Research Article

Design and Application of Risk Early Warning System for Subway Station Construction Based on Building Information Modeling Real-Time Model

Qianlong Tang,^{1,2} Mingfeng Lei³, Binbin Zhu⁴, Limin Peng,⁴ Weimin Wu,⁴ and Chenghua Shi⁴

¹*School of Civil Engineering, Central South University, Changsha, China*

²*Jiangxi Transportation Vocational and Technical College, Nanchang, China*

³*School of Civil Engineering, Central South University,*

Key Laboratory of Engineering Structure of Heavy Haul Railway (Central South University), Changsha 410075, China

⁴*School of Civil Engineering, Central South University, Changsha, China*

Correspondence should be addressed to Mingfeng Lei; mingdfenglei@csu.edu.cn and Binbin Zhu; zhubinbin@csu.edu.cn

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The problems faced by subway stations in the construction process are more complex than those by overground buildings. Therefore, the construction risk for such structures is highly unpredictable and the risk management is difficult. Building information modeling (BIM) technology has strong visualization, simulation, and integration characteristics that make it conducive to the development of a risk early warning system for underground engineering. According to the functional requirements of risk early warning for subway stations, a risk early warning system based on a BIM real-time construction model is designed in this study for a subway station construction. The operation process of the risk early warning system is established through the grey prediction method to propose the operation method of the early warning system. The early warning system is applied to the Xiangjiang New Town Station of Changsha Metro Line 4 in China to verify its feasibility.

1. Introduction

Subway construction is currently developing at high speed, and its large construction scale and high development speed will continue for a long time in the future. According to statistics from the China Urban Rail Transit Association [1, 2], during “the 12th Five-Year Plan” period, rail transit construction mileage in China exceeded 1,900 km with a total investment of 1.2 trillion yuan [3]. The current period is an important time for the country to implement “the 13th Five-Year Plan,” during which China’s investment in urban rail transit will be strengthened constantly. By the end of 2017, 62 cities were approved for urban rail network planning in China, with a total planned length of 7,321 km. In the next 10 years, China’s subway construction investment will involve trillions of funds. In terms of the current situation of subway management in China, the introduction

of efficient management and improvement of labor productivity are urgent concerns [4, 5]. Correspondingly, current subway construction management methods are lagging and the informatization degree is low.

Building information modeling (BIM) technology, a parameterized tool applied to the entire life cycle of project management, can manage the full life cycle of construction projects by considering the computer system as the carrier of technology implementation [6–8]. BIM technology can be called the second revolution in the construction industry. It can effectively analyze and comprehensively manage all types of information data during the whole process of project construction and make all participating units in the full life cycle work as a team based on the same model. Consequently, BIM ensures the accuracy and consistency of construction information obtained by all parties and greatly improved the construction efficiency.

BIM technology has the characteristics of strong visualization, simulation, and integration. The introduction of BIM into subway construction helps to improve the modeling ability of the technology in the face of complex rock-soil mass and the early warning ability of on-site construction risks [9] and also helps to promote the technical innovation of the construction and management of the entire urban rail transit project. This paper conducts a study on real-time construction risk warning technology for metro stations around BIM technology and its combination with information technology such as 3D laser scanning technology. The need for core functions of system development is first introduced. By combining 3D laser scanning technology, the acquisition of site data information and the method of information matching and identification are studied, thus proposing a real-time construction model based on the BIM planning model. Based on this, the grey prediction theory is applied to further design and develop the construction real-time risk prediction system. Finally, the accuracy and practical application value of the real-time risk prediction system proposed in this paper are verified by applying engineering examples.

2. Functional Demands of the Risk Early Warning System

The development of any system originates from the demand for the core functions of the system. The functional demands of this early warning system include the following.

2.1. Data Acquisition Automation. Radio frequency identification (RFID) is adopted to mark several types of construction equipment and components and realize wireless transmission of data in the construction site, which is presented directly on the Internet port. A 3D laser scanner and photographing and measuring equipment are used to obtain real-time 3D data on-site; these data are then updated in the real-time construction model and displayed visually in the BIM platform. The data acquisition automation of the system reduces the manual participation in data collection, thus improving data authenticity and accuracy.

