Research on Real-time Monitoring and Risk Assessment of Structural Deformation of Key Nodes in Urban Subway

Lei JIN

Hefei Rail Transit Group Operation Co., Ltd., Hefei, Anhui, 230000, China

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Abstract: In view of the increasingly prominent structural deformation risk of key nodes in urban subway under high-density operation and complex geological environment, this paper proposes and constructs a set of real-time monitoring and dynamic risk assessment technology system which integrates multi-source sensing, real-time transmission and intelligent analysis. By arranging fiber grating, laser ranging, inclination angle and microseismic sensors, a multi-dimensional monitoring network covering strain, displacement, vibration and other dimensions is formed, so as to realize minute-level real-time sensing of structural deformation of key nodes such as subway crossing tunnels and adjacent sections of deep foundation pits. Digital twinning and machine learning technology are introduced, structural mechanics model and convolutional neural network (CNN) algorithm are combined to extract key deformation features, and ARIMA/LSTM model is combined to realize short-term risk early warning. Furthermore, a dynamic risk assessment model coupled with real-time monitoring data and physical mechanism is proposed. Based on entropy weight -TOPSIS and Bayesian network, risk factors are dynamically weighted and failure probability is updated. A disaster chain propagation model is constructed to quantify risk consequences, and a reinforcement learning decision support module is integrated to realize risk response closed-loop management. The engineering case shows that the system can identify the sudden change of tunnel settlement 12 hours in advance and trigger high-risk warning, and successfully avoid major operational accidents, which verifies its engineering applicability and popularization value in the intelligent management and control of subway structure safety.

1. Introduction

By 2023, 55 cities in China mainland have opened urban rail transit, with the operating mileage exceeding 10,000 kilometers, of which the subway accounts for more than 80% [1]. However, the coupling effect of high-density operation of subway network and complex geological environment leads to the increasingly prominent structural deformation problem. For example, in 2021, a section of Guangzhou Metro Line 21 caused the horizontal displacement of the tunnel to exceed the limit due to the surrounding foundation pit construction, which led to the train running at a speed limit; In 2022, a station of Shanghai Metro Line 15 was forced to stop for maintenance due to long-term uneven settlement and wall cracks [2]. Such incidents have exposed the lag of traditional monitoring methods and the limitations of risk assessment methods, and it is urgent to build a real-time, intelligent and accurate structural safety management and control system. As the "throat" of network operation, the key nodes of subway, such as crossing tunnels, long-span station halls and adjacent sections of deep foundation pits, may cause chain disasters due to their structural deformation [3]. The over-limit convergence of the tunnel leads to the derailment of the train, the collapse of the station hall and the destruction of the evacuation passage; The short circuit of electrical system caused by water seepage and the ground collapse caused by structural instability affect the safety of surrounding buildings. Therefore, the research on real-time monitoring technology and dynamic risk assessment model is of great theoretical value and engineering significance for improving the safety of subway in its whole life cycle and reducing the operation and maintenance cost.

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2. Analysis of deformation mechanism and risk factors of subway key node structure

2.1 Deformation mechanism of subway key node structure

The structural deformation of key joints of subway mainly includes the deformation of foundation pit retaining structure, the deformation of soil around foundation pit and the expansion deformation of soil around foundation pit [4-5].

2.1.1 Deformation mechanism of retaining structure of foundation pit

The deformation of retaining structure of foundation pit is caused by the excavation of subway deep foundation pit, which is mainly related to the deformation of retaining structure around subway deep foundation pit [6]. In the early stage of subway deep foundation pit excavation, due to the installation of the supporting structure, no proper stress was applied, which led to the deformation of the retaining structure around the deep foundation pit, which led to the arc shape of the structure and the large deformation in the middle part, which led to the reduction of the bearing capacity.

2.1.2 Deformation mechanism of soil around foundation pit

The deformation of the soil around the foundation pit is due to the settlement of the soil around the foundation pit. Due to the deformation of the retaining structure during excavation, the load of the soil around the foundation pit is released, which leads to the phenomenon of plastic uplift and rebound of the soil, which leads to the imbalance of the stress of the soil around the foundation pit, thus affecting the surrounding geology and buildings.

2.1.3 Expansion deformation mechanism of foundation pit soil

The expansion and deformation of soil in foundation pit is due to the expansion of soil due to the release of load during the bottom excavation of foundation pit, which leads to the deformation of surrounding geology, ground buildings and underground buildings [7]. The phenomenon of soil expansion is related to the unloading effect of soil, which makes the soil at the bottom of the foundation pit rebound, swell and swell, further triggering the vertical unloading effect of soil, which changes the overall stress of the foundation pit.

2.2 Risk factors of deformation of subway key node structure

The risk factors of structural deformation of subway key nodes mainly include design problems, construction problems and natural environment factors.

