Influence of wear state of forward disc cutter in Ignimbrite on its mechanical characteristics

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Abstract: As the main rock-breaking tool, the disc cutter will directly affect the tunnelling efficiency of TBM. The research on the mechanical characteristics of cutter is the key to determine the TBM tunnelling parameters. The mechanical behaviour of disc cutter is still unclear at present, especially when taking wear state into consideration. Based on the above background, finite element method is used to study the rock-breaking characteristics of disc cutter under different working conditions, and the main research contents are: a numerical simulation model of disc cutter during rock-breaking was established by using ABAQUS. According to the characteristics of high compressive strength and high abrasiveness of the slightly weathered Ignimbrite in Fuzhou area, it is determined that the wear form of disc cutter in slightly weathered Ignimbrite is flat-edged wear. Based on this wear form, a study on the change rule of vertical, rolling and lateral forces, specific energy of rock breaking under different degrees of wear were carried on. Results indicate that vertical and rolling forces, specific energy of rock breaking generally increase with the degree of wear, reduce the tunneling efficiency of the disc cutter.

Keywords: Disc cutter; Wear state; Vertical and rolling forces; Specific energy of rock breaking; ABAQUS

1. Introduction

In order to alleviate the increasingly tense situation of ground space resources, medium and large cities at home and abroad have increased the development of underground space[1]. Many cities have been building subways. Shields and Tunnel Boring Machines(TBM) are widely used in the excavation of subway tunnels. As the key excavation tool of these tunnelling machines, the disc cutters will directly participate in excavation of rock masses during the tunnelling process. Its force has an obvious influence on the tunnelling parameters. Therefore, the study of the mechanical characteristics of the disc cutter is very important.

At present, there have been a lot of researches on the rock breaking mechanism of the disc cutters, among which the more representative ones are: (1) Squeezing. This theory was proposed by Evans[2], who believed that the rock was crushed during the process of penetrating the rock by the hob, and the rock breaking force received by the hob was proportional to the area of the funnel pit in the rock crushing zone; (2) Shearing and crushing. Roxborough and Phillip[3] pointed out on the basis of...
squeezing that the disc cutter not only produces squeezing action during the process of pressing into the rock, but the side of the cutter will also produce shearing action on the rock. (3) Tension. This theory was put forward by the Colorado School of Mines\textsuperscript{[4]}, who believed that rock fragmentation was the result of the combined action of shear and tension. However, there is only a few literature to solve the forces on disc cutters related to their wear state\textsuperscript{[5-7]}. Critically, on the other side, the disc cutters are in direct contact with the rock mass and constant wear. After the cutters are worn, it will cause overload of surrounding cutters, abnormal tunnelling parameters and other unusual phenomena. Therefore, it is important to investigate the mechanical characteristics of disc cutters at wear state.

In this paper, finite element method software ABAQUS was used to establish a numerical simulation model of disc cutter during rock breaking. According to the characteristics of high compressive strength and high abrasiveness of the ignimbrite in Fuzhou area, it is determined that the wear form of the disc cutter is flat blade wear. Based on this form of wear, the change law of rock normal force, rolling force, lateral force and rock breaking specific energy under different degrees of wear was studied.

2. Wear state of the disc cutters in Ignimbrite

The length of the section between Linpu Station and Chengmen Station on Fuzhou Metro Line 4 is approximately 4 359.3m. The strata across the section are silty, silty clay and ignimbrite. It selects the Earth Pressure Balance(EPB)-TBM dual-mode shield for construction. In hard rock ground, the rock-breaking tool of the dual-mode shield are disc cutters. Since the ignimbrite is with high compressive strength and high abrasiveness, it is important to investigate how the disc cutters wear and their performances at different wear states.

According to actual engineering statistics, the main type of damage of the disc cutters during tunneling between Linpu Station and Chengmen Station is uniform wear. Therefore, it is necessary to study the rock breaking characteristics when the disc cutters are uniformly worn.

The wear patterns of disc cutters in the process of tunneling in different grounds are not the same, which are mainly affected by the strength and abrasiveness of the rock mass. These wear patterns can be summarized into three types: flat blade wear, hyperbolic blade wear and sharp edge wear, as shown in Figure 1\textsuperscript{[8]}.  

When tunnelling in high-strength and highly abrasive rock masses such as granite and gneiss, the penetration of the disc cutter are small, the rock is more difficult to break, and the wear of the cutter edge is mainly caused by the abrasion of the fresh rock surface. Therefore, the blade is usually flattened.

When tunnelling in grounds with moderate strength but strong abrasiveness, the wear pattern of the disc cutters is often hyperbolic. Due to the general strength, when the disc cutter breaks the rock, it is not only worn by the fresh rock surface, but also by the point wear of the broken rock powder, thus forming a hyperbolic wear form.

