Stability Analysis of Rock-soil Mixture Slope

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Abstract. This research provides a method of random generation of Soil-rock Mixture (SRM) model depends on digital imaging technology and rock stone database technology. With processed rock shape diagrams, database of rock shape had been built and a method of random generation depend on this database had been provided. The SRM backfilled slope models were generated with random generation method. Couples of SRM slope models had been simulated with ABAQUS CAE to study the stability of SRM slope with different parameters variations. The influence of block stones on the slope stability is main caused by rock stones' slip-resistance effect. When the stone content is 40%-50%, the block stones gradually contact with each other and form a framework. The safety factor gradually increases. The spatial distribution of rock stones at the foot of the slope has the most obvious influence on the stability of SRM slope. With the increase of maximum block size, the slope stability decreases firstly and then increase. The sliding resistance effect is the key factor of the SRM slope stability. Aggregation of small size stones or large size stones can change the shape of the sliding surface and have great influence on the stability of the slope.

1. Introduction
Understanding and mastering the engineering characteristics of rock-soil mixture (SRM) is an urgent problem to be solved in geotechnical engineering. Lots of research had been done to study the structure characteristics and mechanical properties of SRM based on many means such as digital image technology, CT image processing technology, laser scanning reconstruction technology, high-precision geophysical prospecting technology and random generation technology[1]. The methods to establish the finite element model of RSM slope based on digital image technology and its stability is studied with FEM software were proposed[2-8]. He et al. [9] used PFC2D discrete element method(DEM) software to analyse the mesoscopic damage modes and mechanical properties of SRM with different hardness rocks.

Random generation technology is the main method for the establishment of SRM model. Based on the principle of random generation, the main method is to replace the real outline of rock mass with convex polygon or other regular shapes to establish SRM model and analyse it. Based on digital image technology, Xu Wenjie et al. [8] proposed a method to establishment the finite element model of SRM slope. Zhang Sen et al. [9] studied the influence of different stone content on slope stability by using circular particle filling. Based on image processing technology and maximum likelihood estimation method, Zhang Shu et al. [10] studied the distribution law of the length and length axis ratio of block stones.

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At present, the main methods to study the stability of SRM slope are numerical analysis and model test. Because of high cost, random difference and other factors, the model test is unable to carry out large-scale repetitive tests. Therefore, the finite element analysis is a more reasonable and effective method to calculate the stability of SRM slope [9-10]. In this paper, the stochastic generation method is used to simulate the influence of various geometric parameters (shape, particle size and spatial distribution) on the stability and failure form of the SRM slope.

2. The model generation technology of SRM slope based on rock stone shape database
The rock stone shape database is created from a large number of rock stone images that is acquired by the digital camera in situ. The original images (Fig.1(a)) must be pre-processed by image processing technology. First fix the background to white and fill the stone with black((Fig.1(a))), then the pixel point of the stone edge can be extracted by Canny edge detection algorithm and all coordinates of the rock stone's edge can be obtained(Fig. 1(c)). For the stone boundary recognized by using Canny algorithm is zigzagged which is composed of pixels, it should be smoothed to straight line segments which can be used in the finite element model.

Based on the previous studies (Barren et al., 1980), four kinds of rock stone shape parameters are extracted to establish the rock stone shape database.

2.1. Equivalent diameter $D$

$$D = 2\sqrt{A/\pi}$$

Where $A$ is the rock projection area. $D$ is the diameter of an equivalent circle with the same area, used to denote the size of rock stone

2.2. Axial ratio $S_{ab}$

$$S_{ab} = X_a / X_b$$

Where $X_a$ and $X_b$ are the major axis length and minor axis length of rock stone respectively. This parameter is used to indicate the elongated shape of rock stone.

2.3. Area difference ratio $S_{cp}$

$$S_{cp} = A_c / A_p$$

Where $A_p$ is the area of the equivalent elliptic which equal to the area of the rock stone, equal to the major axis and coincident with the centroid of the rock stone. $A_c$ is the area bounded by the boundary of rock stone and equivalent elliptic. This parameter is taken to indicate the roughness of rock stone.
2.4. Angular index $AI$.

$$AI = \sum_{i=1}^{N} A_i = \sum_{i=1}^{N} \frac{d_i}{l_i}$$

Where $l_i$ is the length of segment between two points spaced an angular point and $d_i$ is the vertical distance from the angular point to the segment $l_i$. Angular index $AI$ is the sum of $d_i/l_i$ for each angular point.

