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Research Paper

Internal stress distribution and cracking around flaws and openings of rock block under uniaxial compression: A particle mechanics approach

Xiang Fan[a,c], Kaihui Li[b,*], Hongpeng Lai[a], Yongli Xie[a], Rihong Cao[d], Jun Zheng[e]

[a] *School of Highway, Chang'an University, Xi'an 710064, China*
[b] *Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China*
[c] *Key Laboratory of Bridge Engineering Safety Control by Hunan Province, Department of Education, Changsha University of Science & Technology, Changsha 410114, China*
[d] *School of Resources and Safety Engineering, Central South University, Changsha 410083, China*
[e] *Department of Civil Engineering, Zhejiang University, Hangzhou 310058, China*

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ABSTRACT

Based on experimental results, bonded particle models containing flaws or/and openings were created to investigate the peak stress, crack-initiation stress, number of micro-cracks, local stress distribution and cracking behavior under uniaxial compression. It is found that flaws and openings are distinctly related to the peak stress, the crack-initiation stress and the number of micro-cracks. As the flaw inclination angle increases, the distributions of principal stresses surrounding a flaw vary, while those surrounding an opening present a similar shape with magnitude differences. The distribution of local stress well accounts for the cracking behavior.

1. Introduction

Generally, the stability of an underground natural rock mass may be changed by human excavation such as tunnel construction. The primary stress equilibrium is disturbed resulting in redistribution. The redistribution of stress within a rock mass often induces stress concentration around the opening. The highly concentrated stress may directly damage the surrounding rock mass, and even lead to collapse [1–3]. If the excavation occurs within a jointed rock mass, it makes collapse more likely. Therefore, it seems that a clear and deep knowledge of the stress field and failure around circular openings will strongly benefit the increasing underground engineering constructions.

The geostress redistribution induced by the excavation produces a stress concentration at some locations on the perimeter of the cavern. Failure often first takes place at these high-stress concentrated locations. In underground engineering, failure phenomena are usually observed at the roof and sides of tunnels, such as roof fall and rib spalling [4,5]. For the safety of builders and facilities, in situ stress and displacement monitoring is often performed to predict a potential collapse, but in situ monitoring or field investigation is influenced by many uncertain factors. Therefore, physical model experiments under compression are an idealized approach for simulating the excavation-induced failure behavior of a cavern. Being limited by the testing instrument's small size, the samples were properly prepared for uniaxial, biaxial or triaxial compression. Martino's [6] report obtained from the in situ study showed that the excavation geometry plays a major role in the stability of a tunnel. In most studies, one single circular opening was pre-cut within rock-like or real rock blocks [7–9]. Based on elastic theory, the stress distribution surrounding a circular opening is the best for underground structures. Afterwards, considering the real excavation section shape, the stress fields around the inverted U-shape, elliptical or arc-shape openings under different lateral stresses were also obtained by numerical or experimental approaches, and used to determine the most possible collapse locations [10,11]. Relative to the single hole case, the cracking and stress distribution of the multi-hole case is quite complicated, since the cracking path usually changes with hole locations. The cracking characteristics of three holes arranged in a coplanar or non-coplanar way were experimentally analyzed by Zhao, Huang and Bai [12–14]. The collapse of up to nine holes under compression was investigated by Lajtai [15]. Sometimes, acoustic emission assisted the prediction of micro-crack locations before visual cracks [12,15]. For jointed rock masses, the joint or flaw greatly affects the material failure. The crack type, coalescence pattern and failure mode during the failure process have received much attention in the last few decades [16–18].

Abbreviations: SHWF, single-hole without flaw; SHTF, single-hole and two-flaw; THWF, two-hole without flaw; THSF, two-hole and single-flaw; PFC, particle flow code; BPM, bonded particle model; N, total number of all micro-cracks produced by tensile or shear failure; N_t, the number of tensile failure micro-cracks; N_s, the number of shear failure micro-cracks; T, tensile crack; S, shear crack; SP, spalling; MS, measurement sphere; PSDZ, principal stress distribution zone

[*] Corresponding author.

E-mail address: kaihuili_csu@163.com (K. Li).

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Since both the joint dip angle and persistent ratio strongly affect the failure mode and sample strength, by changing these influential factors, different kinds of failure modes were summarized [19,20]. As a matter of fact, in real engineering, the excavation is often implemented in jointed rock masses. This excavation-induced failure is more complicated than in intact rocks. Sagong et al. [21] carried out an experimental and numerical study on the persistently jointed rock-like models of the joint set with dip angles of 30°, 45° and 60°. It was found that the cracking behavior around the opening was greatly influenced by the joint dip angle.

Currently, numerical simulation or a combination of numerical and experimental approaches have been the most popular methods for investigating the failure behavior of brittle materials, such as rock, concrete, and asphalt. The numerical methods are various, including the finite element method [22–25], the discrete element method [5,13,14,16–18], the boundary element method [26], the discontinuous deformation analysis [27], and the numerical manifold method [28]. For the fracture behavior of rocks or rock-like materials containing flaws or/and holes, most researchers have tried to interpret from two-dimensional models. For instance, the failure mode and strength of rock or rock-like specimens containing a single flaw [29,30], several flaws [31,32] and ubiquitous flaws [33] have been investigated by resorting to PFC^{2D}. In addition, much meaningful work has been done for one hole by [5,21,24,25], and multi-holes by [12–14,34] using rock failure process analysis and PFC^{2D}, respectively. Combining the physical model experiments, Yang [35,36] conducted compressive test simulations on cubic jointed rock models using PFC, and three failure modes were observed including the intact rock failure, step-path failure and planar failure. Bhasin & Høeg [37] established a jointed rock model containing a large cavern and tried to reveal the deformation around an opening. Thus, most results obtained by these models presented the cracking process and repeated the observed failure in physical tests. Furthermore, the numerical approach is able to derive the local stress around flaws and openings, so the stress evolution can be further considered.

