Research Article

Safety Management System Prototype/Framework of Deep Foundation Pit Based on BIM and IoT

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With the huge demand for building underground spaces, deep foundation pits are becoming more and more common in underground construction. Due to the serious effects associated with accidents that occur in deep foundation pits, it is very important for underground construction safety management to be proactive, targeted, and effective. This research develops a conceptual framework adopting BIM and IoT to aid the identification and evaluation of hazards in deep foundation pit construction sites using an automated early warning system. Based on the accident analysis, the system framework of Safety Management System of Deep Foundation Pits (SMSoDFP) is proposed; it includes a function requirement, system modules, and information needs. Further, the implementation principles are studied; they cover hazardous areas, namely, visualization, personnel position monitoring, structural deformation monitoring, and automatic warning. Finally, a case study is used to demonstrate the effectiveness and feasibility of the system proposed. This research provides suggestions for on-site management and information integration of deep foundation pits, with a view to improving the safety management efficiency of construction sites and reducing accidents.

1. Introduction

Urban development often requires the use of underground space. As a result, deep excavation pits for foundations have become more and more common in building construction. Underground space, which today may contain shopping malls, subways, parking lots, civil defence projects, and so on, provides the necessary services to promote social and economic stability. According to the safety regulations and rules [1] in China, deep foundation pit refers to all construction work including the excavation, support, and dewatering of foundation pits with excavation depths of 5 meters and above. A pit with a depth of less than 5 meters could also be considered a deep foundation pit if the surrounding environment is complicated. Due to the large amount of engineering, tight construction periods, low safety reserves, and high uncertainty of deep foundation pit engineering, safety accidents occur. The incidence of accidents in the construction industry remains high. Not only do they impact construction periods, they also cause huge economic losses and casualties.

At the same time, the safety management of deep foundation pits in the construction industry is relatively backward. Extensive research has been conducted on the causes of foundation pit accidents. Many of these accidents, according to Lin and Hadipriono [2], are a result of poor dewatering procedures, inadequate lateral bracings, poor workmanship during construction, poor consideration of soil pressures, and lack of monitoring. By analyzing deep slump failures and shallow slump failures in expansive soil, which underlie most of Hefei District,
Zhang and Wu [3] realized that the frequent foundation pit accidents in that district were due to ignorance of the characteristics of expansive soil. Water inrushes and unchecked engineering geological data have also been identified as important causes of foundation pit accidents [4–6]. Hu et al. [7] identified design and construction factors such as insufficient embedded pile depths and insufficient anchor pull-out resistance as being responsible for foundation pit accidents. Having dynamic loads around deep foundation pits is also a factor in pit collapse [8]. In addition, Xu et al. [4] also identified several main risk events that can cause foundation pit accidents, including failure to follow engineering design, collapse of pit bracing structures, falling from a significant height due to a lack of edge protection, and collapse of the pit due to excavation. Leakage of the diaphragm wall, strut collapse, soil slide in the pit, and pit bottom upheaval are also identified as foundation pit accident causation factors [9]. A series of other factors have also been found to be indirectly responsible for foundation pit accidents. Qian and Lin [5] identified indirect causes of safety accidents in China which were also indirectly responsible for foundation pit accidents. These causes included individual and departmental interests, safety inspections becoming a mere formality, malfunctions of governmental supervision, inadequate employment systems, and an ambiguous experts’ system. Other indirect factors identified were attitudes to safety, inadequate construction site safety, market restrictions, and task unpredictability [10].

The development of Building Information Modeling (BIM) and communication technologies encourages the construction industry to enhance its management capabilities and modernization level. Technology can play an important role in identifying hazards on a construction site [11]. BIM has the features of integration, simulation, and visualization. It helps safety managers to identify and manage safety risks [12, 13]. Communication technologies, such as radio frequency identification (RFID), ultra-wideband (UWB), and wireless sensor network (WSN), have also emerged as means by which construction sites are monitored [14]. Some of them have been used in recent years to enhance the safety performance of construction workers and equipment [15]. However, most studies of BIM related to construction safety focus on single application research such as fall hazard identification [16, 17], workers training [18], and equipment layout planning [19]. Deep foundation pits are complex sites and regulated as being highly hazardous projects. Although real-time data collection by IoT technologies has been studied and applied in some construction practice, most data are shown in 2D site map rather than BIM platform. More importantly, the established real-time data prototype or frameworks could be further tested with more real-world cases. The interoperability among multiple technologies (e.g., BIM and wireless sensor), which allows information exchange during real-time data collection and processing, needs to be further studied [20].

