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Rock Profile Roughness Parameters Appropriateness for Joint Surface Geometrical Characterization

Pedro Alameda-Hernández
Mining Engineering Department, UFOP, Ouro Preto, Brazil, pedroalameda@gmail.com

Rachid El Hamdouni
Department of Civil Engineering, University of Granada, Granada, Spain

Clemente Irigaray
Department of Civil Engineering, University of Granada, Granada, Spain

José Chacón
Department of Civil Engineering, University of Granada, Granada, Spain

SUMMARY: Roughness influences considerably rock joints shear strength, and, consequently, rock mass stability, especially slopes. However, the most common rock mass classification systems, as well as other analysis methods, introduce rock joint roughness by subjective personal estimation. This subjective bias can be avoided by applying roughness parameters calculated through mathematical algorithms to digitized profiles or surfaces. However, a correct rock joint roughness parametrization has not been achieved yet because of the geometrical complexity of these natural surfaces. This paper shows the behavior of the most common roughness profile parameters in different rock joints. Two physical digitization procedures, by means of stylus profilometers, were applied; one is to be applied in field and the other in laboratory; they permitted spatial sampling intervals of 0.8 and 0.0625 mm respectively. In order to select a wide range of roughness morphologies, samples from different rock types were chosen: a quartzite showing a stepped profile, a micaceous schist with a smooth but positively stepped profile, two calcareous schists similar to the micaceous but not so explicitly smooth and stepped, a dolomitic marble, smoother and more undulated than the others, and a granite, undulated and averagely rough. It was found that among the roughness parameters, the first derivative root mean square (Z_2) is not appropriate for stepped profiles characterization because of its huge dependency on a single "step" in the profile, which means a big difference on Z_2 value depending on just one slope among two points in the profile and consequently an important sampling bias due to the area of the joint surface where the profile is recorded. In opposition to this, the variability of the joint roughness parameters in the granite sample was much smaller, for all the roughness parameters applied.

KEYWORDS: rock roughness, rock slope stability, data acquisition, stylus profilometer.

1 INTRODUCTION

Discontinuities are planes of weakness, areas where the rock mass strength decreases very much. Being generally defined as planes of zero or low tensile strength (ISRM, 1978), discontinuities shall increase instability especially in low confined conditions, thus, in superficial phenomena. Hence, discontinuities analysis is crucial for rock slope stability assessment. Discontinuities study encompasses two areas: their geometrical distribution through the rock mass and their nature, their intrinsic attitudes. As far as a discontinuity means an abrupt diminution in the rock mass strength, discontinuities geometrical distribution is obviously essential for rock mass stability. Furthermore, nature shall determine rock joints shear strength, and therefore the mechanical contribution of discontinuities to rock slope stability. Thus, a geometrical feature such as roughness, influences the mechanical phenomenon to be studied. Several parameters have been stablished to connect geometry with mechanical behavior through different shear strength criteria. Barton and Choubey (1977) shear strength criterion (1), the most widely used, applied Joint Roughness Coefficient (*JRC*) as a connection among geometry and peak shear strength (τ_p).

$$\tau_p = \sigma_n \tan(JRC \log_{10} \frac{JCS}{\sigma_n} + \phi_r) \quad (1)$$

σ_n is the normal stress, *JCS* the Joint Compressive Strength and ϕ_r the residual friction angle. 136 shear tests were performed by Barton and Choubey (1977) back-calculating *JRC* in each case (1). Furthermore, ten samples were chosen as the most representative of the whole set and their roughness profiles were recorded conforming the ten Barton typical profiles. Those profiles are an aid for *JRC* visually estimation, which is fast and simple but considerably biased by the evaluator subjectivity (Hsiung et al. 1993, Grasselli and Edger 2003, Beer et al. 2002, Du et al. 2009, Xia et al. 2013) and because of the lack of representatively of those profiles respect all the existing rock types (Alameda-Hernández et al. 2014).

