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ORIGINAL PAPER

Development and Application of Cutterhead Working Status Monitoring System for Shield TBM Tunnelling

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Abstract
During the shield TBM tunnelling, the working status of the cutterhead is difficult to be determined because the pressured chamber is located behind the cutterhead. In this paper, a cutterhead working status monitoring system for shield TBM tunnelling was developed to monitor the working status of the cutterhead in real time. The system consists of data acquisition subsystem, control and data transmission subsystem, as well as data processing and display subsystem. The cutter wear, cutter rotation speed and cutterhead temperature can be monitored and transmitted to the system software through the central port by cable and wireless. The system software can simultaneously display the TBM operating parameters and cutterhead working status parameters, predict the cutter life and present early warning of abnormal working status. The system has been successfully applied in a shield tunnelling project. Based on the analysis of the monitoring data, it was found that the normal cutter wear mainly depended on the rock abrasiveness and cutter rotation distance. The difference in cutter wear rate in the different ground was more than 3 times. The relative sliding between the cutter and the tunnel face was widespread. The sliding distance in low-abrasive formations exceeded 1/3 of the cutter track length. Under the normal tunneling conditions, the cutterhead temperature was lower than 50°. The successful application shows that this system can work stably in long term under harsh work environment and provide guidance for shield TBM tunnelling.

Keywords Shield TBM · Cutterhead working status · Cutter wear · Cutter rotation speed · Monitoring system

List of Symbols

- ω Theoretical rotation speed of cutter, r/min
- N Cutterhead rotation speed, r/min
- R Cutter installation radius, mm
- d Cutter diameter, mm
- φ Cutter wear value, mm

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1 Introduction

Shield TBMs have been extensively employed in urban tunnel construction due to its high efficiency, safe working environment, low project cost for long-distance construction and mitigated environment disturbance (Geng et al. 2016; Xia et al. 2018). The cutterhead directly interacts with the rock mass and soil layer. It has the functions of breaking the rock masses, cutting the soil layers and supporting the tunnel face. With the extensive application of shield TBMs, the more complex geological conditions are encountered, such as hard rock ground, sandy pebble ground, mixed face ground and clayey soil ground. Excessive cutter wear, abnormal cutter wear and clay-cake adhesion to cutterhead result from complicated geological conditions influencing the working performance of the shield TBM. Moreover, the high water pressure and complicated surrounding environment bring enormous difficulties for inspecting and

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replacing cutter when shield TBM tunnels traverse the river, lake and sea (Gharahbagh et al. 2011). During the shield TBM tunnelling, the working status of the cutterhead is difficult to determine because the pressured chamber is located behind the cutterhead. Monitoring the working status of the cutterhead is of vital importance for avoiding the relative accidents of tunnel constructions.

The cutter wear status is one of the key factors affecting the excavation performance of the shield TBM. The untimely replacement of excessive and abnormal wear cutters brings a lot of hazards during the shield TBM tunneling, such as shortening the life of cutters, increasing the wear of surrounding cutters and the ultimate damage of cutterhead (Bilgin et al. 2012; Bilgin and Algan 2012; Tan et al. 2015; Wang et al. 2015). The Deep Tunnel Sewerage System project in Singapore was excavated in granite ground with different weathering grades, causing abnormal cutter wear and excessive cutterhead wear. The cutterhead and screw conveyor were modified to accomplish the subsequent construction (Zhao et al. 2007). Typical sandy pebble ground was encountered by Line 1 of the Chengdu Metro in China. The boulders stuck in the cutterhead opening or between cutters caused many engineering problems to reduce the efficiency of tunneling, including the improper cutter rotation and stoppage, excessive and uneven cutter wear (Gao et al. 2012; Xu and Song 2007; Hunt et al. 2017). The mixed face ground was encountered in the Kerman water conveyance tunnel, more than 63% of the replacement cutters resulted from abnormal cutter wear during TBM tunnelling (Dehnavi et al. 2017). During slurry shield tunnelling on the Qiangtang River tunnel in China, clay adhered to the cutterhead and formed clay-cake result in cutter stoppages, uneven cutter wear, high cutterhead temperature and the obvious reduction of the expected advance rate (Zhang et al. 2011). Besides, the Beijing Metro Line 9 was excavated in gravel and pebble ground, so serious cutterhead wear was observed at the radial area with a maximum width of 670 mm (Yang et al. 2018).

Cutter wear detection methods include manual inspection, threshold detection, adding odorant, operation parameters analysis, rock chips shape analysis, and real-time monitoring method (Zhang 2015; Sun et al. 2016; Wang et al. 2019). Although manual inspection is the most direct method, it is time consuming and dangerous under hyperbaric conditions. Only a setting value can be obtained by the threshold detection method. The adding odorant method is not effective in shield TBM tunnelling because the cutterhead locates in a closed environment. The operation parameters analysis and rock chips shape analysis are affected by many factors, leading these methods do not accurately detect the cutter wear. Thus, real-time monitoring method with the characteristic of accuracy and convenience can be extensively apply in shield TBM tunnelling.

Sensor, computer and communication technology have rapid developments in the past decades, some scholars and institutions conducted extensive studies on the monitoring technology of cutter wear and rotation speed. The non-contact eddy-current sensor is based on the principle of electromagnetic induction, which is insensitive to any non-conductive medium and has strong ability to resist a harsh environment. Wang et al. (2019) applied Ansoft Maxwell simulation to optimize the coil geometry parameters and circuit structure of the eddy current sensor to meet the requirement of disc cutter wear measurement. Zhang et al. (2017) designed a cutter wear monitoring system based on eddy-current sensor technology with a maximum measurement range of 40 mm. Zheng et al. (2015) designed an online monitoring system for cutter wear using eddy-current sensor. The error of cutter wear is less than 0.5 mm during the laboratory tests. However, the system was not applied in the field. Lan et al. (2016) presented a monitoring method of cutter rotation speed by using eddy-current sensor and this method had been verified on the rotary test bench. Sun et al. (2016) and Ren and Sun (2015) developed a wireless cutter wear monitoring system to detect cutter wear based on eddy-current sensors. The designed probe diameter is 48 mm with the measurement range of 0–25 mm and the resolution is 1 mm. On the basis of the above study, Li et al. (2016) applied the system in Nanning Metro Line 1, the calibration curve is obtained by adjusting the distance between the cutter and the sensor. In fact, the engineering applications of these monitoring systems were not unsatisfactory due to the narrow measurement range and large structure volume of the eddy-current sensors. For example, the diameter of the sensor is close to 90 mm when it only has 60 mm measurement range.

Xia et al. (2013) monitored cutter wear by using an inductive displacement sensor with an accuracy of 0.1 mm, realizing the wireless transmission of the signals in soil and water. Zhang et al. (2013) designed an online monitoring device for TBM cutter wear based on the principle that the number of laser lines change with the cutter wear. But the measurement accuracy was greatly affected by the foreign matters on the cutter surface. The magnetic sensor can transform the measured values into induced electromotive forces by the interaction between electricity and magnetic based on electromagnetic induction technology (Wang et al. 2014). Liu et al. (2016) proposed that a Z-element magnetic sensor with a maximum range of 100 mm was used to detect the cutter wear. A cutter instrumentation system was developed by the Robbins Company designed to monitor the cutter rotation speed, vibration and cutter axis temperature by fixing an electronic sensor inside the cutter shaft. The cutter wear can be calculated by the cutter rotation speed. The main shortcoming of this system is that the cutter shaft need to be customized

(Shananan and Box 2011). The Herrenknecht Company designed a cutter rotation monitoring system that can monitor the TBM cutter rotation speed and temperature in real-time. However, the principle of the system was not published. Gharahbagh et al. (2013) designed a hydraulic cone penetration test (CPT) to monitor gauge cutter wear based on the relationship between the overcut length and the length of the gauge cutters.

Based on the above statements, the current monitoring systems were only used to detect single or double parameters of cutterhead conditions, such as cutter wear and cutter rotation speed. Limited monitoring parameters do not accurately estimate the status of cutterhead. Most of these monitoring systems were limited to laboratory testing and few of them were applied to engineering practice. At present, the proposed systems have many shortcomings or the methods limit the extensive application in the practice engineering, including the narrow measurement range, the low accuracy of these sensors affected by the foreign matters, even specified design of the cutter shaft, etc. In this paper, a cutterhead working status monitoring system for shield TBM tunnelling is proposed and developed to accurately monitor the cutter wear, cutter rotation speed and cutterhead temperature. The cutter life is predicted and the cutterhead working status is comprehensively determined combined with the TBM operating parameters and geological conditions. The engineering application of this system showed that it can provide guidance for the shield TBM tunnelling.

2 System Design and Composition

The system goal is to obtain the data relative to the cutterhead working status and to evaluate whether the working status is normal or not. The cutter wear, cutter rotation speed and cutterhead temperature are selected as the measurement parameters in this system. The cutter wear and cutter rotation speed directly show the working status of the cutters, including normal cutter wear or abnormal cutter wear (for example, cutter ring off and flat cutter wear). The cutterhead temperature is an indirect response whether the muck flows smoothly from the tunnel face to the soil or slurry chamber or not. To evaluate the whole working status of cutterhead, the TBM operating parameters and the corresponding geological conditions are input to the system. The system consists of data acquisition subsystem, a control and data transmission subsystem, as well as data processing and display subsystem, as shown in Fig. 1.

The data acquisition subsystem is used to collect and parse the monitoring data of the cutterhead and battery capacity. It is integrated by sensor set, data acquisition module and power supply. The sensor set include the cutter wear sensor, cutter rotation speed sensor, temperature sensor and other variables sensors. Each sensor can work independently or a set of sensors can be flexibly combined into a sensor box to conveniently install inside the cutter housing. The main task of the control and data transmission subsystem is to control the working modes of these sensors. Besides, the data and commands are transmitted between the sensors and

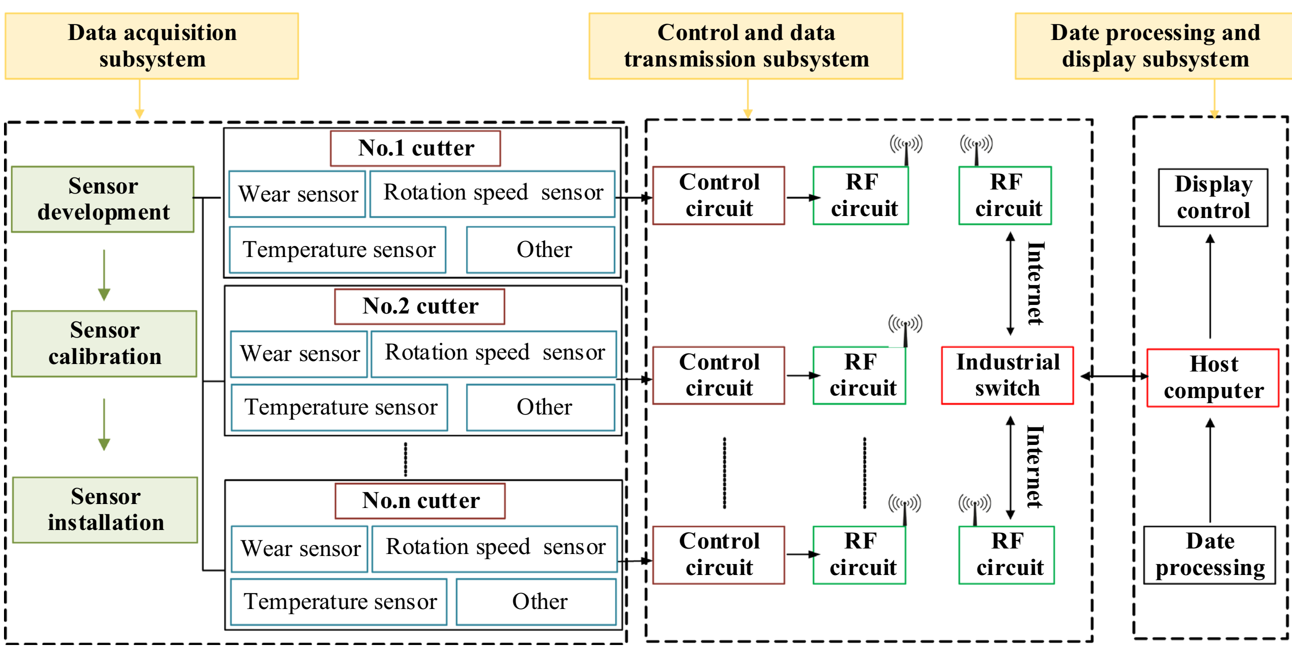


Fig. 1 Scheme design of the monitoring system

the system software. The data processing and display subsystem is mainly used for storing and analyzing the acquisition data, such as the monitoring data by the installed sensors, the TBM operating parameters from the programmable logic controller (PLC) of TBM and some input parameters. Finally, the data processing results are displayed to present the status of the cutterhead.

