5 shows that the soil sensitivity of Site 2 is higher than that of Site 1.

![Figure 5. Distribution of ST with depth at two sites.](image)

The ratio of the average penetration resistance to the initial penetration resistance ($q_{(n)}/q_{in}$) was calculated for the five depth intervals. Figures 6 and 7 show the relationship between the strength degradation, $q_{(n)}/q_{in}$, and the number of cycles, $n$. It can be concluded that the residual penetration resistance at Site 1 tends to be stable after 5–6 cycles, while the number decreases to 3–4 cycles at Site 2. The strength degradation amplitude at Site 2 is greater than that at Site 1, and the difference in soil sensitivity plays an important role in this phenomenon.

![Figure 6. Cyclic degradation curves for three full-flow penetrometers at Site1.](image)
Figure 7. Cycle degradation curves for three full-flow penetrometers at Site2.

A comparison of the normalized strength degradation curves shows that most of the Ball (S) and T-bar curves are like each other (except for the degradation curves at a depth of 1.3–1.6 m at Site1). In contrast, the degradation curves for Ball(N) are more dispersed (the curves are located above or below the T-bar and Ball(S) curves, even with a similar trend). The tests reveal that for the penetrometers with the same projected area, the different shapes can affect the penetration resistance to a certain extent, however, the influence of different shapes is limited for the normalized soil degradation, and the degree of strength degradation will be the same after several repeated cyclic tests. The situations differ for the two spherical penetrometers; the degree of strength degradation is unrelated to the projected area, but it is related to the properties of the soil.

The following equation was used to fit the test data:

\[ y = y_0 + A_1 e^{-x_0/x_1} \]

where \( x_0, y_0, A_1, \) and \( x_1 \) are four key parameters that determine the curve. The parameters for each test are summarized in Table 2.

Einav and Randolph (2005) [14] first proposed the strength degradation model, which was revised by Yafrate et al. (2009) [10] as follows:

\[ q(n) = \frac{q_{\text{rem}}}{q_{\text{in}}} + \left(1 - \frac{q_{\text{rem}}}{q_{\text{in}}}\right)e^{-3(n-1)/N_{95}} \]

where \( q(n) \) is the current penetration resistance, \( q_{\text{in}} \) is the initial penetration resistance, \( q_{\text{rem}} \) is the remolded penetration resistance, and \( N_{95} \) is the number of cycles required to achieve 95% strength degradation.

The equations obtained in these experiments are equivalent to the model proposed by Yafrate et al. (2009) [10] when \( y_0 + A_1 = 1 \) and \( x_0 = 1 \). Through verification based on the parameters in Table 2, it can be concluded that the above strength degradation equation is applicable for the three types of penetrometers in these tests. At the same time, all the fitted curves can accurately predict the relationship between the strength degradation and the number of cycles. The value of \( N_{95} \) can be determined as the value of \( 3t_1 \) from Table 2.
### Table 2. Parameter values of the curve fittings for the three full-flow penetrometers.

| Testing depth interval | Type of full-flow penetrometer | $x_0$ | $y_0$ | $A_1$ | $t_1$ | $y_0^+ A_1$ |
|------------------------|--------------------------------|-------|-------|-------|-------|--------------|
| 0.5–0.8 m, Site 1      | Ball(S)                        | 1     | 0.45  | 0.55  | 1.86  | 1            |
|                        | T-bar                          | 1     | 0.44  | 0.56  | 1.49  | 1            |
|                        | Ball(N)                        | 1     | 0.31  | 0.69  | 0.69  | 1            |
| 1.3–1.6 m, Site 1      | Ball(S)                        | 1     | 0.56  | 0.45  | 1.02  | 1.01         |
|                        | T-bar                          | 1     | 0.47  | 0.56  | 1.23  | 1.03         |
|                        | Ball(N)                        | 1     | 0.65  | 0.35  | 0.87  | 1            |
| 2.0–2.5 m, Site 2      | Ball(S)                        | 1     | 0.17  | 0.83  | 0.54  | 1            |
|                        | T-bar                          | 1     | 0.18  | 0.83  | 0.62  | 1.01         |
|                        | Ball(N)                        | 1     | 0.2   | 0.84  | 0.48  | 1.04         |
| 5.0–5.5 m, Site 2      | Ball(S)                        | 1     | 0.17  | 0.86  | 0.65  | 1.03         |
|                        | T-bar                          | 1     | 0.16  | 0.87  | 0.73  | 1.03         |
|                        | Ball(N)                        | 1     | 0.18  | 0.84  | 0.66  | 1.02         |
| 8.0–8.5 m, Site 2      | Ball(S)                        | 1     | 0.25  | 0.77  | 0.99  | 1.02         |
|                        | T-bar                          | 1     | 0.25  | 0.77  | 0.65  | 1.02         |
|                        | Ball(N)                        | 1     | 0.37  | 0.64  | 0.59  | 1.01         |