2.2.1 Design problem

The design problem refers to that in the process of subway deep foundation pit construction, the design unit does not have the relevant design requirements or has no in-depth understanding of the local geological conditions, and ignores the investigation of the surrounding environment of the subway to be developed, which will affect the design of the subway deep foundation pit, resulting in loopholes in the design and selection of the retaining structure around the subway deep foundation pit [8].

2.2.2 Construction problem

Construction problems refer to the construction safety problems in the process of deep foundation pit construction, which are often related to the following three situations. First, because the selected construction unit lacks relevant construction experience, it will lead to management confusion and construction confusion in the construction process. Second, when the construction party found obvious cracks in the building or ground during the excavation of the deep foundation pit of the subway, it failed to deal with them in time and continued to construct blindly. Thirdly, because the construction standards and requirements of subway deep foundation pit are higher and more detailed than those of ordinary deep foundation pit excavation standards, the construction unit does not know the relevant standards in place during the construction process, and does not follow the relevant construction standards during the construction operation, which will also lead to the surrounding geology and building deformation during the excavation of subway deep foundation pit [9].

2.2.3 Natural environment factors

Natural environmental factors refer to the solid state of foundation pit soil due to precipitation, water leakage and other reasons during subway construction, which leads to the settlement risk of surrounding geology, soil and buildings [10].

3. Construction of real-time monitoring technology system

Aiming at the structural deformation problem of key nodes in subway, a set of technical system integrating multi-source sensing fusion, real-time transmission and intelligent processing is constructed in this study. By scientifically deploying high-precision fiber grating sensors, laser rangefinders, tilt sensors and microseismic monitoring equipment, a multi-dimensional sensing network covering strain, temperature, convergence deformation, structural tilt and geological activities has been formed. The redundant layout of sensors in high-risk areas such as structural joints, weak supporting parts and adjacent construction significantly improves the spatial coverage and data reliability of the monitoring system, and provides a solid data foundation for structural safety assessment. On the data transmission and processing level, the system adopts 5G and industrial Internet of Things protocols to realize low-latency and high-stability data return, and performs real-time filtering, denoising and outlier identification on the original monitoring data at the edge computing nodes, which effectively reduces the data transmission bandwidth requirements and cloud processing burden. Ensuring the efficient flow of massive monitoring data also provides timely and accurate data support for subsequent intelligent analysis and early warning response, and improves the automation and intelligence level of subway structural health monitoring.

A multi-source data fusion and feature extraction mechanism is established. By fusing multi-modal monitoring data such as structural deformation, stress and vibration, combined with machine learning methods such as structural mechanics model and convolutional neural network (CNN), the key features reflecting the structural health state, such as deformation rate, cumulative displacement and spectral characteristics, are effectively extracted. At the same time, the digital twinning technology is introduced to construct a virtual model that is updated synchronously with physical entities, which realizes the visual simulation and dynamic deduction of structural deformation trend, and provides an intuitive and accurate analysis means for state evaluation and decision support.

In the aspect of anomaly diagnosis and early warning, the system adopts multi-level threshold mechanism, integrates the static threshold set by design specifications and the dynamic threshold generated based on historical data learning, and combines ARIMA, LSTM and other time series prediction models to realize early identification and short-term early warning of potential structural risks. By developing a lightweight early warning information push platform, the monitoring data, diagnosis results and early warning instructions are synchronized to the mobile terminal and the control center in real time.

4. Development of dynamic risk assessment model

In order to solve the static and lag of traditional risk assessment, a dynamic risk assessment model coupling real-time monitoring data and physical mechanism is proposed, and the specific framework is shown in Figure 1 below.

