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Research Paper

Numerical investigation of the influence of specimen size on the unconfined strength of defected rocks

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ABSTRACT

A grain-based distinct element model (GBM) is used to investigate the influence of specimen size on the strength of intact (not defected) and defected rocks. The defected specimens are simulated by integrating a previously calibrated GBM with Discrete Fracture Network models representing defect geometries. The results of scale effect analysis conducted on synthetic specimens show that the strength of intact specimens is independent of specimen size. However, depending on the orientation of defects relative to the loading direction, the strength of defected specimens may decrease, increase or fluctuate with increasing specimen size.

1. Introduction

A jointed rock mass is made up of rock blocks bounded by joints and thus its strength depends on the strength of the joints and the strength of the rock block. The rock block strength is therefore an important parameter during the course of rock mass characterization, particularly for the determination of the rock mass strength. A rock block is the solid part of the rock mass that is bounded by open joints, but may contain defects in the form of structural features at different scales such as micro-cracks, fissures, veins and cemented joints, all of which may influence its strength and failure mode under different loading conditions (Fig. 1a).

In this article, the term 'defect' refers to cohesive structures at the laboratory specimen and rock block scales such as veins and cemented joints that may influence the strength and/or failure mode of rocks under different stress conditions. Intact rock is used to describe the non-defected portion of a rock; the material between discontinuities or defects, which might be represented by a hand specimen or piece of drill core examined in the laboratory [4]. In this article, non-defected or intact rock refers specifically to a laboratory specimen that does not contain any strength dominating defects.

When sampling a block of rock, depending on the sampling location, rock cores can be homogenous or heterogeneous. Homogenous cores represent the strongest part of the rock block, whereas heterogeneous cores, those that contain weak defects, are weaker. Fig. 1b shows that the weakest cores taken from a rock block are those that contain defects that are continuous and critically oriented (i.e., oriented parallel to the critical shear stress on defects).

Laubscher [22] and Laubscher and Jakubec [21] developed an empirical approach to determine the rock block strength from the Unconfined Compressive Strength (*UCS*) of weak (heterogeneous) and strong (homogenous) specimens taken from blocks in a jointed rock mass. They discuss that the cores selected for strength testing are usually the strongest pieces of the rock block and do not necessarily reflect the average strength value of both homogenous and heterogeneous cores. Laubscher and Jakubec [21] suggest that the long-term strength of a homogenous rock block that does not contain veins or fractures is 80% of the intact rock strength. In their approach, the values of weak and strong rock *UCS* as well as the percentage of weak rocks present are used with the aid of an empirical chart to obtain the "corrected" value for the average rock strength. This corrected strength is then used to determine the rock block strength by considering adjustment factors to account for the influence of defects (i.e., hardness and frequencies) on rock block strength.

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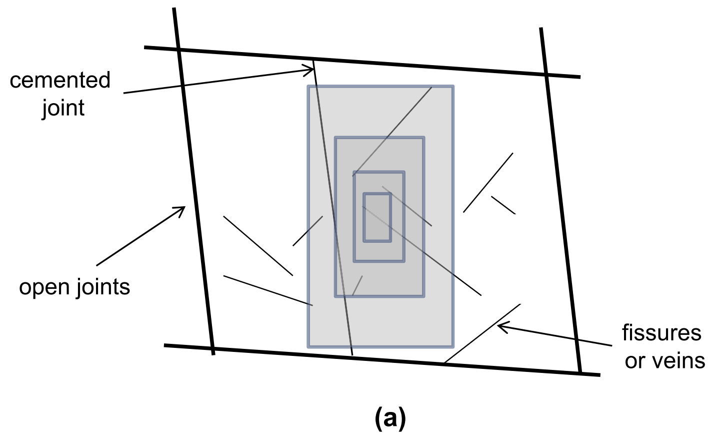

Fig. 1. (a) A defected rock block bounded by open joints (redrawn from [21]), and the increase in the size of sample taken to define rock block strength; (b) demonstration of the *UCS* variability of rock samples taken from the rock block due to the density and orientation of defects. UCS_i: intact rock *UCS*; UCS_d: defected rock *UCS*; UCS_{rb}: rock block *UCS*.

A direct and more reliable approach to obtain the strength of a rock block is to conduct scale effect tests. In these tests, the rock strength varies with increasing size of specimen until the strength becomes independent of the specimen size. The scale at which the density of different types of defects becomes independent of the specimen size is called the Representative Element Volume (*REV*). According to Hudson and Harrison [17], the *REV* is the smallest volume of rock at which the tested specimens contain a sufficient number of defects that the average strength value is reasonably consistent under repeated testing. Fig. 1b schematically demonstrates how the strength of the rock block at its *REV* size lies between the strength of the intact part of the block and the strength of the specimen failed along a single continuous and critically oriented defect.

