J. Cent. South Univ. (2014) 21: 4653−4659
DOI: 10.1007/s11771-014-2473-7

Springer

New criterion for rock joints based on three-dimensional roughness parameters

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Abstract: The shear behavior of rock joints is important in solving practical problems of rock mechanics. Three group rock joints with different morphologies are made by cement mortar material and a series of CNL (constant normal loading) shear tests are performed. The influences of the applied normal stress and joint morphology to its shear strength are analyzed. According to the experimental results, the peak dilatancy angle of rock joint decreases with increasing normal stress, but increases with increasing roughness. The shear strength increases with the increasing normal stress and the roughness of rock joint. It is observed that the modes of failure of asperities are tensile, pure shear, or a combination of both. It is suggested that the three-dimensional roughness parameters and the tensile strength are the appropriate parameter for describing the shear strength criterion. A new peak shear criterion is proposed which can be used to predict peak shear strength of rock joints. All the used parameters can be easily obtained by performing tests.

Key words: rock joint；shear behavior；peak shear strength；three-dimensional roughness parameter

1 Introduction

Rock mass as an engineering material is generally not comprised of homogeneous, isotropic, continuous materials and may contain joints, faults, and/or bedding planes. The presence of joints in a rock mass may affect its mechanical behavior. Therefore, great attention should be paid to the shear behavior of such weakness planes. Correct estimation of the shear behavior of rock joints plays an important role in the design of excavations in rocks, stability analysis of rock slopes. The shear behavior of rock joints can be investigated in the laboratory and many applications could benefit from the study of joint at small scale, such as geo-thermy, petroleum and all other types of energy recovery. In general, there are two dominant normal stress paths in rock joint shearing which are called constant normal stiffness condition (CNS) and constant normal loading condition (CNL). A study on the shear behavior of rock joints at small scale under constant normal loading condition is presented.

In the past decades, a large number of researchers, such as BARTON [1], BARTON and CHOUBEY [2], MAKSIMOVIC [3], KULATILAKE et al [4], ZHAO [5], HOMAND et al [6], GRASSELLI [7] and TANG et al [8−9] have proposed criteria to predict the peak shear strength of rough rock joints. In addition, XIA et al [10] studied the shear strength of rock joint under cyclic loads. Among these, JRC-JCS criterion, proposed by BARTON and his colleague [1−2], is the only one widely used in practice. Although these criteria have improved our understanding of shear behavior, there are still some limitations that should be recognized. As three-dimensional surface existing in rock mass, the mechanical behaviors of rock joints are influenced by three-dimensional topography, but not just a or several profiles (2D). Actually, most of the existed criteria are based on two-dimensional profiles and the associated two-dimensional morphology parameters [1−2, 4−5], which usually resulted in underestimation of the peak shear strength. The realistic three-dimensional roughness parameters, not the averaged one, are used by the Grasselli's criterion [7] and Tang's criterion [8−9] and both of them can be used as a predictive tool.

The shear behavior of rock joints is investigated and then a new failure criterion is proposed with an emphasis on the effect of three-dimensional morphology parameters. Comparison is given among the criteria based on three-dimensional roughness parameters.

Foundation item: Project(41130742) supported by the Key Program of National Natural Science Foundation of China; Project(2014CB046904) supported by the National Basic Research Program of China; Project(2011CDA119) supported by Natural Science Foundation of Hubei Province, China; Project(40972178) supported by the General Program of National Natural Science Foundation of China
Received date: 2013−08−26; **Accepted date:** 2014−01−20
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2 Experimental

A series of laboratory direct shear tests under CNL conditions of joints with varying three-dimensional roughness were performed. In order to study the effect of three-dimensional roughness on the mechanical properties of rock joints, it is necessary to perform direct shear tests on rock joint samples having the same geometrical features under different normal stress conditions. However, it is practically impossible to find rock joints with exactly the same geometrical features in nature. Therefore, replicas of natural rock joints were used.

