Cutting Simulation Analysis of the Cutter Head of the Shield Machine

Jingnan ZHAO1, Xuekang SI1, Jian GUO1, Xiaolei MA1, Yuzhao CHEN1, Zichao LI1, Yinghuai Dong1,*

1Mechanical Engineering College, Tianjin University of Science and Technology, Tianjin, 300222, China

Corresponding author: jingnanzhao@tust.edu.cn

Abstract. In the process of shield machine tunneling, the interaction between cutter head and soil is very complex. In order to meet the requirements of tunneling, the cutter head was designed according to the construction conditions of Tianjin metro and the Archimedes spiral layout method. The granite model and cutter head model were respectively established by the ABAQUS. The granite model was based on the classic Drucker-Pragel model, and the failure criterion including element deletion function was employ to simulate the yield and failure of rock. The force of the cutter head under cutting condition was analyzed. The results show that the maximum equivalent stress of the cutter head is 8.216950 MPa, and the allowable stress of the cutter head material is 230 MPa, which was less than the allowable stress of the cutter head. The results indicated that the cutter head can meet the actual work requirements and has high structural reliability. The research process of cutter head arrangement provides a method for solving practical engineering problems, and the numerical simulation results provide a reference for the design of cutter head.

1. Introduction

Shield machine is widely used in municipal, mining, transportation and hydraulic tunnel construction due to its advantages of environmental protection, rapidity and small impact on the surrounding environment. The cutter head plays a role in cutting the soil layer and supporting the cutting surface of the shield machine, and is an important part of the shield machine[1]. At present, there are many researches on the simulated cutting of the cutters head of shield machine in China. B Cai et al[2] studied the key parameters of cutter arrangement and simulated the cutting process of cutter groups under three geological conditions. Y M Xia et al[3] analyzed the influence of penetration degree and cutter head rotation speed on total torque of cutter head through single factor analysis, and verified it by comparing actual engineering data. S J Li et al[4] used the finite element numerical simulation analysis method to study the dynamic resistance characteristics of the cutter at the beginning and stationary stages of soil cutting. K Chen et al[5] used ANSYS to analyze the stress distribution of the cutter head, and obtained the distribution law of the axial force of the blade blade. In order to study the deformation of soil and the stress of shield cutters in the process of cutting. Firstly, cutter head were arranged by Archimedes spiral method, and then dynamic simulation models of cutter head driving in the rock stratum are established by ABAQUS. Based on the simulation results, the deformation and failure process of the soil and the stress on the cutter head were studied.
2. Cutter Layout Curve of Shield Machine

At present, the most commonly used cutter layout method is Archimedes spiral layout method.

2.1. Spiral of Archimedes

The Archimedes spiral line arranged by the cutter head is shown in Figure 1.

The polar coordinate expression of Archimedes spiral is shown in equation (1) [6].

\[
\rho = \rho_0 + \alpha \theta
\]  

(1)

where, \( \rho \) is polar axis, \( \rho_0 \) is initial value, \( \alpha \) is constant coefficient; \( \theta \) is polar angle.

2.2. Determination of Shield Cutter Head

From the rationality of cutter head layout, structure and load, the cutter is arranged on several spokes (usually even number). The layout diagram of the cutter is shown in Figure 2.

The calculation method for the number of main cutters of shield machine[7].

\[
N = \frac{d_1/2 - d_3/2 - b_2}{b_1}
\]  

(2)

Where, \( d_1 \) is shield machine outer diameter, \( d_2 \) is outside diameter of cutter head cutting, \( d_3 \) is center cutting length, \( b_1 \) is width of the main cutter, \( b_2 \) is width of peripheral cutter.

The clearance amount between the cutter of main and the center cutter is expressed as:

\[
c = b_1 \times (N - N^*)
\]  

(3)

where, \( N^* \) is integer of cutter number.

