Cutterhead mud-caking detection method and application based on cutter wear and temperature measurement

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Abstract
Mud-caking of the cutterhead in a tunnel boring machine (TBM) has been commonly encountered when a TBM is excavating through strongly weathered rock or clay. Not only the opening of cutterhead could be blocked to cause problem for muck flowing through, mud-caking of a cutterhead will also lead to the increase of thrust and torque, as well as compromise of tunneling efficiency. To predict the mud-caking status in real time, a prediction model was established based on cutter temperature characteristics, and a bus-based detection system was designed to monitor cutter wear and temperature in tunneling. Such prediction model and detection system were verified on an earth pressure balance (EPB) TBM at a Shenzhen metro project. The research demonstrated that the detection system performed its function of monitoring cutter wear and temperature changes in real time. A dynamic prediction of cutterhead mud-caking status was also proved using the prediction model.

Keywords: Tunnel boring machine, Prediction of mud-caking status, Detection of cutter wear and temperature

1. Introduction

As a piece of safe and efficient underground construction equipment, TBM is extensively used in tunnel construction of subway, highway, railway, water conservancy etc. (Wang, 2013; Rabbani, 2014). When a TBM is excavating in strongly weathered rock or clay, muck from excavation under constant compacting pressure will form into semi-cured or cured lumps that will stick to cutterhead structure and turn the cutterhead into a “mud cake” (Heuser, 2012; Qiao, 2017; Oggeri, 2014), as shown in Fig.1. Once the cutterhead starts to be “mud-caked”, cutters will lose their penetration performance gradually. When they are completely buried in the “mud cake”, the friction energy and kinetic energy between the cutterhead and the tunnel face will all be converted into heat energy, and consequently the TBM cannot continue to move forward and will completely lose the tunneling capability. In worse cases water gushing and tunnel collapse could happen in water-rich strata (Hasanpour, 2017; Shang, 2005; Shang, 2004).

At present, many scholars studied the formation mechanism and countermeasures of the “mud caking” problem. Zumsteg (Zumsteg; 2016) pointed out that the cutterhead opening rate and soil fluidity were the key contributors to “mud caking”. Bie Yumeng (Thewes; 2015) by analyzing the microstructure of the “mud cake”, pointed out that the fundamental reason of “mud caking” was because of the many clay minerals with strong ion exchange capability, hydrophilicity, water expansion and adsorption capacity in soft rock. Wang Mingsheng (Wang, 2015) pointed out that customizing cutterhead design geologically and selecting the best-fit mud circulation coefficient and excavation parameters could significantly reduce “mud-caking”. Karaguzel (Karaguzel, 2016) and Wu (Wu, 2016) put forward that fluidifying muck with special chemical was an effective way of reducing cutterhead “mud-caking”. The above
researchers analyzed the problem of “mud-caking” from the three differently aspects which were geological condition, equipment structure and construction respectively, but did not exploit the method of mud caking prediction and early warning.

Fig. 1 Clipper mud cake

A lot of researches and experiments on cutterhead temperature have been done. Liu Dianyong (Liu, 2006) calculated heat balance of TBM in tunneling process by analyzing temperature test data of EPB TBM. Tan Qing (Tan, 2013) studied thermal-stress coupling of cutterhead under the action of mud-caking when TBM was in tunneling process and pointed out that the central temperature of the cutterhead increased sharply during mud-caking, and the temperature influence decreased step by step as it changed from center to the outer ring on the cutterhead. Zhang Guiju (Zhang, 2015) explored the pattern of how rock temperature would impact cutter rock-breaking in excavation. Yashiro (Yashiro, 2013) put forward a method to detect cutter temperature in milling of carbon fiber reinforced plastics (CFRP). Zhang (Zhang, 2001) put forward a method to measure the cutter temperature in the field through experimental study.

There have been tremendous researches accomplished on TBM cutter wear detection as well. Herrenknecht developed a scraper with wear detection function, and the wear amount of a cutter was detected by comparing the difference in protruding stroke before and after the wear (Hassanpour, 2017). Wilt obtained cutter wear information by using a special odor additive called MOLYUAN (Shi, 2015), and Robbins monitored the cutter running status based on collective real-time data of the rotational speed, temperature and vibration (Wang, 2011; Entacher, 2013). Lan (Lan, 2016; Lan, 2019) and others realized detection of cutter wear and speed with an eddy-current sensor solution. Liu (Liu, 2017) and Huang (Huang, 2018) developed TBM cutter wear test systems one after another, but there were still many problems in application. So far there hasn’t been a reliable methodology and device to detect mud-caking.

