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Study on the influence of confining stress on TBM performance in granite rock by linear cutting test

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ABSTRACT

Rock stress problems induced by overburden or anisotropic stresses are significant to the TBM tunneling. In this paper, the effect of different confining stressed conditions on TBM performance are investigated by using full-scale cutting tests with large intact granite specimens (1000 mm × 1000 mm × 600 mm). In these tests, the effects of confining stresses on the normal force, rolling force, the cutting coefficient and specific energy are analyzed. It is found that the confining stress has significant impact on the normal force and rolling force. Specifically, for the same cutting spacing and penetration depth, the normal force increases with increasing confining stress due to enhancement of the rock resistance strength; meanwhile the rolling force decreases gradually with increasing confining stress. The stress deviation between two confining directions affects the optimum penetration that corresponds to small specific energy. The results provide better understanding of the effect of confining stress on the TBM performance and also recommend some guidelines for TBM tunneling under stressed geological condition.

1. Introduction

TBM has recently been employed extensively in underground engineering construction for numerous advantages, such as personnel safety, continuous and remarkably high advance rates, high construction quality and less ground disturbance (Rostami, 1997; Gong, 2006). However, with its development and application in deep tunnel and mining industry, TBM has to deal with rock stress problems induced by overburden or anisotropic stresses. The well-known cases include the Jinping II Hydropower Station in China, the Lotschberg base tunnel and the Gotthard Base Tunnel in Switzerland (Gong et al., 2012; Rojat et al., 2009). In situ stress, especially high stress, induced problem for TBM excavation has become a topic for the researchers, engineers, TBM manufacturers and contractors.

A lot of studies have been conducted on the TBM performance under stressed geological condition. By field observation, Gehring (1995) found that the cutter consumption for TBM tunneling under high overburden (800 m) was greater than that under lower overburden even with similar rock conditions, likely due to the higher thrust requirement for the TBM advance under higher stress confinement. Nevertheless, some other experiences (Klein et al., 1995; Tarkoy and Marconi, 1991) in contrast with the results above referred to the favorable effects of high confinement on the TBM advance. By laboratory tests, Bordet et al. (Innaurato et al., 2007, P430) confirmed that rock drillability decreased by almost 30% under the high stress confinement (at the stress level of about 30–50 MPa). Chen and Labuz (2006) conducted the wedge indentation test to describe the transition of rock failure from brittle to ductile with increasing confining stress by laboratory tests. Yin et al. (2014) investigated the rock fragmentation process and rock damage zones induced by TBM cutter with biaxial confining stress conditions by using indentation test and AE technology, and concluded that the force for crack initiation and the size of the crushed zone increased with the increase of the confining stress for granite. So far, by using numerical modeling method, the rock fragmentation mechanism during the cutter indentation process and the corresponding TBM performance under stressed condition were investigated by many researchers (Huang, 1998; Ma et al., 2011).

However, some inevitable limitations were found as these approaches were used to systematically study the effect of confining stress. Specifically, the field study cannot reflect all the different stressed conditions, and also it is not easily available for most researchers; for the laboratory test, nearly all the rock specimens in previous researches were in small scale, which failed to

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present the true stress status and the interactions between two adjacent cutters; while for the numerical method, it is difficult to show the real fragmentation process in three dimensions due to the heterogeneity and anisotropy of rock as well as the complexity of TBM penetration.

Full-scale rock cutting experiments, such as the linear cutting test, have been proved to be reliable for prediction of TBM performance (Balci, 2009; Cho et al., 2013; Gertsch et al., 2007). This approach uses full-scale rock specimens and cutting tools, and allows a realistic range of cutting loads to be applied. Therefore, the results derived from the test can directly applied to prediction of field performance (Cho et al., 2013). After Colorado School of Mines in America, Istanbul Technical University in Turkey and Korea Institute of Industrial Technology, a mechanical rock breakage experimental platform was successfully developed by Beijing University of Technology in China. Besides the function of linear cutting, it can conduct double-cutter cutting test, cutting test under stressed condition and rotation cutting test.

In this paper, by using the mechanical rock breakage experimental platform of Beijing University of Technology, the effect of different confining stresses, i.e., the equal and unequal biaxial stress, on TBM performance are studied with full-scale granite rock specimen. This work can provide some guidance for optimizing the TBM operation and predicting TBM performance in TBM tunneling at great depth.

