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*Research Article*

# Application of Inclination Sensor in Real-Time Remote Monitoring System of Tunnel Structure Deformation

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Through the "real-time monitoring system," the inclination sensor can realize the real-time automatic monitoring of the existing lines within the influence scope of the subway structural engineering, which can provide timely and reliable information for the construction unit, so as to evaluate the safety of the project during the construction and the impact of the construction on the existing line, as well as the possible hidden dangers or accidents that may endanger the construction and the environmental safety of the existing line subway. Make timely and accurate forecast, so as to take effective measures to eliminate hidden dangers and avoid accidents.

## 1. Introduction

During subway construction, the shield construction process of newly constructed tunnels not only affects the initial stress state of the surrounding soil but also disturbs the surrounding strata. It causes the loss of surrounding stratum and the seepage of water in the stratum, resulting in soil consolidation and settlement, which in turn causes horizontal or vertical displacement of the surrounding soil, thereby causing deformation of the surrounding work. The deformation value that the internal structure of the subway and the section equipment can withstand is limited, and serious safety accidents may occur after exceeding a certain limit [1].

Generally speaking, the occurrence of engineering hazards is predictable. Only sufficient monitoring frequency density can detect continuous signs of change from monitoring data and real-time automatic monitoring of existing lines within the influence scope of subway structural engineering; it can provide the construction unit with timely and reliable information to assess the safety of the project during construction and the impact of construction on the existing line and make timely and accurate forecasts for possible hidden dangers or accidents that may endanger construction and the environmental safety of existing subway lines, in order

to take effective measures in time to eliminate hidden dangers and avoid accidents.

Tunnel deformation monitoring generally uses total station monitoring; the total station has the advantages of large instrument size and easily damaged measuring points and is easily limited by measurement conditions. It is difficult to continue to use in the absence of light, and the cost of the instrument is high, and the test accuracy is low. Real-time remote monitoring cannot be realized [2].

Inclination sensor is an instrument for measuring the horizontal angle of a structure, which is widely used in bridge erection and other aspects. However, its application in the deformation monitoring of subway tunnels is still relatively small. Compared with other deflection measurement methods, the inclination sensor has its unique advantages.

This paper takes the application of the inclination sensor in the real-time monitoring system of the tunnel structure deformation of a project as the background. The tilt sensor is easy to install, is not limited by measurement conditions, and has high accuracy, which provides accurate and reliable values for the tunnel structure deformation real-time monitoring system. In order to provide theoretical guidance and data support for the realization of the real-time monitoring system of tunnel structure deformation and by comparing
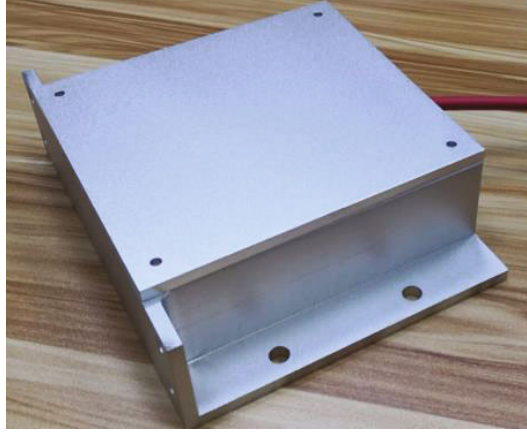
FIGURE 1: Inclination sensor.
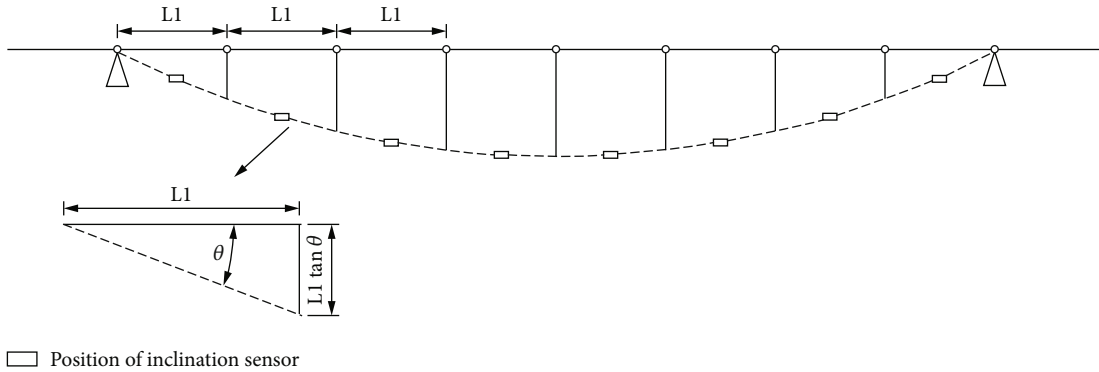


Position of inclination sensor

FIGURE 2: Schematic diagram of deflection calculation method.

the measurement of the inclination sensor with the measurement of the traditional total station, the feasibility of the real-time remote monitoring system for the deformation of the tunnel structure by the inclination sensor is verified.

## 2. Principle of Deformation Measurement by Inclination Sensor

Inclination sensor is an acceleration sensor that uses Newton's second law. It is a fixed inclination measurement instrument produced by using a dual-axis inclination sensor developed and produced by a microelectromechanical system as a sensitive element and combined with intelligent chip technology. It is used to observe the biaxial inclination angle of bridges, buildings, railways, and other structures relative to the horizontal [3]. It is suitable for the deformation of hidden parts that are difficult to be observed by conventional geodetic methods. It can be used for long-term testing with the automation system. The size of the tilt sensor is $120 \, \text{mm} \times 150 \, \text{mm} \times 40 \, \text{mm}$, and the tilt sensor used is shown in Figure 1.

The schemes of converting deflection by inclination angle include using the least squares method to obtain a set of optimal solutions and directly integrating the inclina-

tion angle function to obtain the deflection value, but these methods involve relatively complex mathematical calculations [4]. Therefore, the simplest method of arranging measuring points and calculating deflection in the conversion process is selected for research: that is, select $n$ positions on the structure to place the inclination sensor, as shown in Figure 2, assuming that the structural deformation is within the linear range. By loading the structure, the change value of the inclination angle before and after loading is obtained, and the tangent value of the inclination angle is multiplied by the distance of the segment to obtain the deflection value of the segment.

