Application of the Borehole Shear Test to Loess Slope

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Abstract. It is a fundamental and important task to accurately determine the shear strength parameters of soil in the engineering design of slopes. In this study, an in-situ test method called Borehole Shear Test (BST) was applied for the first time to obtain the shear strength parameters of loess slope. Based on the improved Iowa borehole shear instrument, this paper aims at proving the applicability of BST to loess slope, and revealing the testing principles and influencing factors of normal stress and consolidation time to BST. The results show that the normal stress is proportional to displacement, which indicates that the soil is elastic deformations stage. To ensure the reliability of the results, the time for consolidation under the first stage of normal stress should be greater than 10 min while in the subsequent steps, the consolidation time should be no less than 5 min. The shear stress-displacement curves have obvious peak values and exhibit a general strain-softening type. The shear strength parameters determined have good correlation overall and the corresponding correlation coefficient is greater than 0.98. In general, the borehole shear test shows a good performance on the determination of the shear strength parameters of loess, which provides valuable guidance for slope design and future study.

Keywords: Borehole shear test, Loess slope, Normal stress, Consolidation time.

1. Introduction
Loess is widespread in the north-western part of China. With the deepening of the western development strategy, more and more geo-technique problems relating to loess appear, especially the stability of loess slopes (Liu, 1997; Shi and Shao, 2000; Peng et al., 2019). For evaluating the stability of the slope and the designing of slope reinforcements, the shear strength parameters of soil are the most fundamental and important (Ahmadabadi and Ghanbari, 2009; Ashour and Ardalan, 2012). Nowadays, laboratory and in-situ testing are the main methods to obtain the shear strength parameters of soil (Arnold, 1995; Tsukamoto et al., 2009; Nam et al., 2011). For the laboratory testing, several kinds of disturbance, such as sample collection, transportation, and reprocessing, are involved. Thus, the stress around the soil samples completely changes and the results could not reflect the true state of the soil. For an in-situ
testing (Bachmann et al., 2006), it could measure the desired parameters of soil directly by utilizing the specific devices and avoids the disturbance mentioned above. Therefore, the results can reflect the actual soil characteristics to a large extent. Although the prevalent means of in-suit testing methods is the large-scale field shear test, it is difficult to widely put it into practice due to high cost, low efficiency and especially the complex geological environment of the slope.

Borehole shear test (BST) is an in-suit testing method proposed by Handy and Fox (1967) for determining the shear strength parameters of soil. The test, which is essential the direct shear test in-situ, is conducted on the prepared borehole. The cohesion $c$ and internal friction angle $\phi$ of the soil are determined by a series test on the desired soil layer. As the process of the BST is straightforward and can be applied in a complex geological environment, some countries have succeeded in applying BST to obtain the shear strength parameters of different soil types, such as sand, silt clay, hard soil, residual soil and other kinds of soils with fine particles (Lutenegger et al., 1979; Handy, 2008; Irigoyen and P.Coduto, 2015). Benefiting from the superiority characteristics of loess, i.e., good self-supporting and easy hole-forming, the BST has promising application to determine its shear strength parameters and evaluate the stability of loess slopes (Bechtum, 2012; Yu et al., 2016; Ballouz and Khoury, 2020).

This paper detailed the process of applying the BST to a typical loess slope in Shanxi province, China. Based on the improved Iowa Borehole Shear Instrument, a proper drilling technology has been planned and a series of tests have been carried out on the top and bottom sliding surface of the Chenyun village landslide. The data treatment processes and the results were discussed in detail.

2. Principles and methods of BST

2.1. Test principles

The improved BST device is shown in Figure 1. The aim of the test is to determine the internal friction angle and cohesion by inducing a shear failure on both sides of a pre-drilled borehole. The process mainly involves four steps: 1) the shear head is lowered to certain depth; 2) the normal stress is applied to two symmetrical plates to enforce the teeth on them penetrating into the walls of the borehole; 3) the normal stress is held for a period of time (5-10 min) to allow for any excess pore water pressure to dissipate; 4) an upward shear force is applied sufficiently to the shear head by hand-crank and to fail the soil.
Figure 1. Schematic diagram of BST

It is necessary to conduct at least 3 shear tests at the same location. For each test, under certain normal stress $\sigma$, the maximum shear $\tau$ at failure is recorded. Each pair of $\sigma$ and $\tau$ 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.

2.2. Test apparatus

The typical BST apparatus mainly contains shear head, test platform, worm gear system, and air pump. Compared with the convention Iowa BST, the improved BST was equipped with normal and vertical displacement sensors, an acquisition system, and a force sensor to measure the shear stress. These additional devices could make the testing process more visible and controllable. Moreover, several high-strength aluminum alloy rods with a length of 1m were processed and approximately 50m long trachea was replaced for deep testing. Meanwhile, for relatively hard soil in-situ, the high-pressure shear plate was used. Additionally, by cutting the 76.2*762 mm thin-walled soil sampler inward, the minimum disturbance will result in the loess formation. The overall field measure instruments are presented in Figure 2. During the test, the shear rate is about 0.05 mm/s and the normal pressure ranges from 0 to 550 kPa.
2.3. Test methods

(1) Drill a borehole: Drill a relatively smooth hole 76mm in diameter with a 3-inch Shelby tube cooperated with a drilling machine.

