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Analysis of the Current Research Status on Rolling Cutter Wear in Soil-Rock Composite Strata

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Abstract
Roller cutter wear is one of the most common construction losses in shield tunneling engineering. This article summarizes and analyzes existing research results on this issue, and summarizes the research phenomena from the classification of roller cutter wear phenomena, research methods, wear influencing factors, and predictive models: the wear phenomena are mainly divided into uniform wear, biased wear, ring collapse, and ring wear; the methods for studying roller cutter wear mainly include analytical methods, model test methods, numerical simulation methods, and artificial intelligence algorithms; the influencing factors of roller cutter wear mainly include geological parameters, roller cutter material properties, and shield tunneling construction parameters; and the predictive models of roller cutter wear can be divided into theoretical, empirical, and semi-empirical prediction models. By summarizing he above content, the research status of roller cutter wear is clarified.

Keywords: *Soil-Rock Composite Strata, Rolling Cutter Wear, TBM.*

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I. INTRODUCTION

One of the most common construction losses in shield tunneling engineering is the wear of the cutterhead. To ensure the efficiency of shield construction, it is often necessary to perform inspections and replace severely worn cutterheads. During the construction of the Xiqinling Tunnel on the Lan-Yu Railway, as many as 729 cutterheads were replaced in the 4968m excavation section alone[1]. In the cross-sea section of the Xiamen Rail Transit Line 3 shield tunnel, due to hard rock intrusion and other factors, the distance for batch replacement of the front cutterheads was only 215m, while that of the edge cutterheads was even less than 50m[2]. Excessive cutterhead wear not only significantly increases the cost of tool usage but also affects the progress of shield construction, increasing the risk of inducing geological disasters during construction and causing significant direct economic losses.

Due to the significant impact of cutterhead wear on the efficiency of shield tunneling construction, numerous experts and scholars have conducted a series of studies on this topic. In the 1970s, as the use of shield tunneling became increasingly widespread in tunnel engineering, Sugden[3] began to pay attention to the impact of cutterhead wear on shield construction. Around 1995, research laboratories at the Colorado School of Mines and the Norwegian University of Science and Technology[4,5] began to study the mechanism and predictive models of cutterhead wear. At the same time, Gehring[6] proposed a wear quality prediction model based on the abrasive wear index (CAI). As cutterhead wear data and corresponding shield construction and geological parameters continued to accumulate, researchers such as Hassanpou[7] and Liu[8] proposed empirical prediction models for cutterhead wear based on parameter analysis. The development and use of experimental devices such as the straight-line cutting model test[9-11] and the formation abrasion test device[10,11] further expanded the research methods for cutterhead wear. In recent years, the rapid growth of domestic shield tunneling projects has also promoted the development of research on cutterhead wear. With the rapid development of intelligent detection systems, computer simulation technology, and the rise of artificial intelligence algorithms, research on cutterhead wear has been elevated to new heights. However, there are still certain limitations to existing research on cutterhead wear, mainly in two aspects: (1) the geological conditions studied for cutterhead wear are mostly homogeneous formations, and the applicability of related research results still needs to be further expanded; (2) the focus of wear research is on factor analysis, and there is a lack of research on the mechanism of cutterhead wear, which results in a lack of physical meaning in the research results.

Based on the compilation and analysis of existing research results, a summary and generalization of the research phenomenon on the classification of roller cutter wear phenomena, research methods, wear influencing factors, and prediction models can be made. The wear phenomenon will be introduced according to the existing classification methods; research methods will mainly be introduced from four aspects: analytical method, model test method, numerical simulation method, and artificial intelligence algorithm; influencing factors include three categories: formation characteristic parameters, roller cutter material characteristics, and shield construction parameters; wear prediction models can be divided into theoretical, empirical, and semi-empirical prediction models based on the analysis method. By summarizing and generalizing the above content, the research status of roller cutter wear is clarified.