In addition to the above parameters, the rock stone content, maximum stone’s size, stone inclination angle and spatial distribution are also important factors affecting the stability of SRM slope. According to the characteristics of the random generation algorithm, several slope models with different stone content, different maximum stone’s size and different inclination angle are generated. The size of the slope is shown in Fig 2. According to the literature (Xu et al. 2009), the engineering feature size $L_c$ is 10m, the soil-rock threshold is $D_{thr}=0.05L_c=0.5$m and the largest block size $D_{max}$ is $0.2L_c$.

![Figure 2. The size of the slope.](image.png)

3. FEM model of SRM Slope and reliability analysis of the method

3.1. Model parameters

ABAQUS software, which has strong nonlinear computing capability and can use Python language to import coordinates of rock stones into CAE for modelling, is selected to conduct finite element modelling and analysis. The constitutive model of rock and soil mass adopts the More-Coulomb constitutive model, and the specific parameters are listed in Table 1. The model grid adopts ABAQUS built-in grid CPE4, quadrilateral plane strain grid. Rock and soil parameters are shown in Table 1. While the rock stone size and content are shown in Table 2. Left and right borders use horizontal constraints and the bottom border uses a horizontal and vertical constraints. The strength reduction method is used to analyse the stability of the slop. Fig.3 shows the model mesh example. According to the reach work of Weißenfels and Wriggers (2015), the interface model of rock stone and soil is frictional contact model and the Coulomb’s law can be used. The coefficient of friction is set to 0.363 because the internal friction angle $\phi$ of soil is 20°.

| Table 1. Parameters of rock and soil |
|-------------------------------------|
| Density g/cm³ | Elastic Modulus MPa | Poisson's ratio | Internal friction angle ° | Cohesion KPa |
| Rock | 2.42 | 1090 | 0.2 | 36 | 1200 |
| Soil | 1.81 | 50 | 0.3 | 20 | 20 |

| Table 2. Rock stone size and content |
|-------------------------------------|
| Grain size(m) | 0.5-1 | 1-1.5 | 1.5-2 |
| Rock block content | 55% | 10% | 35% |
3.2. Reliability analysis of the method

For comparative analysis, homogeneous soil slope model is also calculated. The safety factor calculated by Spencer method for homogeneous soil slope is 1.36. This is the same as the finite element simulation result (Fig 4). To study the feasibility of this method, the SRM slope with 50% rock stone content has been analysed.

The major principal stress distribution of homogeneous soil slope and the SRM slope with 50% rock stone content are shown in Fig.5. The major principal stress distribution of homogeneous soil slope presents obvious stratified distribution, which decreases from slope to the slope foot, and stress concentration occurs at slope foot. The major principal stress distribution of the SRM slope with 50% rock stone content still shows a decreasing trend of stratification, but the internal distribution is extremely uneven, and the stress concentration occurs at the soil-rock interface. The difference in stiffness between rock and soil is responsible for this distribution. It also leads to the rough sliding face of soil-rock mixture slope, rather than a smooth face of homogeneous soil slope. Fig.6 shows the displacement of two slopes. Displacement can well reflect the location of the sliding surface of the slope. The monitoring results in situ (Xu et al. 2008 and Ma 2016), shown that the presence of rock mass can change the shape of slip surface.
The distribution of failure zone of SRM slope always locates at the interface of soil and rock stone because the rock stiffness is far greater than that of the soil. Fig.7. shows the plastic zone distribution of the two slopes.

4. Influence of rock stone content on the stability of SRM slope

The rock stone content is an important factor affecting the stability and failure mode of SRM slope. Several models with different rock stone content are calculated to analyse the influence of rock stone content on the stability of SRM slop. The rock stone contents are 20%, 30%, 40%, 50%, 60% and 70%, respectively. Five models are generated randomly with each rock stone content. The mean safety factors of SRM slop with different rock stone content is shown in Fig.8. With the increase of rock content, the mean safety factor shows an increasing trend.

Besides, the rising rate of 20% ~ 60% rock block content range indicated an increasing trend. When the stone content increases from 50% to 60%, the safety factor increases greatly. When the stone content increases from 60% to 70%, the safety factor increases slowly and tends to be a certain value. In addition, for the same rock stone content, the safety factor of slope model may also be different. The safety factor is greatly effected by the shape of the slip surface. Small changes in the shape of the slip surface may result in significant differences in the safety factor.

