Numerical Analysis of Dynamic Response Mechanism of Rock by TBM Disc Cutter

Wang Songtao  
School of Mechatronic Engineering, China University of Mining and Technology, Xuzhou, China, Doctor; e-mail: wst_wst@163.com

Yan Shuai  
School of Mines, China University of Mining and Technology, Xuzhou, China, Lecturer; *Corresponding Author, e-mail: santeer@foxmail.com

Xu Zhiyang  
Mining Products Safety Approval and Certification Center, Beijing, China, Assistant Researcher; e-mail: areord@163.com

Yang Yu  
Yongmei company, Henan Energy Chemical Group, Yongcheng, China, Assistant Engineer; e-mail: sotaang@163.com

ABSTRACT

The dynamic response mechanism of the rock fragmentation and its influential factors by TBM disc cutter are studied in this paper. Firstly, a dynamic response model is established based on the fracture mechanics and finite element theory. Secondly, a fragmentation rule is founded according to the dynamic response model, and then numerical simulations for dynamic response of rock are carried out. Lastly, cutting experiments are carried out in order to check the numerical simulation. The simulation and experiment results for different rocks show that the rock cutting depth and the crushing region decrease with increase of the rock compressive strength. The simulation and experiment results for different loads show that the fragmentation scale is proportional to the cutting force for the same rock.

KEYWORDS: Disc cutter, dynamic response; fracture mechanics, finite element theory

INTRODUCTION

Tunnel boring machine (TBM) is important equipment for the underground engineering with hard geological. In tunneling construction, disc cutters of the TBM are directly used to cut and strip rocks, so the dynamic responses of rocks for disc cutters determine the tunneling efficiency and reliability.

Domestic and foreign scholars have done a lot of research for cutting rocks. Cho tests the disc cutter characteristic for cutting granite [1]. Gong simulates the tunneling rock with double disc cutters, and then analyzes the crack propagation with different joints and optimizes the distance between two disc cutters based on the simulation results [2, 3]. Armin simulates the dynamic progress for cutting rocks, and analyzes the relationship of cutting force between cutting speed and cutting angle [4]. Copur makes cutting experiments on a variety of rock specimen, and
analyzes the relationship between cutting force and brittleness of the rock [5]. 22 cutting experiments are carried out by Bilgin, and the relationship between cutting force and compressive strength, elasticity modulus is obtained [6]. Liu analyzes the effect of cone angle, diameter and compressive strength of coal rock on the cutters by experiments [7, 8]. Experiment methods are accurate for analyzing the dynamic response of the rock, but the high cost and time consuming are the serious disadvantages. Evans [9] and Sun [10] establish the cutting force model according to the maximum tension stress theory, which is widely applied to design mechanisms for the rock crushing machine in Europe and the United States. Nishimatsu obtains the cutting force model by Mohr-Coulomb criterion, which considers the rock property, cutter parameter, and so on [11]. But the dynamic response study of rock has certain limitations by the above cutting force model.

In above references, the dynamic response of rock has been researched by experiment method and cutting force model, but using numerical theory to analyze the dynamic response of rock is still rare. In this paper, a numerical model for dynamic response of rock is established based on the fracture mechanics and finite element theory, and the simulation for the dynamic response of rock is carried out. Lastly, cutting experiments are carried out in order to check the simulation results.

**DYNAMIC RESPONSE MODEL OF ROCK**

Usually, macroscopic mechanical properties of rocks are approximated by brittle cracking constitutive model, which are usually used to simulate the failure and the fracture behavior of brittle and quasi brittle materials, such as the concrete decomposition, rock fracture, and so on. In order to study on the dynamic response of rock, a continuum model of rock is established according to the fracture mechanics and finite element theory, and each nodes of rock is individually calculated out. Crack initiation is measured by the maximum tensile stress criterion [10]. Fig. 1 shows that the crack model based on mode I fracture, and Fig. 2 shows the variation rule of tensile stress changed with crack size.

