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Study on large scale direct shear test on soil-rock mixture with multiple grain grades in high fill slope engineering

Chao Zheng, Shuxiang Song, Nan Zhang, Kangwei Xiong[a, *]

Grandtop Environmental Service Co., Ltd., Guangzhou 510540, China

[a]1481421849@qq.com

Abstract: Soil-rock mixtures are multiphase natural geological materials composed of mineral particles of multiple grain sizes, and have significant natural characteristics of multiscale material groups. In order to investigate the shear strength characteristics and deformation failure characteristics of soil-rock mixtures with multiple grain sizes under in-situ conditions in fill engineering, samples of soil-rock mixtures with multiple grain sizes under in-situ conditions were prepared, and large-scale in-situ direct shear tests were conducted under natural and water-soaked conditions. The test results showed that the shear strength of soil-rock mixtures is relatively high, and after saturated by water immersion, its shear strength decreases significantly, mainly manifested in the decrease of internal friction angle while the cohesion remains basically unchanged. The cohesion of soil-rock mixtures with multiple grain sizes is mainly provided by the shear-breaking cohesion of coarse particles such as gravel in the soil-rock mixture, and its degree of exertion is controlled by the grading characteristics and particle morphology of the soil-rock mixture and affected by constraints. The reason for the significant decrease in shear strength of soil-rock mixtures with multiple grain sizes after water-soaked saturation can be explained as follows: the clay film covering the surface of coarse particles becomes soft after water immersion, resulting in a significant decrease in the sliding friction resistance between coarse particles and the clay film, as well as the occlusion friction resistance generated by the rotation transfer between coarse particles through the clay film interface.

Keywords: Large direct shear test; engineering in-situ test; soil-rock mixtures with multiple grain grades; shear failure surface

1. Introduction

With the rapid development of large-scale infrastructure, the construction of airports, high-speed railways, waste disposal sites, and waste incineration power plants has spread from flat areas to hilly and mountainous areas with complex geological and geomorphological conditions, resulting in the emergence of large-scale high-filling projects (Huang, et al., 2019). Large-scale filling projects usually use the method of "cutting mountains and filling valleys" to achieve earthwork balance to reduce project costs. The hilly areas of southern China are widely distributed with shallow soil-rock mixed weathered zones (Zuo, et al., 1994), and the shear strength parameters of soil-rock mixtures have a key impact on the stability of the filling slope and its supporting structure design. However, due to the complex material composition, irregular structural distribution, and difficulties in in-situ sampling of soil-rock mixtures, it is difficult to accurately determine their shear strength indicators. In general, in-situ large-scale direct shear and push-shear tests, indoor large-scale direct shear and triaxial tests can be used for determination (Dong, et al., 2005). The operation of in-situ large-scale shear tests is relatively complex, and the accuracy of test results is relatively low, which is prone to dispersion, but it can reflect the actual strength of test points on the construction site. Indoor large-scale shear tests are relatively simple to operate, and the boundary conditions are easy to control, resulting in relatively high accuracy of test results. However, using remolded soil to represent undisturbed soil may lead to significant errors in test results. For soil-rock mixture fill projects, soil-rock mixtures can be compacted layer by layer through certain compaction or tamping energy to form artificial fill slopes. The mechanical properties of compacted soil-rock fill materials are different from those of undisturbed soil materials on-site and those of remolded soil materials in the laboratory, and are affected by compaction energy and compaction methods. Therefore, using natural soil-rock mixture in-situ tests to determine shear strength indicators and using remolded soil-rock mixture laboratory tests to determine shear strength indicators cannot reasonably reflect the shear strength characteristics of compacted soil-rock mixtures in the original state of the project. In order to facilitate differentiation and analysis, for soil-rock mixtures used as fill slope materials through manual compaction, the state after on-site compaction is called the original state of the project, which refers to the actual state during construction and use. Currently, the research objects of shear strength of soil-rock mixtures mainly focus on mixtures composed of sand and gravel (Sun, et al., 2014, Wang, et al., 2014, Xu, et al., 2013), and a series of studies have been conducted on key factors affecting shear strength, such as gravel content (Tang, et al., 2018, Coli, et al., 2011, Yang, et al., 2016, Hamidi, et al., 2009) and particle size (Xia, et al., 2019, Zhao, et al., 2017,Simoni, et al., 2006, Weng, et al., 2013), particle breakage (Wei, et al., 2013, Li, et al., 2015), and moisture content (Xue, et al., 2015, Li, et al., 2007, Xu, et al., 2006), from both on-site in-situ tests and laboratory remolding tests, and have achieved consistent results. However, relatively little research has been conducted on the shear strength of soil-rock mixtures with skeleton components spanning six orders of magnitude, from micron-sized clay particles to tens of centimeter-sized rock blocks, in the original state of the project (Zhang, et al., 2016, Liu, et al., 2004).

