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Springer

Journal of Mechanical Science and Technology 38 (6) 2024

Original Article
DOI 10.1007/s12206-024-0508-z

Keywords:
· Tunnel boring machine
· Cutter life
· Rock integrity
· Tunnelling attitude

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Citation:
Guo, Q., Wang, R., Xiao, Y. (2024). Improved TBM side cutter life prediction method considering rock integrity and TBM tunnelling attitude. Journal of Mechanical Science and Technology 38 (6) (2024) 2873~2883.
http://doi.org/10.1007/s12206-024-0508-z

Received May 30th, 2023
Revised January 16th, 2024
Accepted February 20th, 2024

† Recommended by Editor Jun-Hyub Park



# Improved TBM side cutter life prediction method considering rock integrity and TBM tunnelling attitude

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**Abstract** Cutter life is an important economical index for TBM excavation, and its prediction is widely concerned. In our past researches, a TBM cutter life prediction method is proposed. According to the data collected by the 6th section of the Qingdao metro project, it is found that our past method is suitable for predicting the normal cutter life, but the predicting effect of the side cutter life needs to be improved. The key of our past method is to calculate the consumption coefficient of the tunneling area, which means the consumption of cutter life by tunneling through unit length and is a function of uniaxial compressive strength (UCS) and Vicker's hardness number of rock (VHNR). In this paper, the consumption coefficient is modified to be more suitable for side cutters, by involving two new key influencing factors, joint frequency (Jf) and TBM tunnelling attitude (α), into the regression. The modified consumption rate is calculated according to 94 samples collected from test area I, with the total length of 895m. The proposed method is verified by 98 samples collected from another test area with more complexed and different test area, with the total length of 822 m. The prediction results of the proposed method have high consistence with the actual value. Compared with our past method, the side cutter life prediction accuracy of the proposed method is higher, which is only 22.4 %. The results proved the proposed method is effective for predicting the side cutter life.

## 1. Introduction

Disc cutter is one of the most important equipment of the TBM, also the main structures used to break the surrounding rock. For TBM tunnelling, the economic and time cost used to change the worn cutters always account for about 1/3 of the total [1, 2]. Therefore, cutters wearing rules and performance prediction has been a research hotpot in the field of TBM tunnelling [3-8].

Researches on predicting cutter life can be roughly divided into two kinds. The first one is building theoretical model for predicting cutter life [9-12]. The main method of these research is linear cutting test [13, 14] or simulation [15, 16]. Different with the first type, many researchers make efforts on establishing accurate and useful empirical prediction model of the cutter life based on field data. For example, an energy method for predicting cutter life is introduced, in this research, the specific energy (*SE*) is regarded as one of main influencing factors for cutter life [17]. Some researchers studied the influence factors of the surrounding rock on the cutter life, including the uniaxial compressive strength (*UCS*), Cerchar Abrasivity Index (*CAI*), quartz content (*Q*), Vicker's hardness number of rock (*VHNR*), joint count number (*Jv*) and rock abrasivity index (*RAI*) et al [18, 19]. Besides the rock mass parameters, some indexes for classifying the rock mass, such as $Q_{TBM}$, RMR, are also used for predicting cutter life [18, 20, 21].

Above mentioned researches are aiming at predicting the average value of the cutter life, which is useful for estimating the total cutter cost of the whole project. However, according to our past research [22], the life of cutters located in different position of cutterhead are different, even the life of cutter in same position through different strata also varies greatly. Correspondingly, a research aiming at predicting single cutter life instead of its average value is proposed in our past research. In detail, a theoretical life of cutter is defined according to the installation radius. Meanwhile, different consumption coefficient is calculated by multiple regression method based on the geological properties such as UCS and VHNR. Accordingly, the actual tunnelling distance of each single cutters can be calculated by its theoretical life and the consumption coefficient, and the actual life is determined by both the installation radius and the geological properties. Compared with the researches for predicting the average cutter life, research made by Wang et al. proposed a new idea, and the results can be used to not only estimate the cutter consumption, but also formulate the cutter changing scheme [22], which provided a good reference for this study.

Our research is conducted on the basis of our past research [22] (hereinafter referred to as reference method). Actually, the influence factors on the cutter life are including not only the installation radius and geological properties as he mentioned, but also the tunnelling attitude, especially for the cutter located on the edge of the cutterhead. In this research, the tunnelling attitude is involved into the cutter life prediction model of the reference method [22], and a modified model more suitable for the edge cutter is proposed.

This paper is organized as follow: In the 2nd section, the reference method is verified by field tested data, and its shortcomings in side cutter life predicting is introduced. Further, a corresponding modified method by involving TBM tunnelling attitude and the joint frequency is proposed in the 3rd section. In the 4th section, the modified side cutter life predicting method is modified by field data collected in different area, and the accuracy of the modified method is proved.

