Experimental study on the optimal profile and spacing of a rolling cutter with spherical inserted-tooth

Y N Ma¹, Q M Gong¹, L J Yin¹, J D Li¹, M Z Li¹
¹ Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing 100124, China.
gongqiuming@bjut.edu.cn

Abstract: The rolling cutter with spherical inserted-tooth has been an effective tool for mechanical excavation. Significant research has been conducted on the optimization of the tooth shape parameters, tooth spacing, and row spacing of the alloy teeth on the cutter to improve the efficiency of mechanical tunneling and reduce the construction cost. In this study, three spherical teeth with different diameters were designed to perform indentation tests on Beishan granite under various penetration and spacing conditions. The rock fragmentation mechanisms of spherical teeth was analyzed through the fluorescence method, to optimally design the spherical inserted-tooth roller cutter. For Beishan granite, when the tooth spacing and row spacing were about 30 mm and 35 mm respectively, the spherical tooth with a radius of 16 mm gained the highest rock breaking efficiency. Research results provide a guidance for the design of the inserted-tooth roller cutter and the force estimation of cutter head.

Keywords: rolling cutter with spherical inserted-tooth; fluorescence method; rock breaking efficiency

1 Introduction

Deep geological disposal is a highly recognized high-level radioactive waste disposal scheme in various countries [1]. The disposal pit requires high precision and small damage to the surrounding rock, feasible with mechanical excavation. The disposal site of high-level radioactive waste and fuel in China is located in Beishan, Gansu Province, where the rock has high strength and strong abrasiveness. Thus, it is extremely important to choose suitable cutters for the excavation equipment. The rolling cutter with inserted-tooth is important for mechanical excavation of the rock ranging from low strength siltstone to high strength iron flintstone [2]. Because of its unique structure, the rock breaking mechanism of the rolling cutter is different from that of the others. When it indentates into rock, the alloy teeth penetrate into the working face, and as the force and penetration depth gradually increase, the median, lateral, and circumferential crack and debris are produced. Next step is the interaction of adjacent alloy teeth with the rock. As the lateral cracks develop and intersect, rock fragments are formed between the alloy teeth [3]. The tooth profile, tooth spacing, and row spacing of the alloy teeth affect the propagation of lateral cracks, which plays an important role in the formation of rock chips, and affects the construction efficiency of the excavation equipment.

Vast research has been conducted to study the rock fracture mechanism and propagation mode of
cracks under cutters. The failure theory of cutter penetrating into the rock was first proposed by Hertz [4]. Lindqvist et al [5] studied the process of conical indenter penetrating into brittle rocks and found that the force exhibited a load-unload reciprocating change. Each loading and unloading cycle can be divided into six stages: the initial elastic loading stage, dense core stage, stable crack propagation stage, initial unloading stage, residual stress stage, and unloading completion stage. Cook et al [6] studied the process of flat-blade indenter penetrating into granite and found that fracture pits were produced when the indenter penetrated into the rock, including elastic deformation before rock fragmentation, the initiation, propagation and coalescence of cracks, and the formation of fracture pits. Alehossein [7] used contact mechanics to study the development of elastic-plastic interface area in the indentation tests, and proposed the cavity-expansion model (CEM). Chiaia [8] applied fracture mechanics to analyze the conditions and scope of cracks in the rock, and through laboratory tests, the failure process of the rock under cutter was divided into four stages: the establishment of a stress field, formation of a crushing zone, propagation and penetration of cracks, and formation of rock fragments. Yin et al [9] used acoustic emission technology to monitor the failure process of rock under the indenter in real time. It was found that microcracks gathered and formed a conical fracture zone as the indenter penetrated into the rock. Pang et al [10], Kou et al [11] and others have observed the fracture characteristics of rock by scanning electron microscope (SEM). Three damage zones of rock were identified: rock powder area, fragmentation zone, and microcrack area. Zhao et al [12] studied the crack mode of Beishan granite under single and multiple linear penetrations by a single cutter via the fluorescence crack visualization method, and divided the rock damage area into re-compacted, crushed and cracked, and intact rock zones.

