Research Article

Rock-Breaking Laws of Disc Cutters with Different Height Differences in Hard Rock Strata

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When shield machine traverses through hard rock mass, disc cutters will be abraded to different degrees. Excessive height difference exists between adjacent disc cutters, which critically affects the rock-breaking efficiency. Relying on a shield section of hard rock mass in Qingdao, the disc cutter abrasions are measured on site, and the reason for low construction efficiency is analysed. Subsequently, the discrete element method is used to study the rock-breaking law under different height differences of disc cutters. The ultimate cutter height difference for rock breaking is obtained. According to this, the cutter adjustment scheme is proposed to reduce the cutter height differences on site. Comparing shield tunnelling parameters before and after the cutter adjustment, it is found that the construction efficiency is significantly improved. The results are of great significance for improving the rock-breaking efficiency and increasing advancing speed of shield in hard rock mass.

1. Introduction

With the advancement of China’s urbanization process, urban underground space has ushered in unprecedented development [1-4]. As of December 2020, a total of 45 cities in China have opened urban subways, and the total operating mileage has reached 7969.7 km [5-8]. As the main construction method of urban subways, shield tunnelling has the characteristics of high degree of mechanization, fast advancing speed, and safe construction [9, 10]. In Shanghai, Nanjing, and other soft-soil cities of China, the shield construction efficiency is 5 times than the traditional borehole-blasting method [11, 12]. However, in Qingdao, Chongqing, and other hard rock-based cities, shield construction is prone to cutter failure, difficulty in excavation, and even cutterhead jamming [13, 14]. Therefore, how to break the rock efficiently in hard rock mass is the key to improve the efficiency of shield construction.

At present, most scholars believe that rock breaking by disc cutters can be performed in three ways: squeezing failure, shearing failure, and tension failure [15-19], as shown in Figure 1. Among them, tension failure is the main way for disc cutters to break rock, and it is caused by the penetration of tension cracks in rock mass [20, 21]. Moreover, the cutter parameters, including blade type, blade angle, cutter spacing, and so on [22-25], are studied in depth to improve the rock-breaking efficiency of disc cutters. For example, Cho et al. [26] used particle flow code (PFC) to simulate the crushing characteristics of tuff under the conditions of different blade types and cutter spacings. Karami et al. [27, 28] proposed optimal disc cutter spacing for hard rock and jointed rock mass by the discrete element method. However, the above theoretical and numerical calculations are based on the assumption that disc cutters do not wear out. Actually, there are different degree abrasions on the disc cutters during shield construction, especially in hard rock mass.
The existing research on disc cutter wear mainly focuses on the wear mechanism and abrasion prediction [30]. For example, Elbaz et al. [31, 32] found that tunnelling in mixed ground conditions led to severe wear of the cutter discs. Ren et al. [33, 34] proposed a wear-prediction model incorporating both the geological characteristics and the TBM parameters. There are few studies on the cutter height difference after disc cutter wear. In most cases, the shield is driving in broken rock mass, and the effect of cutter height differences on excavation efficiency is not obvious [35, 36]. Nevertheless, excessive cutter height differences have a crucial impact on the rock breaking in full-face hard rock mass, and it cannot be ignored.

The objective of this study is to obtain the reasonable range of cutter height difference in hard rock mass and research the relationship between the cutter height difference and shield tunnelling parameters. The paper is organised as follows. At first, relying on a shield tunnel project in a hard rock mass on Qingdao Metro Line 8, shield tunnelling efficiency is analysed based on the measurement of cutter abrasion on site. Then, the discrete element method is used to study the rock-breaking laws of different height differences of adjacent disc cutters. Finally, shield tunnelling parameters are studied before and after the adjustment of the cutter height differences.