## 2. Limitation of the reference method

### 2.1 Introduction of the reference method

In our past research [22], a method for predicting the life of cutters located in different installation position instead of its average value is proposed. This method can be summarized as 3 steps. Firstly, theoretical cutter life is proposed, which is proportional to the reciprocal of the installation radius of the cutter. Then, the consumption coefficient is calculated according to rock class, *UCS* and *VHNR* by regression. In this step, the consumption coefficient can be regarded as the ratio of the actual and theoretical tunnelling distance. Finally, the starting mileage of each cutter is involved, and the end mileage can be calculated according to the theoretical cutter life and the consumption coefficient, and the actual working distance of the cutter, i.e. the actual cutter life is obtained. The detail working process of the method is described as follow:

1) Define the theoretical cutter life

In the reference methods, the cutter life is measured by the total excavation distance along the direction of the tunnel, also the difference of the starting and ending mileage. In addition, for the cutters with the same size and material, the travelling distance is regarded as the same. The travelling route of each cutter approximately consist of multiple circles, and the number of the circle is recorded as $C_m$. Therefore, the theoretical cutter life $H_T$ can be calculated by Eq. (1) [22].

$$H_T = \frac{C_m \cdot PR_{ev}}{2\pi r} = \frac{K}{r} \,. \tag{1}$$

In Eq. (1), $PR_{ev}$ represent the penetration of TBM, i.e. the tunnelling distance when the cutter head rotated a circle, and $r$ means the installation radius of the cutter. Among the factors for calculating $H_T$, $C_m$ is regarded as constant, $PR_{ev}$ is independent of the cutters position. Therefore, multiple factors in Eq. (1) can be simplified to be $K$, which is also regarded as a constant. In other words, the theoretical cutter life is proportional to the reciprocal of the cutter installation radius. According to the regression of the field test data in the reference research, the value of $K$ is about $2.37\times10^5$.

2) Calculate the consumption coefficient based on the rock mass parameters

The consumption speed of the cutter life is different when the cutter excavated through different strata. Therefore, another definition, i.e the consumption coefficient is proposed in the reference method [22]. The consumption coefficient is regarded as the ratio of the actual and theoretical tunnelling distance. If the consumption coefficient is relatively high, it is means that the consumption speed of the theoretical cutter life is high, while the actual tunnelling distance and the cutter life is short.

In the reference research, multiple consumption coefficient suitable for different class rock is given by regression, as Eq. (2) shows [22]. $K_2$, $K_3$, $K_4$ and $K_5$ are suitable for the rock of class II, III, IV and V, respectively. Among them, the $K_2$ is positively correlated with *UCS* and *VHNR*, $K_3$ and $K_4$ are positively correlated with *UCS* only, and $K_5$ is a constant of 0.37. Generally speaking, the consumption coefficient increases with the increasing of the rock class, *UCS* and *VHNR*. In other words, under the condition of higher rock class, *UCS* and *VHNR*, the cutter life is lower.

$$\begin{cases} K_2 = 4.08\times10^{-3}\times UCS + 7.96\times10^{-4}\times VHNR + 0.88 \\ K_3 = 5.98\times10^{-3}\times UCS + 0.59 \\ K_4 = 5.52\times10^{-3}\times UCS + 0.41 \\ K_5 = 0.37 \end{cases} \tag{2}$$

3) Calculate the actual cutter life

Based on the theoretical cutter life, the consumption coefficient and the starting mileage of the cutter, the ending mileage can be calculated by Eq. (3) [22]. What needs special explanation is that, in the reference research, the surrounding rock along the tunnel is divided in to several sections, and each section is described by the same combination of rock mass parameters. Therefore, the reduction of the theoretical life is calculated in section by section. The product of the length of each section and its consumption coefficient regarded as the reduction of the theoretical cutter life. When the theoretical life reduces to zero, the ending mileage and the corresponding actual cutter life can be obtained.

$$H_T^{'} = \sum_{i=1}^{n} H_{Ti}^{'} = \sum_{i=1}^{n} \left( K_i \cdot H_{Ti} \right) . \quad (3)$$

In Eq. (3), *n* represents the total number of the continuous area with different class rock. $H_{Ti}$ represents the actual distance of the $i^{th}$ area, while $K_i$ means the consumption coefficient suitable for the $i^{th}$ area, which is calculated by Eq. (2). The product of $H_{Ti}$ and $K_i$ is recorded as $H_{Ti}^{'}$, which represents the weighted distance of the $i^{th}$ area. In this method, the weighted distance of all areas through by a same cutter is recorded as $H_T^{'}$, which is the theoretical cutter life of the cutter. The $H_T^{'}$ of cutters located in same position is a constant.

## 2.2 Field data

In this section, the reference method is verified by the field data collected in the Heluobu station to Zhuamashan station of the 6$^{th}$ section of the Qingdao metro project, which is located in Shandong Province, China. This area with the total length about 1750 m is excavated by a TBM with the diameters of 6.0 m, which equipped with totally 41 cutters with the diameter of 17 inches (432 mm). The lithology along the tunnel is mainly consist of gneiss and diorite. In this tunnel, two test areas are selected to conduct the research. Among them, test area I is from the mileage of YDK 50+593 to YDK 49+698, with the length of 895m, which is selected to establish the modified side cutter life prediction method. The test area II is from the mileage of YDK 51+637 to YDK 50+815, with the length of 822 m, which is used to verify the research. The sketch map of the two test areas is shown in Fig. 1.

Test aera I of the mileage from YDK50+593 to YDK49+698 are selected to verify the reference model. In this aera, the mileage and the cutter number of each cutter changing are recorded. On this basis, totally 94 samples of cutter life are calculated according to Eq. (3), which are regarded as the actual value of the cutter life. For obtaining the calculated value of the cutter life by the reference model, there are 4 key factors need to know, i.e. the installation radius of each cutter, the rock class, the uniaxial compressive strength (*UCS*) and the Vicker's hardness (*VHNR*) along the test area. Therefore, the core drilling work and laboratory test are conducted in the test area. The average test values of *UCS* and *VHNR* are approximately considered to describe the whole section with the same rock class. The rock class and rock mass parameters along the test area are shown in Fig. 1. According to the field test *UCS* and *VHNR*, the consumption coefficient of each section in the test area can be calculated as follow.

