Hindawi
Advances in Civil Engineering
Volume 2018, Article ID 6509728, 9 pages
https://doi.org/10.1155/2018/6509728

Research Article

A Systematic Method to Evaluate the Shear Properties of Soil-Rock Mixture considering the Rock Size Effect

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Received 29 March 2018; Revised 23 June 2018; Accepted 2 August 2018; Published 5 September 2018

Academic Editor: Dingwen Zhang

The soil-rock mixture (S-RM) is widely applied in the geotechnical engineering due to its better mechanical properties. The shear strength, an essential aspect of S-RM which governs the stability and the deformation, is rather necessary to be revealed properly. The extraordinary issue of S-RM compared to fine-grained soils is the grain size effect on the strength analysis. This paper proposes a systematic method to obtain the realistic shear strength of S-RM by detecting the rock size effect. Firstly, based on fractal theory, the rock size was determined as 5 mm by the multifractal property of granular size distribution. Then, based on 2 selected specimen sizes combining the engineering dimension, shear gaps (T) effect and specimen size effect on the shear strength of S-RM have been investigated. It is shown that the gap of the direct shear test decides the physical mechanism of particles forming the shear resistance of S-RM based on the variation of apparent cohesion and mobilized internal friction angle. Specimen size effect is weakened by the gap effect considering the boundary effect. Realistic and stable shear strength parameters of S-RM have been researched by a reasonable gap (0.2–0.4D, where D is the largest particle size).

1. Introduction

Soil-rock mixture [1] (sand-gravel mixture [2], bimrocks [3, 4], and gravelly soil [5, 6]) is a kind of special geological material widely distributed in slopes and landslides and frequently exists in geotechnical engineering works such as embankment dam, foundations, and tunnel excavation. Due to the limited understanding of this special geomaterial, the prediction of landslides and engineering failure became an intractable issue recently, and branches of studies have been carried out. Different from the fine-grained soils, the oversized particles in the S-RM lead to complicated mechanical properties such as the size effect and the structural effect.

The S-RM is commonly regarded as a two-phase material by distinguishing the "soil" and "rock," and the rock block content is regarded as the crucial input parameter to evaluate its mechanical properties [7–9]. It was found that the increase of rock block proportion can increase the strength of S-RM [10, 11]. Accordingly, for the geomaterials with wide granular size distributions, the demarcation value between "soil" and "rock" is the essential physical quantity to understand the grading properties. However, the demarcation size of particles in related studies is differently arranged as 2 mm [2, 5], 4.75 mm [6], or undefined standard [12], which makes the related results difficult to be compared. Actually, with the increase of large particle size, the fixed "rock" size is not adaptive to calculate the rock proportion of S-RM. For this question, Medley [3] empirically found that bimrocks such as mélanges are scale independent in terms of engineering dimension—a fractal-like characteristic—and proposed that rock size in bimrocks is $0.05\sqrt{A}$, where A is the engineering dimension. It is assumed that the strength and deformation parameters determined for S-RM with a certain rock proportion can be applied for preliminary engineering design with similar rock proportion depending on the engineering dimension [13]. A series of empirical approaches of artificial S-RM based on the laboratory test have been conducted [7–9], which consider the relative volumetric proportion determined by the characteristic dimension $0.05\sqrt{A}$. The rock size considering the researching dimension is more reasonable to evaluate the effect of rock blocks. Nevertheless, it still possesses the insufficiency which targets at the self-similar regularity of "rock" size, neglecting the description of overall particle size distribution. For instance, the number of blocks in engineering dimension may be different depending on the block size even if volumetric block proportions are the same [9]. In addition, for some coarse-grained soils naturally existed or artificially applied in engineering, the largest particle size is limited with engineering dimension. That is to say, an effective method to describe the granular size distribution is vital for the study of S-RM. Only if these questions have been demonstrated, the related research results can be well referred for engineering design effectively.

The shear strength parameters are valuable for design and failure prediction of engineering, and related laboratory investigations have been carried out to understand the shear behavior of S-RM. Based on the in situ shear test, Zhang et al. [14] found that the existence of rock blocks makes the deformation modulus and the internal friction angle of S-RM greater than that of the soil sample, while decreasing its cohesive force. The fracture plane in S-RM, often rounded rocks and formed in soil, is shown in an irregular shape because of the existence of rock blocks [15]. It was reported that the mechanical behavior of coarse-grained soils is influenced by the cemented properties [16]. The influence of particle size on the shear strength of coarse-grained soils, subjected to different gradation of the specimen, was investigated by numerical and experimental direct shear tests [17]. It is widely believed that the shear resistance of soil is affected by various factors, such as soil type, compactness, and grading properties. Most importantly, no matter what the kind of research purpose of S-RM is, the laboratory test method is definitely vital for acquiring the strength properties [18]. The direct shear test, adopted in this study due to simplicity and convenience, possesses some shortcomings such as the fixed failure plane and the nonuniform stress and deformation in the shear box. The shear resistance of gravelly soils basically originates from sliding of particles and particle rolling, so the formation of the shear band closely depends on specimen size and shear gap dimension which represents the opening between shear box halves. And it is reported that the formation of the shear band is the important cause of the scale effect [19].

