International Journal of Rock Mechanics & Mining Sciences 91 (2017) 40–48

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

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

Numerical simulation of rock fragmentation induced by a single TBM disc cutter close to a side free surface

Y.M. Xia[a,b,*], B. Guo[a,b], G.Q. Cong[a,b], X.H. Zhang[a,b], G.Y. Zeng[a,b]

[a] *College of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China*
[b] *State Key Laboratory of High Performance Complex Manufacturing, Central South University, Changsha 410083, China*

ARTICLE INFO

Keywords:
Free surface
Disc cutter
Rock fragmentation
JH-2 model
Linear cutting experiments

ABSTRACT

A series of numerical simulations were performed to investigate the influence of side free surface on the rock fragmentation induced by single TBM disc cutter. The JH-2 model combined with a Rankine tensile cracking softening model was adopted to define the rock constitutive model to simulate the rock dynamic fracture process. The distance that allows for cracks just to extend to side free surface under a given penetration is defined as the critical distance, which distinguishes the rock fragmentation patterns between induced by disc cutter close to side free surface and conventional single cutter. The former rock fragmentation pattern is that rock chips in the form of wedge-shaped block spalling from rock specimen due to tensile cracks intersection. From the mean rolling force and the rock debris mass, the specific energy to reflect cutting efficiency was calculated for different distances to side free surface. The cutting efficiencies of former patterns are far higher that by conventional single cutter. The rock macro-fracture patterns and cutting efficiency were then compared with those obtained from linear cutting experiments. The critical distance for Baiyun granite is about 100 mm obtained from experiments, in good agreement with that deduced from numerical simulations. The height difference between the inner and outer cutterhead of the two-stage cutterhead should be more than 220 mm and the distance from first disc cutter on the inner cutterhead to free surface should be less than 100 mm for granite ground.

1. Introduction

A Hard Rock Tunnel Boring Machine (TBM) provides not only high advance rates and excellent working safety, but also a reduced extent of the damaged zone beyond the planned excavation limit compared with the traditional drill-and-blast method.[1,2] Therefore, TBMs have been widely used in the large-scale rock tunnel construction, such as highway, railway and water conservation projects. A TBM completes tunnel excavation which depends on disc cutters installed in the cutterhead to break rocks. As the disc cutter penetrations rock, a crush zone develops beneath the cutter tip, then radial cracks initiate from the crushed zone and propagate downwards and sideward. When these cracks extend the upper free surface or interact with other cracks created from neighboring cuts, the rock chipping occurs. This chipping process is known as the rock fragmentation mechanism induced by conventional single cutter.[3–5] Since the 1960 s, extensive researches have been conducted to investigate the rock fragmentation mechanism, evaluate the optimum cutting condition and measure the cutter forces with various approaches, such as full-scale linear cutting tests, numerical methods and field tests.

Full-scale linear cutting tests have been proved to be a reliable and accurate approach because LCM tests can accommodate a full range of forces and cutting setting, scale effect can be excluded basically, and the uncertainties of any unusual rock cutting behavior not reflected in its physical properties was minimized. For those reasons, the results can be directly applied to the performance assessment of TBM in real practice.[2,5–8] Balci[6] conducted LCM tests on the rocks from tunnel route for calculating the TBM design and performance parameters. Gertsch et al.[9] and Chang et al.[10] carried out LCM tests on Colorado Red Granite and Hwandeung Granite respectively to investigate the optimum spacing of disc cutter. Bilgin et al.[11] and Balci et al.[12] investigated the influence of rock mechanical and structural properties on cutting performance and cutting forces through a series of LCM tests on different rocks.

With the rapid development of computer technology, numerical methods have been introduced to simulate the process of rock fragmentation by many researchers. Kou et al.[13] and Liu et al.[14] employed RFPA-2D and R–T2D respectively to simulate the progressive process of inhomogeneous rock fragmentation induced by single and double indenters. Ma [15] and Gong et al.[16,17] used RFPA-2D and

* Corresponding author at: College of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China.
E-mail address: xiaymj@csu.edu.cn (Y.M. Xia).

http://dx.doi.org/10.1016/j.ijrmms.2016.11.004
Received 14 September 2015; Received in revised form 17 October 2016; Accepted 2 November 2016
Available online 16 November 2016
1365-1609/

UDEC respectively to study the effect of confining stress, joint spacing and orientation on rock fragmentation. Moon [18] simulated cracks formation process induced by multi-indenters to study the optimum cutting conditions by PFC-2D. Cho et al.[2] and Choi et al.[19] employed AUTODYN-3D and PFC-3D respectively to simulate three-dimensional dynamic fracturing failure of rock.

Because loosened surrounding rocks, intense vibration and serious water leakage occur frequently, field tests are rather difficult. Though the field environment allows for field tests, there still are many constraints such as limited test space and requirement of no influence on the normal advance of the machine, tunnel support project and equipment maintenance. Samuel and Seow [20] measured the cutter forces in real time and investigated the forces characteristics in frequency domains. Zhang et al.[21,22] and Entacher et al.[23,24] measured three-dimensional cutter forces in the field used by stain gauge and piezoelectric transducer respectively and investigated the relation between the forces and the geological features.

