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Research Paper

Improvements for the smooth joint contact model of the particle flow code and its applications

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ABSTRACT

This paper deals with two shortcomings of the smooth-joint contact model (SJCM) used in the particle flow code (PFC). The first shortcoming is the increase of the shear strength of the joint when the shear displacement of the joint exceeds a specific value that is related to the particle size. This problem is named as the interlocking problem, which is caused by the interlocking particles. It occurs due to a shortcoming of the updating procedure in the PFC software related to the contact conditions of the particles that lie around the intended joint plane during high shear displacements. This problem also increases the dilation angle and creates unwanted fractures around the intended joint plane. To solve this problem two new approaches are proposed in this paper: (1) joint plane checking (JPC) approach and (2) joint sides checking (JSC) approach. These approaches and the regular approach are used to model: (a) the direct shear test using the PFC^{2D} and PFC^{3D}, (b) the biaxial test on a sample having a persistent joint with a dip angle varying from 0° to 90° at an interval of 15° using the PFC^{2D} and (c) the polyaxial test on two samples, one of them having a joint with a dip direction of 0° and the dip angle varying from 0° to 90° at an interval of 15°, and the other sample having a joint with a dip angle of 60° and the dip direction varying from 0° to 90° at an interval of 15° using the PFC^{3D}. All numerical results show that the JPC and JSC approaches can solve the interlocking problem. Also, they proved to be more consistent with the theory compared to the regular approach. However, the JPC approach leads to a slightly softer joint. Therefore, the JSC approach is suggested for jointed rock modeling using the PFC. The other shortcoming of the SJCM dealt within this paper is its inability to capture the non-linear behavior of the joint closure varying with the joint normal stress. This problem is solved in this paper by proposing a new modified smooth-joint contact model (MSJCM). MSJCM uses a linear relation between the joint normal stiffness and the normal contact stress to model the non-linear relation between the joint normal deformation and the joint normal stress observed in the compression joint normal stiffness test. A good agreement obtained between the results from the experimental test and the numerical modeling of the compression joint normal test shows the accuracy of this new model.

1. Introduction

Understanding the mechanical behavior of rock masses is crucial to design safe and economical structures in or on jointed rock masses. Jointed rock masses are known as the combination of intact rock blocks separated by the discontinuities. Therefore, the mechanical behavior of a rock mass is affected by the mechanical behavior of intact rocks and discontinuities as well as the geometry of discontinuities. Finding the mechanical behavior of an intact rock is relatively less complicated compared to that of a rock mass. Estimation of the mechanical behavior of discontinuous rock masses is difficult and challenging, due to the presence of complicated discontinuity geometry patterns, the inherent statistical nature of discontinuity geometrical parameters, and the variabilities and uncertainties involved in the estimation of discontinuity mechanical and geometrical properties [1,2]. The reader is referred to [3] for a state-of-the-art on application of analytical, empirical, and numerical approaches to model mechanical behavior of rock masses.

Nowadays through accessibility to extremely fast computers, the Distinct Element Method (DEM) can be used as an approach to incorporate the mechanical behavior of the intact rocks and rock joints to find the mechanical behavior of rock masses [2,4–6]. The DEM is a discontinuum mechanics based method that defines material by rigid or deformable blocks/particles, and by

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discontinuities between blocks/particles that are modeled by Newton's second law of motion [7]. In the DEM, blocks or particles leading to different approaches resulting from different discretization methods can discretize the domain of interest. UDEC and 3DEC, as the most widely used DEM codes in geomechanics for two and three-dimensional models, respectively use the block discretization approach [8,9]. On the other hand, the Particle Flow Code (PFC) uses rigid discs or spherical elements to represent particles in 2D or 3D respectively [10,11]. The rigid particle assumption reduces the computational time by decreasing the number of degrees of freedom [12–14]. The PFC can conveniently model the fracture initiation and propagation between the particles, as well as the rupture, using the Bonded-Particle Models (BPMs) that adhere particles together in representing the intact rock [12,15].

Moreover, in the PFC software to model the mechanical behavior of jointed rock masses the intact rock is modeled by BPMs, and the discontinuities are modeled by the Smooth-Joint Contact Model (SJCM) [16]. Therefore, the block breakage as well as joint sliding can be accommodated [17].

Compared to other numerical methods, in PFC, macro parameters are not directly used in the model, and micro parameter values applicable between the particles should be calibrated using the macro properties, and then these micro parameter values are used in PFC modeling. Therefore, the calibration is one of the most critical and challenging parts in modeling with the PFC. Several researches [12,18–21] have dealt with this calibration seriously and have indicated their findings between the micro and macro parameters. In addition, several others have used PFC in modeling intact rock or jointed rock masses [22–28]. However, limited efforts [29] have been made on the calibration and modeling of the SJCM. This paper addresses and solves some of the shortcomings of the SJCM to improve its use in modeling jointed rock masses.

