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Effectiveness of Matched and Mismatched Natural Rock Joints Using Experimental Direct Shear Tests

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Abstract

In practice, the shear strength of joints is not only determined by the roughness, but also by the degree of joint matching. Due to alteration or movement, the joints with equal roughness might be mismatched. The matching degree of the joint is a significant factor that controls the normal closure, aperture, stiffness, hydraulic conductivity, and shear strength of the jointed rock mass. Studying the shear behavior of natural mismatched rock joints obtained from core drilling with different morphological characteristics, degrees of matching, and irregular shapes is an issue that has gained less attention due to the lack of samples and difficulty to obtain data. This study investigates the shear behavior of mismatched joints obtained from core drilling. Here, a new criterion is developed based on 35 series of direct shear tests, Barton and other classical theories, three-dimensional morphological characteristics, and matching condition of joints. To validate the proposed criterion, the estimation accuracy of the available classical models is compared with that of the new model. It is observed that the new criterion could achieve higher prediction accuracy for mismatched joints. Moreover, it is found that the average estimation error of the predicted values is reduced by considering the matching conditions.

Keywords

mismatched joints, shear behavior, joint matching, core drilling

1 Introduction

Overall mechanical behavior of jointed rock masses is predominantly controlled by the shear strength of rock joints. A precise evaluation of the shear resistance of natural joints is of great importance because small changes can lead to large changes in the safety of structures in rock masses [1–3]. The study of the shear mechanism of discontinuities has gained growing attention from scholars worldwide. Many factors affect the shear behavior of rock joints such as basic friction angle, morphology and surface matching, normal stress, scale effect, inherent joint properties like compressive or tensile strength, etc. [4]. Many models have been developed to predict the peak shear strength (PSS) of rock joints under Constant Normal Loading (CNL) [5, 6].

Zhao [7], proposed the joint matching coefficient (JMC) as an independent joint surface geometrical parameter. The JMC is based on the percentage of joint surfaces in contact and coupled with the joint roughness coefficient (JRC) to entirely characterize the geometrical parameters. Oh and Kim [8] studied the effect of opening on the shear behavior of regularly shaped rock joints by various horizontal dislocation between the lower and upper joint blocks. To describe the wave propagation across a single joint, Chen et al. [9] developed a one-dimensional contacted interface model (CIM-JMC) by considering the JMC. Several PSS criteria based on advanced techniques (including a method based on the fractal, laser scanner, photogrammetry, etc.) have been developed to evaluate the roughness [10–14]. Based on cohesion and fractal theory, Johansson and Stille [15] proposed a conceptual model to investigate the influence of roughness and matedness at different scales on the PSS of rock joints. Ríos-Bayona et al. [16] presented an objective measurement of the average aperture of natural, unfilled joints to predict the matedness of joints in the prediction of the PSS.

Most of the previous studies were performed on artificial, replica and completely mated joints with regular shapes (rectangular or square) produced in the laboratory. They also assumed that the joints are completely matched at the beginning of the test, an assumption that is not true for natural, mismatched rock joints. Since geotechnical

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engineering studies are performed by core drilling, and the direct shear tests should be performed on the core-shaped sample joints, this issue has received less attention due to the lack of samples and difficulty in obtaining data. This study investigates the shear behavior of natural, mismatched rock joints obtained from core drilling without filling. A novel model is proposed to predict the PSS with an emphasis on the effect of the Initial Matching Condition (IMC) and surface morphological parameters. To evaluate the proposed method, the estimation accuracy has been compared with models based on surface morphological parameters. It is observed that the new criterion can predict the PSS of natural mismatched rock joints with admissible accuracy compared to the existing experimental studies.

2 Sample preparation and laboratory tests

All-natural rock joint samples were obtained from core drilling of the geotechnical and slope stability project. The samples were fresh and without filling. The samples consist of three rock types (Mica-Schist, Quartzite, Amphibolite) and are obtained from different depths with different degrees of matching. This is the reason for the dispersion of shear strength values of the joints. For laboratory preparation, the specimens are set inside the molds and then encapsulated them with plaster (Fig. 1).