2.1 Sample

Joint samples were produced with a size of 300 mm by 150 mm. The material is the mixture of plaster, sand and water at the mass ratio of 3:2:1. All the samples were cured at a constant temperature of 25 ºC in a chamber for about 28 d. According to the surface roughness, these samples were divided into three groups named I, II and III, and each group consists of 5 samples with the same morphology.

The uniaxial compressive strength and density were measured in the laboratory which give an average value of 27.5 MPa and 2200 kg/m^3, respectively. The tensile strength of material was measured by Brazilian tests which gives an average value of 1.54 MPa. The basic friction angle of the interface is 35° measured by performing four direct shear tests on the flat replicas under different low normal stresses. The elastic modulus and Poisson ratio for the model material is 6.1 GPa and 0.16, respectively.

2.2 Apparatus

Direct shear tests were performed on CSS-342 rock mass shear machine (servo-hydraulic) at the Rock Mechanics and Engineering Centre of Tongji University. The maximum shear displacement of the system is 50 mm and shear velocity can be chosen in the range of 0.1 to 5 mm/min. The normal and shear forces were measured by load cells placed in series with the actuators. The shear displacement was measured by two LVDT with a measuring range of 50 mm and an accuracy of 0.1 mm. The normal displacement was measured by four LVDT with an accuracy of 0.025 mm.

Joint surface were scanned by 3D stereo-topometric measurement system developed by XIA et al [11] before direct shear test to obtain its topography data. The principle of this system is shown in Fig. 1 and more details can be found in the related reference. The resolution of the spatial location of each point in the 3D space along x, y and z directions is ±20 μm. Hence, details of the rough surface can be captured precisely. When reconstructing the three-dimensional morphology and calculating the resulted roughness parameters, point interval of triangle mesh is selected as 0.3 mm in the current work.

2.3 Direct shear test

When samples were ready for testing, the normal load was raised steadily to the required level and allowed to stabilize before applying shear force. The normal force was held constant while the shear was applied. Normal load, shear load, dilation, and shear displacement values

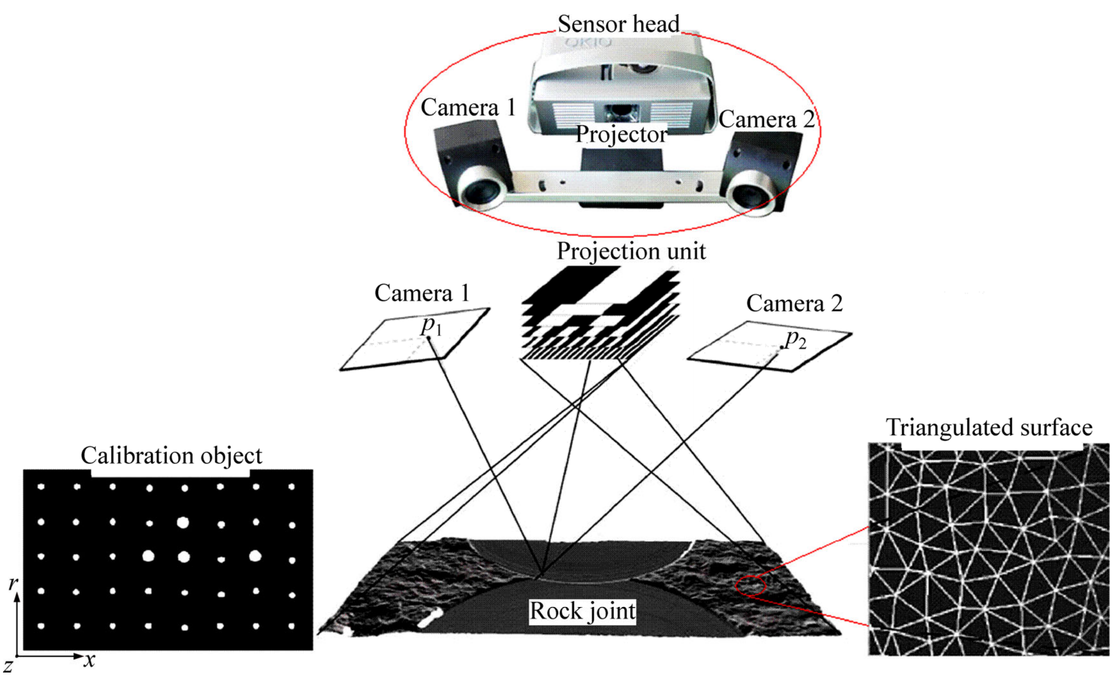

Fig. 1 Stereo-topometric scanner used to digitize surface roughness (Modified from Ref. [11])

