Force Characteristics and Field Test of Shield Tunneling Tools

Lei Chen$^{1,2}$

$^1$I Institute of Rock and Soil Mechanics, CAS, Wuhan, Hubei, 430071, China
$^2$University of Chinese Academy of Sciences, Beijing, 100049, China

chenlei173@mails.ucas.edu.cn

Abstract. This article takes the Wuhan Metro Line 7 project as the background, and statistically analyzes the parameters acquired by shield tunneling. The relationship between the shield parameters is obtained, and the correlation between the shield parameters and the geological conditions is analyzed; based on the obtained data by on site testing, the mechanical characteristics of the scraper and the force distribution characteristics on the cutter head are analyzed.

1. Introduction

Urbanization is accelerating, and a large number of people are pouring into cities, resulting in an increasingly blocked urban traffic. Building a subway is an effective way to alleviate traffic jams in cities. Shield is a common way of subway construction. Reasonable allocation of shield tunneling parameters is an important part of ensuring the quality of subway construction. Scholars have carried out a lot of research work on the parameters of shield tunneling. Lin Shixiang et al [1] The method of proportionally reducing the shield cutter head is used to simulate the rock breaking process of the shield machine, and the relationship between the tangential resistance and the axial resistance and the cutter shield is obtained. Xia Yimin et al [2] Analyze the position and quantity relationship of each tool on the cutter head of a certain type of shield machine, and check the relationship between the radial force and torque of the cutter head. Han Weifeng et al [3] Based on the basic theory, the experimental method of rock breaking mechanism in the soft and hard uneven layer is simulated by the simulated scraper. The force characteristics of the scraper in the uneven formation conditions are analyzed. Wang Hongxin et al [4] Through the data of model test, the relationship between shield thrust, soil pressure and tunneling speed is analyzed, and the mathematical model of shield tunneling is constructed and verified by actual engineering. Most of the research work stays at the stage of model testing, and there are fewer experiments in the field. It is very important to understand the distribution of the force of the scraper on the cutter head of the shield machine, and to control the posture of the shield machine and analyze the wear of the scraper.

This paper relies on the shield tunnel of the Yuejiang section of Sanyang Road, No. 7 of Wuhan Metro, and monitors the mechanical characteristics of the center knife, panel knives and side knives on the cutterhead of the shield machine, and analyzes the blade breaking force and the shield machine knife. The relationship between the heading parameters such as total thrust, cutter torque, and installation radius.
2. Project overview and monitoring data

The tunnel project of this section is located in the Yuejiang section of Sanyang Road, No. 7 Line of Wuhan Metro. The section runs from Jiefang Avenue along Sanyang Road to the riverside, and runs down the Yangtze River to the Wuchang River and along the Qinyuan Road to Heping Avenue. Figure 1 is a plan view of the Yuejiang section of Sanyang Road, Wuhan Metro Line 7.

![Figure 1. Cross-river section of Sanyang Road, Wuhan Metro Line 7](image1)

In the section, the mud-water balance shield is mainly used, and the diameter of the excavation is 15.8m. Figure 2 is a layout diagram of the shield machine.

![Figure 2. Shield machine tool layout](image2)

The data processed in this paper mainly comes from two aspects: First, the various excavation parameters collected on various sensors of the shield machine can be stored and analyzed in the control room, including shield thrust, cutter torque, tunneling speed, The cutter wheel speed, etc.; the second is the parameter monitored by the field test, that is, the blade breaking rock normal force.

A lot of engineering practice shows [5-7], shield machine driving efficiency and cutter torque $M$, total thrust $F$, Cutter speed $n$ and tunneling speed $v$. The parameters are closely related, so the excavation parameters above the 10 tunneling rings from 416 ring to 426 ring are selected for statistical analysis. The data collected by each loop is averaged, and the abnormal data generated due to operational errors and shutdowns are eliminated. The final statistical results are shown in the following table:
Table 1. Statistic results of shield tunneling parameters

| Tunneling speed (mm/min) | Knife speed average (rpm) | Knife thrust average (kN) | Knife torque average (kNm) | Average penetration (mm/r) |
|--------------------------|---------------------------|--------------------------|---------------------------|---------------------------|
| 0 ~ 5                    | 1.49                      | 13389.47                 | 16270                     | 2.47                      |
| 5 ~ 10                   | 1.38                      | 13192.19                 | 17520                     | 5.64                      |
| 10 ~ 15                  | 1.30                      | 13096.25                 | 19760                     | 9.59                      |
| 15 ~ 20                  | 1.28                      | 13131.44                 | 20800                     | 13.38                     |
| 20 ~ 25                  | 1.22                      | 13098.34                 | 21070                     | 17.65                     |
| 25 ~ 30                  | 1.22                      | 12931.27                 | 17930                     | 23.03                     |

