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Effects of grain size-to-particle size ratio on micro-cracking behavior using a bonded-particle grain-based model

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1. Introduction

The strength and deformation behavior of rocks is an important topic in rock mechanics. A good understanding of the rock strength and deformation will facilitate cost-effective design and long-term stability maintenance of engineering structures constructed in or on rocks. Numerous laboratory test results have revealed that the deformation (failure) of rocks is mainly controlled by its inherent microstructure and the associated micro-cracking process.[1–8] The microstructures are usually associated with the different mineral aggregations and varying amounts of micro-defects such as micro-cracks, voids and cleavage planes.[9,10] It is, therefore, of vital importance to comprehensively study the influence of inherent microstructures on the failure behavior and the induced micro-cracking process of rocks.

Besides experimental studies, numerical methods are widely used to investigate the failure behavior of rocks. There are generally two types of numerical methods available: continuum and discontinuum methods.[11] In continuum methods, the micro-scale damage is represented by using average measures of material degradation in constitutive relations. The discontinuum-based methods idealize the material directly as an assembly of separate units such as blocks and particles bonded together at their contact points and use the breakage of the bonds to represent internal damage.[12] Because rock is typically a discontinuous and heterogeneous material, discontinuum-based methods have been increasingly used to simulate the mechanical behavior of rocks. One of the widely used discontinuum methods is the discrete element method (DEM) developed by Cundall[13] and it is commonly adopted to simulate the micro-crack initiation, propagation and coalescence associated with the rock failure processes.

An example of DEM approaches is based on the bonded particle model (BPM) which has been implemented in the particle flow code (PFC).[14] In a PFC model, the rock is treated as an assembly of bonded particles which follow the basic law of motion. The model is capable of numerically capturing many aspects of the mechanical behavior and failure processes of brittle rock from the laboratory to rock mass scale.[12] Since then, the PFC has been extensively used to investigate the micro-cracking process and brittle failure of cylindrical or rectangular rock specimens in parallel with the physical experiments.[15–25]

In numerical simulation using PFC, one important aspect is the assignment of particle size of a numerical model. Previous numerical studies have revealed that the particle size has a significant effect on the PFC simulation results.[12,26–30] However, most of the previous studies simply select the particle size based on the computer capacity and efficiency, without much discussion of its effect on the simulation results. As suggested by Ding et al.,[29] a model diameter-to-median particle size ratio of 25 is recommended to ensure that the variation level of mechanical parameters is smaller than 2%. Wong and Zhang[30] reviewed the relationship between particle size and fracture toughness in PFC.

A grain-based modeling (GBM) approach, which was implemented in PFC, was recently proposed by Potyondy.[31] The idea of GBM in PFC is basically similar to the GBM which is implemented in universal distinct element code (UDEC) using a Voronoi tessellation technique.[32] However, one merit of PFC-GBM is that the model can not only simulate the micro-crack initiation and interaction at the grain boundary, but