2. Analysis of Shield Tunnelling Efficiency in Hard Rock Strata

2.1. Engineering and Equipment Situations. The mileage of this tunnel section in Qingdao Metro Line 8 is K60+121.3~K60+877.4, and the length of the tunnel is 756.10 m. The tunnel section is circular, and excavation diameter is 6.7 m. This tunnel adopts prefabricated assembled segment. The inner diameter of segment is 6.00 m, thickness is 0.35 m, and the width is 1.50 m. The tunnel traverses slightly weathered granite at the ring No. 134~400. The tunnel geological profile is shown in Figure 2. Groundwater of this section is mainly bedrock fissure water by geological exploration, and water volume is not large. According to the standard for engineering classification of rock mass (GBT 50218-2014) in China, the rock mass of tunnel section is classified as grade II.

The tunnel is constructed by CTE6950E-1750 shield machine which is produced by China Railway Engineering Equipment Group. The maximum of thrust force, cutterhead torque, rotation speed, and advancing speed is 5060 t, 6317 kN·m, 5.3 r/min, and 80 mm/min, respectively. Moreover, the maximum excavation diameter of machine is 7.03 m, and the maximum of reverse torque is 7580 kN·m.

The opening rate of cutterhead is 30%. Figure 3 shows the components of shield cutterhead. It can be seen from the figure that three types of disc cutters are equipped on the cutter head, which are central cutters (#1~#12), face cutters (#13~#38), and gauge cutters (#39~#49A/B), respectively. The sizes of these disc cutters are 18 inches, and the disc cutter specifications are shown in Table 1. Besides, the cutterhead is also equipped with 61 scrapers and 12 sets of side scrapers.

2.2. Analysis of Shield Tunnelling Efficiency. It can be seen from the tunnel geological profile that when the shield is driven to the 134th ring, cutting face becomes the full-face...
slightly weathered granite stratum. Then, the shield machine excavates normally. The thrust force of shield is 14000 kN, rotation speed is 4.5 r/min, the torque of cutterhead is 1200–2000 kN·m, and advancing speed is between 15 mm/min and 25 mm/min in this hard rock mass. However, under the condition that thrust force and rotation speed remain unchanged, the torque and advancing speed are significantly reduced (i.e., 900 kN·m and 4 mm/min, respectively), when the shield machine reaches 251 rings.

The cutting face and disc cutter abrasion are inspected by opening the cabin to determine the reason for low efficiency. The cutting face is shown in Figure 4. We can see that the rock mass of cutting face is complete, the joints are not developed, and the groundwater is less. At the same time, it is found that the disc cutters are all abraded normally after the inspection of cutters. The abrasion of central cutters is smaller than the abrasion of face cutters. Also, local face cutters’ abrasion is slightly large.

Judging from slagging situation, it indicates that the rock ballast is mostly in the form of block and powder. The particle size of the block is about 2–4 cm, and the content of rock powder is relatively high. Combined with the theoretical analysis of rock breaking, more blocks and powders are present in the rock ballast, indicating that cutting face is dominated by squeezing failure and shearing failure during the rock-breaking process. Under these circumstances, the higher the rock fragmentation degree is, the greater the energy consumed by shield machine and the lower the rock-breaking efficiency will be. The excessive cutter abrasion may have caused the failure of rock-breaking function, after preliminary judgment. Therefore, the abrasions of disc cutters are conducted on-site. Figure 5 shows the measurement results of disc cutter abrasions.

Through the actual measurement of disc cutter abrasions on site, the abrasions of each disc cutter and the height difference between adjacent disc cutters are obtained, as shown in Figure 5. The maximum abrasion of disc cutter is at #38, and the maximum abrasion is 23 mm. The central cutters (#1–#12) have smaller abrasions, and the average abrasion is 5.67 mm. The abrasions of face cutters are slightly larger than those of central cutters. Also, the average abrasion of face cutters is 15.35 mm. The abrasions of gauge

![Figure 3: Shield cutterhead components.](image)

![Table 1: Disc cutter specifications.](image)

| Cutter types       | Central cutters | Face cutters | Gauge cutters | Scrapers         | Side scrapers |
|--------------------|-----------------|--------------|---------------|------------------|---------------|
| Numbers of cutter  | 6               | 26           | 12            | 61               | 12            |
| Cutter heights     | 165 mm          | 165 mm       | 165 mm        | 115 mm(49) + 135 mm(12) | 135 mm        |

![Figure 4: Cutting face.](image)
cutters are large locally. For example, the abrasion of #40 disc cutter is 21 mm, and that of #42 disc cutter is 19 mm. Although the abrasions of individual disc cutters are extremely large, the abrasions of all face cutters do not exceed the specified value of 25 mm for replacement.

