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Research Article

Monitoring System for the Construction of Arch Cover Method Subway Station Based on DT and IoT

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Aiming at the problems of safety and monitoring beyond the existing experience in the construction of the subway stations with arch cover method in Dalian, China, combined with the real-time monitoring requirements of intelligent construction status, a multi-information construction monitoring system based on digital twin(DT) and Internet of Things(IoT) is proposed, and the digital twin 3D architecture is established. First, on the basis of the IoT monitoring experience of tunnel, the installation plan of the automatic monitoring device of the arch cover method subway station is clarified, and the sensor arrangement is carried out. Then, based on the Revit platform, the establishment of the main structure model of the station and the BIM parametric modeling technology of the sensors are realized, and the monitoring properties of the sensors are expanded. Finally, through the design of the BIM database and in the form of secondary development, a BIM-based construction information visualization monitoring system is established to realize the correlation between the sensor model and the monitoring data and achieve the effect of information visualization query and color change early warning. The system was initially applied at Shikui Road Station of Dalian Metro Line 5 and achieved good results. The system can intuitively reproduce and accurately describe the subway station construction status, which provides an advanced technical means for the informatization and visualization management of the construction of arch cover method subway stations.

1. Introduction

In recent years, subway construction has been increasing day by day, and the geological conditions faced by engineering construction have become more and more complex [1]. Especially, the upper and lower hard geological environments, such as Dalian, Qingdao, and other coastal cities in China, bring challenges to the construction of the underground excavation subway station [2]. The emergence of the construction technology of the arch cover method solves the problem of upper and lower hard strata faced by subway construction [3–6]. However, the arch cover method also faces a complex geological environment and conversion procedures, which are beyond the existing experience in the past. How to ensure construction safety has become an important issue of concern [7, 8].

There have been some reports on the study of the safety of subway station construction. Yu et al. [9] illustrated the surface settlement characteristics of subway station construction in the shallow-buried soft ground using the pile-beam-arch (PBA) approach of the shallow tunnelling method. Kim et al. [10] investigated the correlation between comfort level and brainwaves in a real-world environment. Avci and Ozbulut aim to describe and summarize the results of a Threat and Vulnerability Risk Assessment (TVRA) study designed for a generic subway station complex [8]. Chen [11] presents a combined construction technology that has been developed for use in underground spaces. It can be seen that most of the existing related research reports involve the design and construction of subway stations, and there are few reports on the automatic monitoring of subway station construction.

The monitoring information can reflect the safety status of the project, which is the main basis for the safety early warning in the tunnel construction process [12, 13]. At present, the monitoring and measurement of geotechnical engineering are gradually developing from single information to multiple information, from manual monitoring to IoT monitoring [14–16]. Gómez et al. address the implementation of a Distributed Optical Fiber Sensor system (DOFS) to the TMB L-9 metro tunnel in Barcelona for Structural Health Monitoring (SHM) purposes as the former could potentially be affected by the construction of a nearby residential building [17]. Wang et al. studied an improved method for the accurate measurement of sensors and wireless transmission bands suitable for complex tunnel environments. [18]. Hou et al. presented a method for sensing tunnel cross-section deformation based on distributed fiber optic sensing and a neural network [19]. Compared with manual monitoring, the IoT monitoring is more frequent and the data is more accurate and reliable. However, both manual monitoring and automatic monitoring are faced with the problems of large amount of monitoring data, complicated monitoring result information, and difficult management.

In recent years, technologies such as the Big Data (BD) [20], Artificial Intelligence (AI) [21], and the mobile Internet have developed rapidly. Through the deep integration of information technology and civil construction, the Cyber-Physical Systems (CPS) [22] and Digital Twin (DT) technology [23] in which physical space and information virtual space interact and integrate have become research hotspots in intelligent construction. The civil construction process is changing from the binary system relationship of "human-physical system" in traditional construction to the ternary system relationship of "human-information-physical system" in intelligent construction [23–27], which has become a trend. It is generally acknowledged that Michael W. Grieves' product lifecycle management model is the origin of DT in 2002 [28]. DT applications are emerging with the recent development of the IoT; both technologies share the same nature—connecting physical artifacts and their digital counterparts [29]. In modern cities, digital twins can be built to integrate spatiotemporal data of the life cycle of tunnels to analyze the potential causes and effects of anomalies in civil structures or electromechanical equipment, which will provide reasonable and feasible countermeasures to guide and optimize operations and maintenance (O&M) management [30].

There has been some progress in method visualization and computer vision techniques for detailed internal structures [31, 32]. Lundeen et al. [33] realized autonomous perception and modelling construction robot to adapt to construction objects in emergencies and presented two construction component model fitting techniques. Akula et al. [34] realized real-time monitoring for drilling process hazards by processing and incorporating point clouds from 3D imaging technologies into the drilling process. However, these proposed methods have not been proved in more complex conditions. The DT's development in this field is in its infancy [35]. Building Information Modelling (BIM) technology is a way of realizing digital twin [36]; it is also a research hotspot at the forefront of the current civil construction field and can realize the management and analysis of the whole life cycle of the project in a 3D visualization way, which has been gradually popularized and applied to many geotechnical engineering fields in recent years [37–39]. Costin et al. presented a literature review and critical analysis of BIM for transportation infrastructure [40]. Bueno et al. proposed a novel method for automatic rough registration of BIM models and as-built scan data called the "4-Plane Congruent Set" (4-PLC) algorithm to achieve construction quality and schedule control [41]. Lee et al. aimed to propose an integrated system of BIM and geographic information system (GIS) to improve the performance of current maintenance management system [42].

The current research on digital twin and BIM technology has achieved fruitful results, but the applied research combining monitoring and digital twin (DT) on the construction of subway station are still rare. Compared with the traditional underground engineering, the subway station with the arch cover method faces more complex geological and structural conditions, and the safety problems are more prominent. How to combine the characteristics of the underground excavation station with the arch cover method and combine the DT technology with the real-time monitoring of the subway station construction has important engineering significance. Based on the application background of Dalian Metro Line 5 Shikui Road Station, this study firstly determines the IoT monitoring plan for the underground excavation station with the arch cover method according to the structural characteristics. Then, the parametric modelling technology of the structure and sensors of the arch cover method station is studied, the monitoring information in the database is associated with the relevant BIM model in the form of secondary development, and a multi-information monitoring system based on BIM is developed, which provides a new method for tunnel construction information management.

2. An Integrated Framework for Digital Twins and IoT

2.1. The Characteristics of Arch Covered Subway Station. The subway station arch cover method is based on the PBA method, replacing the side piles with large arch feet, so that the main bearing capacity is attached to the rock foundation, and under the protection of the early buckle arch, the main structure is completed by the reverse method or the forward method [7]; the construction sequence of the arch cover method is shown in Figure 1.

The arch cover method absorbs the engineering experience of the early construction, improves the multispan structure into a single-span large-span structure, and replaces the original design with a supporting structure system of large arch feet and double-layer initial support. The column arch structure in the middle of the building makes full use of the self-stability of the surrounding rock and is supplemented by temporary support to ensure the safety of the structure. The number of pilot tunnels after optimization is significantly reduced, the construction process is simplified, and the number of temporary supports and joints is also reduced, which overcomes the disadvantage of poor integrity caused by alternative construction and is conducive to the improvement of the overall waterproof performance of the structure. After the removal of

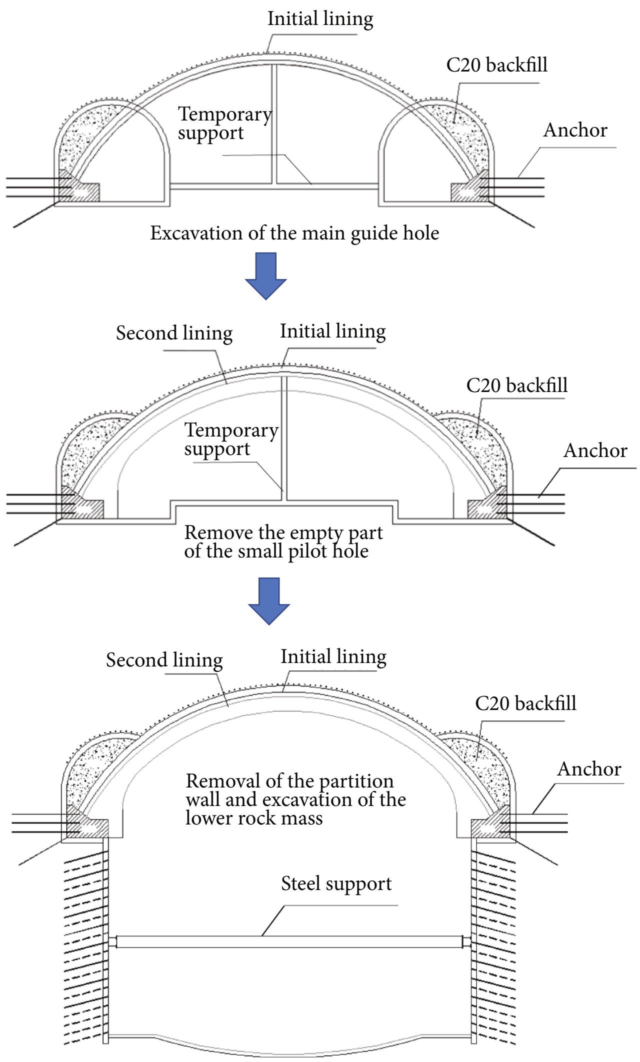


Figure 1: Construction steps of the arch cover method.