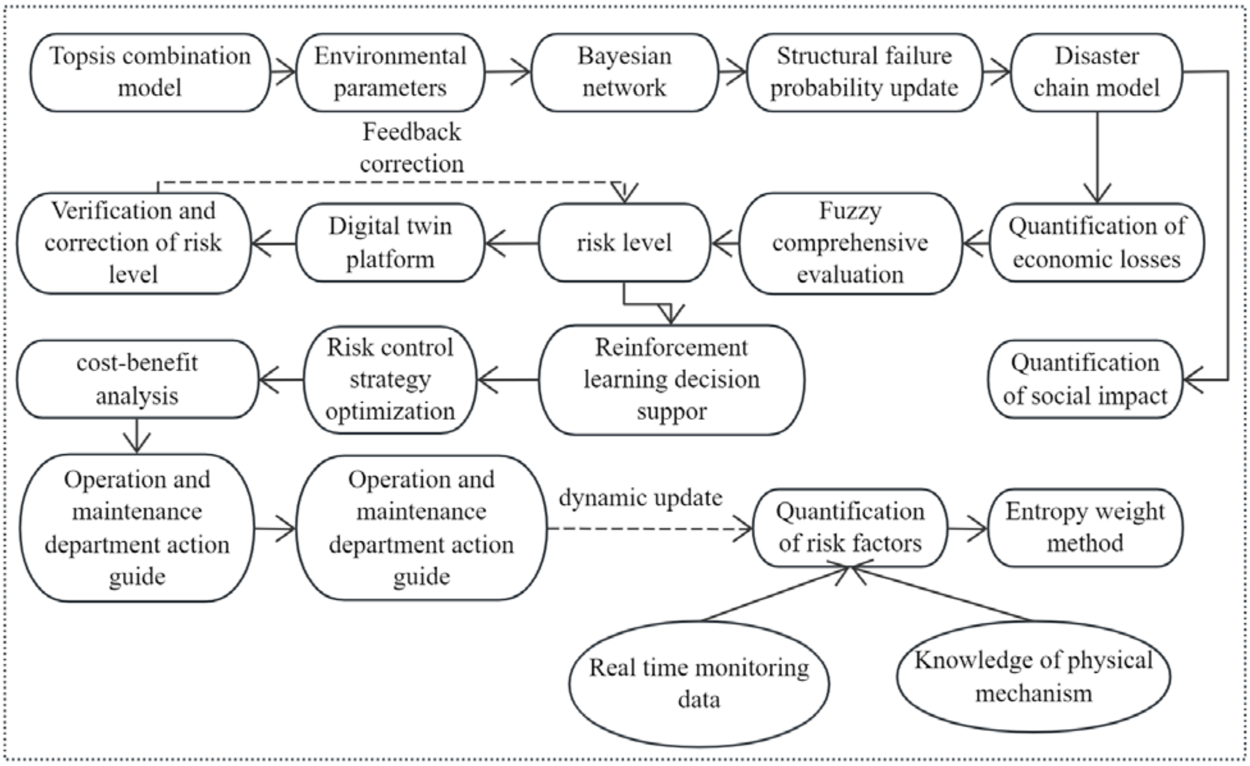

Figure 1 Dynamic risk assessment model framework

Dynamic risk factor quantification and weight adaptive mechanism, based on real-time monitoring data, continuously update key risk factors such as deformation, settlement rate and crack propagation index, and combine entropy weight method and TOPSIS model for combined analysis, realize dynamic adjustment of factor weight, and effectively reflect the change of contribution degree of each risk factor in different operation stages of subway structure. Taking environmental parameters such as groundwater level fluctuation and surrounding construction vibration as external risk inputs can enhance the adaptability and accuracy of the evaluation model in complex and changeable environment.

On the risk assessment level, the system uses Bayesian network to fuse real-time monitoring information and historical prior knowledge, and dynamically deduces and updates the probability of structural failure events such as tunnel convergence overrun, thus realizing the intelligence of probability assessment. In the aspect of consequence assessment, a disaster chain propagation model is constructed to simulate the chain reaction process of "deformation → water seepage → electrical failure → operation interruption", and to quantify the direct economic loss and social impact under different risk scenarios, so as to provide comprehensive and quantitative risk decision support for subway operators.

A dynamic risk classification and visualization mechanism is established, and the structural safety risks are classified into four levels by fuzzy comprehensive evaluation method, namely, normal, concerned, early warning and critical. Based on the digital twin platform, the real-time visual display of risk spatial distribution and evolution trend is realized in the form of heat map, and the risk situation perception ability is improved. At the same time, the cross-validation and dynamic correction of the evaluation results are combined with the historical case base and expert experience knowledge, which effectively improves the accuracy of risk classification, significantly reduces the rate of false positives and false negatives, and enhances the reliability and practicability of the system.

In terms of risk response, the system integrates the decision support module based on reinforcement learning, which can intelligently recommend the optimal control strategy according to the current risk level, such as train speed limit, line outage or emergency reinforcement. By constructing a cost-benefit analysis model, the economic investment, implementation effect and social impact of different strategies are comprehensively evaluated, which provides scientific and feasible action guidance for the operation and maintenance management department, realizes closed-loop management from risk identification to accurate response, and comprehensively improves the intelligent decision-making level of subway system to deal with structural safety risks.

5. Engineering case analysis

The excavation of deep foundation pit adjacent to the existing operating tunnel of a subway interchange station in a city is selected as a typical case. The excavation depth of the foundation pit is 28m, and the minimum clear distance from the existing subway tunnel is only 6.5m, so the construction risk is extremely high. The traditional manual monitoring frequency is once a day, which can't capture the instantaneous change of deformation, so it is urgent to implement automatic real-time monitoring and dynamic risk assessment.