3. Analysis of the relationship between major excavation parameters

3.1. Normalization analysis of shield tunneling parameters

Excavation parameters shield total thrust, cutter wheel torque, scraper rock breaking normal force, tunneling speed, cutter head speed, etc., the dimensions are the same, and the magnitude is also very different, in order to visually reflect the relationship between the excavation parameters, The parameter data needs to be normalized [8]. The specific algorithm is as follows:

\[
\overline{X} = \frac{X_i}{X_{\text{max}}} \tag{1}
\]

\(\overline{X}\) for the normalized value, \(X_i\) for the actual value of each excavation parameter, \(X_{\text{max}}\) The maximum value for each excavation parameter.

Using the data collected in the field, normalize the processing to obtain the normalized value of the cutter head torque \(\overline{T}\) Normalized value with shield thrust \(\overline{F}\) The curve of the change during the tunneling process.

![Figure 3. Relationship between cutterhead thrust, ring number and cutter head torque](image)

It can be seen from Fig. 3 that during the tunneling of the 416 ring to the 423 ring, the blade cutter thrust value and the cutter wheel torque value are basically the same during the shield tunneling process, and the shield thrust and the shield torque variation range are very strong. Synchronization; in the 423 ring to 426 ring tunneling section, the cutter wheel thrust and the cutter wheel torque change amplitude...
are not synchronized, the cutter head thrust is slowly rising, and the cutter head torque is first lowered and then risen. The correlation between the two is the tunneling section is weak.

3.2. Analysis of correlation between excavation parameters and geological parameters
In order to further study the relationship between cutter thrust, cutter torque and various tunneling parameters, the following three concepts of penetration, specific torque and specific thrust were introduced.

The penetration degree is the depth of cut of the cutterhead in the shield tunneling, which is an important indicator to measure the tunneling. Defined as:

\[ P = \frac{v}{n} \]  

In the formula: \( v \) indicates the speed of the tunneling, \( n \) indicates the cutter speed.

Reintroducing specific thrust \( SF \) specific thrust torque \( ST \) the concept of:

\[ SF = \frac{F}{P} \]
\[ ST = \frac{T}{P} \]  

In the formula: \( F \) Represents the cutter head thrust, \( T \) Represents cutter head torque. Specific thrust \( SF \) The normal thrust of the cutter head required to indicate the depth of the unit, reflecting the ability of the soil to resist the cutting of the cutter. Specific torque \( ST \) Indicates the tangential cutting force of the cutter head required for the unit depth of cut, reflecting the ability of the soil to resist the formation of grooving. The specific thrust and specific torque reflect the relationship between the cutter head and the normal and tangential directions of the soil. The two are important parameters for measuring the effectiveness of the shield and the associated geological conditions.

A large number of engineering practices have shown that in a single, soft rock or hard rock formation with good integrity, \( SF \) with \( ST \) There is a good positive correlation between them. But in the following
cases, SF with ST. Uncertainty and complication will occur: ① Rock mass fissure development is high or very loose; ② Rock compression is relatively strong; ③ The stratification or strength change of the rock mass is more significant; ④ The tunnel excavation surface collapsed or encountered obstacles such as boulder. In these cases, the shield parameters tend to be abnormal, and indirectly reflect the differences in the formation.

From Figure 4, we can get 416 ring to 422 ring, the specific law of specific thrust and specific torque is basically the same, and the correlation between them is very strong. The tangential cutting force of the cutter head required for the unit depth of cut is consistent with the normal thrust of the cutter head required for the unit depth of cut, and the soil body has the ability to resist the formation of the groove and the ability of the soil to resist the cutting ability of the cutter. Explain that in the 416 ring to 422 ring tunneling section, the stratum is single and the integrity is good. The 417 ring to 422 ring thrust value and specific torque value fluctuate at a lower level. The tunneling section of the tunneling section is softer, and the soil body is less resistant to tool cutting and the ability to resist grooving.

