Experiment Study on High-efficiency Rock-breaking Mechanism of TBM with a Varying Number of Disc Cutters

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Abstract. It is of significance for Tunnel Boring Machine (TBM) to conduct rock-breaking efficiently and rapidly throughout tunnel construction. The efficient rock-breaking mechanism of TBM has always been a hot yet tough issue in geotechnical engineering. In this paper, by using a self-developed large experiment platform, rock-breaking experiments are conducted with a varying number of disc cutters from one to three. The failure processes of red sandstone, limestone, and granite, are illustrated. The optimal cutter spacing of them is generalized. For further, a formula of wide applicability on optimal cutter spacing is proposed in case the rock's uniaxial strength ranges from 40~170MPa.

Introduction

The development of underground space has entered an unprecedented booming stage in many countries worldwide, especially in China[1]. It is well known that China has an extremely huge number of engineering projects within construction and is faced with historic technical challenges from many aspects, such as project diversity, giant scale, complex geological conditions, complicated structures, etc. TBM is an advanced modern construction machine widely used in tunnel construction and underground space development. TBM can work continuously without a break and accomplish rock-breaking, slag tapping and surrounding rock support independently. Compared with traditional drilling and blasting method, TBM method possesses the advantages of high excavation speed, high efficiency, good tunnel-shaping, less impact on environment, safe operation, labor-saving, etc. The excavation speed of TBM is up to 3~10 times of drilling and blasting method. All these characters make TBM suitable for long and deep tunnels. In all, TBM is being commonly used worldwide in tunnel construction by departments of energy, transportation, water conservancy, national defense, etc.

Many scholars have carried out numerical [2-5]and experiment studies [6-9] on TBM excavation. They investigated the rock-cutting process of TBM. But most previous studies, regardless of numerical or experimental work, are generally conducted on a single disc cutter. The synergistic effect of multiple disc cutters is not fully illustrated therefore still requires deep-going research. Neither has the optimization research be expanded to an entire cutter head containing all disc cutters. In this paper, multiple 17-inch disc cutters are applied, which is of the same size as real TBM cutters, the theory of high-efficiency rock-cutting is illustrated.

Fig.1The self-developed large experiment platform

The Rock-breaking Mechanism of Disc Cutters

In view of the typical geological conditions existing in China, the 17-inch disc cutters used in TBM is used as their search object based on the experiment platform for the function between disc cutter and rock (as shown in Figs.1 and 2), the mechanism of high-efficiency rock breaking is discussed from the aspects of cutter spacing and rock fracture forms.

Fig. 2 The rock-breaking process using the experiment platform

Rock-breaking of a Single Disc Cutter

When the cutter head is rotated and pressed into the rock, the disc cutter hits the rock to produce the comprehensive effects of extrusion, shearing and cracking. In addition to the above-mentioned three kinds of basic cracks, a compacted core, which is similar to the hemisphere, is formed under the indenter. The lateral crack originates from the bottom of the shearing deformation (see Fig.3).

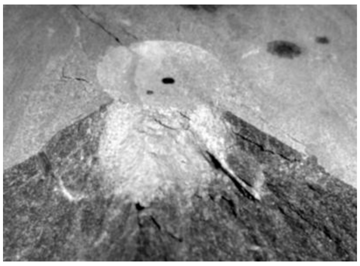


Fig.3 Fissures of rock under a single cutter

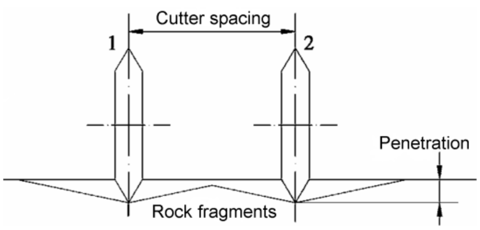


Fig. 4 The synergistic effect of two disc cutters on rocks

Rock-breaking of Multiple Disc Cutters

When multi-tools are applied to the rock at the same time (see Fig. 4), a stress superposition occurs and the crack beneath the tip can have an effect on the crack beneath the adjacent tip. At the same time, the stress concentration at the crack tip and the redistribution of stress after the crack propagation result in the interlocking and super imposing of the crack between the adjacent cutting heads, all of which will accelerate the rock breaking process. By adjusting the cutter spacing on the bench, the position of the disc cutter can be adjusted. When the disc cutter is on the same radius of gyration, when the cutter is located at a different radius of gyration, multi-cutters can be achieved din rock breaking experiment successfully.

It can be concluded from the experimental results of rock-breaking experiments on the bench: In the case of single disc cutter, the rock is dominated by compressive, and the shear is the main factor in the case of multi-disc cutters. Compared to compressive failure, the volume of rock broken by shear failure is larger. The succession of the cutters into the rock has a higher rock-breaking efficiency than the simultaneous impaction of the rock. This is mainly due to the fact that each of the disc cutters, which are pressed in turn, has a free surface of crushed rock, using its shear energy to break rocks, broken the same volume of rock by the energy consumption will be reduced by about 10%.

