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Experimental investigation of jointed rock breaking under a disc cutter with different confining stresses

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ABSTRACT

Extensive and detailed investigations have been made to better understand the rock-breaking mechanism of the tunnel boring machine (TBM) disc cutter, but the crack propagation and failure modes induced by the disc cutter when the confining stresses and joint characteristics vary have not been comprehensively investigated. To address this area of research, a triaxial testing machine (TRW-3000) is modified to investigate the effect of different confining stresses (0, 2.5, 5, 7.5 and 10 MPa) on the rock breaking of different joint angles (0°, 30°, 60°, and 90°) induced by the disc cutter. In this series of tests, the crack propagation and failure modes of the intact and jointed rock with different confining stresses are analysed. During the experiments, four different types of failure modes have been observed. The failure mode is affected by the joint orientation at low confining stress. The existence of joints has no obvious effect on the failure mode when the confining stress increases to a certain extent.

1. Introduction

Because of the high efficiency and safe operation, the tunnel boring machine (TBM) is widely utilised in large-scale infrastructure work, particularly tunnelling engineering [1]. However, in most excavation works, there are various types of discontinuities in the natural rock mass [2–5]. In addition, with the increase in excavation depths, the confining stress has been proven to be a crucial factor that affects the breaking efficiency during the TBM excavation [6–10]. Hence, the investigation of the rock-breaking mechanism under various geological conditions has important theoretical and practical significance. To date, many theoretical studies, laboratory tests, numerical simulations, and site observation investigations have been performed to separately investigate rock-breaking mechanisms such as the joint characteristic and confining stress. In theoretical studies, the scholars have introduced many rock-breaking models. The CSM model is one of the well-known prediction models in TBM tunnelling projects [11]. Based on laboratory tests, Bruland proposed the NTNU model, and the joint angle was considered to predict the penetration rate in this model [12]. Barton introduced the QTBM model with consideration of the joint angle [2].

Recently, many numerical simulation approaches have been widely used to study the rock fragmentation mechanism of the TBM cutter, including the finite element method (FEM), the displacement discontinuity method (DDM), and the distinct element method (DEM). For example, Liu et al. [13] analysed the effect of the confining stress on the TBM performance using

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Table 1
Basic mechanical parameters of the materials.

Rock-like material				Mica sheet			
Tensile strength (MPa)	Compressive strength (MPa)	Elastic modulus (GPa)	Poisson's ratio	Friction angle (°)	Cohesion (MPa)	Cohesion (MPa)	Friction angle (°)
2.75	22.95	22.70	0.23	49	1.16	0.01	10

the rock failure process analysis (RFPA). Marji et al. [14,15] applied the DDM to simulate crack propagation with disc cutters. Gong et al. [3] and Jiang et al. [4] used the DEM to examine the impact of the joint orientation on crack propagation during the indentation process of TBM cutters. Zhai et al. [5] used the General Particle Dynamics (GPD) to simulate the jointed rock failure process by disc cutters. These studies provide the action laws of the joint characteristic or confining stress on the rock-breaking process beneath disc cutters. However, the jointed rock-breaking process by a disc cutter under different confining stresses is notably complex, and there are assumptions in the simulation process, so the jointed rock-breaking mechanism between the cutter and the confining stress remains unclear.

Because of the theoretical difficulties and numerical simulation limitations, many experiments have been performed to investigate the rock-breaking mechanism under different confining stresses in intact rock mass. Innaurato et al. [6] performed indentation tests and found that the increase in confining stress was beneficial to the propagation of lateral cracks. The laboratory tests of Yin et al. indicate that rock breakages are restrained when the confining stress increases to some extent [16,17]. Liu and Wang [18] experimentally and numerically analysed the effect of the confining stress on the crack initiation and propagation. Entacher et al. [19] studied the rock failure process of a cutter, and observed that the median cracks were well developed at low confinement levels, but were restrained when the confining stress increased. The laboratory test by Chen and Labuz shows a similar crack propagation tendency, even for a sharp indenter [20]. Thus, crack propagation in intact rocks varies under different confining stress conditions.

Previous works provided important primary knowledge about the rock fragmentation mechanism of TBM cutters. However, in most of these studies, the effect of the joint characteristic and confining stress on the rock-breaking process under disc cutters was individually studied. During the excavation, the jointed rock mass is commonly under in situ stress conditions. Thus, it is of great importance to reveal the effect of the joint characteristic and confining stress on the rock-breaking process under the disc cutter. To systematically study the combined effect of the joint characteristic and confining stress, a series of laboratory tests were performed to analyse the crack propagation and failure modes of intact and jointed rocks for different confining stress values. In this work, the combined effect of the joint characteristic and confining stress on the cracking process of specimens is investigated, and the failure modes related to the cracking process are analysed. The effect of the joint orientation and confining stress is highlighted in this study.

2. Description of the experiments

2.1. Specimen preparation

Scholars have made different types of joints through natural rock and brittle rock materials, and studied the effect of joints on rock-breaking efficiency [21,22]. Apart from natural rocks, various materials have also been widely used by scholars, such as gypsum [23], concrete [24] and cement mortar [25–27]. For the samples made by cement mortar, because the main framework of the material is cement and sand, the cement is the adhesive material, and the sand can provide the frictional behaviour of the modelling material. This feature is similar to the actual rock failure. Therefore, the cement mortar sample is notably suitable for simulating rock damage. In addition, the specimen is relatively easy to prepare, and the tests are repeatable. Thus, cement mortar is selected as the material for our experiment.

The rock-like specimens are made of water, sand and cement with a volume ratio of 1:2:1. The dimensions (height × width × thickness) of the specimen are 150 mm × 150 mm × 30 mm. To create the existing joint, a mica sheet (70 mm long × 30 mm wide × 0.4 mm thick) was inserted into and remained in the specimen. The specimens were cast in a special steel mould to ensure highly flat surfaces, and the mould was removed when the mortar hardened. Then, the specimens were placed in the tank for three days, and all samples were maintained in the standard constant-temperature curing box for 28 days. During the curing process, the temperature and humidity were maintained at 25 degrees and 90%, respectively. The dip direction of the joint set is assumed to be identical to the cutting load direction [3], and the joint orientation α between the tunnel axis and the joint plane varies among 0°, 30°, 60° and 90°. The distance between the position of indentation and the centre of the joint is 55 mm. The specimen details are shown in Fig. 1. The basic mechanical parameters of the materials are shown in Table 1. Table 2 provides the detailed description of the geometrical parameter values for each specimen in this study. S is the specimen, σ is the confining stress, and α is the joint angle. For example, for S-7.5-30, the confining stress is 7.5 MPa, and the joint angle is 30°.