the double-layer initial support and temporary support, the secondary lining of the arch shall be constructed first, and the construction of the lower main structure shall be carried out under the protection of the secondary lining structure. Compared with other construction methods, the working space is significantly expanded, which is conducive to the construction of large machinery and equipment, and plays a significant role in shortening the construction period and improving the work efficiency.

At present, the existing research on the construction method of arch cover method recognizes that the construction time, structural strength, and construction quality are the key to the construction of arch cover method; however, the mechanical characteristics of arch construction have not been deeply studied; there is not enough research on the appropriate application timing and bearing capacity of the arch cover, resulting in a poor grasp of the application timing. It is essential to strengthen the monitoring of the construction of the arch. For this reason, this paper plans to establish a digital twin 3D monitoring system for the construction of subway stations.

2.2. The Information Composition of Digital Twin 3D Monitoring System. Based on the DT technology of the construction process of the subway station with the arching method, it is oriented to the needs of the construction attitude and safety control of the underground space excavation of the subway station. Condition data fusion display provides a more intuitive, more comprehensive, and more accurate visual monitoring method for intelligent production of subway station construction. At the same time, on the basis of data analysis, the DT monitoring system can integrate data monitoring functions for safety monitoring, construction sequence safety analysis, and support dynamics based on data inversion and improve the monitoring level of intelligent working faces.

Based on DT technology, the construction data-driven monitoring system of the arch cover method subway station obtains the system basic design data and real-time driving data from the geological body excavation, supporting structure, and supporting sensors and conducts modelling and analysis processingthrough the technologies of three-dimensional virtual display and human-computer interaction, the analysis results are provided to construction managers.

The information composition is shown in Figure 2, which mainly consists of 4 parts: (1) the physical entity is the geological body and supporting structure of the subway station construction; (2) the virtual entity is the digital twin of the virtual subway station construction; (3) service data is on-site information, including real-time equipment space attitude data, operating condition data, control command data, and historical data; and (4) feedback decision support system includes intelligent decision support and analysis systems.

The specific relationship is as follows: the arched subway station (physical entity) is the object to be monitored; the virtual entity is the underground station model established based on the basic information of the physical entity, including basic data such as geological information and design information. There is mapping of the three-dimensional virtual space, that is, the digital twin of the subway station; the service data is the data obtained from the on-site sensors of the subway station that can express the safety state and working condition of the surrounding rock supporting structure on site and realize the three-dimensional model of the virtual excavation space. The action-driven and working condition data are dynamically displayed; the auxiliary decision support system (DSS) is the basis for the feedback construction decision of the digital twin model.

2.3. Digital Twin 3D System Framework. Figure 3 shows the platform architecture of the digital twin 3D monitoring system for station excavation. In view of the monitoring characteristics and requirements of the construction of the subway stations with an arch cover method, based on the digital twin technology of the construction excavation process, combined with the three-dimensional virtual display technology, the design and development are designed to realize the real-time three-dimensional display of the station excavation, the three-dimensional real scene fusion of the working condition data, and the monitoring of the operation data. Management and abnormal state alarm are the main functions of the monitoring system for intelligent construction. In the digital twin

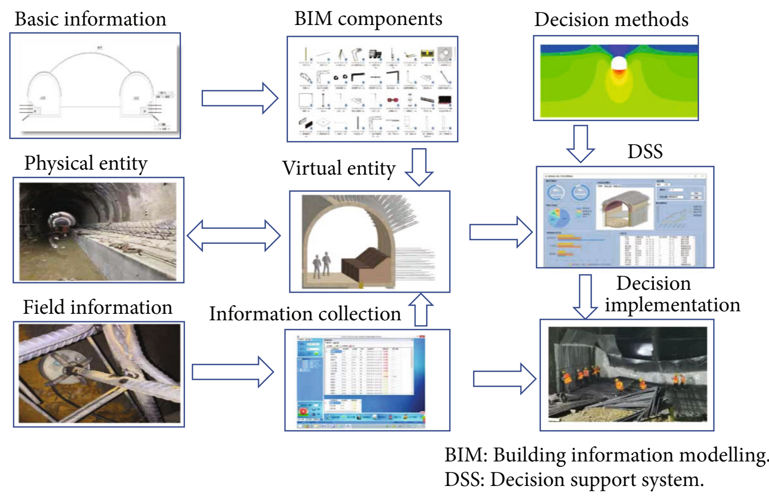


Figure 2: The monitoring system information of arch cover method subway station.

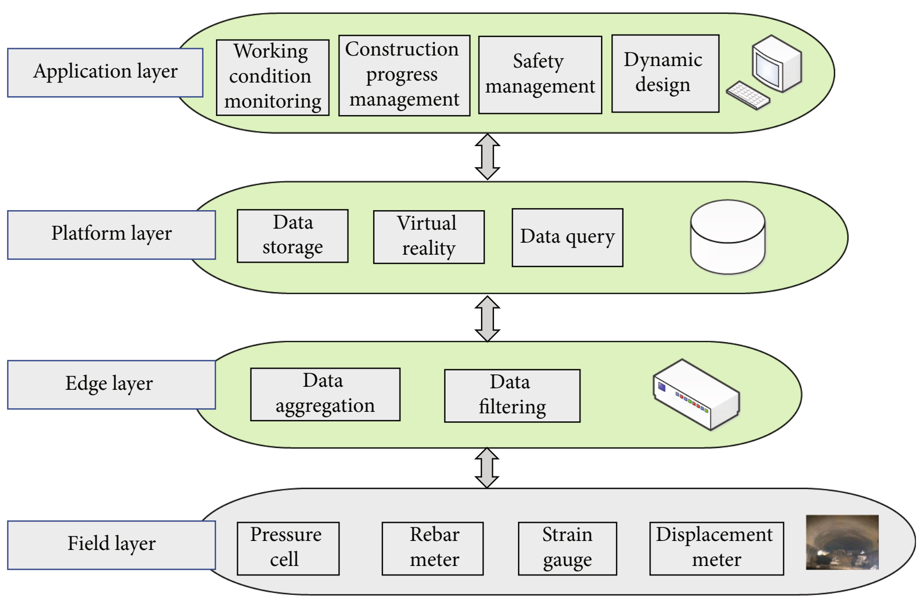


Figure 3: Structure of monitoring system based on digital twin.

3D monitoring system for the construction of the arch cover method station, data is driven throughout. According to the data from collection to application display, it can be designed as a four-layer model architecture of site layer, edge layer, platform layer, and application layer and data collection. It can realize data collection and transmission, data analysis and functional design, human-computer interaction, and other functions in turn.

2.4. Data Collection and Transmission. The Internet of Things (IoT) collection and transmission system for the construction of the arch cover method station was developed. Sensors are arranged for the most critical information in tunnel monitoring, such as top arch settlement, surrounding rock deformation, and steel arch structural stress. Considering the harsh characteristics of the underground engineering environment, the protective structure is used to overcome the damage to the sensor caused by groundwater and blasting disturbance. The monitoring results of the sensor terminal are collected through the vibrating wire data acquisition instrument. In addition, the data acquisition box also includes a wireless module for short-distance transmission and a power supply system. A data transmission box is set up near the tunnel face, and the data collected from each monitoring section is transmitted to this box via the wireless module and then uploaded to the internet by the general packet radio service (GPRS) system inside this structure. The database is accessed through the server to achieve remote acquisition of monitoring data, and on this basis, the data is decoded and the results are released in multiple terminals. Figure 4 shows the data transfer process.