According to the knowledge of material mechanics, we know that the approximate differential equation of the deflection line of the beam is

$$\omega'' = -\frac{M(x)}{\text{EI}}. \tag{1}$$

If it is a straight beam of equal cross-section, its bending stiffness EI is a constant, and the above formula can be rewritten as
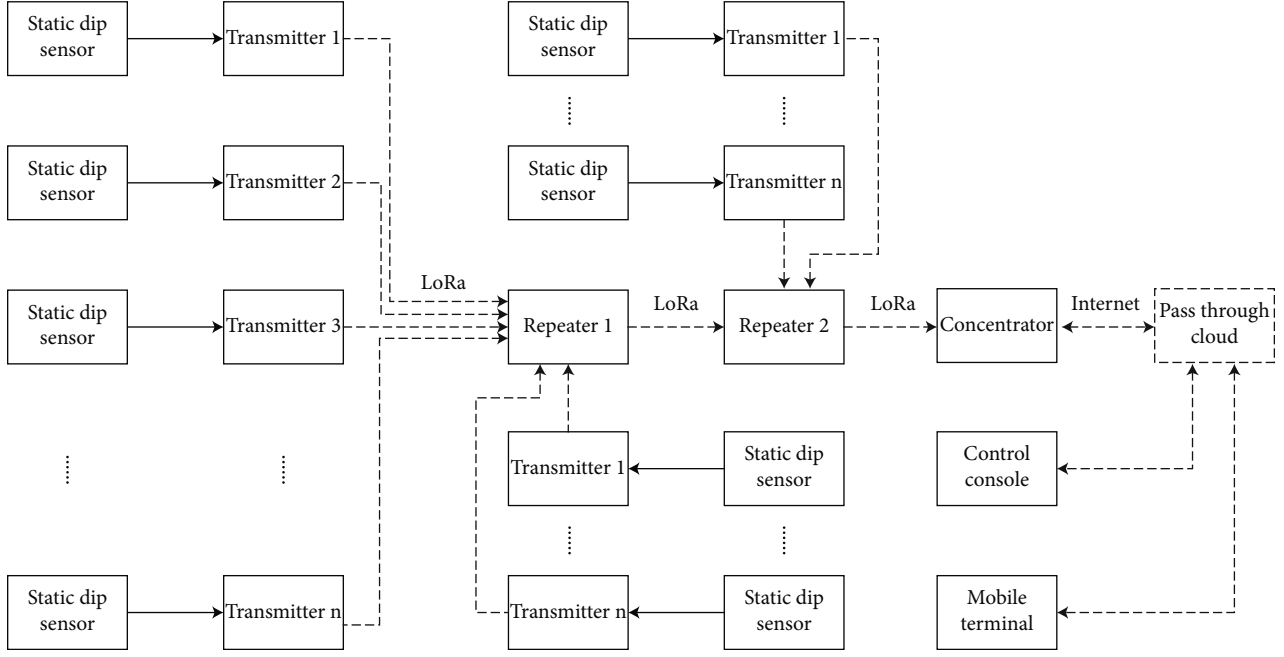
$$\text{EI}\omega'' = -M(x). \tag{2}$$

FIGURE 3: Flow chart of data acquisition.

Integrating the above equation once can get the angle equation of the beam:

$$\mathrm{EI}\omega' = -\int M(x)dx + C_1. \qquad (3)$$

Integrate Equation (3) again to get the deflection curve equation of the beam.

To sum up, the corner of any section of the structure is equal to the corner of the deflection line at that point, that is, the angle between the tangent of the deflection line at this point and the $x$-axis [5]. There is a first-order integral relationship between the deflection of the beam and the corner. From this, we can obtain the deflection of the structure by measuring the angle of rotation at certain points when the structure is bent.

Given a beam of length $L$, divide the beam into $n$ equal sections, each with a length of $L_1 = L/n$, a tilt sensor is placed at the midpoint of each segment. After the beam is loaded at a certain time, the beam deflects. The deflection increment for each segment is

$$\Delta\omega_i = L_1 \tan \theta_i. \qquad (4)$$

Then, the deflection at the end of the $i$-th segment is the accumulation of the deflections of all segments in the previous $i - 1$ segment, namely,

$$\omega_i = \sum_1^{i-1} L_1 \tan \theta_i, \qquad (5)$$

where $L_1$ is the length of each segment, $\theta_i$ is the change value of the inclination angle at the midpoint of the $i$-th
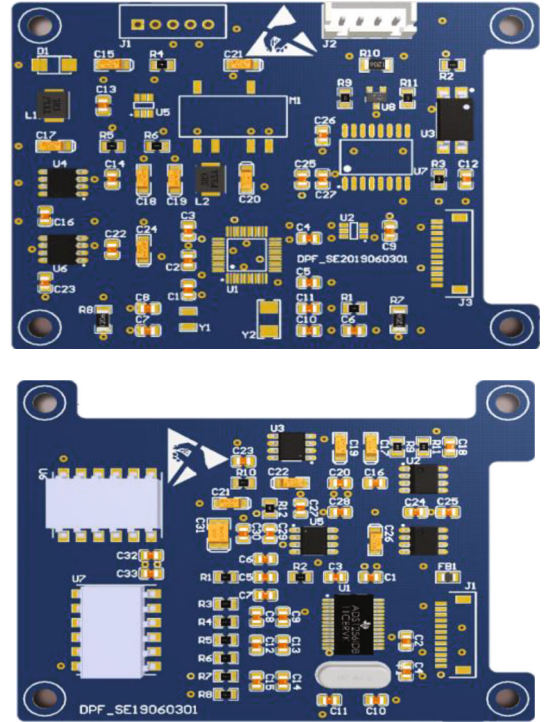


FIGURE 4: Inclination sensor base plate and expansion board.