“Mud-caking” significantly increases the load of TBM cutterhead and cutter in tunneling, and as a result construction efficiency is greatly comprised. Lots of effort is required to clear up the “mud cake” at the cost of stopping TBM from excavation. In conclusion a method of pre-warning on “mud-caking” state of TBM cutterhead will be effective to minimize such negative impact. This paper presented a new detection model on cutterhead “mud-caking”, designed a bus-based detection system to monitor hub wear and temperature status in real time. Such model and system were verified and proved to function flawlessly at a metro tunneling project in Shenzhen.

2. A detection model of cutterhead mud-caking temperature

It is found that in the cutterhead mud caking process, its temperature conductivity loses as the mud-cake thickens. Studying the temperature difference at different radius on a cutterhead, as well as temperature change rate of the cutterhead under mud-caking status or normal excavation condition will provide basis to judge the status of cutterhead mud-caking.

2.1 Temperature difference at different radius of a cutterhead

In Fig.2, $i$ and $j$ cutters are mounted on the cutterhead with different distance $R_i$ and $R_j$ from the center,
respectively. cutter $i$ is closer to the center than cutter $j$, which means $R_i < R_j$. Assuming within the unit distance of cutterhead excavation, temperature rise of cutter $i$ resulted by heat generated in cutting is $A_i$, and at the same time, temperature drop of cutter $i$ due to heat loss caused by temperature conductivity loss in a confined space is $B_i$. In the same way there are $A_j$ and $B_j$ on cutter $j$. $T_i$ and $T_j$ are the initial temperature of the two cutters. There are:

$$
T_{R_i} = 2\pi R_i (A_i - B_i) + T_i \\
T_{R_j} = 2\pi R_j (A_j - B_j) + T_j
$$

Temperature difference between the two cutters is calculated as follows:

$$
\Delta T_{ij} = T_{R_i} - T_{R_j} = \left[2\pi R_i (A_i - B_i) - 2\pi R_j (A_j - B_j)\right] + \left(T_i - T_j\right)
$$

When the cutterhead excavates normally, both initial temperatures are set to be equal, and the temperature rise caused by friction is greater than the temperature drop caused by heat dissipation, that is, the conditions set out in Eq. (4) are satisfied.

$$
T_i = T_j, \quad A_i > B_i, \quad A_j > B_j
$$

Eq. (3) can be simplified as follows:

$$
\Delta T_{ij} = 2\pi \left[R_i (A_i - B_i) - R_j (A_j - B_j)\right]
$$

Making: $R_i = R_j + \Delta R$, $\Delta R$ is the radial distance between cutter $i$ and $j$, that is, the mounting radius difference. If the cutter on the cutter head generates the same heat at the same cutting distance, the temperature of the cutter will rise the same at the same cutting distance, that is $A_i \approx A_j$ and If the cutting environment of the cutter is the same, the temperature drop is the same under the condition of the same cutting distance, that is $B_i \approx B_j$. Eq. (5) can be obtained:

$$
\Delta T_{ij} = 2\pi \left[-\Delta R (A_i - B_j)\right]
$$

Analyze Eq. (6), where $\Delta R > 0$; $A_i - B_j > 0$, therefore $\Delta T_{ij} < 0$. This is because the temperature of the outer cutter is higher than that of the inner one due to its longer cutting distance in the case of no mud-caking.

In the case of mud-caking, both initial temperatures are set to be equal, and the temperature rise caused by friction is greater than the temperature drop caused by heat dissipation, because cutter $i$ meets the requirements:
In the Eq. (7): Because of the mud-caking on the cutter head, the heat transfer environment in mud-caking area has changed (for example, the specific heat capacity of ceramics is large, the heat transfer is slow, and the temperature drops slowly).

Let in a specific environment, the heat generated by the cutter on the disc at the same cutting distance causes the temperature of the cutter to rise and the heat released by the cutter causes the temperature of the cutter to drop, that is \( A_j \approx B_j \), and combined with formula (4) and formula (7), formula (5) can be obtained:

\[
\Delta T_y = 2\pi R_i A_j
\]  

(8)

Analyze Eq. (8), where: \( R_i > 0 \); \( A_i > 0 \), therefore \( \Delta T_y > 0 \). This is because in the case of “mud-caking”, temperature loss in the inner ring of the cutterhead is reduced. Once the mud cake is formed, because \( T_i > T_j \), \( T_{R_i} > T_{R_j} \) can be obtained, the temperature difference \( \Delta T_y > 0 \).