However, according to the author's knowledge, only few articles about shear gap effect on shear strength of coarse-grained materials have been published [20]. Shibuya et al. [21] pointed out that the space between the upper box and lower box should be maintained at a constant value slightly larger than the thickness of a free shear band (approximately 10–20 times D50 for the sands). If the opening between shear box halves is too small, a portion of rock particles within the specified shear band will have crush and fracture failures, which causes the overestimation of actual shear resistance of the coarse-grained soil, while a large opening causes stress reduction and material loss at the specimen edge. To this end, this work attempts to acquire the reasonable shear gap of S-RM in the direct shear test, which is meaningful to obtain the more realistic strength.

2. The Fractal Structure of S-RM Gradation

The first aspect of size effect in S-RM is the particle size distributions (PSDs), which can be applied to predict its mechanical and physical properties. The existence of gravels decides the nonlinear characteristics in PSD of S-RM. Figure 1 presents the original size distribution of S-RM generated in the tunnel excavation in Xuzhou, China. The mixture contains the clayey matrix, gravel, and rock blocks, and the largest particle size of the samples is 60 mm by eliminating the oversize rock block. It can be analyzed that the traditional Talbot grading curve is not effective to depict the size grading properties because of the wide range of size distribution of S-RM.

The fractal theory was mainly used to explain the complex phenomenon in nature, which has also been applied in the geotechnical fields [22]. By using the cumulative solid mass distribution, the fractal representation of PSDs of soils was proposed [23], and the relation between fractal dimension and rock block size was discussed [24]. The fractal properties in two dimensions can be presented as follows [24]:

$$A(r > R) = C_{\mathrm{a}}\left[1 - \left(\frac{R}{\lambda_{\mathrm{a}}}\right)^{2-D}\right], \tag{1}$$

where R is the certain particle size, r is the granular size of S-RM, A is the cumulative area of particles whose sizes are over R, C_{a} is the shape factor, λ_{a} is the largest particle size, and D is the fractal dimension of granularity.

Taking the question into consideration,

$$V(r > R) = C_{\mathrm{m}}\left[1 - \left(\frac{R}{\lambda_{\mathrm{m}}}\right)^{3-D}\right], \tag{2}$$

where C_{m} is the shape factor, V is the cumulative granular volume of particles whose sizes are over R, and λ_{m} is the granular size. By multiplying the density ρ, the fractal characteristic based on the granular mass can be obtained as follows:

$$M(r > R) = \rho C_{\mathrm{m}}\left[1 - \left(\frac{R}{\lambda_{\mathrm{m}}}\right)^{3-D}\right]. \tag{3}$$

Meanwhile, the total mass of S-RM $M(r > 0)$ is presented as follows:

$$M(r > 0) = \rho C_{\mathrm{m}}\left[1 - \left(\frac{0}{\lambda_{\mathrm{m}}}\right)^{3-D}\right] = \rho C_{\mathrm{m}}. \tag{4}$$

Consequently,

$$\frac{M(r > R)}{M(r > 0)} = 1 - \left(\frac{R}{\lambda_{\mathrm{m}}}\right)^{3-D}. \tag{5}$$

Taking R as the largest particle size R_{L} in Equation (5), it is deduced that $\lambda_{\mathrm{m}} = R_{\mathrm{L}}$. The fractal presentation of S-RM can be obtained as follows [25]:

