Failure Modes and Shear Strength of Filled Rock Joints with Saw-Toothed Asperities

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ABSTRACT

Three fundamental failure modes of filled rock joints with saw-toothed asperities are introduced, and the dependence of failure modes on the geometry parameters of asperities is confirmed. The failure mode is important to determine shearing strength of rock joints. The quantitative function relation between the shearing strength of a rock joint and the thickness of the weak infill layer is deduced. Based on the discussion of various combinations of geometry parameters and the shearing strength of infill materials, the failure mode and the corresponding shearing strength of the rock joint can be determined. Finally, the shear strength that conformed to the realistic failure mode can be founded.

KEYWORDS: rock joint; weak infill layer; failure mode; shear strength

INTRODUCTION

Rock joint is the main factor that determines the failure mode and strength of rock mass. In addition, it is usually filled with weak infill materials between relatively rough opposing walls [1]. The shear strength along a joint is governed by a number of factors, including the roughness of the joint surfaces, properties of infill materials, persistence of the joint, presence of climbing slope angle of the rock asperities and etc. Generally, in order to determine strength of weak joints, a series of direct shear tests of rock joints are conducted under different normal stress, and then a linear regression is performed to obtain the shear strength in practical engineering [2]. Conventionally, the shear strength of a joint is investigated under constant normal stress (CNL) boundary conditions where the normal stress remains constant during shearing. Some scholars also have emphasized that a constant normal stiffness (CNS) boundary condition is more proper for field situations [3],[4]. In addition, the failure modes of rock joints may greatly vary when subjected to external force [5],[6]. However, direct shear approach neglects the actual failure modes and may easily cause bad regression result. Therefore it is necessary to study the failure modes of weak joints of different states, and then the strength parameter that can reflect the actual failure state can be picked from the obtained results.

THREE ESSENTIAL STRENGTH OF ROCK JOINTS

The two opposing walls of a joint are usually filled with weak infill materials. The hard asperities on the walls and weak infill materials can make up three sets of strength parameters in terms of Mohr-Coulomb criteria: (1) the shear strength parameters of hard asperities, c_1 and φ_1; (2) the shear strength parameters of weak infill materials, c_2 and φ_2; (3) shear strength parameters of the contact between infill and hard asperities, c_3 and φ_3. Frictional angle of joints play a major role in the course of shear friction. From the scope of micro-structure, mineral grains either detached or attached; thus the cohesive force and internal frictional of Mohr-Coulomb materials cannot exist simultaneously in macro-scale [7]. Therefore this study mainly discusses the interaction between failure modes and frictional angle φ and neglects the influence of cohesive force c.

The frictional angle φ_1 is apparently larger than φ_2 and φ_3 whereas the contrast between φ_2 and φ_3 is still a problem worth discussing. Usually, φ_2 is the shear strength of internal fresh surface when weak infill layer is sheared, and φ_3 is contact strength between the interlayer and hard asperities. In addition, the cementation of the contact surface between soft infill materials and hard asperities is far weaker than that inside infill materials. Besides, when the surface is pressed, hard palisades will play a role as water-resisting layer and make water gather at weak interface to friction strength, and thus φ_2 is usually larger than φ_3. Among numerous cases of many landslides, the slip surfaces of very few of them occurred within the weak layer whereas a majority of them slid along the contact surface between the weak interlayer and , which also verifies that φ_2 is usually larger than φ_3 [8].

FAILURE MODES OF WEAK JOINTS

Figure 1 depicts the structure of a weak joint with saw-toothed asperities. The height of each asperity is h_0, and the slope angle is i_0, the vertical thickness of weak infill layer is h. Based on different combination of h_0, i_0 and h, the weak joint usually has three failure modes.

