Study on Rock Cutting Mechanism and Efficient Shield Tunneling Control in Mixed-Ground with Different Strengths

Hongbing Shi¹,², Xing Huang³*, Bin Liu³, Shuai Luan¹,², Linfeng Li⁴, Shaoran Liu¹,², Xingli Lu³

¹ China Construction Civil Infrastructure Corp. Ltd., Beijing 100029, China
² China Construction South Investment Co., Ltd., Shenzhen, Guangdong 518000, China
³ State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, Hubei, 430071, China
⁴ School of urban construction, Wuhan University of Science and Technology, Wuhan, Hubei 430065, China
*E-mail: xhuang@whrsm.ac.cn

Abstract. Mixed ground condition exerts very significant influences on the rock fragmentation mechanism, rock cutting efficiency, and operational parameters selection of the shield boring machine. In order to reveal the rock cutting mechanism when the shield tunnel boring machine advances through the mixed grounds in Line 13 of the Shenzhen Metro Tunnels, according to several linear cutting tests were conducted using a constant cross-section disc-cutter and five rock types with different strengths. The change of disc-cutter cutting force and rock boreability index were analyzed, and some suggestions were proposed to fulfill the safe and efficient tunneling of the shield machine in mixed ground conditions. The results of this study can offer useful suggestions for the operation parameter selection of the shield tunnel boring machine tunneling through the mixed ground in the Shenzhen Metro Line 13 and similar projects.

1. Introduction
Excavation by tunneling machine (TBM/shield machine) has huge advantages in technology, economy, and schedule, making it the best choice for deep and long tunnel construction. For example, the Dahuofang water diversion Project, LXB water diversion Project, and Han River -to- Wei River diversion project all adopt the TBM construction method. The western route of the planned South-to-North water transfer project in China will be largely constructed with TBM because of the huge project, long line, and many long and deeply buried tunnels, which will inevitably lead to the construction period problems caused by the traditional drilling and blasting method. In order to shorten the construction period, many deep coal mines also began to choose TBM construction, such as Xinjie experimental inclined shaft in Shenhua Taigemiao mining area and new auxiliary inclined shaft in Shendong Bulianta Coal Mine will adopt TBM excavation. Shield tunneling machines are widely used in urban subway construction. Due to the influence of multi-stage complex tectonic movements, the deep geological conditions are complex and changeable, so it is inevitable that TBM/shield tunneling will encounter mixed-ground during the deep-buried long tunnels construction. TBM/shield tunneling performance is very sensitive to geological conditions. When the formation changes greatly, which will lead to tool damage, cutter wear, stuck machine, abnormal attitude, etc., and significantly reduce the tunneling
efficiency.

Rock fragmentation is realized by rotary cutter-head. The cutter-head is the base on which the rock-fragmentation cutters are installed, and it is one of the important parts of the TBM/shield tunneling machine. The resistance of the cutters in the tunnel face acts on TBM/shield machine through the cutter-head. When the tunnel face is of the same lithology, the rock-cutting force of the cutter is roughly the same, and the force on the cutter-head will not occur mutation and eccentricity. However, when there are different lithologies of soft and hard rocks at the same time, there is a big difference in rock cutting force between soft and hard rock, and the cutter is frequently subjected to shock load at the interface of soft and hard rock, so that the load distribution of cutter-head is uneven and changes greatly, which is the fundamental reason of TBM construction disasters in mixed-ground. In order to reveal the interaction mechanism between tunnel face and cutter-head in mixed-ground, it is necessary to carry out a study on the mechanical characteristics of TBM/mixed-shield machine cutters cutting in mixed-ground.

In the past 40 years, many researchers have conducted a large number of valuable studies on the design and operation of tunneling machines. These studies can be classified into theoretical studies, numerical simulations, laboratory studies, and field studies. In terms of theoretical research, scholars have developed many models to predict cutting forces by assuming different rock fracture mechanisms [1-7]. In terms of numerical simulation studies, researchers analyzed rock fragmentation processes and modes in rock penetration and cutting simulations [8-13]. In laboratory experiments, previous scholars conducted many rock penetration tests, rotary cutting, and linear cutting tests to study the rock fragmentation performance of different rocks under different cutting conditions [14-19]. In terms of field research, according to field TBM operating data, previous scholars studied the variation rules of rock mass boreability, advance speed, cutter wear, and specific construction measures under different geological conditions [20-26].