The uniaxial compressive strength (UCS) and Brazilian (indirect tensile) tests were used to determine the compressive and tensile strength of the specimens. Samples with length to diameter ratios of 2.2 to 2.5 and 0.5 are used to perform UCS and Brazilian tests, respectively. The saw cut samples were also used to measure the basic friction angle. All specimens were derived from the nearest depth to shear test samples. To minimize the deviation of the results, each test was repeated six times.

3 Methodology

After sample preparation and before performing the direct shear tests, the morphology of the upper and the lower surfaces of the joint should be captured. The Close-Range Photogrammetry (CRP) to acquire 3D coordinates of the joint surfaces is used in this paper. The settings and arrangement of photogrammetric operations and capturing images are based on the work by Kim et al. [17]. A single-lens reflex digital camera (Canon EOS 1300D), which has a high-resolution CCD sensor (5184 × 3456 = 18 megapixels), is used to capture images of the real joints surfaces. Fig. 2 describes the methodology used for this study and shows the procedure of digitizing joint surfaces using photogrammetry and the research process on natural joints.

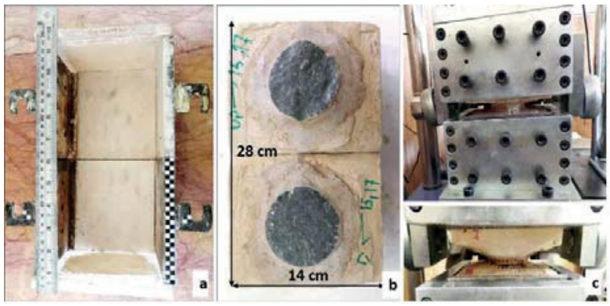

Fig. 1 Sample preparation for laboratory test: a) mold before casting, b) sample after molding and before testing, c) Prepared sample in the shear box

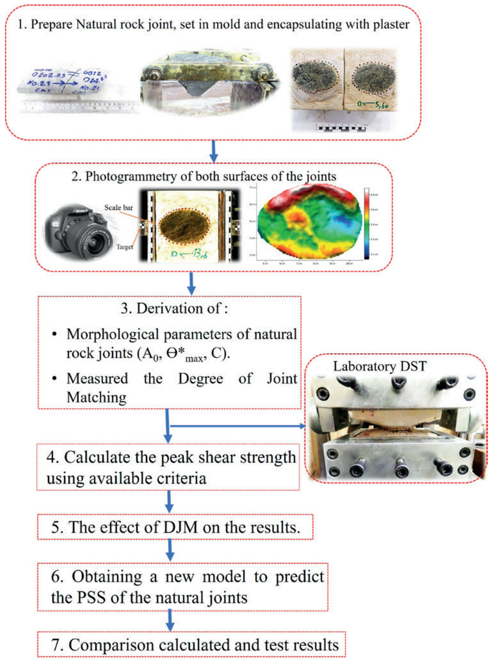

Fig. 2 Flowchart with the main steps of the research process on natural joints of this study

The following steps are followed in this research study (Fig. 2): (1) setting the sample joints in a mold and encapsulate with plaster; (2) using a high-resolution camera to capture the high-quality images and generate digital terrain models (DTM) and 3D images and generate point clouds at the minimum sampling interval for both surfaces; (3) exporting point clouds to MATLAB (Matrix Laboratory) for reconstructing the joint surfaces and setting a specified sampling interval (0.3 mm for this study) and determining the morphological parameters of natural rock joints (A0, θ^*_{max}, C) and measured the IMC; (4) estimating the PSS of natural joints using available classical criteria and also performing direct shear tests; (5) investigating the effect of IMC on the results; (6) developing a new model to predict the PSS of the natural, mismatched rock joints with considering the IMC; (7) comparing the estimation accuracy of the new model with the other classical criteria.

A sampling interval (SI) of 0.300 mm was considered as the optimal interval to reconstruct the joint surfaces. This sampling interval is chosen based on previous research [18–23].

