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A TBM Cutter Life Prediction Method Based on Rock Mass Classification

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ABSTRACT

Cutter life is an important economical index for tunnel boring machines (TBM) excavation, and its prediction is widely concerned. This paper introduces a method for predicting cutter life on the basis of statistics and regression. Traditional researches only evaluate the average mileage or time interval of each cutter change. Differently, the proposed method can accurately predict the mileage position of each cutter relatively, on the premise of knowing the installment radius of each cutter and the rock properties along the tunnel. In this procedure, the influence of the rock classification and rock properties of each cutter passing area on their passing distance is obtained by linear regression. For proposing and verifying the prediction method, totally 1,200 records of cutter changing caused by normal cutter wear are collected from the 4th Section of Water Supply Project from Songhua River. Among them, randomly selected 920 samples are used to determine the regression coefficients involved in the method. The method is verified by the rest 280 samples, and a reliable predicted result is obtained (MAPE = 27%, and R^2 = 0.69).

1. Introduction

Tunnel boring machines (TBMs) play an important role in tunnels construction, especially the long and deep tunnel. As one of the most important part of TBM, TBM cutters' performance attracted much attention of current researchers (Choi and Lee, 2015; Ling et al., 2015; Sun et al., 2015; Choi and Lee, 2016; Tan et al., 2018; Zhou et al., 2019). Among the researches about TBM cutter, the one about cutter life and cutter wearing occupied a large part of them because of its significant practical and economic value. In the tunneling process of TBM, cost of worn cutter changing account for an important part of the total cost. In addition, cutter changing time also results in a major delay of the tunnel excavation. According to previous research and field investigation, the cost and time duration caused by cutter changing always accounted for about one-third of the total cost and time (Wen and Huang, 2002; Su et al., 2010). Therefore, an accurate prediction of cutter life is an effective way for evaluating the cost and the duration time of cutter changing, and it is effective for establishing a reasonable and useful cost and time plan. The consumption speed of cutters is always measured by cutter wear extent or cutter life, former is defined as the radius difference between the original and worn cutter, and the latter is always expressed by the radio of the total excavation distance and the total number of cutters being changed.

In the field of predicting cutter wear and cutter life, a number of attempts were conducted by researchers. These studies can be roughly divided into two categories. Some studies predict the cutter wear by mechanical calculation of the interaction between the cutters and rocks. For example, Wijk (1992) developed a mathematical model for cutter consumption by describe the mechanism of rock breaking process with cutters using uniaxial compressive strength (UCS) and Cerchar Abrasivity Index (CAI) as input variables. Wang et al. (2012) deduced the mathematical relationship between the specific energy (SE) and the cutter wear extent. Differently, the other kind of researches predicted the cutter life by obtaining the statistical principle between the cutter life and the rock condition and TBM behavior. Hassanpour (2018) and Liu et al. (2017b) conducted single and multiple regression analysis to establish the empirical formula for predicting cutter life. Several rock properties were involved in their researches, including UCS, CAI, quartz content (Q), Vicker's hardness number of rock (VHNR), joint count number (Jv) and rock abrasivity index (RAI) et al.. Meanwhile, Nelson et al.

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(1994) studied the effect of joint condition, rock type, and TBM operational parameters on cutter wear extent. In these researches, single or multiple regression analysis were conducted on the field cutter life and rock properties, which provided a good reference for this paper.

Current statistical researches mainly aimed at predicting the average cutter life on the cutterhead. The predicted results of the models are only for evaluating the total cutter consumption of a whole project, but lack of discussion of the difference of the consumption principles of cutters on different position of the cutterhead. Although some researches noticed this point such as research of Wang et al. (2012), lives of cutters with different installment radius are simply described by the ratio of their installment radius. The purpose of this paper is to establish a prediction method of TBM cutter life based on statistical principle of 1,200 cutter changing records. In this paper, each cutter has a unique value of excavation distance according to the difference of its installment radius and the rock condition it passed through. On the promise of the mileage position where the cutter started to excavate, the mileage where the cutter worn to be change can be evaluated by proposed model.

2. Data Selection and Collection

2.1 Data Selection

Before collecting sample data on the engineering field, it is necessary to determine the rock mass parameters mainly influence the cutter life. Previous researchers have adequately studied the influences of geological factors on the cutter life, and the involved factors in previous models are listed in Table 1. In general, these geological factors can be divided as four categories.

The first one is the rock classification index, which is a kind of comprehensive indexes to measure the geological properties, such as rock strength, joint condition, integrity, the ground water conditions and so on. In previous researches, rock classification indexes are widely used in TBM performance, not only the cutter life prediction (Preinl, 2006; Barton, 2000; Hamidi et al., 2010; Benato and Oreste, 2015). In the field of predicting cutter life, the rock classification indexes used as input variables are mainly including the rock mass rating (RMR) and the rock mass excavatability (RME). Hassanpour et al. (2014) investigated the cutter life condition and the geological properties of all of the 27 geological zone of Karaj water conveyance tunnel. According to the results of the research, basic RMR and the cutter life show obvious negative correlation and the R^2 of them reaches about 0.3. Furthermore, on the basis of the data collected from Guadrama tunnel, Bieniawski et al. (2009) established empirical equations for predicting cutter life involved RME as an input variable.

The other category of geological factors is the integrity of the rock mass. This kind of parameters characterize the basic information of the rock joint or fracture, including the shape, direction, and frequency and so on, which is often used in the study of TBM penetration rate prediction. However, in the researches of the cutter life prediction, only J. Rostami used two of this kind of index, i.e., joint count number (Jv) and RQD, and analyzed the influence of the two parameters on cutter life. The R^2 between the two and cutter life reach about 0.3, which proved that their influence on the cutter life needs further investigating.

Strength of the intact rock is also considered as a factor greatly influencing the cutter life. Among this, the uniaxial compressive strength (UCS) is one of the most frequently used parameter in the field of cutter life prediction. The prediction models introduced by Wijk (1992), Gehring (1995), Maidl et al. (2008), and Bieniawski et al. (2009) involved UCS as an input variable and got acceptable prediction results. In addition, tensile strength obtained by point load test are regarded as important factor influencing cutter life in researches of Wijk (1992) and Ewendt (1992). In general, tensile strength are not widely used, and UCS is usually considered to characterize strength in cutter life prediction field.

Finally, the hardness and the abrasion of the rock also have high correlation with the cutter life. There are many parameters

Table 1. The Factors Involved in Previous Cutter Life Prediction Model

No.	Factors	Required geomechanical tests	References
1	RME	-	Bieniawski et al. (2009)
2	RMR	-	Hassanpour et al. (2014)
3	Jv	-	Hassanpour et al. (2014)
4	RQD	-	Hassanpour et al. (2014)
5	UCS	Uniaxial compressive test	Wijk (1992); Maidl et al. (2008); Bieniawski et al. (2009)
6	Tensile strength	Point load test	Wijk (1992)
7	CAI	Cerchar abrasivity test	Gehring (1995); Rostami (1997); Maidl et al. (2008); Frenzel et al. (2008); Bieniawski et al. (2009); Frenzel (2011)
8	SJIP	Sievers' J miniature drill test	Bruland (1998); Dahl et al. (2007); Bieniawski et al. (2009)
9	DRI	Brittleness test and Sievers' J miniature drill test	Bieniawski (2009)
10	VHNR	Vickers hardness test	Hassanpour et al. (2014)
11	ABI	Uniaxial compressive test and Vickers hardness test	Hassanpour et al. (2014)
12	Quartz content	Petrographic analysis	Ewendt (1992)

