Analysis of TBM disc cutter wear: a case study of a water conveyance tunnel project in Xinjiang, China

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Abstract. Disc cutter is one of the most significant tools for TBM excavation and it is also a part that is most likely to consume. Its high cost and complicated maintenance process often bring great troubles to a project. Exploring the wear law of disc cutter can not only promote TBM excavation efficiency but also effectively save the cost. In this paper, the wear data of 671 disc cutters over a 3688-meter-long advancing distance was collected from a water conveyance tunnel project in Xinjiang, China, and the wear law of disc cutter as well as the influence of interactions among cutters on disc cutter wear were analysed. It was found that the wear velocity of one single cutter was high in the initial stage, and then it gradually decreased as the cutter constantly wore. The wear velocity of cutter increases greatly when it’s turned from outer area into front area due to its unbalanced wear while serving in outer area. The wear of a cutter increases with the increase of its installation radius, however, this phenomenon is not obvious in outer area, which is mainly because of interactions among cutters, the weaker the interaction among cutters are, the severe the wear of the cutters will be. This study can provide a useful guidance for cutter replacing process and cutterhead layout design in TBM tunnelling projects.

1. Introduction
In recent years, TBM has been widely used in underground engineering construction in the fields like transportation, city construction, water conservancy, energy, national defense, etc. because of its characteristics, e.g safer, more efficient, better tunnelling quality, better construction environment, less over-digging and easier to solve ventilation problems. Cutter is one of the most significant tools for TBM excavation, and it is also a part that is most likely to consume. Its high cost and complicated maintenance process often bring great troubles to a project. According to statistics, in hard rock tunnel projects excavated by TBM, the consumption of cutters takes at least 10% of the total cost of TBM excavation, and it approximately takes 30%-40% of the total construction time to repair and replace the cutters [¹,²]. It can be seen that it is essential to explore the wear law of cutter. Mastering the wear law of cutter and grasping the best cutter replacing time can not only promote TBM excavation efficiency, but also effectively save costs.

Numerous researches on the wear law of disc cutter in TBM tunnel projects have been conducted by scholars around the world. Wan et al. (2002) [³,⁴,⁵] analysed the wear data of cutters used in Qinling
tunnel project, and it was found that there was a linear relationship between cutter wear and advancing distance. Installation position of cutter and geological factors have great influence on cutter wear. Du et al. (2015) studied the correlation between cutter wear and advancing distance. It was found that there was a linear relationship between cutter wear and advancing distance. Geng et al. (2017) analysed the cutter wear data of 6 tunnels, and studied the influence of cutterhead layout on cutter wear, through which it was found that the spiral layout pattern was better than other layout patterns on cutter consumption and cutterhead force balance. Hassanpour et al. (2014) proposed an empirical cutter wear prediction model based on data collected from Karaj water conveyance tunnel in Iran. Su et al. (2020) analysed the data from a metro tunnel in Shenzhen, China, and established a disc cutter wear model based on the plastic removal abrasiveness motion analyses of the cutter ring. Yang et al. (2019) analysed the data of cutter wear from a water conveyance tunnel in Lanzhou, and proposed countermeasures for the control of tunnelling parameters, inspection and treatment of cutter wear as well as daily management, so as to reduce cutter replacement.

It can be seen that few researches have analysed the wear law of one single cutter and the cutter wear influenced by interactions among cutters. In this paper, based on a water conveyance tunnel project in Xinjiang, China, the wear data of 671 disc cutters over a 3688-meter-long advancing distance was analysed. The wear processes of three cutters were followed up, and the cutter wear and the rolling distance of cutters was analysed. Cutter spacing and phase angle difference were used to characterise the interaction among cutters, and the influence of interactions among cutters on cutter wear was analysed.

2. Project overview

This water conveyance project is located at the east of Xinjiang, which is mainly aimed at solving water shortage in Hami. Water is mainly transported through underground tunnels. This research is based on one of the main water conveyance tunnels in this project, which has a length of 16.3km and a diameter of 7.03m. The tunnel depth is about 400m with a slope of 1/2500. It is excavated by an open-type TBM manufactured by CREG.

