Rock breaking mechanism during TBM tunnelling: insight from DEM simulations of rotary cutting tests

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Abstract. Tunnel boring machine (TBM) has been widely applied to various tunnel construction projects in hard rocks due to its high efficiency and safety. A number of theoretical or semi-empirical models have been proposed to predict TBM performance under different geological conditions. Cutter forces in these theoretical models are derived mainly based on idealized assumptions, related to the cutting pattern and rock breaking mechanism. However, there is no consensus on the rock breaking as well as the cutter-rock interaction mechanisms. In this study, DEM simulations of the rotary cutting tests are conducted using PFC3D. The cutter-rock contacting behaviour is monitored and the cracking events during the cutting process are recorded. The variation of cutting forces is found to be linked to both the occurrence rate and the total number of cracks. The spatial orientation of cracks is also examined, which seems to vary from horizontal-dominant to vertical-dominant with an overall isotropic pattern. Lastly, the distribution of contact forces between the disc cutter and the rock sample is analysed and its potential implication on the development of TBM performance model is discussed.

1. Introduction

Tunnel boring machine (TBM) has been widely applied to construct tunnels due to its high efficiency and safety for crews. The interaction between the TBM cutter head and the rock mass has been abundantly studied but yet still remained a major task for the geotechnical researchers due to its complexity. TBM performance prediction, including cutting force and the wear degree, requires a full comprehension of the specific interaction pattern over the cutter-rock interface. Thus, understanding the rock breaking mechanism and the stress distribution on the cutter-rock interface during the cutting process becomes crucial. The famous CSM model proposed by Rostami et al. [1] is widely adopted in real construction projects for cutter performance prediction due to its satisfactory accuracy. Two rock breaking stages were incorporated in the CSM model: the generation of the crushing zone due to the compression of the disc cutter and the propagation of the major cracks propagated from the crushing zone to the surface. The limitation of CSM model is obvious as it fails to consider the asymmetry during the real cutting process because it is based on a wide range of data obtained from linear cutting test, which indicates asymmetry condition for both sides of the disc cutter. However, the specific breaking mechanism inducing the side force is rather complicated and has not yet well understood. Tosaburo [2] proposed...
two possible breaking mechanisms for the lateral rocks for the further calculation of the side force: the crushing and shearing failure theories. The latter one is adopted by Ouyang [3] to propose a simplified shear slope based on the assumption introduced by Evans et al. [4]. Relationships between the obvious drops on the loading curve and the propagation of the cracks were often studied based on the cutting tests (Entacher et al [5]; Huo et al. [6]; Jeong et al. [7]). However, the cutting tests also cannot provide insights of the specific breaking mechanism within the rock mass. Numerical simulations have also been conducted to investigate the rock breaking characteristics. In particular, the discrete element method which well represents the granular nature of rock mass is a useful tool for modelling the disc cutter induced rock breakage process. A dynamic development of stress and fractures was observed and compared by Liu et al. [8] using PFC2D in order to show the relationships between the generation of the major cracks and the abrupt stress release. The developing pattern of cracks were also analysed by Zhang et al. [9] but under different conditions of confining pressure and loading sequence. Different interaction modes were observed by Fang et al. [10] during cutting process under different penetration depths using 3D DEM. A distribution of fractures generated during cutting was presented by Xue et al. [11], who claimed the tensile fractures to be the dominant form of rock breaking.

The stress distribution on the cutter is important for predicting cutter forces. It also helps for the understanding of cutter-rock interaction mode. The commonly accepted distribution of cutter stress between uniform and linear was argued by Rostami [12] for not satisfying the boundary conditions at both ends of the contact area. By conducting a series of cutting tests with strain gauges installed at the cutter edge, Rostami proposed a general pattern of the stress distribution without giving a specific formula. Similar results were found by Shi et al. [13] using same methods. The stress peak was found by Labra et al. [14] to be located near the middle of the contact angle, corresponding with the action point of the resultant force assumed by CSM model.

This paper provides an insight of a fracture distribution pattern of inclination and density in different directions by conducting rotary cutting simulations using PFC3D. The cutter-rock interaction mechanism was explored. The stress distribution on the interface of cutter and rock was analysed and fit using Weibull [15] and Hertz distributions. The fitting results were presented and compared with other commonly adopted distributions.