were recorded and displayed by a personal computer equipped with a data acquisition system. Each shear sample was subjected to a selected normal stress, 0.5, 1.0, 1.5, 2.0 and 3.0 MPa, respectively. The shear velocity was selected by 0.5 mm/min. All shear tests were performed until residual strength was reached or sample failed.

3 Experimental results and analysis

Using above experimental procedure, a total of 15 direct shear tests for the three group joints were performed. The measured peak shear strength are shown in Fig. 2 and typical experimental curves are plotted in Fig. 3. For joints in the same group (with the same morphology), the peak shear strength increases with increasing normal force and, for the same applied normal stress, the peak shear strength increases with rougher surface. Although all joint samples are rough, residual shear stress was not observed for three joint samples in Group I until sample failure happened. According to the experimental results, it can be found that the peak dilatancy angle decreases with the increasing normal stress, and increases with increasing roughness of rock joint (Fig. 4). The experimental results indicate that the linear Coulomb friction law is inadequate to represent the failure of rough joints. The roughness of surface is a key aspect for the definition of the friction angle and a larger roughness leads to a larger friction angle.

JRC-JCS criterion [2] is the currently widely used criterion to predict joint peak shear strength in practice, which is given by

$$\tau_{\rm p} = \sigma_{\rm n} \tan\left[\varphi_{\rm r} + C_{\rm JR} \cdot \lg\left(\frac{S_{\rm JC}}{\sigma_{\rm n}}\right)\right] \tag{1}$$

where $\tau_{\rm p}$ is the peak shear strength; $\sigma_{\rm n}$ is the normal stress; $\varphi_{\rm r}$ is the residual friction angle; $C_{\rm JR}$ is the joint roughness coefficient; $S_{\rm JC}$ is the joint wall compressive strength.

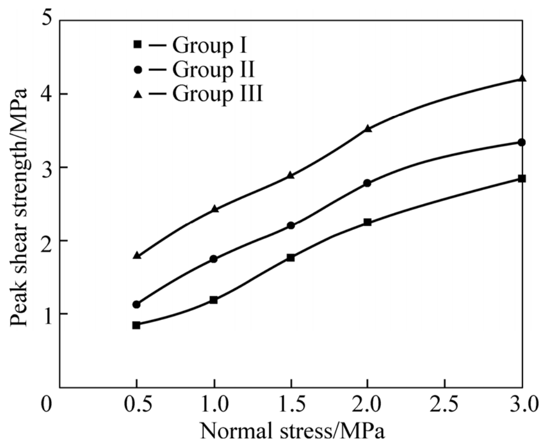

Fig. 2 Variation of peak shear strength versus normal stress for Groups I, II and III

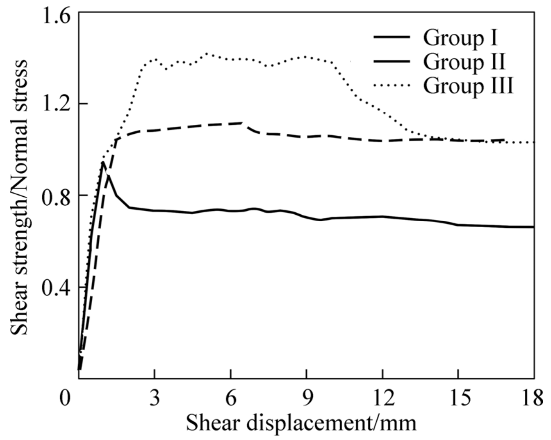

Fig. 3 Shear stress/normal stress vs shear displacement with different morphologies joint under same normal stress [9]