2.1. Engineering geological conditions

The data of this paper is mainly collected from the chainage 116+833~108+666. Geological profile of this project is shown in figure 1. Rock masses of this tunnel mainly consist of class II and class III, and it’s lithology mainly consists of Devonian metaplace Yundukara group (D2ya) tuff and tuff sandstone, Devonian metaplace Gyantsierkuduk group (D3ja) tuff breccia, and Variscan potassium granite. Rock masses are complete, fresh, thick, and stable, with a quartz content ranging from 5 to 30%. The joints of this tunnel are moderately developed. According to survey result of geological exploration holes, there is a large amount of fissure water above the tunnel, but it is intermittent, which is mainly stored in fault zone and fracture dense zones. When TBM goes through these regions, it may encounter seepage, dripping, or linear running water.

Figure 1. Engineering geological profile along tunnel alignment
2.2. Rock mass conditions

According to survey result of geological exploration holes, the detailed information of rock mass condition in this part is listed in table 1.

| Range          | Length (km) | Lithology | Quartz content(%) | UCS (Mpa) | CAI          | Class |
|----------------|-------------|-----------|-------------------|-----------|--------------|-------|
| 116+966~116+024 | 0.942       | Granite   | 20-30             | 111-161   | 3.97-4.52    | II    |
| 116+024~114+803 | 1.221       | Tuff      | 5-10              | 97.6-148  | 3.4-4.12     | II    |
| 114+803~113+314 | 1.495       | Tuff      | 5-10              | 114-145   | 3.72-4.06    | II    |
| 113+314~111+248 | 2.066       | Tuff      | 5-10              | 101-161   | 3.53-4.11    | II    |
| 111+248~109+755 | 1.493       | Granite   | 20-30             | 103-155   | 3.95-4.43    | II    |
| 109+755~108+666 | 1.089       | Granite   | 20-30             | 110-152   | 4.05-4.37    | II    |

2.3 TBM specifications

An open-type TBM manufactured by CREG was selected to excavate the tunnel (figure 2). Parameters of this machine are listed in table 2. Disc cutter arrangement of this TBM is shown in figure 3. Totally 49 disc cutters are installed on the cutterhead, including 8 cutters in the central area with an average cutter spacing of 101.5mm, 29 cutters in the front area with an average cutter spacing of 77.3mm, 12 cutters in the outer area with an average cutter spacing of 41.8mm. Double-edged disc cutters with a diameter of 17 inches are utilized in the central area, and Single-edged disc cutters with a diameter of 19 inches in diameter are utilized in the front and outer area. Detail information about cutters installation is listed in table 3.

Figure 2. Tunnel boring machine utilized in this project
Table 2. Parameters of TBM

| Parameters                        | Value  |
|----------------------------------|--------|
| Diameter                         | 7.03m  |
| The length of TBM                | 340m   |
| The weight of TBM                | 1400t  |
| Minimum turning radius           | 500m   |
| The maximum slope that can be excavated | ±2%    |
| Thrust cylinder stroke           | 1800mm |
| Maximum thrust                   | 19635kN|
| Cutterhead power                 | 2800kW |
| Cutterhead rotate speed          | 0-9rpm |
| Cutterhead torque                | 5664kN·m|
| Breakout torque                  | 8496kN·m|
| Number of disc cutters           | 49     |
| Disc cutter diameter             | 17 inches and 19inches |
| Average cutter spacing           | 71.73mm|