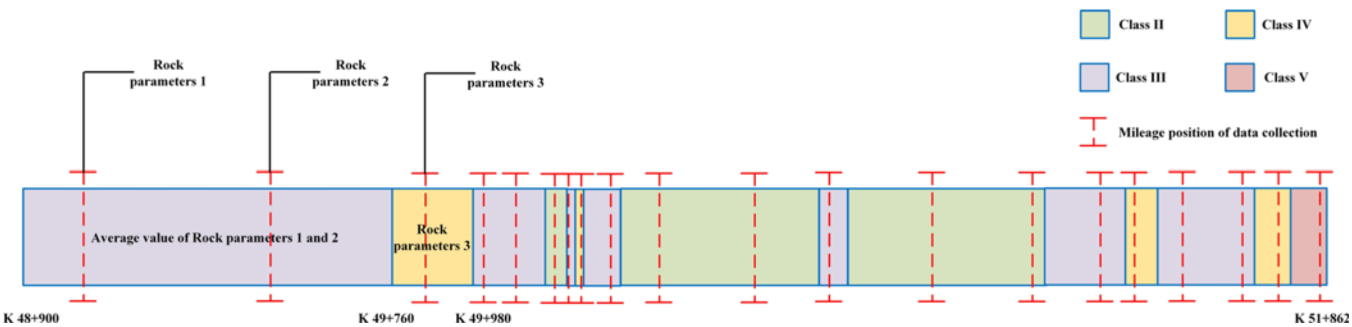

Fig. 1. Rock Class and Data Collection of Partial Mileage

can be used to characterize rock hardness or abrasion and predict cutter life. Cerchar abrasivity index (CAI) is the most widely used rock abrasion measurement index in cutter life prediction researches. Researches of Wijk (1992), Gehring (1995), Rostami (1997), Maidl et al. (2008), Bieniawski et al. (2009), and Frenzel (2011) are involved CAI as an input parameters. Ewendt (1992) used quart content which is obtained by petrograghic analysis and predicted the wear rate. Drilling rate index (DRI) is another abrasion index of rock which is proposed by Selmer-Olsen and Blindheim (1970), and it is assessed on the basis of the Brittleness test (S_{20}) (Matern and Hjelmér, 1963) and the Sievers' J-miniature drill test (SJ) (Sievers, 1950). DRI is used as an input factor in the research of Bieniawski et al. (2009). Bruland (1998) adopt SJ and abrasion value steel cutters (AVS) test to get an index related to rock abrasion, named cutter life index (CLI). Dahl et al. (2007) recorded the variation curve of drilling depth with time, and captured the gradient of the start stage and the fastest changing stage as parameters to characterize the rock abrasion. Especially, several indexes characterizing rock hardness or abrasion is adopted in the research of Hassanpour et al. (2014) and Liu et al. (2017b), including Vicker's hardness number of rock (VHNR), EQC, abrasiveness index (ABS). The regression relationships between these factors and average cutter ring life solid cubic meters (H_f) are calculated. Among these factors, VHNR and ABI have relatively high correlation with H_f, and their R^2 are more than 0.6. According to the simple regression analysis results of Hassanpour, VHNR and ABI are the two factors most relevant to cutter life. In this paper, only VHNR is involved as an input variable because the two parameters are interrelated (ABI is the produce of VHNR and UCS).

2.2 Case Study and Data Collection

All of the field data is collected in the 4th section of the Water Supply Project from Songhua River. The 4th section of this project is located between Jilin and Changchun City, in the middle of Jilin Province, China. The mileage of this section ranges from K 70+900 to K 48+000, and the total length of this section is nearly 23 km. The tunnel of this project mainly moves from NE to SW, with the maximum overburden of 260 m and the longitudinal slope of 0.013°. The tunnel mainly passes through multiple lithologic areas, including diorite, tuff, sandstone,

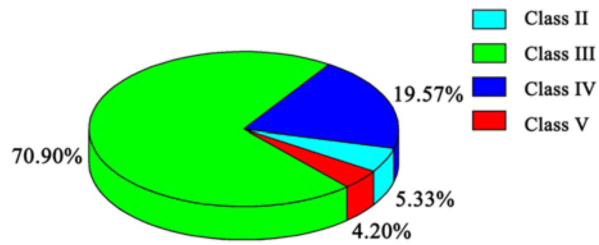

Fig. 2. Pie Chart of Each Class of Rock

limestone and granite. The rock mass classification of the tunnel used the hydropower classification (HC) method. Using HC method, engineers assign a score within the range of 0 to 100 to the surrounding rock, according to its the intact rock strength, rock mass intactness degree, discontinuity characteristics, groundwater conditions and attitude of the discontinuity plane (Liu et al., 2017a). According to the total score, the surrounding rock is divided as five classes. Rock of class I represent the extremely hard and integrate rock and the rock of class V represent the extremely weak or broken rock. The proportion of each class rock in the tunnel excavation area is shown in Fig. 2, 5.33% of the rock are class II, 70.90% of the rock are class III, 19.57% of the rock are class IV, and 4.20% of the rock are class V. With the excavation of the tunnel, the classification of surrounding rock is given by the engineer according to the site investigation results. On this basis, the tunnel is divided into several continuous sections, and each continuous section of the surrounding rock belongs to the same classification. In each section, at least once core drilling and mapping of the tunnel wall is conducted, and several rock strength and integrity parameters of each section are recorded, including UCS, BTS, RQD, and VHNR. The average test values of the above mentioned parameter are approximately considered to describe the whole section. The way to collected rock data of each section is illustrated in Fig. 1. For example, the section 1 is located between the mileage of K 48+900 and K 49+760, and only contains class III of surrounding rock. In this section, 2 samples are investigated, and the investigated results of them are recorded as rock parameters 1 and 2. Then, the average value of rock parameters 1 and 2 are used to characterize section 1. As for section 2 between K 49+760 and K 49+980 in class IV rock, there are only 1

Table 2. The Basic Statistical Information of the Rock Mass Parameters

Name	In class II rock			In class III rock			In class IV rock			In class V rock		
	Ranges	Mean	Std. deviation	Ranges	Mean	Std. deviation	Ranges	Mean	Std. deviation	Ranges	Mean	Std. deviation
RQD	[15.1, 86.6]	50.2	17.02	[13.8, 80.3]	47.6	16.50	[13.0, 77.4]	45.3	15.40	[12.8, 76.7]	41.2	19.78
UCS	[16.0, 147.7]	60.2	18.99	[14.6, 122.7]	55.8	21.61	[14.2, 98.0]	55.4	19.69	[15.3, 88.8]	54.6	22.13
BTS	[3.0, 12.4]	7.3	2.32	[3.0, 11.4]	7.1	2.13	[2.5, 10.9]	6.7	2.11	[2.3, 10.2]	6.4	2.63
VHNR	[189.7, 657.7]	417.2	104.94	[147.7, 604.0]	386.6	103.1	[123.8, 587.2]	361.6	95.98	[116.8, 568.5]	321.3	111.61

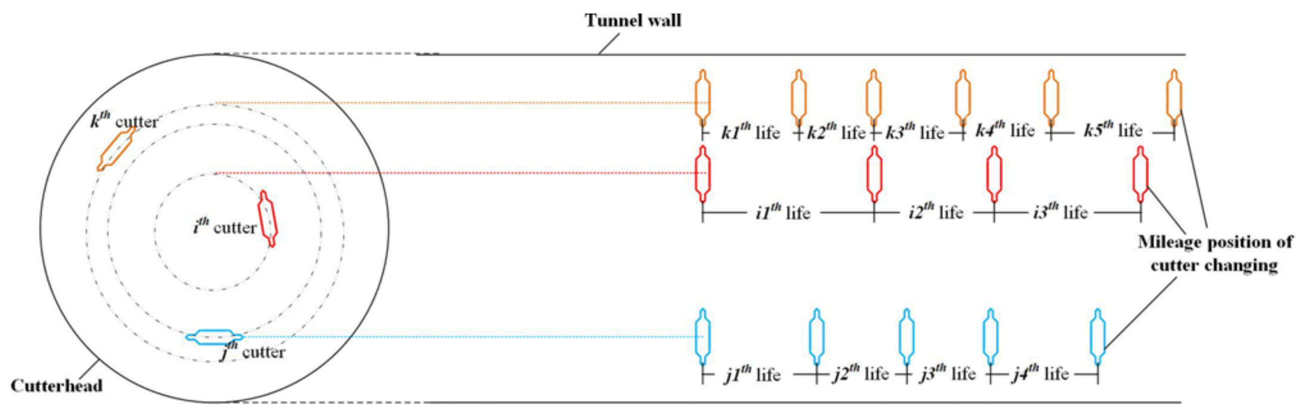

Fig. 3. Illustration of Cutter Life Measurement Used in This Paper

Table 3. Basic Information of the Data Sets

Name	Number of samples	Contents		Purpose
		Cutter life	Rock properties	
1-A	920	Single cutter change	Rock classification and parameters	Establish prediction model
2-A	280	Single cutter change	Rock classification and parameters	Establish prediction model
1-B	56	Each position average cutter life of 1-A	None	Verify prediction model
2-B	56	Each position average cutter life of 2-A	None	Verify prediction model

investigated sample. Thus, the test results, rock parameters 3, are adopted to describe this section. The basic statistical information of these rock mass parameters are listed in Table 2. The influence of these parameters and rock class on the cutter life is studied in this paper.

