Numerical simulation of direct shear tests on mechanical properties of talus deposits based on self-adaptive PCNN digital image processing

WANG Sheng-nian(王盛年)1,2, XU Wei-ya(徐卫亚)1,2, SHI Chong(石崇)1,2, ZHANG Qiang(张强)1,2
1. Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering (Hohai University), Nanjing 210098, China; 2. Institute of Geotechnical Research, Hohai University, Nanjing 210098, China
© Central South University Press and Springer-Verlag Berlin Heidelberg 2014

Abstract: The macro mechanical properties of materials with characteristics of large scale and complicated structural composition can be analyzed through its reconstructed meso-structures. In this work, the meso-structures of talus deposits that widely exist in the hydro-power engineering in the southwest of China were first reconstructed by small particles according to the in-situ photographs based on the self-adaptive PCNN digital image processing, and then numerical direct shear tests were carried out for studying the mechanical properties of talus deposits. Results indicate that the reconstructed meso-structures of talus deposits are more consistent with the actual situation because the self-adaptive PCNN digital image processing has a higher discrimination in the details of soil-rock segmentation. The existence and random distribution of rock blocks make the initial shear stiffness, the peak strength and the residual strength higher than those of the “pure soil” with particle size less than 1.25 cm apparently, but reduce the displacements required for the talus deposits reaching its peak shear strength. The increase of rock proportion causes a significant improvement in the internal friction angle of talus deposit, which to a certain degree leads to the characteristics of shear stress–displacement curves having a changing trend from the plastic strain softening deformation to the nonlinear strain hardening deformation, while an unconspicuous increase in cohesion. The uncertainty and heterogeneity of rock distributions cause the differences of rock proportion within shear zone, leading to a relatively strong fluctuation in peak strengths during the shear process, while movement features of rock blocks, such as translation, rotation and crossing, expand the scope of shear zone, increase the required shear force, and also directly lead to the misjudgment that the lower shear strength is obtained from the samples with high rock proportion. That, however, just explains the reason why the shear strength gained from a small amount of indoor test data is not consistent with engineering practice.

Key words: talus deposits; digital image processing; pulse coupled neural networks (PCNN); direct shear test; mechanical property; granular discrete element method

1 Introduction

Talus deposits [1–2] is a special geological material that is different from the common geotechnical materials. It consists of irregular rock blocks with relative high stiffness and soil particles with relative weak strength, and is widely distributed in the southwest of China, for example, the left bank valley shoulder talus deposits of Xiluodu Hydropower Station located at the gorge reach of Jinsha river between Leibo County in Sichuan Province and Yongshan County in Yunnan Province is about 1400 m long along the river, 600 m wide perpendicular to the river, and the total geo-material volume is about 820 million m³. Another example, Zhenggang landslide talus deposits of Gushui Hydropower Station at Lantsang River is about 1300 m long along the river, 475 million m³ for the total volume and 289 million m³ for the deformed volume in the place with the elevation distribution about 2180 m to 3220 m. The stability of talus deposits has a tightly relationship with the safety of hydro power projects. However, owing to the complexity of grain size characteristics, the random distribution of rock blocks and the special structure features such as typical discontinuity, high heterogeneity and anisotropy, the mechanical behavior of talus deposits is not only determined on the material properties, but also closely related to the internal structures of itself. The deformation characteristics of talus deposits are just controlled by the factors such as the compactness of soil and rock mass, the contact condition and the frictional behavior. Thus, the talus deposits have a quite stronger particularity than the common geotechnical materials in...
mechanical property like deformation behavior and strength characteristics. What’s more, though the talus deposits is treated as a homogeneous, continuous and isotropic medium in current actual engineering to make macroscopic analysis and often neglect the particularity of internal structure [3–5], the problems such as difficulty in getting samples, great discrete experimental data, and disorder statistical laws of the results still make this kind of engineering practice have the characteristics of “trilemma effect”, including the difficulties of determining material parameters, analyzing their safeties, and adopting the reasonable reinforcement measures. Those issues directly cause the difficulty in the analysis of engineering’s viability and economy. Therefore, it can be great significant to the engineering construction that how to analyze and evaluate their mechanical behaviors and carry on corresponding studies of mechanical properties accurately and effectively.

