Proceedings of the 2nd International Conference on Functional Materials and Civil Engineering
DOI: 10.54254/2755-2721/72/20240997

Wear prediction study considering tunnel boring machine (TBM) hob slip

Fan Yang[1], **Xiangjun Liang**[1], **Heng Zhang**[1,2]

[1]School of Mechanical Engineering, Wuhan Polytechnic University, Wuhan, 430048, China

[2]zhangheng@whpu.edu.cn

Abstract. Aiming at the problem of serious tool wear and untimely tool change affecting the construction efficiency when TBM is digging in microfractured tuff strata, the hob wear prediction study is carried out based on engineering examples. By analysing the rock-breaking mechanism of hob wear, a linear wear rate model and a life prediction model considering hob slip are derived based on the CSM model and the abrasive wear theory; the wear rate and the wear amount at the tool change point are further calculated by the prediction model in comparison with the measured value, and the furthest digging distance of the hob is calculated by the life prediction model. The results show that: the relative error between the measured average wear rate and the calculated linear wear rate considering the hob slip is 5.3%; the life prediction model predicts that the longest digging distance of the positive hob is 857 rings and the shortest distance is 198 rings. The results of the study are of guiding significance for the prediction of tool wear and the selection of the timing of opening and changing the hob in TBM tunneling.

Keywords: CSM model, Wear rate, Hob slip, Life prediction.

1. Introduction

In recent years, with the comprehensive development of urban railway track construction in China, the geological conditions faced by TBM construction through tunnels have become more and more complex, and the requirements for the control of schedule and cost have become more and more stringent[1]. According to statistics, the cost of the tool can be up to 1/3 of the total construction cost, and the time required for checking and replacing the tool is about 1/3 of the total construction time[2]. Therefore, the study of hob wear is of great significance to reasonably predict the time and cost of hob replacement and take timely and effective measures to shorten the construction period and reduce the cost.

For the problem of hob wear prediction, many scholars at home and abroad have carried out a lot of research, and the main methods focus on theoretical models[3] (such as CSM model, abrasive wear, wear specific energy) and empirical models[4] (such as regression fitting and machine learning). The theoretical calculation model mainly establishes a mathematical model from the wear mechanism based on the hob structure parameters. Based on the energy method, Geng Qi[5] proposed the unit wear work and equivalent wear function of the hob blade, and established the formula for calculating the unit wear work of the hob blade based on the rock-breaking load of the hob at each cutter position, the hob mounting parameters, and the parameters of the TBM excavation; while the empirical model relies on a large number of excavation parameters, stratigraphic parameters, and structural parameters, and predicts them based on the computer. Tan[6] and others analysed the tool wear values of different cutter positions, the effect of surrounding rock strength and digging parameters on tool wear and the sensitivity of different digging parameters to tool wear based on regression analysis; Shan[7] and others used the method of multiple regression analysis to analyse the relationship between the hob installation radius, stratigraphic parameters, digging distance and frontal hob wear, constructed a frontal hob wear prediction model, and analysed the wear characteristics of frontal hob with different trajectories; Shen[8] and others proposed a model for predicting the wear and tool change position of disc hob considering thrust distribution and energy conversion coefficients; Khalid Elbaz[9] used the nonlinearity of genetic algorithms (GA) to optimise the defects of the GMDH method which is prone to produce locally optimal solutions, and used the GMDH-GA model to predict the hob life of a shield machine in four sectors. life prediction; Zhang[10] used the powerful and efficient processability of BP neural networks for black-box type problems to analyse the nonlinear relationship between the relevant process parameters and the hob wear, and determined the sample combination of the data set through the orthogonal method, which ensured the objectivity and comprehensiveness of the data samples.

In summary, this paper establishes a linear wear rate prediction model and a life prediction model considering hob slip on the basis of the analysis of hob breaking mechanism, and verifies the correctness of the established model based on engineering examples, which provides support for further revealing the hob force and wear law.

