TBM cutter wear prediction in inclined shaft project based on tunnelling parameters

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Abstract. Cutter wear is one of the important factors affecting the safety and efficiency of shield or TBM tunnelling. Based on the inclined shaft tunnelling project with long distance, large slope and constant excavation in Bulianta coal mine, regression analysis is applied to investigate the relationship between cutter wear and tunnelling parameters such as cutterhead rotation velocity, cutterhead torque, advance velocity, total thrust and penetration, and thus the prediction model of cutter wear is established. The results indicate that cutter wear is significantly correlated with each tunnelling parameter, and that the regression model expressed by cutterhead torque, total thrust and penetration can account for 97.8 percent of the cutter wear issue induced by potential influencing factors. The model has good effect on the prediction and could provide certain guidance and reference for the cutter wear problem in similar geological condition.

1. Introduction
The issue of cutter wear is inevitable when TBM excavates hard rock strata, which may cause serious cutterhead wear, shutdown for maintenance and even the occurrence of engineering accidents [1-3]. Therefore, the prediction and control of cutter wear is necessary to investigate [4-6]. Many influencing factors may lead to TBM cutter wear, such as geological parameters, tunnelling parameters and cutterhead parameters. Extensive researches have been carried out on cutter wear from various perspectives. Fowell and Johson (1991) proposed a linear model between cutter wear and rock abrasivity index CAI, but the model is only suitable for cutting high abrasive rocks[14]. Michael Alber (2008) predicted the advance distance of cutter exchange at different positions on TBM cutterhead according to different CAI values[15]. G. Wijk (1992) established a prediction model for cutter life considering hob diameter and cutter edge angle, and found that the cutting distance is inversely proportional to the square of CAI index [16]. Gehring(1995) proposed the concept of cutter ring mass loss rate Vs (mg/m) and established the exponential relationship model between Vs and CAI value[17]. Zhang Fengxiang et al. (2004) proposed a prediction calculation formula for the wear amount of the outermost cutters based on cutterhead diameter and tunnelling parameters such as cutterhead rotation velocity, tunnelling distance and advance velocity[18], and Guan Huisheng [18], Yan Gouhong[18]revised the model, respectively. Tan Qing et al. (2017) established a cutter wear prediction model based on the abrasive wear theory and cutter-rock contact mechanical model and obtained the wear evolution [19].

This paper applies the regression analysis method to analyze the relationship between cutter wear and tunnelling parameters from the perspective of single factor and multiple factors, and establish the
prediction model for cutter wear, expected to provide reference for cutter wear problems when TBM excavating in similar geological conditions.

2. Engineering background
Located in the southeast of Ordos City in Shendong mining area, the inclined shaft of Bulianta coal mine is mainly used as auxiliary transportation roadway. It has a gradient of -5.5 degree and a net tunnel diameter of 6.6m, with a total length of 2744.5m, including 26.3m of open cut section and 2718.2m of TBM construction section, as shown in Fig.1. The depth of the strata inclined shaft passing through has a buried depth of 6.4 to 276.8m, while the length mainly includes Quaternary loose sand layer of about 48 m, Cretaceous Zhidan group of about 460 m, Jurassic An'ding formation and Zhiluo Formation of 1150 m, and Jurassic Yan'an formation of about 1087 m. The RQD value of crossing strata shows a large range of 35% to 85% in different groups, and the difference also occurs in the integrity, weathering degree, joint and fissure development degree, physical and mechanical strength index and porosity of different rock groups. The strata within the scope of inclined shaft excavation are complex, and the rock hardness shows medium abrasive.

![Fig.1 Geological condition of the inclined shaft in Bulianta coal mine](image)

3. Collection of tunnelling parameters
Tunnelling parameters can be monitored in real-time when TBM excavating. Field experience and monitoring indicate that the rock breaking effect and the advance velocity are reduced when the cutterhead thrust and torque increase sharply due to hard rock, thus inducing the increase of cutter wear. Therefore, the on-site TBM tunnelling parameters are important indicators to characterize the cutter wear. This paper focuses on the influence factors of cutter wear such as cutterhead rotation velocity, cutterhead torque, advance velocity, total thrust, and penetration. The cutterhead type and cutter wear situation at the construction site are shown in Fig. 2.