The initial diameter of the spiral of Archimedes is:

\[
\rho_0 = \frac{d_3}{2} + \frac{b_1}{2} \pm c
\]  

(4)

In the formula, the value is - when \( c \) is taken, and the value is - when \( c \) is rounded off.

For Archimedes’ spiral constant coefficient:

\[
\alpha = \frac{b_1}{\Delta \theta}
\]  

(5)

In the formula, \( \Delta \theta \) is the angle between adjacent spokes.

Therefore, the spiral equation of Archimedes in the cutter arrangement of the cutter head is:

\[
\rho = \rho_0 + \alpha \theta = \left( \frac{d_3}{2} + \frac{b_1}{2} \pm c \right) + \frac{b_1}{\Delta \theta} \times \theta
\]  

(6)
2.3. Based on Archimedes Spiral Cutter Head Layout Example

The above theory is illustrated with an example of Tianjin shield machine. The outside diameter of shield head is 6400 mm, the length of the fishtail cutter is 1500 mm, the width of the main's cutter is 100 mm, the width of the peripheral cutter is 150 mm. The use of four spokes, according to formula (2) the number of the layout of the winner cutter is:

\[
N = \frac{d_1^2 - d_3^2}{b_1^2} = \frac{6400^2 - 1500^2 - 150^2}{100} = 23 \quad \text{control}
\]

According to formula (3) the overlap between the main cutter and the center cutter is:

\[c = 100 \times (23 - 23) = 0 \text{ mm}\]

According to formula (4) the archimedes' spiral starts value.

\[\rho_0 = \frac{d_3}{2} + \frac{b_1}{2} \pm c = \frac{1500}{2} + \frac{100}{2} - 0 = 800 \text{ mm}\]

According to formula (5) and (6) the expression of the spiral of the cutter head is:

\[\rho = \rho_0 + a\theta = 800 + \frac{200}{\pi} \times \theta\]

The polar coordinate values of cutter layout are shown in Table 1.

| Serial number | Polar coordinates | Polar angle | Serial number | Polar coordinates | Polar angle | Serial number | Polar coordinates | Polar angle |
|---------------|-------------------|-------------|---------------|-------------------|-------------|---------------|-------------------|-------------|
| 1             | 800               | 0           | 9             | 1600              | 4π          | 17            | 2400              | 8π          |
| 2             | 900               | 0.5π        | 10            | 1700              | 4.5π        | 18            | 2500              | 8.5π        |
| 3             | 1000              | 1π          | 11            | 1800              | 5π          | 19            | 2600              | 9π          |
| 4             | 1100              | 1.5π        | 12            | 1900              | 5.5π        | 20            | 2700              | 9.5π        |
| 5             | 1200              | 2π          | 13            | 2000              | 6π          | 21            | 2800              | 10π         |
| 6             | 1300              | 2.5π        | 14            | 2100              | 6.5π        | 22            | 2900              | 10.5π       |
| 7             | 1400              | 3π          | 15            | 2200              | 7π          | 23            | 3000              | 11π         |
| 8             | 1500              | 3.5π        | 16            | 2300              | 7.5π        |               |                   |             |

3. Cutting Analysis of Shield Cutter Heads

3.1. Model Parameters and Assembly

For soil materials, Drucker-Prager model and linear elastic model are employ to simulate the model parameters of cutter head cutting granite, as shown in Table 2[8].

| Material       | Q345 | Cutting material |
|----------------|------|------------------|
| Modulus of elasticity/Gpa | 210  | 26               |
| Poisson’ratio   | 0.3  | 0.3              |
| Density/(kg/m³) | 7850 | 2580             |
The three-dimensional size of the granite in this model is 7 m x 7 m x 2 m, and the cutter head diameter is 6.4 m. The three-dimensional model of cutter head is shown in Figure 3.

3.2. Damage Failure Criteria
Damage failure of element refers to that after the strength limit of element material is reached, the stiffness of material gradually decays to zero in accordance with a certain rule, and the element gradually loses its bearing capacity, and finally it exits the calculation of finite element model.

