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Modeling of failure characteristics of rectangular hard rock influenced by sample height-to-width ratios: A finite/discrete element approach

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A R T I C L E I N F O

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A B S T R A C T

In the present study, a combined finite/element approach is used to analyze failure characteristics of a rectangular hard rock with different sample height-to-width ratios based on the uniaxial compression test. The objective of this paper is to illustrate the transitional mechanisms from shear fracture to extension failure of brittle rocks and the occurrence conditions of surface-parallel slabbing. Numerical results show that failure modes have experienced the shear, tension with shear and surface-parallel slabbing failure with the decrease of sample height-to-width ratios. It is seen from the simulation results that the shear band in larger height-to-width ratios is composed of an amount of extension meso-cracks that are parallel to the loading direction, and the slabbing failure tends to be the result of the accessible propagation of extension meso-cracks due to short sample height, which validate the essence of extension failure in hard rocks. The good agreement between simulation and laboratory testing also shows the practicability and advancement of a combined finite/discrete element approach.

1. Introduction

With the increasing demand for mineral resources and gradual consumption of shallow resources, more and more metal mines are deeper and deeper. It seems that hard rocks may have extremely distinct mechanical behavior compared to that in shallow geological conditions; surface-parallel slabbing failure is the dominant and prevailing phenomenon for deep highly-stressed hard rocks [1].

Generally speaking, extension fracture and shear fracture, which have been studied by numerous researchers in the laboratory, are the two main failure modes for hard rocks [2,3]. The failure modes loaded in uniaxial compression test under the laboratory conditions are divided into splitting failure and shear failure [4]. In the early 1960s, people began to concentrate on the axial cleavage failure of rocks under the condition of compression load [5]. Such failure mode is not only related to the loading regime, stress condition and degree of brittleness of rocks, but also related to the propagation of extension cracks in rock specimen. The empirical Mohr–Coulomb and Hoek–Brown criteria are applicable for shear failure in rock mechanics, so these criteria may not be suitable for analyzing the mechanical behavior in terms of slabbing or splitting failure. Griffth's theory highlights the importance of the flaws in brittle materials. Under the condition of complex

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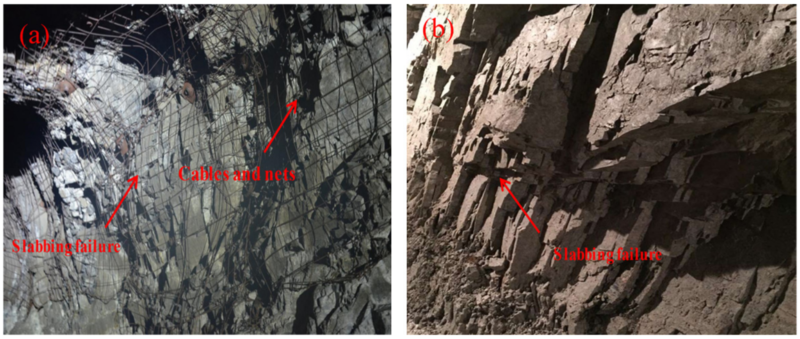

Fig. 1. Slabbing failure and slab buckling rock burst in the 640 level of Maluping mine. (a) Phosphate rock in the stope and (b) dolomite in the level drive.

stress, these flaws and defects will generate tensile meso-cracks, which result finally in brittle tensile failure. Li et al. [6] found that in specimens with larger height-to-width ratios loaded in uniaxial compression test, a great number of extension meso-cracks parallel to the loading direction took place, which finally coalesced together to form a shear band. This failure phenomenon is quite similar to Brace's experimental results [7]. Nevertheless, the hypothesis according to which extension failure is the failure mechanism of brittle-hard rocks still needs further validation and illustration by means of various methods, such as numerical approach.

The uniaxial compression test has been a conventional one in evaluating the intact and hard rock strength and failure mode. Wawersik and Fairhurst [8] conducted some compressive tests on rock specimens using a stiff loading machine and concluded that failure in uniaxial compression of rock can occur in two modes. Fakhimi and Hemami [9] used the bonded particle discrete element method and experimental test to analyze the influence of the stiffness of the loading machine on uniaxial compression. As a consequence of axial and radial cracks, rock pieces in the form of cantilever beams are generated around the specimen free surface, the final failure mode being splitting failure. Reference [6] analyzed the failure characteristics of rectangular prismatic samples of hard rock, and found out that the failure mode of hard rock may be transformed from shear to slabbing when the height/width ratio of the prism specimen is 0.5 under uniaxial compression. Freddi and Royer-Carfagni [10] used a fracture mechanics model together with some heterogeneous inclusions within the compressively loaded specimens to model the axial splitting. Wen et al. [11] studied the influence of different height to diameter ratio on the acoustic emission characteristics of coal rock damage evolution using a microparticle flow PFC^{2D} software platform.

In conclusion, an extensive experimental and numerical research has been carried out for the uniaxial compression test. In-depth study of uniaxial compressive test for hard rocks can also help us understand the failure of pillars in deep mining and tunneling projects. According to Ortlepp's description [12], spalling or slabbing is generally defined as the formation of stress-induced slabs on the boundary of an underground excavation. It initiates in the region of maximum tangential stresses and results in a V-shaped notch that is local to the boundary of the opening. Reference [9] found that higher friction coefficient of pillar-roof interface and enough pillar stiffness can result in tensile splitting failure at the pillar ends. Martin and Maybee [13] observed that the dominant failure mode was progressive slabbing and spalling rather than shear in pillars of some Canadian hard rock mines. In addition to the hard rock pillars, the slabbing and spalling failure can be observed near the tunnel surface and excavation boundaries. The author also observed slabbing failure (seen in Fig. 1) of two typical hard rocks (dolomite and phosphate rock) in Maluping mine, Guiyang Province, China, and recommended that the increase of intermediate principle stress not only promotes the formation of slabbing, but also intensifies the possibility of slab buckling rock burst.

Many researchers employ numerical approaches to study the progressive failure of rock and rock-like materials [14]. During the fracturing processes, the rock has transformed from a stable continuum into a fractured discontinuum due to crack initiation, propagation, and coalescence. Recently, the FEM/DEM combined method, which integrates the FEM and DEM into a single tool, has provided a unified framework for both continuous and discontinuous problems [15]. The numerical results showed good agreement between the final fracture patterns obtained during 2D and 3D simulations. In the present study, a FEM/DEM combined approach (ELFEN, Rockfield Software Ltd.) is adopted to simulate the fracture process of rectangular hard rock samples in uniaxial compression test, with particularly attention paid to the consideration of different height-to-width ratios. A typical hard rock type based on Iddefjord granite is selected for the numerical simulation. The purpose of this paper is to reveal the transitional mechanisms from shear fracture to extension failure of brittle rocks and the occurrence conditions of surface-parallel slabbing. Numerical results based on FEM/DEM show good agreement with the experimental results, which would provide a reasonable and functional way to study various rock mechanics and rock engineering problems.

2. Fundamental principles of the finite/discrete element approach

The combined finite/discrete approach is a numerical method that combines continuum mechanical principles with discontinuum algorithms to simulate multiple interacting deformable solids [16]. It was proposed by Munjiza [17], who takes