Experimental research on dilatancy characteristics of coarse-grained soils by triaxial compression test

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Abstract. Dilatancy is a basic behavior of soils which is closely related to strength and deformation behaviors of soils and makes soils significantly different from normal elastic materials. A large-scale triaxial compression testing machine was used to study the dilatancy characteristics of coarse-grained soils of earth rock dam. The results show that the confining pressure has a significant effect on the dilatancy of coarse-grained soils, the soil first shrinks and then expands under low confining pressure, and the soil mainly produces shear shrinkage deformation under high confining pressure. When the soil changes from shear shrinkage to dilatancy, the strain ratio of soil changes abruptly. Rowe dilatancy model can reflect the dilatancy deformation characteristics of coarse-grained soils. The parameter $K_f$ of the model tends to be constant with the increase of axial strain, and the parameter $K_f$ of coarse-grained soils is smaller when the confining pressure is larger.

1. Introduction

The volume change of soil under shear stress is called dilatancy, which is one of the basic characteristics of soil [1]. Different from the general elastic materials, the dilatancy of soil is very obvious, and the volume change caused by shear stress may be of the same order of magnitude as that caused by compressive stress, which cannot be ignored. The coarse-grained soils which is widely used in earth-rock dam filling is a kind of aggregate filled with soil particles of different sizes, shapes and properties. Due to the relatively large particle size of coarse-grained soils, the mechanism and characteristics of dilatancy and its influence on strength and deformation are different from those of sand and clay.

Several groups of triaxial compression tests on coarse-grained soils have shown that coarse-grained soils show an obvious dilatancy trend under low confining pressure. With the increase of confining pressure, the coarse-grained soils gradually transit from dilatancy to shrinkage until the dilatancy disappears [2-3]. The mutual occlusion between soil particles during shearing, as well as the overturning and rolling between particles, are the fundamental causes of soil dilatancy [4]. The dilatancy of coarse-grained soils is also affected by factors such as density [5], confining pressure [6], particle gradation [7], particle breakage [8], parent rock properties [9], and stress path [10]. Although the existing research results have pointed out the mechanism, law and influencing factors of dilatancy of coarse-grained soil, the dilatancy characteristics and quantitative description of soil under different stresses still need more in-depth research. Therefore, based on the conventional triaxial compression test, it is necessary to quantitatively analyze the dilatancy characteristics of coarse-grained soils from the strength and deformation characteristics of soil.
2. Triaxial compression test

2.1. Test instruments and test methods

The DJSZ-150 large-scale coarse-grained soils dynamic and static triaxial test machine was used in the test. The test machine included confining pressure servo system, dynamic and static loading system, pore pressure measurement system, volumetric strain measurement system and data acquisition system. The size of the sample was allowed to be Φ300 × 600 mm, the maximum axial load was 1500kN, and the maximum confining pressure could reach 3.0 MPa. According to the dry density, sample size and gradation of the test requirements, the soil required for the test is weighed, mixed evenly and filled in three layers. The test condition is consolidated drainage, shearing according to strain rate 1mm /min until the axial strain reaches 15 %.

2.2. Test material and test method

The test material is selected from the rock-fill of Daqiaopo reservoir in Lincang, Yunnan Province. Due to the limitation of the grain size and specimen size of the rock-fill, the indoor test required equal replacement of the original grade of the material for the scale reduction process, and the composition of the test material grade is shown in Table 1. The dry density of the sample is obtained from the relative density test, and the maximum dry density is determined by the shaking table test method, and then the minimum dry density is obtained by the method of the regulation. The dry density of the sample making is controlled according to the relative density Dr=0.9. In the triaxial compression test, the surrounding pressure is designed to be 200kPa, 400kPa, 600kPa, 800kPa and 1000kPa.

