Development of an automatic monitoring system for ground settlement induced by shield tunnelling

Shifu Wan¹, Qiming Huang¹, Hailin Zhao¹, Xingxin Qi¹, Yi Liu², and Wenge Qiu¹,2*

¹Key Laboratory of Transportation Tunnel Engineering of Ministry of Education, Southwest Jiaotong University, Chengdu, Sichuan, 610031, China
²Chengdu Tianyou Tunnelkey Co., Ltd, Chengdu, Sichuan, 610031, China
*Corresponding author’s e-mail: qiuwen_qw@163.com

Abstract. During the construction of the modern subway, it is often the case that subway tunnel construction is close to existing buildings, causing the deformation of existing buildings. In order to minimize the impact of new line construction, real-time monitoring and feedback warning of building deformations are required. This paper is based on the current mature automated monitoring data acquisition system. A comprehensive monitoring management system is developed, which includes engineering information management, monitoring equipment management, monitoring data reception, monitoring data analysis and processing, early warning information release as well as monitoring report automatic output. The developed automatic monitoring system was applied to the monitoring of the construction of Chengdu Metro Line 5, completed the automatic monitoring and real-time data processing and early warning of the underpass process. The operation safety of the existing lines was guaranteed. In the future, this system will also be extended to other tunnel monitoring, gradually forming a comprehensive tunnel construction monitoring and management system.

1. Introduction

Usually, the construction of urban subways often lags behind the construction of cities. As a result, the subway tunnel is close to the existing building in the process of construction. Construction will cause disturbance of the soil and cause ground settlement, which will have a certain impact on existing buildings. Hence, it is necessary to timely monitor the deformation, and properly adjust the construction and minimize the impact of construction [1].

Traditional monitoring of the settlement of existing buildings relies mainly on manual monitoring methods, which is not only time-consuming and laborious but also can not meet the accuracy requirements. Sometimes, it threatens the safety of the workers. Therefore, the use of an efficient automatic monitoring system has become the most reasonable choice.

At present, many manufacturers have provided a mature monitoring data acquisition system [2]. This paper takes Chengdu Metro Line 5 as the project background. Combined with a mature data collection solution, a fully automated monitoring data information management system was developed.

2. Design of the automatic monitoring system

2.1. System Architecture
The architecture of the system is mainly composed of data acquisition layer, data transmission layer, data storage layer, data processing layer, and client.

The system equipment layout scheme uses a distributed Zigbee wireless data collector. Place the network controller at the center of all monitoring points. Ensure the shortest transmission distance with the field network. The monitoring data is transmitted to the network server through the network controller and stored in the database. The data is then processed, analyzed, stored, and distributed by the local control center. The system architecture is shown in Figure 1:

![System Architecture Diagram](image)

Figure 1. Monitoring system architecture.

2.2. On-site instrument

1) Static level

The static level system is a precision sensor that measures the relative elevation changes between two or more points. The principle of the static level using the communicating vessels. By measuring the liquid level of different liquid storage tanks, the calculation can give the relative differential settlement of each static level [3]. It is mainly used for monitoring vertical displacement of dams, high-rise buildings, foundation pits, tunnels, bridges, subways, etc.

2) Data collector

The data collector can connect almost all digital sensors, such as strain gauges, stress gauges, pressure sensors, displacement sensors, etc. The function of the digital collector is to collect the settlement data monitored by the static level and transmit it to the network controller.

3) Network controller

The network controller is used for managing the on-site Zigbee network and transmitting the collected information of all the Zigbee modules to the server. It can also upload data directly through 3G and 4G networks. It also plays a role in the networking and control of the entire Zigbee network [4].

3. Development of monitoring management system

As mentioned before, at present, many manufacturers have provided a complete set of automatic settlement monitoring system. And there are supporting data processing software, but these software functions are relatively simple. It does not have complete engineering information management functions [5]. Therefore, based on WebGL technology and WebSocket long connection technology, a comprehensive monitoring and management system is developed. It realized full automation of data collection, data transmission, data analysis, and data warning.

