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A conceptual model for the peak shear strength of fresh and unweathered rock joints

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ABSTRACT

Several criteria have been proposed over the years in order to predict the peak shear strength of rock joints. The most widely used criterion is the *JRC–JCS* criterion by Barton. It says that changes in the peak shear strength originate from surface roughness, joint wall compressive strength and normal stress. A limitation with this criterion is that the contribution from roughness could be overestimated for natural and mismatched joints if the joint roughness coefficient, *JRC*, is estimated based on the direct profiling method. To account for this effect, Zhao introduced the joint matching coefficient, *JMC*, which accounts for the matedness of the joint. In addition to this, it is known that the scale of the sheared joint could affect the peak shear strength. However, no criterion exists that describes how roughness, matedness and scale interact. In this paper, a conceptual model is proposed. The model is based on adhesion and fractal theory, measurements of surface roughness and the anticipated variation of the number and size of the contact points. The model proposes how the compressive strength and the roughness of the joint surface together with the matedness of the joint interact in order to form the shear strength of the joint under constant normal load conditions. The model also suggests an explanation for the scale effect of rock joints with respect to the surface roughness.

1. Introduction

Weakness planes such as joints significantly affect, and in many cases govern, the shear strength of rock masses. Therefore, for the design of foundations, dams, tunnels and slopes, it is necessary to determine the shear strength of rock joints. The shear strength of rock joints is affected by several parameters, such as the normal stress, the uniaxial compressive strength of the joint surfaces, the surface roughness, scale, weathering, matedness of the surfaces and possible infilling material. The effect on the peak shear strength from each of the parameters, and the interaction between them, make it difficult to derive theoretical models that can be used in engineering practice. As a consequence, the criteria used are mainly based on empirical relations. In rock masses, the joints can occur as both filled and unfilled. For unfilled joints, a number of failure criteria have been proposed by different authors, the most notable among them are those of Patton [1], Ladanyi and Archambault [2] and Barton and Choubey [3]. Other examples are the work carried out by Reeves [4], Jing et al. [5], Kulatilake et al. [6], Amadei et al. [7], Saeb and Amadei [8], Plesha [9], Grasselli and Egger [10] and Seidel and Haberfield [11].

One of the most widely used is the empirical criterion proposed by Barton and Choubey [3]. However, a limitation with this criterion is that the contribution from roughness may be overestimated for natural and mismatched joints if the joint roughness coefficient, *JRC*, is estimated based on the direct profiling method [12]. The reason for this is that the matching between the two opposing surfaces of the joint affects the shear strength. The shear strength decreases when the initially matched joint becomes mismatched. Zhao [13] introduced the parameter joint matching coefficient, *JMC*, in order to describe the matedness of a joint. Furthermore, he proposed that the *JRC* ought to be reduced by the *JMC* in order to account for the degree of matedness [13]. It has also been observed that scale can affect the shear strength of rock joints, see for example [14–16]. To account for the scale effect, Barton and Bandis proposed empirical derived equations [17]. However, they do not describe how roughness, matedness and scale interact.

In this paper, a conceptual model for unfilled, fresh, unweathered and rough rock joints is proposed which account for these factors based on the work in [18]. The model is based on basic prerequisites such as adhesion theory and the understanding of different failure modes for a single asperity. In addition to this, it is based on an idealised description of surface roughness by fractal theory, how the size of the asperities at contact changes due to

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scale and matedness and how the dilation angle changes at grain scale. The model explains how the compressive strength and the roughness of the joint surface together with the matedness of the joint interact to form the shear strength of the joint under constant normal load. The model also suggests an explanation for the scale effect. First, the paper describes the theory behind the conceptual model. This is followed by a comparative study between measured shear strength and shear strength calculated with the conceptual model. Finally, discussion and conclusions are presented.

2. Conceptual model

2.1. Basic prerequisites for one asperity

The failure mode of the asperities is a key factor to understand the conceptual mechanism of the peak shear strength. Several types of failures have been observed. Patton [1] observed that in the primary portion of the failure envelope, under low normal stresses, sliding occurred prior to shearing through the intact rock. In addition to sliding, Ladanyi and Archambult [2], Barton and Choubey [3] and Bandis et al. [15] also considered the contribution from shear failure through the intact asperities. Grasselli [19] found indications that individual asperities broke through tensile failure instead of compressive failure. This means that a single asperity could fail through sliding, shearing or rotational tensile failure.