Considering the safety need for addressing both precise position tracking and real-time on-site monitoring, this paper chose BIM and IoT technologies to create a construction Safety Management System of Deep Foundation Pits (S observational DSDFP). The deep foundation pit was chosen as the study object to develop a prototype system framework for (1) identifying and visualizing the potential hazardous areas during design, (2) integrating the sensor data in BIM model during construction, and (3) providing early warnings and visualized tools in the BIM model according to the monitoring data in web platform.

The structure of this paper is as follows. Section 2 proposes a system framework of Safety Management System of Deep Foundation Pits (S relationship DSDFP) according to the hazard identification and then describes the functional requirements of the safety system and the information that needs to be collected. Section 3 explains the operational principles of the safety management system. Section 4 presents a case study. Finally, possible implementation issues, conclusions, and recommendations for future research are presented in Section 5.

2. Prototype System Construction

2.1. Hazard Identification Based on FTA. In addition to their particularity, deep foundation pits have characteristics similar to other building sites during construction. Besides excavation and dewatering engineering, deep foundation pit construction also involves many kinds of construction equipment and machinery, such as scaffolding, formwork, cranes, and trucks. According to the annual accident statistics report in the website of the Chinese Ministry of Housing and Urban-Rural Development, the most common accident types related to building construction also exist in the construction phase of deep foundation pits. These accident types mainly include collapse, falling, mechanical injury, object strike, and adjacent environment damage.

Among the above five types of accidents, falling, mechanical injury, and object strike are common accidents which could happen in any building part. The other two types, collapse and adjacent environment damage, are closely related to the construction of deep foundation pit. There are many causation analysis methods in safety management theory by which accident hazards are identified, including Fault Tree Analysis (FTA), Analytic Hierarchy Process (AHP), Safety Check List (SCL), Job Safety Analysis (JSA), Systems-Theoretic Accident Model and Process (STAMP), expert interviews, and statistical analysis. FTA is one typical and common method for hazard identification and accident causation mechanism analysis. It is a top-down, deductive failure analysis in which the undesired state of a system is analyzed using Boolean algebra to combine a series of lower-level events. By analyzing 100 accident cases related to deep foundation pits from the public report and news in China over the last five years, the accident FTAs of collapse and adjacent environment damage are drawn as Figures 1 and 2.

In the FTA of collapse accident (Figure 1), 12 factors caused collapse of deep foundation pit. All the 12 factors develop 9 AND gates and 3 OR gates. The Boolean expression is shown in the following equation:
T1
Collapse accident

A1
Support damaged

A2
Soil permeability damaged

B1
Monitoring problem

B2
Improper support

B3
Varying load

B4
Improper water retention

B5
Deformation problem

X1
No monitoring equipment

X2
Untimely data processing

X3
Low level of technology

X4
Improper dewatering method

X5
Load around the pit

X6
Improper monitoring

X7
Bad geological conditions

X8
High load

X9
Improper design

X10
Improper excavation plan

X11
Cross construction

Figure 1: Fault tree of the collapse of deep foundation pit.
Figure 2: Fault tree of adjacent environment damage of deep foundation pit.
According to this Boolean expression, we can find 26 groups of Least Cut Set and 4 groups of Least Path Set. By calculating the structure weight of the 12 factors, the importance sequence is $I_k(X_1) > I_k(X_2) > I_k(X_3) > I_k(X_4)$, where $I_k(X)$ represents the weight of factor $X$. Thus, we can find that absence of proper monitoring equipment and untimely monitoring data process are the two key factors which cause collapse of deep foundation pit. Similarly, FTA of adjacent environment damage (Figure 2) shows that the top key factors are the monitoring problems including absence of proper monitoring equipment, untimely monitoring data or hazardous processing, and improper warning value of monitoring. Thus, the following Safety Management System of Deep Foundation Pits (SMSoDFP) will focus on the above factors related to monitoring problems by BIM and UWB technology.