Figure 8. SRM slope safety factor average value variation according to the rock block content
When the stone content is the same, the safety factors of the five models are different to some extent. While, when the stone content is small, such as 20%-30%, the block stones cannot form a framework and the change of the stone content has little influence on the overall stability. On the other hand, when the stone content range is 40%-50%, the block stones gradually contact with each other and form a framework. The safety factor gradually increases. The distribution of rock stone has a great influence on the slope stability. When the stone content increases to 60%, the skeleton of rock stones has gradually replaced the homogeneous soil and the safety factor of each model is different. The influence of block stones on the slope stability is mainly caused by rock stones' slip-resistance effect. The sliding thrust is transmitted from the top to its bottom, that is, the spatial distribution of rock stones at the foot of the slope has the most obvious influence on the stability of SRM slope. It is discussed in three cases:

i. Slippage resistance effect of large size rock stones: As shown in Fig.9 (a) (b) (c), at the foot of the slope, there are large size rock stones to prevent the slide body from sliding. Due to the high shear strength of rock stones, the slide surface can only bypass the block stones, which changes the shape of the slide surface and increases the slide resistance, so the overall stability of the slope is greatly improved.

ii. The slippage resistance effect of small size stones agglomerates: As shown in Fig.9 (d) (e) (f), at the foot of the slope, there are small size stones agglomerates prevent the slide body from sliding. Due to the dense solids formed from small-sized stones, the slide surface can bypass the the dense solids, which changes the shape of the slide surface and increases the slide resistance. As the slide surface can go through the dense solids when sliding thrust is large enough, the slope is slightly less stable than the case i.

iii. Low slippage resistance effect: As shown in Fig.9 (g) (h) (i), at the foot of the slope, there are no large size rock stones or small size stones agglomerates to prevent the slide body from sliding. The slide surface is generally relatively smooth and similar to the homogeneous soil slip. The safety factor is also close to the homogeneous soil slip.
Figure 9. The analysis results of SRM slope with different stone content

(a) stone content=60% safety factor=1.742
(b) stone content=60% safety factor=1.578
(c) stone content=70% safety factor=1.701
(d) stone content=70% safety factor=1.582
(e) stone content=50% safety factor=1.442
(f) stone content=40% safety factor=1.442
(g) stone content=50% safety factor=1.358
(h) stone content=40% safety factor=1.352
(i) stone content=30% safety factor=1.351

Figure 9. The analysis results of SRM slope with different stone content
5. Influence of maximum size of rock stone on slope stability
In order to study the influence of the maximum size of rock stone on slope stability, four types of SRM slope model with 50% rock stone content are established. The maximum stone size of each type slope is 1m, 1.5m, 2.5m and 3m respectively.

![Figure 10. Average value of the safety factor variety with maximum stone size.](image)

![Figure 11. The analysis results of SRM slope with different maximum stone size](image)

Fig.10 shows the average value of the safety factor of SRM slopes with each stone size group. The stability of the slopes decreases first and then increases with the increase of the maximum size of the rock stone. This is because : (1) when the maximum size of the rock stone is small and the number of the block stones is large, it is easy to form the agglomeration of the small rock stones. As mentioned in the previous section, such a situation has a good slide-resistance effect, so the stability of the slope is better. (2) With the increase of the maximum particle size, due to the same stone content, the number of stones decreases, and the aggregation of small size stones at the foot of the slope begins to decrease. Meanwhile, the size of large size stones is still not large enough or the distribution position is not conducive enough to achieve the sliding resistance effect, so the stability decreases. (3) When the maximum stone size continues to increase, the number of rock stones continues to decrease. The
aggregation of small size stones has reached the minimum. However, the sliding resistance effect of large size stones on the slope keeps increasing, so the stability starts to rise again.

Fig. 11 shows the analysis results of SRM slope with different maximum stone size. The sliding resistance effect is the key factor of the SRM slope stability. Aggregation of small size stones or large size stones can change the shape of the sliding surface and have great influence on the stability of the slope.

6. Conclusions
Based on the rock stone shape database and considering various geometric parameters of rock stones, the SRM slope model can be generated randomly. ABAQUS software is used to analyse the stability of SRM slope, and the influence of stone content and maximum stone size on the stability of the slope are discussed. The influence of block stones on the slope stability is mainly caused by rock stones' slip-resistance effect. When the stone content range is 40%-50%, the block stones gradually contact with each other and form a framework. The safety factor gradually increases. The spatial distribution of rock stones at the foot of the slope has the most obvious influence on the stability of SRM slope. With the increase of maximum block size, the slope stability decreases first and then increase. The sliding resistance effect is the key factor of the SRM slope stability. Aggregation of small size stones or large size stones can change the shape of the sliding surface and have great influence on the stability of the slope.

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