Data acquisition is mainly obtained through reliable sensors and control systems in the station structure and is realized by the field layer and the edge layer. Field-level equipment is not only the physical entity and monitoring object mapped by the digital twin but also the data source of the system. The

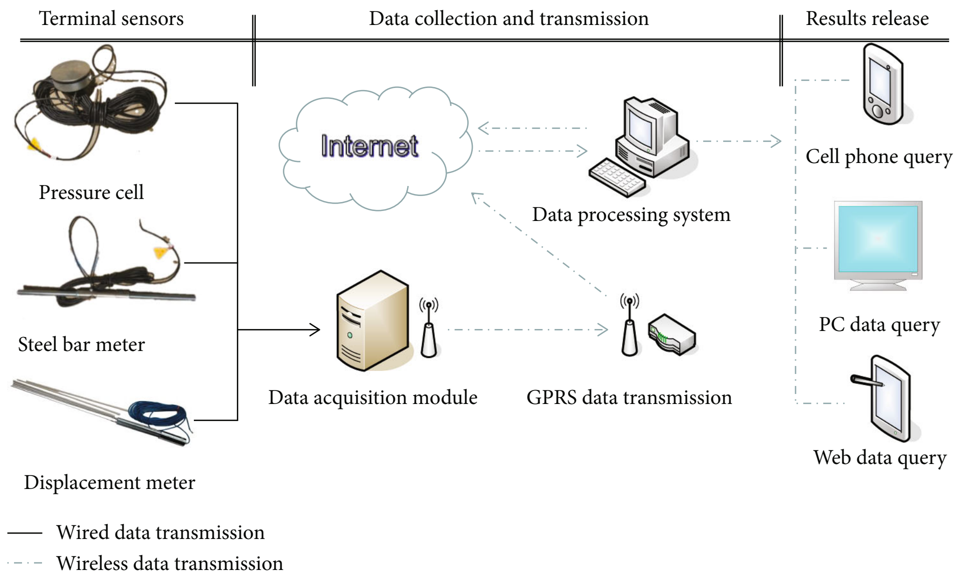


Figure 4: Information flow chart of IoT of metro station.

excavation structure and process conversion of subway stations are relatively complex. Here, the main monitoring of the arch cover structure involving relatively large safety risks is carried out. Pressure cells, rebar meters, strain gauges, and displacement meters are used to design and develop edge nodes to conduct on-site data collection. The edge nodes aggregate and filter the collected data, extract and transmit the valid data to the upper platform for data processing. The edge node terminal communicates with the sensor and the intelligent centralized control system through fieldbus, industrial Ethernet, and other communication methods to obtain data, process and archive it, and transmit it to the digital twin monitoring system database for storage by means of network communication. Figure 5 is the interface of server IoT information collection, which can collect data through the network IP address corresponding to the virtual serial port.

Sensors and data acquisition instruments are used to collect monitoring data, the communication module transmits data remotely through mobile phone GPRS, and the server sends acquisition commands to the edge layer acquisition box. After receiving the data, analyze and postprocess the data. The collection interval can be set, and the channels and sensors of the collection module can be added. The collection operation modes are divided into manual and automatic. You can also check whether the collection status is normal through collection monitoring.

3. Virtual Model and System Development

The digital twin 3D monitoring application platform is oriented to users. Through 3D model display, data, and model fusion display, data analysis, the process, status data, and analysis results of subway excavation construction are reproduced in the virtual space, and the construction process is interactively provided.

3.1. Construction of the Station BIM Model. The development of the digital model mainly includes three aspects: the construction of the station model, the parametric modelling of the lining structure and sensors, and the definition of the sensor monitoring attributes. Revit is a platform for building modelling; although family libraries such as walls, columns, floors, and infrastructure related to buildings are provided in the structural template, these components clearly cannot be used in the modelling of the subway station. The structural features and internal structure of the arch cover subway station are complex. Therefore, based on the modelling method of the platform, this paper independently creates a component family library for the station and realizes the 3D visualization of the subway station by assembling it in the project template. This section takes the metric conventional model as a template, draws a 3D model through operations such as elevation selection, extrusion, and lofting, and edits size parameters and professional attribute parameters to establish subway station parametric component models. After importing the parametric station components in the family library into the project, define the elevation, adjust the assembly position with the commands in the toolbar, such as rotate, move, and array, and change the size parameters of the family components, and the professional attribute parameters of the instance subway station, in turn, realize the assembly of various components such as the subway station lining, inverted arch filling, and anchor rods and finally complete the construction of the overall model of the station. The 3D digital model of arch cover method construction is shown in Figure 6.

Multivariate information monitoring involves the arrangement of various types of sensors, so it is necessary to add monitoring sensor models based on the establishment of the overall station model. However, when building sensor models, there are many problems, such as large number, many types, different positions and angles, and many repetitive tasks. In this regard, this article uses the method of Revit secondary development

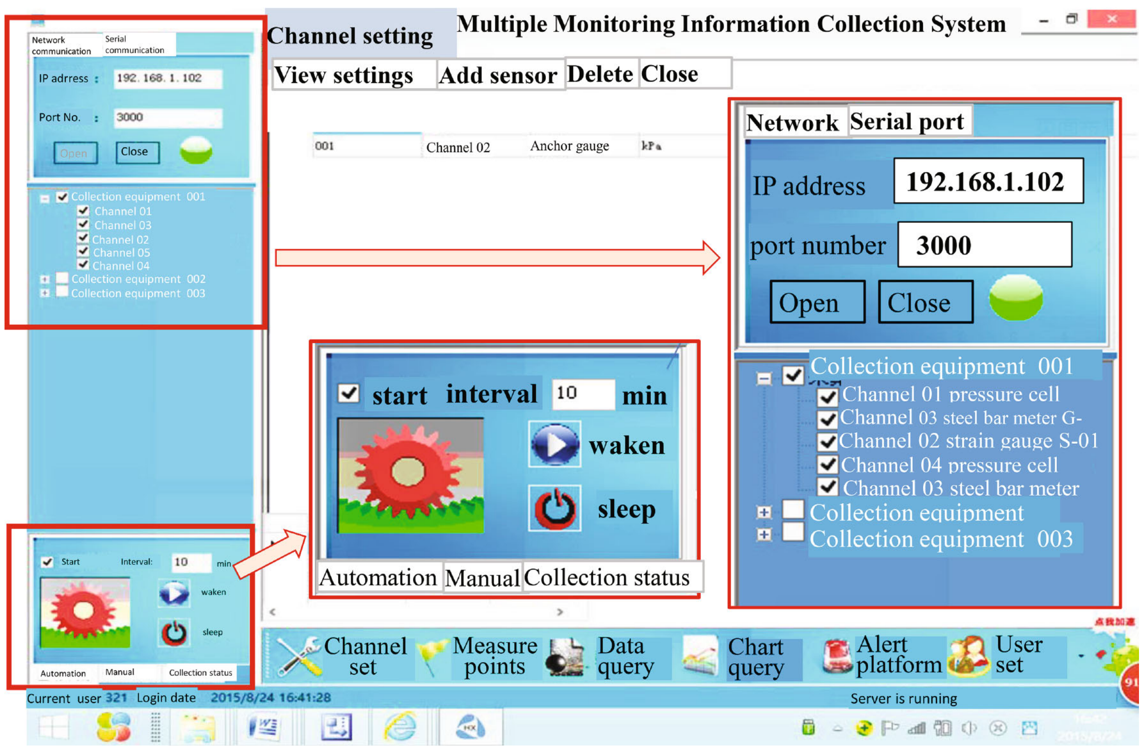


FIGURE 5: The interface of IoT information collection.

to write an automatic modelling program, and input the position parameters such as radius and angle into the specified position in the secondary development form, and the sensor model can be automatically generated efficiently and accurately without manual modelling. The programming process is as follows: using VisualStudio2019 as the platform and using C# language to build Windows Form applications. Reference the revitAPI.dll and revitAPIUI.dll dynamic link libraries in the compiler; establish external interfaces through IExternalCommand; IExternalCommand is a command that implements external extensions, including the Execute function.

The external command calls the Execute function to realize the external interface connection and uses the IExternalEventHandler to add external events, uses the transaction in revitAPI to call the created sensor component, and assembles it at the specified position by offset, rotation, etc. Run the parametric modelling form written through secondary development on the Revit platform, enter the corresponding position parameters, and place the sensor 3D family library model, as shown in Figure 7; enter the position radius and angle into the steel bar meter parameter input box; and the model appears automatically.

