DEM numerical investigation on the effect of back rake angle of PDC bit in drilling hard rock strata

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Abstract. Polycrystalline diamond compact (PDC) drill bits used in the Deep Borehole Placement (DBP) approach for nuclear waste disposal are subjected to highly competent, low-porosity, and low-permeability rock mass that cause severe wear and damage. To augment the penetration rate and minimize the wear-induced cost, a novel interaction rock cutting model with breakable granite and unbreakable cutter was established using two-dimensional discrete element method (2D-DEM). The particle element was used to simulate the granite sample, and the micro parameters of the contact elements between them were calibrated based on the uniaxial compression and Brazilian tests. While the rigid block element was used to reproduce the single PDC cutter including its elastic properties and geometric structure (i.e., back rake angle). The cutting process was simulated by applying normal force and tangential velocity on the single cutter to explore the effect of the back rake angle (5, 10, 15, 20 and 25°) on the stress condition of the cutter and penetration rate. The simulation results show that with the increase of the back rake angle, the maximum shear stress magnitude and stress concentration area decrease simultaneously, in accordance with the decrease of material removal rate, which do good help to decrease the wear and unexpected damage of bit cutter. In addition, the cutting process can be divided into the effective cutting stage when the elastic energy continuously stores and the fragmentation initiation stage when the stored energy suddenly releases and numerous cracks generate. In long term, the established DEM model can be used to optimize the structure of the PDC bit.

1. Introduction
The polycrystalline diamond compact (PDC) bits are commonly used in drilling boreholes in medium-hard and hard rock strata in the fields of oil, gas, coal and geological exploration because of their high penetration rate and long service life [1-4]. The boreholes left are ideal to dispose the nuclear waste due to its advantages in the robust isolation from the biosphere, low cost, high speed of implementation, and modularity. However, considering the average borehole depths are around 2 km, not meet the requirement for nuclear waste disposal [5], the drilling work should continue. With the increase of the depths, the in-situ stress also increases and causing higher hardness and strength. Thus, the PDC bit is usually susceptible to impact wear caused by shear stress, which easily results in premature failure.

To improve the capacity of the PDC bits, on the one hand, some scholars have conducted works in optimizing and improving the PDC cutters (e.g., design specialized diamond and carbide materials, improve sintering processes) [7]. These methods have posed positive effects on impact and abrasion resistance characteristics of the bits.
One the other hand, optimizing cutting structure can also improve the performance of the PDC bits. Researchers designed the crown shape, tooth distribution and density, and number of blades of the PDC bits for different strata to take advantage of its high penetration rate and minimized the deterioration [8]. For instance, in order to be more conducive to break high-hardness and abrasiveness formation and prolong PDC bit life, Wei et al. (2011) designed the crown shape of bits to be line-arc-three paragraphs, and the blades were spiral multi-blade with high-density distribution [9]. Ohno et al. (2002) arranged several polished semi-circular shaped PDC cutters on the bits to reduce the impact damage [10]. Pei (2019) optimized the crown shape of the complex curved PDC bit to increase the average bit life and drilling efficiency [11]. Due to the fact that the aggressiveness and durability of the PDC bit are dependent on the back-rake angle [12], in some hard and high abrasiveness formations, cutters with larger back-rake angle are always applied to provide durability and reduce the impact damage of the cutters [12,13]. However, the mechanism behind this approach is still not clear, so is the accurate effect of the back-rack angle. Furthermore, it is important to investigate the stress condition and cutting effect of PDC slices with different back rake angles when drilling hard rock for further bit optimization.

Attribute to the high-reproduction of rock material, the discrete element method (DEM) attracts much focus in investigating the drilling process. Akbari et al. (2011) studied the effect of bottom hole pressure on the rock surface. The results show that penetration rate decreases proportional to the logarithm of bottom hole pressure [14]. Zhong et al. (2016) simulated the PDC bit drilling experiment with and without the pVARD technology. In that model, the axial amplitude and frequency were adjusted with different settings of spring compliance and dampening layers. The results indicate the pVARD technology could improve drilling performance [15].

In this study, the aim for it is to utilize a two-dimensional discrete numerical code (PFC2D), to simulate the cutting process of PDC cutter when facing hard rock and explore the effect of the back rake angle. The long-term aim is to use the established model to optimize the cutting structure of the PDC bit. This paper is organized as follows: In Section 2, the generation of rock sample was first introduced, and one new method to simulate the cutter was then proposed, and finally the simulation of the cutting process was conducted; The effect of the back rake angle on the cutting efficiency was revealed in Section 3; Finally, Section 4 summarizes the conclusions drawn from this study.