In recent years, the rapid development of computer technology and image theory offers a powerful approach to analyze the talus deposits’ macro mechanical response from their meso-structure characterizations. LEOBURG et al [6] did a research on the sizes and shapes of outwash deposits based on digital images. BJÖRK et al [7] revealed quantifiable differences in the granular material associated with a fault and a clastic dike in granodiorite at the NW contact of the Hornelen basin through combined size, shape and phase recognition analyses. XU et al [8–9] studied the meso-structure differences, meso-damage mechanisms and macro mechanical behaviors of SRM by digital image processing, in which the large scale numerical experimentation based finite element method was adopted to analyze the influence of rock block feature such as shapes, proportions, distributions and grain sizes on the mechanical properties of SRM, it indicated that the mechanical properties of SRM were mainly controlled by its rock proportion and distribution and the increment of internal friction angle had a approximate linear growth relationship with the rock proportion when it lied between 25%–70%. LIAO et al [10–11] analyzed the soil and rock mixture’s deformation mechanism and strength characteristics based on the in-situ photos and simulated the rock blocks’ spatial locations, content, sizes and shapes by Mohr-Coulomb theory. YUE et al [12] went into the meso-structure mechanical characteristics of soil and rock mixture through binarization transformation of SRM digital photos to generate numerical model. DING et al [13] built the particle biaxial compression model from digital pictures and analyzed the failure characteristics of soil and rock mixture. ZHOU et al [14] set up the biaxial compression model to anti-analyze the microscopic parameters of soil and rock mixture based on numerical image processing and discussed the reason why the shearing behavior of medium in a certain rock proportion was better than the homogeneous soil. SHI et al [15–17] studied the mechanical behaviors of outwash deposits through reconstructing the meso-structure based on digital image processing. And SHU et al [18–19] studied the strength properties starting from nonlinear characteristics of earth-rock aggregate through fractal geometry theory and discussed the relationship among the strength parameters, peak stress difference and grain size fractal dimension based large-scale three-axis numerical tests.

All above show that reconstructing material meso-structure by digital image processing can study the macro mechanical properties of material by means of numerical experiments and can make up the defect of insufficiency of field and laboratory tests. In view of this, the meso-structure of talus deposits in this work had been reconstructed firstly by referring the in-situ images based on PCNN digital image processing, and then large scale numerical direct shear tests were carried out to analyze the mechanical properties of talus deposits, finally the laws of shear failure under different factors were discussed.

2 PCNN digital image processing

2.1 Principle of digital image

The premise of image processing using computer is that the images are stored in digital format, in other words, it requires that the simulated images in common continuous form should be discredited and quantized into a two-dimensional digitally encoded pixel matrix in time and space by a sampling and quantifying function. The colorfulness, brightness, contrast and sharpness of each pixel point in this matrix are denoted by different kinds of parameters to express the image information. And since the whole image is composed of the pixel matrices with different information, these pixels corresponding discrete data become the basis of digital image processing. Generally, the common digital images can be divided into four categories: index image, RGB image, gray image and binary image. Among them, the gray image, as one of the main image types, is constituted similarly by a pixel matrix, and can be expressed as a two-dimensional matrix \( I(x, y) \) with non-negative integer gray values for the different color gradations to every pixel at a moment.

\[
I(x, y) = \begin{bmatrix}
G(1,1) & G(1,2) & \cdots & G(1,M) \\
G(2,1) & G(2,2) & \cdots & G(2,M) \\
\vdots & \vdots & \ddots & \vdots \\
G(N,1) & G(N,2) & \cdots & G(N,M)
\end{bmatrix}
\]

where \( M \) and \( N \) denote the pixel number of the image in the horizontal and vertical directions, respectively.

