Numerical Study on Free Face-Assisted Rock Fragmentation Induced by a TBM Disk Cutter

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Abstract. This paper presents a numerical study on the rock fragmentation process induced by a tunnel boring machine disk cutter under different free face conditions. A grain-based discrete element method is incorporated into the particle flow code to synthesize appropriate rock samples, considering macroscopic mechanical properties and fracturing mechanisms. The influences of free face structures (height $H$, spacing $S$, and direction) on rock breaking mode, normal force, and penetration specific energy are investigated via numerical simulations. Results show that the rock breaking force and $PSE$ of the side free face (STFF) model are significantly lower than those of the top free face (TFF) model. Based on the rock fragmentation analyses in rock breaking mode, four critical values were obtained, which can be used as the basis to design free face structures considering the rock breaking performance. The normal force significantly improves with free face spacing while the $PSE$ is primarily influenced by free face height and rock breaking mode. These findings may be useful to understand the rock breaking mechanism of a disk cutter under free face conditions and can be used as guidance for the design of free face structures.

Keywords: Rock Fragmentation, Free Face Condition, DEM Cluster.

1 Introduction

Several problems, such as low rock breaking efficiency, slow advancing speed, and high cutter consumption, can be encountered during excavation using tunnel boring machines (TBMs) excavate hard rock.

Free-face-assisted rock breaking methods have been extensively studied to improve the hard rock breaking performance of TBM disk cutters. To prepare free faces, researchers have employed representative techniques like high-pressure waterjet, undercutting TBM, and multi-stage cutterhead. Ciccu et al. [1] found that waterjet assisted mechanical rock breaking using disk cutters can reduce rock breaking forces and improve cutting efficiency. The China Railway Engineering Equipment Group CO., LTD. [2] developed a high-pressure waterjet assisted TBM
(diameter 3.8 m, water pressure 280 MPa) to excavate a headrace tunnel in Longyan, China. The company Wirth developed a series of undercutting method based continuous mining machines (CMM, 4.25 m in diameter) and tunnel boring extenders (TBE, 14.4 m in diameter), and applied them in mining projects [3]. Geng et al. [4] conducted a series of full-scale rock breaking tests on sandstone under different free face conditions, and proved the ability of free faces to improve rock breaking efficiency. The tests and simulations conducted by Xia et al. [5] and Xu et al. [6] on granite confirmed Geng’s findings, and provided valuable suggestions for the design of free face structures.

For better understanding of the rock breaking mechanisms under different free face structures, detailed rock breaking simulations are required. Based on the previous research on rock breaking simulation [7-16], the finite element method based approaches perform well in large-scale macroscopic 3D simulations while the discrete element method (DEM) based approaches are capable of researching mechanism that chip generation, crack evolution, and some other microscopic indicators. Verifying the of the 2D equivalent model [12,15-16], this study uses the DEM based software particle flow code (PFC) to construct 2D numerical models, analyzes rock fragmentation performances under different free face conditions and provides suggestions for the design of free face structures. Granite is synthesized using a grain-based discrete element method (GB-DEM) where the assembled polycrystalline clusters are breakable from both grain body and grain boundary. The numerical method used in this study can be used in the design of free face structures based on the findings and conclusions.

2 Setup of the Numerical Model using the GB-DEM Approach

2.1 Modeling with GB-DEM Approach

A GB-DEM approach implemented in PFC2D is applied in this study. The linear parallel bond model in PFC is the most widely used contact model for rocks. However, under uniaxial loading, the ratio of compressive strength to tensile strength of synthesized rocks is lower than that of the real rocks when spherical particles are directly connected through parallel bonds [17-18]. Such a discrepancy may be caused by the lack of interlocking friction along the irregular rock grain boundaries that are approximated as smooth surfaces in the spherical particle aggregates [12]. To overcome this problem, the spherical particles are grouped into polygonal grains and the microscopic properties of intragranular and intergranular contacts are assigned. The Voronoi diagram algorithm is used by incorporating the multi-parameter toolbox (MPT) 3.0, presented by M. Herceg et al. [19], into the MATLAB software for grouping the particles into grains to represent polycrystalline rocks. As depicted in Fig. 1, three steps are required to model a synthesized rock: implementing the GB-DEM approach. First, the rock domain is filled up with Voronoi polygons. Then, the grains are generated based on these polygons. Finally, the microscopic properties of the intragranular and intergranular contacts are calibrated and assigned, respectively.
2.2 Calibration of the GB-DEM Model

