Distinct element analysis of mechanism of rock fragmentation induced by TBM cutting rock mass with a couple of cross joints

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ABSTRACT

In this study the Distinct Element Method (DEM) with a size-dependent bond contact model was employed to investigate the fracture mechanism induced by TBM cutting in rock mass with a group of cross joints, where the effect of joint inclination angle under two cutters was analyzed. The center joint outcrop is fixed at a distance of 20 mm with the rock mass center. The DEM results show that the process of rock fragmentation can be divided into three stages: loading stage, unloading stage and residual jump stage. The peak normal thrust decreases gradually with the decrease of joint angle α. During the process, the number of bond failure increases gradually with the increase of invasion depth. There are two distributions of bond failure in different joint angles. One is the bond failure concentrates between the cutter and the shallow joint. The other one is the bond failure crosses the shallow joint and reaches the next joint.

Keywords: TBM, cross joints, cutter, mechanism of rock fragmentation, DEM

1 INTRODUCTION

With the rapid development of underground engineering in China, tunnel boring machine (TBM) has been widely employed in the constructions of major lifeline projects (e.g., transportation, hydraulic and mines) due to its advantages in high boring efficiency and great reliability. It is well known that the efficiency of tunnel boring is affected by many factors, such as joints, caves, high ground stress, etc. Natural rock mass contains many discontinuous planes of different shapes and sizes, which greatly affect the mechanical properties of rock mass. Cross joint is a common form of discontinuous planes in nature rock mass. Thus it is of great significance to study the fracture mechanism of rock mass with a group of cross joints induced by TBM cutting for geotechnical stability.

To date, various laboratory tests have been performed to study the fracture mechanism of rock mass with joints induced by TBM cutting. Yin et al. (2016) studied the influence of joint spacing on rock fragmentation under TBM cutter in linear cutting test. The results showed there was a critical joint spacing for the rock fragmentation process by TBM cutter. When joint spacing is smaller than the critical value, the rock fragmentation process is affected and dominated by the joint. Lin et al. (2018) investigated the crack propagation and failure modes induced by the disc cutter under different confining stresses and joint characteristics. The results showed that the failure mode was affected by the joint orientation at low confining stress. However, when the confining stress increased to a certain value, the joints showed little effect on the failure mode. Liu et al. (2018) investigated the influence of bedding plane orientation on rock breakages in biaxial states by indentation and morphology scanning tests. The results showed that the increase of rotation angle could restrain the propagation of internal and surface cracks, which led to the shrinkage of grooves by the morphology tests. Most researches used rock-like materials (Zou et al., 2012; Ma et al., 2013; Lin et al., 2018) to investigate the fracture mechanism induced by TBM cutting since it was too expensive to perform experiments on the real rock. Thus more work is necessary to extend the above conclusions on rock-like materials to the real rocks.

In 1979, Cundall and Strack (1979) proposed Distinct Element Method (DEM) to reproduce the complex deformation and failure process of granular materials. It is well known that DEM is an effective method and has been widely employed to simulate the mesoscopic fracture expansion, mesoscopic rock mass cumulative damage and complex macroscopic mechanical behaviour under the complex stress paths. Great efforts have been made with DEM to study the fracture mechanism induced by TBM cutting on rock mass with joints where the fracture efficiency and failure modes at different test conditions were further analysed (Bejari and Hamidi, 2013; Eftekhar et al. 2014; Huang and Yang, 2015). Gong et al. (2005, 2006)
explored the influence of joint spacing and orientation on TBM penetration. The results showed that the joint spacing and orientation could significantly affect the crack initiation and propagation as well as the fragmentation pattern, and hence affect the penetration rate of the TBM. Naghadehi and Mikaeil (2017) used two dimensional DEM in to simulate the chipping process in jointed rock. The optimum cutter spacings on the selected hard and jointed rock were identified to be in the range of 110 to 140 mm for different joints frequencies. Jiang et al. (2018) simulated the fragmentation of intact and jointed rock induced by TBM cutting with double cutters using PFC2D. The failure modes for jointed rock breakage can be classified into four types: joint prevent failure mode, joint-propagation failure mode, joint-tendency failure mode and joint-initiation failure mode. However, previous studies mainly focused on the rock mass with one or a group of parallel joints, and little research has been carried out to analyse the failure mechanism on the rock with a group of cross joints. Therefore, this study mainly studies the breaking mechanism on rock with cross joints.