However, Tse and Cruden (1979) proposed an alternative automated *JRC* assessment by digitizing the ten Barton typical profiles in order to find a correlation among any geometrical roughness parameter and the *JRC* values back-calculated mechanically by Barton and Choubey (1977). Best results were achieved with Z_2, first derivative root mean square, defined from a profile vector **y** (y_1, y_2… y_N) with a sampling interval (Δs) (2).

$$Z_2 = \left(\frac{1}{(N-1)(\Delta s)^2} \sum_{i=1}^{N-1} (y_{i+1} - y_i)^2 \right)^{1/2} \quad (2)$$

Thereafter, other authors proposed other parameters for profile roughness characterization, the most relevant, and applied in this work, are Roughness Profile Index (R_P) (Maerz et al. 1990) (3), the Tatone and Grasselli (2009) roughness metric ($\theta^*_{max}/C+1$) (4), proposed initially for surfaces and thereupon adapted to profiles by the same authors (2010), and fractal dimensions (Mandelbrot, 1977). θ^* is an inclination threshold value, *C* is deduced from a regression analysis (4) after setting several θ^* values. L_{θ^*} is the length of the profile part with a higher inclination than θ^* divided by the total profile length, L_0 is the fraction of the profile length with positive inclination, and θ^*_{max} is the highest slope among adjacent points.

$$R_P = \frac{\sum_{i=1}^{N-1} \sqrt{\Delta s^2 + (y_i - y_{i+1})^2}}{\Delta s(N-1)} \quad (3)$$

$$L_{\theta^*} = L_0 \left(\frac{\theta^*_{max} - \theta^*}{\theta^*_{max}} \right)^C \quad (4)$$

In this research, rock joint profiles from different lithologies were analyzed by observing the *JRC* value assessed by applying different correlations with de above-mentioned geometrical parameters. Consequently, the suitability of those parameters for geometrical characterization of those lithologies is here shown. Despite of being the final aim of the geometrical reasoning, no mechanical behavior is here discussed, this is due to the difficulty of a simple geometrically characterization achievement for natural rock joint surfaces.

2 METHODOLOGY

2.1 Lithologies analyzed

Five different lithologies were studied, three of them from de Alpujarride Complex, in the Betic

Cordillera of southern Spain previously digitized and analyzed by Alameda-Hernández et al. (2014) and two more from the Brazilian Shield (Alameda-Hernández, 2014).

117 profiles belonging to the Alpujarride Complex were sampled directly from the outcrop. Those consist of Lower Triassic-Upper Permian micaceous schist and calcareous schist alternated with dolomitic marble and Upper to Middle Triassic dolomitic marble and calcareous schist.

From the Brazilian shield there were chosen and digitized in laboratory samples of a quartzite with a stepped profile due to foliation and a granite offering a regular and undulated surface. The quartzite surface (50x50cm) was obtained by chisel breaking through a foliation plane and the granite surface was the failure plane of a Brazilian test from a 10cm-diameter core.

2.2 Digitization methods

Alameda-Hernández et al. (2014) digitized the profiles form southern Spain applying a stylus profilometer, a Barton comb 15cm-length, similarly to other authors (Stimpson, 1982; Morelli, 2014; Chen et al., 2015) but with a validated methodology. The Barton comb utilized had 0.8mm-width needles, consequently Δs=0.8mm for those sampled profiles.

On the other hand, the quartzite and granite samples were digitized (Alameda-Hernández, 2014) with the equipment developed by Ribeiro et al. (2007) which consists of a computerized micrometer, with a sensibility of 1μm, sliding over the rock surface attached to a rail and with a discrete displacement along this rail of 16 positions each millimeter, which permits Δs as low as 0.0625mm. For the granite sample Δs=0.0625mm, however, the quartzite sample was digitized with Δs=0.5mm. Furthermore, the quartzite sample was digitized through 24 parallel scanlines as shown in Figure 1.

