

# Research on Subway Tunnel Construction Monitoring Technology for Complex Urban Environments

Can Chen<sup>1</sup>, Xi Ni<sup>2</sup>

<sup>1</sup>Chongqing Energy College, Chongqing 402260, China

<sup>2</sup>China Railway Southwest Research Institute Co., Ltd., Chengdu 610000, Sichuan, China

**Copyright:** © 2026 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

**Abstract:** Addressing the technical challenges of subway tunnel construction in complex urban environments—including intricate geological conditions, sensitive surrounding environments, and high safety risks—this study, based on the Phase II project of Guangzhou Metro Line 13, conducts a comprehensive investigation into the entire process of subway tunnel construction monitoring. Through systematic identification of construction risk factors under complex urban conditions, a refined risk engineering checklist is compiled, a customized monitoring system is designed, a risk identification assessment early warning framework is established with operable emergency plans, standardized monitoring operation procedures are formulated, and dynamic optimization of the monitoring scheme is achieved. The research develops a set of monitoring technical systems adaptable to complex urban environments, providing a practical and feasible technical solution and engineering practice reference for subway tunnel construction monitoring under such conditions.

**Keywords:** Complex urban environment; Subway tunnel construction; Construction monitoring; Monitoring system design

**Online publication:** October 28, 2026

## 1. Introduction

The accelerating pace of urbanization has increasingly positioned urban rail transit as a core component of comprehensive urban transportation systems. By March 2025, 326 urban rail transit lines had been opened and operated in 54 Chinese cities, with a total operational mileage of 10,975.8 km. The Outline of the 14th Five-Year Plan and the Long-Range Objectives Through 2035 explicitly sets a development target of adding 3,000 km of new urban rail transit operational mileage<sup>[1,2]</sup>. While the scale of subway tunnel construction continues to expand, construction in urban core areas is frequently plagued by safety accidents due to complex geology and sensitive surrounding environments, often resulting in multiple safety losses.

Construction monitoring serves as the core means of controlling engineering safety. Although domestic practices have progressed toward automation and informatization, incorporating technologies such as the Internet of Things, existing studies predominantly focus on single scenarios, and generalized monitoring models suffer from issues such as unreasonable resource allocation, rendering them inadequate for the demands of complex construction environments. To address this, the present study takes the Phase II project of Guangzhou Metro Line 13 as the subject, conducting a fullprocess investigation of construction monitoring technology, developing a monitoring technical system tailored to complex urban environments, overcoming the limitations of traditional models, enhancing monitoring efficiency and effectiveness, and contributing to the green, safe, and sustainable construction of rail transit.

## **2. Risk factor identification and checklist compilation for subway tunnel construction in complex urban environments**

### **2.1. Project overview and complex environmental characteristics**

This study is based on the Phase II project of Guangzhou Metro Line 13, selecting the Huacheng Square North Station and the section from Magang Station to Tianhe Park Station as typical research objects. The project includes complex sections such as undercrossing the Guangyuan Expressway and water-rich sand layers, presenting difficulties including complex geological conditions, sensitive surrounding environments, high construction technique requirements, and constrained working spaces, which are prone to safety risks such as structural deformation and environmental damage. The characteristics are representative of subway tunnel construction in urban settings, and the research findings can be extended to similar projects.

### **2.2. Systematic identification of multidimensional construction risk factors**

The research systematically identifies construction risk factors from multiple dimensions. First, common risks are summarized into five major categories, including geological hazards and structural deformation. Second, the risk patterns under different construction scenarios are compared to identify scenariospecific risks such as water-rich sand layers and undercrossing of main roads. Finally, combined with the engineering investigation reports and onsite surveys, the specific risks applicable to this project are precisely identified. A systematic identification framework is ultimately established across four dimensions: engineering geology, surrounding environment, construction technology, and construction management, encompassing various specific risks including stratum settlement, building tilting, segment displacement, and untimely monitoring.

### **2.3. Compilation of a refined risk engineering checklist**

Based on the systematic identification, this study deeply integrates macrolevel risks with the actual geological conditions, environmental factors, and construction techniques of the project, conducting customized risk analysis. Inapplicable common risks are eliminated, projectspecific risks are refined, and the source, scope of influence, triggering conditions, and severity of each risk are clearly defined. A refined risk engineering checklist is then compiled, with each risk annotated with its corresponding engineering location, type, grade, and associated factors, enabling precise positioning and systematic management of risk points. This checklist breaks through the limitations of traditional generalized approaches and serves as the core basis for subsequent monitoring design, risk early warning, and emergency response.