Several advanced numerical calculation methods have been used to study the rock breaking mechanism of cutters. Liu et al [13] studied the propagation mode of cracks by Rock–Tool interaction (R-T2D) program rewritten based on rock failure process analysis (RFPA). The results proved that the numerical simulation method would contribute to an improved knowledge of the rock fragmentation process in indentation. Gong et al [14-16] used Universal Distinct Element Code (UDEC) to study the effect of joint spacing, joint angle, and cutter spacing on the rock breaking mechanism of cutter, and these results were consistent with laboratory and field tests. Moon et al [17] used 2D Particle Flow Code (PFC2D) to simulate rock breaking with different cutter spacings, and obtained the relationship between the ratio of cutter spacing to penetration and the specific energy. Li et al [18] used the indentation tests and PFC to study the damage evolution mechanism of the wedge-shaped indenters with different angles. The failure mechanism of rock under wedge-shaped indenters was mainly tensile failure, supplemented by shear failure. However, there are still some limitations in the simulation of rock breaking process, for example, the size of mineral particles used in the model is quite different from that in rock.

The tooth shape parameters, layout, and the distribution characteristics of cracks under the rolling cutter with spherical inserted-teeth were studied from the existing research. In this study, the spherical teeth with different diameters were designed and manufactured, and the indentation tests with different penetration depths, tooth spacings, and row spacings were conducted for Beishan granite. Moreover, the evolution characteristics of cracks under spherical teeth were analyzed by using the fluorescence crack visualization method, and then the design parameters of the rolling cutter with spherical inserted-teeth were comprehensively determined. Research results provide a guidance for the design of the inserted-tooth roller cutter and optimization of construction parameters.
2 Indentation test design

2.1 Test equipment

These indentation tests were performed using the YDL-1000 electro-hydraulic servo universal testing machine with the maximum axial force of 1000 kN. To study the process of alloy teeth penetrating into rock, self-designed indenters and rigid bearing platform were adopted. The loading test platform and self-designed indenters are shown in Figure 1.

![Figure 1 Indentation test platform (a) Loading test platform (after loading) (b) indenter](image)

2.2 Rock sample

Beishan granite was used in the test as the rock sample with the size of 300 mm × 300 mm × 200 mm with the dimension error of ±2 mm and the surface undulation < 0.2 mm. Before testing, physical and mechanical properties of the granite samples were evaluated via corresponding tests conducted as per the ISRM specifications, as shown in Table 1.

| Density (g/cm³) | Elastic modulus (GPa) | Poisson's ratio | Uniaxial compressive strength (MPa) | BTS (MPa) | P-wave velocity (m/s) |
|----------------|-----------------------|----------------|------------------------------------|-----------|----------------------|
| 2.615          | 23.01                 | 0.188          | 105.6                              | 6.4       | 3345.72              |

2.3 Test design

The rolling cutter with spherical inserted-tooth is commonly used to excavate hard rock. To study the failure mechanism of spherical teeth penetrating into rock, the indentation tests were conducted on the three spherical teeth with diameters of 14, 16, and 18 mm. The spherical teeth are abbreviated as Q-r (Q represents spherical tooth, r represents the diameter of the tooth). The specific parameters of the alloy teeth are shown in Figure 2. The tests were divided into three stages:

- Experiments of selecting the alloy tooth: Each indentation test with the penetration of 1, 1.5, 2, 2.5, and 3 mm was conducted at least three times. After loading, the rock debris were collected and weighed, and the depth, width, and area of the pits were measured.
- Arrangement of the alloy teeth: Penetration tests with tooth spacing of 25, 30, and 35 mm and row spacing of 30, 35, and 40 mm under the penetration of 3 mm were conducted at least twice. After loading, the rock debris were collected and weighed, and the depth, width, and area of the
pits were measured.
- Crack analysis: Fluorescent crack visualization method was used to detect the cracks under the alloy teeth. The main experimental design parameters are shown in Table 2.

