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Micromechanical basis for shear strength of rock discontinuities

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ABSTRACT

The theoretical basis for evaluating shear strength in rock joints is presented and used to derive an equation that governs the relationship between tangential and normal stress on the joint during situations of slippage between the joint faces. The dependent variables include geometric dilatancy, the instantaneous friction angle, and a parameter that considers joint surface roughness. The effect roughness is studied, and the aforementioned formula is used to analyse joints under different conditions. A mathematical expression is deduced that explains Barton's value for the joint roughness coefficient (*JRC*) according to the roughness geometry. In particular, when the Hoek and Brown failure criterion is used for a rock in the contact with the surface roughness plane, it is possible to determine the shear strength of the joint as a function of the relationship between the uniaxial compressive strength of the wall with the normal stress acting on the wall. Finally, theoretical results obtained for the geometry of a three-dimensional joint are compared with those of the Barton's formulation.

1. Introduction

Determining the shear strength of rock joints requires understanding the relationship between the mean normal stress on the rupture plane (mid-plane of the discontinuity) and the mean tangential stress produced by the slippage between the two rock faces. The study of the mechanical behaviour of joints has long attracted interest because it governs physical instability phenomena (slopes, tunnels, etc.) when configured by discontinuities. There are many studies that present constitutive theoretical and empirical models with which to simulate joint behaviour.

The aim of this article is to present several theoretical formulations that allow for the definition of shear strength in rock joints. This aim was accomplished by developing a theoretical model capable of capturing the primary mathematical structure of the equation that was reported in 1973 by Barton [1] and the dependence of the variables used in the description of this equation.

2. Background

One of the first models was proposed by Patton [2] in 1966 and was based on tests that were performed on artificially created joints in gypsum material, which were based on a saw-tooth pattern. The study verified results that were adjusted by Newland and Alley [3] according to a bilinear law that attempted to describe the dilatancy of granular materials. Similar models, in which a transition curve was adjusted between lines that corresponded to dilatancy and shear mechanisms, were proposed by Ladanyi, Archambault [4] and Jaeger [5] and were based on empirical models.

Shortly thereafter, more complex models began to appear. Some models compared the angles that defined surface roughness by normal stress [6], while others tried to predict the dilatancy phenomenon using the fracturing of joints subjected to tangential loads. However, it was Barton [1] who had the most success by incorporating into his dilatancy prediction study an empirical formula that considered the effects of joint roughness and dependence on the load level. Heuze and Babour [7] introduced a three-parameter model to predict the dilatancy produced in rock joints by empirically identifying a critical point, beyond which there was no dilatancy. Additionally, Leichnitz [8] developed a model that was capable of considering rock fractures produced by nonlinear behaviour in the material based on experimental results from sandstone.

From the saw-tooth roughness model first used by Patton, Plesha [9] formulated a constitutive model based on classical plasticity theory that incorporated an exponential degradation factor for roughness. Zubelewicz et al. [10] also studied degradation, and some years later, Qiu et al. [11] revised Plesha's model by considering sinusoidal instead of saw-tooth roughness. Saeb and Amadei [12] conducted a similar study based on an empirical ratio of the dilatancy factor that was given in 1970 by Ladanyi and Archambault [4], and in this manner, they described normal joint

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displacement based on tangential displacement and normal stress. Seidel and Haberfield [13] evaluated plastic deformations produced by surface roughness shear by estimating joint dilatancy according to the energetic considerations produced by internal friction. Other investigations of the degradation of roughness in contacts between joint faces were performed by Hutson [14], Hutson and Dowding [15], Huang et al. [16], Lee et al. [17] and Homand et al. [18], among others.

Gens et al. [19] proposed an elastoplastic constitutive model to describe the three-dimensional behaviours of fractures. Similarly, Desai and Fishman [20] used plasticity theory to create constitutive equations that characterised the mechanical responses of fractures under loading, unloading, and reloading conditions.

More recently, Grasselli [21] and Belem [22] have formulated models to account for parameters that consider the three-dimensional natures of joint surfaces. A generalised three-dimensional formulation was created by Samadhhiya et al. [23] to account for joint dilatancy, roughness, and the undulation of discontinuous surfaces.

Among the existing models, Barton's empirical method [1,24,25] is likely the most widely used in practice. This method is based on the selection of the joint roughness coefficient (*JRC*) value, for which various approaches have been proposed to relate this value to the morphologies of the profiles that it defines; these approaches have also evaluated the use of fractal analysis [26–30], or statistical analysis [31], among other procedures.