2.2. Basic Framework of SMSoDFP. By analyzing and designing the functional requirements, the basic framework of Safety Management System of Deep Foundation Pits (SMSoDFP) is proposed as shown in Figure 3. The basic database of monitoring deep foundation pits includes hazardous area information, structural monitoring point, and workers’ position information. All the above safety monitoring information was mapped and linked to the element attributes of the BIM model. After the development in the Revit API (Application Program Interface) and JavaScript language, Revit model could be uploaded to the website interface and correlates the obtained data information with the BIM safety information model. The real-time positioning is responsible for the real-time acquisition of position information pertaining to personnel, materials, and mechanical structure.
equipment in the deep foundation pit construction site. This data is then shown in three-dimensional model. The wireless sensor is responsible for reading the tag information worn by on-site personnel and giving feedback information to the manager. The model parameterization setting is based on the real-time position information of the personnel machine and sets the parameter values of the relevant family members in the model, thereby realizing a visual display of the hazards, the hazardous area, and the monitoring point. In the UI of the web platform, it would realize both the BIM model and the real-time data display of hazards and hazardous areas, the position of personnel, and the automatic warning system related to structural deformation information.

2.3. Function Requirement Analysis for SMSoDFP.

Traditional construction safety management has many shortcomings, such as ignoring preventive management and lacking initiatives for personnel. Accident prevention and early warning systems are weak in the construction industry. Yuan [21] conducted statistical analysis of China’s deep foundation pit accidents and found out that construction work problems which revolved around the violation of regulations, poor construction quality, poor emergency responses, construction organization problems, and poor supervision accounted for 69.46% of accidents recorded. The development of modern information technology provides a new way to change this poor situation. Based on BIM and other communication technologies, the proposed SMSoDFP should include the following functions.

The first one is visualizing the potential hazardous areas in the BIM model based on safety rules. The safety rules are identified based on the design drawings, safety technical specifications, and hazards identified based on FTA. They are applied in order to calculate the area where safety accidents often occur to determine the location and scope of potential hazardous. For example, collapses will not harm personnel outside the foundation pit but may cause those in the pit to be buried alive. Therefore, the safety rule related to foundation pit collapse area should extend a certain distance inward and outward according to the shape around the foundation pit. As shown in Figure 5, \( x_i \pm n \) and \( y_j \pm n \) are the inward and outward corner coordinates of potential collapse hazardous areas, and \( n \) is the distance (1.2 meters) which is presently the construction specification in China.

The second function is collecting safety information automatically. This information includes the location, attributes, and other information required by the system and is automatically collected through monitoring equipment and positioning technology. This reduces inefficiency caused by manual data collection. The deep foundation pit construction site is a complex system that is constantly changing. In order to improve the efficiency of safety management, a series of information must be collected, including personnel, materials, and information on attributes and mechanical position. Data on deformation, displacement, and axial force changes during construction are also of great importance. Wireless sensing technology, positioning technology, and structural health monitoring equipment automation will be used.

The third is visualizing safety monitoring information. All safety information collected including personnel, materials, machinery, and monitoring point locations on construction site should be shown in the BIM safety information model. This will help managers to quickly, comprehensively, and intuitively understand and grasp the construction environment of the deep foundation pit and the safety status of staff. This helps to develop a realistic safety management plan for real-time monitored site conditions.

The fourth is automatic monitoring and early warning. This requirement includes two aspects: (1) automatic monitoring and early warning of personnel approaching hazardous areas and their unsafe behaviors on the construction site; (2) automatic monitoring and early warning of dramatic changes in data information such as deep foundation pit deformation. It could rely on the color display of monitoring points in the BIM safety information model and the monitoring point family link monitoring data curve in the BIM model. At the same time, through the 4D function of the BIM technology, it could realize automatic monitoring and early warning of dramatic changes in data such as deep foundation pit deformation. In the event of an error, the safety manager can give a warning right way.