![Figure 2 Spherical teeth with different diameters](image)

**Table 2 Parameters of indentation tests**

| Alloys tooth | d/mm | Arrangement of alloy teeth | spacing/mm | d/mm |
|--------------|------|---------------------------|------------|------|
| Q-14         |      |                           |            |      |
| Q-16         |      |                           |            |      |
| Q-18         |      |                           |            |      |
| Q-16         |      | Tooth spacing              | (25, 30, 35) |      |
|              |      | Row spacing                | (30, 35, 40) |      |
|              |      | Fluorescent crack          | visualization method |      |

2.4 Experimental procedures
- The rock sample was placed on the test platform, reaction plates were installed on both sides of rock, four screws were added and the nuts were tightened to fix the rock sample to prevent shaking and slipping during the test.
- The position of the indentation points was set, ensuring no interaction among the preset points in each group and other groups.
- The loading equipment was started; loading mode of the alloy tooth was set to axial displacement control with loading rate 0.002 mm/s. During the loading process, the data acquisition system recorded force and displacement in real time.
- After the completion of the test, the rock samples were cut perpendicular to the pits, and the fluorescent crack visualization method was used to obtain the crack propagation characteristics of the rock under the corresponding spherical tooth.

3 Analysis of indentation test phenomena and crack characteristics

3.1 Test process of indentation tests with single tooth

Variation in the force-penetration depth when spherical teeth with different diameters penetrate into the rock at a depth of 3 mm are shown in Figure 3. Evidently, the force did not increase evenly with the increase in the penetration depth, showing a leap-forward rock breaking law. This resulted from an instantaneous gap under the spherical tooth due to the tension of microcracks and the formation of rock chips. Thus, the force of spherical tooth dropped instantaneously.
When the load reached to the peak force, the rock made a violent sound, and some uplifted fragments were found around the spherical tooth. During continuous loading, the influence of dense core and existing cracks [19] resulted in the penetration force, range and sound during failure to increase gradually. When Q-14, Q-16 and Q-18 penetrated into the rock at a depth of 3 mm, the maximum forces required were 124.11, 135.76, and 168.98 kN, respectively. The larger spherical tooth needed more penetration force for the same penetration depth, demanding higher performance from the propulsion system of the equipment. The penetration depths of Q-14, Q-16, and Q-18 under the second peak force were 2.57, 2.68, and 2.51 mm, respectively. It was inferred that although the penetration forces of Q-14 and Q-16 were nearly the same, Q-16 had larger rock breaking volume and higher rock breaking efficiency.

Spherical teeth with different diameters penetrating into the rock at different depths yielded different rock failures. For example, when Q-16 penetrated into the rock at different depths, the volume of rock fragmentation kept increasing as the penetration depth increased, which can be verified by Figure 4(a-e). Penetration depth was 1, 1.5, and 2 mm yielded mainly rock powder without rock fragments, while the penetration of 2.5 mm resulted in more rock powder and small rock fragments. Moreover, 3 mm penetration depth resulted in large and flat fragments. The specific depth and width of the pits, and the size of the rock fragments are shown in Table 3.
Figure 4 Pits and rock chips formed after Q-16 indentated into rock with different depths of (a) 1 mm, (b) 1.5 mm, (c) 2 mm, (d) 2.5 mm, (e) 3 mm.

As evident from Table 3, the profile of the alloy tooth has a great influence on the rock breaking effect. As the penetration depth increased, the proportion of rock fragments gradually increased. When the penetration depth was 3 mm, the proportions of rock fragments produced by Q-14, Q-16, and Q-18 were 53.05%, 81.48%, and 76.32%, respectively. Q-16 produced the highest proportion of rock fragments, which were thin with the length of almost 35.87 mm. Moreover, Q-16 showed the highest rock breaking efficiency, evident from the rock chip formation.

