Research Article

Direct Shear Test on Coarse Gap-Graded Fill: Plate Opening Size and Its Effect on Measured Shear Strength

H. Cai, R. Wei, J. Z. Xiao , Z. W. Wang, J. Yan, S. F. Wu, and L. M. Sun

State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin,
China Institute of Water Resources and Hydropower Research, Beijing 100048, China

Correspondence should be addressed to J. Z. Xiao; xjz2006@sina.cn

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In this paper, three different rock-soil mixtures were reconstituted in laboratory, which were designed to mimic the proportions of coarse and fine particles in the high fill used at the airport construction sites. The shear strength of the reconstituted mixtures was determined by both large-scale direct shear tests (DSTs) with different plate opening sizes and triaxial compression tests. By comparing the test results, the most appropriate plate opening size for DSTs on coarse gap-graded rock-soil mixtures is discussed. The test results indicate that the opening size has a significant effect on the measured shear strength of gap-graded rock-soil mixtures. For DSTs under the same normal stress, the peak strength decreases with increasing plate opening size. For the gap-graded mixture with a small proportion of coarse particles, a plate opening size of one-third to one-quarter of the maximum particle size ($d_{\max}$) is suitable. With a higher coarse particle content, the opening size should be increased appropriately. If the percentage of gravels ($5.0 \text{ mm} < d < 20.0 \text{ mm}$) is more than 47%, a plate opening size of slightly greater or less than one-half $d_{\max}$ is more appropriate.

1. Introduction

With the rapid economic development in China, many airports are being built in southwestern China (Figure 1). Between years 2011 and 2015, investment in the civil aviation industry infrastructure reached 425 billion RMB and 40 new airports were built in mountain areas. The number of airports will reach 272, and the range of aviation services will cover 93.2% of cities and 92% of the population in China by the end of 2020.

In order to save urban land and comply with environmental restrictions, most of the airports are built in mountainous terrain with complex landforms. Enormous amounts of fill are required for airport construction. As a result, most of these airports are high fill airports. The fill materials are usually rock-soil mixtures obtained locally and in most cases by mountain blasting.

The airport fill volume is generally between 1.5×10^7 and $3.0 \times 10^7 \text{ m}^3$. In some airports, such as Jiuzhai, Panzhihua, Liupanshui, Changshui, and Chongqing Airports, the fill

volume exceeds $5.0 \times 10^7 \text{ m}^3$, and that for Changshui Airport is even more than $3.6 \times 10^8 \text{ m}^3$. The maximum fill heights are in many cases 20–60 m. However, for some airports, including Jiuzhai, Panzhihua, Liupanshui, Huairan, Tengchong, Lvliang, Wenzhou, and Chongqing Airports, the fill heights are over 60 m. The maximum fill height at Chengde Airport even exceeds 114 m. The problems related to high fill stability in these projects are prominent.

The rock-soil fill most widely used in high fill airport construction in China is composed of soil and blasted rock fragments. The rock-soil mixture contains a complex mix of various particle sizes, resulting in heterogeneous and irregular fill. The maximum particle size is 800 mm, and, in some extreme cases, rock blocks are more than 1000 mm. Rock-soil mixtures without intermediate particle sizes (gap-graded materials) are commonly used for high fill airport construction.

Under normal conditions, the factor of safety for slopes at high fill airports must not be less than 1.30 [1]. Shear strength is one of the basic engineering properties of

FIGURE 1: Distribution of several high fill airport projects and several other high fill projects in China.

rock-soil mixtures and the basis for stability analysis in high fill engineering. Shear strength directly affects construction and postconstruction settling and also influences the safety of construction and airport operation. Studying the shear properties of gap-graded rock-soil mixture and determining the shear strength index is of great theoretical and practical significance.

Compared to costly and time-consuming triaxial compression tests, the DST is one of the most effective methods to determine the shear strength index of coarse-grained materials [2–8]. It is also one of the two strength test methods recommended by “Code for Geotechnical Engineering Design of Airport” MH/T 5027-2013 [1] for stability analysis of high fill airport slopes. Owing to its advantages in cost and testing process [9, 10], direct shear testing is widely used for high fill design and construction.