2. Analysis of the rock breaking mechanism of hob wear

The root cause of tool wear during TBM construction is the interaction between the tool and the soil, and the rock body produces a strong abrasion effect on the hob, resulting in the hob blade becoming wider and wider, and the contact area with the soil becomes larger and larger, until it changes the original way of breaking the rock by the hob. Hob wear is mechanical energy into other forms of energy in the process of periodic energy consumption, manifested in the phenomenon of material loss on the surface of the object.

Macroscopically, the rock-breaking process of the hob can be divided into three stages: the idling stage of the cutter disc, the contact stage and the rock-breaking stage. Throughout the rock-breaking stage, the motion of the hob is in the form of rotating and pushing of the cutter disc and the rotation of the hob itself, but the force on the hob is different in different rock-breaking stages. In order to simplify the analysis process, an ideal palm surface is assumed and the spatial motion of the hob is converted into plane motion. As shown in Figure 1 the hob is installed with a radius of R in contact with the palisade surface, there exists an initial angle α, and rolls the palisade surface with a certain speed. When passing, the cutter rotates dα angle with angular velocity ω, the hob turns through the angle, the kinematics equation of the rock-breaking point on the hob can be expressed in the column coordinate system as,

$$\begin{cases} \rho_N = \left[{R_i}^2 + (r\sin\theta')^2\right]^{1/2} \\ \theta_N = \varphi + arctan\frac{r\sin(\theta')}{R_i} \\ Z_N = r - \frac{vdt}{2\pi\omega} - r\cos(\theta') \end{cases} \tag{1}$$

From the equation of motion, the trajectory of the hob in the idle stage is a cylindrical helix with $\frac{v}{\omega}$ as the guide, and v is the blade propulsion speed.

As the cutter disc pushes forward, the hob breaks contact with the palm face. Although the advance speed of the cutter disc is small, but the inertia and thrust is large, the contact moment there is a strong impact will make the hob caused by impact damage, and due to the hob and the palm face there is relative stiffness, the impact force is transmitted to the cutter disc, so that the cutter disc and the palm face of the relative stiffness affects the overall cutter disc of the force and vibration, and lead to the bending deformation of the cutter disc, due to the unevenness of the palm face impact force is also into the cyclic

DOI: 10.54254/2755-2721/72/20240997

Due to the unevenness of the impact force on the palm surface, the impact force is also cyclical, which makes the wear of the hob at each position of the cutter disc different.

After contacting with the palm surface, the hob extrudes and shears the palm surface with the degree of penetration h. The rock is pressed into the powder nucleus, and with the powder nucleus being compacted, a series of concentric grooves are left on the palm surface, and with the further in-depth conduction of the hob thrust, cracks are formed inside the rock and further expanded. When the cracks between neighbouring hob penetrate, the rock fragments fall off and the hob completes the rock breaking process. Rock surface for macro-uniform morphology, although the hob is passive rotation, but the hob surface and the rock still exists between the relative sliding, and again impact to the rock, so the process of rock-breaking is actually a periodic impact - sliding composite process.

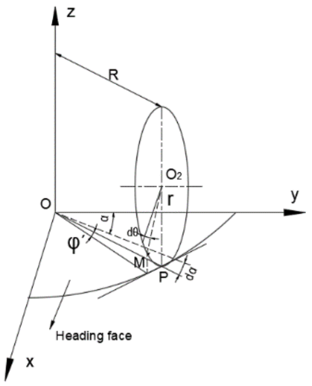

Figure 1. Schematic diagram of rock breaking by hob.

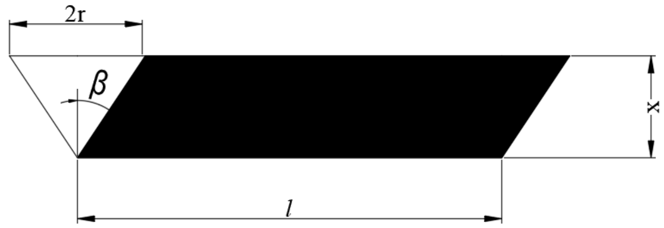

Figure 2. Abrasive wear modelling.