3.2 Crack characteristics of indentation tests with a single tooth

The original crack characteristic images under different spherical teeth were obtained by using fluorescence crack visualization method, as shown in Figures 5-a, 5-c, and 5-e. By using PCAS image processing system, the crack images were processed via binarization, impurity removal and skeletonization [20]. The processed image still retained the crack length and distribution characteristics. Combined with the length of the scale reference object in the previous stage for registration, the processed fracture images were divided into various 3 mm×3 mm grids, and the crack length was measured by the image J software, as shown in Figures 5-b, 5-d, and 5-f.

Variable diameters of spherical teeth affected the initiation and propagation of cracks, and further affected the efficiency of rock breaking, as exhibited by rock damage (Figure 5). Both radial and lateral cracks were obtained for small diameter but the increase in diameter resulted in prominent lateral cracks, propagating to the free surface of the rock. The width of the lateral cracks produced by Q-16 was 49.2 mm, which was 35% larger than that produced by Q-14. Intersection of lateral cracks produced by adjacent alloy teeth finally generates rock fragments. When the diameter was further increased, the propagation of lateral cracks was restrained, resulting in radial cracks developed toward the depth of the rock. To control the the damage to the surrounding rock, the diameter of spherical tooth should not exceed 18 mm for disposal projects.
3.3 Test phenomena of Q-16 under different tooth spacings

The spherical tooth Q-16 successively penetrated into two preset points with certain intervals at a depth of 3 mm. The size of the pits, rock chips, specific energy and crack propagation formed after Q-16 penetrated into the rock at the tooth spacing of 25, 30, and 35 mm are shown in Figure 6, and 7, as well as Table 4. With 30 mm of tooth spacing, the lateral cracks between the two spherical teeth penetrated each other, synergistically forming several cracks parallel to the free surface and more flat rock chips between the two teeth. The length of the longest rock fragments reached 24 mm. However, when the tooth spacing was too small, most of the rock breaking energy was consumed in the re-compacted zone, resulting in more rock powder and granular rock debris. Similarly, when the tooth spacing was too large, the cracks caused by alloy tooth were difficult to extend to the 1/2 of tooth spacing, resulting in "convex lens"-shaped rock debris between the teeth. The fractured rock could not be completely separated from the parent rock. Therefore, the interaction between adjacent alloy teeth could not work at full capacity. In summary, the spherical tooth Q-16 had the highest rock breaking efficiency when the tooth spacing was 30 mm.
3.4 Test phenomena of Q-16 under different row spacings

The spherical tooth Q-16 penetrated into two points with the tooth spacing of 30 mm at a penetration depth of 3 mm, and then penetrated into the third point with the same penetration depth, which was 30, 35, and 40 mm away from the midpoint of the line between the two preset penetration points. The pits, specific energy and rock chips formed after the spherical tooth Q-16 penetrated into the aforementioned rock, are shown in Figure 8 and Table 5.

When the row spacing was 35 mm, the lateral cracks between the two rows interconnected, forming more flat rock fragments, with the proportion of 77.93%. However, for 30 mm row spacing, the rock between the row teeth was excessively broken due to insufficient spacing, resulting in more rock powder and fragment proportion of 28.48%, not conducive to efficient rock breaking. Similarly, when the row spacing was 40 mm, the cracks formed in between could not be fully extended and interconnected due to large spacing. In summary, the spherical tooth Q-16 had the highest rock breaking efficiency when the row spacing was 35 mm.

![Figure 7](image_url)
4 Test data processing and analysis

During the indentation tests of the single tooth, the penetration depth was used as the control parameter. When the preset depth was reached, the test had to be stopped to obtain the relationship between force and penetration depth, and the rock fragments were collected and weighed. Table 3 shows the index values effecting the rock breaking efficiency. 