It is worth noting that the height differences of adjacent disc cutters at different positions are quite different, as shown in Figure 5. For example, the height difference between #45 and #46 gauge cutters is 0 mm. However, the height difference between #31 and #32 face cutters is 18 mm. It can be seen from the shield tunnelling parameters that the penetration of shield is only 10 mm. Thus, whether such a large height difference between the adjacent disc cutters will affect the rock-breaking efficiency is worthy of in-depth study.

3. Rock-Breaking Laws of Disc Cutters with Different Height Differences

3.1. Microparameter Calibration of Granite. Based on the discrete element method, the two-dimensional particle flow code (PFC2D) is used to study the rock-breaking law of different disc cutters’ height differences in hard rock mass. Given that natural granite is a noncontinuous and uneven material, the uniaxial compressive strength test of the granite is initially conducted to obtain the mechanical parameters. Simultaneously, the microscopic parameters of granite are calibrated by PFC2D to make the simulation result of mechanical parameters closer to the real granite.

According to the standard for test methods of engineering rock mass (GBT 50266-2013) in China, the standard samples with a height of 100 mm and a width of 50 mm are made for physical and mechanical test of granite. Then, parameters such as density, porosity, elastic modulus, and Poisson’s ratio of granite are obtained, as shown in Table 2. Subsequently, a uniaxial compressive strength numerical model is established by PFC2D. The size of numerical samples is the same as standard samples in uniaxial compressive strength test. In this model, the minimum particle size of spherical particles is 0.6 mm, and the maximum particle size is 0.9 mm. The ratio of the maximum particle size to the minimum is 1.5, and the porosity of the granite is 0.8%. Moreover, the upper and lower parts of the model use wall commands to generate frictionless rigid walls, which are used as rigid loading plates. Also, two rows of flexible particle films composed of the same size particles are used on the left and right. The particle contact in the model adopts the parallel bonding contact model. After the granite samples are formed, the initial model is obtained with a confining pressure of 1 MPa.

A series of calculations is made by modifying the parameters to make the mechanical parameters obtained consistent with the test results of the uniaxial compressive strength test. When the linear contact modulus is \(5.4 \times 10^9\) Pa, the stiffness ratio is 1.56, the parallel bonding modulus is 10.4 Pa, the bonding stiffness ratio is 1.56, the cohesion is 1.0 \(\times 10^7\) Pa, and the tensile strength is 2.7 \(\times 10^7\) Pa, the simulation result of the uniaxial compressive strength test is shown in Figure 6. The physical and mechanical parameters of the numerical model, such as elastic modulus, Poisson’s ratio, and uniaxial compressive strength, are obtained, as shown in Table 2. Comparing physical and mechanical parameters of granite obtained from laboratory tests and numerical simulation, it is found that the two sets of parameters are basically the same. Therefore, the above model parameters can be used to calibrate the granite on-site.
3.2. Rock-Breaking Model of Two Adjacent Disc Cutters.
By using the above granite mesoparameters, a numerical model for rock breaking with disc cutters is established. The length of this model is 350 mm, and the height is 200 mm. A total of 8975 spherical particles are generated in the model. At the same time, the wall command is used to establish rigid boundaries on the left, right, and bottom. Assume that the disc cutter is a rigid material and the cutters do not abrade out during model calculation. Similarly, the disc cutters are generated by the wall command in PFC2D. To facilitate model building, the CCS-type disc cutters on-site are simplified to hexagons, as shown in Figure 7. The height of disc cutter is 70.20 mm, blade width is 20 mm, and the blade angle is 10°. The distance between adjacent disc cutters is set to 75 mm, according to face cutters of cutterhead specification.