The detailed calibration process of the microscopic contact properties are as follows. First, a series of uniaxial compression strength (UCS) and Brazilian tension strength (BTS) tests are conducted on granite collected from Qin-ling Mountains, Shaanxi, China, according to the testing method suggested by the International Society of Rock Mechanics (ISRM), to obtain the macroscopic mechanical properties shown in Table 1. Then, groups of UCS and BTS tests are simulated using the rock synthesizing approach described before. The size of the rock model for the UCS tests is \(100 \times 50 \text{ mm}^2\), and the diameter of the rock model for the BTS tests is 50 mm. Setting the particle diameter as 0.5±0.1 mm and the porosity as 0.1 g cm\(^{-2}\), the rock models for the UCS and BTS tests are composed of 1732 and 613 grains, 5639 and 2237 particles, respectively. The distribution of the Voronoi polygons for the UCS and BTS samples are illustrated in Fig. 2a and Fig. 2f, respectively. Accordingly, the distribution of the grains for UCS and BTS samples are illustrated in Fig. 2b and Fig. 2g, respectively. To ensure that the PFC software does not collapse, only a few grains are represented with different colors. To ensure that the sample remains in quasi-static equilibrium throughout the UCS and BTS tests, the loading rate is set as 0.1 m/s and the step time is approximately \(5.5 \times 10^{-8} \text{ s}\) according to Cho et al. [18]. Using the microscopic properties depicted in Table 2, the synthesized granite sample presents very similar failure patterns and macroscopic mechanical behaviors to the collected granite specimen (see Table 1 and Fig. 2), indicating the reliability of the numerical method. The curves of axial stress versus strain during the UCS experiment and simulation are close to each other. The errors between the Young’s modulus, Poisson’s ratio, UCS, and BTS of the synthesized granite sample and the collected granite specimen are lower than 4%.

Table 1. Mechanical properties of the synthesized rock sample for simulation and the collected rock specimen for experiment.

| Rock     | Young’s modulus, E/GPa | Poisson’s ratio, \(\nu\) | UCS/MPa | BTS/MPa |
|----------|------------------------|--------------------------|---------|---------|
| Simulation | 40.1                   | 0.1697                   | 176.8   | 12.0    |
| Experiment | 38.6                   | 0.170                    | 177.9   | 12.3    |
| Error%    | 3.9                    | 0.2                      | 0.6     | 2.4     |
Fig. 2. Simulations and experiments for the calibration of microscopic properties: (a) distribution of the Voronoi polygons for the UCS sample; (b) distribution of the grains for the UCS sample; (c) simulation of the UCS test; (d) the physical UCS test; (e) the curves of axial stress versus strain during the UCS test; (f) distribution of the Voronoi polygons in the BTS sample; (g) distribution of grains in the BTS sample; (h) simulation of the BTS test; (i) the physical BTS test.

Table 2. Micro-properties of particles and bonds.

| Particle-based material parameters          | Values     | Bond-based material parameters          | Values     |
|--------------------------------------------|------------|------------------------------------------|------------|
| Ball density (kg/m³)                       | 2610       | Effective modulus (GPa)                  | 20         |
| Ball radius (mm)                           | 0.5±0.1    | Normal-to-shear stiffness ratio          | 1.2        |
| Porosity                                   | 0.1        | Intracrinal tensile strength (MPa)      | 90±9       |
| Effective modulus (GPa)                    | 20         | Intergranular tensile strength (MPa)     | 70±7       |
| Normal-to-shear stiffness ratio             | 1.2        | Intracrinal cohesion (MPa)               | 90±9       |
|                                           |            | Intergranular cohesion (MPa)             | 90±9       |
|                                           |            | Friction coefficient                     | 0.5        |
|                                           |            | Average grain size (mm²)                 | 3.2        |