2.1 Magnetoresistive Sensors Development and Its Installation Structure

The laser displacement sensor has a high cost and rigorous requirement for monitoring environment. Moreover, the eddy-current sensor cannot meet the requirements of wide measurement range and small structure volume at the same time. The non-contact magnetoresistive sensor is designed with a Wheatstone bridge structure, as shown in Fig. 2. Four anisotropic magnetoresistances are used for bridge arm resistance and its resistance is sensitive to applied magnetic field. The resistance of the bridge arm changes and the bridge balance is broken with the change of the applied magnetic field, resulting in the change of the output voltage *V* between *B* and *D*. Moreover, because the applied magnetic field is affected by the shape and thickness of the excitation magnet, the magnetoresistive sensor can simultaneously meet the requirements of a wide measurement range and small size by selecting a suitable excitation magnet. Based on the above analysis, the magnetoresistive sensor is suitable to measure the cutter wear and cutter rotation speed.

The disc cutters are installed in the cutter housing. The usable space of the cutter housing is limited for us to install the magnetoresistive sensors for monitoring the cutter wear and rotation speed. Thus, the installed position and space need to be considered before the magnetoresistive sensors were designed. The back of the cutter housing, namely the opposite side of the tunnel face, need to be used for replacing the cutters, so the magnetoresistive sensors are installed at the side of the cutter housing. It also should be considered that the influence of the sensor installation on the stiffness of cutterhead, the durability of the sensor sets and construction process. Based on the non-contact magnetoresistive sensing technology, the magnetic displacement and magnetic switch sensor were designed to monitor the cutter wear and rotation speed as shown in Fig. 3. A magnetic field around the sensor and cutter is generated because of the installation of the excitation magnet on the cutter wear sensor. As the cutter wear increases, the magnetic flux density changes. This change is detected by the wear sensor and transmitted to the system software as a digital signal. Finally, the system software obtains the monitoring value by table checking or curve fitting according to the pre-calibrated data. The excitation magnet of the rotation speed sensor is mounted in the magnet base, which is welded on the cutter shaft, as shown in Fig. 4. The magnetic field of excitation magnets of wear sensor and rotation speed sensor do not disturb each other by controlling the location of the magnet base. The periodic signal can be monitored by the rotation speed sensor when the excitation magnet rotates with the cutter. Pulse signals are formed by the rotation speed sensor and handled by the processor to obtain the cutter rotation speed. Temperature sensor is used for monitoring cutterhead temperature. Besides, some other variables, including the remaining battery capacity of the sensor sets and tilt angle of the cutterhead, are also monitored. As tested, the wear sensor has a maximum measurement range of 80 mm with an accuracy of 0.2 mm and within the measurement range of 50 mm with

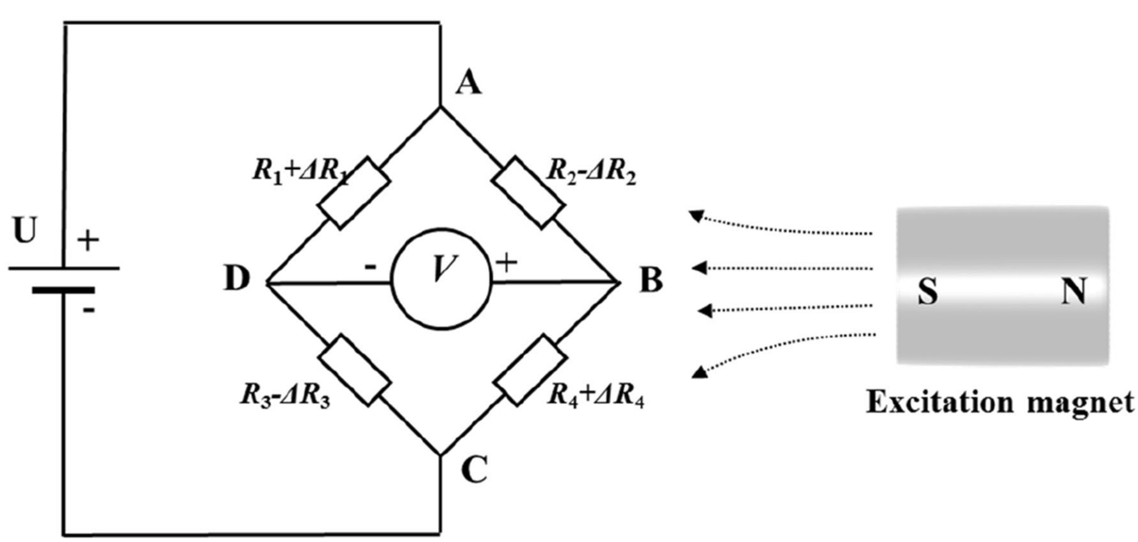


Fig. 2 The principle of magnetoresistive sensor

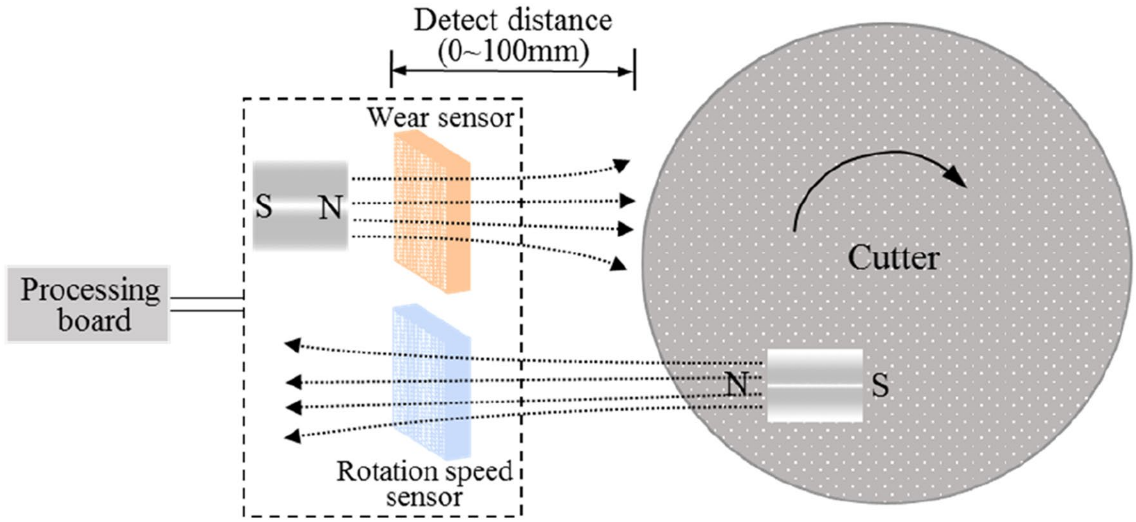
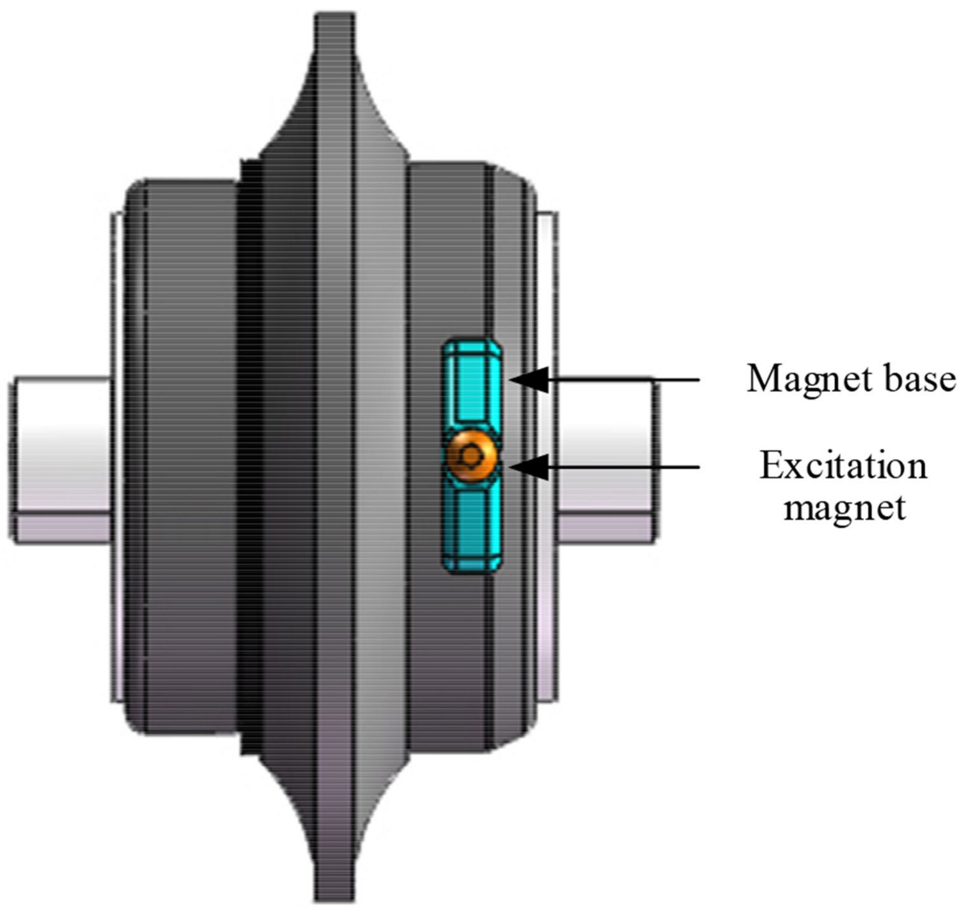


Fig. 3 Working principle of the cutter wear and cutter rotation speed measurement

Fig. 4 Installation location of the excitation magnet of the rotation speed sensor



an accuracy of 0.1 mm. The maximum sensing distance of the rotation speed sensor is 100 mm and the measurement range from 0 to 150 rpm. The temperature sensor resolution is 1 °C.

According to different cutterhead structures and cutter housing positions, a variety of integrated sensor set structures are developed to meet different installation requirements, as shown in Fig. 5. For instance, the integrated tilt

