Mechanical analysis of shield machine cutter head under multiple working conditions based on elastoplastic model

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Abstract. The shield machine's ability to simultaneously cut soft soil and hard rock makes it widely used in subway tunnels, diversion tunnels and other underground engineering constructions. As the core component of the composite shield machine, the shield cutter head has a decisive effect on the work efficiency of the shield machine. When the cutter head of the shield machine is working, the positive pressure of the cutter head directly affects the working performance of the shield machine. However, when the shield machine is working, the positive pressure of its cutter head has been influenced by many factors. Therefore, the problems of evaluating positive pressure of shield machine cutter head and optimizing structure of machine cutter head are needed. In this study, the force balance equation has been used to derive the calculation formula of the positive pressure of the soil on the cutter head. This formula can analyze the positive pressure value of the cutter head under various working conditions under different friction coefficients. At the same time, this research uses Hypermesh software to integrate the cutter head body and the force transmission ring, and uses ANSYS statics simulation analysis method to perform mechanical calculations on the shield machine cutter head. The analysis of the cutter head is 1/6, 1/3, and 1/2 effect of soil on the cutter head when the rotor is locked, and the overall stress distribution of the cutter head is analyzed to optimize the structure design of the cutter head.

1. Introduction
In recent years, the development of tunnels and underground spaces has developed rapidly. As engineering equipment for mechanized excavation, shield machines are widely used in the construction of various tunnel projects such as subways, railways, and highways. The shield machine is a heavy-duty construction equipment for underground excavation that is driven by a rotating cutter head to rotate and squeeze the various tools installed on it to cut and advance. It organically combines various functions such as tunneling, slag discharge and lining, and has the characteristics of fast, safe, small damage to the surrounding rock, can effectively reduce labor intensity and improve the working environment [1]. The shield cutter head is the core component of shield tunneling, and its performance plays a decisive role in the efficiency of the shield machine.

For the shield machine cutter head, the force analysis of the cutter head plays a key role in improving the working efficiency of the shield machine. Liu et al. conducted simulation analysis and research on the earth pressure balance shield machine, analyzed the force of the cutter head structure, and established a simulation analysis model of the cutter head stress characteristics and vibration characteristics on this basis, and obtained various load conditions Under the structural stress and mode
Tian et al. used ANSYS Workbench to perform static analysis on the cutter head, and obtained the stress and deformation of the cutter head. Through the analysis of the mechanical characteristics of the cutter head, it provided a basis for shield selection and determination of tunnel construction parameters. The structure optimization provides a reference. Gao et al. studied the bending moment of the cutterhead when the shield machine cuts the composite rock and soil layer during tunneling, and established a model of the total bending moment in the cutterhead plane during the tunneling of the upper layer of the composite rock by the shield machine, and performed simulation analysis. Liu et al. carried out the design and finite element analysis of the composite shield cutter head, and carried out a numerical analysis by simulating the structural response under the load, and the analysis results were consistent with the actual engineering.

Through previous research, it can be found that the mechanical analysis and structural optimization of the cutter head of the shield machine are an important part of the cutter head design. The static analysis can obtain the stress distribution and deformation of the cutter head under static load. In order to realize the analysis of the force of the cutter head, this study derives the calculation formula of the positive pressure of the soil on the cutter head based on the equation of the force balance. This formula can analyze the positive pressure value under different friction coefficients and is suitable for different Working conditions. At the same time, this research uses ANSYS statics simulation analysis method to carry out mechanical calculations on the cutter head of the shield machine, analyze the effect of the cutter head on the cutter head under different working conditions, analyze the overall stress distribution of the cutter head, and verify the deduction Optimized the structure of the cutter head at the same time.