For example, input the parameters of strain gauge sensor and earth pressure box sensor, and the corresponding sensor family model can be obtained. The established arc and sensor models are shown in Figure 8.

Therefore, to realize the mapping between the monitoring information and the Revit entity model, it is necessary to expand the sensor properties. The Industry Foundation Class(IFC) standard is a computer-processable building data representation and exchange standard. The IFC extension method is used to define the monitoring attributes of BIM sensors. Establishing the mapping relationship between each member of the tunnel monitoring information and the IFC attribute set is the premise of realizing the IFC expression of the tunnel monitoring information. This paper associates the corresponding fields of monitoring information by extending the IFC attribute set, expresses the monitoring information parameters with appropriate attribute values, and associates the corresponding sensor entity attribute set and BIM 3D model. IFC standard description of the monitoring information is shown in Figure 9. The sensor is represented by the IfcSensor entity, and the type of the sensor is included in the enumeration type IfcSensorTypeEnum, which is expressed by the PredefinedType attribute of the entity IfcSensor. The specific monitoring information is represented by IfcProperty and multiple IfcProperty constitute the definition of a property set, that is, IfcPropertySetDefinition. Property sets are associated with sensors through IfcRelDefinesByProperties.

According to the requirements of the monitoring task, select the appropriate IFC attribute value to establish the expression of the corresponding monitoring data; usually select the appropriate attribute in the IfcPropertySetDefinition attribute set to establish the association, such as sensor number, measuring point number, monitoring value, monitoring time, and other information [43]. For the types of monitoring information missing in the IFC standard, IFC attributes should be extended, that is, by adding entity definitions or by extending them based on attribute sets.

3.2. Revit Secondary Development Method. The existing visualization models of tunnel construction management are mainly aimed at the numerical simulation of the tunnel

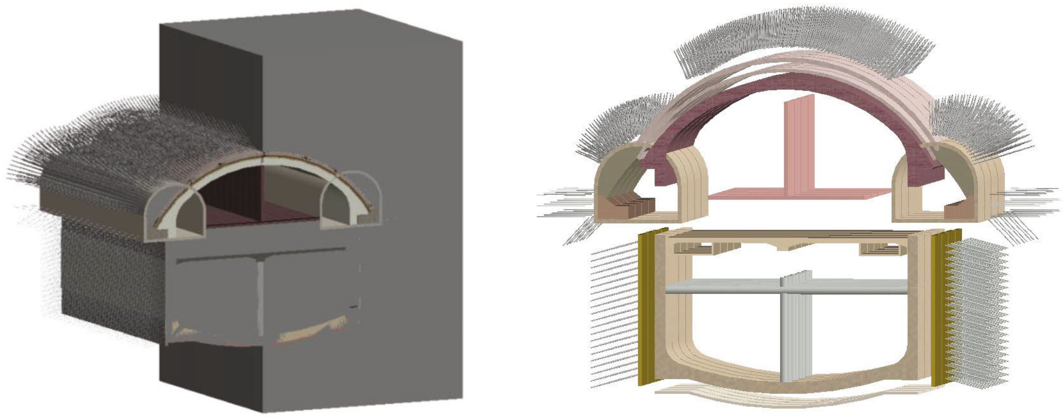


FIGURE 6: 3D digital model of arch cover method construction.

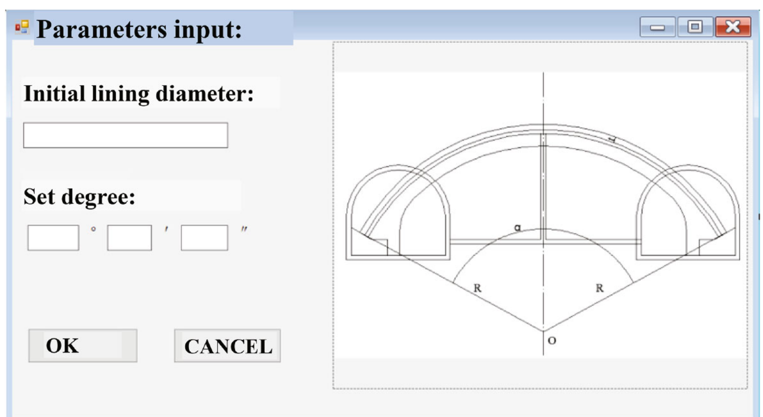


FIGURE 7: Parameter input box.

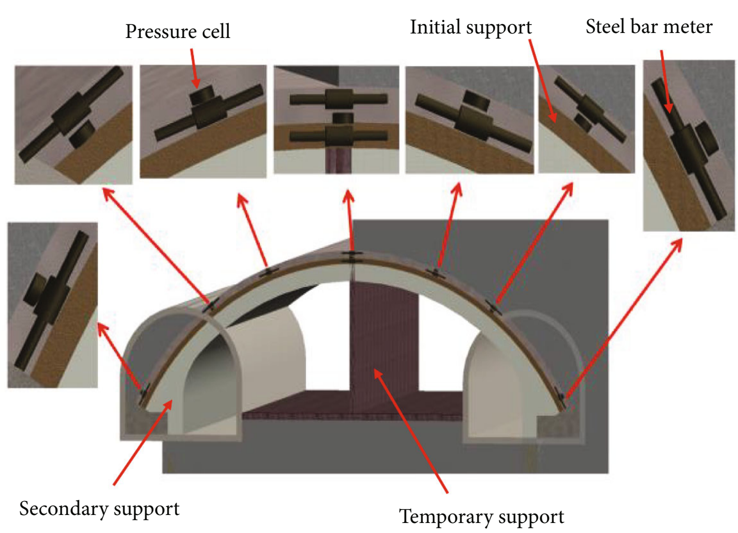


FIGURE 8: The model of arch cover and sensor.

construction process [6] and management information system for operation and maintenance [30]. Compared with the previous models, the model proposed in this paper needs to be oriented to the decision-making of the complex construction process of the arch cover method, integrates a variety of information and analysis methods, and has stronger functional requirements. Specific functions include time series prediction and early warning algorithm, subway station construction step visualization, AHP-FCE-based subway tunnel construction risk assessment algorithm, geological parameter inverse analysis

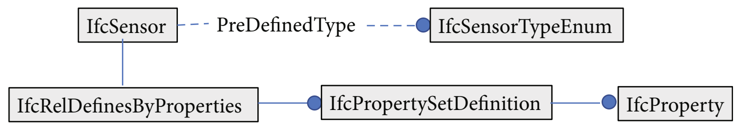


FIGURE 9: IFC standard description of the monitoring information.

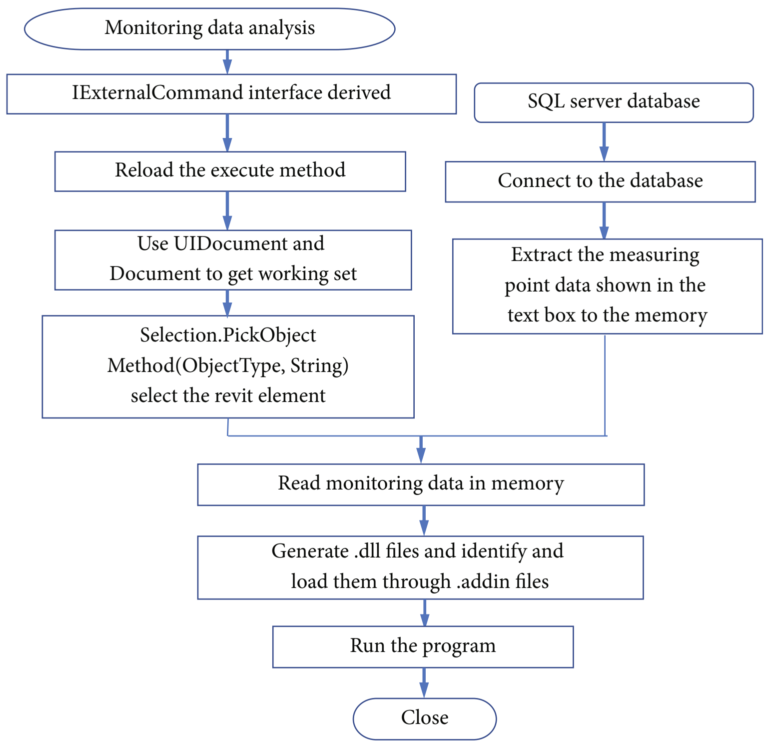


FIGURE 10: BIM model and monitoring information associative development flow chart.

algorithm, and particle swarm-based construction parameter optimization algorithm. The model in this paper represents the geological information, surrounding rock information, support information, construction progress information, personnel information, and other attributes of the subway station BIM through IfcProperty in the IFC physical file. This information is also stored in the SQLserver database at the same time. A digital twin-based multi-information monitoring platform is established through the secondary development of Revit. Using the Microsoft.NET Framework4.6 structural framework, the program is compiled through the C# language, and the RevitSDK2018 is used to make the program run in Revit.

