Finite Element Method for Prediction of Rock Breaking Performance of the Tipped Hob With Different Tooth Profiles

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ABSTRACT The raise boring machine, which plays a crucial role in wellbore construction, has been widely applied in subway tunnels and mine construction projects. High levels of quality and safety, make it recognized and promoted by an increasing number of users. The tipped hob as a rock-breaking cutter of the raise boring machine poses a direct influence on the efficiency of the well-bore construction. In this paper, the finite element software LS-DYNA is employed to establish the model of the crushed rock with the tipped hob, and the accuracy of the model is examined by experiments. On this basis, the variation laws and correlations of feed force, lateral force and positive force under different penetration depths are studied. The results show that as the penetration depth increases, the feed force, lateral force and positive force all grow exponentially. In the geological environment with high rock hardness, spherical tooth can effectively reduce cutter wear and conical tooth can achieve higher crushing ability. The research results provide a theoretical basis for the selection of a suitable tipped hob to improve rock breaking efficiency.

INDEX TERMS Raise boring machine, rock breaking, tooth profile, tipped hob, numerical simulation.

I. INTRODUCTION

In mining development, hydropower and other underground construction projects, shafts or inclined shafts are often used in import and export communication channels and ventilation. However, the construction of shafts and inclined shafts has always been a critical and difficult project during underground construction. Especially in the construction of coal mines, the accumulation of harmful gases in the underground poses a serious threat to construction safety. The raise boring machine (RBM) does not require operators to enter the work surface, making it important in wellbore construction. Compared with other construction methods, RBM has been widely applied in major engineering construction projects because of its obvious advantages in safety, construction speed and engineering quality.

After half a century of research and application since the first RBM was developed by Robbins in 1916, RBM has become the most important well-building equipment. The latest products of Herrenknecht are able to build a wellbore with a diameter of 8 m and a maximum depth of 2000 m. Although the performance of the RBM has been greatly improved, only a few related studies can be found. Therefore, it is necessary to study the rock-breaking performance of diversified tipped hobs and expand their application range to meet diverse requirements of engineering constructions.

Research on the performance of rock fragmentation is mainly carried out by experiments and simulation methods [1]–[4]. The experimental method is the most primitive and most effective, but it is also limited by experimental conditions and costs. There are many kinds of cutting tools for rock, so the mechanism of rock breaking by different cutter is very different. Kang et al. [5] proposed a method for evaluating the rock-cutting performance of a low-cost pick cutter using a small-capacity linear cutting machine (LCM). The finite element analysis method and the LCM test results were compared to prove that the small-capacity LCM structure is very stable, and the cutting force accuracy is 96.7%. Wang and Su [6] studied the rock fracture mechanism cutting by conical picks and analyzed the influence of...
the specific energy of the relevant cutting parameters. They found that the maximum indentation depth increases linearly with the increase of cutting depth, and there is a positive power correlation between the maximum cutting force and the depth of cut. The parameters of the cutter directly affect the performance of rock fracture. Niu et al. [7] used the experimental method to study the rock-breaking mechanism of the disc-like hybrid bit (DLHB). They proposed that the DLHB is very stable during the drilling process and is suitable for drilling in hard formations. Stoxreiter et al. [8] studied cutting performance of high pressure jetting in hard rock, and suggested the stand-off distance, the hydraulic power of the jet and the magnitude of the ambient pressure conditions control the cutting performance. Huang et al. [9] introduce a polycrystalline diamond compact (PDC) drill bit with a special structure that reduces the specific energy by 26.9% compared to a conventional full-cover PDC bit. Guo, Deng, and Zhang [10] investigated the wear of the teeth on the single cone bit and analyzed the load of the Non-spherical tooth. The axial load of the teeth is greater than the tangential and radial loads during the drilling process.

