International Journal of Mining Science and Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

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

Mechanical properties of frozen rock mass with two diagonal intersected fractures

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A R T I C L E I N F O

Article history:
Received 13 September 2017
Received in revised form 26 December 2017
Accepted 18 January 2018
Available online xxxx

Keywords:
Intersected fractures
Fracture morphology
Failure modes
Mechanical properties

A B S T R A C T

Based on previous research results, this paper investigated the influence of fracture morphology on mechanical properties and failure modes of rock mass with two diagonal intersected fractures. This study carried out a series of triaxial compression tests on rock-like specimens with two crossed fractures under negative temperature, concluded the following conclusions. The strength and failure modes of rock mass are significantly influenced by the dips of two crossed fractures. The strength of rock mass with two fractures cannot simply be estimated using the method that was developed for the rock mass with a single fracture. When the intersecting angle is less than 30°, the failure plane initiates at the tip of "artificial ruptures" and extends to the upper and lower ends of the specimen. In case of a higher dip and intersecting angle ranging from 30° to 60°, the failure plane propagates along one of these two fractures. The mechanical parameters of rock mass are not only related to the trace length, but also depend on the trace length ratio. One could roughly calculate the strength parameters using the approximation proposed in this paper. For the rock mass with a trace length ratio <0.3 (short trace length/long trace length), the failure mode is dependent on the fracture with a longer trace length. When the trace length becomes significant and the trace length ratio approximates to 1, the failure plane propagates along two fractures, where an X-shaped failure pattern is presented. For the rock mass with moderate fractures and a trace length ratio of approximately 1, the failure mode is independent on fractures, which is similar to the damage pattern of intact rock. The strength and elastic modulus of rock mass decrease with the increase of spacing between fractures, while Poisson's ratio is independent on the spacing. The failure mode can be determined by the area of triangle created by two fractures. Damage occurs at the smaller triangle area first, and propagates with the two sides of the larger triangle.

1. Introduction

The complexity of rock mass structures can be generally simplified as the rock mass containing a single fracture, two parallel fractures, and two intersected fractures, or the composite rock mass with any combinations of the above three cases [1]. Extensive studies have been conducted to investigate the mechanical characteristics of rock mass.

The fracture angle influences the initiation position of fracture plane, while the trace length affects the scale of fracture plane. To a certain extent, the confining pressure could restrict the influence of crack angle and trace length on the rock mass strength [2]. Based on the Mohr-Coulomb theory, the failure mode of rock mass includes the damage along cracks or through cracks, depending on the stress condition, the stress path, the orientation of fractures and the strength parameters [3,4]. Direct shear tests were simulated on the rock mass with a single fracture using PFC-2D and the results show that the normal stiffness and shear stiffness have negligible effect on the peak shear strength in sliding mode, but the normal stiffness influences the dilation rate in both sliding and shearing modes significantly [5].

The tensile/compressive strength of rock mass with two or three parallel fractures shows a nonlinear relationship with the fracture angle, which controls the initiation location of main cracks. However, the angle of rock-bridge affects the initiation of secondary cracks [6–8]. Joint angle and connectivity rate have significant effects on the strength parameters and deformation characteristics, and failure modes can be categorized as splitting failure, plane failure, stepped damage and destruction of intact rock [9–11]. The rock mass with two overlapped parallel fractures

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https://doi.org/10.1016/j.ijmst.2018.02.005
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can still carry the loads when the rock-bridge begins to crack, showing as a progressive failure or stable crack growth. However, for non-overlapped joints, brittle failure occurs once the rock bridge fails, showing as brittleness unstable damage [12].

Previous studies mainly focus on the mechanical properties and failure modes of rock mass with a single fracture or multi-parallel fractures, and there is a lack of investigation on the behavior of rock mass with intersected fractures. Nevertheless, fracture morphology is intricate in rock engineering, if all of these situations are put down to one single fracture or parallel fractures simply, errors are inevitable. Therefore, research on the mechanical properties and failure modes of intersected fractured rock mass is particularly important. Based on the study by Yang et al., this paper is a further study on the influence of angle, trace length and the spacing of intersected fractures on the mechanical properties and failure modes of rock mass [13].