The mineral particles of soil-rock mixtures span approximately six size scales, ranging from micron-sized clay particles to tens of centimeters of rock blocks, and interact with pore liquids and gases according to complex laws to form the structural properties of soil. They exhibit significant granularity, structuralist, and natural characteristics of cross-scale material groups. The nature of the interaction between particles plays a key role in the strength properties of soil-rock mixtures as a particle aggregate. The interaction is mainly achieved through physical-chemical effects on the particle interface, such as the extrusion and friction of particles, the adsorption of particles and water and gas, and the cementation of sand particles and colloidal particles and clay particles. There are a large number of interfaces within the soil-rock mixture, and different size soil particles and different phase materials interact through interfaces to form different aggregation and contact forms such as adsorption, cementation, and contact. Under external load, particles undergo translation and rotation, as well as interface sliding, to adapt to the geometric compatibility requirements of internal deformation, thus exhibiting plasticity and cohesion and internal friction, resulting in deformation and strength characteristics. The granularity and structural characteristics of soil-rock mixtures change accordingly during artificial compaction, causing special characteristics of their deformation and strength properties in the in-situ state of engineering. Therefore, this article prepares multiple-grain soil-rock mixture samples under different in-situ engineering conditions, conducts large-scale direct shear tests on six groups of 24 samples, analyzes and determines their shear strength characteristics and deformation failure characteristics under natural moisture content and saturated moisture content conditions, and provides a reliable basis for engineering design.

2. In-situ large-scale direct shear test of the project

To accurately simulate the in-situ state of soil-rock mixtures in the project, a hardened floor adjacent to the excavation area is selected in the project area. A sufficient number of soil-rock mixtures are excavated from the excavation area, and the soil-rock mixtures are compacted in layers using the same compaction equipment and compaction method as the subsequent fill engineering, forming a test embankment in the in-situ state of the project. Sample preparation and direct shear tests are conducted inside the embankment.

2.1 Test device

The large-scale direct shear test device mainly consists of three parts: the shear frame, the reaction force providing and load applying system, and the stress and displacement acquisition system. The model and specifications of the main components are as follows:

(1) Four shear frames: In order to accurately obtain the shear strength index of soil-rock mixtures and minimize the size effect, the minimum size of the shear frame for field tests should not be less than 5 times the maximum particle size in the soil-rock mixture. According to the field investigation and the particle size test of the soil-rock mixture, the size of the shear frame is selected as 500mm×500mm×250mm (length × width × height, internal clearance), and a steel plate with a thickness of 10mm is prefabricated in the factory. A customized 495mm×495mm square loading cover plate with a thickness of 15mm is used.

(2) Three pressure transmission plates: rectangular steel plates with a side length of 30mm×25mm and a thickness of 10mm are used.

(3) Loading jack 2 sets: measuring range 200kN, equipped with pressure gauge;

(4) 2 pressure sensors: one for shear direction and one for normal direction, with a measuring range of 200kN;

(5) Four displacement sensors: measuring range of 100mm, arranged at the four corners of the outer side of the rear plate of the shear box;

(6) One set of computer data acquisition system;

(7) Horizontal reaction pier: 1m×1m×1m precast concrete pier + 20 tons of excavator to provide horizontal reaction force;

(8) Vertical reaction pier: 4 prefabricated concrete cubes with a length of 2m×1m×0.25m, each of which can provide a normal stress of approximately 50kPa;

(9) Bearing pads: 4 steel pads, 2.0m×1.0m×0.005m, with 2 pads on each side of the groove;

(10) Rolling arrangement: 3 groups, 1 group on each side of the groove edge, 1 group between the vertical jack base and the sample cover plate, the rolling arrangement is sandwiched between 2 load-bearing plates (groove edges) or 2 pressure-transmitting plates (sample top), and a thin layer of lubricant is applied to the surface during installation;

(11) Other tools: level gauge, level ruler, mixing tools, crowbar, pickaxe, carrying basket, wide-mouth thin shovel, narrow-mouth thick shovel, sling, etc.

2.2 Test steps

(1) Determine the test site: Conduct a site survey and select the hardened floor adjacent to the excavation area as the test site.

