Evaluation of strength characteristics of underwater ultra-soft soil in Taihu Lake based on ball full-flow penetration testing

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ABSTRACT: A large number of ultra-soft soil is widely found in coastal and lacustrine sedimentary areas, which are characterized by high water content, high compressibility, low undrained shear strength, low coefficient of consolidation, and low penetrability. Since the underwater ultra-soft soil can hardly be sampled and tested in the laboratory, it is difficult to evaluate its strength and deformation characteristics by existing common testing techniques. In recent years, the ball-bar full-flow penetration technology developed in the world provides a reliable method for evaluating the engineering properties of underwater ultra-soft soil. In this paper, in the case study of Taihu tunnel in Wuxi City, the field test of underwater ultra-soft soil was carried out by applying the ball full-flow penetration technology, and the field vane shear test was combined. The undrained shear strength of underwater ultra-soft soil in Taihu Lake basin is interpreted by the ball full-flow penetration resistance, which provides a reference for the study of field engineering characteristics.

Keywords: ball full-flow penetration; situ testing; undrained shear strength; underwater ultra-soft soil

1. Introduction

In recent years, with the development of *Belt and Road Initiative strategy* in China, more and more engineering construction and research have been carried out in rivers, oceans, lakes and other waters. In order to accurately grasp the geological conditions of underwater engineering, the application of in-situ testing technology of cone penetration test (CPT) on the water becomes particularly important in the field of water transportation engineering [1]. The device of CPT for underwater first appeared in the 1960s. After decades of development, so far, a variety of water static penetration equipment, such as small jack-up platform, casting platform, the sea bed type, underground static penetration type and submersible cabin type, have been developed [2]. CPT has been an essential part of underwater soil investigations for decades, and significant developments have taken place in this period [3].

Accuracy of traditional piezocone penetration test (CPTU) data in soft clay may decrease as the water depth increases. This is due partly to (i) reduced sensitivity of the load cell in measuring the small load increment from the penetration resistance in soft clays compared with the high ambient pressure at the seabed and (ii) uncertainty in corrections for the unequal area effect and contribution of overburden stress to the cone resistance[4].

This paper based on Wuxi Taihu Lake Tunnel project focused on empirical studies for the interpretation of ball full-flow penetration test data, linking the penetration resistance to undrained shear strength determined from field vane shear test (FVT). The research results provide early field experience and theoretical guidance for evaluating the engineering characteristics of super-soft soil encountered in the construction of underwater areas in China.

2. Ball full-flow penetration

Full-flow penetrometers (T-bar and ball penetrometers as Fig. 1. shown) is that accurate plasticity solutions exist that relate the penetration resistance to the undrained shear strength [5-7]. This means that (in theory) shear strength measurements from full-flow penetrometer tests do not need to be calibrated against laboratory derived measurements. Furthermore, since the soil is able to flow around the probe, the overburden pressure is equal above and below the probe (bar the small shaft area). The larger projected area of the full-flow probes also leads to improved accuracy in soft soil – generally, full-flow probes have a projected area of 10,000 mm^2, i.e. 10 times that of the standard cone[8-10].

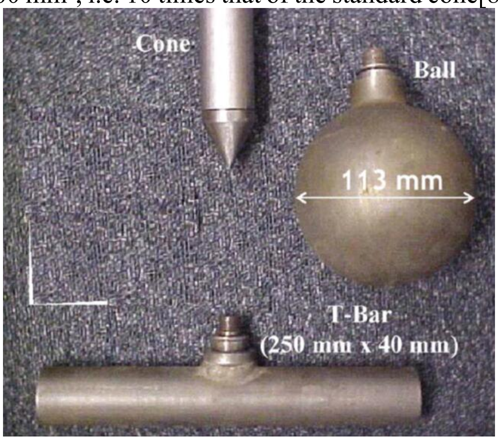

Figure 1. T-bar, ball, and cone penetrometers

The ball penetrometer was introduced to overcome the possibility of bending moments on the T-bar load cell. Centrifuge and in-situ tests have shown that ball and T-bar s_u profiles are similar and give good agreement with laboratory s_u measurements determined from high-quality samples. [11-12]

3. Site description and field tests

3.1. Site description

The Wuxi Taihu lake tunnel project test site is located in the south of Jiangsu Province, China. The geological formations of sites are Quaternary clay, which is mainly Taihu Lake. The formation conditions of the test site are mainly underwater silt and muddy soft soil.