Some researchers have proposed models for different cutters to predict rock fracture performance. Based on the mechanism of rock fragmentation under a single tooth impact indentation, Deng et al. [11] developed a new ROP prediction model for roller cone bit, which replaces rock static strength with rock dynamic compressive strength and can reflect the real process of rock dynamic crushing. Chen et al. [12] proposed a cutting model to study the pressurized rock cutting process, which not only predicts the cutting force and the corresponding MSE, but also give better understands the porous elastic effect during cutting process. The results show that cutter will consume a large amount of energy to deform and remove cuttings under pressurized condition.

There are three main methods for the simulation of rock fragmentation: finite element method (FEM), discrete element method (DEM) and a coupled FEM-DEM method. In the simulation of the finite element method, most of the simulations were performed using LS-DYNA software [13]–[17]. Li and Shi [18] proposed a dynamic material model for expressing the mechanical behavior of a rock material under high confining pressure and high strain rate. It was simulated and analyzed by finite element software LS-DYNA, and successfully described the brittle tensile damage and plastic compression damage of rock materials. Saksala [19] presents a numerical investigation on the effect of hydrostatic pressure and confining pressure on percussive drilling of hard rocks. Simulation results on the influence of confining and hydrostatic pressures showed that the latter had clearly stronger effect of pre-venting damage and thus the rate of penetration. Wang et al. [20] applied the finite element method to study the influence of the shape of the bottom of the PDC bit on the rock-breaking effect. The results show that for soft formations, the outer cone arc radius should be larger, and the inner cone angle should be smaller. Yang et al. [21] studied the rock-breaking mechanism of cross-cutting PDC bit. The results show that the cutting load decreases with the increasing of cutters spacing, and increases with the increasing of rock hardness. Li et al. [22] simulated the cutting processes when a cutter and disc cutter are cutting rock and soil masses by finite element method. The results show that the maximum Mises stress of the rock increases almost linearly with the increase of penetration depth, and plastic strain accumulates constantly, resulting in the increase of stress.

In recent years, more people have used the discrete element software PFC to simulate rock damage [23]. Rojek et al. and Su & Akcin [24], [25] applied the discrete element method to simulate the rock cutting process, which shows that the numerical simulation can provide valuable information about the cutting phenomenon, and the numerical results are in good qualitative and quantitative agreement of numerical results with experimental measurements. Aziznejad et al. [26] simulated the response of jointed rock mass subjected to impact loading. They found that joints play an important role in the impact- induced rock mass damage where higher joint intensity results in more damage to the rock mass. Xuefeng et al. [27] investigated the influence mechanism of rock brittleness on rock fragmentation and cutting performance during the cutting process. With the increase of cutting depth, the fracture mode of brittle rocks translated from ductile to brittle mode, which causes macroscopic crack propagation and large chip are formed, and cutting with large brittleness is more effective than with small brittleness. Afrasiabi, Rafiee, and Noroozi [28] discussed the effect of discontinuity geometrical parameters on the TBM performance in hard rock. The results show that the 60° angle of the joint and TBM forward axis has the greatest impact on TBM performance, and the influence of 0° angle is the smallest; Comparing the results of joint orientation and spacing, the effect of the joints orientation on the TBM performance is much higher than the joint spacing. Yang et al. [29] established a joint rock model with circular holes in the discrete element software PFC 2D to study the interaction between jointed rock and tunnel. The displacement fields of the crack zones reveal that the joints coalescence is mainly caused by tensile cracks, and the shear slipping cracks easily occur at the sidewalls of the circular hole.