2.2 Cutter temperature fluctuation characteristics

Eq. (1) and Eq. (2) are the temperature values generated by cutting a circle with the cutter head. Normally, a tunneling cycle is about 50-60 minutes, and the cutter head cuts 4-5 cycles per minute. So make: the rotating speed of the cutterhead \( n \) rpm, the initial temperature \( T \), and the temperature change of cutter \( i \) within a certain period of time \( t \) is as follows:

\[
T_{R_i} = 2\pi R_i (A_i - B_i)nt + T
\]  

(9)

The derivation of Eq. (9), in case of no mud-caking \( A_i > R_i \), the rate of temperature change (heating rate) is:

\[
\partial T'_{R_i} = \frac{d}{dt} 2\pi R_i (A_i - B_i)nt = 2\pi R_i n(A_i - B_i)
\]  

(10)

The derivation of Eq. (9), in case of mud-caking, \( B_i \rightarrow 0 \), its temperature change rate (heating rate) is:

\[
\partial T''_{R_i} = \frac{d}{dt} 2\pi R_i (A_i - B_i)nt = 2\pi R_i n(A_i - B_i) = 2\pi R_i nA_i
\]  

(11)

There is, \( \partial T''_{R_i} > \partial T'_{R_i} \), therefore, the analysis shows that heating rate of the cutterhead is much faster in the case of mud-caking comparing to it is in normal excavation.

The derivation of Eq. (9), in case of no mud-caking \( A_i = 0 \), the rate of temperature change (cooling rate) is:

\[
\partial T'_{R_i} = \frac{d}{dt} 2\pi R_i (A_i - B_i)nt = 2\pi R_i n(A_i - B_i) = 2\pi R_i nB_i
\]  

(12)

The derivation of Eq. (9), in case of mud-caking \( A_i = 0 \), \( B_i \rightarrow 0 \), its temperature change rate (cooling rate) is:

\[
\partial T''_{R_i} = \frac{d}{dt} 2\pi R_i (A_i - B_i)nt \rightarrow 0
\]  

(13)

There is \( \partial T''_{R_i} \ll |\partial T'_{R_i}| \ll \partial T'_{R_i} \), therefore, the analysis shows that cooling rate of the cutterhead is much slower in the case of mud-caking comparing to it is in normal excavation.

To sum up, when the cutterhead is not mud-caked, temperature close to its center is lower than that on its outer ring, and the heating and cooling rate of the cutter is normal; when the cutterhead is mud-caked, temperature close to its center will be higher, heating rate of the cutter is faster and cooling rate is slower.
3. Performance and status detection device of cutter.

3.1 Wear detection theory

To accurately detect the cutter wear and temperature, an integrated sensor is designed. Series resistance method is used to detect cutter wear, and the electrical scheme is shown in Fig.3.

![Fig.3 Sensor circuit diagram](image)

In Fig.3, R1 to R20 is equivalent resistance R, the detection points 1 to 20 is evenly arranged with equal distance L; V means the electric potential difference between the two ends of the series resistance. The count of R in the circuit is shown by measuring the voltage \( U \) of point A. When the circuit is turned on there is a small current \( I \). When detection points 1 to 20 are connected, a electric potential difference \( U = 0V \) is generated after the current \( I \) flows through the resistance. When detection points 1 to 20 are disconnected one by one, \( n \) represents the number of detection points, the electric potential difference is:

\[
U = nRI
\]  

(14)

Where \( R \) is the known quantity and \( I \) is the set constant current, the number of wear detection points \( n \) can be calculated only by measuring \( U \), and the distance between each detection point is \( L \), so the wear value is:

\[
\text{Length} = nL
\]  

(15)

In combination with the formula (14) and the formula (15), the following can be obtained:

\[
\text{Length} = \frac{UL}{RI}
\]  

(16)

By collecting and obtaining the \( U \) value, the wear amount Length can be calculated. When the driving current is constant, the acquisition voltage \( U \) has a linear relationship to the resistance of the series circuit, which completely solves the nonlinear problem and ensures the consistency of the effective interval accuracy of the sensor.

