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Application of Intelligent Construction Technology in Complex Environment Foundation Pit Monitoring

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Abstract. Manual monitoring has inherent shortcomings, including low efficiency, inability to achieve real-time data acquisition, and relatively high error rates that prevent 24-hour uninterrupted observation. To solve the above problems, this paper constructs a four-layer intelligent monitoring system on the basis of Internet of Things (IoT), which includes perception layer, transmission layer, processing layer and application layer. The system is designed in accordance with internationally recognized IoT architectural standards, which forms a closed-loop process covering signal acquisition, data transmission, and data analysis. This paper details the key functions, composition, technical principles, and coordination mechanisms of each layer. This architecture integrates edge computing and cloud computing, builds a multi-protocol transmission mechanism, and addresses the limitations of traditional monitoring systems, which rely on overly simplistic data processing models and suffer from prolonged response times. Practical application demonstrates that the four-layer framework offers robust real-time responsiveness and scalability, and can greatly improve monitoring efficiency, demonstrating the practical value of the proposed system.

Keywords: Internet of Things, intelligent monitoring, data processing, early warning

1. Introduction

In the process of promoting urban construction, the scale of infrastructure construction in China has continued to expand. In the whole construction project, foundation pit construction is an indispensable part, and the importance of safety monitoring has become increasingly prominent. Foundation pit engineering is a key component of underground construction, and its scale is increasing year by year. In recent years, the complexity and quantity of foundation pit projects have increased significantly, and the pressure to prevent safety accidents such as water inrush, collapse and support instability has increased significantly. Safety monitoring is essential for ensuring construction safety and preventing major accidents such as collapses or water inrush. There is an urgent industry-wide need for more advanced monitoring technologies. Traditional monitoring methods are inadequate for foundation pits in complex geological conditions, making it necessary to promote the intelligent transformation of monitoring systems.

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In recent years, the rapid development of intelligent construction technology has brought breakthroughs in monitoring complex foundation pits and solving problems in the world. European and North American countries have integrated big data, Internet of Things and other technologies into the process of monitoring foundation pits, and put forward more mature solutions. China is also accelerating the development of intelligent construction technology, establishing comprehensive frameworks for digital analysis and automated monitoring. At present, the foundation pit monitoring has been combined with a series of emerging technologies, which can obtain data in real time, and the whole process is intelligent. However, most existing studies focus on individual technologies or isolated functional modules, and do not carry out a systematic analysis of the advantages and disadvantages of the four-level architecture. In order to make up for this deficiency, this paper presents a four-level intelligent monitoring system, clarifies the key technologies, functions and relationship between levels, and validates the rationality of the system by analyzing theory and engineering practice, which can provide reference for the foundation pit monitoring of complex geological conditions.

2. Challenges in traditional foundation pit monitoring under complex environmental conditions

Most foundation pit projects in China still rely on traditional manual monitoring methods, employing instruments such as levels and total stations. This approach has numerous shortcomings under complex geological conditions. Measuring indicators such as displacement and settlement consumes considerable time and manpower. During the initial excavation phase, deformation can reach 90% of the total displacement. It is difficult to capture the changes in a short period of time. In the central area and the corner area, the measurement points are not dense enough, creating monitoring blind spots. Manual measurements are easily disrupted by adverse weather and construction activities, which can block sightlines or damage inclinometers. Soft and muddy site conditions increase operational difficulty, and reading errors can reach 3–5 mm, failing to meet accuracy requirements. In the process of data analysis, the data collected manually should be processed manually and interpreted, and the report should be issued, which is likely to delay by more than 24 hours. Instantaneous deformations caused by vehicle overloading or localized over-excavation cannot be detected in real time, resulting in missed opportunities for timely emergency response. In terms of data utilization, the manual method can only provide a single deformation curve, and the data on support axis, soil displacement and groundwater level are not integrated, which limits the analysis of support stiffness and excavation spacing, hindering support system optimization. In the maintenance of equipment, the measurement points should be repaired repeatedly, incurring high labor costs. Inclinometer damage requires re-measurement, and the deformation data of a certain segment will be lost, compromising the reliability of the monitoring results. The risks that may be encountered in the monitoring of foundation pits are different under different geological conditions, as shown in Table 1.

