Drilling parameters optimization of pick-shaped TCT for raising boring construction of Feng Ning pumped storage power station

To cite this article: Hao Tan et al 2019 IOP Conf. Ser.: Earth Environ. Sci. 237 062023

View the article online for updates and enhancements.
Drilling parameters optimization of pick-shaped TCT for raising boring construction of Feng Ning pumped storage power station

Tan Hao1,2, Liu Zhi qiang2, Tan Jie2 and Meng Yi ping3

1 University of Science and Technology Beijing, Beijing, 100083, China
2 Beijing China Coal Mine Engineering Co. Ltd, Beijing, 100013, China
3 Hefei University of Technology, An Hui, Hefei, 230009, China

*Corresponding author’s e-mail: tanhao365@163.com

Abstract. Under the condition of Feng Ning coarse-grained granite, the consumption of tungsten-carbide-tipped(TCT) cutters in the construction of guide shaft by raising boring machine will be quicker than that of similar projects in the past. In order to ensure the wear resistance and efficiency of breaking rock of the tungsten-carbide-tipped cutter, the pick-shaped TCT can be used in the projects of this kind of rock conditions. Therefore, it is necessary to study the TCT shape, footage and efficiency of breaking rock. In this paper, by studying the rock breaking mechanism of cone-shaped TCT and pick-shaped TCT, numerical simulation and experimental study are carried out on penetration depth, rock fragmentation volume, specific energy and maximum weight of rock debris of cone-shaped TCT and two kinds of pick-shaped TCT under drilling pressure. The results show that the penetration depth of the 3 kinds of TCT increases non-linearly with the increase of drilling pressure in Feng Ning coarse-grained granite. The penetration depth of pick-shaped TCT is deeper than that of cone-shaped TCT, and the penetration depth of pick-shaped tip No.1 with smaller profile angle is the biggest, and the efficiency of breaking rock is better under larger thrust. The rock fragmentation volume of the 3 types of TCT increases non-linearly with the increase of drilling pressure, and the rock fragmentation volume of pick-shaped tip No.1 is the biggest, while that of cone-shaped TCT is the smallest. When the drilling pressure changes, the change trend of specific energy of different tip shapes is not the same: the specific energy of cone-shaped TCT increases slowly with the increase of drilling pressure, while the specific energy of pick-shaped TCT increases first and then decreases slowly with the increase of drilling pressure. These three shapes of tip will produce obvious rock debris under certain drilling pressure, and the maximum weight of rock debris produced by the three shapes of tip is close to each other when the drilling pressure reaches 40kN.

1. Introduction

In Feng Ning pumped storage power station, the raising boring machine is widely used in the inclined shaft project. The raising boring machine is excavated and cut rock through tungsten-carbide-tipped(TCT) cutter installed on the drill bit. The cutter is the key component and loss parts of raising boring drilling engineering. The working condition of the cutter directly affects the excavation efficiency and excavation cost of the drilling. With the increasing of drilling diameter in raising boring construction, The cutter requirements for rock breaking properties have also been improved[1,2].
During the raising boring construction of Feng Ning pumped storage power station, under such coarse grained granite lithology condition, the consumption of conical TCT cutter will be quicker than that of other similar projects. In order to ensure the wear resistance of the cutter and give consideration to rock-breaking efficiency, it is necessary to study the TCT profile, the cutting depth and rock-breaking efficiency.