3.1 Surface Morphology Data

The 3D surface morphology of the rock joints is taken by CRP before the test. The surface morphological parameters such as A_0, θ^*_{max}, and C are calculated. Based on Yang et al. [20] and Liu et al. [24], A_0 is not an appropriate parameter to characterize the three-dimensional surface morphology of rock joints and has no crucial effect on forecasting the PSS. It is not clear whether there is a positive or negative correlation between A_0 and joint roughness. Therefore, A_0 is not a suitable parameter to use in the models to compute roughness and PSS.

3.2 Direct shear test

To perform the direct shear test, each half of the specimen was secured in the specimen holders. The dimensions of the shear boxes were 140 × 140 × 10 mm^3. To investigate the shear behavior of natural joints, direct shear tests were performed on 35 natural sample joints under CNL conditions. The 35 joints were open, clean, and non-weathered without cohesive infill and no indication of prior shearing. The samples were in the form of cores and were obtained from different depths during geotechnical drilling. The test core samples were coming from the slope of an Iron open-pit mine in Southeast Iran. The site is placed at the south-eastern boundary of the Sanandaj-Sirjan zone basement of mostly medium- to high-grade metamorphic rocks of Neoproterozoic age (e.g., amphibolite, gneiss, schist, and marble) [25]. The rock mass is significantly fractured. To perform the direct shear tests the servo-controlled shear machine was used with the capacity of performing shear tests according to the methodology suggested by the ISRM [26].

The normal and shear capacity of the vertical and horizontal hydraulic jacks are 10 and 15 tons, respectively. The shear and normal displacements are also measured by two LVDTs ±50 mm, and a shear rate of 0.1 mm/min (Fig. 3).

4 Determining the Initial Matching Condition of joint surfaces

To achieve the IMC at the beginning of the test, the concept of 'tiny windows' proposed by Fathi et al. [21] is used in this study. Before the test, the upper and lower surfaces of the real rock joint are captured with photogrammetry and both surfaces are gridded with the same interval at 0.30 mm intervals. The grid coordinates of the lower and upper meshes should be face to face (Fig. 4).

Both surfaces are defined in the same coordinate system as a function of x and y, as well as the asperity angle and height of a small area of the joint surface. The height of the whole tiny window is considered the height of the central point of the tiny window (Fig. 5).

Before the test, the lower and upper face to face tiny windows were compared considering their height to determine the IMC. To determine the IMC, the average height of each window was regarded as the whole height of the window. Therefore, the IMC is defined by the height difference of tiny windows (*dz*). According to the resolution of

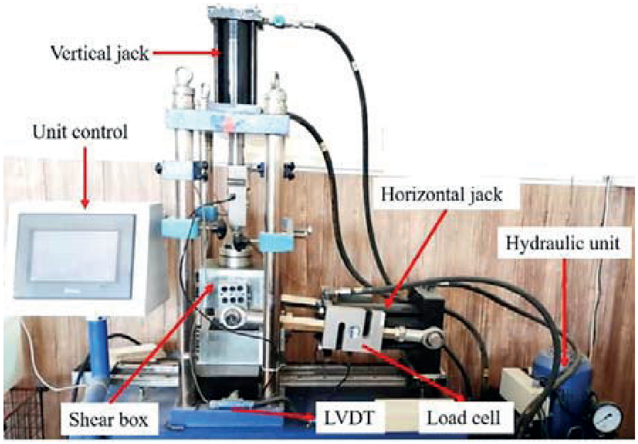

Fig. 3 Servo-controlled direct shear testing machine

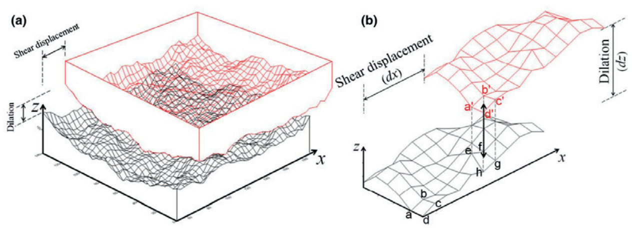

Fig. 4 a) lower and upper surfaces are defined in the same coordinate system. b) both surfaces are gridded with the same interval [21]