3.1. Interface and operation design

1) Interface specification

The system uses the RestFul API interface specification, In order to meet the distributed deployment of the system and improve the coupling of the system. Interface design includes the following principles: The principle of single responsibility; the principle of Dependence Inversion; the principle of opening and closing; the principle of Liskov Substitution, etc.

2) Server
A server is a device that provides computing services, considering the disadvantages of establishing a local server, such as high price, unstable performance, and low operation and maintenance efficiency. The cloud server is a simple, efficient, and flexible computing service with the advantages of low cost, stable security, and high efficiency [6]. Therefore, this system adopts the Cloud server and establishes three servers, namely API server, Web&Cloud server, and database server. The architecture of the server is shown in Figure 2:

![Server Architecture Diagram](image)

**Figure 2. Server architecture.**

### 3.2. System function design

This system is mainly composed of the following modules: Engineering information management module, Monitoring data management analysis module, Monitoring data warning and report generation module. Some of the features of the system are now described as follows:

1) **Information management of monitoring points**

   Monitoring point information, mainly including the location of the monitoring point, latitude, and longitude, instruments, etc. The management platform can automatically obtain equipment information, including sensor model, manufacturer, serial number, etc. And use the corresponding formula manager to convert the measured original data into pending data. And can switch the sensor.

2) **Automatic monitoring**

   When the monitoring point sensor is connected to the management platform, the equipment can be started, and real-time monitoring and real-time collection of the data can be carried out. The monitored data is converted and stored in the server for processing. The management platform can adjust the monitoring frequency quantitatively to allocate monitoring resources reasonably.

3) **Data analysis and early warning**

   The settlement monitoring data are processed mainly by the regression analysis method, and the functions of settlement amount \( U \) and time \( T \) are established [7]. The following three functions are commonly used:

   \[
   \begin{align*}
   &\text{Logarithmic function} \quad U = \frac{a + b}{\log(1 + T)} \\
   &\text{Exponential function} \quad U = a \times e^{(bT)} \\
   &\text{Hyperbolic function} \quad U = \frac{T}{a + bT}
   \end{align*}
   \]

   In the formula: \( a, b \) - regression constant; \( T \)-convergence time (d); \( U \)-displacement value (mm).

   The basis for determining the convergence of surface settlement is: The second derivative of the regression equation \( \frac{d^2u}{dt^2} < 0 \) indicates that the deformation rate is decreasing and the settlement tends to be stable; \( \frac{d^2u}{dt^2} = 0 \) indicates that the deformation rate remains unchanged, a warning is issued, and the
excavation is adjusted in time; $\frac{d^2u}{dt^2} > 0$ indicates that the deformation rate is accelerated and has entered a dangerous state, so it is necessary to stop work immediately and take effective measures for reinforcement.

Meanwhile, the system also uses time series analysis, grey theory to assist in the judgment. Later, machine learning methods will be introduced to predict and analyze the monitoring data.

4) Visualization of monitoring points and data
After the user uploads the monitoring profile to the server, the system can mark the position of the monitoring point in the drawing to manage the monitoring point accurately and intuitively. After the monitoring data is processed, the system will draw the results into corresponding charts and display them intuitively on the interface.

5) Automatic report output
Report templates of various types and periods are prefabricated in the system. With one click, monitoring data fields and monitoring result analysis can be automatically filled in. Automatically generate weekly, monthly, and daily reports. And automatically copy the mail to the relevant party. The main interface of the management platform is shown in Figure 3.

![Figure 3. The main interface of the management platform.](image)

3.3. Mobile management application
In order to facilitate the management of construction anytime and anywhere, and the timely delivery of warning messages, the system has also developed a mobile client. The functions of the mobile client are basically the same as those of the PC. In addition to the functions mentioned above, it also adds practical functions such as industry information. Android mobile phone system and IOS mobile phone system have been supported.