3.2 Temperature detection theory

The schematic diagram of temperature detection using PT100 platinum resistance is shown in Fig.4.

There is a 20mA constant current source that flows through the temperature detection probes PT100 and R4 (high precision 100 resistance) in the direction indicated by the arrow in the figure.), and generates the potential difference between the two ends of the Pt100 and that of the resistor \( \Delta U \) and \( \Delta U_0 \).
Using a high-precision AD converter chip, $U_1$ and $U_0$ shown in Fig.4 can be converted into digital signals and there is:

$$\Delta U_1 = U_1 - U_0$$  \hspace{1cm} (17)$$
$$\Delta U_0 = U_0$$ \hspace{1cm} (18)$$

Because current flowing through $R_t$ is equal to current flowing through $R_4$, there is:

$$\frac{\Delta U_1}{R_1} = \frac{\Delta U_4}{R_4}$$ \hspace{1cm} (19)$$

Combined with formula (17) to (19), the resistance of $R_t$ can be calculated only by measuring the voltage values of $U_1$ and $U_0$. Accurate temperature value can be checked out in PT100 thermal resistance index table, the accurate temperature value is obtained.

### 3.3 General framework of detection system

The wear and temperature detection system is mainly composed of sensor, cutter signal conditioning module, K60MCU data processing module, LORA wireless signal transceiver module and on-line monitoring system host computer platform. The system flow chart is shown in Fig.5. The relevant signals output from the sensor are processed by the processing module and transmitted to K60 MCU for flow calculation and processing. The processing results are emitted and received by LORA wireless signal transceiver module, and finally transmitted to the host computer monitoring platform using a cable.
3.4 Cutter wear and temperature detection system

The wear and temperature sensor is mounted inside the cutter as shown in Fig.6. The circuits in Fig. 3 and Fig. 4 are first made into PCB boards, then the related circuits are welded into PCB boards, and finally sealed as a whole, as shown in Fig. 5. Cutter wear leads to the change of the sensor resistance, which corresponds to the cutter wear; at the same time, the temperature module of the sensor detects temperature status in the cutting process. The signal transmitting and receiving module is shown in Fig. 7.

![Image of cutter wear and temperature sensor](image1)

![Image of signal transmitting and receiving module](image2)

The main interface of the host computer system includes a wear display panel, a temperature display panel, a control panel and a real-time display panel. The wear amount display panel will display cutter wear amount in real time, the temperature display panel will show cutter temperature, and the control panel is used to switch on or off the communication serial port and set the location where the data is stored, exit the detection system and close the current interface; the display window dynamically shows cutter wear and temperature information and can be used to refer back to historical cutter information.

4. Engineering application of cutter wear and temperature detection device

4.1 Overview of the project

The total length of Shenzhen Rail Transit Line 20, Airport North Station to Convention and Exhibition North Station, was 6.7 km, and the outer diameter of the designed segment was 6700 mm, in which the length of the interval between the middle wind shaft and Chongqing Road was about 1600 m. The minimum turning radius was 800 m, and the maximum longitudinal slope was 20‰. Buried depth of the tunnel roof was approximately 10 to 23 m. According to the interval profile and the proportion of each stratum in Fig.8 and Fig.9, the front section was fully-strong weathered mixed granite (54%) and the later section was mainly sandy clayey soil (24%). This means muck from excavation was soft and easy to disintegrate when there was water, and therefore lots of sticky particles could be generated to result in cutterhead “mud-caking”.

![Image of interval profile](image3)

![Image of proportion of strata](image4)
4.2 Cutterhead configuration and installation of testing device

The above-stated tunnel section was constructed by EPB TBM. Cutterhead excavation diameter was 6950 mm, which adopted a six-spoke and six-panel structure style with an opening rate of approx. 32%. 19-inch cutters were arranged in the front and on the edge with average spacing of 80mm. This cutterhead configuration not only met the structure strength and excavation efficiency requirements, but also considered the requirements of cutterhead opening rate, so as to minimize “mud-caking”.

