Simulation Study of Rock Breaking with Hob in Soft and Hard Uneven Composite Stratum

Kai-rong HONG¹, Hai-xia WANG²,* and Wei-feng HAN¹

¹State Key Laboratory of Shield Machine and Boring Technology, Zhengzhou, P.R. China
²Luoyang Institute of Science and Technology, Luoyang, P.R. China

*Corresponding author

Keywords: Soft and hard uneven composite stratum, Hob, Rock breaking.

Abstract. The paper studied the simulation of rock breaking by hob in soft and hard uneven composite stratum. The rock breaking process was simulated by finite element method, and the mechanism of rock breaking was researched. Comparing the simulation result of tri-axial forces with the theoretical calculation result of CSM model, the average error is within 15%, which indicates that the simulation model is accurate. The study laid a foundation for the further research of hob wearing in soft and hard uneven stratum.

Introduction

When the Shield tunneling in complex strata with great variations in strength, hardness and abrasion, the problem of severe wear and tear of hobs, frequent tool replacement and low construction efficiency are in common. Relevant data show that the ratio of tool replacement to total construction time can reach 8%~26%[1-3]. Therefore, it is necessary to study the wear mechanism of hob in hard and soft uneven stratum.

The research on the hob wear mechanism of full-face rock tunnel boring machine (TBM) is more mature[4-8], but the research on the hob wear of shield tunneling machine in the complex stratum with uneven hardness and softness is still less. Most of the research focuses on the theoretical analysis and countermeasures of the hob wear condition and wear reason. Based on the characteristics of composite stratum in Guangzhou area and the application of hob in shield tunneling, Liu analyzed the wear law of hob[9]. Zhu[10] and others analyzed the influencing factors of hob wear such as geology, hob structure, cutter head type, construction control, engineering design, etc. in composite stratum, and proposed that hob configuration and tool combination should be selected according to different engineering geological conditions. Theoretical and Experimental Research on the force of hob in upper hard and lower soft stratum were conducted by Han[11] et al. It is indicated that the force of hob changes periodically with geological changes.

In this paper, three-dimensional simulation of hob breaking rock in upper hard and lower soft stratum is carried out by finite element analysis(FEM), and a suitable three-dimensional model of hob wear is established, which provides a theoretical basis for further study of hob wear in composite stratum.

Analysis of Interaction Mechanism between Hob and Rock

The key of researching the wear and tear of the disc hobs and the force prediction theory of the hobs is the stress distribution model of disc hobs contacting the rock. Jamal Rostami[12], from the Colorado School of Mines, puts forward the stress model of the front of disc hobs cutting ring contacting rock in which the mechanical properties of rock and the geometric parameter of the disc hobs are taken into account, the model is shown in Figure 1.
Disc hobs tri-axial force is a key parameter in researching the driving behavior of the disc hobs and predicting the tunneling performance. The tri-axial force pressed on the disc hobs can be calculated by CSM model, shown as follows,

\[
F_r = \frac{p_0 R \theta}{1 + \varphi} T \\
F_v = F_r \cos \frac{\varphi}{2} \\
F_r = F_r \sin \frac{\varphi}{2}
\]

Where \( F_r \) represents the resultant force of vertical force and rolling force of rock acting on disc hob, it can be divided into the vertical force \( F_v \) and rolling force \( F_r \) of the disc hob.

On the basis of CSM, a formula of the variation range of the lateral force \( F_s \) on the disc hobs established by Tu Changfeng is as follows,

\[
\frac{1}{2} q \frac{h R \sin(\varphi)}{\cos(\alpha/2)} \cos\left(\frac{\pi}{2} - \frac{\alpha}{2} - \xi\right) \leq F_s \leq \frac{1}{2} q \frac{h R \sin(\varphi)}{\cos(\alpha/2)} \cos\left(\frac{\pi}{2} - \frac{\alpha}{2} - \xi\right).
\]

The symbols in Eq.1 and Eq.2 are specified in references[13].

Simulation Analysis of Rock Breaking with Hob under Soft and Hard Uneven Formation

To make a finite element simulation analysis of the disk hobs breaking rock in soft and hard uneven strata is to make a research of the disc hobs stress condition in the left and right composite strata and front and rear composite strata. LS-DYNA software is selected to make the finite element simulation analysis of the disk hobs breaking rock. After the continuous optimization of the finite element model of hob breaking rock, the hob material, rock soil quality, contact conditions and boundary conditions, etc. can be determined. The meshing of the finite element model of disc hob breaking rock is shown in Figure 2. The model of the 17-inch disc hob is simplified. Rock mass can be expressed as hexahedron specimen. The initial parameters of the rock soil are set to 600mm*320mm*40mm. In the simulation process, the geometric model is meshed by hexahedron sweeping, and the mesh in the contact region between the hob and rock mass is encrypted and refined. The total number of nodes is 368710 and the total number of units is 98774.

Due to adopting the linear rock breaking simulation model of hob rotation, the rock breaking simulation of upper hard and lower soft geology is set to the front hard and back soft soil model to simulate the rock breaking process of hob from hard geology to soft geology.

![Figure 1. Contact model between disc hob and rock.](image1)

![Figure 2. Finite element model of rock breaking with disc hob.](image2)

The disc hob is defined as rigid, and the *MAT RIGID constitutive model is selected to reduce the calculation time of the model. The parameters of the material are shown in Table 1 for details.
The contact between the hob and rock can be regarded as the surface contact between rigid body and variable body. In the process of hob cutting, the rock material element loses effectiveness constantly and the new element contacts with the edge of the hob continuously. Set a center shaft to constrain the displacement along the radial direction of the cutter ring with the initial penetration \( p \) is taken as 8 mm and the rotational speed is taken as 6 r/min. The hob ring rotates by the friction with the rock surface, with a friction coefficient of 0.3. Set a non-reflective boundary constraint on the four sides of the rock material forward and backward and sideways. The upper surface is a free boundary and the bottom surface is fully constrained.