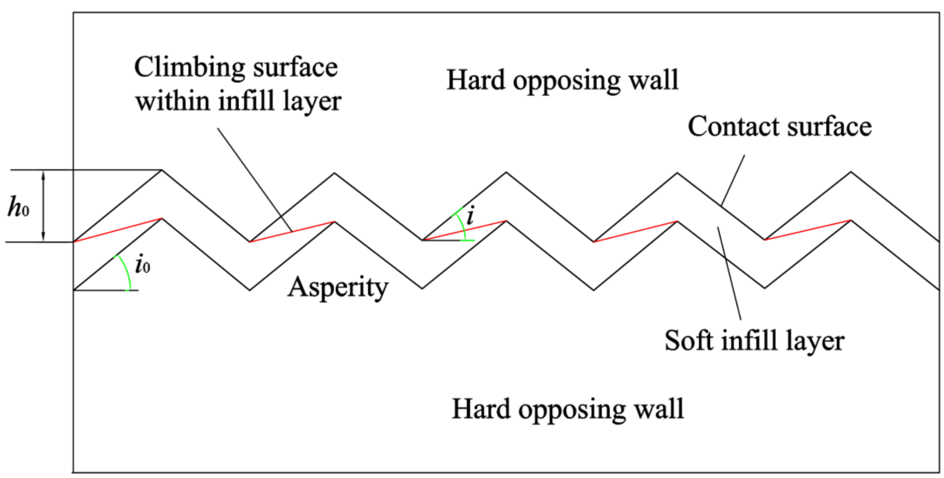

Figure 1: Sketch of a weak joint with saw-toothed asperities

Firstly, when the vertical height of weak interlayer is small enough to be neglected, the two opposing walls slide along the surface between the asperities. In this case, the walls would shear off the asperities or climb along hard rock contact surface. The shear strength corresponding to this failure mode is $f_1=\tan\varphi_1$.

Secondly, when weak infill layer has a certain thickness and the parameters h_0, i_0 are bigger than those in case 1, a fresh slip surface will develop within the infill layer. Given the climbing slope angle of the fresh slip surface i which is usually smaller than i_0, the upper wall layer climbs along this slip surface or plane failure occurs. The shear strength corresponding to this failure mode is f_2= tan (φ_2+i). According to Figure 1, the following geometrical relationship holds

$$\tan(i) = \frac{h_0\text{-}h}{h_0}\tan(i_0) \tag{1}$$

With the assist of Eq. (1), we can obtain the relationship between f_2 and the thickness h of the infill layer,

$$f_2=\tan(\varphi_2+i) = \frac{h_0(\tan\varphi_2+\tan i_0)\text{-}h\times\tan i_0}{h_0(1\text{-}\tan\varphi_2\times\tan i_0)+h\times \tan\varphi_2\times \tan i_0} \tag{2}$$

When $h > h_0$, i will become 0 and f_2 will degrade to tanφ_2. In this case, fresh shear plane will be formed inside the weak infill layer and plane sliding may occur.

Thirdly, when weak interlayer has a certain thickness, hard asperity surface can be considered as a gentle with small slope angle. In this case, the upper wall will probably climb by a small angle along the contact surface between the asperities and weak infill layer. The shear strength corresponding to this failure mode is f_3=tan (φ_3+i_0).

NUMERICAL MODELING OF WEAK JOINTS FAILURE

As shown in Figure1, a fresh slip surface might develop within the weak infill layer under certain combination of h_0, i_0 and h. However, it is troublesome to take samples especially comparatively intact samples for this kind of experiments. Sometimes weak infill materials are replaced with remolded soils, but experiment result is usually not ideal since it is difficult to capture the specific form of failure surface. As a result, the study on this type of failure lacks experimental supports. When the sampling procedure is complicated, numerical simulation is also a useful alternative to obtain the failure process and shear strength of a rock joint[9]. In this section, the finite element analysis is adopted to analyze the forming process of plastic zone within the weak infill layer, which can verify the rationality of the failure mode 2 that proposed.

The commercial FEM tool ABAQUS is used to simulate the failure process of the weak joints. The geometry of the weak joint is shown in Figure 1. The width and height of the sample is 37.5 cm and 20 cm respectively. The height of an asperity is h_0=3cm, and the thickness of the infill layer is h=2cm. The slope angle of the asperity is i_0=arc tan (0.8). The strength parameters of hard rock, infill materials and interface between them are listed in Table 1. The influence of cohesive force is not considered in current stage. The normal pressure of 150 KPa is applied to the sample. Shear displacement is imposed step-by-step until 1 cm displacement is achieved. The evolution of plastic zone inside the weak layer is shown in Figure 2.