4 temperature and wear detection sensors were mounted on the cutterhead. Two were located on # 5 cutter (No.: OB) and # 8 cutter (No.: OD) of arm 5, and the other two were located on # 5 cutter (no.: OA) and # 8 cutter (No.: OC) of arm 11. OA and OB were closer to the center, while OC and OD were on the outer ring of the cutterhead. Wear measurement ranged from 0 to 40 mm with a precision of 2 mm. Temperature measurement ranged from 20 to 125 ℃, with a precision of 1 ℃. Sensor installation location is shown in Fig. 10. The entire cutter temperature detection system installed on the equipment is as shown in Fig. 11.

Fig.10 Detection position of cutter wear and temperature Fig.11 Installation of cutter wear and temperature detection system

5 Data acquisition and result analysis

The project was officially kicked off on 4th August 2017. By October 14, 2017, it was at 300 rings totally 450 m. The detection has been functioning without problem.

5.1 Tunneling data analysis

Excavation data of 7th September 2017 and 14th October 2017 which includes cutterhead thrust (kN), cutterhead torque (kN.m), cutterhead penetration (mm/rev) and FPI parameters (kN.mm/rev) were analyzed as shown in Fig.12 and Fig.13.

(a) Cutterhead thrust and cutterhead torque (b) Penetration degree and FPI coefficient of cutterhead

Fig.12 Excavation data on 7th September, 2017
Figure 13 Excavation data on 14th October, 2017

By average processing of the tunneling parameters in Figs. 12 and 13, there is Table 1 as below:

| No. | Time (min) | Cutterhead torque (kNm) | Total thrust (kN) | Penetration (mm/rev) | FPI (kN/mm/rev) | Note          |
|-----|------------|-------------------------|-------------------|----------------------|----------------|--------------|
| t1  | 14         | 3610                    | 18294             | 33                   | 618            | Excavation   |
| t2  | 173        | 0                       | 0                 | 0                    | 0              | Downtime     |
| t3  | 40         | 4100                    | 15923             | 30                   | 542            | Excavation   |
| t4  | 98         | 0                       | 0                 | 0                    | 0              | Downtime     |
| t5  | 27         | 4532                    | 17297             | 13                   | 1889           | Excavation   |
| t6  | 213        | 0                       | 0                 | 0                    | 0              | Downtime     |

Tab. 1 shows that average torque of in both groups of data ranges between 3600 and 4500kNm, and average thrust ranges between 16000 and 18000kN wit slight fluctuation. Penetration on 14th October was only twice less than that of 7th September, while FPI value was significantly increased from 618 to 1889. This excavation data analysis doesn’t provide solid evidence to prove that there is “mud-caking” in the cutterhead.

5.2 Analysis of cutting tool wear and temperature data

The wear and temperature data of the four cutters are monitored in real time, and the average data of the two time periods are shown in Tab.2.

| Sensor number | 7th September 2017 | 14th October 2017 |
|---------------|--------------------|--------------------|
|               | Wear amount (mm)   | Temperature (°C)   | Wear amount (mm) | Temperature (°C) |
| 0A            | 0                  | 35                 | 4                | 49               |
| 0B            | 2                  | 36                 | 2                | 49               |
| 0C            | 2                  | 35                 | 4                | 38               |
| 0D            | 2                  | 37                 | 4                | 39               |

OA and OB were mounted at the same radius but on different arms. On 7th September, OA was worn by 0 mm and OB was worn 2 mm. By 14th October, OA was worn by 4 mm, while OB was still worn by 2 mm. OC and OD were located on the outering of the cutterhead at the same radius. Data of both time periods shows the larger the installation radius was, the greater the wear amount of the cutter was when the compared cutters were mounted on the same arm in the cutterhead. On 7th September, temperature was shown without obvious difference on OA and OB which were mounted on different arms, and the same with OC and OD. It is clear that the cutterhead was performing excavation without interruption. By 14th October, comparing cutters mounted on the same arm, the larger the installation radius was, the lower the temperature was. Temperature in the center of cutterhead was higher than that of the outer ring on
the cutterhead, indicating that the “mud-cake” has been formed in the center of the cutterhead. To better analyze temperature rising and cooling trend, temperature curves were drew as shown in Fig.14 and Fig.15.

Fig.14 Temperature data for four cutters from 10 to 11 September 2017

Fig.15 Temperature data of four cutters from 14 to 15 October 2017
Fig. 14 and Fig. 15 shows during September 10th to 11th of 2017, the thrust peaked at t1 and t3, and the temperature on OA and OB correspondingly peaked by 5 °C from 38 °C to 43 °C. During October 14th to 15th of 2017, thrust peaked at t5, and the temperatures of OA and OB correspondingly peaked at the same time. OA temperature rose from 58 °C to 72 °C. OB rose from 56 °C to 63 °C. The temperature differences and rates of the four cutters in the heating and cooling intervals were analyzed according to Figs. 14 and 15 as shown in Tab.3 and Tab.4.