The generally accepted theory for friction, the adhesion theory, was first stated by Terzaghi [20]. It states that the contact area is equal to the ratio between the normal stress and the uniaxial compressive strength of the joint wall surface. Later, Bowden and Tabor [21,22] showed that it could explain the frictional behaviour for a wide range of materials. The adhesion theory states that on a microscopic level, all surfaces, even smooth ones, are rough. Contact points will only be developed where the asperities from the two opposing surfaces touch each other. The area of contact will be a small part of the total area of the two surfaces. The normal stresses at these contact points become so high that the yield strength of the material at the asperity scale is reached. However, the concept of adhesion was developed with observations of mainly engineered planar metal surfaces whose roughness is both stationary and regular compared with rough surfaces of rock joints. It is not obvious that the yield strength is reached at the contact points for rough rock joints. Greenwood and Williamson [23] developed an analytical model for contact mechanics of one nominally planar rough surface with its asperity height following a Gaussian distribution and one smooth surface. Their model showed that exact proportionality between contact area and normal load will exist independently of mode of deformation (elastic or plastic). According to their model, the proportionality between contact area and load lies in the statistical distribution of the asperity heights of the surface roughness. A further development of this model was presented by Greenwood and Tripp [24] for the contact between two nominally flat rough surfaces with similar results. Also, the model by Greenwood and Tripp [24] has been used to estimate different joints properties, see for example Swan [25] and Swan et al. [26]. Despite this, measurements exist which have shown that the contact stress is sufficiently high to induce plastic flow of asperities under shearing of rock [27,28]. Therefore, it is assumed that the contact area, A_c, for fresh and unweathered joints can be approximated as the normal load acting over the surface, N, divided by the yield strength of the material, see Eq. (1). In this work, the yield strength of the material is approximated with the uniaxial compressive strength, σ_{ci}. Under these assumptions, the contact area increases proportionally to the area of the sample, A, for a given effective normal stress, σ'_n:

$$A_c = \frac{N}{\sigma_{ci}} = \frac{A\sigma'_n}{\sigma_{ci}} \quad (1)$$

If it is assumed that the contact pressure on the asperity is equal to the uniaxial compressive strength, it can further be assumed that crushing occurs on asperities until the area is large enough to carry the total load.

To study how a single asperity can fail at different angles of the asperity inclination, i, an analysis of an idealised asperity has been performed. The idealised asperity is shown in Fig. 1. In the analysis, it is assumed that only the side of the asperity facing the shear direction is loaded. The width of the asperity is assumed fixed, while the inclination angle of the asperity i varies between 0 and 90°.

For sliding failure of a single asperity, the ratio between the resistance, T, and the normal load, N, along the side of the asperity facing the shear direction is calculated using the primary portion of Patton's criteria:

$$\frac{T}{N} = \tan(\phi_b + i) \quad (2)$$

where ϕ_b is the basic friction angle for dry saw-cut surfaces, and i is the dilation angle which equals the inclination of the asperity for the sliding failure mode.

For a shear failure through the intact rock at the base of the idealised asperity, the ratio T/N is calculated with the Mohr-Coulombs failure criterion:

$$\frac{T}{N} = \frac{c_i L_{asp}^2}{N} + \tan(\phi_i) \quad (3)$$

where c_i and ϕ_i are the cohesion and internal friction angles for the intact rock, respectively. The normal load N is based on the adhesion theory, Eq. (1), and the assumption that the asperity is quadratic with side length L_{asp} and is given by

$$N = L_{asp}^2 \sigma_{ci} \frac{1}{2} \quad (4)$$

since it is only the side of the asperity facing the shear direction that will be in contact. The final equation for the shear failure

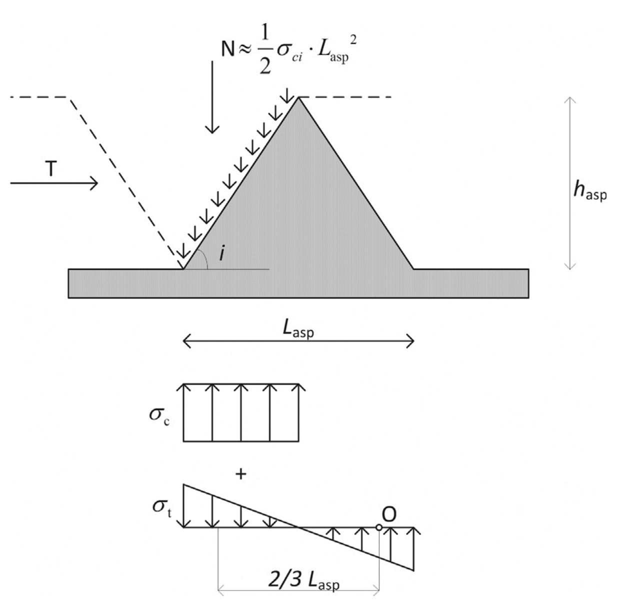

Fig. 1. Figure of a two dimensional idealised asperity used in the calculation with a base area equal to L_{asp}^2, height, h, and inclination, i.