2.2. Information Integration Management. Real-time risk monitoring is dynamic. The accumulated data in the process are very large. Whether the information can be effectively used and managed will largely determine the effect of risk monitoring and early warning [10]. The characteristics of BIM collaborative management will play an important role in the system, providing good platform support for information integration. As a result, efficient and timely monitoring information can be acquired, which greatly improves the efficiency of information management.

2.3. Visualization of Early Warning Information. With the help of BIM software tools such as Revit and Navisworks, early warning information can be visualized through a 3D construction model and early warning signs in the system.

Thus, construction managers, construction workers, owners, and other project participants can intuitively obtain early warning information and understand the real-time dynamic and early warning situation of project construction for the first time. The visualization platform can be adopted to reduce the threshold of multiparty information exchange and improve the efficiency of information exchange, thus enhancing the effect of project risk control [11].

2.4. Real-Time Safety Early Warning. The main potential risk sources in the subway construction stage can be identified and evaluated in real time, automatically providing risk early warning with the help of the safety early warning system [3]. In each stage of construction, early warning indicators can be updated in real time according to the progress change, and the early warning values that can best reflect the actual situation of construction can be provided. For example, in the construction of a foundation pit excavation and support for subway station, the early warning value of ground settlement in different areas around the foundation pit can be reasonably adjusted with the location and depth of the foundation pit excavation [12, 13].

3. BIM Real-Time Model

The BIM real-time model is a 3D model that adjusts the initial model parameters in real time according to the actual construction progress [14, 15]. The 3D BIM original model created in the design process is the base of the BIM real-time model creation. However, a real-time parameter adjustment is required by the real-time model according to the construction progress to ensure that the model can be updated according to the actual progress of the project and synchronized as much as possible with the actual progress of the project construction. The most prominent advantage of the real-time construction model is that the information of both on-site construction data and model parameter data contained in the model will be continuously increased and updated along with the construction progress, so as to ensure the synchronization and accuracy of data information in each construction phase and also facilitate the dynamic control of the project.

3.1. Basic Creation of the BIM Real-Time Model. The core of the BIM real-time model creation is the real-time update of field data information. Model creation includes two processes, namely, field data acquisition and model parameter updating. For the acquisition of field data, the actual situation of the project site in all aspects must be detected, including geometric size, material section, and 3D coordinates of the components for buildings that are constantly updated in the construction. The update of model parameters refers to the identification, extraction, classification, matching, and other operations of the acquired data via BIM technology. The data are transformed into real-time data containing specific project information to update the model components. The real-time adjustment and update of parameter information of the components are completed on

the basis of the original 3D BIM model, and then the BIM real-time model is created. The basic process of model creation is shown in Figure 1.

3.2. Creation of the Real-Time Model Based on BIM Planning Model. Bosche, referred to in (Qiu et al., 2005) [16], put forward a method where laser scanning is used to automatically identify 3D CAD components. On the basis of their approach, the present study proposes a method to create a BIM real-time model based on 3D laser scanning and the BIM planning model. The creation process is shown in Figure 2. The 3D coordinate points on the site acquired using a 3D laser scanner are calculated to match the planning model, which has two gradual calculation processes: coarse registration and fine registration. The collected point clouds are identified quickly to generate the component model. The BIM planning model contains component-related parameter information. Therefore, only the location and direction of the model components must be adjusted according to the identified components to automatically transform the planning model to the real-time model.

The processing of the 3D coordinate point cloud includes the following steps.

3.2.1. Coarse Registration. Coarse registration refers to registering the 3D BIM model without parameters with coordinate points collected coarsely by a 3D scanner. First, the 3D BIM model is transformed and expressed in the format of stereolithography (STL). The application of a surface model with multiple triangles can operate registration in the spherical coordinate system of the scanner. The reference point of the construction facilities in the site can be used to obtain the corresponding point pairs between the model and the scanner in the registration process; these pairs are then input manually. Point cloud analysis software, such as Trimble RealWorks, can be used for registration.

3.2.2. Fine Registration. Fine registration refers to finding the point corresponding to each scanned point in the BIM planning model by calculation. The point in the model corresponding to the scanned point P_D is defined as P_M . The vertex of each triangle divided by the STL format is represented by three parameters of a spherical coordinate system, namely, plane angle φ , dip angle θ , and distance ρ . The 3D model is scanned fictitiously by the scanner for the first time to match the calculation. The same ray direction must be defined for the points in the model and the scanned points. The same plane angle and dip angle are assigned for P_D and P_M to identify the position of each vertex of the triangle in the BIM surface model.