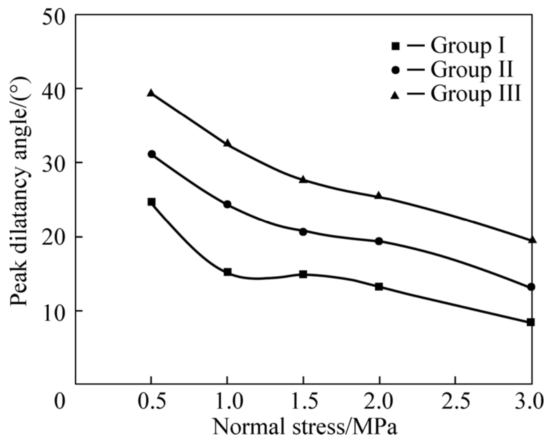

Fig. 4 Variation of peak dilatancy angle versus normal stress for Groups I, II and III

Comparison between the experimental results and the predictions obtained by JRC-JCS criterion is shown in Fig. 5. The value of $C_{\rm JR}$ is determined by the way suggested by BARTON and CHOUBEY [2] and for the three groups, this can be found in Ref. [9]. It seems that a more suitable peak shear strength criterion is needed due to the underestimation of JRC-JCS criterion.

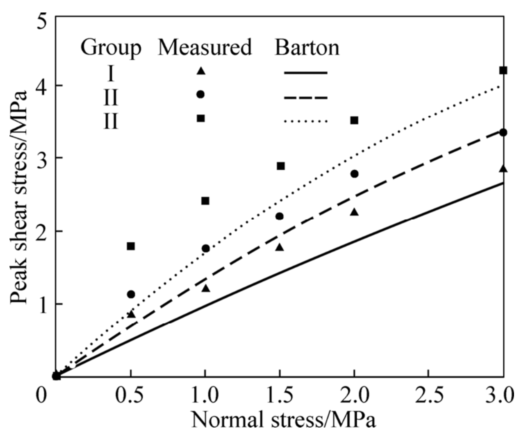

Fig. 5 Comparison between experimental results and calculated by JRC-JCS criterion for Groups I, II and III [9]

4 New peak shear strength criterion

4.1 Appropriate parameters

Again, looking at Eq. (1), the peak dilatancy angle, i_p, caused by roughness is expressed by

$$i_p = C_{JR} \cdot \lg\left(\frac{S_{JC}}{\sigma_n}\right) \tag{2}$$

Both C_{JR} and S_{JC} should be responsible for the underestimation of peak shear strength. To data, most of researchers paid special attention to C_{JR} [12−15] and some researches have been performed to determine suitable surface description [4, 16−18]. However, most of the morphology parameters are not sufficient to capture the fundamental characteristics of three-dimensional roughness of joint surface. From a realistic point of view, the roughness formulation proposed by GRASSELLI et al [17−19] can be considered as the best roughness evaluation technique since the surface is assessed according to the exact geometrical shape of asperities and the actual potential contact areas, without any average value of surface variable [19]. Another reason for underestimation is probable the used parameter, S_{JC}, which is related to the shear mechanism of joints. Several researchers, such as GRASSELLI [7], PARK and SONG [20], GHAZVINIAH et al [21], and BAHAADDINI et al [22], have emphasized that failures of asperities are due to tensile fracture instead of compressive fracture. Hence, the use of tensile strength instead of compressive strength for determining the joint shear strength may be more practical.

4.2 Quantified surface description

It was found that the real contact area is a small portion of the total surface and only by studying the entire surface, not just one profile, will be possible to understand the influence of roughness to its shear behavior. GRASSELLI et al [17] found that the identification of the potential contact areas only requires the determination of the areas which face the shear direction and which are steep enough to be involved.

