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Numerical modeling of rock mechanical behavior and fracture propagation by a new bond contact model

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ABSTRACT

This paper presents a numerical investigation into mechanical behavior and rock fracture using the distinct element method (DEM). Based on a series of laboratory tests on the bonded granules idealized by two glued aluminum rods, a normal force dependent bond contact model was proposed and implemented into a two-dimensional (2D) DEM code. This 2D DEM code was used to carry out a series of numerical simulations, including uniaxial and biaxial compression tests, direct tension and Brazilian tension tests, whose results were compared with experimental data to calibrate the proposed model and identify the microscopic deformability and strength parameters. In addition, the validated model was then used to simulate crack propagation and rock fracture in single-flawed and double-flawed samples with different flaw inclinations, and the simulations were then compared with experimental observations. The numerical results demonstrate that the proposed bond model incorporated into the distinct element method is able to capture the main mechanical behaviors of crystalline rocks (Lac du Bonnet granite and Hwangdeung granite). The limitations associated to a low strength envelope angle and high ratio between tensile strength and compressive strength frequently formed in DEM simulations of rock behaviors are solved. In addition, five distinct stages of the stress–strain curve and the marked stresses can be clearly identified by lateral strain, volumetric response and the cumulative number of bond failures. The mechanical behavior and rock fracture patterns obtained from DEM simulations are in good agreement with experimental observations and the model captures both the geometrical control and the general strength value for crystalline rocks.

1. Introduction

Rock is one of most important and complex materials in geotechnical engineering. A correct design of rock slopes, mines and nuclear waste repositories requires a series of laboratory tests and numerical models of rock behavior under complex loading conditions [1,2]. Numerical analysis methods are useful tools that can support the design and implementation of geomechanical engineering. However, as a result of a variety of geological processes, rock contains a large number of joints, fissures, weak surfaces and faults. These pre-existing discontinuities or cracks make of the rock a discontinuous, inhomogeneous, anisotropic and non-elastic compound structure [3] bringing some major difficulties in numerical study. Hence, a comprehensive study of numerical simulation on rock mechanical behavior is essential due to the complexity of related problems.

Some fundamental researches have been carried out on the numerical simulation of rocks in order to investigate crack propagation and rock fracture. Reyes and Einstein [4] developed an analytical model for simulating secondary crack coalescence formulated by combining a smeared crack/damage mechanics approach with a strain based failure criterion. Bobet and Einstein [5] studied crack propagation and coalescence in rock specimens containing two inclined flaws that were either open or closed by employing a new stress-based crack initiation criterion. Scavia [6] and Vasarhelyi and Bobet [7] studied the mechanical behavior of rocks and the crack growth between two bridged flaws by the displacement discontinuity method (DDM). Tang et al. [8,9] and Wong et al. [10] carried out a series of numerical simulations on models containing pre-existing flaws under uniaxial compressive loading in order to investigate the failure mechanism and fracture mode using a rock failure process analysis code (RFPA^{2D}). In addition, the maximum tangential stress theory [11], the maximum energy release rate theory [12], the maximum energy

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density theory [13] and G-criterion [14] were also proposed for studying crack propagation and rock fracture mode. Distinct element method (DEM) is another suitable method for studying the failure behavior of rocks being able to describe the crack propagation and rock fracture both from the macroscopic and microscopic point of views. In general, any model intending to reproduce the failure process of rocks should allow for the development of a continuous sliding surface [15]. In fact, DEM is able to deal with material failure from micro crack to macro failure [16] and does not require the formulation of complex constitutive models [17,18]. This approach has been adopted to analyze penetration mechanism of cone-penetration tests [19], slope instability problems [20–26], constitutive models for granular material [27,28], the effective stress and shear strength functions of unsaturated granulates [29], strain localization [30,31]. This method has also been applied to model the mechanical behavior of rock considered as a cemented granular material [32,33]. The bonded particle model (BPM) proposed by Potyondy and Cundall [33] has drawn attention for its ability to reproduce the main mechanical behavior of Lac du Bonnet granite using DEM uniaxial and triaxial compression tests. The approach and benefits of BPM are compelling, but the calibration of microscopic parameters to match macroscopic response is inadequate [34]. In order to apply DEM to simulate rock behavior successfully, Wang and Tonon [35,36] developed a distinct element code and applied it to model the mechanical behavior of a crystalline rock such as Lac du Bonnet granite. Their simulations reveal that three stages of stress–strain curve can be well identified and tensile failure appears first, followed by mobilization of residual friction. Christian et al. [37] proposed a progressive failure model and reproduced many features observed during rock failure experiment. However, the bond contact models used by most researchers in their DEM simulations are necessarily hypothesized without any direct experimental verification.

