Numerical Simulation Analysis of Cutter Head of Large Diameter Metro Shield with Soft Upper and Hard Bottom

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Abstract. Taking the large-diameter shield cutter head between Xinglong Station and Tianfu new station in Civil Engineering Section 4 of Chengdu metro line 18 as an example, the numerical simulation is carried out by finite element software to analyze the stress and deformation of large-diameter shield cutter head under different loads in upper soft and lower hard strata. The results show that the stress and deformation of cutter head meet the design requirements, which can provide certain reference value for similar projects in the future.

1. Introduction
As the scale of urban rail transit increases, geological conditions become more and more complex. The upper soft and lower hard composite formation is a common typical formation and also a major driving difficulty in shield construction [1]. The upper part of this type of stratum is unstable, while the lower part is stable, but its strength is higher than that of the upper layer. Therefore, during the construction process, the shield is likely to shift to the weak stratum, resulting in uneven force on the knife disk, easy overload of the hob, and difficult control of the attitude of the shield [2-5]. Therefore, it is necessary to design the cutter plate structure specifically to meet the characteristics of stratum and excavation.

Taking Xinglong Station Tianfu new station section of Chengdu metro line 18 Civil Engineering Section 4 Xinglong Station to Tianfu new station as an example, this paper uses finite element software to carry out numerical simulation analysis of the cutter head to judge whether the stress and deformation of the cutter head under the upper soft and lower hard stratum meets the design requirements, so as to provide reference for related projects in the future.

2. Engineering overview
The section from Xinglong Station to Tianfu new station in Civil Engineering Section 4 of Chengdu metro line 18 is located in the east of Longquan mountains, northeast of Hejiang town and west of
Taihe Road. The starting and ending mileage of the section is yck34 + 030.585 ~ yck39 + 105.469, with a total length of 5074.884m. After leaving Xinglong Station, the line is laid along the planned road from west to East. The line passes through the South extension line of Hongxing Road, luxihe bridge, Chengdu Zigong Luzhou expressway, etc.

The two sides of the section are mainly farmland and woodland, with more hilltops, and the terrain of the site fluctuates greatly. It is low in the northwest and high in the southeast. The northwest end is the Chengdu alluvial plain, and the southeast end is the Longquan Mountain range. The minimum longitudinal slope gradient of the section tunnel is 2 ‰, and the maximum longitudinal slope gradient is 24 ‰. The maximum buried depth of the tunnel is 45.2m, the minimum buried depth is about 4.2m, and the minimum plane curve radius is 1200m. The tunnel in this section mainly passes through moderately weathered mudstone and partially passes through strongly weathered mudstone.

The tunnel has an inner diameter of 7500mm, an outer diameter of 8300mm, a segment thickness of 400mm and a segment width of 1800mm. The single-layer lining of circular prefabricated reinforced concrete segment is adopted, and the concrete strength grade is C50 and the impermeability grade is p12. Each ring segment is composed of one capping block, four standard blocks and two adjacent blocks. The left and right turning wedge-shaped ring is used in the design, and the combination with standard ring can meet the needs of curve section line fitting and construction deviation correction. The wedge-shaped ring is 40mm in shape of double wedge. The lining ring is connected by 19 longitudinal bolts and 14 circumferential seam bolts.

A total of four composite earth pressure balance shield machines are used for tunnel construction from Xinglong Station to Tianfu new station, and one air shaft is set in the section: two starting from Xinglong Station and receiving by air shaft; two from air shaft and received by Tianfu new station; the section is constructed by earth pressure balance shield machine with cutter head diameter of 8.65m. The shield tunneling planning is shown in Table 1.

| Line                              | Distance (m) |
|-----------------------------------|--------------|
| Left line of Xinglong station - air shaft | 2383.41     |
| Right line of Xinglong station - air shaft | 2372.85     |
| Left line of air shaft - Xinglong station | 2712.02     |
| Right line of air shaft - Xinglong station | 2714.29     |

In addition, according to the characteristics of the upper soft and lower hard strata in the interval, and combined with the excavation characteristics of the project, the cutter head of the large-diameter shield is designed specifically, as shown in Table 2. The outer diameter of the large ring of cutter head is 8610mm, and the material of cutter head steel structure is Q345C.