An open-type TBM produced by the China Railway Engineering Equipment Group is used to excavate this tunnel. The cutterhead of this TBM is 7.9 m in diameter, and a total of 56 cutters are equipped on the cutterhead, with a diameter of 19 inch. These cutters are given location serial numbers between 1 and 56. During the tunnel excavation, the mileage position and the cutter number of each cutter changing is recorded by engineers, to calculate the cutter lives of each cutter. As Fig. 3 shows, for the cutters with the same number, the difference between two adjacent changing is considered as a pair of cutter life data. Meanwhile, the average values of the cutter life of same location number is also obtained, respectively, and recorded as average cutter lives. Totally, of more than 1,600 cutter changes and their corresponding reasons are also recorded. Among them, only about 1,200 cutter changes caused by normal wear are selected as the studied samples. In the 1,200 samples of cutter changes, totally 920 samples, are randomly selected to establish the cutter life prediction model and make up the data set 1-A. The remaining 280 samples of cutter changes are used to verify the proposed model and make up the data set 2-A. In general, the excavation area of a single cutter contains multiple sections with different rock mass classification and parameters, these properties are also recorded in these data set. In addition, the total of 56 average cutter life of each position of cutterhead is calculated in both 1-A and 2-A, respectively. These values make up the data set 1-B and 2-B respectively. The basic information of the data sets are given in Table 3, and the order process and the structure of the two data sets are shown in Fig. 4.

What needs special explanation is that the measurement of cutter life is slightly different from the traditional way for obtaining the specific excavation distance of cutters on different installation positions of the cutterhead. In traditional method, the cutter life is always expressed by the ratio of the excavation distance, time or rock volume and the total number of cutter consumption. In this way, the cutter life is a value indicating the

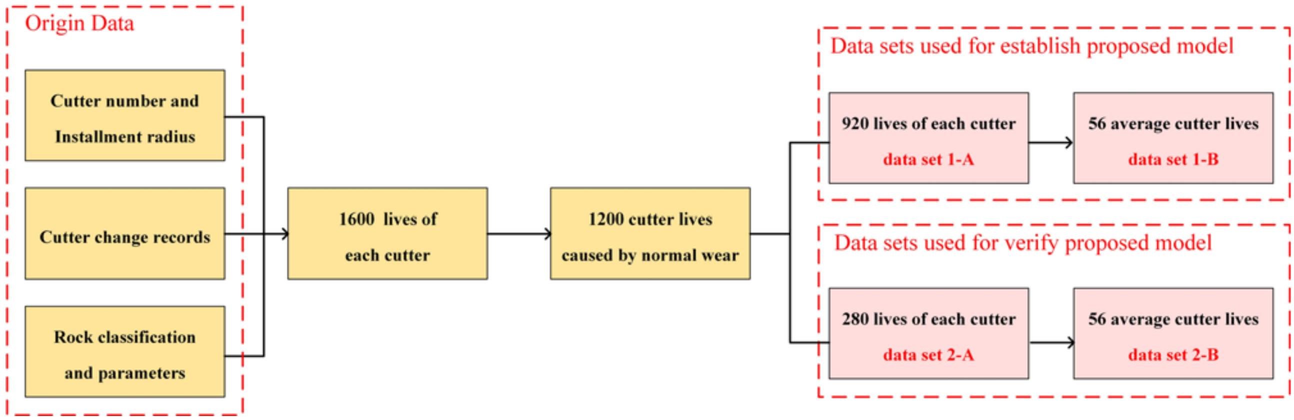

Fig. 4. Illustration of the Data Set Structure

average excavation time or distance of total cutter, without the difference of the installment position. Differently, in this paper, each cutter life is a unique value according to their installment radius and the rock condition they passed through.

3. Establishment of the Cutter Life Prediction Model

3.1 Procedure of the Establishment of Cutter Life Prediction Model

In previous prediction models, the average life of all disc cutters on the cutterhead is regarded as a same value regardless their position. Differently, this paper aims at predicting the lives of each cutter based on their installment radius and the rock mass condition of the area they pass through. For this purpose, the model is established in three steps:

1. There is a strong correlation between the installment radius and the average cutter life. According to this correlation, the theoretical cutter life is introduced. The value of the index is closed to the average lives of cutters on each position of the cutterhead and it is only related to the installment radius of cutters. This step is introduced in Sec. 3.2.
2. The distances of each section divided in Section 2 are weighted for recalculating each cutter lives. The weights of each zone are defined as "the consumption rate" in this paper, which means the consumption of the theoretical cutter life per unit driving distance. The weights are determined by the rock classification and parameters. In Sec. 3.3, multiple regression analysis between the actual cutter life and these rock properties is conducted to determine the weight values of each zone.
3. Based on the theoretical cutter life and the weights of rock classification and parameters, the cutter life prediction model is proposed. On the premise of obtaining the installment radius of each cutter and the rock mass condition of excavation area, the mileage of each cutter change is given by the proposed model. This step is introduced in Sec. 3.4, and the flow chart for establishing the prediction model is shown in Fig. 5.

3.2 Theoretical Cutter Life

With the development of research in the field of evaluating cutter life, several indices are introduced for measuring cutter life. However, none of them are in common use at present. In general, cutter life is mainly measured by the ratio of excavation time or distance to the consumed number of cutters or the cutter wear. These indices for measuring cutter life are listed in Table 4.

Above researches has proved that these indices are reasonable and efficient for measuring cutter life. All of these indices are the average mileage or time interval of cutter changing, and express their the distance or time frequency. Under the calculation way of these indices, the lives of all cutters on the cutterhead are the same value regardless their position. However, in practical engineering, lives of cutters with different installment radius are obvious different. Therefore, a totally different index for measuring cutter life with different installment radius is introduced in this paper, namely theoretical index of cutter life.

