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Numerical simulation of a direct shear test on a rock joint using a bonded-particle model

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ABSTRACT

Rock joints were numerically simulated, and an extensive series of direct shear tests were carried out using the code PFC3D. The feasibility of reproducing a rock joint using the contact bond model was demonstrated, and the effects of the geometrical features and the micro-properties of a joint on its shear behavior were examined. Asperity failure was observed from the micro-cracks and contact force distribution, as well as the stresses and displacements in shear and normal directions. A rough joint with a joint roughness coefficient (JRC) value ranging from 10 to 20 was produced in an intact sample by defining the joint-contacts along a predefined joint surface. To simulate a decrease in joint wall strength (JCS) caused by weathering and alterations, the bond strength between particles involved in the joint-contacts was reduced by up to 70%. The shear behavior and failure progress at a given stress corresponded well to those observed in laboratory tests. The friction coefficient was the most important factor governing the shear strength and dilation angle. The variation in joint roughness and contact bond strength had a larger effect on the cohesion than peak friction angle. In addition, a new approach to represent JRC and JCS values of a joint was proposed for practical use. A numerical 3D-profile scanning technique was developed to evaluate the actual JRC of the simulated joint, and the relationship between the JCS and the contact bond strength was investigated.

1. Introduction

Joints are among the most important factors in understanding and estimating the mechanical behavior of a rock mass. The shear behavior of a joint is combination of complicated phenomena, such as normal dilation, asperity failure and contact area due to undulating surface. This means that the constitutive models for joint behavior need to consider a large number of assumptions and uncertainties. Considerable efforts have been devoted to explaining the shear strength and behavior of joint over the last four decades. Since Patten's bilinear model of saw-tooth joints [1], peak shear strength criteria have been developed by Ladany and Archambault [2], Barton and Choubey [3] and Amadei and Saeb [4], and the post-peak response and asperity degradation have been explained using several empirical and theoretical models [5–8]. With the rapid progress of computer technology, many attempts have been made to demonstrate the joint behavior using numerical methods, such as the finite element method (FEM), boundary element method (BEM) and discrete element method (DEM) [9–11].

In terms of the explicit representation of a joint, the particle flow code PFC is a widely used simulation tool. PFC is a commercial code that was developed by the ITASCA Consulting Group based on DEM theory. It represents a material as an assembly of rigid spherical particles that move independently of one another and interact only at the contact points. The calculation scheme used in PFC requires only simple laws and a few parameters to govern the interactions at the particle and contact level to represent the behavior of a material including a joint. On the other hand, other available tools use some constitutive (stress–strain) relations, which involve many parameters and assumptions. Therefore, the PFC can simulate the effect of the joint roughness and the asperity failure in a direct and realistic manner. Moreover, an explicit finite difference scheme allows observations of the transmission of forces exerted at the contacts, and has the ability to track the propagation of bond breakage events at each stage. However, the total number of particles required to represent an actual situation is limited because of the finite computing capacity, and the properties of the microscopic constituents are usually not known. These unknown properties require tedious calibration process of micro-parameters until the macro-scale response of a model agrees with the results of laboratory tests.

Many studies have examined the effect of micro-parameters on the macro-response for an intact rock and suggested a variety of

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techniques for reproducing the brittle behaviors by performing uniaxial, triaxial and Brazilian tests [12–14]. On the other hand, little attention has been paid to the micro-parameters of joints. Although the micro-properties of joints have a significant effect on their shear behavior, they have been generally assumed to be small values without any calibration using direct shear tests. A direct shear test using PFC have mainly been carried out on granular materials such as soil [15–17], and a few simulations have been reported for the rock joints. Cundall [18] reported the applicability of PFC2D to a direct shear test on a virtual rough joint. In his study, Cundall examined the shear behavior of the joint by measuring its shear strength, dilation angle and micro-cracks. However, all quantities used in the simulation were without any physical units and the joint was assumed to be very rough. Kulatilake et al. [19] determined the micro-parameters of a joint model by performing a series of direct shear tests in modeling the behavior of jointed rock blocks under uniaxial loading with PFC3D. Wang et al. [20] carried out a direct shear test on a joint in an attempt to simulate the behavior of the heavily jointed rock slope using PFC2D. However, the relationship between the micro-parameters and macro-response of a rock joint has not been adequately studied in the literature.