The research methods of rock breaking mechanism of TCT cutter mainly include theoretical research, FEM and experimental research at present. First, theoretical research and FEM are introduced. Cook[3] et al. used symmetrical linear elastic finite element model to simulate the fracture process of circular flat-nosed intruder invading hard and brittle rock. The simulation results are in good agreement with the experimental results. Z H Zhang [4] et al. established the mechanical model of rock under the action of disc hob, and gave the geometric equation, physical equation and equilibrium equation of rock deformation in the process of rock breaking by rolling. Chiaia[5] et al. used FEM model to simulate the penetration process of hard cutter head on heterogeneous materials. It was found that the penetration process included the interaction of many factors, among which the main failure modes were plastic extrusion and brittle fracture. Y H Wu[6] et al. established the finite element model of double hobs by using the finite element software ABAQUS, analysed the rock breaking principle of hobs, and obtained the optimal tool spacing. Q Tan [7] et al. established the finite element model of rock breaking by TBM cutter, and analysed the stress distribution of the hob and rock based on LS-DYNA. J W Cho[8] et al. used AUTODYN-3D to establish the model of TBM hob cutting rock. The influence of the ratio of cutter spacing to depth of penetration on rock fragmentation volume was studied. The results were compared with the results of LCM experiment and the reliability of numerical simulation was verified. G S Yin[9] et al. used the SPH method to simulate the impact penetration of projectiles on concrete. N Xiao[10] et al. And Y P Ouyang[11] et al. used SPH method to simulate the rock breaking process of TCT cutter. Recent experimental studies including: Q S Liu [12] et al. analysed the law of the TBM cutter and deduced the calculation formula of normal thrust and rolling force. K Z Song [13] et al. studied the interaction between TBM disc cutter and the breaking rock, pointing out that the main influencing factors are mechanical factors and geological factors. S J Wu [14] et al. obtained the rock breaking efficiency of hob tooth by studying the shape, material and size of TCT cutter and the physical and mechanical properties of rock. X H Yao[15] et al. have studied the mode of rock failure in the linear invasion test of cutter.

The rock breaking principle of TBM disc cutter and TCT cutter are studied by the above theoretical analysis, numerical simulation and experiment. These methods provide mature and reliable means for design and selection of TCT. On the basis of these researches, the construction background of the inclined well in Feng Ning is studied. Aiming at the relatively wear-resistant pick-shaped TCT, the rock-breaking efficiency law of each tip profile under different tip profile angle parameters is analysed to solve the problem of wear resistance and rock-breaking efficiency balance under such rock conditions.

2. Study on rock breaking mechanism of pick-shaped TCT

The TCT model adopts three types: con-shaped tip, pick-shaped tip No. 1 and pick-shaped tip No. 2. The top circle of pick-shaped tip No. 1 is R3, and the top circle of pick-shaped tip No. 2 is R4, as shown in figure 1. TCT material is defined as *MAT_RIGID rigid-body material model with density of 8000kg/m³, Young's modulus of 210GPa and Poisson's ratio of 0.3. The size of rock specimen is 40mm * 40MM * 40MM, which material is granite. Granite material model is selected byHolmquist-Johnson-Cook(HJC). The granite has a specific gravity of 2610kg/m³, an elastic modulus of 15.0GPa, a Poisson's ratio of 0.23, a cohesive force of 1.3 MPa and an internal friction angle of 45 degrees. The failure criterion is *MAT_ADD_EROSION which defines the main stress failure and the main strain failure.

The element adopts SOLID164. Freely tetrahedral mesh is used to divide the TCT model, which size is 1mm; hexahedral mesh is used to divide the rock specimen which size is 0.5mm. The non-reflecting boundary condition is applied to the bottom and surrounding nodes of rock specimen model.
In order to prevent disturbances from affecting the stability of the simulation model, all displacement constraints are applied at the bottom. Six sets of drilling pressure perpendicular to the rock surface are applied to the TCT, including 10kN, 15kN, 20kN, 25kN, 30kN and 35kN.

