International Journal of Rock Mechanics & Mining Sciences 48 (2011) 1235–1247

Contents lists available at SciVerse ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Study on the shear strength of soil–rock mixture by large scale direct shear test

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ARTICLE INFO

Article history:
Received 26 May 2010
Received in revised form
12 September 2011
Accepted 27 September 2011
Available online 20 October 2011

Keywords:
Soil–rock mixtures
Soil/rock threshold
Digital image processing
Maximal observed dimension
In-situ testing
Shear strength

ABSTRACT

Soil–rock mixtures (S–RM) which formed in the quaternary period are a type of extremely inhomogeneous and loose geomaterial with a certain percentage of rock blocks. They are composed of rock blocks with various sizes and high strength, fine grained soil and pores. The meso-failure mechanism and macro-physical and mechanical characteristics of S–RM are largely controlled by its rock block proportion and the granular distribution. As we know, when the rock blocks in the S–RM are larger, it is difficult to take an in-situ sample for an on-site test. In addition, it is difficult to obtain the granular distribution of rock blocks in S–RM by traditional sieving tests. This paper uses a new method called digital image processing (DIP) in which the rock blocks in S–RM samples are separated from the soil matrix, and the proportion and distribution of the rock blocks is obtained quantitatively. The results are used for the sample preparation of the large scale direct shear tests which provide a new method for the test study of S–RM. According to the results of large scale direct shear tests the rock block size proportion controls the deformation and fracture mechanism of the S–RM. The shape of the shear stress vs horizontal displacement curve and the vertical displacement vs horizontal displacement curve of the S–RM samples are different from that of general "soil" and "rock". With the increment of the rock block proportion the shear band of the S–RM increases. When the rock block proportion lies in the range of 25–70%, the increment of the internal friction angle linearly increases with the increment of the rock block proportion. The cohesion of the S–RM decreases compared with that of the soil. When the rock block proportion is larger than 30%, however, there is only a little decrease in the cohesion with the increment of the rock block proportion.

1. Introduction

Soil–rock mixtures (S–RM) which formed in the quaternary period are a type of extremely inhomogeneous and loose geomaterial with a certain percentage of rock blocks, composed of rock blocks of various sizes and high strength, fine grained soil and pores [1]. As one kind of general geomaterial, S–RM is widely distributed in the natural (such as slopes, landslide dams, foundations, etc.). In recent years, S–RM landslides have become the main geological hazard in the world [2,3]. S–RM is also widely used as a geotechnical material in hydropower engineering and road engineering (such as earth dams and roadbed filling).

With the development of rock and soil mechanics and various kinds of large scale projects, especially the large scale hydropower project, the research on S–RM has attracted much attention. By consolidated-drained triaxial tests, Fragaszy et al. [4] has shown that the stress–strain and the volumetric strain–axial strain behavior of the prototype soil are not influenced by subrounded-to rounded grains floating in the matrix. Vallejo et al. [5–8] studied the shear strength of saturated cohesive soil with floating rock particles through laboratory shear tests, and shown that the shear strength of clay–rock mixtures gradually increases with increasing percentages of floating particles in unsaturated clays. By laboratory triaxial tests, Lindquist et al. [9–11] studied the relationship between the rock block proportion and the shear strength of mélange. Through field rainfall tests, field direct shear tests and laboratory large scale triaxial tests, Springman et al. [12] studied on the physical and mechanical characteristics of the material from an ice-water accumulation slope under saturated and unsaturated conditions, and discussed its failure mechanism under rainfall conditions. Through triaxial tests, Dupla et al. [13] also found that the volumetric fraction of gravels is the main parameter on both the elastic characteristics and material failure characteristics of coarse-grained soils. Through

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doi:10.1016/j.ijrmms.2011.09.018

field and laboratory tests, You and Tang [14] and He [15] studied the shear strength characteristics of S–RM distributed in the Three-Gorges reservoir area. By use of in-situ large scale horizontal push-shear tests, Xu et al. [16–18] studied the shear strength characteristics of S–RM distributed in the Hutiao–Gorge under natural and saturated conditions. Through field direct shear tests, Hou [19] studied the dilatant behavior of diluvia deposited S–RM distributed in the second terrace of the Yellow River in Lanzhou City, Gansu province, China.

All the previous studies indicate that the rock block proportion, rock block size and the composition of fine grains have greatly impacted on the physical and mechanical properties of S–RM, especially its shear strength parameters (such as the internal friction angle,) and the cohesion, c). On-site large scale tests ensure that the S–RM's original internal structural characteristics are maintained (such as rock block proportion, the distribution of the rock blocks, the rock–soil boundaries and so on). But as we know, the spatial distribution of the rock blocks in natural S–RM is variable, so the shear strength parameters of S–RM obtained from on-site tests are also usually variable. Therefore, it is very important to do the tests on the basis of a reconstituted sample of S–RM to study on its shear strength and find out the relationship between the shear strength and the internal meso-structure of S–RM.

In order to make the test results coincident with that of the S–RM being studied, we must firstly specify the rock block proportion and granular distribution of rock blocks in the S–RM of the study area. The size of the rock blocks in S–RM distributed in nature is usually large, it is very difficult to obtain the rock block proportion and its granular distribution in S–RM by a traditional sieving test. As a new technique developed in recent years, digital image processing (DIP) is widely used in the aviation industry, material industry, medical science, geotechnical engineering and other fields. Especially in the field of geotechnical engineering, the DIP has provided strong technical support for its development and made great achievements [20–26].

Built on the previous study, one method of large scale direct shear test using digital image analysis is introduced in this paper. Using DIP, the rock block proportion and the granular distribution of S–RM in the study area are obtained. According to these results, the reconstituted S–RM samples corresponding to the study area are made, which can be used for the large scale direct shear test, the study the shear strength characteristics and the failure mechanism of S–RM.

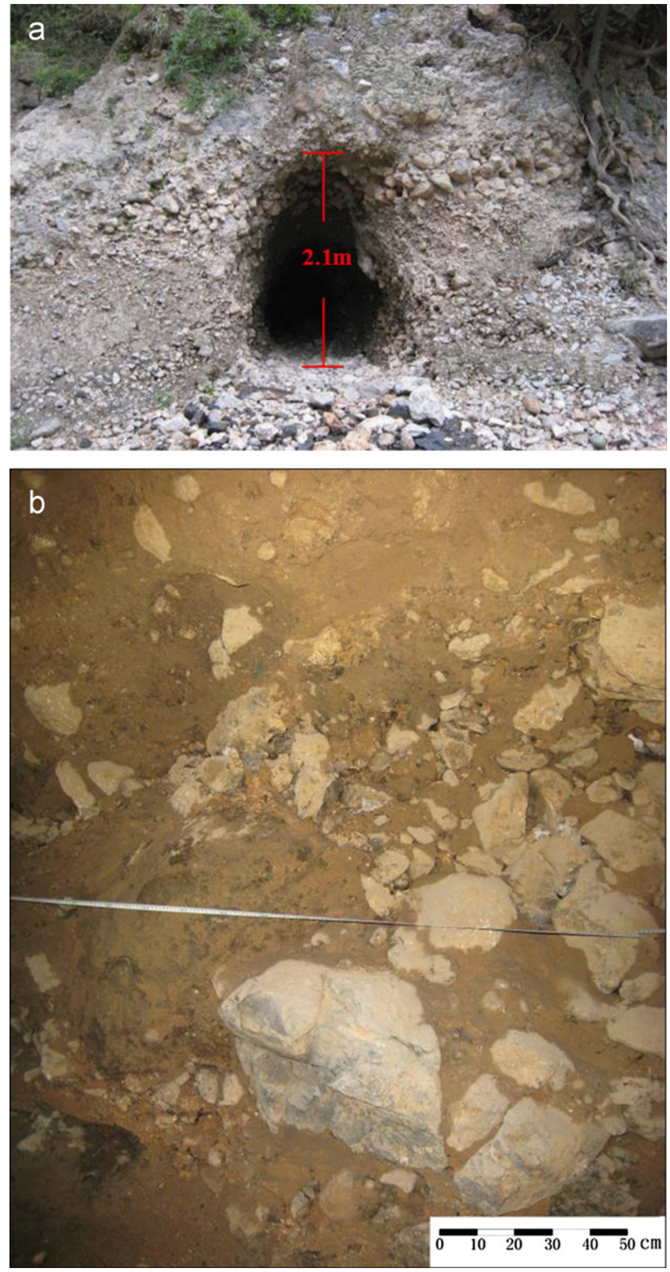

Fig. 1. Main material of the Xiazanri S–RM slope: (a) river phase cobble and gravel and (b) S–RM.

2. Description of the study area

The focus study area is the Xiazanri S–RM slope, which is located in the middle reaches of the Jinsha River in Yunnan province, China. According to field exploration, drilling and caves, the bedrock of Xiazanri slope is the Permian basalt, and the S–RM is about 60 m in thickness which is consist of two parts. One is layered, structured and bonded or semi-bonded river alluvium (Fig. 1a), which composes of the front part of the slope; the other is glacial S–RM (Fig. 1b). The lithological composition of the cobbles and gravels included in the river alluvium is very complicated (includes sandstone, limestone, granite and so on), and most of them are larger than 5 mm. The lithological composition of the rock blocks included in the glacial S–RM is single, and is limestone, but the block size is large (>2 cm, and some of them are larger than 20 cm). The composition fine part of the glacial S–RM is clay.

