Architecture and Application of Enterprise Headquarters-level Security Management Platform Based on Digital Twin: A Case Study of the Xuzhou Geotechnical Engineering and Ecological Restoration Research Center

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Abstract. Under the disturbance of multi-source risk coupling and dynamic environment on the project site, exploring and constructing a more scientific safety management platform is of great value in reducing the accident risk rate. However, the relevant fields are still in the initial stage. With the advent of the Industry 4.0 era, digital twins can simulate and describe the security state of physical entities in real time, breaking through the shortcomings of the traditional BIM platform's real-time monitoring ability. Therefore, taking the Xuzhou Geotechnical Engineering and Ecological Restoration Research Center as an application case, this paper adopts the digital twin technology. It develops the function mechanism and system architecture of the enterprise headquarters-level security management platform. Moreover, we combine quantitative and qualitative research methods and put forward the key technologies in the platform construction process, including data integration and collaboration technology, risk analysis model technology, and platform visual expression technology. It is found that the security management platform driven by digital twins can realize the dynamic link and real-time interaction between physical space and information space. It can accurately judge and predict the security performance of various risk elements. This paper can provide a useful theoretical basis and solution for construction project safety management and disaster diagnosis.

Keywords: Security management platform; Digital twin; BIM; Digital disaster prevention

1 Introduction

With the vigorous development of the global construction industry, how to monitor the complex construction process in real-time and break through the shortcomings of traditional construction project management has become an international issue of global

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concern [1]. Therefore, as early as the 1970s, the United States put forward the concept of building an information model to guide the transformation of actual engineering project safety management to digital and intelligent, and further gradually derived the digital twin technology [1,2]. In fact, under the disturbance of multi-source risk coupling and dynamic environmental effects on the project site, traditional manual inspection methods have limitations in dynamically controlling the process flow, safety technical parameters, and risks of construction activities due to the technical impact of effectiveness and accuracy [3]. Especially for large-scale construction projects such as enterprise headquarters, the management process contains many logic rules and technical parameter associations; thus, it is difficult to achieve safety control over the entire construction cycle, which, to some extent, restricts the intelligent monitoring of construction process safety [2].

In the era of Industry 4.0, digital twin (DT) provides key technical support for improving the efficiency of engineering safety management. Multidimensional, multi-temporal scales and multi-physical virtual entities can be established through digital means to simulate and depict the properties, behaviors, rules, and other aspects of physical entities in real environments in real time [1]. Compared with the traditional building information model, the intelligent management platform coupled with BIM and digital twin can realize the guidance and management of project engineering. It can also monitor the security status of physical entities in real time through intelligent sensors and other ways to further simulate and predict the potential security risks in the project [4]. At present, the relevant scholars at home and abroad have achieved fundamental achievements in engineering practice, but it is still in the initial stage in general [1]. Especially for the more complex, higher risk, and larger construction project environment, it is urgent to further explore the module architecture and key technologies of digital twin technology in security management scenarios [1,4]. Therefore, taking the Xuzhou Geotechnical Engineering and Ecological Restoration Research Center as an application case, this study uses BIM, digital twin, and other technologies. Combined with real-time data, historical data, twin data, and other intelligent data, it aims to develop a headquarters-level security management platform based on the digital twin technology. It then puts forward key technologies and methods to provide strong technical support for improving the accuracy and effectiveness of project safety management.