2. Force analysis of soil and cutter head

Many scholars have done a lot of detailed research on the analysis of the force between the soil and the cutter head during the cutting process of the shield machine cutter head. The cutter head at 1/6 blocked rotation has been taken as an example. At this time, only the area shown in Figures 1 and 2 is subjected to the force of the soil, and the soil and the cutter head are friction. This friction force is relative to the center of the cutter head. The torque is the same as the output torque of the shield machine.

![Figure 1. Forced area when locked 1/6 rotor area.](image1)

![Figure 2. Enlarged force area when locked 1/6 rotor area (half displayed).](image2)

Therefore, the force balance formula can be expressed as formula (1)

\[ M = \sum_{i=1}^{n} \mu \frac{s_i}{S} Fr_i, \]

where M represents the output torque of the cutter head, S is the total area of the locked rotor, \( s_i \) is the local area of the locked rotor, \( \mu \) is the friction coefficient between the soil and the cutter head, F is the total force, is the area of the i-th block, and \( \mu \frac{s_i}{S} F \) represents the area on the Friction, \( r_i \) is the
distance from the area to the center of the circle. Among them, \( \mu \), \( F \), and \( S \) are constants, so formula (1) can be written as formula (2). \( F \) is the force of the soil on the cutter head that we require to solve. Therefore, in order to find \( F \), only need to solve \( \sum_{i=1}^{n} \frac{S_i}{S}r_i \).

\[
F = \frac{M}{\mu \left( \sum_{i=1}^{n} \frac{S_i}{S}r_i \right)} \tag{2}
\]

This paper uses a simpler approximation method proposed to estimate the value of \( \sum_{i=1}^{n} \frac{S_i}{S}r_i \) \cite{13}. The accuracy of this method can meet the requirements of this project. In SolidWorks, the cutting method is used to cut each Si surface, and then directly measure the area of \( s \) and the length of \( r \), and then add each \( s \) surface to obtain it. Figure 3 is a schematic diagram of the method of cutting a small area, and Figure 4 is a schematic diagram of the small area cut (blue).

![Figure 3. Schematic diagram of the method of cutting a small area.](image1)

![Figure 4. Schematic diagram of the small area cut out (blue).](image2)

3. Case study

In this study, a case study was carried out with a shield machine of a Chinese company as an example to analyze the force of its cutter head under various working conditions. In this study, the force of the cutter head when the cutter head is locked at 1/6, 1/3, and 1/2 is analyzed, and the values of the area \( S_i \) of the area and the distance from the area to the center of the circle are as shown in Table 1 to Table 1. Table 3 shows. The soil and the cutter head generate friction, and the torque produced by this friction force relative to the center of the cutter head is the same as the output torque of the shield machine, which is 45937.5 KN.m.

| Area (mm²) | Distance (mm) | \( \frac{S_i}{S}r_i \) |
|-----------|--------------|-----------------|
| S1=76529.48 | r1=5530 | 0.17629488 |
| S2=604512.81 | r2=5380 | 1.354795011 |
| S3=622770.04 | r3=5080 | 1.317884131 |
| S4=479265.19 | r4=4780 | 0.954310248 |
| S5=422890.32 | r5=4480 | 0.789208153 |
| S6=175234.23 | r6=4180 | 0.305127275 |
| S7=19366.94 | r7=4030 | 0.032512612 |
Table 2. Parameters of various parameters in the discrete area when 1/3 locked-rotor.

| Area (mm²) | Distance (mm) | $\frac{s_i}{S}r_i$ |
|------------|---------------|-------------------|
| S1=337846.89 | r1=5408 | 0.2345 |
| S2=1050964.82 | r2=5258 | 0.7094 |
| S3=1040866.5 | r3=4958 | 0.6625 |
| S4=1022330.32 | r4=4658 | 0.6113 |
| S5=805612.12 | r5=4358 | 0.4507 |
| S6=639179.7 | r6=4058 | 0.3329 |
| S7=563437.98 | r7=3758 | 0.2718 |
| S8=699163.02 | r8=3458 | 0.3103 |
| S9=571385.17 | r9=3158 | 0.2316 |
| S10=503765.72 | r10=2858 | 0.1848 |
| S11=342988.22 | r11=2558 | 0.1126 |
| S12=187308.84 | r12=2258 | 0.0543 |
| S13=25109.05  | r13=1958  | 0.0063 |