To illuminate the fracture mechanism induced by TBM cutting on rock mass with cross joints, this paper employed DEM to study the cutter-rock interaction from macro to micro perspectives with a reasonable micro contact model of DEM (Jiang et al., 2015).

2 DEM MODEL OF JOINTED ROCK AND CUTTERS

2.1 Jointed rock

The DEM with model proposed by Jiang et al. (2015) was employed to simulate rock mass in this paper. The model was developed based on results of laboratory tests on cemented rods, which took the influence of cementation size on strength envelope into consideration. This model has been proven to be able to capture the main mechanical properties of the rock (Jiang et al. 2016). The simulated rock is marble, whose uniaxial compressive (tensile) strength, modulus of elasticity, poisson ratio, internal friction angle and cohesion are 101.24(20) MPa, 30 GPa, 0.210, 35.23° and 24.6MPa respectively. The microscopic parameters of bond contact model shown in Table 1 have been calibrated by uniaxial compression test, brazilian split test and general tri-axial test (Liao, 2018). The parameter value can be set very small to simulate the joints (Kulatilake et al. 2001; Park and Song, 2009). Thus, the normal and tangential bonding strengths of joints are set as 1kPa respectively in this study.

2.2 Model of cutter

The disc cutter with constant section is adopted in this study which is widely employed in construction. The single cutter is a closed hexagon with six rigid independent walls, where the width and angle are fixed. The distance between two cutters is 200 mm. The normal and tangential stiffness of the wall are slightly larger than that of particles and the friction coefficient is zero.

2.3 DEM simulation scheme

The DEM sample is shown in Fig.1, where the grey blocks stand for the small intact rock and the black lines are the joint plane with thickness being twelve times the minimum particle diameter or 0.3 cm. The grain size distribution of the samples is provided in Fig.2, and the initial void ratio is 0.20. The size of rock mass model is 760mm×380mm and number of particles is about 300,000. The joints are symmetric along the centerline, and the center joint outcrop is fixed at a distance of 20 mm to the rock mass center. The distance between two parallel joints is 80 mm. In order to study the effects of jointed angle $\alpha$ (i.e., the angle between the penetration direction and joints) on rock breaking, the rock models with different values of $\alpha$ (15°,30°,45°, 60°, 75°) were established.

The cutters penetrate into rock mass with cross joints was simulated as follows. Firstly, a homogenous DEM sample with certain microscopic parameters for rocks was generated using the Multi-layer Under Compaction Method (Jiang et al., 2003), which was then compressed to a vertical stress of 38.02MPa by keeping the left and right walls fixed and moving the top and bottom wall inward. Afterwards, the micro bond model was applied to the particles, allowing the sample to arrive at an equilibrium state. Then the top wall was deleted and the DEM sample was cycled to a new stable state. Finally, two cutters were generated and invaded into the jointed rock at a constant speed of 0.1m/s.

3 DEM SIMULATION RESULTS

3.1 Load-invasion curve

Fig.3 provides the thrust-penetration curves with different $\alpha$. Note that only the first leap stage is studied usually for simplification. Because a complete thrust-penetration curve has a group of continuous leaps, we often pay more attention to leap amplitude and frequency, both of which can be reflected by cutter penetration depth and speed in the first leap stage. Fig.3 shows that the rock failure process can be divided into three stages: loading stage, unloading stage and residual jumping stage. During the loading stage, the thrust increases linearly with the penetration depth until a peak value. In the unloading stage, the thrust quickly falls from the peak value to a small value. At the same time the rock mass under the cutter breaks out and the cutter head appears hang in the air, which result in that the cutter head may fall off. In the residual jumping stage, the thrust fluctuates which may be caused by the failure of rock mass. Such fluctuation is often accompanied by a stable value.
Table 1. Microscopic parameters in DEM rock and joint.

