KSCE Journal of Civil Engineering (2018) 22(10):4155-4162

DOI 10.1007/s12205-018-0577-6

Tunnel Engineering

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Comparison Study on the Rock Cutting Characteristics of Disc Cutter under Free-face-assisted and Conventional Cutting Methods

Xuhui Zhang*, Yimin Xia, Qing Tan***, and Dun Wu******

Received May 8, 2017/Revised 1st: November 5, 2017, 2nd: January 30, 2018/Accepted March 5, 2018/Published Online June 23, 2018

Abstract

To improve the excavation efficiency of Tunnel Boring Machines (TBMs), the free-face-assisted rock cutting method induced by TBM disc cutter (FM) was explored and the differences between the FM and the conventional Cutting Method (CM) were also compared based on a series of rock cutting tests. The results show that when the free face distance is less than a critical value, the FM can promote the tensile failure of the rock and the formation of big rock debris effectively. Moreover, the cutting efficiency and the cutting forces including normal force, rolling force and side force of the disc cutter under the FM are also significantly reduced and improved, respectively, compared to that under the CM. The FM can be applied in multi-stage cutterhead TBMs to improve the cutting efficiency and reduce the failure of the disc cutter, the research results indicate that the free face distance should be controlled within 80 mm to use the free face effectively.

Keywords: *free face, cutting method, disc cutter, TBM*

1. Introduction

Tunnel Boring Machines (TBMs) are widely employed in tunnel excavation due to their high excavation efficiency, high construction quality and less ground disturbance (Ma *et al*., 2016). They are applicable for various ground conditions including the soil condition, rock condition and soil-rock mixed condition. Generally, TBM performance and efficiency are heavily dependent on rock breaking characteristics induced by the cutters including disc cutters and chisel cutters (sometimes named scrapers or rippers) which are installed on the cutterhead (Bilgin *et al.*, 2012). In hard rock applications, the most efficient and most popular cutting tool is single disc cutter which has become the standard tool on hard rock TBMs (Rostami, 2013). The rock cutting process by disc cutter has been extensively studied by researchers with experimental and numerical methods.

Rostami (1997) and Gertsch *et al.* (2007) conducted series of rock cutting tests on Linear Cutting Machine (LCM) and studied the cutting force and cutting efficiency under different cutting depths and cutter spacings with disc cutter. Balci and Tumac (2012, 2015) carried out series of LCM cutting tests with two kinds of disc cutters to study the influence of different rock types on the rock cutting effect. Cho *et al.* (2013) investigated the optimum cutting condition and cutting efficiency of disc cutter by using LCM tests and AUTODYN model. Geng *et al.* (2016a, 2016b) investigated the rock cutting process of normal and gage disc cutters based on Rotary Cutting Machine (RCM) tests and ABAQUS model. Liu *et al.* (2016, 2015a, 2015b) studied the effect of confining stresses on rock breaking by conducting sequential indentation tests and PFC (particle discrete code) model. Choi and Lee (2015, 2016) studied the optimum cutter spacing and cutting power with different joint characteristics based on PFC. Gong *et al.* (2006) and Bejari *et al.* (2013) used UDEC to simulate the initiation and propagation process of cracks induced by the disc cutters under different joint spacings and orientations.

The above-mentioned researches all have facilitated the comprehensive understanding of the conventional rock Cutting Method (CM) by disc cutters. However, with the rapid development in the area of TBM excavation in recent years, there are also a series of problems for TBMs, especially for larger-diameter TBMs when tunneling in rock grounds of high Uniaxial Compressive Strength (UCS) and high in-site stress. For instance, TBM encountered with quartz diorite containing 5% iron ore whose UCS exceeded 200 MPa in a Chinese water diversion tunnel project in September to October 2016. Under such a serious

*Ph.D. Candidate, State Key Laboratory of High Performance Complex Manufacturing, Central South University, Changsha 410083, China (E-mail: csuxuhui@163.com)
**Professor, State Key Laboratory of High Performance Complex Manufacturing, Central South University, Changsha 410083, China (Corresponding Author, E-mail: xiaymj@csu.edu.cn)
***Professor, State Key Laboratory of High Performance Complex Manufacturing, Central South University, Changsha 410083, China (E-mail: jds-share@163.com)
****Engineer, The tunnel project Co. Ltd. of China Railway Bureau 14 Group, Jinan 250013, China (E-mail: 460891643@qq.com)

ground, the cutterhead penetration rate was less than 2 mm/rev and mean normal thrust was over 300 kN per cutter, leading to low excavation efficiency and rapid consumption of disc cutter.

In order to improve the excavation efficiency and reduce the costs of tunneling projects when faced with these complex grounds, some new rock breaking methods by TBMs are gradually being introduced. For example, Ciccu and Grosso (2014) investigated the rock breaking process by the disc cutter assisted with high-velocity jets of water. Hassani *et al*. (2016) proposed a method of breaking rock by the disc cutter assisted with microwave irradiation. Geng *et al.* (2014, 2015) proposed a free-face-assisted rock Cutting Method (FM) based on the multi-stage TBM cutterhead.

The multi-stage TBM cutterhead is divided into the first-stage cutterhead and the second-stage cutterhead, as shown in Fig. 1, and it is totally different from the conventional TBM cutterhead who only has one cutterhead. These two stage cutterhead can be driven separately during excavating process. Therefore, the rock cutting force are distributed into two stage cutterhead. As a result, the thrust and torque of the multi-stage TBM are reduced since the thrust and torque are also divided into two parts compared with the conventional TBM.

