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著者	Kusumi Harushige, Sakai Takashi, Nishida Kazuhiko, Nakamura Hitoshi
journal or publication title	Proceedings of JSCE
page range	637-642
year	1999
その他のタイトル	岩盤不連続面の開口状況の定量的評価とそのせん断強度式への適応性
URL	http://hdl.handle.net/10112/5577

Estimation Method of Aperture Condition with Rock Joints and its Application for Shear Equation

Dr. Eng. Kusumi, Harushige; Nishida, Kazuhiko; Sakai, Takashi;
Nakamura, Hitoshi; Yamada, Ryosuke – *Japan*

ABSTRACT: The factors of discontinuity plane which affect the shear behavior of rock joint are the strength of intact rock, roughness, aperture etc. In these factors, there is many researches in related with the roughness. However, although the aperture condition of rock joint is important factor, the many researches with this factor have not been performed. In this paper, the effects of which the shear behavior of rock joint is depended on the magnitude of aperture condition are discussed. Especially, the numerical index representing the degree of the aperture condition with rock joints is proposed, and furthermore, we applied this index on the shear strength equation proposed by authors.

1. Introduction

Factors affecting the shear strength of a discontinuity plane in a rock mass include the strength of the rocks forming the discontinuity plane and the roughness and aperture condition of the discontinuity plane. There are many reports of research related to the shear strength and deformation characteristics of rock mass discontinuity planes, including, Ladanyi and Archambault, Barton and others Many of these are mainly observations on the roughness of discontinuity planes, Barton's JRC is particularly noteworthy, but there are few studies that deal with the effect of the aperture condition of a discontinuity plane on shear strength. Zhao proposes an index called JMC to express the interlocking of a discontinuity plane but there is a problem with this in that it is strongly subjective and the numerical value varies according to the observer.

In this research, using a rock sample with a single discontinuity plane, we have measured the shape of the discontinuity plane by means of a laser displacement gauge in order to study the effect of the aperture condition of a rock mass discontinuity plane on shear strength, and we have proposed a method of quantifying the aperture condition of a discontinuity plane. Then, it has mainly been an experimental study concerning the possibility of applying this coefficient to a certain shear strength.

2. Revised Shear Strength Equation, Ladanyi et al

Ladanyi and Archambault propose a shear strength equation such as the following, which takes account of the variation of dilation ratio (dv/du dv, du: vertical and horizontal displacement components) due to different vertical strains and the variation of proportional shearing of the rock material, with respect to regular triangular tooth-shaped discontinuity planes.

$$\tau = \frac{\sigma_n (1 - a_s)(\dot{v}_p + \tan\phi_u) + a_s \cdot S_R}{1 - (1 - a_s)\cdot \dot{v}_p \cdot \tan\phi_u} \qquad (1)$$

Where, σ_n is the normal stress. S_R is the shear strength of the intact rock substance. ϕ_u is the angle of friction sliding resistance along the contact surface of the teeth. a_s is the shear area ratio of the intact rock substance. $\dot{v}_p$ is the rate of dilation at failure.

In order to apply the range of application of Ladanyi's shear strength equation to irregularly shaped discontinuity planes, by measuring the surface shape of a gypsum sample having an irregularly shaped discontinuity plane, Kusumi et al propose a roughness angle that quantifies the extent of the primary roughness of the discontinuity plane. In addition, by incorporating i_0 into the shear strength equation of Ladanyi et al, and amending the experimental equation to express the shear parameters a_s and $\dot{v}_p$, its range of application is extended to irregularly shaped discontinuity planes. These i_0 , a_s and $\dot{v}_p$ are expressed by the following equation. For details of i_0, please refer to reference 7).symbols omitted from kuku3.j.wc (2).doc are indicated by i_0.

$$i_0 = i_{ave} + \sqrt{2} \cdot SD_i \tag{2}$$

Where, i_0 is the dilation angle. i_{ave} is the average angle. SD_i is the standard deviation of angle.

$$\dot{v}_p = \left\{ 1 - \left(\frac{\sigma_n}{b \cdot \sigma_T} \right)^a \right\} \cdot \tan i_0 \tag{3}$$

Where, σ_T is the transition pressure for the rock substance. $a = 0.45 - 5.1 \times 10^{-3} \cdot i_0$, $b = 0.18$

$$a_s = \frac{(\sigma_n / \sigma_T)}{c + d \cdot (\sigma_n / \sigma_T)} \tag{4}$$

Where, σ_T is the transition pressure for the rock substance. $a = 0.45 - 5.1 \times 10^{-3} \cdot i_0$, $b = 0.18$

The specimens used at this time are gypsum-sandstone specimens that are 100% bonded, or nearly so. A normal direct single shear test was implemented under conditions designed so that the shear strength equation of Ladanyi and Archambault, which is proposed with respect to specimens having a regular tooth-shaped form, would be extended to specimens with irregularly shaped discontinuity planes. The shear strength equation of Ladanyi and Archambault that was amended in this way will be referred to from now on as "the amended equation".