The shear test on rock-soil mixture is performed in rigid shear boxes under the constraint of shearing frames and fixed shear surfaces. The orientation and position of coarse gravels are constantly adjusted during testing. However, gravels can hardly deflect or roll in the shear zone when a large normal stress is imposed. Therefore, in order to avoid particle breakage and allow the specimen to shear along the weakest plane, it is necessary to open a gap between the upper and lower shear boxes before shearing. Few studies have been carried out on appropriate plate opening size for DSTs and the opening size is not even mentioned in most studies on DSTs.

Some studies [11, 12] have shown that particles would fall out during the test if the plate opening size is large. As a result, the effective shear area decreases, and the soil density on the shear surface decreases. Subsequently, a lower

strength is measured. On the contrary, if the opening size is too small, the influence of the constraint imposed by the normal force cannot be eliminated, resulting in a higher measured strength. The size of the opening between the upper and lower shear boxes directly affects the free movement of the particles during shearing [11, 13] as well as the validity of the test results. Therefore, in order to study the shear strength of a gap-graded rock-soil mixture in depth, the DST opening size is an important issue, which needs to be solved for the optimal design and continued construction of high fill airports in China.

In this paper, a series of DSTs were conducted on the typical rock-soil mixtures reconstituted from the high fill of Chengde Airport. After field investigation, three gap-graded rock-soil mixtures were reconstituted to mimic the proportion of coarse and fine particles at the airport construction site. The shear strength of the gap-graded rock-soil mixtures was measured by large-scale DSTs with different opening sizes. By comparing the results obtained by DSTs and triaxial compression tests, the most appropriate DST opening size for the rock-soil mixtures was determined. This research can provide some reference for the design and construction of similar high fill projects.

2. Gap Gradation and Plate Opening Size for the Direct Shear Test

2.1. Gap Gradation. Gap-graded soil is one of the two types of poorly graded soil [14]. It can be defined as soil containing coarse particles and fine particles, but the proportion of one or more intermediate sizes is low or absent altogether [15, 16]. Particle size and grain composition are two of the most important physical properties that determine the mechanical properties of soil. It is important to note that studies have shown that, during shear testing, the relative proportions of coarse and fine particles in a specimen have a direct influence on the interlocking and embedding of particles and thus have an important effect on the shear strength of rock-soil mixtures used for fill [17].

2.2. Plate Opening Size for the Direct Shear Test. A small space between the shear boxes may restrict the development of the shear band, but a large opening causes stress reduction and material loss at the specimen edges or small portions of the specimen escaping into the gap [13]. The ASTM standard [18] recommends an aperture of 0.64 mm for tests on specimens composed of fine sand but a wider opening for tests on specimens made up of coarser materials [19]. Concerning tests on coarse materials, Standard Test Method for Direct Shear Test [20] indicates that “there may be instances when the gap between the plates should be increased to accommodate sand sizes greater than the specified gap. Presently there is insufficient information available for specifying gap dimension based on particle size distribution.”

Based on the DST test results reported by 21 geological exploration institutes in China, Guo [11] found that most of the opening sizes used for DSTs on coarse materials were

between one-third and one-quarter of the maximum particle size ($d_{\max}$). This is consistent with the opening size for DSTs on coarse-grained soil suggested by Specification of Soil Test SL237-1999 [21]. That is, it is recommended that the opening size for DSTs should be wider for coarse particles and narrower for fine particles.

The plate opening is usually set at 0.5 mm for conventional materials. This value is used widely in the UK [22]. For sandy specimens, the minimum constant shear resistance in the peak shearing region matches the thickness of the shear band observed in plane-strain compression tests well. Therefore, it seems reasonable to specify the opening as a size slightly larger than the thickness of the free shear band. This is approximately 10 to 20 times the median particle diameter (d_{50}) of the material tested [19, 23]. Simoni and Houlsby [13] recognized that the size of the opening between the upper and lower boxes constituted another possible source of unwanted effects. Considerable practical difficulties arose when the opening size of 10–20 d_{50} was applied to samples composed of coarse-grained particles because the required size of opening would be several centimeters. The solution suggested by Simoni and Houlsby [13] was to fix the initial opening to 1 mm for all tests.