3. Life prediction modelling

3.1. Theory of abrasive wear

Abrasive wear is a form of wear in which the rock crushing particulate matter takes away the projections on the surface of the hob material during friction leading to a reduction in the volume of the hob, and it is the main cause of normal wear of the hob. For the calculation of wear volume, MIT has developed a model of abrasive wear based on the micro-cutting hypothesis that views the abrasive grains as a cone of hard particles sliding on a soft material and ploughing a furrow (Figure 2).

In Figure 2, the half angle of the cone is β, the diameter of the bottom of the cone is 2r (i.e., the width of the ploughed groove), the depth of indentation is x, the sliding distance is l_0, and the yield strength of the material to be abraded is σ_s. The area of the projected area in the vertical direction is πr^2, and the abrasive grains are loaded on only half of the conical surface (the conical surface in the forward direction) when they are sliding, assuming that the abrasive grains have M micro-convex bodies on the contact surface, then the normal load of the M micro-convex bodies is,

$$F_n = \mathrm{M}\frac{\pi r^2}{2}\sigma_s \tag{2}$$

The unit wear volume of the hob is the volume ploughed away, and taking into account the probability k of abrasive particles generated by microconvex body interactions, the wear volume per unit of sliding trajectory is,

$$\mathrm{V} = k\frac{2}{\tan\beta}\frac{F_n}{\pi\sigma_s} = K\frac{F_n}{\pi\sigma_s} \tag{3}$$

F_n is the normal load for the hob normal thrust, derived from the CSM model,

$$F_n = 0.8T^{5/6}S^{1/3}(2r)^{1/2}\sigma_c h^{1/3} \tag{4}$$

For one revolution of the hob, the radial wear of the cutter ring Q is,

$$\mathrm{Q} = \frac{l_0 V}{2\pi rT} = \frac{K\frac{F_n}{\pi\sigma_s}l_0}{2\pi rT} = 0.08\mathrm{K}\frac{S^{1/3}\delta_c h^{5/6}}{\delta_s T^{1/6}} \tag{5}$$

Where K is the abrasive wear coefficient, which is the product of the geometric factor $\frac{2}{\tan\beta}$ and the probability number k, and is related to the hardness of the abrasive grains, their shape and size, and the number of abrasive grains acting as cutters.

Abrasive wear coefficient on the accuracy of the hob wear prediction, the value of the coefficient with the type of abrasive wear, abrasive grain size, material properties and other factors related to the abrasive wear coefficient of many scholars through the test to obtain the abrasive wear coefficient is shown in Table 1.

Table 1. Abrasive wear coefficient.

Vintages	Researcher	Type of wear	Grit size /μm	Materials	K/10^{-3}
1956	Sayer	Two bodies	70	Steel	16
1958	Nikita Khrushchev	Two bodies	80	Many kinds of	24
1958	Mikhail Tobarov	Three bodies	150	Steel	6
1961	Viktor Feyedovic	Three bodies	80	Steel	4
1961	Viktor Feyedovic	Three bodies	40	Many kinds of	2

3.2. Linear Wear Rate Prediction Model Considering Hob Slip

In order to accurately predict the digging distance of the hob, according to the literature, the wear of the hob occurs on the contact trajectory line with the palm face, and the wear rate model is introduced, then the wear rate of the hob ω_0 is,

$$\omega_0 = \frac{X}{L} = \frac{QR_i/r}{h} = 0.08K\frac{S^{1/3}\delta_c R_i}{\delta_s T^{1/6} r h^{1/6}} \tag{6}$$

Where X is the cumulative wear of the hob for the L distance of shield excavation.

Through the analysis of the hob movement and rock breaking, it can be obtained that the movement of the hob breaking point during shield tunneling is a circular movement with the hob installation radius R_i as the radius and the centre of the cutter disc as the centre, but affected by the rotational speed ω of the cutter disc and the forward propulsion speed v of the cutter disc, the trajectory is a cylindrical helix with the guide range $\frac{v}{\omega}$. Therefore the length of the trajectory of one revolution of the hob is,

$$l = \left(L^2 + 4\pi^2 n^2 {R_i}^2\right)^{1/2} = L\left[1 + 4\pi^2\left(\frac{\omega}{v}\right)^2 {R_i}^2\right]^{1/2} \approx 2\pi\omega R_i\frac{L}{v} \tag{7}$$