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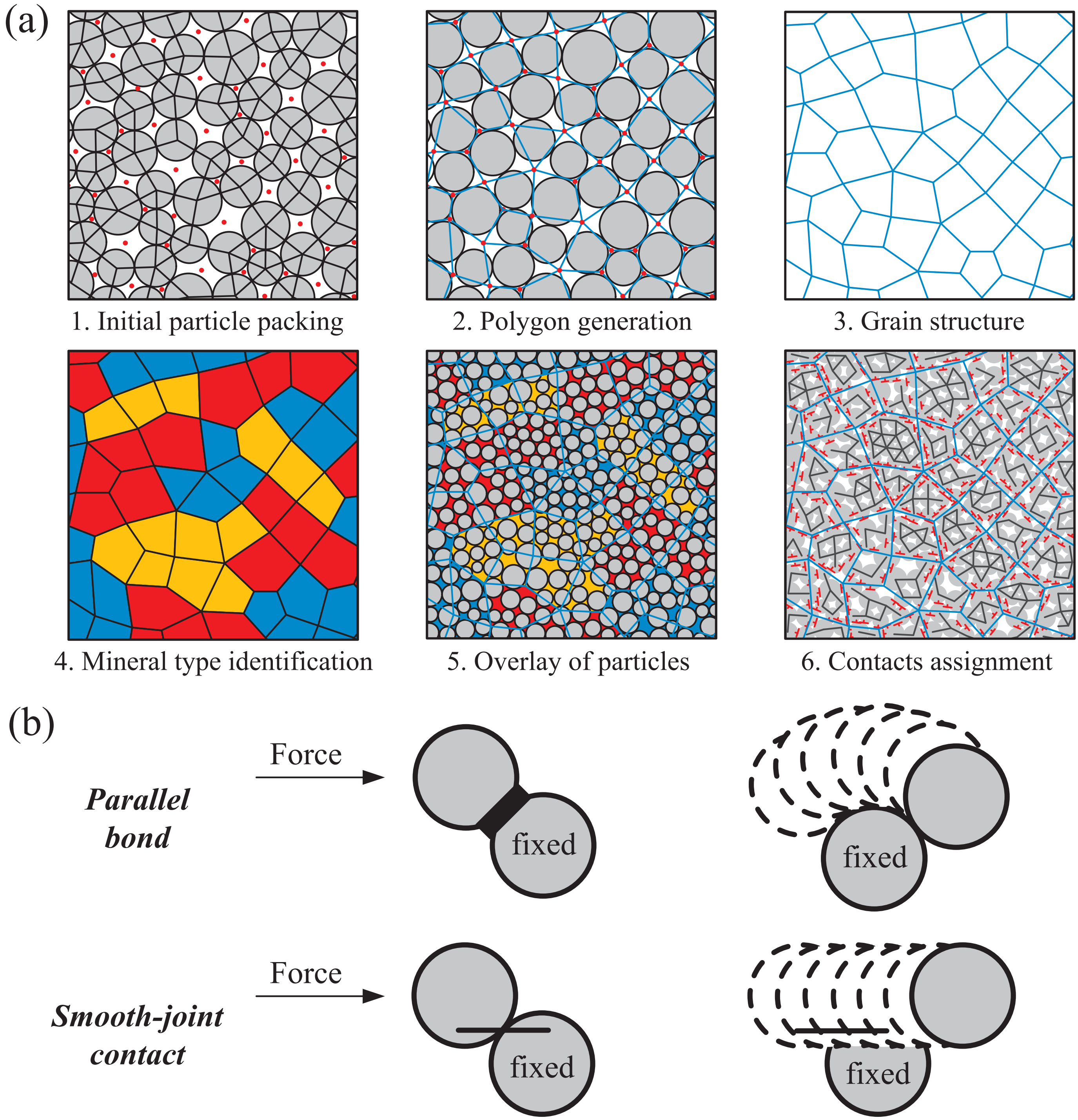

Fig. 1. (a) Procedures for generation of PFC-GBM: 1. Initial particle packing; 2. generation of polygons; 3. polygonal grain structure (the initial particles are deleted); 4. identification of three grain types; 5. bonded particle model overlaid on the grain structure; and 6. GBM consisting of discs bonded together with parallel bonds (grey) inside the grains and smooth-joint contacts (red) along the interfaces between the grains. (b) Illustration of disc movements after breakage of parallel bond and smooth-joint contact (reproduced from[33]). (color figure online).

also capture the micro-cracking behavior inside the grains which is associated with intra-granular micro-cracking. This method has been demonstrated to be capable of simulating the failure behavior and micro-cracking process of crystalline rocks.[33–38] In a PFC-GBM, the mineral composition and the grain size distribution of minerals in a real rock specimen can be reflected. Each grain in the model contains a certain number of particles bonded together by parallel bonds (see details in Section 2). Hence, the selection of a proper grain size-to-particle size ratio is a pertinent issue of modeling the failure behavior and micro-cracking process of rocks using PFC-GBM. Our approach is different from that of Gao et al.[39] who numerically studied the micro-cracking behavior of breakable grains using UDEC-GBM. The UDEC-GBM used by Gao et al.[39] generates breakable grains by creating several contacts from the center of the grain to its apex; however, the PFC-GBM produces deformable grains by assembling several particles inside the grain and assigning parallel bonds between contacts of these particles.

In the present study, we numerically investigate the effects of grain size-to-particle size ratio on the PFC-GBM simulation results. The