(2) Preparation of the test embankment: According to the design requirements for the filling slope of the soil-rock mixture, the filling material is compacted in layers with a compacted thickness of 0.3m and a pre-compacted thickness of 0.35m. The compacting equipment is a 14-ton road roller. In order to measure the shear strength index of the soil-rock mixture in the original state of the project, before the test, a sufficient amount of soil-rock mixture is excavated from the excavation area of the project site. It is evenly mixed by an excavator, and then compacted in 3 layers with a 14-ton road roller according to the pre-compacted thickness of 0.35m per layer, as shown in Figure 1. The test embankment is 28m long, 0.9m high, with a top width of 4.0m and a bottom width of 5.8m. The edge slope ratio of the test embankment is controlled at 1:1.

Fig1. The test earth embankment preparation

Fig.2 The preparation of in-situ samples

(3) Sample excavation and finishing: After the rolling of the test embankment is completed, the excavation of the sample is carried out on the embankment. During sample preparation, the top surface of the embankment is firstly set out and positioned according to the preset sample position (see Figure 2), and then a narrow-mouthed thick shovel is used for manual excavation. While excavating the test trench, the sample is carefully and carefully finished into a 500×500×300mm sample as shown in Figure 2(b). At the same time, in order to minimize the rolling resistance of the rolling row, mortar is filled and leveled on the edge of the trench, and the levelness is calibrated by a level gauge, with the levelness controlled within 0.5cm. The whole process of this step is handled manually.

(4) Installing the shear frame: The shear frame is placed on top of the sample, and after the shear frame is placed steadily, the protruding part of the sample at the lower part of the shear frame is scraped off, and the shear frame is pressed down while being trimmed, so that the shear frame slowly slides down until it falls on the pre-shearing position of the sample. The disturbed topsoil of the sample is removed, and the levelness of the top surface of the sample is calibrated using a level ruler and a level gauge. The height difference of the entire sample plane is controlled within 0.5 cm, and the required flatness is achieved. After that, a cover plate is placed, as shown in Fig. 3. For samples that need to be saturated by immersion in situ, after the shear frame is installed, four water injection holes with a diameter of 2 cm and a depth of 25 cm are opened inside the sample, and the water injection holes are filled with coarse sand, as shown in Figure 3(b). Water is continuously injected into the holes for 20 hours to maximize the saturation state of the sample. During the shear process of the sample, water injection is maintained. After the shear process is completed, three points are taken on the shear surface of the embankment, the bottom of the sample, and the middle part of the sample to test the water content to determine its saturation. After the shear frame is installed, rollers are installed on the top surface of the sample cover plate and the groove edge, as shown in Fig.3.

Fig3. Shear box installation

(a) The assembly of the in-situ large scale direct shear apparatus

(b) The computer data automatic acquisition system

Fig.4 Photos of assembly of large scale direct shear apparatus

(5) Placing concrete counterforce prefabricated parts: The concrete prefabricated parts are deployed by a 20-ton excavator, and shear force counterforce piers are placed in the trench, and normal force counterforce blocks are placed on the top of the trench, as shown in Figure 4(a).

(6) Install the jack with pressure sensor: align the axis of the jack with the center point of the pressure plate.

(7) Installing displacement meters with sensors: Install four sensors (four in total) on the outer corners of the back plate of the shear frame, as shown in Figure 4(b).

(8) Direct shear test: Shake the jack to apply vertical load, and apply horizontal shear force after the normal stress remains stable. The shear force is applied using incremental loading method, and gradually and evenly applied according to the estimated shear strength classification (at least 10 levels) to control the shear rate. The shear rate is controlled at 0.1-0.3mm/s, and the shear rate is adjusted in time through the computer display of the displacement sensor. When the shear stress reaches a peak or the shear displacement reaches 30mm, the test is ended. After the test is over, disassemble the equipment, slowly lift the specimen with an excavator, and observe and record the damage pattern of the shear surface. The actual installation of large-scale direct shear test equipment on site is shown in Figure 4.

2.3. Test plan

To consider the influence of rolling times on the compactness of soil-rock mixtures, the test embankment was divided into three rolling areas, as shown in Figure 10. The north area was rolled 12 times per layer, the middle area was rolled 10 times per layer, and the south area was rolled 8 times per layer. The middle area was the shear test area. After each area was compacted, samples were taken for the determination of physical and mechanical indicators such as moisture content, density, specific gravity, grading, liquid-plastic limit, compatibility, and compactness.

To consider the effect of immersion on the shear strength of multi-grain soil-rock mixtures, the intermediate test area is divided into natural state sample area and saturated sample area, represented by TR and BS, respectively. The direct shear test of natural state samples is conducted first. To consider the possible dispersion of test results under in-situ conditions, three parallel tests are conducted on both natural state samples and saturated samples.