Because the gray image is a kind of monochrome
image, each pixel of which just has one sample color with gray level of 256 to display from the darkest to the brightest. Therefore, the objective image also needs to be converted from the RGB color photo into the mono-color gray image before image processing since each pixel of the common color photos captured by a digital camera is made up by different colorfulnesses of red, green, and blue, and usually stored in RGB format. In general, there are three ways to realize format conversion, including the maximum value method, the average value method and the weighted average method, among which the result of the third method is relatively reasonable, since the weighted value is based on the sensitivity of the human eye to colors and obtained from three channels’ colorfulnesses. The weighted average method is adopted to convert the in-situ image from RGB format into objective format in this work. The corresponding conversion formula is expressed as follows:
\[
g(x, y) = 0.30G_R(x, y) + 0.59G_G(x, y) + 0.11G_B(x, y) \tag{2}
\]
where \(g(x, y)\) is the gray level of the pixel, \((x, y)\) denotes the \(x\)-th line and the \(y\)-th column, \(G_R, G_G\) and \(G_B\) are colorfulnesses of three channels.

### 2.2 Simplified PCNN model

Pulse coupled neural network (PCNN) [20] is a space-time coding feedback artificial neural network based on the mechanism of biological vision systems. It is different from the common artificial neural networks because of its processing capacity of analog-to-digital hybrid, series-parallel hybrid and dynamic self-adaption. More specifically, it is a two-dimensional monolayer neuron array made up of several pulse coupled neurons connected based on coupling weights in local. Because the features of nonlinear dynamic variable threshold, nonlinear modulation coupling, synchronization pulse issuance, dynamic pulse issuance and space-time synthesizing make up the space of the input data as well as the small changes in the amplitude, PCNN can reserve the region information more completely. So, the related researches, such as image processing, automatic target recognition, combinatorial optimization, have attracted widely attention.

If there is no distinction between neuron structures, the individual neuron of PCNN is composed of three parts, including input field, modulation field, and impulse generator. The simplified and improved model is shown in Fig. 1.

Because PCNN is a two-dimensional monolayer neuron arrays, so its mathematic iteration equations in the discrete form for the improved model can be expressed as follows:
\[
F_y(n) = e^{-\alpha E} F_y(n-1) + V_F \sum_{kl} W_{ijkl} Y_{kl}(n-1) + S_y \tag{3}
\]

![Fig. 1 Simplified and improved PCNN model](Image)

\[
L_y(n) = e^{-\alpha E} L_y(n-1) + V_L \sum_{kl} W_{ijkl} Y_{kl}(n-1) \tag{4}
\]

\[
U_y(n) = F_y(n)(1 + \beta L_y(n)) \tag{5}
\]

\[
E_y(n) = e^{-\alpha E} E_y(n-1) + V_E Y_y(n) \tag{6}
\]

\[
Y_y(n) = \begin{cases} 
1, & \text{if } U_y(n) > E_y(n-1) \\
0, & \text{otherwise} 
\end{cases} \tag{7}
\]

\[
T_y(n) = \begin{cases} 
\text{mark}^y_y(n) = 1, & \text{if } Y_y(n) = 1 \\
\text{mark}^y_y(n) = 0, & \text{otherwise} 
\end{cases} \tag{8}
\]

\[
\text{mark}^y_y(n) = \begin{cases} 
\alpha, & \text{if } E_y(n) = 1 \\
e^{-\alpha E} E_y(n-1), & \text{otherwise} 
\end{cases} \tag{9}
\]

\[
E_y(n) = \begin{cases} 
\alpha, & \text{if } E_y(n) = 1 \\
e^{-\alpha E} E_y(n-1), & \text{otherwise} 
\end{cases} \tag{10}
\]

\[
M_{ijkl}, W_{ijkl} = \frac{1}{(i-k)^2 + (j-l)^2} \tag{11}
\]

