



A new peak shear strength criterion of three-dimensional rock joints considering the scale effects

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Abstract

The scale effect is one of the important factors affecting the shear behavior of rock joints. However, the nature of the scale dependency of rock joints is still unknown. In this study, to evaluate the effect of scale on the mechanical behavior of the joint, we selected three natural surface joints with different geometries. The sizes of these surfaces were greater than 2500 cm². The replica joints were prepared from these three surfaces with dimensions of 50 × 50 mm², 100 × 100 mm², and 200 × 200 mm². Three types of materials were used with uniaxial strengths of 12.5, 26, and 35.2 MPa. In total, 90 direct shear tests were carried out on joint samples. Finally, using the results of direct shear tests on joint specimens, a criterion was proposed for estimating the shear strength of natural joints which considered the scale effect. Compared to the previous similar criteria, in the present criterion, to quantify the roughness of the surfaces, the joint surfaces were considered three-dimensional and several roughness parameters (instead of one parameter) were used to capture both first- and second-order roughness of surfaces. The scale effect was also considered the changes in the joint dimensions (in some previous similar criteria, changes in scanning resolution of the surfaces have been considered the scale effect). Furthermore, since the surfaces of artificial joints were copied from the natural joint surfaces (instead of tensile joint surfaces), it can be expected the results of the present criterion would have a better estimate of the shear strength of natural joints.

Keywords Scale effect · Shear behavior of rock joints · Joint degradation · Shear strength criterion

Introduction

In the design of rock structures, the mechanical and hydraulic properties of the rock mass should be determined. In recent years, rock mechanics studies have shown that the mechanical and hydraulic properties of rocks vary from laboratory to field scale. Thus, significant studies have been done so far on the effect of scale on the mechanical properties of rocks, and especially on rock joints. In these studies, the effect of the scale has been investigated on the joint surface geometry or joint shear strength.

Many studies in this regard have found conflicting results, however. Some have shown a decline in strength and roughness with increasing the discontinuity size (Krsmanovic and Popovic 1966; Pratt 1974; Barton and Choubey 1977; Lechnitz and Natau 1979; Bandis 1980; Bandis et al. 1981; Yoshinaka et al. 1991; Yoshinaka et al. 1993; Castelli et al. 2001; Fardin et al. 2001; Fardin et al. 2004; Ueng et al. 2010; Bahaaddini et al. 2014; Giwelli et al. 2014; Oh et al. 2015; Buzzi and Casagrande 2018). Other studies have revealed positive scale effects (Locher and Rieder 1970; Leal-Gomes 2003), a combination of positive and negative scale effects (Swan and Zongqi 1985; Maerz and Franklin 1990; Kutter and Otto 1990; Giani et al. 1992; Fardin 2008; Tatone and Grasselli 2009; Tatone and Grasselli 2013), or no scale effects (Muralha and Pinto Da Cunha 1990; Hencher et al. 1993; Ohnishi and Yoshinaka 1995; Ueng et al. 2010; Johansson 2016). Thus, the effect of scale on the mechanical behavior of rock joints is still an ongoing debate.

Recent studies suggest that the differences in scale effect results can be attributed to the accuracy of roughness measurement tools (measurement resolution), roughness quantifying

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methods, dimensions of the selected surfaces, and sampling methods of surfaces (measuring windows) (Tatone and Grasselli 2013; Azinfar et al. 2016; Yong et al. 2019).

Regarding measurement resolution, high measurement resolutions lead to larger and more accurate roughness values of a specific surface. With higher accuracy of the measuring instrument, smaller asperities can be scanned, resulting in larger roughness values. In the past, due to the lack of accurate equipment, the measured roughness values were underestimated. Concerning roughness quantifying methods, many methods have been proposed to quantify the surface roughness, which are divided into two categories: two-dimensional and three-dimensional methods. In the two-dimensional method, parts of the surface roughness are always ignored, which can explain the differences in the results of surface quantification. Regarding the dimensions of joints, a wide range of dimensions of the joints has been reported in the studies related to the scale effect, which can cause differences in reported results.

However, the factor neglected is the type of surface roughness, i.e., how to combine primary and secondary asperities on the joint surface. The previous work of authors (Azinfar et al. 2016) showed this factor affects the scale-dependent behavior of rock joints. According to that study, in smooth joints consisting of only secondary asperities (unevenness), shear strength diminishes with increasing the scale from 25 to 100 cm². However, in this range of scale and the joints consisting of a combination of primary (waviness) and secondary asperities or only primary asperities, shear strength will increase with increasing the scale. On the scale of 100 to 400 cm², the shear strength values for the three studied surfaces were almost constant. Thus, in the shear strength criterion considering the scale effect, the surface roughness parameters used should be able to show both the effect of primary and secondary roughness.

In the present study, using the results of the previous research, a new joint shear strength criterion has been proposed using the 3D roughness parameters considering the scale effects. The innovation of the proposed criterion compared to the previous similar criteria is capturing the effect of scale (joint dimensions) and using several three-dimensional roughness parameters instead of only one roughness parameter for quantifying the surface roughness (considering the primary and secondary roughness effects on joint shear strength). As well, since the present criterion is based on tests performed on joints with natural surface geometry (instead of tensile joints), it can be expected to provide a more accurate estimation of the joint shear strength in the field.

Regarding the organization of the paper, first, the preparation of joint samples and three-dimensional scanning of their surfaces are explained. After preparing the cloud points of the joint surfaces, the roughness of the surfaces should be determined using different roughness parameters, which are described in a separate section. Next, the distribution of the

first- and second-order roughness on the studied surfaces has been investigated. The distribution and combination of these asperities is important when examining the joint shear behavior in various scales and has been considered in the proposed criterion. Then, using the results of shear strength of joint samples and roughness values obtained from different roughness parameters, the method of obtaining the shear strength criterion has been described. Thereafter, due to the existence of similar shear strength criteria, the proposed criterion has been compared against some criteria and the strengths and weaknesses of each criterion have been examined.

Sample preparation and shear tests

Initially, three natural joints were selected classified in smooth, undulating, and stepped joints according to ISRM (1978). Then, the replica joints were prepared from these natural joints in the dimensions of 50, 100, and 200 mm. These three different geometry surfaces have been named S1, S2, and S3, respectively. The joints were molded with mortars with different ratios of cement and plaster (Table 1). In total, 90 shear tests were carried out on the joint samples under CNL conditions.