Energy consumption of rock breaking is an important index to evaluate the rock breaking effect, and specific energy is the energy required to break a unit volume of rock. The specific energy formula is as follows:

$$SE = \frac{W}{V} = \frac{\int_0^d F(p)dp}{V}$$

where: SE is the specific energy of rock breaking, KJ/cm³; W is the work done during rock breaking, KJ; V is the volume of debris, cm³.

| Spherical tooth | d (mm) | average force (kN) | pits width/depth (mm) | longest debris length/thickness (mm) | proportion of debris (%) | quality of debris (g) | SE (KJ·cm⁻³) |
|-----------------|--------|--------------------|-----------------------|-------------------------------------|--------------------------|----------------------|--------------|
| Q-14            | 1      | 14.21              | 20.22/2.32            | 9/0                                 | 0                        | 0.0486               | 0.7609       |
|                 | 1.5    | 24.16              | 21.21/3.13            | 0/0                                 | 0                        | 0.1135               | 0.8301       |
|                 | 2      | 25.69              | 33.31/3.36            | 13.88/3.07                          | 36.31                    | 0.2663               | 0.5017       |
|                 | 2.5    | 38.67              | 65.54/3.67            | 18.56/5.27                          | 53.05                    | 0.6265               | 0.4012       |
|                 | 3      | 40.36              | 46.43/5.32            | 18.56/5.27                          | 53.05                    | 0.9075               | 0.3469       |
| Q-16            | 1      | 26.08              | 18.43/2.41            | 0/0                                 | 0                        | 0.0734               | 0.9236       |
|                 | 1.5    | 32.69              | 26.76/3.21            | 16.34/1.73                          | 22.86                    | 0.1568               | 0.8129       |
|                 | 2      | 38.26              | 35.25/3.54            | 16.53/2.34                          | 28.05                    | 0.4547               | 0.4375       |
|                 | 2.5    | 47.29              | 32.56/3.87            | 12.67/2.84                          | 70.68                    | 0.8775               | 0.3503       |
|                 | 3      | 50.03              | 34.78/6.31            | 35.87/5.89                          | 81.48                    | 1.4268               | 0.2735       |
| Q-18            | 1      | 32.46              | 11.67/2.45            | 0/0                                 | 0                        | 0.1004               | 0.8405       |
|                 | 1.5    | 38.78              | 25.89/3.32            | 13.42/1.76                          | 26.74                    | 0.2034               | 0.7436       |
|                 | 2      | 40.65              | 34.75/3.87            | 15.51/2.73                          | 50.16                    | 0.4377               | 0.4829       |
|                 | 2.5    | 50.36              | 33.21/4.33            | 10.78/2.73                          | 55.79                    | 0.8809               | 0.3716       |
|                 | 3      | 56.78              | 34.78/6.31            | 22.84/5.73                          | 76.32                    | 1.4384               | 0.3079       |

Table 4 Indentation test data under different tooth spacings
Spherical tooth row spacing (mm) average force-tooth1 (kN) average force-tooth2 (kN) quality of debris (g) volume of debris (cm$^3$) SE (KJ/cm$^3$)

Q-16

25 50.32 43.49 4.8975 1.8837 0.1494

30 49.68 40.31 6.0499 2.3269 0.1160

35 50.15 46.72 2.4758 0.9522 0.3052

Table 5 Indentation test data under different row spacings

4.1 Influence of indentation force on rock breaking effect

The average indentation and peak forces of spherical teeth with different diameters are shown in Figure 9. The average indentation forces, $F_{t1}$ and $F_{t2}$ of Q-14 and Q-18 were 40.36, 84.88, and 124.11 kN; 56.78, 114.92, and 168.98 kN respectively. It can be seen that the spherical tooth with larger diameter needed the equipment to provide more thrust force to cut rock. The proportion of rock debris under $F_{t2}$ was larger as evident from rock chip analysis. Comparing with the size of rock fragments produced by three spherical teeth, shown in Table 3, Q-16 produced larger fragments under smaller $F_{t2}$, with higher rock breaking efficiency.