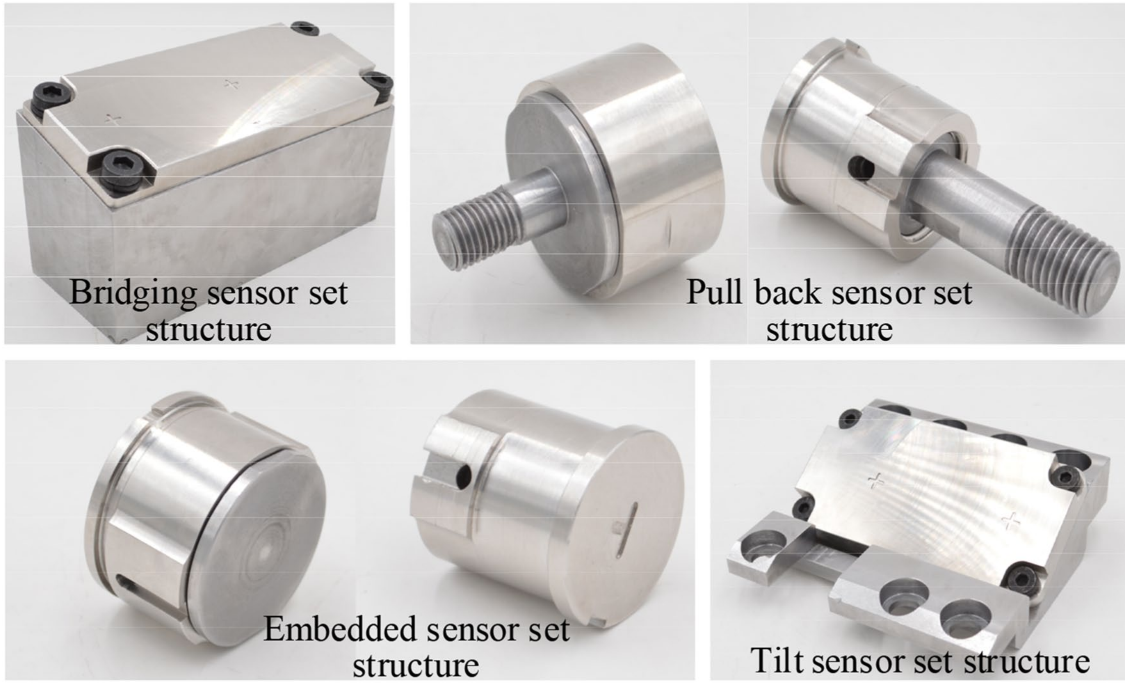


Fig. 5 Integrated sensor set structures

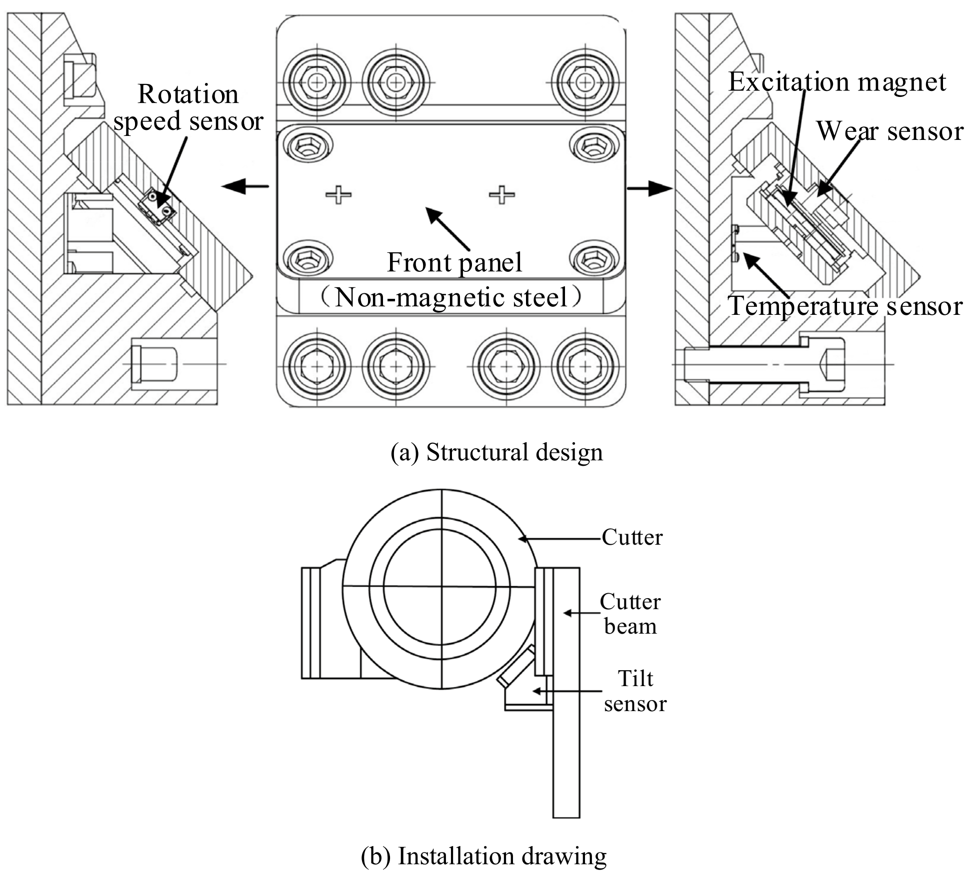


Fig. 6 Installation structure of the integrated tilt sensor set

sensor set is installed on the inside of the cutter housing. Its structure and installation method are shown in Fig. 6. Non-magnetic steel is used as the front panel of the sensor set structure for eliminating the influence of ferromagnetic material on the magnetic field of the excitation magnet. Non-magnetic steel also has better wearability and higher strength than ordinary steel.

2.2 Automatic Control and Data Transmission

2.2.1 Data Transmission Module

The data transmission module is distributed in each sensor set and the center port. The main task of the data transmission module is to transmit the sensor monitoring data to the system software and send the control command of the system software to the sensors, as shown in Fig. 7. According to the cutterhead structure and actual working environment, wireless and cable data transmission mode can be adopted. The wireless transmission mode adopts LoRa spread spectrum communication technology with a radio frequency (RF) of 433 MHz. In the cable transmission mode, each sensor set is connected to the concentrator using an RS-485 communication bus. The concentrator collects all RS-485 signals and transmits to the central port by a slip ring. The central port converts the RS-485 signals into network signals and transmits them to the host computer. The wireless transmission mode is flexible for the sensor sets installation and the system has more monitoring nodes. While the cable transmission mode has higher stability and faster rate of data transmission. However, the monitoring nodes of the cable transmission mode are limited due to the heavy protective structure of the cable in the cutterhead.

2.2.2 Automatic Control Module

The system software is always in working status for continuously obtaining TBM operating parameters, accepting the monitoring results and issuing the commands to the sensor sets. Usually, there are two modes for each sensor, one is standby mode and the other is working mode. As the TBM stops tunnelling, all of the sensors are set to standby to lower the power consumption of the sensor sets. Once the system software detects that the rotation speed of the cutterhead is greater than 0 and the data acquisition command is issued to the sensor sets, then the sensors go into the working mode. Under the working mode, cutter wear, cutter rotation speed, cutterhead temperature, and battery capacity are monitored at a set interval. These monitoring data are sent to the central port by cable or wireless and then transmitted to the host computer according to the sensor serial number. While the rotation speed of the cutterhead is detected as 0 by the tilt angle sensor, the system software will issue the commands to the sensor sets to switch into the standby mode.

2.3 Software Framework and Visualization

2.3.1 Software Framework

The system software needs to implement six functions, including parameters setting, data acquisition and storage, data analysis, data inquiry, result display and user management. Five parallel modules in the system software are set, including data acquisition module, data analysis module, data display module, parameters setting module and user management module, as shown in Fig. 8. Each module is divided into relatively independent submodules depending on its functions. For example, the data acquisition module is composed of two parts, one is set to collect

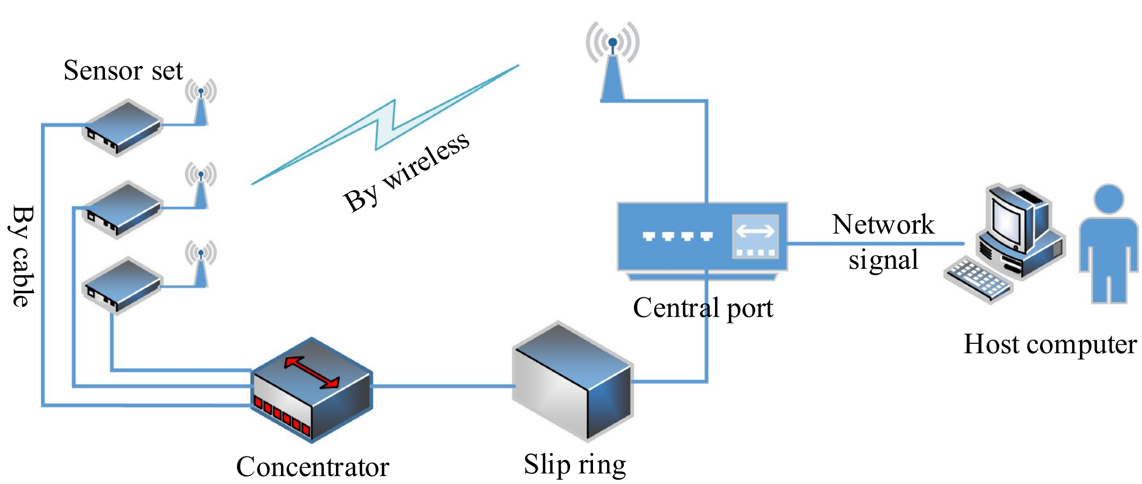


Fig. 7 Data transmission of the system

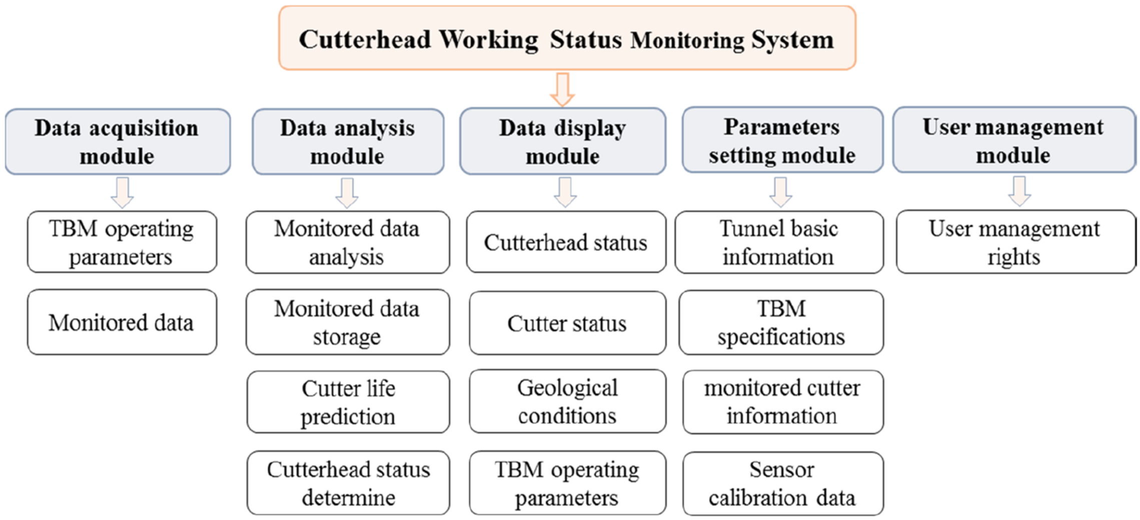


Fig. 8 Software framework

the monitoring data by all of the sensor sets, the other is set to accept the TBM operating parameters simultaneously. The system software is developed by Qt and vc++ programming language, using SQLite as the database.

2.3.2 The Interfaces of the System Software

Figure 9 shows the main interface of the system software. The left side of the main interface shows the cutterhead working status and the positions of these monitored cutters. The color of the cutter is green when the cutterhead works normally. As the color changes to red, it presents an alarm status. The possible problems include that the cutterhead

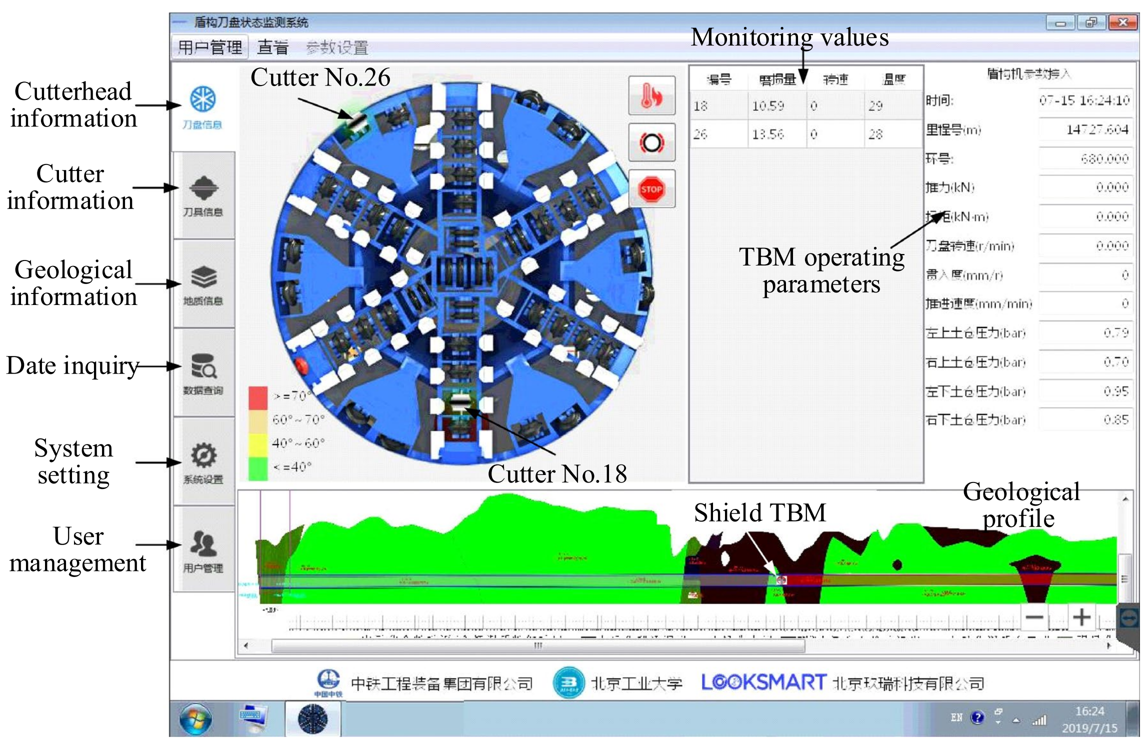


Fig. 9 Main interface of the system software

has an extremely high temperature, the cutter wear exceeds the setting wear limit or cutter rotation stopping, etc. This interface can also be displayed as a simple concentric circle mode according to the cutter installation radius. The middle part displays these monitoring values of each sensor set. The right side displays the real-time TBM operating parameters. And the engineering geological profile along the tunnel alignment and the current position of the TBM are displayed at the bottom.