Because the slope lies in the upper reaches of a hydropower dam, and there is only 0.5 km between the slope and the dam, the stability of the slope is very important to the safety of the hydropower station. To have a good evaluation of the stability of Xiazanri S–RM slope, the key problem is obtaining the physical and mechanical parameters of its geomaterials. However, the scales of the rock blocks in the S–RM in the study area changes greatly, and according to the exploratory adits the largest bock size may be larger than 3 m. It is very difficult or impossible to prepare a sample for an in-situ test.

To obtain some reasonable strength parameters of the slope, and to find some effective methods of obtaining the S–RM's mechanical parameters, we used the technical flowchart in this paper, shown in Fig. 2. First, section images of the S–RM need to be taken in the field. Then, using DIP techniques we can obtain the rock block proportion and block size distribution. Based on the analysis of results, we can make the reconstituted samples of S–RM used for large-scale direct shear tests ($L\times W=60$ cm $\times$ 60 cm, and the height of the shear box is 40 cm). This opens the door to remodeling sample tests of S–RM and other similar geomaterials in a new way.

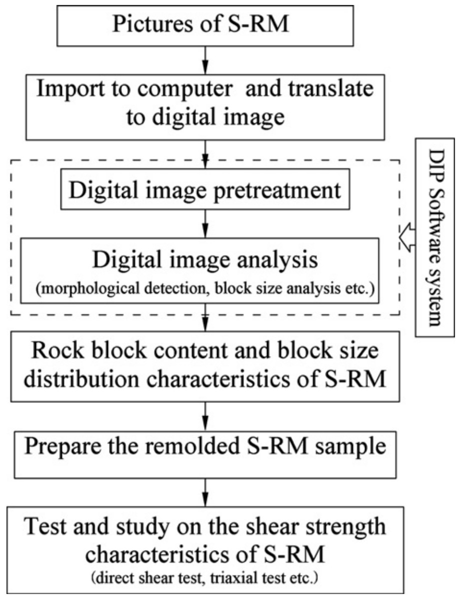

Fig. 2. Technical flowchart for study on the tests of S–RM.

3. Granular distribution characteristics of S–RM

3.1. Soil/rock threshold (S/RT)

As mentioned above, S–RM is made up of fine-grained ''soil'' and bigger rock blocks. The rock block proportion has a great effect on the physical and mechanical properties of S–RM. How to divide ''soil'' and ''rock'', or how to determine the value of S/RT is one important part of the study of S–RM. This value has important theoretical and practical implications to reasonably determine the rock block proportion and to evaluate the physical and mechanical properties of S–RM.

In terms of meso-structural mechanics, at a certain scale of study, those grains whose size does not control the macro-mechanics of S–RM are considered as ''soil'', while others whose size has great effect on the failure mechanism and macro-mechanics of S–RM are considered as ''rock''. According to this, the conception of ''soil'' and ''rock'' in the S–RM is relative, and depends on the study scale (Fig. 3).

Only under the determined geological conditions and study scale, can the S/RT of S–RM be uniquely determined [1]. In a small study scale (such as the sample scale used for laboratory tests), small grains (or rock blocks) may control the macro-mechanics of S–RM. However, when the study scale becomes larger, those grains may not affect the macro-mechanics of S–RM, so at this time it cannot be considered as ''rock'' but ''soil''. In terms of how to determine the value of S/RT, Lindquist et al. [1,9,11] carried out a detailed study, and gave the criteria for judging ''soil'' and ''rock'' fractions of S–RM as follows:

$$f = \begin{cases} R & (d \geq d_{\text{thr}}) \\ S & (d < d_{\text{thr}}) \end{cases} \tag{1}$$

where

$$d_{\text{thr}} = 0.05 L_c \tag{2}$$

and where S and R, respectively, represents ''soil'' and ''rock'' in the S–RM; d is the diameter of the rock block; d_{thr} represents S/RT of S–RM; L_c represents the characteristic engineering scale of S–RM, and is an index which varies according to the working scale of the engineering problem under investigation: to a study plane in 2D, L_c is equal to the square of the study area; to a tunnel, L_c is equal to its diameter; to a triaxial sample, L_c is equal to its diameter; while to a slope, L_c is equal to its height.

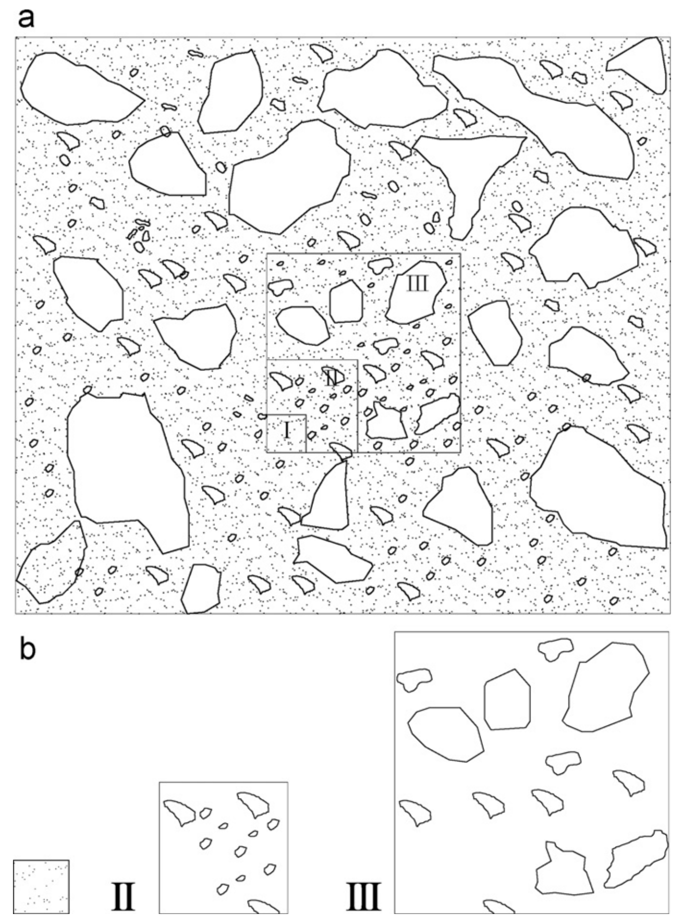

Fig. 3. Relationship between the internal structure and study scale of S–RM [1]. (a) The whole structural model of S–RM and (b) simplified model of S–RM under different study scale.

According to the direct shear test size used in this paper, the characteristic engineering scale (L_c) is equal to the shear box's height, namely L_c=40 cm, and based on Eq. (2) the value of S/RT (d_{thr}) should equal to 0.05×40 cm=2 cm.

3.2. Block size analysis of S–RM based on DIP

In recent years, the DIP technique has been widely used in the analysis of the internal structure of geomaterials. Using the DIP technique, Xu [1] have studied the meso-structural characteristics of S–RM in details. In connection with this approach, this paper studies the rock block proportion and granular characteristics of S–RM of the study area. The results of the analysis provides the basis for the next large-scale direct shear tests.

3.2.1. Rock block size

Due to the limitation of the existing technical conditions, it is very difficult to obtain the image series of the S–RM in three-dimensional space. That is to say, by using the existing technique it is impossible (or very difficult) to obtain the 3D structural characteristics (such as 3D morphological parameters, rock block proportion, spatial distribution characteristics of the rock blocks in the S–RM, etc.) of the S–RM's undisturbed sample.

Because of the uncertainty of the spatial distribution in three-dimensional space of rock blocks, the rock block size obtained from 2D section is not always its real size in 3D. In this paper, we

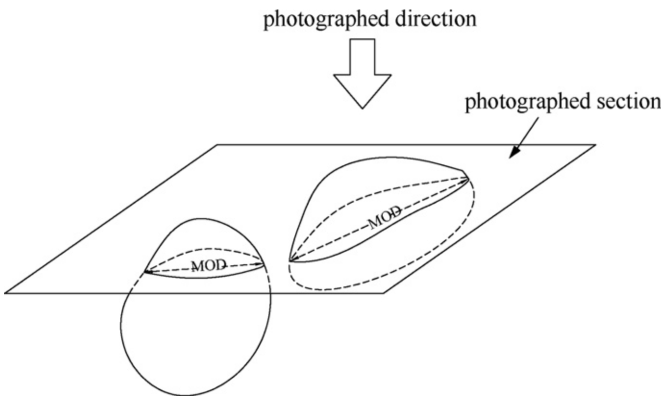

Fig. 4. Relationship between the maximum observed dimensions (MOD) of rock blocks in S–RM and the photographed section.

call the rock block size obtained from two-dimensional section as maximal observed dimension (MOD) [11], which means the maximal dimension that can be observed from the rock block (Fig. 4). Because of the random spatial distribution of the internal rock blocks, in a statistical, the MOD distribution can approximately reflect the in-situ size distribution characteristics of S–RM [1].