segment, that is, the measured value of the inclination sensor of this segment, $\Delta\omega_i$ is the deflection difference between the front and rear ends of the $i$-th segment, and $\omega_i$ is the deflection value at the end of the $i$-th segment. Calculation of deflection by measuring inclination is an indirect method, and deflection calculated by different mathematical models
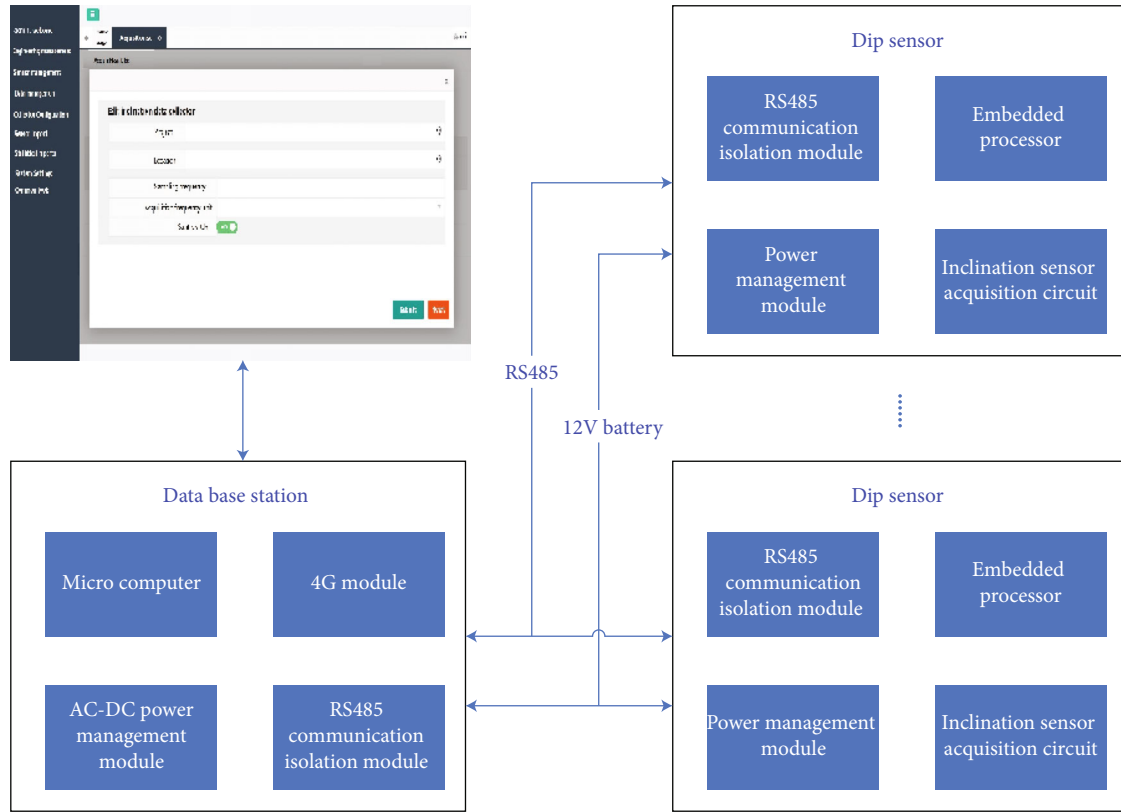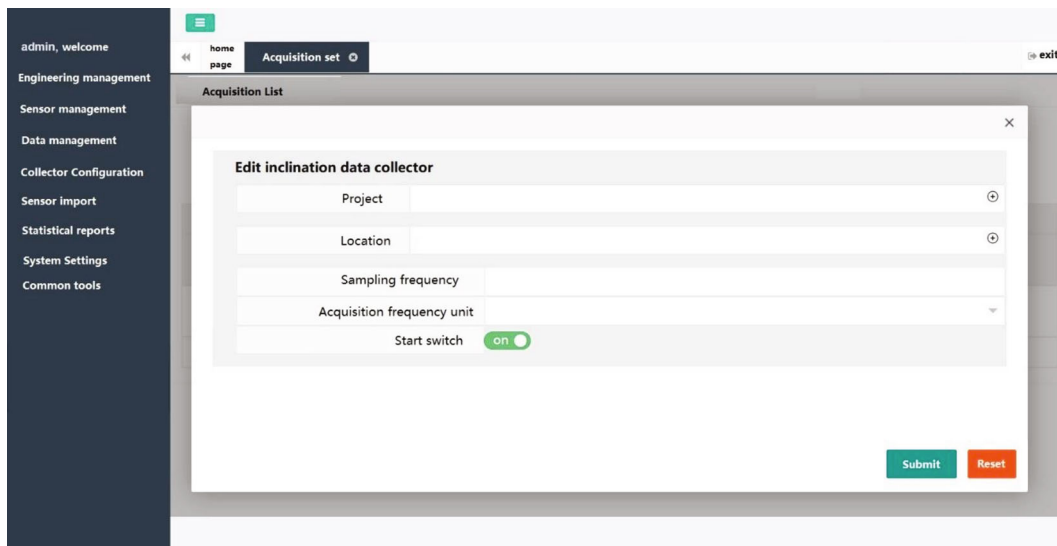
Figure 5: System topology.



Figure 6: Data collection frequency setting diagram.

is an approximate result, not an exact deflection value. In this segmented calculation model, the calculation accuracy increases with the increase of the number of segments. Generally, when the number of segments is the same as the number of curves, the relative error between the calculated value and the actual value can reach a range of less than 5% [6].