In addition to the main interface, the system software also includes the monitored cutter information interface, geological information interface, data query interface, system setting interface and user management interface. The monitored cutter information interface shows all of the monitoring informations of one cutter at present, such as cutter wear, cutter rotation speed and cutterhead temperature, as shown in Fig. 10. The distribution of cutter wear in the cutter circle is on the upper left, the relationships between cutter wear and chainage is on the upper right and the changes of cutter rotation speed with the increase of chainage is on the lower left. Besides, the predicted cutter life with the change of chainage is on the lower right of this interface. The geological information interface displays the engineering geological profile and rock mass conditions along the tunnel alignment and the corresponding TBM operation parameters. The system setting interface is mainly used to set the cutterhead and cutter parameters and input the calibration parameters of each sensor.

3 System Assembly and Verification Tests

3.1 System Assembly

Figure 11 shows the procedure of system assembly based on the following design. The system is composed of a host computer, a central port and many sensor sets. The central port links with these sensor sets by wireless or cable and connect with the host computer through a network cable.

3.2 Laboratory Testing

A calibration device was designed and manufactured to verify the system workability and the accuracy of the developed

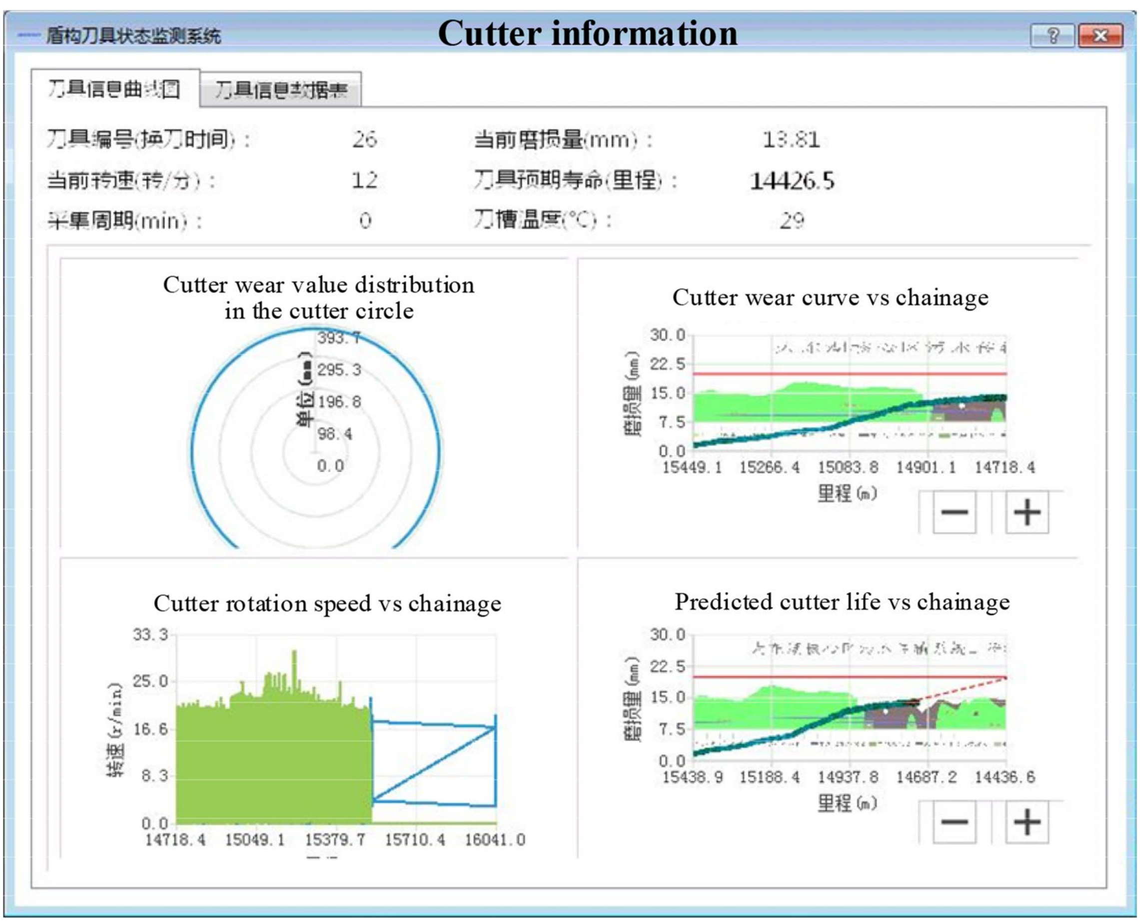


Fig. 10 Cutter information interface

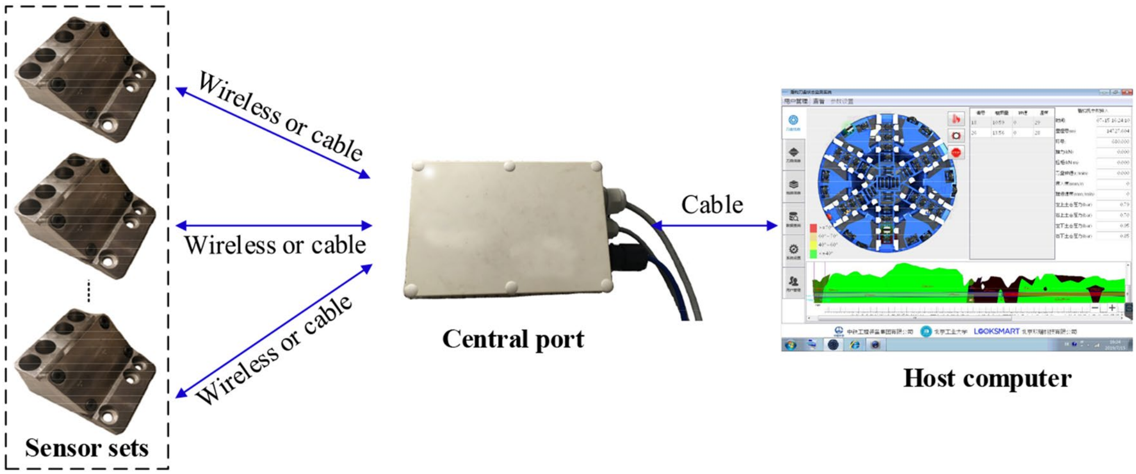


Fig. 11 System assembly

magnetoresistive sensors, including the cutter wear and the cutter rotation speed. The calibration device consists of a calibration box, a rolling cutter, a motor, a guide rail, a grating ruler, a sensor bracket and the developed sensor sets, as shown in Fig. 12. The calibration box can be filled with water, slurry, muck and other media. The cutter is placed in a calibration box and rotated by a connected motor. The grating ruler is installed above the guide rail and used to measure the moving distance of the bracket. The bracket is installed below the guide rail and used to hold the sensor set. The cutter wear sensor faces the cutter tip. Moving the sensor bracket can precisely adjust the distance between the sensor and the cutter tip.

The stability and reliability of wireless transmission mode were verified before the verification and calibration tests. After that, a verification test was carried out to check the performance of the rotation speed sensor. During the verification test, a real disc cutter was installed in the calibration box and a sensor set was also installed to the sensor bracket. After that, the motor drove the cutter to rotate. The rotation speed monitoring by the sensor set is in good agreement with that of the motor at different motor speed, verifying the accuracy and stability of the rotation speed sensor. The cutter wear was simulated by moving the sensor bracket and the movement was measured by the grating ruler and the monitoring system simultaneously. The output voltage of the cutter wear sensor varies with the changes of the cutter wear, verifying that the system is workable. Then, a series of calibration tests were conducted to simulate the working condition of the sensor set in the different media. Figure 13 shows the media in the calibration box was changed into water, slurry and soil muck, respectively. The sensor set was completely immersed in the media to simulate actual working conditions. The calibration curves in different media are shown in Fig. 14. Obviously, the cutter wear value increases as the output voltage of the cutter wear sensor decreases gradually. In other words, each output voltage has a unique corresponding cutter wear value. The calibration curves show great consistency in four media, indicating that the sensor works well in the different media, as shown in Fig. 14. The calibration test results are used to improve measurement accuracy in the actual monitoring environment. The actual monitoring environment of the sensors is determined based on the geological profile along the tunnel alignment and the type of residue soil on the belt.

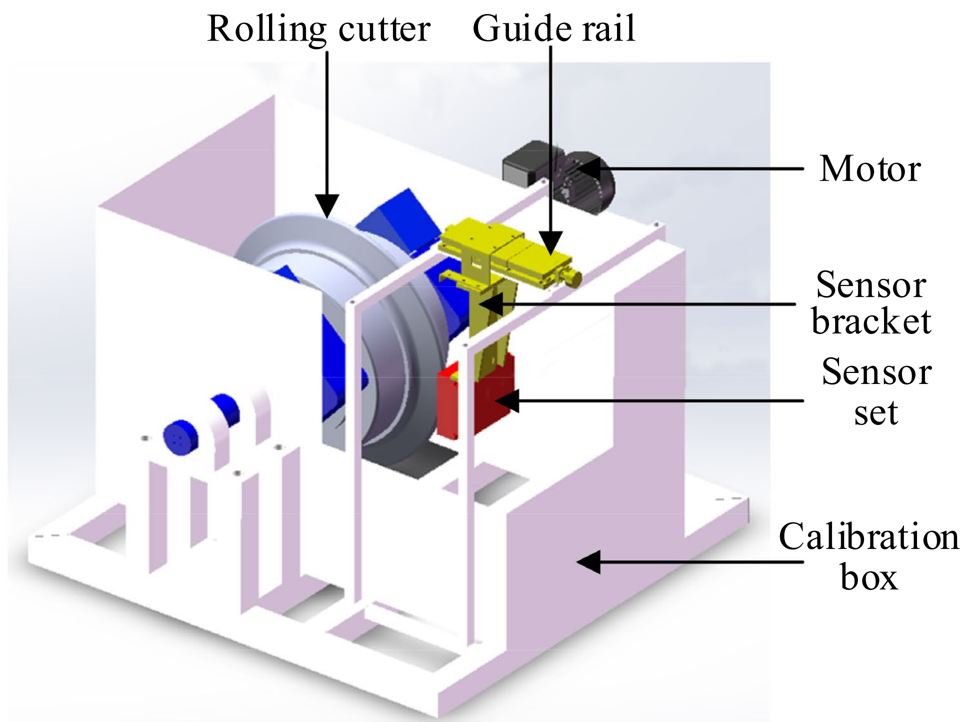
4 Engineering Application

4.1 Project Overview

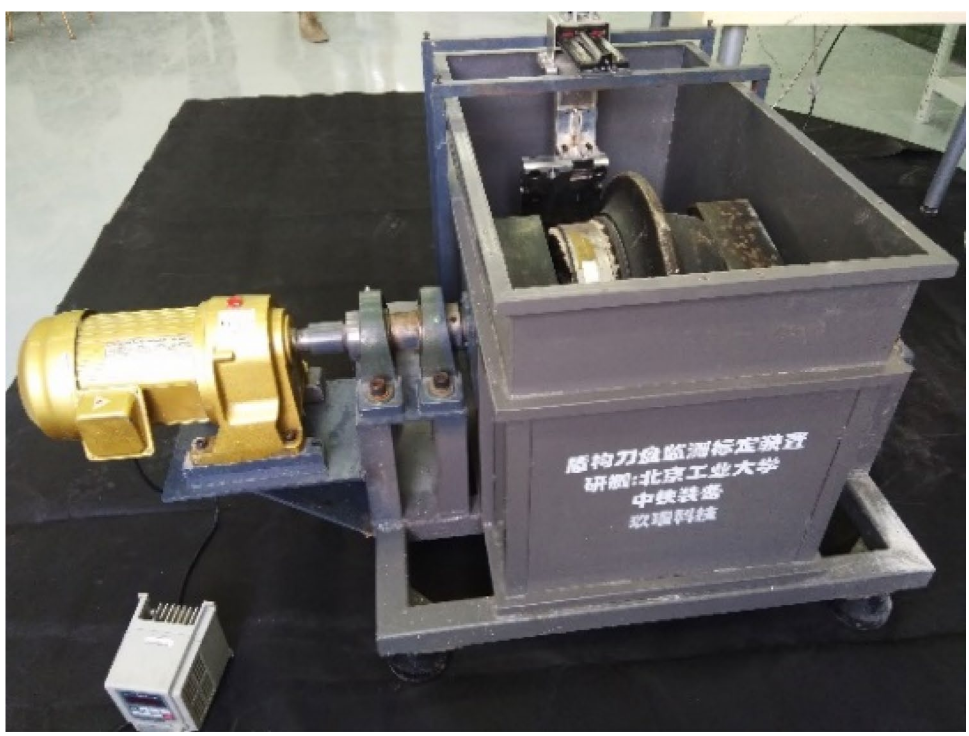
The cutterhead working status monitoring system has been applied to a TBM tunnelling section between No. 7 shaft and No. 8 shaft of the sewage transportation system project at the Dadonghu area, Wuhan, as shown in Fig. 15. The total length of the section is about 1612 m. An earth pressure balanced (EPB) shield TBM with a diameter of 6.56 m was used in this project, as shown in Fig. 16. The maximum RPM is 3 and the maximum advance rate is 80 mm/min. The maximum thrust and the rated torque of this machine are 2811 t and 3500 kN m, respectively. The cutterhead is equipped with 30 disc cutters and 26 scrapers, 8 of which are side scrapers. The nominal diameter of the disc cutter is 15.5 in (394 mm), the actual circumference of the cutter is 1250 mm and the actual cutter diameter is about 15.7 in (398.0 mm).