To study the effects of the different height differences of adjacent cutters on the rock-breaking efficiency, assume that the left disc cutter does not abrade and the abrasion is fixed at 0 mm. 4 sets of rock-breaking models with right disc cutter abrasion of 0, 3, 6, and 9 mm are established. That is, the height differences in the 4 groups of models are 0, 3, 6, and 9 mm. Since the blade angle of disc cutters does not change, the blade width increases as the cutters wear. So, the blade widths of the right disc cutter after abrasion are 20.00, 21.06, 22.16, and 23.17 mm, respectively. The disc cutter parameters of 4 groups of models are shown in Table 3.

The rock-breaking process is simulated by applying a vertical speed to disc cutter to load the upper surface of the model. The disc cutter loading speed is 0.05 m/s. Combined with the actual penetration of disc cutters in the current rock mass, the penetration depth is set to 0.01 m in this numerical model.

3.3. Rock-Breaking Laws of Disc Cutters with Different Height Differences. Through the numerical calculation by PFC2D, the rock-breaking effect of disc cutters under the condition of different height differences is obtained, as shown in Figures 8–11. As shown in Figure 8, the rocks on both sides of disc cutters have shear failure, and massive rocks are peeling off. At the same time, under the vertical force of disc cutter, the rock produces tension cracks and extends to the

![Figure 6: Test results of rock’s unconfined compressive strength.](image)

![Figure 7: Numerical calculation model of rock breaking by disc cutters.](image)
surroundings, and the depth of tension cracks is consistent. When the tension cracks between disc cutters are connected and penetrated, the rock will be tensioned, broken, and detached. As a result, the synergistic rock breaking effect of disc cutters is better, when the height difference is 0 mm.

As shown in Figures 9 and 10, when the right disc cutter abrasion is 3 mm and 6 mm, the left disc cutter penetrates the rock initially, causing compression and shear damage to the granite, and forms a tension crack extending to the periphery. However, it only causes squeezing damage to the rock, after the right disc cutter penetrates the rock. The crack of squeezing failure is connected with the tension crack, and the rock between two cutters is squeezed out afterwards. In comparison with the left disc cutter, the right disc cutter penetrates into the rock with a smaller depth, and the cracks produced are shallower.

As shown in Figure 11, when the cutter height difference is 9 mm, the left disc cutter breaks the rock normally. Conversely, the right disc cutter only touches the rock, and the rock does not produce crushing and shear failures and no tension cracks appear; that is, the right disc cutter does not participate in the rock breaking of disc cutters.

According to the numerical calculation results, when the height difference between adjacent disc cutters is controlled within 6 mm, the disc cutter has a good rock-breaking effect. However, when the height difference of disc cutters exceeds 9 mm, the synergistic rock-breaking ability of disc cutters is invalid, and the rock breaking of disc cutters is mainly based on the squeezing and shearing failure.

4. Analysis of Shield Tunnelling Parameters after Adjustment

4.1. Height Difference Adjustment Scheme of Disc Cutters. As is known to all, shield tunnel excavation mainly relies on central cutters and face cutters to break the hard rock. The abrasions of central cutters are small, so the height differences of face cutters are adjusted on-site. To control the height differences between adjacent disc cutters within 6 mm, the face cutters with the larger height difference are adjusted to other positions. Then, the abraded #44–#49B gauge cutters are replaced with a new disc cutter, which do not play a major role in cutting face excavation. The height difference adjustment scheme of disc cutters is formulated, as shown in Table 4. After adjustment, the new disc cutter abrasions and the new statistics of cutter height differences are shown in Figure 12.

4.2. Comparison of Tunnelling Parameters before and after Cutter Height Difference Adjustment. Through the Qingdao Metro shield construction management information system, the thrust force, cutterhead torque, and advancing speed of shield before and after the adjustment of cutter height difference are extracted for analysis, as shown in Figure 13.