Where L is the digging distance, n is the number of revolutions of the knife disc rotation. However, the hob in the actual digging, in its rolling at the same time there is also sliding relative to the palm surface, the superposition of the two movements makes the hob's trajectory is smaller than the actual hob distance, the actual hob movement distance can be expressed as,

$$L_R = \xi l \tag{8}$$

Where ξ is the slip rate, the slip rate can be expressed as,

$$\xi = 0.045h^{1/2}\mu\left[1 - \left(1 - \frac{C}{\mu}\right)^{1/2}\right] \tag{9}$$

Where μ is the rock friction factor, the value range is shown in Table 2; C is the cutting coefficient, usually calculated by the digging parameters,

$$C = \frac{M_T N}{F_T \sum_{i=1}^{N} R_i} \tag{10}$$

M_T is the total torque of the cutter, F_T is the total thrust, and N is the number of hobs. From the above equation, it can be seen that the hob slip rate is determined by the hob parameters, geological parameters and digging parameters together. The hob penetration depth calculation formula $h = \frac{v}{\omega}$, then the actual rolling distance L_R is,

$$L_R = 0.09h^{-1/2}\mu\left[1-\left(1-\frac{C}{\mu}\right)^{1/2}\right]\pi R_i \mathrm{L} \tag{11}$$

Table 2. Abrasive wear coefficient.

Name of geotechnical body	Silty clay	Sandy soil	Rubble soil	Limestone
Friction factor μ	0.25	0.3-0.4	0.4-0.5	0.4-0.6

In order to further investigate the wear resistance of the hob, the linear wear rate prediction model is optimized, then the linear wear rate ω_x of the hob is,

$$\omega_x = \frac{X}{L_R} = \frac{\omega_0 L}{L_R} = 0.8K\frac{S^{\frac{1}{3}}\delta_c h^{\frac{1}{3}}}{\delta_S T^{\frac{1}{6}} r\mu\pi\left[1-\left(1-\frac{C}{\mu}\right)^{1/2}\right]} \tag{12}$$

From the above equation, the cumulative wear X is,

$$X = \omega_x L_R = 0.09h^{-\frac{1}{2}}\mu\left[1-\left(1-\frac{C}{\mu}\right)^{1/2}\right]\pi R_i \mathrm{L}\omega_x \tag{13}$$

It can be seen that the TBM hob line wear rate, which is affected by hob slip, is related to a number of factors. The main influencing factors are: geological conditions, tool material parameters and boring penetration. By calculating the radial wear amount of the hob blade circle, the linear wear rate of the hob and the cumulative wear amount for the abrasive wear mechanism analysis, it can provide reference data for the construction of the hob life prediction model.

3.3. Life prediction model considering hob slip

Through the above abrasive wear mechanism analysis, in order to intuitively get the data results, the normal digging distance of the hob for the life of the hob, according to geological conditions, tool parameters and digging parameters and other influencing factors to get,

$$L = \frac{X}{0.09h^{-\frac{1}{2}}\mu\left[1-\left(1-\frac{C}{\mu}\right)^{1/2}\right]\pi R_i \omega_x} \tag{14}$$

Through the analysis of tool change data, the average value of tool change wear of the hob under this stratum is 30mm, and the wear limit is set to 35mm to predict the service life of the hob. Substitute the maximum value of 35mm to get the maximum digging distance L_{max} is,

$$L_{max} = \frac{35}{0.09h^{-\frac{1}{2}}\mu\left[1-\left(1-\frac{C}{\mu}\right)^{1/2}\right]\pi R_i \omega_x} \tag{15}$$

From the above equation, the linear relationship between the hob life and the influences of different propulsion parameters can be seen.