Figure 17 presents the geological profile along the tunnel alignment between No. 7 shaft and No. 8 shaft. The depth and the slope of the tunnel are 40–42 m and 0.65‰, respectively. According to the suggested methods

Fig. 12 Laboratory calibration device



(a) The design of the calibration device



(b) The Photo of the calibration device

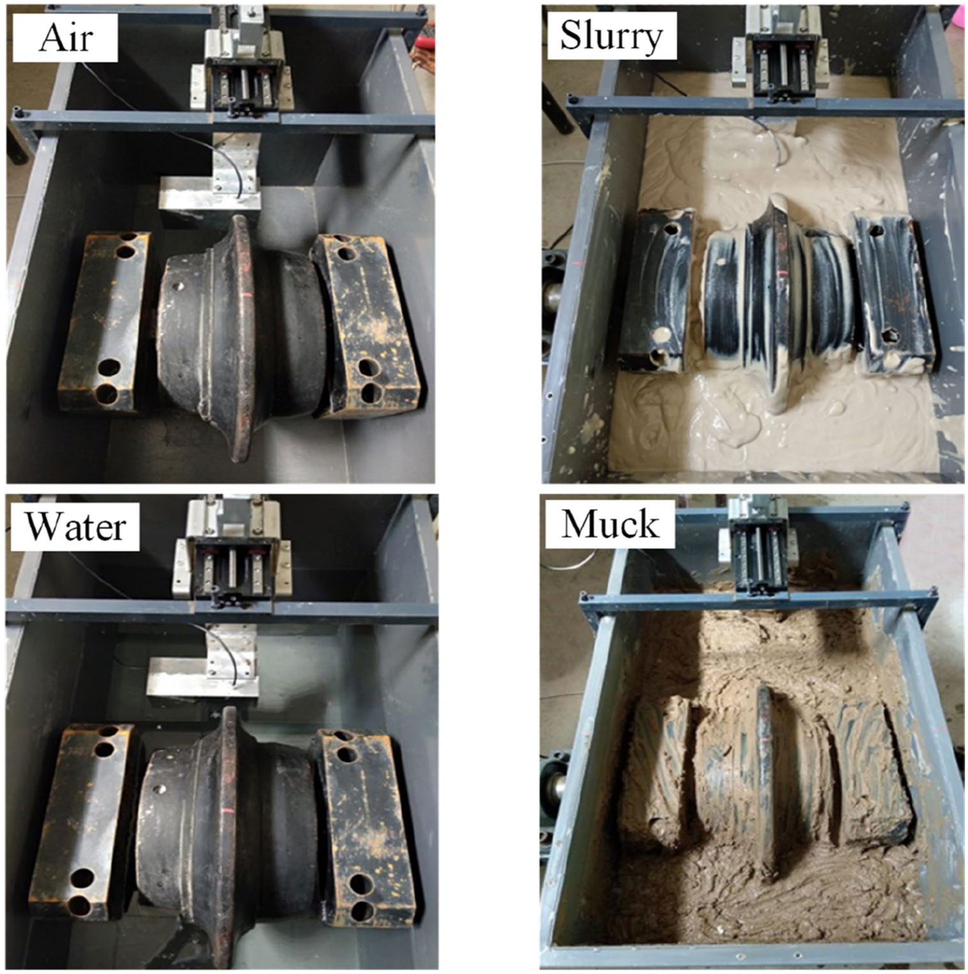


Fig. 13 Calibration tests in four media

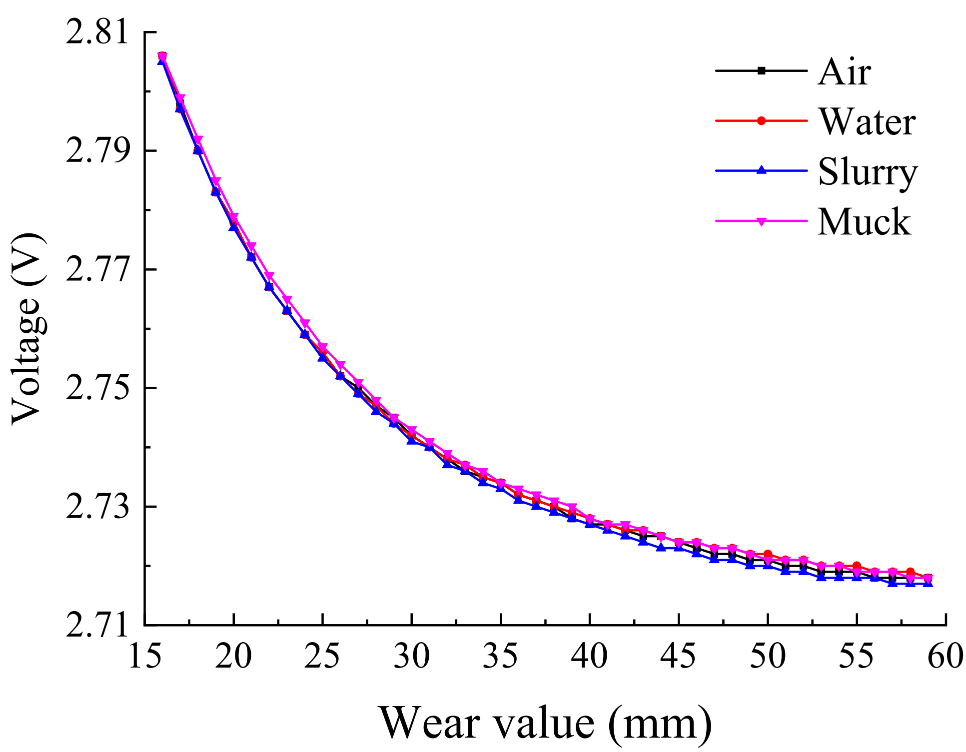


Fig. 14 Calibration curves of the cutter wear sensor in four media

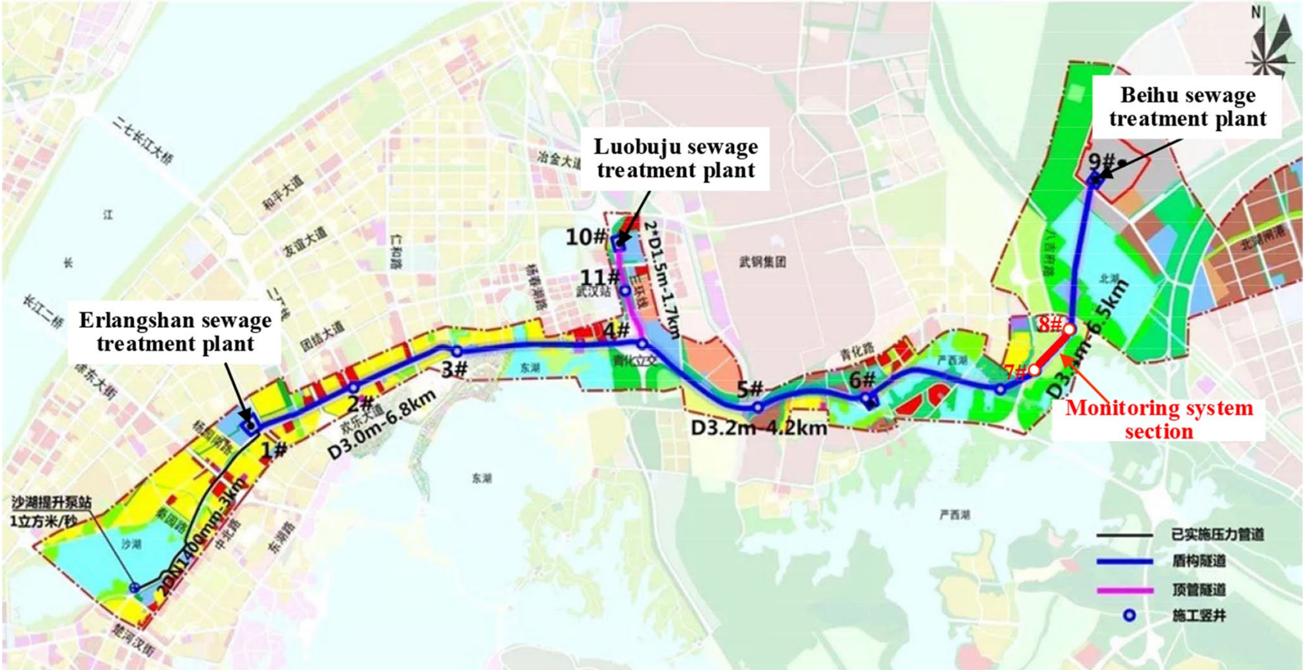


Fig. 15 Layout of the monitoring system section

Fig. 16 Earth pressure balanced shield TBM

for quantitative description of discontinuities in rock masses by ISRM (1981), the tunnel went through different rock grounds and the dominant weathering grades are moderately and highly weathered (GIII and GIV). The shield TBM started from the No. 8 shaft and the rock

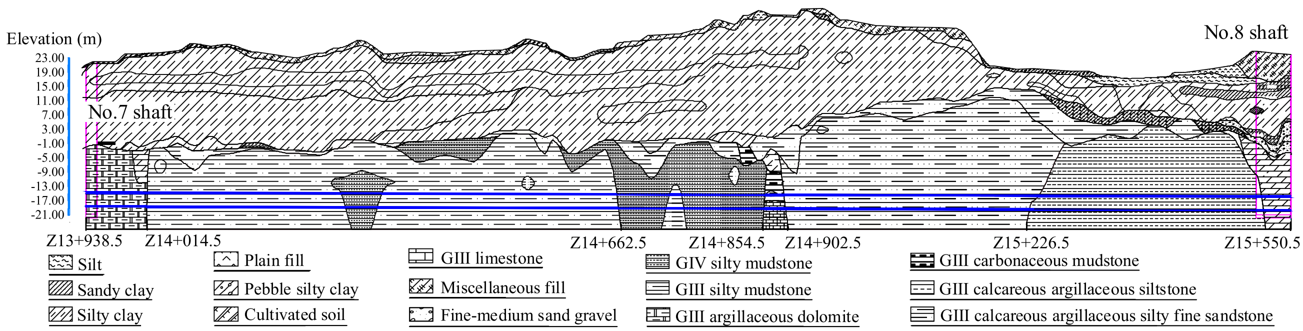


Fig. 17 Geological profile along the tunnel alignment

Table 1 Geological information

Ground number	Chainage (m)	Ring number (*N*)	Geological condition	Weathering grade
18e-2	15,550.5–15,226.5	0–270	Calcareous argillaceous siltstone	GIII
15a-2	15,226.5–14,902.5	270–540	Calcareous argillaceous silty fine sandstone	GIII
18g-2	14,902.5–14,854.5	540–580	Carbonaceous mudstone	GIII
18a-2	14,902.5–14,854.5	540–580	Limestone	GIII
18d-1	14,866.5–14,662.5	580–740	Silty mudstone	GIV
18d-2	14,662.5–14,014.5	740–1280	Silty mudstone	GIII
18c-2	14,014.5–13,938.9	1280–1343	Argillaceous dolomite	GIII

mass conditions distributed in different chainages are list in Table 1.

4.2 System Installation

Two cutters located in different positions of the cutterhead were selected as the monitoring points for the system. The cutter No. 18 is a face cutter with an installation radius of 1.518 m and the cutter No. 26 is a gauge cutter with an installation radius of 2.149 m. On the basis of the cutterhead design, the integrated tilt sensor set was selected to install at the side of the cutter housing, as shown in Fig. 18. The layout of the system on site is shown in Fig. 19. Limited by the cutterhead structure, the data transmission mode by cable was adopted. The whole system was tested after the installation of this system and the results showed that the system worked normally.