The geometry of the joint surfaces was digitized by a precise 3D optical scanner (the average distance of the points in the obtained cloud point was 0.25 mm) (Fig. 1). The molding process, preparation of joint samples, shear test conditions, and digitizing of the surfaces have been described in detail in the authors' previous study (Azinfar et al. 2016).

The averages of the normalized shear strengths (vs. normal stress) of joint samples in three different normal stress of 0.3, 0.8, and 1.4 MPa against the scale are depicted in Fig. 2. According to Fig. 2, the shear strength changes are approximately the same for all three types of material relative to the scale. However, the trends of shear strength changes at the three surfaces of S1, S2, and S3 are different. These differences are due to the differences in the natures of the three surfaces (how to combine primary and secondary roughness) which has been fully investigated in the previous research (Azinfar et al. 2016).

Quantifying the roughness of joint surfaces

To investigate the effect of the scale on the surface roughness more accurately, three surfaces were scanned by a 3D optical scanner (with an accuracy of 0.01 mm). Some important roughness parameters were extracted from the digitized surfaces in ASCII (point cloud) and STL (triangular meshes) formats. These parameters included D , A , $2A_0\theta_{\max}^*/(C+1)$, R_s , $CLA(R_a)$, RMS , $\theta_{ave}(\theta_s)$, and Z_2 indicating fractal

Table 1 Selected mortars and its proportions in the sample materials

Material	Gypsum (%)	Cement (%)	Dental plaster (%)	Water (%)	σ_c (MPa)	σ_t (MPa)	E (GPa)
Type 1	31.5	31.5	0	37	12.5 ± 1	2.2	3.5
Type 2	26 (#30)	0	43	31	26 ± 2	3.8	5.4
Type 3	0	0	73	27	35.2 ± 3	3.8	7.8

dimension, amplitude parameter (Malinverno 1990), Grasselli’s roughness parameter (Tatone and Grasselli 2009), surface roughness coefficient (El-Soudani 1978), central line (surface) average American Standards Association (1955), root mean square of asperity heights American Standards Association (1955), average angle of surface asperity (Belem et al. 2002), and root mean square of the first derivative of the profile Z_2 respectively. As the Z_2 parameter has been introduced for the joint profile, in this research, the surfaces have been divided into profiles with the spacing of 4% of the surface dimensions and the results have been averaged. Grasselli 2001 introduced θ_{max}^* (inclination of steepest triangle or facet in a triangulated joint surface) parameter. The surface area of the joint with an inclination steeper than θ^* is obtained from the following equation (Grasselli (2001):

$$A_{\theta^*} = A_0 \left(\frac{\theta_{max}^* - \theta^*}{\theta_{max}^*} \right)^C \tag{1}$$

In Eq. (1), the C parameter represents a fitting parameter related to the distribution of the asperities. The area under the curve of A_{θ^*} is equal to $2A_0\theta_{max}^*/(C + 1)$. As A_0 is typically very close to 0.5, Tatone and Grasselli (2009) proposed the roughness metric as $\theta_{max}^*/(C + 1)$. The Grasselli roughness parameter is a directional parameter, i.e., it calculates different amounts of roughness in different directions. The rest of the parameters have been obtained from the following equations:

$$CLA = \frac{1}{N} \sum_{i=1}^N |v_i| \tag{2}$$

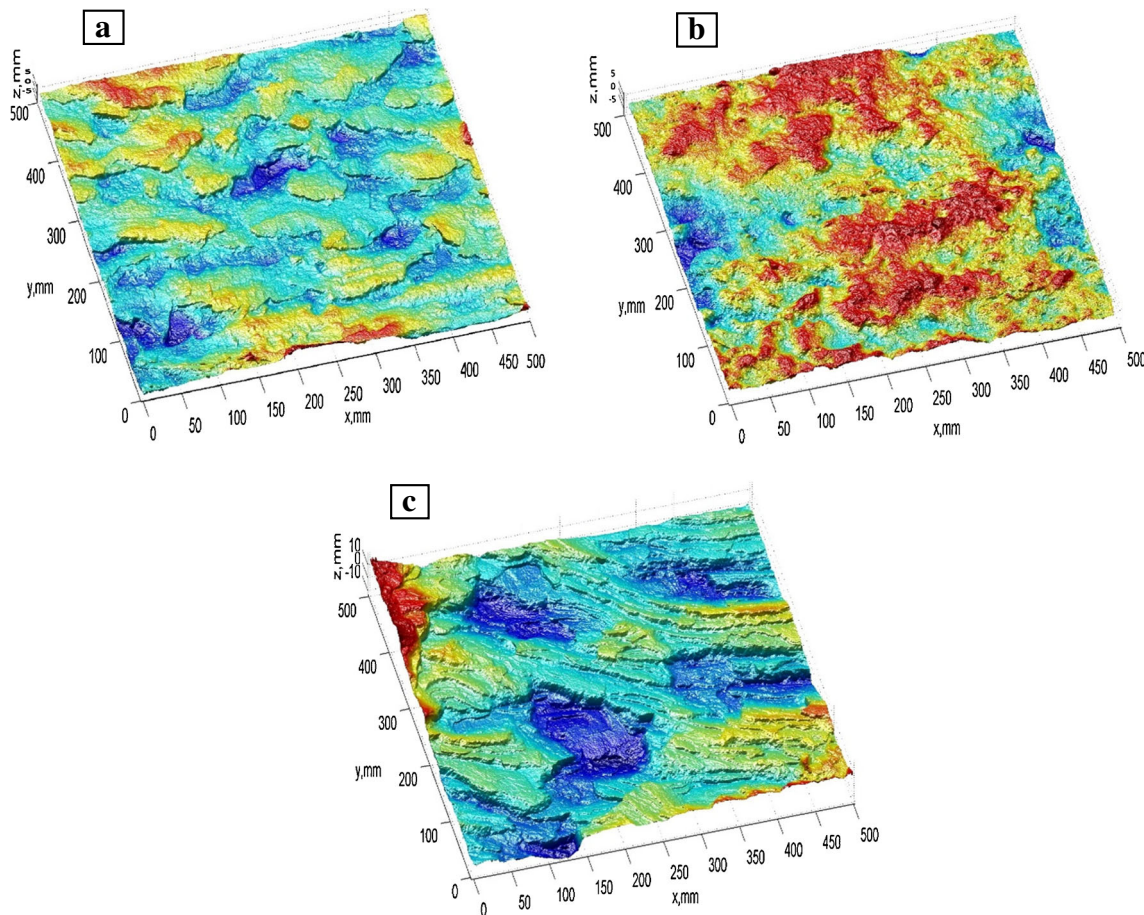


Fig. 1 STL (Standard Triangle Language) files prepared from three large-scale fractures ($500 \times 500 \text{ mm}^2$)

