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Borehole shear test and its application to saturated silty clay

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Abstract. An improved borehole shear test (BST) instrument was utilized to obtain the shear strength index of the soil layer *in-situ.* The results show that the shear strength index of the saturated silty clay measured by the improved borehole shear apparatus has a good linear correlation with the normal pressure, and the correlation coefficient can be greater than 0.98. The testing results were also compared with those obtained by the direct shear test (DST) in the laboratory. It was found that when the soil layer has a depth of less than 8.75m, the difference in the internal friction angle by the BST and DST is small. The former is 8%–33% larger than the latter. The deviation in the cohesion is obvious, which ranges from 20% to 61%. For the soil layer deeper than 8.75m, the situation is different. The difference in the cohesion measured by the two methods is small, which ranges from 8% to 9%, while the difference in the internal friction angle is distinct, and reaches 62%–85%.

1. Introduction

In 1967, Professor Handy and his colleagues at Iowa State University[1] firstly proposed an *in-situ* testing method, which was later called Borehole Shear Test (BST), for the shear strength index of the soil layer. This method utilizes the pre-drilling on the ground and then conducts tests at a predetermined depth in the hole. Due to its superiority over the existing *in-situ* testing and laboratory tests, such as the cost of drillings, depth limitation and the disturbance due to sample collection and transportation, it has attracted a great deal of engineers’ attention. Handy et al.[2] analysed three landslides in Iowa (including loess, glacial surface and clay shale) based on the results of borehole shear test (BST), and concluded that the cohesion of shear zones after landslide is zero. Theodore Bechtum et al.[3] realized the automatic shearing of borehole shear apparatus and simulated the test process of borehole shear test with Abaqus, which provided an important basis for the research of borehole shear apparatus. France, the United States and other countries have formulated the borehole shear test standards[4-5]. Yu Yongtang et al.[6] discussed in detail the test principles, equipments, test procedures of the borehole shear tester and finally successfully applied it in the loess area. Moreover, compared with the results of direct shear test (consolidation quick shear) and triaxial test (CU), the bore shear test shows lower cohesion and larger friction angle. Wang Gang et al.[7] conducted *in-situ* borehole shear test on loess in Lintong, Xi 'an, and concluded that the shear strength of the loess was positively correlated with the depth of borehole. The dispersion of cohesion was larger than the Angle of internal friction angle. Lou Yihong et al.[8] summarized the important control conditions of the normal stress during the first stage and normal stress increment required by the borehole shear test in different soils. They also carried out the borehole shear test on the highway slope in a certain area of Fujian Province, and measured the shear strength parameters of slope soil, residual soil and other soil layers. Although the borehole shear test is widely used in practical engineering, the existing borehole shear equipment cannot measure the normal displacement and shear displacement. Moreover, the test process mainly relies on the engineering experience, and it cannot be applied to soil layer beneath the groundwater level, which greatly limits its application.

In view of the problems existing in the convention borehole shear apparatus, a set of high-precision displacement sensors which can measure the shear displacement and normal displacement are added to the original equipments. A set of improved drilling shear equipments which can be applied to soil layer below the groundwater level is integrated. The improved borehole shear apparatus is then applied to the saturated soft clay in the construction site of the regional medical centre (as Figure 1 shows) in the western Yunnan Province, and the results are compared with those of the direct shear test. The application of the borehole shear test in this project show its potential value of determing the shear strength parameters of saturated soil.

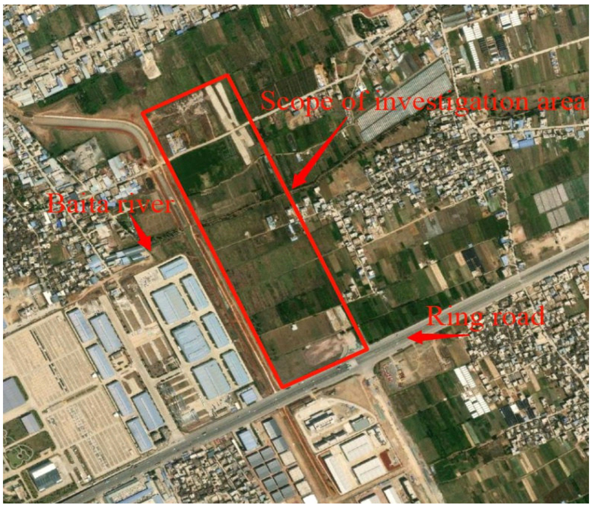


Figure 1. Location map of Yunnan Regional Medical Center position.