2. Simulation of rotary cutting tests

Figure 1 shows the numerical model of the rotary cutting simulation conducted on PFC3D. The rock sample is 1.0 m in diameter, with a height of 0.4 m. The cutter with a width of 25 mm is adopted. The cutter spins around the central axis of the rock sample after penetrated to the prescribed depth. The linear parallel bond contact model (PB model) is chosen for simulating the cementing effect between the rock matrix grains. PB model provides initial tensile and shear strengths for each contact between two particles. A ‘bond-break’ event is recorded once any of these two strength limits is reached. Then, the PB model is directly transferred to a normal linear model (if two particles still contact) without any tensile strength. Due to this similarity with the common rock medium, PB model is widely used in the simulation of rocks.

Parametric studies have shown that the penetration depth and cutting radius are the key influential factors for the cutting behaviour (Gertsch et al. [16], Pan et al. [17], Ren et al. [18]). While all the three cutting forces increase with increasing penetration depth, different cutting radii mainly cause bigger variation of the side force compared to the other two force components. Due to the limiting space, only the simulation results with a penetration depth of 12 mm and a cutting radius of 350 mm are presented herein. The disc cutter is set to rotate only around the central axis of the rock sample but does not rotate around its own axis. The rotation speed is set to be 5 revolutions per second in order to maintain an acceptable simulation time. The target rock type is a mudstone. The input parameters have been calibrated by Jia [19] against the laboratory triaxial testing data as shown in Figure 2. The contact properties of the rock sample are listed in Table 1. A uniform particle gradation between 2.5 mm and 4.25 mm is adopted. The total number of particles comprising the rock sample is around 0.6 million.
Table 1 The value of micro parameters for the rock model in PFC3D

| Micro Parameters                     | Unit | Value |
|--------------------------------------|------|-------|
| Contact Modulus                      | MPa  | 60.70 |
| Ratio of Rigidity                    | -    | 1     |
| Parallel Bond Contact Modulus        | MPa  | 60.70 |
| Parallel Bond Ratio of Rigidity      | -    | 3.49  |
| Parallel Bond Tensile Strength       | MPa  | 0.68  |
| Parallel Bond Cohesion               | MPa  | 1.00  |
| Parallel Bond Friction Angle         | °    | 60    |
| Parallel Bond Friction Coefficient   | -    | 0.1   |

Figure 1 The rotary cutting simulation model established in PFC3D

Figure 2 Comparing the stress-strain curves obtained in numerical simulations and laboratory testing (‘t’ and ‘s’ denote laboratory test and numerical simulation, respectively.)

3. Analysis of the simulation results

Evolution curves of the cutting forces and the increment of bond-breakage number during the cutting process are provided in Figure 3. A period of 0.5 π from cutting angle of π to 1.5 π during the stable cutting stage was chosen for better illustration of the major curve characteristics. The cutting forces fluctuate during the cutting process. The normal force is large than the rolling force, while the side force is relatively small in comparison to the other two cutting force components. Apparent
correlations between the evolution of cutting forces and that of crack number increment can be observed as the peaks and troughs of these curves coincide. A reasonable assumption is taken to explain this phenomenon. Once the disc cutter contacts with the rock mass, the contact force rises quasi-linearly by a ratio related to the elastic modulus of the rock mass. The elastic modulus of rock mass within the impact region will degrade due to crack generation, so is the rock strength. When the cutting force is below the rock strength, the force curve shown in Figure 3 will only evolve nonlinearly with a degrading modulus. However, when the density of the fractures accumulates to a threshold value, the rock strength limit will be reached. Thereby, macro failure happens along a certain weak surface, causing abrupt drops of the average elastic modulus and rock strength, which further leads to abrupt drops in the cutting forces. This cycle of rising and sudden drop of cutting forces is repeated during the whole cutting process. Similar observations have also been reported by other researches. Detailed fracture distribution patterns were also provided and analysed in this part.