![Figure 9 Average indentation and peak forces of spherical teeth with different diameters](image)

The relationship between the average indentation force and penetration depth was closely related to the volume and efficiency of the rock breaking of the cutters. From Figure 10, it can be seen that the force tended to increase with the increase in the penetration depth regardless of the size of spherical tooth, but the increasing amplitude differed slightly with the size change.

During Q-16 penetration into the rock, the penetration depth increased in a certain proportion with the increase of the indentation force. On reaching a critical value, the indentation force began to decrease. That is, during the excavating process, the excavating rate was sensitive to the change in thrust. Furthermore, during Q-16 penetration, the curve of indentation force and depth had an obvious
inflection point, which was beneficial to control the operation parameters. However, for Q-14, as the penetration increased, the growth rate of the average indentation force fluctuated greatly, affecting the stability of the cutterhead during excavation. For Q-18, the indentation force was always the largest, and when the penetration depth was 3 mm, its average force still increased rapidly. In summary, when the average indentation force of Q-16 reached a critical value, increasing a little thrust force enhanced the excavation rate greatly, as reflected by the relationship between average indentation force and penetration depth.

![Figure 10](image)

**Figure 10** Rationship between the average indentation force and penetration depth

4.2 Analysis of rock breaking efficiency

For mechanical rock breaking, under the same rock conditions and operation parameters, minimizing the energy consumption of rock breaking can significantly reducing construction cost. As evident from Figure 11, as the penetration depth increased, the specific energy gradually decreased. The specific energy of all spherical teeth was the lowest when the penetration depth was about 3 mm, which was consistent with the fact that more rock fragments were produced under this penetration depth. A lower specific energy value may have appeared around the penetration depth of more than 3 mm. Due to the condition limitation, the tests with greater penetration depth could not be performed, thus, they were reserved for verification after the conditions were met.

![Figure 11](image)

**Figure 11** The trend of the specific energy of rock breaking with the penetration depth under each spherical tooth

The specific energy changed the same way for tooth spacing and row spacing, that is, as the spacing increased, the specific energy decreased gradually until the critical spacing was reached. The rock breaking efficiency increased gradually during the process. As shown in Figure 12, the critical values of tooth spacing and row spacing were 30 mm and 35 mm, respectively. The specific energy
value corresponding to the critical spacing was the lowest, while the rock-breaking efficiency was the highest. When the spacing was larger than the critical spacing, the specific energy increased again and the rock breaking efficiency decreased. It was consistent with the analysis of rock chips and crack propagation mode of Q-16 under different spacings.

![Figure 12 Relationship between SE and spacings](image)

5 Conclusion

Based on the indentation tests of different diameter spherical teeth penetrating into Beishan granite, the indentation force, rock breaking efficiency, and crack characteristics of the rock were studied for different penetration depths and tooth spacings. The main conclusions are as follows:

When the spherical teeth with different diameters penetrated into the rock, the force did not increase with the increase of the penetration depth, and they all showed a leap-forward rock breaking law. For the same penetration depth, the average forces of the spherical teeth with different diameters were different, and the rock breaking efficiency also varied greatly.

The crack propagation characteristics under different spherical teeth were displayed via fluorescence crack visualization method, and the crack propagation characteristics and scope of the damage zone under different spherical teeth were compared and analyzed. The lateral cracks of Q-16 were the largest and with the smallest depth, which was most conducive to the formation of rock chips.

For the geological disposal of high-level radioactive waste, the control requirements of surrounding rock damage were strict. The generation and propagation of cracks under cutters easily formed a potential nuclide migration channel. According to the requirement of this project, the maximum depth of cracks under the action of alloy teeth was used as the standard to judge the damage range of surrounding rock. In this study, the damage range of surrounding rock under spherical teeth with different diameters was less than 30 mm, which can provide guidance for the damage control of surrounding rock in the excavation construction of repository pits in Beishan.