Table 3. Parameters of various parameters in the discrete area when 1/2 locked-rotor.

| Area (mm²) | Distance (mm) | $\frac{s_i}{S}r_i$ |
|------------|---------------|-------------------|
| S1=487275.7 | r1=5408 | 0.2059 |
| S2=1482483.94 | r2=5258 | 0.6092 |
| S3=1279018.55 | r3=4958 | 0.4956 |
| S4=1303606.77 | r4=4658 | 0.4745 |
| S5=1048914.35 | r5=4358 | 0.3572 |
| S6=962371.24 | 4058 | 0.3052 |
| S7=857524.71 | 3758 | 0.2518 |
| S8=1154920.83 | 3458 | 0.3121 |
| S9=947800.37 | 3158 | 0.2339 |
| S10=847992.02 | 2858 | 0.1894 |
| S11=591500.17 | 2558 | 0.1182 |
| S12=578584.96 | 2258 | 0.1021 |
| S13=339648.54 | 1958 | 0.0519 |
| S14=253671.2 | 1658 | 0.0328 |
| S15=163782.51 | 1358 | 0.0173 |
| S16=245524.78 | 1058 | 0.0203 |
| S17=250714.05 | 758 | 0.0148 |

For 1/6 locked-rotor, the data in Table 1 can be used to obtain equations (3) and (4):

$$\sum_{i=1}^{n} \frac{s_i}{S}r_i = \frac{s_1}{S}r_1 + \frac{s_2}{S}r_2 + \frac{s_3}{S}r_3 + \frac{s_4}{S}r_4 + \frac{s_5}{S}r_5 = 4.9$$  \hspace{1cm} (3)
\[ F = \frac{M}{\mu \left( \frac{s_i}{2} r_i \right)} = \frac{45937.5 \times 10^3}{0.3 \times 4.9} = 31250 \times 10^3 \text{ N} \]  

Among them, \( \mu = 0.3 \).

For 1/3 locked-rotor, the data in Table 1 can be used to obtain equations (5) and (6):

\[ \sum_{i=1}^{n} \frac{s_i}{S} r_i = \frac{s_1}{S} r_1 + \frac{s_2}{S} r_2 + \cdots + \frac{s_{13}}{S} r_{13} = 4.17 \]  

\[ F = \frac{M}{\mu \left( \frac{s_i}{2} r_i \right)} = \frac{45937.5 \times 10^3}{0.3 \times 4.17} = 36720 \times 10^3 \text{ N} \]  

Among them, \( \mu = 0.3 \).

For 1/2 locked-rotor, the data in Table 1 can be used to obtain equations (7) and (8):

\[ \sum_{i=1}^{n} \frac{s_i}{S} r_i = \frac{s_1}{S} r_1 + \frac{s_2}{S} r_2 + \cdots + \frac{s_{17}}{S} r_{17} = 3.79 \]  

\[ F = \frac{M}{\mu \left( \frac{s_i}{2} r_i \right)} = \frac{45937.5 \times 10^3}{0.3 \times 3.79} = 40402.37 \times 10^3 \text{ N} \]  

Among them, \( \mu = 0.3 \).

The material elastoplastic mechanical parameters of this shield machine are shown in Table 4 below.

| Parameters                     | Value                  |
|--------------------------------|------------------------|
| Cutterhead material            | Q345                   |
| Elastic Modulus                | 206GPa                 |
| Poisson's ratio                | 0.28                   |
| density                        | 7850kg/m³              |
| Yield stress                   | 345MPa                 |
| tensile strength               | 675MPa                 |
| Yield strain                   | 0.15%                  |
| Strain at the beginning of hardening | 2.5%               |
| Tensile strength strain        | 16.5%                  |

4. Results and discussions

In order to realize the structural optimization of the cutter head of the shield machine, the force of the soil on the cutter head when the cutter head is 1/6, 1/3, and 1/2 blocked is used for analysis.