Recently, researchers presented a coupled discrete element method (DEM) and finite element method (FEM) method to study rock fragmentation. Onate and Rojek [30] proposed a combination of DEM and FEM to analyze geomechanical problems and analyze them with rock cutting. The discrete formulation can be used to model tools in rock cutting operations, which allows us to reproduce tool wear by simply removing the worn particles from the tool surface to reproduce material loss in a realistic manner. Wu et al. [31] using a coupled FEM-DEM method successfully applied to simulate the rock failure process caused by a TBM cutter under different confining pressures. Confining pressure has a significant inhibitory effect on the generation of median cracks. For the same penetration, the normal force at a high
The most important structure in RBM is the cutter head for reaming, which not only determines the performance of the drill, but also directly affects the rock-breaking performance. As shown in Figure 1, the cutterhead consists of a drill pipe and a hob. In this paper, four types of tipped hobs, including wedge tooth, pick tooth, conical tooth and spherical tooth, are studied. These four tooth profiles are the most widely used in engineering applications. The finite element software is utilized to analyze the force during rock-breaking process, and the influence of different tooth profile on rock fragmentation is explored. The rock-breaking theory of the hob provides a solution to the selection of a tipped hob, thus helping to achieve low energy consumption and high efficiency in different geological environments.

II. MODELS AND METHODS

To reduce the calculation time, both the cutter body and the cutter tooth that do not directly contact the rock are removed, and the tipped hob is simplified into regularly arranged teeth as depicted in Figure 2. The rock is modeled as a cuboid with a length of 500 mm, a width of 200 mm and a thickness of 30 mm, and is meshed by a hexahedron with a number of units with 537,072 and 587,925 nodes. The finite element model is present in Figure 3.

Since the rotation speed of the drill pipe is 5 rpm (0.5236 rad/s), the front cut rotates at a speed of 2.609 rad/s according to the position of the radius. To analyze the influence of different pressures on rock fragmentation, we set the depths of the rock erosion at 2 mm, 3 mm, 4 mm, 5 mm, and 6 mm respectively. The vibration and inclination of the hob in the rock-breaking process are not allowed. It not only limits the translation of the cutter body in the y-axis direction and the rotation around the x-axis and z-axis, but also releases the rotation of the cutter body around the x-axis. In the contact model, the static and dynamic coefficients of friction are set to 0.45 and 0.4, respectively. The hob and the rock are in contact with the surface-to-surface erosion, and the bottom of the rock is completely constrained. In addition, the surrounding and bottom nodes of the rock are added with non-reflection
TABLE 1. Material properties of the rock.

| P (kg/m³) | G (GPa) | A | B     | C   | N |
|-----------|---------|---|-------|-----|---|
| 2630      | 22.14   | 0.41| 1.84  | 0.007 | 0.61 |

| K₁ (GPa) | K₂ (GPa) | K₃ (GPa) | f’ₚ (MPa) | T (MPa) | pₑ (MPa) |
|----------|----------|----------|------------|----------|-----------|
| 85       | -171     | 208      | 122.3      | 9.5      | 41.43     |

| µc | f₀ (GPa) | µ₁ | D₁ | D₂ | Sᵧ |
|----|---------|----|----|----|----|
| 0.00192 | 0.9 | 0.04 | 0.04 | 1 | 15 |

boundary conditions to simulate the infinite boundary of the rock.

Herein, the explicit nonlinear finite element program LS-DYNA is used for numerical simulation. The rock is regarded as a homogeneous material to ignore the presence of initial cracks and initial stress fields on the rock, and the rock is removed immediately after the damage. Since the stress distribution and deformation of the teeth are not considered in the analysis, the teeth are set to a rigid body, with an elastic modulus of 600 GPa, a density of 14600 Kg/m³, and a Poisson’s ratio of 0.22. The above settings have no impact on the results. In the finite element simulation, bluestone is used as the rock material, and a HJC (Holmquist-Johnson-Cook) material model is used so that the model can describe the large deformation of the rock at a high strain rate. The failure mode of the rock is defined as shear strain failure.

The rock is made of bluestone with a compressive strength of 122 MPa, which is the most common and representative material in the wellbore construction. The main parameters of the HJC model are listed in Table 1.

III. RESULTS AND DISCUSSION

As can be seen from Figure 4, since the four types of tipped hobs are in the same order because of the arrangement of the teeth, and the arrangement rules of the crushing pits formed on the rock are also the same. On the same hob, the teeth are installed in different positions, resulting in different crushing results. Because the tipped hob has a taper angle, it causes slip phenomenon, so the crushing pit formed by the teeth near the small end of the hob is larger [32].