4. Engineering Example Verification

4.1. Project Overview

Binhai Express (Fuzhou to Changle Airport Intercity Railway Project), the second section of the total length of 29.15km, a total of 4 stations and 5 intervals, the specific pile number YBK15+907 to

DOI: 10.54254/2755-2721/72/20240997

YBK45+060, passing through Cangshan, Minhou, Changle District, across the Wulong River and Amoy River, crossing the pillow peak mountain, Daxiang Mountain, wild island, Daigong, Lotus Hill, along the route of the geological features are complex, the engineering layout map is shown in Figure 3. In this paper, relying on Xiangqian Station ~ Shouzhim Station interval pillow peak mountain tunnel, Daxiangshan Tunnel, TBM through the Ⅱ, Ⅲ, Ⅳ, Ⅴ perimeter rock, as well as water-rich strata, faults, joints and other strata of the dense zone. Pillow Peak left tunnel length 1525.275m, Elephant Mountain left tunnel length 4515.230m, stratigraphic lithology is mainly slightly weathered tuff. The uniaxial compressive strength of the rock is 30~100MPa, which belongs to hard rock~hard rock; the abrasive index of the rock is 2.0~3.2, which is strong abrasive.

Xiangqian Station ~ Shouzhanyuan Station interval tunnel is constructed by DZ772 TBM, the diameter of the cutter plate is 8.64m, in order to adapt to the smooth excavation of this interval, the cutter plate is arranged with 58 hobbing knives, S1~S8 is the centre hobbing knives, S9~S45 is the front hobbing knives, and S46~S57B is the edge hobbing knives, and the arrangement of the hobbing knives on the cutter plate panel is as shown in Figure 4.

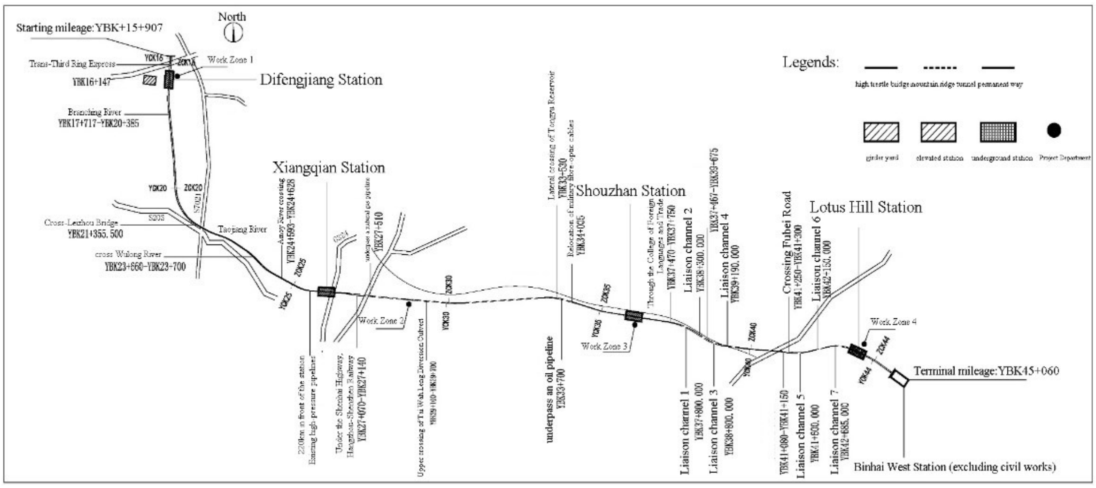

Figure 3. General Layout Plan for Construction of Section 2 of Binhai Express Line (Fuzhou to Changle Airport Intercity Railway Project).