For the FM of the multi-stage TBM, the first-stage cutterhead first excavates a cave with a small diameter to create the free face. Then, the second-stage cutterhead will excavate based on the existing free face to enlarge the tunnel diameter, as shown in Fig. 1. This cutting method is derived from the Undercutting Method (UM). As shown in Fig. 2, it can be found that both of these two cutting conditions have a free face. When cutting rock with the FM, the disc cutter penetrates into rock vertically. However, when cutting rock with the UM, the disc cutter penetrates into rock obliquely. Thus, it may cause the difference in side force of the disc cutter for these two kinds of cutting methods.

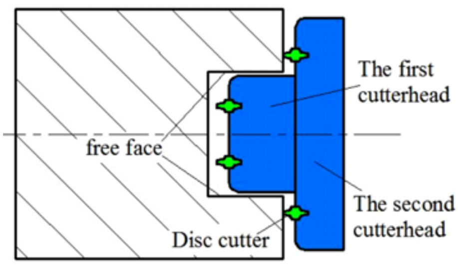

Fig. 1. Multi-stage Cutterhead TBM

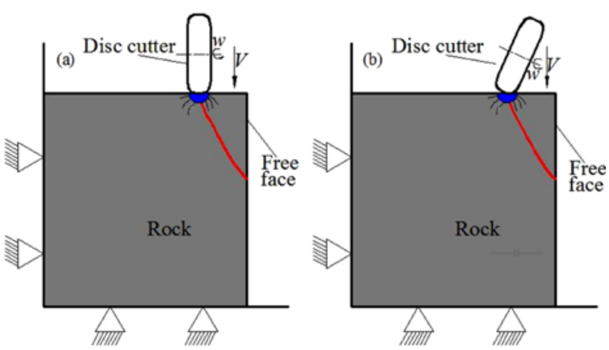

Fig. 2. Schematic Diagrams of FM and UM: (a) FM, (b) UM

Ramezanzadeh *et al.* (2010) and Hood *et al.* (2000) pointed out that the cutting force and cutting efficiency of the disc cutter can be improved significantly when cutting rock with the UM. During the 1980s-1990s, the German company Wirth manufactured a continuous mining machine based on the UM (Ramezanzadeh *et al*., 2010) which was used to excavate a 4.25-m-diameter tunnel. Then, the continuous mining machine was moved to a nickel mining project in Canada, where the UCS was reported as 250 MPa and the Brazilian Tensile Strength (BTS) as 16 MPa. An excavation was started but unfortunately withdrawn after excavating only some 200 m^3 of rock due to massive failures of disc cutters caused by large side force and high rock abrasivity. If the FM was employed to cutting this hard rock, the high side force and the high failure of the disc cutter may be improved due to the difference in the motion mode of the disc cutter.

To understand the FM more deeply and promote the development of the FM, the cutting method of the FM induced by disc cutter was explored in this paper based on linear cutting tests. Meanwhile, the differences in rock breaking states, rock cutting forces and cutting efficiency etc. between the FM and the CM were compared. It indicates the FM is a promising cutting method to improve the rock cutting efficiency and cutting forces, which can provide a new idea for TBM excavation and promote the application of the FM to the multi-stage cutterhead TBM.

The cutting conditions under the CM and the FM are illustrated in Fig. 3. When cutting rock under the CM, the rock was cast into the concrete in an open-bottomed steel box without free face, and this is similar to the conventional cutting condition for disc cutter, as shown in Fig. 3(a). The cutter spacing (S_1) is defined as the distance between the two cutting grooves. When cutting rock under the FM, the rock side near the disc cutter is free face, as shown in Fig. 3(b). And the free face distance (S_2) is defined as the distance between the cutting groove and the free face.

2. Test Design

2.1 Test Equipment

The LCM in the Shield Laboratory of Central South University

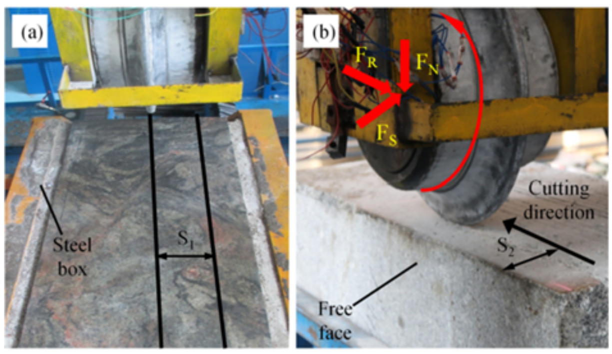

Fig. 3. Two Kinds of Cutting Methods: (a) CM, (b) FM

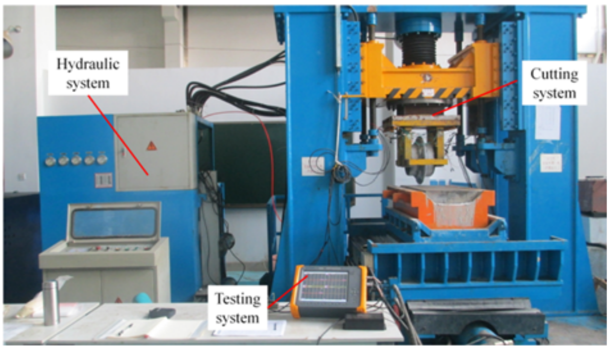

Fig. 4. The LCM

was used to conduct the cutting tests which mainly consists of three parts: hydraulic system, testing system and mechanical cutting system, as shown in Fig. 4. By changing the transition structure of the tool carrier, the cutting tools with different structures such as disc cutters and chisel cutters can be installed. The strain gauges are pasted on the tool carriers in full-bridge mode, and the strain signals under different loads are obtained by calibration. Thus, the cutting forces of the disc cutter can be obtained by collecting the strain signal with the aid of the dynamic strain detector.