II. Classification methods of roller cutter wear phenomena

The classification methods for roller cutter wear phenomena differ depending on the roller cutter wear conditions in different shield tunnel engineering projects. By compiling construction and blade replacement data under different geological conditions, it was found that there are many types of existing roller cutter wear, in addition to common wear types such as uniform wear and uneven wear, there are also many other types of roller cutter wear.

2.1 Uniform wear

The main characteristic of uniform wear is that the wear caused by contact compression is relatively evenly distributed on the front of the cutter ring, as shown in Figure 1. The main function of the roller cutter in shield tunnel excavation is to break the integrity of hard rock in the excavation face through compression cutting, thereby achieving shield tunnel excavation. When encountering strong and hard rock formations, the rock mass in the excavation face is characterized by high strength and good integrity, which allows the roller cutter to generate sufficient contact compression between the cutter ring and the excavation face during the cutting of hard rock formations, and to maintain continuous rotation around the cutter axis during the cutting process. Therefore, the wear of the roller cutter along the radial direction shows a uniform distribution.

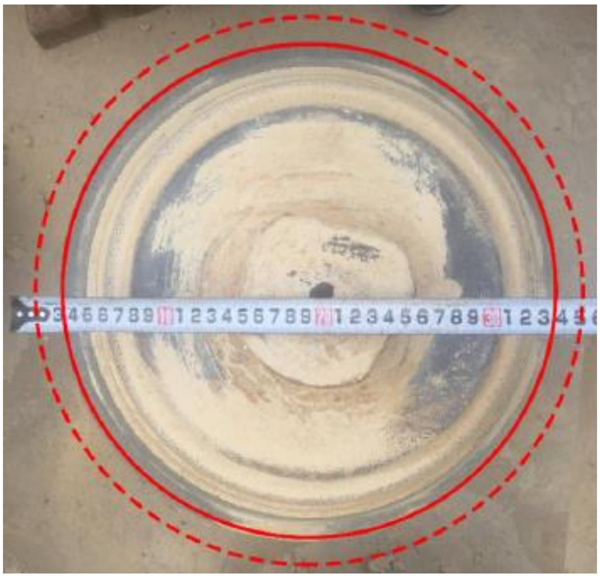

Fig.1:Phenomenon of wear uniformly occurring on normal side of cutter ring

2.2 Eccentric wear

The main difference between eccentric wear and uniform wear is that the wear of eccentric wear only occurs in local positions of the cutter ring, rather than being uniformly distributed along the outer edge of the cutter ring, as shown in Figure 2. Eccentric wear often occurs in loose formations with low strength on the excavation face. Although the placement of the roller cutter is usually not considered in the design of the cutterhead, with the increase of the distance of shield tunneling, it becomes difficult to maintain uniformity and stability of the tunneling formation, which may result in encountering loose formations and hard rock formations during the construction process. In order to improve the adaptability of the shield machine to the formations, modern shield cutterheads often adopt a composite cutterhead form with both roller cutters and disc cutters arranged[12-14]. However, due to the low strength of loose formations, the contact friction between the excavation face and the roller cutter cannot provide enough rotational force to drive the roller cutter to rotate around the axis, resulting in wear occurring easily in specific parts of the cutter ring and eventually forming local roller cutter wear phenomenon.

Fig.2: Phenomenon of wear occurring on local region of cutter ring

2.3 Cutter ring breakage

The typical characteristic of a cutter ring breakage is that the local material of the cutter ring experiences overall peeling, causing a large area of missing pieces, and even resulting in the detachment of the cutter ring, as shown in Figure 3. During shield tunneling in the upper soft and lower hard strata, the excavation face of the shield tunnel usually consists of various strata with significantly different strengths, making the force situation of the disc cutters extremely complex during the cutting process. Liu Xiaoyi [15] found that the upper soft and lower hard strata could accelerate the overload failure of the disc cutters when studying the wear condition of the disc cutters in the Tianhua shield tunnel section of Guangzhou Metro Line 3. Zhao et al. [16] found that the upper soft and lower hard strata accounted for about 15% of the total excavation strata during the construction of the deep tunnel drainage system in Singapore. Due to the insufficient consideration of the complexity of the strata when setting the shield tunnel excavation parameters, the disc cutters continuously hit the hard rock strata in the excavation face at a fast speed as the cutterhead rotates, resulting in the failure of the cutter ring.