2 Literature review: security management platform development status and demand

2.1 Research progress of security management platforms

In the past few decades, the causes of serious engineering accidents mainly come from the man-made or physical safety hazards generated in the construction and operation of buildings, such as extensive production methods and aging of main structures [5]. Among them, the building safety management platform can help overcome the problem of data loss or untimely transmission in traditional project information management and carry out real-time interaction and simulation for key danger and risk points; it effectively improves the efficiency of building safety management [3]. After about 30 years of continuous exploration, such digital information platform tools based on BIMBase have been widely promoted [1]. For example, in the official BIM pilot case in Italy, the digital platform system effectively improved communication efficiency between multiple disciplines and reduced the security risks of the project [6]. At present, domestic scholars have carried out a lot of research on the safety management platform, including theoretical research and engineering practice. For example, Zhang et al. discussed the method of establishing a BIM safety production management platform under the cooperation of BIM technology, VR technology, UWB positioning technology, and other digital technologies [5]. Yang et al. took the construction of a smart site platform as an example to discuss the digital intelligent transformation path of safety management in construction enterprises [3]. Hence, the significant positive impact of digital information technology on building safety management has reached a certain consensus in engineering practice at home and abroad. It has accumulated valuable experience for subsequent engineering construction. However, some scholars further pointed out that although BIM technology has achieved initial results, it still fails to cope with the real-time dynamic interaction between virtual models and physical entities; there are certain lags and limitations in mapping virtual and real data [1]. For example, the security operation and maintenance management mainly realize security control by building an operation and maintenance management platform around the main business system; the coordination and correlation of the system need to be strengthened [1,3]. Therefore, strengthening site safety management and schedule management under the premise of ensuring project quality is still an important research topic facing the construction industry.

2.2 Digital twins: a new technology for building security management

The information age has brought great changes to the traditional industry, especially the emergence of digital twin technology, which has greatly improved the design, construction, and application efficiency of the traditional civil construction industry and also improved the digital disaster prevention capability of the project [4]. Looking back at the development process of “traditional construction” to “intelligent construction”, digital twin technology usually describes the characteristics of physical objects based on multiple dimensions such as space dimension and time dimension; three key links are included: twin data acquisition and processing, digital twin construction and digital twin application [1]. First, regarding twin data acquisition and processing, various types of multi-source heterogeneous data are the digital baseboards for the safety management of digital twins in construction projects, mainly including Internet of Things monitoring data, geospatial and temporal data, user perception big data, etc. Relevant studies also mainly focus on data noise reduction [7], data restoration [8], and data fusion [9]. Secondly, for the construction of digital twins, the multi-scale basic model is usually constructed with the help of LiDAR, oblique photography, semantic segmentation, and other technologies. Then, further “virtual-real” data mapping processing is carried out to realize the dynamic twin expression of real-time field data on the virtual simulation model. The research focuses include modeling technology [4]. Finally, the constructed digital twin highlights the features of full-factor modeling, full information collection, and whole-process simulation. It can be applied to important links such as structural operation evaluation [10], disaster simulation and deduction [11], and smart site management [12]. To sum up, digital twin technology can not only realize the integration of project objectives in the whole life cycle under a high degree of information coordination but also carry out a deep visual expression of the complex environment of the construction site in the information space. This is of great value for the fine construction of a safety management platform. However, there is still a certain lag in the introduction of digital twins into security management at present. Therefore, taking the Xuzhou Geotechnical Engineering and Ecological Restoration Research Center as an application case, this study is based on the digital twin technology. It develops the enterprise headquarters security management platform architecture and key technologies to form integrated scheduling of large-scale scenes and visual expression of multi-scale spatial models. Finally, it realizes the digital twin of construction engineering information space to provide a decision-making basis for relevant enterprise functional departments such as construction engineering management.

3 The architecture of enterprise headquarters-level security management platform based on digital twin

3.1 Case application

The Xuzhou Geotechnical Engineering and Ecological Restoration Research Center is located in Yunlong District, Xuzhou City, Jiangsu Province. It has a total land area of 30.04 acres and a total construction area of about 28, 000 square meters. In the future, the project will become a first-class research and testing center in the field of coal mining hollow area management and ecological restoration in China. Hence, for such large-scale construction projects, establishing an efficient security management platform is of great value in reducing the incidence of project risks. More importantly, traditional BIM management techniques cannot monitor the safety status of the project in real time. Therefore, we developed an enterprise headquarters-level security management platform based on digital twin, taking the Xuzhou case as a demonstration project. We proposed the architecture and key technologies of the platform (Figure 1).