During TBM excavation, the movement track of cutters approximates a helical curve, which can be regarded as the combination of circle and forward direction, as Fig. 6 shows (Liu et al., 2017b). The spacing between two adjacent sections of the helical curve is the penetration rate per revolution of cutterhead (PR_{ev}), usually within 10 mm. Compared with the installment radius of the cutters, the PR_{ev} is small enough to ignore. Therefore, the movement track of the cutters can be regarded as a circle whose radius is the installment radius. Under the same advanced distance of the cutterhead, the movement distances of the cutters increase from inside to outside in turn and are proportional to the installment radius. Meanwhile, the cutter wear extent, which is considered to be inversely proportional to the cutter life, is linearly increases with the cutter movement distances (Wang et al., 2012). Therefore, the ratio of the undetermined coefficient K to the cutter installment radius is considered as the basic equation for estimating the theoretical cutter life, as Eq. (1) shows:

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

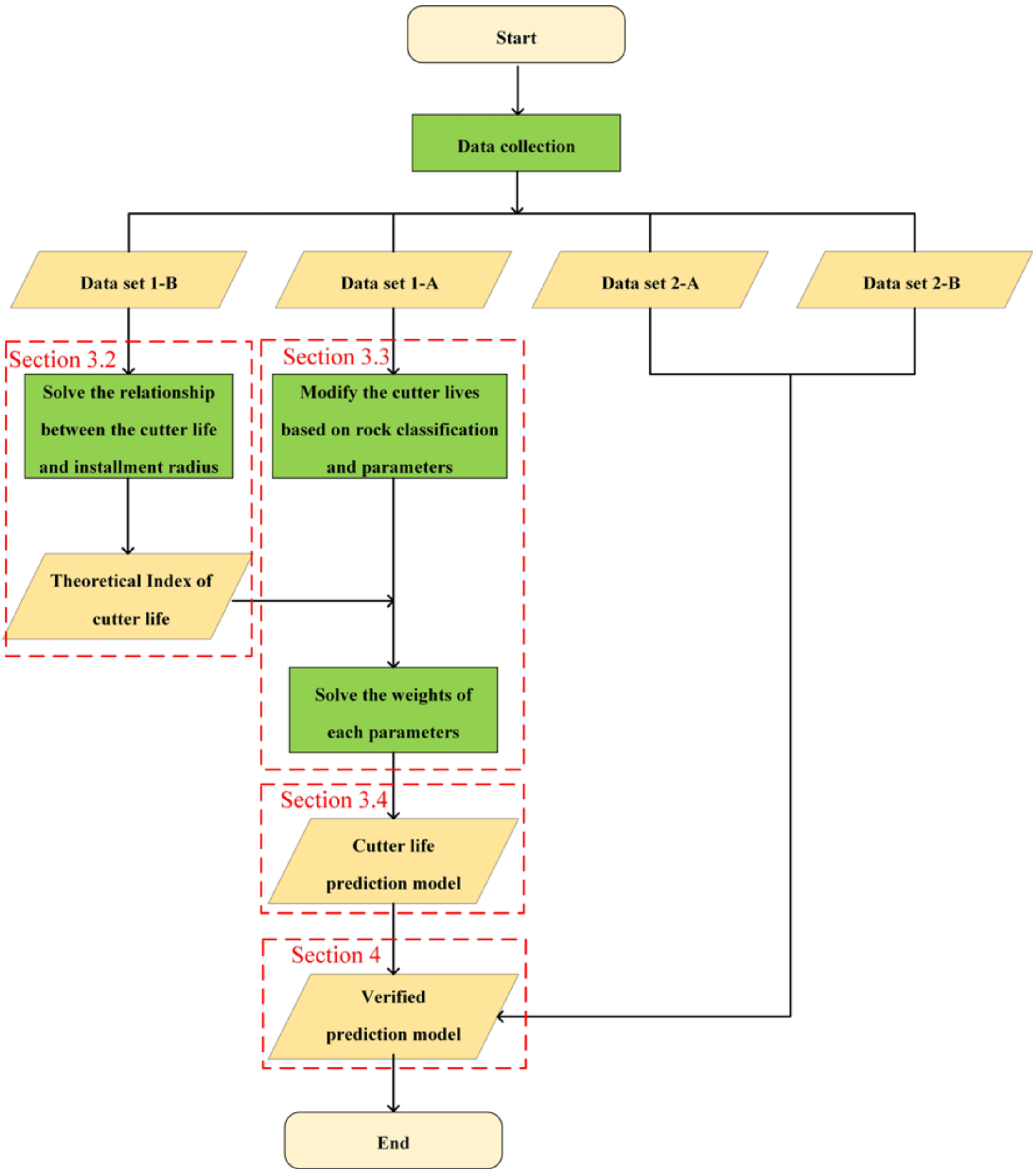

Fig. 5. The Flow Chart of the Establishment of the Cutter Life Prediction Model

Table 4. Indices for Measuring Cutter Life

Name	Symbol	Dimension	Reference
Hours used per cutter	H_h	h/cutter	Bruland, 1998
Rolling distance per cutter	H_m	m/cutter	Bruland, 1998
Rock excavation volume per cutter	H_f	m^3/cutter	Hassanpour et al., 2014
Rock excavation volume	V_c	m^3	Frenzel, 2011
Cutter extent per rolling distance	V_m	mm/m	Du et al., 2015

In Eq. (1), H_T represents the theoretical index of cutter life which introduced in this paper as a new index for measuring cutter life. For instance, the H_T value of the *ith* cutter means the mileage length of the TBM excavated during the period when the TBM equipped with the *ith* cutter. The H_T value of the cutters installed in each location is unique and it is different with the

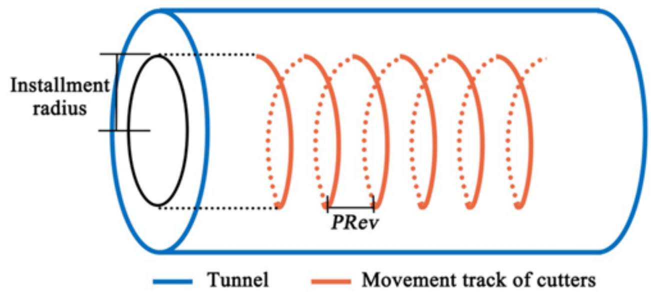

Fig. 6. Illustrator of the Cutter Movement Track (Liu et al., 2017b)

value of cutters installed in the other location. C_m represent the total distance traveled along the helical movement track by each disc cutter from installation to failure. Both C_m and H_T indicate the distance the cutter travels. Different from the H_T representing linear distance, the C_m represent the actual distance along the spiral track, so the conversion between the two variables is related to the installation radius of the cutter. The value of C_m is considered as a constant for the same kind of cutters and calculated by regression of field data. PR_{ev} represent the penetration per revolution, which means the advanced distance while a single revolution of the cutterhead. As Eq. (1) shows, H_T is proportional to the reciprocal of the installment radius and the ratio is K. In order to solve the H_T value of cutters in each location, only the ratio K needs to be calculated by field cutter changing data.

For verifying the rationality of the index for measuring cutter life with different installment radius, the relationship between average cutter life of the 56 cutters and the reciprocal of their installment radius is identified as linear trend and the results are shown in Fig. 7. The value of the constant K of the studied TBM is calculated as 2.37×10^5, and there is a very high correlation and a clear proportional relationship between the two quantities. The correlation coefficient between the two quantities reaches to 0.92, and except the two marked point, which represent the average life of 1# and 2# cutter, all errors of other samples are under 300 m/cutter. The results show that the theoretical index of cutter life is reasonable, and closed to the average cutter life with different installment radius.

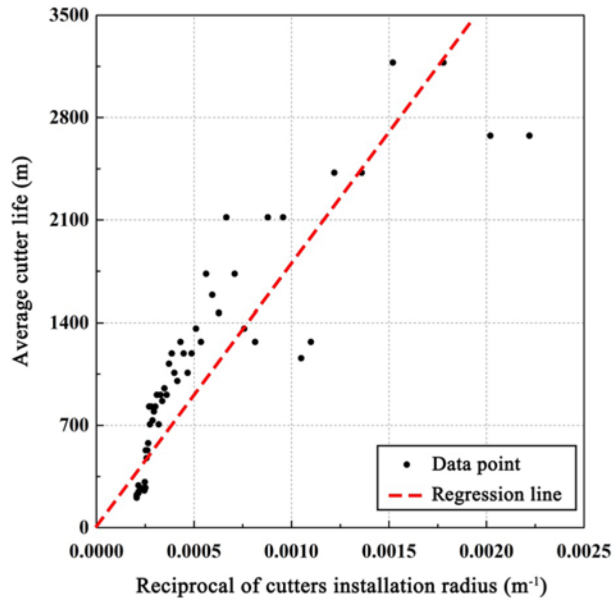

Fig. 7. Scatter Plot of the Average Life and the Reciprocal of Installation Radius of Each Cutter