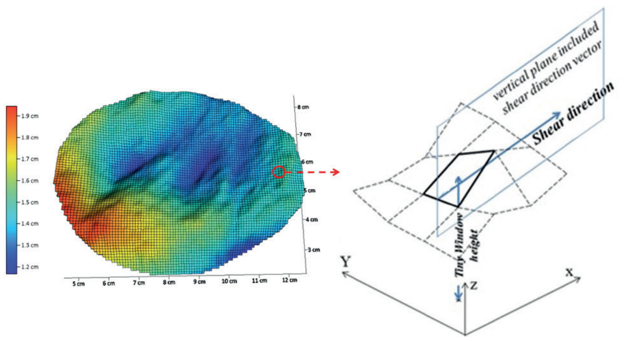

Fig. 5 Reconstructed Joint surfaces with desired/regular intervals

the meshed model and considering the Sampling Interval (SI = 0.300 mm), if the *dz* of each window is in the range of ±SI/2, that window is known as the in-contact; otherwise, it is not an in-contact window. Finally, the ratio of the in-contact windows to total (in-contact and not in-contact) windows gives the value of the IMC.

It should be noted that due to the irregular shapes of the natural rock joints, in some cases, the area of both surfaces will not be equal. Therefore, for the samples where the number of tiny windows of both surfaces are not equal, the number of tiny windows of the smaller surface is considered for calculating the IMC.

5 A new peak shear strength criterion

5.1 New peak shear strength criterion for natural, mismatched rock joints

Fresh tensile induced rock joints that have been horizontally displaced and natural rock joints that have undergone geological processes such as weathering or deformations in the rock mass, exhibit a mismatch between the upper and lower surfaces. This mismatch between the contact surfaces generates fewer but larger contact points compared to the perfectly matched rock joints. A drawback of the empirical constitutive models based on the morphological parameters is that they presume the rock joint surface to be fully exposed. This, therefore limits its applicability to in-situ conditions and does not entirely address the influence of matedness. Therefore, the criteria which relate the 3D morphology characteristics to the PSS by considering the effect of mismatching of natural joints are urgently needed.

Barton [27] suggested an empirical criterion based on experimental results to estimate the shear strength of rock joints as follows:

$$\tau = \sigma_n . \tan(\phi_b + JRC.Log_{10}(JCS / \sigma_n)) \,, \tag{1}$$

where τ_p is the peak shear strength, σ_n is the applied normal stress, ϕ_b is the basic friction angle, i_p is the peak dilation angle, *JRC* is the joint roughness coefficient, and *JCS* is the joint wall strength which is equal to the compressive strength of rock.

Since the JRC-JCS model tended to overestimate the shear strength for mismatched joints, Zhao [7] proposed a joint matching coefficient (JMC) as an independent joint surface geometrical parameter. This coefficient is based on the percentage of joint surfaces in contact and coupled with the joint roughness coefficient (JRC) to entirely characterize the geometrical parameters and assign the hydro-mechanical behavior of joints. The following model was proposed:

$$\tau = \sigma_n .tan(\phi_b + JRC.JMC \; Log_{10}(JCS / \sigma_n)) \,. \tag{2}$$

By considering Barton's model, the JRC values are obtained by back-calculation. The IMC values are also determined according to Section 4. It is found that the JRC back-calculated values show a good correlation with the 3D morphology parameters. Regression analysis by the root-mean-square method was conducted based on JRC back-calculated values and surface morphology parameters. Thus, the JRC can be expressed as:

$$JRC = \left(\frac{\theta^*_{\max}}{1+C} \right)^k , \tag{3}$$

where *k* is a fitting coefficient.