2. Improved borehole shear test device and principle

2.1 Improved borehole shear test device

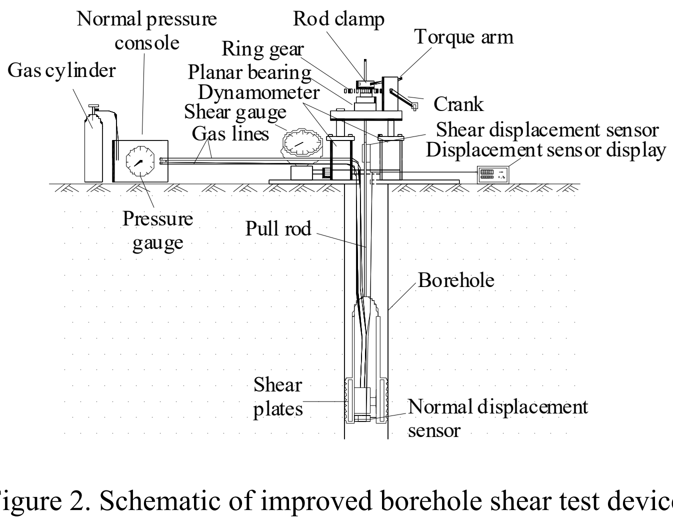


Figure 2. Schematic of improved borehole shear test device.

Improved borehole shear test equipment is shown in figure 2. It consists of borehole shear instrument, micro displacement measurement system, air pump and so on.

Borehole shear instrument: the width and length of the shear plate are 50.8mm and 63.5mm, respectively. The height of teeth on the shear plate is 2.2mm. Before expansion, the shear head diameter is 75 mm. For every rotation of the worm, the pull rod is lifted up by 0.025mm. The normal stress rangs from 0 to 440 *k*Pa. In view of the disadvantages of the existing instruments, which cannot be used under the groundwater level, the borehole shear instrument is sealed to ensure that the instrument can be tested safely and stably under the water.

Micro displacement measurement system: the displacement is measured by a miniature wire rope sensor with an effective displacement of 25.0mm and a linear accuracy of ±0.2% F.S. It is installed on the upper tension belt of the shear head, and the end of the rope is fixed on the bolt inside the steel tension belt. It can measure the penetration of the teeth into the soil and determine whether the consolidation of the soil is stable. It plays an important role in determining the first stage of normal pressure, normal pressure increment, consolidation time and other factors affecting the test results. The shear displacement sensor is fixed on the test platform above the drilling ground. The use of shear displacement sensor is of great significance to the control of shear process.

Air source: Nitrogen cylinder with output pressure of 12.5 MPa is used and the pressure reducing valve is also installed. The output air pressure can be kept a constant and connected to pressure regulating control system on the control panel.

2.2 borehole shear test principle

As shown in figure 3, two arc-shaped ribbed shear plates on the shear head are contracted by applying reverse shrinkage pressure, and then the shear head is put into the pre-made drilling depth through the pull rod. By applying appropriate expansion pressure, the plate teeth on the front of the shear face are penetrated into the soil and hold for a period of time to dissipate the excess pore pressure. The pull rod is lifted vertically, which forces the soil around the teeth to shear directly.

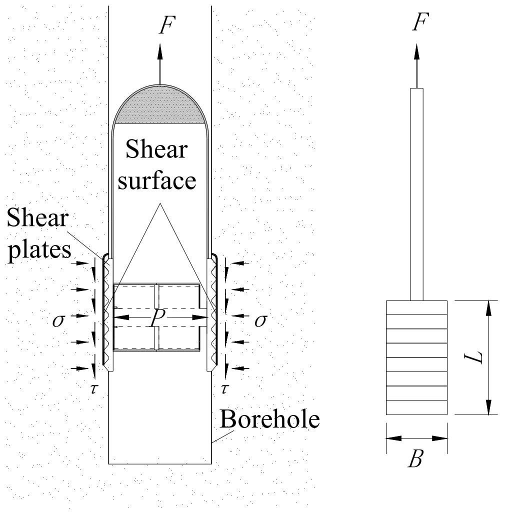


Figure 3. Schematic of borehole shear test principle.