3.3 Cutter Life Prediction Model

The theoretical cutter life has a high consistency with the average cutter life of each position. However, predicting the cutter life by directly using this index leads to large errors, because of the high discreteness of the cutter lives at the same position. Fig. 9 shows the comparison of the actual lives and the theoretical index of each cutter. As shown in the figure, the carve of the theoretical index is a stepped broken line, because of the index of each position is a same value, while the actual cutter lives of each position is highly discrete, this lead to a large prediction error. The prediction MAPE and R^2 are 53% and 0.44, which reflected that it is unreasonable and inaccurate to directly use the theoretical

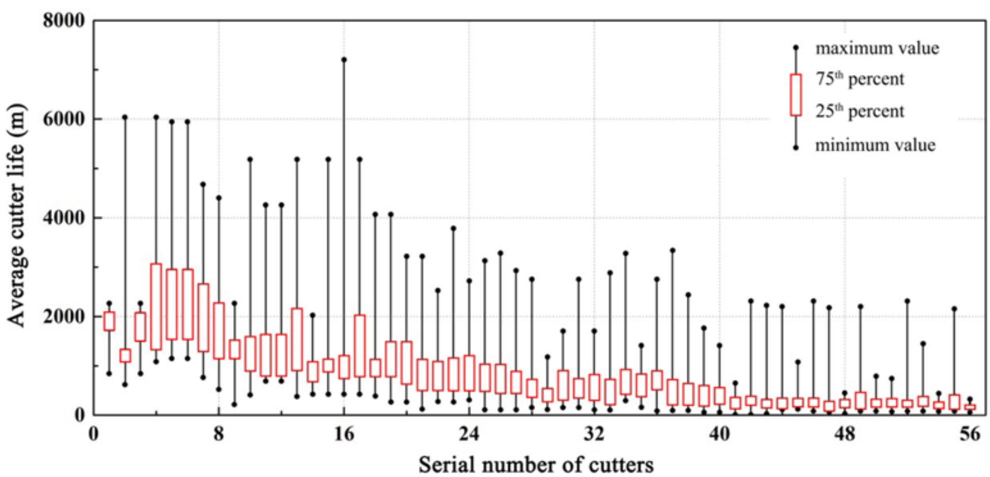

Fig. 8. Life Distribution of Cutters of Each Position on the Cutterhead

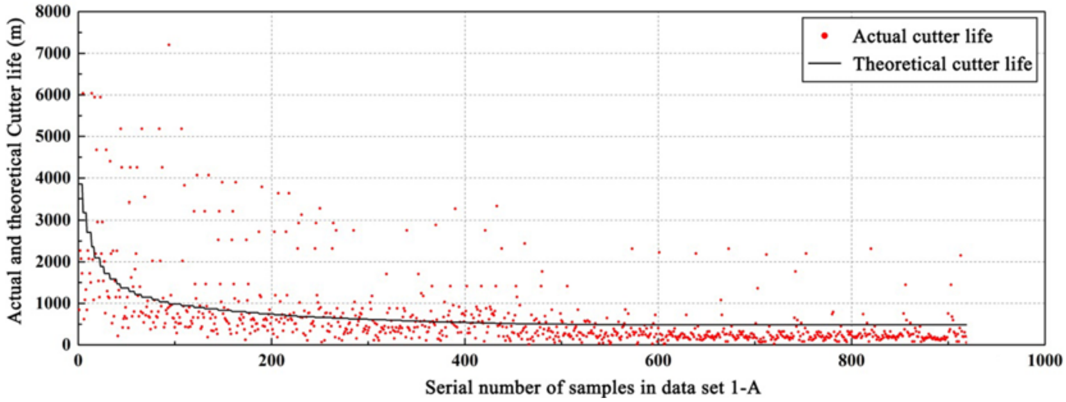

Fig. 9. Comparison of the Actual and Theoretical Life of Each Cutter

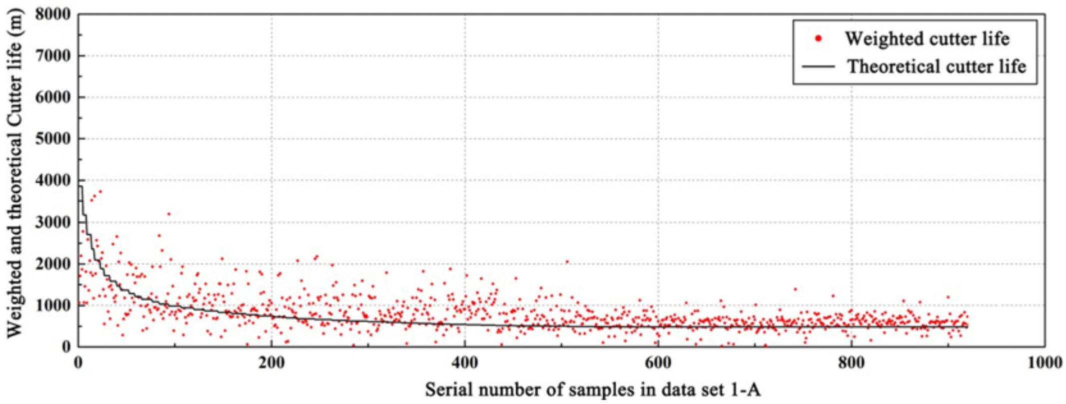

Fig. 10. Comparison of the Weighted Excavation Distance and the Theoretical Cutter Life of the 920 Samples in 1-A Data Set

index for predicting.

Working under different rock mass condition may results in the different excavation distance of cutters with the same installment position. Take the life of 16# cutter as an example, the values range from 364 m to 7,256 m, as Fig. 8 shows. For solving the difference of the same position cutter life caused by the rock mass condition, we weights each excavation distances according to their rock condition. These weights are defined as "the consumption rate" of cutter life, which related to the rock class and parameters. The consumption rate K_i is obtained using multiple regression analysis and its basic form is shown as follows:

$$K_i = k_{i1}RQD + k_{i2}UCS + k_{i3}BTS + k_{i4}VHNR + b_i \quad (2)$$

In Eq. (2), k_{i1}, k_{i2}, k_{i3}, and k_{i4} are the weight of the rock mass parameter of RQD, UCS, BTS and VHNR under class i, respectively. Once the value of k_{i1}, k_{i2}, k_{i3}, k_{i4}, and b_i are finally obtained by linear regression, the consumption rate of cutter life can be calculated, on the premise that the rock classification and parameters of the excavation area of each cutter are known.

The 920 sample of data set 1-A was used for calculating reasonable weights (k_{ij}) of these rock parameters under different rock class. The excavation area of each cutter are weighted as Eq. (3) shows:

$$H'_T = \sum_{i=1}^{n} H'_{Ti} = \sum_{i=1}^{n} (K_i \cdot H_{Ti}) \quad (3)$$

In Eq. (3). n means the total number of areas that a single cutter passed through. H'_{Ti} and H_{Ti} represent the weighted and actual distance of the i^{th} area, respectively. H'_T characterizes the life consumption of the weighted total excavation distance. Reasonable weights (k_{ij}) make the theoretical cutter life H_T and H'_T as close as possible, and they are calculated by the least square method. Finally, the weights of those rock mass parameters are obtained by solving Eq. (4).

$$\min_{k_{ij}, b_i} |H_T - H'_T|^2 \quad (4)$$

Compared with the excavation distance simply counted, weighted distances obtained by regression analysis are closer to the theoretical cutter life as Fig. 10 shows. The optimal weight combination reduces the discreteness of cutter lives. Compared with the cutter lives obtained by direct measurement, the modified cutter lives have higher R^2 (0.72, compared to 0.44) and lower errors (22%, compared to 54%), which reflect that there is a higher correlation of the weighted excavation distances and the theoretical cutters lives. The results prove that the consumption rate of cutter life under different rock mass condition can be well characterized by the calculated weights (k_{ij}). The consumption rate obtained by regression will be used to predict the mileage position of changing of each cutter combined with their theoretical life.