![Figure 1. cross-sectional size of the tips (mm)](image)

Calculate the established finite element model. According to the calculation results, the Von Mises stress cloud map during the failure process of rock is obtained, as shown in figure 2. The red area indicates that the rock is in a state of strong equivalent stress. The surface of the rock begins to crumble under the drilling pressure. At first the compressive is formed on the surface of the rock with the increase of rock stress. At this time, the rock is in the stage of linear elastic deformation. As the penetration depth increases, plastic deformation occurs rapidly. When the equivalent stress of the rock exceeds the failure stress of the material model, the rock begins to collapse outward. Then the unit failure is deleted and the rock breaking area is formed. Second, the rock unit near the bottom of TCT is completely invalid under the action of TCT and spalling from the rock mass. The plastic units around the TCT began to undergo plastic deformation, But the stress is not reached the stress value when it fails. Although the rock unit is damaged, it has not been peeled off from the rock mass. Rock elements far away from TCT are not affected by TCT penetration and are still in the linear elastic stage rather than the plastic deformation stage.

![Figure 2. The Von Mises stress clouds of the rock under the action of single tooth.](image)

3. Relationship between drilling pressure, penetration depth and rock breaking volume

The relationship between drilling pressure and penetration depth of TCT is closely related to the advancing speed and rock breaking efficiency of drill bits. From figure 3, the above three tip shapes have a deeper penetration tendency with the increase of drilling pressure, but the increasing amplitude is slightly different which is nonlinear. When the drilling pressure is small, the penetration increases linearly with the increase of drilling pressure. When the drilling pressure reaches a critical value, the sudden increase in the depth of penetration occurs. The phenomenon that the penetration depth does not increase uniformly with the increase of drilling pressure is related to the heterogeneity, anisotropy
and brittleness-plasticity of rock. Moreover, when the TCT is penetrate into the rock with greater drilling pressure, the damage zone extends deeper into the rock and the penetration depth increases accordingly.

As shown in the three curves in figure 3, the penetration depth of the pick-shaped tip No.1 which with a smaller top circle is the largest, and the penetration depth of the pick-shaped tip No.2 is the smallest. The penetration depth of con-shaped tip, pick-shaped tip No.1 and pick-shaped tip No.2 is almost the same when drilling pressure is small. With the increase of drilling pressure, the penetration depth of pick-shaped tip No.1 deepens rapidly. When drilling pressure is bigger, the penetration depth of pick-shaped tip No.1 is far greater than that of the other two types. So it can be seen that pick-shaped tip No.1 has better rock breaking effect under larger thrust.

![Figure 3. Relationship between drilling pressure and penetration depth.](image)

As can be seen from figure 4, the rock breaking volume of the above three TCTs increases with the increase of drilling pressure, and the curves are nonlinear. When drilling pressure is small, the penetration depth of TCT is shallow, the damage area of rock is small, and the number of units with failure is less. Therefore, the rock breaking volume is very small. With the increase of drilling pressure, TCT penetration deepens, rock damage area expands, rock elements are invalidated and deleted, and rock breakage volume increases. This is also consistent with the actual situation, the increase of drilling pressure, the rock formation of micro-cracks extended to the deeper under the teeth, macro-cracks penetrated each other after the formation of rock volume fragmentation, rock mass volume is increasing. The rock fragmentation volume of the 3 types of TCT increases non-linearly with the increase of drilling pressure, and the rock fragmentation volume of pick-shaped tip No.1 is the biggest, while that of cone-shaped TCT is the smallest.
4. Relationship between drilling pressure and specific energy

For mechanical rock breaking, under the same rock conditions and the same cutters effect, to minimize the energy consumption of rock breaking has always been one of the goals pursued in construction. The energy consumption is an important factor of rock breaking effect. In order to evaluate the rock breaking effect of the TCT, the parameter specific energy is introduced. Generally speaking, the smaller the specific energy of rock breaking mines that the smaller wear, the lower the power, and the higher the rock breaking efficiency. Specific energy can reflect the energy required to break rock of unit volume. For TCT, the equation is as follows:

\[
SE = \frac{F \times P}{2V}
\]

In the equation: \(SE\) is rock breaking specific energy, with unit J/m³; \(F\) is drilling pressure, with unit N; \(P\) is penetration depth, with unit m; \(V\) is the rock breaking volume, with unit m³.