Asadollahi [32] introduced a modification of the original Barton's shear failure criterion, which was based on limitations in Barton's criterion concerning the estimation of peak displacement or post-peak shear strength.

3. Failure mechanisms

The interaction between two surfaces in contact initially occurs at a finite number of points through a small number of atoms in their respective crystalline structures. These contact points are constituted by the peaks of the rough surfaces.

Terzaghi [33] proposed that the normal load acting on two bodies in contact causes the plastification of the corresponding surface roughnesses, wherein real contact takes place between the two bodies such that the frictional force is proportional to the normal force and is independent of the size of the two bodies in contact. The explanation of these empirical findings constitutes the Terzaghi adhesion theory. However, not all contacts must be plastified. Some contacts might experience elastic forces such that when the load increases, the elastic elements will slowly become plastic, while new elastic state contacts might appear simultaneously. The contact behaviour in the elastic state can be estimated by Hertz's law [34] of two elastic spheres in contact.

When accounting only for irregularities of this order, it is not possible to correctly model the shear strength of joints, as the shear strength force depends on both the strength of the particles that constitute the rock and the strength of the rock matrix at a higher hierarchical level. The manner in which these mechanical characteristics are connected to joint strength depends on the morphology and, in particular, the roughness of the joint. Thus, various successive degrees of roughness can present themselves on the surface of a rock and could be modelled with a fractal surface if they are statistically self-similar.

It is therefore necessary to consider a higher geometrical model than that described above; this model can be created supposing a simple geometry for the joint profile. In this sense, saw-tooth profiles have been commonly used in theoretical and experimental studies. Obviously, the joint profile can be modelled using more realistic models than the saw-tooth. In any case, for joint movement, the need to retain the geometric roughness implies a greater degree of energy consumption than would be necessary if there were only irregularities of a lower hierarchical rank, such as those described herein.

When contact occurs through surface roughness, two failure mechanisms result. In the first mechanism, the joint slips and forms angle α with the mid-plane of the joint (Fig. 1); this mechanism is used for low normal loads. In the second mechanism, the roughness is plastified and breaks (Fig. 1); this is used for high normal exterior loads.

The critical normal load N_{crit} discriminates between both mechanisms such that for normal stresses below this critical load, failure occurs through the first mechanism; the second mechanism applies to loads above the critical level (Fig. 2).

3.1. First mechanism analysis

It is considered the *i*th contact between the roughnesses according to the joint profile. It is assumed that the tangential plane in the *i*th contact forms the maximum angle α_i with the mid-plane of the joint in a section over the vertical plane, Π_i, that is perpendicular to the mid-plane in the direction of the shear load. Slippage is produced when

$$\frac{T_i^*}{N_i^*} \geq \tan \varphi_b \quad (1)$$

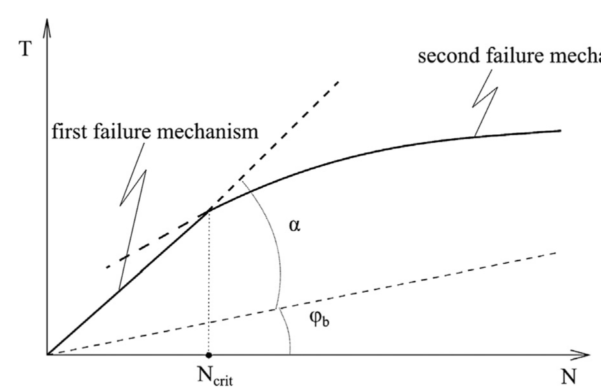

Fig. 2. Peak shear strength governing law.

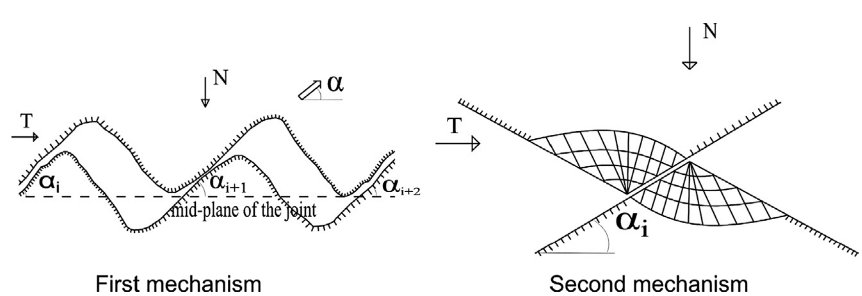

Fig. 1. First failure mechanism (slippage) and second failure mechanism (plastification of the contacts).