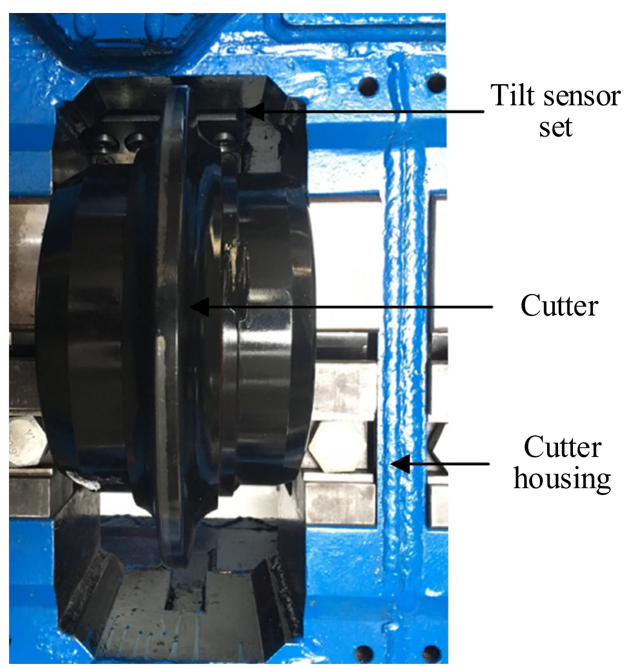
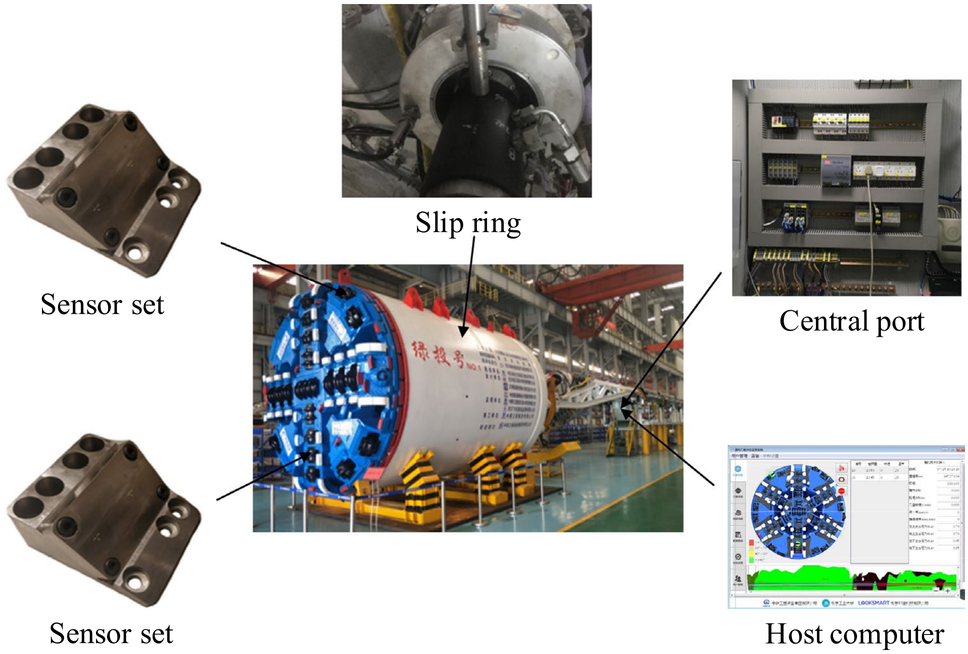


Fig. 18 Sensor installation

4.3 System Operation Results

The shield TBM started tunnelling from No. 8 shaft on April 6, 2019 and drove out the tunnel for maintenance at No. 7 shaft on September 28, 2019. A total length of about 1600 m (1343 rings) were excavated during this period. The monitoring system was in good working condition

Fig. 19 System layout



throughout the whole construction period. The monitoring results showed that cutter No. 26 stopped with the 19.2 mm wear and an alarm in Ring No. 1343. Moreover, the cutter No. 18 stopped and the cutter wear exceeded the wear limitation with an alarm in Ring No. 1280. After the shield TBM arrived to the maintenance shaft, it is observed that the cutter No. 26 had a multi-flat wear with cutter circumference of 112.8 cm and average wear of 19.4 mm, while the cutter No. 18 was ring off, as shown in Fig. 20. The installed sensor sets were intact without damage. The actual conditions of two monitored cutters were consistent with the monitoring results and the difference of cutter wear was only 0.2 mm. The field application showed the stability and accuracy of the system.

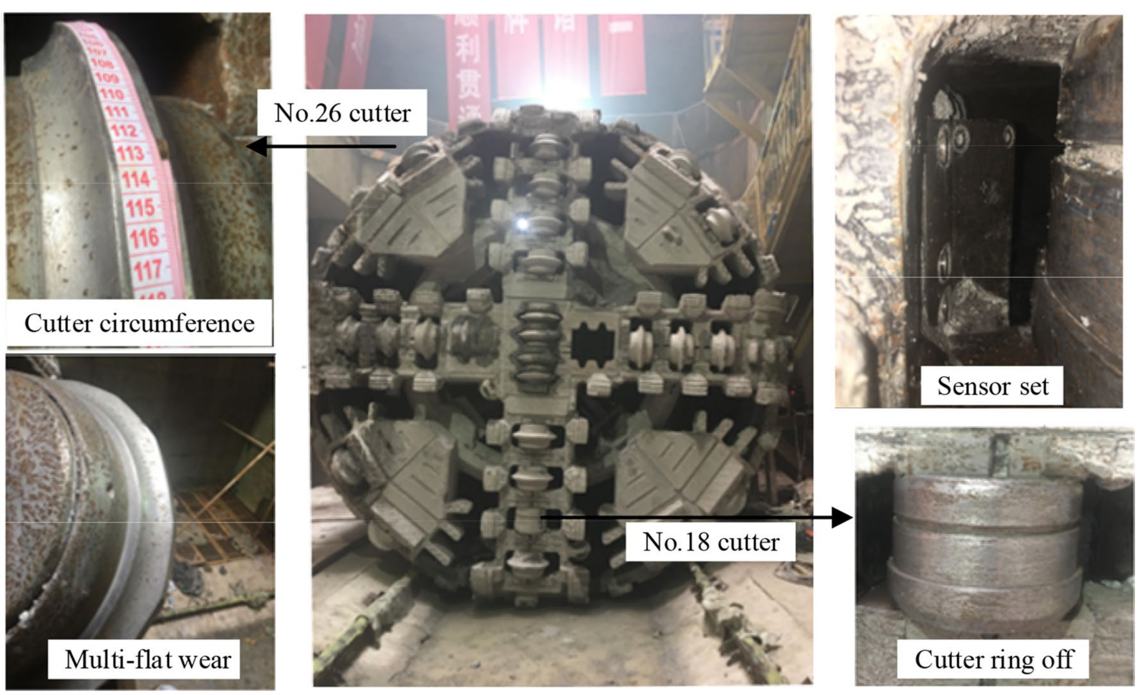
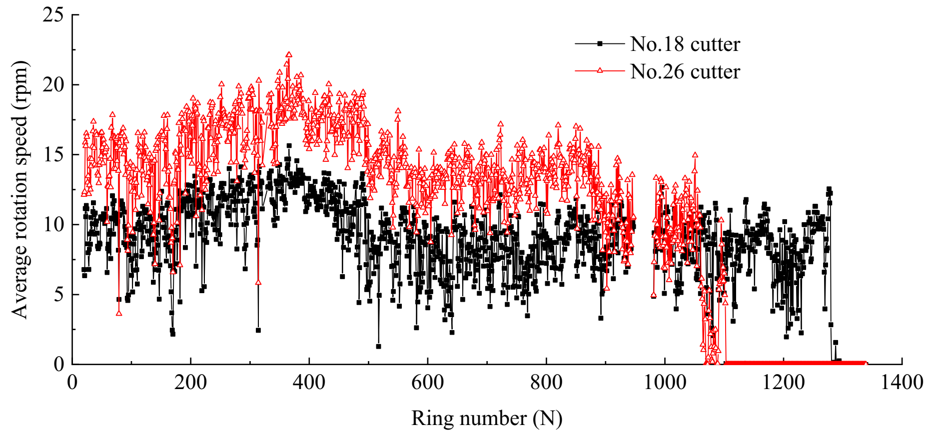


Fig. 20 Conditions of cutter and sensor

Fig. 21 Variations of cutter rotation speed with ring number



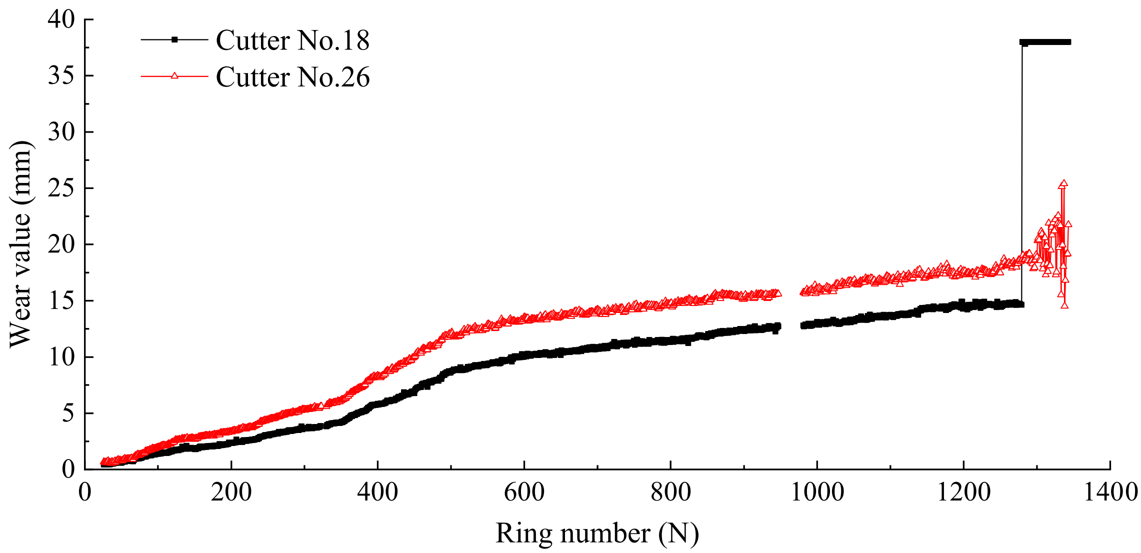


Fig. 22 Variations of cutter wear with ring number

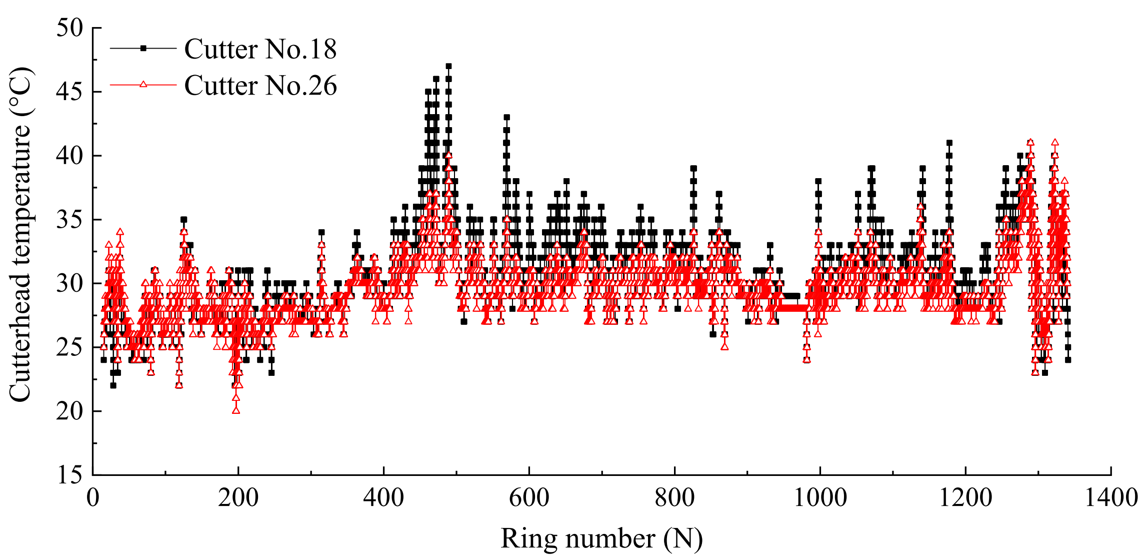


Fig. 23 Variations of cutterhead temperature with ring number

Figures 21, 22, 23 presented all of the monitoring data during shield TBM tunnelling in this section. As can be seen that the rotation speed of the two cutters are fluctuating. It indicates that slipping between cutters and the tunnel face occurs usually. The rotation speed of the cutter No. 26 is greater than that of the cutter No. 18. The cutter wear gradually increases with the increase of ring number and the wear value of the cutter No. 26 is larger than that of the cutter No. 18. For the whole monitoring process, the cutter wear and cutter rotation speed show obvious change with the change of the ground conditions. The cutterhead temperature is in good agreement with the actual tunnel condition and fluctuates in the normal range, indicating that the muck flows smoothly.