2.2 Disc Cutter and Rock Sample

The disc cutter used for tests was a 432 mm (17 in.) diameter cutter with a constant cross-section type. The granites were selected as the hard rock samples whose length, width and height are 900 mm, 550 mm and 300 mm, respectively. The main material parameters of the granite measured from the laboratory tests are shown in Table 1.

2.3 Cutting Scheme

In the rock cutting process under the two cutting methods, the cutting speed and cutting length are set to 20 mm/s and 400 mm, respectively. Since this paper mainly investigates the differences of rock cutting characteristics between the FM and the CM, only one penetration of the disc cutter was chosen to perform in all cutting tests. In general, the penetration of the disc cutter in the hard rock engineering site field is about 6 mm according to a large number of TBM field statistics. Thus, the cutter penetration in the cutting tests was controlled at 6 mm. Both the S_1 and the S_2 are set at 20 mm, 40 mm, 60 mm, 80 mm and 100 mm respectively when cutting rock under the two cutting methods. In addition, to keep a same surface condition for the observation of the rock breaking states, the rock surface was not conditioned compared with the real TBM tunnel face.

Table 1. Mechanical Parameters of Rock Samples

Density (kg·m^{-3})	2516
Young's modulus (GPa)	11.5
Uniaxial compressive strength (MPa)	100.3
Brazilian tensile strength (MPa)	5.7

3. Experimental Results and Analysis

3.1 Rock Breaking States

The rock breaking states under two cutting methods are shown in Fig. 5 and Fig. 6. For cutting rock under the CM, when the S_1 is less than 60 mm, the rock ridge between the cutting grooves was peeled off, as shown in Fig. 5(a), 5(b) and 5(c). It can be explained that the preceding cutting will affect the succeeding cutting and the lateral crack induced by the succeeding cutting could propagate to the preceding cutting groove. However, when the S_1 is more than 60 mm, the rock ridge between the cutting grooves could be observed obviously and the width of the cutting groove is always larger than that of the cutter tip due to the crack propagation, as shown in Fig. 5(d) and 5(e). It shows there has no synergistic effect between the two cutting grooves when the S_1 increases to a certain extent. This phenomenon was also observed by Rostami (1997) and Cho *et al.* (2010).

For cutting rock under the FM, when the S_2 is less than 80 mm, the main crack induced by the disc cutter could propagate to the free face and large rock debris was formed, as shown in Fig. 6(a), 6(b), 6(c) and 6(d). Meanwhile, the broken surface of rock sample is smooth and little small rock debris or powder occurs. It may be explained that the rock breaking process under the FM is dominated by tensile failure rather than shear failure. Furthermore, the crack depth between the deepest crack point and the working face of the rock sample increases with the increase of the S_2, which is about 50.4 mm, 90.1 mm, 110.8 mm and 140.1 mm when the S_2 is 20 mm, 40 mm, 60 mm and 80 mm, respectively. When the S_2 is more than 80 mm, the main crack couldn't

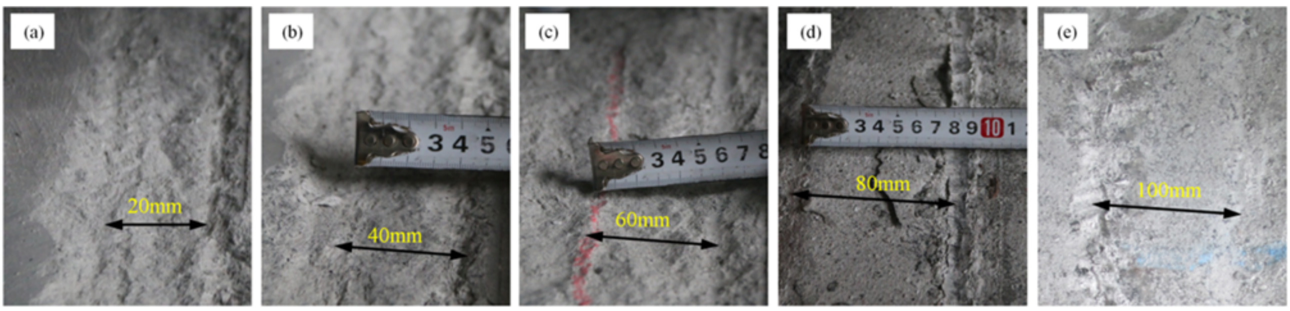

Fig. 5. Rock Breaking States under the CM: (a) S_1 = 20 mm, (b) S_1 = 40 mm, (c) S_1 = 60 mm, (d) S_1 = 80 mm, (e) S_1 = 100 mm