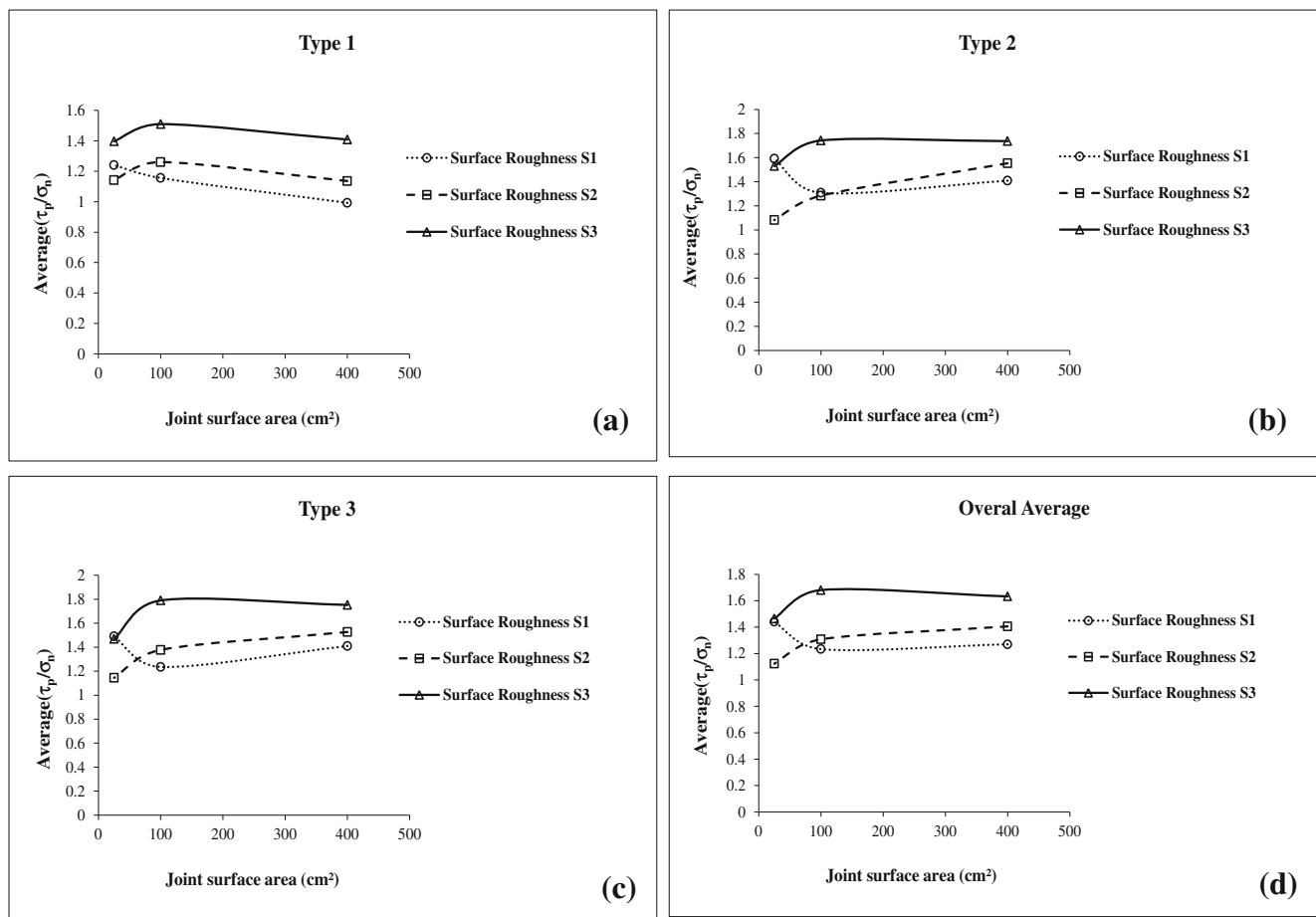


Fig. 2 Average of τ_p/σ_n vs. scale for different surface roughness. **a** Type 1; **b** type 2; **c** type 3; **d** average of three types of materials (Azinfar et al. 2016)

$$RMS = \sqrt{\frac{1}{N} \sum_{i=1}^N y_i^2} \tag{3}$$

$$\theta_s = \frac{1}{m} \sum_{i=1}^m (\alpha_k) \tag{4}$$

$$Z_2 = \sqrt{\frac{\sum_{j=1}^M \sum_{i=1}^{N-1} (z_{i+1} - z_i)^2}{\sum_{j=1}^M L_j}} \tag{5}$$

In equations of 2, 3, and 4, N , y_i , m , and α_k represent the number of surface points, heights of the surface points relative to the mean surface, the number of elementary surfaces (in triangulated surfaces), and the inclination angle of the normal vector of each elementary surface respectively. In Eq. 5, (x_i, z_i) , M , N , and L_j denote the coordinates of the point of the profile, the total number of profiles in a surface, the number of the points in a profile, and the length of each profile, respectively. The variations of these roughness parameters for joint surface sizes of 25 to 400 cm² have been depicted in the Appendix. All the mentioned roughness parameters have been examined for quantifying the surface geometry in the proposed criterion.