4.1. 1/6 locked-rotor analysis

As shown in the figure below, the displacement constraint is imposed on the force transmission ring, and the positive pressure and torque are simultaneously applied to the 1/6 model, that is, as shown in Figure 5, the positive pressure value is 31250KN and the torque value is 45937.5KN.m.

The model is imported into ANSYS for calculation, and the maximum displacement is 483.8mm, which occurs on the outermost cutter head structure in the locked-rotor area. The maximum stress is 6.14e8Pa. The displacement and stress distribution of the cutter head are shown in Figures 6-9.

Figure 10 shows a schematic diagram of the stress distribution on the front of the cutter head. The parts less than the yield stress have been hidden. The areas shown in the figure are all stress areas that exceed the yield limit. Since the maximum stress value exceeds the yield limit more, the method of rounding corners or changing the wall thickness is difficult to obtain a better improvement effect. In-depth communication with the structural designer is required to make major changes to these local structures, such as increasing the thickness of multiple plates or using stiffeners, etc.
Figure 5. Schematic diagram of restraint and load application for 1/6 locked-rotor analysis.

Figure 6. Displacement distribution on the front of the cutter head for 1/6 locked-rotor analysis.

Figure 7. Displacement distribution on the back of the cutter head for 1/6 locked-rotor analysis.
Figure 8. Displacement distribution on the front of the cutter head for 1/6 locked-rotor analysis.

Figure 9. Displacement distribution on the back of the cutter head for 1/6 locked-rotor analysis.

Figure 11 shows a schematic diagram of the stress distribution on the back of the cutter head. The part less than the yield stress has been hidden. The areas shown in the figure are all stress areas that exceed the yield limit. They are similar to the front structure, with only simple rounding or changes. The method of wall thickness is difficult to obtain a better improvement effect, and it is necessary to make major changes to the structure, such as increasing the thickness of multiple plates or using stiffeners.

Figure 10. Stress distribution on the front face of the cutter head (only the part that exceeds the yield stress is shown) for 1/6 locked-rotor analysis.

Figure 11. Stress distribution on the back of the cutter head (only the part that exceeds the yield stress is shown) for 1/6 locked-rotor analysis.
4.2. 1/3 locked-rotor analysis

As shown in the figure below, the displacement constraint is imposed on the force transmission ring, and the positive pressure and torque are simultaneously applied to the 1/3 model, that is, as shown in Figure 12, the positive pressure value is 36720KN, and the torque value is 45937.5KN.m.

![Figure 12. Schematic diagram of restraint and load application for 1/3 locked-rotor analysis.](image)

The model is imported into ANSYS for calculation, and the maximum displacement is 18.093mm, which occurs on the outermost cutter head structure in the locked-rotor area. The maximum stress is 1.28e9Pa, which is greater than the yield stress 3.45e8Pa. The displacement and stress distribution of the cutter head are shown in Figures 13-16, and the maximum stress is concentrated in the 1/3 of the force-bearin area.

![Figure 13. Displacement distribution on the front of the cutter head for 1/3 locked-rotor analysis.](image)
Figure 14. Displacement distribution on the back of the cutter head for 1/3 locked-rotor analysis.

Figure 15. Stress distribution on the front face of the cutter head for 1/3 locked-rotor analysis.

Figure 16. Stress distribution on the back of the cutter head for 1/3 locked-rotor analysis.