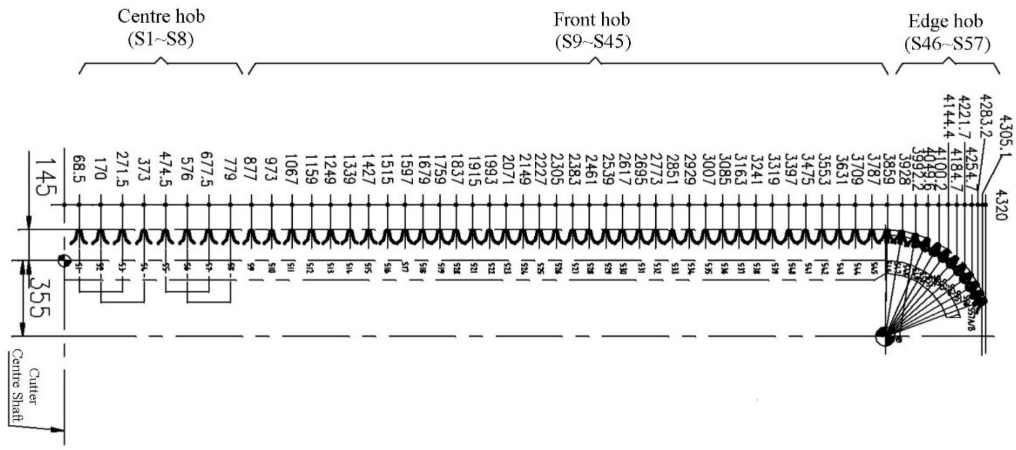

Figure 4. Hob arrangement.

4.2. Data analysis of tool change

Combined with the measured data of the interval between Xiangqian Station and Shouzhanyuan Station of Binhai Express Line, the data of hob changing is analysed, and the linear wear rate prediction model established considering the hob slipping is verified, so as to further predict the service life of the hob in the interval of the project.

Selected TBM digging interval tool change data for analysis, this stage of digging mainly through the micro-differentiated tuff, hob failure is serious, as shown in Table 3 for the number of tool change in different tool positions on the cutter plate.

From Figure 5 and Figure 6 pie charts, we can see the distribution of hob failure forms and the number of tool changes. In the interval of TBM digging, the hob wear and tool change is 824, and the edge hob wear and tool change is 521, occupying 63% of the total number of tool change, which indicates that the frequency of tool change of the edge hob is higher than that of the centre hob and the frontal hob, and the tool ring bias wear accounts for 23% of the total number of edge hob wear and tool change, which is due to the edge hob suffers from the secondary wear in the TBM digging and the tool ring breakage and other situations may occur, therefore, the It is necessary to focus on monitoring the wear of edge hob in digging. The total number of positive hob changes is 284, occupying 34% of the total number of worn hob changes, with 71% of the normal wear loss form. The normal wear of the centre hob accounted for 0%, which is mainly due to the phenomenon of bias wear caused by slippage or lateral force in rock breaking. As can be seen from Figure 5, the hob failure caused by the knife ring bias wear accounted for 23% of the whole failure form.

Table 3. Statistics on the number of hob failures for tool change (unit: pcs).

Hob type	Failure form					Number of tool changes
	normal wear	Knife ring bias grinding	Knife rim cracking	Knife circle displacement	else	
Centre hob	0	9	4	1	5	19
Front hob	202	57	13	11	1	284
Edge Hob	357	120	19	16	9	521
Total number of tool change	559	186	36	28	15	824

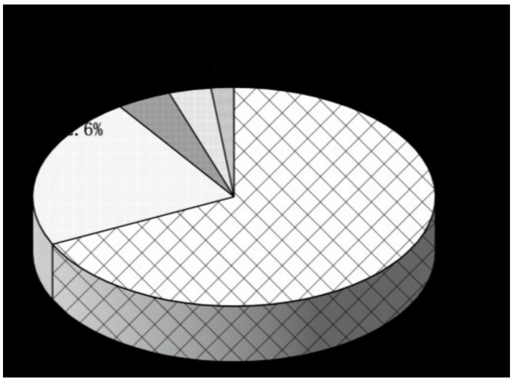

Figure 5. Hob Failure Percentage Distribution Chart.

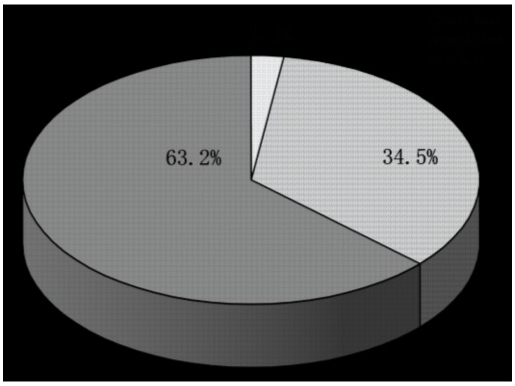

Figure 6. Distribution of the number of hob changes.