Figure 3. Disc cutter arrangement

Table 3. Detail information of cutter installation

| Cutter ID | Cutter type     | Diameter(inches) | Installation radius(mm) | The phase angle difference from the previous cutter(°) | The phase angle difference from the next cutter(°) |
|-----------|-----------------|------------------|--------------------------|-------------------------------------------------------|--------------------------------------------------|
| 1         | Center cutter   | 17               | 60                       | —                                                      | 180                                              |
| 2         | Center cutter   | 17               | 161.6                    | 180                                                   | 180                                              |
| 3         | Center cutter   | 17               | 263.2                    | 180                                                   | 180                                              |
| 4         | Center cutter   | 17               | 364.8                    | 180                                                   | 90                                               |
| 5         | Center cutter   | 17               | 466.4                    | 270                                                   | 180                                              |
| 6         | Center cutter   | 17               | 568                      | 180                                                   | 180                                              |
| 7         | Center cutter   | 17               | 669.6                    | 180                                                   | 180                                              |
| 8         | Center cutter   | 17               | 771.2                    | 180                                                   | 270                                              |
| 9         | Face cutter     | 19               | 861                      | 90                                                    | 180                                              |
| Cutter ID | Cutter type | Diameter(inches) | Installation radius(mm) | The phase angle difference from the previous cutter(°) | The phase angle difference from the next cutter(°) |
|-----------|-------------|-----------------|-------------------------|-----------------------------------------------------|--------------------------------------------------|
| 10        | Face cutter | 19              | 949                     | 180                                                 | 135                                              |
| 11        | Face cutter | 19              | 1037                    | 225                                                 | 180                                              |
| 12        | Face cutter | 19              | 1123                    | 180                                                 | 90                                               |
| 13        | Face cutter | 19              | 1203                    | 270                                                 | 180                                              |
| 14        | Face cutter | 19              | 1283                    | 180                                                 | 235                                              |
| 15        | Face cutter | 19              | 1363                    | 125                                                 | 160                                              |
| 16        | Face cutter | 19              | 1438                    | 200                                                 | 285                                              |
| 17        | Face cutter | 19              | 1513                    | 75                                                  | 185                                              |
| 18        | Face cutter | 19              | 1588                    | 175                                                 | 285                                              |
| 19        | Face cutter | 19              | 1663                    | 75                                                  | 220                                              |
| 20        | Face cutter | 19              | 1738                    | 140                                                 | 185                                              |
| 21        | Face cutter | 19              | 1813                    | 175                                                 | 75                                               |
| 22        | Face cutter | 19              | 1888                    | 285                                                 | 160                                              |
| 23        | Face cutter | 19              | 1963                    | 200                                                 | 215                                              |
| 24        | Face cutter | 19              | 2038                    | 145                                                 | 180                                              |
| 25        | Face cutter | 19              | 2113                    | 180                                                 | 235                                              |
| 26        | Face cutter | 19              | 2188                    | 125                                                 | 180                                              |
| 27        | Face cutter | 19              | 2263                    | 180                                                 | 225                                              |
| 28        | Face cutter | 19              | 2338                    | 135                                                 | 290                                              |
| 29        | Face cutter | 19              | 2413                    | 70                                                  | 275                                              |
| 30        | Face cutter | 19              | 2488                    | 85                                                  | 320                                              |
| 31        | Face cutter | 19              | 2563                    | 40                                                  | 235                                              |
| 32        | Face cutter | 19              | 2638                    | 125                                                 | 205                                              |
| 33        | Face cutter | 19              | 2713                    | 155                                                 | 100                                              |
| 34        | Face cutter | 19              | 2788                    | 260                                                 | 140                                              |
| 35        | Face cutter | 19              | 2863                    | 220                                                 | 55                                               |
| 36        | Face cutter | 19              | 2938                    | 305                                                 | 25                                               |
| 37        | Face cutter | 19              | 3013                    | 335                                                 | 320                                              |
| 38        | Gage cutter | 19              | 3084                    | 40                                                  | 125                                              |
| 39        | Gage cutter | 19              | 3152                    | 235                                                 | 70                                               |
| 40        | Gage cutter | 19              | 3216                    | 290                                                 | 80                                               |
| 41        | Gage cutter | 19              | 3276                    | 280                                                 | 245                                              |
| 42        | Gage cutter | 19              | 3330                    | 115                                                 | 345                                              |
| 43        | Gage cutter | 19              | 3376                    | 15                                                  | 190                                              |
| 44        | Gage cutter | 19              | 3415                    | 170                                                 | 280                                              |
| 45        | Gage cutter | 19              | 3447                    | 80                                                  | 320                                              |
| 46        | Gage cutter | 19              | 3473                    | 40                                                  | 205                                              |
| 47        | Gage cutter | 19              | 3494                    | 155                                                 | 235                                              |
| 48        | Gage cutter | 19              | 3508.5                  | 125                                                 | 170                                              |
| 49        | Gage cutter | 19              | 3515                    | 190                                                 | —                                                |

