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Research Paper

Mechanical properties of brittle rock governed by micro-geometric heterogeneity

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ABSTRACT

This research presents a new heterogeneity index to describe micro-geometric heterogeneity induced by grain size variation in intact rock. Micro-geometric heterogeneity is considered in a grain-based numerical model to study its effect on the mechanical properties of rock. Characteristic stresses of the specimens with different degrees of heterogeneity such as crack initiation stress, crack damage stress, and peak strength are determined numerically. The result shows that the proposed heterogeneity index measures the micro-geometric heterogeneity effectively in a large range of grain size distribution, even if the mean grain sizes of different constituent minerals are the same.

1. Introduction

Rock is a heterogeneous material because of the variability of grain shape, mineral type, and the existence of initial defects. The strengths of intact rock are determined by laboratory tests such as uniaxial compression, triaxial compression, and Brazilian tests. Rock specimens of the same rock type may exhibit different behaviors of crack propagation due to material heterogeneity and hence different strengths [1,2]. Over the past several decades, many studies have been conducted to investigate the effect of material heterogeneity on rock strength and deformation [3–6]. The main influence of material heterogeneity on rock strength is that it causes local stress concentration, which may accelerate rock failure in the loading process [7,8]. The research by Tang et al. [9] suggests that a homogeneous specimen has a higher strength than a heterogeneous one with different grain properties, and it has a more linear deformation behavior prior to peak stress. Their investigation shows that more diffused AE events or microcracks appear in the heterogeneous specimens at an early stage of loading. Nicksiar and Martin [10] found that heterogeneity introduced by grain size variation influences not only the peak strength but also the crack initiation stress of rock.

With the development of micrometer-scale observation technology, digital image processing (DIP) techniques have become a powerful tool for exploring material microstructures and mineral spatial distribution [11,12]. An important aspect of the application of these techniques is incorporating DIP images into mechanical modeling to generate numerical specimens with microstructures extracted from the images of rock slices. Yue et al. [13] presented a 2D DIP-based finite element method (FEM) for geomaterial analysis by taking into account material inhomogeneity and microstructures. Chen et al. [14] exhibited the inhomogeneity of granitic rocks from color images of the cross sections using the DIP-based approach. This provides a simple method to transform the actual image data into vector data for generating FEM meshes. To analyze the 3D heterogeneity of rock, 2D image microstructures are further extrapolated to 3D cuboid microstructures by assuming that the material surface is a representation of the inner material heterogeneity in a small depth [15]. DIP techniques can mimic the actual micro-geometric inhomogeneity and microstructures of rock in numerical modeling; however, these techniques depend on a large amount of representative slice images of rock.

A simple approach for incorporating material heterogeneity into numerical models is achieved by assigning a stochastic distribution of rock properties. In this method, inhomogeneity of rock is introduced by defining element stiffness and strength distributions via a statistical distribution function such as Weibull distribution [16,17]. Lan et al. [18] classified the inhomogeneity induced by different strength of mineral grain as strength heterogeneity. Valley et al. [19] found that the stiffness heterogeneity between mineral grains can generate tensile stresses leading to local tensile failure and a reduction in the compressive strength of intact rock. By incorporating different site-strength distributions in a lattice-based model, Blair and Cook [20] showed that local stress field heterogeneity (due to grain shape and loading) has a

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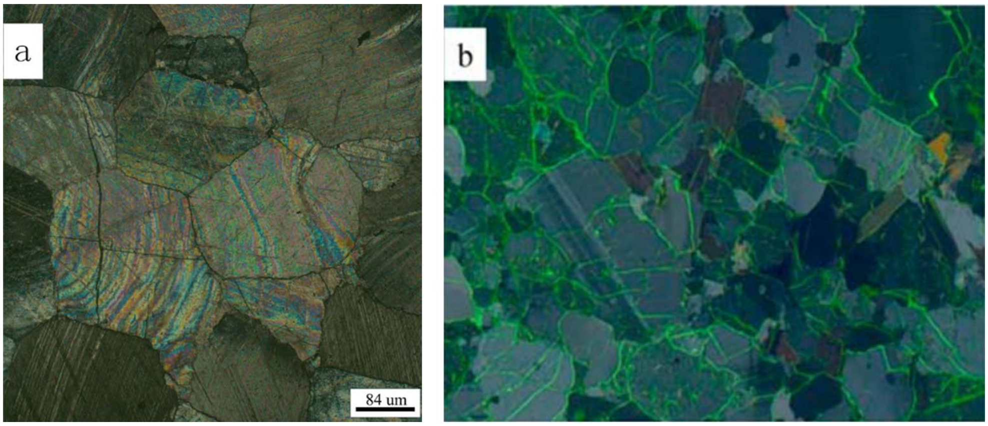

Fig. 1. Microscopic images showing grain structures in rocks. (a) A microscopic scanning image of a thin section of marble from Henan, China [36]. (b) Polarized and fluorescent image of LdB granite from the URL [18,37].

first-order effect on the material's macroscopic properties. This approach can replicate the material heterogeneity; however, a great challenge for it is how to verify the grain strength distribution of rock in actual laboratory test results.

