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Prediction of lateral continuous wear of cutter ring in soft ground with quartz sand

Dong-Jie Ren[a], Shui-Long Shen[a,*], Annan Zhou[b], Jin-Chun Chai[a]

[a] State Key Laboratory of Ocean Engineering, Department of Civil Engineering, School of Naval Architecture, Ocean, and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] Department of Civil Engineering, Royal Melbourne Institute of Technology, Victoria 3001, Australia

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ABSTRACT

This note presents an investigation on the lateral continuous wear caused weight loss of disc cutter in soft ground condition with quartz sand. The energy consumed during the wearing process is evaluated by analysing the friction process. The contact pressure on cutter ring is analysed by the cavity expansion theory. A regressed equation is proposed to convert the consumed energy into the weight loss of a disc cutter. A new model to predict the lateral continuous wear of cutter rings is then proposed. The model is validated using the field observed data from tunnel constructed in Shenzhen, China.

1. Introduction

With the increase in underground constructions, geohazards such as groundwater leakage, land subsidence and ground collapse, have threatened the safety of urban development [1–9]. Complex geological conditions such as soft clay, sandy layer, and mixed-face ground further increase the difficulty of construction [10–14]. Owing to its advantages in cutting efficiency and environmental preservation, shield tunnelling has been widely used in the construction of subway tunnels [15–18], hydraulic tunnels in sponge city construction [19–21], and municipal pipelines [22–24]. During shield tunnelling, the shield machine is the main device for cutting the soil and protecting other relevant devices [25–29]. However, Zhao et al. [30] found that mixed-face ground induces high cutter wear. Frenzel et al. [31] found that either improper thrust force or penetration rate affects the capability of the cutting tool. Therefore, complex cutting conditions increase the risk of cutting tool failure and lead to excessive cutter replacements.

Predicting the cutter wear status is an important step to estimate the performance of disc cutter. The NTNU model is a typical empirical model, which correlates the life of the disc cutter with the rock properties and shield machine parameters [32,33]. The CSM model analyses the contact pressure between the disc cutter and rock first, and then predicting the disc cutter replacement time [34]. The Gehring model [35] employed the weight loss as an essential index for the wear estimation of cutters. The model developed by Wang et al. [36] established an energy equation to calculate the friction energy during the wearing process of the cutter.

However, the above models are suitable for the uniform cutter wear in the hard rock ground. In the soft ground, the quartz sand contained in the soft clay has strong abrasion effect on disc cutter ring [37,38]. The long-term friction process on lateral cutter ring results in a self-sharpening phenomenon of the cutter ring which is difficult to be measured [39,40]. Therefore, a new method to predict the lateral continuous wear in soft ground with quartz sand is needed.

This study aims: (i) to summarise the characteristics of lateral continues wear and (ii) to propose a robust predictive model for lateral continuous wear. This note is organised as follows. The characteristics of lateral continuous wear of cutter rings are presented at first. An equation for evaluating the energy consumed in lateral continuous wear is derived based on a mechanical analysis. Then, a new predictive model is proposed by considering the correlation between the friction energy and weight loss. Finally, the validity of the model is confirmed through analysis of a field case.

2. Characteristics of lateral continuous wear

The lateral continuous wear is due to the continuous friction between the cutter ring and soft ground. The lateral continuous wear becomes more distinct if more quartz sands contain in the soft ground. In the soft ground, the excavation of cutting face is caused by developing a large plastic deformation in the cutting groove. During the cutting process, the cutter ring is surrounded by the composite

* Corresponding author.
E-mail addresses: blink2mm@sjtu.edu.cn (D.-J. Ren), slshen@sjtu.edu.cn (S.-L. Shen), annan.zhou@rmit.edu.au (A. Zhou), jcchai@sjtu.edu.cn (J.-C. Chai).

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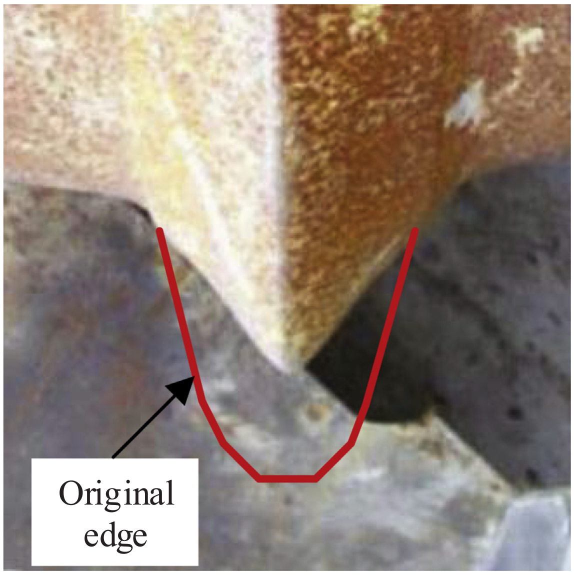

Fig. 1. Field observation of lateral continuous wear on disc cutter ring [39].

materials (soft clay with quartz sand), causing the friction process both on the normal and the lateral sides of cutter ring. The rolling process driven by the cutterhead makes the cutter ring uniformly contact with the cutting groove. As the lateral contact area is larger than the normal contact area, the lateral cutter wear becomes the dominant form of continuous wear in the soft ground. As shown in Fig. 1, the cutter ring is gradually sharpened by the lateral continuous wear, leading to a decrease in cutter diameter, consumption of the ring material, and reduction in cutter life.