With a direct shear apparatus, Lings and Dietz [22] studied how the internal friction angle and the dilation angle of dry Leighton Buzzard sand differed for various initial plate openings. A 100 mm × 100 mm modified conventional direct shear apparatus with an opening size of 4 mm (five times d_{50}) was adopted for all their tests. Their results showed a reduction of peak strength and an increase in rotation with increasing gap size. Kim et al. [12] examined the influence of the DST opening size on the shear behavior of seven soil specimens. Six opening sizes, 0.2, 0.5, 1.0, 2.0, 3.0, and 4.0 mm, were investigated and it was found that the width of opening influenced the extrusion, shear strength, and dilatancy of the soil specimen significantly. The opening sizes for which the shear strength abruptly dropped were identified.

From the previous studies, it is clear that although the opening size has an important influence on the DST results, the research on the appropriate opening size for rock-soil mixtures is not complete, especially for DSTs on gap-graded rock-soil fill materials. No systematic studies and reasonable suggestions for the appropriate opening size with respect to grain size have been made for large-scale DSTs. It is also questionable whether the opening size of one-third to one-quarter $d_{\max}$ recommended for coarse-grained specimens by Specification of Soil Test SL 237-1999 [21] is applicable to gap-graded rock-soil mixtures.

3. Experimental Procedures

3.1. Test Equipment. A series of large-scale DSTs were conducted in laboratory using a direct shear apparatus, ShearTrac-III (GeoComp, Acton, MA, USA) (Figure 2). The ShearTrac-III employs a 305 mm square shear box with a height of 200 mm. The opening between the upper and lower shear boxes can be adjusted freely (Figure 3).

FIGURE 2: Large-scale direct shear apparatus ShearTrac-III.

FIGURE 3: Opening size adjusting device on ShearTrac-III.

Triaxial compression tests were also conducted on the gap-graded rock-soil mixtures, using a triaxial testing system, LoadTrac-II/FlowTrac-II (Figure 4), manufactured by GeoComp. The sample chamber diameter is 101.0 mm and the height is 200.0 mm.

3.2. Test Specimens. The grain size distributions were determined by field investigations for different high fill materials at a number of airports; test samples were taken from the rock-soil high fill of Chengde Airport (Figure 5(a)).

Specification of Soil Test SL 237-1999 [21] suggests that, for DSTs on coarse-grained soil, the value of $D/d_{\max}$ should be 8–12 and that of $H/d_{\max}$ should be 4–8, where D is the length of direct shear box, H is the height of the straight shear box, and $d_{\max}$ is the size of the largest particle in the sample being tested.

In the actual project, the particle size of the fill materials generally varies in a large range, and the rock-soil mixture with large difference in particle sizes and the gap-graded fill material are very common. The grain size distribution of typical gap-graded high fill for Kunming New Airport is shown in Figure 5(b). Due to the size limit of test equipment, when large rock fragments are contained in fill materials, a method of scaling down has to be adopted [9, 10]. Therefore, according to the typical gap-graded fill materials for airport high fill, three gap-graded rock-soil mixtures with a maximum particle size of 20.0 mm were reconstituted for the DSTs, which can approximately reflect the gap-graded rock-soil mixture of the actual project in this way. The particle size distributions of the mixtures, G1, G2, and G3, are shown in Figure 6.

FIGURE 4: Triaxial compression apparatus LoadTrac-II/FlowTrac-II.

According to Standard for Engineering Classification of Soil GB/T 50145-2007 [24] and Technical Code for High Filling Engineering of Airport MH/T 5035-2017 [25], 5 mm is defined as the boundary between coarse-grained and fine-grained materials. Therefore, the percentage (by weight) of the gravel material with a particle size > 5.0 mm (P_5 material) is specifically considered in this study. The P_5 material in the gap-graded G1, G2, and G3 specimens is 23.73%, 47.40%, and 75.09%, respectively. In simple terms, the mixture G1 is prepared by adding some coarse particles to a fairly larger volume of fine particles. The proportion of gravel in G1 is relatively small and the fine particles completely enclose the coarse particles [26]. In the mixture G2, the coarse-grained particle content is higher but the coarse particles do not form a skeleton for the mixture. The fine particles do not fully enclose the coarse particles. In the mixture G3, the proportion of coarse grains is much higher and the fine particles only partially fill the spaces between coarse particles.

