Research Article

Analysis of the Variation of Friction Coefficient of Sandstone Joint in Sliding

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The friction coefficient of rock joints is closely related to the stability of the slope. However, it is difficult to predict the friction coefficient due to the influence of surface roughness and mechanical properties of rocks. In this study, we use a method that combines theoretical analysis with a sandstone sliding friction test and propose a model to predict the friction coefficient of Sandstone Joint. A sandstone sliding friction test was performed on a self-made reciprocating sliding friction test device. Good agreement between the estimated values and test values verified the validity of the friction coefficient prediction model. Through an analysis of the friction coefficient in sandstone sliding, it was established that the larger the wear mass, the larger the friction coefficient in sliding, and the larger the wear area, the smaller the friction coefficient. With the cycles increasing of sandstone, the friction coefficient gradually decreased before finally reaching a stable value. Comparisons between the estimated value and test results showed that when the wear difference coefficient $c = 2.0$ and the meshing friction amplification coefficient $K = 1.4$, the minimum error was $2.89\%$. The results obtained are significant in the control of slope sliding.

1. Introduction

Sandstone slopes are common in open pit mining. Sandstones usually contain joints, which when penetrated cause slope movement due to the slope sliding along the joints. The friction coefficient of rock joints is closely related to the stability of the slope [1–5], though it is difficult to predict as it is associated with several geometrical and mechanical properties, such as surface roughness and asperity strength. When joint is subjected to repeated shearing during the slope sliding process, it becomes more difficult to predict any variations of the friction coefficient [6]. This creates hidden dangers for mine production and threatens the safety of life and property. Understanding any variation of the friction coefficient of rock joints plays an important role in the control of slope sliding. Consequently, an analysis of the variation of the friction coefficient of rock joints is vital if we are to minimize the threat of landslides and other related natural disasters.

Friction between two solid surfaces is usually characterized by friction coefficient. The friction angle can also be defined using the friction coefficient. Over the years, many models have been proposed to estimate the composition of the friction angle for rock joints. One of the earliest models for friction angle is Patton’s criterion, which demonstrated that the total friction angle can be separated into components of the basic angle of friction, peak dilatation angle, and contribution of asperity failures [7]. Maksimovic [8] provided an analytical model to describe the nonlinear failure for rock discontinuities, which contains the basic angle of friction, roughness angle, and median angle pressure, putting forward the expression of the dilatancy angle. Ladanyi and Archambault [9] presented an analytical model that contains the ratio of the degraded area of asperities and considers the effect of dilatation and failure of asperities on the shear strength of joints. Saeb [10] and Seidel [11] made a case for factors affecting the failure rate of asperities and modified the Ladanyi-Archambault model accordingly. Huang et al. [12] put forward a micromechanics model for the stress-displacement behavior of rock joints. The model explicitly accounted for the influence of the asperity shape on the deformation and strength of rock joints. Through the
above study, it was found that a number of factors influence the friction coefficient, among which the dilatancy angle is critical, and consequently it has been extensively studied. Schneider [13] studied the effect of roughness on the dilatancy angle of rough joints and presented a negative exponential model to describe the evolution law of the joint dilatancy angle. In other works, Plesha et al. [14,15] deduced a constitutive law for the behavior of geologic discontinuities with dilatancy and contact surface degradation, based on cyclic shear test results of artificial joints. Leong and Randolph [16] investigated the degradation of surface roughness using the wear theory and proved that it could be applied to describe the complex behavior of two sliding bodies. Lee et al. [17] found that the degradation of asperities under cyclic shear loading also followed the exponential degradation laws for the asperity angle and proposed an elastoplastic constitutive model, which considered the degradation of second-order asperities. Homand et al. [18] analyzed the variation of the joint surface during cyclic shearing and defined the degradation degree by the change of surface area before and after shearing and studied the evolution of initial joint roughness during the course of shearing. Liu et al. [19] proposed a generalized damage model for a residual form of tooth-asperity and established the mathematical relationships between the snipped rate of tooth-asperity, dilatancy rate, angle of base friction, and average dilatancy angle, separately. Hong et al. [20] conducted a series of direct shear tests on artificial rock joint surfaces and obtained the spatial distribution and statistical parameters of degradation roughness by analyzing the damage area of a specimen after shearing. Liu et al. [21] discussed the fatigue damage mechanism of rock joints with first- and second-order triangular asperities under a prepeak cyclic load.

