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Discrete modeling of rock joints with a smooth-joint contact model

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ABSTRACT

Structural defects such as joints or faults are inherent to almost any rock mass. In many situations those defects have a major impact on slope stability as they can control the possible failure mechanisms. Having a good estimate of their strength then becomes crucial. The roughness of a structure is a major contributor to its strength through two different aspects, i.e. the morphology of the surface (or the shape) and the strength of the asperities (related to the strength of the rock). In the current state of practice, roughness is assessed through idealized descriptions (Patton strength criterion) or through empirical parameters (Barton JRC). In both cases, the multi-dimensionality of the roughness is ignored. In this study, we propose to take advantage of the latest developments in numerical techniques. With 3D photogrammetry and/or laser mapping, practitioners have access to the real morphology of an exposed structure. The derived triangulated surface was introduced into the DEM (discrete element method) code PFC3D to create a synthetic rock joint. The interaction between particles on either side of the discontinuity was described by a smooth-joint model (SJM), hence suppressing the artificial roughness introduced by the particle discretization. Shear tests were then performed on the synthetic rock joint. A good correspondence between strengths predicted by the model and strengths derived from well-established techniques was obtained for the first time. Amongst the benefits of the methodology is the possibility offered by the model to be used in a quantitative way for shear strength estimates, to reproduce the progressive degradation of the asperities upon shearing and to analyze structures of different scales without introducing any empirical relation.

1. Introduction

The presence of discontinuities is inherent to almost any rock mass and is a major contributor to strength and deformation of rock structures (natural or engineering). The characteristics of those discontinuities not only control structurally controlled failures but also greatly influence the shear strength of the rock mass. Being able to describe the structure of a rock mass is critical to an understanding of its potential behavior. The development of various mapping techniques leads to a higher level of confidence on crucial characteristics such as location, orientation and persistence from which stochastic discrete fracture network (DFN) representations of the rock fabric are developed (Dershowitz, 1995; Rogers et al., 2007). Based on numerical methods, equivalent rock mass can be created and tested in order to characterize its constitutive behavior (Pierce et al., 2007; Pine et al., 2007; Deisman et al., 2010). These approaches are now able to model the engineering responses of rock and rock masses using some basic measured properties of the rock and the rock mass geometry as inputs. Offering a wider spectrum of predictions than the classical empirically-based classification schemes (anisotropy, heterogeneous, etc.), the synthetic rock mass approach and equivalents (Pierce et al., 2007; Pine et al., 2007; Deisman et al., 2010) are turning to be a step forward for rock mechanics practitioners. However, the question of the shear strength of the discontinuities is in many cases poorly addressed in engineering practice despite having a significant impact on the rock mass strength (Lambert, 2008).

The shear behavior of discontinuities is a combination of various complex phenomena and interactions, such as dilation, asperity failure, deformation and interaction. Direct shear tests on natural rock discontinuities quickly enhanced the influence of roughness on the mechanical behavior of discontinuities. Barton (1973) proposed to assess roughness with an empirical parameter, joint

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roughness parameter (JRC), from which the shear strength of the discontinuity can be established. Initially estimated by visual comparison with standard roughness profiles, correlations between JRC and various statistical parameters or fractal dimension were established (Tse and Cruden, 1979; Carr and Warriner, 1989). More recently, laser scanner and photogrammetry were used to define the surface topography and estimate its roughness (Grasselli, 2001; Hans and Boulon, 2003; Haneberg et al., 2007). The dependence of shearing on the location and distribution of the three-dimensional (3D) contact area was demonstrated (Gentier et al., 2000) and new constitutive relations were developed based on a general description of roughness (Grasselli and Egger, 2003). Laser scanning and 3D photogrammetry techniques were applied in the field (Fardin et al., 2004) for large-scale surface measurements. Asperity shape and distribution on a discontinuity can now be measured with a great detail and potentially incorporated in any analysis. However with the complexity of the interaction between the two walls, a complete analytical formulation remains a hard task. Since the first idealized "saw-tooth" description proposed by Patton (1966), various constitutive models were developed that accommodate effect of asperities (Barton and Choubey, 1977; Saeb and Amadei, 1992) and their progressive degradation during shearing (Plesha, 1987; Hutson and Dowding, 1990; Lee et al., 2001; Misra, 2002) to name a few. Despite being each time more advanced, these models still rely on empirical relations or simplified descriptions of the surface asperities.