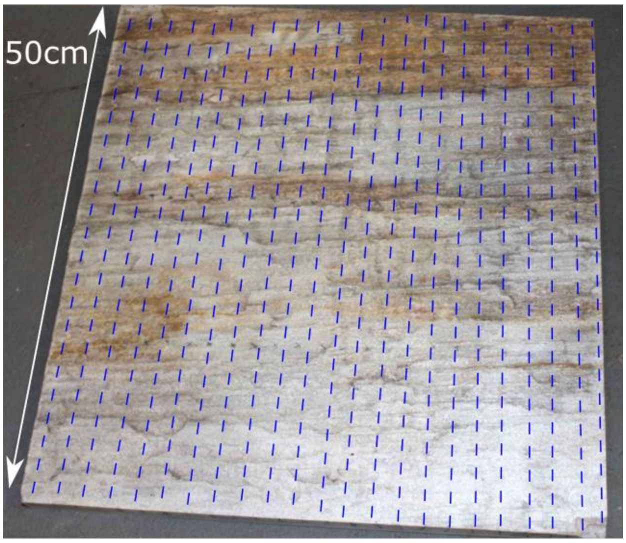

Fig. 1. Quartzite sample digitized. (Modified from Alameda-Hernández, 2014)

2.3 *JRC* assessment from the geometrical parameters

The behavior analysis of the different geometrical parameters has been performed by correlating their values with *JRC*, in order to bring them to the same order of magnitude simplifying consequently the comparison among them. Because of the importance of Δs (Yu and Vayssade 1991), different Δs were applied. Thus, for Δs=1mm, the equations chosen were those proposed by Yu and Vayssade (1991) (5) and Tatone and Grasselli (2010) (6), (7) and (8), for Δs=0.5 (9) and (10) from Tatone and Grasselli, (2010) and (11) from Yu and Vayssade, (1991), for Δs=0.25 (12) from Yu and Vayssade, (1991). On the other hand (13) from Lee et al. (1990) was applied, with the fractal dimension (*D*) assessed by the divider method, regardless Δs, simply considering that the lowest Δs is, the more representative *D* will be.

$$JRC = 64.22Z_2 - 2.31 \quad (5)$$

$$JRC = 55.03Z_2^{0.74} - 6.1 \quad (6)$$

$$JRC = \left(0.038 + \frac{0.00107}{\ln(R_P)}\right)^{-1} \quad (7)$$

$$JRC = 2.4\left(\frac{\theta^*_{max}}{C+1}\right)^{0.85} - 4.42 \tag{8}$$

$$JRC = 51.85 Z_2^{0.6} - 10.37 \tag{9}$$

$$JRC = \left(0.036 + \frac{0.00127}{\ln(R_P)}\right)^{-1} \tag{10}$$

$$JRC = 61.79 Z_2 - 3.47 \tag{11}$$

$$JRC = 60.32 Z_2 - 4.51 \tag{12}$$

$$JRC = -0.87804 + 37.7844\left(\frac{D-1}{0.015}\right) - 16.9304\left(\frac{D-1}{0.015}\right)^2 \tag{13}$$

2.4 Proposal for application in geomechanical classifications

JRC is a parameter widely used that encompasses roughness in a single value, with no distinction among waviness and asperity or any other involved geometrical characteristic. Furthermore, it can be automatically assessed by inexpensive profile digitization (Alameda-Hernández et al., 2014). Thus, the subjective roughness evaluation applied in the most common geomechanical classification systems could be substituted by applying correlations between an automatically calculated *JRC* and the roughness parameter in the classification system. An example for *JRC* application to Rock Mass Rating (RMR) (Bieniawski, 1989) is shown in Table 1.

Table 1. Alameda-Hernández (2014) proposal of automatization for roughness parameter in RMR

Roughness description	*JRC*
Slickensided	0-3
Smooth	4-8
Slightly rough	9-12
Rough	13-16
Very rough	17-20

3 RESULTS AND DISCUSSIONS

3.1 Micaceous schist, calcareous schists and dolomitic marble

Data was recorded directly in the outcrop, separately for each one of the discontinuity sets providing the information shown in Figures 2, 3 and 4.