4.3. Analytical validation of the wear rate model

Through the analysis of the above tool change data, the edge hob is frequently changed, and the bias wear is serious, while the frontal hob wear has a certain regularity, and the frontal hob is now selected for analysis. In order to accurately analyse the actual wear rate of the hob, the relevant parameters affecting tool wear are extracted through the field hob wear test. Among them, the tool used in the boring

DOI: 10.54254/2755-2721/72/20240997

interval is mainly the Tiangong hob produced in Shandong, and the hardness value of the hob cutter ring is 56~58HRC, with reference to GB / T 1172-1999 “ferrous metal hardness and strength conversion value”, the tensile strength of the cutter ring δ_b is 2181MPa, and the yield ratio of alloy steel is 0.85, which gives the yield strength δ_s of 1853.85MPa. The uniaxial compressive strength of rock σ_c is 50.83 MPa, the average value of hob penetration is 0.00713m/rev, the pitch of front hob S is 78mm, the width of knife edge T is 19.3mm, the radius of hob r is 241.5mm, and the friction factor of hob is 0.004 according to Table 1.

The wear rate of the hob can be used as an indicator of how fast or slow the cutter ring wears during the TBM excavation process. For this purpose, the speed of wear of the tool ring is analysed and studied by using formula (6). Since the measured wear is measured at each tool change, the measured wear rate is obtained from the ratio of the hob wear and the digging distance, and the calculation results are shown in Figure 7.

In order to analyse the magnitude of radial wear of the hob unit digging ring, the measured linear wear rate and calculated linear wear rate considering the hob slip are obtained according to equation (22) as shown in Fig. 8. As can be seen from Fig. 8, the measured average wear rate and calculated linear wear rate of TBM positive hob are 0.112 and 0.106 mm / m, respectively, with a relative error of 5.3%. Therefore, the relative error of the hob linear wear rate prediction model is less than 10%, which indicates that the linear prediction model considering the hob slip has a certain degree of reliability in the prediction of the wear rate of the positive hob; it also indicates that the linear wear rate of the hob breakout can be used as a measure of the speed of the rock breakout rate of the TBM hob in this tunnel stratum.

Through the formula (13) to calculate the tool change point wear amount and the measured value comparison analysis (Figure 9), with the increase of the hob number, that is, the increase of the hob installation radius, the number of digging rings at the tool change point decreases, and the wear amount is relatively reduced. Comparison of calculated and measured values shows that the relative error is 18.2%, which is less than 20%.

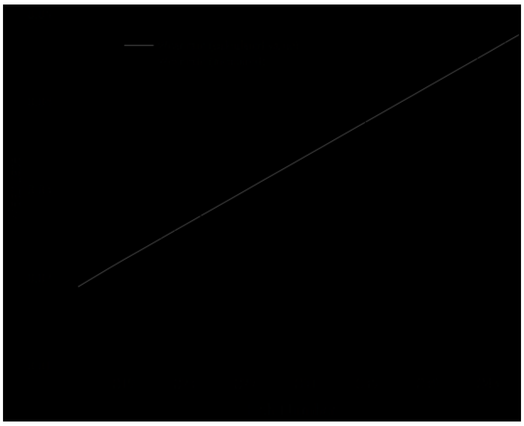

Figure 7. Measured wear rate vs. calculated value.

Figure 8. Measured and Calculated Wear Rates Considering Hob Slip Linear Wear Rates.

DOI: 10.54254/2755-2721/72/20240997

Figure 9. Comparison of the amount of wear at the tool change point.

Figure 10. TBM Hob Life Prediction Statistical Bar Chart.

4.4. Lifetime prediction analysis

From Figures 8, 9 and 10, it can be concluded that the longest digging distance of the TBM tool hob can be used to indicate the service life of the frontal hob. From the figure, it can be seen that the service life of TBM is negatively correlated with the installation radius, i.e., the service life decreases with the increase of the installation radius, and the maximum service life of the frontal hob in the microdifferentiated tuff strata is 857 rings, and the shortest service life is 198 rings.