Discuss the nature of the roughness of joint surfaces

According to ISRM (1978), discontinuity roughness comprises large-scale waviness and small-scale unevenness components. Furthermore, based on Lee’s definition, the geometry of the joint consists of two types of roughness, the primary and secondary asperities (Lee and Ahn 2004). In this regard, Belem et al.’s (2002) studies on shear strength mechanism showed that both small-scale and large-scale asperities control the joint shear strength of rocks. Thus, the criterion which takes into account the primary and secondary asperities in quantifying the surface roughness can expectedly have a better estimation of the joint shear strength.

In quantifying the roughness of joint surfaces, the altitude and angular parameters determine the characteristics of primary and secondary roughness, respectively. Also, by increasing the scale, the effect of secondary asperities diminishes in determining the shear strength of rock joints, while the effect of primary asperities of the joint surface will increase (Bahaaddini et al. 2014).

In this study, according to the surface observations, the prepared joints have three different roughness natures. In the

surfaces of S1 and S3, detailed observations of the joint surface geometries and the degradations of the surface roughness before and after the shear tests show that in these surfaces first- and second-order asperities are dominant, respectively (Fig. 3a and c). The surface of S2 consists of both first- and second-order asperities (Fig. 3b). The first-order asperities of waviness are large-scale undulations which cause dilation during shear displacement since they are too large to be sheared off, and the second-order asperities or unevenness are small-scale roughness that tends to be degraded during shear displacement.

Proposing a new joint shear strength criterion

In this research, the joint wall material strengths were constant given the similarity of the molding conditions of samples on various scales. According to some previous research (Azinfar et al. 2016; Kutter and Otto 1990; Ueng et al. 2010), the base friction angle was also independent of the scale. Studies have shown that the effect of surface roughness on shear strength is more pronounced at relatively low values of effective stress (Flamand 2000; Huang et al. 2002; Grasselli and Egger 2003).

Here, in the joint samples tested, the normalized normal stresses with UCS of the material joints have been between 0.008 and 0.1. Thus, the variations of shear strength with scale would expectedly depend on the joint surface roughness. The general form of the proposed equations for determining the shear strength is as follows:

$$\frac{\tau_p}{\sigma_n} = \tan(\varphi_p), \quad \varphi_p = \varphi_b + i \tag{6}$$

where φ_p denotes the peak friction angle, and φ_b is the basic friction angle. Also, i is the dilation angle of the joint. The

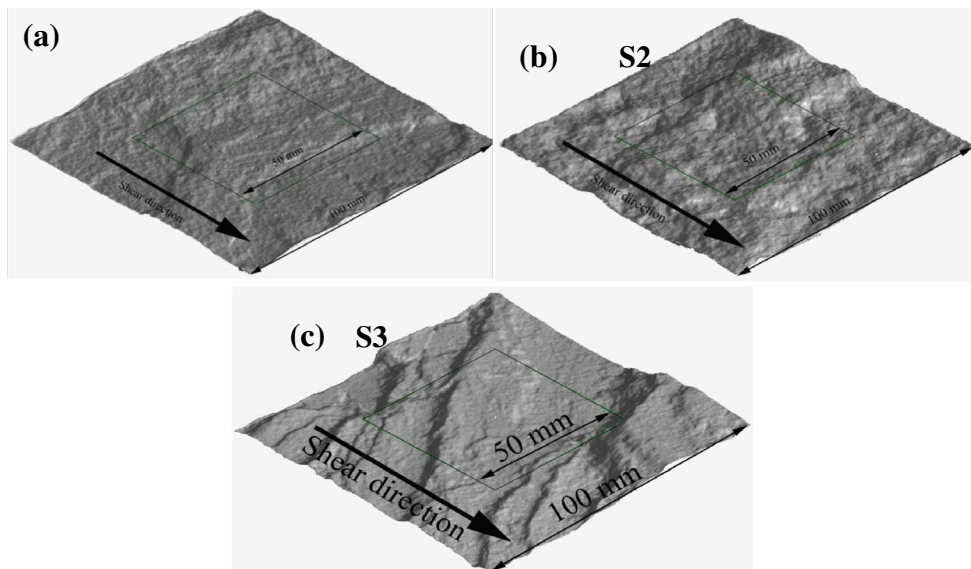
peak friction angle depends on the basic friction angle of the joint, the normal load, surface roughness, and the strength of joint wall materials. In this research, to provide a more precise shear strength criterion, the first- and second-order of asperities have been used in the proposed criterion. Among investigated parameters, Grasselli's roughness parameter, RMS , CLA , and θ_s are in agreement with the experimental results compared to other parameters. It can be stated that RMS and CLA (altitude parameters) represent the first-order asperities while θ_{smax}^* and θ_s (angular parameters) reflect the second-order asperities.

The peak dilation angle is the angle indicating the vertical displacement of the joint relative to its horizontal displacement at the point of peak shear strength. To achieve an appropriate joint shear criterion, in the first step, the peak dilation angles of the joints should be calculated from experimental results. The values of the dilation angles are a function of surface geometry, material strength, and normal load.

A microscopic view of the joint shear mechanism has indicated that tensile fractures in joint wall materials are dominant (Armand 2000; Fishman 1990; Park and Song 2009; Ghazvinian et al. 2012). Thus, tensile strength (from Brazilian tests) of joint materials was selected as joint material strength. Figure 4 displays the variations of the experimental dilation angle with σ_t / σ_n . According to this figure, with increasing normal loads, the dilation angles increase. However, the slope of this increment varies according to the roughness of the surfaces and the normal load values.

At this stage, it should be fitted with the best function for the boundary conditions ($\sigma_n \rightarrow 0 \rightarrow \infty$ and $\sigma_n \rightarrow 0 \rightarrow \infty$) on the curves. To achieve the boundary conditions of $\sigma_n \approx 0$, nine tests were carried out on different joint surfaces, on Type 3 materials, and only with the weight of the joint block. The dilation angle in the case where the normal load is close to zero is almost independent of the normal load and joint material and

Fig. 3 Photographs of three surface roughness with a scale of 100 cm². **a** Surface roughness S1; **b** surface roughness S2; **c** surface roughness S3 (Azinfar et al. 2016)



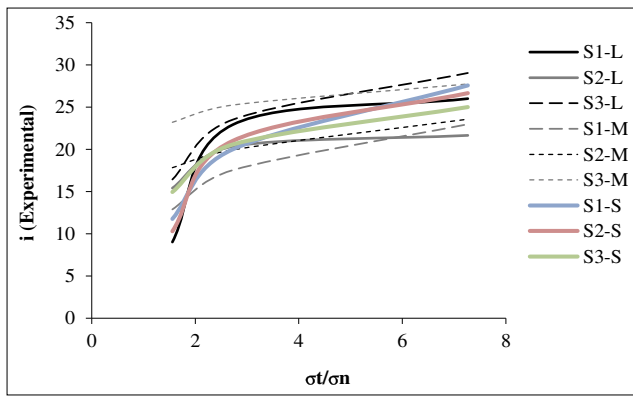


Fig. 4 The variations of experimental dilation angle with σ_t/σ_n

depends on the scale and joint surface geometry. Thus, the values of the dilation angles have been calculated from the experimental results. Their relationship to the scale and $\theta_{max}^*/(C + I)$, CLA, and RMS has been evaluated and shown in Fig. 5.

