Numerical Simulation Study on Rock Breaking Efficiency of Shield Cutters in Large-Size Boulder Strata

Jinguo Cheng¹*, Hua Jiang¹, Xingtong Qu², Yusheng Jiang¹ and Changhao Li¹

¹School of Mechanics and Civil Engineering, China University of Mining and Technology, Beijing, China
²CSCEC Prefabricated Architectural Design & Research Institute Co., Ltd, Beijing, China
Email: chengjinguo1991@student.cumtb.edu.cn

Abstract. Tearing cutters are generally applied to break rocks when shield tunnelling in the strata with large size boulders. To improve rock breaking efficiency, the processes of tearing cutter impacting rock model are simulated, and the effects of cutter mass, impact velocity and spacings on specific energy of rock breaking are studied. The results indicate that the impact energy rises significantly by increasing the cutter mass or impact velocity. With the increase of cutter mass or impact velocity, the specific energy decreases rapidly at first and then increases slowly. The rock breaking efficiency increases firstly and then decreases, and the specific energy has a minimum value. Under the same impact energy, the rock breaking effect by changing the cutter mass is better than changing impact velocity. When cutter spacing increases, the specific energy decreases gradually and then increases. Once the cutter spacing is optimized, the specific energy of rock breaking is the minimum and the rock breaking efficiency is the highest. The research results can provide reference for the cutter design and layout in the similar strata.

1. Introduction

The strata of shield tunnelling are mainly soft soil or hard rock in most metro construction. However, large areas of sand gravel strata rich in large-size boulders may be encountered when shield tunnelling in cities such as Beijing and Chengdu. This kind of strata is characterized by high boulder content, large particle size, high strength and strong abrasion, which brings great challenges to the construction of shield tunnel [1-2]. Many researches have been carried out to study the rock breaking of shield cutter in large-size boulder stratum. Gong and Hasanpour [3-7] used numerical simulation to investigate the rock breaking efficiency according to the parameters such as cutter spacing, rock joint, rock confining pressure. Hasanpour, Rostami et al. [8-10] studied the contact force between shield cutter and rock also by numerical simulation. Zhang et al. [11] studied the continuous process of rock breaking under the rotary-impact loading by ABAQUS and calculated the optimal rotation speed and impact frequency. Xie et al. [12] analyzed the internal stress distribution and crack propagation law of rock under impact load by means of numerical simulation and experimental research and found that the optimal impact energy for rock breaking under impact load exists. Tan et al. [13-15] found that the side slip and stress concentration of the cutter ring is the main reasons for the cutter failure, and the crack propagation law of the rock under cutter impact is obtained. Other researchers have also studied such issues on rock breaking by cutters.
In this paper, ABAQUS finite element analysis software is used to establish the model of tearing cutter impacting large-size boulder, and the rock breaking effects of tearing cutter under different conditions such as cutter mass, impact velocity and cutter spacing are studied, aiming to provide reference for shield cutter selection design in similar strata.

2. Engineering Background
In the Jun-Dong Section (Military Museum Station to Dongdiaoyutai Station) of Beijing Subway Line 9, the total length of the shield construction section is about 1211 m. Due to the complex stratum conditions, the section is key and difficult in the whole construction. The strata can be divided into two categories: conglomerate stratum and pebble layer (7), as shown in figure 1. A composite stratum exists in the transition area of the two strata. The starting shaft and receiving shaft of shield machine and Dongdiaoyutai Station are located in gravel stratum, and the middle section of East Lake in Yuyuantan is sandy pebble stratum. Boulders with super large particle size are randomly distributed in the two stratum structures, and the detected maximum boulder particle size is even greater than 2.0 m, as shown in figure 2(a), which brings great challenges to shield tunnelling and rock breaking by tearing cutters, with high construction risk and difficult shield tunnelling.

![Figure 1. Stratum profile of shield tunnel in Jun-Dong Section.](image1)

3. Model Establishment and Simulation Scheme Design
3.1. Establishment of Model
The model includes two parts: cutter and rock. The cutter size is established according to the actual size of the tearing cutters. The head shape of cutter is simplified to arc shape with the specific size of 250 mm×70 mm×190 mm. The rock is simplified as a cube model with the size of 800 mm×500 mm×500 mm, the largest boulder in the practical engineering. The model establishment and mesh generation are shown in figure 2.