Figure 1 shows the relationship between roughness angle and JRC value of discontinuity planes in natural rock specimens taken from drill cores. Rock specimens G1 to G4 used in these tests are plotted at the same time. The linear relationship between the roughness angle and JRC value of the discontinuity planes suggests that i_0 could become an index to express the degree of roughness of a discontinuity plane. JRC values were obtained from Equation (5) proposed by Xianbin et al.

$$\left. \begin{aligned} JRC &= 64.22 \times Z_2 - 2.31 \;(dx = 1.0\text{mm}) \\ Z_2 &= \sqrt{\frac{1}{L} \int_{x=0}^{x=L} \left(\frac{dy}{dx} \right)^2 dx} \end{aligned} \right\} \tag{5}$$

Where, dx is the measuring intervals. dy is the height of the x direction when moved dx unit. L is the length of discontinuity planes.

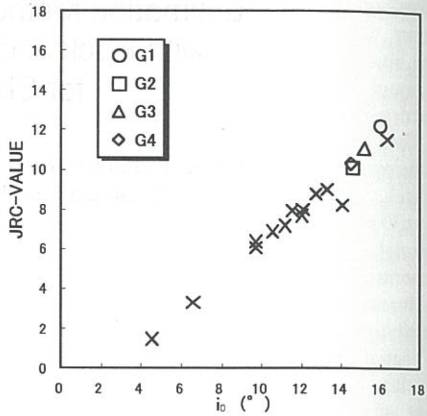

Fig.1 Relation between JRC and i_0

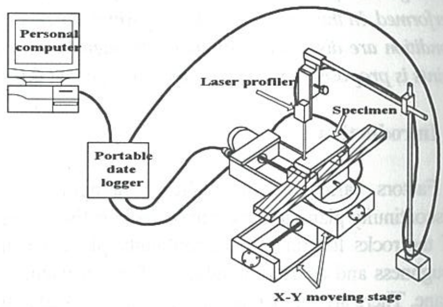

Fig.2 Measuring system of discontinuity plane

3. Specimens and Discontinuity Plane Shape Measurement

Hard rock types belonging to Inada granite that are difficult to break down under low vertical stress (up to 2.0 MPa) were used for these tests. The weight per unit volume of this rock is 25.6 kN/m3 and the uniaxial compressive and tensile strengths are 187.8 MPa and 4.76 MPa respectively. The specimens were cylindrical, 50 mm in diameter and 100 mm high, with a single axial discontinuous surface formed artificially by cleavage. The number of specimens used is four Inada granites (G1 to G4). As shown in Figure 2, the system for measuring the shape of a discontinuity plane consists of a stage capable of X-Y movement (movement range ±60 mm, movement precision ±0.015 mm), a laser displacement gauge (standard

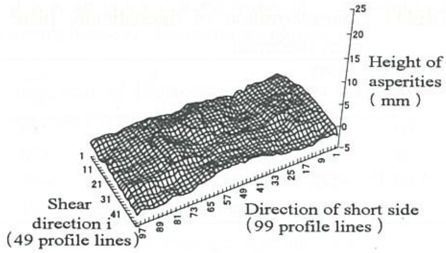

Fig.3 Measuring section of discontinuity plane

distance 40 mm, range of measurement ±10 mm), and a data relay. Measurement involves mounting a specimen on the stage, the X-Y of which is controlled automatically by a personal computer, and capturing the analog output data from the laser displacement gauge with the personal computer. Measurements were taken before the test and after each test, in other words five times for each specimen, a total of 20 times. The measurement interval is 1.0 mm and the number of measurement points on one discontinuity plane is 4851, being 49 profile lines in the shear direction (the i direction) and 99 profile lines in the direction of the short side (the j direction). Figure 3 shows a 3D-profile of the section obtained by measuring plane A of G2.