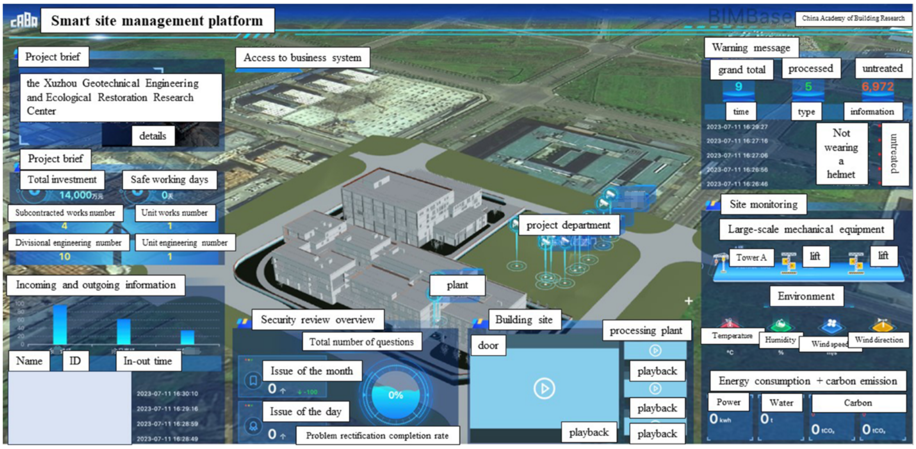

Fig. 1. The enterprise headquarters-level security management platform of the Xuzhou Geotechnical Engineering and Ecological Restoration Research Center project

3.2 Operation mechanism of the enterprise headquarters-level security management platform

Different from the general scale operation and maintenance platform, the core of the enterprise headquarters-level security management platform is the modeling mapping between the building's physical entity and the security twin model (Figure 2). Therefore, it requires a larger amount of data collection and more diverse information tools, including construction technology and process data, management information security data, structural health monitoring data, image text data, and other multi-source heterogeneous data. To realize the requirements of information coordination, such as effective mining of digital twin data and accurate and efficient information transmission, this platform integrates and constructs the all-element information database of the security management platform. This is achieved with the help of three-dimensional point cloud technology, Internet of Things technology, computer vision technology, and other methods. These methods can not only carry out information perception and transmission but also play the role of simulation and data storage. With the twin data of the safety management platform, the platform will provide functions such as anomaly identification, safety early warning, and dynamic monitoring. They can effectively promote safety information interaction and management information feedback to assist enterprise management in accident prevention and decision-early warning. Ultimately, the life safety and disaster prevention level of construction structures can be improved.

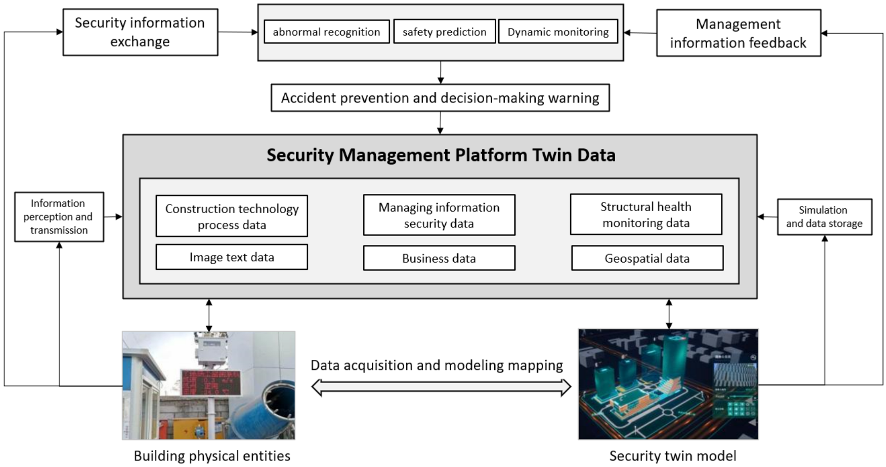

Fig. 2. Operation mechanism of the enterprise headquarters level security management platform

3.3 The architecture of enterprise headquarters-level security management platform

The headquarters-level security management platform based on the digital twin technology is a smart management system that integrates digital and intelligent control technologies (Figure 3). In the Xuzhou case, the platform deeply integrates BIM data, remote sensing data, IOT sensing data, and other "island data". This is achieved through the utilization of industrial Internet, cloud computing, and other information technologies. Technical barriers, such as miscommunication of data and difficulties in professional coordination, are broken down.