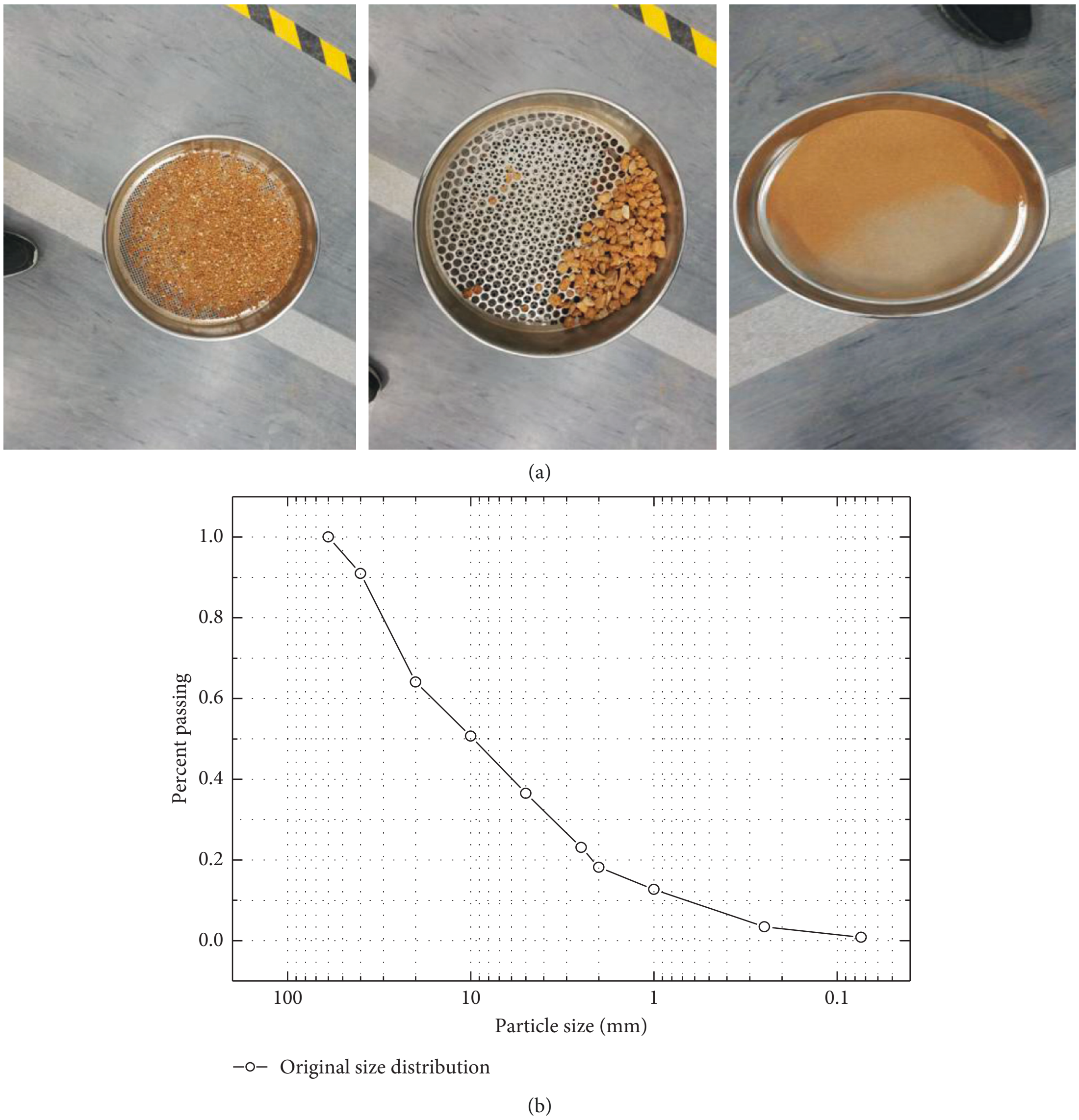

Figure 1: (a, b) Typical component and particle size distribution of S-RM.

$$\frac{M(r<R)}{M(r>0)} = \left(\frac{R}{R_L}\right)^{3-D}. \quad (6)$$

That is to say, the granular size properties can be characterized by the fractal exponent D if the plot $\lg(M(r<R)/M_T) - \lg R$ has the linear properties.

As soil is an open and self-organized system, and the quantity of fractal dimension, connected to evolutionary environment and mechanical properties, can effectively depict the gradation structure of S-RM. In order to obtain the fractal representation of S-RM, 3 series PSDs were calculated based on the Equation (6), and the average PSDs in Figure 2 is matched with the curves in Figure 1. The red solid line, fitted by the whole plot in Figure 2, indicates that the complexity of S-RM particle sizes can be well measured by a fractal exponent $D = 2.31$, which confirms the self-similar characteristic of S-RM. It is noted that the plots in Figure 2 do not strictly satisfy the strict linear relationship in the whole scale, which means the multifractal behavior in S-RM. Taking $R = 5$ mm as the boundary, the granular sizes in the two domains have the more rigorous fractal features, which can be depicted by $D_1 = 2.10$ and $D_2 = 2.59$, respectively. By this way, it is proposed that the investigated S-RM has two self-similar size intervals, which reveal the different spatial structure of S-RM gradation corresponding to "soil" and "rock." In this paper, $R = 5$ mm is regarded as the demarcation (rock size) which is not associated with the engineering dimension.

3. Experimental Procedure considering Size Effect

3.1. Determination of Specimen Size. In order to reveal the strength characteristic of S-RM further, the objective of this study is to attempt to investigate the proper relationship between rock block size and shear gap. Based on the size analysis in Figure 2, the largest particle size of the tested samples is selected as 10 mm, representing the "rock" (5–10 mm), and mass proportion is 28%. There has been some