Because the laboratory rock cutting test is more accurate than the theoretical and numerical simulation research, and the cost is less than the field test, the linear rock cutting test is considered to be the most reliable and economical method to study the performance prediction and efficient rock fragmentation mechanism of TBM/shield machine. Based on Liuxiandong-Baimang tunneling section in Shenzhen metro line 13, combined with the full-size linear cutting machine cutting rocks with different rock strength, revealing the influence law of rock strength on cutter fragmentation the rock of dual-mode shield TBM in mixed-formation, so as to provide guidance for shield machine safe and efficient driving, and in further reduce the damage to the cutters, improve the service life of the shield machine in the complex formation.

2. Project Overview

The dual-mode shield machine of Shenzhen Metro Line 13 mainly passes through Liuxiandong to Baimang station. After leaving Liuxiandong Station, the tunneling machines advance along Tongfa Road, passing through the stadium of Shenzhen Vocational and Technical College, then turn into Shahe West Road, pass through Xili Reservoir - Tiegang Reservoir diversion tunnel along Shahe West Road, and pass through Xili Reservoir drinking water source protection Zone, and then enter into Baimang Station.

The length of the tunneling section is 4607.404 m, which is the longest section of Line 13. It is divided into two tunnels and constructed by a TBM/EPB dual-mode shield tunneling method. The left and right tunnels are composed of six curved tunneling segments and seven straight tunneling segments. The minimum radius of the horizontal curve of the left and right tunnels is 650 m, and the distance between the left and right tunnels is 11.0-17.3 m. The longitudinal profile of the tunnel is a W-shaped slope with a maximum of 28% and a minimum of 2%. The radius of the vertical curve is 5000 m, and the burial depth of the tunnel roof is about 10.6-49.6 m (figure 1). Four dual-mode shield tunneling machines are used in this area, two of which are started from the big chainage end of Liuxiandong and hoisted out from the small chainage end of the interval air shaft. The other two were started from the big chainage end of Baimang station and hoisted out at the small chainage end of the interval air shaft.
Figure 1. Schematic diagram of Shenzhen Metro Line 13.

The tunnel excavation diameter is 6980 mm, and the disc-cutter is φ457.2 mm. The prefabricated segmental lining is adopted with the strength grade C50 and impermeability grade P12. The segmental lining thickness is 350 mm, the ring width is 1.5 m, and each ring is assembled with six pieces of segments. The TBM and shield machines are usually suitable for boring in simple and homogeneous formations. However, the stratum conditions of shield machine traversing in the Liuxiandong-Baimang region are complex. The shield machine mainly advanced through moderately weathered granite, weak weathering granite, and strong and weak weathering upper soft and lower hard mixed-ground (figure 2). Preliminary investigation data show that the saturated uniaxial compressive strength of the weak weathering granite and its broken blocks mainly ranges from 34.2 to 83.2 MPa, which is far greater than the strength of the adjacent soil. Therefore, the shield tunneling zone can be identified as a typical mixed-ground.

Figure 2. Geological profile of the mixed ground in Liuxiandong to Baimang tunneling section.

3. Rock Cutting Mechanism for Tunneling in Mixed-Ground
Previous studies performed full-scale linear cutting rock fragmentation tests on five rock types (Cement mortar, Longchang sandstone, Hezhou marble, Miluo granite, and Yueyang granite) (figure 3) [27]. Among them, the used granite sample is similar to the granite taken from Liuxiandong to Baimang section of Shenzhen Metro Line 13, and the other four rocks may be encountered during the shield machine tunneling.
Figure 3. Full-scale linear cutting tests.

The uniaxial compressive strength of these five rock types varies from 21.25 to 176.88 MPa, and the Brazilian tensile strength of these five rock types ranges from 1.59 to 7.66 MPa (table 1). They can generally represent the commonly encountered mixed-ground during tunneling.

Table 1. Mechanical properties of the five rock types.

| Parameter (MPa) | Cement mortar | Longchang sandstone | Hezhou marble | Miluo granite | Yueyang granite |
|----------------|---------------|----------------------|---------------|---------------|-----------------|
| $\sigma_c$     | 21.25         | 37.02                | 79.07         | 127.24        | 176.88          |
| $\sigma_t$     | 1.59          | 1.75                 | 3.26          | 5.14          | 7.66            |

According to the field experience of TBM/ shield tunneling project [28], a constant cross-section disc-cutter with a diameter of 432 mm and a spacing of 80 mm was adopted. Low-strength rocks are easy to be cut, so the employed cutter penetration rates are large, i.e., ranges from 4 to 12 mm for Cement mortar and Longchang sandstone. However, high-strength rocks are difficult to be cut, so the employed cutter penetration depth is small, i.e., ranges from 1 to 4 mm for Yueyang granite. Each penetration is repeated at least three or four times. In the test, the three-dimensional cutting force of the cutter was measured. The variation rule of cutting force and rock boreability index are obtained.