![Figure 2. Finite element model of rock breaking by cutter impact.](image2)
In the simulation, the rock remains fixed in the process of shield cutter impacting, and the horizontal constraint of X direction is applied in the X direction of rock model. The horizontal constraint of Z direction is applied to the Z direction, and the upper boundary of the rock model is taken as the free, and the lower boundary is taken as the fixed. Fix the horizontal displacement of the cutter model in X and Z directions to ensure that the cutter only moves along the Y direction during the impact process. The shield cutter adopts elastic model with density of 14200 kg/m$^3$, elastic modulus of 210 GPa and Poisson's ratio of 0.3. Drucker-Prager constitutive model is adopted, and relevant parameters obtained by consulting engineering data are shown in table 1.

Table 1. Rock model parameters.

| Density /kg·m$^{-3}$ | Modulus of elasticity /MPa | Poisson's ratio | Internal friction angle / (°) | Expansive angle / (°) | Yield strength /MPa |
|---------------------|--------------------------|----------------|-------------------------------|----------------------|--------------------|
| 2590                | 50000                    | 0.22           | 43.5                          | 10                   | 37.1               |

3.2. Simulation Scheme Design

When shield tunnelling in the large size boulder stratum, the impact energy of tearing cutters at different positions on the cutterhead is different in the process of cutterhead rotating, so the rock breaking effect is also different. Generally, specific energy represents the energy consumption for crushing unit volume rock. This paper adopts the specific energy to measure the rock breaking efficiency of cutters. From the energy point of view, the rock breaking effects based on cutter mass, impact velocity and cutter spacing are analyzed.

According to the cutterhead design and initial cutter configuration, the weight of the tearing cutter is 52 kg, the maximum linear velocity of rotation (i.e. impact velocity) is 0.4 m/s, and the impact energy of the tearing cutter is about 4.16 J. To study the rock breaking effect under different cutter mass conditions, the corresponding impact energy is calculated by simulating the conditions of 2 to 10 times of the cutter mass (interval of 2). The corresponding cutter impact velocity is calculated in order to obtain the same impact energy with the setting of cutter mass constant (52 kg). The schemes 1 and 2 are shown in table 2, and then the cutter spacing under the maximum impact velocity based on the optimal cutter mass selected in scheme 1 is studied to analyze the rock breaking effect.

Table 2. Simulation scheme of different cutter mass and impact velocity.

| Scheme | Impact energy/J | Cutter mass/kg | Impact velocity/m·s$^{-1}$ | Remarks |
|--------|-----------------|----------------|-----------------------------|---------|
| 1      | 4.16            | 52             | 0.4                         | Impact velocity 0.4m/s |
| 2      | 8.32            | 104            | 0.57                        | Cutter mass 52kg    |
|        | 16.64           | 208            | 0.80                        |                     |
|        | 24.96           | 312            | 0.98                        |                     |
|        | 33.28           | 416            | 1.15                        |                     |
|        | 41.60           | 520            | 1.26                        |                     |

4. Simulation Study on Rock Breaking Effect of Cutter Under Different Working Conditions

4.1. Comparative Analysis of Different Cutter Mass

According to scheme 1, the simulation cloud pictures of rock breaking with impact velocity of 0.4 m/s under different cutter mass are obtained, as shown in figure 3. The rock fragmentation degree under different cutter mass conditions is analyzed by observing the changes of SDEG cloud image in ABAQUS. SDEG represents the total stiffness damage of the cohesive element. When its value is equal to 1, the cohesive element is considered to be damaged and shows red in the cloud images.

From the top view, with the increase of cutter mass, the damage evolution region of rock surface tends to expand obviously at the beginning and then the expansion speed gradually decreases. This phenomenon indicates that the rock breaking effect has an extreme value. When exceeding the optimal cutter mass, the continuous increase of cutter mass has little effect on the rock breaking. From the sectional view, under the initial impact state, the damage evolution region extends to about 1/3 both
along the rock depth and surface directions. The damage evolution area gradually develops to the horizontal and vertical directions, and the length and width of the area increase, and finally a vertical through crack emerges.

![Figure 3](image1)

**Figure 3.** Top view (first row) and sectional view (second row) of SDEG with different cutter mass.

4.2. **Comparative Analysis of Different Impact Velocity**

According to scheme 2, the simulation cloud pictures under different impact velocity with cutter mass of 52 kg are obtained, as shown in figure 4. The development trends of rock surface damage evolution region are basically the same as that under different cutter mass. However, along the depth direction of rock, with the increase of impact velocity, the crack almost does not extend along the depth direction. The phenomenon shows that increasing the impact velocity has little effect on the crack penetration along the depth direction, which can only increase the surface fracture area of the rock, while not the internal rock fracture.