<table>
<thead>
<tr>
<th>Category</th>
<th>Density ([\text{kg/m}^3])</th>
<th>Elastic Modulus ([\text{Gpa}])</th>
<th>Poisson Ratio</th>
<th>Compressive Strength ([\text{Mpa}])</th>
<th>Tensile Strength ([\text{Mpa}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hob ring</td>
<td>7900</td>
<td>206</td>
<td>0.3</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Stratum 1</td>
<td>2450</td>
<td>40</td>
<td>0.23</td>
<td>62</td>
<td>5</td>
</tr>
<tr>
<td>Stratum 2</td>
<td>2450</td>
<td>15</td>
<td>0.23</td>
<td>30</td>
<td>1.36</td>
</tr>
</tbody>
</table>

Finite Element Analysis of Rock Breaking with Hob after Optimization Model

The rock breaking process of the front and rear composite strata is shown in Figure 3. From the point of view of energy, with the continuous forward rolling of the hob, the blade is deformed when contacting with the element of rock material. The stress of rock below and in front of the blade diffuses forward and downward, and the rock below the blade will form a dense core. The dense core expands to form cracks at the angle of the minimum crushing energy. The rock unit begins to break and the dense core decreases after crushing. The stress of the rock element near the broken unit decreases, but residual stresses and strain are produced. From the point of view of stress and strain, when the cutter ring cuts into the rock, the rock element will be automatically deleted by the erosion contact algorithm on the condition that the rock element exceeds the yield limit of material and the set deformation criterion. With the hob rolling in cycles, a notch will be left on the surface of rock mass, as shown in Figure 4.

![Figure 3. Rock breaking process in composite stratum.](image1)

![Figure 4. Generation process of rock trench.](image2)

The curve of the tri-axial force of the hob breaking rock changing with time in the front and rear composite strata is shown in Figure 5. The theoretical result was calculated by Eq.1 and Eq.2.

The analysis shows that due to the instability of the characteristics and internal properties of brittle rock materials, the vertical and rolling forces exhibit periodic unstable fluctuation in the same geological condition in the process of the hobs breaking rock. Cutting rock with hob is a typical step...
fracture breakage. The first load applied in simulation is the penetration load, that is, the hob invades the specified penetration of the rock first and then rolls the rock surface. When the hob begins to establish contact with rock, with the depth the hob cutting into the rock increasing, the rock has a great impact on the hob and the force of the hob increases sharply with great fluctuation. At the same time, the rock produces plastic deformation dense core. With the increasing of the dense core, the load of the hob increases continuously. When it reaches the damage rule of the rock, the erosion contact algorithm removes it and the force of the hob decreases. As the hob continues to move forward and the load continues to increase, the pressure exceeds the rock damage rule and the rock unit is deleted.

At the same time, it is observed that the variation of rolling force and vertical force is basically the same, that is, there is a certain proportional relationship between rolling force and vertical force.

At the junction of the front and rear geology (t=300ms), it can be seen that the rolling force and vertical force decrease greatly and the force of the hob decreases, which accords with the characteristics of the composite geology hard in the front and soft in the back. In the same geology, the lateral force fluctuates up and down around 0 points, and the mesh element is strained because the two sides of the hob contact the rock simultaneously.

Comparing the simulation results with the results of CSM calculation, the force simulation results in geology 1 and 2 are slightly lower than the theoretical results. But within one order of magnitude, the error between the simulation results and the theoretical results is less than 15%, which verifies the feasibility of the simulation model.

![Figure 5. Tri-axial forces of hob in front and rear composite formation.](image)

**Summary**

The paper mainly studies the contact characteristics of disc hob in soft and hard uneven stratum, including rock breaking process, formation process of rock groove, contact force of hob and contact characteristics of rock unit. Firstly, the semi-empirical and semi-theoretical formula of contact stress between disc hob and rock in homogeneous formation and the calculation model of hob wear are given. Then, the rock breaking process of disc hob in soft and hard uneven stratum is simulated by finite element method. The rock breaking finite element model is optimized and analyzed. The process of rock breaking is compared, and the theoretical calculation result is compared with the simulation result. A summary is given as following:

(1) The front hard and behind soft rock breaking model of hob was established by finite element method to simulate the tunneling in upper hard and lower soft composite stratum. The FEM simulation results of rock breaking by hob show that the groove generated on the rock surface is
slightly wider than the width of the edge of the hob, and the groove depth is slightly deeper than the penetration. The force of the hob fluctuates up and down with the removal of the rock mesh element. 

(2) The influence of geological change on the force of hob is analyzed. The tri-axial forces decrease obviously at the hard-soft stratum junction. The variation trend of vertical force and rolling force of hob is basically similar, showing a certain proportion relationship. The lateral force fluctuates up and down at 0.

The contact force error between the calculated result by CSM model and the simulation result of the hob force under homogeneous stratum is less than 15%, which verifies the correctness of finite element model.

Acknowledgement

This research was supported by National Natural Science Fund (51327802), funded by Research Fund for the Doctoral Program of Higher Education of China (2013-08), Science & Technology Department of Henan province of China (172102210395) and Education Department of Henan Province of China (18B460008).

References


