Shear strength determination of very rough and partially filled extension fractures in thick-bedded and karstified limestones

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ABSTRACT: Extension fractures that appear as very rough and irregular and with or without infill material, are common in thick-bedded and karstified limestones for which present-day methods for shear strength estimations are inappropriate. With the aim of determining the shear strength of such discontinuities, field research was carried out, in which large samples of blocks with discontinuities, as well as samples of filling material were prepared, on which then detailed laboratory tests were performed. Based on the obtained results, a modification of Barton's JRC-JCS empirical model was made in such a way that the friction angle of the built-in filling material in the case of discontinuity with a filling was applied, instead of the residual friction angle. In addition, the joint contact coefficient (JCC) was introduced as the measure of the actual contact area between discontinuity walls by means of which the normal stress on the discontinuity surface can be corrected.

Keywords: extension fractures, shear strength, friction angle, joint roughness coefficient, joint contact coefficient, Barton's empirical model.

1 INTRODUCTION

It is generally known that the process of karstification creates specific morphological forms of grounds such as: caverns, sinkholes, shafts, swallow-holes, karstic depressions, karstic fields, and plateaus. However, apart from the specific morphological forms of ground, the process of karstification can create specific morphological forms of discontinuity wall surfaces (Hrženjak et al. 2019). Through the process of karstification, a process of chemical weathering of carbonate rocks under the influence of water acting like a weak carbonic acid, the walls of certain discontinuities are dissolved, resulting in very irregular and rough surfaces with prominent irregularities on both a small and large scale. This is especially prominent in thick-bedded and karstified limestones with many extension fractures that can be very rough and irregular, with or without filling material, as is the case in dimension stone deposits. A typical example of a such situation is the "Kanfanar" deposit, in which underground exploitation of dimension stone was introduced by the room-and-pillar excavation method (Figure 1). "Kanfanar" is one of the biggest limestone quarries in Croatia located on the Istrian peninsula.

Figure 1. Typical example of discontinuities in thick-bedded and karstified limestone deposits.

It is obvious that the shear strength of discontinuities has a great effect on the stability of underground rooms and pillars. In the last few decades, extensive investigations were undertaken with the aim of determining the shear strength of discontinuities, starting with Patton, Barton and his coworkers and many others. Based on research results and a modification of the original Barton's JRC-JCS empirical model (Barton 1973) the final equation for the estimation of peak shear strength of discontinuities was proposed by Barton & Choubey (1977) in the following form:

$$\tau = \sigma_n \cdot \tan\left(JRC \cdot \log_{10}\left(\frac{JCS}{\sigma_n}\right) + \varphi_r\right) \quad (1)$$

where:

τ – peak shear strength (MPa),
σ_n – normal stress on the discontinuity surface (MPa),
φ_r – residual friction angle (friction angle on the weathered wall of discontinuity) (°),
JRC – joint roughness coefficient,
JCS – joint wall compressive strength (MPa).

Many researchers suggested certain improvements to Barton’s JRC-JCS empirical model or provided entirely new empirical models for estimating the shear strength of natural discontinuities. The results of these model evaluations were presented in detail by Singh & Basu (2018). However, due to the simplicity of the model and the determination of corresponding input quantities, Barton’s JRC-JCS empirical model has been retained, although in some conditions it has not proved to be reliable enough (Singh & Basu 2018).

All the above mentioned models are applicable only in the case of discontinuity without filling. In the case of discontinuity with filling, when the thickness of the filling is not significantly greater than the surface unevenness of the walls, most of the other authors, starting with Barton, suggested that in such cases shear strength of the discontinuity can only be determined by testing (Barton & Choubey 1977). Therefore, for the geological setting in the “Kanfanar” quarry, field research was carried out, in which large samples of blocks with discontinuities as well as samples of filling material were prepared, on which then detailed laboratory tests were performed and analyzed leading to the proposed modification of Barton’s JRC-JCS empirical model and the introduction of a new parameter called JCC - joint contact coefficient (Dobrilović et al. 2021).