where \(F_y\) is the input item of neurons, \(S_y\) is the external excitation of neurons excited mandatorily, \(V_F\) and \(\alpha_F\) are the amplification coefficient of the feedback input field \(F\) and the constant of decay time, respectively, \(L_y\) is the connected input of neurons, \(V_L\) and \(\alpha_L\) are the amplification coefficient of the coupled connection field \(L\) and the decay time constant, respectively, \(M_{ijkl}\) and \(W_{ijkl}\) are the connection weight array of the feedback input field and coupled connection field, the weight value of each neuron and its adjacent neurons is the reciprocal of squared Euclidean distance, \(U_y\) is the internal active item of neuron, \(\beta\) is the connection coefficient of internal active item, \(E_y\) is the dynamic threshold value of neuron, \(V_E\) and \(\alpha_E\) are the amplification coefficient of the dynamic threshold limit \(E\) and the decay time constant respectively, \(Y_y\) is the pulse output of neuron, \(T_y\) is the PCNN time matrix based on the time domain message reflected from image spatial information.

### 2.3 Preprocessing of image denoising

During the process of image acquisition, the information of image should be interfered inevitably and randomly by environment conditions and self-quality of sensing components, which impedes the understanding
of images and may even directly affects the image’s subsequent processing, such as image recognition and image segmentation. Therefore, the processing of image denoising is a necessary step in image preprocessing. The essence of image denoising preprocessing is to eliminate interference information affected by the unacceptable factors, meanwhile to reserve the image’s high-frequency detail in order that the objective image is clear and vivid. Time matrix is a mapping table converting spatial image information into time information by PCNN. It records the ignition time information of each neuron faithfully. If the information is taken as a basis, the influence of outer factor can be effectively eliminated better recovered through common image denoising processing, such as nonlinear median filtering and linear Wiener filter other than image filtering and linear Wiener filter.

Supposing that the gray value ranges of background and the background region. Each single object has consistent properties while the adjacent objects are exclusive mutually.

\[
G(x, y) = \begin{cases} 
1, & g(x, y) \in \text{Objectives} \\
0, & g(x, y) \in \text{Background} 
\end{cases}
\]

Supposing that the gray value ranges of background and target region are \([R_{\text{amin}}, R_{\text{amax}}]\) and \([R_{\text{bmin}}, R_{\text{bmax}}]\). If \(R_{\text{amax}} > R_{\text{bmin}}\), the background region will overlap the target region. The threshold segmentation will not split the image well. In this case, if PCNN segmentation method that can commendably reduce the difference between the similar gray values of pixels is adopted, then those overlaps can be handled. The discontinuity of the image edge generated by the slight gray value difference can also be compensated.

\[
A_{\text{max}} = k \ln S_{ij} + r = -k a E T_{ij} + r
\]

where \(k\) and \(r\) are constants.

2.4 Principle of image segmentation

Image segmentation is an important image processing techniques, the essence of which is a clustering process of pixel attribute. It divides the image into two no overlap physical objects: the target region and the background region. Each single object has consistent properties while the adjacent objects are exclusive mutually.

3 Meso-structural modeling of talus deposits based on granular discrete element method

3.1 Principle of PFC<sup>2D</sup>

PFC<sup>2D</sup> [21] is a two dimensional particle flow code based on the theory of discrete element method. It is mainly used for the mechanical behavior analysis of granular materials, such as stability, deformation and constitutive relation of structure consisting of particle cluster, and the simulation of the large deformation problems on solid mechanics. Therefore, it is a powerful tool to study the meso-mechanical characteristics of talus deposits.

PFC<sup>2D</sup> separates an object into arbitrary shape blocks formed by the connection of representative particle element so that the structure problems of the object, the medium movement and the interaction between each other are simulated. Meanwhile, it expects that the problem of boundary value continuous calculation can be solved by the results of those local simulations. The essence of this method is mapping the material mechanical response from the physical domain to the mathematical domain based on medium meso-structure. The explicit difference algorithm is adopted to apply Newton’s laws of motion and the force-displacement law alternatively to update the particles’
position and inspect contact relation constantly, so that the movement and interaction of the material is simulated. The calculation principle is shown in Fig. 2.