The scale parameter is considered (L / l) , where l is the distance between the points of measurement (resolution) and L is the dimension of the joint. According to the curve of Fig. 5, assuming the constant measurement resolution, the dilation angle generally increases with increasing the scale and the surface roughness.

The data were imported to a curve fitting software and several functions were investigated. Finally, according to squared values of correlation coefficients, the best fitting function is selected as follows.

$$i_{(\sigma_n \rightarrow 0)} = 7 \left(\frac{CLA \cdot \theta_{max}^*}{RMS \cdot (C + 1)} \frac{L}{l} \right)^{0.2} \tag{7}$$

If we assumed that normal stress tends to infinity, the dilation angle should be zero. Because in very high normal stresses, all asperities are cut, and the friction between the two joint surfaces is affected by the base friction angle. Since the actual maximum normal stress that can be applied to the joint is

equal to the UCS strength of the joint material, this assumption is possible only in theory. After investigating several functions, the best function that can be fitted while considering the boundary conditions on the variations in the dilation angle relative to σ_t/σ_n is as follows:

$$i = a \frac{(\sigma_t/\sigma_n)}{d + (\sigma_t/\sigma_n)} \tag{8}$$

Given Eq. 8, the values of the dilation angle in two boundary states will be as follows:

$$\begin{aligned} \lim_{\sigma_n \rightarrow 0} i &= \lim_{\sigma_n \rightarrow 0} a \frac{(\sigma_t/\sigma_n)}{d + (\sigma_t/\sigma_n)} = \lim_{\sigma_n \rightarrow 0} a \frac{\sigma_t}{\sigma_n \left(\frac{d \cdot \sigma_n + \sigma_t}{\sigma_n} \right)} \\ &= a \left(a = 7 \left(\frac{CLA \cdot \theta_{max}^*}{RMS \cdot (C + 1)} \frac{L}{l} \right)^{0.2} \right) \end{aligned}$$

$$\lim_{\sigma_n \rightarrow \infty} i = \lim_{\sigma_n \rightarrow \infty} a \frac{(\sigma_t/\sigma_n)}{d + (\sigma_t/\sigma_n)} = \lim_{\sigma_n \rightarrow \infty} a \frac{\sigma_t}{\sigma_n \left(\frac{d \cdot \sigma_n + \sigma_t}{\sigma_n} \right)} = 0$$

Thus, the proposed criterion will be as follows:

$$\tau_p = \sigma_n \tan \left[\varphi_b + 7 \left(\frac{CLA \cdot \theta_{max}^*}{RMS \cdot (C + 1)} \frac{L}{l} \right)^{0.2} \frac{(\sigma_t/\sigma_n)}{d + (\sigma_t/\sigma_n)} \right] \tag{9}$$

The only unknown parameter left is the d parameter. The value of d is calculated based on the back-calculation of experimental shear strength as the following equation:

$$\begin{aligned} \frac{\tan^{-1}(\tau_p/\sigma_n) - \varphi_b}{7 \left(\frac{CLA \cdot \theta_{max}^*}{RMS \cdot (C + 1)} \frac{L}{l} \right)^{0.2}} &= \frac{(\sigma_t/\sigma_n)}{d + (\sigma_t/\sigma_n)} \rightarrow d \\ &= \frac{7(\sigma_t/\sigma_n) \left(\frac{CLA \cdot \theta_{max}^*}{RMS \cdot (C + 1)} \frac{L}{l} \right)^{0.2}}{(\tan^{-1}(\tau_p/\sigma_n) - \varphi_b)} - (\sigma_t/\sigma_n) \end{aligned}$$

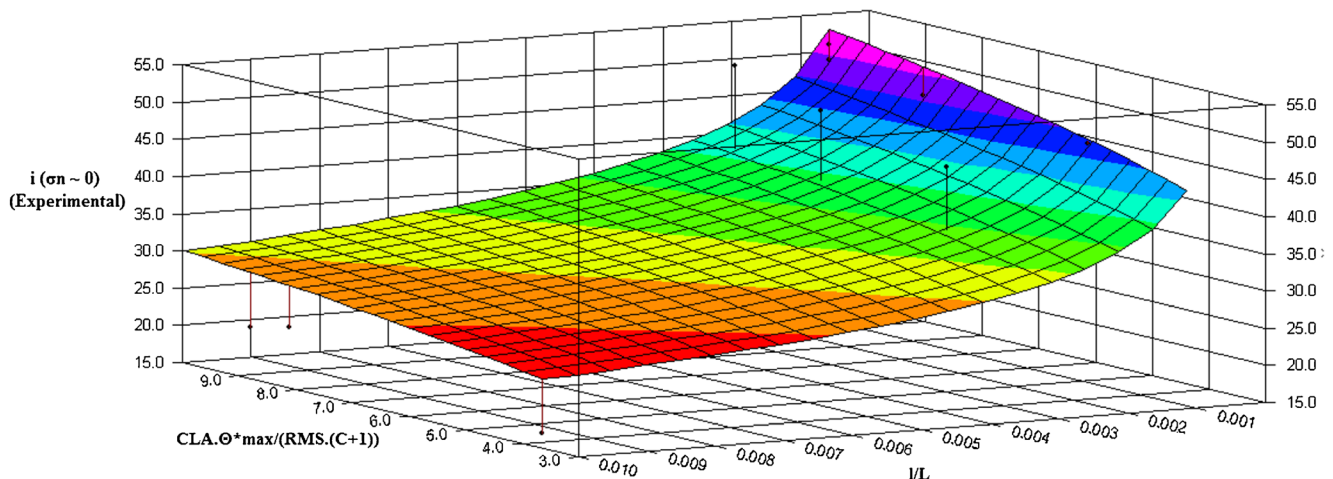


Fig. 5 The variations of experimental dilation angle in zero normal stress condition, vs. scale and surface geometry