## 2.3 Verification results and the limitation of the reference method

To compare the actual cutter life and verifying the reference method, the corresponding predicted cutter life are calculated by the reference method based on the field rock mass data and Eqs. (1)-(3). According to the reference research, the constant value of *K* in Eq. (1) is $2.37 \times 10^5$. Combination with the installation radius of each cutter and the geological data, the predicted cutter life is calculated and compared with the actual one as Fig. 2 shows.

The investigated TBM is equipped with 42 cutters. Among them, 10 cutters (33#-42#) are side cutter, whose included angle with the tunnel face is acute. As Fig. 2 shows, the samples of the normal cutter are evenly distributed on both sides of

Table 1. Rock mass parameters and corresponding consumption coefficient of each section.

| Starting | Ending | Length (m) | Rock class | VHNR | UCS (MPa) | $K_i$ |
|---|---|---|---|---|---|---|
| YDK 50+593 | YDK 50+321 | 272 | IV | 240 | 37 | 0.61 |
| YDK 50+321 | YDK 50+101 | 220 | V | 214 | 26 | 0.37 |
| YDK 50+101 | YDK 50+011 | 90 | IV | 223 | 40 | 0.63 |
| YDK 50+011 | YDK 49+781 | 230 | V | 202 | 21 | 0.37 |
| YDK 49+781 | YDK 49+698 | 83 | II | 268 | 52 | 1.31 |

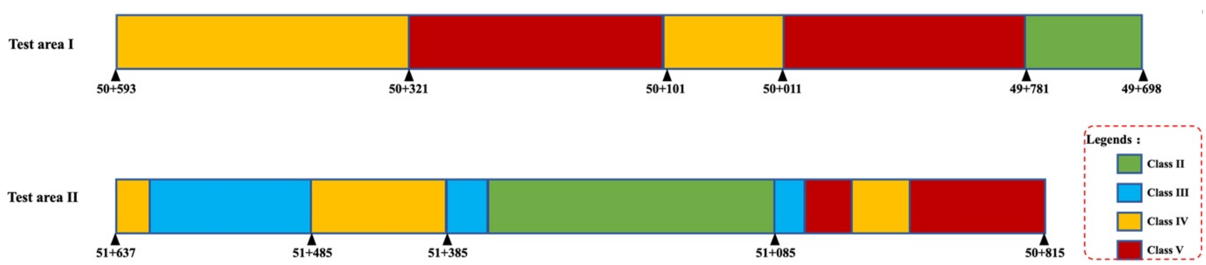
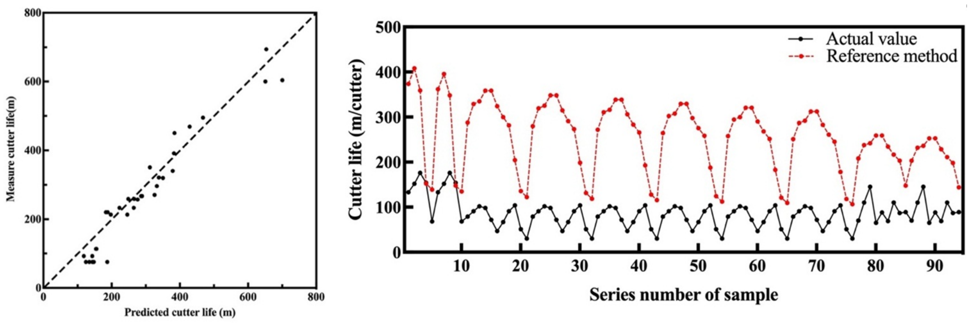



Fig. 1. Section division and corresponding rock mass parameters.




(a) (b)

Fig. 2. The comparison results of the measured and predicted cutter life by the reference method: (a) comparison of the average side cutter life; (b) comparison of all of the side cutter life samples.

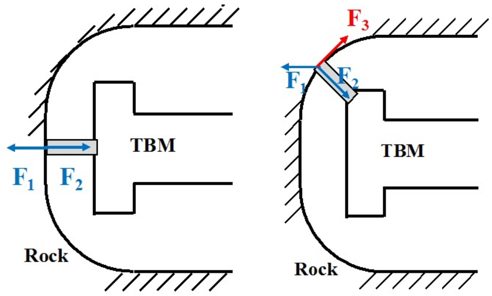



Fig. 3. The arrangement and tunnelling force of normal and side cutters.

the 1:1 line. However, all of the side cutter samples are distributed below the 1:1 line. Compared with the normal cutters, the errors of side cutter samples are relatively large. Some predicted side cutter lives even reach 3 times of the actual values. The results show that, although the reference method has acceptable prediction effect of the normal cutter, it underestimates the wear degree of the side cutter, and the predicted side cutter lives are far beyond the actual values.

Theoretically, there are differences of the arrangement mode and worn principle between the normal and side cutter. In TBM tunnelling, the thrust of the cutterhead is along the tunnel ($F_1$ in Fig. 3). The reaction force of the tunnel face on the normal cutter ($F_2$ in Fig 3(a)) is nearly opposite to $F_1$. Differently, the rock surface in contact with the side cutter is inclined, resulting the reaction force on the side cutter ($F_2$ in Fig. 3(b)) and $F_1$ not being in the same line. Therefore, the side cutters bear greater lateral forces ($F_3$ in Fig. 3(b)) compared with the normal cutter, which has large negative influences on the cutter life, and it is also the one of the main reasons why the regression suitable for normal cutter overestimates the side cutter life. It is necessary to modify the prediction effect of the side cutter life.