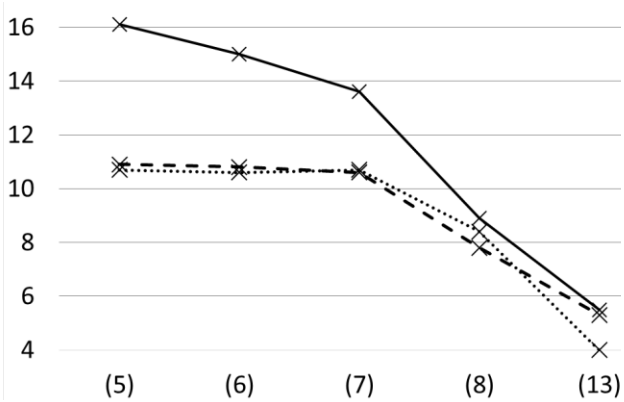

Fig. 2 *JRC* values obtained through the five different equations in the mica-schist outcrop regarding the family set developed from schistosity, dotted line, and the two joint sets, dashed and solid lines. (Data obtained from Alameda-Hernández et al., 2014).

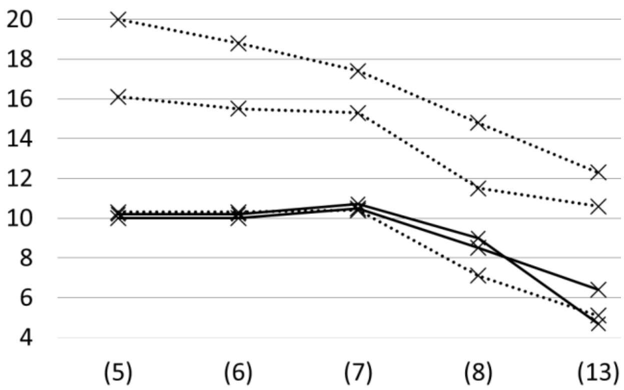

Fig. 3 *JRC* values obtained through the five different equations in the calcareous schists outcrops. The dotted lines represents the tow joint sets in the calcareous schist alternated with marble outcrop, the solid lines represent the purely calcareous schist. (Data obtained from Alameda-Hernández et al., 2014).

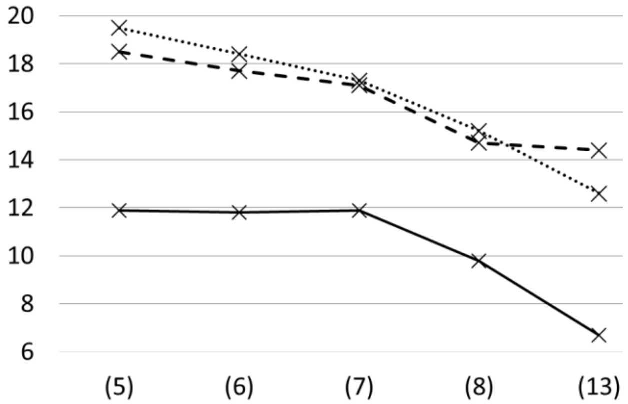

Fig. 4 *JRC* values obtained through the five different equations in the dolomitic marble outcrop. The three lines represent the three joint sets respectively. (Data obtained from Alameda-Hernández et al., 2014).

It can be seen that the *JRC* values obtained from *D* (13), are inconsistent with those from the other equations and parameters, ($\theta^*_{max}/C+1$) (8) present slightly the same problem. It must be considered that there are just 150 sampled points in these digitized profiles and that the algorithms for obtaining *C* and, especially *D*, are not appropriate for profiles with few sampled points.