In roughness characterization, joint surface is discretized into adjacent triangles with each triangle orientation uniquely identified by its azimuth angle (α) and dip angle (θ) (Fig. 6). The apparent dip angle (θ^*) describes the apparent inclination of each triangle with respect to the chosen shear direction. The relationship among apparent dip angel (θ^*), dip (θ) and azimuth (α) was given by [17]

$$\tan\theta^* = -\tan\theta \cdot \cos\alpha \tag{3}$$

The variation of the potential contact area (A_{θ^*}) versus the apparent dip angle (θ^*) was given by [16]

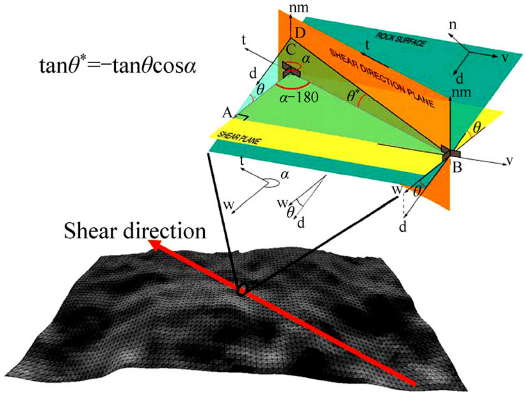

Fig. 6 Apparent dip angle θ^*, measured along shear direction with respect to shear plane [17]

$$A_{\theta^*} = A_0\left[\frac{\theta^*_{max} - \theta^*}{\theta^*_{max}}\right] \tag{4}$$

where θ^*_{max} is maximum apparent dip angle in the shear direction; C is the fitting coefficient, characterizing distribution of apparent dip angles over joint surface.

Larger area under the curve defined by Eq. (4) indicates a larger proportion of steeply dipping asperities and greater relative roughness on the surface [18]. By evaluating the definite integral of Eq. (4) between 0 and θ^*_{max}, the area under the curve was given by [18]

$$\int_0^{\theta^*_{max}} A_0\left[\frac{\theta^*_{max} - \theta^*}{\theta^*_{max}}\right]^C d\theta^* = A_0\left(\frac{\theta^*_{max}}{C+1}\right) \tag{5}$$

The function determined by Eq. (4) can be considered as the best roughness evaluation technique since the surface is assessed by the exact geometrical shape of asperities and the actual potential contact areas, not by any average value of surface variables [19], and the calculated value by Eq. (5) is selected as the roughness parameter to describe joint surface called as the three-dimensional roughness metric. The curves of the three group joints given by Eq. (4) are plotted in Fig. 7. It can be stated that Group III is the roughest.

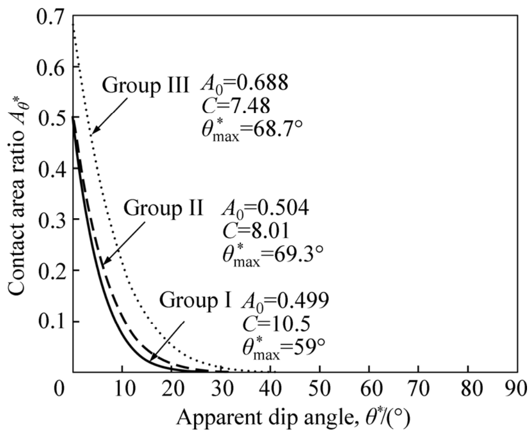

Fig. 7 Contact area ratio versus different threshold values in shear direction for Groups I, II and III [9]

4.3 New criterion

As using proper values for the peak dilatancy angle would yield acceptable shear strength predictions, thus by assuming an efficient function for i_p instead of the term of Eq. (2), one can obtain the shear strength. The mathematical expression for the function can be assumed by considering the boundary conditions and tendency of the measured peak dilatancy angle. Peak dilatancy angle approaches the steepest asperity angle in zero normal stress and equals zero by approaching the normal stress to physical infinity (very high normal stresses causing zero dilation angle). Regarding the boundary conditions, the relations between peak dilatancy angle and normal stress can be given [23]:

$$\begin{cases}(\sigma_t/\sigma_n)\to 0 \Rightarrow i_p = 0 \\ (\sigma_t/\sigma_n)\to \infty \Rightarrow i_p = i_{p0}\end{cases} \tag{6}$$

where σ_t is tensile strength; i_{p0} is initial dilatancy angle.