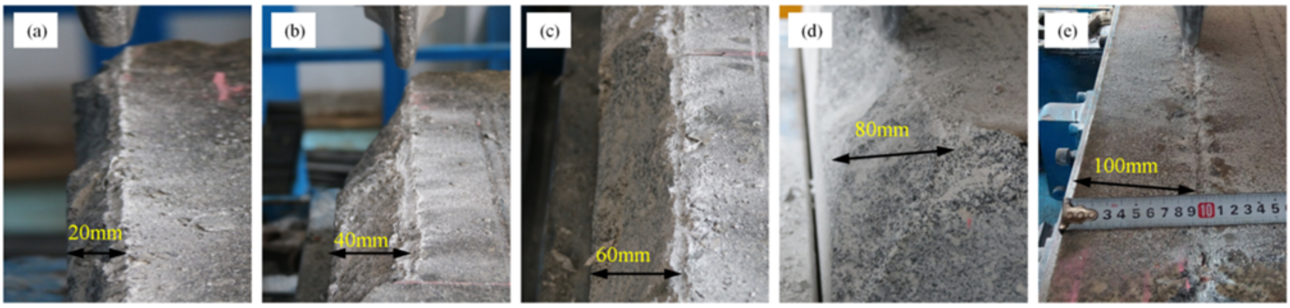

Fig. 6. Rock Breaking States under the FM: (a) S_2 = 20 mm, (b) S_2 = 40 mm, (c) S_2 = 60 mm, (d) S_2 = 80 mm, (e) S_2 = 100 mm

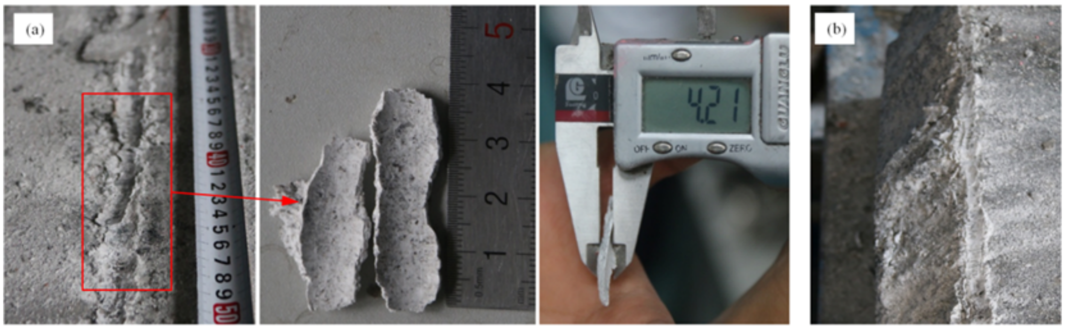

Fig. 7. Damage Conditions in the Cutting Grooves under the Two Cutting Methods: (a) Under the CM, (b) Under the FM

propagate to the free face and the rock broken area just occurs below the disc cutter, as shown in Fig. 6(e). It can be obtained that the S_2 Should be less than 80 mm to use the free face to promote the rock failure effectively. Compared the two cutting methods, the rock breaking range and the crack propagation ability under the FM are greater than that under the CM. When cutting rock under the CM, the cracks tend to propagate to horizontal direction and reach the working face, resulting in smaller rock breaking range. When cutting rock under the FM, the cracks tend to propagate along the vertical direction and reach the free face if the free face distance is less than a certain value, such as 80 mm in this paper, resulting in bigger rock breaking range.

Figure 7 shows the damage conditions in the cutting grooves under the two cutting methods. When cutting rock under the CM, a thick powder layer which is called dense nucleus can be observed in the cutting grooves and its thickness is about 4.2 mm, as shown in Fig. 7(a). This is mainly caused by the compression between the disc cutter tip and the rock surface. However, when cutting rock under the FM, there is no obvious powder layer in the cutting groove, as shown in Fig. 7(b). That is to say, the rock breaking under the FM is more prone to tensile failure when compared to that under the CM.

3.2 Rock Debris

Rock debris collected under different cutting methods is

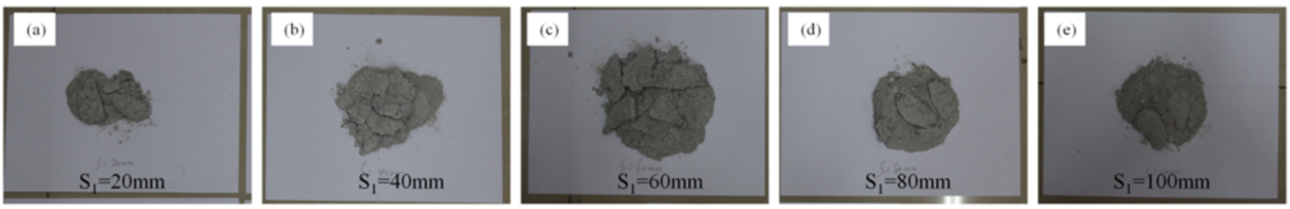

Fig. 8. Rock Debris under the CM: (a) S_1 = 20 mm, (b) S_1 = 40 mm, (c) S_1 = 60 mm, (d) S_1 = 80 mm, (e) S_1 = 100 mm

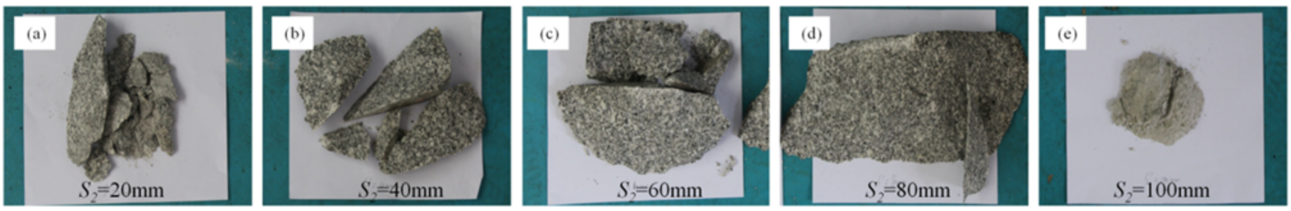

Fig. 9. Rock Debris under the FM: (a) S_2 = 20 mm, (b) S_2 = 40 mm, (c) S_2 = 60 mm, (d) S_2 = 80 mm, (e) S_2 = 100 mm