![Fig. 2 Calculation principle of PFC2D [20]](image)

### 3.2 Meso-structural modeling based on granular discrete element method

#### 3.2.1 Relationship between actual model size and image pixel

There is a certain conversion ratio between the actual model size and the distance of adjacent squared pixel points. So, the meso-structure of talus deposits can be converted from the digital image, in which the internal composition will be reflected very well. The corresponding conversion ratio is expressed as

\[ S = \frac{L}{N} \]  

(17)

where \( S \) is the actual size of each pixel, \( L \) is the actual size of the model, \( N \) is the number of pixels in the horizontal or vertical direction.

In this work, the actual size of talus deposit model is 50 cm×50 cm, and the image pixel size is 100 pixel×100 pixel. Therefore, the conversion ratio is \( S=50 \text{ cm}/100 \text{ pixel}=0.5 \text{ cm/pixel} \).

#### 3.2.2 Corresponding relationship between pixels and particles

The common corresponding relationships between image pixel and PFC model particle include the direct correspondence model, the interlayer dislocation model and the double-ball combination model, as shown in Fig. 3. In such models, the particle is in accordance with the image pixel. However, the directly corresponding relationship between image pixels and particles in the model is bad to the simulation of deforming mechanical properties of soil and rock mixture, the interlayer dislocation model may be in inconsistent with the model size and corresponding actual size, and the double-ball combination model will lead to the model material in inconsistent with the actual image. Therefore, all of them are not suitable for simulating the mechanical properties of talus deposits.

In order to overcome these drawbacks, the particle model had been generated randomly in this work above all, which was in accordance with the actual model size. And then soil and rock particles were distinguished according to the image pixel attribution in different positions. In other words, the common expansion method was adopted firstly to generate the low-stress model, in which the particle radii were less than the actual size corresponding to the image pixel point and the low-stress state of model could be obtained by the servo mechanism. Then, the interpolation method of nearest neighbor was used for the low-stress model to attribute the particles into different material group according to the pixel information of different position. Finally, a granular discrete element analysis model of the mixed media would be established.

### 3.3 Meso-structural model of talus deposits

The meso-structure direct shear model of talus deposits based on the self-adaptive PCNN digital image processing can be reconstructed as following procedure, as shown in Fig. 4.

The typical in-situ talus deposit image had been selected as shown in Fig. 5. The actual model size was 50 cm×50 cm, and the image pixel size was 100 pixel×100 pixel. The corresponding gray image of the sample is shown in Fig. 6. The denosing image based on PCNN time matrix image processing technology is shown in Fig. 7. According to the systematic researches in Franciscan etc, MEDLEY and LINQUIST et al indicated that the mechanical behaviors of the soil and rock mixture shown obvious dimension independence, and the threshold \( d_{\text{thr}} \) could be defined by \( d_{\text{thr}}=0.05L_{\text{c}} \), where \( L_{\text{c}} \) is the height of single shear box. So, the threshold of the soil and rock mixture in this work should be \( d_{\text{thr}}=0.5\times50 \text{ cm}\times0.05=1.25 \text{ cm} \), which was taken as a cut-off point to realize the binary image segmentation. The corresponding result is shown in Fig. 8.

The particle model had been generated through the particle expansion technique, in which the radius of the particles lied between 0.6–1.2 mm and the actual model size was in accordance with the reflection of the image.

The servo mechanism was adopted to ensure all particles in a low-stress state, and then the soil and rock particles were distinguished by the interpolation method of nearest neighbor based on the binary image information. During the process of image segmentation,
all particle clusters had been taken as soil mass once the size of the cluster was less than 1.25 cm. The numerical shear model of talus deposits was established using granular discrete element method, as shown in Fig. 9. The height of each shear box was 25 cm, the bottom width of the box was 50 cm, and the top width of the box was 30 cm. The plates in the two sides of box were reserved a certain length in order to keep from the particle overflowing in the shear process. When the direct shear test was implemented, the bottom box was
4 Numerical simulations of direct shear tests on meso-mechanical properties of talus deposits