3. TBM cutter wear database
The database of this paper mainly consists of two parts: cutter wear data and TBM tunnelling parameters. The cutter wear data was obtained from daily cutter checking report which is recorded in each morning when TBM stops for maintenance. The daily cutter checking report contains the current...
wear value of each cutter on cutterhead. The TBM tunnelling parameters of each second were obtained through automatic acquisition system installed on TBM, it’s mainly used to calculate the rolling distance of cutters in later section. The data was collected from 116+745 to 115+126, and 112+333 to 110+264, which was a 3688-meters-long advancing distance in total. 671 disc cutters were replaced in this section, including 46 centre cutters, 327 face cutters and 298 gage cutters, as is shown in figure 4. It must be noted that this is not the actual number of replacements, instead, it’s calculated by summing up the cutter wear value at each position, and then divided by 25mm/cutter. The cutter life in this section is 5.5m/cutter or 213m^3/cutter. Figure 4 shows that cutter wear of those disc cutters has a certain correlation with the installation radius of cutters on the cutterhead, the cutter wear increases with the increase of installation radius, which is mainly caused by the increase of the rotational speed and rolling distance along with the increase of installation radius.

![Figure 4. Consumption of cutters in different position](image)

4. Analysis of the disc cutter wear

4.1. The wear law of one single cutter

In order to analyse the wear law of a single cutter, wearing processes of three cutters numbered 101#, 119# and 137# were followed up. All the three cutters were initially installed in the outer area, then as the cutters constantly wore, the cutter wear reached the maximum value allowed in the outer area, which were then transferred into the front area and continuously utilized until they failed. The information of using processes of these three cutters was listed in table 4. The relationship between cutter wear of these three cutters and rolling distance is shown in figure 5. The daily rolling distance of each day could be calculated by Eq.(1), and the wear data was collected from the cutter checking report.

\[ D = v \cdot t \cdot 2\pi R \]  

(1)

Where v is the average rotation speed of the cutterhead, t is the tunnelling time of TBM of each day, and R is the installation radius of a cutter.

| Number | Mileage                | Installation position | Installation radius(m) | Cutter wear per kilometre(mm) |
|--------|------------------------|-----------------------|------------------------|-------------------------------|
| 101#   | KS116+030 ～ KS115+982 | 44#                   | 3.415                  | 0.063                         |
|        | KS115+982 ～ KS115+787 | 35#                   | 2.863                  | 0.025                         |
| 119#   | KS116+419 ～ KS116+377 | 43#                   | 3.376                  | 0.061                         |
|        | KS116+377 ～ KS116+179 | 23#                   | 1.963                  | 0.031                         |
| 137#   | KS116+053 ～ KS115+998 | 48#                   | 3.509                  | 0.027                         |
|        | KS115+982 ～ KS115+787 | 36#                   | 2.938                  | 0.024                         |
Figure 5 shows that there is a certain consistency in the relationship between cutter wear of the three cutters and the rolling distance. When the cutter wear is less than 15mm, wear velocities of the three cutters are 0.075mm/km, 0.061mm/km, and 0.051mm/km, which are far higher than the average wear
velocity during the whole process. Then the wear velocities gradually decreased as the cutters were constantly worn, which was mainly caused by the increase of the width of the cutter ring along with the cutter wear. As is shown in figure 6, the width of cutter ring increases with the wear of cutter, and the wear velocity decreases with the increase of cutter ring’s width. Because these three cutters were in service at different times, their installation positions, cutter forces, rock mass conditions and the wear of adjacent two cutters were different, so that wear velocities of these three cutter are different in figure 6.

![Figure 6. The relationship between the width of cutter ring and wear velocity](image)

Figure 6. The relationship between the width of cutter ring and wear velocity

![Figure 7. Wear process of face cutter and center cutter](image)

Figure 7. Wear process of face cutter and center cutter

Also can be seen from figure 5 that the wear velocity increases greatly when cutters are just transported from the outer area to the front area. According to analysis, the main reason for this phenomenon is associated with the wear formation of cutters in outer area. As is shown in figure 7, the wear formation of face cutter and center cutter is symmetrical and uniform. However, in the process of TBM excavation, gage cutters bear great a lateral force, which causes a result that the cutter wear is often asymmetrical, as is shown in figure 8. When cutters are transported to the front area, they are
completely perpendicular to the tunnel face because there is no installation inclination angle. In this case, only one side of the cutter ring breaks the rock mass, which makes the wear velocity of cutters increase greatly in this period.