(2) Install instruments: The shear head is lowered to desired depth in the hole through the high-strength aluminum alloy rods. The air pump is connected to the instrument control panel, and the normal and vertical displacement sensors and data acquisition equipment are initialized thereafter.

(3) Apply normal stress: Depending on the degree of hardness of the soil, the normal stress of the first stage should be applied properly and the consolidation time should be 10~20min. Combined with the displacement indicators, the increments of normal stress and consolidation time are reasonably set to judge whether the shear plates are fully expanded.

(4) Apply shearing stress: Turn the hand-crank clockwise to apply shear stress and record the maximum value from the force sensor.

(5) Return shear stress to zero: Unloading the shear stress to return the shear head to its origin place before applying the subsequent normal stress.

(6) Data processing: Repeat at least four or five tests and plot the corresponding data in the coordinate system $\sigma-\tau$. According to the Mohr Coulomb strength criterion, $\tau = \sigma \tan \varphi + c$, the slope of the line is the friction angle $\varphi$, and the intercept is the cohesion $c$ (Lutegger, 1987).

3. Engineering application

3.1. Engineering situation

Chenyun village landslide is situated on the right bank of Jinghe River, Taiping Town, Konggang New city, Xixian New Area, Shaanxi Province, as shown in Figure 3. It is a shallow medium-sized landslide induced by river erosion and human irrigation on the Loess Plateau. This landslide is an old-type landslide with low moisture content, high density and strong cohesive strength. As it is a challenging task to make a drill and collect high quality soil, the borehole shear apparatus was used to test the shear strength parameters in-suit in parallel with the geological survey. The test points were located top and bottom sliding surface of the landslide. The study focused on the effects of several factors, such as initial normal stress, stress increments and consolidation time on normal and shear displacement.
3.2. Influence of the normal stress

The normal stress directly affects the accuracy of the test results. If the applied stress is too low, the shear plates cannot penetrate into the soil and the shear occurs on the surface of the borehole. If too much pressure is applied, the soil will be damaged. In both cases, the actual shear strength cannot be measured. Therefore, the initial normal stress and the increment should be selected appropriately for different soil types. For this project, the relationship between normal stress and displacement at different depths was tested, as shown in Figure 4.

![Figure 3. Geographical location of test site](image)

![Figure 4. Relationship of normal stress-displacement](image)
The results show that the normal stress-displacement curves mainly consist of two parts. The nonlinear section starts at 0kPa and ends at initial normal stress, the slope of the curve gradually increases with increasing displacement. After the turning point, the distribution of scattered points is approximately linear, indicating that the soil may be in the elastic stage.

### 3.3. Consolidation time

The consolidation time of BST determines whether the shear plates are in close contact with the borehole wall and the excess pore pressure is fully dissipated. It plays an important role in the success of the test (Lutenegger and Tierney, 2010). The relationship between consolidation time and displacement of the shear plate under different normal stress was studied, as shown in Figure 5.

![Figure 5. Relationship of consolidation displacement-time](image)

It can be seen from the results that the consolidation time-displacement curves under each normal stress initially increases sharply, then deviate, and eventually tend to be stable, showing a typical type of bending line. The tests suggest that for the first stage of load, 10 minutes is sufficient while for the subsequent stages, 5 min may meet the test requirements.
3.4. Shear stress-displacement relationship
The relationship between shear stress $\tau$ and displacement $s$ is shown in Figure 6 (a) and (b). When the normal stress is low, the shear stress-displacement curves present an ideal elastic-plastic type. With the increase of normal stress, the curves show obvious peak values and perform a kind of strain-softening deformation, which is in consistent with the laboratory shear test of undisturbed loess (Ying et al., 2006). The distribution generally consists of three stages.

1. The elastic deformation stages. As the pulling force is applied slowly, the shear displacement increases and the contact between soil particles tighten. The soil is in a nearly linear elastic deformation phase.

2. The plastic deformation stage. With the continuous tensile force application, the curves arrive at elasticity-plasticity transition point. After that point, the shear stress-displacement curves deviate from the straight-lines. Micro cracks begin to initiate, propagate and finally lead to a shear failure. Meanwhile, the shear force reaches the peak value.

3. The plastic yielding stage. After the peak value, the shear stress obviously decreases and the curve moves downward. With the increase of the shear displacement, the curve tends to a stable stage and the residual strength is obtained.

![Shear stress-displacement curves of BSTs under different normal stress](image1.png)

![Shear stress-displacement curves of BSTs under different normal stress](image2.png)

Figure 6. Shear stress-displacement curves of BSTs under different normal stress
3.5. Shear strength parameters

Figure 7 shows 11 soil shear strength parameters tested by borehole shear test and the corresponding Mohr-Coulomb failure envelopes obtained by linear regression using least square method. The details of the data are summarized in Table 1.