### Table 3 Heating data for the four cutters

| No. | t1 | t3 | t5 |
|-----|----|----|----|
| 0B  | 4  | 3  | 7  |
| ΔT(°C) | 0.286 | 0.075 | 0.259 |
| ΔT(°C/min) | 0.0429 | 0.175 | 0.111 |
| 0D  | 6  | 7  | 3  |
| ΔT(°C) | 2  | 3  | 14 |
| ΔT(°C/min) | 0.143 | 0.072 | 0.559 |
| OA  | 2  | 4  | 4  |
| ΔT(°C) | 0.143 | 0.100 | 0.148 |
| ΔT(°C/min) | - | - | - |
| OC  | 2  | 4  | 4  |
| ΔT(°C) | 0.143 | 0.100 | 0.148 |
| ΔT(°C/min) | - | - | - |

### Table 4 Cooling data of four cutters

| No. | t2* | t4* | t6* |
|-----|-----|-----|-----|
| 0B  | 4   | 3   | 5   |
| ΔT(°C) | Δt(min) | ΔT(°C) | ΔT(°C/min) |
| 61 | 0.066 | 8 | 0.072 |
| 79 | 0.038 | 8 | 0.143 |
| 190 | 0.026 | - | - |
| 0D  | 8   | 8   | 10  |
| ΔT(°C) | Δt(min) | ΔT(°C) | ΔT(°C/min) |
| 111 | 2    | 56  | 2   |
| 0.063 | 0.044 | 0.053 |
| 0A  | 2   | 2   | 10  |
| ΔT(°C) | Δt(min) | ΔT(°C) | ΔT(°C/min) |
| 32  | 2    | 45  | 189 |
| 0.143 | 0.044 | 0.053 |
| 0C  | 4   | 3   | -   |
| ΔT(°C) | Δt(min) | ΔT(°C) | ΔT(°C/min) |
| 104 | 3    | -   | -   |
| 0.038 | 0.054 | - | - |

Analyzing heating rate of the four cutters in Table 3, it can be seen the maximum $\hat{\Delta T}$ was 0.429 °C / min when the cutterhead was performing excavation in normal state. When cutters were mounted on the same arms, cutters at out ring were heated more quickly (OD>OB, OC>OA). In contrary, as the cutterhead was “mud-caked”, the maximum $\hat{\Delta T}$ value was 0.519 °C/min, and cutters were heated in the opposite way (OB>OD, OA>OC). Looking at cooling rate of the 4 cutters in Table 4, $\hat{\Delta T}$ was between 0.038 and 0.143 °C / min in normal state. When mud-cake was formed in the cutterhead, $\hat{\Delta T}$ ranged between 0.026 and 0.053 °C / min. To clarify, the greater the temperature difference is, the stronger the radiation is, which means the faster the cutter should cool down. If the cutter cools down slower than normal, it is an indication of a “mud-caked” cutterhead. Once the mud-cake was formed, temperature conduction and the radiation of the cutterhead would be comprised. It would only rely on the steel structure of the cutterhead for temperature conduction. Table 4 shows OC and cutter OD temperatures maintained the same at t6 because heat in the high temperature region was transmitted to the low temperature zone, and the heat in the low temperature zone was kept unchanged.

### 6 Conclusion

(1) Through the analysis of the formation mechanism of mud-cake on the cutterhead, it is concluded that the formation of the mud cake is related to the three factors of geological condition, equipment structure and construction. A discriminant model of cutterhead mud-caking was established based on cutter temperature characteristics.

(2) A bus sensor for cutter wear and temperature detection was designed to completely solve the non-linear problem and ensure accurate measurement of cutter wear and temperature. The hardware and software of the detection system were both designed to realize the remote detection of cutter wear and temperature.

(3) The cutter wear and temperature monitoring system was applied to a Shenzhen subway tunnel construction project. Analysis of the monitoring data preliminarily showed that the mud-cake has been formed in the central area of the cutterhead. The feasibility of the monitoring system and its accuracy were verified indirectly for early warning of cutterhead mud-caking in such tunnel construction project.

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