The main aim of this study is to demonstrate the feasibility of PFC3D to reproduce a rock joint and examine the effects of the micro-properties on its shear behavior by simulating the direct shear tests at different normal stresses. A total of 25 simulation cases were established according to the particle size, roughness, friction coefficient and bond strength, and a parametric study on peak shear strength and dilation angle was carried out. The failure mechanism was observed from the micro-cracks and contact force distribution, as well as the stresses and displacements in shear and normal directions, by taking advantage of PFC calculation schemes. In addition, a new approach to represent JRC and JCS values of a joint was proposed. A numerical technique to scan the 3D-profile of a simulated joint surface was developed in order to evaluate the actual JRC. The test results were compared with the estimations from Barton's empirical model and the relationship between the contact bond strength of particles along a joint and the JCS was investigated.

2. Particle model of a rock joint

2.1. Discrete element method-PFC3D

PFC3D is a three dimensional discontinuum program to describe the mechanical behavior of collection of spherical particles based on the DEM theory introduced by Cundall and Strack [21]. The rigid particles within an assembly displace independently of one another and interact only at each contact points. The calculation cycle in PFC3D is a time-stepping algorithm, in which the motion of each particle is determined by Newton's second law, while the contact force at each contact is updated by force–displacement law. When particles come into contact, the contact force is calculated as a function of a relative displacements and specified stiffness. The normal stiffness (K_n) is a secant stiffness because it relates the total normal force (F_i^n) to the total normal displacement (U_n), Eq. (1), while the shear stiffness (k^s) is a tangent stiffness because it relates the increment of shear force (ΔF_i^s) to the increment of shear displacement (ΔU_i^s), Eq. (2). The linear relationships can be expressed as follows [22]:

$$F_i^n = K^n U^n n_i \tag{1}$$

$$\Delta F_i^s = k^s \Delta U_i^s \tag{2}$$

where n_i is the unit normal vector to the contact plane. PFC3D provides two contact-stiffness models: a linear model and a simplified Hertz–Mindlin model.

The slip condition at contact with no normal strength is checked by calculating the maximum allowable shear contact force:

$$F^s_{\max} = \mu |F_i^n| \tag{3}$$

where μ is the friction coefficient at the contact. If the shear force (F_i^s) reaches the maximum allowable shear contact force, slip is allowed to occur by setting the magnitude of F_i^s equal to $F^s_{\max}$ using the following equations:

$$F_i^s \leftarrow F_i^s (F^s_{\max}/|F_i^s|) \tag{4}$$

Blocky shapes, such as rock material, are represented by bonding spherical particles together at contact. There are two bonding models supported in PFC3D: a contact-bonded model and a parallel-bonded model. Both bonds approximate the physical behavior of a cement-like substance lying between and joining the two bonded particles. The contact-bond glue is of a vanishingly small size that acts only at the contact point, while the parallel-bond glue is of a finite size that acts over a circular cross-section. Therefore, the contact bond can only transmit a force while the parallel bond can transmit both a force and a moment. Both bonding models can be active at the same time but the existence of a contact bond precludes the slip model, since these last two models describe the constitutive behavior for particle contact occurring at a point. Both types of bond can be broken if their strengths are exceeded. In contact-bonded model, bond breakage may not significantly affect the macro stiffness because contact stiffness is still active even after bond breakage as long as particles are kept in contact. In the parallel-bonded model, however, stiffness is contributed by both contact stiffness and bond stiffness. Thus, bond breakage immediately results in stiffness reduction. In this sense, the parallel-bonded model is known as a more realistic model for rock-like materials where the bonds may break in either tension or shearing with an associated reduction in stiffness [13].

However, the emphasis of our study is on the shear behavior of a joint plane between two opposite blocks along which the particles are at initially unbounded contacts. In view of the fact that the thickness of material controlling the shear strength is as little as a fraction of a millimeter up to a few millimeters [3], the bonding type applied to the interior of the blocks may not significantly affect the shear behavior of the joint. A preliminary study to examine its effect suggested that the respective joints generated in contact and parallel-bonded models showed similar behaviors in the direct shear tests. When the micro-properties of each sample were calibrated to the same compressive strength, there was little difference in the peak shear strength, normal dilation and the shear stiffness even though the parallel-bonded model exhibited more micro-cracks along the joint and reached the residual state faster than did the contact-bonded model. For this reasons, the contact-bonded model which has less micro-parameters was used in our study and applied to all modeling discussed in this paper.

2.2. Shear behavior of a rock joint in PFC3D

The shear behavior of a rock joint is dependent on the effective normal stress acting across the joint. At a low level of normal stress, the joint slides along the inclined surface with little damage in asperity and shows relatively high values of dilation and friction (peak τ/σ_n). At high normal stress, the constraint of normal displacement leads to large asperity failure resulting in the observation of low friction [23]. Thus, it is important to