The diversified microstructure of rock is a key factor leading to rock heterogeneity. The research by Diederichs [21] showed that geometric heterogeneity can generate tensile stresses inside a rock specimen under an overall compressive stress field. Thus, microstructures in rock should be introduced into rock property modeling considering material heterogeneity. Potyondy [22] proposed a grain-based distinct element method to generate deformable polygonal grain-like structures to mimic microstructures in rock. Using the grain-based model to replicate the microstructures of rock, Lan et al. [18] found that the compressive strength of a numerical specimen is closely related to the extent of tensile cracking, which in turn is controlled by the ability of the micro-geometric heterogeneity and property heterogeneity of the mineral grains to generate tensile stress. Bewick et al. [23] extended the work by Lan et al. [18] using grain-based models generated by the finite element code Phase2 and the distinct element code PFC2D.

In general, material heterogeneity can be divided into micro-geometric heterogeneity [5,24] and property (strength and stiffness) heterogeneity [25–27] of the mineral grains. The micro-geometric heterogeneity is governed by micro-geometric factors such as grain size, shape, and structure. This heterogeneity can be explicitly described in numerical specimens, and this approach is known as the explicit approach [24,28,29]. The study on micro-geometric heterogeneity considers mainly the effect of heterogeneity on the mechanical response by numerically generating a few specimens with different microstructures.

At the grain level, mineral grains with various sizes and the associated grains boundaries as well as preexisting defects affect crack initiation and propagation. When the exterior load is applied to a granular material, internal forces of granular are transmitted by the grain skeleton. Grain boundaries tend to move or slip to reduce the total interfacial energy under loading [30]. The collapsing strength for granular interior is higher than the intergranular strength. Because grain boundaries serve as initial stress concentrators during the failure process of rock, crack initiation stress is inversely proportional to the mean grain size [31]. Although several investigations on microscopic heterogeneities have been carried out to establish a connection between microstructure and macroscopic response of granular materials [32,33], the influence of microscopic heterogeneity on the macroscopic mechanical behavior of brittle rock remains one of the most challenging research topics.

The primary objective of the present study is to investigate the influence of micro-geometry-induced heterogeneity on the macro-mechanical properties of rock. The grain-based numerical modeling approach is used to capture the ratio of tensile to compressive strengths. A simplified formula is derived to estimate the mean grain size of real rock according to the mean grain size of component minerals. A heterogeneity index is introduced to quantify the micro-geometric heterogeneity. By performing numerical tests on specimens with different heterogeneities, microcrack initiation and propagation as well as strength of the specimens are studied. The relations between the heterogeneity index and the characteristic stress thresholds (i.e., crack initiation and rock damage stresses) are investigated.

2. Numerical model setup

In this section, we discuss the process of setting up grain-based numerical models. A brief review of the theory of grain-based model is provided first, followed by model parameter calibration of synthetic rock samples using the experimental data of Lac du Bonnet (LdB) granite from the Underground Research Laboratory (URL) in Canada [1].

2.1. Grain-based model in PFC

Rock is a granular material with strong cementation. Fig. 1 presents the mineral grain structures of Henan marble from China and LdB granite from the URL. The two dimensional grain structures have the shape of polygon. From the point of view of grain structure, a synthetic rock sample should replicate the microstructure of rock grains, because the grains influence the macroscopic mechanical behavior of rock [28,34]. The bonded-particle model (BPM) in the particle flow code (PFC) is widely used to model cemented materials. Due to the assumption of unbreakable grains and an idealization of circular (2D) and spherical (3D) particles, it is difficult to capture the ratio of tensile to compressive strengths of rock using the BPM [22,35].

A grain-based model (GBM) in PFC was proposed by Potyondy [22] to study the failure process of Äspö diorite. This method mimics a synthetic material which consists of a large number of deformable and breakable polygonal grains cemented along their adjoining sides. In a grain-based model, each grain includes several bonded particles and the contacts of interface grains are depicted by smooth-joint contacts.

Fig. 2 illustrates the procedure to create a polygonal grain structure. A polygonal grain structure is extracted by linking the internal-void centroids of the contact network from the initial disc packing [22,38]. The initial discs are generated according to the grain sizes and the contents of each mineral in crystalline rocks. Afterwards, an assembly of discs, which represents a rock specimen, is overlaid by the generated polygonal grain structure. In the grain structure network, the contact of two discs along every edge will be set to the smooth-joint contact, which models a microscopic grain boundary that traverses two discs. The discs located in each polygonal mesh are bonded by parallel bond (a type of BPM) to form a mineral grain of crystalline rock. In our research, the parallel bond parameters within a grain vary with the type of minerals, but the parameters for the smooth-joint contact remain the same regardless of the type of grain boundary.