Taking n-direction crack as an example to illustrate the brittle fracture equation, the tensile stress of crack $\sigma_n'$ can be expressed as:

$$\sigma_n' = f(d_n^{ck})$$  \hspace{1cm} (1)

with

$$d_n^{ck} = \varepsilon_n^{ck} h$$  \hspace{1cm} (2)

where $f(d_n^{ck})$ is the tensile softening evolution function, and $d_n^{ck}$ is the cracking displacement of the crack. $\varepsilon_n^{ck}$ is the cracking strain of the crack and $h$ is the characteristic length of geometric element.

When the rock has cracked, the shear modulus of material $G_c$ can be expressed as:

$$G_c = \rho(\varepsilon_n^{ck}) G$$  \hspace{1cm} (3)

with
\[ \rho(\varepsilon_n^c) = \left(1 - \frac{\varepsilon_n^c}{\varepsilon_{\text{max}}^c}\right)^p \]  

(4)

where \( \varepsilon_n^c \), \( \rho(\varepsilon_n^c) \) and \( G \) are the maximum cracking strain of crack, the shear retention function and shear modulus of materials, respectively. \( P \) is the parameter related to the shear retention function, which can be obtained according to the mechanical properties of materials. In this paper, the material is rock, so \( P = 2 \).

According to the above analysis, the fragmentation rule of rock (n-direction is taken as an example) can be defined as:

\[ d_i^{ck} \geq d_i^{ck} \]  

(5)

or

\[ \varepsilon_n^i \geq \varepsilon_i^{ck} \]  

(6)

where \( d_i^{ck} \) and \( \varepsilon_i^{ck} \) are the failure displacement and failure strain of rock, which can be calculated out by the method in reference [10]. In this paper, Eq. (6) is selected as the fragmentation rule, and \( \varepsilon_i^{ck} = 0.005\text{mm} \). When the cracking strain is larger than the failure strain, the element is considered to be failure element. So the dynamic response of the rock can be analyzed.

ESTABLISHMENT OF NUMERICAL MODEL

The numerical model includes geometric model establishment, materials definition, element division and load application. According to the parameters in Tab. 1, the geometric model of the rock and disc cutter can be established, as shown in Fig. 3. In Tab. 1, the friction coefficient is the friction between the rock and disc cutter. The type of the disc cutter is 17 in (432 mm).
Table 1: Parameter of geometric model

<table>
<thead>
<tr>
<th>Cutter radius $R$ (mm)</th>
<th>Length $l_x$ (mm)</th>
<th>Width $l_y$ (mm)</th>
<th>Thickness $l_z$ (mm)</th>
<th>Friction coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>216</td>
<td>250</td>
<td>500</td>
<td>1800</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Because the elastic modulus of disc cutter is quite larger than the rock, the disc cutter is assumed to be rigid body in analysis in order to improve computing speed. The rock material is defined according to the actual rock and the rock body is meshed by the tetrahedral element with 4 nodes. The contact between the rock and disc cutter is point-face relationship, as shown in Fig. 4.

![Disc cutter and rock](image)

Figure 3: Cutting model  
Figure 4: Definition of rock and disc cutter

NUMERICAL SIMULATION AND EXPERIMENT ANALYSIS

Dynamic Response For Different Rocks

According to the actual engineering, four different rocks are selected and the property parameters are shown in Table 2. The load is set as 80Mpa, and then the dynamic response simulation is carried out.

The load is applied along y-axis on the disc cutter, and then the strain distribution of the rock can be obtained. In order to clearly reflect the strain distribution, the results are enlarged $10^4$ times to display, as shown in Figure 5 ~ Figure 8. The unit is $10^{-3}$mm.