#### 3.2.2. Relationship between strength degradation and soil sensitivity.

Figure 8 shows the relationship between $q_{in}/q_{rem}$ and soil sensitivity with the three full-flow penetrometers during stable cyclic penetration. The results show a strong linear relationship between $S_T$ and $q_{in}/q_{rem}$. A similar conclusion was drawn by Yafrate [10] in tests of Ball(S) and T-bar penetrometers at several locations. However, in that study, the linear relationship was modified to an exponential relationship when considering soils with high sensitivity ($S_T > 60$). This test results indicate that a linear relationship can be adopted for penetrometers, not only for the standard penetrometers, but with different shapes and projected areas, within the range of low soil sensitivities ($S_T < 8$).

By comparing the fitting curves of the three full-flow penetrometers, we can find that the slope of the fitting line for Ball(S) is slightly larger than that of the T-bar penetrometer. The fitting line for Ball(N) has the lowest slope and intersects the fitting curves of Ball(S) and T-bar at points A and B, respectively. An interesting result is that Ball (N) with a larger protected area exhibits smaller values of $q_{in}/q_{rem}$ in the case of low soil sensitivity ($S_T < 4.5$). Further studies will be conducted to further explore this phenomenon.
3.3. Estimation of the strength factor

3.3.1. Strength factors of three full-flow penetrometers. It is of great significance to obtain the undrained shear strength of soil by ensuring the value of strength factor accurately. In general, the strength factor can be calculated using Equation 3,4:

\[ S_u = \frac{q_{\text{Ball}(S)}}{N_{\text{Ball}(S)}} = \frac{q_{\text{T-bar}}}{N_{\text{T-bar}}} = \frac{q_{\text{Ball}(N)}}{N_{\text{Ball}(N)}} \]  

\[ S_{ur} = \frac{q_{\text{rem,Ball}(S)}}{N_{\text{rem,Ball}(S)}} = \frac{q_{\text{rem,T-bar}}}{N_{\text{rem,T-bar}}} = \frac{q_{\text{rem,Ball}(N)}}{N_{\text{rem,Ball}(N)}} \]

where \( S_u \) and \( S_{ur} \) are the undrained shear strengths of undisturbed and remolded soils, respectively, obtained by FVT; \( q_{\text{Ball}(S)} \), \( q_{\text{T-bar}} \), and \( q_{\text{Ball}(N)} \) are the initial penetration resistances for Ball(S), T-bar, and Ball(N), respectively; \( N_{\text{Ball}(S)} \), \( N_{\text{T-bar}} \), and \( N_{\text{Ball}(N)} \) are the strength factors of Ball(S), T-bar, and Ball(N), respectively; \( q_{\text{rem,Ball}(S)} \), \( q_{\text{rem,T-bar}} \), \( q_{\text{rem,Ball}(N)} \) are the remolded penetration resistances for Ball(S), T-bar, and Ball(N), respectively; and \( N_{\text{rem,Ball}(S)} \), \( N_{\text{rem,T-bar}} \), \( N_{\text{rem,Ball}(N)} \) are the remolded strength factors of the Ball(S), T-bar, and Ball(N) penetrometers, respectively.