3.2.2. Obtaining the cross-section images of S–RM

To obtain the cross-section images of S–RM, we select an existing section or excavate a new section in the study area, and then clean its surface to take good pictures.

In this paper, a prospecting drift (Fig. 1a) is selected as the image acquisition section of S–RM in the study area. The photos are continuously taken from the outer to the inner of the left side of the drift by using a Canon camera. About thirty pictures are obtained, and the resolution of each picture is 40 pixel/cm. A ruler is used when taking photos, so we can translate the dimension in digital image of S–RM (unit is pixel) to its actual dimension (unit is centimeter or meter). Fig. 1b shows a picture obtained in the drift.

3.2.3. Digital image processing (DIP)

DIP includes the removal of noise, contrast enhancement, recovery, segmentation and characteristic extraction of images (from camera, scanner, CT machine, etc.) through computers. In computers, the digital image is composed of a rectangular array of pixels. Each pixel is the intersection area of a horizontal scanning line with a vertical scanning line. Each pixel is assigned an integer value, which is used to present the brightness at this point, and named as the gray level. For the mostly used 256 Gy images or binary images, their gray levels have an integer interval from 0 to 255 and from 0 to 1. The digital image is composed of an array of pixels with different gray levels, and different gray levels represent different internal structure information of the image. So we can use a discrete function $f(i,j)$ in the i and j Cartesian coordinate system to express the digital image, and then use this discrete function as the base of the digital image processing.

Images of geomaterials, from cameras or other image obtaining equipment, contain abundantly structural information about the materials. The information can be represented by an array of the gray levels or the discrete function of gray levels $f(i,j)$. Therefore, the components, rock block proportion, rock-size distributions, morphological properties of the rock block and other useful information of S–RM can be obtained from the gray level of each pixel by using DIP.

3.2.4. Block size analysis of S–RM in study area

For the influence of the external factors (such as illumination, smooth degree of the section, the contrast between the rock blocks and the surrounding "soils", etc.), the cross-section image of S–RM from the camera may have image noise that affects their use in DIP. To accurately obtain the internal structural characteristics of S–RM, noise removal, contrast enhancement and other pre-treatments should be carried out on the original images by existing image processing software (such as Photoshop).

After going through the image pre-treatments, the images of S–RM can be used for the extraction of the internal structure by using image segmentation technique. Firstly, by using binary processing, these rock blocks in the image of S–RM will be separated from the surrounds "soils". Fig. 5 shows the binary image which is shown in Fig. 1 after noise removal and binary processing, and the black blocks represent the rock blocks in the S–RM.

Then, by edge detection and other digital image analysis, the MOD and section area of the rock blocks can be obtained from the binary image (such as Fig. 5). But the unit of the MOD from the digital image is a pixel (the unit of the area is: pixel $\times$ pixel). To get the real size (or area), the pixel unit must be transformed to centimeters or meters by the following formula:

$$S = \frac{L_{ab}}{N_{ab}} \tag{3}$$

where S is the transforming scale of length (the transforming scale of area may be S^2), which means the actual dimension of each pixel in the digital image; L_{ab} is the actual dimension between point a and b in the image; N_{ab} is the number of pixels number between point a and b in the image.

Through the unit transformation, the value of the MOD can be transformed to its actual dimension. Then according to the S/RT (d_{thr}=2 cm) of S–RM, those blocks whose MOD is larger than d_{thr} are classified as "rock", while those blocks whose MOD is less

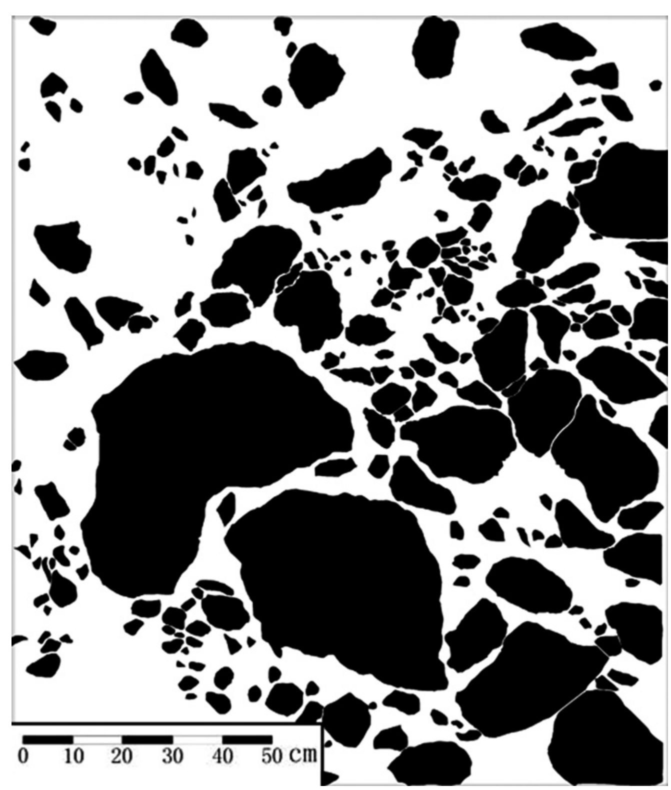

Fig. 5. Binary image of the S–RM's internal structure after digital image processing.

than d_{thr} are classified as "soil". Then, according to the rock density (ρ_R) and soil density (ρ_S) of the study area, the granularity accumulation distribution of the rock blocks can be calculated from

$$P_r = \frac{A_{R_r}\rho_R}{A_R\rho_R + A_S\rho_S} \quad (4)$$

where P_r is the weight percentage proportion of the rock blocks whose MOD is less than r; A_R is the total area of the rock blocks in the measurement area; A_S is the total area of the soil in the measurement area; A_{R_r} is the total area of the rock blocks whose MOD is less than r.

The lithology of the rock block for our study is limestone, and by field measurement its density is about 2700 kg/m^3. The density of "soil" that composed to the S–RM is about 1950 kg/m^3.

3.3. Rock block size distribution of S–RM in the study area

Based on the above technology, and to meet the requirements of the statistical analysis, seven S–RM images were selected for the study of granulometric characteristics of the S–RM by DIP. The total measuring area is about 26 m^2, and each region looks like a rectangle with about 2 m in length and about 1.5 m in width. Fig. 6a shows the rock block size distribution curve of each S–RM image.

Fig. 6a indicates that the rock block (with MOD larger than 2 cm) proportion of each S–RM sample in the study area is very inhomogeneous (from 33% to 75%), which shows that high heterogeneity is a typical structural characteristic of S–RM. For the convenience of the study, the average rock block size distribution curve is obtained (Fig. 6b) from the analysis results of each sample, which is shown in Fig. 6a. From Fig. 6b, we can find that the average rock block proportion of the study area is about 52%. Furthermore, we can see from Fig. 7 that the frequency distribution of the rock blocks has multimodality characteristic and the rock block size is larger. In the measuring range, the mass proportion of the rock blocks whose MOD is larger than 30 cm is about 57.57% of the total rock blocks, and those larger than 50 cm is about 36.3% of the total rock blocks.

3.4. Selection of rock block size distribution of the test samples

As we know, S–RM includes various sizes of rock blocks. However, it is impossible to include all these sizes of rock blocks in our test sample. So there should have a limitation in the size of rock blocks in the test sample. There are two issues concerning the large scale reconstituted sample test of the S–RM (such as direct shear test, triaxial test, etc.): (1) how to determine the maximum rock block size in the sample; (2) how to treat those over-size rock blocks? For the over-size rock blocks, three main methods are usually used in tests: the "scalping method", the "replace method" and the "parallel gradation" [27]. For S–RM, the "large" rock blocks have a great effect on their macro-mechanics [1], and the "replace method" (replace larger particles, whose dimension larger than the test requirement size, with the same mass of particles in the largest size of the test requirement) may consider more about the "large" rock blocks. So the "replace method" is used in this paper.