Fig. 3. Enterprise headquarters-level security management platform based on digital twin

As shown in Figure 4, the architecture of the enterprise headquarters-level security management platform has five major components, including the physical layer, data layer, business layer, digital twin, and interaction layer. They can complete the whole process of security management, such as data collection, security analysis, and visualization of effects.

(1) Physical layer: To identify potential risks and disasters such as structural risks, behavioral risks, and environmental risks in a refined manner, the platform adopts sensing equipment such as physical sensors, RFIDs, readers, and other sensing equipment to monitor multi-scenario physical entities. The physical objects involved in the safety management system, including cranes, scaffolding, and building structures, obtain real-time vibration, wind pressure, and other critical diagnostic data of the physical entities. From physical entities to sensing devices, the two together support the description and modeling of all elements and life cycles of all kinds of entities, environments, and information in the information space.

(2) Data Layer: Based on the physical layer, the security management platform mainly constructs the overall platform database through BIM data, Internet of Things data, remote sensing data, and other data. Additionally, it is done with the assistance of cloud storage, cloud technology, cloud processing technology, cloud exchange, noise reduction, integration, and sharing processing of the above key data. Finally, the platform provides structured and unstructured effective data such as real-time data, historical data, and twin data to the business layer for analysis.

(3) Business layer: Guided by the actual needs of enterprise users, the platform builds simulation and decision support models of various entities, environments, and parameters in the information space. It is established through accurate mapping of relationships between twins and physical entities in terms of location, geometry, behavior, and rules. Among them, the model content includes the terrain scene model and engineering structure model. The terrain scene comprises remote sensing images, digital elevation models, and oblique photography. The engineering structure model uses the project design drawings to model the representative main structure of the project in the dimension of digital twin construction. It associates asset data and construction data, including ArcGIS graphic service, data fusion integration, spatial data analysis service, simulation, decision warning, and other business service functions.

(4) Digital twin: For the security management platform, the digital twin is the key component, reflecting the real operating state of the real building scene. Five modules are covered, including project management, map management, statistical management, system management, and security early warning. Among them, project management covers the application of project declaration, project inquiry, project approval, and so on. Graph management includes graph browsing, graph query, graph analysis, and other functions. Statistical management includes data classification, data summary, graph scope, and other functions. The system management module provides user management, role management, and rights management services. The safety early warning module comprises auxiliary decision-making, safety training, risk assessment, and other functions. Finally, real-time interaction between virtual and real information, twin updates, and security simulation decisions are realized.

(5) Interaction Layer: Driven by the digital twin, the security management platform realizes the interaction between the digital twin and the owner through the Web portal terminal, mobile terminal, VR/AR terminal, and other ports. With the help of the interactive port, the three-level management service system of "enterprise headquarters level - branch office level - project ministry level" is connected. Moreover, the platform realizes the step-by-step responsibility implementation of engineering safety early warning. It provides data basis and decision support for the security management of enterprise headquarters.