The majority of laboratory and in situ experiments on the influence of scale on rock strength such as those reported by Bieniawski [3], Pratt et al. [30], Hoek and Brown [13] and others suggest an asymptotic reduction in the strength with increasing specimen size until the strength remains essentially constant (i.e., at the *REV* size). However, a few examples have been reported in the literature that do not follow this trend. Among those are the tests conducted by Symons [32] and Thuro et al. [33], which did not show any clear trend in the strength with increasing specimen size, and Hoskins and Horino [16] and Hawkins [12], which showed an increase in the strength or an initial increase followed by a decrease in the strength with increasing specimen size.

The majority of numerical investigations on the influence of scale on rock strength such as those by Pierce et al. [24], Elmo and Stead [7], Esmaieli et al. [8], and Mas Ivars et al. [23] have simulated conditions leading to a decrease in the strength with increasing specimen size. These investigations along with the results of numerical analyses reported by Zhang et al. [36] and Poulsen and Adhikary [29] suggest that other factors such as the change in the density of defects and joints with increasing specimen size as well as the boundary conditions contribute to the occurrence of the observed scale effect in rock strength.

In the following, a synthetic grain-based specimen, previously calibrated to the properties of intact Wombeyan marble by Bahrani et al. [2], is used to first investigate the influence of specimen size on the strength of intact and defected rocks under unconfined condition. The Grain-Based Model (*GBM*) is used to simulate homogeneous rocks and Discrete Fracture Network (*DFN*) models are used to simulate discrete defects. The *GBM* is then integrated with the *DFN* models to generate synthetic defected specimens, and to investigate the influence of specimen size on the strength of defected rocks with various defect orientations relative to the loading direction.

2. Background

Bahrani et al. [2] used the Particle Flow Code (*PFC*) in two-dimensions ([19]) and its Grain-Based Model (*GBM*; [27]) to simulate the laboratory behavior of intact (untreated) and heat-treated (called granulated) Wombeyan marble reported by Gerogiannopoulos [10]. *PFC* is a numerical code based on the Distinct Element Method (*DEM*) developed by Cundall [6]. In *PFC*, a rock

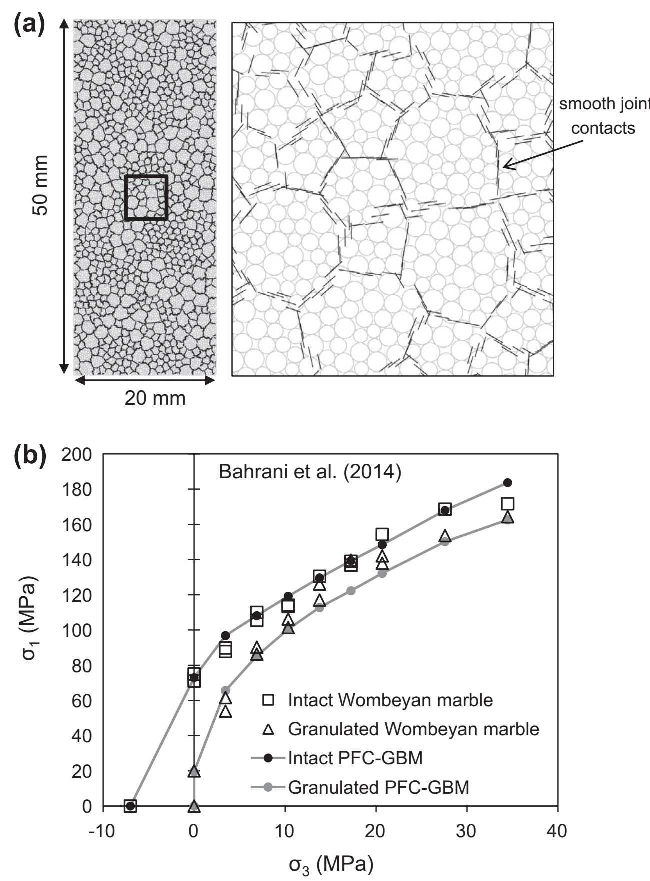

Fig. 2. (a) Grain-Based Model of Wombeyan marble with grain boundaries simulated using the smooth-joint contacts and grains that consist of a number of disks (after [2]). Note that parallel bonds between the disks inside the grains are not shown in this figure; (b) correspondence between laboratory triaxial test results on untreated and heat-treated Wombeyan marble and those from numerical simulations (after [2]).