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Numerical simulations of failure behavior around a circular opening in a non-persistently jointed rock mass under biaxial compression

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ABSTRACT

Pre-existing discontinuities change the mechanical properties of rock masses, and further influence failure behavior around an underground opening. In present study, the failure behavior in both Inner and Outer zones around a circular opening in a non-persistently jointed rock mass under biaxial compression was investigated through numerical simulations. First, the micro parameters of the PFC^{3D} model were carefully calibrated using the macro mechanical properties determined in physical experiments implemented on jointed rock models. Then, a parametrical study was undertaken of the effect of stress condition, joint dip angle and joint persistency. Under low initial stress, the confining stress improves the mechanical behavior of the surrounding rock masses; while under high initial stress, the surrounding rock mass failed immediately following excavation. At small dip angles the cracks around the circular opening developed generally outwards in a step-path failure pattern; whereas, at high dip angles the surrounding rock mass failed in an instantaneous intact rock failure pattern. Moreover, the stability of the rock mass around the circular opening deteriorated significantly with increasing joint persistency.

1. Introduction

The original state of a surrounding rock mass is disturbed due to the interactions between the excavation and the far field loading [1,2] and some modifications will occur. The region of significant modification of the rock mass state, involving irreversible deformation with fracture propagation and the development of new cracks, is defined as the Excavation Damaged Zone (EDZ) [3]. The formation of the EDZ is accompanied by progressive failure around the underground excavation. For example, the development of progressive failure of the surrounding rock mass was reported in the large-scale tunnel experiment at the Underground Research Laboratory (URL) [4,5]. Furthermore, Lajtai et al. [6,7] conducted biaxial compression tests at laboratory scale to observe the development of fracture patterns and described the fracture phenomena. In the EDZ, the degree of damage varies with the level of stress concentration relative to rock strength near the opening [8]. The stress concentration (primarily the redistribution of original stress) triggers crack generation which combines with the pre-existing discontinuities and considerably reduces the strength of the rock mass [9]. To effectively estimate the stability of underground openings, a better understanding is required of the mechanical behavior of existing discontinuities as well as the mechanism of crack initiation, propagation and coalescence.

The rock masses in a construction site of an underground opening often exhibit anisotropy due to the presence of discontinuities such as bedding, joints, faults and fractures. Such discontinuities can aggravate stress concentration and strength degradation, thus resulting in different patterns of rock mass failure around the opening compared with the patterns observed in isotropic rock masses. According to the number of discontinuities considered, related analytical models can be classified into three main categories, namely: a 'one-joint' model [10–13]; a 'single set of joints' model [8,14–18]; and a 'multiple set of joints' model [19–22]. The 'one-joint' model is particularly used to investigate the effect of a fault, which is a large geological discontinuity, on the deformation and failure behavior of an underground opening. Hao et al. [11] carried out a parametric study using UDCE and concluded that fault dip, fault shear strength and fault location relative to the underground structure are critical for underground structure stability, whereby the fault induces an increase in the extent of plastic zones and displacements and causes both to become asymmetrically distributed in the rock mass. Yan et al. [12] conducted

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an investigation on the deformation mechanism and stability control of a roadway driven along a fault subjected to mining using theoretical analysis, numerical simulation and field trials. They demonstrated that the deformation of the surrounding rock caused by unloading in the drivage period is large and asymmetric, roadway convergence increases with activation of the fault, and secondary fractures develop during the mining period.

Use of the single set of joints model is extensively debated due to the consensus that stratified rock is commonly encountered in underground engineering. Bedding planes and stratification influence the mechanical properties of the rock mass which behaves as an anisotropic or transversely isotropic material, and makes the surrounding rock mass of an opening exhibit a wide spectrum of behavior. Mostly, bedding planes or strata are simplified as one single set of joints in physical and numerical experimental work. Jia et al. [14] utilized a numerical code called RFPA to study the influence of the dip angle of a single set of layered joints and the lateral pressure coefficient on the stability of an opening in a jointed rock mass. Numerical analysis indicated that both the dip angle of joints and the lateral pressure coefficient have significant impact on the failure pattern and displacement characters of a tunnel. Sagong et al. [8] implemented experimental and numerical analyses to study the rock fracture and joint sliding behavior of jointed rock masses with an opening under biaxial compression. They found that the propagation direction of the tensile cracks is roughly normal to the joint surface and, with propagation of tensile cracks, removable rock blocks are generated. Wang et al. [16] conducted a series of numerical simulations of the failure process for a circular opening in transversely isotropic rock masses. Based on the simulations, two major failure patterns around circular openings are produced: tensile failure across laminated layers and shear failure along laminated layers. Which pattern predominates depends on the orientation of the laminated layers, the confining pressure and the strength ratio of the laminated layers to the intact rock.