4. Test Method

Since natural rock is being used in this study, it is not possible to make many test specimens with discontinuity planes having exactly the same shape. In order to obtain a failure envelope from one specimen while changing the shape of the discontinuity plane as little as possible, direct single shear tests were conducted successively on the same specimen from a low normal stress. Consequently, in the second and subsequent shear tests, any scraps were removed and the upper and lower end faces were aligned to the initial conditions as in the first test. The direct single shear test equipment that was used is capable of obtaining shear characteristics with a shear displacement of up to 5 mm while maintaining a constant vertical stress. This test equipment uses a hydraulic loading system and the shear box measures 130 mm x 130 mm x 62 mm with a thickness of 8 mm. Normal stress was applied in four stages of 0.4, 1.0, 1.4 and 2.0 MPa. Shear tests were conducted with constant normal stress and a strain control system, at a shear displacement speed of 0.1 mm/min until the shear displacement reached 5 mm. The discontinuity plane was measured before the shear test and after each shear

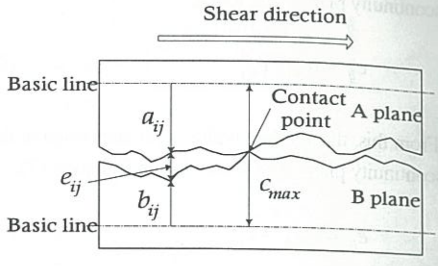

Fig.4 Contact condition between A and B plane

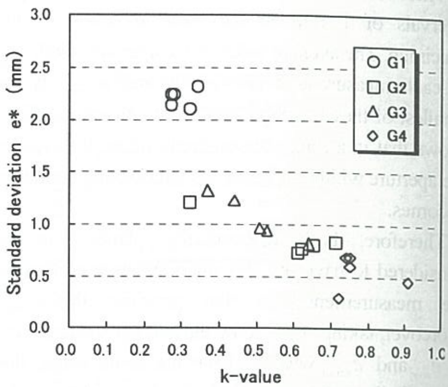

Fig.5 Relation between e* and k

test. In all, sixteen shear tests were implemented, four times on each sample at different normal stresses, the one sample being subjected in stages from a low normal stress.

5. Procedure for Evaluation of Discontinuity Plane Aperture Condition

Since the discontinuity planes of one specimen are completely separated, shape measurements of each were made with a discontinuity plane shape measurement system. Aperture widths for each specimen are obtained on the basis of these data and an attempt is made to evaluate the aperture conditions from the aperture widths. The procedure is shown below.

As in Figure 4, one side of the discontinuity plane is labeled A and the other side is labeled B and the coordinates from the uneven base lines are respectively a_{ij} and b_{ij} (i = 1, 2, .., 49; j = 1 , 2, .. 99). As shown in Equation (6), c_{ij} is the sum of a_{ij} and b_{ij} and c_{max} is the maximum value of c_{ij}. When both sides are put together, c_{max} is taken to be the point at which both discontinuity planes first touch.

$$c_{ij} = a_{ij} + b_{ij} \quad (6)$$

From this, the aperture width e_{ij} at each point in the discontinuity plane is expressed as in Equation (7)、

$$e_{ij} = c_{\max} - c_{ij} \quad (7)$$

There are now 49 measurement lines 99 mm long at intervals of 1 mm in the shear direction of the specimen. The average value of the aperture width e_{ij} in each measurement line is e_{sj} and $e_{s\min}$ is the smallest of these average aperture width values. Zhao shows that in a rough discontinuity plane, the smaller the aperture width, the better the interlocking condition becomes.

Therefore, both discontinuity planes can be considered to have the best interlocking condition on the measurement line that provides this $e_{s\min}$ Moreover, taking e_{ave} to be the average value of e_{sj}, if e_{ave} and $e_{s\min}$ were to have the same value, this would indicate that there is absolutely no scatter in the average aperture widths in the shear direction and if both were to have widely different values, this could be considered to be a broad scatter. Therefore, by obtaining the ratio of $e_{s\min}$ and e_{ave} as shown in Equation (8), this is thought to be an expression of the aperture condition of the discontinuity plane for this specimen and we shall call it the aperture coefficient k ($0<k\leqq1.0$). since all 4851 points that were measured on the discontinuity plane are statistically treated values, the aperture coefficient k can be thought to be an expression of the aperture condition of the entire discontinuity plane. Also, since $e_{s\min}$ is the measurement line with the least aperture of all 49 measurement lines in the shear direction, our attention is drawn to $e_{s\min}$ as it can be considered to affect the shear behavior of the discontinuity plane. Furthermore, if two discontinuity planes are offset, the aperture coefficient k will have a different value so, since it must always be determined unambiguously, this aperture coefficient k is to be obtained in a state where the end faces of the specimen are aligned (a condition of no displacement in the shear direction).