Previous studies have shown that surface roughness is the main factor affecting the dilatancy angle, and so many researchers have focused on the relationship between the joint surface roughness and dilatancy angle. Barton [22,23] proposed an empirical model in which he creatively introduced the joint roughness coefficient used to describe the roughness of joint surfaces with different morphologies. Grasselli et al. [24,25] conducted a large number of direct shear tests on rock joints and obtained the statistical function relationship between the effective shear angle of the microelement of the joint surface and its corresponding contact area. In doing so, they established the relationship between three-dimensional morphology parameters and the friction coefficient. The study of the relationship between the joint surface morphology parameters and dilatancy angle has drawn increasing attention [26–28].

Although the above studies have conducted experiments and theoretical analyses on the composition of the friction angle, the change of dilatancy angle, and the relationship between the surface roughness and the dilatancy angle, there has been less research conducted on the variation of the friction coefficient of rock joints during the sliding process. Yet, the variation of the friction coefficient of rock joint is of great significance to the control of slope sliding and the production safety of mines. In this paper, a prediction model for the friction coefficient of Sandstone Joint is proposed, combining theoretical analysis with sliding friction tests of sandstone, starting from the single sliding process of sandstone and extending through to multiple sliding processes. The sliding friction test on a self-made reciprocating sliding friction test device was performed. The variation of the friction coefficient of Sandstone Joint was investigated, so as to verify the rationality and correctness of the friction coefficient prediction model, which uses the surface roughness, wear area, and wear mass as variables, and then to determine the model parameters.

2. Prediction Friction Coefficient Model of Sandstone Joint in Sliding

Joints develop widely on natural and open slopes, Figure 1(a) illustrates an example of a joint at the top of a slope in Aishihik River bank, Canada (D. S. 1 is the number of the crack group) [29], and Figure 1(b) is an example to illustrate a joint of a slope south of Xilinhaote open-pit mine. As can be seen from Figure 1, the joint surface is usually rough. During slope sliding, the highest asperities are sheared off and ground flat, and as sliding develops the second-highest asperities are sheared off and ground flat, with this cycle being repeated again and again. The asperities on the surface of Sandstone Joint wear each other during the sliding process, which makes the prediction of the friction coefficient of Sandstone Joint very complicated. Therefore, the Sandstone Joint was used as the research object. The interaction between the rigid asperities and asperities on the surface of Sandstone Joint was used to simulate the slope sliding process.

2.1. Prediction Friction Coefficient Model of Sandstone Joint in the First Sliding. It is assumed that the Sandstone Joint surface was covered with a series of equally spaced conical asperities of different heights. For the first sliding process, the interaction between the asperities of height \( H_w \) with the rigid asperities was the meshing friction. The upper part of the asperities was sheared off, with the height removed by the first sliding being \( h_{nm} \). The wear process of the asperities is shown in Figure 2.

To simplify the derivation process, the following basic assumptions were proposed:

1. The adjacent asperities that come into contact are independent of each other during each sliding process.
2. The height and cone angle of the asperities which produce meshing friction are the same during each sliding process.

Accordingly, Patton [7] conducted a large number of tests on regular joints and proposed the shear stress calculation model. The shear force in sliding can be rewritten as

\[
\tau = \sigma_n \tan (\phi_b + \iota),
\]

where \( \tau \) is the shear stress, \( \sigma_n \) is the normal stress, \( \phi_b \) is the basic friction angle, and \( \iota \) is the dilatancy angle.
If the left and right sides of equation (1) are divided by $\sigma_n$, the following expression for the friction coefficient of a Sandstone Joint is obtained:

$$ \mu_1 = \tan (\phi_0 + i_1), $$

(2)

in which $i_1$ denotes the initial dilatancy angle of Sandstone Joint during the first sliding process.