![Figure 4](image2)

**Figure 4.** Top view (first row) and sectional view (second row) of SDEG at different impact velocity.

4.3. **Comparative Analysis of Different Cutter Spacings**

Cutter spacing is an important design parameter in the layout of shield cutters. The spacing between each adjacent tearing cutter is generally about 90 mm in practical engineering. Different cutter spacing such as 45 mm, 90 mm, 135 mm, 180 mm and 225 mm are simulated, respectively. The cutter mass is set as 208 kg and the impact velocity is 0.4 m/s, as shown in figure 5.

![Figure 5](image3)

**Figure 5.** Cloud pictures of rock breaking effect with different cutter spacings.
When the cutter spacing is 45 mm, the cracks extend along the impact direction to the rock bottom. Due to the close adjacent distance, the broken rock area between the two cutters overlaps obviously. Although the rock breaking effect is significant, the impact energy utilization rate of the cutter is very low. With the increase of the cutter spacing, when the cutter spacing reaches 180 mm, the distance between the two cutters is moderate, and the transverse crushing area intersects, forming a large crushing area, which can peel off the rock block. Almost no overlap exists in the broken area between the two cutters, and the impact energy is fully utilized. When the cutter spacing increases to 225 mm, the transverse crushing area cannot form intersection due to the long adjacent cutter distance. The rock breaking effect of the two cutters does not form an influence superposition area, which is consistent with the rock breaking effect of a single cutter and cannot form a large broken area with the poor rock breaking effect.

4.4. Analysis of Specific Energy for Rock Breaking in Each Scheme
In ABAQUS, the rock breaking part is the failure element in the simulation process. As the end of the tearing cutter is approximately rectangular, and the cross-sectional area of each group of crushing pits is almost unchanged, so the crushing volume of rock is considered basically the same when the cutter invades the same depth in the simulation crushing process. In order to simplify the calculation, the energy consumed per unit depth of rock invasion is used to describe the specific energy of rock breaking, thus analyzing the rock breaking effect of the three schemes.

The specific energy of rock breaking under different cutter mass or impact velocity is firstly analyzed, as shown in figure 6. The impact energy can be significantly increased by increasing the cutter mass or impact velocity. With the increase of the impact energy (i.e. cutter mass or impact velocity), the specific energy decreases rapidly at first and then increases slowly, that is, the rock breaking efficiency increases at first and then decreases. When the impact energy is 16.64 J (i.e. the cutter mass is 208 kg or the impact velocity is 0.8m/s), the specific energy occurs as the minimum. Under the same impact energy, changing the cutter mass gain lower specific energy (i.e. better rock breaking effect) than changing impact velocity.

Secondly, the influence of cutter spacing on rock breaking effect is discussed as shown in figure 7. With the increase of cutter spacing, the specific energy gradually decreases and then increases, that is, the impact energy utilization of the tearing cutter increases first and then decreases. When the cutter spacing is 180 mm, the specific energy gains the minimum value, and the rock breaking efficiency of the tearing cutter is the highest. Therefore, the optimal cutter spacing is considered as 180 mm for shield tunnelling in similar boulder stratum with large size. This can effectively avoid the impact
energy waste caused by too small cutter spacing or excessive consumption of impact energy due to the difficult formation of impact crack penetration caused by too long cutter spacing.

5. Conclusions
In this paper, the dynamic simulation analysis of rock breaking by tearing cutter in the large-size boulder stratum is carried out. The rock breaking effects under different conditions of cutter mass, impact velocity and cutter spacing are analyzed, some conclusions are drawn as follows.

(1) The increase of cutter mass or impact velocity can significantly increase the impact energy of the cutter. The optimal values can be found to minimize the specific energy of rock breaking, i.e. reach the best rock breaking effect under different cutter mass, impact velocity and cutter spacings.

(2) With the increase of impact energy, the specific energy first decreases rapidly and then increases slowly. With the increase of impact velocity, the crack almost does not expand along the rock depth direction, which indicates that increasing the impact velocity has little effect on improving the rock breaking effect. Under the same impact energy, changing the cutter mass has better rock breaking effect than changing impact velocity.

(3) Too close adjacent tearing cutter spacing can cause lower utilization rate of impact energy, while too long cutter spacing also results in low rock breaking efficiency due to the difficult interaction influence of two cutters. With the increase of cutter spacing, the specific energy decreases gradually and then increases, and the rock breaking efficiency can reach the highest when the cutter spacing is 180 mm.

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