Considering the difficulty in providing a vertical load for the stacking height of prefabricated concrete blocks and the large number of samples, the maximum normal stress of the samples was set at 144 kPa (approximately 70% of the maximum normal stress provided by 4 concrete weights). The normal stresses for each set of tests were 36, 72, 108, and 144 kPa, and the normal stress was loaded in 3 levels. The large direct shear test scheme is shown in Table 1.

Table1 Scheme of large scale direct shear tests

Test group	State	Normal stress /kPa	Sample Quantities /个
TR1	Natural state	36、72、108、144	4
TR2	Natural state	36、72、108、144	4
TR3	Natural state	36、72、108、144	4
BS1	Saturation state	36、72、108、144	4
BS2	Saturation state	36、72、108、144	4
BS3	Saturation state	36、72、108、144	4

2.4. Test results

(1) Basic physical and mechanical indicators of soil-rock mixture

The main components of the soil-rock mixture used in the test were sandy mudstone and silty clay. The results of the basic physical and mechanical properties of the soil-rock mixture are shown in Table 2 and Figure 5. For the water content, specific gravity, and liquid-plastic limit tests of the soil-rock mixture, the soil particles with a particle size greater than 2mm in the soil material were removed before the test. According to relevant specifications (The Professional Standards Compilation Group of People’ s Republic of China, 2000), Figure 5 shows that the soil-rock mixture can be named gravelly soil, with a non-uniformity coefficient Cu=117 and a curvature coefficient Cc=1.2, which is a well-graded gravelly soil.

Table 2 Basic physical parameters of experiment materials

w/%	d_s	w_L/%	w_P/%	Ip	w_{op}/%	ρ_{dmax}/g/cm^3
17.0	2.69	38.0	18.0	20	18.0	1.87

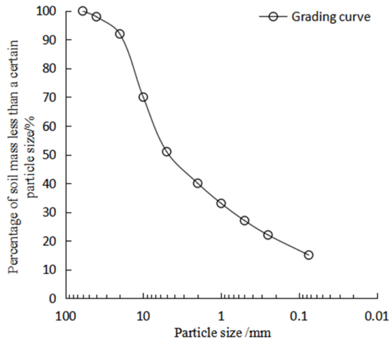


Fig.5 The grading curve of soil-rock mixture

(2) Shear stress-shear displacement relationship of soil-rock mixture

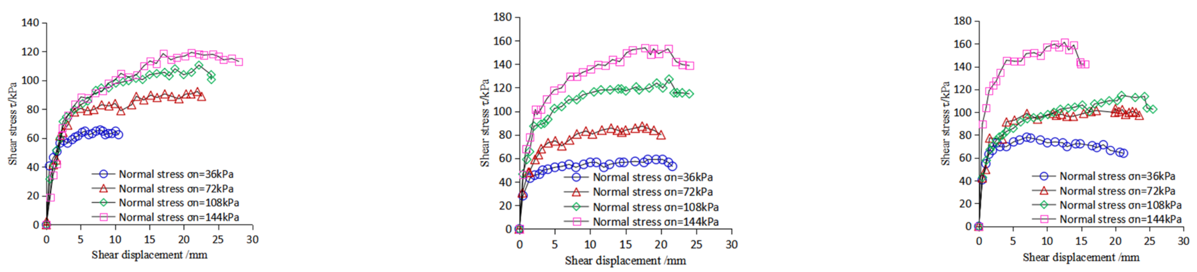
The shear stress-shear displacement curves of the natural and saturated state samples of soil-rock mixture are shown in Figures 6 and 7, respectively.

(3) Average shear strength envelope and shear strength index of soil-rock mixture

The equivalent (average) shear strength envelope of soil-rock mixtures is shown in Figure 8, and the summary of shear strength indicators for each group of soil-rock mixtures is shown in Table 3.

(5) Saturation test results of saturated soil-rock mixture samples

After the immersion test sample was sheared and the photo record of the shear failure surface was completed, 3 points were immediately taken on the soil embankment shear surface, the bottom of the sample, and the middle of the sample for water content testing and calculation of the average saturation. The calculation results are shown in Table 4. From Table 4, it can be seen that the sample can be close to saturation state by continuous water injection for 20 hours under the condition of 4 water injection holes.

