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Investigation of natural rock joint roughness

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ABSTRACT

The paper provides a comprehensive review on rock joint roughness measurement and quantification procedures. Superiority of fractal based methods over JRC, statistical parameters and statistical functions in quantifying roughness is discussed in the paper. Two of the best fractal based methodologies available in the literature, the modified 2-D divider and variogram methods, are used to quantify natural rock joint roughness in 3-D and 2-D, respectively. The capability of these two methods in accurate quantification of natural rock joint roughness is shown in the paper by applying the procedures to four natural rock joints. A good comparison has been obtained from the values obtained through the two methods. Both these methodologies have two parameters to capture the stationary roughness. The fractal dimension captures the spatial auto correlation of roughness; the other parameter captures the amplitude of roughness. Anisotropic roughness has been studied by applying two other methodologies: (a) a triangular plate methodology and (b) a light source methodology to the same four natural rock joints. A reasonably good comparison has been obtained through the results of these two methodologies. All four roughness quantification methodologies can be applied to any size of sample covering from laboratory to field scales. The results of the triangular plate and light source methodologies provided possible sliding direction values (under the gravitational loading) close to that reported in the literature for the rough discontinuity planes used in the study.

1. Introduction and literature review

Strength, deformability and flow properties of rock joints depend very much on the surface roughness of joints. These effects arise from the fact that the surfaces composing a joint are rough and mismatched at some scale. The shape, size, number, and strength of contacts between the surfaces control the mechanical properties. The separation between the surfaces or the "aperture" determines the hydraulic properties. Therefore, accurate quantification of roughness is important in modeling strength, deformability and fluid flow behaviors of rock joints. Rock mass strength, deformability and fluid flow behaviors in turn depend very much on the properties of joints.

Many different methods have been used to measure rock fracture surface roughness. These methods can be categorized broadly into contact and non-contact methods. The contact methods require the operator or instrument to physically contact the surface for recording the measurements along the chosen profiles or over the defined area. The linear profiling method [1], the compass and disc clinometer method [1], the shadow profilometry method [2], the tangent plane sampling and pin sampling technique [3] and mechanical or electronic stylus profilometry [4,5] are typical examples for contact methods. They are time consuming and may not provide a sufficient number of data for detailed, accurate roughness quantification. However, they are relatively cheap compared with the equipment belonging to the non-contact category. Also, some of them may be sufficient to quantify roughness approximately at a large scale for field samples. The non-contact methods use a technique to record the measurements without physically touching fracture surfaces. Laser profilometry [6–13], and methods based on structured light projection techniques such as Laser scanning [14–17] and stereo topometric cameras [18,19] are examples for non-contact methods. The aforementioned non-contact methods provide a large number of measurements at a high resolution within a short time. The main drawback of the aforementioned non-contact methods is the cost of the equipment. Rock joint roughness data obtained from a laser scanner is used in this paper to quantify rock joint roughness.

To quantify rock joint surface roughness, several methods have been proposed in the literature. The joint roughness coefficient (JRC) proposed by Barton [20] has been widely used in engineering practice. Shortcomings of JRC in quantifying rock joint roughness

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have been pointed out by several researchers [2,7,9,21,22]. The following statistical parameters or statistical functions have been used to quantify a roughness profile or a roughness surface: (1) The centerline average value of the profile, CLA [23]; (2) The mean square value of the profile, MSV [23]; (3) The root mean square value of the profile, RMS [23,24]; (4) The mean inclination angle of the profile, θ_P [12,25]; (5) The mean positive inclination angle of the profile, θ_{P+} [12]; (6) The mean negative inclination angle of the profile, θ_{P-} [12]; (7) The standard deviation of the inclination angle of the profile, SD θ_P [25]; (8) The root mean square of the slope of the profile, Z_2 [23–25]; (9) The root mean square of the first derivative of the slope of the profile, Z_3 [23,24]; (10) The % excess distance measured along the profile where the slope is positive over the distance where the slope is negative, Z_4 [23,24]; (11) The auto correlation function, ACF [23,26]; (12) The structure function, SF [23,25,27]; (13) The spectral density function, SDF [26]; (14) The mean inclination angle for the surface, θ_S [12]; (15) The root mean square of the slope of the surface, Z_{2S} [12]; (16) The maximum apparent dip angle in the shear direction/an empirical roughness parameter + 1, ($\theta_{Max}/C + 1$) [18,28]; (17) The roughness profile index (the ratio of actual length of a roughness profile to its projected length on the horizontal surface), R_P [2,25,30]; (18) The surface roughness coefficient (the ratio of actual area of a roughness surface to its projected area on the horizontal surface), R_S [12,29]; (19) The surface Tortuosity coefficient, T_S [12]. The aforementioned parameters (1) through (3) can be categorized as amplitude parameters of a roughness profile. The parameters or functions (4) through (16) are various measures of either the slope or spatial variation of the roughness profile or roughness surface. The parameters (17) through (19) are measures of both the amplitude and slope or spatial variation of the roughness profile or roughness surface. Note that both the amplitude and the slope or spatial variation contribute to roughness. Therefore, out of the aforementioned statistical parameters or statistical functions, the last three are the best parameters. Even though these statistical parameters or statistical functions have contributed to early development of roughness quantification, the value obtained for each of the aforementioned statistical parameters or values obtained for statistical functions depend on the sampling interval used to calculate the statistical parameter or statistical function. Therefore, for each statistical parameter or statistical function, infinite many values or functions are possible. In other words, statistical parameters or statistical functions show scale effect. This is not a desirable feature for roughness quantification. This led researchers to look into application of other methods, which have scale invariant properties for all the scales or at least for a range of scales, to quantify rock joint roughness.