Figure 17 shows a schematic diagram of the stress distribution on the front of the cutter head. The parts less than the yield stress have been hidden. The areas shown in the figure are all stress areas that exceed the yield limit. It can be seen that there are many areas that exceed the yield stress. You need to contact the structural designer to conduct in-depth communication and make corresponding changes to the structure, such as increasing the thickness of multiple panels or using stiffeners.
Figure 18 shows a schematic diagram of the stress distribution on the back of the cutter head. The parts less than the yield stress have been hidden. The areas shown in the figure are all stress areas that exceed the yield limit. It can be seen that there are many areas that exceed the yield stress. Modifications, such as increasing the thickness of multiple panels or using stiffeners, etc.

4.3. 1/2 locked-rotor analysis
As shown in Figure 19, the displacement constraint has been imposed on the force transmission ring, and the positive pressure and torque have been simultaneously applied to the 1/2 model. In this case, the positive pressure value is 40402.37KN, and the torque value is 45937.5KN.m.

The model is imported into ANSYS for calculation, and the maximum displacement is 8.925mm, which occurs on the outermost cutter head structure in the locked-rotor area. The maximum stress is 6.46e8Pa, which is greater than the yield stress 3.45e8Pa. The displacement and stress distribution of the cutter head are shown in Figure 20 to 23, and the maximum stress is concentrated in the area where the force is 1/2.
Figure 20. Displacement distribution on the front of the cutter head for 1/2 locked-rotor analysis.

Figure 21. Displacement distribution on the back of the cutter head for 1/2 locked-rotor analysis.

Figure 22. Stress distribution on the front of the cutter head for 1/2 locked-rotor analysis.
Figure 23. Stress distribution on the back of the cutter head for 1/2 locked-rotor analysis.

Figure 24 shows a schematic diagram of the stress distribution on the back of the cutter head. The part less than the yield stress has been hidden. The areas shown in the figure are all stress areas exceeding the yield limit. The structure is modified accordingly, such as adding multiple plates Thickness or the use of reinforcing ribs and other methods.

5. Conclusions

In this study, the formula of the positive pressure of the cutter head has been developed based on the force balance equation. The developed formula can be used to analyze the positive pressure value of the cutter head under various working conditions under different friction coefficients. Also, the mechanical calculation on the shield machine cutter head has been performed based on the ANSYS statics simulation analysis. The following conclusions have been drawn from the study:

- In present study, the mechanical calculations on the cutter head of the shield machine have been carried out by using ANSYS statics simulation analysis method. The effect of the soil on the cutter head when the cutter head is locked at 1/6, 1/3, and 1/2 conditions have been analyzed. Also, the knife for the overall stress distribution of the disc has been evaluated. The force balance equation has been used to derive the calculation formula of the positive pressure of the soil on the cutter head, which can analyze the positive pressure value under different friction coefficients.
• When the cutter head is locked in 1/6, when under positive pressure and torque, the maximum displacement of the structure is relatively large, the maximum can reach 483.8mm, the maximum stress can reach 6.14e8MPa, which exceeds the yield stress, and because it exceeds the yield stress value Therefore, it is difficult to reduce the stress level through small local changes. According to the principle of force, the rigidity and strength of the structure are strengthened by adding the thickness and number of plates and using reinforcing ribs.

• When the linear elastic model is used for calculation, when the cutter head is locked at 1/3, the maximum displacement of the structure can reach 35.487mm, and the maximum stress can reach 1.15e9Pa, which greatly exceeds the yield stress, and there are many areas that exceed the yield stress. According to the principle of force, the rigidity and strength of the structure are strengthened by adding the thickness and quantity of the plates and the use of reinforcing ribs.

• When the linear elastic model is used for calculation, when the cutter head is locked at 1/2, the maximum displacement of the structure can reach 18.065mm, and the maximum stress can reach 7.01e8Pa, which exceeds the yield stress. According to the principle of force, the rigidity and rigidity of the structure are strengthened. Strength, the method used is to add the thickness and quantity of the plate and the use of stiffeners and other means.

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