2.3 Setup of the Numerical Model for Rock Fragmentation

The rock-indentation numerical model is illustrated in Fig. 3b. This model focuses on the rock breaking process of cutter 1 that is near the free face prepared in pilot excavation stage of a two-stage TBM cutterhead, as illustrated in Fig. 3a. With the dominant side-free face, the top rock surface is prepared flat without considering the pre-cutting process. Considering parameters of free face height (H, 100-400 mm) and spacing (S, 75-200 mm), 42 models are constructed. To minimize the boundary effect, the length
and width of the rock samples are both set as 500 mm. Each rock is tessellated by approximately 77,400 grains that are synthesized with ~282,000 spherical particles. The rock sample is modeled using the GB-DEM approach, presented in section 2.1, the calibrated microscopic parameters are listed in Table 2. The disk cutter is a commercial constant cross section cutter with a ring tip width of 20 mm. To reduce the simulation cost, the penetration speed is set as 0.2 m/s, which is much higher than the real condition. However, the vertical displacement rate can be translated to approximately $1.6 \times 10^{-8}$ m/step when the timestep $\Delta t$ is set as $8 \times 10^{-8}$ s making sure that the model remains in quasi-static equilibrium. The maximum penetration depth is set as 4 mm. The simulations were run on a PC of AMD 3975WX 32 CPU @ 3.5 GHz and 64.0 GB memory.

![Illustration of the rock-indention model in this study: (a) the two-stage cutterhead; (b) the rock-indentation model.](image)

3 Results and Analyses

3.1 Influence of the Free Face Direction

To compare the effect of free face direction, two simulations were conducted, as shown in Fig. 4. The model illustrated in Fig. 4a includes the side and top free faces, thus called the ‘STFF’ model, while the ‘TFF’ model in Fig. 4b only comprises a top free face. The cutter spacing of the ‘TFF’ model was set as 100 mm, and the free face height ($H$) and spacing ($S$) of the ‘STFF’ model were set as 250 and 100 mm, respectively.

The average peak normal force of the two cutters in the ‘TFF’ model is about $1.75 \times 10^7$ N/m, while the peak normal force of the ‘STFF’ model is about $1.19 \times 10^7$ N/m, indicating that the peak normal force is reduced by 32% in the side free face condition. The total chip areas of the ‘STFF’ and ‘TFF’ models are 11490 and 4090 mm$^2$, respectively, and the number of chips of the two models are 147 and 357, respectively, meaning that the average chip sizes of the two models are 78.2 and 10.9 mm$^2$. 
respectively. The areas of the largest chips of the ‘STFF’ and ‘TFF’ models are 10367 and 1305 mm$^2$, respectively, which accounts for 90.2% and 31.9% of the total chip areas, respectively. Therefore, more rocks are broken into fewer pieces with larger size in the side free face condition. The penetration specific energy ($PSE$), indicating the work consumed by the normal force to produce a unit area of rock fragment, is used to evaluate the rock breaking efficiency. The $PSE$ of the ‘STFF’ and ‘TFF’ models are calculated as 1.58 and 8.02 kN/mm$^2$, respectively, which means that the $PSE$ is reduced by 80.4% in the side free condition. It indicates that the rock breaking efficiency is greatly improved via the side free face because the rock is easily broken into large pieces, thus less energy is wasted in crushing it.

![Fig. 4](image)