As shown in Figure 13, before the adjustment of cutter height difference, the thrust force is between 15000 kN and 16000 kN, the cutterhead torque is 400–700 kNm, and the advancing speed is 4–7 mm/min. From the perspective of shield tunnelling parameters, the thrust force of shield is reduced, and the torque of the cutterhead and the advancing speed are increased before and after the adjustment of cutter height difference. After adjusting the cutter height difference, the cutterhead torque is increased to 1200–1500 kN·m and the advancing speed increases to 14–20 mm/min with rotation speed remaining unchanged. Moreover, the thrust force of shield is reduced to 12000–13000 kN. Among them, the advancing speed is increased by 3 times than itself before height difference adjustment. In terms of excavation time, it is reduced from 16515 s to 5295 s, and the tunnelling efficiency of shield machine is significantly improved.

The reason for the increase in cutterhead torque is that more disc cutters are in contact with the rock to participate
Figure 9: Rock-breaking effect of model 2: (a) before loading; (b) after loading.

Figure 10: Rock-breaking effect of model 3: (a) before loading; (b) after loading.

Figure 11: Rock-breaking effect of model 4: (a) before loading; (b) after loading.

Table 4: Disc cutter height difference adjustment scheme.

| Adjustment scheme | Original disc cutter | Replacement disc cutter |
|-------------------|----------------------|-------------------------|
| Number            | Abrasions (mm)       | Number                  | Abrasions (mm) |
| #44–#16           | 5                    | #44                     | 12             |
| #41–#20           | 20                   | #41                     | 13             |
| #47–#22           | 19                   | #47                     | 11             |
| #43–#32           | 1                    | #43                     | 13             |
| #49A–#33          | 18                   | #49A                    | 11             |
| #46–#36           | 19                   | #46                     | 12             |
| #45–#38           | 23                   | #45                     | 12             |
| #49B–#40          | 21                   | #49B                    | 8              |
| #48–#41           | 13                   | #48                     | 6              |
| #16–#42           | 19                   | #16                     | 5              |
| #52–#43           | 13                   | #32                     | 1              |
Figure 12: Adjusted disc cutter abrasion and height difference.

Figure 13: Continued.
in rock breaking. In turn, it can prove the beneficial effect of the adjustment of cutter height difference on shield tunnelling efficiency.

Besides, in view of the slagging situation, most of the rock slag produced by shield tunnelling is flaky and blocky after adjusting the cutter height difference. The particle size of the flaky rock slag is about 4–7 cm, and the content of rock powder is less. That is to say, the rock breaking by disc cutters is mainly tensile and shear failures after the cutter height difference is adjusted. The adjacent disc cutters play a synergistic rock-breaking function, which is beneficial to improve the shield tunnelling efficiency in hard rock mass.

4.3. Discussion. Comparing operational parameters of shield before and after adjusting the height differences, it is found that the construction efficiency of shield is obviously improved. It is verified that the height differences of disc cutters have a nonnegligible effect on the rock breaking efficiency in hard rock mass. But, as is known to all, shield tunnelling parameters are influenced by many other factors. The improvement in construction efficiency may not be entirely due to the adjustment of cutter height differences. Furthermore, the authors will study the significance of the cutter height differences on the construction efficiency.

During the establishment of models, the authors made appropriate simplification for disc cutters. Besides, only 4 sets of numerical models with height differences are made, which have certain limitations. Subsequently, the rock-breaking laboratory test with different cutter height differences will also be carried out to determining precisely reasonable height differences in hard rock mass. At the same time, the numerical results can also be further verified.

5. Conclusion

(1) When the shield tunnels in full-face hard rock mass, thrust force and rotation speed remain unchanged and torque and advancing speed are slow. Then, it is necessary to check disc cutters. It may be caused by the excessive height difference of disc cutters.

(2) It is obtained that the height difference of disc cutters should be limited within 6 mm, through discrete element numerical analysis. When the height difference between adjacent disc cutters exceeds 9 mm, it leads to the failure of coordinated rock-breaking function.

(3) The height difference adjustment scheme of disc cutters is proposed. After adjusting the position of disc cutters, it can effectively reduce thrust force and increase advancing speed, as seen from shield tunnelling parameters. Especially, the advancing speed is increased by 3 times than before.

The research results have been preliminarily verified by shield tunnelling parameters on site. It helps to improve the rock-breaking efficiency of disc cutters and increase the advancing speed of shield in hard rock mass. It also can provide a reference for shield construction.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.
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