True Triaxial Study on Aeolian Sand Subgrade

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Abstract. The drained shear tests of aeolian sand in Tengger Desert were carried out by using the British GDS true triaxial apparatus, and the shear strength and stress-strain relationships of aeolian sand were studied under the conditions of constant average principal stress and different intermediate principal stress coefficients. The test results showed that the variation trends of principal strains in the three principal stress directions were correlated with the variation of the intermediate principal stress coefficient, and the stress-strain relationships in the three principal strain directions were hardening type. With the increase of intermediate principal stress coefficients, the shear strength of the specimen decreased, and the peak value of shear strength was the lowest when \( b = 0.8 \).

1. INTRODUCTION
Aeolian sand has uniform particles, small particle size, good stability and strength, and has been used in projects such as aeolian sand concrete, aeolian sand mortar, pavement structure and subgrade construction [1]. Especially in desert areas, aeolian sand is an excellent roadbed filling material, which can solve the problem of the lack of roadbed materials.

In order to make better use of aeolian sand in practical projects, researches have been carried out on the fundamental properties of aeolian sand. Yuan et Al. [2], Shu et Al. [3], and Yang et Al. [4] have studied the compaction characteristics of aeolian sand. It was found that the compaction curve of aeolian sand was “S” shape, and the best compactness was achieved when the moisture content was zero or the optimum water content.

The mechanical properties of granular materials such as aeolian sand are mainly studied by triaxial tests. Many triaxial tests on sand showed that the intermediate principal stress coefficient \( b \) was closely related to the strength of sand. Wang and V. Lade [5] studied the strength of Santa Monica Beach sand. The results showed that the strength of the specimens increased with the increase of \( b \)-value, and then remained unchanged, and decreased slightly when \( b = 1.0 \). He and Jiang [6] simulated true triaxial drained tests of energy soils with different \( b \)-value by discrete element method, and found that the changes of principal stress and principal strain were well correlated with \( b \). In the triaxial case, the stress–strain curve varies with the properties of the sand and the stress path. The true triaxial tests of clay and coarse-grained soil were studied by Liu et Al [7] and Shi et Al. [8] respectively, which minor principal stress and \( b \)-value were kept constant. The results showed that the failure stress state of clay was close to the Mohr-Coulomb criterion, while the relationship between \( b \) and friction angle in coarse-grained soil was not in accordance with the failure criterion such as Lade-Duncan. Li et Al [9] analyzed the stress-strain relationship of aeolian sand under different intermediate principal strain coefficient, and found that the peak value of generalized shear stress increased with the increase of intermediate principal
strain coefficient. Liu et al. [10] carried out a series of true triaxial tests under constant average principal stress with different \( b \) by using the discrete element method, the test results showed that the shear stresses of granular materials under different three-dimensional stress paths were different in peak and critical states.

Although many researches have been carried out on the sand under true triaxial condition, there were few of them aimed at aeolian sand. Therefore, a series of drained shear tests with constant average principal stress and different intermediate principal stress coefficients under true triaxial stress were carried out to study the stress-strain characteristics and shear strength of aeolian sand in Tengger Desert. It could provide reference for the construction of desert highway.

2. INTRODUCTION TO THE GDS TRUE TRIAXIAL APPARATUS

The British GDS true triaxial apparatus mainly consists of mainframe, pressure chamber, pressure controller and GDSLab data acquisition system, as shown in Fig. 1. The host uses high-speed servo motor to control the loading of the major principal stress \( \sigma_1 \) and the intermediate principal stress \( \sigma_2 \) independently, which can realize the fast load of multiple dynamic and static stress paths. The minor principal stress \( \sigma_3 \) is controlled flexibly, and it is loaded by the pneumatic controller. The test data are collected and analyzed by GDSLab system.

3. TEST PROCEDURE

3.1. Basic characteristics of the specimen

The aeolian sand selected for the test was taken from the central area of Tengger Desert in Shapotou, Ningxia, China. The grain size distribution of aeolian sand specimen range from 0.075 to 0.5 mm, the maximum dry density is 1.62 g/cm\(^3\), the minimum dry density is 1.36 g/cm\(^3\), and the natural density is 1.52 g/cm\(^3\). The water content of aeolian sand is 0.14\% and the void ratio is 0.7 [9].