Due to the cutter exchange and TBM maintenance induced by serious cutter wear, or the reduction of cutterhead torque when tunnelling hard rock strata, many tunnelling parameters are collected in abnormal working state. Also, the obtained data may have a lot of noise and deviation owing to the different acquisition frequency and accuracy of tunnelling data. Therefore, the original collected data are preprocessed to obtain the normal tunnelling parameters and then regression analysis is carried out.
4. Multiple regression model and hypothesis tests

In order to study the influence of tunnelling parameters on cutter wear during the process of TBM passing the complex strata in the inclined shaft, the statistical relationship between cutter wear and tunnelling parameters is established. According to the mathematical statistics, the multiple regression model is firstly established, and five influencing factors are finally selected as dependent variables including cutterhead rotation velocity, cutterhead torque, advance velocity, total thrust and penetration.

After the establishment of the model, hypothesis tests should be performed to test whether the whole equation or regression coefficient is significant, as well as the fitting degree with the sample data and the linear correlation of the model. The commonly used statistical tests are R-test, F-test and T-test. Among them, R-test and F-test are used to test the overall regression effect of regression model, and T-test the significance of the regression coefficient of each variable.

Due to the huge amount of calculation, mathematical software such as SPSS can carry out multiple linear regression, which greatly simplifies the manual calculation process. In this paper, SPSS software is applied to discuss and study the single factor and multiple factors influencing cutter wear through the methods of univariate linear regression and multiple linear regression.

5. Regression analysis of cutter wear

5.1. Single factor analysis

Cutter exchange generally occurs when TBM excavating the rock strata in inclined shaft. In engineering practice, the situation of cutter exchange at different positions of cutterhead is counted from the beginning of TBM tunnelling. The tunnelling parameters and cutter wear values selected from the 436th to 702nd segment of the tunnel section are performed by regression analysis. The statistics of each parameter is shown in Table 1.
Table 1. Tunnelling parameters and cutter wear values when TBM tunnelling

| Cutter No. | n/r·min⁻¹ | T/kN·m | v/mm·min⁻¹ | F/kN | p/mm·r⁻¹ | w/mm |
|------------|-----------|-------|------------|------|---------|------|
| 15#        | 2.7       | 4624.2| 59.7       | 6582.4| 20.96   | 19   |
| 21#        | 2.9       | 4635.1| 63.9       | 7086.8| 24.55   | 24   |
| 13#        | 2.3       | 4520.5| 50.2       | 5742.6| 20.29   | 17   |
| 32#        | 3.0       | 4933.7| 80.7       | 7857.4| 32.65   | 28   |
| 19#        | 2.9       | 4682.6| 62.3       | 6878.4| 22.53   | 23   |
| 25#        | 2.9       | 4791.6| 68.5       | 7143.2| 25.28   | 26   |
| 23#        | 2.9       | 4777.0| 68.4       | 7143.2| 24.74   | 25   |
| 28#        | 2.9       | 4868.6| 77.1       | 7399.3| 25.74   | 27   |
| 31#        | 3.0       | 4890.4| 78.7       | 7814.9| 26.82   | 27   |
| 17#        | 2.8       | 4673.6| 61.9       | 6656.8| 22.29   | 20   |
| 36#        | 3.1       | 5015.1| 94.0       | 8527.0| 33.55   | 31   |
| 14#        | 2.7       | 4609.6| 52.7       | 6495.9| 20.61   | 18   |
| 34#        | 3.0       | 4973.3| 87.2       | 8160.8| 32.12   | 29   |
| 12#        | 1.6       | 4519.1| 47.9       | 5637.2| 19.32   | 14   |

As mentioned above, cutter wear increases and advance velocity decreases when the thrust and torque increase due to the complex geological conditions. Although the single influencing factor is not the whole cause of cutter wear, the main components and proportion of each factor can be determined by single factor analysis. In order to find out the relationship between cutter wear and tunnelling parameters, the correlation between cutter wear (w) and cutterhead rotation velocity (n), cutterhead torque (T), advance velocity (v), total thrust (F) and penetration (p) was analyzed by using univariate linear regression, respectively. The specific analysis results are shown in Fig. 3 and Table 2.

The results in Table 2 indicate that cutter wear is strongly correlated with each tunnelling parameter n, T, v, F, p (R²=0.70~0.94), among which cutter wear (w) and penetration (p) show the best correlation. The analysis shows that each tunnelling parameter has a significant effect on cutter wear when TBM tunnelling.