About the first problem, in the ASTM standards the maximum particle size is 1/6 of the minimum sample dimensions. However, if using 1/6 of the minimum sample dimensions as the maximum rock block size, it may greatly neglect the actual function of those "large" rock blocks in the S–RM, resulting in test errors. To study the influence of the large rock blocks on this kind of inhomogeneous geomaterials, Medley et al. [11,29] firstly select 3/4 of the minimum sample dimensions as the maximum size in the test, and have performed some serious study on this approach. To

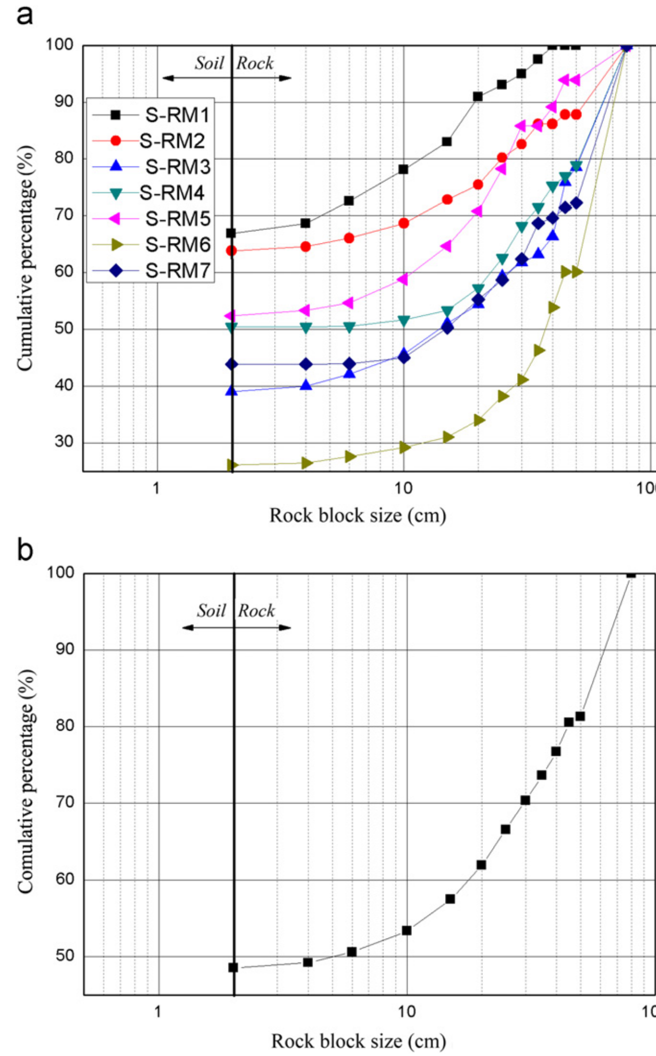

Fig. 6. Digital image processing results of the rock block size analysis of the S–RM in study area: (a) the rock block size accumulation curves of each S–RM sample and (b) the average rock block size distribution curve of the S–RM in the study area.

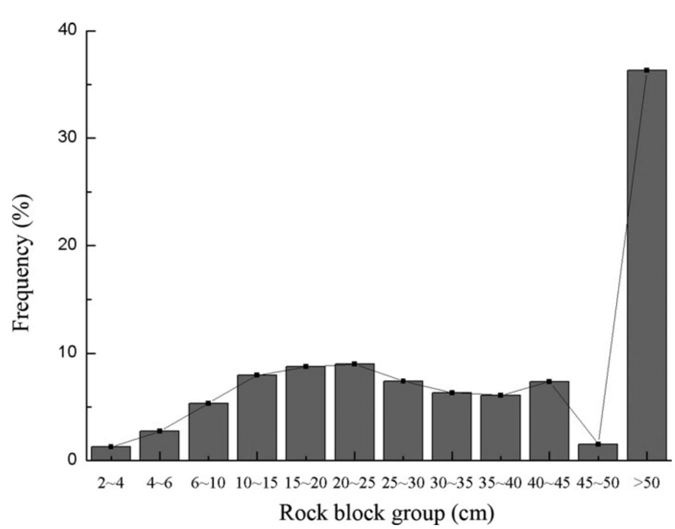

Fig. 7. Rock block frequency distribution to the total rock blocks in S–RM of the study area.

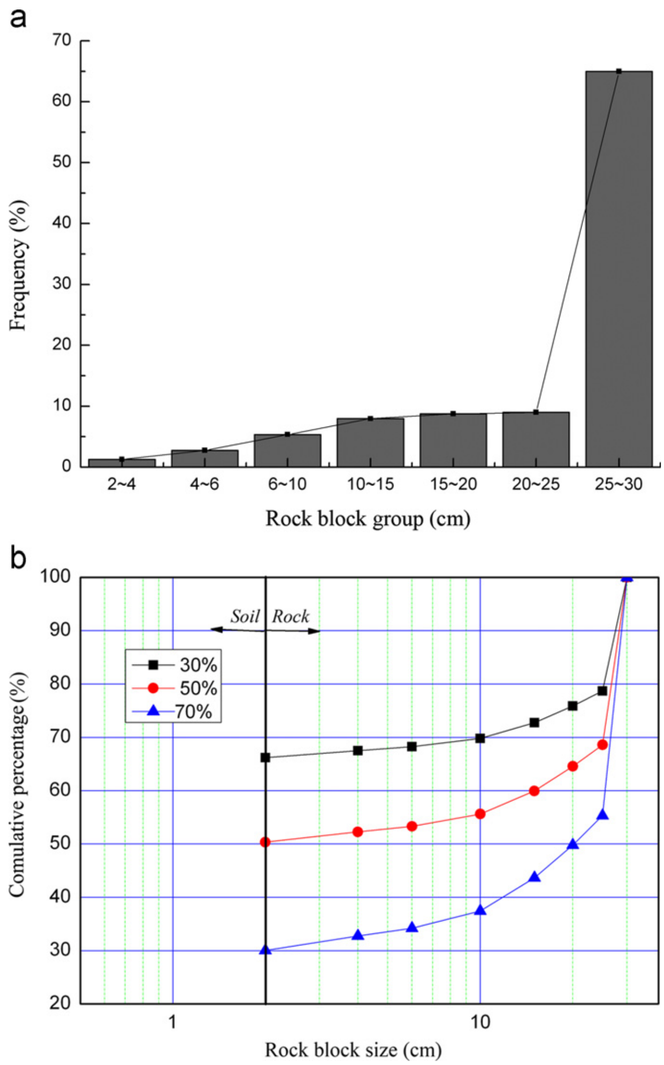

Fig. 8. Rock block size distribution used for the large scale direct shear tests of S–RM: (a) frequency distribution of rock block groups and (b) the rock block size accumulation curves of S–RM sample with different rock block proportion.

make the rock block size distribution of the sample close to the actual distribution, and to consider the limitation of the test scale, we used the following distribution scope of rock block size of S–RM samples [28]:

$$D_R = (0.05-0.75)L_c \quad (5)$$

where D_R is the rock block size in the S–RM sample; L_c is the characteristic a engineering scale. In direct shear test, it is equal to the height of the single shear box, and in triaxial test, it is equal to the diameter of the sample. In this paper, the height of the single shear box is 40 cm, and from formula (5) the distribution scope of the rock block (D_R) should be 2–30 cm. For the over-size rock blocks (with diameter larger than $0.75L_c$=30 cm) we use the equivalent mass with rock blocks whose size lies in the range 20 cm–30cm to replace them (“equivalent mass replacement method”). According to the frequency distribution characteristics of the rock blocks of S–RM in the study area (Fig. 7), and by using “equivalent mass replacement”, we get the frequency distribution of the rock blocks of the S–RM samples used for our study tests (Fig. 8).

To study the relationship between the shear strength of S–RM and its rock block proportion, four groups of S–RM sample with different rock block proportion (0%, 30%, 50% and 70%) are used for our large scale direct shear test. For each sample with different rock block proportion, the frequency distribution of the rock block is kept constant. According to Fig. 8a, the cumulative curves of the rock block proportion of each group can be obtained and is shown in Fig. 8b.

During the sample preparation, to keep the characteristics of the “soil” component (such as composition, particle size distribution, etc.) and the rock blocks (such as lithology, morphology, etc.) be consistent with the original S–RM as much as possible, in this paper, the “soil” used for the tests is obtained from the in site S–RM in the study area and sieved using a round hole sieve of diameter equaling to 2 cm. The rock blocks are also obtained from the in-situ S–RM in the study area.

4. Test procedures

In general, we perform the direct shear test on the reconstituted sample in the laboratory. However, because many materials used for our large scale direct shear test, and for the limitation of the traffic conditions of the study area, we perform the test in the field. The test procedures used in this paper are described as follows:

(1) *Preparing the test-bed*: First, a groove is excavated in the test site. The depth of the groove is about 20 cm, and the width should be equal to or larger than the width of the sample. The length is determined by the test equipment (the length of the jack), the length of the sample and other factors.
When the groove is finished, it will be filled with gravel, tamped and poured with cement mortar. Then the foundation of the test-bed of the field direct shear test is formed. According to the sample size (60 cm × 60 cm × 80 cm), the lower shear box and the reaction bearing of the jack is precast with concrete (Fig. 9). The two sides of the lower shear box are transparent, and act as the observation windows in the testing process. During the test they are blocked and fixed with organic glass.
(2) *Preparing the upper shear box*: For the limitation of the field condition, in this paper, we use the upper shear box, which is made of hard planks of pine. To keep the stiffness of the shear box, we select the hard planks of pine with 30 mm in thickness as the material for the upper shear box, and they are nailed according to the predetermined scale (Fig. 10a). Then, the upper shear box is bound with a steel strand, and reinforced ribs are added at its four corners as shown in Fig. 10b. All of these will keep the shear box to have good stiffness, and not to distort during the testing process, which will meet the test standard requirements.
(3) *Installing back pressure system*: In general, the methods used for normal pressure of direct shear tests include lateral wall fraction, ground anchor, heaped load and so on. We can

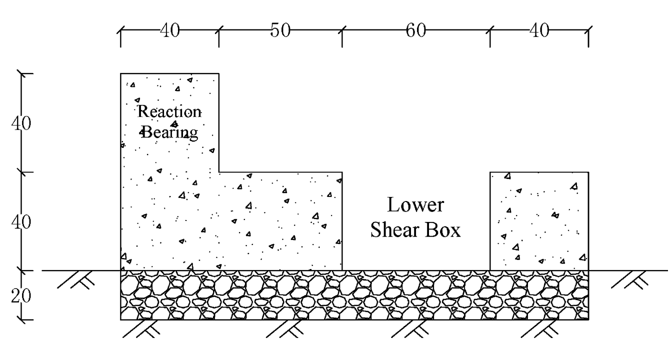

Fig. 9. Section diagram of the large scale direct shear test bed in field (unit: cm).