### **3. Riskoriented customized design of the monitoring system for subway tunnel construction**

#### **3.1. Determination of monitoring content and monitoring objects**

Based on the refined risk project inventory as the core reference, and taking into account the construction characteristics of typical stations and sections of Phase II of Guangzhou Metro Line 13, this study carries out a riskoriented customized design of the monitoring system, achieving precise alignment between the monitoring system and construction risks. In determining the monitoring content and objects, the three key dimensions—structural deformation of the works, changes in the surrounding environment, and stress states during construction—are taken as the primary focus. Accordingly, the core monitoring items include surface heave and settlement, settlement and inclination of buildings and structures, segment displacement, settlement of underground pipelines, and support axial force. The monitoring objects are precisely targeted at the highrisk locations identified in the inventory, covering the deep foundation pit of Huacheng Square North Station, the waterrich sand layer section between Magang Station and Tianhe Park Station, the section underneath the Guangyuan Expressway, and the construction zones adjacent to important buildings, structures and underground pipelines.

#### **3.2. Selection of monitoring instruments and accuracy specifications**

The selection of monitoring instruments follows the principles of “precision, automation, and strong adaptability”. Dedicated equipment is matched to different monitoring items: for example, total stations are used for surface and building settlement monitoring, crack gauges for crack observation, and axial force gauges and water level gauges for monitoring support axial force and groundwater level, respectively. At the same time, automated equipment is introduced to reduce manual intervention and improve data acquisition efficiency <sup>[3]</sup>. In accordance with the project risk control requirements and relevant standards, specific accuracy specifications for each item are established, with clear parameters such as instrument measurement error and resolution. For instance, the accuracy for surface heave and settlement monitoring is controlled within  $\pm 2$  mm, and the inclination accuracy for buildings and structures within  $\pm 0.1\%$ , thereby ensuring the reliability of the monitoring data.

#### **3.3. Dynamic design of monitoring frequency and period**

The monitoring frequency and period are not based on a fixed pattern but adopt a dynamic design approach. The monitoring period is divided into three phases according to the construction schedule: the preconstruction baseline period, the construction period, and the postconstruction stabilization period. During the construction period, the frequency is adjusted according to the risk level of each work procedure. For highrisk procedures such as deep foundation pit excavation and underpassing of major roads, the frequency is set at once per day; for periods with stable procedures and lower risk, the frequency is reduced to once every three days. In parallel, a dynamic adjustment mechanism is established: when monitoring data become abnormal or a risk alert is triggered, the frequency is immediately increased to once every half day or even realtime monitoring, until the project returns to a stable state.

#### **3.4. Monitoring control indicators and layout scheme of monitoring points**

The formulation of monitoring control indicators follows relevant specifications, engineering geological conditions, and safety requirements for surrounding facilities. Based on the risk prevention and control

objectives, warning values and control values for each monitoring parameter are clearly defined. For example, the warning value for surface heave and settlement is set at +10 mm/30 mm, while the control values for building settlement are differentiated according to structure type and safety grade, thus achieving quantitative risk management for construction. The layout of monitoring points adheres to the principles of “full coverage, clear emphasis, ease of monitoring, and resistance to damage”. First, a deformation monitoring network comprising reference points, working base points, and deformation monitoring points is established; then, specialized monitoring points are arranged for different monitoring items, precisely covering highrisk locations and sensitive areas. At the same time, a point inventory is compiled, specifying numbering, locations, monitoring contents and frequencies, so as to achieve standardized management of monitoring points and ensure comprehensive and accurate capture of changes in the monitored objects <sup>[4]</sup>.

## **4. Metro tunnel construction monitoring risk early warning and emergency technology system**

### **4.1. Risk assessment model and classification of monitoring risk levels**

Based on the actual conditions of the second phase of Guangzhou Metro Line 13, this study constructed a construction risk assessment model adapted to the complex urban environment. Taking a refined risk inventory as the foundation, the model incorporates monitoring data as a core quantitative indicator, and integrates the probability of risk occurrence, the degree of hazard, and the scope of impact. Through a combination of qualitative and quantitative methods, it analyzes the deviation between monitoring data and control indicators, and quantitatively evaluates the status of each risk factor. According to the assessment results, construction monitoring risks are classified into three levels: Level I alert status (data approaching the warning value), Level II alarm status (data reaching the warning value), and Level III emergency status (data exceeding the control value), with clear criteria for determination, thereby enabling graded control of construction risks <sup>[5]</sup>.

### **4.2. Construction of a multiindicator linkage risk early warning system**

Based on the risk level classification, this study constructed a multiindicator linkage risk early warning system to overcome the limitations of singleindicator warnings. A realtime analysis mechanism for monitoring data was established to rapidly compare the data against the risk level criteria. Three levels of warning signals—yellow, orange, and red—were set to correspond to different risk levels, with clearly defined triggering conditions. Multiindicator linkage warning rules were formulated: when a single indicator reaches the warning value or when multiple related indicators exhibit anomalies, the corresponding warning is immediately triggered. Through onsite notifications and system push messages, the information is promptly delivered to relevant management personnel, ensuring efficient transmission of early warnings.