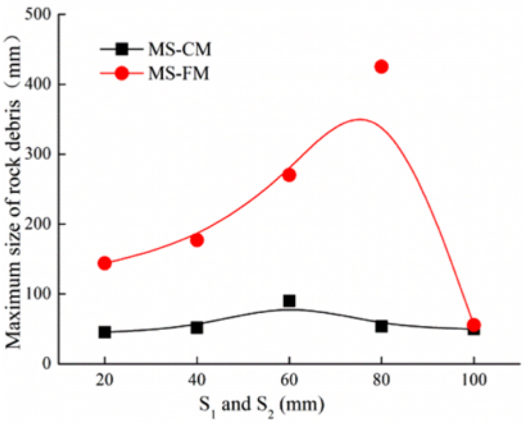

Fig. 10. Maximum Size of the Rock Debris under Two Cutting Methods

illustrated in Fig. 8 and Fig. 9. Compared the two cutting methods, the rock debris size under the CM is smaller than that under the FM when the S_1 and the S_2 are less than 80 mm, respectively. Moreover, the rock breaking volume under the CM is also far less than that under the FM. When the S_1 and the S_2 are 100 mm, the rock debris size under the CM is similar to that under the FM. This also indicates that the two cutting methods are similar when the values of the S_1 and the S_2 are more than 100 mm.

The maximum size of the biggest rock debris (*MS*) under different cutting methods is shown in Fig. 10. For cutting rock under the CM, the *MS* first increases and then decreases with the increase of S_1, and the maximum values of *MS* is obtained when S_1 is 60 mm which is 89.9mm. It can be explained that the rock debris will crush overly due to the smaller value of S_1, resulting in a strong interaction between two cutting grooves and a small value of *MS*. When the S_1 is proper, such as 60 mm in this paper, the rock ridge between the cutting grooves will be peeled off integrally due to the proper crack propagation, resulting in a increase in *MS*. However, when S_1 is large relatively, such as 80 mm and 100 mm in this paper, the rock ridge will not be peeled off as stated in section 3.1, resulting in a decrease in *MS*.

For cutting rock under the FM, the *MS* also first increases and then decreases with the increase of S_2, and the maximum values of *MS* is obtained when S_2 is 80 mm which is about 425.0 mm. It can be explained that when S_2 is less than 80 mm, the free face can promote the crack propagation along the vertical direction and the formation of long cracks effectively, resulting in big rock debris. And the greater the S_2 is, the larger the *MS* is. However, when S_2 is more than 80 mm, the free face effect will not exist and the cracks couldn't propagate to the vertical direction effectively, resulting in a decrease of *MS*.

3.3 Cutting Force

The cutting forces of the disc cutter include normal force (F_N), rolling force (F_R) and side force (F_S) as shown in Fig. 3(b). The average and peak cutting forces of the disc cutter under the two cutting methods are illustrated in Fig. 11. The average normal