In this step, the correlation between d parameter and parameters of σ_n , $\theta^*_{max} / (C + 1)$, CLA / RMS , and K_a (surface heterogeneity parameter) was investigated. The best correlation between the data is obtained when σ_t / σ_n and CLA / RMS are considered independent parameters (Fig. 6). Figure 6 shows that the value of the parameter d increases with increasing σ_t / σ_n and CLA / RMS . Many functions were fitted over the data, and considering the degree of correlation of the data with the fitted function, the following equation was selected:

$$d = 7 \left(\frac{\sigma_t}{\sigma_n} \right)^5 \left(\frac{CLA}{RMS} \right)^{0.6} \tag{10}$$

Hence, finally, the modified shear strength of the joints, taking into account the scale effect, can be presented as follows:

$$\tau_p = \sigma_n \tan \left[\varphi_b + 7 \left(\frac{CLA \cdot \theta^*_{max}}{RMS \cdot (C + 1)} \frac{L}{l} \right)^{0.2} \frac{\left(\frac{\sigma_t}{\sigma_n} \right)}{7 \left(\frac{\sigma_t}{\sigma_n} \right)^5 \left(\frac{CLA}{RMS} \right)^{0.6} + \left(\frac{\sigma_t}{\sigma_n} \right)} \right] \tag{11}$$

The parameters σ_n , $\theta^*_{max} / (C + 1)$, RMS , and CLA represent normal stress, Grasselli’s roughness parameter, root mean square of the asperity heights, and centerline average, respectively. The parameters l and L show the distance between the points of measurement (measurement resolution) and the dimensions of the joint, respectively. In Fig. 7, the values obtained from the proposed relationship have been compared with the experimental joint shear strength results. There is a high correlation between the experimental results and the values estimated by the proposed criterion.

Due to the tensile nature of the failure mechanism in the joint shear test, the tensile strength is used as the determining parameter for the joint strength. According to the load range, the validity of this criterion has been investigated for the following stress interval:

0.008 < σ_n / σ_t < 0.65 or 0.001 < σ_n / σ_c < 0.11

In the problems related to stability analyses, the maximum effective normal stresses on the joints considered critical joints lie within the range of 0.1 to 2 MPa (Barton 1978). Regarding the rock strengths, the range of normal stress investigated in this study covers a wide range of rock mechanics projects in terms of normal loads.

Comparison of experimental and estimated shear strength by other criteria

In the literature, many studies have been done on the effect of scale on the behavior of rock joints. However, only a few studies have been able to propose the shear strength criteria considering the scale effect. Considering the joint surface in three dimensions, the proposed previous criteria are limited to Cottrell (2009) and Tang et al. (2016). To evaluate the new proposed criterion, a comparison is made between these criteria and the present criterion. In these two criteria, the joint surface roughness has been quantified by three-dimensional parameters where the scale effect has been considered on shear strength. Cottrell (2009) revised the shear criterion originally proposed by Grasselli and Egger (2003) as follows:

$$\tau_p = \sigma_n \tan \left(\varphi_b + \left(\frac{\theta^*_{max}}{C + 1} \right)^B \right) \left[1 + e^{\left(\frac{-\theta^*_{max} \sigma_n}{9A_0 \cdot (C+1) \cdot \sigma_t} \right)} \right] \tag{12}$$

where B was an empirical fitting parameter considered equal to 1.15 in the criterion proposed by Cottrell (2009). Then, Tatone et al. (2010) modified the B parameter by changing the surface measurement resolution (point spacing) from 0.044 to 4 mm and performing six shear tests on joint replica samples with the same sizes. Finally, the B parameter was proposed as the following equation:

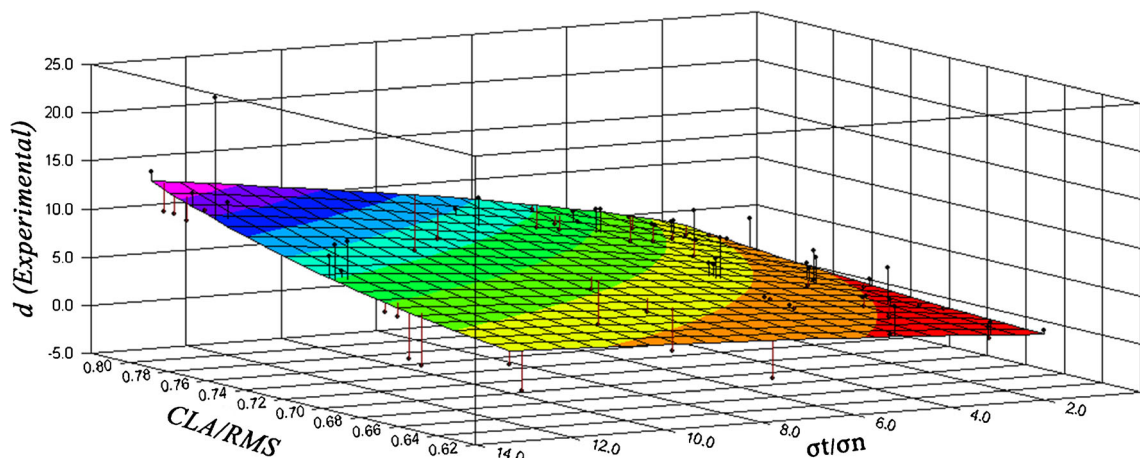
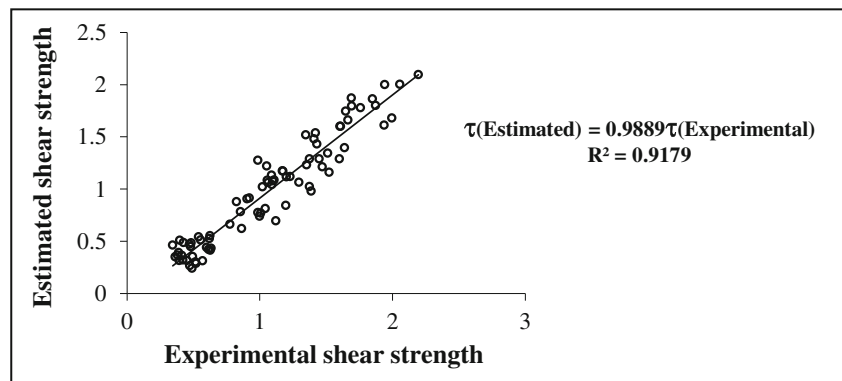