If the compressive strength and abrasiveness of the excavated stratum rock mass are both low, such as mudstone, shale, etc., the edge of disc cutter usually appears sharp after being worn. This phenomenon is mainly due to the low compressive strength of this type of rock mass, and the disc cutter easily penetrates the rock to produce more slag. These particles flow through the side of the disc cutter and
become the main abrasive when the tool wears. Therefore, the edge is often worn into a sharp edge shape. The ignimite in Fuzhou is a hard and highly abrasive, so the wear form of the dis cutter represent as flat blade wear. As shown in Figure 2, the dis cutters are indeed in flat-edged states after being worn.

![Figure 2. Picture of on-site worn tools.](image)

3. Analysis of mechanical characteristics of disc cutters considering wear state

3.1. Model building

The disc cutters used in the Fuzhou Metro Line 4 project are 17-inch. The geometric parameters of the disc cutter edge are shown in Figure 3. The elastic modulus of the disc cutter material is $E = 210 \text{GPa}$, and the Poisson's ratio is 0.3. Since only the edge of disc cutter is in direct contact with the rock mass during excavation, and the material stiffness is much greater than that of the rock mass, the disc cutter can be regarded as a rigid body. Therefore, only the edge of disc cutter (Figure 4) was established in the numerical model to improve computational efficiency.

![Figure 3. Geometric parameters (unit: mm).](image) ![Figure 4. FEM model.](image)

3.2. Setting of contact and boundary conditions

The contact type between the disc cutter surface and the rock mass is set to surface-to-surface contact. The contact properties include tangential behaviour and normal behaviour. The tangential behaviour adopts the "penalty" contact method, and the friction coefficient is 0.3; the normal behaviour is selected as "hard". In the whole process of numerical simulation, the bottom and surrounding surfaces of the rock always maintain fixed constraints. The movement of the disc cutter is controlled by the reference point at the centre. The constraints between the reference point and the cutter are rigid-body. In the initial step, the disc cutter is in a static state. The hob will perform a linear cutting motion at a certain speed to
simulate rock-breaking progress. Assuming that there is no relative sliding between the hob and the rock mass, the rotation speed of the hob at this time is:

$$\omega = \frac{v}{R}$$ (1)

3.3. Rock breaking forces with different wear degrees under the Same Penetration:

3.3.1. Calculation condition of worn disc cutter breaking rock:

When the disc cutter wears, the radius of the disc cutter edge becomes smaller and the blade becomes wider, and the contact area with the rock under the same penetration degree will change, so the rock breaking forces will also be affected. In actual engineering, the critical wear of the disc cutters at different positions on the cutter head is also different when changing. The centre disc cutter needs to be replaced when the radial wear is 25mm, and the critical radial wear of the edge disc cutter is 20mm, so it needs to be replaced. In order to explore the relationship between the change of the disc cutter's three-dimensional forces and the degree of hob wear, a disc cutter is used as an example to establish the working conditions shown in Table 1. Since the linear cutting speed of the hob remains unchanged, its rotation speed increases with the increase in radial wear. The schematic diagram of disc cutter edge wear is shown in Figure 5.

| Radial wear (δ) | Penetration (h) | Linear cutting speed (v) | Rotation speed (ω) | Exercise time (t) |
|----------------|----------------|--------------------------|--------------------|------------------|
| 0              | 4              | 500                      | 2.315              |                  |
| 10             | 4              | 500                      | 2.427              | 1                |
| 20             | 4              | 500                      | 2.551              |                  |

Table 1. Calculation condition table of worn disc cutter.

Figure 5. Schematic diagram of tool edge wear (unit: mm).

3.3.2. Rock breaking forces after disc cutter wear:

Table 2 shows the vertical force of the disc cutter under different levels of wear the vertical force increment and increase when it is relatively worn. As it is a straight-line breaking rock, the resultant disc cutter lateral force is close to 0, so no further analysis of the lateral force is made. The average value of the vertical force when the penetration is 4mm and the radial wear of the disc cutter is 0mm, 10mm, and 20mm are shown in Figure 6, and the time history curve of the vertical force of the hob changing with time under each working condition is shown in Figure 7.
It can be seen from the figure that the average value of the vertical force of the disc cutter at a certain cutting penetration increases with the increase of radial wear. When the disc cutter wears out, the contact area between the cutter edge and the rock increases linearly, so the average vertical force also shows a linear increase. At a cutting penetration of 4mm, the average value of the vertical force of the unworn hob is only 147.304kN; when the amount of wear is 10mm, the vertical force increment is 20.585kN, and the corresponding increment percentage is 13.97%. When the disc cutter radial wear continues to increase to 20mm, the average value of the vertical force increases greatly, increasing by 28.75% from the initial value, and its value reaches 189.656kN. In the same way, the greater the penetration of the disc cutter, the greater the vertical force of rock-breaking, and the corresponding increase in vertical force after the disc cutter is worn will be greater than when the penetration is lower, which will seriously affect the tunnelling efficiency of the shields or TBMs.

**Table 2. Changes in the vertical force of the disc cutter under different degrees of wear.**

| Hob radial wear (mm) | Average vertical force (kN) | Relative increase |
|----------------------|-----------------------------|-------------------|
| 0                    | 147.304                     | —                 |
| 10                   | 167.889                     | 20.585 (13.97%)   |
| 20                   | 189.656                     | 42.352 (28.75%)   |

![Figure 6. The vertical force of the disc cutter versus the amount of wear.](image)

(a) average vertical force versus the amount of wear.  
(b) the vertical force and percentage increments versus the amount of wear.