Bosche suggested that the point-to-point ICP algorithm is used to accurately register a 3D CAD model point cloud with the scanning points of the scanner [16]. The closest orthogonal projection point of P_D on the top of the model triangle is the corresponding point P_M on the model. Figure 3 shows a quadrangular pyramid that is constructed as follows [15]:

$$\varphi = \theta = 2 \arctan\left(\frac{\tau_D}{\rho}\right), \quad (1)$$

where τ_D is the assumed distance threshold from a point to a face; φ is the point P_D plane angle; θ is the point P_D dip angle; and ρ is the distance from point P_D to the laser scanner.

Based on equation (1), the intersection between STL triangular faces can be determined to identify and exclude them. Each scan point is calculated by a computer program to gradually exclude the faces that cannot identify the corresponding points, thus completing the matching of faces on the model where the corresponding points are.

The hierarchical boundary value of the model must be calculated (bounding volume hierarchy, BVH) to use the accelerated point-to-point IPC algorithm. In BVH, a boundary value is a quadrangular pyramid that is calculated based on the above method. All matching points in the model can be found. Finally, the point P_M that eventually needs to match is the orthogonal projection point of P_D on the 3D model surface. The pseudocode of the matching algorithm is shown as follows:

```

Input: Scan Model
Result:  $\{P_M\}$ 
ModelBVH ← CalculateModelBVH (Model);
ModelBVH ← FrustumModCulling (ModelBVH, Scan. Frustum);
ModelBVH ← BackFacingCulling (ModelBVH, Scan. Oringin);
For each Scan.  $P_D$  do
    Dist ← ∞;
    For each ModelBVH. Object do
        If Intersect ( $P_D$  Frustum, ModelBVH. Object. Frustum) = True then
            For each ModelBVH. Facet do
                If Intersect ( $P_D$  Frustum, ModelBVH. Facet. Frustum) = True then
                     $P_M' \leftarrow$  Project (ModelBVH. Facet,  $P_D$ );
                    If Exist ( $P_M'$ ) = True and  $\|P_M' - P_D\|$ 
                    < Dist then
                         $P_M \leftarrow P_M'$ 
                        Dist ←  $\|P_M - P_D\|$ ;
                    End
                End
            End
        End
    End
End.

```

3.2.3. Object Recognition. Object recognition refers to matching the points on each model component with the scanning points one by one to complete the identification of the component object. Given that the same slope angle and

FIGURE 1: Modeling process of real-time construction model.

FIGURE 2: BIM real-time model creation process based on planning model.

plane angle are defined in the spherical coordinate system, the key of recognition is the distance between the two points. With the unavoidable deviation in construction and system error caused by registration, the maximum distance between two points is defined as the sum of two errors, as shown in the following formula:

$$\Delta\rho_{\max} = \varepsilon_{\text{reg}} + \varepsilon_{\text{con}}, \quad (2)$$

where ε_{reg} is the average registration error and ε_{con} is the maximum deviation allowed in the construction.

If the distance between the scanning point and the corresponding model point $\Delta\rho$ in the computer system is less than $\Delta\rho_{\max}$, then the two points are determined to be registered. When the registration of each of the model component objects with the scanning points is completed, the recognition of the object can be judged according to the number of recognized points.

3.2.4. Determination of Component Position and Direction. Through the above steps, the point cloud data collected by the scanner are preliminarily registered with the BIM planning model, and the actual construction status of components of the scanned building (or structure) is

expressed. However, each component appears in a separate form and disregards the position and direction in the complete model; thus, it still must pass the secondary registration, which is called the fine registration of the component. Similar to point cloud registration, fine registration is made for components by using the ICP algorithm to determine the direction and position of components.

At this point, every component object in the BIM planning model can obtain the point cloud of the component state with complete and real-time information, thus supporting the planning model to update component information according to the actual construction state to generate the real-time construction model.

4. Safety Early Warning System Based on a Real-Time Model for Subway Station

4.1. Operation Process of Safety Early Warning System. The main working principle of the safety early warning system is realizing the automatic acquisition and update of on-site monitoring data, real-time construction status, and other pieces of information in the construction stage by using various modern information technologies, such as integrated digital image recognition, RFID, and BIM visual

FIGURE 3: Scanning points construct quadricone diagram.

simulation [17]. On this basis, real-time risk assessment is carried out, and early warning information is generated with the general prediction method of safety risk [18].