## 3. Real-Time Monitoring System

The real-time monitoring system consists of four parts: inclinometer, data acquisition system, data transmission system, and main control computer terminal system. Data transmission adopts LoRa wireless network transmission. The relevant process is shown in Figure 3.
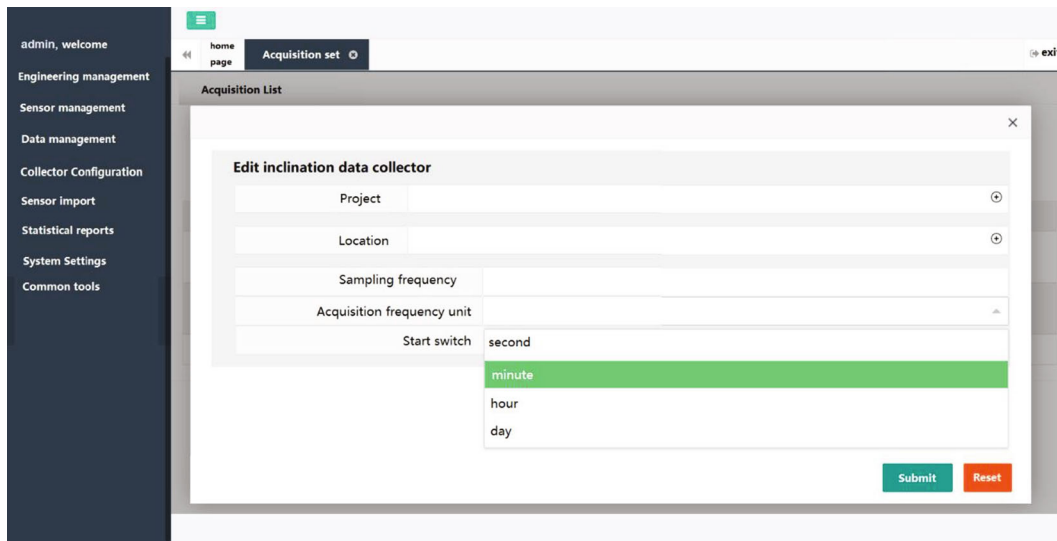
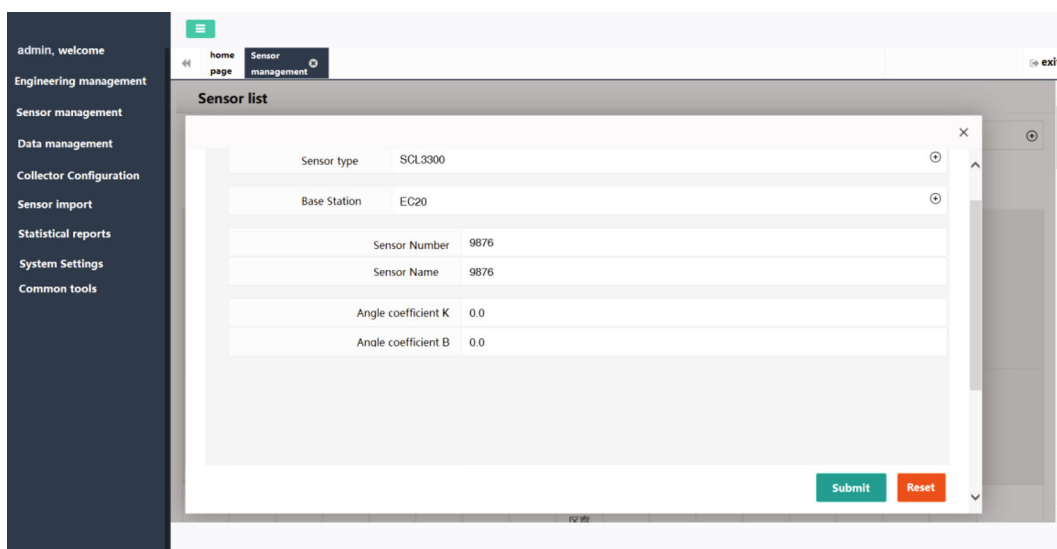Figure 7: Data collection frequency setting diagram.



Figure 8: Start acquisition setup diagram.

The field implementation of the inclination sensor is carried out according to the following steps:

(1) 13 inclination sensors are arranged at the waist of the subway section, and the collection frequency and collection method are set on the collection software

(2) Click to start the measurement, and send the acquisition command to the sensor. The hardware can make all the inclination sensors receive the command at the same time. After receiving the command, the measurement is performed at the same time interval, and the measured data is stored in the sensor

(3) After sending the collection command, the sensor collects data at the same time interval. The collected data is first stored in the sensor, and then, the sensor returns the collected data to the terminal and decodes the data to obtain the sensor inclination value

## 4. Inclination Sensor Data Collection and Analysis

Currently, the on-board sensor has synchronous and synchronous detection, which is extremely important for structural measurements. The method of realizing synchronization can be realized by means of hardware and software, and the method of software can be realized by interpolation [7].

Synchronous acquisition technology is a bit synchronous communication technology. To achieve hardware
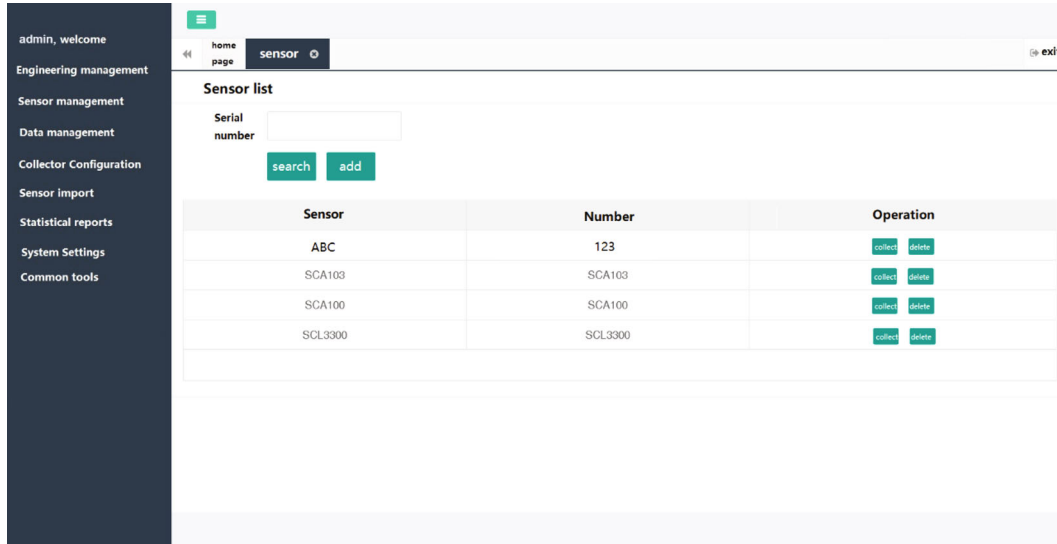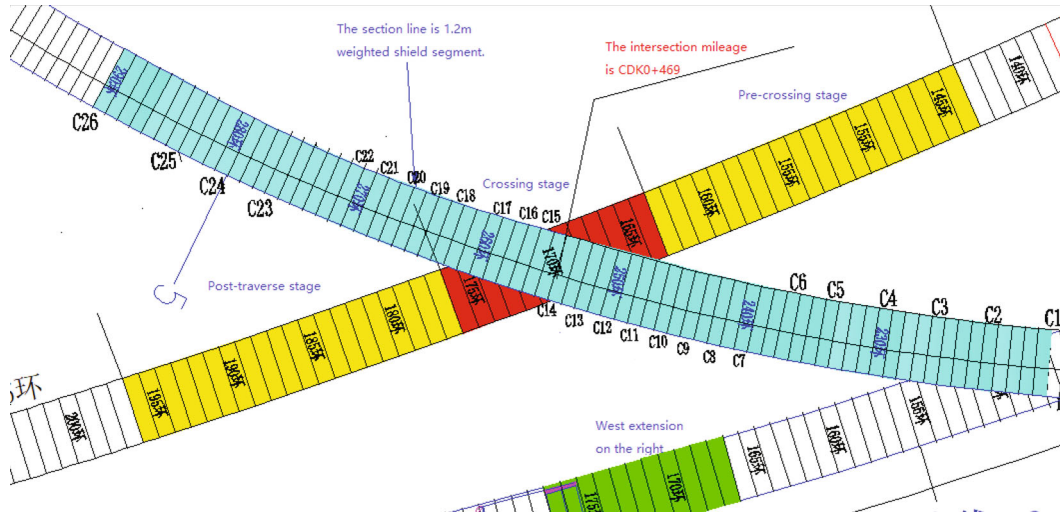
Figure 9: Collection result viewing diagram.