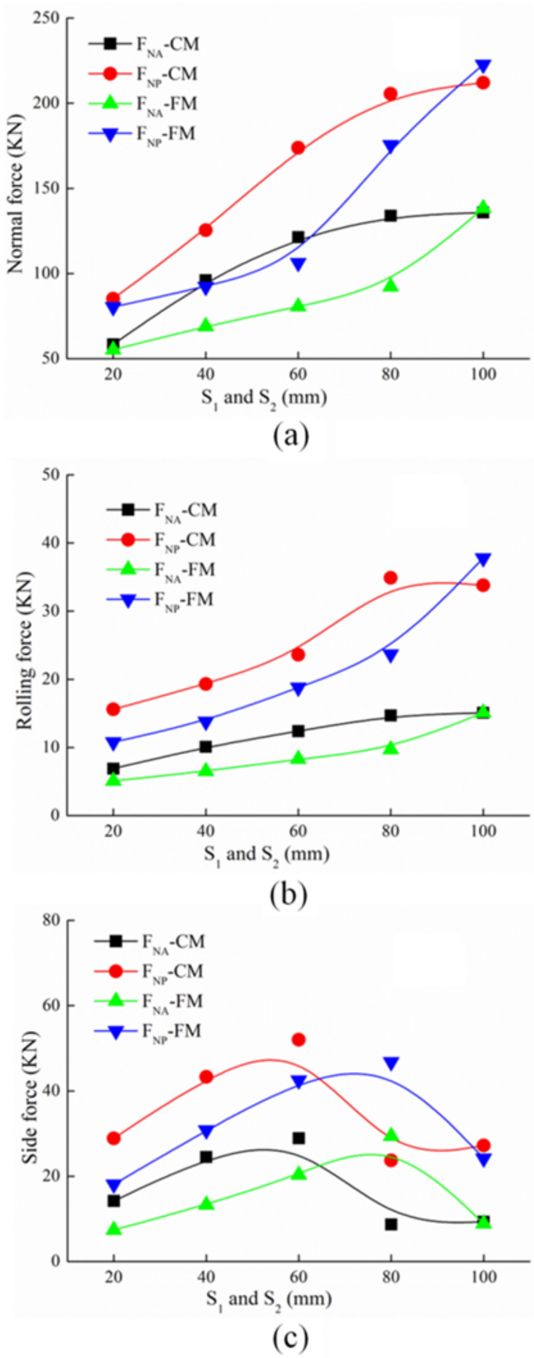

Fig. 11. Cutting Force under Two Cutting Methods: (a) F_N, (b) F_R, (c) F_S

force (F_{NA}) and the peak normal force (F_{NP}) under two cutting methods all increase with the increase of the value of S_1 and S_2. However, the increase speed of F_N under the CM will slow down rapidly when S_1 is more than 80 mm as shown in Fig. 11(a). It can be explained that the cutting conditions are the same that the rock ridges are not peeled off when S_1 is more than 80 mm, resulting in little difference in F_N. Compared the two cutting methods, the F_N under the CM are always greater than that under the FM when the value of S_1 and S_2 is less than 80 mm. It shows that the rock cutting method under the FM can reduce the cutting force significantly. When the value of S_1 and S_2 is more than 80 mm, there is little difference in F_N between the two kinds of cutting methods. This is consistent with the above analysis about rock breaking states and rock debris. On the whole, the variation trend of F_R is similar to that of F_N as shown in Fig. 11(b).

The F_S under two cutting methods first increases and then decreases with the increase of the value of S_1 and S_2. And the maximum values of F_S are obtained when the S_1 is 60 mm and the S_2 is 80 mm, as shown in Fig. 11(c). It may be explained that the fragment formation on one side of the disc cutter mainly depends on the F_S, the larger the fragment is, the greater the F_S of the disc cutter is. when the S_1 is less than 60 mm and the S_2 is less than 80 mm, lots of large fragment will be produced just on one side of the disc cutter, resulting in a difference in force on both sides of the disc cutter. However, when the S_1 is more than 60 mm and the S_2 is more than 80 mm, the rock breaking states and the forces on both sides of the disc cutter all are almost the same, resulting in a decrease in F_S. It is worth noting that the F_S under the FM are always lower than that under the CM when the value of S_1 and S_2 is not equal to 80 mm, as shown in Fig. 11(c). Thus, cutting rock under the FM will not increase the side force of the disc cutter. This is completely different from the UM, as stated in section 1.

3.4 Cutting Efficiency

Specific Energy (*SE*) refers to the energy consumed by breaking unit volume of rock (Tiryaki and Dikmen, 2006), and the greater the *SE* is, the lower the rock cutting efficiency is. The *SE* is shown in Eq. (1).

$$SE = \frac{w}{v} = \frac{F_R l}{v} = \frac{F_R l \rho}{m} \quad (1)$$

where w denotes the cutting work, v denotes the rock broken volume, l denotes the cutting stroke, ρ denotes the rock density, m denotes the rock broken mass.

The *SE* under the two cutting methods is illustrated in Fig. 12. The *SE* under two kinds of cutting methods all first decreases and then increases with the increase of the values of S_1 and S_2. It indicates that there exists an optimal value of S_1 and S_2 to achieve the minimum *SE* and the highest cutting efficiency which are 60 mm and 80 mm, respectively. As stated in section 3.2, for cutting rock under the CM, the rock ridge between the cutting grooves will crush overly when the S_1 is less than 60 mm. However, when the S_1 is more than 60 mm, the rock ridge will not be peeled off due to little interaction between the cutting grooves, resulting in a optimal S_1. For cutting rock under the FM, when the S_2 is less than 80 mm, the free face can promote the crack propagation well. And the fragment size will increase with the increase of the S_2, resulting in a decrease in *SE*. However, When the S_2 is more than 80 mm, the cracks can't propagate to the free face, and the *SE* will increase with the increase of the S_2. Compared the two cutting methods, when the values of S_1 and S_2 are less than 80 mm, the *SE* under the CM are much higher than

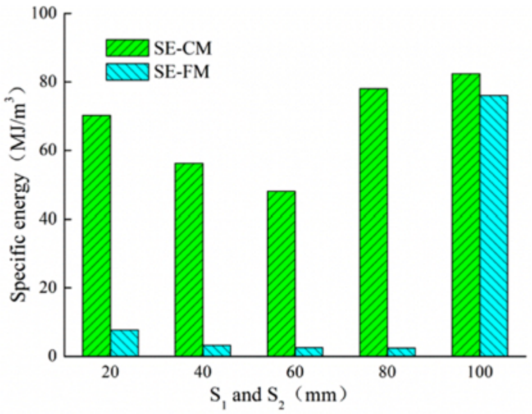

Fig. 12. *SE* under Two Cutting Methods

that under the FM, the former is about 10 times more than the latter. It shows that the rock cutting efficiency under the FM is much higher than that under the CM, and the rock cutting method under the FM can improve the rock cutting efficiency significantly. When the value of S_2 is more than 80 mm, the rock cutting method under the FM is similar to that under the CM, resulting in little difference in rock cutting efficiency.

4. Discussion

According to the above research, the FM induced by disc cutter is a promising and innovative approach compared with the CM. The rock debris size and the rock cutting efficiency of the former are much larger than that of the latter, and the cutting force of the former is much smaller than that of the latter.

The results can strengthen the confidence to promote the development of the FM induced by the disc cutter in cutting engineering by machine. For example, this cutting method can be applied to the multi-stage cutterhead TBM which are shown in Fig. 1. Based on the study in this paper, the free face distance should be controlled within 80 mm to ensure the crack can propagate to the free face effectively. Thus, the distance between the disc cutter in the second-stage cutterhead and the free face should be controlled within 80 mm for multi-stage cutterhead TBM. Since the rock surface was not conditioned, the critical free face distance can be set at a bigger value when designing multi-stage cutterhead TBM and this will be investigated in future studies.