3.2 The influence of the interaction between cutters on the cutter wear

Installation radius is a key factor to cutter wear, which increases with the increase of installation radius. However, this phenomenon is not obvious in outer area. Figure 4 shows that, from Cutter No.43 to Cutter No.49, the consumption of cutters decreases as the installation radius increases, and the consumption of Cutter No.48 is extremely smaller than others in outer area. According to analysis, this phenomenon is caused by the interactions among cutters.

Cutter spacing and phase angle difference are the most significant characteristics to describe the interactions among cutters. Cutter spacing is the minimum radial distance between two cutters. Phase angle difference refers to the angle between two cutters in the direction of the cutterhead rotation. As is shown in figure 9, there are three adjacent cutters installed in turn on the cutterhead. Taking the calculation of the sum of phase angle difference of C2 as an example, the phase angle difference between C2 and C1 is $\beta_1$, and that between C2 and C3 is $\beta_2$. If cutter spacing and phase angle difference are small, cutters can help each other by providing a free surface for cutters on both sides during breaking the rock mass. In this case, the rock mass is easy to be broken, which will reduce the wear velocity of cutters.

Figure 9. The diagram of calculation of phase angle difference between cutters

In order to analyze the influence of the interactions among cutters, the wear velocity of cutters (wear of cutters per 1km of rolling) in the outer area is calculated, and as is shown in figure 10. The sum of cutter spacing and the sum of phase angle difference of each cutter in the outer area as well as their changing rate are showed in figure 11 and figure 12. The changing rate is calculated by the difference between two cutters divided by the value of the previous one.

As can be seen from figure 10, figure 11 and figure 12, the sum of cutter spacing of Cutter No.35 to Cutter No.37 varies little, but the sum of phase angle difference increases gradually, which makes the wear velocity of Cutter No.35 to Cutter No.37 increase gradually. Although the sum of cutter spacing and the sum of phase angle difference of Cutter No.38 is much lower than that of Cutter No.37, but Cutter No.38 is the first gage cutter, it gets much more lateral force during excavation. Besides, as is analysed in Subsection 3.1, new cutters are usually put into outer area firstly, when the wear velocity of a cutter is high, so the wear velocity of a gage cutter should be higher than that of a face cutter.
Therefore, it’s reasonable for the wear velocity of Cutter No.38 to be higher than that of Cutter No.37. From Cutter No.43 to Cutter No.49, the sum of cutter spacing gradually decreases, and theses cutters’ sum of the phase angle difference are all smaller than that of Cutter No.42, so we can see that the wear velocity of cutters from Cutter No.42 to Cutter No.49 decreases gradually. Both the sum of cutter spacing and the sum of phase angle difference of Cutter No.48 are much smaller than that of No.47, which makes the wear velocity of No.48 extremely small.

![Figure 10. The wear velocity of cutters in the outer area](image1.png)

![Figure 11. The sum of cutter spacing of cutters in the outer area](image2.png)

![Figure 12. The sum of phase angle difference of cutters in the outer area](image3.png)
5. Conclusion
In this paper, the wearing process data of 671 disc cutters over a 3688-meter-long advancing distance was collected from a water conveyance tunnel project in Xinjiang, China. It was found that the wear velocity of one single cutter was high in initial stage, which then gradually decreased as the cutter constantly worn. The wear velocity of a cutter increased greatly when it was turned from outer area into front area due to its asymmetric wear formation during serving in the outer area. The consumption of cutter increased with the increase of installation radius, and the consumption in outer area was much larger than that in the front area and the central area, because the cutter replacing strategy in project was that new cutters were utilized in outer area firstly. The phenomenon that the consumption of cutter increased with the increase of installation radius was not obvious in outer area, it’s mainly because of the interactions among cutters, which were described through cutter spacing and phase angle difference. It can be figured out from the data that the weaker the interaction between the cutters were, the severer the wear of the cutters would be.