In an attempt to address this problem, many authors used numerical tools to assess the shear strength of discontinuities. Two-dimensional DEM (discrete element method) simulations were first presented as they offer a provision for asperity degradation (Cundall, 2000; Lambert et al., 2004). They have been successfully used to investigate gouge formation and evolution upon shearing (Zhao et al., 2012; Zhao, 2013). However these simulations were at this stage limited to qualitative observations. Hybrid FEM/DEM (Karami and Stead, 2008) and FEM (Giacomini et al., 2008) methods proved their ability to reproduce typical behavior of rock joints including dilation and asperity degradation. Using 3D DEM, Kulatilake et al. (2001) showed that realistic macroscopic friction (i.e. at the joint level) could be obtained combining very small particles at the joint interface and extremely low contact friction. However this approach appears to be not very practical for engineering purposes. No formulation is available to calibrate the micro-properties of the joint model material against a given macroscopic behavior and the macroscopic friction targeted was quite high (friction coefficient of 0.7). In the field, discontinuities often exhibit a much lower strength. The particle size required may hence increase the computational cost to unpractical levels. Park and Song (2009) performed numerical shear tests on standard roughness profiles using the DEM code, PFC3D. This work once again highlighted the current limitations of particulate description as the discrete nature of the medium can introduce an artificial roughness to the discontinuity. The apparent roughness of the numerical specimen is higher than the introduced roughness (i.e. the initial roughness of the introduced surface or profile). The consequence is a slight overestimation of the strength and most importantly unrealistic predictions of dilation. The later point can be of major importance as joint aperture controls fluid flow in the discontinuities (Hans and Boulon, 2003; Buzzi et al., 2008). The recent development of a new contact model named "smooth-joint model" (SJM) (Pierce et al., 2007) in PFC3D where particles are allowed to slide past one another without over-riding one another was a major breakthrough to represent discontinuities as planar surfaces associated to a realistic behavior for structural defects. In this study, we propose to develop in PFC3D a synthetic rock joint where a digital representation of a surface is introduced and described as a series of SJMs. The mechanical behavior of the synthetic rock joint is then analyzed performing numerical direct shear tests.

Table 1
Target (laboratory) and calibrated (calculation) bulk properties of the granite.

Method	Uniaxial compressive strength (MPa)	Young's modulus (GPa)
Laboratory	142.5	48.4
Calculation	143.8	48.6

2. DEM simulations of constant normal stress shear tests

2.1. The discrete element method

The commercially available PFC3D (Itasca, 2008) software package was used for the 3D DEM simulations presented here. Unlike continuum codes, materials are described in PFC3D as a discontinuous medium as a collection of spherical rigid particles. The particles displace independently of one another following Newton's second law and interact with each other through contact forces that are generated at each contact point. Rock and more generally cohesive materials are represented as a bonded particle assembly, adding parallel bonds to create a synthetic material. A parallel bond acts like a conceptual cementitious material between particles. It has a finite dimension defined as a fraction of the particle diameter, a tensile and shear strength and a normal and tangential stiffness. When the contact force exceeds either tensile or shear strength, the parallel bond breaks and a micro-crack forms between the particles. Micro-cracks can eventually coalesce as external loading is applied and form fractures that can split the material into clusters. The location and the failure mode of the cracks are recorded. A detailed description of contact and bond models is provided in the user manual (Itasca, 2008).

The mechanical response of such assemblies, observed at a macroscopic level, is an emergent property of the complex interactions between the particles. Input parameters of the bonded particle model are micro-properties, contact properties and bond strength, and are not measurable with conventional laboratory apparatus. They are calibrated through an iterative process. Once a particle size distribution has been selected, cylindrical particle assemblies are generated and unconfined compression tests are simulated varying micro-properties until the mechanical response of the synthetic material conforms to the mechanical properties (i.e. uniaxial compressive strength, UCS; Young's modulus; Poisson's ratio) of the physical material (measured in the lab). A detailed description of the calibration procedure can be found in Potyondy and Cundall (2004). Once properly calibrated, such bonded assemblies proved their ability to reproduce typical behavior of rock-like materials (Kulatilake et al., 2001; Potyondy and Cundall, 2004).

Properties of the granite considered for the scope of this study are given in Table 1. The micro-properties were calibrated accordingly. Normal and shear stiffnesses for contact and parallel bonds have impact on elastic properties of the particle assembly whereas bond shear and normal strengths mainly control UCS values. Various studies by Cundall (2000), Kulatilake et al. (2001) and Park and Song (2009) illustrated the necessity to introduce low particle friction to reproduce the shearing behavior of fracture planes in cohesive materials. In this study, bond strengths were calibrated considering zero friction between particles ($\phi_p = 0^\circ$).

Besides Potyondy and Cundall (2004) showed that particle friction impacts mainly on the post peak behavior of bulk material with little effect on peak strength. The influence of ϕ_p will be discussed with more detail in Section 3.3. The result of the calibration is given in Table 2 and the emergent bulk properties of the synthetic material are listed in Table 1.