## 3. Method

The 2nd section of this paper analyzed the prediction effect of the reference method. Generally, the reference method has acceptable prediction accuracy. However, there is still some limitation in the prediction of the side cutter life according to the prediction results (Fig. 2) and the theoretical analysis (Fig. 3). Therefore, this research proposed a prediction method used to predict the side cutter life on the basis of the reference method.

### 3.1 Analysis of influencing factors of cutter life

In the reference method, the key factor resulting in the difference of cutters in the same position is the consumption coefficient, which is determined by the rock class, *UCS* and *VHNR*. This method has been proved to be suitable for predicting of the normal cutter life. However, there are still some factors influencing the cutter life ignored by the reference method needs to be analyzed. These factors might be good for improving the predicting effect of the side cutter life. There are 2 factors ignored by the reference model, and they are involved in this research and described as follow.

1) Integrity of the surrounding rock

Rock is a kind of complex material containing structural planes. Integrity is used to comprehensively measuring the tensity, quantity, size and distribution of the structural planes. In general, surrounding rock with low integrity is beneficial to prolong the cutter life, because the existing structural planes accelerates the rock breaking and reduces the force for tunneling. However, too broken surrounding rock also leads to irregular rock slice, which may have negative influence on the cutter by impacting. Therefore, the influencing of the rock integrity on the cutter life is significant and complexed. In this paper, the joint frequency ($J_f$) is used to measure the rock integrity. It can be manually counted in the field, means the joints number in unit length, as shown in Eq. (4).

$$J_f = N / L . \tag{4}$$

In Eq. (4), N represents the joints numbers in the survey line, while L means the length of the survey line. In the field investigation, the survey lines are set along the tunnelling direction, while the joints with large size and nearly parallel with each other are selected and counted. The photo of the joint frequency collection is shown in Fig. 4.

2) Tunnelling attitude

No matter the types of the TBM, the common point of controlling tunnelling attitude is to change the direction of the main beam and the cutterhead. In controlling the TBM attitude, cutterheads are always not to be parallel to the tunnel face, which leads to the penetration changes of the cutters. Especially, the installation radius of the side cutter is larger than the one of the normal cutters, and the penetration changing range of the side cutter is also larger. Therefore, the influence of controlling tunnelling attitude to the side cutters cannot be ignored.

Although the TBMs are always equipped with mechanical data acquired system, the deflection angle of the main beam or the cutterhead are not included in the acquired system. In this research, the deflection angle of the cutterhead is calculated indirectly, on the basis of the stroke of the thrust cylinders. In detail, the TBM is equipped with 4 groups of the thrust cylinder located to the top, bottom, left and right of the main beam, as Fig. 5 shows. Multiple thrust cylinders are divided into four groups. The stroke differences between the four group thrust cylinders result in the bias of the cutterhead, which is also the basis for calculating bias angle (Eq. (5)).

$$\begin{cases} \alpha_H = \tan^{-1}\dfrac{s_C - s_A}{d_{AC}} \\ \alpha_V = \tan^{-1}\dfrac{s_D - s_B}{d_{BD}} \end{cases} . \quad (5)$$

In Eq. (5), $\alpha_H$ and $\alpha_V$ means the deflection angle of the cutterhead in horizon and vertical direction, $s_A$, $s_B$, $s_C$ and $s_D$ represents the cylinders stroke of each group, $d_{AC}$ means the distance between the geometry center of group A and C, and $d_{BD}$ means the distance between the geometry center of group B and D. According to Eq. (5), the deflection angle of the cutterhead can be collected and used to measure the TBM tunnelling attitude. On the basis of the horizon and vertical bias $\alpha_H$ and $\alpha_V$ , the included angle between the tunnelling direction and the design route $\alpha$ can be calculated by Eq. (6).

$$\alpha = \tan^{-1}\left(\sqrt{\tan^2\alpha_H + \tan^2\alpha_V}\right) . \quad (6)$$

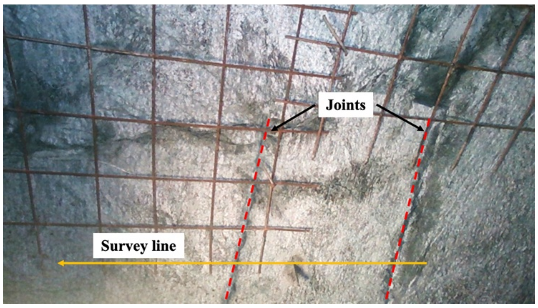


Fig. 4. Field collection photo of the joint frequency.

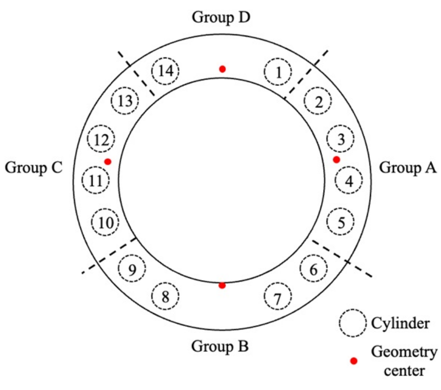


Fig. 5. The diagram of the thrust cylinder distribution.

## 3.2 Modification of the reference method

To improve the reference method to be suitable for the side cutter, joint frequency $J_f$ and tunnelling attitude $\alpha$ are involved to modify the consumption coefficient by multiple regression. There are two steps to achieve this target. First, the consumption coefficient of the 5 areas mentioned in the 2nd section are modified to reduce the difference between the predicted and actual side cutter life. By this step, a series consumption coefficient of the 5 areas can be obtained. In the second step, a relationship between the old and new consumption coefficient is obtained, and the relationship is including two new factors, $J_f$ and $\alpha$ , which are ignored in the reference method. In this section, the 2 steps of the method will be described in detail.