2. Bonded particle models

In the PFC the intact rock is represented by the BPMs as an assembly of rigid discs (2D) or spheres (3D) while adjacent discs or spheres are bonded together at their contacts. Since particles are rigid, displacement occurs through the penetration, sliding and rotation of particles around each other, and the separation of particles. In the PFC, contacts are created between each pair of adjacent particles whenever the distance of two adjacent particles (or the contact gap, g_c,) is lower than the user specified value which is known as the reference gap (g_r). In the PFC, the result of the subtraction of the reference gap from the contact gap is known as the surface gap ($g_s = g_c - g_r$) [12,13].

In BPMs each contact has two modes: (1) the bonded mode, and (2) the unbonded mode [12,13]. The contact is in the bonded mode when the two particles are bonded to each other at the time of assembly. Then if the bonded contact fails due to the applied stress and its strength limit, the contact mode changes to the unbonded mode. The Linear Contact Model (LCM) is the common unbonded contact model of BPMs [12,13]. It should be mentioned that it is possible that in the particle assembly mode, due to the positive surface gap between the two particles, a bonded contact to be non-existent between them. However, during the execution of the model, their surface gap can become zero (or negative), and a new contact can emerge between them. This new contact is also a LCM.

The LCM provides the linear elastic behavior in the normal and shear directions by having the constant normal stiffness, k_n, and the constant shear stiffness, k_s, at the contact point. However, in the shear direction, the maximum shear force is limited by imposing the Coulomb criterion with the friction coefficient of μ. Moreover, the LCM cannot bear a tensile force. This means that when the surface gap becomes positive the contact is deactivated. It should also be mentioned that since the LCM considers a contact as an infinitesimal interface, it could not resist relative rotation.

The first BPM is the Linear Contact Bond Model (LCBM) [12,13]. In the LCBM, the linear elastic behavior is the same as the LCM. However, the LCBM can bear a tensile force, T_F, and a shear force, S_F. When the bond breaks in the LCBM due to either the shear force or the normal force exceeding the corresponding resistive capacity, the contact changes from the bonded mode to the unbonded mode. It should be mentioned that if the bonded contact breaks due to the tensile failure, the contact deactivates because the broken contact moves to a LCM, and the surface gap becomes positive.

The LCBM like the LCM, cannot resist relative rotation. In order to solve this problem, the Linear Parallel Bond Model (LPBM) was introduced [12,13]. This model assumes the two particles are cemented to each other with a notional rectangular (2D) or cylindrical (3D) shape of contact with the dimension equal to the average diameter of the two particles ($2\bar{R}$). Therefore, this model can represent the intact rock behavior better. The LPBM in the bonded mode has two interfaces. The first interface is exactly the same as the LCM, and the second interface is called the parallel bond. The parallel bond can carry the moment as well as the force. It also has the linear elastic behavior with the tensile strength cap ($\bar{\sigma}_c$), and the shear strength cap ($\bar{\tau}_c$). In the first proposed LCBM, the shear strength had a constant value while currently this value can vary by changing the normal stress according to the Mohr-Coulomb failure criterion. In the Mohr-Coulomb failure criterion, the cohesion, $\bar{C}$, and the friction angle, $\bar{\varphi}$, should be specified for the contact bond. When the parallel bond breaks due to either the tensile stress or the shear stress exceeding the corresponding strength value, the parallel bond interface is removed, and the LCM interface is activated.

3. Smooth-joint contact model

Before the SJCM was introduced to the PFC, joints were modeled by removing the bonds of the contacts around the intended joint plane or degrading their strength. This process also included reducing the shear stiffness, the normal stiffness, and the friction coefficient. First, the bond removing or degrading was applied on any contact in which the centers of the two particles lied on the opposite sides of the intended joint plane. Later, by defining a region with a thickness for the intended joint, bond removing or degrading was applied on any contact in which the particle centers were located inside this region, or on any contact in which the center of one of the two particles was located inside this region and the center of the other particle was located outside this region (Fig. 1). This method was first used on the bonded particle assembly with LCBM by Cundall [30] in 2D, and Kulatilake et al. [18] in 3D. Later other researchers [23,31] used this method on the bonded particle assembly with LPBM to study on the shear behavior of rock joints. As shown in Fig. 2a, in this method the particles on the opposite sides of the intended joint should slide on their perimeters. Therefore, the imposed joint plane of the LCM of the PFC code is not the intended joint plane. The imposed joint plane is a tangent line to the contact point of the two particles and it results in an inherent roughness on the joint [18]. This roughness leads to unrealistic behaviors such as a preliminary dilation and a higher friction angle. In order to solve this problem Cundall and his colleagues [32] proposed the SJCM.

In the SJCM, a hypothetical joint plane is created at the contact between each pair of particles parallel to the intended joint plane if the two particle centers lie on the opposite sides of the intended joint plane (Fig. 2b). On this hypothetical joint plane,