According to the elastic theory, the shear stress and normal stress on the soil surface gradually decrease with the increase distance from the surface where the external load is applied. The diffusion velocity of the shear stress is much higher than that of the normal stress (as shown in figure 4) [1, 6]. Therefore, the principle of borehole shear test can be considered as the forced direct shear test between the soil embedded in the shear plate teeth and the soil in contact with it.

The right figure of figure 3 shows the shear plate on one side of the shear head, and the shear plate is two symmetrical ribbed arc-shaped plates. Pressure is applied to the top of the shear plate to make it expand, and then pressure is exerted on the soil by squeezing the borehole wall. After consolidation and stabilization of soil, the normal stress and shear stress are calculated as:

$$\sigma = \frac{P}{L \times B} \tag{1}$$

$$\tau = \frac{F}{2 \times L \times B} \tag{2}$$

where P is the additive force exerted by a cylinder piston rod and F is an upward force by tie rod. L and B are height and width of shear plate, respectively.

The experiment needs to be repeated 4-5 times. Each pair of σ and τ is plotted on a graph with the shear stress on the vertical axis and the normal stress on the horizontal axis. The vertical intercept of the curve which fits the test results is the cohesion, and the slope of the line is the friction angle. To make the results reliable, the regression coefficient R^2 should be no less than 0.98.

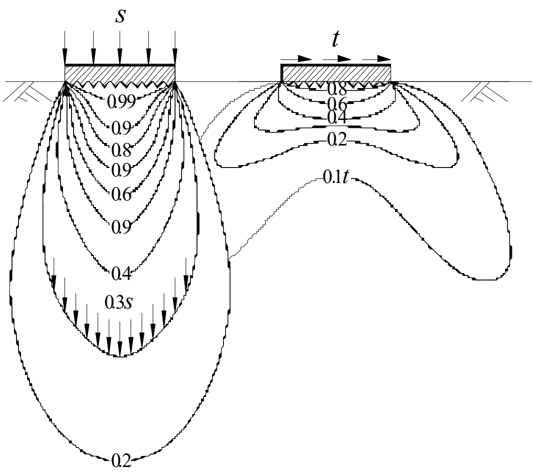


Figure 4. Normal and shearing stress distribution in elastic medium.

3. Borehole shear test procedure

- The borehole is firstly formed at the predetermined position. The diameter of the hole should be strictly controlled, with the size of 76mm-80mm. The lower limit is to make sure the shear head can be easily put into the hole, while the upper limit ensures the borehole wall can be touched when the shear plate is fully expanded.
- The shear head is then installed at desired depth and fixed with the pull rod clamp.
- The shear plate is penetrated into soil by applying certain magnitude of normal pressure. To ensure the full disposition of excess pore pressure, the change of normal displacement should be less than 0.01mm within five minutes. Generally, the soil is stable after 15-20min [9-11].
- When the worm gear system is rotated clockwise and uniformly, the pull-up shear force will cause shear failure of soil.
- Turn the worm gear system anticlockwise to return the shear head to its original place, and the next stage normal pressure is then applied
- Repeat steps 1-5 to obtain at least 4-5 normal stress and shear stress values. According to the Mohr-Coulomb strength theory, the strength failure envelope is drawn on a coordinate system σ-τ . Finally, the test data are regressed and the shear strength c and φ are calculated according to the following formula.

$$\tau = \sigma \tan\phi + c \quad (3)$$

4. Engineering application

The western Yunnan Regional Medical Center is located in Fengyi District of Dali Economic Development Zone. It extends to planning Weiyi road in the north, Dali expressway connecting line in the south, planning Jingyi road in the West and planning Jinger road in the East. It is 0.1kilometers wide in the north and 0.716 kilometers long in the East and West. The planned land area is 0.715km^2. The western Yunnan Medical Center project consists of several different medical institutions. The scope of the preliminary survey is phase I. The preliminary survey scope includes three project sites: the south to Dali expressway connecting line, the west to the planned Jingyi Road (along Baita River), the north to the planning line Weiyi Road (about 0.180km to the north of the old Guanbin line), with a length of 0.10km from north to South and a width of 0.250km from east to west. The external traffic conditions are extremely convenient.