Fig. 6 The variations of d values vs. σ_t / σ_n and CLA / RMS

Fig. 7 The estimated joint shear strength values by proposed criterion vs. experimental results



$$B = 1.69(l/L)^{0.057} \tag{13}$$

where l and L are point spacing and the dimension of the joint, respectively.

Tang et al. (2016), based on 130 experimental shear test results available in the literature, modified Grasselli and Egger (2003). These tests had been done on induced discontinuities for six different rock types and fracture replica samples. They also considered the effect of the scale by changing the point spacing of surface measurement in modified Grasselli and Egger (2003) and proposed their criterion as follows:

$$\tau_p = \sigma_n \tan \left[\varphi_b + 9l^{0.1} \frac{A_0 \theta_{max}^* (C + 1)}{1 + \sigma_n / \sigma_t} \right] \tag{14}$$

where l is the point spacing of the surface measurement. Figure 8 compares the estimated values of both criteria with the new criterion. Compared to Cottrell’s criterion (Cottrell 2009), the proposed criterion is based on the Mohr-Coulomb criterion, and it is more physically understandable. According to Fig. 8a, Cottrell’s criterion has overestimated the shear strength values almost twice the experimental values. According to Eq. 12, for very small θ_{max}^* values, which means the surface is completely smooth and non-roughness, the shear strength is approximately equal to $[2\sigma_n \tan(\varphi_b)]$ which is different from the shear strength criterion $[\sigma_n \tan(\varphi_b)]$ for smooth or saw-cut rock discontinuity.

On the other hand, Cottrell’s criterion has been proposed based on the shear test results performed on the tensile joint samples. In such joints, sharp roughness and interlocking of the surfaces lead to higher shear strength than natural joints. The overestimation of Cottrell’s criterion can be due to these two reasons.

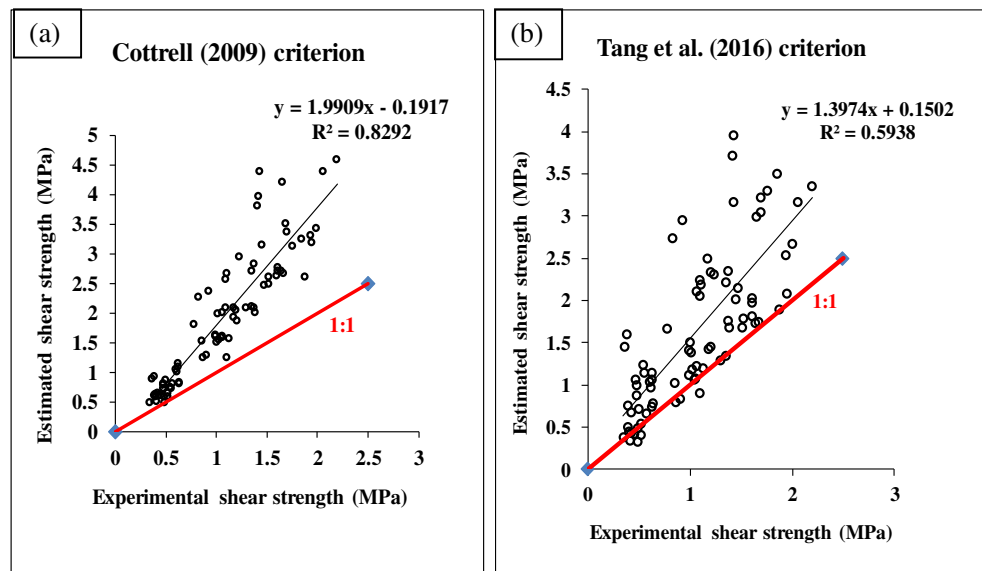
According to Fig. 8b, the criterion of Tang et al. (2016) has also been an overestimation of about 40%. This criterion is also based on the shear test results of other researchers on tensile joints. This overestimated value can be due to using tensile joints instead of natural joints in Tang et al. (2016) research. Tang et al. (2016) modified the Grasselli and Egger (2003) model and proposed their new model in the general form of Mohr-Coulomb’s criterion. Hence, the estimated values of their model are lower than those of the Cottrell model.

In both Cottrell (2009) and Tang et al. (2016) criteria, shear tests were performed on joints with the same dimensions, and the effect of the scale was considered the point spacing of measurement (measurement resolution). Although the l/L ratio has been used in Cottrell’s criterion, the L (joint dimensions) has been constant, and only the measurement resolution has changed. In Tang et al.’s (2016) study, the joint dimension has been ignored in the model. In the current model, the joint dimension has changed, and the measurement resolution has been constant for all joints (0.25 mm). Considering the concept of scale effect, this method seems to provide better results in estimating the shear strength of joints with different dimensions.