The operation of the safety early warning system also carries out real-time construction creation and construction dynamic simulation through calling relevant data information in the BIM data system. Through real-time construction simulation, the construction information of each stage is extracted, the most probable advanced construction status is obtained, which is automatically compared with the early warning threshold of construction safety status, and the risk assessment results are obtained by referring to the relevant regulations for early warning classification. Finally, the warning information is generated and the warning report is formed. The early warning information is fed back to relevant management personnel through the BIM platform for the first time so they can quickly make risk responses and minimize risk losses. The operation of the early warning system is shown in Figure 4.

4.2. Real-Time Safety Risk Prediction of Subway Station Construction. Real-time risk assessment of subway station construction includes the timely analysis of the risk situation under the current construction state and the prediction of the future risk state. The real-time construction model based on BIM acquires and stores a large amount of on-site monitoring data information. Combined with the design of the safety early warning threshold for subway station construction, the current risk situation can be judged, while the corresponding early warning information can be generated. Similarly, the current monitoring data collected can be used to extract and predict the future risk status. The following research focuses on the real-time safety risk prediction based on the grey prediction method.

4.2.1. Real-Time Safety Risk Prediction Based on Grey Prediction Method. Grey system theory is an applied mathematics subject first proposed in 1982 by Deng, a famous Chinese scholar. The core idea of the grey theory is to extract uncertain information by using some certain information. A series of seemingly irregular data at the data level can be transformed into data with searchable laws by a

mathematical transformation method. The practical value of grey theory lies in its capability to extract other pieces of unknown information of the system with high value by regularly exploring and searching some certain information in the system.

The calculation model of risk prediction through the grey prediction method is established as follows. A set of time series of raw data $x^{(0)}$ is defined as

$$x^{(0)} = (x_t^{(0)} | t = 1, 2, \dots, n) = (x_1^{(0)}, x_2^{(0)}, \dots, x_n^{(0)}). \quad (3)$$

In conducting the first accumulative calculation, the sum of the first t th items of raw data $x^{(0)}$ is regarded as the value of the t th item of the new data series $x^{(1)}$:

$$x_i^{(1)} = \sum_{k=1}^i x_k^{(0)} = x_{i-1}^{(1)} + x_i^{(0)}, \quad (i = 1, 2, \dots, n). \quad (4)$$

On the basis of series $x^{(1)}$, the differential equation is established as follows:

$$\frac{dx^{(1)}}{dt} + ax^{(1)} = b. \quad (5)$$

Series a and b are undetermined coefficients. Equation (5) is discretized and obtained as follows:

$$\Delta x_t^{(1)} + ax_t^{(1)} = b. \quad (6)$$

Again,

$$\Delta x_t^{(1)} = x_t^{(1)} - x_{t-1}^{(1)} = x_t^{(0)}. \quad (7)$$

From equations (6) and (7), the following can be obtained:

$$x_t^{(0)} + ax_t^{(1)} = b. \quad (8)$$

The mean generation with consecutive neighbors of $x_t^{(1)}$ is Z_t . Then,

$$Z_t = \frac{1}{2}x_t^{(1)} + \frac{1}{2}x_{t-1}^{(1)}, \quad t = 2, 3, \dots, n. \quad (9)$$

After Z_t is used to replace $x_t^{(1)}$ in equation (8), a linear equation with one unknown quantity, with $x_t^{(1)}$ as the dependent variable and Z_t as the independent variable, can be obtained:

$$x_t^{(0)} + aZ_t = b. \quad (10)$$

The column matrix of raw data is recorded as $\mathbf{Y}$. Thus,

$$\mathbf{Y} = [x_2^{(0)} \ x_3^{(0)} \ \dots \ x_n^{(0)}]^T. \quad (11)$$

The cumulative generation matrix is recorded as $\mathbf{X}$. Thus,

$$\mathbf{X} = \begin{bmatrix} -Z_2 & -Z_3 & \dots & -Z_n \\ 1 & 1 & \dots & 1 \end{bmatrix}^T. \quad (12)$$

The coefficient vector is recorded as $\mathbf{B} = [a, b]^T$, and the estimated value of $\mathbf{B}$ is

FIGURE 4: Running process of real-time security early warning system.

$$\mathbf{B} = [\hat{a}, \hat{b}]^T = (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \mathbf{Y}. \quad (13)$$