The first phase of the medical center construction project is composed of 18-22 floors of high-rise buildings, 5-story podium and 2-story basement. The estimated excavation depth is 13m below the existing ground. Based on the results of field drilling and laboratory geotechnical measurement, the stratum structure and genetic type within the exposed depth range (the maximum drilling exposure depth is 105.4m) are analyzed. The site is a medium complex foundation, and the stratum structure is multi-storey. The shallow surface layer of the foundation soil of the site is cultivated soil layer, under which is the Quaternary alluvial lacustrine (Q_4^{al+l}) facies accumulation stratum, which has the characteristics of multi cycle deposition rhythm in the alluvial proluvial facies sedimentary stratum. According to the structure of rock and soil layer revealed by drilling, according to the genetic type, combined with lithology and physical and mechanical characteristics, the foundation soil layer within the drilling depth range of 30m is divided into two stratigraphic units and 4 main layers. During the survey, the stable water level was measured in all boreholes of the proposed site, with buried depth of 0.2-3.0m under the local surface, elevation of 1971.12-1974.84m, and water level difference of about 3.5m.Combined with the surrounding environmental conditions and engineering geological conditions of the proposed site, the seasonal variation range is predicted to be 0.5-1.0m.Combined with the comprehensive analysis of the soil layer composition structure and the macro -geological environment of the site, the groundwater type in the exploration depth range is quaternary pore diving.

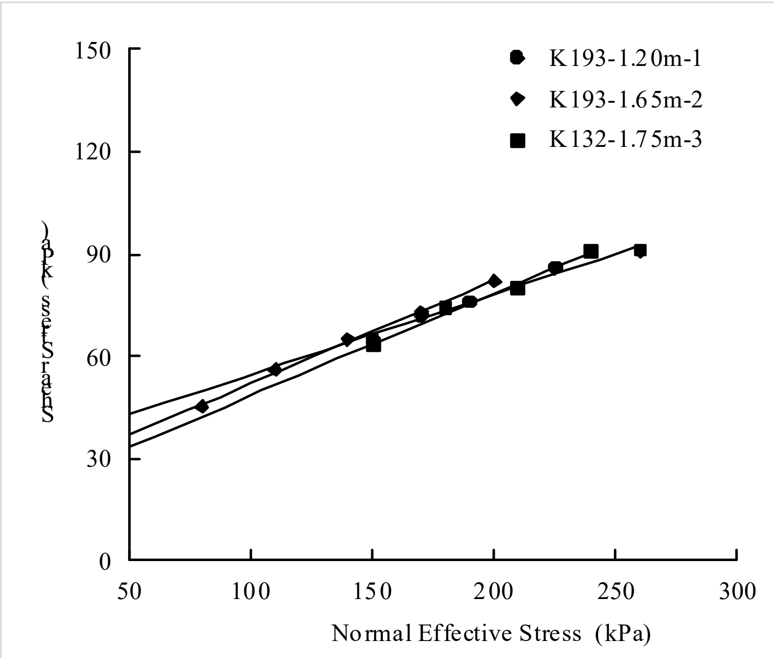
Four typical boreholes K193, K132, K148 and K128 were selected for the borehole shear test in the proposed site of the first phase of Yunnan Regional Medical Center. All holes are made by the rotary drilling method. The drilling stops 1m above the predetermined depth. To minimize the disturbance, the rest of the excavation is formed by a Shelby tube. The pressing speed and the perpendicularity of the borehole are strictly controlled. In view of safety, the test depth h is within 1.2-30.0m. Based on the statistical analysis of the drilling data from the preliminary geological data, it can be concluded that there are three kinds of silty clay with different mechanical properties in the test range of h = 0-30.0m, and 11 groups of borehole shear tests have been carried out in these three formations.