Figure 10: Layout of side points of total station.

synchronization, it is necessary for the sender and receiver to have clock signals with the same frequency and phase. When no data collection is required, the connection line is in the MARK state. When starting a measurement, the sender sends one or two sync characters. When the two sides are synchronized, they can send a large block of data continuously with a single character, so that the start and stop bits are no longer needed. During the sending process, both parties need to coordinate with a clock to determine the position of each bit in the serial transmission. When starting the measurement, the two sides use the synchronization character to keep the clock internally synchronized with the sender, and then input the data behind the synchronization character bit by bit, convert it into parallel format at the same time, and let the CPU read the data until the end character is received.

The synchronous acquisition adopts a common clock, and the synchronous acquisition has a high transmission frequency and realizes high-speed, large-capacity data transmission. The monitoring center application management system is at the heart of data analysis and display [8]. During data transmission, both parties must maintain complete synchronization, requiring the receiving and sending devices to have the same clock and maintain strict synchronization.

*4.1. Technical Scheme of Inclination Sensor Acquisition.* The system will adopt a bus topology [9] and connect the tilt sensor to the data base station through a 5-core shielded cable (12V, GND, D+, D-, S). The inclination sensor adopts the DPF_SE2019060301 version of the inclination sensor. As shown in Figure 4, the base plate and the expansion board of the inclination sensor are, respectively, packaged into an integrated inclination sensor through an aluminum casing. Electrical energy is the most precious resource of wireless sensor network, which determines the lifetime of wireless sensor network [10].
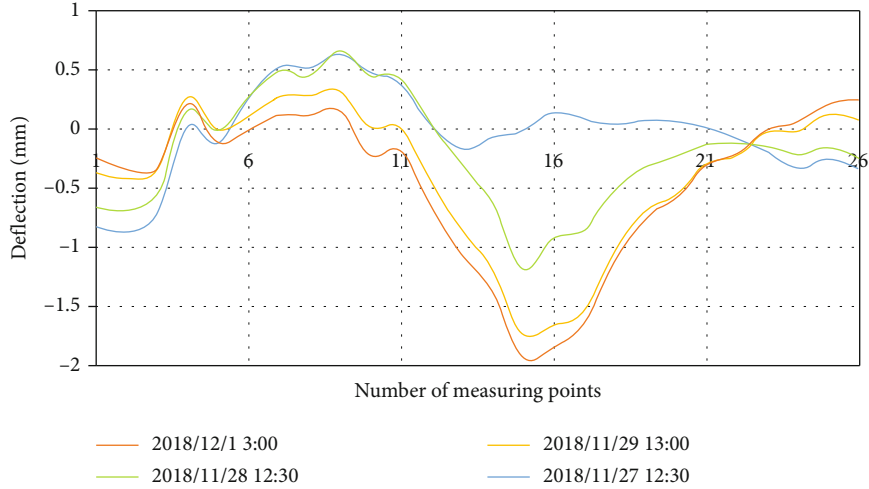
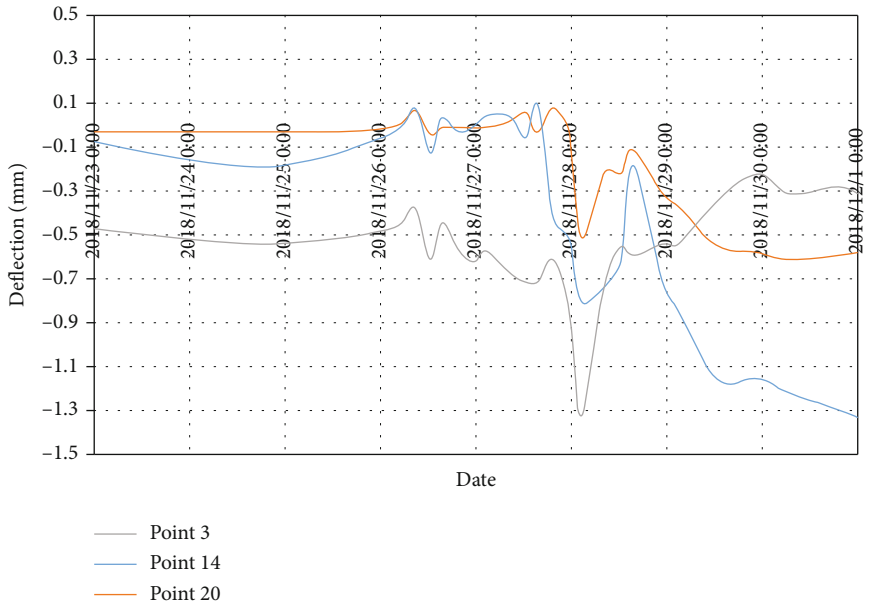FIGURE 11: Deformation curve measured by total station.