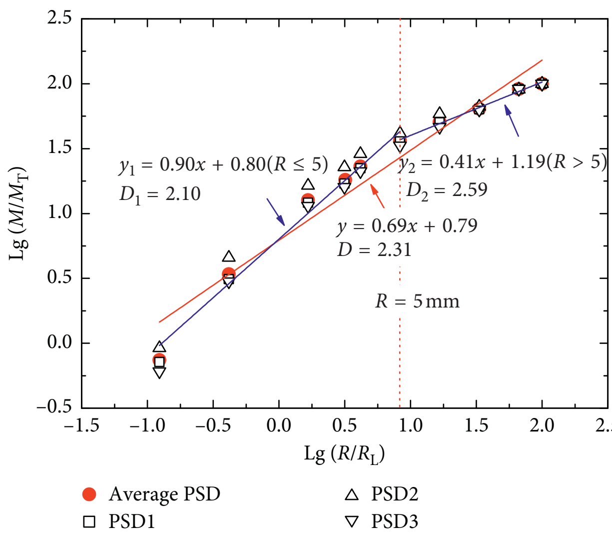

Figure 2: The multifractal properties of SRM.

controversy about the threshold ratio between specimen size and the characteristic particle size which bring out the size effect on the shear strength. In order to relatively avoid the specimen size effect on the testing results [26], the specimen sizes are determined as 300 mm (length, L) × 300 mm (height, H) × 300 mm (width, W) and 200 mm (radius, R) × 300 mm (height, H). Essentially, the size of the largest particle is larger than $0.05L_c$ ($0.05H/2 = 7.5$ mm), which can be regarded as the S-RM in engineering dimension [3]. The shear test was repeatedly performed based on the same specimen with little result departure existed in the same test condition. The residual strength is adopted to analyze the strength regularity with gaps as the abrasion and crushing of sample is little in the iterative test under low stress. In this case, the strength structural effect of large gravel acting on the specimen can be ignored and test duration can be reduced notably. It is noted that water effect was not taken into account to reveal the gap effect of S-RM in the present study. In order to avoid the cores in samples, the S-RM was made in the shear box compacted by 3 layers, respectively.

3.2. Testing Apparatus. The shear tests were carried out on the large-frame shear device ADS-500, as shown in Figure 3, with the corresponding standards in mind (ASTM, ISO, DIN 18137, part 3). The shear gap (T) can be adjusted according to the size of tested soils, and the sample surface can be selected as the effective surface area which produced the effective tangential stress of materials.

3.3. Arranging Shear Gaps and Related Parameters. As known, the failure surface of the soil specimen tested in the conventional direct shear test is along a straight plane without a certain thickness, which deviates from the real deformation and strength properties of the shear zone. On the one hand, the heterogeneity of stress and deformation is enhanced by the dislocation of the rock block in the shear process. Figure 4 presents the nonuniform deformation of

Figure 3: The large-frame shear device.

Figure 4: The nonuniform deformation of S-RM after the shear process without shear gap.

S-RM after the shear process without shear gap, which leads to the formation of the shear zone which is not a localized process. On the other hand, the shear strength of a single rock particle is much greater than that of a contact between particles in the shear zone.

The shearing process is achieved by moving the lower shear box above the guideway, and the upper shear box subjected to the vertical stress is fixed on the surrounding frame. In common conditions, the shear boxes are close to each other without space. In this study, by adding the prefabricated shim between the upper box and the surrounding frame, the upper box will be raised correspondingly after sample preparation. By this way, following the test procedure with a shear gap can be accomplished. The suggested shear gaps for the test of coarse-grained soils are not coherent [20, 21, 27], meaning that more work from an experimental or numerical aspect to discuss relation between grain size and gap effect is rather needed. In order to present the gap effect on the strength reduction properties of S-RM, the shear gaps were arranged from 0 mm to 8 mm with an increment amplitude of 2 mm in this work as the largest particle size is 10 mm. Then, the flat segment of shear strength varying with gaps and the regularity of strength parameters can be obtained, which indicates a suitable gap considering the rock size effect. The related information of direct shear tests of S-RM is presented in Table 1. Considering the excavated depth of samples, the vertical stresses are arranged at 100 kPa, 200 kPa, and 300 kPa, respectively,

Table 1: The related parameters of the direct shear test of S-RM considering the gap effect.

Largest particle size D_{max} (mm)	Testing scale (mm)					Gap (mm)	Vertical stress (kPa)	Shear velocity (mm/min)	Water content (%)
	L	W	H	R	H				
10	300	300	300	200	300	0/2/4/6/8	100/200/300	1.4	0

and the shear velocity was set as 1.4 mm/min for a slow shearing process [28, 29].

4. Results and Discussion

The relationship between effective tangential stress and shear displacement with the shear box of $L = 300$ mm, $W = 300$ mm, and $H = 300$ mm is presented in Figure 5. The curve of tangential stress can be approximately divided into 2 parts of an increased stage and a balanced stage. The increased part can be regarded as the elastic strain transfer of soils which is not a rigid material, and the balanced status means the formation of shear zone containing the plastic interaction of particles. With the increment of shear gap, the decline of shear stress can be easily observed. In the test of S-RM with lower shear gaps presented in Figures 5(a) and 5(b), the nonlinearity of shear stress curve is very conspicuous, and the variation of tangential stress with different vertical stress levels is not trenchant compared to Figures 5(c) and 5(d). By this, the systematic analysis needs to be performed to reasonably recognize the size effect induced by the rock size and thus to propose a suitable testing shear gap for evaluating the tangential properties of coarse-grained soils rigorously.

