Mechanical Effect Analysis of Joint Surface of Rock with Different Roughness

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Abstract. Using the same material to make test blocks with different undulating angles for straight cutting test, the correlation between peak strength and residual strength values and the undulating angle and deformation characteristics of the section surface is studied, the residual strength criteria obtained fit with the existing strength criteria, the use of matrix calculation method, parameter correction, and the revised strength criterion.

1. Introduction

In 1973, Barton [1-2] deduced the empirical formula of peak shear strength of rock surface by experiment. For the first time, the joint roughness coefficient JRC was put forward to describe the roughness of structural plane quantitatively. Li Shurong [3] introduced the concept of fractal dimension, quantified the roughness of the rock section surface, carried out the shear test, established the strength relationship between the roughness of the section surface and the shear effect, and verified it, which is applicable to the existing strength criteria correction formula. Shen Mingrong [4] conducts shear tests on regular serrated joints under different normal stresses, studies the main mechanical characteristics of strength and deformation, obtains shear deformation curve and variation law, and explores the relationship between expansion characteristics of structural planes and normal stresses. Performing artificial joint test pieces different methods to repeated shear experiment under stress, to analyze the relationship between the peak shear strength and repeated direct shear number of joints roughness coefficient, Caichu Xia, Yinglong Song [5] proposed attenuation equation. Scholars [6-10] never stopped research to rock face, but an important factor affecting the surface properties of the structure as a roughness structure being bonded together more scholars and parting plane theory, undulating surface thereof wherein, the friction angle with the size of the degree of fluctuation of a size to distinguish. In this paper, direct shear tests are carried out on rock structural planes with different roughness under different normal stresses. The strength characteristics of deformation characteristics of structural planes under shear are studied in depth. The relationship between deformation characteristics of structural planes under shear and roughness of structures is obtained, and the remnants are obtained. The strength criterion is fitted with the existing strength criterion, and the parameters are revised to obtain the revised strength criterion.

2. Design of test scheme

Making a size of 75mm × 150mm × 150mm, for two test pieces of the same angle agreement, to test the size of 150mm × 150mm × 150mm, the shear surface relief angle are 0 °, 5 °, 15 ° and 30 °. The legal pressure is taken 0.5MPa, 1MPa, 2MPa, 3MPa and 4MPa, the specimen uses 32.5R cement,
standard sand, the experimental block is m (water): m (sand) 1:2:3 match ratio, Experimental test block 60, after 24 hours after pouring mold, at a temperature of 20 degrees C, to maintain the water content of 90% after 28 days of maintenance.

3. Test results and analysis

3.1. Experimental phenomena
As can be seen from figures 1 and 2, for the rock section test block at the same fluctuation angle, when the normal stress is small, the destruction of the structural surface is mainly characterized by slip-type destruction (figure 1), and the restriction of shear when the climbing effect occurs is not very limited. When the normal stress is large, the failure is mainly shear failure (figure 2). The climbing effect of shear is greatly restricted, and it begins to turn into a tangential effect, so it is mainly shear type. However, the magnitude of normal stress does not affect the magnitude of the shear strength peak of the structural plane, which is mainly controlled by the roughness of the structural plane.

3.2. Analysis of test results
According to the experiment, the shear stress-shear displacement curve is obtained as follows:

When the normal stress is 0.5MPa, the peak strength corresponding to the various undulating angles is 0.43, 0.71, 1.48MPa, indicated in figure 3(a), but the slope before the peak strength is relatively flat, there is no interval of steep rise and steepdrop, the difference between peak strength and residual strength is small, 0.14, 0.29, 1.05MPa, vertical displacement is not obvious at first, because the stress is small enough, the rock internal structure has not been destroyed, the maximum normal displacement is between 4 to 5mm, in the cut-directional displacement of 2mm to produce vertical displacement, the maximum structural surface shear displacement is 0.52, 0.63, 0.7mm, It can be concluded that the type of section surface destruction is slip-type destruction, the larger the angle of the ups and downs, the stronger the wear effect, the greater the serrated cut volume.

Figure 3. Normal stress is 0.5MPa
In the comparison study of the above two figure 4(a) and 4(b), the vertical displacement is the change curve at the time of the first cut, the 5-degree section interview block, increased from the peak strength 0.43MPa to 1.02MPa, increased by 137.2%, and the peak strength of the 15-degree section test block increased from 0.71MPa to 1.46MPa, the percentage increase is 105.6%, the peak cutting stress of the 30-degree experimental test block changed from 1.48MPa to 2.42MPa, increased by 63.5%, the form of structural surface destruction from slip to shear, when the effect on the cutting stress of the structure surface increases, the corresponding peak strength shows a relatively large increase. The wear phenomenon of the structural surface is obvious, the fine particles produced by the destruction reduce the angle of the ups and downs of the structure surface, so the trend of the second half of the increase is decreasing and the growth is slow.