FIGURE 12: Deformation curve measured by total station.

The data base station uses the RS485 bus to connect with each sensor and realizes the synchronous acquisition between each sensor through the 12V level output. The incoming data from the pin sensors is uploaded via the 4G network to the server platform, which calculates and displays it. Real-time data transmission between the monitoring center and the monitoring terminal is realized [11].

In summary, the system consists of a server-side data processing platform, a data base station, and an inclination sensor to form a complete system topology, as shown in Figure 5.

### 4.2. User Data Collection Operation Steps

(1) 13 inclination sensors are arranged at the waist of the subway section, and the collection frequency and collection method are set on the collection software, as shown in Figures 6–9

The acquisition mode 0 in the figure means that after clicking to start acquisition, a measurement value is returned every 1 s, and the measurement value is the measurement value of the inclination sensor in the $x$-axis direction. If the frequency is 20 Hz, the returned value is the average of 20 numbers measured within 1 s.

The acquisition method 20 in the figure represents that measuring the inclination value of the wall angle sensor in the $x$ and $y$ directions, the first 20 s returns the inclination value in the $x$ direction measured by the inclination sensor, and the second 20 s returns the inclination value in the $y$ direction measured by the inclination sensor.
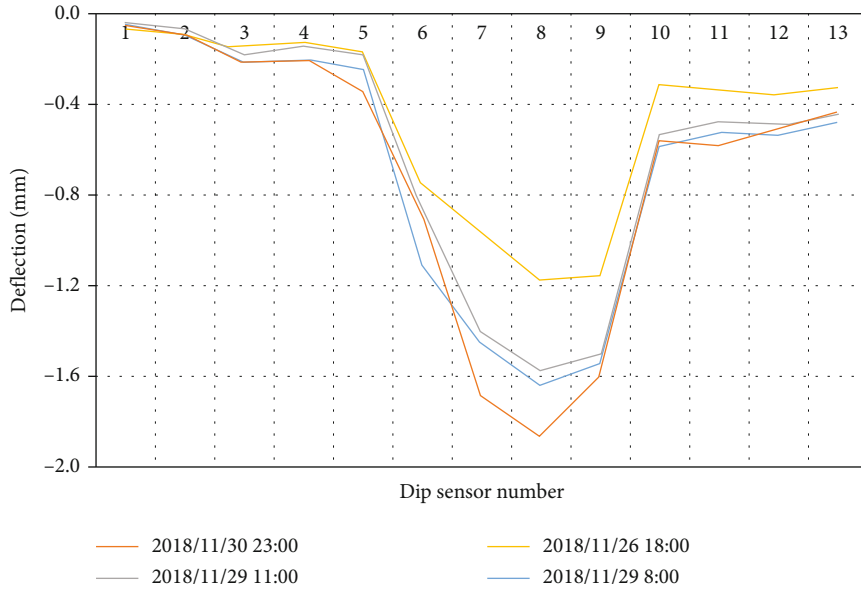
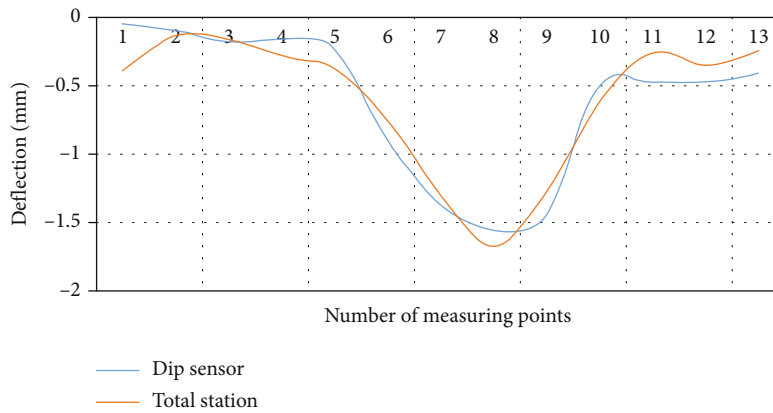FIGURE 13: Measured deflection curve of inclination sensor.



FIGURE 14: Measured deflection curve of inclination sensor and total station.

(2) Click to start measurement, and send the acquisition command to the sensor. The hardware can make all the inclination sensors receive the command at the same time, measure at the same time interval after receiving the command, and store the measured data in the sensor, as shown in Figure 8

(3) After sending the collection command, the sensor collects data at the same time interval. The collected data is first stored in the sensor, and then, the sensor returns the collected data to the terminal and decodes the data to obtain the sensor inclination value. The collection results are viewed as shown in Figure 9

TABLE 1: Measurement errors between inclination sensor and total station.

| Point | Error (mm) | Point | Error (mm) |
| --- | --- | --- | --- |
| 1 | 0.3 | 8 | 0.1 |
| 2 | 0.0 | 9 | -0.2 |
| 3 | 0.0 | 10 | 0.1 |
| 4 | 0.1 | 11 | -0.2 |
| 5 | 0.1 | 12 | -0.1 |
| 6 | -0.1 | 13 | -0.2 |
| 7 | -0.1 | — | — |