Fig.3: Phenomenon of cutter ring breakage

2.4 Cutter ring sharpening

Cutter ring sharpening refers to the shape of the cross-section of the worn cutter ring, which appears as a needle-like shape, as shown in Figure 4. When loose strata contain a large amount of highly abrasive minerals such as quartz, it further increases the complexity of the strata conditions, making the cutter materials more susceptible to wear [17]. Jin Yanqiu [18] found that when the cutter cut through strata with low strength but high quartz mineral content, the contact friction between the lateral cutter ring and the excavation face caused significant wear on the side of the cutter ring. When the sharpened disc cutter enters hard rock strata, its rock-breaking ability will be significantly weakened. The cutting can only form small cutting grooves on the rock surface, and it is difficult to form cracks between adjacent cutting grooves, which makes it impossible to achieve the effect of breaking rock with the disc cutter, leading to a significant reduction in the efficiency of shield tunneling.

Fig.4 Phenomenon of self-sharpened cutter ring

2.5 Other wear

In addition to the above-mentioned types of roller disc wear such as uniform wear, uneven wear, roller disc failure, and roller disc tip wear, there are many other types of roller disc wear that appear in different shield construction cases. Roller disc cracks, roller disc corner failure, and roller disc failure are similar to roller disc failure, all of which belong to the brittle failure of materials, but the difference is that the damage range of roller disc cracks and roller disc corner failure is relatively small. Roller disc cracks refer to the appearance of slender cracks only on the roller disc. Because the roller disc has a certain overall rigidity, even if there are some cracks, it can still maintain good integrity and cutting ability. Therefore, roller disc cracks often appear with forms of wear such as uniform wear or uneven wear, as shown in Figure 5.

Fig.5 Phenomenon of fractured and non-uniform cutter wear

III. Research methods for the wear of the disc cutters.

Roller wear is caused by the contact friction between the roller and the excavation face, so it can be analyzed and studied from two aspects: the wear and tear of the roller under force and the deformation and damage of the excavation face. Different types of methods can be used for research according to different research objects.

3.1 Analytical methods

The analytical method is suitable for research objects where material properties, stress conditions, and initial boundary conditions are relatively certain. During the cutting process, the deformation of the rolling cutter relative to the excavation face is small, and the rolling cutter material is basically homogeneous hard alloy, so it is suitable to use the analytical method to analyze the stress of the rolling cutter and study the mechanism of rolling cutter wear based on the changes in stress. Roxborough and Philips [19] proposed a rolling cutter stress model based on a V-shaped rolling cutter.

3.2 Model test methods

Roller wear occurs during the shield tunneling process, and on-site tests to observe roller wear are difficult due to observation conditions and other limitations. Therefore, model testing, mainly using proportionally scaled linear cutting test devices and scaled circular cutting devices, has gradually become the main method for studying roller wear. The linear cutting model test, as a representative full-size roller cutting test, has been widely used in the study of roller rock-breaking mechanisms. The scaled circular cutting model test uses a circular path for roller cutting tests, which is closer to the actual cutting trajectory of the roller. Macias et al. [22] conducted roller circular cutting tests using scaled models.

3.3 Numerical simulation methods

Compared with model tests, numerical simulation methods have advantages such as low cost, short time, convenient parameter setting, and easy scaling, and are widely used in the study of the effects of different parameters on rolling cutter wear. The commonly used numerical simulation methods for rolling cutter wear include the finite element method and the discrete element method. The finite element method is better suited for continuous media, but has limited solutions for non-continuity problems such as rock fragmentation. Generally, the finite element method analyzes the wear mechanism of rolling cutters by simulating the stress conditions during the cutting process, rather than directly simulating the wear process of the rolling cutter [21]. The discrete element method can better simulate the development of rock cracks and has gradually become the preferred method for numerical simulation of rock fragmentation effects [22-24]. However, due to computational limitations, the discrete element method generally chooses two-dimensional models or smaller three-dimensional models for simulation analysis [25-28].