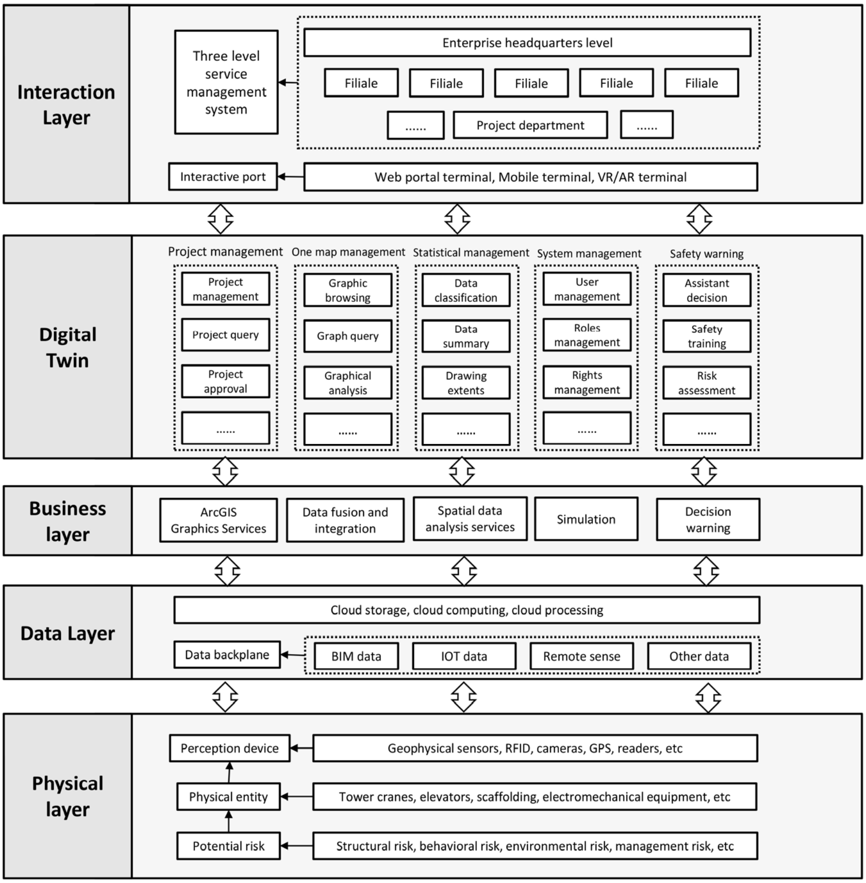

Fig. 4. The architecture of the enterprise headquarters-level security management platform

4 Key technologies of enterprise headquarters-level security management platform based on digital twin

4.1 Data integration and collaboration technology

In the design of the security management platform, the efficiency of twin data transmission, integration, and collaboration determines the platform's security calculation precision and response speed. Distinguished from the previous digital management mode, the new management platform driven by digital twin technology can perform format normalization and resource sharing of various types of real-time data using cloud computing and cloud storage. Thus, the synergy between different departments can be significantly enhanced. As shown in Figure 5, in the application case of Xuzhou, the data types involved in this platform mainly include intelligent remote inspection data, special equipment monitoring data, environmental energy management data, and outdoor environmental monitoring data. For example, this smart platform features real-time worker location, wage supervision, deformation monitoring, carbon emissions, and other data functions.

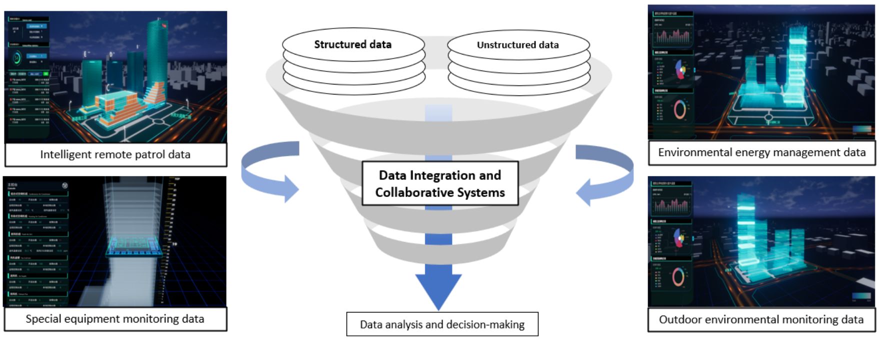

Fig. 5. Data integration and collaboration system

The study aims to further integrate resources and improve the communication efficiency between functional units at all levels, such as the enterprise headquarters, branch offices, and project departments. Therefore, we develop a data integration and synergy system. The system uploads the collected real-time IOT data, using relevant file transfer protocols, to the cloud server for noise reduction, storage, and processing. As a result, the participating units can obtain the data information they need at any time and in any place. At the same time, the data and information of the project are centrally stored and effectively managed. Perfect security strategies and reliable security measures are adopted to guarantee the normal operation of the platform and the security, confidentiality, and integrity of the data and information. Consequently, the information acquirer can decide the information to be acquired according to the needs of business processing and decision-making work. In addition, we also use the above structured and unstructured data to train the machine learning model to feed back the twin model. We then construct a two-way optimization mechanism between the real-time data and the simulation model. Overall, In the Xuzhou Geotechnical Engineering and Ecological