$$k = \frac{e_{s\min}}{e_{ave}} \quad (8)$$

Table.1 Characterization of discontinuity plane for each specimen

No.	JRC	i_o (°)	k	e_{ave} (mm)
G1	12.23	15.93	0.32	2.68
G2	10.12	14.57	0.61	1.70
G3	11.07	15.12	0.64	1.30
G4	10.30	14.96	0.72	1.21

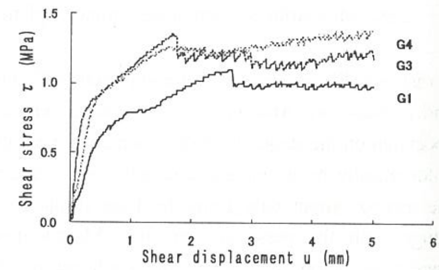

Fig.6 τ - u curves of each specimen (σ_n=1.0MPa)

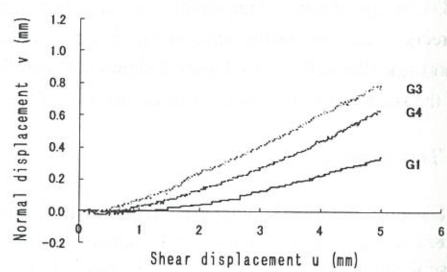

Fig.7 Dilation curves of each specimen (σ_n=1.0MPa)

Distributions of aperture widths were obtained by measuring the shape of the discontinuity plane after shear tests that were conducted under different normal stresses for each specimen. Figure 5 shows the relationships between their standard deviations e* and aperture coefficients k. The following equation was used to obtain standard deviations e*.

$$e^* = \left[\frac{1}{N}\sum_{i=1}^{49}\sum_{j=1}^{99}\left(e_{ij} - e_{ave}\right)^2\right]^{1/2} \quad (9)$$

Where, N is the number of all measurement points (4851points)

From Figure 5, since the standard deviation e* of the distribution of aperture width is increasing as the aperture coefficient k becomes smaller, it is clarified that k is an index that expresses the condition of the aperture between discontinuity planes.

6. Behavior of Discontinuity Planes with Different Aperture Conditions under Shear

Table 1 shows the discontinuity plane JRC value, discontinuity plane roughness angle i_0 ,aperture coefficient k and average aperture width e_{ave} for each specimen before shear testing. From this, whereas the JRC and i_0 values for specimens G1, G3 and G4 are almost the same, the k value for specimen G1 is rather smaller than the others. Figure 6 shows shear stress-shear displacement curves for specimens G1, G3 and G4 under a normal stress of 1.0 MPa. Since the roughness of the discontinuity planes for each specimen before shear tests under this normal stress were implemented is almost the same as the value in Table 1, it is considered that perhaps the difference in maximum shear force is being influenced by the aperture condition. Figure 7 shows normal displacement-shear displacement curves for each specimen at the time of Figure 6. the dilation angles for specimens G3 and G4 near maximum shear are 7.19° and 6.86° respectively, and whereas they are about the same, that of specimen G1 is greatly different at 2.43°. A remarkable difference in dilation due to the different aperture coefficient k can also be seen in this diagram. We noticed from the test results in Figures 6 and 7, that the shear behavior of rock specimens with discontinuity planes of the same degree of roughness differs due to their different aperture conditions, and that the smaller the scatter of average aperture widths in the shear direction of the discontinuity planes, in other words, the greater the area of the discontinuity planes that is in contact, the greater the maximum shear force becomes. Generally, under such unusually low normal stress that the irregularity of the discontinuity plane itself does not shear, dilatancy will occur due to the uneven space sliding up over the discontinuity plane and its value is thought to reflect the roughness of the irregularity and its angle of dip. On comparing specimens G1 and G3, under each vertical stress, specimen G1 has a smaller dilation angle than sample G3. From Table 1, both specimens have similar roughness angles i_0, being 15.93° and 15.12° respectively, but the aperture coefficients k are 0.32 and 0.64 respectively. This difference in the values of the aperture coefficients k can be expected to