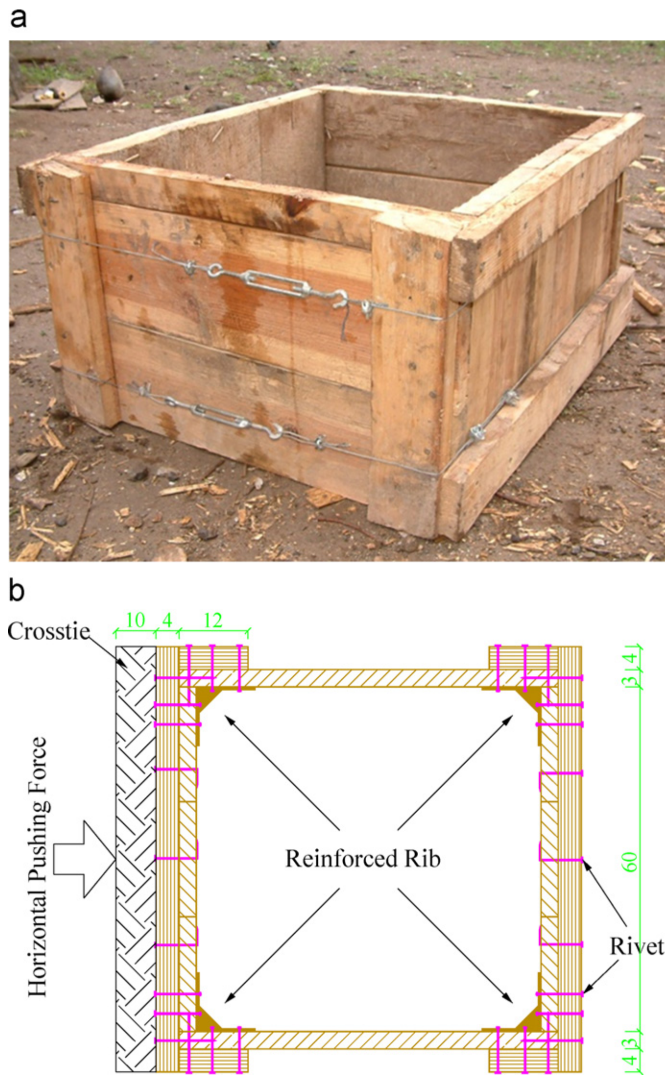

Fig. 10. Shear box used for the direct shear tests: (a) the picture of the upper shear box (60 cm × 60 cm × 40 cm) and (b) the cross section of the upper shear box (unit: cm).

select a suitable method according to the field conditions and engineering requirements. In this paper, the heaped load method is used as the back pressure system.

(4) *Preparing the test materials*: The water content of the "soil" of the S–RM sample is determined by the water content of the field sample (about 20%). The rock block proportion and rock block size distribution of the sample are obtained by the method mentioned in Section 3.4. To ensure that the distribution of the rock blocks in the S–RM sample are uniform, the "rock" blocks and the "soils" are fully mixed and the total mass of the materials is about twice of the actual mass used for our test.

(5) *Loading the sample*: The two sides of the lower shear box are sealed with the organic glass which is about 2.0 cm in thickness, so we can observe the development of the shear zones and the failure mechanism of S–RM during the whole testing process. To prevent the deformation, the organic glass must be fixed well. Then the test materials are placed into the shear box layer by layer (the thickness of each layer is about 15 cm) and tamped.

To keep the uniformity of each layer and to prevent the separation of the "soil" and the rock blocks, one iron hoe with about 1.5 times of the largest rock block size is used to spade the materials randomly. In addition, to prevent the separation of the two adjacent layers, each layer should be loosed about 5 cm in thickness before the next layer is placed. When there is about 10 cm in thickness before the lower shear box is fully filled, the upper shear box is placed with a gap about 6 cm between the upper and lower shear box. Then fix the upper shear box and continue to load the sample. To avoid a discontinuity of the test sample between the lower and upper shear box, the thickness of the loading layer should be about 25 cm. After this, the test materials are loaded as before until the shear box is full.

To study the deformation and failure mechanism of S–RM, in this paper noodles are placed as marks inside the organic glass of the lower shear box each 5 cm (Fig. 11). The noodles will deform with the deformation of the sample. That is to say the deformation of the noodles may easily indentify the deformation of the sample.

Based on the field measurement, in this paper the density of the samples with rock block proportion equal to 0%, 30%, 50%

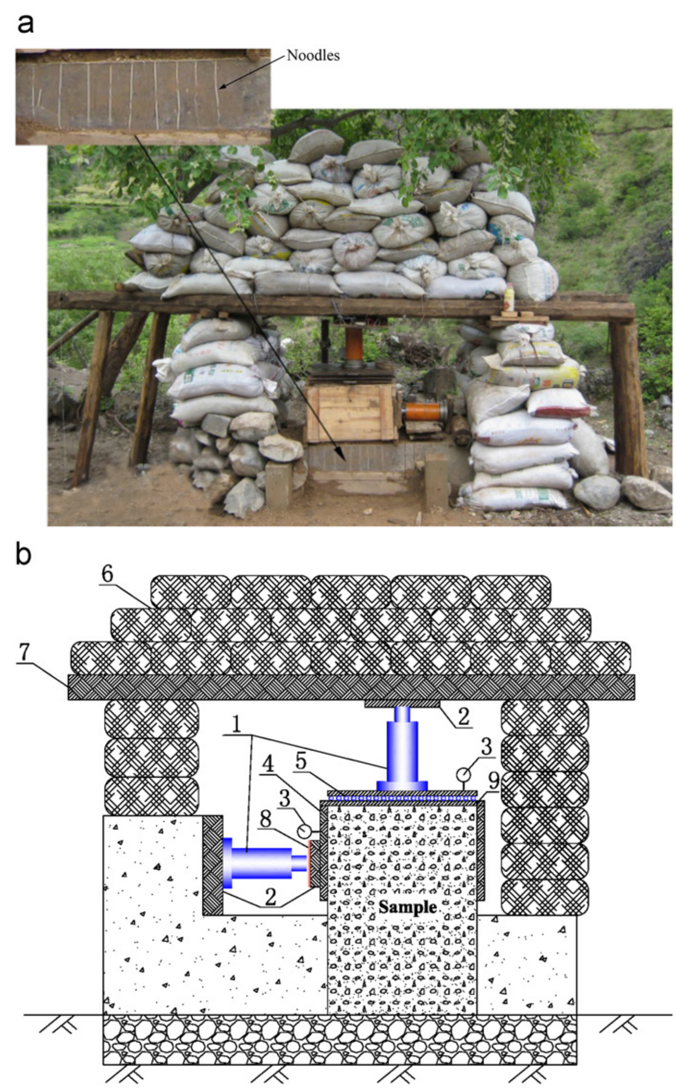

Fig. 11. Test equipment of the large-scale direct shear test of S–RM in field: (a) overall perspective of the field test, (b) profile of the test equipment. 1—jacks; 2—crosstie; 3—dial indicator; 4—shear box; 5—sliding steel plate; 6—back pressure system; 7—beam; 8—slideway; 9—bearing plate.

and 70% is about 1943 kg/m^3, 1987 kg/m^3, 2044 kg/m^3 and 2088 kg/m^3, respectively. The density of the in-situ S–RM is about 2051 kg/m^3, which is equivalent to that of the reconstituted sample at 50% rock block proportion.

(6) *Installing the test equipment*: After loading the sample, the bearing plate, sliding steel plate and jack are placed on the sample successively. The central axis of the jack should be consistent with that of the sample, and ensure that the jack is perpendicular to the top surface of the sample so the normal stress of the jack can apply on the sample perpendicularly. To minimum the side friction effects of the shear box, the bearing plate and the upper shear box are connected together, so that they can move consistently in vertical and horizontal directions.

Then the crosstie, slideway and jack are placed on the side of shear box where the horizontal shear stress is applied, and to keep the horizontal shear stress applied on the sample horizontally, the medial axis of the jack should lie in the medial plane of the sample. The slideway is used to make the upper shear box to move freely together with the upper part of the sample in the vertical direction in the test process, which will also minimize the side friction effects of the shear box.

When the normal and horizontal jacks are successfully placed, the measuring equipment installed accordingly: a LVDT pressure sensor (precision: 5%) connected with the jack, which is used for the pressure measurement of the jack; the dial indicators that are used for the measurement of the horizontal and vertical displacements. All the pressure and displacement measurements were recorded manually at every load step.

When all the test equipment is successfully installed, the fixing devices of the upper shear box removed. Fig. 11 shows the final test equipment.