2.4. Information Need Analysis for SMSoDFP.

According to the function requirement analysis and the basic framework of SMSoDFP, there are four kinds of safety information which need to be collected:

The first is the list of hazards for deep foundation pits, for instance, the edge of the pit, the wellhead, the tower
A deep foundation pit engineering BIM safety information model is created based on the design drawings and the hazard identification list. This BIM safety information model includes the deep foundation pit engineering earthwork model, pile foundation model, support model, trestle floor model, temporary facility model, construction machinery model, and safety protection model. To visualize the hazards and the hazardous area, the IF conditional statement of the family function in the BIM software is used to realize the color display distinction between the hazards and the hazardous area in the BIM safety information model of the deep foundation pit’s engineering.

The second is the location information of personnel, materials, and machinery. The location information of personnel and construction machinery on construction site is a function based on time because this information changes over time. Real-time location information pertaining to personnel and machinery is imported into the BIM safety information model to automatically alert the objects when entering the hazardous area. The location information can be realized by real-time positioning equipment.

The third is the attribute information of the personnel on the construction site including name, gender, health status, operation type, violation situation, and construction area. Tags will be placed in each person’s overalls or helmets to obtain the relevant attributes of the person by reading the tag information. Information on the wearing of protective equipment for personnel can be obtained through wireless sensing technology. The safety management system realizes individualized early warnings pertaining to the working conditions of the site personnel with different construction requirements in the hazardous area according to the jobs undertaken by the individual people.

The fourth is the monitoring element position information and element deformation information of the deep foundation pit. This is important to ensure the safety of the deep foundation pit’s structure and surrounding buildings. According to the characteristics of the project, combined with the existing safety monitoring specifications of the given pit, monitoring points are set in and around the engineering structure. The structural health monitoring equipment is used for real-time monitoring of the groundwater level, support, horizontal and vertical displacement of the foundation, support axial forces, and so on. The monitoring information is imported into the BIM safety information model, and the 4D function is used to realize real-time monitoring of displacement and deformation during deep foundation pit construction. By setting the function (IF) conditional statement of the family function in the BIM software, the color change of different monitoring points of the deep foundation pit
is simulated, and the monitoring and early warning systems are realized.

The on-site monitoring information can be mapped to the attributes in the IFC standard in the web platform (as shown in Figure 6). Data information in the SQL Server-based deep foundation pit monitoring information database can be put together with the lightweight BIM model, which can be generated and uploaded from Revit model by Revit API in the IFC standard (Figure 7). The lightweight BIM model can then be used to monitor information changes in the deep foundation pit.

3. System Principle

There are three major functional objectives in the construction Safety Management System of Deep Foundation Pits: visualization and automatic warnings of hazardous areas, personnel monitoring, and real-time monitoring of structural deformation. The implementation principle for the safety management system for the construction site is analyzed as follows.

3.1. Principle Analysis for Visualization of Hazardous Area.
In order to realize the automatic warning function pertaining to personnel entering hazardous areas, this study uses the relevant attributes of the deep foundation pit engineering BIM safety information model to integrate the hazards information of the deep foundation pit. Hazardous areas can be divided into two categories: hazards that can be identified at the design stage which have a relatively fixed position, such as a hole’s edge. The other type of hazardous areas is generated during the construction process due to the operation of the construction machine. Table 1 provides a summary while Figure 8 shows the basic flow that identifies and creates Revit elements of hazardous area in different colors.

3.2. Principle for Personnel Position Monitoring. Based on the visualization of hazards and hazardous areas in the BIM safety information model of deep foundation pits, it is necessary to use positioning technology to obtain the position information of the personnel in real time and to warn personnel entering the hazardous area automatically. There are many common position-tracking technologies including GPS location, infrared positioning, RFID, WiFi, Bluetooth, Zigbee, and ultra-wideband (UWB) technologies. All these position-tracking technologies can be categorized into active (such as UWB) and passive types (such as WiFi, RFID, and Zigbee). They are compared in terms of their characteristics in Table 2. Active type technologies use algorithm of AOA (angle of arrival), TDOA (time difference of arrival), and TOA (time of arrival). The active type has high positioning accuracy and is not easily disturbed, while the passive type is easily affected by obstacles such as water and metal due to the strength of the signal, and its position results exhibit more deviation and lower accuracy.

