Experimental study on the shearing and crushing characteristics of talus-like rock mass

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Abstract. Talus-like (T-L) rock mass is a special kind of engineering material in the nature, which owns a mixed fabric of coarse rock blocks and fine grinded rock powder. The basic mechanical properties of T-L rock mass are difficult to know due to its special composition and structure. This paper carried out a series of large-scale direct shear tests on the T-L rock mass collected in site considering four normal pressure levels. The shearing characteristics and the associated block crushing phenomena were analysed. The shear strength of the T-L rock mass increased as the normal pressure increased. The T-L rock mass had a large internal friction angle but a small cohesion. The shear stress-displacement curves can be divided into three stages: material densification, shear failure and plastic flow. The T-L rock mass showed obvious dilatancy under a low normal pressure of 50 kPa, but behaved contractively when the normal pressure became larger than 50 kPa. This indicates that the T-L rock mass may have a loose mixed fabric structure, which can be easily compressed under large normal pressures. The sieving analyses showed that the grading curve of T-L rock mass shifted upwards after shearing, suggesting that external shearing under different normal pressures led to particle crushing and changed the grain composition. The particle crushing mainly happened to the grains larger than 10 mm, which caused the portion of grains larger than 10 mm to decrease and the portion of grains smaller than 5 mm to increase. Nonetheless, the portion of grains in the size range of 5-10 mm remained approximately unchanged. Three breakage indices were adopted to quantify the crushing characteristics of the testing materials, which all increased with increasing normal pressures.

1. Introduction
In the western China, the talus-like (T-L) rock masses were frequently encountered because of the complex terrain and complicated geological conditions. The T-L rock mass is a special kind of rock mass, which mainly consists of coarse rock blocks and fine grinded rock powder. The main characteristics of T-L rock mass are similar to the soil-rock mixture (SRM) or block-in-matrix rocks (bimrocks), which has been widely investigated [1]-[5]. Nevertheless, the T-L rock mass possesses some distinct properties, which make its behavior different from other engineering materials. In general, the soil-rock mixture or bimrocks are mainly distributed on the surface of the stratum [6], with different parent rock types [1]. In contrast, the T-L rock mass may distribute in both the surface area and also deep in the ground. The matrix and composition of T-L rock mass are also similar. The coarse rock blocks are disintegrated from the parent rock, while the fine grinded rock powders are
generated by the squeezing, friction and corrosion of the parent rock or coarse rock blocks. The basic characteristics of the soil-rock mixture or bimrock have been studied comprehensively by laboratory testing. Lee et al. [7] used the large-scale shear test to determine the mechanical properties of crushed rocks sourced from local quarries in Korea, and conducted parametric studies on the influences of some factors on both the stress-strain characteristics and the crushing features. Coli et al. [8] carried out the in-situ shear test to investigate the strength properties of the Shale-Limestone Chaotic Complex bimrock, which shows that generally the bimrock has high friction angle and low cohesion. Large scale in situ direct shear tests were also presented by Xu et al. [9] and Zhang et al. [10] to study the shear strength of soil-rock mixture. Chang and Phantachang [11] performed shear test to investigate the shearing characteristics of gravel soils, and the results revealed that the shear strength of gravel soils depends on the packing condition of dominant particles and the inclusion of gravel content reduces the strength by no more than 20% compared to that of pure sand. Liu et al. [12][13] and Lei et al. [14] carried out the large scale direct shear tests to study the mechanical property and block breakage characteristics of soil-rock mixture, which all show that the shear properties and rock block breakage characteristics were related to the normal pressure, rock contents and water contents. Zhang et al. [15] performed in-situ shear test to obtain the realistic shear strength parameters of the filling soil-rock mixture, and they indicated that the strength is related to both the volumetric block proportion (VBP) and block strength. Although the aforementioned studies provide informative references to the mechanical characteristics of mixed geomaterials, the T-L rock mass shows obvious differences in constitution, feature and distribution area with those have been widely investigated. Thus, more efforts are needed to explore the behavior of the T-L rock mass.

The purpose of this study is to examine the shearing and crushing characteristics of the T-L rock mass. A series of large-scale shear tests were performed on the reconstituted T-L rock mass collected from the Tayi tunnel in Yunnan Province in the western China, considering four normal pressure levels. The basic shearing characteristics and strength parameter were analysed, and the amount of particle crushing of the samples under different normal pressures were also presented. The results may give some new insight to the tunnelling problem constructed in the T-L rock mass.