In addition, the geostress (confining stress) which is a important factor to affect the rock breaking efficiency was not studied in this paper. Indeed, the TBM will encounter high geostress when tunneling in deep rock ground, such as Chinese Jinping II tunnels. On the one hand, the high geostress will increase the cutting force and reduce the cutting efficiency when geostress is high relatively (Liu *et al.*, 2016). On the other hand, the high geostress may improve the cutting force and cutting efficiency when the geostress is high enough to cause the stress-induced rock failure ahead of the tunnel face (Yin *et al*., 2014a, 2014b).

For the FM under the high geosstress, the cutting force and cutting efficiency can be reduced and improved since a cave with a small diameter was created firstly and the free face was also produced based on above research. In addition, if the geostress is high enough to cause the stress-induced failure (Yin *et al.*, 2014a, 2014b), the first cave produced by the first-stage cutterhead my induce the rock breaking automatically and improve the rock breaking efficiency of the TBM. In this sense, the FM can also be applied to high geostress condition.

It should be pointed out that the formation of the big rock debris induced by FM will have a negative effect on the rock debris discharging. Thus, the layout and the size of the multi-stage TBM slag holes should also be studied deeply to improve the discharging efficiency in future studies.

5. Conclusions

In this study, the rock cutting tests by the disc cutter were carried out and the rock cutting characteristics were also compared under the two cutting methods. The main conclusions can be drawn as follows:

1. The rock fracture patterns under the two cutting methods are totally different, the rock fracture under the FM is more prone to tensile failure when compared to that under the CM. The cracks tend to propagate along the vertical direction and reach the free face when cutting rock under the FM, resulting in bigger rock debris when the free face distance is less than a certain value. When cutting rock under the CM, the cracks tend to propagate to horizontal direction and reach the working face, resulting in smaller rock debris.
2. The F_N and F_R all increase with the increase of the values S_1 and S_2 on the whole, and the F_N and F_R under the CM are always greater than that under the FM when the value of S_1 and S_2 is less than a certain value. The F_S under the two cutting methods first increases and then decreases with the increase of the values of S_1 and S_2 due to the difference in rock breaking states on both sides of the disc cutter.
3. It exists an optimal value of S_1 and S_2 to achieve the highest cutting efficiency. The rock cutting efficiency under the FM are much higher than that under the CM when the values of S_1 and S_2 are less than 80 mm. The FM induced by the disc cutter can be applied in multi-stage cutterhead TBMs to improve the excavation efficiency.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (Granted No. 51475478), the Major State Basic Research Development Program of China (973 program) (Granted No. 2013CB035401), the Science and Technology Project of Strategic Emerging Industry in Hunan (Granted No. 2015GK1029) and the Hunan Provincial Innovation Foundation For Postgraduate (Granted No. CX2017B048).

References

Balci, C. and Tumac, D. (2012). "Investigation into the effects of different rocks on rock cuttability by a V-type disc cutter." *Tunnelling and Underground Space Technology*, Vol. 30, No. 4, pp. 183-193, DOI: 10.1016/j.tust.2012.02.018.

Bejari, H. and Khademi Hamidi, J. (2013). "Simultaneous effects of joint spacing and orientation on TBM cutting efficiency in jointed rock masses." *Rock Mechanics and Rock Engineering*, Vol. 46, No. 4, pp. 897-907, DOI: 10.1007/s00603-012-0314-2.

Bilgin, N., Copur, H., and Balci, C. (2012). "Effect of replacing disc cutters with chisel tools on performance of a TBM in difficult ground conditions." *Tunnelling and Underground Space Technology*, Vol. 27, No. 1, pp. 41-51, DOI: 10.1016/j.tust.2011.06.006.

Cho, J. W., Jeon, S., Jeong, H. Y., and Chang, S. H. (2013). "Evaluation of cutting efficiency during TBM disc cutter excavation within a Korean granitic rock using linear-cutting-machine testing and photogrammetric measurement." *Tunnelling and Underground Space Technology*, Vol. 35, No. 4, pp. 37-54, DOI: 10.1016/j.tust.2012.08.006.

Cho, J., Jeon, S., Yu, S., and Chang, S. (2010). "Optimum spacing of TBM disc cutters: A numerical simulation using the three-dimensional dynamic fracturing method." *Tunnelling and Underground Space Technology*, Vol. 25, No. 3, pp. 230-244, DOI: 10.1016/j.tust.2009.11.007.

Choi, S. and Lee, S. (2015). "Three-dimensional numerical analysis of the rock-cutting behavior of a disc cutter using particle flow code." *KSCE Journal of Civil Engineering*, Vol. 19, No. 4, pp. 1129-1138, DOI: 10.1007/s12205-013-0622-4.

Choi, S. and Lee, S. (2016). "Numerical study to estimate the cutting power on a disc cutter in jointed rock mass." *KSCE Journal of Civil Engineering*, Vol. 20, No. 1, pp. 440-451, DOI: 10.1007/s12205-015-2265-0.

Ciccu, R. and Grosso, B. (2014). "Improvement of disc cutter performance by water jet assistance." *Rock Mechanics and Rock Engineering*, Vol. 47, No. 2, pp. 733-744, DOI: 10.1007/s00603-013-0433-4.

Geng, Q., Wei, Z., and Meng, H. (2014). "Numerical and experimental method to determine the boring diameters of a two-stage TBM cutterhead to prevent rock burst." *Journal of Mechanical Science and Technology*, Vol. 28, No. 11, pp. 4613-4620, DOI: 10.1007/s12206-014-1029-y.