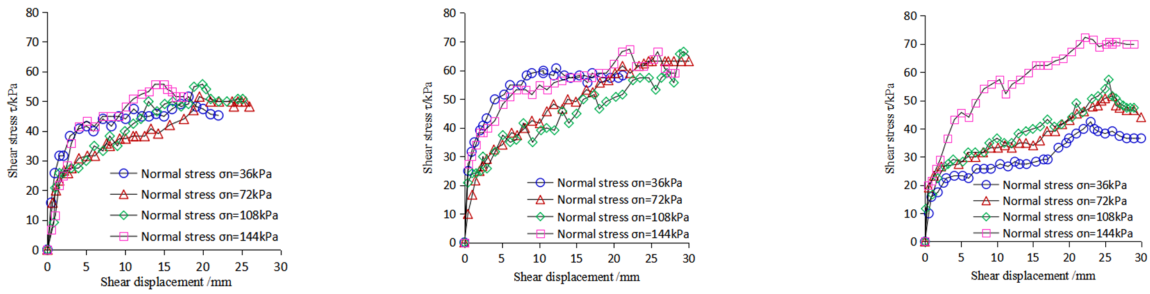


(a) The first group of shear stress-shear displacement relationship

(b) The second group of shear stress-shear displacement relationships

(c) The third group of shear stress-shear displacement relationships

Fig.6 Curves of shear stress and shear displacement of soil-rock mixture samples in a natural state



(a) The first group of shear stress-shear displacement relationship

(b) The second group of shear stress-shear displacement relationships

(c) The third group of shear stress-shear displacement relationships

Fig.7 Curves of shear stress and shear displacement of soil-rock mixture samples an water immersion state

Table3 Summary of shear strength indexes of different test groups

Test group	Normal stress/kPa Shear strength/kPa	Cohesion /kPa	Angle of internal friction /°	Regression correlation coefficient R^2	Average value of shear strength index
TR1	36、72、108、144 66、93、111、119	53.0	26.4	0.9485	
TR2	36、72、108、144 59、87、127、154	25.8	42.0	0.9940	c=44.0kPa φ=34.7°
TR3	36、72、108、144 78、103、115、161	49.1	36.0	0.9361	
BS1	36、72、108、144 52、52、56、56	49.4	2.7	0.8000	
BS2	36、72、108、144 61、63、67、67	58.7	3.7	0.9547	c=45.7kPa φ=7.7°
BS3	36、72、108、144 42、52、57、72	35.4	11.9	0.9851	

2.5. Analysis of test results

Figures 6-8 show the shear stress-shear displacement curves and shear strength test results of large-scale direct shear tests on samples in the in-situ state of the project. Using these test results, which vary with the normal stress and moisture content of the samples, it is possible to analyze the shear strength and deformation characteristics of soil-rock mixtures in the in-situ state of the project.

As shown in Figure 6, for samples with natural moisture content, when the shear displacement of the sample is less than 5mm, the shear stress increases rapidly with the increase of shear displacement, and then the shear stress gradually stabilizes and may show a slight softening phenomenon. The shear stress-shear displacement curve shows a slight sawtooth characteristic. As shown in Figure 7, for samples with saturated moisture content, the shear stress continues to increase with the increase of shear displacement. When the shear displacement is greater than 20mm, the shear stress gradually tends to stabilize and finally enters the softening stage. Figure 9 shows the shear stress-shear displacement curves of two samples in the two states before and after immersion at 72kPa normal stress (drawn by averaging the values of three parallel samples, and other normal stresses also show the same rule). It can be seen that for saturated samples immersed in water, the shear strength needs to be provided by a large shear displacement.

As shown in Figure 8 and Table 3, after saturation of the sample with water, its shear strength decreases significantly compared to that before saturation, and this decreasing trend becomes more pronounced with the increase of normal stress. At the same time, the average cohesion of the natural state sample is c=44.0kPa, and the internal friction angle is φ=34.7°; the average cohesion of the saturated sample is c=45.7kPa, and the internal friction angle is φ=7.7°; after saturation with water, the internal friction angle of the sample decreases significantly, while the cohesion remains basically unchanged. It should be noted that the test results of shear strength indicators between different parallel groups show some dispersion, but the average results of the same group and parallel groups have good consistency, as shown in Figure 8. Therefore, the test results can provide a reliable objective basis for engineering design and slope stability analysis.