3.2. Equipment descriptions

The full-flow ball penetrometers used in this study was developed by Southeast University, which has a 100-cm^2 projected area that, in combination with a 10-cm^2 projected area of the load cell (and push rod), results in a 10:1 area ratio (Fig. 2.). The ball is 113mm in diameter. The surfaces are lightly sandblasted to ensure a rough interface[13-14].

Figure 2. Ball full-flow penetrometer developed by Southeast University

3.3. Testing procedures

The standard test procedure was to equilibrate the load cell to the in situ temperature prior to each sounding all electronics were connected and powered throughout the equilibration process. Baseline measurements (load cell voltages under zero load) were taken immediately before and after each sounding. A penetration rate of 20 mm/s was adopted to ensure undrained penetration at all sites and to conform with standard piezocone penetration practice.

Ball full-flow penetration tests were performed at the testing section for seventeen times as Fig. 3. shown. In addition, ten times of FVT was made at the same points, which were adopted as reference points. Results of FVT (undrained shear strength) were used to back-calculate the strength factor (N_{ball}). In turn, penetration resistance of ball full-flow penetration tests provided a rapid alternative method to estimate undrained shear strength of underwater ultra-soft soil in Wuxi Taihu Lake. The summary of the situ test is presented in Table 1.

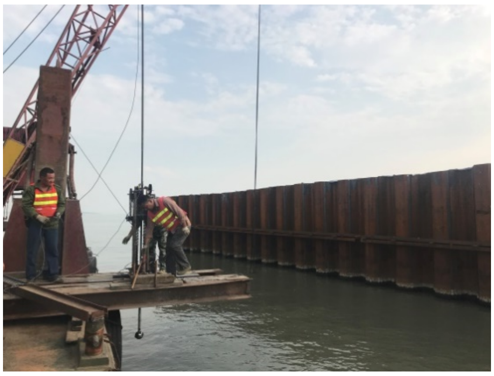

Figure 3. Figure 1. Test in Wuxi Taihu Lake site

Table 1. The summary from situ tests in Wuxi Taihu Lake site

In situ test	Sites
Ball full-flow penetration	No.
test/set	17
Field vane shear test（FVT）	No.
/set	10

4. Test results and discussion

4.1. Correction of penetration resistance

To account for the differential overburden stress due to the push rod above the penetrometer, Randolph (2004) recommended the computation of net penetration resistance ($q_{net-ball}$) using the followingcorrection[15-17]:

$$q_{net-ball} = q_m - [\sigma_{v0} - u_{v0}(1-a)]\frac{A_s}{A_p} \quad (1)$$

Where $q_{net-ball}$ is the net ball resistance , q_m is the measured cone resistance, σ_{v0} is total stress; u_{v0} is pore water pressure; a is load cell area ratio, and A_s/A_p is the ratio of the shaft area to the area of the probe.

Since the value of As/Ap is generally 0.1 for the ball penetrometer, the correction to the measured resistance is usually small.

The profile of penetration resistance of three representative sets of Wuxi Taihu Lake site is obtained by using ball full-flow penetration penetrometer, as shown in Fig. 4. In the process of single penetration, the corrected penetration resistance increased with depth. For the underwater super soft soil of Taihu Lake with low shear strength, the evaluation parameters can be effectively obtained by using ball full-flow penetration test.