On the basis of equation (4), which shows that if $x_1^{(0)} = x_1^{(1)}$, and by substituting the estimated values of a, b into equation (5), then the solution of the differential equation of equation (5) is obtained as

$$\hat{x}_{t+1}^{(1)} = \left[x_1^{(0)} - \frac{b}{a} \right] e^{-at} + \frac{b}{a}. \quad (14)$$

The predicted value of the original series is

$$\hat{x}_{t+1}^{(0)} = \hat{x}_{t+1}^{(1)} - \hat{x}_t^{(1)}. \quad (15)$$

The prediction accuracy of the grey prediction model usually decreases with time. Therefore, the raw data must be updated while the real-time risk prediction is conducted. The first group of raw data must be eliminated while each group of the latest data is collected. This process comprises the grey prediction method on future data based on real-time data, which can be used to effectively predict the risk.

4.2.2. Safety Risk Case Analysis. Several monitoring data of settlement at surface monitoring site A around a certain subway station shown in Table 1 (the first six times of measured data used as raw data in this study to predict the seventh settlement) are used to verify the reliability of the grey prediction method.

First, on the basis of equations (3) and (4), the raw data series and the first cumulative sequence are obtained, respectively, as follows:

$$\begin{cases} x^{(0)} = (15.37, 16.10, 16.56, 17.32, 17.36, 17.68), \\ x^{(1)} = (15.37, 31.47, 48.03, 65.26, 82.62, 100.30). \end{cases} \quad (16)$$

The accumulative generation sequences $\mathbf{X}$ and $\mathbf{Y}$ are then constructed:

$$\begin{cases} \mathbf{Y} = [16.1 & 16.56 & 17.23 & 17.36 & 17.68]^T, \\ \mathbf{X} = \begin{bmatrix} -23.42 & -39.75 & -56.645 & -73.94 & -91.46 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix}^T. \end{cases} \quad (17)$$

Substituting equations (16) and (17) into equation (13) can obtain the estimated value as follows:

$$\begin{cases} \hat{a} = 0.024, \\ \hat{b} = 15.603. \end{cases} \quad (18)$$

To predict the 7th group of data, it must only be substituted into equations (14) and (15):

$$\hat{x}_7^{(0)} = \hat{x}_7^{(1)} - \hat{x}_6^{(1)} = 18.04. \quad (19)$$

Finally, an error analysis is conducted:

$$\begin{aligned} \text{absolute error: } \Delta_7^{(0)} &= |x_7^{(0)} - \hat{x}_7^{(0)}| = 0.02, \\ \text{relative error: } \Phi(t) &= \frac{\Delta_7^{(0)}}{x_7^{(0)}} \times 100\% = 0.11\%. \end{aligned} \quad (20)$$

The error analysis results show that the grey prediction method in real-time risk prediction is very reliable.

TABLE 1: Measured data of settlement at point A.

Number	1	2	3	4	5	6	7
Settlement/mm	15.37	16.10	16.56	17.23	17.36	17.68	18.02

5. Case of Engineering Application

5.1. Project Profile. The Phase 1 Project of Changsha Metro Line 4 in China covers 33.6 km with 24 stations. Among the stations, Xiangjiang New Town Station is located at the junction of Yuelu District and Wangcheng District of Changsha, China. It is the third station of Changsha Metro Line 4. The station is in the south of the “L” junction of Yinxing Road and Yinshan Road, arranged along Yinshan Road. The site is shown in Figure 5(a). Xiangjiang New Town Station is an island-type open-cut station with two floors underground, both ends of which are connected with shield zones. The station is covered with soil 2.7 m thick. The shield original well is in the north end of the station, while the shield hang-out well is in the south of the station. The outside of the station is 208.8 m long, the outside of the standard segment is 20.7 m wide, the foundation pit of the standard segment is about 16.13 m deep, and the foundation pit of the shield well segment is approximately 17.7 m deep (see Figures 5(b)–5(d)).

5.2. Real-Time Data Acquisition

5.2.1. Layout of Monitoring Device. In the risk early warning system, the monitoring device required in the creation of the real-time construction model includes a 3D laser scanner and RFID equipment. No fixed requirements are imposed for the layout of the 3D laser scanner in use, but special operators are needed to repeatedly collect the multiangle data of the same object in the construction process to ensure the accuracy of the collected data. The field layout of RFID includes two parts, sensor and reader. The receiving range of the RFID reader selected for construction is 40–50 m. Given the site construction space of Xiangjiang New Town Station, four readers are needed in the layout to ensure that their working range covers the entire foundation pit and the surrounding construction field. RFID readers must be installed in all staff, construction vehicles, and construction materials in and out of the site.