The dry densities of the mixtures G1, G2, and G3 are 1.47 g/cm^3 , 1.78 g/cm^3 , and 1.77 g/cm^3 , respectively. The physical parameters of the samples are listed in Table 1.

Figures 7–9 show the photos of reconstituted rock-soil mixture samples. As can be seen, the gravels are subangular to angular. Obvious differences in the sample appearance and soil structure can be observed. As shown in Figure 7, the mixture G1 has a low proportion of P_5 gravels, and the gravels are suspended in the mixture. Figure 9 shows that the soil particles of the mixture G3 fill up the gaps in the skeleton formed by the P_5 gravels. The mixture G2 has an intermediate proportion of coarse particles compared to G1 and G3 (Figure 8). Due to the absence of silt- or clay-sized particles in the samples ($d > 0.075 \text{ mm}$, Figure 6), all the three mixtures appear “loose” and are unconsolidated.

Relative density can reflect grain size, particle shapes, and structure of the specimens and the shape of the particles has an important influence on the physical properties of a soil [15]. In order to better analyze the test results of the gap-graded soil-rock mixtures, the same relative density of 0.60 is adopted as an important index. The moisture content of the air-dried specimens is 3%.

3.3. Testing Procedures. At present, few references and specifications for DSTs on similar gap-graded rock-soil mixtures are available. In consideration of the large amount

(a)

(b)

FIGURE 5: (a) Rock-soil mixture at high fill construction site for Chengde Airport. (b) The typical particle size distribution of gap-graded high fill for Kunming New Airport.

FIGURE 6: Particle size distributions of the gap-graded rock-soil mixtures G1, G2, and G3 for the direct shear and triaxial tests.

TABLE 1: Physical properties of gap-graded rock-soil mixtures G1, G2, and G3.

Specimen	D_r	$\rho_{d\max}$	$\rho_{d\min}$	$d_{\max}/(\text{mm})$	$d_{\min}/(\text{mm})$	C_u	C_c
G1	0.60	1.59	1.32	20.0	0.075	2.81	0.88
G2	0.60	1.92	1.60	20.0	0.075	68.67	0.02
G3	0.60	1.94	1.57	20.0	0.075	11.41	9.94

of laboratory tests, the mixture G1 with more fine particles and the mixture G3 with more coarse particles were tested with priority. The test on G2 is based on the test experience of G3.

The testing procedures suggested by ASTM D3080 (standard method for DST), ASTM D4767 (standard method for the consolidated undrained triaxial test), and SL237-1999 were followed to determine the shear strength of the gap-graded rock-soil specimens. The rock fragments and

FIGURE 7: Photograph of rock-soil mixture G1.

FIGURE 8: Photograph of rock-soil mixture G2.

soil were thoroughly mixed and then loaded into the shear box in four layers. During loading, each layer is tamped until a specified height is reached.

The DSTs and triaxial compression tests on the specimens were carried out sequentially. As the gap-graded rock-soil specimens were air-dried without consolidation or drainage, the normal pressure was 100, 200, 300, or 400 kPa, respectively, and the shearing rate was set to 0.8 mm/min as recommended by ASTM D3080. The total shear displacement was 60.0 mm. For the triaxial compression tests, the

FIGURE 9: Photograph of rock-soil mixture G3.

confining pressure was 100, 200, 300, and 400 kPa, respectively, the shearing rate was 0.06%, and the axial strain was 18%.

3.4. Determination of Plate Opening Size. The axially symmetric stress is considered in triaxial compression tests whereas a direct shear test is a plane-strain problem. Hence, the internal friction angle ϕ obtained by a direct shear test is generally slightly higher than ϕ' obtained by a triaxial compression test [13]. However, the internal friction angle ϕ' for a completely submerged sand is about 1° or 2° less than ϕ for the same sample in a perfectly dry state [16]. This is applicable to gravel samples without silt and clay. Therefore, it can be applied to the gap-graded rock-soil specimens in this study. The previous studies have also compared shear strengths determined by DSTs with those from triaxial compression tests [9, 10, 23]. Based on the above research, the opening sizes for the large-scale DSTs in this study were determined by comparing the internal friction angles obtained by the direct shear and the triaxial compression tests on the same gap-graded rock-soil mixture.