### **4.3. Formulation of graded prevention and control technical measures**

Targeting different risk levels, this study formulated graded prevention and control technical measures to ensure precision and operability. Under the Level I yellow warning, monitoring data are reexamined, causative factors are investigated, monitoring frequency is increased, highrisk procedures are suspended, and preventive measures are implemented. Under the Level II orange warning, construction in the affected area is halted, expert evaluation is organized, and a specialized plan is developed; protective measures such as

reinforcement and support are applied to the project and surrounding environment, while realtime monitoring of risk changes is maintained. Under the Level III red warning, emergency response is immediately activated, construction personnel are evacuated, and the hazardous area is cordoned off; experts develop an emergency disposal plan, and rapid riskcontrol measures such as emergency reinforcement and drainage and pressure relief are executed.

#### **4.4. Compilation of operational emergency response plans**

Furthermore, based on the risk inventory, level classification, and graded prevention and control measures, and in combination with the construction characteristics and onsite conditions, operational emergency response plans were compiled. The plans clearly define the emergency organization structure and the responsibilities of each level and team, and standardize the complete emergency response procedures from warning trigger to project resumption. Emergency resources such as support materials and drainage equipment are preplanned, and professional rescue teams are assigned. Regular emergency drills are scheduled, and the plans are optimized based on drill results to enhance their practicality, ensuring rapid and effective response when unforeseen risks occur.

### **5. Standardized monitoring operations and data processing technology for metro tunnel construction**

#### **5.1. Formulation of standardized technical procedures for monitoring operations**

Based on the monitoring item list, measurement point list, and onsite construction conditions, a standardized operating procedure was developed encompassing monitoring preparation, sensor installation, data acquisition, onsite recording, and data transmission <sup>[6]</sup>. During the preparation phase, instrument calibration and onsite reconnaissance are performed to ensure equipment condition and operational environment. In the installation phase, construction is carried out strictly according to the plan, with proper marking and protection of measurement points. In the acquisition phase, data are collected at the required frequency and precision to ensure their originality and accuracy. In the recording phase, detailed documentation of collected information and site conditions is made. In the transmission phase, raw data are uploaded to the management system in a timely manner for realtime storage and sharing. These standardized procedures define the operational and quality standards for each step, reducing human error and enhancing the level of standardization in monitoring operations.

#### **5.2. Precise data acquisition and quality control for monitoring data**

To ensure the precision and reliability of monitoring data, a fullprocess quality control system encompassing acquisition, transmission, and verification has been established <sup>[7]</sup>. During the acquisition phase, instruments are regularly calibrated and maintained, professional training for personnel is conducted, and automated equipment is deployed to reduce manual errors. In the transmission phase, encrypted transmission methods are employed to prevent data loss or tampering. In the verification phase, a dualpersonnel verification and multilevel review mechanism is implemented, with comparative analysis of data from the same points and onsite remeasurement for abnormal data. To address the issue of sensor drift and failure in complex environments, dualsensor redundant nodes are deployed in key areas, with regular equipment calibration and a fault early warning mechanism, thereby avoiding distortion of monitoring data.

### **5.3. Monitoring data processing and analysis techniques**

Scientifically rigorous processing and indepth analysis are conducted on the monitoring data that have passed quality control, so as to uncover the inherent engineering patterns. The first step is data preprocessing, including elimination of outliers and imputation of missing values, to ensure data integrity and validity. Subsequently, statistical analysis and curve fitting are performed to generate spatiotemporal variation curves for each monitoring item, visually presenting the deformation patterns and development trends of the engineering structure and surrounding environment. Finally, in combination with the engineering geology and construction techniques, the causes of data variations are analyzed, the engineering stability is assessed, and potential risks are identified, providing data support for adjustment and optimization of the construction plan. Meanwhile, a monitoring data management system has been established to realize informationbased data management, supporting query, statistics, and visual display, thereby improving data processing efficiency.

### **5.4. Technical specifications for monitoring report compilation**

Technical specifications for the compilation of monitoring reports have been formulated, clarifying the content, format, and reporting cycles. Reports are compiled in three categories: daily, phasebased, and final. Daily reports are prepared each day, reflecting the monitoring data of that day, changes, and onsite construction status. Phasebased reports are compiled at each construction milestone, summarizing monitoring data, analyzing deformation patterns, evaluating risks, and providing prevention and control recommendations. The final report, prepared upon completion of monitoring work, provides a comprehensive summary of the monitoring activities, assesses engineering stability, and offers technical recommendations. The report content is required to be comprehensive and detailed, covering key elements such as project overview, monitoring system design, operation implementation, data processing, and risk assessment, with appended data tables and variation curves, thereby providing a reliable and comprehensive basis for construction management decisionmaking.