1) Modified consumption coefficient of each area

The consumption coefficient is calculated by regression according the side cutter life samples. Assuming that the testing area is including *m* area with different rock class and rock mass parameters, and there are totally *n* samples of the side cutter samples. The actual and predicted value of the $j^{th}$ number is record as $H_{Aj}$ and $H_{Tj}$. The predicted cutting length of the sample in the $i^{th}$ area are expressed as $H_{Tji}$. Obviously, the relationship between $H_{Tj}$ and $H_{Tji}$ can be expressed by Eq. (7).

$$H_{Tj} = \sum_{i=1}^{m} H_{Tji} . \quad (7)$$

The modified consumption coefficient in each area is recorded as $k_i^{'}$ , and the new predicted side cutter life ( $H_{Tj}^{'}$ ) can be approximately expressed Eq. (8).

$$H_{Tj}^{'} = \sum_{i=1}^{m} k_i^{'} \cdot H_{Tji} . \quad (8)$$

The target of modifying the consumption rete is to make the predicted and actual side cutter life as close as possible. In this research, the least square method is used to achieve this target, and the error square sum is regarded as the objective function, as Eq. (9) shows.

Table 2. Optimal regression using different mode and the corresponding error.

| Mode | Equation | Consumption coefficient results | | | | | Error square sum |
|---|---|---|---|---|---|---|---|
| | | $k_1$ | $k_2$ | $k_3$ | $k_4$ | $k_5$ | |
| 1 | $k_i^* = k_i + 0.6 \cdot \alpha - 0.9 \cdot J_v - 0.9$ | 4.66 | 2.94 | 3.99 | 3.48 | 3.29 | 1.57 |
| 2 | $\boldsymbol{k_i^{''} = 0.20 * \alpha \cdot (k_i - 1.2 \cdot J_v + 6) - 4.4}$ | 4.05 | 2.77 | 4.56 | 4.21 | 2.83 | **0.49** |
| 3 | $k_i^* = (k_i + 1.4 \cdot J_v - 1.6)^{-5\alpha} + 3.4$ | 3.40 | 3.40 | 4.99 | 3.40 | 3.44 | 0.95 |

$$\min_{k_i^{'}} \left[ \sum_{j=1}^{n} \left( H_{Aj} - H_{Tj}^{'} \right)^2 \right]. \tag{9}$$

By Eq. (9), a series of consumption coefficients ( $k_i^{'}$ ) can be calculated, which is used as the basis of the next step.

2) Correction equation of the consumption coefficient

The consumption coefficient of $i^{th}$ area in the reference method can be expressed by $k_i$. By involving $J_f$ and $\alpha$, the consumption coefficient is modified as $k_i^*$, and this process can be expressed by Eq. (10).

$$k_i^* = f\left(k_i, J_f, \alpha\right). \tag{10}$$

In the reference method, the consumption coefficient $k_i$ is a function of *UCS* and *VHNR*, and the two rock mass parameters are linear terms. Therefore, the new added rock mass parameter $J_f$ also involved in calculating $k_i^*$ as linear term. Based on the $k_i$ calculated by the reference method, $J_f$ and TBM attitude $\alpha$ are involved to build new regression equations. In this paper, three different forms of the regression equations are tried as Eqs. (11a)-(11c). In reference method, $k_i$ is a function of rock mass parameters, therefore, in the new equations, rock mass parameter $J_f$ is weighted and linearly superimposed with $k_i$. After superimposing *J* to $k_i$, $k_i + b \cdot J_v + c$ is formed as a fixed term. On these bases, tunnelling parameter $\alpha$ is tried as different mode, including independent first-order term (Eq. (11a)), coefficient of the fixed term (Eq. (11b)), and index of the fixed term (Eq. (11c)), to form different equations. The Eqs. (11a)-(11c) are tested by the collected data, and the one with highest accuracy is chosen to be used in the proposed method.

$$\begin{cases} k_i^* = k_i + a \cdot \alpha + b \cdot J_v + c & \text{(11a)} \\ k_i^* = a\alpha \cdot \left(k_i + b \cdot J_v + c\right) + d\ . & \text{(11b)} \\ k_i^* = \left(k_i + b \cdot J_v + c\right)^{a\alpha} + d & \text{(11c)} \end{cases}$$

In Eqs. (11a)-(11c), $k_i^*$ is the calculated value of the consumption coefficient of $i^{th}$ area. Different with the regression results $k_i^{'}$ in the 1st step, the $k_i^*$ is directly related with the rock mass parameters and the TBM attitude, while $k_i^{'}$ is regarded as the most reasonable consumption coefficient according to the actual measured side cutter life. In this step, a series of undetermined coefficients a, b, c and d should be determined by the least square method, to make $k_i^*$ and $k_i^{'}$ as closed to each other as possible. The objective function of this step is shown in Eq. (12).

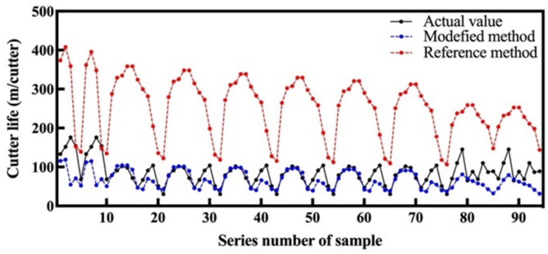



Fig. 6. Test results of the modified method by the data collected in test area. I.

$$\min_{a,b,c,d} \left[ \sum_{i=1}^{m} \left( k_i^{'} - k_i^* \right)^2 \right]. \tag{12}$$

### *3.3 Modification of the reference model*

According to Eq. (12), the most reasonable regression form and the undetermined coefficients can be obtained. Further, the modified consumption coefficient and the predicted side cutter life are obtained. In this research, the 94 samples of side cutter life collected in the 5 areas, which is mentioned in 2nd sections, are used to solve the series of regressions in Sec. 3.2.