For the 423 to 426 ring tunneling section, the correlation between specific thrust and specific torque is weak. The tangential cutting force of the cutter head required for the unit depth of cut and the change of the normal thrust of the cutter head required for the unit depth are weak. Explain that the 423 ring to 426 ring tunneling section, the geological conditions of the tunneling formation are more complicated than the 416 ring to 422 ring tunneling section. In the 423 to 426 ring, the specific thrust and specific torque values gradually enter a high level of fluctuation, the strength of the soil gradually increases, and the ability of the soil to resist cutting and forming the groove is gradually enhanced.

4. Analysis of field test results
During the tunneling process, the measured values of the 416 ring to 426 ring scraper normal force are selected to obtain the average value of each scraper in each ring excavation, and the singular data caused by the downtime or operation error is removed. At the same time, consult the engineering data to obtain the installation radius of each scraper. The analysis statistics are as follows:

4.1. The relationship between the normal force of the scraper and time

![Scratch force versus time curve](image)

**Figure 5.** Scratch force versus time curve

Figure 5 is a graph showing the measured change of the normal force of the blade over time. During the tunneling process, the normal force values of the scrapers at different positions on the cutter head vary greatly (see Figure 5). The center knife normal force value is the smallest and the data points are concentrated. The variation of the force value of the edge knife is the most significant, and the dispersion
of the data points is the largest. Generally speaking, in the tunneling section, the variation rules of the center knife, the face knife and the side knife are relatively uniform.

4.2. The relationship between the installation radius and the normal force of the scraper

The normal force of the scraper increases along the radial direction with the installation radius (see Figure 6), and the force of the tool decreases sequentially, which is roughly satisfied. \[ f = 50.313e^{-0.048r} \]
\[ R^2 = 0.5936 \] The degree of fitting is good. Among them, the central knife has the highest average force, and the average edge force of the knife is the smallest, while the average force of the face knife is relatively close.

5. Summary

(1) Normalize the shield tunneling parameters, analyze the relationship of each tunneling parameter, and use this as a criterion for identifying geological conditions.

(2) The normal force of the scraper during the tunneling process was measured and its force characteristics were analyzed.

(3) According to the monitoring results of the tool force, the function of the tool force and the installation radius is given. The overall force characteristics are as follows: along the radial direction, as the installation radius increases, the force of the tool decreases sequentially. It is roughly a power function relationship.

(4) The parameter analysis of the excavation and the distribution law of the tool force will provide the basis for the adjustment of the tunneling parameters and the design of the cutterhead.

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References

[1] Lin Shixiang, Hou Zhende, Wang Yihan, Chen Chao, Yue Cheng, Wang Yanqun. Study on the force of cutterhead during simulated shield tunneling [J]. Journal of Experimental Mechanics, 2013, 28 (02): 235-241.

[2] Xia Yimin, Zhou Xiwen, Liu Yujiang, Wu Wei. Study on the Law of Knife and Knife of a Type of Earth Pressure Balance Shield [J]. Journal of Natural Science of Xiangtan University, 2009, 31 (04): 92-96.

[3] Han Weifeng, Chen Fu, Li Fengyuan, Zhang Bing. Study on the mechanical characteristics of shield hobs with soft and hard formation [J]. Construction Mechanization, 2016, 37 (09): 55-58.

[4] Wang Hongxin, Fu Deming. Mathematical physics model of soil pressure balance shield tunneling and its relationship between various parameters [J]. Chinese Journal of Civil Engineering, 2006 (09): 80-90.

[5] Song Kezhi, Yuan Dajun, Wang Mengshu. Fuzzy Judgment of Tunnel Surrounding Rock Based on Shield Tunneling Parameters Analysis [J]. China Civil Engineering Journal, 2009, 42(01): 107-113.

[6] Song Kezhi. Research on shield tunneling efficiency of mudstone sandstone interactive stratum crossing tunnel [d]. Beijing: Beijing Jiaotong University, 2005

[7] Zhang Houmei, Wu Xiuguo, Zeng Weihua. Research on earth pressure balance shield tunneling test and mathematical model for tunneling [J]. Chinese Journal of Rock Mechanics and Engineering, 2005 (s2): 5762-5766.

[8] Li Zheng. Study on the correlation between Ф7m complex shield tunneling parameters and stratum in Shenzhen composite stratum [D]. Beijing: Beijing Jiaotong University, 2016.