Figure 5 ~ Figure 8 reflect the strain distribution for different rocks. According to Eq. (6), the crushing region of the rock can be judged. The results from Fig. 5 to Fig. 8 show two main aspects: (1) the maximum strain appears at the contact region, and the strain decreases when the location keeps away from the contact region, but the area of the strain increases; (2) the strain of the rock increases when the compressive strength decreases, and the crushing region becomes bigger.
Table 2: Rock parameters

<table>
<thead>
<tr>
<th>Rock</th>
<th>Density (kgm⁻³)</th>
<th>Elastic modulus (GPa)</th>
<th>Poisson ratio (MPa)</th>
<th>Compressive strength (MPa)</th>
<th>Internal friction angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite</td>
<td>2640</td>
<td>73.8</td>
<td>0.22</td>
<td>175</td>
<td>51</td>
</tr>
<tr>
<td>Limestone</td>
<td>2600</td>
<td>41</td>
<td>0.29</td>
<td>100</td>
<td>42</td>
</tr>
<tr>
<td>Phyllite</td>
<td>1700</td>
<td>10</td>
<td>0.25</td>
<td>90</td>
<td>30</td>
</tr>
<tr>
<td>Conglomerate</td>
<td>2400</td>
<td>14</td>
<td>0.12</td>
<td>80</td>
<td>35</td>
</tr>
</tbody>
</table>

Figure 5: Strain distribution of granite
Figure 6: Strain distribution of limestone
Figure 7: Strain distribution of phyllite
Figure 8: Strain distribution of conglomerate

Dynamic Response For Different Loads

Taking the phyllite as the research object, the loads 60MPa and 100MPa are applied on the disc cutter. The strain distributions for different loads are shown in Figure 9 and Figure 10, and the results are also enlarged 10⁴ times to display in order to clearly reflect the strain distributions.

In Figure 9 and Figure 10, the region is the cracking region when the strain is larger than the failure strain according to Eq. (6). The results in Figure 9 and Figure 10 also show that the maximum strain appears at the contact region and the strain decreases when the location keeps away from the contact region. In addition, the results show that the strain and cracking region increase when the loads become larger.
Experiment Analysis

The cutting experiments with disc cutter are carried out for four kinds of rocks. The parameters of four rocks are shown in Table 1. The experiments for three kinds of loads are also carried out for the phyllite. The experiment results are shown in Figure 11 and Figure 12.

Figure 11 is the fitting curve for four kinds of rocks. Along the cutting direction, ten points are selected to measure the cutting depth. Then the fitting curve can be obtained from the measurement results. Figure 11 shows that the cutting depth is the wavy horizontal line along cutting direction for each rock when the rocks bear the same load. This is because the rock is the brittle material. When the rock is cut, the rock is disengaged in blocks. As a block disengages, the...
force which the disc cutter applies on the rock decreases in a short time, so the cutting depth becomes lower in the short time. In addition, Figure 11 denotes that the cutting depth decreases with the increase of the compressive strength, which is consistent with the simulation results of four kinds of rocks in Figure 9.

Figure 12 is the fitting curve for three forces. In Figure 12, the cutting depth is also the wavy horizontal line along cutting direction for each type force, which is the same as in Figure 11. The results in Figure 12 show that the strain and cracking region increase when the force becomes larger, which is consistent with the simulation results for three forces in Figure 10.

CONCLUSIONS

In this paper, cutting model of rock is established based on the fracture mechanics and finite element theory, which can reflect the dynamic response of rock by the disc cutter. Through the presented fragmentation rule, the dynamic responses of rocks under different conditions are simulated, and experiments are carried out in order to check the simulation results. By simulation and experiment results, three main comments can be obtained: (1) the strain of the rock increases when the compressive strength decreases; (2) the strain and cracking region increase when the loads become larger; (3) the cutting depth is the wavy horizontal line along cutting direction which denotes that the disc cutter suffers the impact force from the rock. The research results in this paper can be used to optimize the tunneling program which can improve the tunneling efficiency of TBM and reduce experimental time and cost.

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