Figure 9 shows the distribution of \( N \) with depth for the three full-flow penetrometers at two test sites. For Ball(S), the value of \( N \) varies from 12–18 with a mean value of 15. The range of variation is 10–17 with a mean value of 13 for the T-bar penetrometer. The strength factor of Ball (N) appears more dispersed (19–30) than those of Ball(S) and T-bar, with a mean value of 23. These results are consistent with those previously reported by DeJong (2011) in that (1) the value of \( N \) has no relationship with depth, and (2) Ball(S) exhibits a slightly greater value of \( N \) than that of the T-bar penetrometer [9]. In addition, the dispersion trend of Ball(N) indicates that this type of penetrometer is more sensitive and more readily affected by other factors, consequently, may cause the larger deviation of calculation results.

Figure 9. Distribution of the strength factors for three full-flow penetrometers.
3.3.2. Relationship between the strength factor and soil sensitivity. The relationship between the soil sensitivity ($S_T$) and the strength factor of undisturbed soil ($N$) and remolded soil ($N_{rem}$) were statistically analyzed, as shown in Figure 10. Within the scope of this test, the values of $N_{rem}$ were more dispersed than those of $N$. For Ball(S), $N$ increased gradually with increasing $S_T$, while $N_{rem}$ decreased gradually with increasing $S_T$. For T-bar, $N$ and $N_{rem}$ exhibited the same decreasing trend with increasing $S_T$. For Ball(N), the results show that $N$ decreased with increasing $S_T$, while no obvious relationship was observed between $N_{rem}$ and $S_T$.

![Figure 10](image.png)

Figure 10. Distributions and fitting curves for the relationship between $S_T$ and $N$, $N_{rem}$ obtained with three full-flow penetrometers.

Based on the variation trends, fitting equations for the three types of full-flow penetrometers were estimated as follows:

$$N_{rem} = 15 \times S_T$$
$$R^2 = 0.6693$$

$$N_{rem} = 24 \times S_T$$
$$R^2 = 0.5625$$

$$N_{rem} = 20 - 7 \times S_T$$
$$R^2 = 0.6326$$

$$N_{rem} = 20 - 7 \times S_T$$
$$R^2 = 0.5763$$
The curves described above can effectively represent the distribution trend of each penetrometer test point in low-sensitivity soils ($S_T < 8$). It should be noted that the same denominator of $1 + \left(\frac{S_T}{4}\right)^{-3}$ is observed in all the fitted equations, which determines the range over which the curve varies. These fitting equations are quite different from that of Yafrate et al (2009) and DeJong et al (2011), which means the application full flow penetration should be combined with the specific conditions of soil [9,10].

In fact, there is no direct mechanism connecting the soil sensitivity and full-flow measurements because the soil failure mechanism induced by full-flow penetrometers (flow failure) differs from that in FVT test (shear failure). It should be noted that the difference between the two failure mechanisms is highlighted with a larger projected area and caused the dispersed results of Ball(N). On the other hand, the difference observed with literature may be related to the $S_t$ which was calculated from FVT. Nevertheless, the above formulas were proposed to be used as a reference for the engineering calculation of soft soil around Shanghai coast area.

4. Conclusions

This study presents an experimental investigation of the penetration process in marine soft clay in the Shanghai coastal area using three different types of full-flow penetrometers. Based on the test results, the following conclusions can be drawn:

(1) The shape of the penetrometer and the difference in soil caused different shear strains on the surrounding soils during penetration and influenced the initial penetration resistance. The size of the projection area is likely to be the determining factor for penetration resistance compared with the contributions of the soil properties and penetrometer shape.

(2) The cyclic penetration tests show a strong linear relationship between $S_T$ and $q_{in}/q_{rem}$ for the three full-flow penetrometers within the range of low soil sensitivity ($S_T < 8$), and the strength degradation laws of these penetrometers can be expressed using the same model. The strength degradation of Ball(N), a non-standard penetrometer, is more readily affected by the properties of the soil.

(3) There is a certain relationship between soil sensitivity ($S_T$) and the strength factors of undisturbed soil (N) and remolded soil (Nrem) for Ball(S) and T-bar in the low-sensitivity soils ($S_T < 8$); however, this relationship is not observed with Ball(N). The proposed formulas could be used as a reference for the engineering calculation of soft soil around Shanghai coast area.

(4) In order to obtain the appropriate rules for Ball(N) penetrometer, future research should focus on two main aspects: on the one hand, different projected areas of Ball(N) penetrometers need to be taken into consideration. On the other hands, more suitable test sites should be conducted to get more uniform rules for further application.

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