Table 1: Friction angle of materials

Hard rock φ_1(^{o})	Infill materials φ_2 (^{o})	Interface φ_3(^{o})
45	25	15

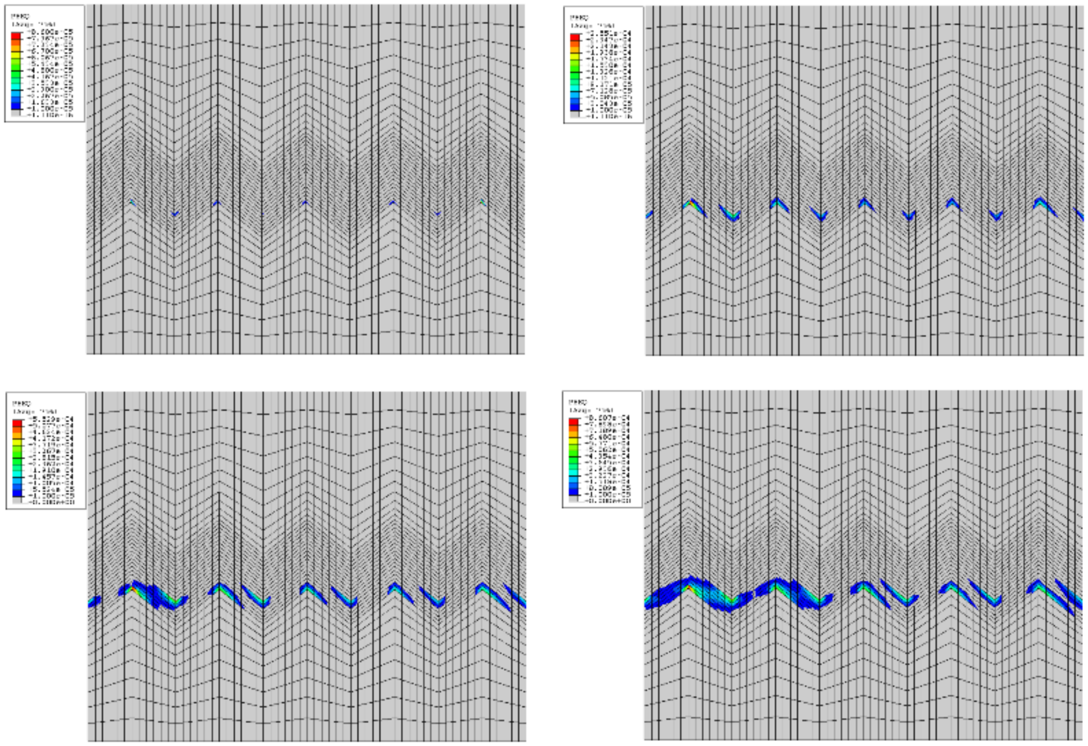

Figure 2: Evolutionary process of plastic zone inside weak layer

As shown in Figure 2, stress concentration and plastic zone firstly appeared at the bulgy part of hard asperities and extend to two sides of them. The shortest intersection path by extending of plastic zone is the newly developed climbing surface inside the weak layer. The subsequent evolution diagrams of plastic zone show that the new plastic zone mainly distributes symmetrically along two sides of newly developed climbing surface. The plastic zone continues developing until it cuts through the weak layer and the joint gets failed. Therefore, it is comparatively simple and feasible to select newly developed climbing surface inside weak layer as the failure plane during failure process of the joint. Note that the numerical simulation only illustrate the evolution of plastic zone in weak layer that results from imposing shear force statically to the sample. It does not really explain the dynamic loading process and final failure mode from real physical process. Therefore, it is still necessary to study and design more reasonable and ingenious experiment to study quantitative relation between the thickness of weak layer and comprehensive shear strength.

EFFECT OF FAILURE MODES ON SHEAR STRENGTH OF JOINT

It is known from the analysis of the failure modes of weak joints that the different combination of h_0, i_0 and h of joints will lead to different failure modes and shear strengths.

Generally, weak infill layers play a role as lubricant between hard asperities, and φ_1 is much bigger than φ_2 and φ_3. Therefore, shearing off the hard asperities or climbing along hard rock contact surface can hardly happen, and usually the latter two failure modes will occur.

From the above analysis, it can be known that $\varphi_2 > \varphi_1$ and $i < i_0$, where φ_1, φ_2 and φ_2 are known as the strength parameters of the weak joint, h_0 and i_0 are known geometrical parameters and i is a variable changing with the thickness of weak infill layer h. The dependence of the joint shear strength on these parameters is discussed for a few circumstances.

First of all, if climbing angle of hard asperities i_0 is so small that $\varphi_3+i_0<\varphi_2$, the failure mode of a joint will not be influenced by the thickness of weak layer. It tends to fail along the contact surface between the hard asperity and weak infill layer, the shear strength is $f=f_3=\tan(\varphi_3+i_0)$.

Second, when $\varphi_3+i_0\geqslant\varphi_2$, there will be two different conditions: (1) The thickness of the weak layer is comparatively thick (i.e. $h\geqslant h_0$) and the climbing angle i inside weak layer is 0. In this case, the joint will slide along newly developed shear plane inside weak layer and $f=\tan(\varphi_2)$; (2) the thickness of the weak layer is comparatively small (i.e. $h<h_0$) and climbing angle i inside weak layer is not 0. In this case, the weak infill layer has a thickness limit h_c. We have $\varphi_2+i=\varphi_3+i_0$ when $h=h_c$, and $\varphi_2+i>\varphi_3+i_0$ when $h<h_c$. The joint will fail along the contact surface between the hard asperity and weak infill materials and the corresponding shear strength $f=\tan(\varphi_3+i_0)$. When $h>h_c$, the joint will fail along a shear surface inside the weak layer. In this case, it is $\varphi_2+i>\varphi_3+i_0$ and the corresponding shear strength is $f=\tan(\varphi_2+i)$.