Various monitoring and measuring devices are required in real-time data acquisition during construction. The layout of surveying points for Xiangjiang New Town Station is shown in Table 2. According to the construction monitoring technical requirements of Xiangjiang New Town Station and the layout of actual surveying points in the site, the surveying points are arranged accordingly in the BIM real-time construction model, the monitoring data are updated through the BIM platform in real time, and the model is updated.

5.2.2. Spatial Data Acquisition. Prior to the construction, the geographic location information of relevant projects is obtained from the design drawings of Xiangjiang New Town Station. High-definition aerial photos (Figure 6) and geographic coordinates of Xiangjiang New Town Station are further obtained via Google Earth software, and the required map information is

FIGURE 5: Diagram of Xiangjiang New Town Station Site and Design. (a) Location of station. (b) Plane. (c) Structure of station. (d) Geological section.

stored in KML format. If the site map is needed to guide the construction, then format conversion must be redone using the ArcToolBox tool and the information finally saved in SHP format. According to the design scheme of Xiangjiang New Town Station, the specific location information of the foundation pit and its surrounding environment can be determined and stored in the form of data to prepare for the acquisition of 3D information in the later stage of construction.

5.3. Analysis of Safety Risk Early Warning. The real-time early warning for Xiangjiang New Town Station is classified into no warning, mild warning, medium warning, and severe warning according to different warning situations, which are

represented by blue, yellow, orange, and red, respectively, in the 3D BIM model. Figure 7 shows the real-time early warning of surveying points around the foundation pit during the construction of Xiangjiang New Town Station as displayed by the BIM construction model.

The real-time construction model based on BIM is adopted to analyze the monitoring data in each construction stage on a unified visual platform. The computer is used to automatically calculate and predict the development trend of safety risk based on the grey prediction method, and a group of real-time risk prediction data is obtained. Four typical monitoring items are selected to analyze the monitoring data in the corresponding monitoring period. The real-time prediction data obtained from the BIM platform and the

TABLE 2: Layout of surveying points for monitoring project.

Items	Monitoring range	Layout and spacing of surveying points	Accuracy
Subsidence	1–3 times of the ground around the foundation pit and soil in the depth of the foundation pit	1 every 15–20 m along the longitudinal direction of the station	0.3 mm
Horizontal displacement and settlement of wall top	Upper of continuous wall	1 every 15–20 m along the longitudinal direction of the station	1.5 mm
Wall deformation	Within the enclosure	20 m spacing and 0.5 m spacing in the same hole in the vertical direction	1.0 mm
Axial force for support	1/3 of the steel support between two points at the end	Set for each layer at 30% of support, at least 3	$\leq 0.5\%$ (F.S)
Groundwater level	Surrounding of the foundation pit and objects to be protected	Layout in 20–50 m spacing to monitor the section	10 mm
Settlement and horizontal displacement of surrounding buildings	Buildings (structures) to be protected	Four corners of a building, every 10–15 m along the outer wall	1.0 mm
Settlement and displacement of underground pipeline	Important municipal pipelines around the foundation pit, such as power tunnel, gas pipe, and water supply pipe	5–10 m spacing	0.5 mm
Soil pressure	Within the enclosure	20 m spacing	$\leq 0.5\%$ (F.S)
Observation of building cracks	Related building (structures)	It depends	0.1 mm

FIGURE 6: Aerial map of Xiangjiang New Town Station site.

changes of the actual monitoring data with construction progress are plotted, as shown in Figures 8–11.

After the analysis of the above curves, the following conclusions are reached:

- (1) Figure 8 shows the change trend of the maximum subsidence around the foundation pit within 20 weeks of the foundation pit excavation. The surrounding surface settlement gradually increases with the construction of the foundation pit excavation and support. The change trends of the predicted and measured values are almost the same. The predicted value of the first 12 weeks is slightly larger than the measured value. From the 12th week, the settlement curves intersect, but the change trends remain synchronous. When the excavation of the foundation pit is completed, the measured value of the maximum

ground settlement is 23.6 mm. Its predicted value is 24.1 mm, which does not reach the warning value.