1) Change rule of cutting force in rock fragmentation process

The test result (figure 4) shows that there is a good power function relationship between normal cutting force and penetration rate for rocks with different strengths [28]. For each rock strength, the normal cutting force decelerates with the increasing penetration rate. In other words, the penetration rate increases with the increasing normal cutting force. This shows that the influence of penetration rate on normal cutting force is more obvious when the penetration rate is low. When the penetration rate increases from a small value, the normal cutting force increases rapidly and significantly. When the penetration rate increases from a more significant value, the normal cutting force increases slowly and slightly. At the same time, it also shows that the influence of normal cutting force on penetration rate is more obvious when the normal cutting force is larger. When the normal cutting force is small, the cutter cannot penetrate the rock surface effectively, so the cutter penetration rate increases slowly with the growing normal cutting force. When the normal cutting force is large, the rock surface is excessively broken, so the penetration rate can increase rapidly with the normal cutting force without hindrance.
Figure 4. Relationship between normal cutting forces and penetration rate of different rock types.

(2) Variation rule of rock boreability index in the rock cutting process

Figure 5 shows the change curves of boreability index of different rocks under different penetration rates. It can be found that the relationship between rock mass boreability index and penetration rate in these curves all meet the power function. Gong Qiuming et al. from Beijing University of Technology conducted similar tests, the index of the relationship between the boreability index and penetration rate is -0.57. In this study, the index of the relationship between the boreability index and penetration rate is approximate. It can also be seen from figure 5 that the tunneling indexes of these rocks all decrease with the increasing penetration rate, indicating that with the increasing penetration rate, the growth range of the normal force acting on the single tool becomes smaller and smaller. Comparing these five curves (figure 5), it is found that the rock mass boreability index increases gradually with the increasing rock strength.

Figure 5. Relationship between rock boreability index and rock strength of different rock types [28].

4. Efficient Shield Tunneling Control Technology in Mixed-Ground

The above linear cutting rock fragmentation test results of TBM/shield machine for five kinds with different strengths show that the cutter has a different cutting force and rock fragmentation efficiency under the same operating parameters (cutter penetration rate). When shield tunneling machine is driving in mixed-ground, the construction risk can be reduced by tunneling control because the equipment has been determined. At present, the construction reports of mixed-ground are mostly seen in urban subway tunnels, which is a typical composite stratum structure form of soft soil at the upper layer and rock at the lower layer. Therefore, relevant experience can be learned from other historical cases to provide a
basis for shield tunneling in mixed-ground.

(1) Selection of driving mode. TBM mode can be adopted when the formation at the tunnel face is relatively stable. When the soft rock at the tunnel face is relatively broken and the stability is poor, the earth pressure balance mode must be adopted. And the earth cabin pressure and the tunnel face balance should be maintained during driving.

(2) Tunneling parameter selection. In order to prevent the cutter-head vibration and frequent shock on the cutters, the driving speed should be appropriately reduced. The above analysis shows that the big cutter penetration rate has an adverse impact on the cutter-head plate stress state, or even make cutting load exceed the safety limit at the hard rock. Therefore, the driving speed can be adjusted according to the penetration rate evolution. To alleviate the instantaneous shock when cutting from the soft rock into hard rock, the thrust of the cylinder and the rotational speed of the cutter-head should be reduced appropriately.

(3) Muck improvement technology. According to the muck improvement situation, mud, bentonite, and foam can be chosen to cool the cutter and improve the muck condition simultaneously. So that the much has good liquidity. Besides, a little water or no water is added depending on the muck situation. Under the action of the muck modifier, the effective torque acting on the face from the cutter-head can be increased. And the cutter wear under the continuous working condition can be reduced.

(4) Precautions for tunneling. The shield machine driver and the civil engineer should judge the geological situation in time according to the geological survey, and judge the hardness of the advance stratum according to the parameters such as the thrust of the oil cylinder, the driving speed, and the temperature of each system of the shield machine. Observe the color, shape, and temperature of the muck at all times to determine the properties of the muck. And determine the condition of the cutter according to the temperature. According to the above information, the correct tunneling parameters should be chosen in time to ensure that the equipment will not be damaged under normal load. For example, the speed of the cutter-head should be reduced, the thrust of the oil cylinder should be reduced, the torque variation of the cutter-head should be observed to prevent being stuck. When the driving speed is reduced and difficult to improve, torque change is reduced, muck temperature becomes high, indicating that the cutter-head and cutter wear is serious. The cutter should be checked in time and reasonable cutter change, to protect the cutter from damage.