In Eqs. (7)-(12), *m* and *n* equal 5 and 94, respectively. $H_{Tji}$ used the value predicted by the reference method, and $H_{Aj}$ is the actual measured results. The calculated results of $k_1$, $k_2$, $k_3$, $k_4$, and $k_5$ are 4.02, 3.13, 4.86, 3.72, 2.83, respectively. The results are obtained by field data and regarded as reasonable consumption coefficient s. On this basis, take the results from $k_1$ to $k_5$ as $k_i^{'}$ of the five samples, while the calculated results of Eqs. (11a)-(11c) as $k_i^{'}$. Substituting $k_i^{'}$ and $k_i^{'}$ into Eq. (12) and adjusting undetermined coefficient *a, b, c,* and *d*, the optimal undetermined coefficient of the three equation modes in Eqs. (11a)-(11c) are obtained, and the corresponding equations and their error square sum are listed in Table 2. In detail, when $\alpha$ is used as the independent first-order term, coefficient, and index, the corresponding lowest error square sum is 1.57, 0.49, and 0.95, which means the 2nd regression (in bold) has an obvious advantage in accuracy.

Based on the calculated results, the 2nd regression it is used in the proposed method, and all of the following results are obtained by the regression. On this basis, the side cutter life can be predicted by the modified method, which is shown in Fig. 6. Compared with reference method without modification,

Table 3. Data collected from test area II.

| Starting | Ending | Length (m) | Rock class | VHNR | UCS (MPa) | $J_f$ (m$^{-1}$) | $\alpha$ (mm/m) | Unmodified $k_i$ | Modified $k_i$ |
|---|---|---|---|---|---|---|---|---|---|
| YDK 51+637 | YDK 51+615 | 22 | IV | 230 | 45 | 2.2 | 6.4 | 0.66 | 0.75 |
| YDK 51+615 | YDK 51+485 | 130 | III | 236 | 62 | 1.5 | 8.6 | 0.96 | 4.48 |
| YDK 51+485 | YDK 51+385 | 100 | IV | 233 | 35 | 1.9 | 9.5 | 0.60 | 3.80 |
| YDK 51+385 | YDK 51+345 | 40 | III | 242 | 57 | 1.4 | 6.3 | 0.93 | 2.24 |
| YDK 51+345 | YDK 51+085 | 260 | II | 280 | 68 | 0.8 | 6.7 | 1.38 | 3.82 |
| YDK 51+085 | YDK 51+055 | 30 | III | 278 | 44 | 1.6 | 6.1 | 0.85 | 1.60 |
| YDK 51+055 | YDK 51+005 | 50 | V | 214 | 32 | 2.6 | 7.1 | 0.37 | 0.20 |
| YDK 51+005 | YDK 50+950 | 55 | IV | 225 | 43 | 1.8 | 6.4 | 0.65 | 1.35 |
| YDK 50+950 | YDK 50+810 | 140 | V | 228 | 30 | 3.3 | 11.3 | 0.37 | 1.05 |

the predicted results of the proposed method are more accurate. The largest error of the modified method is only 121 and 123 m/cutter (3# and 8# sample), and the average percentage error is 24.3 %, which reaches an acceptable degree for the actual project. The test area I data proved that the modified consumption coefficient $k_i^*$ is useful for predicting side cutter lives, which is obtained by the same data. Therefore, in order to verify the universal applicability of the modified $k_i^*$, new data with significant difference should be used, and the verifying results of the new data will be shown in the 4th section.

## 4. Results and discussion

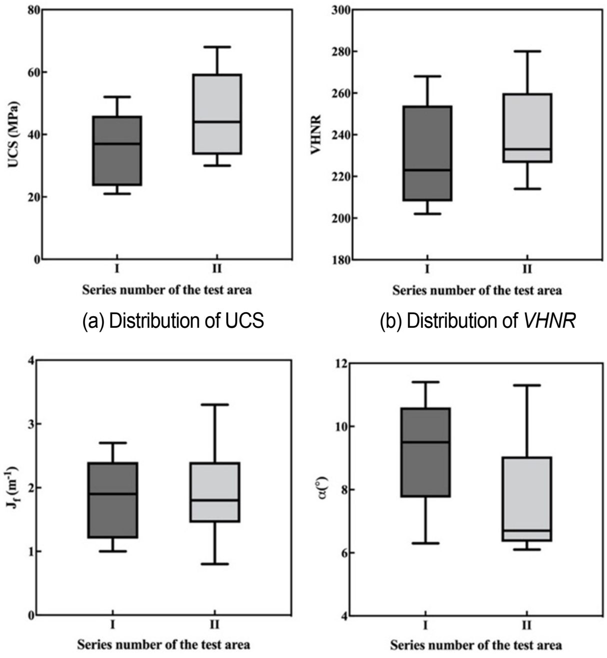
### 4.1 Testing data overview

In 3rd section, the regression of the consumption coefficient is obtained according to the field data collected in test area I. For further verifying the accuracy of the modified method, the method is used in a new area, i.e. the test area II, which is introduce in the 2nd section. The statistic information of the data collected in test area II are summarized in Table 3.

