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Mechanism and numerical analysis of cutting rock and soil by TBM cutting tools

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ABSTRACT

The rock and soil cutting efficiency and reliability of cutting tools are critical factors to tunneling. However, due to its complexity, in-depth researches on some problems existing in rock fragmentation has not been conducted. This paper introduces the mechanism of cutting rock and soil by cutting tools. On the basis of this mechanism, it establishes finite element models using ABAQUS software to simulate the cutting processes when a cutter and disc cutter are cutting rock and soil masses. The results show that when the cutting force of a cutter is stronger than the shear strength of soil mass, breakage occurs at the interface between the cutting edge and the soil mass, leading to a successful cutting. When a disc cutter is pressed into a rock mass, with penetration depth increasing, the maximum Mises stress of the rock increases almost linearly, and plastic strain accumulates constantly, resulting in the stress growing as well. The plastic deformation zone in the rock mass is larger than the area compressed by the disc cutter. Along the working direction of the disc cutter, the rock mass is subject to continuous compression, producing plastic deformation until a fragment is broken off from its parent body. In this paper, a finite element model is established to simulate the process of cutting rock and soil by cutting tools, and a method for analyzing the interactions between cutting tools and the rock and soil is provided.

1. Introduction

Shield driving and pipe jacking technologies are widely applied in tunnel construction. A tunnel boring machine (herein after referred to as a TBM) may run into different layers with various characteristics while tunneling such as mucks, sands, clays, soft rocks and hard rocks. Cutters and disc cutters shown in Figs. 1 and 2 are a TBM's major tools to break and strip rock and soil, which directly bear loadings and shocks from cutting activities. Their rock breaking abilities are strongly associated with TBM driving efficiency and liability (Piaoping, 2014). Therefore, the aspect of tunneling technique that focuses on the interaction between cutting tools and rock and soil mass is a key technique in the tunnel construction process (Marilena and Pierpaolo, 2012).

Domestic and overseas scholars have carried out some researches on the rock fragmentation mechanism (Gunes Yilmaz et al., 2007, Hegadekatte et al., 2010, Moon et al., 2007). Because the form of the knife plate, the configuration and arrangement of the cutter are different, and the soil layer is complicated. There are many uncertainties in the fragmentation process, it is difficult to select an accurate and reliable model. Some studies have been carried out by using traditional and theoretical analysis methods (Zhiyong 2009), but the tunnel driving process is too complicated to be satisfied by traditional calculation methods, and many problems are still unresolved. With the rapid development of numerical calculation methods, especially the development of finite element technique, this issue is being solved step by step (Qing, 2013a, 2013b). Modern numerical simulation methods are applied more and more widely and deeply in the field of tunneling analysis, which includes traditional analysis method (Laikuang, 2013), discrete element method and finite element method. This paper introduces the mechanism of cutting rock and soil by cutting tools, establishes a finite element model of the cutting processes on the basis of the finite element method, and studies the characteristics of the interactions between cutting tools and the rock and soil mass while tunneling.

2. Failure mechanisms of cutting rock and soil

2.1. 2.1Rock and soil failure zones

As shown in Fig. 3, disturbed zones of the soil mass at the working face induced by tunnel construction include: compresso-disturbed zone, shear-disturbed zone and two unloading-disturbed zones (Qinghe et al.,

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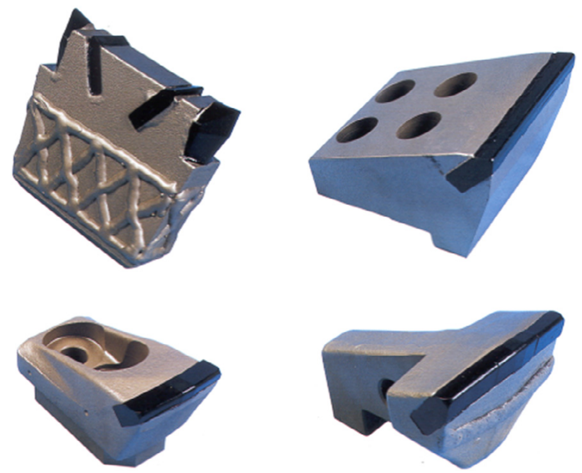

Fig. 1. Cutter.

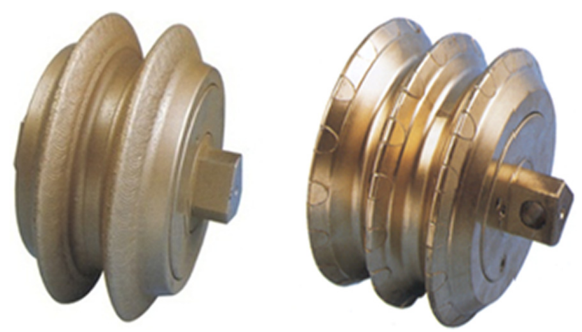

Fig. 2. Disc Cutter.