Hyperbolic function is easy to satisfy the above boundary conditions and then can be used to predict the peak dilatancy angle, which is given by

$$i_p = i_{p0}\frac{(\sigma_t/\sigma_n)}{1+(\sigma_t/\sigma_n)} \tag{7}$$

As the peak dilatancy angle starts from steepest asperity angle under zero normal stress, i_{p0} is needed as an independent parameter which is just influenced by surface topography. KUSUMI et al [24] proposed a statistical formula, Eq. (8), which can be applied for calculating the steepest asperity angle of a periodic profile.

$$i_{max} = i_{ave} + \sqrt{2}D_i \tag{8}$$

where i_{max} is maximum angle; i_{ave} is average angle; D_i is standard deviation of the angle.

The exact features usually cannot be thoroughly captured by averaged parameters and, considering the non-periodic characterizes, Eq. (8) would be non-efficient for natural joint.

A regression analysis by root-mean-square method was conducted based on measured peak dilatancy angles and normal stresses by Eq. (7). The obtained initial peak dilatancy angles are 29.2°, 31.0°, 54.0° when σ_n=0 for the three group joints investigated here, respectively. The relationship between the initial dilatancy angle and three-dimensional roughness metric defined by Eq. (5) is shown in Fig. 8, which depicts a very good linear tendency between them. Thus, the initial dilatancy angle can be expressed as

$$i_{p0} = 10A_0[\theta^*_{max}/(1+C)] \tag{9}$$

Then, the peak dilatancy angle defined by Eq. (2) can be replaced by Eq. (10) with more appropriate parameters.

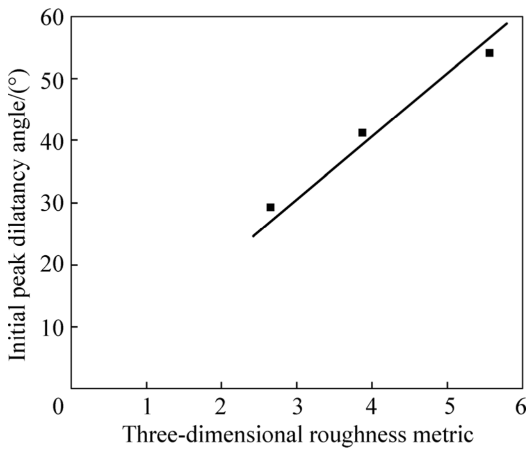

Fig. 8 Correlation of initial dilatancy angle with three-dimensional roughness metric

$$i_p = 10\frac{A_0\theta^*_{max}}{(1+C)}\cdot\frac{(\sigma_t/\sigma_n)}{1+(\sigma_t/\sigma_n)} \tag{10}$$

By substituting the proposed function of the dilatancy angle into Mohr-Coulomb type of formulation, the proposed non-linear peak shear strength criterion for rock joints can be given as

$$\tau_p = \sigma_n \tan\left[\varphi_b + 10\frac{A_0\theta^*_{max}}{(1+C)}\cdot\frac{(\sigma_t/\sigma_n)}{1+(\sigma_t/\sigma_n)}\right] \tag{11}$$

Comparison between the experimental results and the calculated values by using Eq. (11) is shown in Fig. 9.