With the expression $\varphi_2+i=\varphi_3+i_0$, there is

$$\tan(i)=\tan\left[i_0-\left(\varphi_2-\varphi_3\right)\right]=\frac{h_0-h_c}{h_0}\tan(i_0) \tag{3}$$

Then, h_c could be expressed as Eq.(4) as below:

$$h_c=h_0\cdot\left\{1-\frac{\tan\left[i_0-\left(\varphi_2-\varphi_3\right)\right]}{\tan(i_0)}\right\} \tag{4}$$

Taken $\alpha=\frac{\tan\left[i_0-\left(\varphi_2-\varphi_3\right)\right]}{\tan(i_0)}$, Eq. (4) can be rewritten as

$$h_c=h_0\bullet(1-\alpha) \tag{5}$$

Figure 3 plots the variation of shear strength f with the thickness of weak layer h. Assuming that h_0=3cm, $i_0=45^o$, $\varphi_1=45^o$, $\varphi_2=25^o$, $\varphi_3=15^o$, the parameter $\tan(\varphi_2+i)$ in the second circumstance is calculated with Eq. (2).

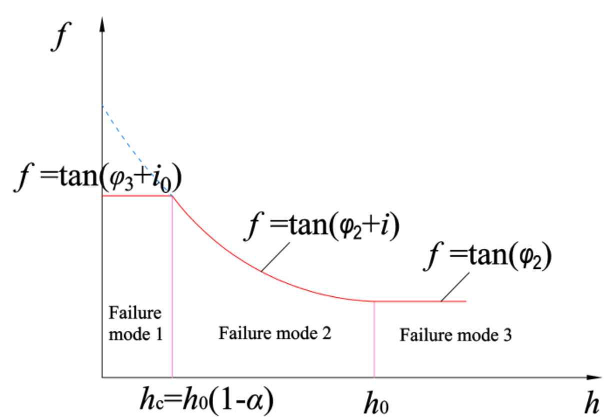

Figure 3: Variation of joint shear strength with weak layer thickness

Figure 3 indicates that even if the strength parameters of hard rock, infill materials and interface between them are same for the same set of joints, different geometry of hard asperities and weak infill layer will cause different failure modes of joints. Therefore, the shear strength of joints obtained from conventional experiments comparatively scattered. It is difficult to get ideal shear strength parameters after regression. When selecting shear strength obtained from direct shear tests, it is necessary to observe the failure modes of every sample and determine its location in Figure 2 with the assistance of geometry parameters, so that shear strength parameter that conforms to the actual failure mode can be determined.

DISCUSSION

In this study, the assumption that strength of contact surface is smaller than that inside weak layer is consistent with actual behaviors of rock mass failure by and large. However, the assumption that a new shear plane will develop inside weak layer is still in lack of theoretical or experimental support. The numerical simulation only illustrate the evolution of plastic zone in weak layer that results from imposing shear force statically to the sample. It does not really explain the dynamic loading process and final failure mode from real physical process. However, it is troublesome to take samples especially comparatively intact samples for this kind of experiments. Sometimes weak infill materials are replaced with remolded soils, but experiment result is usually not ideal since it is difficult to capture the specific form of failure surface. Therefore, it is still necessary to study and design more reasonable and ingenious experiment to study quantitative relation between the thickness of weak layer and comprehensive shear strength.

CONCLUSION

According to the above analyses, the following conclusions can be reached:

(1) There are three types of basic strength on weak joints: shear friction φ_1 between hard asperities, shear strength φ_2 of weak infill materials and shear friction strength $\varphi_3$of contact surface between them. Usually we have $\varphi_1 > \varphi_2 > \varphi_3$.

(2) Different combination of h_0, i_0 and h of weak joints will result in three basic failure modes: shearing off hard asperities or climbing along hard rock contact surface, climbing or planar sliding along newly developed shear plane in weak layer, and climbing or planar sliding along soft-hard contact surface. In fact, the latter two failure modes dominate.

(3) If climbing angle of hard asperities i_0 is so small that $\varphi_3+ i_0< \varphi_2$, the failure mode of joints will not be influenced by the thickness of weak layer and failure always occurs along soft-hard contact surface. When the weak layer is comparatively thick as $h\geqslant h_0$, the failure of joints will not be influenced by the thickness of weak layer too. Joint will slide along newly developed shear plane inside weak layer.

(4) When the thickness of weak layer is comparatively small, there is a thickness limit h_c. When $h< h_c$, joints will get failed along soft-hard contact surface. When $h> h_c$, joints will get failed along shear plane inside weak layer;

(5) When determining shear strength of joints, the geometrical parameters and failure modes must be combined to locate the sample in Figure 3. Then the shear strength that conforms actual behaviors of joints can be given.

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