According to the size of specimen in GDS true triaxial apparatus, the total mass of aeolian sand for dense sand specimen with relative density \( D_r = 0.7 \) is 1291g. The expression for the relative density \( D_r \) is:

\[
D_r = \frac{e_{\text{max}} - e_0}{e_{\text{max}} - e_{\text{min}}} = \left(\frac{\rho_d - \rho_{\text{dmin}}}{\rho_{\text{dmax}} - \rho_{\text{dmin}}}\right) \rho_d
\]

where \( e_{\text{max}} \) is the void ratio of sand in the loosest state. \( e_0 \) is the void ratio of sand in its natural state. \( e_{\text{min}} \) is the void ratio of sand in its densest state. \( \rho_{\text{dmin}} \) is the dry density of sand in its loosest state. \( \rho_{\text{dmax}} \) is the dry density of sand in its densest state. \( \rho_d \) is the dry density of sand in its natural state.

3.2. Specimen preparation and loading

The specimen size is 75mm \( \times \) 75mm \( \times \) 150mm. In order to ensure the stability of the test, the height error of the specimen is generally controlled not to exceed 3mm, that is less than 2\%. The sand-dropping method was used to make the specimens. Loaded the aeolian sand into the specimen preparation device in 10 layers, and ensured that each layer had the same height and uniform particles. It was necessary to apply 10kPa negative pressure to fix the sand specimen with a vacuum pump, and then took down the
specimen preparation member to load the sand specimen. Specimen preparation and installation are shown in Fig. 2.

![Specimen preparation](image1)

![Specimen installation](image2)

**Figure.2** Specimen preparation and installation

### 3.3. Saturation and consolidation

The purpose of saturation test is to change the specimen from a triphase to a biphase. The saturation test was divided into two steps, namely hydraulic saturation and back pressure saturation. The hydraulic saturation time was 30 minutes in the test. When the volume of water flowing out is 2 times of the specimen and there is no gas in the water, the head saturation is completed. Then the step back pressure saturation was carried out until the saturation reaches the test requirement.

The degree of saturation of the specimen is determined by pore-water pressure coefficient $B$. If $B \geq 0.95$, saturation is over, if not, continue to increase back pressure until $B$-value meets the test requirement.

After the saturation test, the specimen was isotropic consolidated. Consolidation is completed when the volume of water discharged from a sand specimen is less than 1% within 30 minutes. In this test, the consolidation time was about 2 hours.

### 3.4. Load program

In order to study the shear strength and stress-strain relationship of aeolian sand in Tengger Desert under different $b$, six types of test schemes were set up. Table 1 shows six loading schemes when the average principal stress $p$ is constant and the $b$-values are 0, 0.2, 0.4, 0.6, 0.8 and 1 respectively. The principal stress was controlled by two rigid loading plates and a flexible loading surface, and the value of $b$ was kept constant during the loading process.

The loading path was controlled by stress, and $b$ was controlled by the proportion of stress distribution in three orthographic directions. In accordance with the definition of $b$, the expression is:

$$b = \frac{\sigma_3 - \sigma_1}{\sigma_1 - \sigma_3}(0 \leq b \leq 1)$$  \hspace{1cm} (2)

The expression of the average principal stress $p$ is

$$p = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$$  \hspace{1cm} (3)
where $\sigma_1$ is the major principal stress, $\sigma_2$ is the intermediate principal stress and $\sigma_3$ is the minor principal stress. By using the formula (2) and formula (3), the true triaxial tests with different $b$ could be controlled theoretically.

