Computers and Geotechnics 88 (2017) 182–198

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

Strength failure behavior and crack evolution mechanism of granite containing pre-existing non-coplanar holes: Experimental study and particle flow modeling

Yan-Hua Huang [a], Sheng-Qi Yang [a,*], P.G. Ranjith [a,b], Jian Zhao [b]

[a] State Key Laboratory for Geomechanics and Deep Underground Engineering, School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou 221116, PR China

[b] Deep Earth Energy Research Laboratory, Department of Civil Engineering, Monash University, Melbourne, VIC 3800, Australia

ARTICLE INFO

Article history:
Received 12 January 2017
Received in revised form 22 March 2017
Accepted 22 March 2017

Keywords:
Granite
Three non-coplanar holes
Strength
Crack coalescence
Stress field

ABSTRACT

In this study, uniaxial compression tests were conducted on granite specimens containing three non-coplanar holes. The relationships between the stress, acoustic emission (AE) and crack evolution process were analyzed using AE measuring and photographic monitoring techniques. Particle flow code (PFC) was then used to simulate the strength failure behaviors of the specimens with three non-coplanar holes under uniaxially loading. Four typical crack coalescence patterns were identified, i.e., shear, mixed tensile and shear, and tensile. The crack evolution mechanisms around the pre-existing holes in the granite specimens were revealed by an analysis of the force and displacement fields.

1. Introduction

In underground engineering projects, such as mines, tunnels and hydropower stations, rock mass stability is influenced by the excavations. Studies on the strengths and failure behaviors of pre-holed rock are important for predicting unstable failures in rock engineering structures. In previous studies, rock specimens were often machined with pre-existing holes to investigate the mechanical and cracking behaviors, making it easy to control the loading/boundary conditions and increasing data acquisition during the failure processes of the specimens [1]. On the macroscopic scale, the pre-existing holes simulate underground openings because the circular openings are cross-sectional structures in underground engineering [2]. On the microscopic scale, the pre-existing holes are one kind of common flaw in natural rock. Pre-existing flaws in natural rock have crack-like or pore-like shapes [3]. Based on previous studies of crack-like flaws [4–11], it has been recognized that cracks always initiate from the tips of flaws due to high stress concentrations, and the strength of pre-cracked rock is often lower than that of intact rock. However, compared with the number of studies of crack-like flaws, there are relatively few studies on pore-like flaws. Zhao et al. [12] conducted uniaxial compression tests on a granite specimen with a single hole to investigate the fracture evolution around the hole using an acoustic emission (AE) spatial location technique. Their experimental results showed that the tensile and compressive stresses have an important influence on the fracture evolution process. To study the temperature effects on the mechanical properties of rock, Yin et al. [13] conducted uniaxial compression tests on granite specimens containing a central hole after high-temperature exposure. Based on the experimental results, they concluded that the peak strength and elastic modulus first increased and then decreased with temperature. Liu et al. [14] analyzed the crack development process of a one-holed granite specimen subjected to uniaxial compression by adopting the AE technique and moment tensor (MT) analysis.

However, the above studies focused on the effects of a single hole on the mechanical properties and crack evolution but ignored the interactions among multiple holes. In a rock mass, multiple holes may exist simultaneously, and the interactions among multiple holes will greatly affect the mechanical behavior of rock. Rock mass instability after excavation often occurred due to the strong stress interactions between holes [15]. Fracture evolution behaviors and crack coalescence mechanisms in situations with multiple openings have received attention but have not been fully investi-

* Corresponding author.
E-mail address: yangsqi@hotmail.com (S.-Q. Yang).

http://dx.doi.org/10.1016/j.compgeo.2017.03.015
0266-352X/

gated. Tang et al. [16] simulated the failure behavior of porous solids that contained multiple pre-existing holes using material failure process analysis (MFPA). In their modeling, the hole diameters, specimen widths and geometrical arrangements of the hole locations were all investigated, which revealed that specimens containing diagonally arrayed holes are more conducive to interaction than those with horizontally or vertically arranged holes. Lajtai and Lajtai [17] tested a model material specimen with pre-existing openings under polyaxial compression. In their experiment, four crack types (i.e., primary tensile, normal shear, secondary tensile and inclined shear fracture) were identified under different confining pressures. Wang et al. [1] used RFPA^{2D} to simulate crack initiation and propagation from pre-existing holes in brittle rock under static and dynamic loads. Their numerical results showed that the tensile fractures were dominated around a single cavity with a zero lateral compressive coefficient, whereas shear fractures became increasingly dominant with an increasing lateral compressive coefficient. To examine the cracking mechanism and failure behavior of granite with multiple holes, a series of uniaxial compression tests were conducted by Lin et al. [18]. In their study, the influences of bridge length, bridge angle, hole diameter, number of holes on initiation, coalescence and peak stress and crack distribution were all systematically investigated. Although strength failure behavior with multiple holes has been experimentally studied, limitations still exist, such as the small scale of the rock specimen and absence of investigating the stress and displacement fields during crack evolution in the laboratory experiments.