2. Test design

2.1. Parameters design of linear cutting tests

Five levels of confining stressed conditions are investigated as given in Table 1. σ_x represents the stress in the direction parallel to the cutting direction, while σ_y perpendicular to the cutting direction, as shown in Fig. 1. In this paper, "$\sigma_x\_\sigma_y$" is used to represent the confining stressed condition of the rock sample, e.g., "5_5" represents the confining stress of $\sigma_x = 5$ MPa, $\sigma_y = 5$ MPa. Based on the field experience of TBM tunneling, the constant-cross section disk cutter with diameter of 432 mm and cutter spacing of 80 mm are adopted, and the range of penetration is from 0.5 mm to 2.5 mm with the interval of 0.5 mm, as listed in Table 1. The mechanical rock breakage experimental platform and the granite rock specimen for linear cutting test are shown in Fig. 2. The specimens were collected from Beishan area of Gansu Province, China, with the size of 1000 mm × 1000 mm × 600 mm which is large enough to avoid scaling effect. The physical and mechanical parameters of Beishan granite rock are listed in Table 2.

2.2. Test procedure and data analysis

(1) Test procedure

The rock specimen surfaces were very smooth while the true tunnel heading face is rough with cutting grooves. Thus, several cuts were firstly performed on each specimen to ensure the rock surface fully conditioned. Then, according to test design, the cutting tests were conducted from small penetration depth to large penetration depth under each confining stress condition, and the cutter forces (i.e., normal force, rolling force and side force as shown in Fig. 1) and displacements were recorded at the same time. For each penetration depth, cutting of 5–8 layers (or passes) were performed to ensure the collected data valid. After each cutting layer, the fragmentation chips were collected and weighed.

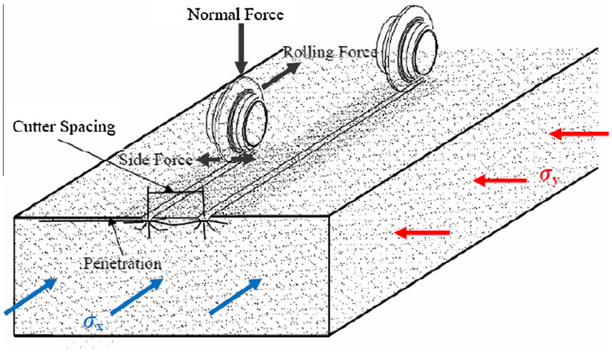

Fig. 1. Schematic representation of lining cutting test (after Gong (2006), p18).

(1) Data analysis and results

Based on analysis of the collected data, the results of the average normal force, the average rolling force, the cutting coefficient (*CC*) and specific energy (*SE*) are obtained, as shown in Table 3. Whereas, the average force is the average value of all the valid data collected from tests of the same penetration depth; *SE* is defined as the energy requirement for excavating unit volume of rock fragments, calculated by Eq. (1).

$$SE = \frac{F_r \times L}{V} \tag{1}$$

where F_r is the rolling force, L is the length of each cutting, V is the volume of rock fragments.

One thing during data analysis should be noted is that, how to identify the validation of collected data for each penetration depth. When the cutting test with a lower penetration was finished, the test with a higher penetration was performed on the same rock specimen. The data of cutting forces present great variation during first one or two layers' cutting. Therefore, the data were invalid until the stable status was obtained during the next layers' cutting.

3. Discussions

3.1. Influence of confining stress on normal force F_n

Normal force determines the thrust requirement. Moreover, since rock cutting by roller disk cutters is in fact an indentation process, the normal force dominates the rock fragmentation. Under a certain cutterhead rotation speed, the penetration per revolution (PRR) in field can be equivalent to the penetration depth in the linear cutting test. Thus, the relationship of normal force and penetration subject to different confining stresses by cutting tests (see Fig. 3) is investigated, in order to predict the effect of confining stress on TBM penetration rate on site.

(1) Equal biaxial confining stressed condition ($\sigma_x = \sigma_y = 5$, 10, 15)

Table 1
Parameters of rock cutting tests.

Confining stress $\sigma_x\_\sigma_y$ (MPa)	Penetration depth P (mm)	Cutter size (mm)	Cutter spacing (mm)	Sample size (mm)
(5_5), (5_10), (5_15) (10_10), (15_15)	0.5, 1.0, 1.5, 2.0, 2.5	432	80	1.0 m ∗ 1.0 m ∗ 0.6 m