The main issue with the expression of the peak dilation angle (Log (JCS/σ_n)) in the JRC-JCS Barton's model is that the peak dilation angle will tend to infinity when the normal stress σ_n approaches zero, which is inconsistent with reality. As the appropriate values of the peak dilatancy angle would lead to more accurate estimates of the PSS, by assuming an efficient function for i_p instead of the term (Log (JCS/σ_n)), one can obtain the shear resistance. To overcome this problem, regarding the boundary conditions, Ghazvinian et al. [28] proposed the relations between peak dilatancy angle and normal stress as the followings:

$$\begin{aligned} &\left(\frac{\sigma_t}{\sigma_n} \right) \to 0 \Rightarrow i_p = 0, \\ &\left(\frac{\sigma_t}{\sigma_n} \right) \to 0 \Rightarrow i_p = i_{p0}, \end{aligned} \tag{4}$$

where i_{p0} is the initial dilation angle and σ_t is the tensile strength.

To satisfy the above boundary conditions, a hyperbolic function can be used to estimate the peak dilatancy angle, which is given by:

$$i_p = i_{p0} \frac{\left({}^{\sigma_t}\!/_{\sigma_n} \right)}{1 + \left({}^{\sigma_t}\!/_{\sigma_n} \right)} \tag{5}$$

Knowing that under zero normal stress the peak dilatancy angle starts from the steepest asperity angle, i_{p0} is needed as an independent parameter that is just affected by surface morphology. Thus, the JRC can represent the initial peak dilatancy angle which is calculated by Eq (3).

Analyzing the 3D morphology parameters and the test results, taking into account the IMC of joints at the beginning of the test, and substituting the proposed function of the peak dilatancy angle into Barton's criterion, the subsequent model for prediction of the PSS for natural mismatched joints is developed:

$$\tau_{p-nat} = \sigma_n . \tan\left[\varphi_b + \left(\frac{\theta^*_{max}}{1+C}\right)^k . IMC . \left(\frac{\left(\sigma_t/\sigma_n\right)}{1+\left(\sigma_t/\sigma_n\right)}\right)\right], \tag{6}$$

where τ_{p-nat} is the peak shear strength of the natural joint, σ_n is the applied normal stress, ϕ_b is the basic friction angle, IMC is the initial matching condition at the beginning of the test, (θ^*_{max}/1 + C) represents the initial dilation angle, σ_t is the tensile strength, C is the metric of surface roughness, and k is a fitting coefficient. Conforming to this study, the PSS is affected by the roughness and matching condition of joint surfaces.

6 Comparison with available classical criteria

6.1 Barton's estimate of shear strength

Barton and Choubey [29], based on their direct shear test results for 130 samples of variably weathered rock joints, proposed this equation:

$$\tau = \sigma_n . tan(\phi_r + JRC.Log_{10}(JCS/\sigma_n)), \tag{7}$$

where ϕ_r is the residual friction angle. Barton and Choubey suggest that ϕ_r can be estimated from:

$$\phi_r = (\phi_b - 20) + 20(r/R), \tag{8}$$

where r is the Schmidt rebound number for wet and weathered fracture surfaces and R is the Schmidt rebound number on dry unweathered sawn surfaces. The JRC is the joint roughness coefficient that can be estimated either by back-calculation of direct shear tests results or by visual comparison with ten standard profiles given by Barton and Choubey 1977, and JCS is the joint wall strength that can be estimated based on suggested methods for estimating the joint wall compressive strength were published by the ISRM [26].

To verify the global adequacy of the new criterion, 37 data of Grasselli et al. [10], 45 data of Xia et al. [19]and Tang and Wong [22], 20 data of Yang et al. [20], and 35 sets of direct shear test data of this study are used to compare the prediction accuracy. The Grasselli, Tatonel, Xia, Tang, Yang, and Tian criteria are also used to compare the prediction accuracy of the new criterion. The formulations of the mentioned criteria are listed in Table 1.

The estimated results by the mentioned criteria and the test PSS are shown in Fig. 6.

The distribution of $\tau_{peak,measured}$ versus $t_{peak,calculated}$ for the new model is close to the ideal line $\tau_{peak,measured} - t_{peak,calculated}$ compared to Grasselli's model, Xia's model, and slightly further from the ideal line compared to Yang's model. It means that the new model can be considered generally applicable to estimate the PSS of natural rock joints with an admissible precision.