6. References
[1] Bruland A. Hard rock tunnel boring. Fakultet for ingeniørvitenskap og teknologi, 2000.
[2] Jinzhi Liu, Xiaohui Zhi, and Jingbo Guo. A brief discussion on cutting tools for shields. Construction Machinery and Equipment., 2009,40(6): 50-53.
[3] Zhichang Wan, Mingyuan Sha, Yanling Zhou. Study on disk cutters for hard rock (1), application of TB880E TBM in Qinling Tunnel. Modern Tunn. Technol., 2002, 39 (5), 1-11.
[4] Zhichang Wan, Mingyuan Sha, Yanling Zhou. Study on disk cutters for hard rock (2), application of TB880E TBM in Qinling Tunnel. Modern Tunn. Technol., 2002, 39 (6), 1-12.
[5] Zhichang Wan, Mingyuan Sha, Yanling Zhou. Study on disk cutters for hard rock (3), application of TB880E TBM in Qinling Tunnel. Modern Tunn. Technol., 2003, 40 (1), 1-6.
[6] Lijie Du, Shanshan Ji, Lifu Zuo, Haixia Kong, Jinlin Xu, Yanliang Du. Wear and consumption of large diameter disc cutters for hard rock TBM under giant porphyritic granite. Journal of China Coal Society. 2015, 40(12).
[7] Geng Q, Bruland A, Macias F J. Analysis on the Relationship Between Layout and Consumption of Face Cutters on Hard Rock Tunnel Boring Machines (TBMs)[J]. Rock Mechanics and Rock Engineering, 2017.
[8] J. Hassanpour, J. Rostami, S. Tarigh Azali, et al. Introduction of an empirical TBM cutter wear prediction model for pyroclastic and mafic igneous rocks; a case history of Karaj water conveyance tunnel, Iran[J]. Tunnelling & Underground Space Technology Incorporating Trenchless Technology Research, 43(4):222-231.
[9] Weiling Su,Xinggao Li,Dalong Jin, et al. Analysis and prediction of TBM disc cutter wear when tunneling in hard rock strata: A case study of a metro tunnel excavation in Shenzhen, China[J]. Wear,2020,446-447.
[10] JiHua Yang, XiaoPing Zhang, PeiQi Ji, et al. Analysis of disc cutter damage and consumption of TBM1 section on water conveyance tunnel at Lanzhou water source construction engineering[J]. Tunnelling and Underground Space Technology incorporating Trenchless Technology Research,2019,85.
[11] Yadong Xue, Wenliang Yang, Hongwei Huang, Xueqiang Zhang. Cutting rock modes of TBM guage cutters under confining pressure. Journal Of Southeast University. 2017,47(6):1239.
[12] Q.M. Gong, J. Zhao. Influence of rock brittleness on TBM penetration rate in Singapore granite[J]. Tunnelling & Underground Space Technology, 2007, 22(3):317-324.
[13] Zhanxin Zhao. Research on the Wear of TBM Disc Cutter during the Excavating of the Mountain Tunnel[J]. Chinese Journal of Underground Space & Engineering, 2015.
[14] Michael Alber. Stress dependency of the Cerchar abrasivity index (CAI) and its effects on wear of selected rock cutting tools[J]. Tunnelling & Underground Space Technology Incorporating Trenchless Technology Research, 2008, 23(4):351-359.
[15] Quansheng Liu, Jianping Liu, Yucong Pan, et al. A Wear Rule and Cutter Life Prediction Model of a 20-in. TBM Cutter for Granite: A Case Study of a Water Conveyance Tunnel in China[J]. *Rock Mechanics & Rock Engineering*, 50(5):1303-1320.

[16] Q.M Gong, L.J Yin, Q.R She. TBM tunneling in marble rock masses with high in situ stress and large groundwater inflow: a case study in China[J]. *Bulletin of Engineering Geology & the Environment*, 72(2):163-172.

[17] H.M Zhang. Study on relational between repeated cutting and secondary wear of TBM disc cutter. *Tunn. Constr*, 2016, 36 (2), 131-136.