2 RESEARCH METHODS AND RESULTS

2.1 Sampling and testing methods

To obtain representative results of discontinuity shear strength by laboratory testing, large sample blocks of approximate dimension of 150 × (200-400) × 300 mm were prepared with a discontinuity surface in the middle section of the sample (Figure 2 – left). The basic friction angle was determined by a simple "tilt" test on the sawed surface through intact material according to the method suggested by ISRM (Alejano et al. 2018) and the standard method of shear strength testing by direct shear under constant normal load (CNL), also suggested by ISRM (Muralha et al. 2014). According to this method the tests of peak shear strength of discontinuity with and without filling material were then performed (Figure 2 – right). The filling material from the discontinuity was sampled at several locations to obtain the required amount of soil materials for laboratory testing of soil properties.

The discontinuity wall features were determined according to the Suggested methods for the quantitative description of discontinuities in rock masses (ISRM 1978). The joint roughness coefficient JRC_{10} was determined using a profilometer and standard profiles proposed by Barton & Choubey (1977). In addition, by using the ShapeMetriX3D system (3GSM GmbH 2021), discontinuity surfaces were recorded with stereo pairs of digital photographs, based on which digital surfaces and discontinuity wall profiles were created. On the basis on the digital profiles, the values of the statistical parameter Z_2 (i.e. the root mean square of the first derivative of the profile) were first calculated, after which the values of the joint roughness coefficient JRC_{Z2} were estimated according to the formula proposed by Tse & Cruden (1979). The compressive strength of the discontinuity walls JCS was determined by Schmidt's hammer in accordance with the recommendations of ISRM (Aydin 2009), through which the values of hardness on the weathered walls and on the unweathered intact material were obtained.

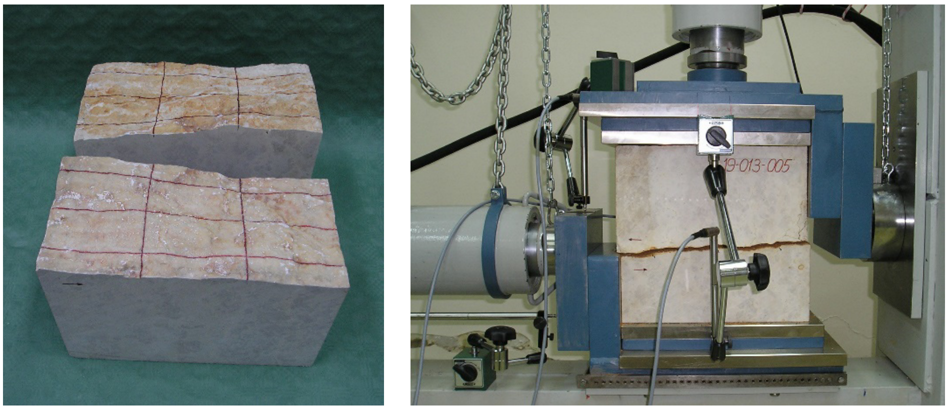

Figure 2. Prepared specimen and direct shear testing of discontinuity.

2.2 Basic friction angle and discontinuity wall features

For determining the basic friction angle three sets of samples were prepared. On each sample set five "tilt" tests were performed followed by direct shear tests under different values of normal stresses (0.75, 1.5, 3.0 MPa). The basic friction angle of 35.4° was obtained.

Apart from determining the joint roughness coefficient JRC_{10} by comparing the roughness profile of specimen surfaces with the proposed standard profiles and by estimating JRC_{Z2} by applying the statistical parameter Z_2, the JRC_{BC} was obtained by the back calculating procedure based on direct shear test results of blocks with discontinuities. Since the sample blocks with discontinuities had a length of 300 mm, the JRC_{10} and JRC_{Z2} were corrected (normalized) to that dimension.

Due to the fact that a large irregularity and mismatch of the discontinuity walls was detected, a new dimensionless coefficient called JCC (joint contact coefficient) was introduced, referring to the ratio of the surface area of the walls in contact with the total surface area of the sample discontinuity.

The determination of the surface area of the walls in contact was carried out by digitizing the traces on the surface profiler film, formed by the overlapping discontinuity walls, and using the Image Vectorizer software (Massow 2020) for calculating the traced areas. All discontinuity wall features with normalized JRC_{10n} and JRC_{Z2n} are presented in Table 1.

Table 1. Discontinuity wall features.