Table 1 Shear strength criteria used in this study

Models	References
$\tau_p = \left[1+\exp\left(\frac{-1}{9A_0}.\frac{\theta^*_{max}}{C}.\frac{\sigma_n}{\sigma_t}\right)\right].\sigma_n.\tan\left[\varphi_b + \left(\frac{\theta^*_{max}}{C}\right)^{1.18\cos(\beta)}\right]$	Grasselli et al. [10]
$\tau_p = \left[1+\exp\left(\frac{-1}{9A_0}.\frac{\theta^*_{max}}{1+C}.\frac{\sigma_n}{\sigma_t}\right)\right].\sigma_n.\tan\left[\varphi_b + \left(\frac{\theta^*_{max}}{1+C}\right)^{1.24l^{0.058}}\right]$	Tatone [18]
$\tau_p = \sigma_n.\tan\left\{\varphi_b + \frac{4A_0.\theta^*_{max}}{1+C}.\left[1+\exp\left(\frac{-1}{9A_0}.\frac{\theta^*_{max}}{1+C}.\frac{\sigma_n}{\sigma_t}\right)\right]\right\}$	Xia et al. [19]
$\tau_p = \sigma_n.\tan\left\{\varphi_b + 10\frac{A_0.\theta^*_{max}}{1+C}.\frac{(\sigma_t/\sigma_n)}{1+(\sigma_t/\sigma_n)}\right\}$	Tang et al. [30]
$\tau_p = \sigma_n.\tan\left\{\varphi_b + \frac{\theta^*_{max}}{C^{0.45}}.\exp\left(-\frac{\sigma_n}{\sigma_c}.C^{0.75}\right)\right\}$	Yang et al. [20]
$\tau_p = \sigma_n.\tan\left(\varphi_b + \frac{160.C'^{-0.44}\theta^*_{max}}{\sigma_n/\sigma_t + 2}\right)$	Tian et al. [23]

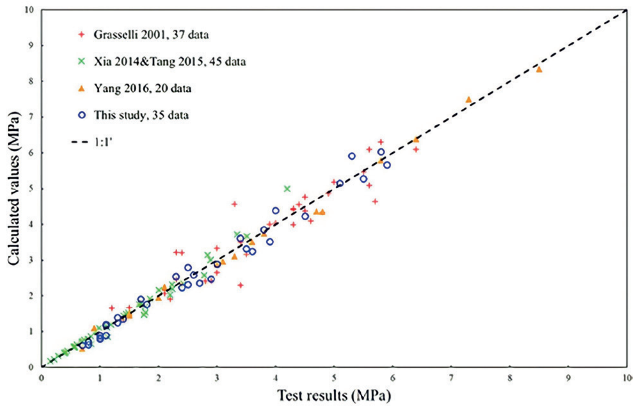

Fig. 6 Comparison between tested and estimated PSS in different models

6.2 The predictive accuracy of the new criterion

To examine the accuracy of some new and reliable classical models and the proposed model, the average relative error (δ_{avg}) is used to represent the average value of the error. The standard deviation (μ) of the relative error is used to represent the degree of error deviation as follows:

$$\delta_{avg} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{\tau_{mea} - \tau_{cal}}{\tau_{mea}}\right| \times 100\%, \tag{9}$$

$$\mu = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\delta_i - \delta_{avg}\right)^2}, \tag{10}$$

Table 2 Comparative analysis of the estimated value of PSS for the data of previous studies

Criterion	Grasselli's, 37 data		Yang's, 20 data		Tang's, 45 data		all 102 sets of data	
	δ_{avg} (%)	μ (%)	δ_{avg} (%)	μ (%)	δ_{avg} (%)	μ (%)	δ_{avg} (%)	μ (%)
Grasselli	10.9	14.7	17.1	8.0	13.3	9.9	13.1	10.6
Tatone	18.7	49	16.5	8.2	13.7	10.5	16.0	16.9
Xia	17.8	41.5	16.9	13.8	6.4	3.6	12.6	14.3
Tang	49.5	42.8	22.5	36.6	7.5	8.4	25.6	34.7
Yang	20.2	51.3	5.5	6.5	8.8	6.2	12.3	18.2
Tian	19.2	44.6	14.9	7.0	11.5	6.8	15.0	15.7
Current study	20.1	19.6	14.3	19.4	12.3	7.0	15.5	13.1

where τ_{mea} is the measured value of the PSS, τ_{cal} is the estimated value of the PSS, n is the total number of tests, and δ_i is the relative error of the ith group.