3.4 Method for Evaluating the Mileage Position of Cutter Changing

On the basis of the theoretical cutter life and the consumption rates of each area, the mileage position of changing of each cutter can be easily predicted. In this prediction method, the initial life of each cutter when it is installed on the cutterhead equals its theoretical cutter life. With the TBM advancing, the excavation distance of each cutter increases and their lives decreases. The decrease speed of the cutter life equals to the consumption rate, which is determined by the rock properties of the area the cutter passed through. When the life of a cutter used up, the cutter is considered to be worn and need to be replaced. All known information required to obtain the mileage position of cutter changing includes the mileage position for starting excavation and the installment radius of each cutter, and the rock classification and parameters along the tunnel. On this basis, the mileage position for ending excavation of corresponding cutter can be obtained by the proposed model. Take an arbitrary cutter as an example, on the mileage position for starting excavation, its remaining cutter life is equal to the theoretical index value. With excavation proceeding, its remaining cutter life decreases, and the decreasing value equals the product of the modified coefficient (K) and the excavated distance by this cutter. When the remaining cutter life reduces to zero, the current mileage is where this cutter is worn to be changed. Before that, if the rock classification changed, the equation used for calculated the modified coefficient (K) changes correspondingly. The flow chart of the way the model works is shown as Fig. 11.

In Sec 3.2 and 3.3 of this paper, the theoretical cutter life and

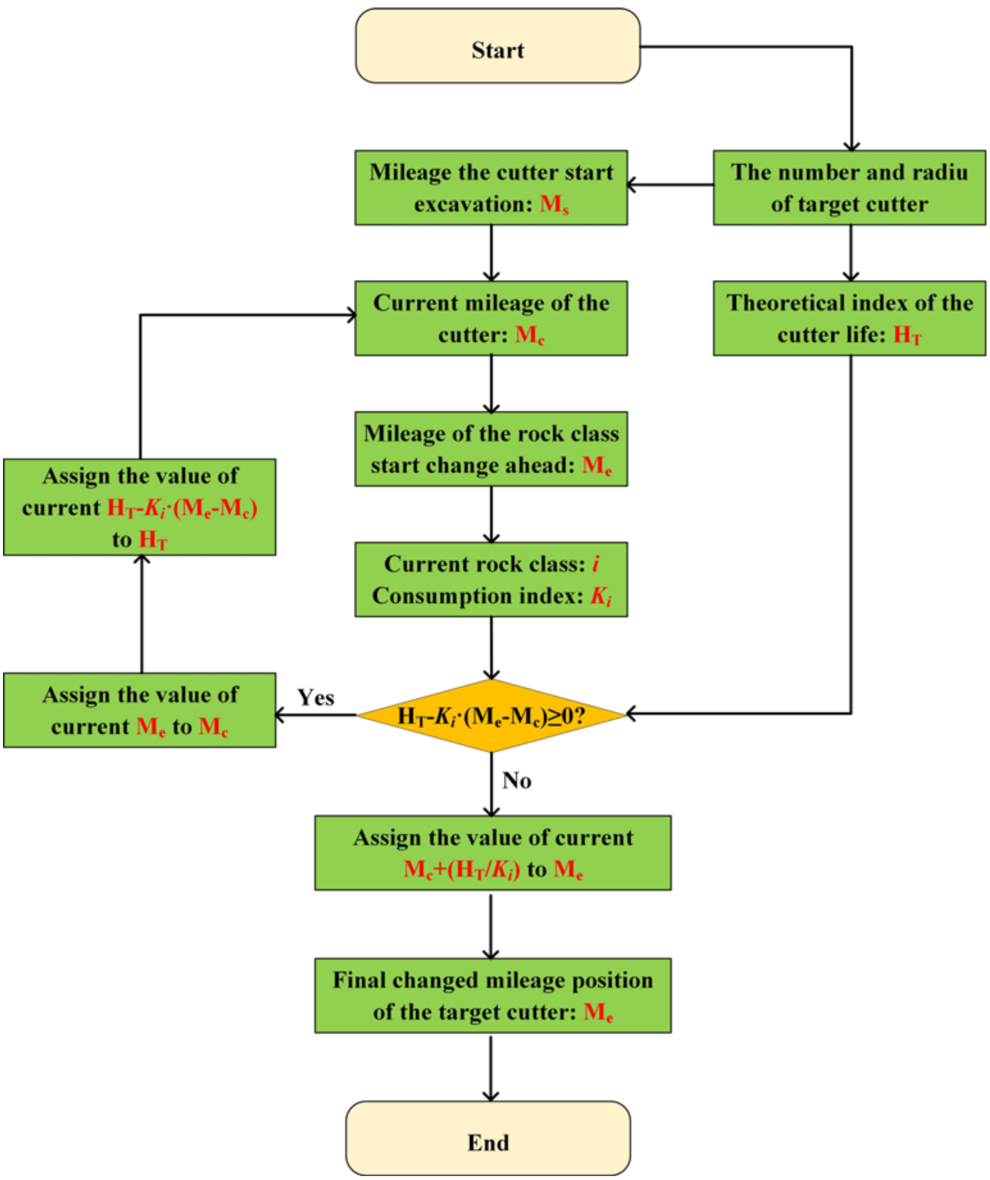

Fig. 11. The Flow Chart for Prediction Cutter Lives by Proposed Model

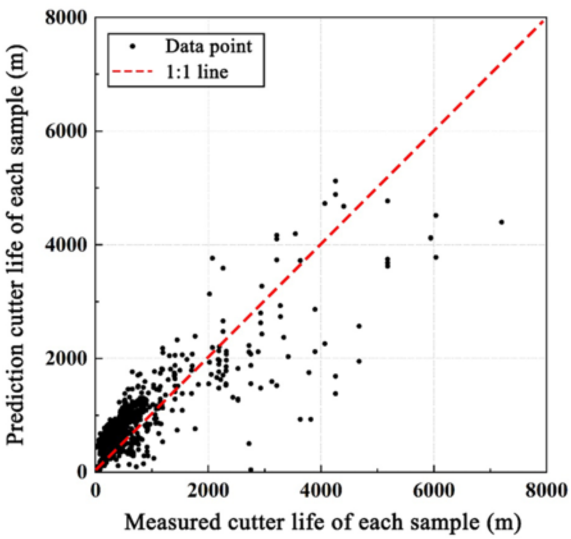

Fig. 12. Comparison of the Actual and Evaluated Excavation Distance of the 920 Samples in 1-A Data Set

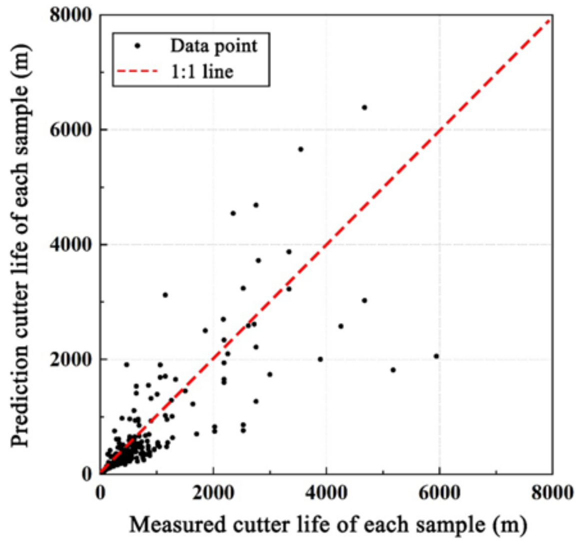

Fig. 13. Comparison of the Actual and Evaluated Excavation Distance of the 280 Samples in 1-B Data Set

the consumption rate is calculated. These calculation equations are applied on the 920 samples in 1-A data set, and the cutter changing mileage position of each samples are evaluated. We compare the actual excavation distance and the evaluated one of each sample for testing the method. In this paper, the prediction results of the cutter life are evaluated by the mean absolute percentage error (MAPE) and the square of correlation coefficient (R^2). Furthermore, ZeroR method is also used in these samples, and its prediction MAPE and R^2 are regarded as a baseline to evaluate the prediction accuracy of the model. In the method of ZeroR, the average value of cutters on same position is used as the prediction results of each samples in the dataset. The results of the prediction model (shown in Fig. 12) is relatively accurate with the mean absolute percentage error of 21% and the R^2 of 0.74, while the corresponding results of ZeroR is 77% and 0.40. The results are much better than the results of ZeroR method and acceptable for predicting the changing location of each cutter, which proves the method has relatively good performance on the samples of dataset 1-A. However, the samples of dataset 1-A have been used for ensuring the coefficients of the prediction model, we still need other samples for verifying the generalization of the model. This work is conducted using samples of dataset 2-A and introduced in Sec. 4 of this paper.