![Figure 3](image)

**Figure 3** Evolutions of cutting forces and increment of bond breakage number with respect to the cutting angle

### 3.1. Fracture distribution pattern

For better illustration, the curved cutting groove is stretched horizontally. The distributions of bond breakage event along the stretched grooves at different cutting instants are shown in Figure 4. This illustrates the dynamic developing pattern of the bond-breakage events at different locations. The cutting direction was marked in each sub-figure. The cracks are roughly symmetrically distributed with respect to the cutting groove center. However, a protrusion can be found in the front of the distribution along the cutting direction, indicating that cracking is initiated directly under the cutter and gradually propagates laterally. Similar observations have been reported by Xue et al. [11]. A wider distribution of cracks is identified on the upper side along the cutting direction, i.e., the outer side of the disc cutter away from the rock sample center. This may be because during rotary cutting outer-side rock needs to overcome the centripetal force compared with the inner-side rock.
The majority of bond breakage events are due to tensile failure. This might be because the mudstone is very soft with low tensile strength. Therefore, tensile failure is dominant. Apart from the mechanical origin of broken bonds, it is also important to know the main cracking direction. Here the bond-breakages are sorted into two categories according to their orientations: the horizontal bond-breakages of which inclination angles are smaller than 45° with respect to the horizontal plane, and vertical bond-breakages of which inclination angles are larger than 45° with respect to the horizontal plane. The distribution of the horizontal bond-breakage proportion in the vertical cross-section is shown in Figure 5. The space occupied by the disc cutter is marked as a white square to compare with the entire impact area of the cutter penetration. The distribution area of the bond breakage events can be approximated as a triangle with a rather flat bottom.

It should be notified that the bond breakage displayed in the figure is different from the concept of the major cracks, which is defined as assemblies of a large number of breaks distributed in the same direction. As shown in Figure 5, while a vertical crack is formed by linearly distributed horizontal broken bonds, a horizontal crack can be created by an accumulation of the vertical ones.

The layer located in the surface of the rock indicates that the fractures generated at the initial penetration stage were mostly horizontal. This is reasonable as the rock sample was mostly intact at the start of cutting. When the penetration depth is shallow, initial vertical cracks are generated due to the intrusion of disc cutter which breaks horizontal bonds between two parts of rock mass aside the cutter. Meanwhile, particles beneath the cutter also get compacted directly at this stage. As the disc cutter penetrates further, particles within a wider range get compacted and the horizontal bond-breakages propagate to the lateral areas.

After surpassing a critical penetration depth, the intactness of the rock mass is fully disturbed as the cutting groove starts to form. Two bevels show up on the two sides of the disc cutter, providing initial free-face condition for the generation of the cracks. While the intrusion still persists at the bottom of the cutter, creating horizontal bond-breakages and resulting in particle compaction. It also drives the rock mass on the two sides of the cutter to get pushed aside. As there is rock mass not compacted or
cut off below the disc cutter at this moment, the contacts between them and the rock mass in the two sides are likely to break in a shear-like form. The cracks, in other words, the developing direction of the bond-breakages tends to be along the free-face which is the groove bevel in this situation. Two forms of rock breaking mechanisms exist simultaneously at this moment as the distribution of the break inclination is quite even. Below a certain depth where the rock mass is less disturbed, the bond-breakages are mainly generated by the stress induced by the cutter compression. Cracks fail to develop along a regular pattern but with a discrete and random distribution.

![Figure 5 Vertical distribution contour of the proportion of horizontal bond-breakages](image)

The distribution of proportion of horizontal bond-breakages along the depth was provided in Figure 6, along with the specific distribution pattern of the fracture inclination at two extreme points for comparison. The analysis above can be divided into three stages:

1. **Initial penetration stage**
   The rock sample is rather intact as merely the contact bonds located at the very surface of the rock mass get cut off, while particles directly under the disc cutter get compressed.

2. **Penetration persisting stage**
   The rock mass on the side of the cutter gets pushed further aside, leading to the generation of a shear-like failure surface under a certain depth. While the break form within the initial stage still persists contemporarily as the disc cutter is still intruding, multiple failure modes co-exist at the same time, making the average proportion of the horizontal bond-breakages remains stable at the value around 50%.