4.1 Brief introduction of borehole shear test process

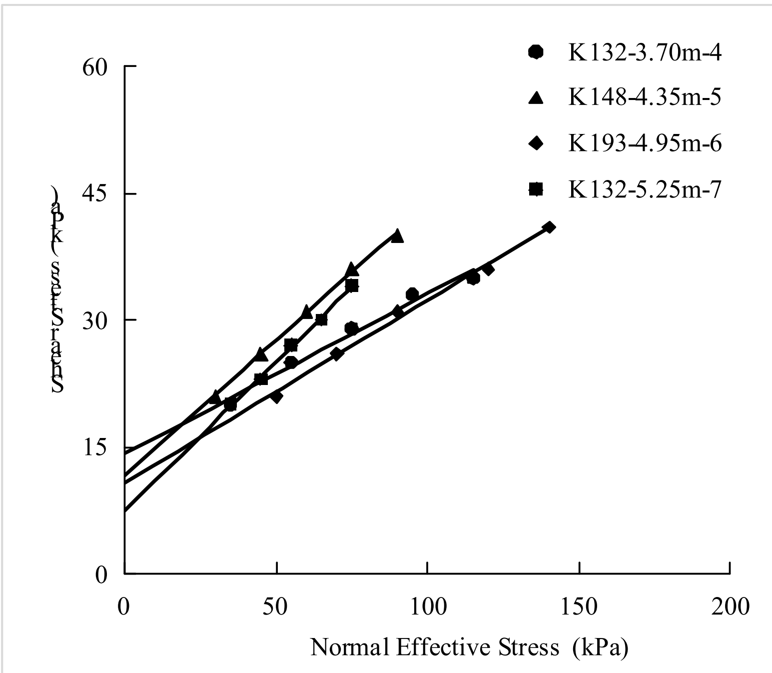
The displacement sensor installed in front of the shear head is used to measure the penetration of the teeth. The new device facilitates the determination of the magnitude of the normal pressure applied in the first stage as in this stage the teeth on the shear plate are required to fully penetrated into soil. The application of subsequent normal pressure increment should meet two conditions: 1) the depth of the penetration reaches 1.0mm within 1 min; 2) the variation of displacement should be less than 0.01mm within 5 minutes. If the above two conditions are satisfied, it is considered that the consolidation of corresponding soil layer is stable under the normal pressure. The shear stress was applied by rotating the hand-crank uniformly at the speed of 2 r/s, and the shear strength under current level of normal pressure was measured.

In addition, the undisturbed soil samples were extracted from the same position of borehole. The direct shear test was then conducted (consolidation quick shear test) in the laboratory. The mohr-

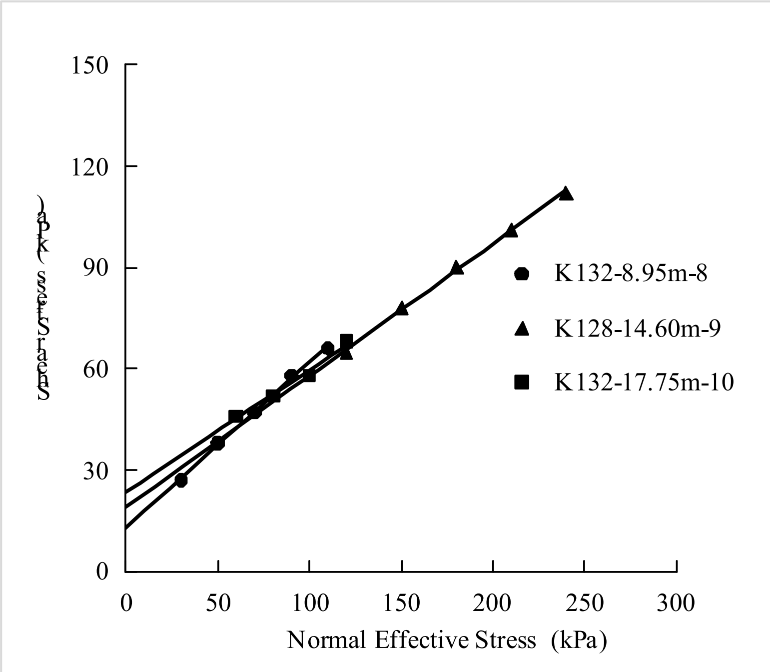
Coulomb failure envelope is obtained by regression analysis of borehole shear test data using the least square method, as shown in figure 5. The basic parameters of the test soil layer are shown in table 1, and the results of borehole shear test and direct shear test are shown in table 2.