2. Testing apparatus and material

2.1. Testing apparatus

The shear test in this study was carried out by the large scale Interface Shearing Apparatus as shown in Figure 1. The shearing system consists of a shear box of dimensions \( L = 600 \text{ mm}, \ W = 400 \text{ mm}, \ H = 200 \text{ mm} \), vertical and shearing loading units, a steel frame, an oil pressure controller and a control/data acquisition system. The vertical load is exerted on the top of the shearing specimen by moving the rectangular loading plate down utilizing a high-precision oil cylinder with a capacity of 100 kN. A shearing load is applied to the lower shear box to the left while keeping the upper shear box fixed. During the test, all the load and displacement data are monitored through the load cell installed at the end of the loading system.

![Figure 1](image)

Figure 1. The large scale Interface Shearing Apparatus
2.2. Properties of testing material

The T-L rock mass collected from the Tayi tunnel of Jian-Ge-Yuan Highway Project in Yunnan province of the western China are used for the test, which is shown in Figure 2. Due to weathering, the T-L rock mass is very loose and has a lower water content of 1.51%. The density is 2.80 g/cm$^3$. In order to meet the maximum allowable particle size for a large shear box test, a maximum particle size of 31.5 mm was selected which is 1/6.35 of the box height, in line with the criterion proposed by Lee et al. [7].

![Figure 2. The tunnelling site and the collected T-L rock mass](image)

The original particle size distribution curves of the experimental material is shown in Figure 3. In the studies about the soil-rock mixture, the grain size 5 mm is usually used as the boundary value of soil and rock particles [12][13]. This is followed in this study, namely the particles larger than 5 mm are considered as the coarse particle, while the ones smaller than 5 mm are the fine particles. On this basis, the content of the coarse particles is about 57.90%.

![Figure 3. The original particle size distribution curve](image)

3. Testing procedure and program

The weight of material was used to determine the quantity of various sizes of materials required to achieve the grading curve in Figure 3 for preparing the specimen. Each of these fractions was mixed sufficiently and the mixture was then divided into several equal parts for compacting into three layers within the shear box. Each filling layer is about 70 mm deep and is compacted by tamping rammer. Initially, the specimen was subjected to the specified normal pressure and was then sheared horizontally until a 75 cm horizontal displacement was reached under a loading speed of 1.6 mm/min. Four different normal stresses, 50 kPa, 150 kPa, 250 kPa and 350 kPa, were used in this study. The shear-displacement relationships were analysed and the shear strength parameters were induced. After the tests have been
finished, the material was sieved again to get the grading curve. The particle crushing characteristics were analysed according to the difference between the grading curves before and after shear tests.

4. Testing results and discussion

4.1. Shear-displacement relationship

Figure 4 shows the shear-displacement relationships of the T-L rock mass for different normal stresses. It shows that the shear-displacement behaviour of T-L rock mass is nonlinear, inelastic and stress dependent. The shear-displacement curves can be divided into three stages: material densification, shear failure and plastic flow. At the beginning of shearing, especially under the larger normal stress conditions, the shear deformation is mainly caused by densification due to compaction of the internal voids and the flow of fine particles, leading to a linear stage. Then, with the increase of shear displacement, the translational and rotational motions of the coarse particles lead to closer contact with each other, which increases the resistance of the specimen and the shear stress gradually increase. At this stage, squeezing and rubbing of particles against each other may disturb or even destroy the particles as well as inner structures, leading to the particle crushing and the reductions of the growth rate of shear stress. Lastly, after the shear stress has reached the peak value, the displacement increases further at an approximately constant shear stress, leading to a plastic flow. Thus, the strain hardening is observed. The observed relationships show some differences with the previous studies for the SRM or similar geomaterials. Obvious strain softening was observed by Liu et al. [12] when studying SRM by large-scale shear tests. Although a similar plastic stage was also observed during the direct shear test by Zhang et al. [2] for SRM, Lee et al. [7] for crushed rocks and Chang and Phantachang [11] for gravel soils, the yield stress in their studies emerged at about 1/4 [2], 1/3 [12] and 1/2 [7][11] of the total shear displacements, which were earlier than the current study as shown in Figure 4.

4.2. Shear strength parameter

Figure 5 summarizes the shear strength parameters (i.e., cohesion c and internal friction angle φ) induced from the shear-displacement relations in Figure 4. It is noted that the T-L rock mass possesses a small cohesion of $c = 4.5583$ kPa, indicating that the T-L rock mass is a typical loose geological material without obvious inner bonding. This is in accord with the occasional collapse of the Tayi tunnel during construction. A large internal friction angle $\phi = 45.8012^\circ$ is obtained, which is close to the angle of repose of the tunnel collapse deposit, as shown in Figure 5. In general, the testing results correlate well with the in-situ observations, which will be useful for the interpretation of the actual tunnelling situation in site.
4.3. Dilatancy

The mixed geomaterials either dilate or contract during shearing. The dilatancy feature has a significant effect on the physical and mechanical properties. Figure 6 illustrates the vertical displacement-shear displacement curves at different normal stresses. As shown in Figure 7, the T-L rock mass showed obvious dilatancy under a low normal pressure of 50 kPa. The sample dilated initially but quickly became compressive. As the normal pressure increases, a large range of compressive displacement level is observed. The transition of contraction to dilation happens latter as the normal pressure increases. Dilation is mainly resulted from the translational and rotational of the coarse particles, which will be compressed as normal pressure increases. This indicates that the T-L rock mass may have a loose mixed fabric structure, which can be easily compressed under large normal pressures. The compressive behaviors are similar for samples under the normal pressures 150 kPa and 250 kPa. The compressive displacement of the 150 kPa case is even larger than that of the 250 kPa case at the second half of the test. This may be caused by the local inhomogeneity of internal structure in the preparing the specimen.