3.4 Artificial intelligence algorithms

With the rapid development of computer technology in recent years, artificial intelligence (AI) has gradually infiltrated various traditional fields. Algorithms such as fuzzy logic, genetic algorithms, and neural networks are based on big data and high-performance computing, and establish a mapping relationship between input and output values by building weight functions and other methods. By using function relationships to replace the inherent connections between input and output values, AI algorithms can be applied to the problem of predicting roller cutter wear under multiple influencing factors. Acaroglu et al. [29] used fuzzy logic algorithms to establish a rock breaking energy prediction model based on a large amount of data obtained from linear cutting tests at the Colorado School of Mines. The prediction model included influencing factors such as rock compression and shear strength, roller cutter size, cutting depth, and roller cutter spacing.

IV. Analysis of Factors Affecting Roller Cutter Wear

The analysis of influencing factors is critical to the study of roller wear, as specific factors need to be determined for both mechanism analysis and correlation research. Roller wear involves two objects, the roller and the formation, and the roller's motion state is determined by the shield construction status. Therefore, the influencing factors of roller wear can be summarized into three categories: formation characteristic parameters, roller material characteristic parameters, and shield construction parameters.

4.1 Geological characteristics

The geological conditions have an impact on the fragmentation process of the excavation face as well as the friction characteristics within the contact surface. Under high stress levels, the excavation face is less likely to undergo fragmentation under the cutting action of the roller disc, and the fragmentation process of the excavation face is dominated by brittle failure. Tan Qing [30] used the discrete element method to establish a roller cutting model under different confining pressures and found that the surrounding rock conditions of the rock sample have an impact on the specific energy required for rock fragmentation. Zhang Kui [31] also found that low confining pressures are conducive to lateral crack propagation during the roller cutting process, while under high confining pressures, it is easier to cause lateral cracks to intersect with the middle zone of the surface layer cracks.

4.2 Roller shape and material properties

The shape, size, and material composition of the roller cutter have been continuously improved with the development of shield tunneling operations and material technology. The shape of the cutter ring has undergone changes from V-shaped to constant-section type. Su Lijun et al. [28] studied the rock breaking effects of three types of wedge-shaped cutter rings and three types of flat-blade cutter rings. The radial cracks produced by V-shaped wedge cutter rings develop faster and deeper into the rock, but they are more prone to abrasion from minerals such as quartz due to the large contact stress, which affects the rock breaking effect. Constant-section flat-blade cutter rings can withstand larger loads and have stronger anti-wear ability when cutting high-strength rocks.

4.3 Tunneling construction parameters

The construction parameters of shield tunneling mainly include thrust force, cutterhead torque, cutterhead rotation speed, and excavation speed. Rostami [20] believes that there is a close relationship between the thrust force and the stress distribution on the contact surface, and integrating the stress acting on a single disc cutter can obtain the thrust force. The research results of Song Tiantian et al. [14] and Li Chao et al. [32] show that the frictional torque between the cutterhead and the ground accounts for about 80% of the cutterhead torque, and the size of the cutterhead torque will affect the rolling force of the disc cutter. When the rolling force is insufficient, the disc cutter is prone to wear and tear. On the other hand, the cutterhead rotation speed affects the cutting speed of the disc cutter on the excavation face. When encountering soil-rock transition conditions such as soft soil and hard rock, excessive rotation speed can exacerbate the impact load applied by the ground interface on the cutterhead disc cutter, resulting in disc cutter damage and other wear phenomena.

V. The predictive model for shield cutter wear

Prediction of cutter wear is key to optimizing shield tunneling and cutter lifespan. The development of related prediction models has always been a hot topic in this field. Based on their reasoning process, existing wear prediction models can be divided into three types: theoretical prediction models, empirical prediction models, and semi-empirical prediction models.