4. Practical application case

4.1. Project Overview
Chengdu Metro Line 5 Saiyuntai Station - North Railway Station is a subterranean section with a total length of 526.983 m. Construction by shield method. The section line passes through the mileage of YDK17+370~YDK17+400 and passes through the Bao-cheng Railway Road’s throat area, a total of six tracks in operation. The minimum clear distance from the tunnel top to the base of the Bao-cheng Railway is 13.958 m. The longitudinal section of the line is shown in Figure 4:
This monitoring index is the settlement of railway tracks, to evaluate its safety and impact on train operation. The benchmark control value of railway subgrade settlement is ±1mm, and the early warning value is ±0.7mm [8].

4.2. Layout of monitoring sections and monitoring points

6 tracks within the influence scope of tunnel construction were monitored, and 4 sections were arranged in total. A total of 24 monitoring points. The base was first made at the monitoring point, and then the static level monitor was fixed with expansion bolts. The monitoring point layout and scene pictures are shown in Figure 5. The instruments used in the monitoring site are shown in Table 1:

| Number | Name                  | Type      | Quantity |
|--------|-----------------------|-----------|----------|
| 1      | Network controller    | MIC-NAC-R | 2        |
| 2      | Digital collector     | MIC-DCD-4 | 6        |
| 3      | Static level          | MIC-TD-SM | 24       |

4.3. Monitoring data management and early warning

The system was used for monitoring and management in the tunneling of Chengdu Metro Line 5. The automatic dynamic monitoring was implemented, and the monitoring interval was adjusted within 0.5~2h according to the tunneling situation. The effect showed: The system ran stably, realized the real-time collection and analysis of the monitoring data, and could push the early warning information in time, which reflected the law of surface subsidence. It played a good guiding role in the construction, ensured the safety of the operation line, and generated a complete analysis report of the monitoring results. The application benefited all parties. The real-time monitoring is shown in Figure 6:
5. Conclusion

Based on the mature automatic settlement data acquisition system on the market, a set of integrated monitoring management system was developed, which includes engineering information management, monitoring equipment management, monitoring data reception, monitoring data analysis and processing, early warning information release and monitoring report automatic output. It was used in the construction monitoring of Chengdu Metro Line 5. The dynamic monitoring of ground settlement during the whole process of shield tunnelling was automatically completed, and the timely processing of monitoring data and the pushing of warning information were achieved. The monitoring results were used to guide the construction of the shield to ensure the safety of the upper structures during the construction process, which benefited all parties. The system is not only suitable for monitoring and management of ground settlement. This system can be used in other monitoring projects of the tunnel by simply adjusting the data interface, modifying the data analysis mode, and adding functional modules. Gradually forming a comprehensive tunnel construction monitoring and management system.

References

[1] W.Y.Yan, S.N.Xu, W.B.Yan.(2011)The Application of Automatic Monitoring in the Guangzhou Metro.Construction & Design for Project, (06):153-155+160.
[2] F.Yang, J.Zhao, X.X.Zhou. (2012) Application and analysis of automatic real-time monitoring in the construction of subway tunnels.Chinese Journal of Geotechnical Engineering, 34(S1):162-166.
[3] S.H.Bai.(2003)The Application of Static Force Level on Monitoring the Urban Railway of Beijing.China Instrumentation, (11):34-36.
[4] S.L.Xu, W.B.Wang.(2013)Design of industrial wireless data collector based on ZigBee.Industry and Mine Automation, 39(07):88-90.
[5] YJXu, WLLi. (2018)Application of Automatic Hydrostatic Level System in Deformation Monitoring of Tianjin Subway Line 6.Construction Technology, 47(S4):1514-1517.
[6] X.Y.Xie, J.Li, Q.Wang.(2016)Automatic monitoring and mobile data publishing system of ground settlement induced by shield tunneling. Rock and Soil Mechanics, 37(S2):788-794.
[7] J.G.Xu, Y.C.Cai.(2008)Convergence Deformation Monitoring of Tunnel and Characteristic Parameter Back Analysis of Surrounding Rock.China Journal of Highway and Transport, (03):81-85.
[8] T.L.Cui, H.Q.Xiao, G.Wang. (2008) Application of automatic monitoring technology in Construction of Works Crossing blow Existing Metro Line. Tunnel Construction, (03):359-361.