For other monitoring systems that have been tested, the maximum measurement range and accuracy of the system designed by Li et al. (2016) were 5 mm and 1 mm, respectively. Zheng et al. (2015) designed an on-line monitoring system for cutter wear with the error of 0.5 mm during the laboratory tests. Lan et al. (2016) proposed an on-line rotational speed monitor system with a monitoring error of less than 1.5%. Actually, the effect of field application was not mentioned and only one parameter can be detected in the previous researches.

5 Data Analysis

The cutter wear process, the reasons for the abnormal cutter wear and the cutter slipping phenomenon were discussed by comprehensively analyzing the system monitoring data combined with the operation parameter during the shield TBM tunnelling.

5.1 Cutter Rotation Stoppage Analysis

According to the monitoring data of the cutter No. 26, the cutter rotation speed gradually reduced to 0 (less than 1 r/min) in Ring No. 1072 and the main interface of the software showed that this cutter stopped with an alarm. After that, the cutter recovered rotation with a lower rotation speed and the alarm was eliminated at the same time. The cutter rotation speed of the cutter No. 26 showed 0 in Ring No. 1103 and an alarm was given again until the shield TBM arrived at the maintenance shaft. The consecutive 20 times monitoring data of the cutter wear sensor at Ring No. 1343 are shown in Fig. 24. The monitoring data show that the cutter has suffered from severe multi-flat wear. The difference between the maximum and the minimum cutter wear is close to 7 mm. The average wear of the cutter No. 26 was 19.20 mm in Ring No. 1343, which is consistent with the actual wear result of the cutter, as shown in Fig. 20.

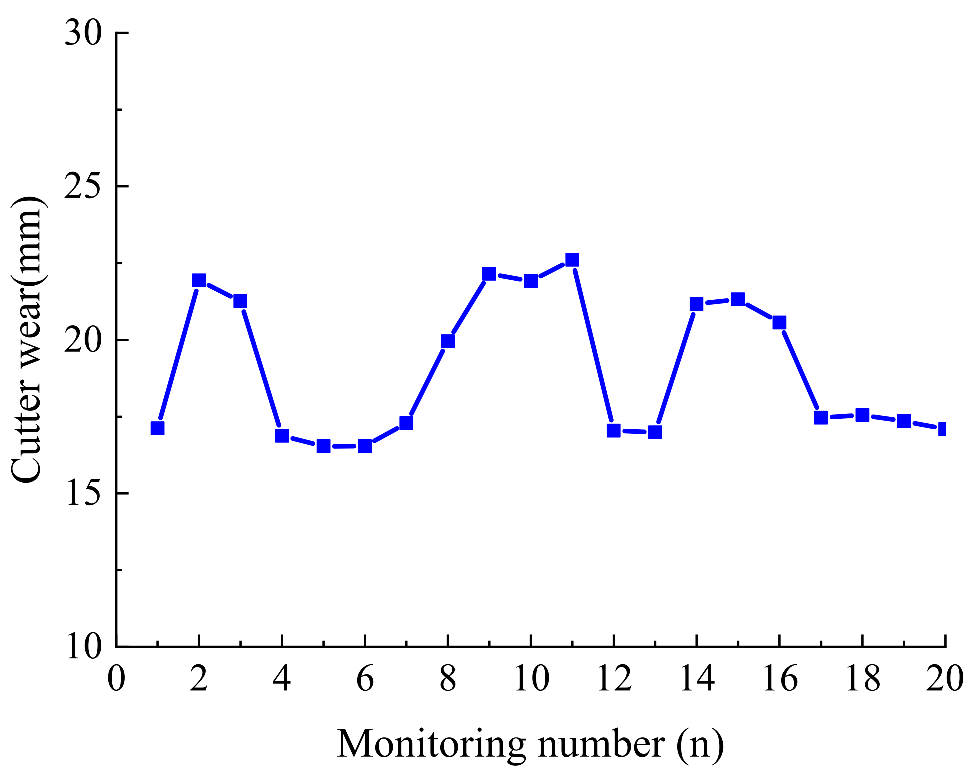


Fig. 24 The monitoring wear value of the cutter No. 26 in Ring No. 1343

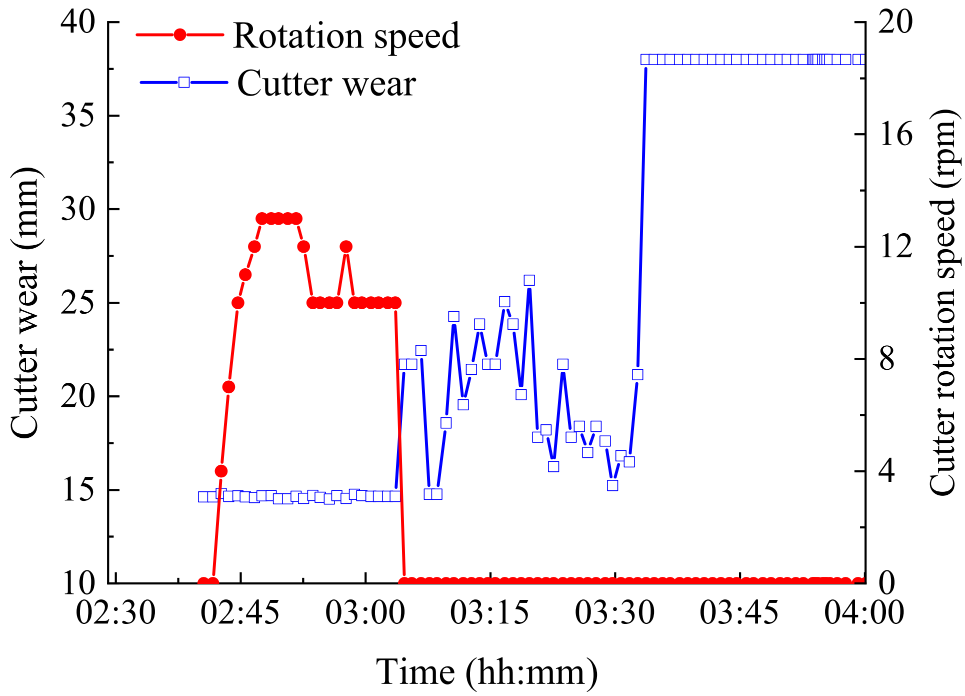


Fig. 25 Curves of the cutter wear and rotation speed of the cutter No 18 in Ring No. 1280

The cutter rotation speed suddenly decreased to 0 and the cutter wear rapidly changed to 38 mm in Ring No. 1280 based on the monitoring data of the cutter No. 18, as shown in Fig. 25. Initially, the cutter No. 18 worked normally and the wear was about 14.6 mm. Then, the wear fluctuated irregularly between 14.7 and 25.1 mm. At last, the wear increased to 38 mm and remained constant. Obviously, the cutter No. 18 was ringing off because the upper limit of the wear was set to 38 mm. It is consistent with the actual failure of the cutter No. 18, as shown in Fig. 20.

5.2 The Influence of the Ground on the Cutter Wear

Figure 26 illustrates that the relationship between the cutter wear and cutter track length in different grounds. It is noted that only the wear data collected during the normal rotation of cutter were analyzed. Basically, these analytical data only included the monitoring data of the first 1280 and 1100 rings for the cutter No. 18 and No. 26, respectively. The cutter wear is the average of the last 10 monitoring data of each ring. It can be found that the cutter wear is a linear relationship with the cutter track length in the same ground, but the slopes of the linear relationships

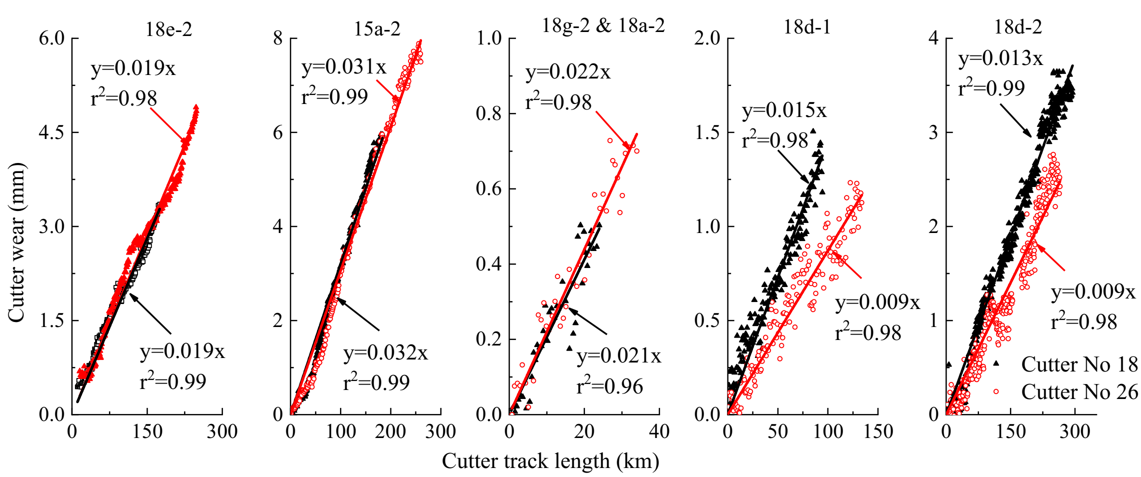


Fig. 26 Relationships between the cutter wear and cutter track length

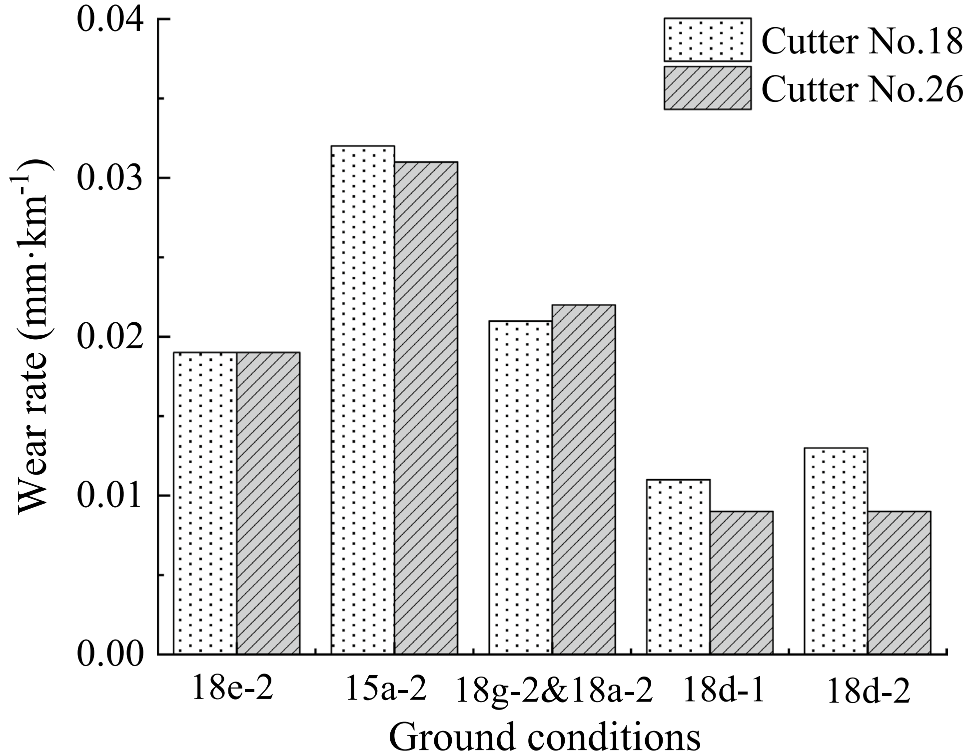


Fig. 27 Cutter wear rate in difference grounds

are quite different in the different grounds. Namely, the rate of the cutter wear intensively depends on the rock abrasiveness.

Figure 27 shows the rate of the cutter wear in different grounds for the No. 18 and No. 26 cutter. The rate of the cutter wear shows a great change in the different grounds, which is mainly resulted from the difference of the rock abrasiveness. It is also shown that the cutter wear is sensitive to the rock abrasiveness. For No. 26 cutter, the rate of the cutter wear in the GIII fine sandstone is 0.031 mm km^{-1}, which is 3 times that of the GIV silty mudstone. The wear rate of the cutter No. 26 is lower than that of the cutter No. 18 in the latter two grounds. This is caused by the difference in the cutter tip width. Two cutters with different wear values and cutter tip width due to the different installation radius at the same chainage. The wear difference between the cutter No. 18 and cutter No. 26 reached about 4 mm when the shield TBM entered the GIV silty mudstone ground. The wider cutter tip width is the main reason for the lower wear rate of the cutter No. 26 in the latter two grounds.

The relationships between cutter wear and chainage are obtained based on the current cutter wear and rate of the cutter wear in the different ground condition. Then, the cutter life can be predicted by the monitoring system when the cutters encounter the same ground during subsequent tunnelling.