## 5. On-Site Measured Data Analysis

According to the measured data of the inclination sensor, the deformation curve of the subway tunnel and the deflec-

tion change of each sensor during the excavation process are analyzed, and the data of the inclination sensor and the total station data are compared with the theoretical curve to analyze the reasons.
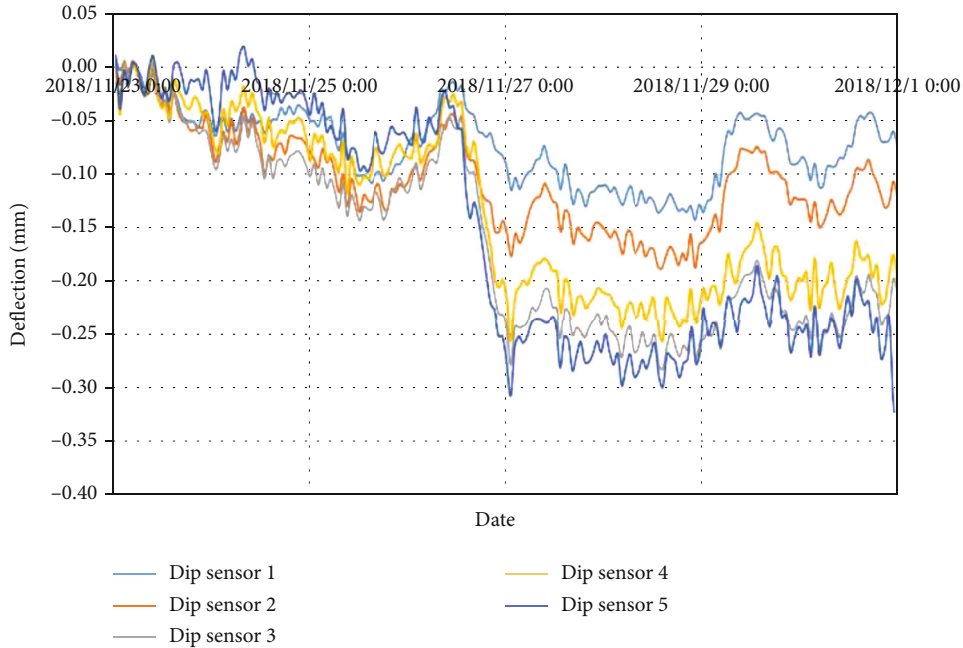
Figure 15: Curves of the measured deflections of 1~5# inclination sensors with time.

5.1. Point Layout and Data Analysis of Total Station. A total of 26 measuring points are arranged in the affected area of the subway by the total station, and 5 measuring points are arranged in each section. The total station has a total of 5 measuring points on the cut surface during the measurement process. To compare the data of the pillow sensors, data were selected that are identical in the cross-section of the pillow sensors: approximately 2# points. Tunnel preparations are carried out in the pre-, sluice-, and the replenishment phase. The location of the measuring point is shown in Figure 10.

Since the total station cannot perform real-time measurement, the data of the crossing stage is collected every half an hour, and part of the data of the crossing stage is taken for analysis, and the actual deformation curve of the tunnel is fitted as shown in Figure 11.

It can be seen from the above figure that as time goes by, the deflection value of the subway tunnel continues to increase. At 3 am on December 1, 2018, due to the end of the crossing stage, the deflection value reaches the maximum value of 1.91 mm, which is less than the maximum theoretical calculation. The value is 8.23 mm, which is less than the limit value of 10 mm, so the deformation of the existing tunnel structure meets the requirements.

It can be seen from the figure that the deformation curves of the affected area of the tunnel are basically the same, the deflection value of the measuring point in the crossing stage is larger, and the measured deflection value of other measuring points is relatively small due to the distance from the crossing stage. The accuracy of the theoretical calculation model can be verified.

The measured data were selected for analysis at the pre-travel settlement, the transition stage, and the posttravel stage, respectively. The results are shown in Figure 12.

5.2. Inclination Sensor Acquisition Data Analysis. During the construction of the subway tunnel, the data of one week of a project passing through the existing tunnel section is taken for analysis, and the time period is 2018.11.23 0:00~2018.11.30 23:59, to achieve continuous data collection, and the user terminal can obtain an inclination angle acquisition value every minute. This allows an overview of the end of the tunnel, allowing the pin sensor and the positioning systems to be monitored in real time.

The tilt sensor can collect data 20 times within 1 s according to the frequency, and the data obtained by the user on the client is the average of 20 data within 1 s. Due to the large amount of real-time monitoring data, the values in one minute are averaged to obtain one value per minute. Take the measured inclination value from 0:00 to 23:59 on November 23, 2018.

Multiply the inclination value by the segment length to obtain the deflection value of each segment, and then obtain the deflection value of each point by the segment stacking method. During the excavation process, the deflection values at four different moments were analyzed and fitted into a deformation curve, as shown in Figure 13. Deflection measurement results of total station and inclination sensor are shown in Figure 14. Measurement errors between inclination sensor and total station are shown in Table 1.