(5) Attitude control of the TBM/ shield machine. When the TBM/ shield machine is driving in the upper soft and lower hard strata, it is necessary to prevent the TBM/shield machine from raising and deviating. The main treatment measures are: strengthening construction measurement, mastering the attitude of the shield machine, timely and effectively adjusting various tunneling parameters, especially the setting of earth chamber pressure and rational distribution of jack thrust. In order to prevent excessive head up of the shield machine, the thrust of the jack cylinders should be adjusted, the thrust of the jack at the top should be appropriately increased. Balance the uneven pressure of the upper and lower jacks of the shield machine due to the inhomogeneous soft-hard rock tunnel face. The attitude of the shield machine is easier to adjust by adopting TBM mode. In order to adapt to the attitude control of the shield machine, the turning annular segment is assembled at the right time. According to the measured value of the floating data of the segment, the synchronous grouting parameters are reasonably selected, and the control axis of the shield machine is adjusted. The vertical attitude can be controlled within ±30° to ±20 mm, and the horizontal attitude within ±20 mm is the best.

For shield machine tunneling steadily, cutter inspection and replacement should be conducted in time. Cutter inspection should be strengthened or even replaced, especially for the edge cutter wear, to ensure the excavation diameter and prevent the shield tunneling machine from running up at the same time. The machine position can be adjusted in the running down trend. When the shield machine posture deviates obviously, comprehensive rectification should be conducted, including adjusting the jack thrust at different districts and articulated cylinders, using copying knife, and shield tail wall targeted after grouting measures. The rectification process should be performed by adjusting the tunneling parameters along the line direction according to the geological conditions to adjust the driving direction. During shield tunneling, the difference between each ring is best within ± 5 mm to avoid segmental lining
misalignment and breakage.

5. Conclusion
Mixed-ground greatly influences rock fragmentation mechanism, rock fragmentation efficiency, and driving parameter selection of the TBM/ shield machine. In order to reveal the rock fragmentation mechanism of TBM/EPB dual-mode shield machine and perform efficient tunneling control on Shenzhen Metro Line 13 tunneling through mixed-ground, linear cutting rock tests with different rock strengths were carried out to analyze the normal cutting force and rock boreability index change rule.

For rocks with different strengths, there is a good power function relationship between normal cutting force and penetration rate. For each rock strength, the normal cutting force decelerates with the increase of cutter penetration rate.

The relationship between the boreability index and the cutter penetration rate of the rock masses satisfies the power function. The tunneling index all decreases with the increasing penetration rate, indicating that with the increasing cutter penetration rate, the increase of the normal force on the single cutter becomes smaller and smaller, and the cutting force increases with the increasing rock strength, the rock mass boreability also increases gradually.

According to the linear cutting tests in mixed-ground with different rock strengths, the driving mode selection, parameter adjustment, muck improvement, and tunneling attitude regulation were put forward, which has significant guidance for safe and efficient tunneling in Shenzhen Metro Line 13 and similar composite formation.

Acknowledgments
This work was financially supported by the China State Construction Engrg. Corp. Ltd. Fund Project (No. CSCEC-2019-Z-19), China Construction Civil Infrastructure Corp. Ltd. Fund Project (No. CSCIC-2020-KT-(04)), National Natural Science Foundation of China (Grant No. 52074258), and Open Project of State Key Laboratory of Shield Machine and Boring Technology (Grant No. E01Z440101). Their support is gratefully acknowledged.

References
[1] Roxborough FF and Phillips HR 1975 Rock excavation by disc cutter Int. J. Rock Mech. Min. Sci. Geomech Abstr 12(75):361-366.
[2] Bilgin Nuh 1977 Investigations into the mechanical cutting characteristics of some medium and high strength rocks. Newcastle University.
[3] Ozdemir L and Wang FD 1979 Mechanical tunnel boring prediction and machine design. Nasa Sti/recon Technical Report N80.
[4] Sanio HP 1985 Prediction of the performance of disc cutters in anisotropic rock Rock Mech. Min. Sci. Geomech. Abstr 22(3):153–161.
[5] Rostami J and Ozdemir L 1993 A new model for performance prediction of hard rock TBMs. In: Proceedings of Rapid Excavation and Tunneling Conference. USA, pp:794–809.
[6] 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. PhD Thesis. Colorado School of Mines, Colorado, USA.
[7] Tumac D and Balec C 2015 Investigations into the cutting characteristics of CCS type disc cutters and the comparison between experimental, theoretical and empirical force estimations. Tunn Undergr Space Technol 45: 84–98.
[8] Liu H Y, Kou S Q, Lindqvist P, and Tang C A 2002 Numerical simulation of the rock fragmentation process induced by indenters Rock Mech. Min. Sci 39: 491–505.
[9] Zhang K. Study on rock breaking and cutter vibration characteristics under the action of disc-cutter of shield machine. Master’s thesis, Changsha: Central South University, 2010.
[10] Cho JW, Jeon S, Yu SH, and Chang SH 2010 Optimum spacing of TBM disc cutters: A numerical simulation using the three–dimensional dynamic dynamic fracturing method Tunn. Undergr. Space
Technol. 25(3):230–244.