Although the rock mass is commonly considered as being isotropic or transversely isotropic, much research is concentrated on establishing analytical models with multiple sets of joints which cut the rock mass into blocks. The aim is to further investigate the effect of discontinuities on underground opening stability in much more detail. Bhasin et al. [19] conducted a parametric study for a large cavern in a jointed rock mass involving changes in joint spacing (block size) and showed that the deformations around an opening are dependent on the size or the number of blocks adjacent to the excavation. Jiang et al. [20] discussed the relationship between deformational behavior and fractal dimension and orientation of joint sets based on fractal analysis and numerical simulation of underground opening in jointed rock masses. Wang et al. [21] investigated the anisotropic deformation of a circular tunnel excavated in a rock mass containing sets of ubiquitous joints. They demonstrated that where a rock mass has two joint sets with unfavorable joint orientations, the area with joint sliding failure can deteriorate mutually, resulting in large anisotropic deformation. Nevertheless, for a rock mass containing three joint sets with well distributed orientations, joint sliding in various joint sets and associated stress variations can counter balance each other, resulting in less anisotropic deformation than those of rock masses containing one or two joint sets.

The joint in the above mentioned models is basically persistent, which means the joint usually passes through the rock mass surrounding an underground opening. The numerous investigations of a fully persistent jointed rock mass sheds light on understanding the failure mechanism of underground excavations and provides guidelines for their stability control. However, compared with the fully persistent jointed rock mass, very few studies have concentrated on damage due to the growth of non-persistent fractures around an opening [1]. The deformation and failure mechanism and stability of underground openings in discontinuous rock masses depend not only on the existing discontinuities but also on the new cracks generated which thereafter continue to propagate because of the stress redistribution induced by excavation [8]. Non-persistent joints commonly exist in underground rock engineering due to the fact that some disturbances, such as blasting, can initiate numerous trivial fractures and damage the rock mass. Lajtai et al. [7] discovered two types of fracture patterns-an 'en echelon' tensile crack-array and a shear crack-array-in the yield pillars of the potash mines of Saskatchewan. The non-persistent joints could also be indentified from the borehole images of the surrounding rock mass of underground tunnels [23]. Stability of the rock mass around an opening or excavation depends strongly on the persistence of the joints [24]. Therefore, to have more understanding of the stability of underground excavations, a fundamental study of failure behavior around an opening in a non-persistently jointed rock mass is of great importance.

In this paper, the failure behavior around a circular opening in a non-persistently jointed rock mass is investigated numerically using PFC^{3D} version 4.0 software package (Particle Flow Code in Three Dimensions), utilizing the discrete element method. First, the micro-mechanical parameters of the numerically-simulated intact rock material are calibrated using the macro-mechanical properties of the same intact rock models. Then, the micro-mechanical parameters of the joints, especially the joint aperture, in the jointed rock model are calibrated using the macro-mechanical results of the physical experiments performed by Wong et al. [1]. Next, the failure behavior in both Inner and Outer zones around a circular opening is investigated using biaxial compression tests. The effect of confining stress, joint dip angle, and joint persistency are demonstrated by performing a parametric study on the failure pattern, resistance capacity, and crack evaluation of the rock mass around the opening.

2. Numerically simulated models and micro-parameter determination

2.1. DEM models

Wong et al. [1] proposed a conceptual model to investigate, in the laboratory, the creeping damage and failure mechanism around an opening in a rock-like material containing non-persistent joints, as shown in Fig. 1. In the present study, reference is made to their modeling work, and a parametric study has been undertaken to provide a better understanding of the failure behavior of the rock mass around an opening using the PFC^{3D}.

PFC^{3D} is a commercial software package based on the principle of DEM and, of particular interest, is capable of making predictions of rock mass failure behavior, anisotropy, and

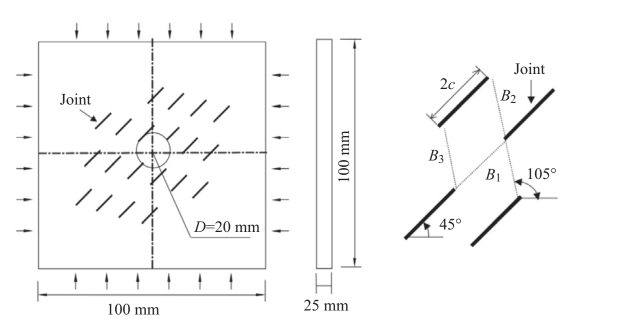

Fig. 1. Conceptual model with non-persistent joints and an opening. B_1, B_2 and B_3 are the distance between joints, $B_1 = B_2 = B_3 = 10$ mm [1].