![Figure 4](image_url)

(a) Normal stress is 1MPa

(b) Normal stress in figure 5(a) and 5(b) is 2MPa, and the change curves of tangential stress and vertical displacement are similar to those of figures 4(a) and 4(b), but with the increase of stress, the tangential displacement corresponding to the peak strength is progressively advanced, becoming smaller and smaller, from 4mm to 3mm. It is shown that with the increase of the angle of ups and downs and the increase of stress, the cutting effect is obvious, the climbing effect is weakened, the destructive state of the structural surface is changed from slip to shear, the higher the angle of the ups and downs, the greater the slope of the elastic stage before the peak, and the rate of decline of the peak backward residual intensity change stage is also accelerated. The stage of rapid development and destruction of the fissure of the change curve (2 to 3mm): entering this stage, the development of micro-fracture appears a qualitative change, due to the pressure concentration effect caused by micro-fracture is significant, even if the external load remains unchanged, the rupture will still develop, and first of all in some weak areas of destruction, stress redistribution, The result is the destruction of new weak parts, and then goes on until the test piece is completely destroyed. The test piece is changed from volume compression to expansion, and the axial strain and volume strain rate increase the carrying capacity of the test piece to the maximum. For dense and solid experimental blocks with rigid junctions, the should variables in this stage are very small, while the corresponding variables in this stage are very large. The corresponding shear strength at 3mm is called the peak shear strength.
Under the condition that the normal stress is 3MPa, the section test block is destroyed, along with the shearing phenomenon of the structural surface. As can be seen from figure 6(a), when stress is small, the difference between the peak strength of the structure surface and the value of the residual strength is not small, at 0.71, 1.45, 2.91MPa, the relative percentage is 27.2%, 39.2%, 45.7% . The vertical displacement is not obvious at the stage of 0 ~ 1mm, and the internal structure of the rock has not been damaged. The maximum dilatation displacement of the structural plane is 0.7, 1.43, 1.51 mm. Compared with the sawtooth height, the degree of reduction is more than 50%, which belongs to shear failure. The larger the angle of fluctuation, the more obvious the wear phenomenon is, which further indicates that the superstructure is cut. After the destruction phase (tangential displacement of 3 ~ 6mm): Carrying Capacity of the test piece after reaching peak intensity, its internal structure is completely destroyed, but the specimens are still substantially maintain the overall shape. At this stage, the rapid development of the fissure and the formation of a macro fracture surface, the deformation of the rock is mainly reflected in the slip along the fracture surface, the carrying capacity of the test piece with the deformation rapidly decline, but not to zero, indicating that the rock after the rupture still has a certain carrying capacity, 6mm of the corresponding force called residual shear strength.
Combined with the comparative analysis of figure 7(a) and 7(b), when the undulating angle is 5 and 15 and the tangential displacement is 1-2 mm, the peak shear strength is reached. When the tangential displacement is 4-5 mm, the vertical displacement reaches the maximum, and the wear condition is serious. When the angle of the ups and downs is 30 degrees, the peak strength is reached when the tangent displacement is 2 to 3mm, the peak strength is 8.28MPa, the difference with the residual strength is 4.99MPa, the tangent displacement is 3 to 4mm, the vertical displacement is the largest, and the serrated height is reduced by 34.3%. When the angle of the ups and downs is small, the difference between the crucified surface change is flat, the difference between the anti-shear strength and the residual strength is not large, the maximum value of vertical displacement is also small, the different normal stress of the same angle of fluctuation, the greater the stress, the more obvious the vertical displacement, the more obvious the degree of damage.

4. Lowering angle derivation of theoretical formulas of residual strength

4.1. Coulomb-Moore criterion fitting
According to the Coulomb-Moore criterion, the relationship curve is drawn in figure 8. When the joint angle is 5 degrees, the cohesion and internal friction angle are the smallest under the condition of strength weakening, 0.267MPa and 39.2 degrees respectively. So the residual strength relationship is: $\tau_{\text{min}} = 0.267 + 0.8156\tau$. With the increase of the angle of the fluctuation, the parameters also increase, the angle of the section surface fluctuation is 15 degrees, the adhesive force is 0.283MPa, the friction angle is 41.1 degrees. Residual strength relationship is $\tau_{\text{min}} = 0.283 + 0.872\tau$. The related residual strength relationship is obtained: $\tau_{\text{min}} = 0.295 + 0.916\tau$. 