（**a**） Q_4^{ml} Silty clay.



（**b**） Q_4^{al+l} Silty clay.



（**c**） Q_4^{al+l} Silty clay.
Figure 5. Borehole shear test curve.

Table 1. Basic properties of different soil layers in the site.

Test	Drilling serial	Test Depth, h (m)	Water Content, ω (%)	dry density (g/cm^3)	Plasticity Index	liquidity index
1	K193	1.20	25.7	1.56	18.0	0.10
2	K193	1.20	25.7	1.56	18.0	0.10
3	K132	1.65	44.2	1.21	15.6	0.52
4	K132	1.75	44.2	1.21	15.6	0.52
5	K148	3.70	27.5	1.51	14.8	0.46
6	K148	4.35	30.4	1.46	15.6	0.51
7	K193	4.95	29.4	1.49	15.8	0.42
8	K132	5.25	53.2	1.09	18.2	0.82
9	K132	8.95	56.9	1.04	17.9	0.71
10	K128	14.60	31.5	1.38	15.7	0.54
11	K132	17.75	43.2	1.24	16.2	0.74

Table 2 Summary of borehole shear test and direct shear test results.

Test[b]	Borehole Shear Test (BST）			Direct Shear Test (DST)		Remarks
	Cohesion (*k*Pa)	Friction Angle（°）	R^2	Cohesion (*k*Pa)	Friction Angle（°）	

1	30.83	13.34	0.981	46.9	14.5	σ_0=150kPa
2	2.06	15.68	0.976	46.9	14.5	σ_0=100kPa
3	21.73	16.88	0.997	27.2	12.7	
4	18.50	16.71	0.988	27.2	12.7	
5	14.15	10.76	0.981	26.4	15.2	Containing silt
6	11.60	17.75	0.998	27.5	13.8	Containing silt
7	10.68	12.21	0.994	27.3	13.5	
8	7.55	19.30	0.994	19.0	5.6	containing gray gravelly sand
9	13.8	26.12	0.998	23.0	6.4	Containing silt and gravel sand
10	27.00	21.32	0.999	29.5	13.2	
11	23.60	19.81	0.982	21.7	10.7	

[b.] The soil layers of groups 1-4 are Quaternary artificial accumulation layer (Q_4^{ml}), and group 5-11 are Quaternary alluvial diluvium (Q_4^{al+L}), and σ_0 is the first normal pressure.

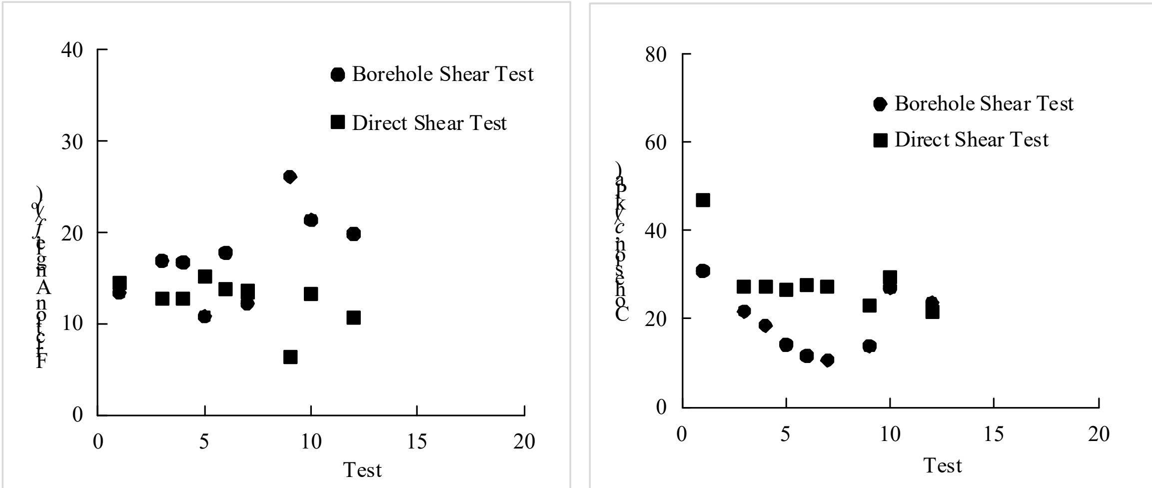
4.2 Analysis of borehole shear test process