| Parameters                        | Intact rock | Joint |
|-----------------------------------|-------------|-------|
| Density $\rho$ (kg/m$^3$)         | 2700        | 2700  |
| Particle normal stiffness $k_n$ (N/m) | $3.1\times 10^6$ | $3.1\times 10^6$ |
| Particle shear stiffness $k_s$ (N/m) | $2.05\times 10^6$ | $2.05\times 10^6$ |
| Particle frictional coefficient $\mu$ | 1.0        | 1.0   |
| Particle rolling resistance coefficient $\beta$ | 1.5        | 1.5   |
| Maximum bond thickness $h_{max}$ (m) | $1.3\times 10^{-4}$ | $1.3\times 10^{-4}$ |
| Bond peak tensile force $\sigma_t$ (Pa) | $1.60\times 10^7$ | 1000  |
| Bond peak compressive force $\sigma_c$ (Pa) | $1.07\times 10^7$ | 1000  |
| Bond modulus of elasticity $E_b$ (Pa) | $1.07\times 10^{10}$ | $1.07\times 10^{10}$ |
| Bond elongation $\varepsilon_p$ | 0.15        | 0.15  |

Fig. 1. DEM model of rock cutting.

Fig. 2. Particle size distribution in DEM samples.

Fig. 3. Thrust-penetration curve.

3.2 Peak normal thrust

Fig. 4 summarizes the peak normal thrust at different $\alpha$. It shows that the peak normal thrust decreases gradually with the decrease of joint angle $\alpha$. Note that the peak normal thrust on the left and right cutter is different at a same joint angle $\alpha$. This is because that the DEM sample is unsymmetrical.

3.3 Bond failure types

Fig. 5 presents the percentage of different types of bond failure when $\alpha=75^\circ$. It shows that there are three types of bond failure during the process of invasion: tensile failure, tensile-shear failure and compression-shear. Tensile-shear failure is significantly more than compression-shear, and tensile failure is the least. The data at other angles are not provided since a same conclusion can be obtained.

3.4 Distribution of bond failure

Table 2 provides the distributions of bond failure when $\alpha=15^\circ,45^\circ,75^\circ$. Note that the line stands for walls and cutters, the points stand for the bond failure. It shows that the number of bond failure increases gradually with the increase of penetration depth.

According to the effects of joints on rock failure, two failure modes are classified as the following:

(1) Bond failure concentrates between the cutters and the shallow joints, and joints prevent further development of the cracks, when $\alpha=15^\circ,45^\circ$.

(2) The bond failure crosses the shallow joints and reaches the next joints. Cracks first initiated around the joint planes and under the cutters, and then they converge with the increase of penetration depth, when $\alpha=75^\circ$.

The second mode is probably because that the vertical distance between two joint is lower than that at the other conditions.

4. CONCLUSIONS

An improved DEM bond contact model based on the laboratory test was employed to simulate the whole process of rock fragmentation by TBM cutters. The effect of jointed angle on fragmentation of the rock with a group of cross joints was investigated and the main conclusions can be summarized as follows:

(1) The process of jointed rock fragmentation can be
divided into three stages: loading stage, unloading stage and residual jumping stage according to the thrust-penetration curves.

(2) There are three types of bond failure during the process of invasion: tensile failure, tensile-shear failure and compression-shear. The bond breaks mostly due to tensile-shear, while least bond breaks due to tensile.

(3) The peak normal thrust decreases gradually with the decrease of joint angle α. During the process, the number of bond failure increases gradually with the increase of invasion depth.

Fig. 5. Bond failure types.

Table 2. Distribution of bond failure.

| Invasion | α=15° | α=45° | α=75° |
|----------|-------|-------|-------|
| 1mm      |       |       |       |
| 2mm      |       |       |       |
| 3mm      |       |       |       |
| 4mm      |       |       |       |
| 5mm      |       |       |       |

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