Taking monitoring data information as an example to introduce the information integration technology of BIM, the BIM model and monitoring information associative development flow chart is shown in Figure 10. Firstly, create a new class library or form, add the IExternalCommand external interface, call the Execute method, write a function command to traverse and read the Id property of each component, and associate it with the database. Then generate a file with a suffix of.dll, load it into Revit through the Add-In Manager interface, and complete the Revit secondary development process. Furthermore, load the execute code to obtain all attributes of the model, and obtain the unique ID of the component with Revit.UI.Selection through the topology relationship of the component, define the SQL data connection parameters and create a connection instance. When the database is connected, define the database adapter and data set, create the DBOoperate database operation object, execute the database operation instruction, realize the filtering of the data fields in the sensor attribute table, and use the foreach statement to identify the primary key field row by row. After the primary key field is identified, other fields corresponding to the primary key ID in the data table are called out and output to the dataGridView to realize the query function of clicking monitoring data.

On this basis, by adding the DundasChart control, a complete basic chart structure is established, and by setting the Series-related properties, the monitoring data corresponding to the measurement point number in the database is screened, so that the data is generated in the form of a graph, and the history is realized. The DataGridView control supports the standard Windows Form data binding model, making the data presentation very simple and intuitive. With the help of Revit API and C# language, the monitoring data table query is realized. For example, the typical programming language is as follows:

3.3. Design and Realization of the System. The multi-information monitoring platform based on digital twin is combined with the database to realize the intuitive display of multi-information monitoring by the dome method. The

```
string sqlstr3 = "select Sensor ID, Sensor type, Measuring point number, Monitoring value,Unit, Temperature, Monitoring time,
from monitoring data table where(Measuring point number ='" + comboBox2.Text + "')order by Monitoring time desc";
DataSet ds = database.getSet(sqlstr3, " monitoring data table ");
dataGridView1.DataSource = ds.Tables[0].......
```

Code 1

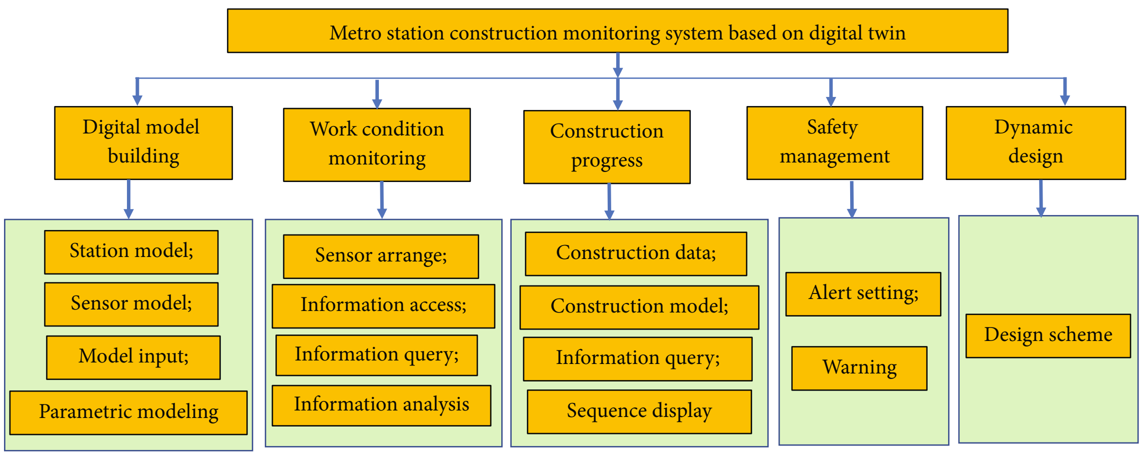


Figure 11: Functional block diagram of the system.

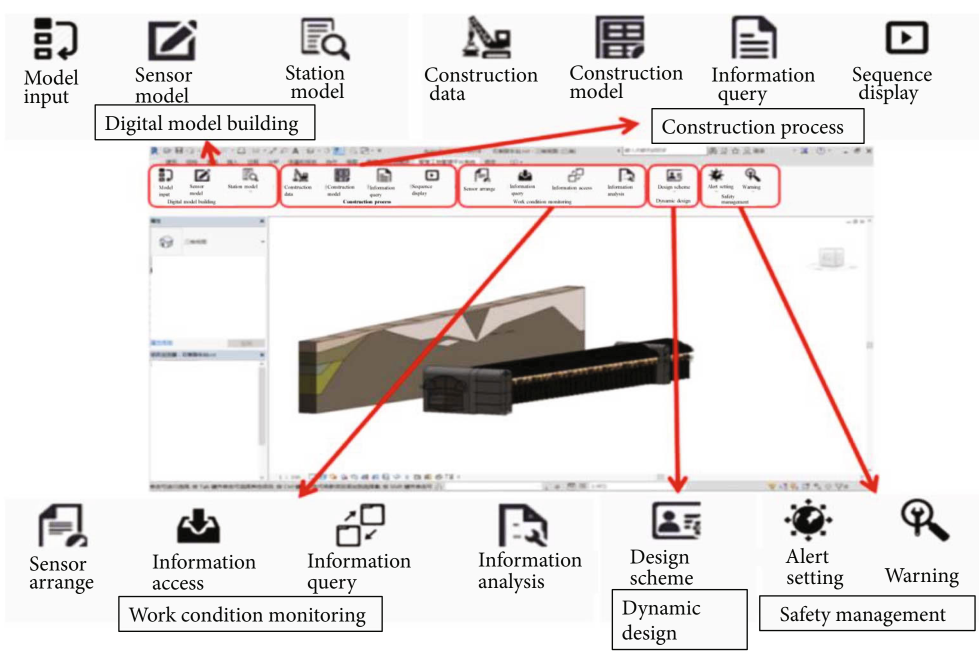


Figure 12: Multisource information subway station construction monitoring system based on digital twin.

functional planning of the developed multi-information monitoring platform based on digital twin is mainly divided into five parts, as shown in Figure 11. The five functional modules are digital model establishment, working condition monitoring, construction progress, safety management, and dynamic design. Firstly, the multi-information monitoring scheme of the underground excavation station with the dome-cover method is established, and the sensors are arranged to realize the acquisition of monitoring sensor data such as the earth pressure box. Then, by means of parametric modelling, the establishment of the main structure model of the station and the sensor model of the Internet of Things is completed.

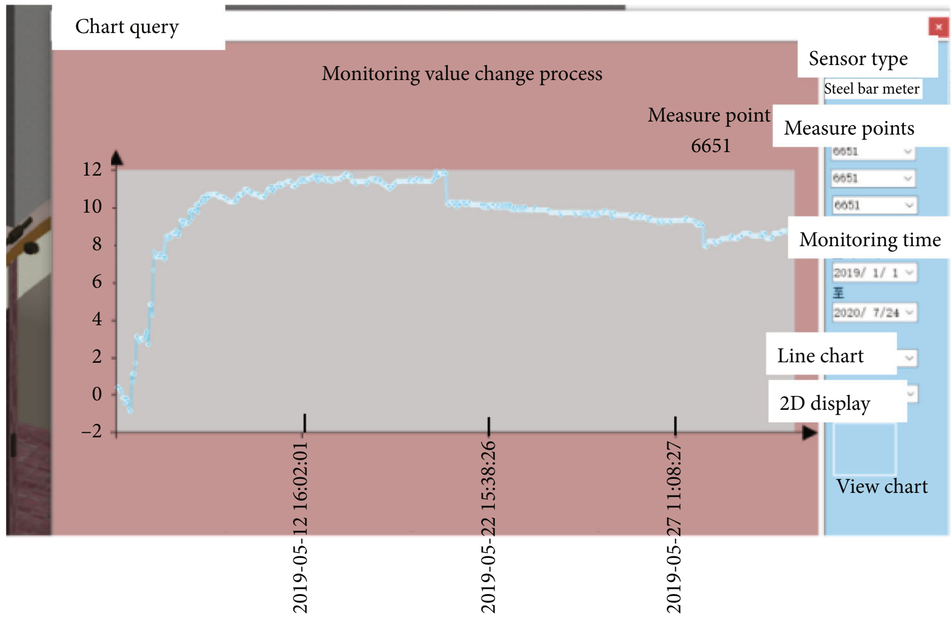


FIGURE 13: Historical graph.