| Number | Targeted design                                                                 | Purpose of design                      |
|--------|--------------------------------------------------------------------------------|----------------------------------------|
| 1      | The center of the front face is made of rounded thick plate with rib plate     | Reduce stress, improve strength        |
|        | The main structure is made of high-strength thick steel plate with the front thickness of 600mm and the edge of 700mm | and stiffness                           |
| 2      | Structural design of multi group force transfer ring                          | Ensure the structural strength and     |
|        |                                                                                  | stiffness of the main structure        |
| 3      | Equipped with 12 edge hobs                                                     | It is convenient to assemble and       |
|        |                                                                                  | improve the rigidity of main body     |
| 4      | Combination design of 1 center block + 2 side block                            | Guaranteed excavation range            |
| 5      | Equipped with 18 inch and 19 inch hob mounting base                            | Easy welding, good rigidity            |
| 6      | Equipped with 6 shell knives                                                   | Both general and specific              |
| 7      |                                                                                  | Protect edge hob life                  |
3. Numerical simulation results
Using finite element analysis software simulated the stress and deformation of cutterhead structure under full load condition, 1/3 partial load condition and 1/2 partial load condition, so as to judge whether the stiffness and strength of cutter head structure meet the standard. The finite element mesh model of cutter head structure is shown in Figure 1.

![Figure 1. Cutter head mesh model.](image)

According to the full load condition, the thrust on the cutter head is applied to all the cutterheads, and the outer ring of the large ring of the cutter head is applied with the breakout torque. The thrust of cutterhead is 14250kN and the breakout torque of cutterhead is 28740kN·m. The stress nephogram is shown in Figure 2a and the deformation nephogram is shown in Figure 3a.

According to the 1/3 unbalanced load condition, the front hob thrust is loaded on the 12 hobs of tool beam 1 and tool beam 11, the thrust of edge hob is loaded on the 4 edge hobs of tool beam 10 and tool beam 12, the thrust of center hob is loaded on 6 central hobs of tool beam 1, the outer ring of large ring of cutter head body is applied with breakout torque, and the cutter head bears 1/3 unbalanced load torque. The thrust of cutterhead is 4750kN and the breakout torque is 28740kN·m. The stress nephogram is shown in Figure 2b and the deformation nephogram is shown in Figure 3b.

For 1/2 unbalanced load condition, the front hob and edge hob on the left side of the cutter head body exert thrust, the outer ring of the large ring of the cutter head body applies the breakout torque, and the cutter head bears 1/2 of the unbalanced load torque. Cutter head thrust is 7125kN, and its breakout torque is 28740kN·m. The stress nephogram is shown in Figure 2c, and the deformation nephogram is shown in Figure 3c.

![Figure 2. Stress nephogram of cutter head under different load conditions /MPa.](image)
Figure 3. Deformation nephogram of cutter head under different load conditions /mm.

The maximum stress of cutter head is 157.3MPa from the analysis results of full load condition. The maximum stress of cutter head is 171.8MPa according to the analysis result of 1/2 unbalanced load condition. The maximum stress of cutter head is 195MPa according to the analysis result of 1/3 unbalanced load condition. Due to the influence of unbalanced load, the maximum stress of cutter head structure increases. The maximum stress of cutter head structure under 1/2 unbalanced load condition is increased by 9.22% compared with that under no unbalanced load condition, while that under 1/3 unbalanced load condition is increased by 23.97%. Therefore, the greater the degree of unbalanced load, the more the maximum stress of cutter head structure increases. The maximum stress of cutter head structure occurs in 1/3 unbalanced load condition, and its maximum value is 195MPa. The allowable strength of the cutter head is 254MPa, which is greater than 195MPa, and the structural strength of cutter head meets the design requirements.

From the results of finite element analysis, it can be concluded that the total deformation of cutter head structure under full load condition is 2.416 mm; that under 1/2 unbalanced load condition is 2.532 mm; under 1/3 unbalanced load condition, the total deformation of cutter head structure is 2.807 mm. The deformation law of cutter head structure under different load conditions is the same as that of stress change, that is, with the increase of unbalanced load, the deformation value also increases. The maximum deformation value is 2.807mm, less than the control value of 5mm, and the structural stiffness of cutter head under different load conditions meets the requirements.

4. Conclusion
According to the stratum characteristics and excavation characteristics of Xinglong Station to Tianfu new station section of Civil Engineering Section 4 of Chengdu metro line 18, the shield cutter head of this section is designed to meet the engineering requirements. The numerical simulation analysis is carried out by finite element software. The results show that the stress and deformation meet the design requirements, which can provide experience for related projects in the future.

Acknowledgments
This work was financially supported by China Power Major Project (DJ -ZDXM-2017-23).

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