Restoration Research Center, the cloud computing platform stores, shares, and collaborates with heterogeneous big data from multiple sources. It realizes real-time interconnection between different types of data and completes vertical and horizontal integration of heterogeneous big data from multiple sources. It improves the effectiveness of linking historical data, twin data, and predictive data under different scenarios. It also effectively guarantees the timeliness, accuracy, and uniqueness of the data and information processing. Safety management for construction projects can be implemented accurately.

4.2 Risk analysis modeling technology

Risk analysis is one of the core functions of the enterprise headquarters-level security management platform. However, the traditional management platform is relatively simple in risk analysis and calculation, ignoring the difference and uncertainty between different risks. Therefore, taking the Xuzhou Geotechnical Engineering and Ecological Restoration Research Center as an application case, the study adopted the interview method and content analysis method. The methods are commonly used in qualitative research to uncover the common risk elements in engineering projects. We eventually invited a total of 15 experts with extensive project management experience to be interviewed. The interviews included a risk assessment of the whole process of project planning, construction, and management. After that, we processed the 63, 702 words of text data using NVivo12 software to identify the elements of a security risk as perceived by the experts. The data analysis consisted of 3 stages: open coding, axial coding, and selective coding. Ultimately, the data analysis found that project safety management can include the five aspects of "personal, machine, material, regulation and environment"(Table 1). The highest frequency of the theme words was found in the environmental area, while the lowest frequency of 53 was found in the regulatory area. Based on the identification results, we build a corresponding index evaluation system. The system completes the safety control of construction projects by real-time monitoring and analysis of danger source status.

Table 1. Project safety risk identification results

Selective coding	Axial coding	Open coding
Personnel (84)	Regulatory capacity (29)	Supervision efficiency (12), Regulatory norm (17)
	Risk awareness (19)	Disaster awareness (5), Risk understanding (14)
	Hazardous operations (36)	Bad behavior (7), Unprofessional operation (21), Facility wear (8)
Machine (65)	Repair efficiency (15)	Maintenance frequency (8), Failure frequency (7)
	Reliable equipment (23)	Equipment damage (15), non-failure duration (8)
	Fault hazards (27)	Malfunction (6), Wear (17), Short circuit (4)
Material (60)	Materials quality (31)	Material standard (18), Materials acceptance (13)
	Construction matching (14)	Matched degree (10), Proficiency (4)
	Management level (15)	Dedicated raw materials (9), Stock-sales ratio (6)
Regulation (53)	Institutional improvement (25)	Management system (21), Construction system (4)
	Reasonable method (19)	Management method (7), Construction technology (12)

	Sound regulations (9)	Punitive measure (5), Reward mechanism (4)
Environment (90)	Air humidity (38)	Humidity (24), Water vapour content (14)
	Airflow velocity (30)	Wind pressure (18), Wind speed (12)
	Structural vibration (22)	Swing frequency (17), Structural vibration (5)

Note: Frequency of subject terms in parentheses

Among them, the risk analysis of personnel covers the aspects of regulatory capacity, risk awareness, and hazardous operations. Machine risk analysis consists of repair efficiency, reliable equipment, fault hazards, and so on. The risk analysis of materials includes material quality, construction matching, management level, and other indicators. The risk assessment of regulations is carried out considering institutional improvement, reasonable methods, and sound regulations. Air humidity, airflow velocity, structural vibration, and other indicators constitute the risk assessment analysis of the built environment (Table 1).