Geng, Q., Wei, Z., and Meng, H. (2016b). "An experimental research on the rock cutting process of the gage cutters for rock Tunnel Boring Machine (TBM)." *Tunnelling and Underground Space Technology*, Vol. 52, No. 2016, pp. 182-191, DOI: 10.1016/j.tust.2015.12.008.

Geng, Q., Wei, Z., He, F., and Meng, H. (2015). "Comparison of the mechanical performance between two-stage and flat-face cutter head for the rock Tunnel Boring Machine (TBM)." *Journal of Mechanical Science and Technology*, Vol. 29, No. 5, pp. 2047-2058, DOI: 10.1007/s12206-015-0425-2.

Geng, Q., Wei, Z., Meng, H., and Chen, Q. (2016a). "Numerical and experimental research on the rock-breaking process of tunnel boring machine normal disc cutters." *Journal of Mechanical Science and Technology*, Vol. 30, No. 4, pp. 1733-1745, DOI: 10.1007/s12206-016-0329-9.

Gertsch, R., Gertsch, L., and Rostami, J. (2007). "Disc cutting tests in Colorado Red Granite: Implications for TBM performance prediction." *Int. J. Rock Mech. Min. Sci.*, Vol. 44, No. 2, pp. 238-246, DOI: 10.1016/j.ijrmms.2006.07.007.

Gong, Q. M., Jiao, Y. Y., and Zhao, J. (2006). "Numerical modeling of the effects of joint spacing on rock fragmentation by TBM cutters." *Tunnelling and Underground Space Technology*, Vol. 21, No. 1, pp. 46-

55, DOI: 10.1016/j.tust.2005.06.004.

Hassani, F., Nekoovaght, P. M., and Gharib, N. (2016). "The influence of microwave irradiation on rocks for microwave-assisted underground excavation." *Journal of Rock Mechanics and Geotechnical Engineering*, Vol. 8, No. 1, pp. 1-15, DOI: 10.1016/j.jrmge.2015.10.004.

Hood, M. and Alehossein, H. (2000). "A development in rock cutting technology." *International Journal of Rock Mechanics and Mining Sciences*, Vol. 37, Nos. 1-2, pp. 297-305, DOI: 10.1016/S1365-1609(99)00107-0.

Liu, J., Cao, P., and Han, D. (2016). "Sequential indentation tests to investigate the influence of confining stress on rock breakage by tunnel boring machine cutter in a biaxial state." *Rock Mechanics and Rock Engineering*, Vol. 49, No. 4, pp. 1-17, DOI: 10.1007/s00603-015-0843-6.

Liu, J., Cao, P., Du, C., Jiang, Z., and Liu, J. (2015a). "Effects of discontinuities on penetration of TBM cutters." *Journal of Central South University*, Vol. 22, No. 9, pp. 3624-3632,DOI: 10.1007/s11771-015-2903-1.

Liu, J., Cao, P., Liu, J., and Jiang, Z. (2015b). "Influence of confining stress on fracture characteristics and cutting efficiency of TBM cutters conducted on soft and hard rock." *Journal of Central South University*, Vol. 22, No. 5, pp. 1947-1955, DOI: 10.1007/s11771-015-2714-4.

Ma, H., Gong, Q., Wang, J., Yin, L., and Zhao, X. (2016). "Study on the influence of confining stress on TBM performance in granite rock by linear cutting test." *Tunnelling and Underground Space Technology*, Vol. 57, pp. 145-150, DOI: 10.1016/j.tust.2016.02.020.

Ramezanzadeh, A. and Hood, M. (2010). "A state-of-the-art review of mechanical rock excavation technologies." *Journal of Mining and Environment*, Vol. 1, No. 1, pp. 29-39.

Rostami, J. (1997). *Development of a force estimation model for rock fragmentation with disc cutters through theoretical modeling and physical measurement of crushed zone pressure*, Ph.D. Thesis, Colorado School of Mines, Golden, Colorado, USA.

Rostami, J. (2013). "Study of pressure distribution within the crushed zone in the contact area between rock and disc cutters." *International Journal of Rock Mechanics and Mining Sciences*, Vol. 57, No. 1, pp. 172-186, DOI: 10.1016/j.ijrmms.2012.07.031.

Tiryaki, B. and Dikmen, A. C. (2006). "Effects of rock properties on specific cutting energy in linear cutting of sandstones by picks." *Rock Mechanics and Rock Engineering*, Vol. 39, No. 2, pp. 89-120, DOI: 10.1007/s00603-005-0062-7.

Tumac, D. and Balci, C. (2015). "Investigations into the cutting characteristics of CCS type disc cutters and the comparison between experimental, theoretical and empirical force estimations." *Tunnelling and Underground Space Technology*, Vol. 45, No. 45, pp. 84-98, DOI: 10.1016/j.tust.2014.09.009.

Yin, L. J., Gong, Q. M., and Zhao, J. (2014a). "Study on rock mass boreability by TBM penetration test under different in situ stress conditions." *Tunnelling and Underground Space Technology*, Vol. 43, No. 45, pp. 413-425, DOI: 10.1016/j.tust.2014.06.002.

Yin, L. J., Gong, Q. M., Ma, H. S., Zhao, J., and Zhao, X. B. (2014b). "Use of indentation tests to study the influence of confining stress on rock fragmentation by a TBM cutter." *International Journal of Rock Mechanics and Mining Sciences*, Vol. 72, No. 72, pp. 261-276, DOI: 10.1016/j.ijrmms.2014.07.022.