(7) *Consolidation*: Based on the value of the normal stress that is used for the test, each load step should be applied on the sample step by step. When each load step is applied and reaches a stable value, record the reading of the pressure transducer and vertical dial indicator. Then, apply the next load step until the normal stress reaches the predetermined value, and keeps stable for 1–2 h.

(8) *Shear*: When the consolidation step is finished, the horizontal shear stress will be applied step by step, and controlled so that the horizontal deformation rate is about 2 mm/(15–20) s. At each horizontal shear stress step, we should check the reading of the normal stress transducer and keep it at about the predetermined value. If the reading of the normal stress transducer deviates from the predetermined value, the vertical jack should be adjusted to make its pressure return to the predetermined value.

After each horizontal shear stress step is finished and becomes stable, record the reading of the horizontal pressure transducer and the dial indicators (vertical and horizontal). Through the organic glass, we may observe the deformation and failure of the shear zone and take photos during the whole shear test process. Go on applying the next shear step, until the test is over.

(9) *Test over*: Dismantle the test equipment, record the final state of the shear zone, deformation characteristics of the marking noodles and take photos, all of which will be used for the research on the deformation and failure mechanism of S–RM.

(10) *Test results treatment and analysis*: The horizontal shear stress vs horizontal displacement curve and vertical displacement vs horizontal displacement curves will be drawn.

5. Test results analysis

5.1. Characteristics of the test curves

Based on the field test results, Fig. 12 shows the horizontal shear stress–horizontal displacement curves and the vertical displacement–horizontal displacement curves of the direct shear tests of S–RM under different rock block proportion and different normal stress conditions. In the vertical displacement vs horizontal displacement curves, the vertical displacement shows compression when its value is positive and shows dilation on the contrary.

From Fig. 12 we can find:

(1) With the increment of the normal stress, the shear strength of S–RM will increase gradually. The rock block proportion of S–RM has great effects on its shear strength. Under the same normal stress condition, the shear strength of S–RM will increase with the increment of its rock block proportion.

(2) From the shear stress–horizontal displacement curve of the S–RM we can find that there is a gentle curve segment (initial yield stage) after the elastic deformation stage and before it reaches to the peak strength, and with the increment of the rock block proportion and normal stress, this segment becomes more and more obvious. In the initial yield stage, the “soil” in the S–RM will be damaged, and local cracking may appear near the shear zone. When the shear displacement reaches the latter part of the initial yield stage and because the large rock blocks bite each other, the shear stress of the sample will increase again (Fig. 13), until it reaches to the maximum shear strength and the biting force between rock blocks reaches to its maximum value (Fig. 13c). When the shear displacement increases continuously, the rock blocks will continuously move and rotate under the action of the biting force. Even some rock blocks may jump over other blocks on the other side of the shear surface, the arrangement of the rock blocks will adjust continuously (Fig. 13d). As a result, the shear stress of the sample decreases and reaches to its residual strength.

Because the difference of the rock block proportion and the arrangement of rock blocks in the S–RM, the shear stress vs horizontal displacement curve of some sample may show many transformation processes from “gentle segment” to “steep segment” (or the transformation processes from yield stage to strain hardening stage).

(3) From the vertical displacement vs horizontal displacement curves, we can find that:

   (a) Under the lower normal stress, dilatant behavior appears both in the soil (with rock block proportion equaling to 0%) and the S–RM, and then reaches to a stable state. The shear dilatant value will increase with the increment of the rock block proportion.

   (b) When the normal stress increases, the soil sample will experience a long shear dilatant stage. Then with the development of the shear displacement, it will transfer to the shear shrinking stage and reach a stable state. For the S–RM sample, there is only a short shear dilatant stage, and then this becomes a shear shrinking stage. But with the development of the shear displacement, the curve of the S–RM sample will transfer to another shear dilatant stage again, and with the increment of the rock block proportion, this kind of phenomenon will become more obvious.

During the shear process (or the formation of the shear zone) of the S–RM, the biting and friction actions among the rock blocks results in the rotating or transferring of blocks, even moving perpendicularly to the shear zone of the sample. Under these results the vertical deformation of the S–RM sample transforms from the shear shrinking stage to the shear dilatant stage. Fig. 12 indicates that associated with this kind of translation, the shearing stress of the sample will rise (or strain harden), and the shearing stress vs horizontal displacement curves may change from the initial yield stage (gentle curve segment) to the peak strength stage (steep curve segment).

(4) From Fig. 12, we can observe a jump phenomenon with different degrees in shear stress vs horizontal displacement curve and vertical displacement vs horizontal displacement curve of the S–RM sample, and there is a good corresponding relationship of this kind of jump between the two curves. When the shear stress sharply reduces, the vertical displacement will increase sharply accordingly, and when the shear stress sharply increases, the vertical displacement will reduce sharply.

During the shearing process, some rock blocks that bit into each other before will slide and pass the other one, so the strain energy that stored for the biting of the blocks will release suddenly. These may result in the shear stress of the sample decreasing suddenly, and then going back to the original stress state (which will show the shape "V" in the shear stress–horizontal displacement curve). At the same time, because of the adjustment of the rock blocks' spatial position, the S–RM sample becomes more stable than before. In this stage, the S–RM sample shows the state of "pressure consolidation" (or shear shrinking) at the macro-scale, and in the vertical displacement–horizontal displacement curve, it shows a jumping phenomenon.

During the shear process, if the rock blocks are dense in the shear zone of the sample, the biting force between the rock blocks will increase sharply. As a result, the shear stress–horizontal displacement curve will sharply translate from the initial yield stage to the peak strength stage (in the shear stress–horizontal displacement curve, the strain hardening stage may be sharper than others), and the shear stress will also sharply jump up. At the same time, the biting force among the rock blocks, and the continuous increasing of shear displacement will result in the vertical displacement and rotational deformation adjusting sharply to meet the new stress state. In this process, the S–RM sample shows shear dilatant behavior, and the vertical displacement–horizontal displacement curve shows a jump down. This phenomenon only appears when the rock block proportion of the sampler is higher or the sample is at the higher normal stress (Fig. 12d, the normal stress equals 35.5 kPa).

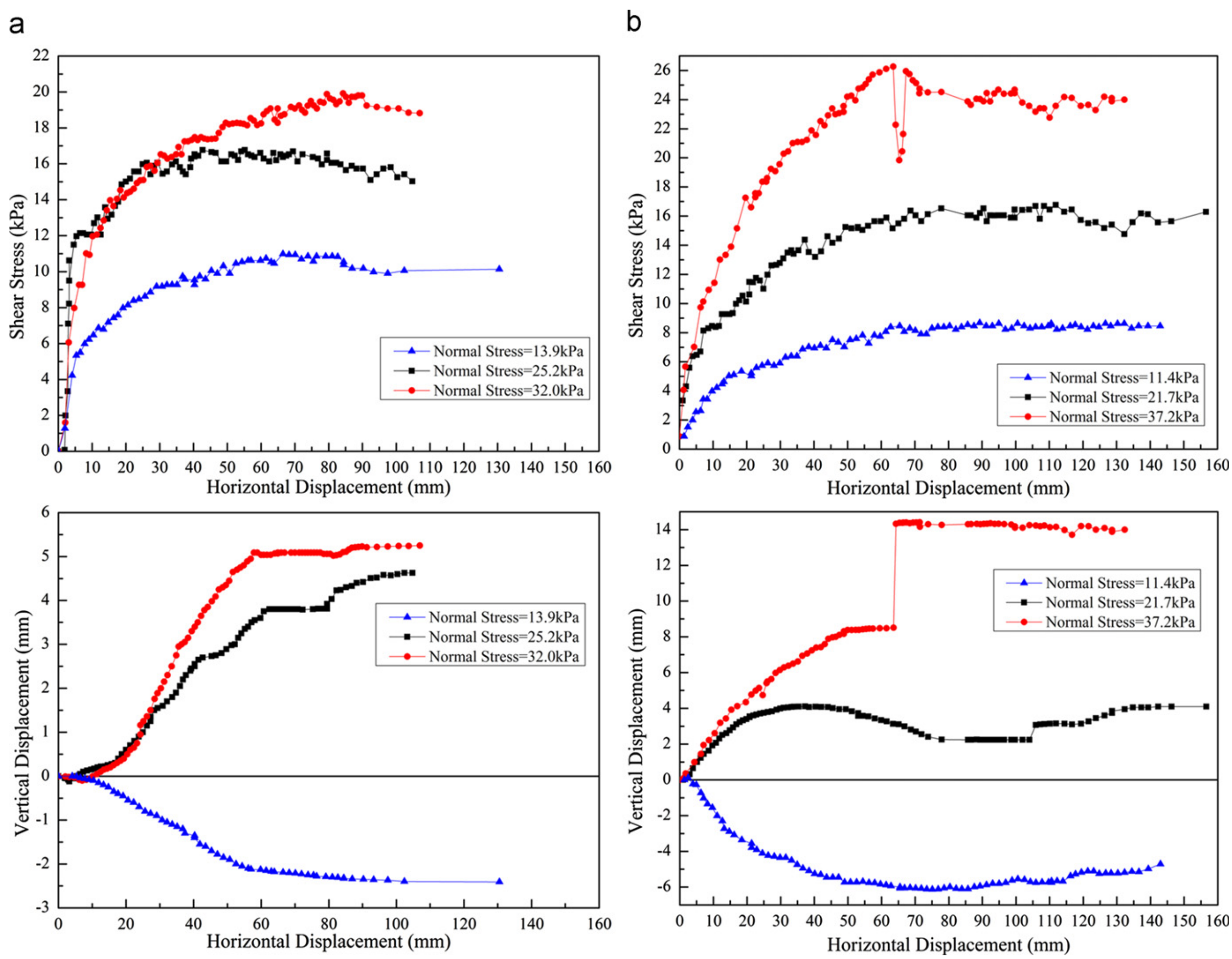

Fig. 12. Result curves of direct shear tests under different rock block proportion: (a) rock block proportion equals to 0%, (b) rock block proportion equals to 30%, (c) rock block proportion equals to 50% and (d) rock block proportion equals to 70%.