Equation (2) implies that the total friction angle is the sum of the two components listed above.

In order to investigate the contribution of the components of the friction angle, Maksimovic [8] conducted a large number of direct shear experiments on rock joints and found that, under low normal stress, the base friction angle remained unchanged and that the dilatation angle had a greater impact on the friction angle, implying that the dilatation angle was the main factor affecting the friction coefficient. The dilatation of Sandstone Joint is accompanied by the wear of asperities during the sliding process. Leong and Randolph [16] proposed a model to describe the frictional resistance of two sliding bodies and demonstrated that the wear theory can be applied to describe the complex behavior of two sliding bodies. Consequently, wear mass and wear area were used to calculate the dilatancy angle.

In the first sliding, the removal height of the asperities on the surface of Sandstone Joint is expressed as follows:

$$ h_1 = \frac{3m_1}{\rho A_1}, $$

(3)

In the first sliding, the average base radius of the asperities on the surface of Sandstone Joint can be written as

$$ r_1 = \sqrt{\frac{A_1}{N_1 \pi}}. $$

(4)

In the first sliding, the initial dilatancy angle of Sandstone Joint is determined as

$$ i_{11} = \arctan \frac{h_1}{2r_1} = \arctan \left( \frac{3m_1 N_1^{(1/2)} \pi^{(1/2)}}{2 \rho A_1^{(3/2)}} \right). $$

(5)
where $\rho$ is the density of sandstone, $A_1$ is the wear area in the first sliding, $m_1$ is the wear mass in the first sliding, and $N_i$ is the number of asperities in Wear Zone 1. $\rho$ is a constant, and wear area $A_1$ and wear mass $m_1$ can be measured during the sliding process, so it is a feasible method to predict the friction coefficient of Sandstone Joint using wear area and wear mass. The number of asperities $N_i$ is related to $A_1$. The value of $N_i$ can be corrected by the results of a sliding friction test of the Sandstone Joint.

2.2. Prediction Friction Coefficient Model of Sandstone Joint in the Second Sliding. In the second sliding, for asperities of height $H_n$ on the surface of the Sandstone Joint, the height removed was $h_{n+1}$ due to the residual friction interaction with the rigid asperities resulting in the angle of the asperities being passivated and worn flat. For asperities of height $H_{n-1}$, the height removed was $h_{n+1}$ due to the meshing friction interaction with the rigid asperities. The interaction between the asperities on the surface of the Sandstone Joint and rigid asperities was meshing friction and residual friction during the sliding process. In order to calculate the friction coefficient of the wear zone, Ladanyi and Archambault [9] divided the wear zone into a sliding zone and shear zone and expressed the shear strength using the shear area ratio. Consequently, the failure rate of asperities on the surface of the Sandstone Joint was introduced to calculate the friction coefficient. The change of the wear zone on the surface of the Sandstone Joint during the second sliding process is shown in Figure 3.

As can be seen from Figure 3, the friction coefficient of the Sandstone Joint in the second sliding can be divided into two parts: one is the meshing friction coefficient corresponding to Wear Zone 2 (solved for as per Section 2.1), and the other is the residual friction coefficient corresponding to Wear Zone 1. The asperities on the surface of Wear Zone 1 had residual friction interaction with the rigid asperities, the wear area did not change, and the asperities were not changed or worn flat. The surface roughness was also reduced to $S_{aij}$ ($S_a$ is the arithmetic mean deviation of the surface height, with the first subscript indicating the number of new wear zone and the second representing the sliding number). At the same time, the initial dilatancy angle $i_{11}$ becomes the residual dilatancy angle $i_{12}$ (the first subscript indicates the number of new wear zone and the second represents the sliding number). Considering that the surface roughness of Wear Zone 1 decreased and part of the asperities did not have contact with the rigid asperities during the sliding process, the contribution of the meshing friction coefficient of Wear Zone 2 to the total friction coefficient was reduced. Therefore, we introduced the meshing friction amplification coefficient $K$ to modify the friction coefficient of the Sandstone Joint during the second sliding as follows:

