Triaxial shear strength of undisturbed unsaturated loess

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Abstract. The strength of unsaturated loess was explored with triaxial instrument for unsaturated soils. The test covered 3 different water contents of unsaturated loess and the saturated loess at initial confining pressures of 100 kPa, 200 kPa and 400 kPa. The matric suction and volume change were obtained during shearing procedure. Test results showed that the shear of saturated and unsaturated loess was strain-hardening with no obvious peak and contracted in volume. The matric suction during shearing was affected by both stress state and initial moisture content. The internal friction angle remained unchanged basically with variation of initial water content, and total cohesion decreases with an increase of initial water content, which can be expressed by an exponential expression.

1. Introduction

Loess accounts for about 9.3% of the area of earth land. In China the loess is mainly distributed in the Yellow River Basin. Loess is a kind of aeolian sediment, characterized by loose soil, strong structure, developed vertical joints, and subject to collapse and deformation when exposed to water. Collapsibility of loess is determined by its structural and historical causes, and its strength and deformation are closely related to moisture content. A large number of tests show that the shear strength of unsaturated soils (including unsaturated loess) varies with the change of matric suction. In various strength expressions for unsaturated loess, the influence of additional strength caused by matric suction is considered [1-2], and it is also recommended to consider the structural properties of loess [3]. Interestingly, different types of loess strength tests have reached some common conclusions, such as the internal friction angle of loess with different moisture content is basically close, and the effective cohesion increases linearly or exponentially with the increase of moisture content [4-8].

In the past, researches were focusing on the shear strength of unsaturated loess under controlled constant suction. A large number of failure cases showed the unsaturated soil ground or slopes failed under a variation of loads. In such cases, the unsaturated soil had constant water content but a varied suction due to deformation. Therefore, this paper focuses on the shear strength of unsaturated loess under constant water contents.

2. Test program

2.1 Physical properties of loess
The advanced triaxial apparatus for unsaturated soils (GDS) was used to study the unsaturated strength properties of undisturbed loess taken from Xianjiang Uygur Autonomous Region of China. The sample was taken at depth of 13.5 m to 14.0 m and then enveloped with plastic film and sealed with wax. The grain size distribution of the loess was shown in Figure 1. The specific gravity was 2.70, the liquid limit 29.8, and plastic limit 19.8.

The soil specimen was made by the following procedures. First, cut the undisturbed soil blocks into a soil sample in a diameter larger than 40 mm, then prepare the soil sample to the target water content by the water film transfer method; bury the soil sample in loose loess with the target moisture content, and let it stand for 7 to 10 days; finally, cut the soil sample to a specimen with a diameter of about 39.1 mm and a height of about 79 mm.

2.2 Test method

The strength of the undisturbed unsaturated loess was tested by four groups, corresponding to average degrees of saturation of saturated 100%, and unsaturated 45 %, 29 % and 16.7 %. Each group contains 3 specimens at mean net stresses (for unsaturated loess) or isotropic consolidation stresses(for saturated loess) of 100 kPa, 200 kPa and 400 kPa except for the 16.7% group where only 2 specimens were tested at mean net stresses of 100 kPa and 400 kPa.

Unsaturated loess tests were conducted with GDS unsaturated triaxial apparatus. The air intake value of the ceramic disk on the pedestal is 500 kPa. The axial translation method was applied to control the pore air pressures ranging from 100 kPa to 300 kPa according to the moisture content of the specimen. In order to prevent the rubber membrane from dilation, the confining air pressure was always kept with 5 kPa higher than the pore air pressure in this stage. After stabilization was attained on the specimen volume and the matric suction, the target mean net stress was applied in a double progressive stress values i.e. 25, 50, 100, 200 and 400. The loading rate was 30 min to 200 min/level according to the size of the applied stress. Then let stand and wait for the volume change to stabilize(According to ASTM 2432–2011 Standard test methods for one-dimensional consolidation properties of soils using incremental loading), and the stability time was not less than 1 day. It took 1 to 3 days for each level of applied stress to stabilize. The shear loading rate for unsaturated loess was controlled at 0.008 mm / min, i.e. 20% of axial displacement in 2000 min.

Saturated loess tests were tested with GDS dynamic triaxial apparatus which was suitable for common triaxial shear test. After the specimen was installed on the pedestal, it was first subjected to several back pressure saturation procedures with a B value of 0.95 or more. The effective consolidation stresses were also applied in a double progressive stress procedure. Consolidation duration for each load increment should be judged by plot the volume change on log scale to obtain an end of primary consolidation. These shear tests were kept under undrained condition. The axial loading rate was determined according to ASTM 4767–95 Standard test method for consolidated undrained triaxial compression test for cohesive soils. For saturated soil specimen under 400-kPa virgin effective stress, the axial load rate was controlled to attain 25% of axial strain within 450 min.
3. Test result

3.1 Strength of saturated loess
All the saturated loess specimens had no obvious peak on the deviator stress curve and were considered as failure when the axial strain attained 15% (not presented here). Figure 2 shows the stress paths, Mohr stress cycle and strength envelope for saturated soils. The shear stresses increased by a slope until the axial strain reached 15%. It is concluded that the cohesion of the saturated sample is 1.7 kPa and the effective internal friction angle is 22.5°.