The average estimation error (δ_{avg}) and the standard deviation (μ) of the relative error of all the 102 data points of matching rock joints of previous studies for mentioned criteria and the new model are presented in Table 2.

For Grasselli's data, the δ_{avg} of the new model is 20.1%, which is smaller than the δ_{avg} of Yang's criterion and Tang's criterion but higher than other criteria. For Yang's data, the δ_{avg} of the new model is 14.3%, which is higher than the δ_{avg} of Yang's model and smaller than other models. For Tang's data, the δ_{avg} of the new model is 12.3%, which is smaller than the δ_{avg} of Grasselli's model and Tatone's model and higher than other criteria. For all 102 data points of matching rock joints of previous studies, the δ_{avg} of the new model is 15.5%, which is smaller than the δ_{avg} of Tang's model and Tatone's model and higher than the other criteria. In contrast, the predicted value of Grasselli's model and the new model is more consistent with the test data than other criteria.

The average estimation error (δ_{avg}) and the standard deviation (μ) of the relative error of all the 137 data used in this study (35 data of mismatched rock joints of this study and 102 data of matching rock joints of previous studies) for mentioned criteria and the new model are presented in Table 3.

For the 35 data points of mismatched rock joints of this study, the (δ_{avg}) and the (μ) of the new model are the smallest and Barton's criterion presents a more accurate prediction than other criteria. For all the 137 data points (35 data of mismatched rock joints in this study and 102 data of matching rock joints of previous studies), the δ_{avg} of the new model is the smallest and the Yang's criterion has a more prediction accuracy than other criteria. In contrast, the predicted value of Grasselli's model, and the new model are more consistent with the test data than other models.

Table 3 Comparative analysis of the predicted value of PSS for all data of this study and previous studies

Criterion	current study, 35 data		all 102 sets of previous data		all 137 sets of data	
	δ_{avg} (%)	μ (%)	δ_{avg} (%)	μ (%)	δ_{avg} (%)	μ (%)
Grasselli	33.9	12.9	13.1	10.6	18.5	11.2
Tatone	37.4	13.2	16.0	16.9	21.5	16.0
Xia	27.3	17.7	12.6	14.3	16.3	15.2
Tang	46.5	26.4	25.6	34.7	30.9	32.8
Yang	25.0	12.6	12.3	18.2	15.5	16.9
Tian	38.5	11.1	15.0	15.7	21.0	14.7
Barton	13.1	10.4	--	--	--	--
Current study	9.1	5.5	15.5	13.1	13.8	11.7

7 Discussion

Rock joints with various matching degrees are widely present in nature. Thus, the effect of the matching condition should be considered when studying the shear behavior of natural mismatched rock joints.

7.1 Influence of matching condition on shear behavior

According to the obtained results, the currently available models do not have sufficient accuracy in estimating the shear strength of natural, mismatched joints obtained from core drilling. A significant difference was observed in the estimation accuracy based on the newly proposed model in this study and previous models. It is due to not considering the influence of joint matching conditions and roughness parameters simultaneously.

Fig. 7 shows the average relative error (δ_{avg}) of 35 data points of mismatched rock joints of this study for mentioned criteria in two conditions, by considering IMC and ignoring IMC.