3.2 Quartzite sample

Fig. 5 (a) show a stepped profile and *JRC* values obtained through Z_2 and R_P on different profile portions (b) (c). The steps in the profile means enormous slope values which shall elevate Z_2 decisively making this value depend excessively on the inclusion or not of one of these steps. This drawback is not so considerable for R_P.

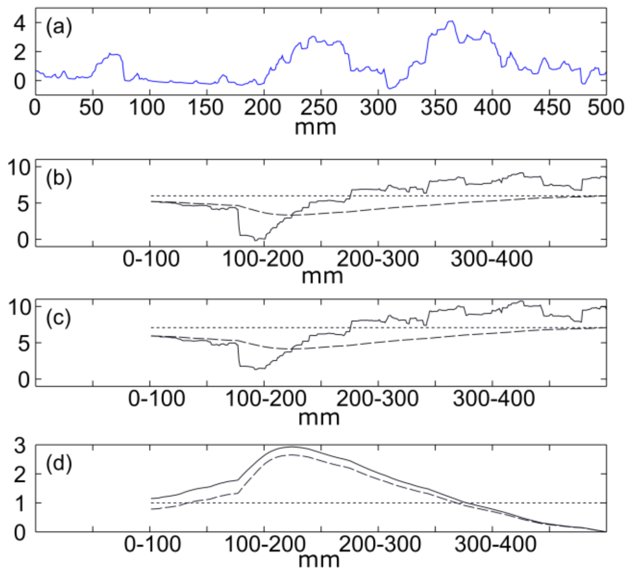

Fig. 5 One of the 24 digitized profiles in the quartzite sample. a) Roughness profile (mm). b) *JRC* (9) for each 100mm profile section up to the point where it is shown (solid line), the mean value up to this point (dashed line) and the profile global mean (dotted). c) The same with (10) d). Differences between *JRC* global mean and the partial means for (9) (dashed line) and (10) (solid line). (Modified from Alameda-Hernández, 2014).

D behavior, obtained from the divider method, can be seen in Figure 6, where it has been calculated in different portions with different lengths of the same profile. *JRC* values obtained through *D* (13) in different portions show different values, but the mean value of all sections with same length is very similar among them. This possibility of portioning a profile and calculate the roughness parameter value for each portion for a further assessment for the whole profile is clear for Z_2 and R_P because of their definition, nevertheless, Figure 6 shows it for *D*.

Furthermore, Figure 7 shows consistent values for *JRC* calculated through *D*, in contrast with the profiles sampled with the Barton comb. In this situation there are 1024 sampled points in the profile.

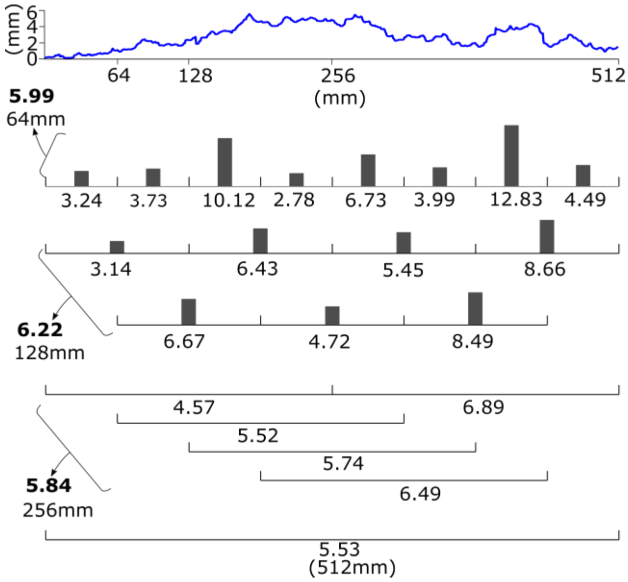

Fig. 6 *JRC* values obtained through (13), with *D* obtained through the divider method in different profile segments in one of the 24 digitized profiles in the quartzite sample. The values below the bar are the *JRC* calculated for each one of the 64, 128, 256 and 512 mm length segments, the values in bold are the mean value for all the 64, 128 and 256 segments respectively. (Modified from Alameda-Hernández, 2014).