4.1 Parameter determination

It had been found by YOON [22] in the sensibility analysis between the six kinds of mesoscopic parameters, including contact modulus, stiffness ratio, friction coefficient, normal bond strength, shear bond strength and particle size, and the macroscopic parameters such as uniaxial compressive strength, elastic modulus and the Poisson ratio through using the Plackett–Burman experimental design method that the elastic modulus was closely related by the contact modulus, the Poisson ratio was controlled significantly by the stiffness ratio, while the uniaxial compressive strength was mainly affected by the normal and shear bond strength. Similarly, CHO et al [23] who used the parallel bond model in the tension-compression test of granite also indicated that the particle size was sensitive on the ratio of tensile strength and uniaxial compressive strength peak value. Unfortunately, there is still no straightforward theoretical solution to transform the macroscopic parameters into the corresponding mesoscopic parameters at the present stage, as the macroscopic behavior of the granular media is mainly determined by the contact mechanical properties of the materials. The meso-scale parameters of material were still mainly gained through trail-and-error by comparing results of numerical and laboratorial tests.

Therefore, the meso-mechanical parameters of “pure soil” (particle size<1.25 cm) were calibrated through the results of the indoor experiment, while the meso-mechanical parameters of rock blocks in accordance with the macro mechanical behavior were calibrated by the retrieval analysis based on the monitoring data in this work. The selected meso-mechanical parameters of the talus deposits are listed in Table 1. It should also be noted that the contact model was used for the “pure soil” while the parallel bond model was used for the rock blocks in this work.

<table>
<thead>
<tr>
<th>Material</th>
<th>Rock blocks</th>
<th>Pure soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density/(kg·m⁻³)</td>
<td>2450</td>
<td>2000</td>
</tr>
<tr>
<td>Normal stiffness, (k_n/(MN·m^{-1}))</td>
<td>5000</td>
<td>100</td>
</tr>
<tr>
<td>Stiffness ratio ((k_s/k_n))</td>
<td>0.4</td>
<td>1/3</td>
</tr>
<tr>
<td>Normal bond strength/MN</td>
<td>0.5</td>
<td>0.001</td>
</tr>
<tr>
<td>Shear bond strength/MN</td>
<td>0.5</td>
<td>0.001</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>1.2</td>
<td>0.5</td>
</tr>
</tbody>
</table>

4.2 Result analysis of direct shear tests

The simulations of direct shear tests were taken on stresses 0.5, 1.0 and 1.5 MPa. The shear stress–displacement curves of “pure soil” are shown in Fig. 10, and the shear stress–displacement curves of talus deposits (rock proportion is 25%) are shown in Fig. 11. It can be found from the figures that the shear stress–
displacement curves show a certain amount of compaction process at the beginning of loading process since the deformation modulus of the “pure soil” and the talus deposits are relatively low, and then it takes on a obvious linear elastic changes. But once it reaches a certain elastic deformation, the initial yield signs will appear on the shear stress–displacement curves, and the shear stress will be no longer a linear improvement with the increasing of shear displacement. Some local cracks emerge in the shear zone because of the interactions of internal particles. During this state, the shear stress increment of “pure soil” mainly depends on the inter friction of particles while the shear stress of talus deposits improves with the occlusion strengthening of internal larger rock blocks. When the curves reach the peak shear stress, the main interaction of “pure soil” particles in shear zone becomes the sliding friction. The deformation modulus decreases, and the peak shear stress decreases rapidly till the strength reaches the residual deformation strength. The shear stress–displacement curves take on an obvious strain softening. With regard to the talus deposits, the time reaching its peak shear stress is just the one that the internal occlusion among the large rock blocks is the strongest value. After the shear stress reaches the peak value, the internal occlusion begins to impel the rock blocks in the shear zone to cause the phenomenon of translating, rotating and throwing with the shear displacement continuing to increase. The strain energy is released through adjusting the distribution of rock blocks continuously till the corresponding residual strength is achieved. Moreover, the reason why the shear stress–displacement curve obviously shows a V-shaped change in this process is just because that when the internal large particles in the shear zone are throwing over other large particles, the normal deformation of the “low stiffness pure soil” increases suddenly.