Compared with the test area I, the data of this area are more complexed, and there is significant difference between the test area I and II. Totally 9 rock mass sections in the test area II, which is more than the 5 sections in test area I. In addition, there are 4 rock classes in test area II, which is including class II, III, IV and V rock. Meanwhile, there is not class III rock in the test area I. In addition, as Fig. 7 shows, the strength and hardness of the test area II are higher than the one of the test area I. The integrity of the test area II ranges larger than the one of the test area I. In order to verify the effect of the modified model, data with significant difference should be used, and the data collected from the test area II meets this require.

### 4.2 Results

Totally 98 side cutters are worn in test area, and the modified model are tested based on the 98 samples. The comparison between the prediction results of the reference method and the modified method and the actual values are shown in Fig. 8.

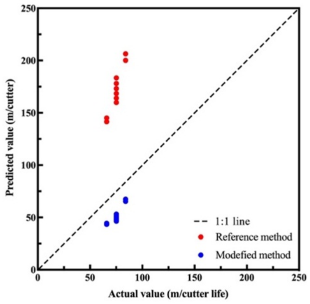



(a) Distribution of UCS (b) Distribution of *VHNR*

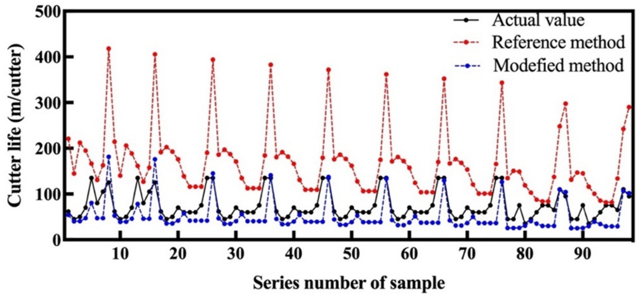
(c) Distribution of $J_f$ (d) Distribution of $\alpha$

Fig. 7. Distribution of the field data of test area I and II.

In Fig. 8, the black line with points represents the actual value of the side cutter life, which is recorded in the field. The red line and the bule line represent the reference and the modified method, respectively. Visually, there are large difference between the predicted value by the reference method and the actual side cutter life, and the predicted side cutter life of most samples are about 150 m/cutter higher than the actual one. For some samples, the difference even reaches about 300 m/cutter, such as 8#, 16#, 26#, 36#, 46#, 56#, 66# and 76#. On the contrary, the predicted results by the modified method (blue line) have relatively high consistence with the actual value. The ranges of the predicted results and the actual value is [25.2, 184, 4] m/cutter and [35, 135] m/cutter, and the largest difference are 93.1 m/cutter. The average percentage error is only 22.4 %. Comparing with the one of the reference results




(a)




(b)

Fig. 8. Comparison between the predict results of the reference method and the modified method: (a) comparison of the average side cutter life; (b) comparison of the side cutter life of each sample.

(142.9 %), the error of the modified method is relatively low. This proves that the modified method is more suitable for predicting the side cutter life.

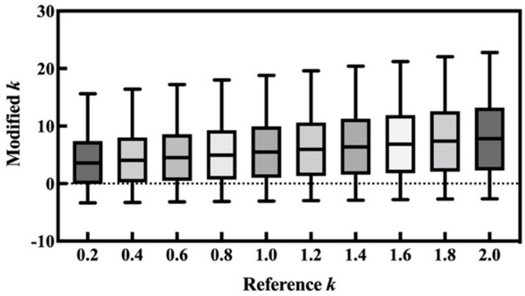
## 5. Discussion

This research is based on the reference research [22]. The reference mothed can accurately predict cutter life in different position. However, the prediction effects of side cutter life are needed to be improved. In this research, TBM tunnelling attitude and joint frequency are involved into calculating the consumption coefficient, and the side cutter life prediction effects of the modified method are proved to be acceptable. In this section, the influence of the new involved factors on the modified consumption coefficient are analyzed. Meanwhile, the limitations of this research are also declared.

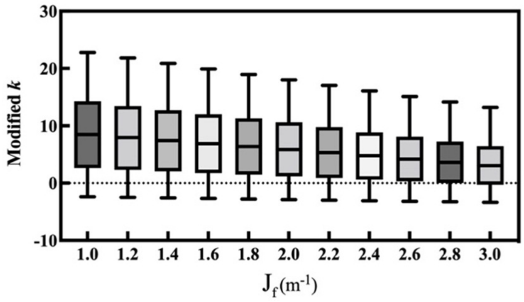
### 5.1 Sensitivity analysis of consumption coefficient

No matter in the reference method or the modified method, the life differences of cutters in same installment position is determined by the consumption coefficient, which is related to the rock mass condition. In this research, a new way involving the TBM tunnelling attitude and joint frequency to calculating the consumption coefficient is proposed. In this section, the effect of the new involved factors on the modified consumption coefficient is studied. In detail, several combinations of reference consumption coefficient $k_i$, joint frequency $J_f$ and the TBM attitude $\alpha$ are set, and corresponding modified consumption coefficient $k_i^*$ is calculated. Among them, $k_i$ ranges from 0.2 to 2, with the step of 0.2, and $J_f$ ranges from 1.0 m$^{-1}$ to 3.0 m$^{-1}$, with the step of 0.2 m$^{-1}$, and the $\alpha$ ranges from 2° to 20°, with the step of 2°. The distribution of the calculated results is shown in Fig. 9.