3.5. Test Results. Large-scale DSTs and medium-scale triaxial compression tests were both carried out on the gap-graded rock-soil mixtures G1, G2, and G3. The failure envelopes are plotted for the triaxial compression tests, which are compared with the peak shear strength determined by the DSTs with reasonable opening sizes. The results are described below.

3.6. Plate Opening for G1. From Figure 10(a), it can be seen that, for a plate opening of 5.0 mm, the shear stress increases rapidly the horizontal displacement after the normal stress is initially applied. For a normal stress of 100 kPa, the peak shear stress for the mixture G1 occurs at a shear displacement of about 10 mm. As the normal stress increases, the peak shear stress occurs at a larger horizontal displacement. For a normal stress of 400 kPa, the peak shear stress is observed at a shear displacement of about 12 mm.

The relative abundances of coarse and fine particles affect the shear strength of rock-soil mixtures directly [17]. In the mixture G1, the weight percentage of the P_5 gravel is 23.73% and the coarse-grained particles can be fully enclosed by the large proportion of finer grained particles in the sample.

Because of the low P_5 content, the coarse particles can hardly interact with each other. Almost no breakage or dislocation of large particles occurs during shearing and the shear surface is mainly composed of fine particles. The closely packed fine particles contribute most of the shear strength. The deformation of G1 mainly depends on the fine particles, resulting in lower overall shear strength. The measured peak strength of G1 corresponding to a normal force of 400 kPa is only 270.7 kPa. Figure 10(b) shows that the internal friction angle is 29.8° and the cohesion is 44.8 kPa for G1.

Medium-scale triaxial compression tests were also carried out on the mixture G1. The variations of deviatoric stress with axial strain under different normal stresses are shown in Figure 11(a). The failure envelopes derived from the triaxial test results are compared with the peak shear strength obtained by the large-scale DSTs, as shown in Figure 11(b). It can be seen that the internal friction angle determined by the DSTs is 29.8° , which is very close to the effective internal friction angle obtained by the corresponding triaxial tests, 29.1° .

3.7. Plate Opening for G2. The variations of shear stress with horizontal displacement for the mixture G2 are shown in Figure 12(a). It appears that the deformation is affected by the interaction between fine particles and coarse particles. The peak shear stress of the mixture G2 under a normal pressure of 400 kPa occurs at a shear displacement of around 13 mm. Compared to Figure 10(a), it can be seen that the peak shear strength increases with increasing percentage of P_5 gravel. For the mixture G2, the shear strength is partially controlled by the gravel phase. Figure 12(b) shows that the internal friction angle for G2 is 36.1° , an increase of 6.3° compared to G1, and the cohesion is 118.9 kPa.

The variations of deviatoric stress with the axial strain obtained by the triaxial tests are plotted in Figure 13(a). The failure envelopes obtained by the triaxial tests are compared with the peak shear strength obtained by the DSTs shown in Figure 13(b). It can be seen that the internal friction angle for G2 determined by the DST with an opening width of 10 mm is 36.1° , which is close to the effective internal friction angle from the corresponding triaxial tests, 36.9° . This is similar to the mixture G1.

3.8. Plate Opening for G3. When the percentage of the gravel was increased to 75.09% in G3, the gravel formed a skeleton for the rock-soil mixture and the gravel also became dominant in the shear plane (the shear band). For the mixture G3, the shear strength mainly depends on the interactions between the coarse-grained particles.

During shearing, the gravels of larger size move and deflect in the shear zone. The particles slide against each other and roll, and the smaller particles are more likely to roll. Because the main materials for high fill at the airports are produced by hard rock blasting, the surface of rock fragments is rough and the coefficient of friction is high. The interlocking and embedding forces between particles are two of the most important factors causing dilatant deformation of dense rock-soil mixtures. The dilatancy is mainly caused

FIGURE 10: (a) Variation of shear stress with horizontal displacement obtained by direct shear tests on G1 with a plate opening of 5.0 mm. (b) Failure envelope for G1 (plate opening 5.0 mm).