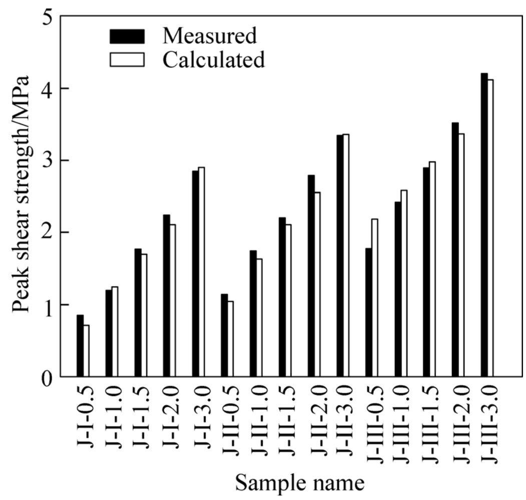

Fig. 9 Comparison between measured and predicted peak shear strength for Groups I, II and III

4.4 Validate

The proposed criterion was obtained from performed tests on artificial rock joints. To assess this criterion, the peak shear strengths of natural joints obtained experimentally in laboratory tests by

GRASSELLI [7] were compared with the values calculated by Eq. (11), as listed in Table 1. The compressive strength of the materials used in the present work is $0.18 \le \sigma_n/\sigma_c \le 0.107$; hence, only marble joint studied by GRASSELLI were used for the comparison. According to correlation analysis, the calculated value is little larger than the measured value (shown in Fig. 10), but the predicted shear strength from Eq. (11) is also close to the experimental shear strength of natural joints. Hence, it can be deduced that the proposed shear strength criterion is capable of predicting the shear strength of rough joints.

Table 1 Comparison of peak shear strengths of natural joints obtained experimentally in laboratory tests by GRASSELLI [7] and predicted peak shear strengths by Eq. (11)

Sample	φ_b/(°)	σ_n/σ_c	σ_t/MPa	$\frac{A_0\theta^*_{max}}{1+C}$	Shear strength/MPa	
					Measured	Predicted
M1	37	0.010	9.2	3.66	1.7	2.454
M2	37	0.020	9.2	2.91	2.3	3.182
M3	37	0.010	9.2	2.66	1.2	1.591
M4	37	0.043	9.2	3.43	5.8	6.910
M5	37	0.030	9.2	3.17	4.4	4.832
M6	37	0.030	9.2	2.74	4.3	4.216
M7	37	0.043	9.2	3.01	5.6	6.133
M8	37	0.044	9.2	2.87	6.4	5.956
M9	37	0.030	9.2	2.57	4.5	4.004
M10	37	0.010	9.2	2.93	1.5	1.763
M12	37	0.021	9.2	2.85	3.0	3.210

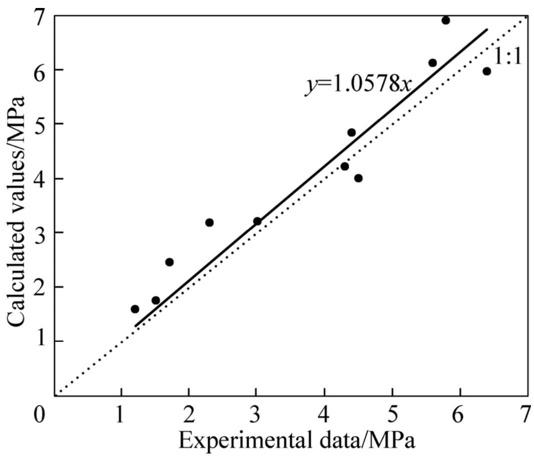

Fig. 10 Calculated versus experimental peak shear strength by GRASSELLI [7]

5 Conclusions

Shear behavior of rock joints is investigated under CNL conditions. The shear strength increases with the increasing normal stress and the roughness. Underestimation of JRC-JCS criterion is analyzed thoroughly and it is concluded that three-dimensional roughness metric and tensile strength may be the more appropriate parameters for peak shear strength criterion. A dilatancy angle function is developed based on the dilatancy angle boundary conditions under zero and infinity normal stress. Then, a new criterion is proposed. The contribution of roughness to peak shear strength is captured by the entire surface (not only on single profiles) without any averaging variables. The proposed criterion can be used as a predictive tool to assess the peak shear strength of rock joints.

Acknowledgments

The main experimental work was done by the first author during the course of studying for his PhD degree at Tongji University. Prof. XIA Cai-chu, the supervisor of the first author, and Mr. SONG Ying-long were acknowledged.

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(Edited by HE Yun-bin)