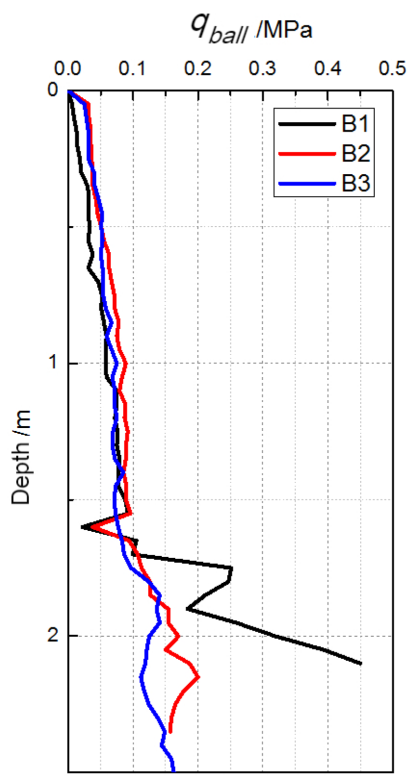

Figure 4. Ball penetrometer profile from Wuxi Taihu Lake test site

4.2. Strength factor (N_{ball}) of the full-flow ball penetrometers

For this study, the correlations are determined by comparing penetration resistance measured by ball full-flow penetrometer to strength data measured from FVT at the same depth. FVT provide values for undrained shear strength and as a result, the back-calculated strength factor (N_{ball}) will vary accordingly. The results of field vane shear test data are summarized in Table 2.

Table 2. Summary of field vane shear test data results

Sites No.	Undrained shear strength s_u/kPa (in different depth)			
SEU 1	1m	2m	3m	4m
	4.21	26.77	-	-
SEU 2	1m	2m	3m	4m
	6.66	11.7	-	-
SEU 3	1m	2m	3m	4m
	6.21	10.11	-	-
SEU 4	1m	2m	3m	4m
	4.55	5.8	-	-
SEU 5	1m	2m	3m	4m
	4.99	6.88	6.55	-
SEU 6	1m	2m	3m	4m
	7.01	5.63	5.22	7.48
SEU 7	1m	2m	3m	4m
	1.9	7.66	8.55	-
SEU 8	1m	2m	3m	4m
	4.17	7.11	7.33	10.05
SEU 9	1m	2m	3m	4m
	5.09	6.14	8.7	10.55
SEU 10	1m	2m	3m	4m
	4.01	-	-	-

Fig. 5. shows the result the back-calculated of a given site of Wuxi Taihu Lake tunnel project that the value of N_{ball} is 12.8. This approach helps to minimize the influence of variations in the soil on the correlations. Regardless, appropriate selection of the reference strength is critical and must be well documented.

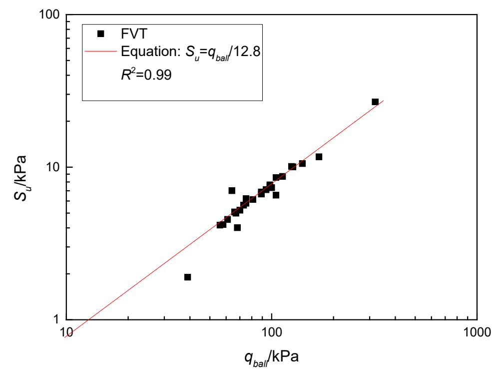

Figure 5. The back-calculated strength factor (N_{ball}) of Wuxi Taihu Lake site

4.3. Evaluation of undrained shear strength

Full-flow penetration resistance can be used to estimate shear strength as through a strength factor, N_{ball}. The relationship used to estimate undrained strength (s_u) is as follows[18-20]:

$$s_u = q_{ball}/N_{ball} \tag{2}$$

Where s_u is undrained shear strength obtained from a reference of FVT, q_{ball} is initial net penetration resistances for the ball penetrometer; and N_{ball} is undrained shear strength factors for the ball penetrometer.

Table 3 presents some previous empirical values of strength factor (N_{ball}) obtained from ball full-flow penetration test [21] and the value of strength factor (N_{ball})

empirical based on ball full-flow penetration test of Wuxi Taihu Lake site.

Table 3. Summary of site conditions and data measured from in situ tests[21]

Sites (Country)	Undrained shear strength s_u/kPa (in different depth)			
Amherst, America	Depth/m	s_u/kPa	q_{ball} /kPa	$N_{Ball\text{-}FVT}$
	7.1	34	362	10.6
	12.1	33	327	9.9
Burswood, Canada	Depth/m	s_u/kPa	q_{ball} /kPa	$N_{Ball\text{-}FVT}$
	8.8	18	246	13.6
	13.7	23	366	15.9
Gloucester, Canada	Depth/m	s_u/kPa	q_{ball} /kPa	$N_{Ball\text{-}FVT}$
	4.4	20	119	6.0
	8.3	34	197	5.8
Louiseville, Norway	Depth/m	s_u/kPa	q_{ball} /kPa	$N_{Ball\text{-}FVT}$
	7.8	40	349	8.7
	11.6	50	413	8.3
Onsøy, Norway	Depth/m	s_u/kPa	q_{ball} /kPa	$N_{Ball\text{-}FVT}$
	5.4	15	176	11.4
	15.2	28	345	12.5
Wuxi Taihu Lake, China（In this paper）	Depth/m	s_u/kPa	q_{ball} /kPa	$N_{Ball\text{-}FVT}$
	1	-	-	12.8
	2	-	-	