4. Result and Discussion

In the cutter life prediction method proposed in this paper, the theoretical life of each cutter in different position on cutterhead is defined firstly, and then the consumption rate of theoretical cutter life is calculated according to the rock condition, including the rock class and parameters, passed by each cutter. For the convenience of the engineering application, the prediction results of the proposed model are given in the form of concrete mileage position of each cutter changes, and the prediction errors are measured by the residuals between the actual and predicted mileage position of cutter changes. In this section, the model is tested by the data set 2-A and 2-B.

4.1 Result

On the basis of a reasonable theoretical life and its consumption rate involved in the proposed model, the mileage position of each cutter change can be obtained. The excavation mileage length of each cutter is used as the predicted target, and the actual and predicted one is compared. The model is applied in the 280 samples in data set 2-A, and the comparison results are shown in Fig. 13.

As Fig. 13. shows, the red line (represent the predicted cutter life) is closed to the black line (represent the actual cutter life), and the MAPE and R^2 between the actual and predicted cutter life of samples in data set 2-A is 27% and 0.69, while the corresponding value of ZeroR is 79% and 0.37. The highest residual of the totally 280 samples reaches about 3,700 m/cutter (sample 8 of 4# cutter). Totally, there are only 8 samples with predicted error more than 2,000 m/cutter and 22 samples whose predicted error more than 1,000 m/cutter, accounting for 2.86% and 7.93% of the total samples. The prediction accuracy of the model is acceptable in practical engineering.

Accurately prediction of the excavation distance changing trend of the cutter in each position of the cutterhead is of significance for judging the cutter working state and designing the scheme of cutter change. To verify the ability of the model for judging the changing trend of cutter life, part of the samples are labeled as 'sharply rise' and 'sharply full' according to their actual excavation distance. The samples whose excavation distance exceed three times and below the one-third of the average value of corresponding series number of cutter are defined as 'sharply rise' and 'sharply fall' sample, respectively. When their predicted results are in the same range as the actual values, i.e., more than three times or less than the one-third of the average value, the changing trend of the sample is considered to be corrected. On the basis of the definition, 32 'sharply rise' samples and 60 'sharply fall' samples are selected, and the changing trend of 28 'sharply rise' samples and 44 'sharply fall' samples are corrected predicted, accounting for 87.5% and 73.3% of the total, respectively. This proved the relatively good ability of proposed model for judging the changing trend of the excavation distance of each cutter.

4.2 Discussion

There are two key concepts proposed in this model for predicting cutter life, i.e., the theoretical life and its consumption rate. In this section, we try to discuss the reasonability of the two concepts respectively. Firstly, the theoretical lives of the 56 samples in data set 2-B are calculated, and they are compared with their actual lives, which represent the average lives of the 56 cutters in different position on cutterhead. The theoretical lives is calculated according to Eq. (1), the value of K is 2.37 × 10^5, which is same as the value of K calculated in data set 1-B. The comparison of the theoretical and average lives of the 56 samples in data set 2-B is shown in Fig. 14.

The R^2 between the average cutter life of samples in data set 2-B and their theoretical life reaches 0.86. This shows that the fitting degree of data set 2-B is not as good as the one of data set 1-B. As can be seen from Fig. 14, there are only 6 samples whose residuals are more than 800 m/cutter, i.e., 1#, 2#, 3#, 4#, 6# and 7# cutter. These cutters are located near the center of cutterhead with relatively small installment radius, and it results in long average lives and small numbers of samples. Therefore, the random selection procedure of samples is more likely have an impact on the predicted results of these samples. Besides, all the residuals of cutter life in other position of cutterhead are less than 600 m/cutter, which is relatively acceptable. In general, the red line has a similar downward trend as the black line. The results proved that the theoretical life can also characterize the average cutter life in the testing data set 2-B.

Now that the reasonability of the concept of theoretical life is verified, we further analyze its consumption rate K. The value of K under different rock class is shown in Eqs. (5) – (8).

$$K_2 = 4.08\times10^{-3}\times UCS+7.96\times10^{-4}\times VHNR+0.88 \quad (5)$$

$$K_3 = 5.98\times10^{-3}\times UCS+0.59 \quad (6)$$

$$K_4 = 5.52\times10^{-3}\times UCS+0.41 \quad (7)$$

$$K_5 = 0.37 \quad (8)$$

As these equation of the K under different class rock shows, K_2 is influenced by VHNR and UCS, and the two factors are positively correlated with K_2. This reflected that under class II rock, the consumption rate of theoretical cutter life almost increases with VHNR and UCS increasing, and the actual excavation distance almost decreases accordingly. For the samples with class II rock in total data set, the value range of VHNR and UCS are [16 MPa, 147.7 MPa] and [139.7, 607.7], respectively. Accordingly, the range of K_2 is [1.06, 1.97]. K_2 differs by 0.37 when VHNR takes the maximum and minimum values on the data set while the UCS stay the same constant. Similarly, K_2 differs by 0.54 when UCS takes the maximum and minimum values while the VHNR remains unchanged. Therefore, under the class II rock condition, the influence on K_2 of UCS is larger than the one of VHNR.

Unlike K_2, K_3 and K_4 are only influenced by UCS instead of VHNR, and the UCS is also positively correlated with K_3 and K_4 with the coefficient of 5.98 × 10^{-3} and 5.52 × 10^{-3}. As can be seen in these equations, the influence of UCS on the consumption rate K under class III rock is slightly higher than the one under class IV rock.

Referring to the range of VHNR and UCS values in the data set, the range of K_2, K_3 and K_4 is calculated to be [1.06, 1.97], [0.68, 1.32], and [0.49, 1.02], and K_5 is a constant of 0.37. This reflects that the consumption rate K decreases from class II to class V rock on the whole. In other words, for the same excavation distance in class II and class V rock, the former consume the cutter life about 2.86 (the ratio of 1.06 to 0.37) to 5.32 (the ratio of 1.97 to 0.37) times of the latter theoretically. However, the consumption rate of different rock classes overlaps, which means

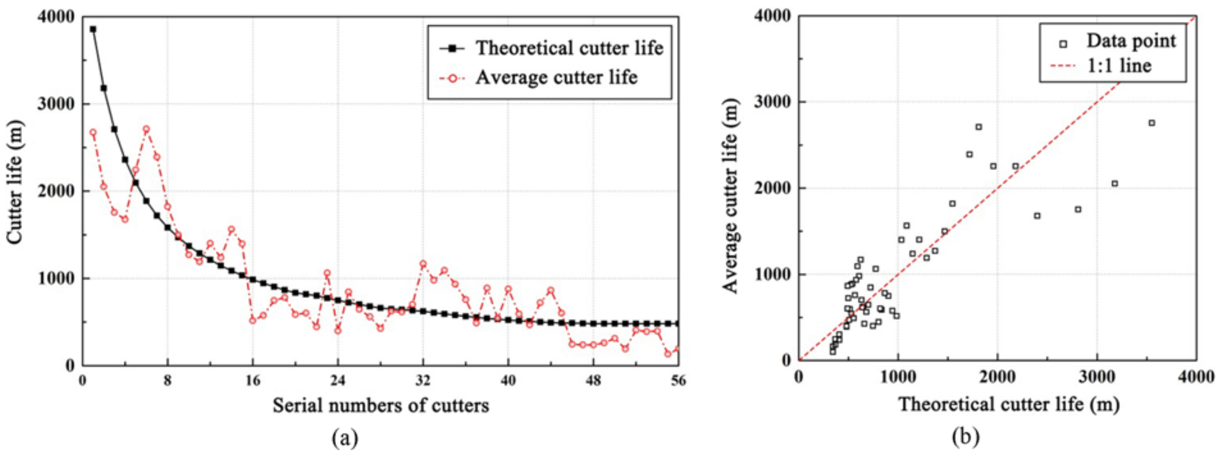

Fig. 14. Comparison of the Theoretical Life and Average Life of Cutters on Each Position of the Cutterhead: (a) Fold-Line Chart, (b) Scatter Plot