$$
\mu_2 = Ka_2 \tan (\phi_0 + i_{22}) + a_1 \tan (\phi_0 + i_{12}),
$$

and the failure rate of asperities on the surface of Sandstone Joint is

$$
a_1 = \frac{A_1}{A_1 + A_2},$$
$$a_2 = \frac{A_2}{A_1 + A_2},$$

where $A_1$ is the new wear area during the first sliding and $A_2$ is the new wear area during the second sliding.

In equation (6), $i_{12}$ is the residual dilatancy angle, indicating that the initial dilatancy angle $i_{11}$ on Wear Zone 1 attenuates during the second sliding. In order to analyze the variation of the dilatancy angle with sliding, Schneider [13] and Plesha [14] conducted a large number of direct shear experiments and found the attenuation of the dilatancy angle to be a negative exponential. The surface roughness of the Sandstone Joint on the wear area is accompanied by the attenuation of the dilatancy angle during the sliding process; thus, the attenuation of the dilatancy angle is expressed by the variation of surface roughness. The relationship between $i_{12}$ and $i_{11}$ can be expressed as

$$
i_{12} = i_{11} e^{-(S_{amax} - S_{a}) / (S_{amax} - S_{amin})},$$

where $S_{12}$ is the surface roughness of Wear Zone 1 after the second sliding, $S_{amax}$ is the maximum surface roughness of the new wear zone, and $S_{amin}$ is the optimal roughness. In the second sliding, the friction coefficient of the Sandstone Joint can be expressed as

$$
\mu_2 = Ka_2 \tan (\phi_0 + i_{22}) + a_1 \tan (\phi_0 + i_{12} e^{-(S_{amax} - S_{a}) / (S_{amax} - S_{amin})}),
$$

The total wear mass in the second sliding is

$$m_2 = m_{2,1} + m_{2,2},$$
where \( m_d \) is the total wear mass in the second sliding, \( m_{d2} \) is the meshing wear mass in the second sliding, and \( m_{r2} \) is the residual wear mass in the second sliding. Considering the difference in the contribution of meshing friction and residual friction to total wear, the wear mass on Wear Zone 2 with the total wear mass has the following relationship:

\[
m_{d2} = cm_{2}a_{2}. \tag{11}
\]

The wear difference coefficient \( c \) is related to lithology and surface roughness. The initial dilatation angle of the Sandstone Joint in Wear Zone 2 is

\[
i_{22} = \arctan \frac{3N_2^{(1/2)} n^{(1/2)} ca_2m_2}{2pA_2^{(3/2)}}, \tag{12}
\]

where \( N_2 \) is the number of asperities in Wear Zone 2.

Analysis of the second sliding process found that the friction coefficient was the combination of the meshing friction coefficient and residual friction coefficient. The attenuation of the initial dilatancy angle was characterized by the variation of the surface roughness, and the residual friction coefficient was calculated by introducing the failure rate of asperities on the surface. At the same time, the wear difference coefficient \( c \) was introduced to calculate the meshing friction coefficient, and the meshing friction amplification coefficient \( K \) was introduced to correct the friction coefficient of the Sandstone Joint.

### 2.3. Prediction Friction Coefficient Model of Sandstone Joint in the \( N^{\text{th}} \) Sliding

For the \( N^{\text{th}} \) sliding process, the change of the wear zone on the surface is shown in Figure 3, and the interaction is the same as that described in Section 2.2. The friction coefficient can be divided into two parts: one is the meshing friction part corresponding to the new zone \( n \), of which the asperities on the surface are sheared off, and the other is the residual friction corresponding to Wear Zones 1, 2, \ldots, \( n-1 \). Similarly, for the residual friction in the first \( n-1 \) zones, the wear area remains unchanged, and the asperities are worn flat; the surface roughness decreases, and the residual dilatancy angle is \( i_{jn} \) (\( j = 1, 2, \ldots, n \)).