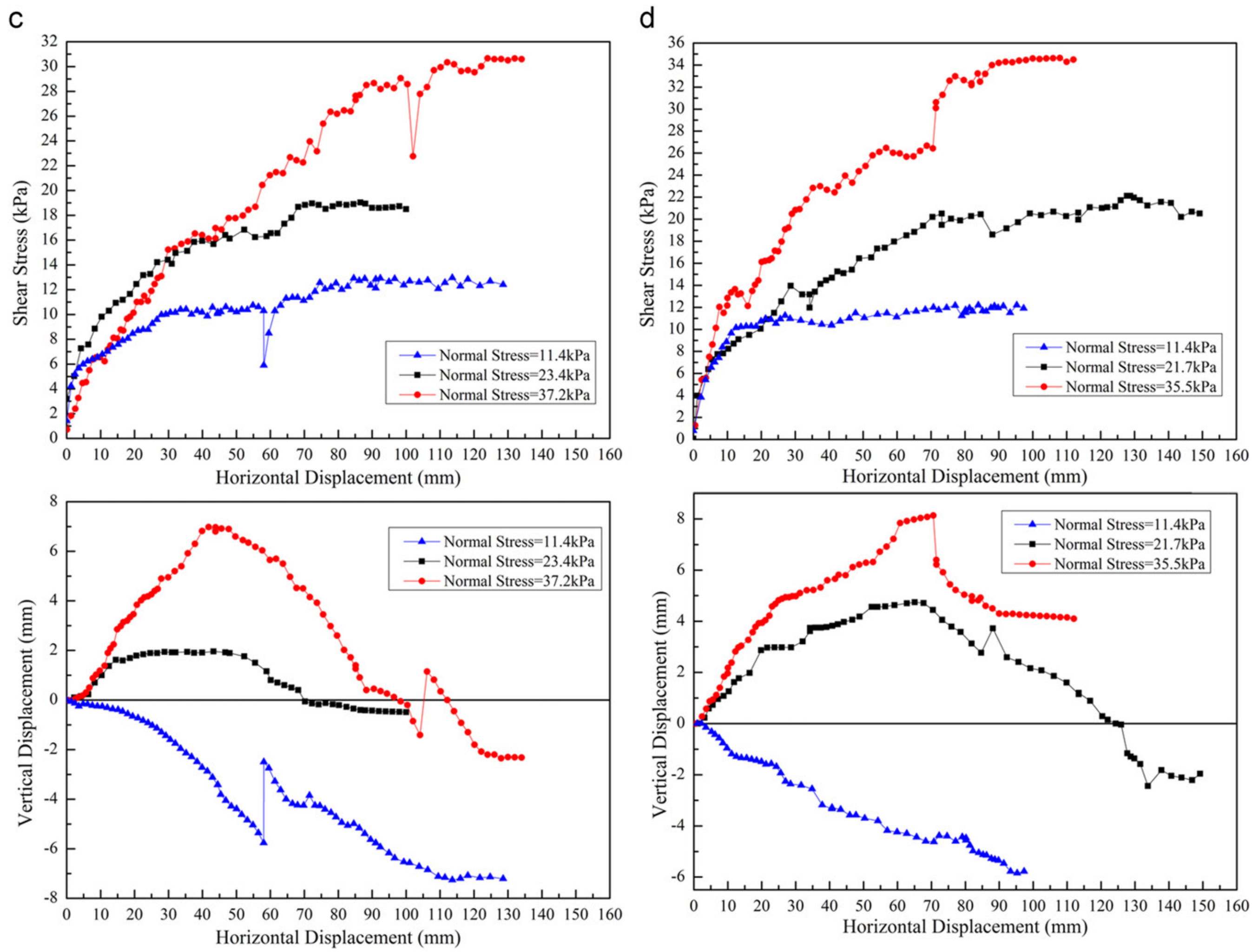

Fig. 12. (*continued*)

5.2. Shear zone characteristics

For the detailed study of the relationship between the characteristics of the shear zone and the rock block proportion of the S–RM sample, in this paper, the organic glass is used as the sides of the lower shear box and noodles are placed to mark the process of the deformation failure and the former of the shear zone.

Fig. 14 shows the development of the shear zone during the direct shear test of the S–RM sample under different rock block proportion. From Fig. 14 we can find: when the rock block proportion of the sample is equal to 0% (or the soil sample), the shear zone is a narrow band that lies near the preset shear face and parallels to the shear direction; with the increment of the rock block proportion, the shear zone becomes wider and wider and even associates with the generation of several cracks (Fig. 14c).

During the shearing process, with the increment of the rock block proportion, the probability of the contact and biting among the rock blocks may also increase, so the value of the rotation and movement of the rock blocks increase (Fig. 13), the shear zone wider and several cracks may be generated.

5.3. Shear strength characteristics

According to the direct shear test, we obtained the shear strength parameters of the S–RM (c, ϕ) with different rock block proportions (0%, 30%, 50% and 70%) in the study area, as shown in Fig. 15. To have a deep study on the relationship between the shear strength parameters and rock block proportion of the S–RM sample, Fig. 16 shows the curves for the variation of the shear strength parameters with the increment of the rock block proportion of S–RM.

From Fig. 16a we can find that there is a liner relationship between the increment of the internal friction angle (comparing to the "soil" sample) and the rock block proportion of the S–RM sample. According to the previous research results [10,29] we can obtain

$$\Delta\varphi_{P_R} = \begin{cases} 0 & (P_R < 25\%) \\ -5.1 + 0.33P_R & (25\% \le P_R \le 70\%) \\ \Delta\varphi_{70} & (70\% > P_R) \end{cases} \tag{6}$$

where $\Delta\varphi_{P_R}$ (°) is the increment of the internal friction angle of S–RM sample with rock block proportion equals to P_R comparing to that of "soil" sample (rock block proportion is equal to 0%); P_R (%) is the rock block proportion of the S–RM sample; $\Delta\varphi_{70}$ (°) is the increment of the internal friction angle of S–RM sample with rock block proportion equals to 70% comparing to that of the "soil" sample.

According to Eq. (6) we can find: that when the rock block proportion of the S–RM is less than 25%, the internal friction angle of the S–RM changes little and approximately equals to that of the "soil" sample. On the other hand, when the rock block proportion

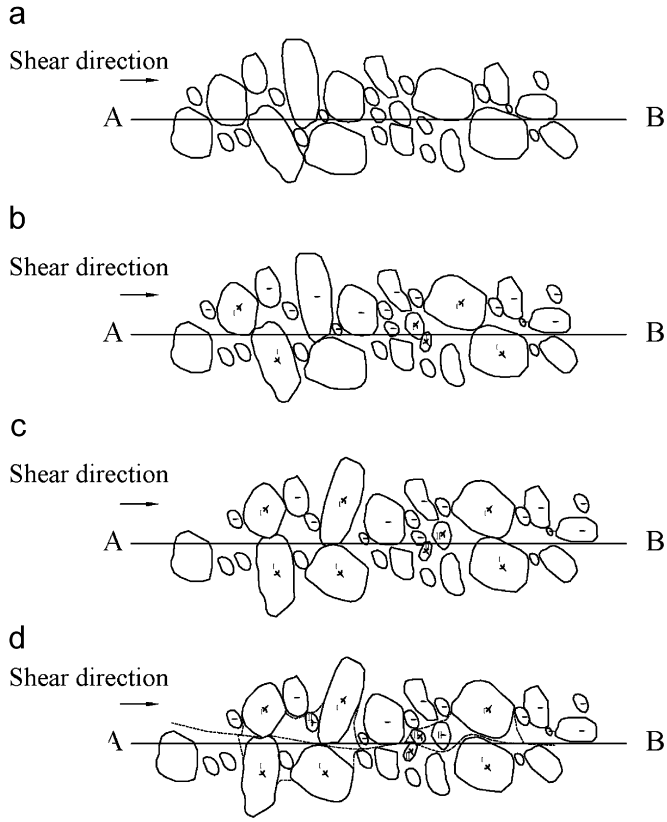

Fig. 13. Sketch map of the development of S–RM's shear band and the movement of the internal rock block: (A–B is the preset shear face; arrow shows the moving direction of the rock blocks; broken line is the actual shear zone).