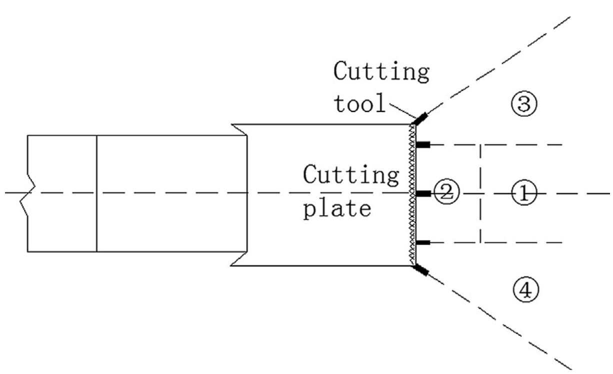

Fig. 3. Longitudinal disturbed zones induced by tunneling.

1999).

① is the compresso-disturbed zone, where the soil mass is a little far away from the excavation face and mainly undertakes compressional deformation caused by compressive stress. As the compressive stress increases with tunneling, the horizontal stress of the soil mass increases accordingly. The vibrating load and cutting force of the cutter head has little impact on this zone. ② is shear-disturbed zone in front of the TBM. Due to combined action of TBM thrust, shearing force from the cutter head and the vibrating load, the stress state here is very complicated. On the one hand, horizontal stress decreases because of stress relaxation induced by excavation. On the other hand, it increases because of the TBM thrust and the pressure from slurry or excavated material in the excavation chamber. ③ is one unloading-disturbed zone, where the soil mass is near to the excavation face. It affected by the compressive stress and shear stress from the compressor-disturbed zone. ④ is another unloading-disturbed zone under the pipe. The stress state in this zone is similar to ③, except that the stress was a little stronger because this area is located below the pipe.

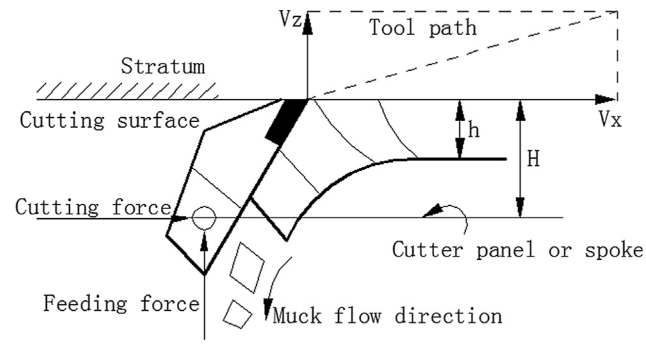

Fig. 4. Cutting schematic diagram of the cutter.

2.2. *Cutting principle of the cutter*

As shown in Fig. 4, as the TBM moves on, the cutter produces a shearing force along tunneling direction and a cutting force in the tangential direction of rotating to the excavation face. With the joint action of these two forces, stress and deformation occurs inside the rock or soil mass at the excavation face (Yimin et al., 2012). When the stress is stronger than the yield strength of the rock and soil mass, a portion of the face is broken and released from the excavation face, obtaining rock and soil fragments.

2.3. *2.3Cutting principle of the disc cutter*

When a disc cutter cuts and breaks a rock face, the following phenomenona occur: At the interface between the rock and the disc cutter, there is a hard area called the dense core generated by plastic deformation of the rock where a large number of deformation energies gather (Bilgin et al., 2012). Hence, many cracks appear around the core. Under the pressure of the disc cutter, they grow and meet each other continuously. When lateral cracks completely mix with free surface or with adjacent cracks, broken blocks are made. To explain why the rock breaks around the dense core suddenly, scholars hold different opinions and put forward different rock fragmentation mechanisms. Most representative of them are the following three:

(1) Compressional rock fragmentation mechanism: The disc cutter breaks the rock mass because it overcomes compressive strength.
(2) Shear rock fragmentation mechanism: There are compressive deformation and shear deformation on the rock mass induced by the disc cutter.
(3) Tension and shear rock fragmentation mechanism: in the fragmentation process, shear failure occurs accompanied by compressional deformation and tension deformation. The compressive failure mainly happens near to the dense core, and tension failure and shear failure generate cracks.

This paper is intended to analyze the cutting performance of a single disc cutter, the rock fragmentation mechanism of which is shown in Fig. 5. The disc cutter squeezes the rock mass under it. As a result, cracks appear in the rock mass and form a central broken zone. Outside this zone, loads from the disc cutter have less impact on the rock mass. Thus, this part bears minor stress and is called the transition area. The rock under the disc cutter has to undertake differential pressures. That is to say, the area nearer to the disc cutter suffers a large pressure while the farther area bears minor load. That is why tensile stress are formed inside the rock, and then cracks are created (Alber, 2008).