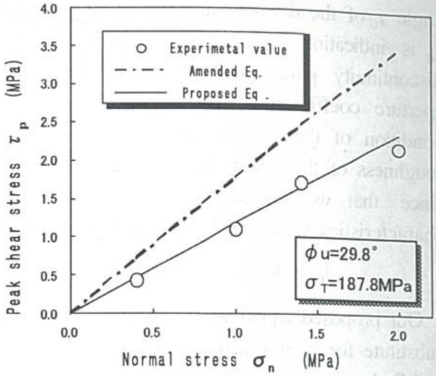

Fig.8 Comparison experimental value with calculating curves for G1

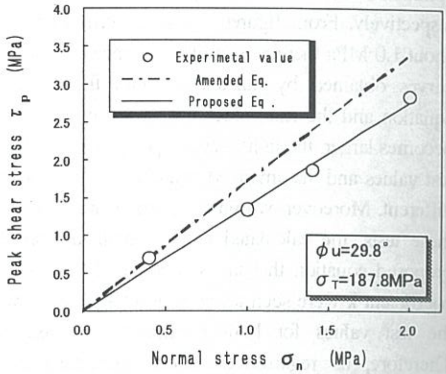

Fig.9 Comparison experimental value with calculating curves for G3

have a major influence on the nature of the dilatancy near the maximum shear force. In short, for specimens that have a large scatter of aperture widths, the initial dilation angle can be thought to become small compared to the roughness angle i_0.

7. Failure Envelope

The shear parameters $\dot{v}_p$ and a_s had been amended for tests using granite samples but because we are using granite specimens with completely bonded discontinuity planes, the amended equation mentioned above does not take into account the factor of the aperture condition of the discontinuity planes. Therefore, in this study, it is tried to consider the aperture condition factor for the amended equation by multiplying the aperture coefficient k by the roughness angle i_0 of the discontinuity planes. That is to say, i_0 is indicating the degree of roughness of the discontinuity planes and, by multiplying by the aperture coefficient k that expresses the aperture condition of the discontinuity planes, the apparent roughness of the discontinuity planes is altered and since that is reflected in the shear strength characteristics, we defined i_{0k} as in Equation (10).

$$i_{0k} = i_0 \times k \tag{10}$$

Our proposed equations have this i_{0k} applied as a substitute for i_0 in Equations (3) and (4). Figures 8 and 9 show comparisons of curves calculated by the amended equation and the proposed equation and test values obtained by means of single shear tests conducted this time for specimens G1 and G3 respectively. From figure6, up to a normal stress of about 1.0 MPa there is a small difference between the curves obtained by calculating with the amended equation and the test values but as the normal stress becomes larger, the failure envelope lines according to test values and the amended equation are increasingly different. Moreover, within the normal stress range of these tests, the calculated curves obtained from the proposed equation that takes account of the aperture coefficient k were seen to be in good agreement with the test values for both specimens G1 and G3. Therefore, as regards the shear characteristics of discontinuity planes, including the roughness of the discontinuity planes, the fact that aperture conditions exert a considerable influence with respect to the maximum shear strength has been clarified.

8. Conclusion

This study has conducted single shear tests with respect to 100% bonded granite specimens having discontinuity planes of irregular shape. In order to take account of the aperture conditions of discontinuity planes in the shear strength equation that is being proposed by Kusumi et al, we have shown that aperture conditions are expressed quantitatively from aperture width characteristics obtained by measuring the surface shape of the discontinuity planes of rock specimens. Furthermore, by incorporating an aperture coefficient k into the amended equation, we have proposed a shear strength equation that takes account of aperture conditions. The results obtained are summarized as follows.

(1) Even with the same degree of roughness angle i_0 of specimen discontinuity planes, the dilatancy of the discontinuity planes varies widely due to different aperture coefficients k. In short, for samples having highly scattered average aperture widths in the shear direction, compared with the roughness angle i_0 of the discontinuity planes, the initial dilation angle was seen to become smaller.

(2) By multiplying the roughness angle i_0 of the discontinuity planes, which is a parameters in the amended equation, by the aperture coefficient k, the maximum shear strength of a natural granite sample that is not completely bonded was able to be expressed precisely.

Acknowledgment

The authors wish to thank to Mr.H.Kawamato of Japan Highway, former the student of Kansai University for his assistances.

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