| $b$ (min) | Time | $\Delta \sigma_1$ (kPa) | $\Delta \sigma_2$ (kPa) | $\Delta \sigma_3$ (kPa) | Loading Method |
|-----------|------|-------------------------|-------------------------|-------------------------|----------------|
| 0         |      | 0.1                     | -0.05                   | -0.05                   | According to formula (2) and formula (3), the target values of each principal stress are set by determining the intermediate principal stress increment $\Delta \sigma_2$ and the minor principal stress increment $\Delta \sigma_3$, that is, the stress path of constant $b$ and $p$ is loaded. |
| 0.2       | 0.1  | -0.0333                 | -0.0667                 |                         |                |
| 0.4       | 240  | 0.1                     | -0.0125                 | -0.0875                 |                |
| 0.6       |      | 0.1                     | 0.0143                  | -0.1143                 |                |
| 0.8       |      | 0.1                     | 0.05                    | -0.15                   |                |
| 1         |      | 0.1                     | 0.1                     | -0.2                    |                |

4. RESULTS OF TRUE TRIAXIAL DRAINED TEST

Fig.3 is a three-dimensional $q$-$\varepsilon$ relationship diagram of different intermediate principal stress coefficients under the condition that the average principal stress is constant ($q$ is the generalized shear stress, $\varepsilon$ is the principal strain in the three principal stress directions). In all the tests, the stress-controlled loading path was adopted, and the intermediate principal stress coefficient and the average principal stress were kept relatively constant during the shear process.

In Fig. 3, it can be concluded that the three-dimensional $q$-$\varepsilon$ curve changes obviously with the difference of $b$. Taking Fig. 1 as an example, when $b = 0$, the major principal strain $\varepsilon_1$ is in the state of compression. At the beginning of loading, the curve is steeper, and the shear stress increases rapidly. With the increase of $\varepsilon_1$, the curve becomes slower, and the whole curve is hardening. The intermediate principal strain $\varepsilon_2$ and the minor principal strain $\varepsilon_3$ are drawn synchronously, which shows that the specimen is isotropic in the horizontal direction. Under different $b$-values, $\varepsilon_1$ is always in the state of compression and $\varepsilon_2$ and $\varepsilon_3$ are gradually different, where $\varepsilon_3$ is always in the state of stretch and $\varepsilon_2$ is transformed from stretching state to compressive state. When $b = 0.2$ and $0.4$, the $\varepsilon_2$ curve approximates to a straight line.
Fig. 4 is the $q$-$\varepsilon_1$ diagram with different intermediate principal stress coefficients. It can be drawn from the diagram that under the condition of constant $b$ and constant $p$ loading, except $b = 0.2$, the $q$-value of Tengger Desert sand increases rapidly at first and then increases slowly with the change of $\varepsilon_1$, and tends to be stable after reaching the peak value. The stress-strain relationships present a hardening type. Only when $b = 0.2$, with the increase of $\varepsilon_1$, the $q$-value increases first, then decreases gradually after reaching the peak value and finally becomes stable, and the stress-strain relationships shows softening type. Except $b = 1$, the peak value of $q$ decreases with the increase of $b$. Of all tests, the peak value of $q$ is the largest when $b = 0$ and the smallest when $b = 0.8$.

5. CONCLUSIONS
This paper took the aeolian sand in Tengger Desert as the research object, and the shear strength and stress-strain relationship of aeolian sand under the loading condition of constant $b$ and constant $p$ stress path were analyzed by using GDS true triaxial apparatus.

(1) The major principal strain $\varepsilon_1$ was always in a state of compression, the minor principal strain $\varepsilon_3$ was always in a state of stretch, and the intermediate principal strain $\varepsilon_2$ was gradually changed from a state of compression to a state of stretch. When $0.2 < b < 0.4$, there was a critical value $b^*$, which makes $\varepsilon_2$ neither stretching nor compressive. The stress-strain relationships in the three principal strain directions were hardening type.

(2) With the increase of the intermediate principal stress coefficient, the shear strength of the specimen decreased. In all tests, the peak value of $q$ was the highest when $b = 0$, and the peak value of $q$ was the lowest when $b = 0.8$. 
ACKNOWLEDGMENTS
This work was financially supported by the Key R&D Program of Ningxia Hui Autonomous Region Projects of International Cooperation and Exchanges (no. 2018DWHZ0084), Ningxia Science & Technology Innovation Leading Talent Project (no. KJT2019001), the National Nature Science Foundation of China (no. 51669027), and the National Key R&D Program of China (no. 2017YFC0504404), and these supports are gratefully acknowledged.

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