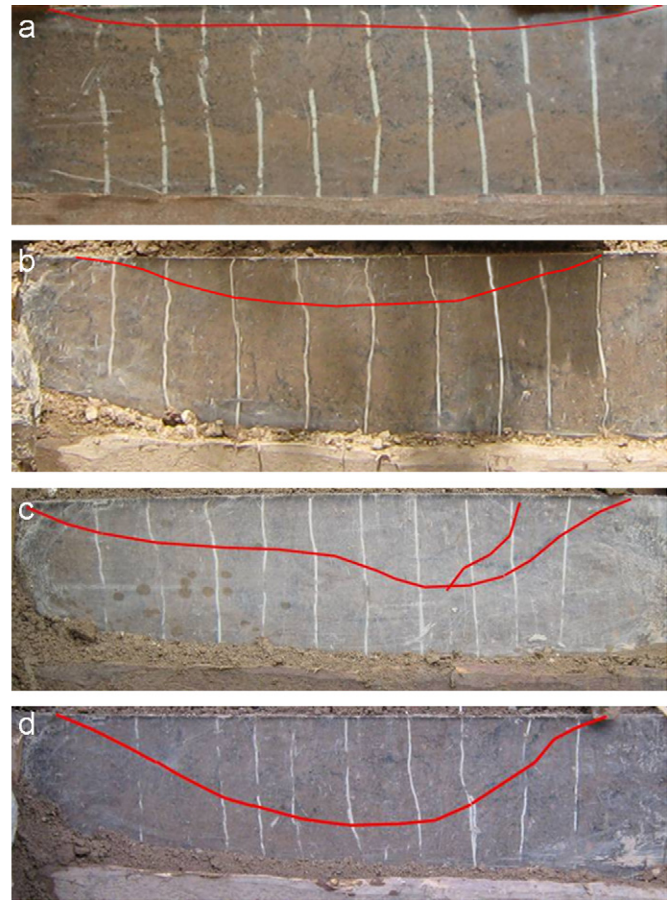

Fig. 14. Development of the shear zone during the direct shear tests under different rock block proportions: (a) rock block proportion equals to 0% and normal stress equals to 32.0 kPa, (b) rock block proportion equals to 30% and normal stress equals to 37.2 kPa, (c) rock block proportion equals to 50% and normal stress equals to 37.2 kPa and (d) rock block proportion equals to 70% and normal stress equals to 35.5 kPa.

lies in the range of 25–70%, there will be an approximate linear relationship between the increment of the internal friction angle of the S–RM and the changes of the rock block proportion; and when the rock block proportion is over 70%, the internal friction angle will change little or have no changes.

Fig. 16b shows the relationship between the cohesion and the rock block proportion of the S–RM sample. From Fig. 16, we can find the cohesion of the S–RM will decrease compared with that of the "soil" sample; when the rock block proportion lies in the range of 30–70%, the cohesion will decrease slowly with the increment of the rock block proportion, and the variable quantity is very small (according to the test results of this paper, the cohesion only decreases 0.33 kPa when the rock block proportion increases from 30% to 70%).

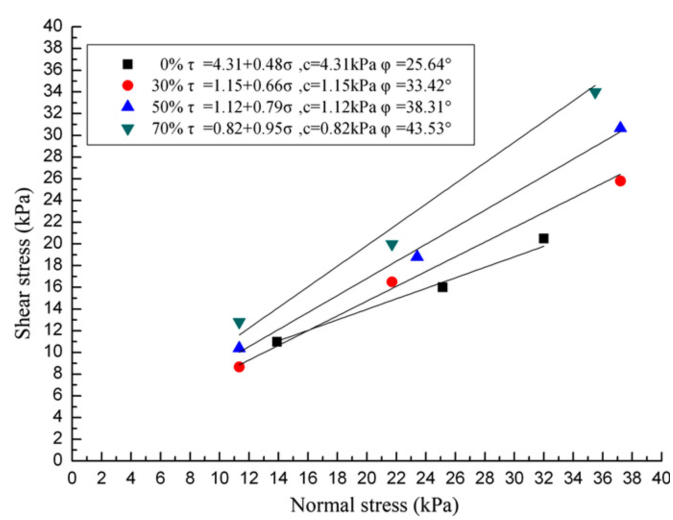

Fig. 15. The relationship curves between shear strength and normal stress of S–RM under different rock block proportion.

6. Conclusions

The rock block proportion and the rock block composition have a great effect on the shear strength characteristics of S–RM. In general, the dimension of the rock blocks in S–RM is larger, so it is difficult and expensive to obtain the rock block distribution characteristics by normal sieving methods. Based on the digital image processing technique, this paper uses DIP to gain the rock block proportion and the rock block size distribution in the S–RM, and the results are used to prepare for the S–RM sample for a large scale direct shear test. This research provides a new method for the study of this kind of inhomogeneous geomaterials:

(1) In the study area, the rock block size distribution curves of the S–RM have multimodality characteristics.

(2) Before arriving at the peak strength during the shear test, the S–RM sample has a yield stage (or even have several translation stages from yield to strain hardening), and with the

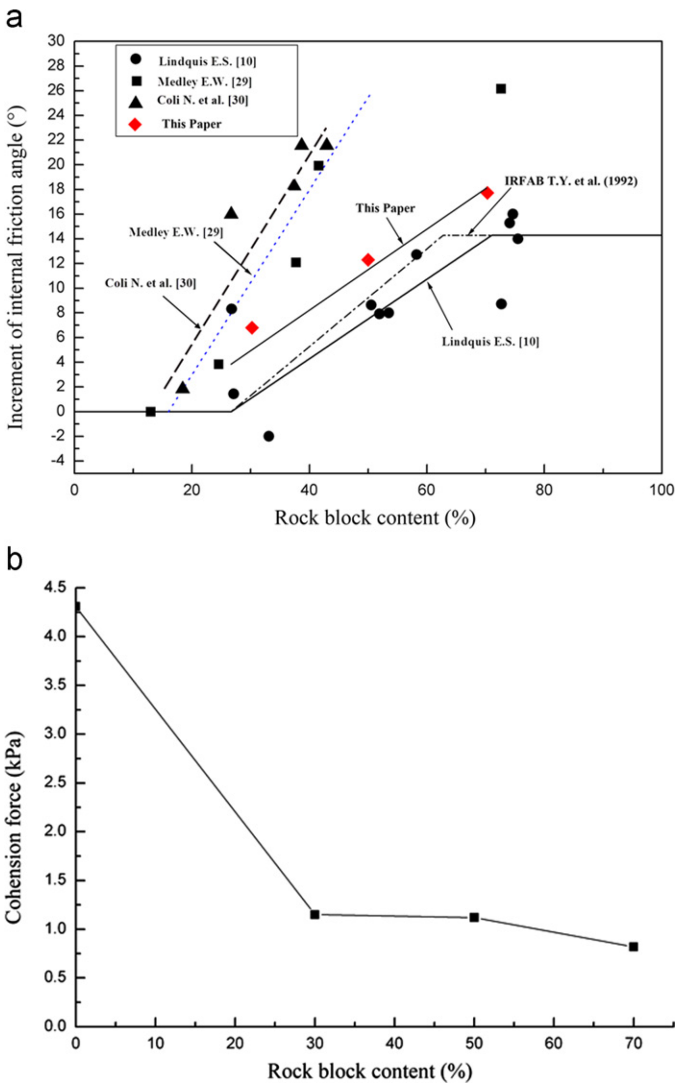

Fig. 16. Relationship between the shear strength of S–RM and its rock block proportion: (a) relationship between the increment of internal friction angle and rock block proportion (after [28]). (b) Relationship between the cohesion and rock block proportion.

increment of the rock block proportion and the normal stress, this stage may become more and more obvious.

(3) There are differences between the vertical displacement vs horizontal displacement curve of S–RM and that of the "soil" (with rock block proportion equals to 0%). After the shear shrinking stage at the beginning of the test and with the increment of the shearing displacement, the S–RM sample will translate from the shear shrinking state to the shear dilatant state.

(4) There are jumping phenomena with different degrees in the shear stress vs horizontal displacement curve and the vertical displacement vs horizontal displacement curve of the S–RM sample, a close interaction among the rock blocks in S–RM.

(5) The development characteristics of the shear zone have deeply related with the rock block proportion of S–RM. With the increment of the rock block proportion, the shear zone will become wider and wider, and even may associate with the generation of several cracks.

(6) When the rock block proportion lies in the range of 25–70%, there will be an approximate linearly relationship between the increment of the internal friction angle of the S–RM and the changes of the rock block proportion. The cohesion of the S–RM decrease compared with that of the soil sample; when the rock block proportion is larger than 30%, the cohesion tend to have small decrement with the increment of rock block proportion.

Acknowledgments

The work presented in this paper was supported by the project of "(Opening fund of State Key Laboratory of Geohazard Prevention and Geoenvironment Protection (Chengdu University of Technology) (SKLGP2011K015, GZ2007-10)", "Natural Science Foundation of China (51109117)" and "National Basic Research Program of China (2010CB732103)".

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