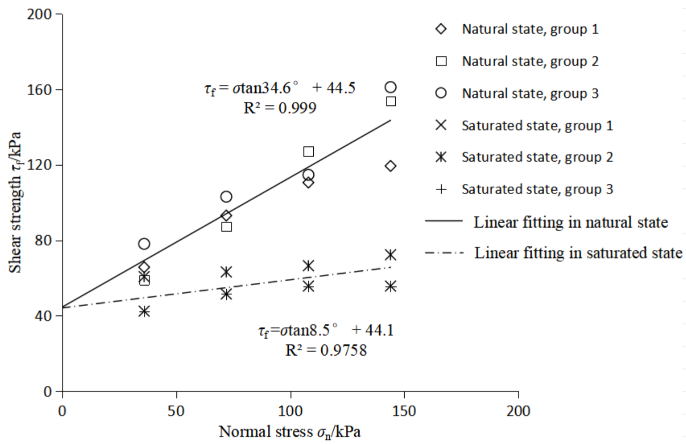


Fig.8 Shear strength envelopes of soil-rock mixture samples

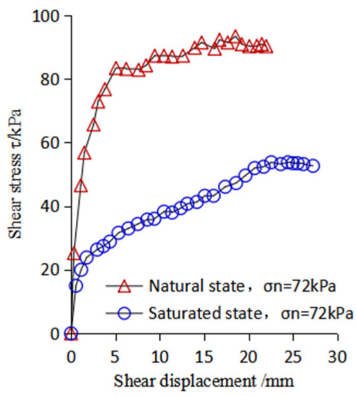


Fig.9 The comparisons of shear stress-shear displacement relationship of large scale direct shear test samples in a natural state and an water immersion state

2.6. Explanation of the physical mechanism of shear strength and water-soaked softening of soil-rock mixtures

(1) Shear strength characteristics of soil-rock mixture

The mineral particles of soil-rock mixtures span about 6-7 particle size scales, ranging from micron-sized clay particles to tens of centimeter-sized rock blocks, and interact with pore liquids and gases according to complex laws to form the structural properties of soil-rock mixtures. Therefore, soil-rock mixtures have significant granularity, structural properties, and natural characteristics of cross-scale material groups. The interaction properties between particles critically affect the strength characteristics of soil-rock mixtures as a particle aggregate. The interaction is mainly achieved through physical-chemical effects on the interface, such as the extrusion and friction of particles, the adsorption of particles and water and gas, and the cementation of sand particles with colloidal particles and clay particles. The interfacial properties of particles and their specific surface area directly determine the interaction properties, showing the interaction effects between different minerals and particles of different sizes. For example, the friction effect between sand particles, the cohesion effect between clay particles, the cementation effect of small particles (clay and colloidal particles) on coarse particles, and the deformation coordination effect of large-sized rock blocks through the interaction with clay particles or gravel through the interface (Fang, et al., 2016, Ding, et al., 2012).

The grading curve given in Figure 5 shows that the soil-rock mixture in the test consists of clay, sand, and gravel, accounting for 15%, 25%, and 60% of the total mass, respectively. The shear strength of the soil-rock mixture consists of two parts, namely, the frictional resistance and cohesion of the soil-rock mixture (Wei, et al., 2018, Xue, et al., 2015). The frictional resistance can be expressed by $f=\sigma n \tan\varphi$, where the internal friction angle φ physically represents the frictional resistance generated by sliding friction, rolling friction, and interlocking effects of mineral particles. The cohesion c physically represents the joint resistance generated by microscopic force interactions such as van der Waals force, Coulomb force, and liquid bridge force between clay particles (Mitchell, et al., 2005). According to the Mohr-Coulomb shear strength criterion, cohesion represents the shear strength between soil particles when the normal stress is zero, and is independent of the normal stress. The cohesion and friction strengths defined by the Mohr-Coulomb shear strength criterion are easy to understand and distinguish, but it should be noted that for soil-rock mixtures with particle sizes spanning multiple particle size fractions, the cohesion c obtained does not only refer to the true cohesion, but rather refers to the apparent cohesion generated by the interaction of multiple particle size fractions of mineral particles and multiphase media. It mainly consists of two parts: the shear bond strength of weathered rock blocks (such as gravel, crushed stone, and block stones) with large size and high strength in the soil-rock mixture, and the true cohesion of cohesive soil in the soil-rock mixture. Based on the above analysis, the shear strength characteristics of soil-rock mixtures and the differences in strength before and after immersion can be explained based on microscopic physical mechanisms.