In the data analysis stage, this platform first normalizes all the indicator data. Then, different weights are assigned to each indicator according to the opinions of experts in the field and the actual situation on site. The risk assessment results are calculated through data processing. Finally, based on the quantitative analysis results of the data, the corresponding targeted security warning and response plan is proposed. For example, in Figure 6, the management platform identifies the risk of structural deformation on the Xuzhou construction site after data calculation and expresses it in the visualization module. Especially for multi-risk coupling engineering scenarios, the risk analysis model is constructed by relying on the enterprise headquarters-level security management platform. It is conducive to the fine measurement of risk levels and the identification of danger to facilitate the reasonable management and control of security risks.

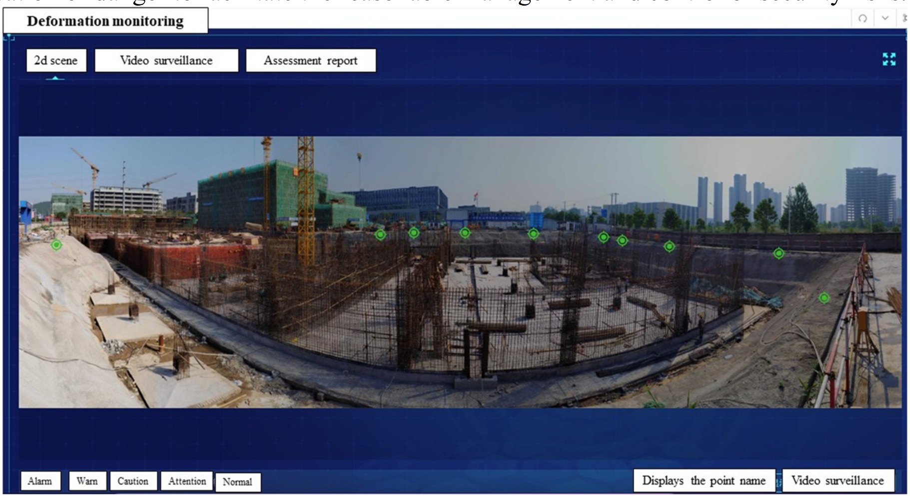

Fig. 6. Structural deformation risk monitoring module

4.3 Platform visualization technology

Compared with the traditional construction BIM management platform, the digital twin-driven project safety management has significant visual, intuitive, and real-time effects. The data visual expression technology is the key link. In the application case of Xuzhou, the enterprise headquarters-level security management platform is based on the digital twin technology. The international mainstream advanced front-end and back-end separation development mode is chosen. Among them, the Angular platform framework is selected for user interaction in the front end. JavaWEB architecture is selected for business logic development in the back end. Postgresql and MongoDB are used for spatial data, BIM data, and attribute data storage and management in the database to build a digital twin platform for enterprise headquarters-level security management. The REST web service architecture is implemented to realize various types of professional security management based on the HTTP protocol. REST Web service architecture based on HTTP protocol can achieve data exchange and model integration of various professional models. Through the visual management module provided by the platform, it integrates data analysis of the whole process of engineering design, construction, and management. It is visually shown in the form of "one map". This includes the safety simulation model of engineering projects, the BIM-based building model, the master control interface of engineering projects, the monitoring of engineering project equipment, etc. (Figure 7).