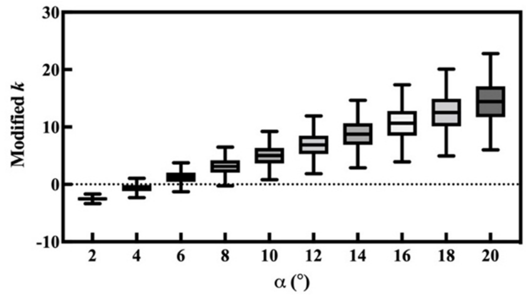
Fig. 9(a) shows the distribution of the modified consumption coefficient under different reference $k_i$. The average value of the $k_i^*$ slightly increases from 3.96 to 7.92, with the increasing of $k_i$. Among them, $k_i$ has a positive correlation with *UCS* and *VHNR*. On the contrary, average $k_i^*$ slightly decreases from 8.58 to 3.3, with the increasing of $J_f$, as Fig. 9(b) shows.




(a)




(b)




(c)

Fig. 9. Distribution of the calculated side cutter lives under different factors.

For the side cutters on the same installment position, the larger the consumption coefficient, the lower the cutter life. According to the calculated results, the strata with low strength, hardness and integrity has advantages for protecting the side cutters.

Compared with $k_i$ and $J_f$, the influence of $\alpha$ on the consumption coefficient is larger. The average $k_i^*$ under different

$\alpha$ is ranges from -2.52 to 14.4. In addition, the 25 % to 75 % ranges length of $k_i^*$ under the same $k_i$ or $J_f$ is about 7 to 10. For the same $\alpha$, the corresponding distribution of $k_i^*$ is relatively concentrated, the 25 % to 75 % ranges length is less than 5. From the perspective of relevance, the correlation coefficient between $k_i$, $J_f$, and $k_i^*$ is only 0.22 and -0.27, whose absolute values are less than 0.3. The correlation coefficient between $\alpha$ and $k_i^*$ reaches 0.92, which proves that the compared with the rock mass parameters, the TBM attitude is the most important factors for the side cutter life.

### 5.2 Limitation

The proposed method is proved to be more suitable for predicting the side cutter life. However, there are still several limitations of this research.

1) As mentioned in Sec. 2.3, lateral force of the side cutter is the reason of the life difference between normal and side cutter. According to Fig. 3, the lateral force of side cutter is affected by its installation angle, which is also a key factor on the cutter life. The normal cutter is vertical with the tunnel face, differently, the included angle between the ring of the side cutters and the tunnel face is ranges from 70° to 90°. However, the installing angles of the side cutter are the secrets of the TBM manufacturer, which is not involved in this research. Therefore, studying the worn rules of cutters with different installment angles might be an effective way for improving the predicting effect of the side cutter life, and it will be conducted in the future research.

2) As the field test cutter life of the two test areas, the lives of the 10 side cutters are similar with each other. In detail, totally 13 samples of the 32# and 33# side cutters in test area I and II are exactly the same. In addition, samples of from 34# to 39# cutters, and the samples of 40# and 41# cutters are also the same. In many actual cases, adjacent side cutters are changed synchronously, and their life is also the same. It is because that the height of the worn rings of the adjacent cutters should not be exceed a permitted value. In the synchronous cutter changing, not every changed cutter reaches its worn limitation. However, in the reference method and the proposed method, every changed cutter reaches its worn limitation and the predicted cutter life is related with the installment radius, which results in the predicted life differences of side cutters in different installment position. In the future research, the lives of adjacent cutters should be considered integrally instead of separately.

## 6. Conclusion

This research is conducted on the basis of Wang et al. [22], which proposed a method to predict cutter life of TBM. Tested by the 6th section of the Qingdao metro project, it is found that the reference method predicted results of side cutter lives need to be improved. In the reference research, only *UCS* and *VHNR* is considered as key factors on the cutter life, and it might be one of the reasons of the defective predicted results. In this research, a modified method on the basis of the reference research is proposed. By involving the rock integrity of the rock and the TBM attitude, better and acceptable predicted effect is achieved. The main conclusion of this paper is summarized as follow.

1) The reference method is tested by the data collected from the 6th section of the Qingdao metro project. The test results of the most samples (from normal cutters) are acceptable, which proves that the reference method is generally acceptable. But the predicted results of the side cutter lives generally reach several times of the actual values, which needs to be improved.

2) The reference method proposed a definition called consumption coefficient to describe the cutter wearing speed under different rock mass condition, which determines the difference of cutter life in the same installment position. In this method, the consumption coefficient is modified by involving the joint frequency $J_f$ and TBM tunnelling attitude $\alpha$. On the basis of the field data collected in the test area I, a modified consumption coefficient is obtained by multiple regressions. According to the modified consumption coefficient, the predicted effect of the side cutter life is improved. The predicted results are shown high consistence with the actual value, and the average percentage error is only 24.3 %.

3) For verifying the universal applicability of the modified, 98 samples collected in test area II is used to the modified method. Compared with the test area I, the geological condition of the test area II is more complexed and significantly different. Along the test area II, the surrounding rock has larger strength and hardness, and the floating ranges of the joint frequency is larger too. The verified results by the test area II are also shown acceptable, and average percentage error reaches 22.4 %. Comparing with the one of the reference results (142.9 %), the error of the modified method is relatively low. This proves that the modified method is more suitable for predicting the side cutter life and has high universal applicability.

## Acknowledgments

The research was supported by the Natural Science Foundation of Shandong Province (No. ZR202103010903), the Doctoral Fund of Shandong Jianzhu University (No. X21101Z), and Science and technology project of University of Jinan (XKY2060&XBS2007).

## Nomenclature

*CAI* : Cerchar abrasivity Index
$J_f$ : Joint frequency
*Q* : Quartz content
*RAI* : Rock abrasivity index
*SE* : Specific energy
*UCS* : Uniaxial compressive strength
*VHNR* : Vicker's hardness number of rock

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