(2) Comparison of cohesion c before and after the sample is immersed in water

It can be seen from Figure 8 and Table 3 that for natural state samples, the cohesion c=44.0kPa, and for saturated samples, the cohesion c=45.7kPa. The cohesion of the samples before and after immersion is basically unchanged. From the shear stress-shear displacement curve of natural state samples given in Figure 6, it can be seen that the shear displacement at all levels of normal stress increases sharply with the gradual application of shear stress before 5mm, and the slope of the steep increase section of the curve increases with the increase of normal stress, indicating significant friction effects. Therefore, it can be approximated that the displacement before 5mm is mainly caused by overcoming the frictional resistance of soil-rock mixtures. The displacement in the 5-25mm range is caused by the increase of shear displacement under the condition of no or little increase in shear stress, and the slope of the shear stress-shear displacement curve gradually slows down or tends to be horizontal, with each curve appearing and having the same shape, indicating that it is independent of the magnitude of normal stress. Therefore, the displacement in the 5-25mm range is mainly caused by overcoming the apparent cohesion provided by the large-size and high-strength weathered rock blocks of soil-rock mixtures. During the direct shear test, the weathered rock blocks undergo almost no shear deformation due to their high relative stiffness, and the shear strain of soil-rock mixtures is mainly concentrated in the matrix formed by fine particles (such as sand and clay particles). Under the action of shear stress, different grain group mineral particles undergo shear displacement through translation, rotation, and interfacial sliding, accompanied by the appearance of micro-grain compaction effect. When the shear displacement is small, the friction effect of soil-rock mixtures is fully utilized. As the shear stress continues to increase, the fine particles are compacted to the limit, and the shear stress needs to bypass the rigid weathered rock blocks to transmit stress, resulting in shear stress bypassing effect. The shear stress bypassing effect causes relative rotation between the weathered rock blocks and the compacted fine particles, resulting in shear resistance, which is manifested as the apparent cohesion of soil-rock mixtures macroscopically. Due to the strong shear resistance of weathered rock blocks, only a portion of them is used in the actual shearing process, and their degree of play is mainly controlled by the grading characteristics and surface morphology of soil-rock mixtures and affected by constraints. Therefore, the shear bond strength of weathered rock blocks is a key component of the apparent cohesion of soil-rock mixtures. Due to the presence of a certain proportion (15%) of fine-grained soil in soil-rock mixtures, this part of the soil itself has a certain cohesive strength. However, due to the low content of fine-grained soil, the skeleton of soil-rock mixtures is still composed of gravel with a content of 60% (Vallejo, et al., 2001). Fine-grained soil mainly covers the surface of coarse particles or fills in the larger pores formed by stacking of coarse particles, mainly affecting the contact morphology of coarse particles (Mitchell, et al., 2005). Based on the proportion of fine-grained soil and gravel content, for the sake of simplicity, assuming that fine-grained soil evenly covers the surface of spherical gravel, the geometric relationship between the two can be drawn. It can be seen that the film formed by fine-grained soil is only 0.2mm thick, providing limited cohesion, and is quickly destroyed with the movement of coarse particles. However, for spherical particles, the ideal dense packing porosity ratio is 0.26, which can be converted to indicate that when the content of fine-grained soil exceeds 30%, the soil-rock mixture begins to transition to using fine-grained soil as the skeleton, at which point the true cohesion provided by fine-grained soil begins to emerge gradually.

The shear stress-shear displacement curve of the saturated sample given in Figure 7 shows that the shear stress under various levels of normal stress gradually increases with the application of shear displacement, and each curve exhibits the same regularity and similar morphology. Overall, it slightly increases with the increase of normal stress, indicating that the increase of shear stress in the sample is not significantly affected by normal stress, which is manifested as a small friction resistance of the sample and a continuous increase in apparent cohesion. Therefore, the continuous increase in shear displacement may mainly be due to the overcoming of the apparent cohesion of the soil-rock mixture. Under the action of shear displacement, the mineral particles will produce a compaction effect, but under the continuous saturation of water, the physical state of the clay film covering the surface of coarse particles changes from hard to plastic, and a certain thickness of weakly bound water appears on the surface of the clay film. The change in the plastic properties of the clay film microscopically leads to the need to overcome the displacement of the clay film due to plastic deformation in the compaction process between the matrix particles, which macroscopically leads to an increase in the shear displacement when the sample reaches the compaction limit. The development of the shear bond strength of large-sized weathered rock blocks in the soil-rock mixture requires greater shear displacement to provide. Therefore, the apparent cohesion provided by the shear bond strength of rock blocks still plays a role in the saturated sample, but the required shear displacement increases accordingly. At the same time, after saturation of water, the grading characteristics of the soil-rock mixture and the constraint effect it undergoes during loading do not change significantly, and the degree of apparent cohesion provided by the shear bond strength of weathered rock blocks is approximately equal. Macroscopically, the cohesion of the sample before and after saturation remains basically unchanged, but the corresponding shear displacement increases.