Through the above data calculation, the correctness of this paper's prediction model is verified, and the model can accurately calculate the linear wear rate of each ring of the frontal hob, and in the actual project, there is a small difference between the calculated value of the life span and the longest digging distance of the hob. Therefore, this model can be used to predict the frontal hob wear of TBM in similar stratum, which can promote reasonable hob change, reduce the time of hob change and improve the construction efficiency.

5. Conclusions

In order to accurately predict the service life of TBM when it is digging in microfractionated tuff strata, it is found through the analysis of the rock breaking mechanism of the hob that the rock breaking process of the hob is a composite process of cyclic impact-sliding, therefore, a linear wear rate model and a service life prediction model considering the hob slip are established, and the prediction model is analysed and verified by combining with the measured data of the interval between Xiangqian Station and Shouzhanyuan Station of the Coastal Express Line. The results show that: the measured average linear wear rate and calculated linear wear rate of positive hob considering hob slip are 0.112 and 0.106mm/m respectively, with a relative error of 5.3%; the analysis of the hob life prediction model shows that, when the TBM traverses through the microdifferentiated tuff strata, the life span of the hob is negatively correlated with the installation radius, and the maximum life span of the frontal hob is 857 rings, and the shortest life span is 198 rings. The maximum service life of frontal hob is 857 rings and the minimum service life is 198 rings.

References

[1] Huang D, Ma H & Yang X C, et al. (2023). Current Research and Prospect on Cutter Wear of Tunnelling Boring Machine. Geotechnical Engineering Technique, 37(3), 253-261. https://doi.10.3969/j.issn.1007-2993.2023.03.001

[2] Wan Z C, Sha M Y, & Zhou Y L. (2005). Study on disk cutters for hard rock—Application of TB880E TBM in Qinling Tunnel. Modern Tunnelling Technology, 39(5), 1-11. https://doi.10.13807/j.cnki. mtt

[3] Wang L H, Li H P & Zhao X J, et al. (2017). Development of a prediction model for the wear evolution of disc cutters on rock TBM cutterhead. Tunnelling and Underground Space Technology, 67, 147-157. https://doi.10.1016/J.TUST.2017.05.003
[4] Ding X B, Xie Y X & Xue H W, et al. (2023). A Method for Disc Cutter Wear Prediction Based on Neural Network. Journal of Zhengzhou University (Engineering Science), 44(1), 83-88+95. https://doi.10.13705/j.issn. 1671-6833. 2022. 04. 009
[5] Geng Q, Wei Z Y, & Ren J H. (2018). Analytical Research on the Wear Mechanism of TBM Disc Cutters Based on an Energy Approach. Journal of Mechanical Engineering, 54(1), 36-43. https://doi.10.3901/JME. 2018.01.036
[6] Tan Z S, Zhou Z L & Li Z L, et al. (2021). Research on wear law of cutters for TBM tunneling in hard rock, 54(12), 104-115. https://doi.10.15951/j.tmgcxb. 2021.12.010
[7] Shan Y W, Jiang Y S & Shao X K, et al. (2023). Characteristics of Wear and Prediction Model of Face Cutter of Shield Tunneling in Hard Rock. Railway Standard Design, 67(12), 1-7. https://doi.org/10.13238/j.issn. 1004-2954.202206040002
[8] Shen X, Chen X & Fu Y, et al. (2022). Prediction and analysis of slurry shield TBM disc cutter wear and its application in cutter change time. Wear, 498-499, 204314. https://doi.org/10.1016/j.wear. 2022.204314
[9] Khalid E, Shui-Long S & Annan Z, et al. (2021). Prediction of Disc Cutter Life During Shield Tunneling with AI via the Incorporation of a Genetic Algorithm into a GMDH-Type Neural Network. Engineering, 7(2), 238-251. https://doi.10.1016/j.eng. 2020.02.016
[10] Zhang J D & Qi X M. (2017). Research on Wear and Life Prediction of Hobbing Cutter by Cold Cutting in Cryogenic Air with MOL. Machine Tool & Hydraulics, 45(20), 62-65. https://doi.10.3969/j.issn. 1001-3881.2017.20.016