5.3 The influence of the Cutter Wear on the TBM Operation Parameters

The curves of the cutter wear and the average of the TBM operation parameters vs the ring number are shown in Fig. 28. As can be seen that the thrust increased firstly and then fluctuated smoothly. Especially in the first 500 rings, the thrust increased from 4500 to 9500 kN and the penetration rate did not vary clearly. On the basis of the monitoring results, the wear of two monitored cutters were more than 10 mm. Thus, the cutter tip width varies greatly with the increase of the cutter wear. A larger thrust is needed to reach the same penetration depth with the wider cutter tip width. In addition, the increase of the cutter wear also results in a small increase of the torque.

5.4 Cutter Rotation Speed Analysis

The monitoring data showed that the rotation speed of the cutter No. 18 was relatively stable in the first 1280 rings and then the cutter stopped. While the rotation speed of the cutter No. 26 was relatively stable in the first 880 rings and then greatly reduced. Only these stable rotation speed data were adopted to analyze the variations of the cutter rotation speed in different grounds, as shown in Fig. 29. The theoretical rotation speed of the cutter can be calculated by Eq. (1).

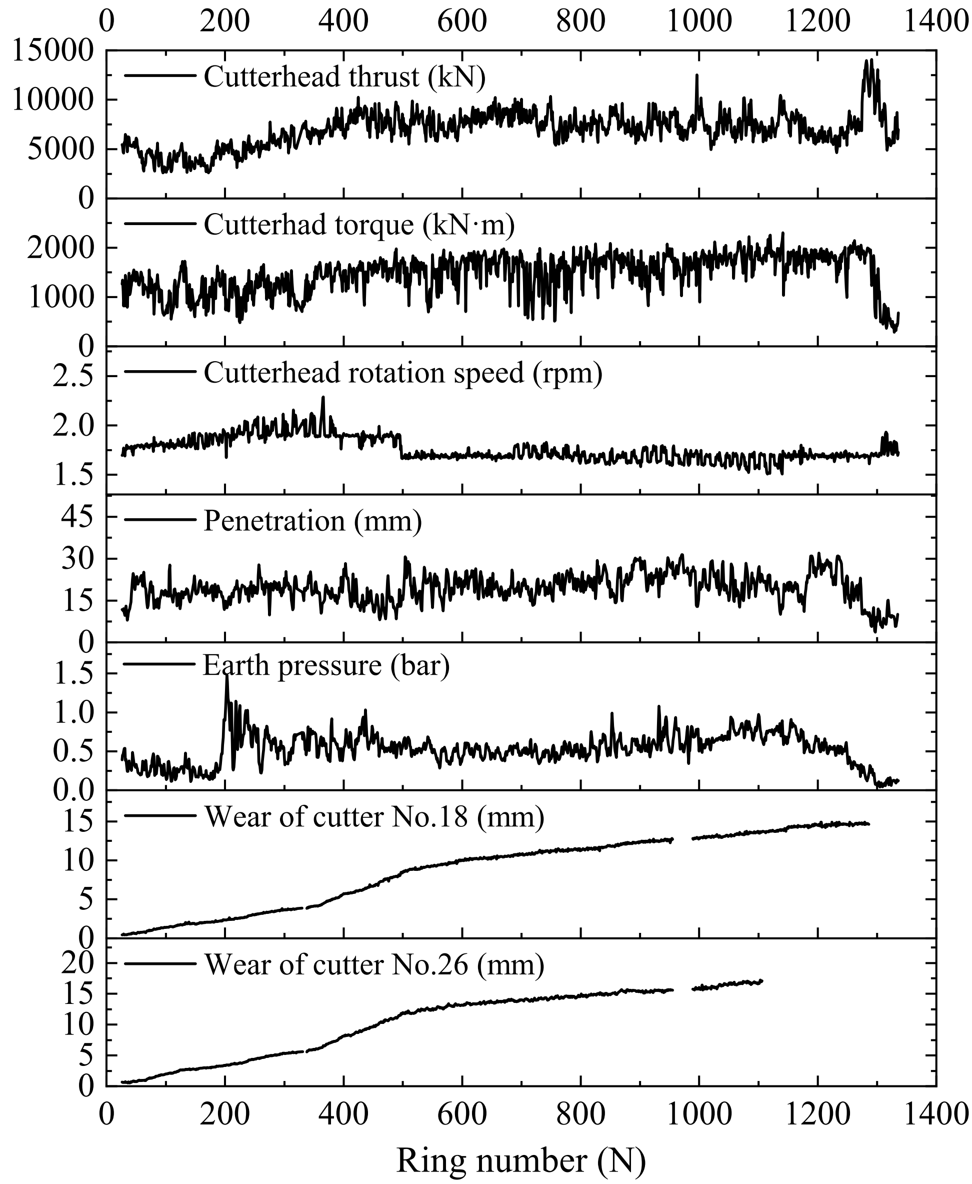


Fig. 28 The TBM operation parameters, cutter wear variation with the ring number

$$\omega = \frac{N \times R}{(d/2) - \varphi} \tag{1}$$

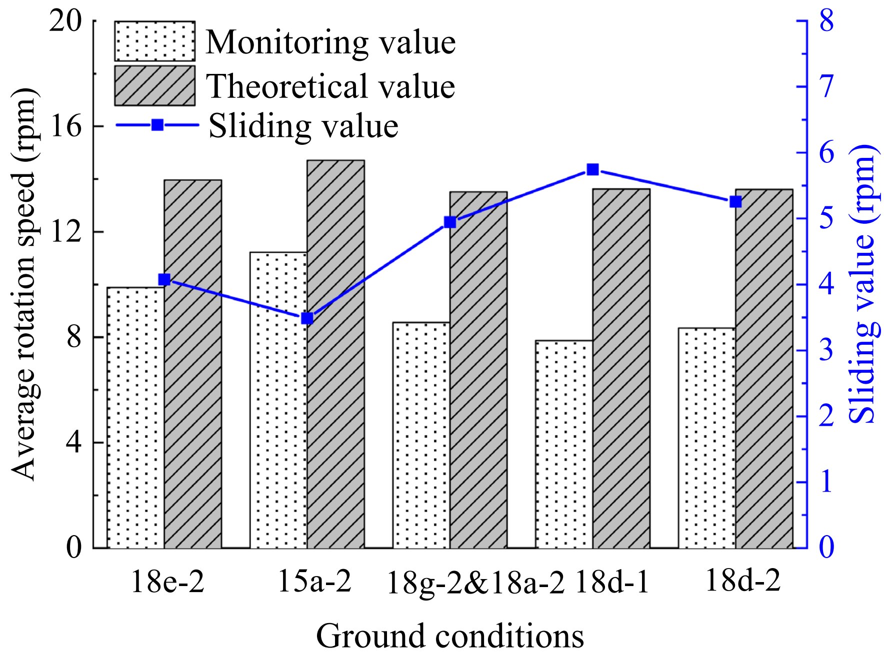
where ω is theoretical rotation speed of cutter, r/min; N is cutterhead rotation speed, r/min; R is cutter installation radius, mm; d is cutter diameter, mm; φ is cutter wear, mm.

The sliding value is defined by the difference between the average theoretical rotation speed and the average monitoring rotation speed of the cutter. For the same cutter, the sliding value increases with the decrease of the rock abrasiveness. For example, the average theoretical rotation speed of the cutter No. 26 is 20.2 rpm in the GIV silty mudstone ground and the sliding value exceeds 7 rpm. Thus, the cutter No. 26 has more than 1/3 of the time for sliding in the low abrasiveness ground. The results indicate that the relative sliding between the cutter and the tunnel face exists in all kinds of grounds. The more serious the relative sliding is, the easier the uneven cutter wear is.

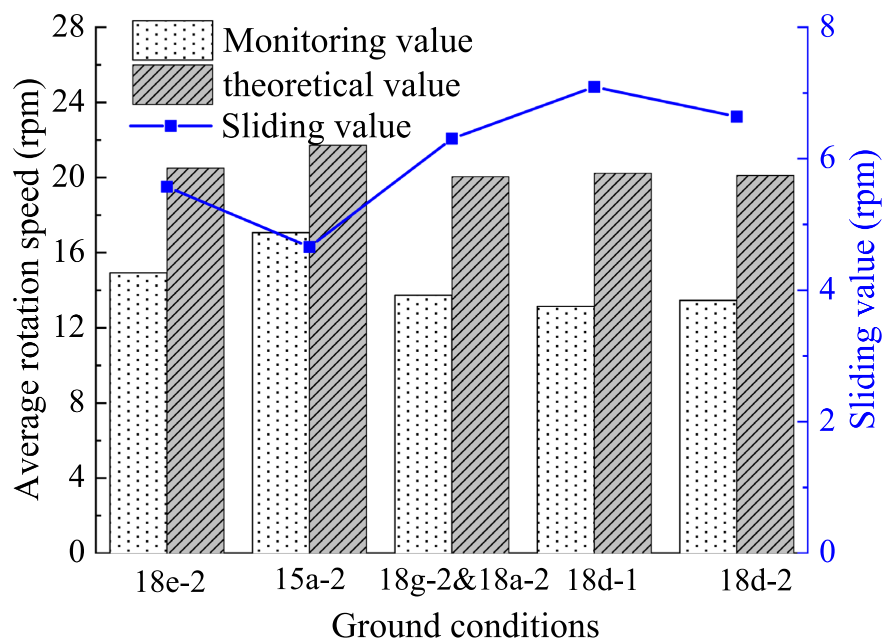
The sliding value of the cutter No. 26 is larger than that of the cutter No. 18 at the same ground condition, as shown in Fig. 29. The sliding value difference of two monitored cutters increase with the decrease of the rock abrasiveness. In other words, compared with the cutter with small installation radius, the cutter with a larger installation radius has a longer relative sliding distance and a greater possibility of uneven cutter wear.

6 Conclusions

In this paper, a cutterhead working status monitoring system for shield TBM tunnelling was proposed and developed. A series of verification and calibration tests were



(a) Rotation speed of cutter No. 18



(b) Rotation speed of cutter No. 26

Fig. 29 Variations of cutter rotation speed in different grounds

carried out in the laboratory based on the new designed calibration device. Finally, this system was applied to a tunnelling project. The monitoring data were analyzed combined with TBM operation parameters. The major conclusions from this study are summarized as follows.

1. The system consists of three subsystems, including data acquisition subsystem, control and data transmission subsystem, as well as data processing and display subsystem. Based on the non-contact magnetoresistive sensing technology, the magnetic displacement and magnetic

switch sensor are designed to monitor the cutter wear and cutter rotation speed. Four installation structures integrated all of sensors are designed to satisfy the requirements of TBM cutterhead structure and lower the disturbance of the tunnelling process. The sensors and system software achieve communication with each other through the central port by wireless and cable. The system software is used to analyze and display the received data. Besides, it alarms the abnormal working status of the cutterhead.

2. A calibration device was designed for verifying the workability and accuracy of the developed cutter wear and cutter rotation speed sensors. The sensor works well no matter what media because the calibration curves present great consistency in the four media. The results of the calibration test provide guidance to improve measurement accuracy in the actual monitoring environment.
3. In the field application, the monitoring system has been working stably for nearly 6 months. The trends of the cutter wear, cutter rotation speed and cutterhead temperature are reasonable with the increase of chainage. The ring off of the cutter No. 18 and the multi-flat wear of the cutter No. 26 are successfully monitored by the proposed system. Based on the monitoring data, the cutter wear is linearly correlation with the cutter track length. The rate of the cutter wear increases with the increase of the rock abrasiveness. For example, the rate of the cutter wear in high-abrasive formations exceeds 3 times that in low-abrasive formations. The increase of the cutter tip width results in a slight increase in the cutterhead thrust and torque. The sliding between the cutter and the tunnel face exists in all kinds of grounds, which is directly affected by the rock abrasiveness. Especially in low-abrasive formations, the cutter is slide or stop for almost 1/3 of the time. In addition, cutters with large installation radius easily result in the long sliding distance and uneven wear.
4. In this project, the shield TBM works normally with the failure of several cutters. Thus, it is necessary to research the relationship between the cutterhead working status and the TBM tunnelling performance. The stability and reliability of the wireless transmission mode were verified by a laboratory test. But it was not applied in practical engineering. In the following research, the wireless transmission mode needs to be validated in subsequent engineering applications. In the meantime, further experiments should be conducted to propose the quantitative relationships between mechanical properties of rock mass, rock abrasiveness and cutter wear.

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Author contributions Conceptualization: [QG]; Methodology: [QG] and [HQ]; Formal analysis and investigation: [QG] and [FW]; Writing—original draft preparation: [QG] and [FW]. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Compliance with Ethical Standards

Conflict of interest The authors have no conflict of interest to declare that are relevant to the content of this article.

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