According to the equation, the specific energy of 3 types of TCT under different working conditions is calculated. As shown in figure 5, when the drilling pressure changes, the change trend of specific energy of different tip shapes is not the same: the specific energy of cone-shaped TCT increases slowly with the increase of drilling pressure, while the specific energy of pick-shaped TCT increases first and then decreases slowly with the increase of drilling pressure. The specific energy required by pick-shaped tip No.1 is slightly smaller than that of pick-shaped tip No.2. When drilling pressure is about 10kN, the two kinds of TCT have the lowest specific energy. The specific energy of con-shaped tip is minimum when drilling pressure is about 15kN. This is also consistent with site construction data.
5. Relationship between drilling pressure and the maximum weight of rock debris

The state of rock debris is an important way to evaluate rock breaking effect. Generally speaking, the rock breaking effect is good if the rock granularity increases. But in a single TCT penetrating rock experiment, the number of rock debris usually produced is very small. Therefore, the maximum weight of rock debris is used as the basis for evaluating the effect of rock breaking in this paper. Because it is difficult to get a good shape of rock debris by numerical calculation, single TCT experiment is used to study the maximum weight of rock debris.

The BC-300 type full automatic constant stress cement testing machine is used for the test press. In the process of test, the treated core and the concrete should be poured together into the designed circular steel cylinder for internal fixation, and the concrete is used to simulate the infinite rock surface. According to the test requirements, a total of 8 steel tubes with a diameter of 180 * 120mm were processed. The rock samples were cut into 80mm long and grinding at both ends with a grinder. The rock samples are put into the steel cylinders and poured by the concrete. Make the surface of the rock sample is even with the upper edge of the cylinder. Make the surface of rock samples parallel to the upper edge of the cylinders. Then concrete is brushed up with the upper surface of the rock. Put these steel cylinders in constant temperature curing box for curing. The curing time is 8 days. After the test is completed, the maximum weight of rock debris is weighed and the average value is obtained. The average value is maximum weight of rock debris under this drilling pressure.

Because the formation of rock debris is affected by the joint and weak surface of natural rock samples near the TCT action area, the value in this experiment is unstable and the law is not obvious. As shown in figure 6, the relationship between drilling pressure and maximum weight of rock debris of coarse-grained granite in Feng Ning pumped storage power station is determined by three types of TCT’s drilling pressure. Con-shaped TCT and pick-shaped tip No.1 start to produce obvious blocky debris under drilling pressure of 30kN. The rock fragments below this pressure are all powdery. The maximum weight of rock debris is stable between 0.06g~0.08g when the drill pressure exceeds 25kN. The maximum weight of rock debris produced by pick-shaped tip No.1 is smaller when the drilling pressure is below 30kN, and stabilizes between 0.09 g and 0.1 g when the drilling pressure is above 35kN. For pick-shaped tip No.2, the debris will occur only when drilling pressure is above 35kN.
After drilling pressure reaches 40kN, the maximum weight of rock debris of TCT is closer to each other.

![Graph showing the relationship between drilling pressure and maximum weight of rock debris](image)

**Figure 6. Relationship between drilling pressure and maximum weight of rock debris.**

### 6. Conclusion

By studying the rock breaking mechanism of cone-shaped TCT and pick-shaped TCT, numerical simulation and experimental study are carried out on penetration depth, rock fragmentation volume, specific energy and maximum weight of rock debris of cone-shaped TCT and two kinds of pick-shaped TCT under drilling pressure. The following conclusions can be drawn.

(a) The results show that the penetration depth of the 3 kinds of TCT increases non-linearly with the increase of drilling pressure in Feng Ning coarse-grained granite. The penetration depth of pick-shaped TCT is deeper than that of cone-shaped TCT, and the penetration depth of pick-shaped tip No.1 with smaller profile angle is the biggest, and the efficiency of breaking rock is better under larger thrust.

(b) The rock fragmentation volume of the 3 types of TCT increases non-linearly with the increase of drilling pressure, and the rock fragmentation volume of pick-shaped tip No.1 is the biggest, while that of cone-shaped TCT is the smallest.