4.1. Gap Effect on the Shear Strength of S-RM. Taking the residual tangential stress at a shear displacement of $0.1L$ to be analyzed, it can be found that the relation between tangential stress and vertical stress with different gaps satisfies the Coulomb criterion as shown in Figure 6(a). At the lower vertical stress (100 kPa), the tangential stress without gaps is much larger than that with gaps. Although the dispersion of tangential stress reduces at higher vertical stress (200 kPa and 300 kPa), the results are overestimated at the smaller shear gap. It is noted that the tangential stresses with $T = 2$ mm and $T = 4$ mm are closely connected at different vertical stresses. The gap effect on tangential stress at the same vertical stress is presented in Figure 6(b). Peak tangential stress experiences a decline with the increment of shear gap from $T = 0$ mm to $T = 2$ mm and is kept at a stable status with the increment of shear gap changing to $T = 4$ mm. Accordingly, the reasonable gap dimension can be ensured as $T = 2$–4 mm. Meanwhile, in order to reveal the mechanism of granular interaction in the shearing process, the strength parameters, $\tan(\varphi)$, where φ is the internal friction angle, and cohesion, are obtained as shown in Figure 6(c). As believed, the internal friction angle is connected to the particle chain action, and the cohesion is mainly linked to particle occlusion and particle friction in coarse-grained soils. It is interesting that the relationship between cohesion and $\tan(\varphi)$ is in negative correlation with the increment of gaps, meaning the different particle interaction mode which forms the shear resistance of S-RM. From $T = 0$ mm to $T = 2$ mm, the apparent cohesion has an obvious decrease because the behavior of rock block in the shear band is transforming from shearing to sliding and rolling. Apparent cohesion and internal friction are balanced with $T = 2$ mm and $T = 4$ mm, while the cohesion apparently decreased lower than 0 in the case of large shear gap with $T = 6$ mm, which indicates the direct shear test loses the physical meaning as the specimen within the shear gap cannot form a normal shear zone. The $\tan(\varphi)$ increases obviously when $T = 6$ mm; thus, it can be seen that the particle chain action provides the prominent sources of shear resistance of S-RM.

In the small gap, as shown in Figure 4, the location of the rock in the shear zone is constrained, and the granular dislocation leads to the nonuniform deformation and the intense friction formed by applied stress between particles. In the large gap, the shear resistance is mainly originated by the granular collusion within the shear band. However, as shown in Figure 5(d), the residual shear stress decreases with the increase of shear displacement because the effects of stress reduction during consolidation and shear would influence the results, which is probably caused by the collapse of the material at the edge and the structural failure of soils in the shear band rather. So a reasonable gap is suggested for testing the realistic strength parameters of S-RM.

The results derived from another shear box ($R = 200$ mm and $H = 300$ mm) are shown in Figure 7. As shown in Figure 7(a), the tangential strength at different vertical stress levels is sensitive to the gap T, and the tangential stresses at $T = 2$ mm and $T = 4$ mm are very adjacent. The relationship between residual tangential stress and gap T is presented in Figure 7(b). By comparison with Figure 6(b), the coherent conclusion can be drawn that the reasonable gap for obtaining appropriate tangential strength of S-RM is $T = 2$ mm–4 mm. In addition, the relation between cohesion and $\tan(\varphi)$ is shown in Figure 7(c), which also indicates the different form of particle interaction to produce the shear resistance of S-RM with the variation of T. As shown, both the particle chain action and the particle occlusion have the significant contribution to shear resistance when $T = 2$ mm and $T = 4$ mm. In other cases, the particle behaviors in the shear zone are deviated from the real mechanism of the actual shear zone.

As presented in Figure 8, the failure plane is set in advance without gap, which restricts the development of the shear band. Under lower stress levels, as shown in Figure 4, the dislocation of particles is notable during the shearing process which leads to the inhomogeneous deformation of the specimen. Under higher vertical stress, abnormal crush and failure of the sheared rock block give the unreal strength parameters, while the contact between particles in a suitable gap, containing the particle rolling and particle sliding,