The different fractal methods have the potential to use in quantifying rock joint roughness. They are the divider [30], box counting [31], variogram [32], spectral [33], roughness-length [34], and the line scaling [35] methods. Fractals can be either self-similar or self-affine. A self-similar fractal is a geometric feature that retains its statistical properties through various magnifications of viewing. That means self-similar fractals provide scale invariant values. A self-affine fractal remains statistically similar only if it is scaled differently in different directions. Fig. 1 illustrates the concepts of self-similarity and self-affinity. In the case of a rock joint profile formed by a profilometer or a structured light projection technique, controversy has existed over self-similarity and self-affinity. Russ [36] has asserted that a section taken at any orientation other than parallel to the mean surface orientation would result in a self-affine object. Therefore, it is not appropriate to consider natural rock joint profiles to be self-similar. They are self-affine profiles. The original divider and the original box counting methods are self-similar methods and they provide accurate results only for self-similar profiles. Problems are encountered when

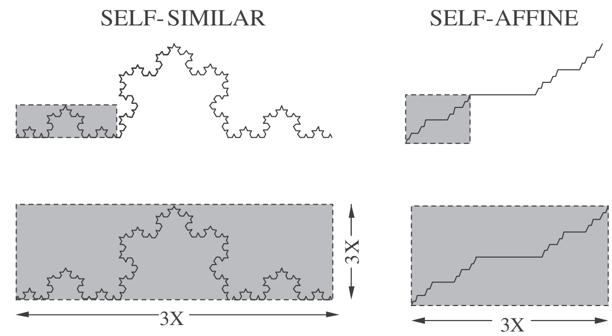

Fig. 1. Illustration of self-similar and self-affine fractals.

self-similar methods are used in the calculation of fractal dimensions for self-affine objects. The next two paragraphs explain the problems associated with using the original divider method in calculating correct fractal dimension values for self-affine profiles and how to modify the method to produce correct fractal dimension values.

Linear roughness of natural rock joint profiles can be measured accurately either using a stylus profilometer, laser profilometer or a light projection technique device. Each device has a smallest horizontal step at which the height of the roughness profile can be measured. Therefore, even though the roughness profiles of a natural rock joint surface are continuous, roughness profile data obtained through a measurement device are available only at a certain interval of horizontal spacing. When these roughness data are plotted, they may produce a profile as shown in Fig. 2. In this profile, the adjacent data points are connected through linear segments. Even though the horizontal length of each segment is the same, the inclined length (length of the segment) changes from one segment to another, depending on the inclination angle of the segment. Then the minimum feature size of a profile may be defined as the minimum segment length out of all the segment lengths between two adjacent data points on the profile (Fig. 2). This minimum distance cannot be less than the horizontal distance at which roughness height data are available. The maximum feature size may be defined as the maximum segment length out of all the segment lengths between two adjacent data points on the profile (Fig. 2). The difference between the maximum and minimum feature sizes of a profile reduces, as the profile gets smoother. Also, it is important to realize that both the estimated minimum and the maximum feature sizes of a profile depend upon the resolution of the instrument used in measuring roughness. The concepts mentioned above on the minimum and the maximum feature sizes are equally applicable for generated roughness profiles too, because the generated values are available only at a certain interval of horizontal spacing.

The original divider method is best visualized by considering a pair of dividers set to a particular span and then walked along the roughness profile. The number of divider steps required to cover the entire profile is counted, and then multiplied by the divider

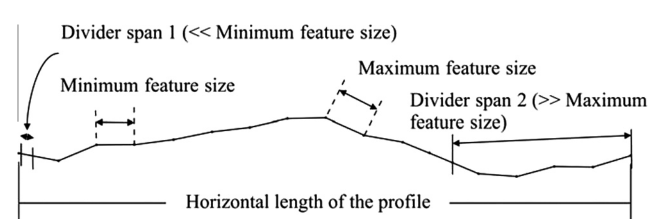

Fig. 2. Concept of minimum and maximum feature sizes of a roughness profile.