The test equipment applied the first time to soil layer under the water. According to the primary geological survey, there exists gravel, pebble and reddish-brown silty sand interbedding within the test depth. The gravel layer plays a decisive role in the success of the test as the gravel layers will not only cause shrinkage and even hole collapse, but also the upper layer of gravel will adhere to the wall of borehole due to drilling. For example, in the tests conducted at 5.3m and 17.3m of borehole K132, due to the presence of gravel sand, the cohesion c measured in the experiment is far less than that of the same group, and the internal friction angle φ is 29%–53% higher than that of the same soil layer. The existence of sediment will also lead to a large dispersion between the five groups of data. It can be seen from table 2 that the correlation coefficient R^2 of this group is 0.976. According to the requirement of R^2, which should be greater than 0.98, this group of data is not available.

In addition, the normal stress-strain curve of each representative soil layer should be made before the test. Previous studies have shown that there will be a quasi-elastic deformation stage in the process of compression before failure, and reliable results can be obtained by loading the normal stress within this range[12-13]. At the depth of 1.2m in borehole K193, only the shear plate is applied with additional pressure, and then the displacement of shear plate under different normal pressure is recorded and the normal stress-strain curve is drawn. It can be seen that there is an obvious linear section on the curve, and the test within this range can obtain good results. Two groups of test data measured in 1.2m yellowish brown silty clay in borehole K193 are shown in table 2. On the premise of the same normal pressure increment, the improper selection of the first stage normal pressure will lead to the lower shear stress and accordingly the larger slope of the failure envelope and the smaller intercept.

4.3 Comparison of borehole shear test and direct shear test results

According to the test data in table 2 and figure 6, the cohesion and internal friction angle show obvious dispersion. Combined with the soil analysis *in-situ*, the shear strength parameters given by the borehole shear test are more sensitive to gravel and other impurities. When the depth is less than 8.95m, the difference in the internal friction angle given by two methods is very small, ranging from 8% to 33%, while the difference of cohesion is distinct, ranging from 20% to 61%; when the depth is greater than8.95m, the situation is different. The difference in the cohesion measured by the two methods is small, ranging which ranges from 8% to 9%, while the deviation between difference in the internal friction angle is distinct, reaches 62%-85%.



(a) Comparison of friction angle. **(b)** Cohesion comparison.

Figure 6. Comparison of shear strength between borehole shear test and direct shear test.

5. Conclusions

- It is the first time that the borehole shear test is applied to saturated soil sand a large number of *in-situ* test data are obtained, which is of great significance for future application of BST to the similar saturated soft clay.
- The normal stress-strain curve for a reprentative soil layer play an important role in the success of the test as it defines the magnitude of the normal stress applied during each stage.
- For saturated silty clay, the internal friction angle and cohesion given by the borehole shear test have a certain relationship with those given by the direct shear test. Morever, the relationship depends on the depth of soil layer. When the soil layer has a depth less than 8.75m, the difference in the internal friction angle by the BST and DST is small. The former is 8%–33% larger than the latter. The deviation in the cohesion is obvious, which ranges from 20% to 61%. For the soil layer deeper than 8.75m, the situation is different. The difference in the cohesion measured by the two methods is small, which ranges from 8% to 9%, while the difference in the internal friction angle is distinct, and reaches 62%–85%. Generally speaking, the strength parameters given by borehole shear test can truly reflect the situation of formation.

Acknowledgments

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