It can be seen from the above figure that as time goes by, the deformation value of the existing tunnel increases continuously. Each inclination sensor is within the range of the crossing stage, and the existing tunnel is most affected. From the above figure, it can be seen that the maximum deflection value of the existing tunnel is 1.86 mm, which is less than the theoretical calculation value of 8.23 mm, which meets the requirement that the early warning value is less than 10 mm, and is relatively close to the measurement value
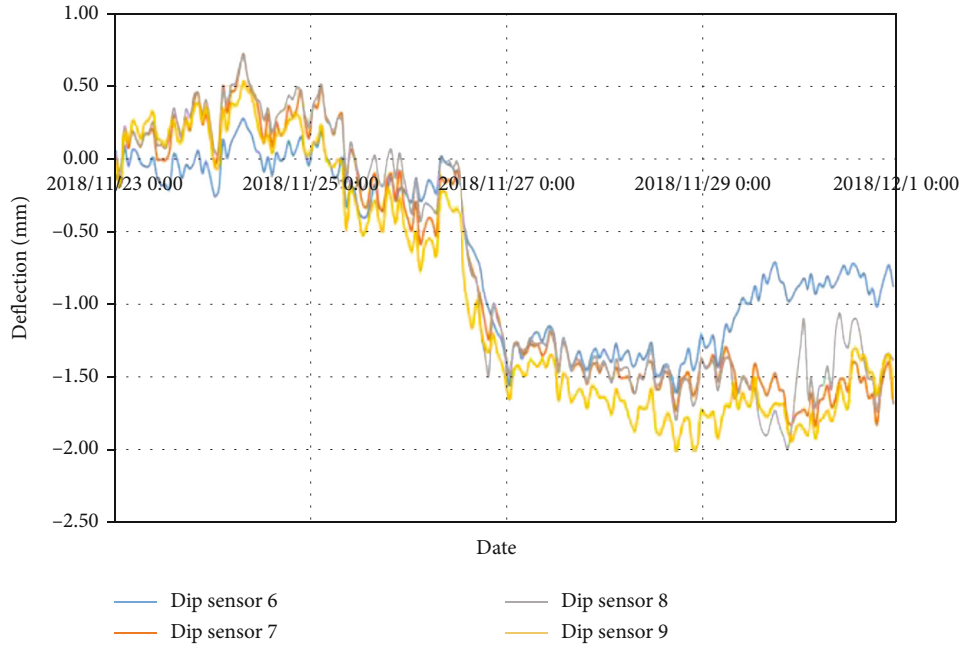
FIGURE 16: Curve of measured deflection with time of 6~9# inclination sensor.
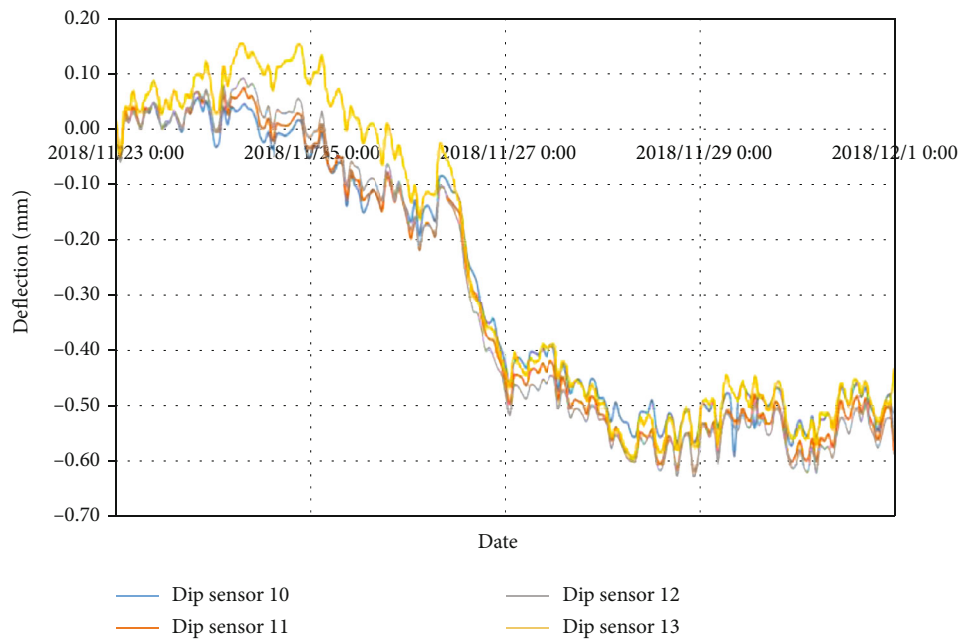


FIGURE 17: Curve of the measured deflection of the 10~13# inclination sensor with time.

of the total station. A method to measure the deflection of the tunnel is available.

The deflection changes of each inclination sensor during the crossing stage are plotted as shown in Figures 15–17.

Similar to the curve of the total station, the deflection values measured by the 13 inclination sensors all changed greatly around November 27, 2018, probably because the excavation was just below the existing tunnel. Among them, the deflection value of 6~9# tilt sensor has the largest change, and the change amount is 1.3 mm. The 1~5# incli-

nation sensor, because it no longer passes through the section where the stage is located, has less influence and less deflection value change. The 10~13# inclination sensor is also not in the section of the crossing stage, so the deflection change is also relatively small. The above three graphs can reflect the real-time deflection change of the tunnel and can realize real-time monitoring.

5.3. Summary of Data Analysis. By converting the inclination value measured by the inclination sensor into the

deflection value, the deformation curve of the existing tunnel is obtained, and the maximum deformation value of the existing tunnel is obtained at the same time. Therefore, the following conclusions are drawn:

(1) The measured deflection curve obtained by the inclination sensor using the segmented superposition method has the same shape as the theoretical deflection curve, which shows the feasibility of the inclination sensor in tunnel deformation measurement

(2) The maximum deflection value measured by the inclination sensor is 1.86 mm, which is less than the theoretical calculation value of 8.23 mm and less than the early warning value of 10 mm. The existing tunnel will be affected by the tunnel excavation, but it is generally safe

(3) The measured value of the inclination sensor can reflect the real-time change of the structure, and the result is reliable

## 6. Conclusion and Outlook

*6.1. In Conclusion*

(1) The inclination sensor is small in size and easy to carry. Its size is $120 \, mm * 150 \, mm * 40 \, mm$, which can be carried in large quantities

(2) The inclination sensor is easy to install, and the measuring point is not easy to be damaged. The aluminum casing can ensure its long-term use and is not limited by the measurement conditions and can be used in the absence of light

(3) Compared with the total station, the inclination sensor has low instrument cost and can be recycled

(4) The test accuracy of the inclination sensor is high, and the measured inclination can reach 9 decimal places, while the deflection value measured by the total station can only be accurate to two decimal places after the decimal point

(5) The tilt sensor can realize real-time monitoring in the office under the premise of unattended. Using the user platform and computer control, real-time monitoring can be achieved, which greatly reduces the workload and on-site testing time. And the acquisition of the inclination sensor can achieve high frequency; that is, 20, 50, and 100 numbers can be collected in 1 s, and real-time monitoring can be achieved

*6.2. Outlook.* The data acquisition method of the inclination sensor described in this paper, by comparing the data measurement and data acquisition of the total station and the inclination sensor, can reflect the advantages and feasibility of the inclination sensor in the real-time remote monitoring system for the deformation of the tunnel structure, which can be done faster. The purpose of strengthening real - time engineering monitoring is to eliminate potential safety hazards and avoid accidents. It has important practical engineering significance for the application and promotion of the inclination sensor in the real-time remote monitoring system of tunnel structure deformation.

## Data Availability

The original data used to support the findings of this study have been deposited in the 4TU.ResearchData. The DOI of this data is 10.4121/20097617. You can download the data from this website https://figshare.com/s/9d5fdc8dd30c8dd4e5ab.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

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