Multi-source sensor clusters integrating static level, inclinometer, fiber grating strain sensor and microseismic monitor are deployed in the key section (K12+350) of the existing tunnel adjacent to the foundation pit, which are used to monitor the vertical settlement, horizontal displacement, segment convergence and joint deformation of the tunnel and vibration signals caused by foundation pit excavation respectively. All sensors realize real-time data transmission through pre-laid industrial Ethernet, and the sampling frequency is once every minute, and the data is connected to the cloud management platform in a unified way.

Figure 2 below shows the real-time monitoring data of settlement and horizontal displacement of key sections of the tunnel within 24 hours from the 15th day of foundation pit excavation. On that day, the foundation pit floor was being poured, and the unloading rate was accelerated. Table 1 below shows the output of risk assessment model and the results of system response.

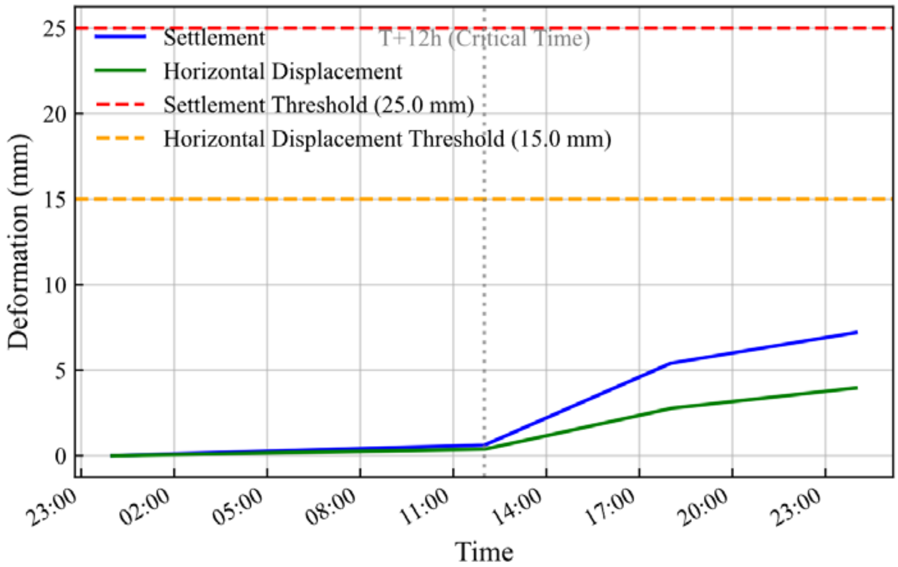

Figure 2 Real-time monitoring curve of key section deformation (24 hours)

Table 1 Output of risk assessment model and system response (time point: T+12h)

Risk index	Real-time monitoring value	Threshold value	Risk level	System automatic response measures
Sedimentation rate	0.8 mm/h	0.5 mm/h	High-risk	1. Push the highest level alarm to the project management group. 2. Automatically trigger the pressurization instruction of foundation pit supporting system. 3. It is suggested to reduce the excavation speed of foundation pit.
Cumulative settlement	18.2 mm	25.0 mm	Medium danger	Continuous monitoring, including cumulative effect calculation.
Horizontal displacement	9.5 mm	15.0 mm	Medium danger	Continuously monitor and pay attention to the change of displacement direction.

Through this case, we can know that the system successfully captured the instantaneous accelerated settlement of the tunnel caused by the accelerated unloading rate of the foundation pit (T+12h node in Figure 2), and found the danger at least 12 hours earlier than the traditional daily manual monitoring. Based on the sudden change of real-time settlement rate (core risk factor), the dynamic risk assessment model accurately raised the risk level from "concern" to "high risk" and triggered an accurate automatic response process (Table 1). Through the immediate warning of the system, the construction party quickly took measures such as slowing down the excavation speed and increasing the support pressure. In the follow-up monitoring, the tunnel settlement rate was successfully controlled below 0.3 mm/h (after T+18h), which effectively avoided a major accident that might lead to tunnel structure damage and subway line shutdown, and proved that the technical system and model have high engineering application value.

6. Conclusion

The engineering case analysis verifies the effectiveness of the technical system and model. In the excavation of a deep foundation pit adjacent to an existing operating tunnel in a city subway interchange station, the system successfully captured the instantaneous accelerated settlement of the tunnel caused by the accelerated unloading rate of the foundation pit, and found the danger at least 12 hours earlier than the traditional daily manual monitoring. The dynamic risk assessment model is based on the sudden change of real-time settlement rate (core risk factor), which accurately raises the risk level from "concern" to "high risk" and triggers an accurate automatic response process. The construction party quickly took measures such as slowing down the excavation speed and increasing the support pressure, which effectively avoided a major accident that might lead to the destruction of tunnel structure and the suspension of subway lines, and proved that the technical system and model have high engineering application value.

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