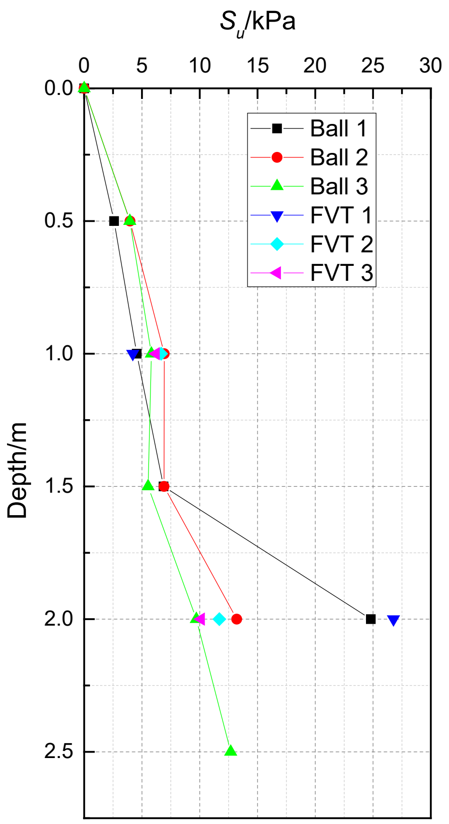

Figure 6. Undrained shear strength calculated using N_{ball}=12.8 and Eq. (2), and obtained Su from FVT at Wuxi Taihu Lake site

Fig. 6. shows the undrained shear strength calculated by N_{ball} (12.8) and Eq. (2), and obtained s_u from FVT at Wuxi Taihu Lake site. Based on the undrained shear strength factors (N_{ball}), of ball full-flow penetration in the Taihu Lake area, the undrained shear strength of the site was estimated rapidly. It is found that the average shear strength of the shallow surface layer of the lake bottom is less than 15 kPa, which tends to increase with the depth. The soil layer is natural sediment deposited under the action of self-weight, which is less affected by human activities and slowly consolidated under the action of gravity. The gravity stress of the lower soil layer is greater, the consolidation degree of the soil is better, and the structure of the soil is stronger, so the higher the strength of the soil is. Compared with the undrained shear strength measured by field vane shear test, it is found that the predicted the undrained shear strength estimated by penetration resistance of ball full-flow is close to that of FVT, and the continuous undrained strength can be obtained.

5. Conclusion

A series of penetration tests carried out at a number of soft soil sites in the Taihu Lake area have been presented. The test results have been compared with other in situ data (field vane shear test) to assess the usefulness of the piezoball in quantifying the undrained shear strength of soft soil.

The formation conditions of the test site are mainly silt and muddy soft soil. Penetration resistance measured by ball full-flow penetration is accurate, which can better reflect the variation of penetration resistance with depth and can effectively reduce the use-cost of the instrument and equipment. This field test is the first time in China that the continuous measurement of penetration resistance, friction resistance and pore water pressure of underwater soft soil layer has been realized by using ball full-flow penetration.

Through the full-flow penetration test, the undrained shear strength value s_u obtained by field vane shear test (FVT) is linearly fitted with the net penetration resistance (q_{ball}), and the undrained shear strength factors (N_{ball}) of ball full-flow penetration in Taihu Lake area is obtained, which provides an empirical reference for evaluating the undrained shear strength of super soft soil in Taihu Lake sediment.

Based on the undrained shear strength factors (N_{ball}), of ball full-flow penetration in the Taihu Lake area, the undrained shear strength of the site was estimated rapidly. It is found that the average shear strength of the shallow surface layer of the lake bottom is less than 15 kPa, which tends to increase with the depth. The predicted value of ball full-flow penetration of undrained shear strength is close to that of the vane shear test, and the continuous strength value of underwater soft soil can be obtained, which provides a reference for subsequent engineering construction.

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