Fig.3 Relationship between cutter wear and each tunnelling parameter
Table 2. Relationship and coefficient of determination (R²) between cutter wear and tunnelling parameters

| Parameters | $R^2$ | Regression type | Regression model | Equation No. |
|------------|-------|-----------------|------------------|--------------|
| $n$        | 0.7056 | Linear          | $w=10.761n-6.3834$ | (1)          |
| $T$        | 0.9168 | Linear          | $w=0.0297+114.31$ | (2)          |
| $v$        | 0.9166 | Linear          | $w=0.3496v-0.3723$ | (3)          |
| $F$        | 0.9341 | Linear          | $w=0.0058F-17.901$ | (4)          |
| $p$        | 0.9370 | Linear          | $w=1.0267p-3.2438$ | (5)          |

5.2. Multiple factor analysis

Compared with single factor analysis, multiple factor analysis can more accurately reflect how the interaction of various tunnelling parameters affect the degree of cutter wear. Through the correlation analysis of different parameters, cutterhead rotation velocity ($n$) and advance velocity ($v$) are found both significantly correlated to penetration ($p$), respectively, that is, $n$ or $v$ can be expressed by $p$. Therefore, in multiple factor analysis, the cutter head torque ($T$), the total propulsion force ($F$) and the penetration ($p$) are selected to conduct the stepwise regression by SPSS. Also, variance analysis and hypothesis tests are carried out on the regression model as shown in Table 3.

Table 3. Results of multiple regression analysis and three tests

| Model | R     | R Square | Adjusted R Square | Standard Error of the Estimate |
|-------|-------|----------|-------------------|-------------------------------|
| 1     | 0.989 | 0.978    | 0.971             | 0.859                         |

Analysis of Variance and F-test

| Parameters | Sum Square | df | Mean Square | F       | Sig. |
|------------|------------|----|-------------|---------|------|
| Regression | 328.056    | 3  | 109.352     | 148.327 | 0.000|
| Residual   | 7.372      | 10 | 0.737       |         |      |
| Total      | 335.429    | 13 |             |         |      |

Regression Coefficients and T-test

| Parameters | Unstandardized Coefficients | Standardized Coefficients | t     | Sig.  |
|------------|----------------------------|---------------------------|-------|-------|
| (Constant) | 56.977                     |                            | 2.100 | 0.062 |
| $T$        | -0.019                     | -0.625                    | -2.533| 0.030 |
| $F$        | 0.004                      | 0.684                     | 4.293 | 0.002 |
| $p$        | 0.991                      | 0.935                     | 4.303 | 0.002 |

The analysis on the regression results in Table 3 are given as follows.

1. Through R test, $R$ equal to 0.989 shows the significant fitting effect of the regression model, and $R$ square equal to 0.978 also account for 97.8 percent fact of the cutter wear affected by cutter head torque ($T$), the total propulsion force ($F$) and the penetration ($p$) in all potential tunnelling parameters.

2. Through F test, the significance level close to 0 reflect the whole regression model passing F test and acquiring the great significance.

3. Through T test, the regression coefficients of variables $T$, $F$, $p$ all less than 0.05 indicate their great significance in the regression model and passing the T test.

Thus, the regression model for cutter wear prediction based on tunnelling parameters by multiple factor analysis can be expressed as below:

$$w=56.977-0.019\ T+0.004\ F+0.991\ p$$

(1)

The above expression shows that cutter wear can be described and expressed by tunnelling parameters. Therefore, when studying the practical engineering problems such as cutter wear prediction, tunnelling parameters can be selected as the main influencing factors to establish the prediction model.
6. Prediction effect verification
In order to verify whether the prediction model obtained by regression analysis can accurately estimate the cutter wear in real time, ten groups of tunnelling parameters and cutter wear value selected from a large number of sample data of the 735th to 1015th segment are analyzed, and the predicted cutter wear is calculated by Expression (6), which is compared with the measured cutter wear shown in Fig. 4.

![Fig 4](image)

**Fig.4** Comparison analysis between the predicted and the measured cutter wear

According to the error analysis of predicted cutter wear value, the error is in the range of 0.5%~5.6%, basically kept within 6%. Therefore, the accuracy of cutter wear prediction model is relatively accurate, and the model deduced by multiple regression achieves the required prediction effect.

7. Conclusion
Based on the real-time collected tunnelling parameters and measured cutter wear values in inclined shaft tunnelling project, the influencing factors of cutter wear are discussed and relevant conclusions are drawn as follows:

(1) Cutter wear is the result of the comprehensive interaction of various tunnelling parameters. Regression analysis effectively reveals the relationship between cutter wear and cutterhead rotation velocity, cutterhead torque, advance velocity, total thrust, penetration. Each tunnelling parameter is correlated with cutter wear and penetration shows the significant correlation.

(2) Considering the multiple factors, the regression model for cutter wear prediction based on cutterhead torque, total thrust and penetration achieves significant regression effect, which can explain 97.1 percent of the fact inducing cutter wear in all potential tunnelling parameters.

(3) The comparison between the predicted and the monitored cutter wear values further verifies the accurate effect of the cutter wear prediction model by multiple regression.

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