Given the complex environment of the construction site and the high accuracy requirements needed for safety management, the UWB position-tracking technology using the TDOA algorithm was chosen as the technology by which the location information of personnel in real time is collected in this SMDsDFP prototype test. During the test, one label was placed on the helmets of personnel to read their individual attribute information. An antenna was placed on the edge of each hazardous area of the deep foundation pit construction site according to the danger source, and when someone entered the area wearing a helmet with the label, the alarm sounded. Through the specific API of Revit software, the real-time position of the person could be displayed in a 3D mode manner; this was important so that the manager could intuitively grasp the scene where the person wearing the helmet was and efficiently manage their safety while they were in the deep foundation pit construction site.

The functional realization of the automatic warning required the use of the BIM safety information model, the real-time positioning system, and a wireless sensing system. By reading the tag information the real-time positioning system transmitted the data to the BIM model. Through the secondary development of BIM software and the API interface, the position and movement path of the person were displayed in real time in the BIM model.

3.3. Principle for Structural Deformation Monitoring and Early Warning. In this study, the structural health monitoring equipment is used to monitor the axial force variations, the displacement changes, the groundwater levels, and the surrounding environment in the construction of deep foundation pits in real time. At the same time, BIM is used to realize the visualization of structural deformations and the automatic warning function during deep foundation pit construction.

According to the characteristics of deep foundation pit engineering, each component is treated as a kind of family in the process of model creation. It is necessary to complete the parametric family creation of models such as the earthwork model, the support model, and the trestle floor of deep foundation pit engineering. According to the positional relationship of each component plane in the design drawing, the component family is reasonably placed, and the BIM model of the deep foundation pit is initially formed. Construction machinery models (such as excavators, earth moving machines, tower cranes) and construction facility models (such as construction enclosures, material processing production areas) in the BIM model of deep foundation pits should be created. Reasonable site planning before the implementation of the project improves space utilization and reduces the occurrence of space conflicts and secondary handling events. At the same time, the hazards and the corresponding hazardous area are represented by different colors, and relevant precontrol measures are given to form a deep foundation pit structure monitoring model.

Deep foundation pit construction is a dynamic and complex process, and there are many projects to be
monitored; therefore, there is a huge amount of data information. In order to improve safety management, it is necessary to ensure the real-time acquisition of various data information on the site and to realize the rapid processing of this data information. The overall framework of the deep foundation pit structure deformation monitoring and early warning system is divided into the sensing layer, the transport layer, the model layer, the data processing layer, the application layer, and the user layer (as shown in Figure 9).

In the process of structural deformation monitoring with regard to deep foundation pits, each time the BIM model acquires a monitoring value, it will compare it with its corresponding alarm value. Once the monitoring data exceeds the alarm value, it will sound an automatic early warning (as shown in Figure 10). The implementation principle of the automatic positioning of the monitoring points which are out of the alarm value is shown in Figure 11. Among them, the ID number automatically assigned to each primitive by Revit software in the BIM model is used to distinguish different primitives. When the monitoring data of a monitoring point exceeds its alarm value, the system automatically obtains its monitoring point ID and the corresponding sensor’s ID. The software can then traverse the function of the model primitives to traverse the Element ID corresponding to all sensor primitives in the deep foundation pit model. By comparing the Sensor ID corresponding to the alarm value monitoring point with the Element ID of all the sensor elements in the model, the monitoring points with the same ID number are found and highlighted by the Element.ID method.

### 4. Case Study of SMSoDFP Prototype

#### 4.1. Case Description and Site Experiment Design

A case study of a deep foundation pit project in Shanghai is presented to demonstrate the system. The China State Construction Engineering Corp (CSCEC) is the principal contractor of the project. The site layout is shown in Figure 12. The foundation pit is 20 m long and 13 m wide at the maximum. Its area is almost 240,000 square meters. The underground area has two floors, its foundation pit has been excavated to a depth of 10.05 m, and the deepest pit depth is 13.2 m.