In the \( N^{\text{th}} \) sliding, the friction coefficient of the Sandstone Joint can be developed as

\[
\mu_n = Ka_n \tan (\phi_b + i_{nm}) + \sum_{j=1}^{n-1} a_j \tan \left( \phi_b + i_{jn} + \left( (S_{a_{max}}-S_{a_{min}}) \right) \left( S_{a_{max}}-S_{a_{min}} \right) \right). \tag{13}
\]

The \( f^{\text{th}} \) failure rate of asperities on the surface of the Sandstone Joint after \( n \) cycles is

\[
a_j = \frac{A_j}{\sum_{j=1}^{n} A_j}. \tag{14}
\]

The \( f^{\text{th}} \) dilatancy angle of the Sandstone Joint after \( n \) cycles is

\[
i_{jn} = \arctan \frac{3cN_j^{(1/2)} n^{(1/2)} m_{d,j}}{2pA_j^{(3/2)}}, \quad j = 1, 2, 3, \ldots, n. \tag{15}
\]

Based on the assumption that the asperities shear off and are worn flat and that new asperities shear off in a cyclical fashion on the surface of the Sandstone Joint in sliding, the wear area \( A_i \) and wear mass \( m_i \) which can be easily measured during the sliding process were used to calculate the friction coefficient of the Sandstone Joint.

A prediction model was proposed for the friction coefficient of the Sandstone Joint with surface roughness \( S_{a_i} \), wear area \( A_i \), and wear mass \( m_i \) and the wear difference coefficient \( c \) and the meshing friction amplification coefficient \( K \) were introduced to modify the prediction model of the Sandstone Joint friction coefficient. In order to verify the correctness of the model and determine the values of the number of asperities \( N_i \), the basic friction angle \( \phi_b \), the wear difference coefficient \( c \), and the meshing friction amplification coefficient \( K \), a reciprocating sliding friction test was performed on the surface of the Sandstone Joint.

### 3. Reciprocating Sliding Friction Test of Sandstone

In order to verify the correctness of the model, a reciprocating sliding friction test of the sandstone was carried out using the self-made reciprocating sliding friction test device, and the surface roughness, wear mass, and wear area were measured. For calculating the experimental value of the friction coefficient of Sandstone Joint, the shear stress in sandstone sliding was recorded.

#### 3.1. Joint Specimen Preparation

Artificial rock joints have been widely used to investigate their friction characteristics in order to better reflect the change of surface roughness from initial sliding to stable sliding [17,20,25,26]. To obtain artificial rock joints, the sandstone block was split (with dimensions of \( 20 \times 20 \times 40 \) mm), and then the splitting test was carried out on the sandstone block with the testing machine, and the joint specimen’s dimensions are \( 20 \times 20 \times 20 \) mm. The density of the specimen was 2.36 g/cm\(^3\), and the tensile strength was 5.68 MPa. Before being subjected to the reciprocating sliding friction test, the surface of the specimen was colored with black ink, such that the surface damage zone could be easily identified by comparing the specimen surface before and after the test.

#### 3.2. Test Procedure

The reciprocating sliding friction test was carried out between the diamond lapping and the Sandstone Joint surface on the self-made reciprocating sliding friction test device, as shown in Figure 4. The particle size of the diamond lapping was 120 mesh, with a cross section of \( 150 \times 80 \) mm. The diamond lapping was adhered to the upper friction box, which was fixed to the vertical beam (without sliding). The cross section of the sandstone specimen was \( 20 \times 20 \) mm, and it was installed in the lower
friction box. The lower friction box was connected to the guide rail. During the shearing process, the specimen reciprocated uniform motion between the initial position and maximum displacement (50 mm), and the sliding speed of the guide rail was 10 mm/s. The total weight of the upper friction box and diamond lapping was 4573 g, cross section area of sandstone specimen was 4 cm², and normal pressure that the specimen was subjected to during the test was 0.11 MPa.