References

[1] Baldwin T, Chapman N, Neall F. 2008: Geological disposal options for high-level waste and spent fuel. Report for the UK Nuclear Decommissioning Authority.
[2] Liu Z Q. 2017.Raise boring machine [M]. Beijing: Science Press. (in Chinese)
[3] Wu F, Yin L J, Zhang H, Gong Q M. 2018. Rock Fragmentation Mechanism and Efficiency Under Inserted-tooth Roller Cutter by Rotary Cutting Test [J]. China Journal of Highway and Transport. 31(10): pp.150-159. (in Chinese)
[4] Hertz H. 1881.Hertz's miscellaneous papers [M]. London: Macmillan.
[5] Lindqvist P-A. 1984. Stress fields and subsurface crack propagation of single and multiple rock indentation and disc cutting [J]. 17(2): 97-112.

[6] Cook N, Hood M, Tsai P. 1984. Observations of crack growth in hard rock loaded by indenter[J]. International Journal of Rock Mechanics and Mining Sciences Geomechanics, 21(2): 97-107.

[7] Alehossein H, Detournay E, Huang H. 2000. An analytical model for the indentation of rocks by blunt tools. Rock Mech Rock Eng,33(4). pp. 267-284.

[8] Chiaia B. 2001. Fracture mechanisms induced in a brittle material by a hard cutting indenter[J]. International Journal of Solids Structure. pp.7747-7768.

[9] Yin L J, GONG Q M, MA H S, et al. 2014.Use of Indentation Tests to Study the Influence of Confining Stress on Rock Fragmentation by a TBM Cutter [J]. International Journal of Rock Mechanics and Mining Sciences. 51(2). pp .261-276.

[10] Pang S S, Gldsmith W. 1990. Investigation of crack formation during loading of brittle rock[J]. Rock Mechnics and Rock Engineering. 23(1). pp .53-63.

[11] Kou S, Lindqvist P A, Tan X. 1997. Modelling of excavation depth and fractures in rock caused by tool indentation [M]. SKB.

[12] Zhao X B, Yao X H, Gong Q M, et al. 2015. Comparision Study on Rock Crack Pattern Under a Single Normal and Inclined Disc Cutter by Linear Cutting Experiments [J]. Tunnelling and Underground Space Technology. 50. pp.479-489.

[13] Liu H Y, Kou S Q, Lindqvist P A, Tang C A. 2002. Numerical simulation of the rock fragmentation process induced by indenters [J]. International Journal of Rock Mechanics and Mining Sciences, 39(4): 491-505.

[14] Gong Q M, Zhao J, Jiao Y Y. 2005. Numerical modeling of the effects of joint orientation on rock fragmentation by TBM cutters [J]. Tunnelling and Underground Space Technology, 20(2): 183-191.

[15] Gong Q M, Zhao J, Hefny A M J T. 2006a. Research U S T I T T. Numerical simulation of rock fragmentation process induced by two TBM cutters and cutter spacing optimization [J]. 21(3-4): 263-263.

[16] Gong Q M, Jiao Y Y, Zhao J. 2006b. Numerical modelling of the effects of joint spacing on rock fragmentation by TBM cutters [J]. Tunnelling and Underground Space Technology, 21(1): 46-55.

[17] Moon T, Oh J. 2012. A Study of Optimal Rock-Cutting Conditions for Hard Rock TBM Using the Discrete Element Method [J]. Rock Mechanics and Rock Engineering, 45(5): 837-849

[18] Li X F, Li H B, Liu Y Q, et al. 2016.Numerical simulation of rock fragmentation mechanisms subject to wedge penetration for TBMs [J]. Tunnelling and Underground Space Technology. pp.96–108.

[19] Innaurato N, Oggeri C, Oreste P P, et al. 2007.Experimental and Numerical Studies on Rock Breaking with TBM Tools under High Stress Confinement [J]. Rock Mechanics and Rock Engineering, 40(5):pp.429-451.

[20] Liu C, Wang B J, Shi B, et al. 2008. Analytic method of morphological parameters of cracks for rock and soil based on image processing and recognition[J]. Chinese Journal of Geotechnical Engineering, 30(9). pp . 1383–1388. (in Chinese)