Optimal Cutter Spacing

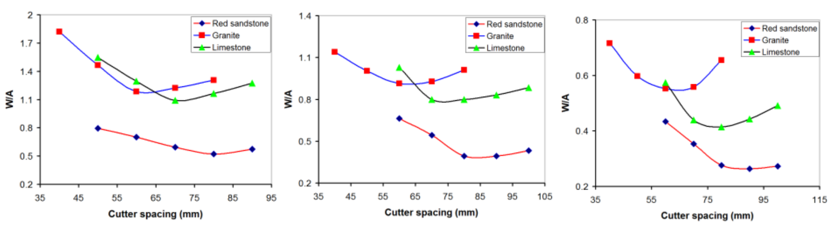
When the cutter spacing is too large, the crack is difficult to penetrate or even through; and when the cutter spacing is too small, the broken unit volume of rock required energy is too large, not economical. Therefore, a reasonable choice of cutter spacing is an important topic in the mechanism of rock breaking.

By means of the multi-blade rolling experiment and numerical simulation analysis of the rock bench of the TBM, the basic rules of the cutter rock breaking are studied, and the conclusions are as follows:

(1) The synergistic effect exists between the multi-heads, and there is stress super imposed between the adjacent heads, and the crack propagation is complicated. In the complex stress environment, the cracks between the tips are relatively developed in the zigzag form.

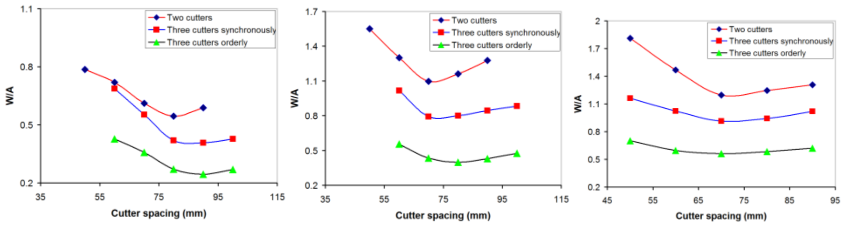
(2) Through the comparison of red sandstone, limestone, and granite, under the same conditions, the soft rock has a large scale of failure, and the lateral crack develops to a free surface, and the hard rock is hard to break. The optimal spacing of cutter, granite is the smallest, followed by limestone, and red sandstone is the largest. Breaking the same area of rock, granite needs to consume the most energy, followed by limestone, red sandstone is minimum. Therefore, the essential properties of rock play an important role in rock breaking process.

(3) By comparing the two-pronged rock-breaking, three-tool-breaking rock-breaking and three-cutting-sequence rock breaking data and cutter spacing optimization curves(as shown in Figs. 5 and 6) based on the experimental bench, the ratio W/A of all working conditions decreases first and then increases with the increase of tool spacing. There is an optimal tool spacing. Under the condition of two-pronged rock-breaking, three-tool-breaking rock-breaking and three-cutting-sequence rock breaking, the optimal cutter spacing of red sandstone is 80, 83 and 85mm, respectively. Limestone is70, 75,80mm,Granite is60, 64,67mm.From the energy consumption point of view, for all types of rock, double head damage to the energy required per unit area up to the same time into the next three-bit pressure into the situation, the three-blade pressure into the case of the least.



(a) Two cutters (b) Three cutters perform synchronously (c) Three cutters perform orderly

Fig.5 Relationship between W/A and cutter spacing



(a) Red sandstone (b) limestone (c) granite

Fig. 6 The optimal cutter spacing of three common rocks

From above research, we could conclude that the optimal cutter spacing of the three typical rocks(red sandstone, limestone, and granite) is approximately 80mm, 70mm and 60mm, respectively. A formula on optimal cutter spacing is proposed in case the rock’s uniaxial strength ranges from 40~170MPa. The relationship between the optimal cutter spacing S and the rock compressive strength σ_c is as follows.

$$S=-0.333\sigma_c+108,\ 40\le\sigma_c\le170\text{MPa} \quad (1)$$

Results Analysis on Rock-breaking Efficiency

Through the above rock-breaking experiments of one to three disc cutters, conclusions can be made as follow:

(1)In the case of a single disc cutter, the rock failure is mainly induced by compression cracks. In the case of two and more disc cutters, secondary cracks are mostly shear cracks, which will eventually lead to rock failure. Compared with the compression failure of single-cutter case, the rock fragments in multi-cutter case show a larger size. Besides, disc cutters will perform a lower rock-breaking efficiency when they are pressed into rocks at the same time than in sequence.

(2)Cutter head’s thrust is one of the main factors that contribute to penetration and tunneling rate. According to the results of excavation experiments, it can be clearly seen from the relation between cutter penetration and cutter head thrust: Penetration of the cutter head increases with its thrust, and the rising rate of penetration is higher than that of thrust. The tunneling speed of TBM is inversely related to the rock strength and rock wear resistance indexes yet show a proportional relationship with the cutter head thrust, cutter head torque, and cutter penetration.

(3)Under the optimal cutter spacing, the energy consumed by disc cutters is mostly spent in rock crushing. When the proportion of crushed fragments accounts for the lowest, the specific energy required will be the smallest, and the crushing effect will be best, therefore the driving efficiency is the highest.

Conclusions

In this paper, based on the comprehensive experiment platform of rock cutting machine, the mechanism of single-cutter and multi-cutter rock-breaking of TBM is discussed, and the optimal disc cutter spacing of red sandstone, limestone, and granite, is given. The composite TBM is deduced. Thrust and torque calculation. From the two aspects of rock breaking mechanism of the cutter and the coupling rule between cutter and surrounding rock, the mechanism of high-efficiency rock-breaking of TBM is improved, which can be used as cutter tool, cutter drive system, drive system of TBM system design, manufacture and used to provide a theoretical reference. This program is of great practical use in providing theoretical support for TBM tunnel projects.

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