2. Test scheme

Fig. 1 is a schematic view of the geometric parameters of rock mass, in which a_1 and a_2 are the trace length of two intersected fractures (the midpoint of fracture is on the same generatrix), θ_1, θ_2 are the corresponding dip angle is respectively, and b is the fracture spacing (the distance between fracture midpoints).

2.1. Similar materials and production

There are two ways to get fractured rock specimens. One is drilling rock core directly according to certain angle. This approach has both advantages and disadvantages. The parameters and spatial variation can be obtained directly for use in theoretical analysis and engineering practice. But it is necessary to ensure the unity of the rock and the difference of fracture morphology, which is difficult to be satisfied in practical engineering, and most of tests on original rock are not repeatable. Another method is to ensure the original rock and rock specimens have similar mechanical properties by a series of proportioning tests. The advantage is that these artificial rock specimens have a high variety in characteristics, especially on the crack occurrence. Using similar materials could produce rock samples that can be representative for the field conditions, although the test results need to be interpreted carefully as the test objects are not real rocks. Ultimately, with considering all the factors, the second method was adopted to make fractured specimens.

We selected density ρ, elastic modulus E, Poisson's ratio v, uniaxial tensile strength σ_c, cohesion C, internal friction angle φ as control parameters. According to the similarity Eq. (1) [14]:

$$C_\varphi = C_v = 1 \quad C_E = C_{\sigma_c} = C_C = ML^{-1}T^{-2} \tag{1}$$

Therefore, as long as the mechanical parameters of cement mortar and red sandstone are approximately equivalent, this study can use cement mortar (specimens) instead of red sandstone in the tests [15].

As is shown from Table 1, the strength and deformation parameters of specimens and red sandstone are approximately equivalent under negative temperature. Thus, the rock-like materials can be used instead of red sandstone to study the effects of fractures on the mechanical properties and failure morphology.

Taking anisotropy and dilatancy of red sandstones into account, artificial graded gravel and soft wood are selected appropriately on the basis of the original ratio. After a number of ratio screening, the ratio of the respective components of the specimen is 1 (cement): 2 (sand): 0.45 (water): 0.6% (super plasticizer): 0.1% (soft wood). Artificial graded gravel with 0:2:3:4:6:5 (sieve residue in descending order). The specimen has a diameter of 40 mm and a height of 80 mm.

2.2. Test loading scheme

Frozen triaxial compression tests were carried out using the frozen triaxial testing machine in the Underground Engineering Laboratory, CUMTB. The axial load is controlled by displacement, with a rate of 0.12 mm/min. Confining pressure is applied by real-time confining pressure: axial compression = 1:1 (hydrostatic pressure), with a loading rate of 50 kPa/s. Confining pressure is kept constant after it reaches a pre-set value, and axial pressure is increased until the specimen fails.

3. Analysis of test results

3.1. Influence of dip angle on rock mass

Test condition is as follows: temperature T = −10 °C, confining pressure σ_3 = 8 MPa, fracture trace length $a_1 = a_2$ = 20 mm, spacing b = 0 mm, the dip of fracture θ_1, θ_2 is assigned respectively as 0°, 30°, 45°, 60°, 90°, 120°, 135°, 150° and 180°. In total, 81 sets of tests need to be introduced. However, because of the symmetry of intersected fractured rock mass, the results of 16 tests as shown in Table 2 are performed. The measured rock parameters, including σ_f, E, v and the axial and radial strain at the ultimate strength are listed in Table 2. In tests, JD3, QQ1, QQ2, QQ3, QQ4, QQ3, QQ2, QQ1 and JD3, the dip of a_1 is 0° and the dip of a_2 changes from 0° to 180°. When the dip of a_2 increases, the strength and elastic modulus decreases first, then increases, reduces again, increases subsequently. The maximum value is obtained at a_2 = 90° and the minimum is measured at a_2 = 60° or 120°. Furthermore, this variation showed symmetry obviously. The nature of the fractured rock

(a) Schematic diagram of fractures (b) Processing patterns (c) Intersected fractures rock

Fig. 1. Two intersected fractured rock.

Please cite this article in press as: Yang H et al. Mechanical properties of frozen rock mass with two diagonal intersected fractures. Int J Min Sci Technol (2018), https://doi.org/10.1016/j.ijmst.2018.02.005