The hob is impacted by three distinct directions of forces during the rock-breaking process, which are the feed force, lateral force and positive force. The curve of the three forces in the penetration depth of 4 mm is shown in Figure 5. For data extraction and analysis, this curve is filtered to obtain a smooth curve, as presented in Figure 6. It can be seen that the simulation result after smoothing has certain volatility and periodicity. To facilitate data analysis, the values of feed force and lateral force in subsequent charts are multiplied by −1. Furthermore, the data of 4s~44s is taken for a statistical analysis to determine the value of the force of the hob in each direction. The magnitude of the force is represented by the average value in the range of 40s, and the fluctuation of the force is denoted by the standard deviation.
### TABLE 2. Data from the tipped hob with different tooth profiles.

| Tooth profile | Penetration depth (mm) | Feed force (kN) | Lateral force (kN) | Positive force (kN) | Crushing volume (cm³) | Crushing Energy (kJ) | Specific energy consumption (MJ/m³) |
|---------------|------------------------|-----------------|-------------------|--------------------|-----------------------|----------------------|-----------------------------------|
| Wedge tooth   |                        |                 |                   |                    |                       |                      |                                   |
| 2             | 2.2                    | 1.6             | 19.8              | 18.5               | 1.04                  | 56.4                 |                                   |
| 3             | 4.8                    | 4.1             | 36.3              | 31.2               | 2.92                  | 73.4                 |                                   |
| 4             | 8.8                    | 7.7             | 57.8              | 47.8               | 4.22                  | 88.2                 |                                   |
| 5             | 15.0                   | 12.4            | 83.7              | 65.9               | 7.20                  | 109.3                |                                   |
| 6             | 24.1                   | 18.6            | 113.8             | 88.5               | 11.56                 | 130.6                |                                   |
| Pick tooth    |                        |                 |                   |                    |                       |                      |                                   |
| 2             | 3.0                    | 1.9             | 25.3              | 23.5               | 1.43                  | 60.9                 |                                   |
| 3             | 6.6                    | 4.2             | 44.8              | 38.3               | 3.16                  | 82.4                 |                                   |
| 4             | 11.8                   | 7.7             | 66.7              | 54.5               | 5.66                  | 103.8                |                                   |
| 5             | 18.2                   | 12.4            | 90.0              | 72.3               | 8.75                  | 121.1                |                                   |
| 6             | 26.1                   | 17.8            | 114.1             | 91.8               | 12.55                 | 136.8                |                                   |
| Conical tooth |                        |                 |                   |                    |                       |                      |                                   |
| 2             | 4.5                    | 1.5             | 23.4              | 33.3               | 2.17                  | 65.1                 |                                   |
| 3             | 10.7                   | 2.4             | 37.5              | 46.3               | 5.13                  | 110.8                |                                   |
| 4             | 18.6                   | 4.8             | 64.4              | 68.1               | 8.93                  | 131.1                |                                   |
| 5             | 27.6                   | 7.7             | 94.6              | 89.8               | 13.23                 | 147.3                |                                   |
| 6             | 38.6                   | 9.2             | 124.7             | 113.0              | 18.55                 | 164.1                |                                   |
| Spherical tooth|                        |                 |                   |                    |                       |                      |                                   |
| 2             | 3.5                    | 0.6             | 26.1              | 28.2               | 1.70                  | 60.3                 |                                   |
| 3             | 7.8                    | 1.9             | 51.8              | 49.2               | 3.76                  | 76.5                 |                                   |
| 4             | 15.6                   | 3.6             | 83.7              | 70.0               | 7.46                  | 106.6                |                                   |
| 5             | 24.9                   | 6.7             | 124.0             | 97.5               | 11.95                 | 122.6                |                                   |
| 6             | 37.3                   | 9.6             | 168.7             | 124.4              | 17.91                 | 144.0                |                                   |