![Figure 7. The results of BST in loess slope](image)

### Table 1. Summary of the testing results and Mohr-Coulomb equations of BSTs

| Test group | Borehole | Soil layer | Depth, m | Friction angle φ,° | Cohesion c, kPa | Fitting coefficient, \( R^2 \) | Mohr-Coulomb fitting equations |
|------------|----------|------------|----------|-------------------|----------------|---------------------------|-------------------------------|
| L1         | ZK2-3    | Silty clay | 2.30     | 26.23             | 10.26          | 0.993                     | \( \tau = 0.4924 \sigma + 10.26 \) |
| L2         | ZK2-3    | 4.30       | 26.43    | 35.40             | 0.994          | \( \tau = 0.4967 \sigma + 35.40 \) |
| L3         | ZK2-3    | 7.30       | 22.27    | 87.35             | 0.987          | \( \tau = 0.4093 \sigma + 87.35 \) |
| L4         | ZK2-4    | 2.00       | 42.84    | 37.38             | 0.996          | \( \tau = 0.9267 \sigma + 37.38 \) |
| L5         | ZK2-4    | 5.30       | 34.53    | 39.01             | 0.996          | \( \tau = 0.6877 \sigma + 39.01 \) |
| L6         | ZK2-4    | 7.75       | 43.25    | 23.30             | 0.988          | \( \tau = 0.9399 \sigma + 23.30 \) |
| L7         | ZK2-5    | 1.70       | 40.73    | 15.78             | 0.994          | \( \tau = 0.8605 \sigma + 15.78 \) |
| L8         | ZK2-5    | 2.60       | 36.64    | 33.61             | 0.983          | \( \tau = 0.7433 \sigma + 33.61 \) |
| L9         | ZK2-5    | 4.00       | 44.45    | 28.96             | 0.998          | \( \tau = 0.8413 \sigma + 28.96 \) |
| L10        | ZK2-5    | 4.55       | 41.67    | 17.10             | 0.994          | \( \tau = 0.8894 \sigma + 17.10 \) |
| L11        | Clayey silty | 6.00     | 39.52    | 8.60              | 0.999          | \( \tau = 0.8243 \sigma + 8.60 \) |

As shown in Figure 7 and Table 1, the measured intercepts (cohesion) of L1 and L11 are low. Combined with field analysis, the L1 was tested at a depth of 2.3 m over a sliding surface, where the soil is backfilled with loose soil and construction wastes. The L11 is at the depth of 6.0 m at the bottom of the slope, where the stratum is clayey silt, so the \( c \) value is lower. For the L3 tested at the depth of 7.3 m below sliding surface, the \( c \) value is increasingly high while friction angle \( \phi \) is relatively low, reaching 87.35 kPa and 22.27. Nevertheless, based on all test results, the linear regression coefficients
$R^2$ of 11 datasets are generally greater than 0.98, and the test results are more reliable to truly reflect the in-situ soil resistance index.

4. Discussions and suggestions

(1) The cohesion $c$ of some test points is higher than that of similar soil layers. Combined with the previous paper, it is inferred that the magnitude of initial opening pressure and pressure increment applied are too large, which results in the shear plates unable to penetrate into the fresh soil during the subsequent compression processes. Thus, the shear plates may undergo friction shear on the original damaged soil surface.

(2) The initial normal stresses and stress increments applied in different types of soils should be distinguished. The initial opening pressure shall be slightly above the static earth pressure to ensure that the test soil in a normal state of consolidation. Furthermore, the increment of normal stress shall be selected appropriately so that the maximum stress does not exceed the ultimate bearing capacity of the soil, and thus the soil will not be destroyed in advance. On the basis of this study, future work needs to conduct on the normal stress-strain relationship to acquire the entire soil process curve from elastic deformation to failure to provide guidance for normal stress determination.

(3) For this project, the consolidation time for the first stage and the stages thereafter should be 10 min and 5 min, which can meet the test requirements and ensure the success of the test. In this way, the test time and the cost of the project can be reduced. Moreover, the conclusions made can serve as a reference for further borehole shear tests of different engineering projects with similar soil layers.

5. Conclusion

(1) Based on the original Iowa borehole shear apparatus, normal and vertical micro-displacement sensors were added to make the test more visible and controllable, as well as the continuous connecting rod, the long gas tube and high-pressure shear plates. Thus, the modified BST apparatus can be applied in great depth and high-strength loess layers.

(2) This study has proposed an appropriate borehole forming technology, which can be applied in the engineering projects with a complex geological environment. The proposed technology can significantly avoid soil disturbance and ensure the borehole's verticality, which improves the success of borehole shear test.

(3) Borehole shear test was applied for the first time to the loess slope. The reliable results have shown its potential value for determining the shear strength parameters of loess.

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