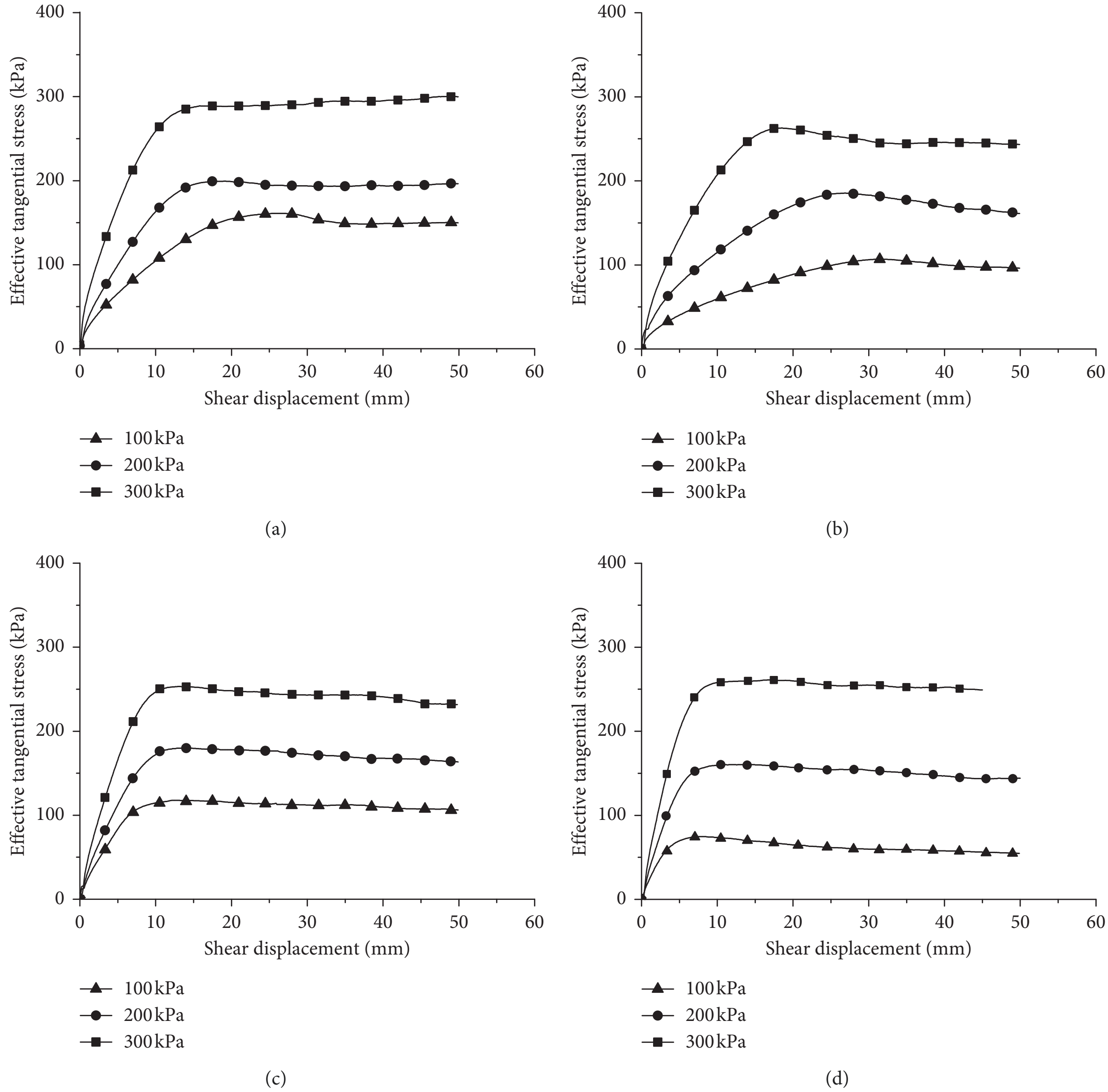

Figure 5: The relationship between tangential stress and shear displacement at $L = 300$ mm, $W = 300$ mm, and $H = 300$ mm: (a) $T = 0$ mm, (b) $T = 2$ mm, (c) $T = 4$ mm, and (d) $T = 6$ mm.

provides the stable resistance indicated by the flat segment in strength variation with T [20].

4.2. Specimen Size Effect on the Shear Strength of S-RM. In order to understand the specimen effect on the shear strength of S-RM, considering the gap effect, we choose the testing results at a vertical stress of 200 kPa for analysis. It is shown in Figure 9 that the shear strength reduces with the increase of specimen size, no matter whether there are gaps or not. By this, it can be found that the specimen effect with gap variation corresponds to the previous recognition without gap effect. Besides, increasing gap dimension can reduce the specimen size effect on S-RM shear strength caused by the boundary effect in different shear box sizes, which can generate the realistic granular mechanism of shearing coarse-grained soils.