Sample	JRC_{10n} [-]	JRC_{Z2n} [-]	JRC_{BC} [-]	JCS [MPa]	JCC [-]	Aperture [mm]
001DS	11.7	11.0	6.0	89.7	0.49	2.6
002DS	10.6	11.8	10.3	97.8	0.61	2.8
003DS	15.0	13.8	13.1	94.6	0.59	3.5
004DS	11.5	12.4	7.9	88.8	0.13	4.8
005DS	12.9	12.7	11.5	92.0	0.55	5.5
006DS	13.5	12.7	13.7	90.5	0.52	4.3

2.3 Filling material features

The summary of laboratory test results of the filling material is shown in Table 2. According to the results, high plasticity clays were present between the discontinuity walls, the clay containing detritus with maximum grain size of 71 mm in diameter.

Table 2. Results of laboratory testing of the filling materials.

Grain size		Distribution	Other parameters		
> 63 mm	[%]	1	Liquid limit, w_L	[%]	70
> 20 – 63 mm	[%]	7	Plastic limit, w_P	[%]	29
> 6.3 – 20 mm	[%]	4	Linear shrinkage, w_S	[%]	18
> 2 – 6.3 mm	[%]	3	Plasticity index, I_P	[%]	41
> 0.63 – 2 mm	[%]	4			
> 0.2 – 0.63 mm	[%]	6	Particle density, ρ_s	[g/cm^3]	2.65
> 0.063 – 0.2 mm	[%]	5	$CaCO_3$	[%]	21
> 0.002 – 0.063 mm	[%]	12	Moisture content, w	[%]	3.96
< 0.002 mm	[%]	58			

One of the main goals in this research was to determine the influence of filling material on the shear strength of discontinuities. Based on the results of shear strength of discontinuity with fillings obtained by many authors, Indrartna & Haque (2000) concluded that a significant reduction in shear strength occurs by adding even a thin layer of filling material. Therefore, additional tests were performed in the same way as in the case of determining the basic friction angle, but with built-in filling materials between the sawed surfaces of sample blocks. The tests were performed for two filling states: F1 representing the material in dry state, and F2 representing the material prepared to the moisture content of 45%. In both cases the average thickness of filling was from 2 to 3 mm, and the maximum grain size was 2 mm in diameter. The obtained friction angle was 24.9° and 12.6° for the filling states F1 and F2, respectively. As expected, the testing results showed a significant reduction of the friction angle in the case of filling materials built in between the sawed surfaces compared to the basic friction angle, especially in wet conditions.

2.4 Shear strength of discontinuities

The shear strength testing of discontinuities was performed on a device for testing large soil and rock samples, developed at the Geomechanical laboratory of the Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb. The shear strength testing was carried out under constant normal load with normal stresses at the approximate values of 0.02, 0.75, 1.5 and 3.0 MPa.

For the samples 001DS and 004DS the peak shear strength was determined without filling material (filling state F0), for the samples 002DS and 005DS with dry material (filling state F1) and for the samples 003DS and 006DS with a material prepared for the moisture content of 45% (filling state F2). Based on the statistical analyses of the obtained results for the peak shear strength values, input values of the basic friction angle, friction angle of the built-in filling material and discontinuity wall features, a modification of Barton's JRC-JCS empirical model was proposed in the form:

$$\tau = \sigma_n \cdot \tan\left(JRC \cdot \log_{10}\left(\frac{JCS \cdot JCC}{\sigma_n}\right) + \varphi_{rf}\right) \quad (2)$$

where:

τ – peak shear strength (MPa),
σ_n – normal stress on the discontinuity surface (MPa),
φ_{rf} – residual or friction angle of the built-in filling material (°),
JRC – joint roughness coefficient,
JCS – joint wall compressive strength (MPa),
JCC – joint contact coefficient.

The evaluation of the model proposed by equation (2) was performed by the linear regression analysis of the measured and estimated values of the peak shear strength of discontinuities. The mentioned evaluation was performed for all samples with and without filling material, for each method of determination of JRC and for the estimation with and without the introduced parameter of joint contact coefficient JCC. The evaluation results are shown in Figure 3 and Table 3.