**Fig. 4.** The rock breaking results of (a) the ‘STFF’ model; (b) the ‘TFF’ model.

### 3.2 Rock Breaking Modes Under Different Free Face Heights and Spacings

As shown in Fig. 5, the rock breaking modes are divided into three types: 1) “Mode 0” wherein the rock is not broken into large chips (model a and m); 2) “Mode 1” wherein the rock is broken and lateral cracks grow toward the bottom end of free face (model b, c, d, e, j, k, and l); 3) “Mode 2” wherein the rock is broken but lateral cracks do not propagate till the free face end (model f, g, h, and i). As shown in Figs. 5a-g, rock breaking changes from mode 0 to mode 1 and then to mode 2 as free face height increases from 100 mm to 400 mm. Two critical values (CH1 and CH2) of the free face height are derived to illustrate the variation in the rock breaking mode. The first critical value (CH1) is the minimum free face height required for the rock to be broken into large chips, estimated to be between 100 mm and 150 mm for the studied models. It means that the rock on the free face side cannot be broken if free face height is lower than CH1. The second critical value (CH2) is between 300 mm and 350 mm where rock breaking changes from mode 1 to mode 2. It means that the effect of the free face to assist rock breaking reaches the upper limit at CH2, and free face height need not be increased further. It suggests that the free face height should be set between CH1 and CH2 to properly exploit the effect of the free face to assist rock breaking. As shown in
Figs. 5h-m where free face spacing increases from 75 mm to 200 mm, decreases trend of the rock breaking mode with the increase trend of the critical values of free face spacing (CS1 and CS2) can be observed. The free face spacing is set larger than the first critical value (CS1), between 100 mm and 125 mm, and smaller than the second critical value (CS2), between 175 mm and 200 mm. As shown in Fig. 5n, the peak normal force decreases with an increase in the free face height but increases with free face spacing, which indicates that the rock breaking difficulty is in negative and positive correlation with the free face height and spacing, respectively. These results are in accordance with the analyses of the rock breaking modes in Figs. 5a-m.

3.3 Rock Breaking Angle and Chip Height Under Different Free Face Heights and Spacings

This study focuses on the rock breaking of the cutter that is nearest to the side free face. After the rock breaking completes, the ruptured surface becomes the new free face to assist the rock breaking by the neighboring cutter. The newly generated free face is inevitably tilted and hence, not as efficient as the initial side free face to assist rock breaking. To fully exploit the effect of free faces to assist rock breaking, the rock breaking angle (α), the angle between the ruptured surface of the cutter and the horizontal direction, is preferred to be near 90⁰. For the simulated models in modes 1 and 2, the rock breaking angle (α) generally increases with the free face height but...
decreases with an increase in the free face spacing (Fig. 6a). The general development trend is that the rock breaking angle increases as model position moves from the bottom corner to the top corner. It suggests that the optimal model position considering free face height and spacing should be close to the top corner of Fig. 6a.

Even though large rock chips basically mean large rock breaking angle and high rock breaking efficiency, they are prone to be stuck in mucking chutes, causing low muck passing and advancing rates of TBM cutterhead, and even results in severe secondary wear and tear of TBM cutters. As shown in Fig. 5, the chip width is approximately 10-20 mm smaller than the free face spacing. It means that the maximum width of rock chips is smaller than the width of TBM mucking chute (generally larger than 200 mm). As a result, only the chip height is measured and listed in Fig. 6b. It is found that chip height generally increases with free face height and spacing, leading to a trend that chip height increases as the model position moves from the left corner to the right corner of Fig. 6b.

![Fig. 6. Granite breaking angle (a), and chip height (b) under different free face heights (H) and spacings (S).]

### 3.4 Normal Forces and PSE Under Different Free Face Heights and Spacings

The normal rock breaking forces under different free face heights and spacings were analyzed (Fig. 7). The peak normal force significantly increases with free face spacing (S), and slightly decreases with free face height (H). The slope of the linearly increasing normal force curve increases with free face spacing (S) without any evident effect with respect to free face height (H). The PSEs of the “Mode 0” models are quite larger than the other models because the rock in the free face side is not broken into large chips, resulting in low rock breaking efficiency. For certain free face spacing (S), the PSE generally decreases with an increment in the free face height (H). For certain free face heights (H), the PSE of the “Mode 1” and “Mode 2” models do not have an evident effect with respect to S. Based on these results, the main factors influencing rock breaking efficiency are rock breaking mode and free face height.
Fig. 7. Normal rock breaking force versus penetration depth (a) and the penetration specific energy of the studied models under different free face conditions (b)

4 Conclusions

GB-DEM approach was effective in modeling rock materials. The rock breaking efficiency can be significantly improved if the penetration direction is parallel to the free face. Based on the three rock breaking modes, four critical values were obtained, which can be used as the basis to design free face structures considering the rock breaking performance. The peak value and increasing slope of normal force significantly improve with free face spacing. The PSE is mainly influenced by rock breaking mode and free face height.