[11] Ma H S, Yin L J, and Ji H G 2011 Numerical study of the effect of confining stress on rock fragmentation by tbm cutters Rock Mech. Min. Sci. 48(6): 1021-1033.

[12] Ouyang T. Cutting characteristics of the typical cutters combination of shield machine. Master’s thesis, Changsha: Central South University, 2011.

[13] Geng Q, Wei Z Y, and Ren J H 2017 New rock material definition strategy for FEM simulation of the rock cutting process by TBM disc cutters. Tunn. Undergr. Space Technol 65: 179-186.

[14] Gertsch R, Gertsch L, and Rostami J 2007 Disc cutting tests in Colorado Red Granite: Implications for TBM performance prediction Rock Mech. Min. Sci. 44(2):238-246.

[15] Balci C and Tumac D 2012 Investigation into the effects of different rocks on rock cuttability by a V–type disc cutter. Tunn. Undergr. Space Technol 30(4):183–193.

[16] Cho JW, Jeon S, Jeong HY , 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. Tunn. Undergr. Space Technol 35(4):37–54.

[17] Gong Q M, He G W, Zhao X B, Ma H S, Li X Z, Zhang H, and Miao C T 2015 Influence of different cutter spacings on rock fragmentation efficiency of Beishan granite by TBM. Chinese J. Geotech. Eng 37(1):54-60.

[18] Yin L J, Gong Q M, Ma H S, Zhao J and Zhao X B 2014 Use of indentation tests to study the influence of confining stress on rock fragmentation by a TBM cutter Rock. Mech. Min. Sci. 72(72):261-276.

[19] Gong Q M, Miao C T, Ma H S and Zhao X B 2015 Effect of joint spacing on rock breaking under disc cutter by linear cutting experiments. China Civil Eng. J. (6):97-105.

[20] Armaghani DJ, Mohamad ET, Narayanasamy MS, Narita N and Yagiz S 2017 Development of hybrid intelligent models for predicting TBM penetration rate in hard rock condition. Tunn. Undergr Space. Technol. 63:29-43.

[21] Hou ZS, Gong QM and Sun ZH 2011 Primary Failure Types and Their Failure Mechanisms of Deep Buried and Intact Marble at Jinping II Hydropower Station. Chinese J. Rock Mech. Eng. 30(4):727-732.

[22] Gong QM, Yin LJ, Wu SY, Zhao J and Ting Y 201 Rock burst and slabbing failure and its influence on TBM excavation at headrace tunnels in Jinping II Hydropower Station. Eng. Geol. 124:98-108.

[23] Fukui K, Okubo S 2006 Some attempts for estimating rock strength and rock mass classification from cutting force and investigation of optimum operation of tunnel boring machines. Rock Mech. Rock Eng 39(1):25-44.

[24] Farrokh E, Rostami J and Laughton C 2012 Study of various models for estimation of penetration rate of hard rock TBMs. Tunn. Undergr. Space Technol 30(4):110-123.

[25] Wu SY, Gong QM, Wang G, Hou ZS and She QR. Experimental Study of Slabbing Failure for Deepburied Marble at Jinping II Hydropower Station and Its Influences on TBM Excavation. Chinese J. Rock Mech. Eng. 29(6):1089-1095.

[26] Delisio A, Zhao J and Einstein HH 2013 Analysis and prediction of TBM performance in blocky rock conditions at the Lütschberg Base Tunnel. Tunn. Undergr. Space Technol. 33:131-142.

[27] Pan YC, Liu QS, Peng XX, Liu Q, Liu JP, Huang X, Cui XZ and Cai T 2019 Full-Scale Linear Cutting Tests to Propose Some Empirical Formulas for TBM Disc Cutter Performance Prediction. Rock Mech. Rock Eng. 52: 4763–4783

[28] Gertsch R, Gertsch L and Rostami J 2007 Disc cutting tests in Colorado Red Granite: implications for TBM performance prediction Rock Mech. Min. Sci. 44(2):238–246.