5. Conclusions

This paper proposes a systematic approach to evaluate the shear properties of S-RM. By considering the spatial distribution of particle size, the fractal theory is introduced to reveal the structural features existed in S-RM. Meanwhile, the realistic granular interaction in the shear band of S-RM and the gap effect on the shear strength have been discussed through experimental results. Based on the direct shear test considering the rock size effect, the main conclusions can be stated as follows:

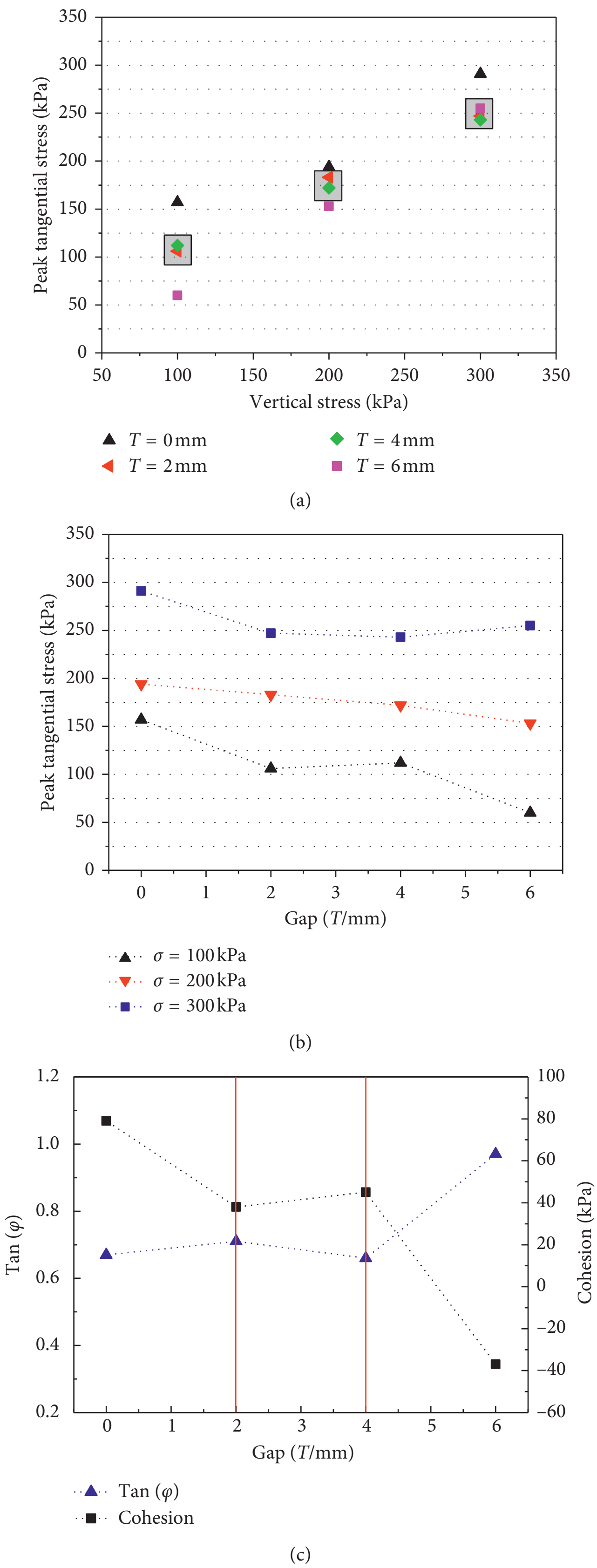

Figure 6: (a–c) The gap effect on the tangential properties of S-RM (shear box, $L = 300$ mm, $W = 300$ mm, and $H = 300$ mm).