FIGURE 11: (a) Variation of deviatoric stress with axial strain for G1. (b) Comparison of shear strength determined by direct shear test (opening size 5.0 mm) and triaxial tests for G1.

by rotation and rearrangement of the particles on the shear surface or in the shear zone. The rough contact surfaces between the coarse particles will also produce friction and lead to higher shear resistance.

With a higher P_5 content, the sliding, rolling, and shear deformation between the coarse and fine particles in the mixture are even more complex during shearing. The different shear box opening sizes directly affect grain rearrangement and breakage on the shear surface and in the shear zone. Hence, it has a significant impact on the shear strength. As few studies on DSTs of gap-graded rock-soil mixtures similar to G3 are available in the literature; DSTs were performed on the mixture G3 with different plate opening sizes, namely, 5.0, 10.0, 15.0, 20.0, 25.0, and

30.0 mm, in this study. Except the DST with a plate opening size of 5.0 mm (Figure 14(a)), the remaining tests were performed under the same test conditions and the test results are illustrated in Figures 14(b)–14(g).

As can be seen from Figure 6, the percentage of P_{10} material (particles with a diameter greater than 10.0 mm) in the rock-soil mixture G3 is more than 69%. As shown in Figure 14(a), squeezing, sliding, or rolling of coarse particles under the upper shear plate are difficult when the shear box opening is only 5.0 mm wide. Interactions among the coarse particles in the shear zone are dominated by friction and contact. In addition, the hard rock particles can hardly deform. As a result, the peak shear stress reaches 436.5 kPa under a normal pressure of 200 kPa. Note that in order to

FIGURE 12: (a) Variation of shear stress with horizontal displacement obtained by direct shear tests on G2 with a plate opening of 10.0 mm. (b) Failure envelope for G2 (plate opening 10.0 mm).

FIGURE 13: (a) Variation of deviatoric stress with axial strain for G2. (b) Comparison of shear strengths determined by direct shear test (plate opening 10.0 mm) and triaxial tests for G2.

perform the test on the mixture G3 with a 5.0 mm opening on the shear box, the maximum normal stress on the specimen can only be 200 kPa. This is restricted by the maximum allowable horizontal thrust of ShearTrac-III.

The variations of shear stress with horizontal displacement for G3 corresponding to the opening size of 10, 15, 20, 25, and 30 mm are shown in Figures 14(b)–14(f), respectively. A comparison of the DST results shows that, in the initial stage of shearing, the deformation is continuous and the shear stress-displacement curves are all relatively smooth. As the shear displacement increases and the peak shear strength is approached, the rock-soil mixture is further

disarranged and compressed as the particle interlocking, embedding, and breakage occur. The curves begin to fluctuate to some degree. For the same opening size, higher normal stress leads to local stress concentration at the point contacts between particles and the particles break, resulting in a higher shear strength. Under the same normal stress, the larger the opening size is, the more easily the particles roll and rearrange themselves along the shear surface. Separation and extrusion of particles in the shear zone are also more pronounced and the amplitude of the fluctuations increases with increasing opening width. As shown in Figure 14(f), compared to the shear stress-displacement curves for other

FIGURE 14: Continued.

FIGURE 14: Variation of shear stress with horizontal displacement obtained by direct shear tests on G3 with a plate opening of (a) 5.0 mm, (b) 10.0 mm, (c) 15.0 mm, (d) 20.0 mm, (e) 25.0 mm, and (f) 30.0 mm. (g) Failure envelopes for G3 under direct shear with different plate openings.

opening widths, the fluctuation near the peak shear stress under a normal stress of 400 kPa is the most obvious even though the opening width is 30.0 mm.

Under the same normal stress, the peak shear stress for the mixture G3 decreases as the opening width increases [27, 28]. For example, for a normal stress of 100 kPa, the peak shear stresses are 267.6, 146.3, 140.0, 129.0, 119.3, and 96.8 kPa for opening sizes of 5, 10, 15, 20, 25, and 30 mm, respectively.