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Table 1. Typical risks and monitoring deficiencies in foundation pit monitoring under complex geological conditions

Geological Type	Key pain points in core monitoring	Typical risk of sudden occurrence	Key shortcomings in monitoring systems
Soil in inland areas with low bearing capacity	Creep accumulates over time, involving multi-parameter coupling	The elevation of the bottom of the pit has changed, and there are cracks in the surrounding pipelines	Short-term monitoring cannot predict long-term settlement
karst	The existence of deep cavities will lead to the instability of reference points	Instantaneous cave collapse, sudden water and mud influx	Surface monitoring has deep blind spots
confined water	Dual control of head and deformation, surges occur instantly	The pit suddenly encountered water inflow, and the sand was gushed up to the ground due to the penetration of the pipe	In the early stage of leakage, the warning signal is relatively weak, which can not be found
Soil in inland areas with low bearing capacity	Creep accumulates over time, involving multi-parameter coupling	The elevation of the bottom of the pit has changed, and there are cracks in the surrounding pipelines	Short-term monitoring cannot predict long-term settlement
Reclaimed soil sludge	Seawater corrosion, periodic interference from tidal forces, and extreme deformation	The lateral displacement of the enclosure structure is relatively large, and the settlement of the seawall is uneven	The biggest problem of the sensor is that it is easy to be corroded, and it needs to be powered for a long time

3. Key technologies for intelligent monitoring

The monitoring system for foundation pits can be described as a typical intelligent system, with a layered structure and four levels, namely perception layer, transmission layer, processing layer and application layer, in sequence from data acquisition to end-user services. The perception layer is the front-end link, which can collect the required data, the transmission layer is responsible for data transmission, the processing layer is responsible for cleaning and storing data, the application layer can provide visual services for users. The system has strong scalability and modularity, and can meet the monitoring needs of multiple projects.

3.1. Perception layer technologies

The perception layer is the key content of the monitoring system, which converts physical parameters into digital signals and performs preliminary noise filtering.

According to the data type, it can be divided into two types: one is spatial geometric morphology sensing, and the other is point-based physical-mechanical parameter sensing. In the process of obtaining physical mechanical parameters, the system relies primarily on contact sensors, whereas spatial geometric morphology sensing requires non-contact technologies.

In the process of obtaining physical mechanical parameters, contact sensors are the most commonly used, which can monitor groundwater level, deep horizontal displacement, soil pressure, support structure strain and other contents. In recent years, distributed optical fiber sensing technology and wireless sensor network technology have been widely used. Optical fiber sensing technology has outstanding advantages in complex environments, making it a valuable tool in intelligent construction monitoring and of significant value in foundation pit monitoring. Distributed

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optical fiber sensors provide continuous strain measurements along the entire length of the optical fiber, and the measurement accuracy is relatively high. In the case of karst or soft soil strata, the sensor has strong anti-corrosion ability, strong anti-interference ability and high stability, which can make up for the shortcomings of traditional resistive sensors. In the process of monitoring foundation pits, wireless sensor networks can make up for the shortcomings of traditional technologies, have outstanding performance, and bring convenience to the whole system. By setting up a large number of wireless sensor nodes, a network covering the entire excavation area can be formed, and a large number of parameters can be monitored at the same time, including the inclination angle, groundwater level, soil pressure, and other parameters. In complex construction environments, wireless sensor networks can not only reduce maintenance costs, but also avoid the need for extensive wiring.

In the process of acquiring spatial geometric data, the corresponding measurement technology should be selected, and the measurement technology should have the characteristics of non-contact. In the process of intelligent construction, three-dimensional laser scanning technology is a relatively advanced technique, which can play an important role in the process of foundation pit monitoring. This technology can collect point cloud data with the help of laser beams, and the accuracy of three-dimensional measurement can reach millimeters. Due to its non-contact characteristics, the technology is widely used in challenging environments such as soft soil and karst areas, and can also be used in the measurement of special geological conditions. By building a three-dimensional model of the foundation pit, a deeper understanding of the structural changes of the foundation pit can be obtained, and the displacement of the support system as well as soil settlement can also be accurately determined, which can guarantee the safety of the foundation pit. In the monitoring of the foundation pit, the photogrammetry technology is adopted, and the spatial information is obtained by the close-range photogrammetry technology and the oblique photogrammetry technology, and the photographs taken from different angles are analyzed. This method has the advantages of low cost, ease of operation, and wide coverage, and can be used in the monitoring of large projects. In a complex geological environment, the technology can capture the surface texture of the object to be measured quickly, grasp the geometric characteristics of the object, and identify the displacement pattern through image matching, which can play a role in deformation monitoring. The integration of this technology with drones can overcome the spatial limitations of traditional technology, monitor dangerous areas remotely, quickly and safely, and ensure the safety and timeliness of monitoring.