2. Numerical simulation
In this section, we conducted a cutting test simulation to compare the stress condition of cutting teeth with different back angles when facing one specific hard rock layer. Based on the PFC2D, the crack evolution behavior can also be monitored. Although PFC2D is only two-dimensional, it has been widely used to simulate many scientific problems related to the rock mechanics and rock engineering, including laboratory experiments on the failure mechanical behavior of rock material [16-18], crack initiation, propagation, and coalescence in rock specimens containing a circular hole [19], split Hopkinson pressure bar (SHPB) dynamic test problems [20], etc.

2.1. Rock sample establishment
To establish a suitable particle model of rock, it is vital to select one bonded-particle model. Granite is one of the widely-distributed and hard rock which is appropriate for nuclear waste disposal with low permeability. Thus, the flat-joint contact model (FJM), which can highly-mimic the mechanical behaviour of hard and brittle rock, was applied [21].

The details of the FJM can be found in the cited reference [22]. To simulate the mechanical behavior of granite sample, the ‘cluster’ technology and calibration were conducted as Zhou et al. (2020) suggested. The micro parameters after calibration were shown in Table 1.
Table 1 Micro-properties of balls and contacts [21]

|                     | Quartz | Feldspar | Biotite |
|---------------------|--------|----------|---------|
| **Volume composite, \( r_{\text{exc}} \) | 30.7%  | 50.6%    | 18.7%   |
| **Particle**        |        |          |         |
| Minimum ball radius, \( r_{\text{exc}} \) (mm) | 0.1    |          |         |
| Maximum/Minimum, \( r_{\text{exc}}/r_{\text{exc}} \) | 1.66   |          |         |
| Ball density (kg/m\(^3\)) | 2650   | 2600     | 2900    |
| **Intragranular Contacts** |        |          |         |
| Bonded element fraction, \( \phi_b \) | 1      |          |         |
| Slit element fraction, \( \phi_t \) | 0      |          |         |
| Total number of elements, \( N \) | 2      |          |         |
| Stiffness ratio      | 2.4    | 2.6      | 3.0     |
| Effective moduli (GPa) | 78    | 50       | 30      |
| Mean and standard deviation bond tensile strength, \( \sigma_\text{b} \) (Mpa) | 18±1.8 | 27.5±2.75 | 12.5±1.25 |
| Mean and standard deviation bond cohesion, \( c_\text{b} \) (Mpa) | 100±10 | 88±8.8   | 60±6    |
| Local friction angle, \( \phi_\text{b} \) (°) | 3      | 5        | 8       |
| Residual friction angle, \( \phi_\text{r} \) (°) | 7      | 10       | 13      |
| **Intergranular Contacts** |        |          |         |
| Stiffness ratio      | 3.1    |          |         |
| Effective moduli (GPa) | 23    |          |         |
| Mean and standard deviation bond tensile strength, \( \sigma_\text{c} \) (Mpa) | 9.5±0.95 |          |         |
| Mean and standard deviation bond cohesion, \( c_\text{c} \) (Mpa) | 40±4   |          |         |
| Local friction angle, \( \phi_\text{c} \) (°) | 10     |          |         |
| Residual friction angle, \( \phi_\text{r} \) (°) | 15     |          |         |

After generation of the rock sample, the upper wall element was removed, and the cutting teeth will be further established. The other three sides were restricted with stationary walls. This is not completely realistic considering horizontal stresses in real geologic formations. Therefore, the dimensions were chosen large enough compared with the cutter size to make the boundary effect as small as possible. The rock sample size is 30×70 mm, and there are 31460 particles in the rock model.

2.2. Cutting teeth model

Previous rock cutting simulations based on the DEM have proven the excellent ability of this method in simulation of rock failure (e.g., failure mode) during the drilling process. Thus, this method likely highly-reproduce the mechanical behavior of the cutting teeth. Early attempts of the simulation of the cutting teeth were based on the wall element which does not obey the equations of motion and can only be applied with velocity condition. Thus, this kind of loading boundary cannot reflect the stress condition of cutting teeth and further the failure mode of it. For the clump element, although the stress condition of it can be obtained, limited by the circle shape of its constituent unit (pebble), it is essential to use a large number of pebbles to fully simulate the shape of the cutting teeth. This will significantly increase the calculation time. Furthermore, each pebble of a clump is considered as a piece, often
resulting in multiple contacts between a multi-pebble clump and another piece [23]. Such an increase in the number of contacts can also be detrimental to computer performance. Fortunately, one new object called the rigid block element (rblock) was proposed in PFC6.0 [24]. Zhou et al. (2020) have proven its high ability to simulate dynamic loading condition [21]. As this kind of element obeys the equations of motion; thus, it is feasible to obtain the stress condition of cutting teeth if simulated by numerous rblock elements. In addition, the rblock can directly model a convex object and does not need to use overlapped pebbles in the clump element.