Natural rock masses do not usually contain parallel arrayed holes and are generally composed of irregularly arranged holes. Regarding the crack coalescence processes around multiple pre-existing holes with irregular arrangements, little information has been reported in the literature. To advance the understanding of strength and the mechanisms of crack evolution around pre-existing holes with irregular arrangements, it is necessary to investigate the mechanical behaviors of rock specimens containing non-coplanar holes. Because the mechanism of crack coalescence in multiple holes is complicated, three pre-existing holes were cut in real rock specimens to form an irregularly arranged combination, at first, a one-hole geometry effect (e.g., bridge angle) was investigated under uniaxial compression in this study. Therefore, a series of uniaxial compression tests for granite specimens containing three non-coplanar holes were carried out in the laboratory using photographic monitoring and AE measuring techniques. Discrete element modeling was then conducted on numerical specimens with three pre-existing holes with the same arrangement as in the experiment. Finally, the force and displacement fields were analyzed in detail to reveal the mechanisms of crack coalescence between pre-existing holes under uniaxial compression. The goal of this laboratory experimental and numerical simulation study is to provide more fundamental knowledge of the crack initiation and coalescence mechanisms of real rock.

2. Experimental and numerical details

2.1. Granite material and specimen preparation

Granite taken from Quanzhou city, in the Fujian province of China was used as the test rock material in this study. Fig. 1 shows the microscopic structure of the tested granite obtained from thin section and scanning electron microscopy (SEM). The rock was a medium-grained heterogeneous material with an average density of approximately 2730 kg/m^3. According to the XRD analysis, the mineral components of the tested granite material were primarily feldspar, quartz, dolomite and other minerals.To investigate the interactions of the irregularly arranged holes and their influence on the strength failure behavior of granite, three non-coplanar holes were cut in the rectangular specimens shown in Fig. 2. A prepared intact specimen had a height-to-width ratio of 2.0 to minimize the end friction effect on the test results [19]. Furthermore, to neglect boundary effects on the crack propagation, the width of the granite sample was designed to be 80 mm, which was much wider than the pre-existing hole diameter. In detail, the geometry of the pre-existing holes was described as follows. The diameter of the three holes was $2r$. Hole ① was located a vertical distance $2a$ from the center of the specimen, whereas hole ② was fixed at a horizontal distance $2b$ from the center of the specimen. The bridge length, $2c$, was the distance between the centers of hole ① and hole ③. The bridge angle, β, was defined as the angle between the line connecting the centers of hole ① and hole ③ and the vertical direction. A high-pressure water jet cutting machine was used to cut three holes with a designed '$2r$' of 10.5 mm into the intact specimen. In this research, different hole geometries were designed by varying β from 0° to 225° at intervals of 45° while holding the other parameters constant. The bridge lengths $2a$ and $2b$ were fixed to 16.3 mm. When β equaled 0°, the parameter $2c$ was designed to be equal to $2a$ (or $2b$), which was 16.3 mm; in other situations, $2c$ was designed to be equal to $2\sqrt{2}\,a$ (or $2\sqrt{2}\,b$), which was 23 mm, to create a symmetrical distribution of holes.

2.2. Testing system and loading procedure

An MTS816 rock mechanics servo-controlled test system was used for the laboratory uniaxial compression tests and is shown in Fig. 3. The maximum loading capacity of the MTS816 was 1459 kN, and the maximum displacement capacity was 100 mm. The axial force was imposed on the rock specimen surface under displacement- controlled conditions with a strain rate of $1.25 \times 10^{-5}\ s^{-1}$ until failure occurred.

During the uniaxial compression tests, the AE signals were recorded in real time using a DS2 full-information AE measurement system (Fig. 3). Two AE sensors were attached to the back face of the granite specimen near the pre-existing holes in the granite specimens using a hot bar as a coupler and gently affixed with cellulose tape. A Sony digital video camera (HDR-XR550E) was used to capture the fracture images of the granite specimen.

2.3. Numerical model and micro-parameters

In this research, particle flow code (PFC), a discrete element method, was used to simulate the mechanical behavior of the granite specimens containing pre-existing holes under uniaxial compression. The parallel bond model (PBM) has been successfully used to reproduce the mechanical behaviors of rock materials; additional detailed information about the model can be found in Cho et al. [20], Lee and Jeon [21] and Yang et al. [22]. As a result, the parallel bond model was selected for the numerical study in this research. The fractures at the front and back surfaces were very similar except for minor differences due to the heterogeneity of the rock. The observations of cracking after failure indicate that the crack coalescence behavior was essentially two-dimensional (2D) even though the laboratory granite is a three-dimensional (3D) specimen. In addition, 3D PFC simulation has long computational times and the loading/boundary conditions are difficult to control [22]. Therefore, in this research, the numerical simulations of the granite specimen were conducted using a 2D plane stress model [22,23].

An 80 mm × 160 mm rectangular numerical model was constructed, which was the same scale as the experimental granite specimen. The particle sizes followed a uniform distribution and