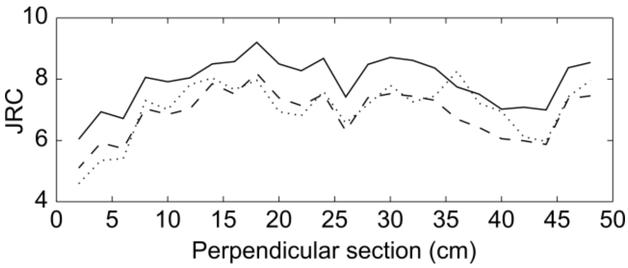

Fig. 7 *JRC* total values for each one of the 24 digitized profiles assessed through Z_2 (9), dashed line, R_P (10), solid line, and *D* (13), dotted line. (Modified from Alameda-Hernández, 2014).

3.3 Granite sample

In spite of being short, the profile shown in Figure 8 has 1465 sampled points, which permitted to divide it in smaller portions in order to compare the *JRC* values among them. It can be seen again an inconsistent behavior of the values obtained from *D* (13). On the other hand, Z_2 and R_P give similar *JRC* values for each Δs, while it is shown a clear dependency of Δs in this profile.

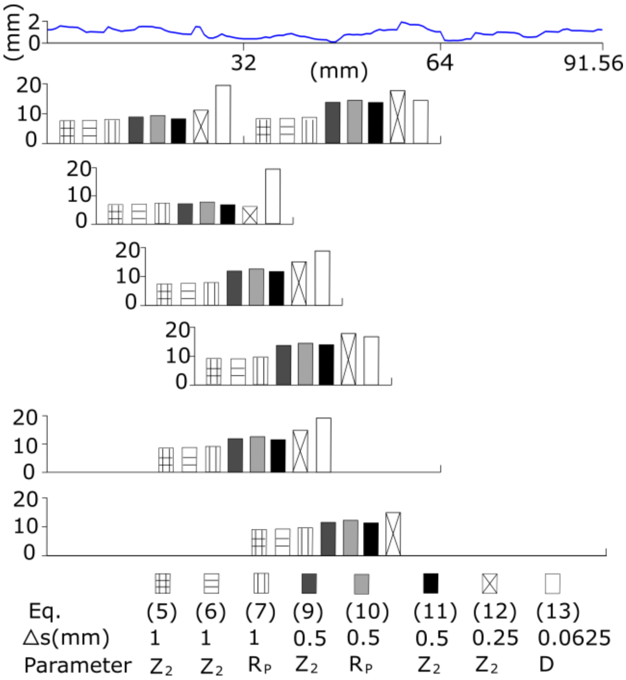

Fig. 8 *JRC* values obtained for a granite profile in different segments applying different parameters, sampling intervals and equations. (Modified from Alameda-Hernández, 2014).

4 CONCLUSIONS

As a result of this research, the following conclusions can be drawn.

Rock joint roughness can be analyzed by an inexpensive and simple digitization and parametrization procedure in order to avoid the evaluator subjectivity sampling bias.

Roughness parametrization should be introduced in the classical classification systems.

Fractal dimension *D* obtained through the divider method needs a large quantity of sampled points in the profile, at least 256, for offering a reliable result.

When a long profile is segmented in smaller portions, *D* obtained through the divider method on the whole profile is similar to the mean value of the parameter assessed on each portion. This property is obviously presented, because of their definition, by the Roughness Profile Index (R_P) and the profile first derivative root mean square (Z_2).

In stepped profiles, Z_2 suffers an excessive dependency on a single step among two points, because of the enormous value of the inclination of this step. Thus, Z_2 is not appropriate for stepped profiles roughness analysis.

In spite of the existence of roughness parametrization equations considering the spatial sampling interval, it still conditions significantly the obtained results.

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