Prediction Model for TBM Disc Cutter Wear in Mixed-face Ground Condition

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ABSTRACT: The disc cutter failures during shield machine tunnelling in mixed-face ground were summarised by classifying the wear data gathered from the construction of Guangzhou Metro Line 7. The stress state of disc cutter and different effective factors in mixed-face ground condition were analysed. A prediction model for disc cutter wear in mixed-face ground was proposed taking the working status of TBM and the characteristics of geological conditions into consideration. The TBM parameters and geological characteristics of the north tunnel in Guangzhou Metro Line 7 was used to determine the prediction model. With the prediction model, the disc cutter wear of the south tunnel was predicted. The effectiveness of the prediction model was verified by comparing the predicted value and the actual value of the south tunnel.

INTRODUCTION

With the development of machine industry and automatic technology, tunnel boring machine (TBM) has been widely adopted in various kinds of tunnel constructions (Shen et al., 2014). The working performance of cutter head has a great influence on the penetration efficiency. With rapid urbanization development, underground constructions have to face more mixed-face ground condition, which is composed of two or more geological materials with significant differences in properties (Ma et al., 2015; Tóth et al., 2013; Gong et al., 2005; Gong et al., 2006; Cho et al., 2010). The mixed-face ground conditions introduced in these cases process two or more different geological formations. Although composite cutter head can improve the adaptability of TBM, excavating in mixed-face ground may still cause excessive disc cutter wear. Frequency opening of soil chamber and disc cutter replacement may increase the risk of geo-hazards, raise the economic cost and delay the construction schedule. In this paper, a prediction model will be proposed to evaluate the disc cutter wear in mixed-face ground.
METHODOLOGY

Classification of disc cutter failures
Disc cutters, working as the essential cutting component, can hardly avoid being worn during TBM penetrating in mixed-face ground. Due to various conditions in the cutting face, disc cutter failure gathered from Guangzhou Metro Line 7 shows different types including: even disc cutter wear, uneven disc cutter wear and breakage of cutter ring, as shown in FIG. 1. Even disc cutter wear is suggested as the only one which have thoroughly utilized the material of cutter ring. The uneven disc cutter wear and breakage of cutter ring are also remarkable factors for disc cutter failure in mixed-face ground condition.

Figure 1. Different kinds of disc cutter failures: (a) even disc cutter wear; (b) uneven disc cutter wear; (c) breakage of disc cutter ring.

Mechanical analysis of cutting process
TBM penetration and cutter head rotation make disc cutter move in two types during cutting process: moving in horizontal helix and also rolling along the tangential direction (Wang et al., 2015). The stress state of disc cutter in mixed-face ground is shown in FIG. 2. $F_n$ is the thrust force caused by jacking force in TBM penetration; $F_t$ is the rolling force caused by cutter head rotation which is controlled by cutter head torque; $F_r$ is the normal reaction force generated to balance $F_n$ and $F_t$; $f$ presents the friction force existed in the interaction of the rolling disc cutter and cutting face. $F_d$ is the impact loading caused by the change of strata.

Figure 2. Stress state of disc cutter in mixed-face ground condition.
Effective factors

Different disc cutter failures are caused by various factors. In mixed-face ground, impact loading can increase the risk of cutter ring breakage. To evaluate the resultant strength of the strata in mixed-face ground, the ratio of strata distribution which represents the proportion of hard area and soft area is proposed. The position of interface in the cutting face also has great influence on the impact loading. According to the interacting features, the dynamic factor $n_d$ which is used to evaluate the effect of impact loading on disc cutter can be determined.

Prediction model of disc cutter failure

The wear resulting from friction energy consumption is the main cause of disc cutter failure (Nakayama, 1965; Chang et al., 2006). The method for determining the prediction model in this paper is to use friction energy to estimate the disc cutter wear. The hypothesis that there is linear correlation between disc cutter wear and friction energy is put forward after comparing the abrasive value and the calculated energy value

$$W = k \cdot \zeta$$

where, $W$ is the friction energy of each disc cutter, $Q$ is the wear value gathered after disc cutter replacement, $k$ is a constant coefficient. The disc cutter wear $Q$ is proposed in the condition of even disc cutter wear. To make Eq. (1) applicable for uneven disc cutter wear, a method is implied to converse uneven disc cutter wear into even disc cutter wear.

ANALYSIS OF FIELD CASE

The geology in Guangzhou is famous of its polytrope, irregularity and complexity, which can probably make the mixed-face ground exist in the tunnel face. Guangzhou Metro Line 7 is located in the Panyu district, the south of Guangzhou, as shown in Fig. 9. In this case, two TBM machines were respectively adopted in the south and the north tunnel. Based on the data of TBM construction in the north tunnel gathered in Xie-Zhong Section, the prediction model was determined then applied in the south tunnel to verify the effectiveness.

As supposed in above analysis, the friction energy of each disc cutter during single section of cutter replacement can be calculated. After deducing the friction energy equation, the prediction model can be expressed as

$$q = \frac{n_d \cdot F_n^4 \cdot n \cdot 2\pi r \cdot l}{(3.32 \times 10^9) \times S \cdot T^2 \cdot v}$$

For verifying the reliance, the prediction model was used to predict the disc cutter wear in the south tunnel during TBM construction. The predicted value can match the actual value well. And the correlation factor between prediction values and measured values reached 0.86.
DISCUSSION
The aim of this study is to put forward a simple but reliable model for predicting the disc cutter wear in mixed-face ground condition. The model is proposed based on friction energy theory, utilizing field data to determine the correlation between disc cutter wear and friction energy. The model can calculate the disc cutter wear based on the field data when shield machine is advancing in mixed-face ground. The reliability of the prediction model can be tentatively confirmed. And the comprehensive correlation factor for the actual value and predicted value reaches 0.82. The deviation is possibly blamed for the assumption of the integrated cutting face. Because the tunnel face with developed fractures will aggravate the disc cutter wear.

CONCLUSION
In this paper, the failure form of disc cutter in mixed-face ground is studied and classified as even disc cutter wear, uneven disc cutter wear and cutter ring breakage. The cutting process of disc cutter during TBM advancing is analysed. And the stress state of single disc cutter is determined. The effective factors for disc cutter wear are quantitatively analysed. As a result, the friction energy equation is deduced to calculate the energy consumed and derive the prediction model. The effectiveness of the prediction model is verified by being applied in the south tunnel. The result of this study shows that the proposed model can be applied in mixed-face ground to predict the disc cutter wear.

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REFERENCES