![Figure 7. Normal stress is 4MPa](image)
4.2. Propose a correction factor

The experimental data and the empirical formula Coulomb Moore criterion still have 15% to 20% error, so the matrix decomposition method is used to correct the parameters and reduce the error value.

\[ P = \left\{ X = x / P(x; \theta_1, \theta_2, \ldots, \theta_k) \right\}, \quad \text{Among } \theta_1, \theta_2 \text{ are parameters.} \]

\[
K = M \times N \begin{bmatrix}
X_{11}, X_{12}, X_{13}, X_{14}, X_{15} \\
X_{21}, X_{22}, X_{23}, X_{24}, X_{25} \\
X_{31}, X_{32}, X_{33}, X_{34}, X_{35}
\end{bmatrix}
\]

Quantitative processing

\[
M' = \begin{bmatrix}
Y_{11}, Y_{12}, Y_{13}, Y_{14}, Y_{15} \\
Y_{21}, Y_{22}, Y_{23}, Y_{24}, Y_{25} \\
Y_{31}, Y_{32}, Y_{33}, Y_{34}, Y_{35}
\end{bmatrix}
= \begin{bmatrix}
X_{11} / X_{11}, X_{12} / X_{11}, X_{13} / X_{11}, X_{14} / X_{11}, X_{15} / X_{11} \\
X_{21} / X_{21}, X_{22} / X_{21}, X_{23} / X_{21}, X_{24} / X_{21}, X_{25} / X_{21} \\
X_{31} / X_{31}, X_{32} / X_{31}, X_{33} / X_{31}, X_{34} / X_{31}, X_{35} / X_{31}
\end{bmatrix}
\]

\[
M'' = \begin{bmatrix}
Z_{11}, Z_{12}, Z_{13}, Z_{14}, Z_{15} \\
Z_{21}, Z_{22}, Z_{23}, Z_{24}, Z_{25} \\
Z_{31}, Z_{32}, Z_{33}, Z_{34}, Z_{35}
\end{bmatrix}
= \begin{bmatrix}
Y_{11} / Y_{11}, Y_{12} / Y_{11}, Y_{13} / Y_{11}, Y_{14} / Y_{11}, Y_{15} / Y_{11} \\
Y_{21} / Y_{21}, Y_{22} / Y_{21}, Y_{23} / Y_{21}, Y_{24} / Y_{21}, Y_{25} / Y_{21} \\
Y_{31} / Y_{31}, Y_{32} / Y_{31}, Y_{33} / Y_{31}, Y_{34} / Y_{31}, Y_{35} / Y_{31}
\end{bmatrix}
\]

\[ K' = M'' N \] is the final correction factor. The calculated results are as follows:

\[
\begin{bmatrix}
0.92 \\
0.886 \\
0.913
\end{bmatrix}, \quad \text{The residual strength factor into the relational expression, the correction results obtained with the experimental relationship is as follows:}
\]

\[ 5^\circ \text{Undulation angle, } \tau_{\text{min}} = 0.245 + 0.7503\tau, \quad R^2 = 0.9984; \]
15° Undulation angle, $\tau_{\text{min}} = 0.251 + 0.773 \tau$, $R^2 = 0.9893$;
30° Undulation angle, $\tau_{\text{min}} = 0.269 + 0.836 \tau$, $R^2 = 0.9917$.

The resulting residue was corrected strength equation agreement with the experimental conclusion criterion.

5. Conclusion
This test carries on the shear test under the different normal stress of 5 levels, studies the graph chart of the relationship between cutting stress, vertical displacement and tangent displacement, and the destructive pattern of the sectional surface, and obtains the following research results:

(1) Shear strength weakening phase, with the increase of the lowering angle, cohesion and angle of internal friction is also an increasing trend, and corresponding peak intensity greater residual strength will eventually become a constant value. The correlation between residual strength and sticky force (c) and internal friction angle ($\phi$) is discussed, and the linear relationship is shown.

(2) In order to obtain a more accurate residual intensity change relationship, the existing Moor-Cullen criteria parameters are compared, the matrix calculation method is used to make corrections, and the correction formula in line with the experimental conclusions is deduced, and used in practical engineering.

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