Brittle rock can be represented as an assembly of cemented mineral grains that can be described by its internal microstructures. The intact crystalline rock consists of a variety of mineral grains of different sizes, and of close contacts between mineral grains and microscopic defects in the form of cracks and holes [38]. The mechanical behavior of such geo-material is controlled by irregular pre-existing defects, as well by mineral grains and associated contacts. In order to establish an effective bond contact model for these cemented granules in DEM simulation, Delenne et al. [39] first presented an experimental investigation on the mechanical behavior of cemented granules by performing simple tests on a pair of aluminum rods glued together by epoxy resin. This study is attractive and impressive but the effect of normal force on the mechanical behavior of cemented aluminum rods is neglected probably due to technical difficulties. Moreover, the bond material adopted in the experiment is an epoxy resin whose mechanical properties are quite different from a real rock material. Hence, taking these two unsatisfactory aspects into account, Jiang et al. [40,41] conducted a series of experimental tests on a pair of aluminum rods glued together by cement. The cemented rods were prepared by means of a specially designed sample preparation device. Then, the mechanical behavior of the analogous cementation samples was examined in both simple loading and complex loading tests using the newly developed auxiliary loading devices in order to propose a bond contact model for rocks.

The main objective of this paper is to perform a distinct element modeling of rock mechanical behavior and fracture propagation. For this purpose, based on the laboratory tests on the analogous cementation sample, a normal force dependent bond contact model was proposed and implemented into a two-dimensional DEM code. A series of laboratory tests on rock, including uniaxial compression, biaxial compression, direct tension as well as Brazilian tension tests were simulated. DEM macroscopic responses were calibrated by the published experimental data [42,43] in order to identify a set of microscopic material parameters. By means of calibrated parameters, crack propagation and rock fracture in single-flawed and double-flawed DEM samples under uniaxial compressive loading were modeled and compared against experimental observations [44].

2. A bond contact model for rock

2.1. Experimental set-up

Fig. 1 presents the analogous cementation sample used in the laboratory tests consisting of a pair of aluminum rods glued together by the rock-like material in the inter-particle voids, i.e. cement, with a bond thickness of 0.6 mm and a width of 3 mm. The aluminum rods have a 12 mm diameter and are 50 mm long. This assembled sample was used to carry out a series of tests under various loading conditions, as illustrated in Fig. 2. Five different types of test were designed to characterize the mechanical behavior of the cemented samples. The following loading paths are referred to as tension, compression, shear under different normal forces, rolling under different forces and shear-rolling tests under different normal forces.

2.2. Mechanical response

The mechanical response of the bond contact model was established firstly through reasonable theoretical derivation [45–47], and then it was verified by a series of laboratory tests on the cemented samples [40]. The mechanical response is characterized by three stiffness coefficients k_n, k_s, k_m, three bond strength coefficients R_t, R_s, R_r, and the related residual strength R_{sr} for friction and R_{rr} for rolling, as illustrated in Fig. 3.

Fig. 3(a) presents the normal mechanical response which is composed of tension and compression directions. In tension, the normal contact force F_n between two particles is a product of normal stiffness coefficient k_n and tension displacement u_n before its value reaches the normal bond strength R_t. When the force arrives at the normal bond strength R_t, the bond is broken and the normal force abruptly reduces to zero. In compression, the contact force is always a product of k_n and compression displacement, u_n. Fig. 3(b) presents the tangential force-displacement relationship. The shear force increases linearly with the increasing of tangential displacement u_s up to the shear strength, R_s. After the peak value is reached, the bond breaks and tangential force drops to the residual frictional shear strength, R_{sr}. In Fig. 3(c), the mechanical response on rolling contact direction is similar to that on tangential direction, the moment, M, is a product of rolling stiffness, k_m, and relative rolling rotation θ, and then it drops to the residual strength, R_{rr}, that mimics particle shape effect on rolling.

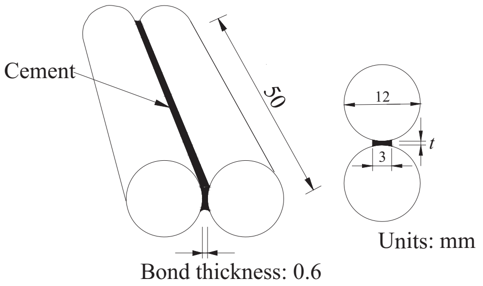

Fig. 1. The analogous cementation sample used in experiments (after Jiang et al. [41]).