(c) When the drilling pressure changes, the change trend of specific energy of different tip shapes is not the same: the specific energy of cone-shaped TCT increases slowly with the increase of drilling pressure, while the specific energy of pick-shaped TCT increases first and then decreases slowly with the increase of drilling pressure.

(d) These three shapes of tip will produce obvious rock debris under certain drilling pressure, and the maximum weight of rock debris produced by the three shapes of tip is close to each other when the drilling pressure reaches 40kN.

(e) The pick-shaped tip No.1 is used in the construction of Feng Ning pumped storage power station.
Acknowledgments
This paper is supported by the Tiandi Science and Technology Foundation Youth Project (2018-TD-QN007). The authors thank the anonymous reviewers for their valuable and instructive comments that greatly help improve the quality and completeness of this paper.

References
[1] Zhang, Y.C., Sun J., Wang, A.S. (2008) Drilling technology. Coal Industry Press, Beijing.
[2] Liu Z.Q. (2013) Development and prospect of mechanical shaft boring technology. Journal of China Coal Society, 38(7):1116-1122.
[3] Cook, N.G.W., Hood, M., Tsai, F. (1984) Observations of crack growth in hard rock loaded by an indenter. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 21(2): 97-107.
[4] Zhang, Z.H., Ye, D.H., Yuan, X. (2011) Study on rock mechanical properties under the effect of disc cutter head. Journal of water conservancy, 42(10):1247-1251.
[5] Chiaia, B. (2001) Fracture mechanisms induced in a brittle material by a hard cutting indenter. International Journal of Solids and Structure, 38: 7747-7768.
[6] Wu, Y.H., Zhang, J.M. et al. (2012) Optimal analysis for cutter space of linear cutter machine based on abaqus. Journal of Shenyang Construction University, 28(5): 927-931.
[7] Tan, Q., Yi N.E., Xia, Y.M., et al. (2012) Research on rock dynamic fragmentation characteristics by TBM cutters and cutter spacing optimization. Chinese Journal of Rock Mechanics and Engineering, 31(12):2453-2464.
[8] Cho, J.W., Jeon, S., Jeong H.Y., et al. (2013) Evaluation of cutting efficiency during TBM disc cutter excavation within a Korean granitic rock using linear-cutting-machine testing and photogrammetric measurement. Tunneling and Underground Space Technology, 35: 37-54.
[9] Yin, G.S., Gao, Y., Zhao, T. (2014) Numerical simulation for penetration of rigid projectile based on SPH method. Journal of Chang’an University (NATURAL SCIENCE EDITION), 34(3): 74-79.
[10] Xiao, N., Zhou, X.P., Cheng, H., et al. (2015) Mechanism of rock fragmentation by TBM cutters using 3D FEM-SPH coupling method. Journal of China Coal Society, 40(6): 1263-1269.
[11] Ouyang, Y.P., Yang Q. (2016) Numerical simulation of rock cutting in 3D with SPH method and estimation of cutting force. Journal of Shanghai Jiao Tong University, 50(1): 84-90.
[12] Liu, Q.S., Shi, K., Zhu, G.Y., et al. (2013) Calculation model for rock disc cutting forces of TBM. Journal of China Coal Society, 38(7): 1136-1142.
[13] Song, K.Z., Yuan, D.J., Wang, M.S. (2005) Study review on the interaction between disk cutter and rock. Journal of Railway Engineering Society, 3(6):66-69+92.
[14] Wu, S.J. (2007) Study on rock breaking effect of Pick shaped carbide insert cutter with raising boring machine. China Coal Research Institute.
[15] Yao, Y.H., Zhao, X.B., Geng, Q.M., et al. (2014) Linear cutting experiments on crack modes of rock under indentation of a single disc cutter. Chinese Journal of Geotechnical Engineering, 36(9): 1705-1712.