Pressure sensors were installed on both sides of the specimen, and data of the shear stress were collected by the pressure sensors and output to a computer via a dynamic strain gauge (sampling frequency: 20 Hz) during the sliding process.

The test value of the friction coefficient of the Sandstone Joint is determined by the following:

\[ \mu_i = \frac{\tau_i}{\sigma_n} \]  

where \( \sigma_n \) is the normal pressure and \( \tau_i \) is the maximum shear stress in the \( N^{th} \) sliding.

The specimen was disassembled every time it slipped, and images of the specimen surface were taken with a high-resolution camera. Then, the wear zone was traced with drawing software, and the wear area \( A_i \) was calculated via photo image analysis. The electronic analytical balance FA1004 (measuring accuracy 0.1 mg) was used to weigh the mass of the specimen. The measuring datum was repeated three cycles, and an average was applied, and the wear mass is denoted as \( m_c \). A laser confocal scanning microscope OLS4000 was used to test the surface morphology of the new wear zones and the existing wear zones, respectively. Each of the worn zones had three locations selected on which to perform the surface roughness test (an average of a set of numbers) and the surface roughness was denoted as \( S_{a_i} \) (the first subscript indicates the number of the new wear zone, and the second represents the sliding number, \( i \leq j \)). In order to reduce the deviation of results, the sandstone specimen was slipped ten cycles in total during the test.

4. Results and Discussion

4.1. Analysis Variation of Wear Zone on the Surface of Sandstone Joint. During the process of sliding, the asperities on the surface of the Sandstone Joint were often worn. For the study of the failure characteristics of asperities, Hong performed a large number of direct shear tests on rock joints and analyzed the degradation mechanism by using the failure characteristics of asperities after shearing [20]. So, we analyzed the sliding process through changes of the wear zone in this study. The surfaces of the Sandstone Joint after the 1st, 5th, and 10th cycles are shown in Figure 5. The black areas on the surface indicated the undamaged areas, of which the surface was rough and there were many asperities. The white areas underwent shearing off or were worn and became relatively flat.

In Figure 6, the variation of the damage zones on the surface of the Sandstone Joint by sliding cycle is shown. The range of the red line in the figure shows the newly damaged zone, indicating that meshing friction occurred in the zone. The range of the blue line shows the damage augmentation zone, which indicates that meshing friction and residual friction occurred in the zone. The green line shows the damage invariant zone, indicating that residual friction occurred in the zone. As can be seen from Figure 6(a), the wear zones are within the red line, indicating that meshing friction occurred in the zone and that the asperities were sheared off. Figure 6(b) shows that the wear zones in the figure are within the range of the red line, green line, and blue line, respectively. The red line shows that meshing friction occurred in the zone, and the asperities were sheared off, while the green line shows that the interaction in the zone was residual friction, the asperities were worn flat, and the surface roughness decreased. The blue line shows that meshing friction and residual friction occurred together in the zone. As a result of the residual friction, the overall height of the new surface dropped, and new asperities around it engaged with the diamond lapping. The interaction between the asperities on the surface of the Sandstone Joint and the diamond lapping in Figures 6(c)–6(j) is the same as 6(b). Therefore, sandstone sliding is a cyclical process of asperities shearing off, being worn flat, with new asperities shearing off. Consequently, the process of sandstone sliding in the prediction model was validated.

4.2. Analysis of the Variation of Sandstone Joint Friction Coefficient and Determination of Model Parameters

4.2.1. Test Results and Determination of Surface Roughness Parameters. In Figure 7, the surface morphology of positions A and B of Figure 5(a), using the laser confocal scanning microscope OLS4000, is shown. The surface roughness test results are shown in Table 1. The rate of the new wear area on the surface of the Sandstone Joint in sliding was calculated using Figure 6 and expressed by the following:
where $A_i$ is the wear area added to the surface of Sandstone Joint during the first sliding process and $A_c$ is the cross-sectional area. The test results of the wear mass and the new wear area rate are shown in Table 1.