Through the support of CSCEC, the contractor permitted the researchers to carry out a SMSoDFP prototype experiment and shared their foundation construction monitor data for comparison purposes. Table 3 shows the monitoring plan of the foundation contractor. All the data processing by the contractor was performed manually, and the monitoring result is not in real time. This case experiment took monitoring task of items 2 and 7 listed in Table 3 as the request by the contractor so that it would not disturb their construction. The contractor also agreed to make workers position test in specific safety area of its site. All the experiment equipment including deformation monitoring and UWB position tracking is shown in Table 4.

According to the SMSoDFP framework, the experiment collected information of both the UWB tag position and the monitoring elements’ deformation. All collected data was imported automatically into a lightweight BIM model using the JavaScript API platform. After data processing based on the safety rule, the SMSoDFP prototype was verified. It has three functions: the visualization of hazardous areas, real-time monitoring of personnel, and real-time monitoring of structural deformation and automatic alarms. The effectiveness and feasibility of the system in performing such tasks were also demonstrated.

#### 4.2. Visualization of Hazardous Area Test

The color simulation module includes two subfunction modules: the hierarchical display of the hazardous area and the color simulation of the structural deformation point. The classification of the hazardous area comprehensively identified the existing hazards in the BIM model based on the identified list of hazards in the construction site. It automatically arranged safety protection facilities at locations such as the edge of the hole to reduce the occurrence of accidents. The color deformation function of the structural deformation point was based on the monitoring information obtained by the structural deformation monitoring equipment during the construction of the deep foundation pit. This helped the construction site managers to quickly, comprehensively, and intuitively understand the on-site environmental status of the deep foundation pit and formulate a feasible safety management plan for the real-time monitored site conditions.

Hazardous area is displayed in different colors according to the hazardous level in Revit (as shown in Figure 13). After being uploaded to the web platform, the lightweight BIM model is shown in Figure 14. The red color represents a Class I hazardous area (set within 0.3 m from the hazards), indicating that there is a high probability of an accident. Yellow indicates a Class II hazardous area (set within 0.5 m from the hazards and indicating a greater likelihood of an accident). Green represents a Class III hazardous area (set to the edge of the hazardous area and indicating the presence of a hazardous area).

The color simulation of the structural deformation point was based on the real-time structural monitoring data of the
The color simulation of the structural deformation point was realized by setting the relevant attribute values of the monitoring point family parameters. If the monitoring value exceeds the warning value, it is displayed in red; otherwise, it is displayed as green.

### 4.3. Personnel Position Monitoring Test.

The experiment installed wireless sensors in the northwest corner, southwest corner, and southeast corner of the foundation pit, and all the collected data was transmitted to the computer. This formed a complete staff positioning network. The range

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**Table 1: Classification of hazardous areas in deep foundation pit construction site.**

| Type of accident | Hazardous area |
|------------------|----------------|
| **Collapse**     |                |
| Pit edge         | 1.2 m from foundation pit edge |
| Foundation pit support | The inspection is qualified, and the lack of the latest safety inspection record is regarded as a hazardous area |
| Scaffold         | The inspection is qualified, and the lack of the latest safety inspection record is regarded as a hazardous area |
| **Falling from a height** |                |
| Manual digging pile hole | 1 m from the edge of the orifice |
| The edge of the hole | 0.6 m from the edge of the hole |
| Scaffolding formwork | Coverage of formwork collapse |
| Tower crane use   | The range of the circle is centred on the hanging object, and the instantaneous reaction distance of the person is the radius |
| **Object strike** |                |
| Support erection | The inspection is qualified, and the lack of the latest safety inspection record is regarded as a hazardous area |
| Scaffolding      | The inspection is qualified, and the lack of the latest safety inspection record is regarded as a hazardous area |
| Tower crane use  | Plane projection area |
| Formwork         | Detecting tower crane speed, with overspeed being considered unsafe area |
| **Mechanical injury** |                |
| Crane            | Plane projection area |
| Concrete pumps   | Work area and moving route |
| Other moving equipment or machine | Work area and moving route |
| **Adjacent environment damage** |                |
| Crane            | The maximum range of the circle centred on the hanging object |
| Support system   | Retaining structure or other support element |
covered by the triangle (as shown in Figure 15) is the range in which the entire network could collect tag data.