Discussion and conclusion

A review of studies on the effect of scale on the shear behavior of rock joints shows that in some cases, there are contradictions in results. These contradictions are mainly caused by the accuracy of roughness measurement tools, roughness quantifying methods (2D or 3D), and ignoring the effects of the primary and secondary roughness on joint surfaces. In this study, to reduce the

Fig. 8 Estimated values of shear strength of joints vs. experimental values. **a** Cottrell (2009) criterion, **b** Tang et al. (2016) criterion



errors caused by the mentioned factors, a constant point spacing of 0.25 mm was selected for scanning all joint surface dimensions with 3D roughness parameters used for quantifying the surface geometries. Finally, a new joint shear strength criterion was proposed using the results of direct shear tests on joint specimens with regard to the scale effects. Compared to the previous similar criteria presented in this field, for the following reasons, we can expect a better estimate of the joint shear strength by the proposed criterion:

- 1- Consideration of the effects of first- and second-order roughness using several 3D roughness parameters (instead of one parameter) to quantify joint surfaces; the parameter $\theta^*_{max} / (C + I)$ is an angular parameter which is more representative of second-order roughness. The CLA / RMS parameter represents the height differences of surface asperities, and it can be stated that it is representative of the first-order roughness. In previous similar criteria, only one roughness parameter had been used to quantify the surface.
- 2- Consideration of changes in the joint dimensions as a change in scale; in the similar previous criteria, the change in measurement resolution (point spacing) has been considered the effect of scale.
- 3- Use of natural joint surfaces to make replica joint samples; most of the shear strength criteria have been proposed based on the shear tests done on tensile joints or replica joint samples molded from tensile joints. Generally, such joints have jagged and interlocked

surfaces, and use of these criteria to estimate the shear strength of natural joints may lead to overestimated results.

However, this model has been proposed by the following assumptions which should be considered when it is applied:

- All tests have been performed under constant normal load conditions.
- Regarding molding the joint samples, the joint surfaces completely fit. Use of this criterion to estimate unmated natural joints will lead to an overestimation. In these cases, a larger safety factor should be adopted.
- The openings of the joints are minimal, and the joints have no filling and weathering.

Regarding the use of the criteria in the field, although it is necessary to obtain several roughness parameters to use the proposed criterion, by scanning the joint surface once and using the relevant relationships, all parameters can be calculated in the field. With normal stress, Brazilian tensile strength of rock, and measuring resolution, the shear strength of the joint can be calculated at any desired scale using the present criterion. Given that the proposed criterion is based on three joint geometries with constant measurement resolution, further research needs to improve the model considering both joint dimension and measurement resolution changes as well as a wider range of joint surfaces and materials.

Appendix

The variations of roughness parameter values for joint surface sizes of 25 to 400 cm² have been depicted in Fig. 9.

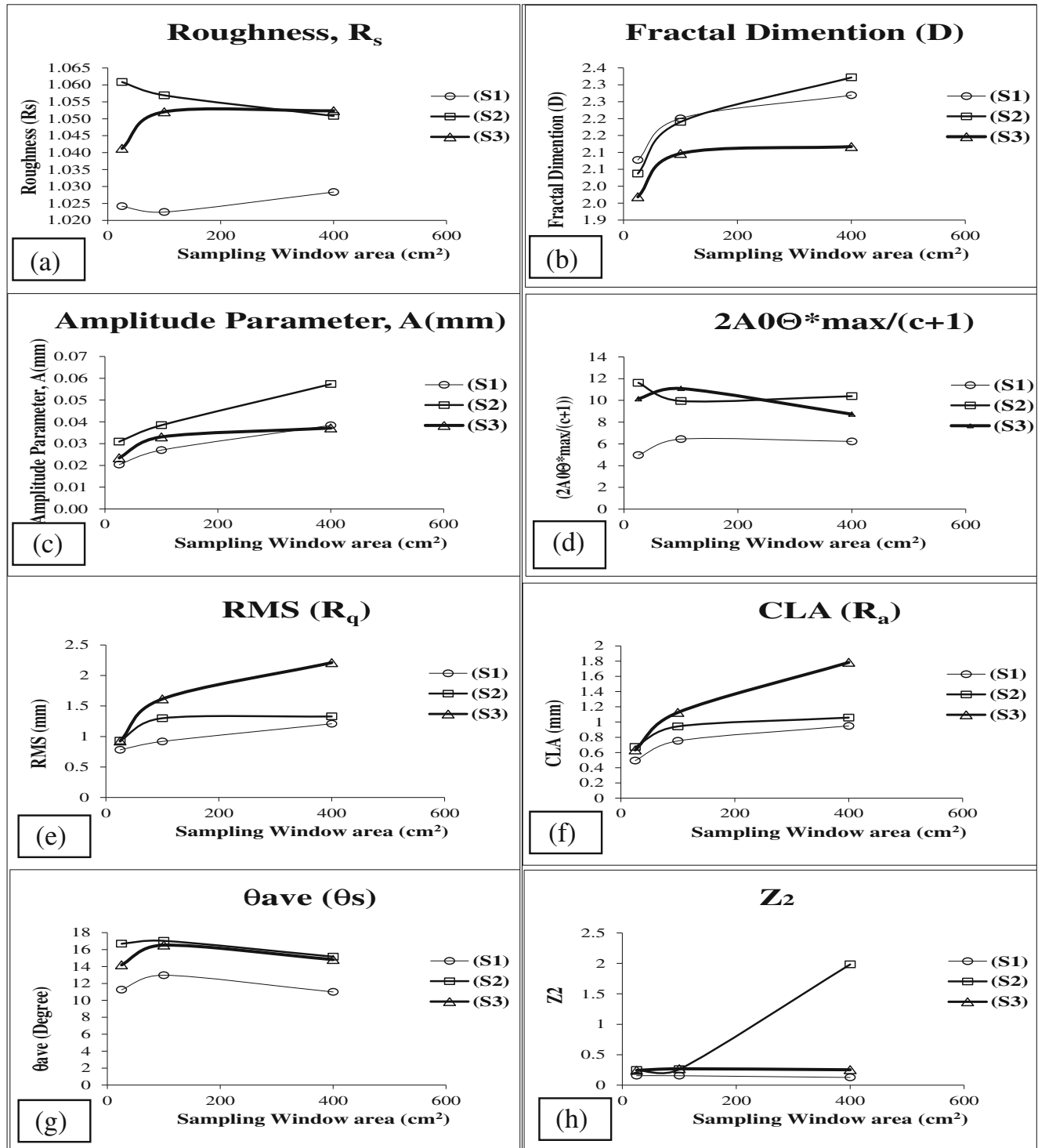


Fig. 9 a Surface roughness coefficient, b fractal dimension, c amplitude parameter, d Grasselli’s roughness parameter, e root mean square of asperity heights, f central line (surface) average, g average angle of surface asperity, and h root mean square of the first derivative of the profile

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Declarations

Conflict of interest The authors declare no competing interests.

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