3. **Stress dissipation stage**
   After the disc cutter stops at its prescribed penetration depth, the cutting stress dissipates with the increasing depth. Fewer fractures are induced and the horizontal fractures gradually becomes dominant at this stage. This stage can be referred to as a quasi-static state which is same as the contact of the disc cutter and rock mass prior to penetration.
Figure 6 Distribution of the proportion of horizontal bond-breakages along the depth

Figure 7 shows the vertical cross-sectional distribution of the bond-breakage density. The white square is marked to indicate the space occupied by the cutter. An overall radial distribution is obtained as the density of the bond-breakages reduces along the depth as well as from the center outwards. The three stages could also be identified in accordance with the inclination distribution in the direction of depth as shown in Figure 8. But there is a slight difference in the ranges of different stages in comparison to Figure 6. Only a few bond-breakages were generated in the very surface of the rock, corresponding to the initial stage where there was not enough penetration depth for the side rock to fail in the shear-like form. With the increase of penetration depth, the density suddenly rises to a maximum level and remains stable within a certain range of depth. This may be because crushing and shearing failure happen simultaneously both under and aside the cutter. There are some differences in the depth of the boundaries of the two phases, which requires further analysis. The density of bond-breakages starts to reduce after surpassing a certain depth, which is similar to the inclination distribution curve.

Figure 7 Vertical distribution of bond-breakage density
3.2. Cutter-rock interaction stress distribution

The stress distribution on the cutter-rock contact interface not only reflects the specific interaction between the cutter and rock, but also determines the resultant force experienced by the disc cutter. Thus, an appropriate cutter stress distribution model is very crucial for any prediction models of cutting forces. Figure 9 shows the contour of interaction stress distribution. The stress distributions at 20 equally-spaced instants were averaged as a single sample was too discrete to show a general distribution pattern. An evident stress peak point was found to be located in the middle front of the interface, which does not agree with the common assumption of a distribution between uniform distribution and linear distribution. The stress variation on the tangential (the cutting direction) and radial (pointing to the rock center) directions were fit separately using the Weibull and Hertz distributions in Figure 10. The cross-section of the data used for Weibull distribution fitting is the symmetry plane of the disc cutter at radius of 0.35 m. The one for Hertz distribution is the plane perpendicular to the cutting direction right beneath the center of disc cutter. The fitting result of the stress distribution on the cutting direction is also compared with other distribution assumptions to show its validity.

![Figure 8](image1.png) Distribution of the average bond-breakages density along the depth

![Figure 9](image2.png) Stress distribution contour on the cutter-rock interface
The distribution in the original CSM model between a uniform and linear distribution obviously provides the worst fitting result as it fails to satisfied the boundary conditions which demands a zero value at both departure points of the interface. A normal distribution with the mean value fixed at the location corresponding to the middle of the contact angle is also proposed referring to the assumed action point of the resultant force within the CSM model. Although the data show some scatters, the middle of the contact angle is basically at the same place with the peak point of stress. However, the curve segment fails to provide a good fitting result for the data at the front departure point as the Weibull distribution does.

While the Hertz distribution provides an almost perfect fit for the radial stress distribution, the stress located in the middle of the interface still shows some discrepancies from the Hertzian model. This indicates that the real disc-rock interactional mechanism over the disc cutter center area is rather complicated and requires further investigation.

![Graph](image)

(a) Along the tangential direction  
(b) Along the radial direction

**Figure 10** The fitting results of contacting stress distributions along the tangential and radial directions

4. Conclusion

A rotary cutting simulation was conducted in this study via PFC3D, based on which the bond-breakage characteristics and average stress distributions acting on the cutter-rock interface were explored. The major findings include:

(a) The evolutions of cutting forces are coincident with the increments of bond-breakage number. The broken bonds initially appear under the middle of the cutter. The lateral breaks are then induced as cutting goes forward.

(b) Three breaking stages along the depth are observed from the inclination and density distributions of broken bonds: the initial penetration stage with merely crushing under the cutter, the penetration persisting stage with crushing under the cutter and shear-like failure occurring on the lateral direction, and the stress dissipation stage at which few fractures were generated under a quasi-static state.

(c) The peak value of the stress acting on the cutter is located at the middle front of the cutter-rock interface, which agrees with the assumption of the CSM model. Despite the slight discrepancies beneath the cutter, the Weibull and Hertz distributions provided a satisfactory fitting for the tangential and radial distributions of cutter-rock interaction stress, respectively.

5. References

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