![Figure 7. The time history of the vertical force of the disc cutter with different wear amounts.](image)

(a) 0mm.  
(b) 10mm.  
(c) 20mm.
Refer to Table 3 for the rolling force when the radial wear of the disc cutter is different and the rolling force increment and increase when it is relatively worn. The rolling force average value when the penetration degree is 4mm and the hob radial wear is 0mm, 10mm, and 20mm respectively is shown in Figure 8, and the time history curve of the rolling force change with time under each working condition is plotted in the Figure 9.

Similar to the vertical force, the average rolling force also tends to increase with the increase in the degree of disc cutter radial wear. When the disc cutter is not worn, the average rolling force is 15.225kN, and when the amount of wear is 10mm and 20mm, the average rolling force was as large as 17.417kN and 21.376kN, respectively, compared to the increments when the hob was not worn. 2.192kN (14.40%) and 6.151kN (40.40%), the corresponding increase percentage is slightly larger than the vertical force increase percentage.

### Table 3. Changes in the rolling force of the disc cutter under different degrees of wear.

| Hob radial wear | Average vertical force | Relative increase |
|-----------------|------------------------|-------------------|
| δ(mm)           | (kN)                   |                   |
| 0               | 15.225                 |                   |
| 10              | 17.417                 | 2.192 (14.40%)    |
| 20              | 21.376                 | 6.151 (40.40%)    |

![Figure 8](image8.png)

(a) average rolling force versus the amount of wear.
(b) the rolling force and percentage increments versus the amount of wear.

![Figure 9](image9.png)

(a) 0mm.
(b) 10mm.
(c) 20mm.

Figure 9. The time history of the rolling force of the disc cutter with different wear amounts.
3.3.3. Specific energy of rock-breaking by worn disc cutter

Table 4 and Figure 10 show the rock-breaking specific energy of the disc cutter under different degrees of radial wear.

Figure 10 shows that the specific energy of rock breaking generally increases with the degree of radial wear, and the rock breaking efficiency gradually decreases. It is worth mentioning that the increase in contact area only increases the amount of rock fragmentation in the horizontal plane rather than increasing the amount of rock fragmentation along the depth of cut. In actual engineering, the arrangement of hobs usually considers the optimal knife spacing, so increasing the amount of rock fragmentation in the plane cannot improve the tunnelling efficiency of the shield/TBM well.

Table 4. Rock-breaking specific energy at different degrees of hob wear.

| Penetration (mm) | Hob radial wear (mm) | Rock breaking specific energy (MJ/m³) |
|------------------|---------------------|-------------------------------------|
| 4                | 0                   | 39.38                               |
|                  | 10                  | 45.43                               |
|                  | 20                  | 46.38                               |

4. Conclusions

When the shield/TBM is tunnelling in hard rock, the total thrust of the cutter head is mainly composed of the friction between the side of the cutter head and the rock masses, the friction between the parts of the shield/TBM and the vertical force of each disc cutter. The torque is mainly composed of the friction between the side of the cutter head and the rock masses and the product of the rolling force of each disc cutters and the installation radius. The wear of the disc cutter increases its vertical force (28.75% growth when radial wear reaches 20mm) and rolling force (40.40% growth when radial wear reaches 20mm). It also increases the rock breaking specific energy by 17.78%. Therefore, tunnelling with worn tools not only increases the thrust and torque of the shield/TBM, but also reduces its tunneling efficiency. Therefore, in engineering tunneling, attention should be paid to the wear status of the tools, and worn tools should be replaced in time to avoid more waste of resources.

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References

[1] Chen ZY and Shen ZY. Urban underground space utilization and sustainable development[J]. Undergr Space. 2001(03): 188-191.
[2] Evans I and Pomeroy CD. The strength fracture and work ability of coal[M]. London: Pergamum Process, 1966.
[3] Roxborough FF and Phillips HR. Rock excavation by disc cutter[J]. Int J Rock Mech Min Sci Geomech Abstr. 1975, 75(12): 361-366.
[4] Hassanpour J, Rostami J and Zhao J. A new model for performance prediction of hard rock TBM[J]. Proceedings of rapid excavation and tunneling conference. 1993: 794-809.
[5] Zhao WG, Yang C, Du YL, et al. Analysis on interface between rock and tunnel boring machine using in Qinling-Tunnel[J]. Journal of Northern Jiaotong University. 1999(02): 44-48.
[6] Liu K. Research on the cutting mechanism simulation and wear of TBM disc cutter [D]. Northeastern University, 2013.
[7] Jia Q. Research on wear life prediction model and numerical simulation of disc cutter on shield machine[D]. Southwest Jiaotong University, 2016.
[8] Qiao SS, Mao CJ, Liu C and et al. Full-face rock boring machine[M]. Petroleum Industry Press, 2005.