To construct the simulated cutting teeth, each rblock unit is with same size and is selected to be 0.2×0.2 mm. The size of rblock unit is small enough to guarantee the smoothness of obtained data of the cutter teeth. The diameter and thickness of the cutting teeth were selected as 13.44 mm and 4 mm, respectively, the size of which is based on the practically used PDC bits. For the single cutter model, it consists of 800 rblocks. Then, the contact bond strength of the teeth is assumed to be large enough (by setting the contact bond strength between the particles at an extremely high value) since the teeth is assumed to be unbreakable. Final, the established rock cutting model is shown in figure 1.

![Image of rock and cutter models]

**Figure 1.** The numerical rock and cutter models (the red part in the granite rock model is felspar, the grey is quartz, and the black is biotite).

2.3. Cutting process simulation
During the cutting simulation process, a single cutter with back rake angles of 25, 20, 15, 10 and 5 degrees is placed on top of the rock specimen. The spin of the cutter is constrained. A vertical component of force (3000 N) is applied to the cutter representing the conventional constant WOB drilling. A constant horizontal velocity of 0.5 m/s is applied to the cutter which was used to simulate constant rotary speed of about 200 RPM. As the topic of the work is monitoring the moment when the cutter starts to cutting hard rock, the simulation stops when the cutting distance reaching 0.075 mm according to the initial trial when the first macro fragment generates.

3. Simulation results
When the cutter starts to run into a hard rock formation, the gross fracturing is easily to occur, which is mainly due to the sudden increase of shear stress. Thus, to explore the effect of back rake angle to the cutting teeth, the development of the shear stress was obtained, as shown in figure 2. It can be found that for the cutting process, it can be divided into two stages. The first stage is the effective cutting stage, during which, the shear stress gradually increases and in the initial of this stage, the shear stress curves of the cutter with different back rake angles are almost overlapped and then separate each other. The cracks start to generate and coalesce. When the shear band occur, it will be followed by the initiation of fragmentation. The energy stored in the rock will release then and result in the sudden decrease of shear stress.
Figure 2. The development of the shear stress of the bit with different back rake angles.

The typical development of shear stress fields of the cutter with different angles (i.e., 5° and 25°) are shown in figures 3-4. The stress concentration areas of both the two cases are the same, which are located in the place where the cutter in contact with the rock sample. The magnificence of shear stress for the back rake angle of 5° is larger than that of 25° during the cutting process. In addition, the stress concentration area for Case 1 is more severe, which means that smaller the back rake angle is, it is easier to fracture when cutting hard rock.

Figure 3. The development of the shear stress fields for a bit with the angle of 5°.
Figure 4. The development of the shear stress fields for a bit with the angle of 25°.

For drilling project, the key point is maintaining the balance between the bit wear and the penetration rate. Thus, it is essential to further evaluate the effect of back rake angle to the cutting performance by the simulation. In the present work, the parameters used to analyze are the material removal rate (MRR) and crack evolution rate. The crack evolution is directly obtained by calculating the number of the breakage of the bonded contact in the simulation. To measure the MRR, the fragmentation volume parameter was used. The removal rate is calculated from the following formula:

\[
MRR = \frac{\text{Fragmentation Volume}}{\text{Cutting time}}
\]  

where Fragmentation Volume is the volume of the isolated particles/particle clusters caused by cutting in the simulation.

The MRR simulation results are shown in figure 5. The drilling performance generally decreases with the back rake angle except for the angle of 20°, and this is consistent with the shear stress in figure 2, which means that the penetration rate is related to the stress condition of the cutter. Although the MRR is high for the angle of 20° compared with 25°, the shear stress is also higher 11.6% than the latter one. Therefore, there may exist an optimum back rake angle for hard rock cutting which would provide an effective penetration rate, and at the same time, the wear rate is not the highest.

Figure 5. MRR for the single cutters with different back rake angles.
4. Conclusion
In the present work, the DEM simulations were conducted to model the drilling process of the single cutters. The block element in the PFC 6.0 was used to model the cutter, which can well reproduce its dynamic behavior and geometric characteristic. The numerical results show that before generating initial fragment, the drilling process can be divided into two stages. During the effective cutting stage, the shear stress gradually increases and in the initial of this stage, the shear stress curves of the cutter with different back rake angles are almost overlapped and then separate from each other. After that stage, the shear band generates, and followed by the initiation of fragmentation. The energy stored in the rock will release and result in the sudden decrease of shear stress.

With the increase of the back rake angle, the maximum shear stress and stress concentration degree decrease in general, which illustrates that increasing back rake can effectively decrease the damage of the cutter. Simultaneously, the MRR decreases with the increase of the back rake angle. Thus, further study can focus on the balance between the shear stress and MRR to optimize the back rake angle for rock strata with different hardness based on this DEM model.

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