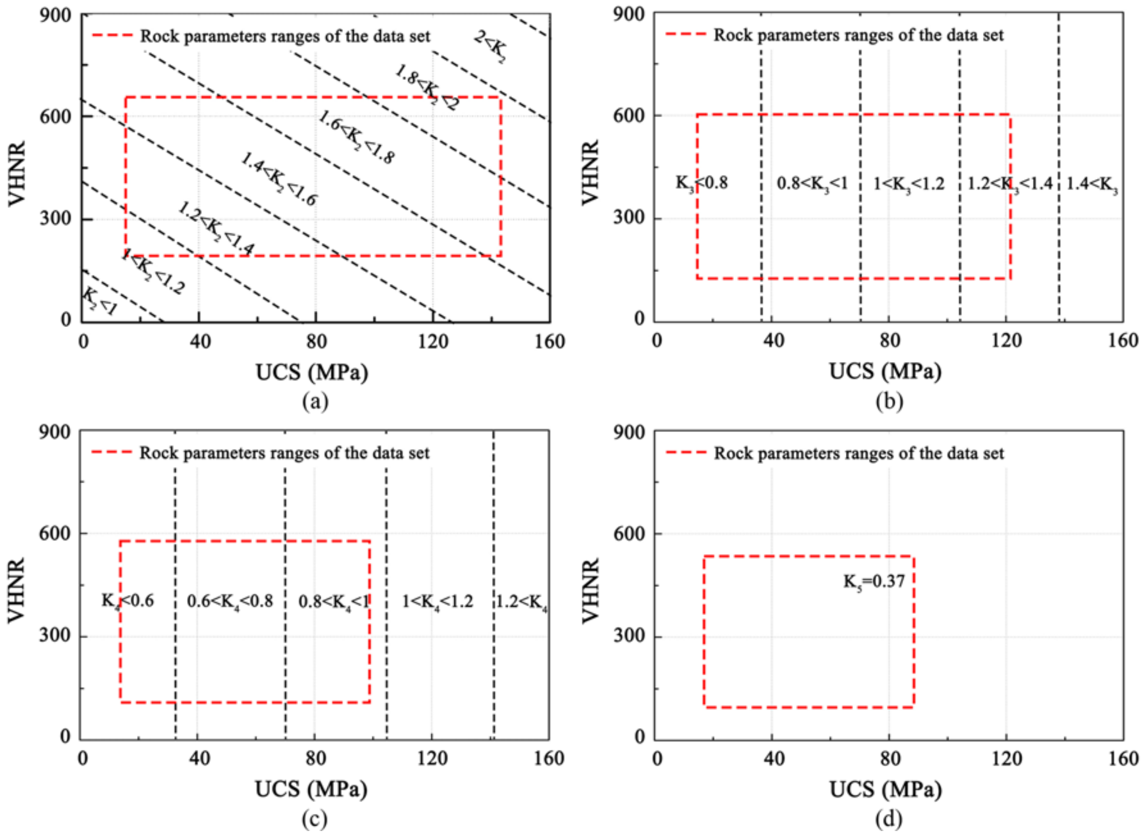

Fig. 15. Charts of the Consumption Rate of II to V Class Rock Change with Rock Properties: (a) Consumption Rate under Class II Rock, (b) Consumption Rate under Class III Rock, (c) Consumption Rate under Class IV Rock, (d) Consumption Rate under Class V Rock

the consumption rate of theoretical cutter life of high-class rock sometimes might be smaller than the one of low-class rock. Besides the classification, the rock mass parameters also have a significant effect on the consumption rate *K*.

4.3 Limitation and Expectation

In this paper, a prediction model with the ability to predict cutter lives in different position on the cutterhead is proposed based on the rock class and parameters. Although the model has been proved to be accurate and reasonable by the field data collected in the 4th Section of the Water Supply Project from Songhua River, there are still several limitations of the model applicability.

One of important factors of the proposed model is the consumption rate *K* under different rock class condition. However, the calculate equation of *K* under the rock condition of class I is not obtained and introduced in this paper, because the data basis for establishing the proposed model is only from the 4th Section of the Water Supply Project from Songhua River whose route does not passes through the rock of class I. For this reason, this model is not suitable for the rock condition of class I temporarily. Similarly, only one size of the cutter is involved in this paper, i.e., the 19-in. cutter, which is also limited to the data set collected in field. This model is not suitable for the TBM equipped with other size of cutters theoretically. For extending the applicability of the proposed model, the record of cutter changes and corresponding rock condition, especially the one under the rock of class I and other size of cutters, need to be collected for the future research.

In this method, traditional linear regression method is adopted to establish the relationship between cutter life and the rock properties. With the rapid development of artificial intelligence, machine learning algorithms are used in geotechnical field (Li et al., 2020a; Liu et al., 2020), and the effects are significant. For improving the prediction accuracy of the cutter life, machine learning methods are considered to use in the future.

5. Conclusions

This study introduces a method for predicting the life of each cutter of the TBM based on the regression analysis on the cutter changing records during the excavation of the 4th section of the Water Supply Project from Songhua River. Different from the traditional cutter life prediction method, the prediction target of this method is the excavation distance of each cutter instead of the average mileage interval of the cutter changing. Based on the proposed method, the mileage position where the cutter needed to be changed can be evaluated. The main conclusion of this paper is summarized as follow.

1. A method for predicting cutter life is proposed, and this method can be divided into 3 steps. Firstly, theoretical life

of each cutter is defined, which is only related to their installment radius. Then, the theoretical cutter life is consumed by weighted excavation distance, and the weights are calculated by the rock class and parameters of the excavation area. Finally, the mileage position where the theoretical cutter life consumed to be 0 is evaluated. The method is verified by the field cutter changing records of the 4th section of the Water Supply Project from Songhua River.

2. The average lives of the cutters on each position of the cutterhead are nearly proportional to the reciprocal of their installment radius. Therefore, this paper proposed a concept of theoretical cutter life for characterizing the average life of each cutter on the corresponding position on the cutterhead. The theoretical cutter life is proportional to the reciprocal of installment radius, and its proportional coefficient is calculated by regression analysis.
3. The consumption rate of the theoretical cutter life is related to rock condition. The consumption rate K under different rock classification and properties are calculated based on statistical analysis. Under the class II rock, the consumption rate of the theoretical cutter life is positively correlated with UCS and VHNR. Unlike the class II rock, the consumption rate under the class III and IV rock is only related to UCS. However, the consumption rate under class V rock is almost independent of the rock properties and approximately considered as a constant. In general, the consumption rate is decreasing from the class II to class V in turn.
4. On the basis of the statistical analysis, the theoretical life and its consumption rate is calculated. Therefore, the mileage position where the theoretical life of the cutter used up, i.e., the position where the cutter needed to be changed can be evaluated. The specific theoretical life of each cutter and the consumption rate is obtained from 920 samples of cutter changing records, and the cutter changing mileage position of these samples are evaluated to compare with the actual one. The mean average percentage error of the results is 21% and the corresponding R^2 reaches to 0.74. The theoretical cutter lives and their consumption rate calculated by the 920 samples are tested by another 280 samples, which is randomly selected in the total data set. The MAPE and R^2 of the test samples are 27% and 0.69. The test results show that the method is effective and reasonable for evaluating the cutter life.

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