Table 1. Particle gradation composition of coarse-grained soils

| grading type | Percentage content of granules /% |
|--------------|----------------------------------|
|              | <2mm    | 2-5mm   | 5-10mm  | 10-20mm | 20-40mm | 40-60mm | >60mm |
| original     | 8.88    | 4.61    | 9.98    | 18.47   | 28.25   | 14.61   | 15.2  |
| Shrinkage    | 8.88    | 4.61    | 12.12   | 22.41   | 34.27   | 17.71   | -     |

3. Analysis of test results

3.1. Analysis of stress-strain characteristics

The curve of deviation stress-axial strain relationship of consolidation drainage test for coarse-grained soils is shown in figure 1. In figure 1, the stress-strain curve is not smooth and fluctuates locally. When the axial strain is less than 5%, the soil presents linear elastic deformation, and the initial elastic modulus of the soil increases with the increase of confining pressure. Under low and medium confining pressure (200, 400, 600kpa), the stress-strain curve of soil has a peak value, and after the peak value, there is an obvious trend of stress softening. Under the high confining pressure (800, 1000kPa), the stress-strain curves of soil show weak hardening characteristics. Until the strain reaches 15% failure, the stress increases, but the strength increases slowly after the strain is more than 9%. The reason is that there is almost no relative movement between particles in the initial stage of soil shear, and the main deformation is elastic deformation. After that, due to the close contact between particles, some particles roll and friction, which need to overcome the larger bite force and show higher shear strength. In low or medium confining pressure, the soil structure becomes loose and the shear strength remains unchanged or decreases slightly. When the pressure is high, the contact point of particles breaks, and the fine particles fill into the original pores, which makes the structure more compact and can still bear large stress.

3.2. Analysis of deformation characteristics

Volume strain of soil consolidation drainage test $\varepsilon_v$ and axial strain $\varepsilon_a$ relationship curve is shown in figure 2, and the volume reduction is positive in the figure. In figure 2, at the initial stage of axial
strain, the volume strain is positive and the soil is subject to shear shrinkage. With the increase of axial strain, the volume strain curve appears inflection point and develops to the direction of volume increase. When the confining pressure is 200 kPa and 400 kPa respectively, the volume strain of the soil becomes negative after the axial strain is 6% and 11%, and the dilatancy occurs. When the confining pressure is greater than 600 kPa, the soil does not show dilatancy, but shows shear shrinkage. Therefore, under low confining pressure, the soil first shrinks and then expands, while under high confining pressure, the soil mainly shrinks. The reason is that there are still a certain number of pores in the soil after isotropic consolidation and drainage. In the initial stage of shear, the axial load increases, the soil is compacted, the pore water is discharged, and the volume of soil decreases, resulting in shear shrinkage. With the increase of axial load, the particles roll and bite gradually, and the volume of soil presents the tendency of swelling. When the confining pressure is low, the radial stress limit of the sample is small, and the stiffness of the soil particles is large, so the mechanical action between the particles is more significant, and the volume of the soil changes strongly until the shear failure, and the soil presents dilatancy. The radial stress of the sample is limited greatly when the confining pressure is high. With the increasing axial load, the particles will break gradually in the rolling, friction and bite action. The broken small particles will be further filled into the large particle pores until the shear failure, and the soil still presents shear shrinkage.

Figure 1. Deviation stress-axial strain curve
Figure 2. Volume strain curve

The ratio of axial strain to volume strain is defined as the strain ratio. The figure 3 shows the variation of strain ratio under different confining pressures.