By comparing the position of the worker tracked by the wireless sensor with their actual position, it was found that the system could monitor the real-time position data of the worker. The position of the label tracked on the computer was compared with the actual position of the label (as shown in Figure 16), where the green line indicates the true motion path and the broken line indicates the motion path tracked by the system. It can be seen that, due to the need to measure the entry of personnel into the hazardous area, an experiment was conducted in which the person gradually approached the base point (as shown in Figure 17). The upper right corner indicates the time when the person was close to the base point, and the lower left corner indicates the distance (in millimeters) of the person from the base point. It was found through this experiment that the position of the tag was not easily tracked when it is in a particularly concealed place such as a stairway. Therefore, there was a need to place more receivers in the monitoring area to ensure the accurate tracking of the tag.

Through this test, it was shown that the UWB system can track the position of the tags. As per the UWB provider (brand: Decawave) instructions, the level of accuracy is related to both the movement speed and the position of the tag. The slower the movement speed of the tag, the more accurate the positioning. When the location of the tag is lost, there is a need to place more anchors in the monitoring area.
to ensure monitoring accuracy. Finally, the data collected by the system will drive the movement of the personnel in the model, visualize the movement of the personnel, and monitor the movement of the construction personnel.

4.4. Structural Deformation Monitoring and Early Warning Test. The real-time display function of the structural deformation monitoring data is realized by reading the data in the monitoring data subtable of the deep foundation pit engineering SQL Server database. At the same time, the data is also displayed in the drawing area in the form of data curves. The manager can visually grasp the monitoring status of the deep foundation pit by viewing the data curve. In the experiment, the data collected by both displacement and clinometer is not significant.
changes for the reason of short time or good construction quality. The following is the analysis of the data collected by surface strain gauge. In this project, the design strength of the deep foundation pit supporting concrete was C35, and the section size was 800 mm × 1000 mm. According to the requirements of the code, the warning value of the foundation pit support structure was 70%–80% of the design value. The calculated alarm value was 19600 kN–22100 kN. Therefore, this article set the warning value to 20000 kN. When the monitoring value exceeds the warning value, the manager is reminded in the form of a pop-up warning. The real-time monitoring data curve for deep foundation pit deformation was controlled by the MSChart plug-in.

The realization of the automatic early warning function includes two parts: the pop-up window warning and the automatic positioning for the alarm value. When the monitoring data of a certain monitoring point exceeds the alarm value, the system will pop up prompt tags window, and it will show the history monitoring data when double-clicking the prompt tags (as shown in Figure 18). This system also could connect the monitoring camera in construction site. The camera video can pop up when clicking the camera element in BIM model (as shown in Figure 19). Besides, it could draw the simulation of deformation field based on the collected data of giving deformation monitoring point. Figure 20 shows the deformation simulation according to the value of displacement meters placed in construction site.
Table 3: Monitoring plan of the foundation contractor.

| Monitoring item                                             | Monitoring frequency |
|-------------------------------------------------------------|----------------------|
|                                                            | Pile | Dewatering | Excavation | Base floor concreting after 7 days | Support demolishing and 3d after |
| 1 Displacement of surrounding roads and buildings           | 1 per day | 2 per week | 1 per day | 2 per week | 1 per day |
| 2 Upper displacement of support system                      | —     | —           | 1 per day | 2 per week | 1 per day |
| 3 Bottom displacement of support system                     | —     | —           | 1 per day | 2 per week | 1 per day |
| 4 Outside soil displacement out of support system           | —     | —           | 1 per day | 2 per week | 1 per day |
| 5 Underground water level out of support system             | —     | 2 per week | 1 per day | 2 per week | 1 per day |
| 6 Supporting axial force                                    | —     | —           | 1 per day | 2 per week | 1 per day |
| 7 Settlement of support columns                             | —     | —           | 1 per day | 2 per week | 1 per day |
| 8 Water pressure out of pit                                 | —     | —           | 1 per day | 2 per week | 1 per day |

Table 4: Equipment list in the prototype experiment.

| Type                      | Name                               | Quantity |
|---------------------------|------------------------------------|----------|
| Name                      | Laptop, 1 (quantity)               |          |
| Name                      | Tripod, 4 (quantity)               |          |
| Name                      | Camera, 1 (quantity)               |          |
| Name                      | UWB anchor/tag, 4 (quantity)       |          |
| Name                      | Tape measures, 1 (quantity)        |          |
| Name                      | Flexible displacement meter, 2 (quantity) | |
| Name                      | Clinometer, 2 (quantity)           |          |
| Name                      | Surface strain gauge, 6 (quantity) |          |
| Name                      | Wireless communication node, 10 (quantity) | |

Figure 13: Top view of hazardous area in Revit.
Figure 14: Hazardous area visualization in lightweight BIM model on web platform.