Finally, based on the Revit platform, the monitoring data in the SQL database is linked with the relevant sensor models in the form of secondary development.

The BIM core modelling software Revit is used as the development platform, and C# is used as the basic development language to build the Revit API secondary development environment. According to the Revit secondary development process, the monitoring information visualization plug-in program was developed, and the BIM-based dynamic analysis information system function menu of the arch cover method subway station was developed in the Revit software interface. During development, the two methods of OnStartup() and OnShutdown() are mainly overloaded by external applications to complete the creation of the toolbar Ribbon Tab and the drop-down button PushButtonData. The function menu creates Ribbon Tabs called digital model establishment, work status monitoring, construction process, safety management, and dynamic design, as well as PushButtons corresponding to different function programs.

Through the interaction of monitoring information and models, functions such as automatic warning, graphic display of monitoring data, data analysis, real-time roaming, and information sharing are realized, which effectively improves the visualization level of monitoring information and the function of analysis and decision-making. The system interface is shown in Figure 12.

Digital model building menu includes submenus of model input, sensor model, and station model; construction process menu includes the submenus of construction data, construction model, information query, and sequence display. Work condition monitoring menu includes the submenus of sensor arrange, information access, information query, and information analysis. The menu of dynamic design includes the submenus of the design scheme. The safety management menu includes the submenus of alert setting and warnings.

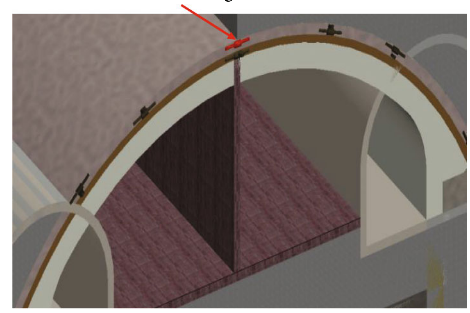
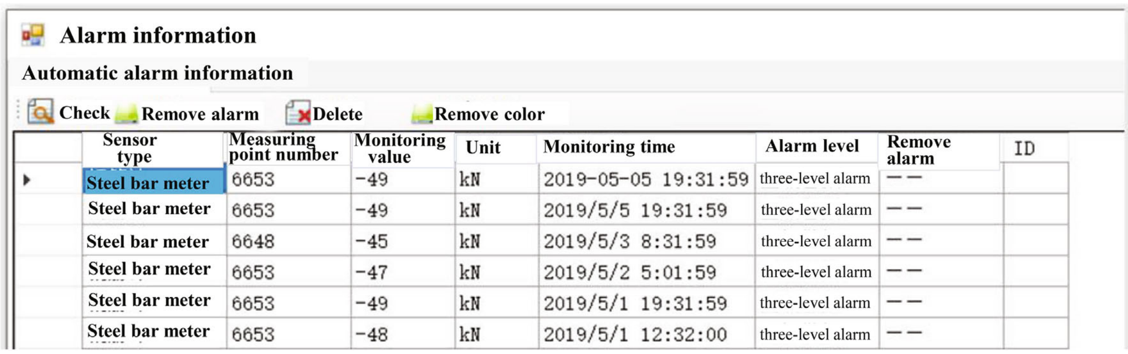


FIGURE 14: Color-changing display of virtual sensor alarms.

4. Case Study: Dalian Subway Station Application

4.1. Project Overview. The subway station, named Shikui Road station, is located in Dalian, China, on the north side of the intersection of Jiefang Road and Shikui Road and is arranged along Jiefang Road in a north-south direction. The terrain in the site fluctuates greatly. The absolute elevation of the ground within the station is 32.8-40.0 m, which is low in the South and high in the north. There are dense residential and commercial areas around the site, with large road traffic flow; many pipelines laid under it and in the air, which is a dense area of people and traffic flow.

The construction of Shikui Road station is carried out by arch cover method; that is, the upper arch cover is excavated first and reinforced by the initial support and a temporary middle support. After the temporary support is removed, the arch secondary lining structure is molded. Due to the complex construction process and the large number of process conversion times and joints, the secondary lining



Alarm information

Automatic alarm information

Check | Remove alarm | Delete | Remove color

	Sensor type	Measuring point number	Monitoring value	Unit	Monitoring time	Alarm level	Remove alarm	ID
▸	Steel bar meter	6653	-49	kN	2019-05-05 19:31:59	three-level alarm	— —	
	Steel bar meter	6653	-49	kN	2019/5/5 19:31:59	three-level alarm	— —	
	Steel bar meter	6648	-45	kN	2019/5/3 8:31:59	three-level alarm	— —	
	Steel bar meter	6653	-47	kN	2019/5/2 5:01:59	three-level alarm	— —	
	Steel bar meter	6653	-49	kN	2019/5/1 19:31:59	three-level alarm	— —	
	Steel bar meter	6653	-48	kN	2019/5/1 12:32:00	three-level alarm	— —	

Figure 15: Early warning sensor data output.

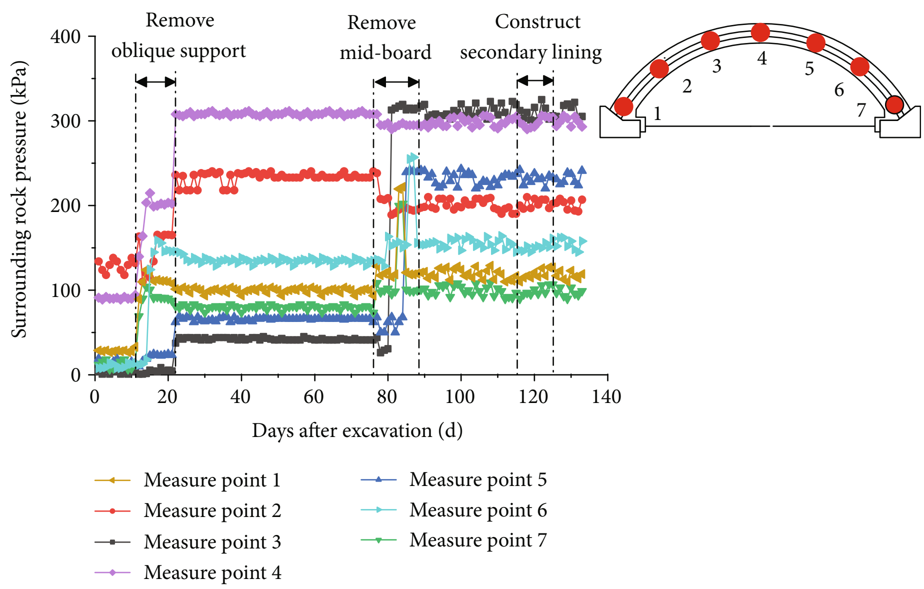


Figure 16: Pressure monitoring results of the initial lining on the first layer.

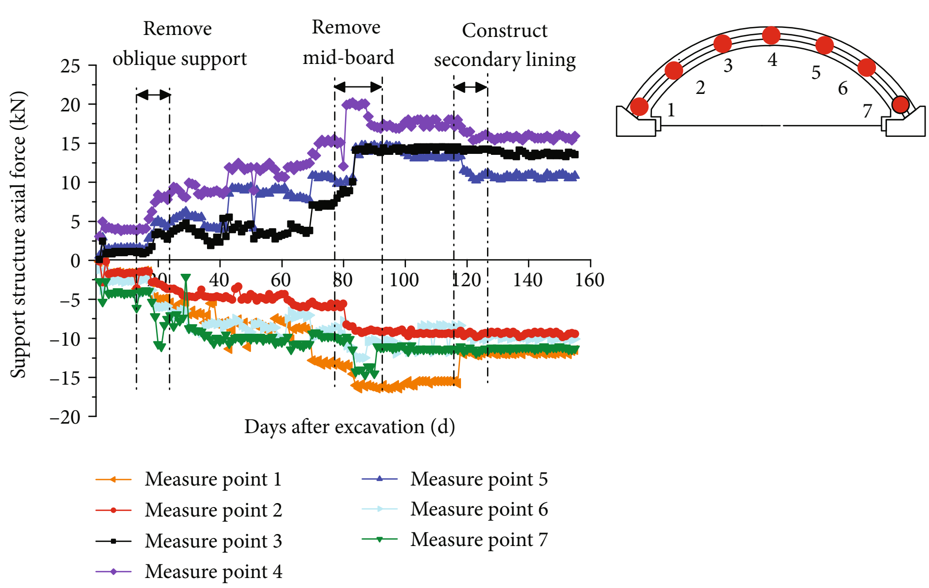


Figure 17: Internal force monitoring results of the initial lining on the first layer.

structure is constructed alternately, which is prone to structural safety problems. The excavation and support of pilot tunnel construction shall be carried out in the order of down first and then up side first and then middle. After the construction of the upper part is completed, the lower half section shall be excavated by drilling and blasting method in order, and the initial support shall be constructed in time. After the side wall is completed, the inverted arch shall be formed. Due to the complexity of the on-site construction structure and procedures, it is necessary to fully consider the problems that the excavation of the subway station may cause changes in the pressure and axial force of the surrounding rock of the vault. During the construction process, timely feedback information should be based on the monitoring and measurement results. To guide the design and construction and adjust the support parameters and construction methods in time, it is essential to collect multiple information on the Internet of Things in subway stations in real time.