3.3. Cutting Principles and Processes
The contact algorithm of symmetric penalty function was used to simulate the interaction between cutter head and soil, the shear failure criterion including element deletion function is applied to avoid soil element grid distortion, the ABAQUS/Explicit display algorithm for complex nonlinear problems was used to simulate the cutting process of the cutter on the cutter head. (1)In the initial state, the cutter head was about to contact with the rock mass; (2)The rotation speed of the cutter head was 2 r/min; (3)The advancing speed of the cutter head was 40 mm/min; (4)The simulation time was 15 s.

3.4. Force on Cutter Head
Figure 4 shows the distribution of Mises stress on the front of the cutter head, and the stress on the cutter head when t = 15s. The stress distribution cloud diagram shows that the stress is relatively concentrated at the cutter, the stress at the center of the cutter head is relatively large, and the stress value at other parts is relatively small.

Figure 3. Three-dimensional model of cutter head head cutting

Figure 4. Stress condition of cutter head plate when t = 15s

The maximum equivalent stress of the cutter head is 8.216950 MPa, located at the cutter, as shown in figure 4. The allowable stress of cutter head material is 230 MPa, which meet the intensity requirement[9].

4. Conclusion
In this paper, the cutter head of shield machine is designed by Archimedes spiral layout method. Using The three-dimensional simulation model of shield cutter cutting soil was established by ABAQUS, simulated the process of the cutter head cutting soil. The PEEQ condition of soil and the stress on cutter surface were studied in the process of cutting simulation, the main draw the following conclusions.

(1) By the Archimedes spiral arrangement method, the designed cutter head of the shield machine can completely cut the soil.
(2) The three-dimensional rock breaking simulation model of cutter head was established, and the damage and failure criterion including element deletion function is applied to simulate the
formation and separation of cutting, and the direct numerical simulation of the driving process of cutter head was realized.

(3) Through the analysis of the cutting rock of the cutter head, the maximum stress of the cutter head is 8.216950 MPa, far less than the allowable stress of 230 MPa. The result meets the intensity requirement and the structure was reliable.

(4) The simulate results can provide some basis for the design and research of the cutter head, so as to improve and optimize the design of the cutter head.

Reference

[1] Q J Zhou, Y X Zheng, B J Li, et al. Finite element analysis of shield tunneling cutter head plate modification [J]. Chinese journal of construction machinery, 2008, 6(2): 65-70. (in Chinese)

[2] B CAI, K J Shi, W H Zhu. Research on simulated cutting of shield tunneling cutter head group based on ABAQUS [J]. Tunnel construction, 2017, 37(10): 1334-40.

[3] Y M Xia, X H Zhu, Z B Lin, et al. Research on influencing factors of tunneling load of TBM cutter head head [J]. Modern manufacturing engineering, 2015, 9): 1-6.

[4] S J Li, S Yu, J Chui, et al. Finite element simulation analysis of soil cutting process with shield machine cutter head [J]. Journal of underground space and engineering, 2013, 9(6): 1346-9.

[5] K Chen, C X Su, Y Q Wang. Finite element parametric modeling and analysis of shield cutter head [J]. Tunnel constructio Yn, 2010, 31(12): 57-60. (in Chinese)

[6] G S Chen. Application of Archimedes spiral in shield technology [J]. Heavy industry and lifting technology, 2006, 2): 18-20.

[7] R Y Pei. Analysis and research on cutter wear and layout of shield tunneling machine [D]. Tianjin university, 2009.

[8] C Zheng, W Zhao, H F Zhang, et al. Dynamic numerical simulation of excavation with earth pressure balance shield cutter head [J]. Tunnel construction, 2015, 35(8): 855-60.

[9] Q Fang, Y Li, L Guo. Stress analysis and optimization design of pressure packer for long-distance pipeline based on ANSYS Workbench [J]. Chemical machinery, 2013, 40(2): 197-202.