The above researchers provide thorough understanding about rock fracture process and guide cutter layout and cutterhead design. In recent year, TBMs have encountered challenges in the high compressive strength rock grounds. For instance, TBM encountered with quartz diorite containing 5% iron ore in the water diversion tunnel project in September to October 2015. Under such a serious situation, the cutterhead penetration rate was less than 2 mm/rev and mean normal thrust was over 300 kN per cutter, leading to rapid consumption of disc cutter. Aim to improve cutter cutting efficiency, some new rock fragmentation methods and assistant technologies were introduced by researchers. Raimondo et al.[25] studied the cutter cutting performance by high-velocity and high-pressure water jets assistance. Hassani et al.[26] investigated the influence of microwave irradiation on rocks strength and introduced microwave-assisted mechanical to full-face tunneling machines and drilling. Researchers in the Shield Laboratory of Central South University (CSU) observed large-volume rock blocks spalling from rock specimens as the side face of rock specimen was free surface in the linear cutting experiments, which indicated side free surface had positive function on rock fragmentation.

In the present study, numerical models of rock fragmentation induced by single TBM disc cutter were established to investigate the influence of side free surface on rock fragmentation mechanism. The rock dynamic fracture process were simulated and compared with that induced by conventional single cutter. Then, the effect of distances between cutter and side free surface on rock debris mass, cutter forces and cutting efficiency were analyzed. Later, the linear cutting experiments with different distances were carried out. The rock fracture patterns and cutting efficiencies obtained from numerical simulations were compared with the results from cutting experiments. Finally, the applications of free surface in rock fragmentation and cutting field were discussed.

2. Numerical model

2.1. Modeling of disc cutter

Constant cross section (CCS) and V-prolife cutters are the two choices for hard ground tunneling. But V-prolife cutters encounter so serious tip wear that cause a rapid loss of cutting efficiency. Therefore, they are replaced by CCS cutters for higher load-carry duty, cutting efficiency and long-term durability.[1,2,12] Since the dynamic response of the inner components of cutters is beyond the scope of the research, the CCS cutter ring model was established in present simulation. Cutter ring was 17 in. in diameter with an external diameter of 432 mm, an inner diameter of 384 mm and a width of 76 mm. Generally speaking, the cutter ring was made of H13 steel for its high wear resistance. In present study, however, the steel-4340 material model without yield or failure models was employed to substitute for the H13 steel, which was considered appropriate because the present study puts emphasis on the rock dynamic fracture process rather than the wear resistance.[2]

Table 1
Physical and mechanical parameters of granite.

Parameters	Unit	Value
Density	g/cm^3	2.7
Uniaxial compressive strength	MPa	100.3
Uniaxial tensile strength	MPa	9.8
Bulk modulus	GPa	35.8
Poisson's ratio	–	0.28
Shear modulus	GPa	18.5

2.2. Modeling of rock specimen

Baiyun Granite was selected as rock specimen for numerical simulation, and its physical and mechanical parameters are summarized in Table 1.

2.2.1. Granite material model-JH2 model

In order to simulate the rock dynamic fracture process by disc cutters, the JH-2 model that originally formulated for description of dynamic damage behavior of ceramics[27,28] was adopted to define the rock constitutive.

Polynomial Equation of State: The equation of state of JH-2 model relates the hydrostatic pressure with the same magnitude in all directions to density and internal energy, as follows:

$$P = K_1\mu + K_2\mu^2 + K_3\mu^3 + \Delta P \quad \mu > 0 \tag{1}$$

where P is the hydrostatic pressure; K_1, K_2 and K_3 are material parameter; $\mu$is the volumetric strain, $\mu = \rho/\rho_0 - 1$, ρ is current density and ρ_0 is reference density.

Fig. 1 shows the relation between pressure-P and volumetric strain-μ in JH-2 model. When damage (D) accumulates, an incremental pressure-ΔP is added. And the magnitude of ΔPdepends on the level of damage that material experienced.[28] This extra pressure results in the conversion of distortion energy into a potential hydrostatic energy and the conversion amount is controlled by the fraction $0 \le \beta \le 1$.

Strength model: JH-2 model consists of the strength models of intact, damaged and fractured materials. The strength of intact materials follows the J_2 material theory in the plastic mechanics as follows:

$$J_2 = \frac{1}{2}S_{ij}S_{ij} = \frac{1}{6}[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2] + \tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2$$
$$= \frac{1}{6}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \tag{2}$$

where J_2 is the second invariant of the deviatoric stress tensor; S_{ij} are

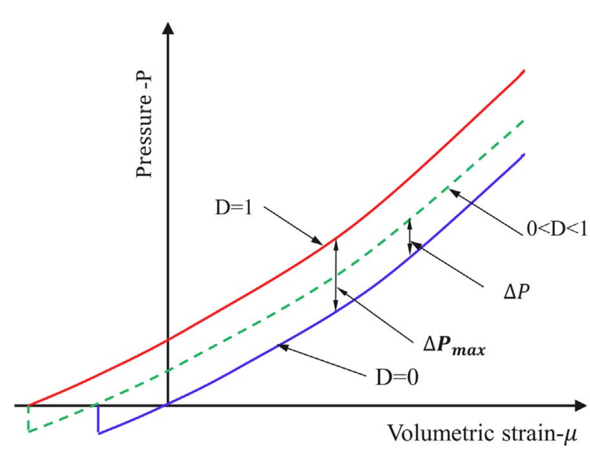

Fig. 1. Relation between pressure and volumetric strain in JH2 model.