Figure 3. Variation of strain ratio under different confining pressures. (a) low confining pressure; (b) medium and high confining pressure

In figure 3(a), when the confining pressure is low (200, 400 kPa), the strain ratio begins to be positive and increases slowly with the increase of shear strain, reaches an extreme point, then suddenly changes, decreases to a negative value, and finally slowly decreases, and gradually tends to a stable negative value. The location of the mutation point is consistent with the axial strain of the soil in figure 2. Therefore, the mutation point can be defined as the critical point of the soil from shear shrinkage to dilatancy. The volume strain of soil is composed of axial strain and lateral strain. At the initial stage of the test, the soil sample mainly produces axial strain, and the lateral strain is small, so
the strain ratio increases gradually, and the soil sample is mainly shear shrinkage. When the axial deformation develops to a certain extent, the lateral strain increases gradually, and the rolling between particles is more intense. The volumetric strain is mainly dilatancy. At this time, the strain ratio suddenly changes to a negative value, and the pores of soil particles show the phenomenon of inverted water absorption. Analysis of figure 3(b) shows that under high confining pressure (600, 800, 1000kPa), the strain ratio first decreases and then increases with the increase of shear strain, and the strain ratio is always positive, and the soil sample presents shear shrinkage state. The larger the confining pressure is, the more slowly the soil strain ratio increases.

3.3. Analysis of Rowe dilatancy model

The research on soil dilatancy is mostly based on Rowe dilatancy model, and mainly focuses on sand, while the research on coarse-grained soil is relatively less. Therefore, the applicability of Rowe dilatancy model for coarse-grained soil needs to be further analyzed. Under the condition of conventional triaxial compression test, the Rowe dilatancy equation can be expressed as follows:

\[
\frac{\sigma_1}{\sigma_3} = 2K_f \left( -\frac{d\varepsilon_1}{d\varepsilon_3} \right)
\]  

(1)

Where \( \sigma_1 \) is large principal stress, \( \sigma_3 \) is small principal stress. \( K_f \) is Rowe dilatancy parameter. \( d\varepsilon_1 \) is axial strain increment. \( d\varepsilon_3 \) is lateral strain increment.

The expression of \( K_f \) can be obtained by formula (1), giving:

\[
K_f = -\frac{\sigma_1 d\varepsilon_1}{2\sigma_3 d\varepsilon_3}
\]  

(2)

According to equation (2) and the test data, the relationship between the parameter \( K_f \) of Rowe dilatancy equation and the axial strain can be obtained, as shown in figure 4.

![Figure 4. Relationship between dilatancy parameters \( K_f \) and axial strain](image)

In figure 4, the parameter \( K_f \) of Rowe's dilatancy equation is discretized at the initial stage of shear (\( \varepsilon_3 < 3\% \)). This is because Rowe's dilatancy model reflects the irreversible sliding deformation between particles, and the soil is similar to elastic deformation at the initial stage of loading deformation, and there is particle breakage phenomenon. With the increase of axial strain, the dispersion of parameter \( K_f \) decreases, and when the axial strain exceeds 5\%, the parameter \( K_f \) shows significant normalization, which is characterized by the close filling between coarse-grained soils particles, and the deformation energy of coarse-grained and fine-grained soil gradually develops harmoniously. On the other hand, the Rowe dilatancy parameter \( K_f \) of coarse-grained soils is smaller when the confining pressure is larger. Therefore, Rowe equation which reflects the dilatancy of soil can be used to analyze the deformation characteristics of coarse-grained soils.

4. Conclusions
(1) Under the condition of low and medium confining pressure, the strength characteristics of coarse-grained soils tend to soften. Under high confining pressure, the stress-strain curve of coarse-grained soils is hardening.

(2) The coarse-grained soil presents a significant dilatancy trend in the shear process. Under low confining pressure, coarse-grained soil first shrinks and then expands. Under high confining pressure, coarse-grained soil mainly produces shear shrinkage deformation.

(3) Rowe dilatancy equation can describe the dilatancy of coarse-grained soils. When the shear strain of coarse-grained soils is over 5%, the Rowe dilatancy parameter $K_f$ has the characteristic of normalization.

(4) Understanding the variation of dilatancy of coarse-grained soil and the relationship between dilatancy and stress-strain properties has important application value for further understanding the engineering characteristics of coarse-grained soil and providing reasonable basis for engineering analysis.

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