4.2. Sensor Arrangement and Mapping Implementation with Modelling. According to the actual construction situation and requirements of the site, the terminal sensor for monitoring is prepared and installed at the arch cover according to the engineering requirements. The sensors include earth pressure cells, steel bar gauges, strain gauges, and settlement gauges, which are to be buried in the arch cover, and the pressure cells are located between the surrounding rock and the primary support. The rebar gauges are located on both sides of the upper and lower rebars of the arch, and the strain gauges are located at the partition wall. Seven monitoring points are set for each section, which are, respectively, embedded in the tunnel centerline and at 30° and 60° on the left and right sides of the tunnel centerline, and are arranged symmetrically on the arches. Real-time acquisition of data of subway stations is realized through the installed automation equipment.

In addition, through secondary development, the monitoring data is associated with the sensors of the BIM model. Figure 13 is a historical graph of a monitoring point. Click "Alarm" in the development function panel, as shown in Figures 14 and 15; the program will filter the monitoring data associated with the sensor model. When the monitoring data of an associated sensor exceeds the preset safety value, the program will output the corresponding excess data. The overlimit data corresponds to the element ID. Clicking the color-changing display button can change the color of the model corresponding to the overlimit data and display it intuitively in the Revit platform to realize the early warning function.

4.3. Real-Time Data Acquisition and Analysis of Station Excavation Process. Since the monitoring data laws of all sections are basically the same, take K6+467 as an example for analysis. The mechanical response of different supporting structures to the construction process is shown in Figure 16. The "constructed the secondary lining" is marked in Figure 16 which means that the secondary lining structure forms an effective support strength. It is shown that the force of the first layer initial lining structure has two transitional rises, which are located in the removal process of the oblique support and the midboard. From Figure 16, the largest increase point is at the

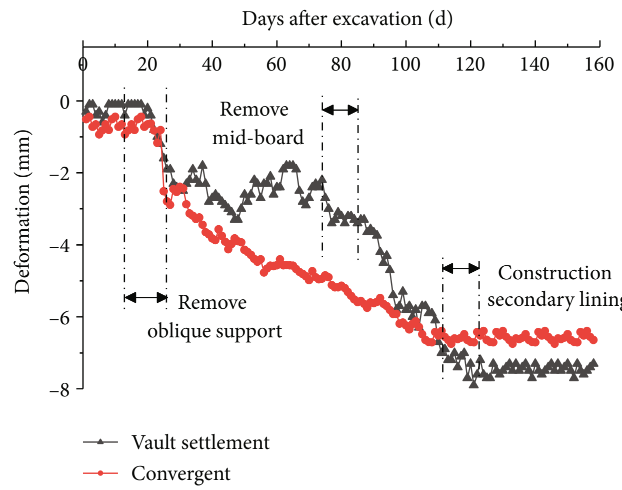


Figure 18: Tunnel deformation monitoring results.

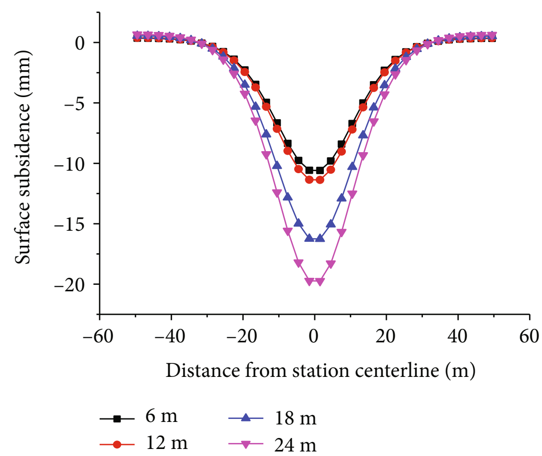


Figure 19: Surface settlement curve.

left shoulder (measure point 3), which increases by 260 kPa after the midboard is removed. The pressure on the vault position (measurement point 4) increased by 206 kPa after the oblique support was removed, and there was no significant change when the midboard was removed thereafter. The reason for this phenomenon is that this monitoring point is located directly above the middle plate. As the main support point, the force balance is quickly reached when the oblique support is removed, so there will be no significant pressure changes in the subsequent construction.

As shown in Figure 17, the internal force of the first layer initial lining reflected by the steel bar meter does not show a significant sudden change point. The upper parts of the structure (measure points 3, 4, and 5) are under a maximum tension of 20 kN, while the middle and lower parts (measure points 1, 2, 6, and 7) are under compression with a maximum pressure of 17 kN. After the secondary lining is formed, the internal force of the first layer initial lining decreases by 5 kN, and then it forms a joint supporting body with the second layer initial lining and the secondary lining structure.

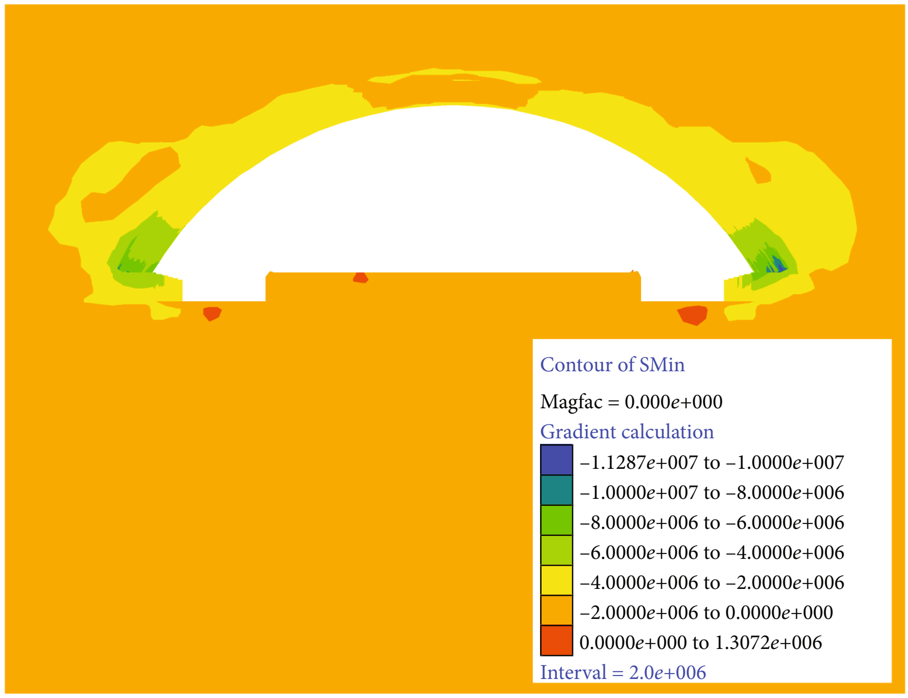


Figure 20: Minimum principal stress diagram after the temporary support is removed.