One of the main differences between the normal and lateral continuous wears is the ground condition. Unlike the lateral continuous wear, the normal continuous wear mainly occurs in homogeneous ground condition, e.g., full-face hard rock. In hard rock ground conditions, the breaking of the ground in the cutting face is caused by fractures due to the penetration of disc cutter. The contact between the disc cutter and the hard ground is usually limited to the normal side of cutter ring. While in the soft ground with quartz sand, the cutting groove is filled by mixtures of soft clay and quartz sand. The lateral contact area on the cutter ring becomes larger than the normal contact area.

Due to the difference of contact area, the wearing positions for these two wearing forms are different. The wearing position of lateral continuous wear is on the lateral side of cutter ring. The sharpened cutter ring is the characteristic of lateral continuous wear. The normal continuous wear is caused by the friction process on the normal side of cutter ring. The blunted cutter ring is the characteristic of normal continuous wear.

3. Analysis of lateral friction process on disc cutter ring

The mechanical analyses in the hard ground and soft ground conditions are different. In hard rock ground, researchers usually determine the stress state of disc cutter by the thrust force and the rolling force. In soft ground, the plastic deformation rather than the fractures around the disc cutter makes the cutter ring easy to penetrate into the cutting face. Then, the cutting face will contact with the panel of cutterhead. Therefore, the thrust force and rolling force will both apply on the panel of cutterhead and disc cutter rings. Using the theory for the hard ground in the soft ground condition may overestimate the disc cutter wear. Therefore, a new method to calculate the friction force in soft ground condition is in demand.

The friction force can be determined by the contact pressure and the frictional coefficient. The contact pressure not only can be calculated by the thrust force and the rolling force, but also can be figured out by the deformation of soft ground. Fig. 2 shows the mechanical situation of disc cutter in soft ground. In the sectional view, the deformation of soft ground induced by cutter penetration is similar to the process of cone penetration. The cutting process of disc cutter can be considered as a half of the cavity expansion in cone penetration, as shown in Fig. 3. Vesic [41] proposed the cavity expansion theory to estimate the contact stress by calculating the plastic and elastic deformation of the surrounding ground. This theory also has been adopted in deep mixing and jet-grouting column installation [42–44]. According to the similar deformation behaviour, the cavity expansion theory is suitable for cutter penetration process.

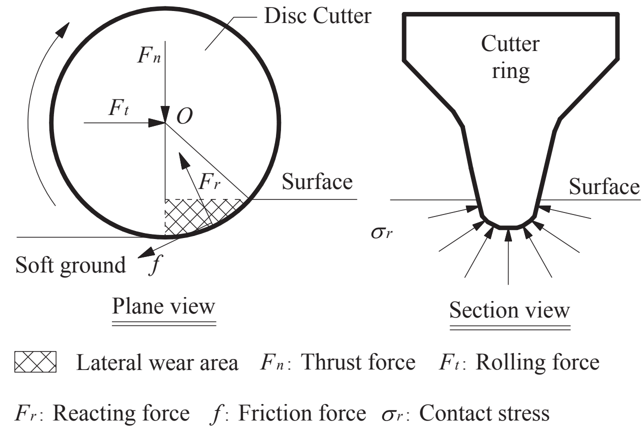

Fig. 2. Mechanical analysis of disc cutter in soft ground.

In the common region of cutter penetration, the shape of cutter ring is similar to a semicircle curve. The section of cutter ring can be simplified as a semicircle edge and two vertical boundaries. The radius of semicircle edge equals to a half of tip width of cutter ring. The evolution of ground deformation induced by the penetration of simplified cutter ring can be described as follows. At first, the initial penetration of disc cutter only causes the elastic deformation around the semicircle edge. Then, the plastic deformation occurs with the penetrating process. When the penetration depth reaches the radius of semicircle edge, the shapes of elastic and plastic regions are two adjacent semi-annuluses with the same centre. The penetration depth keeps increasing, the semi-annulus region will move together with the semicircle edge, and uniform region of ground deformation will occur along the vertical edge.

For the last stage, the ground deformation can be divided into the uniform region and the cavity expansion region as shown in Fig. 4. As

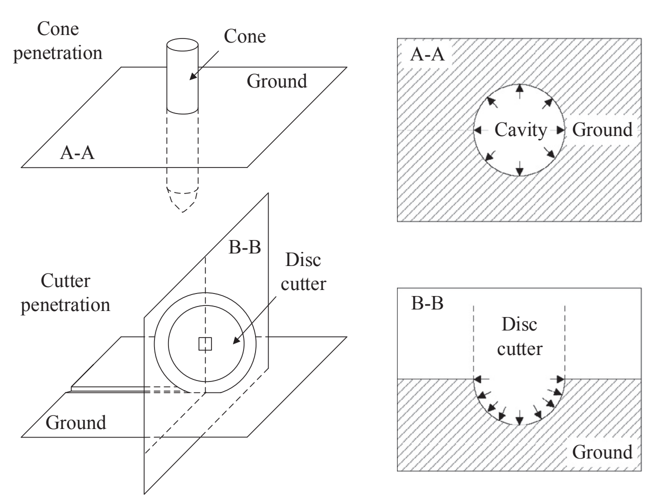

Fig. 3. Similarity in cone penetration and cutting process of disc cutter.