It is also not difficult to find that the peak shear strength and residual strength of the “pure soil” has a positive correlation relationship with the normal stress. The displacements at the peak strength in a high normal stress are larger than the one in a low normal stress. The relationship between the normal and shear stresses for the “pure soil” is analyzed through the numerical simulation results as shown in Fig. 10. The cohesion of the “pure soil” is 97 kPa, and the internal friction angle is 14°. But for the talus deposits, though the changes of peak shear strength and residual strength with the normal stress changing are consistent with that of the “pure soil”, the required displacement of talus deposits at the peak shear strength is less than that of the “pure soil”. The initial shear stiffness of talus deposits is slightly higher than that of “pure soil” as well. All above show that the shear strength of the talus deposits is improved directly because of the existence of rock blocks.

5 Effect of rock blocks on mechanical properties of talus deposits

5.1 Effect of rock proportion on mechanical properties of talus deposits

Since the talus deposit is a binary mixed medium, comprising of coarse-grained rock blocks and fine stuff “pure soil”, the corresponding shear strength is formed by both strength and their interaction. In particular, when the talus deposits is at a higher rock proportion, its strength properties will be mainly controlled by the interaction of internal rock blocks, while when at a lower rock proportion its strength properties are similar to the “pure soil”. The strength properties of the talus deposits are obviously controlled by the features of internal coarse-grained rock blocks. Therefore, analyzing and discussing the effect of rock blocks on the talus deposit mechanical properties are important to cognize the mechanism of their shear strength.

In this work, the numerical shear model using granular discrete element method was established effectively based on the talus deposit images, and then the direct shear tests were implemented. The corresponding shear stress–displacement curves are shown in Figs. 12–14. Through the comparative analyses, it can be found that the features of the talus deposits’ shear stress–displacement curves gradually have a changing trend from the plastic strain softening deformation to the nonlinear strain hardening deformation with the increase of rock proportion. When the rock proportion is lower, the shear stress–displacement curves decline to a certain range after the peak stress by degree, and then take on a V-shaped change, which belongs to the mode of plastic deformation. But with the increase of rock proportion, the fluctuations of shear stress–displacement curves

![Fig. 12 Shear stress vs displacement curves of talus deposits in a proportion of 15% rock blocks](image-url)
weaken under a same normal stress, the falling range of the strain softening deformation decreases, and the corresponding features of the strain softening deformation gradually disappear. When the rock proportion is higher, the shear stress improves rapidly with the increase of shear displacement. The shear stress–displacement curve shows a non-linear strain hardening deformation feature, which indicates that the rock proportion has a significant effect on the shear strength of the talus deposits.

The talus deposits’ normal and shear stresses relationship under different rock proportions is shown in Fig. 15. The increments of the shear strength under different rock proportions are shown in Table 2, which were compared with that of the “pure soil”. It clearly shows that the existence of rock blocks makes the internal friction angle improve rapidly. When the rock proportion reaches about 20%, the internal friction angle has been doubled compared with the “pure soil”. When the rock proportion is greater than 20%, the internal friction angle increases gradually with the increase of rock proportion. But with regard to the cohesion, the improvements caused by rock blocks are more limited. When the rock proportion is about 30%, the increment of cohesion is only about 25.8% compared with that of the “pure soil”. So, it can be concluded that the effect of the existence of rock blocks on the talus deposits is mainly to make the internal friction angle have a significant improvement but not obvious for the improvement of the cohesion.

5.2 Effect of rock distribution on mechanical properties of talus deposits

Results in Fig. 16 show that when the rock
proportion of the talus deposits is same, the features of shear stress–displacement curves also give a performance of obvious difference because of the randomness of rock distributions.