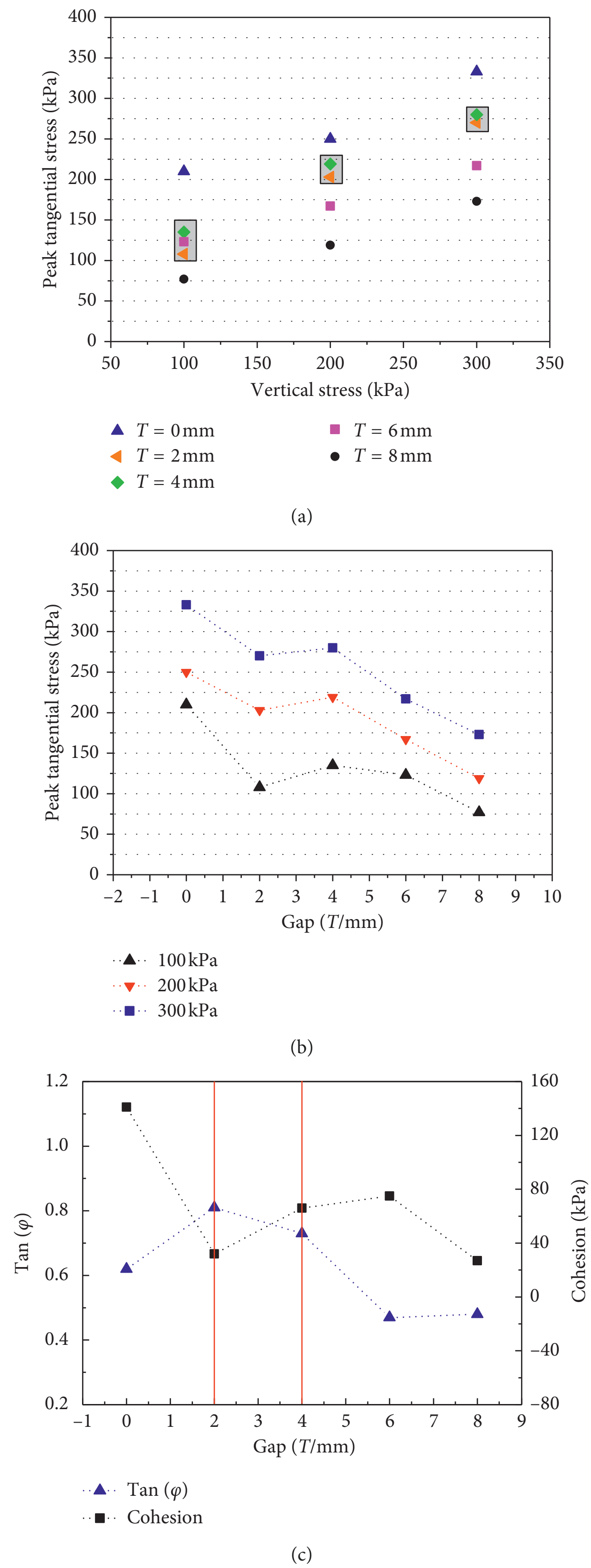

Figure 7: (a–c) Gap effect on the tangential properties of S-RM (shear box, $R = 200$ mm and $H = 300$ mm).

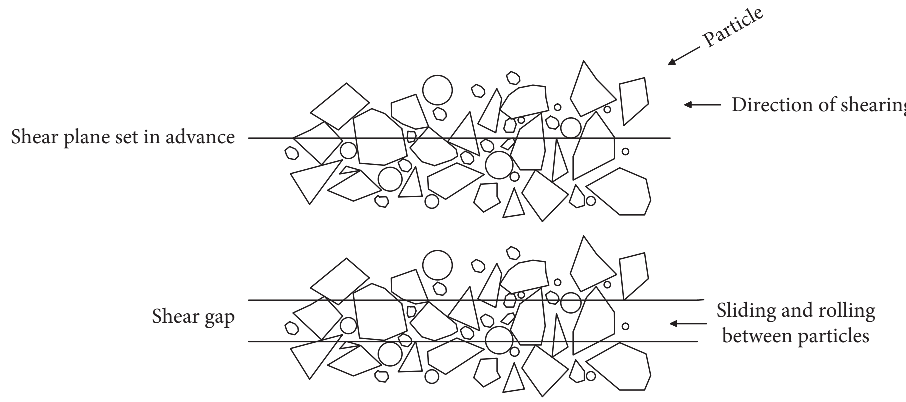

Figure 8: Illustration of the shear gap effect on the particle interaction behavior during shearing.

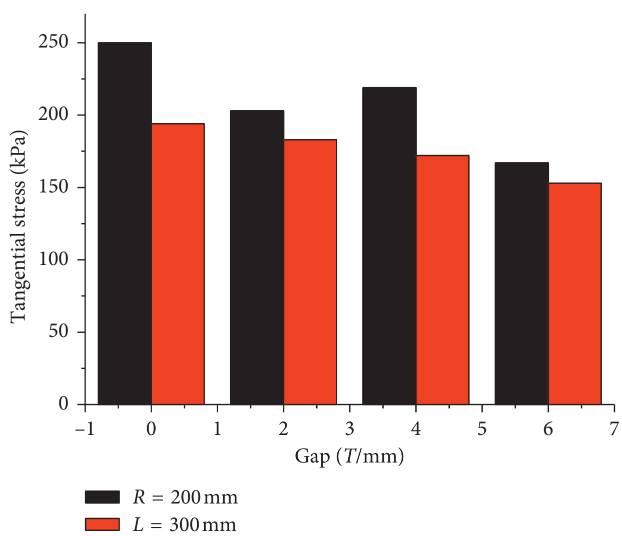

Figure 9: Comparison of tangential stress of different specimen sizes at a vertical stress of 200 kPa.

(a) The fractal presentation is a more effective method to evaluate the PSD of S-RM. These special soils with multifractal properties can be regarded as two-phase materials, and the distinguished size between "rock" and "soil" is the demarcation of scale-invariant interval.

(b) The shear behavior of S-RM is apparently controlled by the shear gap. With the gap increment, the relationship between internal friction angle and cohesion is in negative correlation. Stable and realistic shear strength of S-RM can be obtained in suitable gaps, and the specimen size effect also exists with the gap effect.

(c) The impact of the shear gap on shear strength has been analyzed from the granular interaction and the formation of the shear zone. Based on different sizes of the specimen, the reasonable shear gap of S-RM which considers rock size distribution with $D = 2.31$ is determined as $0.2D_{\max}$–$0.4D_{\max}$.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This study was supported by the Fundamental Research Funds for the Central Universities (no. 2014QNB38) and the National Natural Science Foundations of China (no. 41672343).

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