The failure envelopes for G3 under various opening sizes are shown in Figure 14(g). The corresponding DST results are listed in Table 2. It can be seen that the opening size has an important influence on the shear strength of G3. The smaller the opening size, the steeper the strength envelope. As shown by the DST data, under the same normal stress, the peak strength decreases with increasing opening size. For instance, for an opening size of 5.0 mm, the internal friction angle is 53.3° and the cohesion is 160.0 kPa. For an opening size of 30.0 mm, the internal friction angle falls to 27.8° and the cohesion decreases to 51.3 kPa. During the shearing process, the position of particles in the rock-soil mixture is constantly adjusted. Dislocation, rolling, and shear loss occur in the shear area. The sample in the direct shear apparatus is restrained by the shear box and the shear plane is fixed. When the opening size between the upper and lower shear boxes is small, the coarse particles can hardly roll and dislocate, which leads to particle breakage during shearing, resulting in high measured strength. For example, the measured strength of G3 is obviously larger for the opening size of 5 mm.

The relative concentration and proportion of coarse and fine particles in rock-soil mixture directly affect interlocking and embedding of particles during the shear failure process and subsequently have an important impact on the shear strength of the rock-soil mixture [17]. The maximum particle size of G3 is 20 mm. The proportion of P_5 gravel in G3 is 75.09%. The percentage of coarse particles with size between

TABLE 2: Peak and residual internal friction angle (ϕ) and cohesion (C) obtained by direct shear tests on G3 with six different plate opening sizes.

Opening size/(mm)	Peak values		Residual values	
	$\phi/(^{\circ})$	C/(kPa)	$\phi/(^{\circ})$	C/(kPa)
5.0	53.3	160.0	51.56	38.65
10.0	39.1	66.5	27.28	16.49
15.0	37.0	59.5	26.30	22.13
20.0	38.3	51.5	29.79	17.48
25.0	34.1	43.3	25.88	0.00
30.0	27.8	51.3	20.52	5.30

10 mm and 20 mm is 68%, and that with size between 15 mm and 20 mm is 47% (Figure 6). When the DST opening size increases from 10 mm to 20 mm, which is equivalent to 0.5 and 1.0 times of the maximum particle size, the lateral confinement on the shear zone decreases, and the effective shear area decreases accordingly. As the rock-soil mixture is a material formed by rock fragments with rough surfaces and large friction coefficient, coarse particles can move and dislocate in the shear zone and interlock in the process of gap filling. As a result, the measured shear strength and residual strength fluctuate when the opening size increases from 10 mm to 20 mm (Table 2). When the opening size is increased to 15 mm and 20 mm, although the extrusion effect of the sample particles is more prominent at the edge of the shear box during the shear process, the measured shear strength corresponding to the opening size of 15 mm and 20 mm is not much different (Figure 14(g)).

Residual strength is the residual shear stress on the shear surface after shear damage occurs. It reflects the strength deterioration after a material is damaged. It is also an important parameter for evaluating slope stability. As shown by the DST results in Table 2, the residual internal friction angle of G3 also decreases as the opening width increases. The

FIGURE 15: (a) Variation of deviatoric stress with axial strain for G3. (b) Comparison of shear strengths determined by direct shear test (plate opening 10.0 mm) and triaxial tests for G3.

residual internal friction angles are 51.56° , 27.28° , 26.30° , 29.79° , 25.88° , and 20.52° for opening sizes of 5, 10, 15, 20, 25, and 30 mm, respectively.

The failure envelopes obtained by the triaxial tests are compared with the peak shear strengths from DSTs on G3 in Figures 15(a) and 15(b). Similar comparison for G1 and G2 is presented in Figures 11(a) and 11(b) and Figures 13(a) and 13(b), respectively. For G3 with an opening width of 10.0 mm, the internal friction angle from the DST is 39.1° , and the effective internal friction angle from the corresponding triaxial tests is 41.4° . Again, the results from the two test methods are close.

The shear strength and friction angle obtained by DST and triaxial compression tests for the three mixtures G1, G2, and G3 are listed in Table 3.