When the rock proportion is about 30%, the initial shear stiffness, the shear stress peak strength and the residual strength all show an obvious difference with the uncertainty of rock distribution in the talus deposits. For instance, when the rock proportion of the talus deposits is 29%, the difference of the initial shear stiffness is about 22%, the difference of the peak strength is about 25%, and the difference of the residual strength is about 31%. It also can be found by the comparison of the shear stress–displacement curves under the rock proportions of 29%, 30% and 31% that the phenomenon of “low rock proportion while high shear strength” is just caused for the uneven distribution of rock blocks though the shear strength is improved with the increase of the rock proportion. This, however just similarly explains the reason why the shear strength obtained from a little test data in the engineering of the talus deposits is not in accordance with the actual conditions in the engineering.

Because the stiffness of rock blocks in the shear zone is relatively higher than that of the “pure soil” particles in the talus deposit samples, the rock blocks appear the properties of rigid body and do not break during the shearing process. The existence of rock blocks is directly influenced on the width range of shear zone. When the distribution of rock blocks is relatively intensive within the shear plane, the change of the width range will be more intensive. In other words, because the rock proportion is higher in the shear zone, the translation and rotation of the rock blocks require more free space in the shear process compared with the “pure soil”, which directly leads to the expansion of the shear zone and the increase of required shear force. Thus, the final performance is that the initial shear stiffness, the peak strength and the residual strength are all improved. Meanwhile, owing to the phenomenon such as rock blocks’ translation and rotation, the rock blocks are redistributed continuously. So the shear stress–displacement curves keep on a rising to a certain range first and then decline rapidly. The larger the size of rock blocks and the higher the proportion of rock blocks, the greater the fluctuation of the curves. The redistribution of rock blocks in the shear failure of the talus deposits is an acute release process of strain energy.

Theoretically, the differences from the different distributions of rock blocks can decrease and even be eliminated by a large amount of indoor test. However, the statistical results are still difficult to be obtained for a lot of difficulties such as actual test conditions and insufficient samples. But the proposed approach in this work that the internal meso-structure of the talus deposits is reconstructed to carry on the numerical simulations can remedy those deficiencies very well, thus it can provide more accurate statistical parameters of shear strength for the actual engineering.

6 Conclusions

1) The digital image processing based on the pulse coupled neural network can distinguished the soil and rock mass well so that the internal meso-structure of the talus deposits is remodeled better. It provides an effective approach for a lot of numerical analysis of the talus deposits.

2) The numerical simulation results of direct shear tests based on the reconstructed meso-structure show that the existence and randomness of rock blocks in the talus deposits improves the shear strength, such as the initial shear stiffness, peak strength and residual strength, compared with that of the “pure soil”, while reduces the required displacement for the peak strength. With the increase of rock proportion, the features of the shear stress–displacement curves gradually have a changing trend from the plastic strain softening deformation to the nonlinear strain hardening.

3) Compared with the shear strength of the “pure soil”, the increase of rock proportion has an obvious effect on the improvement of the macro internal friction angle but not significant influence on the cohesion. The rock blocks’ rotation and crossing over of the others make the range of the shear zone expands, the required shear force increase, and the shear strength improve such as the initial shear stiffness, peak strength and residual strength. The uncertainty and heterogeneity of rock blocks’ distributions make the rock proportion different in the shear zone so that the phenomenon of “low stone content high shear strength” occurs in the test results, which just an important reason for the shear strength obtained from a few test data in the engineering of the talus deposits is not in accordance with the actual conditions in the engineering.

4) Though the proposed method can provide a convenience for the recognition of failure mechanism to those special engineering geo-materials, such as the talus deposits, as well as for studying of the macro mechanical behavior through reconstructing medium meso-structure from the view of the plane to reveal the law of internal structure on the strength parameters, there are still many issues about the talus deposits needed to further analyze, such as the failure mechanism under different consolidation degree, bonding strength, water content, etc, the problem of seepage flow, the three-dimensional meso-structure reconstruction and the statistics/dynamic structural responses. Therefore, researches on the talus deposits are still a significant challenge for engineers.
References


(Edited by HE Yun-bin)