It is observed that the mentioned models tend to over-predict the PSS for natural mismatched joints. By taking into consideration the IMC which represents the contact area ratio of the joint surfaces at the beginning of the test to the

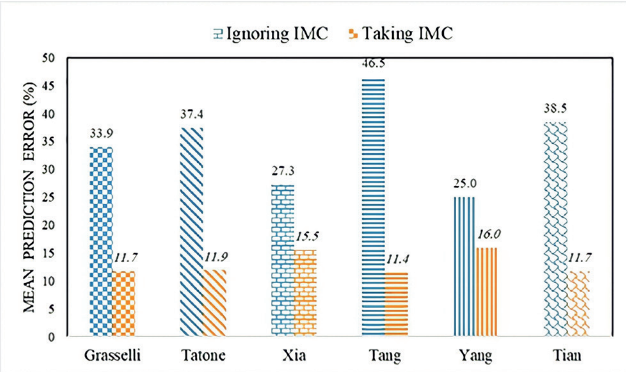

Fig. 7 Comparative analysis of the predicted value of PSS by taking into consideration the influence of IMC on mismatched rock joints of this study

classical mentioned models, the estimation accuracy significantly increases. It means that the PSS of rock joints is dictated not only by the surface roughness, but also by the matching of the joint. Thus, the matching degree of joint surfaces is a critical parameter that should be considered to determine the PSS of natural mismatched rock joints.

7.2 Highlights and limitations

One of the distinguishing features of this study is that the morphological examination is carried out on 35 natural, mismatched joints obtained from core drilling with the same stratigraphic formation. Thus, each joint with equal roughness might be mismatched due to alteration or movement/dislocation, and its orientation. This is the cause of scattering in the results that should not exist with regular artificial joints. However, it is also an opportunity to work on natural, mismatched rock joints having the same tectonic history and different joint matching degrees.

The new model has some shortcomings that should also be discussed. First, this model contains a fitting parameter. The roughness component of the new model is improved based on Grasselli's surface morphology parameters while obtaining these parameters is complex. The new proposed criterion is based on the test results of cored sample joints without filling and further research and improvement are needed to verify the criterion proposed in this study.

8 Conclusions

This study aimed to provide a practical CNL model for estimating the shear strength of natural mismatched rock joints using experimental data obtained from core drilling. For this purpose, laboratory analysis was conducted on 35 natural mismatched rock joints with three different rocks in various depth conditions. The surface morphological parameters were captured by photogrammetry before the test. Considering Barton's model, the JRC values were obtained by back calculating. Regression analysis by the root-mean-square method was conducted based on JRC back-calculated values and surface morphology parameters and the JRC was derived as $(\theta^*_{\max}/1 + C)1.8$. To accomplish the Initial Matching Condition (IMC) at the beginning of the test, the concept 'tiny windows' proposed by [21] was used. Regarding the boundary conditions, and assuming an efficient function for peak dilation angle (i_p) instead of the term of (Log (JCS/σ_n)) in Barton's model, the relations between peak dilatancy angle and normal stress was given as ($i_p = i_{p0}(\sigma_t/\sigma_n)/1 + (\sigma_t/\sigma_n)$). Finally, a modified JRC-JMC model was developed based on the morphological parameters and laboratory test results of 35 natural mismatched rock joints. To verify the global adequacy of the new criterion, 102 data points of matching rock joints of previous studies and 35 data points of mismatched rock joints in this study are used to compare the prediction accuracy. The Grasselli, Tatone, Xia, Tang, Yang, and Tian criteria are also used to compare the prediction accuracy of the new criterion. The estimation accuracy of the new model was appropriate for all 102 data points of matching rock joints of previous studies. In contrast, the estimated value from Grasselli's model and the new model is more consistent with the test data than other models. For the 35 data points of mismatched rock joints of this study, the (δ_{avg}) and the (μ) of the new model were the smallest. For all the 137 data points (35 data of mismatched rock joints in this study and 102 data of matching rock joints of previous studies), the δ_{avg} of the new criterion is the smallest and the Yang's criterion has a more prediction accuracy than other criteria. In contrast, the predicted value of Grasselli's model and the new model are more consistent with the test data than other models. Experimental validation of the model showed an acceptable confidence level. Hence, it can be used in similar geotechnical projects with natural mismatched rock joints obtained from core drilling with different morphological characteristics and matching degree and irregular shapes.

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