In the present study, flaws and circular openings were simultaneously prepared within real rock material by changing the flaw inclination angle and combining ways of producing them. Based on the experimental results, a particle flow code was employed to reveal the stress distribution surrounding flaws and openings and to explain the cracking mechanism of rock specimens containing flaw(s) and circular opening(s) under uniaxial compression. This study aims to understand the relation between the excavation-induced stress field and the failure behavior when flaws exist.

2. Establishment of numerical models

2.1. Calibration of micro-mechanical parameters

Among a series of numerical approaches, particle flow code was frequently employed to simulate the cracking process of rock specimens, due to the priorities relative to the other approaches [13,14,16–18,31–33]. In the present study, the PFC^{3D} program was adopted to generate bonded particle models with or without flaw(s) and/or hole(s) following the standard procedure suggested by Itasca Consulting Group [38]. It was found that the thickness effect is not significant when dealing with the problem of through-going defects rather than with part-through-going defects [24]. Therefore, the dimensions of all numerical specimens are the same as the experimental ones except in the direction of thickness (see Fig. 1), aiming to save the calculation time. Moreover, considering the particle size used in this model, the model thickness was determined to be 10 mm, which satisfies the size requirement suggested by the American Society for Testing and Material [39]. The parallel-bonded contact model was adopted in this study. First, an intact prismatic specimen was generated. The particle size follows a uniform distribution. The intact numerical model consists of 195,070 particles and 724,294 parallel-bonds installed between particles with the distance equal to or less than g_{ratio} times the minimum radius of the contact connecting particles. The choice of installation gap ratio (g_{ratio}) follows two requirements: (1) it must be less than R_{min}/R_{max}, preventing particles from being embedded in connecting pairs, and (2) it must ensure an appropriate average coordination number of the generated model. In this study, the installation gap ratio (g_{ratio}) was chosen to be 0.1 resulting in the average coordination number of the specimen being 7.4, in the range of 6–10 found in the homogeneous, two-mixed and multi-mixed assemblies [40]. Then, uniaxial compression and Brazilian tensile simulations were conducted to calibrate the model micro-parameters. It is an iterative procedure between specimen generation and numerical tests. Two principles are required for the calibration: (1) strength and elastic parameters and (2) the failure mode. As reported in publication [41], sandstone was used to manufacture the intact blocks with dimensions of 100 mm × 100 mm × 30 mm (height × length × width). According to the experimentally obtained results [41], a trial and error procedure was repeated to calibrate the experimental macro-mechanical parameters. After several calibrations, the optimized micro-parameter values listed in Table 1 were determined. As listed in Table 2, the numerically obtained macro-parameters match those obtained experimentally well. Compared in Fig. 2, numerical failure is analogous to experimental failure. Therefore, the aforementioned two principles are satisfied. Next, the intact numerical model was used to further generate models with flaw(s) or/and hole(s).

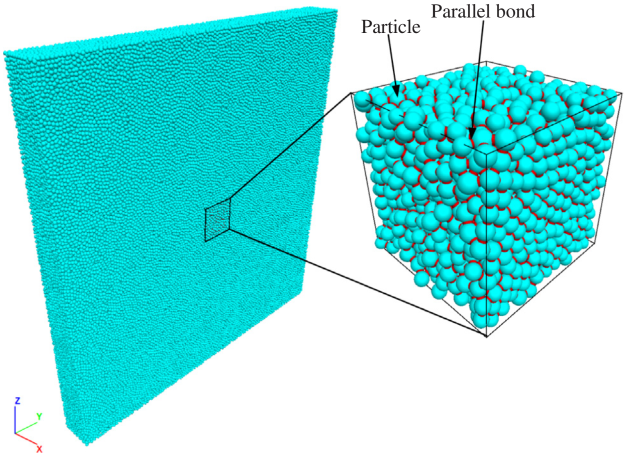

Fig. 1. The intact bonded particle model.

2.2. Numerical models and the compressive test

The rectangular block without flaws or holes is regarded as an intact model as shown in Fig. 3a (Series I) and was also used to derive basic

Table 1
Micro-parameters of the intact numerical model.

Micro-parameters	Values
Minimum particle radius, R_{min} (mm)	0.39
Particle size ratio, R_{max}/R_{min}	1.2
Installation gap ratio, g_{ratio}	0.1
Bulk density, ρ (kg/m^3)	2530
Particle contact modulus, E_c (GPa)	33
Ratio of particle normal to shear stiffness, k^n/k^s	3.0
Particle friction coefficient, μ	0.55
Parallel-bond modulus, E_c (GPa)	33
Ratio of parallel-bond normal to shear stiffness, $\bar{k}^n/\bar{k}^s$	3.0
Parallel-bond normal strength, mean σ_m (MPa)	48
Parallel-bond normal strength, standard deviation σ_{sd} (MPa)	9.5
Parallel-bond shear strength, mean τ_m (MPa)	48
Parallel-bond shear strength, standard deviation τ_{sd} (MPa)	9.5