Figure 6. Vertical displacement-shear displacement curves.

Figure 7. Dilatation of T-L rock mass at the normal pressure 50 kPa.

Figure 8. Particle size distribution curves before and after tests.

Figure 9. Histogram of contents of each grain group before and after tests.
4.4. Particle crushing property

The close contact, translation and rotation of the coarse particle during the shear test may destroy the particles and lead to the particle crushing. The particle size distribution curves after each test are compared with the original one, as shown in Figure 8.

It is noted that the particle size distribution curves shifted upwards after each shear test, meaning that the grain composition was changed after the test. A larger normal pressure gives a higher particle size distribution curve, which indicates that large normal pressure increases the degree of particle breakage.

**Figure 10.** Changes of content of coarse particles.

Furthermore, the percentages of individual grain size before and after the shear test are illustrated in Figure 9. It can be found that the percentage of grain size larger than 10 mm decrease after test for each normal pressure level, while the content of grain size smaller than 5 mm increases for each normal pressure level. Nonetheless, the portion of the grains in the size range of 5-10 mm remained approximately unchanged. This result suggest that the particle crushing mainly happen to grains larger than 10 mm, which were mainly crushed to pieces smaller than 5mm. The proportion of the coarse particles (larger than 5 mm) remained after the shear test decreases with increasing normal stress, which can be better represented by the quadratic polynomial than a linear function as shown in Figure 10. The crushing behavior could be further quantified using the breakage indices. Three breakage indices, namely, the Marsal’s method [16], Hardin’s method [17] and Lade’s method [18] were adopted in this study.

**Figure 12.** Particle breakage at different normal stress.

The crushing behavior could be further quantified using the breakage indices. Three breakage indices, namely, the Marsal’s method [16], Hardin’s method [17] and Lade’s method [18] were adopted in this study.
Figure 11. Illustration for three different definitions of particle breakage indices, (a) Marsal’s method, (b) Hardin’s method, (c) Lade’s method.

Marsal’s breakage measure $B_g$ [16] corresponds to the largest increase in percentage of grains size in the grading curves after tests. Hardin [17] defined the breakage potential $B_g$ as the area between the line defining the upper limit of the silt size $D = 0.074$ mm, and the part of the particle size distribution curve before test with $D > 0.074$ mm. The total breakage $B_t$ is equal to the area between the particle size distribution curves before and after test. Thus, the relative breakage, which is Hardin’s final index, is defined as $B_r = B_t / B_g$. Lade [18] noted that $D_{10}$, which is the characteristic grain size with a weight percentage of 10%, is very important, and thus defined a relative breakage $B_{10} = 1 - D_{10f} / D_{10i}$, of which $D_{10i}$ is the grain size at a weight percentage of 10% of the original particle size distribution curve and $D_{10f}$ is that of the particle size distribution curve after test. The aforementioned definitions of these three indices are presented in Figure 11. The particle breakage of the T-L rock mass represented by the three indices were shown in Figure 12. It is clear from Figure 12 that higher normal stress results in greater particle crushing.

5. Conclusions
This paper carried out a series of large-scale direct shear tests to investigate the shearing and crushing characteristics of talus-like (T-L) rock mass. The major observations are summarized below.

1) The shear-displacement behaviour of T-L rock mass was nonlinear, inelastic and normal stress dependent. The shearing curves could be divided into three stages: material densification, shear failure and plastic flow. Strain hardening was mainly observed. The T-L rock mass possessed a large internal friction angle but a small cohesion, both could reflect the actual collapse characteristics of the tunnelling site.

2) An obvious dilatancy was observed when the normal pressure is 50 kPa. The behavior gradually changes to compression as the normal pressure further increases. This indicates that the T-L rock mass can be more easily compressed as the normal pressures increase due to its loose mixed fabric structure.

3) The particle crushing mainly happened to the grains larger than 10 mm, leading to the decrease of coarse grain proportion and the increase of fine grain proportions, while the grains in the size range of 5-10 mm remained almost unchanged. The adopted three typical particle breakage indices all increased as the normal pressure increased, which indicated that the degree of particle crushing increased with increasing normal pressures.

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