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References

1. Ciccu, R., Grosso, B.: Improvement of Disc Cutter Performance by Water Jet Assistance. Rock Mechanics and Rock Engineering 47, 733–744 (2013).
2. Zhang, J.L., Li, Y.C., Zhang Y.S., et al.: Using a high-pressure water jet-assisted tunnel boring machine to break rock. Advances in Mechanical Engineering 12(10), 1–16 (2020).
3. Ramezanzadeh, A., Hood, M.: A state-of-the-art review of mechanical rock excavation technologies. Journal of Mining and Environment 1, 29–39 (2010).
4. Geng, Q., Wei, Z., Meng, H., et al.: Free-face-Assisted Rock Breaking Method Based on the Multi-stage Tunnel Boring Machine (TBM) Cutterhead. Rock Mechanics and Rock Engineering 49, 4459-4472 (2016).
5. Xia, Y., Guo, B., Cong, G., et al.: Numerical simulation of rock fragmentation induced by a single TBM disc cutter close to a side free surface. International Journal of Rock Mechanics and Mining Sciences 91, 40-48 (2017).
6. Xu, H.G., Geng, Q., Sun, Z.C., et al.: Full-scale granite cutting experiments using tunnel boring machine disc cutters at different free-face conditions. Tunnelling and Underground Space Technology 108, 1-12 (2021).
7. Liu, H., Kou, S., Lindqvist, P.: Numerical simulation of the rock fragmentation process induced by indenters. International Journal of Rock Mechanics and Mining Sciences 39, 491-505 (2002).
8. Ma, H., Yin, L., Ji, H.: Numerical study of the effect of confining stress on rock fragmentation by TBM cutters. International Journal of Rock Mechanics and Mining Sciences 48, 1021-1033 (2011).
9. Cho, J.W., Jeon, S.: Optimum spacing of TBM disc cutters: A numerical simulation using the three-dimensional dynamic fracturing method. Tunnelling and Underground Space Technology 25, 230-244 (2010).
10. Moon, T., Oh, J.: A study of optimal rock-cutting conditions for hard rock TBM using the discrete element method. Rock Mechanics and Rock Engineering 45, 837-849 (2012).
11. Labra, C., Rojek, J., Oñate, E.: Discrete/Finite Element Modelling of Rock Cutting with a TBM Disc Cutter. Rock Mechanics and Rock Engineering (2016).
12. Li, X.F., Li, H.B., Liu, Y.Q., et al.: Numerical simulation of rock fragmentation mechanisms subject to wedge penetration for TBMs. Tunnelling and Underground Space Technology 53, 96-108 (2016).
13. Han, M., Cai, Z., Qu, C., et al.: Tunneling Simulation and Strength Analysis of Cutterhead System of TBM, in 8th International Conference, ICIRA 2015. Springer, Portsmouth, pp. 445-455 (2015).
14. Han, M.D., Cai, Z.X., Qu, C.Y., et al.: Dynamic numerical simulation of cutterhead loads in TBM tunneling. Tunnelling and Underground Space Technology 70, 286-298 (2017).
15. Gong, Q.M., Zhao, J., Jiao, Y.Y.: Numerical modeling of the effects of joint orientation on rock fragmentation by TBM cutters. Tunnelling and Underground Space Technology 20, 183-191 (2005).
16. Innaurato O.C., Oreste PP, et al.: Experimental and Numerical Studies on Rock Breaking with TBM Tools under High Stress Confinement. Rock Mechanics and Rock Engineering 40, 429-451 (2007).
17. Potyondy, D.O.: A bonded-particle model for rock. International Journal of Rock Mechanics and Mining Sciences 41, 1329-1364 (2004).
18. Cho, N., Martin, C.D., Sego, D.C.: A clumped particle model for rock. International Journal of Rock Mechanics and Mining Sciences 44, 997-1010 (2007).
19. Herceg, M., Kvasnica, M., Jones, C.N., Morari, M.: Multi-Parametric Toolbox 3.0. In Proc. of the European Control Conference, pages 502–510, Zurich, Switzerland, July 17–19 2013.