Figure 15: Experimental preparation.

Figure 16: Comparison of real and calculated position.
Figure 17: Distance between BS and staff.

Figure 18: Pop-up warning real-time data and history curve display.
5. Discussion and Conclusion

In this research, a system framework prototype was proposed for the safety management of deep foundation pits based on BIM and IoT. This prototype system has proven to be feasible and effective within the limits set by the experiment. The contractor who supported this experiment made the following comments and suggestions:

Firstly, the proposed system framework has great potential value for on-site safety management. It is the main controlling factor for on-site safety management of deep foundation pits and strengthens on-site real-time monitoring at the construction site, rationally arranging safety protection measures, strictly monitoring personnel positions to avoid entering hazardous areas, and rationally carrying out construction organization design.

Secondly, BIM is one of the most important technologies for the modernization of the construction industry. BIM has also been vigorously promoted by the Chinese government in recent years. The proposed SMSoDFP prototype gives more application ideas for construction management, especially with regard to visualization hazardous area and the combination of that data with other information technologies such as position tracking and deformation monitoring.

Thirdly, the SMSoDFP has many merits for improving contractor capabilities with regard to construction safety management. For example, the hazard identification FTA could help with safety education and

Figure 19: Pop-up monitoring camera video.

Figure 20: Deformation simulation based on values of monitoring points.
training. The visualization of hazardous areas could also be better for the quality of construction planning and the effective disclosure of safety matters. The best thing that arose from the experiment was that the system can show monitoring sensor location and collected data in real time in the BIM model. Even though the early warning depends on the threshold values, the history curve could be very helpful in understanding the status of construction and as a means by which changes in next phase are predicted.

On the other hand, the contractor also gave many suggestions with regard to areas in which the SMSoDFP still needed to improve its effectiveness if it was going to be a practical application within constructions sites. For example, while it was good that position tracking by the UWB could provide real-time 3D coordinates, there remained the case that it was easy to lose the tag signal in the complex environment. Although this problem could be relieved by increasing anchor quantity, this is an obstacle to its application. For structural deformation monitoring, the contractor hoped that the system could provide more kinds of commercial graphics other than only showing the data via the curve.

In general, the prototype of SMSoDFP could be helpful in hazardous area identification in deep foundation pits sites, as it provides rich on-site information, timely updates, feedback, storage, and processing. The visualization of hazardous areas can help on-site technicians to make technical disclosures, which helps managers to understand situations in a convenient manner. The system realizes the real-time positioning of construction site personnel and real-time monitoring of deep foundation pit structure and produces automatic alarms. This makes it easy for field managers to react when they have problems. When a danger is about to occur, the reaction time of the personnel involved can be reduced, thereby lowering the accident rate. This can significantly improve the level of safety management.

In order to improve the level of safety management within deep foundation pit construction, a framework of SMSoDFP was established based on combination of BIM and IoT. Through carrying out site experiment, the three functions of visualization, personnel monitoring, and structural deformation monitoring were tested and found to be feasible and effective within the limits of the experiment. In future, research that includes a detailed hazardous database should be carried out—building on that contained herein—so that big data and artificial intelligence (AI) could be incorporated into broader considerations of construction safety. At the same time, further study combining BIM and other information communication technologies, such as image recognition, UAV-assisted aerial photogrammetry for site work, big data technology, and IoT supported by 6G wireless network, needs to be undertaken in order to improve construction safety at a management level.

Data Availability
The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure
Wenhan Fan, Jianliang Zhou, and Jianming Zhou are joint first authors.

Conflicts of Interest
The authors declare no conflicts of interest.

Authors’ Contributions
Wenhan Fan, Jianliang Zhou, and Jianming Zhou contributed equally to this work.

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