## **6. Monitoring information feedback and dynamic optimization technology of monitoring schemes**

### **6.1. Realtime feedback technical mechanism for monitoring information**

A comprehensive monitoring information feedback mechanism has been established, specifying the content, procedures, recipients, and timelines of feedback, to ensure realtime and efficient information transmission. The feedback content includes monitoring data, change analysis, risk warnings, and onsite construction conditions. A threetier procedure involving “onsite monitoring personnel–technical management department–construction decisionmaking department” is adopted to ensure that data and abnormal conditions are transmitted level by level and analyzed promptly. The feedback covers relevant entities and personnel including construction management, technical staff, construction workers, and supervision units. Routine information is fed back within 24 hours, while earlywarning information is reported immediately. Additionally, a multichannel feedback network is constructed by combining online data push with offline meetings and written reports.

### **6.2. Technical implementation of dynamic optimization of monitoring schemes**

Based on monitoring feedback results, construction progress, risk changes, and onsite conditions, the

monitoring scheme is dynamically optimized. When data indicate that deformation has stabilized and risks have decreased, the monitoring frequency is adjusted and monitoring points in low-risk areas are reduced. When entering new construction phases, emerging new risks, or encountering abnormal data, monitoring content is supplemented, monitoring points and frequency in high-risk areas are increased, and instrument selection and accuracy are optimized. When construction conditions change, the layout of monitoring points and operational procedures are adjusted. The optimization follows the principles of “risk-oriented, demand-based adjustment, and precision-driven efficiency”, adapting to the actual needs of the project.

### **6.3. Technical verification of the optimized monitoring scheme**

Technical verification is carried out on the optimized scheme to ensure its scientific soundness and operability. The scheme is applied to the actual construction of Guangzhou Metro Line 13 Phase II. Its accuracy and effectiveness are validated by collecting data and analyzing structural and environmental changes. Expert reviews are organized to verify the scientific basis from a theoretical perspective. Further refinements are made based on onsite feedback to ensure that the scheme meets construction needs, thereby providing reliable monitoring support for subway tunnel construction.

## **7. Conclusions**

Monitoring of subway tunnel construction in complex urban environments is a core technical means for ensuring construction safety and promoting the sustainable development of urban rail transit construction. In response to the shortcomings of traditional generic monitoring models, such as insufficient targeting and low efficiency, this study, based on the Guangzhou Metro Line 13 Phase II project, has conducted a full-process technical study on monitoring for subway tunnel construction, yielding a series of research outcomes. The resulting monitoring schemes, monitoring reports, and technical research reports provide feasible technical solutions and engineering practice references for subway tunnel construction monitoring in complex urban environments, and hold significant practical relevance for advancing innovation and development of construction monitoring technologies in China’s subway construction sector.

## **Funding**

Research on Monitoring Technology for Subway Tunnel Construction in Complex Urban Environments (Project No.: ZRKX202501)

## **Disclosure statement**

The authors declare no conflict of interest.

## **References**

- [1] Guangming Online, 2025, In March This Year, 326 Urban Rail Transit Lines Were in Operation in 54 Cities Across the Country, Carrying 2.88 Billion Passenger Trips.
- [2] People’s Daily Online, 2021, The 14th Five-Year Plan for National Economic and Social Development of the

People's Republic of China and the Outline of Long-Term Objectives for 2035.

- [3] Yuan Q, Chi G, Li X, et al., 2026, Detection, Localization, and Control Strategies for Leakage in Urban Water Supply Networks. *Water Purification Technology*, 45(2): 1–11 + 59.
- [4] Duan G, 2025, Application of Intelligent Detection Technology in Routine Maintenance Inspection of Highway Tunnels. *Transport Manager World*, 2025(34): 112–114.
- [5] Shi M, 2025, Brief Analysis of Monitoring and Early Warning Technology for Geological Hazards on Mountainous Expressway Slopes. *China ITS Journal*, 2025(S2): 302–305.
- [6] Cheng Y, Wang L, Zhao P, 2023, Construction and Application of a Monitoring Management Platform for Urban Rail Transit During Construction Based on GIS + BIM Technology. *Northwest Hydropower*, 2023(4): 108–112 + 118.
- [7] Jiang Q, 2025, Research on Multi-Source Data Fusion Monitoring Method for Equipment Status of Subway Power Supply Systems. *People's Public Transport*, 2025(24): 63–65.

**Publisher's note**

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.