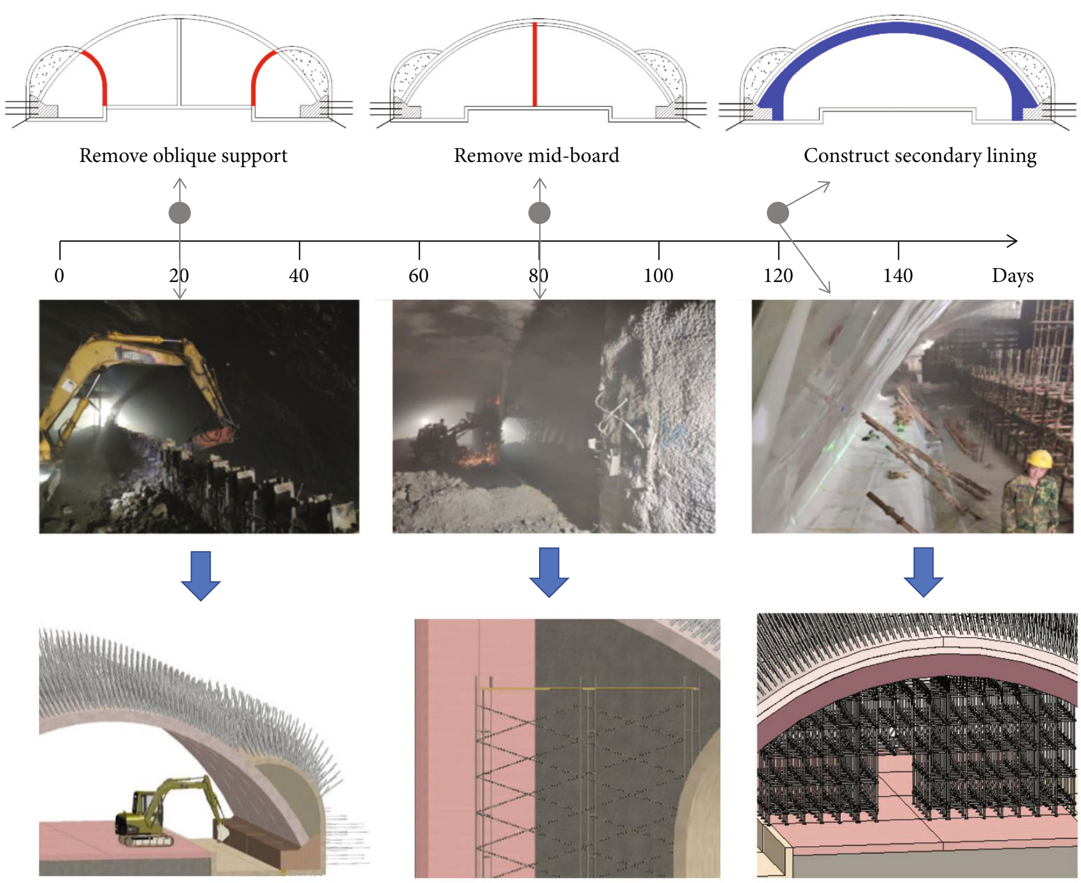


Figure 21: Key construction steps.

Figure 18 shows that the oblique support and the midboard effectively limit the displacement growth after the excavation of the main tunnel. However, when these two kinds of temporary support structures are removed, the settlement of the vault and the convergent displacement around the cave will increase continuously for a period of time.

The above monitoring data reflects the stress change law of the construction of the arch cover method station, indicating that the timing of temporary support removal is crucial. Through the interaction law of the surrounding rock support, it can also reflect the surrounding rock geological parameters, to guide the construction to ensure the safety of the project.

4.4. Construction Control Based on Data Analysis. During the construction process of the underground excavation subway station, based on the self-developed multi-information collection technology of the underground excavation subway smart construction site, based on the monitoring data, the inverse analysis of the surrounding rock parameters was carried out, and the data obtained from the actual inspection of the project was used as the control value [44]. The mechanical parameter group obtained by inverse analysis is $E = 1.3$ GPa, $\mu = 0.24$, $c = 0.2$ MPa, $\varphi = 38.16^\circ$, and $t = 0.1429$ MPa. Based on the inverse analysis of surrounding rock parameters, the numerical simulation of each construction step of the arch-cap method is carried out, and it is concluded that the excavation of the middle pilot tunnel, the dismantling of the bracing, and the construction of the arch cap are the key processes affecting the settlement. The numerical simulation results show that the removal of the temporary support in the construction of the arch cover method has a great influence on the stability of the support structure, and the selection of the removal length of the temporary support is particularly critical. Therefore, during the construction process, it can be dismantled in sections, and the temporary support and the middle partition can be removed crosswise. The demolition area next door shall be pre-reinforced and other measures to ensure the safe construction of the project.

In order to select the most reasonable removal length of the middle partition, based on the identified stratigraphic parameters, the subsidence of the surface subsidence vault under different lengths of the removal of the middle partition was analyzed by numerical simulation. The original design plan determined that the demolition length of the temporary support was 6 m, and the demolition lengths of the middle partition were selected as 6 m, 12 m, 18 m, and 24 m for analysis. The ground surface settlement curve is shown in Figure 19. It can be seen from the figure that during the demolition process, the subsidence of the ground surface is symmetrically distributed with the vault as the center line, and the maximum subsidence of the ground surface occurs at the center line of the subway station. When the demolition lengths are 6 m, 12 m, 18 m, and 24 m, the corresponding maximum settlements are 10.59 mm, 11.37 mm, 16.26 mm, and 19.74 mm, respectively. In the demolition stage of the middle wall, it is determined that the demolition length of the middle wall will be 12 m for construction.

The stress distribution of the surrounding rock after the completion of the main pilot tunnel construction and the removal of the temporary support in the key construction steps is analyzed, and the results are shown in Figure 20. It is shown that, after the dismantling of the temporary support, the stress distribution of the rock around the cave has changed significantly, and the compressive stress value of the arch has increased, but the stress distribution of the entire arch is relatively uniform. In the lower part of the excavation face, the rock mass is uplifted due to the excavation and unloading, and a small part of the tensile stress concentration occurs.

Then, the excavation spacing of the pilot hole, the construction sequence of the substructure, and the construction of the steel support were optimized based on numerical calculation. The excavation spacing of the tunnel face was optimized from 30 m to 20 m. The physical and digital models of key procedures of the arch construction are shown in Figure 21. This optimization scheme has achieved good construction results.

5. Conclusion

To provide a solution for the construction monitoring of the dome method station, this research develops an automatic multi-information monitoring system based on DT and IoT. The developed system can be used to monitor the construction process of the arch cover method station, which is essential to ensure construction safety management. It not only shows the designed IFC extension and DT's station excavation construction model application but also facilitates the research progress as follows:

(1) A new station construction decision-making framework based on DT and IoT is established; furthermore, a multi-information monitoring system for subway stations based on BIM is developed to realize the visual query and early warning of monitoring data corresponding to each sensor model. The monitoring data time-history curve can be drawn to facilitate the automation of the construction decision-making process

(2) The 3D model of the subway station with the arch cover method established by Revit software intuitively shows the main structure of the station and the location of the sensor and realizes the intuitive expression of the engineering construction structure. Through the parametric modelling of the secondary development, the modelling efficiency is improved, and the monitoring information integration and expression are realized by extending the sensor attributes

(3) The IFC extended data integration structure based on the construction of the arch cover method station is designed, the monitoring data is managed through the IFC attribute set and the SQLSERVER database, and the storage, exchange, query, and update of the heterogeneous construction data are realized

(4) The developed system was initially applied to Shikui Road Station of Dalian Metro Line 5, and the expected visual expression effect was obtained. The method in

this paper provides an advanced technical means for the information construction management of the arch cover method subway station. The results show that the provided solution realizes the continuous condition monitoring of the construction process of the arch-cap method and helps in the safety evaluation and the dynamic adjustment of the construction plan in the construction management

The digital twin monitoring technology can provide an effective means for realizing the construction of the arch cover method station. This research promotes the application of DT technology in the construction of complex underground projects and promotes the intelligent construction technology of subway stations, thereby contributing to the knowledge system. The intelligent construction of subway stations is a process of continuous development. Future work will focus on three main avenues of research:

(1) Due to the complexity of the structure of the large-section underground excavation station, further improvement is needed in the equipment supporting sensors; especially the research and development of anticorrosion and anti-interference sensors such as laser ranging and grating fiber sensors is required

(2) The next stage of work should further establish a comprehensive analysis and prediction algorithm based on the additional information on the digital twin and improve the numerical analysis model to better realize the two-way mapping between the digital world and the physical display and help managers make more accurate decisions on station construction

(3) The digital twin realizes the virtual-real interaction and coevolution of station construction. At present, it is only suitable for a single station project. With the advantages of emerging technologies such as web, GIS, 5G, and blockchain, a more complete and powerful digital twin can be further built, forming a smart construction system for unified management of multiple station projects

Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

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