For large-scale DSTs on gap-graded rock-soil mixtures with a fairly small proportion of coarse particles, a plate opening size of one-third to one-quarter $d_{\max}$ is suitable for mixtures similar to G1. If the content of coarse particles is higher, the opening should be increased appropriately. If proportion of gravels with size in the range of $5.0 \text{ mm} < d < 20.0 \text{ mm}$ is more than 47%, like the mixtures G2 or G3, a plate opening of slightly greater or less than one-half $d_{\max}$ is more suitable.

4. Applications of Test Results

Due to the huge volume of excavation and filling in the airport high fill projects, the particle size of the rock-soil mixture changes significantly and is often difficult to control. If the grading requirements for the fill material are too high, a large amount of waste materials will be produced during construction, which directly affects the progress and cost of the airport project. DST is one of the most effective methods to determine the shear strength of the rock-soil mixture, and it is of great practical significance to study the reasonable

TABLE 3: Summary of testing results for direct shear tests and triaxial compression tests.

Specimen/opening size (mm)	$\phi/^\circ$	$C/(\text{kPa})$	$\phi'/^\circ$	$C'/(\text{kPa})$
G1/5.0	29.8	44.8	29.1	88.0
G2/10.0	36.1	118.9	36.9	48.0
G3/10.0	39.1	66.5	41.4	17.3

opening size of the DST for the gap-graded rock-soil mixture which is often encountered in the projects.

Based on the test results on gap-graded rock-soil mixtures in this paper, the possible applications are suggested as follows.

For DSTs on the gap-graded rock-soil mixture under the same normal stress, the larger the plate opening size is, the more easily the particles are rolled and rearranged on the shear surface. Therefore, the opening size has an important influence on the shear strength. In order to obtain reliable shear properties and shear strength indexes of rock-soil mixtures, the plate opening size used during DSTs should be clearly stated, which can provide reference for the design and construction of the increasing number of high fill airports in mountain areas.

The shear strength of rock-soil mixture depends on the interaction between coarse and fine particles. When there is a large amount of coarse particles in the rock-soil mixture, the plate opening size between the upper and lower shear boxes should be increased accordingly.

In addition, it is necessary to consider the particle size distribution of the rock-soil mixture when determining the reasonable opening size for large-scale DSTs on gap-graded rock-soil mixtures. A plate opening of one-third to one-quarter $d_{\max}$ is suitable for the G1-type material. For mixtures with higher coarse-grained particle content, the opening size should be increased appropriately. If the

proportion of gravels with size in the range of $5.0 \text{ mm} < d < 20.0 \text{ mm}$ is more than 47%, like the mixtures G2 and G3, a plate opening of slightly greater or less than one-half $d_{\max}$ is more suitable.

5. Conclusions

In this study, three types of rock-soil mixtures were tested by DSTs and triaxial compression tests. The mixture G1 was obtained by adding some gravels to a fairly large volume of fine particles, and the fine particles completely enclose the coarse particles. The mixture G2 had a higher proportion of coarse-grained particles. However, the coarse particles cannot form a skeleton for the soil, and the fine particles were not enough to fill the space between coarse particles. For G3, the proportion of coarse grains was much higher, and the fine particles partially filled the space between coarse particles. The shear strength is determined by the extrusion, interlocking, and embedding of the coarse particles.

The plate opening size has an important influence on the shear strength of the gap-graded specimens. Under the same normal stress, the larger the plate opening size is, the more easily the particles are rolled and rearranged on the shear surface. As a result, the measured peak strength and residual strength decrease with increasing plate opening size. Therefore, the plate opening size adopted for DSTs should be clearly stated.

During large-scale DSTs on gap-graded rock-soil mixtures, a plate opening of one-third to one-quarter $d_{\max}$ is suitable for mixtures similar to G1. If the proportion of gravels with size in the range of $5.0 \text{ mm} < d < 20.0 \text{ mm}$ is more than 47%, like the mixtures G2 and G3, a plate opening of slightly greater or less than one-half $d_{\max}$ is more suitable.

Data Availability

The data used to support the findings of this study are included within the article

Conflicts of Interest

The authors declared that they have no conflicts of interest regarding this work.

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