![Figure 2. Test result for saturated loess: (a) Effective stress paths; (b) Mohr stress cycles and strength envelope.](image)

3.2 Strengths of unsaturated loess
In the process of shearing, all the unsaturated loess specimens tended to contract and not dilation was observed in volume, and no obvious peak was observed on the deviator stress curve so it was deemed as the failure for the axial strain of 15%. The test results of unsaturated loess with an initial degree of saturation of 29% are shown in Figure 3. In Figure 3(a), it can be seen that the suction increased during shearing, except for the 400-kPa initial confining net stress case in which it slightly reduced. It was difficult to explain this imharmony. Since the shearing caused a contraction in volume it seemed that the suction should decreased with an increase of relative water content. However the development of suctions of other groups of unsaturated loess was all similar to that of this group.

It can be seen that at higher water content, the suction would increase during the shearing at lower net confining pressures (200 kPa or less), but decrease at higher net confining pressure (400 kPa or more). At lower water contents, the suction will increase even when shearing at higher net confining pressure stress (400 kPa or more). More researches should be conducted to explore the shearing mechanism of unsaturated loess.

The envelope for unsaturated loess was similar to that for saturated loess as shown in Figure 3(b), which can be expressed by a linear relation. By arranging the shear data and drawing Mohr stress circles, it was found that the strength of loess with the same initial moisture content can be expressed by a straight line on the plane of net confining pressure stress versus shear strength, which is consistent with the experimental results[9]. Therefore, the strength of loess can be expressed by the following equation:

$$q_f = \xi + (\bar{p} - u_s)_t \tan \omega$$

(1)

where \(\xi\) is the total cohesion, \(\omega\) is the internal friction angle, \((\bar{p} - u_s)_t\) is the average net stress on at the time of failure, and \(q_f\) is the shear stress at failure. In this equation, \((\bar{p} - u_s)_t\) would be replaced with average effective stress for saturated soils.
According to the strength parameters of unsaturated loess, the total cohesion increased obviously with an increase of initial degree of saturation (moisture content), from 1.7 kPa to 37.2 kPa, as shown in Figure 4(a), and the internal friction angle also increases from 22.5º to 27.9º, as shown in Figure 5(b). In contrast, the internal friction angle changed in a small variation, which is basically consistent with the experimental phenomenon \cite{5}. The change of cohesion with saturation can be represented by a fitted exponential expression:

$$\xi = 67.133e^{-0.038 \frac{S_r}{100}}$$  \hspace{1cm} (2)

An expression for unsaturated soils was also proposed by Frendlund\cite{10}:

$$\tau_f = c' + (\sigma - u_r) \tan \phi' + (u_a - u_w) \tan \phi^b$$  \hspace{1cm} (3)

where $c'$ is the intercept of shear stress for the extension of Mohr stress cycle envelope; $(\sigma - u_r)$ is the net normal stress on the failure surface at the time of failure; $\phi'$ is the internal friction angle related to the net normal stress state variable; $(u_a - u_w)$ is the matrix suction on the failure surface at the time of failure; and $\phi^b$ indicates the rate at which shear strength increases with suction.

An additional variable $\phi^b$ is introduced in Equation (3) to consider the contribution of matrix suction to shear stress.
Comparing Equations (3) and (1), it can be found that the total cohesion in Equation (1) includes the strength addition term caused by effective cohesion and matrix suction in Equation (3). By using the parameters of internal friction angle of saturated loess and effective cohesion matrix suction equal to zero, all unsaturated shear data are sorted out and analysed, and statistics are made by using the principle of least square method. When the least square variance is the minimum, the suction influence angle is 27.97º.

4. Conclusions

The strengths of undisturbed unsaturated and saturated loess were explored and the shearing characteristics were observed. The following conclusions were drawn:

1) The shear of saturated and unsaturated loess is strain-hardening with no obvious peak with a contraction in volume.

2) The matric suction during shearing is affected by both stress state and initial moisture content. It can be seen that at higher water content, the suction would increase during the shearing at lower net confining pressures (200 kPa or less), but decrease at higher net confining pressure (400 kPa or more). At lower water content, the suction will increase even when shearing at higher net confining pressure stress (400 kPa or more).

3) The strength envelope of unsaturated loess with the same saturation can be represented by a straight line. The internal friction angle remains unchanged basically with variation of initial water content, and total cohesion decreases with an increase of initial water content, which can be expressed by an exponential expression.

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