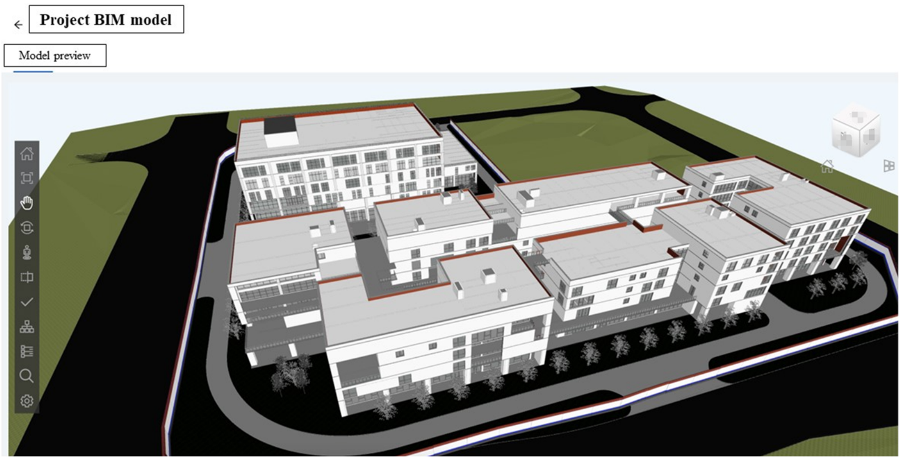

Fig. 7. Visual information model of the platform

Moreover, the platform can realize the function of summarizing, analyzing, and presenting abnormal data analysis, safety prediction, early warning, accident prevention, and disposal. It can help to provide the data foundation and decision support for the security management of enterprise headquarters. As shown in Figure 8, we introduced AI intelligent technology in the platform. It can identify unsafe behaviors during the construction process while monitoring the project site in real time, reducing the potential risks of accidents in the Xuzhou project.

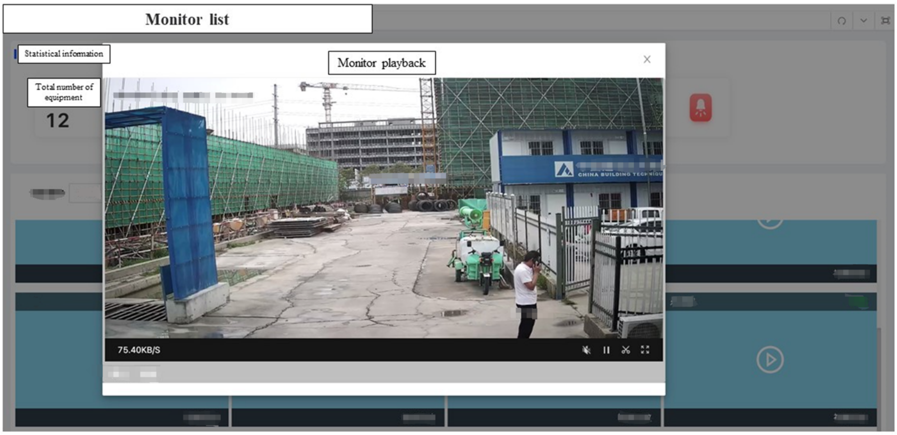

Fig. 8. Unsafe behavior recognition module based on AI technology

5 Conclusion

Under the background of intelligent transformation and upgrading of the construction industry, exploring the construction of a more scientific safety management platform is of great value in reducing the incidence of accident risks. The digital twin technology provides a new solution to this problem. In this paper, taking the Xuzhou Geotechnical Engineering and Ecological Restoration Research Center as an application case, the digital twin technology is introduced. It analyzes the role mechanism and system architecture of developing an enterprise headquarters-level safety management platform. The key technologies for platform construction are proposed from three aspects: data integration and collaboration technology, risk analysis model technology, and platform visual expression technology.

(1) The study aims to explore the problems of difficult safety supervision, heterogeneous data from multiple sources, and untimely information acquisition in construction project management. A method is proposed for constructing an enterprise headquarters-level safety management platform based on digital twin technology. It can realize dynamic linkage and real-time interaction between the physical space and the information space. Moreover, it can help to enhance the whole-process supervision and all-factor disaster mitigation capability of construction projects.

(2) Based on the digital twin-driven enterprise headquarters-level safety management platform, with the help of data integration and collaboration technology, BIM data, Internet of Things data, geospatial data, and user-perceived big data are deeply fused. According to the proposed risk analysis model, the safety performance of each risk element is accurately judged and predicted. A comprehensively perceived, real-time, interconnected intelligent management system is formed.

(3) With the data visual expression technology developed by this platform, the enterprise headquarters-level safety management platform based on digital twin can present the results of safety risk interpretation in the form of "one map". It can provide

refined feedback to the “enterprise headquarters-level - branch level - project department level” three-level safety management system. As a result, it can effectively and efficiently improve the safety performance of the enterprise. The three-level safety management system effectively realizes the implementation of the responsibility of safety risk elements. It improves the ability to deal with dangerous factors from the enterprise to the workers.

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