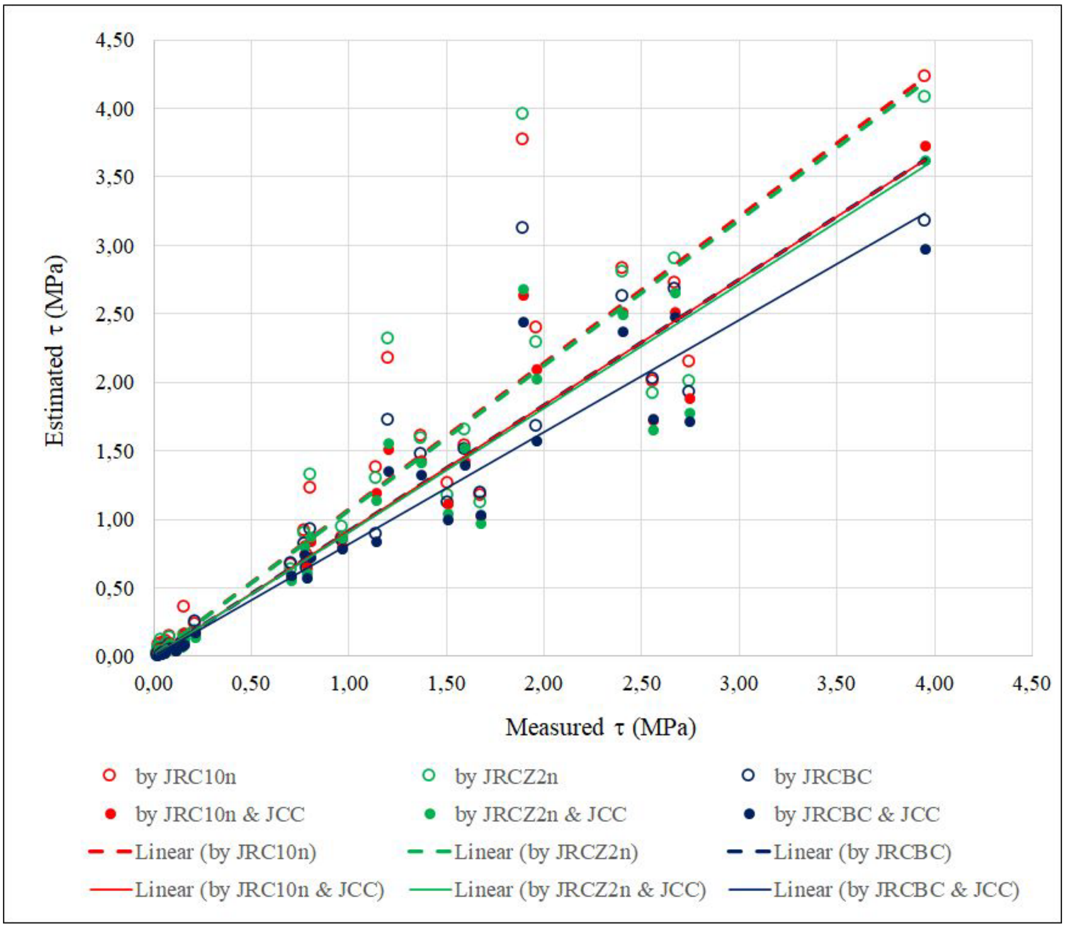

Figure 3. Linear regression analysis of the proposed model.

Table 3. Evaluation results of the proposed model by linear regression analysis.

Parameter	JRC_{10n}	JRC_{Z2n}	JRC_{BC}	JRC_{10n} & JCC	JRC_{Z2n} & JCC	JRC_{BC} & JCC
Slope	1.070	1.061	0.919	0.916	0.906	0.819
R^2	0.93	0.91	0.94	0.96	0.95	0.96

3 CONCLUSION

The evaluation of the proposed modified Barton's JRC-JCS empirical model carried out by applying the linear regression analysis proved that the model is accurate enough in estimating the peak shear strength of discontinuity without filling material and with filling material with different moisture content. Regarding the determination of JRC, both the method of comparing the roughness surfaces with standard profiles and of using the statistical parameter Z_2 have proven to be equally valuable. When the JRC was determined by back analysis, slightly lower shear strength values were obtained. In addition, in most cases of estimation without a correction by JCC parameter, slightly higher values of the peak shear strength were obtained. Regarding the determination of the real value of JCC, as the measure of the actual contact area between discontinuity walls during shearing, further investigation is needed.

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