As can be seen from Table 1, the surface roughness of the wear area gradually decreased with increasing cycles. Because the surface of the Sandstone Joint did not match the...
surface of the diamond lapping, the interaction between the asperities was meshing friction when sliding occurred, and the asperities on the surface of the Sandstone Joint were sheared off, resulting in decreasing surface roughness. When the worn zone continued to slide for five cycles, the asperities on the surface of the Sandstone Joint were worn flat, and the surface roughness finally reached a stable value. On the basis of the test results, the maximum surface roughness of the new wear zone was 69.88 μm, and the maximum surface roughness was 70 μm. If the new wear zone continued to slide for five cycles, the surface roughness would be 3031 μm, and the optimal roughness would be 30 μm.

4.2.2. Analysis of the Variation of Friction Coefficient. It can be seen from Figure 8 that the correlation of the wear mass and the friction coefficient is consistent. The larger the wear mass, the larger the friction coefficient, while the change of the wear area and the friction coefficient is the reverse. As the wear area increased, the friction coefficient gradually decreased. When the wear area increased to a certain value, the friction coefficient decreased slowly before finally reaching a constant value. The wear area on the surface of the Sandstone Joint was small in the initial stages of sliding, while the meshing friction occurred between the asperities. The friction coefficient was only the meshing friction coefficient. The meshing friction coefficient transformed into a combination of meshing friction coefficient and residual friction coefficient with an increase in cycles. The area of the residual friction zone gradually increased, the proportion of the residual friction coefficient increased, the roughness decreased continuously, and the residual friction coefficient decreased. Due to the fact that the height and cone angle of the asperities on the new wear zone surface of the Sandstone Joint were inconsistent, the meshing friction force generated by the top of the shearing asperity was different, which eventually led to a local jump in the friction coefficient. At this time, the surface of the Sandstone Joint and the diamond lapping gradually changed from the initial mismatch to mutual matching, and the contribution of the meshing friction coefficient and the residual friction coefficient to the friction coefficient was alternately dominant. As the number of cycles continued to increase, the wear area also increased. When the wear area reached a certain value, the residual friction gradually dominated, and the friction coefficient reached a relatively stable state.

4.2.3. Correction of Sandstone Joint Friction Coefficient Model Parameters. Because the sandstone sliding process in the model agrees well with test results, it is expected that the model can give good predictions of the friction coefficient of Sandstone Joint. The undetermined parameters in the model were corrected by using the test values of ten friction coefficients. The number of asperities \(N_i\) and the basic friction angle \(\phi_b\) were obtained from the results of the first sliding friction test. The wear difference coefficient \(c\) and the meshing friction amplification coefficient \(K\) were corrected using the results of the sliding friction test (over 2–10 cycles). The friction coefficient depends on \(N_i\), and if \(N_i\) is determined, \(\phi_b\) can also be determined. Meanwhile, \(c\) and \(K\) vary with \(N_i\), so the value of \(N_i\) is first determined.

The values of \(c\) and \(K\) are strongly influenced by \(N_i\). The curve of the initial dilatancy angle versus the number of asperities in the first sliding is shown in Figure 9. In this figure, when the value of \(N_i\) is 1–20, the range of \(i_{11}\) is between 4.5 and 19.3°; when \(N_i\) is 21–40, the range of \(i_{11}\) is...
between 19.8 and 26.4°; when $N_i$ is 41–60, the range of $i_{11}$ is between 26.7 and 31.3°; when $N_i$ is larger than 60, $i_{11}$ is greater than 31.5°.

According to equation (2), the following can be obtained:

$$\phi_b + i_{11} = \arctan \mu_1.$$  \hspace{1cm} (18)

Based on the test results, the test value of the friction coefficient was 0.731 during the first sliding, and, according to equation (18), the friction angle of Sandstone Joint was 36.2°. According to the experimental results [8,10–12], for the same specimen, the basic friction angle of rock joints is unchanged, which is always larger than 20°; then the same specimen, the basic friction angle of rock joints is that is, meshing friction coefficient to the total friction coefficient, obtained:

$$\text{test}$$

Figure 9: Changes of the initial dilatancy angle versus the number of asperities in the first sliding.