5.1 Theoretical prediction models

Due to the inherent connection between the force situation of the rolling cutter and the wear amount being difficult to determine through theoretical analysis, existing theoretical models generally only predict and analyze parameters closely related to the wear of the rolling cutter, such as contact stress and rolling force. The Evans formula [21] was the first to calculate and analyze the contact force during the cutting process based on the uniaxial compressive strength of the rock and the contact area.

5.2 Empirical prediction models

Empirical models typically analyze the factors influencing the cutting and wear characteristics of the rolling cutters, and use regression analysis to determine the numerical relationship between these factors and the wear of the cutters. Gehring's model [6] takes the rock abrasiveness parameter CAI as the main influencing factor of cutter wear, and obtains the correlation between the CAI value and the cutter wear mass through fitting analysis. Gehring also proposed a formula for predicting cutter wear mass, with the wear mass limit value as a reference for cutter replacement. Liu et al. [8] based on the rock abrasion index, further considered the influence of uniaxial compressive strength (UCS) on cutter wear. Based on the statistical results of field cutter usage life, they determined the relationship between CAI, UCS and cutter usage life.

5.3 Semi-empirical prediction models

The main difference between semi-empirical models and empirical models is that the former mainly uses theoretical analysis methods such as force analysis of the rolling cutter or wear energy calculation to study the relationship between influencing factors and rolling cutter life, and only fits a few parameters, so the physical meaning of semi-empirical models is more reasonable. The CSM model [33] is derived by simplifying the force situation during rolling cutter cutting and deriving the rolling cutter cutting force theoretically. Rostami [20] verified through linear cutting tests of three types of rock that the rolling force increases with the increase of cutting depth, and the curve of the rolling force change is basically consistent with that of the vertical force, proving that there is a linear relationship between the rolling force and the vertical force under the same conditions, and the magnitude of the rolling force is generally 10-20% of the vertical force.

VI. CONCLUSION

The impact of roller cutter wear on the efficiency and cost of shield tunnel construction in soil-rock transition strata is becoming increasingly apparent. Many scholars have studied the characteristics of soil-rock transition strata and roller cutter wear. This chapter provides an overview of the current research on roller cutter wear, including the classification of wear phenomena, research methods, factors affecting wear, and prediction models. The following conclusions are drawn:

(i) Common types of wear that occur at the cutterhead position in soil-rock transition strata include even wear, uneven wear, cutterhead collapse, cutterhead cracking, cutterhead breakage, and tip wear. Even wear is more common in homogeneous and high-strength formations, where the material properties of the cutterhead can be fully utilized. Uneven wear is caused by insufficient rolling force and is not conducive to the full and effective utilization of the material properties of other parts of the cutterhead. In formations with soft upper layers and hard lower layers, impact loads can easily cause cutterhead collapse, cracking, and breakage. Tip wear is more common in formations with high abrasive mineral content and low strength.

(ii) Research methods for roller cutter wear can be divided into analytical methods, model test methods, numerical simulation methods, and artificial intelligence algorithms. Although analytical methods have strong logical reasoning, there is some difference between theoretical analysis results and actual situations. Full-scale model testing can effectively avoid size effects, but it has the limitation of high testing costs. Reduced-scale models have the advantages of smaller size and easier operation. The finite element method has significant advantages in modeling difficulty and mechanical analysis, while the discrete element method is more suitable for simulating the process from crack generation to failure of rock particles. Artificial intelligence algorithms have outstanding data processing capabilities.

(iii) Factors affecting roller cutter wear can be divided into three categories: geological parameters, cutter material parameters, and shield construction parameters. Geological parameters include stress state, material abrasive properties, and excavation face distribution. Cutter material parameters include cutter shape and size and material properties. Shield construction parameters that have a significant impact on cutter wear include thrust, cutterhead torque, cutterhead speed, and excavation speed.

(iv) Roller cutter wear prediction models can be divided into three types based on the reasoning process: theoretical prediction models, empirical prediction models, and semi-empirical prediction models. Theoretical prediction models are limited to indirect predictions of rolling force and other results. Empirical prediction models are suitable for use in shield tunneling projects with large amounts of related data. Semi-empirical prediction models can balance the rationality of the model and its engineering applicability.

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