### A. DATA EXTRACTION

The impacts of the tooth profile on feed force, lateral force and positive force of the hob are analyzed below. Through the results of the numerical simulation listed in Table 2, the values of the three forces at different penetration depths are obtained. Specifically, the hob has a small penetration depth under a positive force and its work is at a low level. Based on the work of the feed force during the breaking of the rock, the effective distance of the hob movement is calculated as 0.48m.

\[ E = F_s \]  
\[ w = E/V \]

The crushing energy and specific energy consumption of the hob are shown in Equations 1 and 2, where, \( F_s \) represents the feed force of the tipped hob; \( s \) represents the movement distance of the tipped hob; \( w \) and \( E \) are the specific energy consumption and the rock-breaking energy consumed by the tipped hob, respectively; \( V \) is the crushing volume by the tipped hob.

### B. MODEL VERIFICATION

To check whether the force of the hob during the simulation is consistent with the actual situation, a linear rock breaking experiment of the hob was carried out, as shown in Figure 7. The performance parameters of the experimental equipment are shown in Table 3.

### TABLE 3. Performance parameters of experimental equipment.

| Parameter name               | Value     | Unit  |
|------------------------------|-----------|-------|
| Loading speed                | 0~300     | mm/s  |
| Vertical loading speed       | 0~20      | mm/min|
| Horizontal stroke            | 1500      | mm    |
| Vertical stroke              | 400       | mm    |
| Maximum horizontal thrust    | 200       | kN    |
| Maximum vertical thrust      | 600       | kN    |
| Experiment box size          | 1500×500×300 | mm |
| Thrust accuracy              | ±1%       | F.S   |
| Stroke accuracy              | ±1%       | F.S   |

Figure 8 compares the experimental results with the simulation ones. It can be seen that the simulation has a slightly larger result regarding the hob, but a smaller result regarding the feed force. However, the experiment and simulation show close values with respect to the positive force on the tipped hob and the periodic fluctuations of the curve. It indicates that the result of the simulation can largely represent the actual rock-breaking process of the hob.

### C. DATA ANALYSIS

The positive force of the hob in different penetration depths is depicted in Figure 9. The periodicity of the positive force...
The periodic variation of the positive force can be attributed to the arrangement rule of the teeth on the tipped hob. In addition, it can be seen that the magnitude of the positive force becomes larger as the penetration depth increases. The amplitude of the spherical tooth and the conical tooth fluctuate more greatly than that of the wedge tooth and the pick tooth, as shown in Figure 10.

Under a small penetration depth, different hobs have substantially the same forces, as shown in Figure 11. However, the feed force rises constantly as the depth of penetration increases. In the mean time, the difference between the four teeth gradually becomes more apparent, as demonstrated by Figure 12. It indicates that the increase in the feed force is exponentially changed. In addition, the feed forces of the four hobs can be ranked as conical tooth > spherical tooth > pick tooth > wedge tooth.

From Figure 13 and Figure 14, we can see that similar to the feed force, the lateral force changes exponentially as the depth of penetration increases. Moreover, the lateral forces of the wedge tooth and the pick tooth are substantially the same, significantly larger than those of the conical tooth and the spherical tooth, which are at similar levels. This result can be explained by the larger width of the wedge tooth and the pick tooth. The result of lateral forces for the four hobs is wedge tooth > pick tooth > conical tooth > spherical tooth.
Similarly, the feed force undergoes exponential growth as well, as shown in Figure 15 and Figure 16. Except for the increase of the spherical tooth, the values of the other three tooth profiles are much close. In other words, the hob with
spherical tooth bears a much stronger positive force than other hobs, which will greatly enhance the pulling force of the drill pipe and reduce the depth of penetration.