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$$\text{test}$$

Figure 10: Comparison between the test value and the estimated value with cycles.

So, the range of $c$ is between 0 and 5. When $c$ takes on different values, according to equation (15), the change curve of the initial dilatancy angle $i_{1m}$ with cycles can be derived, as shown in Figure 11. From this figure, $i_{1m}$ decreased with
increasing cycles, and the larger the value of $c$, the larger $i_m$, with $K$ being constant, and the larger the value of $c$, the greater the coefficient of friction. The value of $i_m$ was corrected by $\mu_t$, and it was found that when $c > 2.0$, the estimated value of the meshing friction coefficient was 0.843, which was quite different from the actual value. Hence, the value of $c$ was between 1 and 2. We then tried to calculate the error with a larger interval value of $K$ between 1 and 5 in the case of $c = 1.5$ and found that, with $K > 3$, the error between the estimated value and the test value was larger. In order to reduce the error, the error of the model was further calculated, the error results of which are shown in Table 2.

From Table 2, it can be seen that when the value of $c$ is between 1.0 and 1.1 and the value of $K$ is larger, the error is smaller. When the value of $c$ is between 1.2 and 1.7 and the value of $K$ is 1.4–2.0, the error is smaller. When the value of $c$ is between 1.8 and 2.0 and the value of $K$ is smaller, the error is smaller. As such, the value of $K$ affects the spatial position of the friction coefficient. When the value of $K$ is approximately 1.4, the estimated value of the friction coefficient is close to the spatial position of the test value.

![Figure 11: Variation of initial dilatancy angle with cycles at different c values.](image)

![Table 2: Error estimation table of friction coefficient estimated value and test value.](table)

![Figure 12: Variation of friction coefficient with cycles.](image)
The value of $c$ influences the trend of friction coefficient with cycles. When $c=2.0$, the estimated value of the friction coefficient is close to that of the test value. When $c=2.0$ and $K=1.4$, the error between the estimated value of the friction coefficient and the test value was 2.89%, and the estimated value agreed well with the test value. The change of the estimated value and the test value with cycles is shown in Figure 12. From Figure 12, it can be seen that the larger error between the predicted value and the test value in the fourth sliding was due to the uneven distribution of the asperities on the surface of the Sandstone Joint, which led to a larger fluctuation of the test value of the friction coefficient and increasing the margin of error.

5. Conclusions

For the prediction of the friction coefficient of a Sandstone Joint during the sliding process, a method of combining theoretical analysis with a sandstone sliding friction test was used, and the following conclusions were obtained:

1. Based on the assumption that the sliding of sandstone is a cyclical process where the asperities on the surface of the joint were sheared off and worn flat and new asperities were sheared off, a prediction model of the friction coefficient of Sandstone Joint was proposed, which was a function of the surface roughness, wear area, and wear mass. The components of the friction coefficient of Sandstone Joint are different at different stages: there is only the meshing friction coefficient during the initial stage, which transforms into a combination of meshing friction coefficient and residual friction coefficient with an increase in cycles.

2. Analyzing the change trend of friction coefficient predicted value and test value with the number of cycles, it is found that the error caused by the height and cone angle of the asperity on the surface has a gradually reduced influence on the overall trend of friction coefficient with the cycles increasing. The proposed model can give a good prediction of the friction coefficient. When the wear difference coefficient $c=2.0$ and the meshing friction amplification coefficient $K=1.4$, the minimum error was 2.89%, and the predicted value is in good agreement with the experimental value.

3. Analyzing the influence of the wear area and wear mass on the friction coefficient during multiple sliding, it was established that, in the single sliding, the larger the wear mass, the larger the friction coefficient, and the larger the wear area, the smaller the friction coefficient. With the cycles increasing of sandstone, the friction coefficient gradually decreased and finally reached a stable value.

The above research results are significant to the control of slope sliding.

### Data Availability

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

### Conflicts of Interest

The authors declare no conflicts of interest.

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