- (2) Figure 9 shows the change trend of the maximum horizontal displacement of the top of the enclosure wall within 40 weeks of the foundation pit excavation. In the period from 25 days to 75 days since the construction (from the excavation of the foundation pit to the construction of the second support), the measured displacement value is evidently larger than the simulated value but fails to reach the warning value. Such finding requires considerable attention but no measures need to be taken. After 75 days of construction, the predicted value is almost the same as the measured value in both value and change trend. When the main structure of the station is completed, the measured value of the maximum

FIGURE 7: Three-dimensional display of real-time early warning of Xiangjiang New Town Station. (a) Temporary engineering. (b) Enclosure structure. (c) Excavation and support of foundation pit. (d) Main structure of station. (e) Display of monitoring points.

FIGURE 8: Maximum surface settlement change curve.

FIGURE 9: Maximum horizontal displacement curve of wall top.

displacement of the wall top during the construction is 23.2 mm and its predicted value is 22.5 mm, both of which fail to reach the warning value.

- (3) Figure 10 shows the change trend of the maximum horizontal displacement of the deep wall under different depths of foundation pit excavation. The positive value represents the displacement to the inside of the foundation pit, and the negative value represents the displacement to the outside of the foundation pit. The predicted displacement of

enclosure wall level is close to the measured displacement in different depths, and the change trend is almost the same. The maximum horizontal displacement is reached at the position where the excavation is 13 m deep. Later, it is decreased with the increase of excavation depth. During the entire construction process, the measured value of the maximum deep horizontal displacement is 12.5 mm and the predicted value is 12 mm, both of which fail to reach the warning value.

FIGURE 10: Maximum horizontal displacement curve of wall.

FIGURE 11: Minimum variation curve of groundwater level.

- (4) Figure 11 shows the change trend of the maximum groundwater level outside the foundation pit within 40 weeks of the foundation pit excavation. The drawdown of groundwater level outside the pit increases with the excavation of the foundation pit. The predicted drawdown of groundwater level after 125 days of construction reaches the standard for severe warning, so safety risk control measures must be taken. The measured drawdown of water level is evidently decreased after 125 days of construction because the predicted data are ahead of the measured data; thus, control measures can be taken in advance.

After control measures are taken, the measured drawdown of maximum groundwater water outside the pit during the construction reaches 877 mm but does not reach the warning value, showing that the control effect is good.

According to the above analysis results and Figures 8–11, the development trend of risk prediction data based on the BIM real-time construction model is the same as that of the measured data, and the monitoring values have a minimal difference between different projects. This result indicates that the prediction method is highly reliable. Moreover, the safety risk can be determined in advance, and the actual risk can be avoided effectively because the predicted data are ahead of the measured data.

6. Conclusions

Starting from the functional requirements of subway station risk warning system, this paper combines BIM with emerging information technology to develop a BIM-based construction real-time risk warning system, which is applied to subway station engineering examples. The main research results are as follows:

- (1) A real-time construction model creation method based on 3D laser scanning technology is proposed. Based on the BIM planning model created in advance, the 3D point cloud information collected by the 3D laser scanner is automatically matched through coarse registration, fine registration of the model, object recognition, and fine registration of the components to realize the real-time updating of the planning model component information and create the real-time construction model.
- (2) A BIM-based construction real-time risk warning system is designed. According to the application requirements of the metro station risk warning system, a system architecture consisting of four parts, data collection system, data processing system, BIM data system, and functional application system, is proposed, and the real-time risk data prediction is combined with grey prediction method.
- (3) The BIM-based construction real-time risk early warning system is applied to the Xiangjiang New Town Station project of Changsha Metro Line 4, and the early warning analysis of construction safety risk is carried out. In this study, four key monitoring contents are selected, namely, maximum ground settlement, maximum horizontal displacement of the top of diaphragm wall, maximum horizontal displacement of the deep wall, and lowest level of the groundwater. Real-time analysis of the changes of risks in each construction stage shows that the predicted values of all risk items of this early warning system are highly consistent with the actual monitoring values. Therefore, we can effectively predict and preprocess various risks, which greatly reduce the probability of risk occurrence in the construction

stage and verify that the proposed model has good engineering application value.

Data Availability

The monitoring data used to support the findings of this study are included within the article. The stratigraphic data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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