Based on the consideration of obvious volatility and periodicity of the force, the fluctuation value of the force applied to the hob is also analyzed. Figure 17 shows a fluctuation of the X/Y/Z direction forces of the four different tipped hobs, obtaining a result of positive force > feed force > lateral force. The fluctuation amplitudes on the tooth profile can be ranked as spherical tooth > conical tooth > pick tooth > wedge tooth.

The correspondence between positive force and feed force is present in Figure 18, showing a linear correlation between the feed force and the positive force. In other words, the feed force increases linearly with the increase of the positive force. This finding is much valuable for the new hob design, because the positive force reacts to the torque on RBM, making it one of the most important parameters for the machine.

From Figure 19 and Figure 20, the rock-crushing volume becomes larger as the penetration depth increases, and the change of the tipped hobs of different tooth profiles increases linearly. In most cases, the result of crushing volume on the...
The spherical tooth has a small level of the specific energy consumption, despite its large positive force. When the spherical tooth is rolling rock, the force is widely distributed, which can reduce the wear of the tooth, especially when the geological environment with high rock hardness is complicated. Moreover, the conical tooth has a strong crushing ability and can break the rock more deeply.

**REFERENCES**

[1] J. Rostami, “Hard rock TBM cutterhead modeling for design and performance prediction,” Geomechanik und Tunnelbau, vol. 1, no. 1, pp. 18–28, Feb. 2008.

[2] J. Futó, F. Krepelka, and L. Ivanicova, “Optimization of rock cutting process using the simulation methods,” in Proc. 12th Int. Carpathian Control Conf. (ICCC), Velké Karlovice, Czech Republic, May 2011, pp. 120–122.

[3] Z. Wang, W. Wang, J. Wang, and C. Liu, “Cutting simulation and test based on different rock parameters,” in Proc. IEEE Int. Conf. Inf. Autom. (ICIA), Aug. 2013, pp. 735–740.

[4] M. Entacher and J. Rostami, “TBM performance prediction model with a linear base function and adjustment factors obtained from rock cutting and indentation tests,” Tunnelling Underground Space Technol., vol. 93, Nov. 2019, Art. no. 103085.

[5] H. Kang, J.-W. Cho, J.-Y. Park, J.-S. Jang, J.-H. Kim, K.-W. Kim, J. Rostami, and J.-W. Lee, “A new linear cutting machine for assessing the rock-cutting performance of a pick cutter,” Int. J. Rock Mech. Mining Sci., vol. 88, pp. 129–136, Oct. 2016.

[6] X. Wang and O. Su, “Specific energy analysis of rock cutting based on fracture mechanics: A case study using a conical pick on sandstone,” Eng. Fract. Mech., vol. 213, pp. 197–205, May 2019.

[7] S. Niu, H. Zheng, Y. Yang, and L. Chen, “Experimental study on the rock-breaking mechanism of disc-like hybrid bit,” J. Petroleum Sci. Eng., vol. 161, pp. 541–550, Feb. 2018.

[8] T. Stoxreiter, A. Martin, D. Teza, and R. Galler, “Hard rock cutting with high pressure jets in various ambient pressure regimes,” Int. J. Rock Mech. Mining Sci., vol. 108, pp. 179–188, Aug. 2018.

[9] K. Huang, Z. Ai, Y. Yang, and Z. Xie, “The improved rock breaking efficiency of an annular-groove PDC bit,” J. Petroleum Sci. Eng., vol. 172, pp. 425–435, Jan. 2019.

[10] Z. Guo, R. Deng, and W. Zhang, “Non-spherical single cone bit tooth failure analysis and tooth load test,” Eng. Failure Anal., vol. 105, pp. 1–11, Nov. 2019.

[11] Y. Deng, M. Chen, Y. Jin, Y. Zhang, D. Zou, and Y. Lu, “Theoretical and experimental study on the penetration rate for roller cone bits based on the rock dynamic strength and drilling parameters,” J. Natural Gas Sci. Eng., vol. 36, pp. 117–123, Nov. 2016.