(3) Comparison of internal friction angle before and after sample immersion

As shown in Figure 8 and Table 3, for natural state samples, the internal friction angle φ=34.7°, and for saturated samples, the internal friction angle φ=7.7°. After saturation, the internal friction angle of the sample decreases significantly, which is only 1/5 of that of the natural state sample. For soil-rock mixtures composed of mineral particles with particle sizes spanning multiple size fractions, there are a large number of interfaces within the sample. Interactions between mineral particles of different sizes and different phases occur through the interfaces, resulting in different aggregation and contact forms such as adsorption, cementation, and contact. Under external load, particles undergo translation and rotation, and the interfaces slide to adapt to the geometric compatibility requirements of deformation between different materials within the soil-rock mixture, thus exhibiting plasticity and cohesion and internal friction, which are the characteristics of deformation and strength. The internal friction of soil-rock mixtures generated by the sliding, rolling, and inlaying effects of mineral particles, as well as the particle characteristics such as shape, grading, and surface morphology, affect the coordination number of particles and change during loading, thus playing a key controlling role in the frictional resistance generated through interface contact. For samples before and after saturation, the particle shape and grading remain basically unchanged, but due to the surface of coarse particles being covered by a clay film, the properties of the clay film strongly affect the interface contact characteristics of gravel and other coarse particles, thus affecting the internal friction angle of the soil-rock mixture. For natural state samples, the clay is in a hard state due to low water content, and the sliding friction resistance between gravel and hard clay film, as well as the biting friction resistance generated by the rotation of gravel through the hard clay film interface and the transfer and diffusion of shear stress to adjacent mineral particles, are relatively large, and they are fully utilized at small shear displacements, which is manifested macroscopically as a large internal friction angle of the soil-rock mixture. For saturated samples, the water content of the clay increases (from 17% to 24%), and the physical state of the clay changes from hard to plastic. The surface of the clay film on the coarse particles such as gravel begins to contain a certain thickness of weakly bound water, and the sliding friction resistance between gravel and plastic clay film is actually generated by the relative sliding of gravel and weakly bound water film. At the same time, the existence of weakly bound water film greatly weakens the ability of gravel to transfer shear stress to adjacent mineral particles through rotation, resulting in a significant reduction in the biting friction resistance between soil particles, On a macro level, the internal friction angle of soil-rock mixtures under saturated conditions is relatively small, which is consistent with the viewpoint of Mitchell JK that "fine-grained soil can control the properties of soil mass by taking up only 1/3 of the solid portion of soil mass, while coarse-grained soil cannot directly contact it”. To analyze the influence of the water content state of clay film on the shear stress transfer ability between coarse particles such as gravel, after each sample shear test, the damage shape of the shear surface was photographed and described. The statistical analysis results showed that the damage surfaces of all samples exhibited the same regularity. For natural state samples, the ability of gravel on the shear surface to transfer shear stress to adjacent soil-rock particles through rotation was strong, and the range of concentrated shear load on the shear surface diffusing downward to the shear plane was large, which was macroscopically manifested as a wide shear band development width of the sample and a development towards the lower soil mass of the shear plane, forming a pot-bottom-shaped curved shear failure surface with shallow edges and deep centers.

3. Conclusion

This article conducted six sets of large-scale in-situ direct shear tests on soil-rock mixtures composed of soil particles with particle sizes spanning multiple particle size groups to explore the strength characteristics and water-physical properties of soil-rock mixtures under in-situ engineering conditions. The main conclusions are as follows:

(1) The shear strength of soil-rock mixtures in the natural state is relatively high. The shear strength indicators determined by three parallel tests are cohesion c=44.0kPa and internal friction angle φ=34.7°. When the soil-rock mixture is saturated with water on site, its shear strength decreases significantly. The shear strength indicators determined by three parallel tests are cohesion c=45.7kPa and internal friction angle φ=7.7°.

(2) The cohesion of soil-rock mixtures determined according to the Mohr-Coulomb shear strength criterion is not a true cohesion, but mainly an apparent cohesion provided by the shear bond strength of coarse particles such as gravel in the soil-rock mixture. Its test results are high and not affected by immersion;

(3) The reason for the significant decrease in shear strength of soil-rock mixtures after saturation can be explained as follows: the clay film covering the surface of coarse particles becomes soft after being soaked in water, resulting in a significant decrease in the sliding friction between coarse particles such as gravel and the clay film, as well as the biting friction generated by the rotation transfer between coarse particles through the clay film interface.

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