3.2. Transmission layer technologies

The transmission layer provides a high-speed data channel that transfers raw data from the perception layer to the processing layer, ensuring reliability and security while delivering control instructions to front-end terminals.

In the field of transmission technology, wired transmission is the most common technology, which can be divided into many types, such as Ethernet, industrial fiber optic ring network and RS485/Modbus bus. The most prominent advantage of this technology is that it has a high bandwidth and is not prone to packet loss, which can resist interference and is suitable for fixed wiring applications in tunnels and factory buildings. Wireless transmission can be divided into mobile communication network and low power wide area network, which can achieve stable signal coverage, save power and have long transmission distance in tunnels and underground excavation sites. 4G/5G mobile communication supports high-bandwidth transmission for video surveillance data. ZigBee and WiFi can play an important role in the deployment of local area networks [1].

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At this level, the Network Time Protocol (NTP) clock synchronization module, protocol conversion unit and other modules are important components. In this layer, a series of protocols are processed, including Open Platform Communications Unified Architecture (OPC UA), Modbus and Message Queuing Telemetry Transport (MQTT), and Secure Sockets Layer/Transport Layer Security (SSL/TLS) encryption technology is used to ensure data security [2].

3.3. Processing layer technology

The processing layer is the computing center of the monitoring system, which is also called the platform layer. Unlike conventional three-tier architectures, where data is simply forwarded, the independent processing layer in this system performs in-depth data analysis, storage, and risk assessment [3]. The processing layer employs two submodules, one is the centralized cloud computing module and the other is the local edge computing module. The edge computing module can be deployed in the industrial gateway, which is responsible for the filtering of monitoring data, the removal of outliers, and the triggering of alarms. Edge computing technology can respond to sudden anomalies in milliseconds and eliminate the shortcomings of remote cloud processing [4]. The central computing module is a core component of the system, which can carry out intelligent analysis and data governance. In the process of data governance, the system can use a series of time series databases, such as TimescaleDB, to store a large amount of monitoring data for a long time, to achieve the purpose of data cleaning, and to integrate data from multiple sources to generate standardized monitoring data [5]. In real-time computing, the Flink stream processing engine can process a large amount of monitoring data, compare it with the data in the Foundation Pit Monitoring Standard to determine the state of the monitoring object in real time, and use a variety of algorithm models to carry out intelligent analysis, including deformation trend fitting and stress increment analysis, as well as machine learning-based time series prediction. The processing layer uses a digital twin simulation engine to map real-time monitoring data onto a three-dimensional structural model, achieving synchronized state updates between the physical structure and its virtual counterpart [6]. The simulation results can be exported through the standard interface to the application layer for visual display. The rule engine of the warning mechanism can be divided into four levels, and the safety status of the foundation pit can be evaluated in real time according to the multi-dimensional criteria, and the monitoring data can be transmitted to the application layer for subsequent processing.

3.4. Application layer technologies

The application layer provides a business interaction platform for users to play a variety of roles, which can convert the simulation results, early warning information and analysis results of the processing layer into business functions, so as to provide personalized services for operators and managers, and form a closed-loop system.

At the application level, a series of functions need to be realized, including report generation, development trend prediction, visual monitoring, data query and alarm issuing. The monitoring module can reflect the operation of the monitoring object in an intuitive way, which requires timely updating of the data curve, real-time monitoring of the distribution of monitoring points, and the use of cloud maps to reflect the stress.

This layer adopts Browser/Server (B/S) architecture, uses PC-based web management platform, mobile app, centralized control dashboard and other interfaces, and realizes integration with safety

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supervision system and Building Information Modeling (BIM) platform through Application Programming Interface (API) [7].

The core business of the application layer is to realize the monitoring of the whole process, issue warnings, analyze data, generate reports, predict the development trend of things, and provide reference for the formulation of decisions. The monitoring module is an important part of the application layer, which can zoom and rotate the model, and data for any specific area can be obtained quickly through the interface. The alarm notification module receives early warning results from the processing layer, which can issue early warning information to users through multiple ways. The data statistics module can not only analyze the monitoring data, but also track and analyze the development of things, and the system can automatically generate monitoring reports that comply with engineering documentation standards. The decision support module uses intelligent algorithm to evaluate the safety of the structure and predict the development trend, and provides reasonable suggestions for the operation and construction of the project, which plays a key role in preventing risks [8].

4. Case analysis

4.1. Project overview and monitoring challenges

Taking the super large deep foundation pit project in Tianjin Yujiafu Financial District as an example, the site features thick deposits of silty and soft clay, which are common in the area. This site is a typical composite adverse geological environment, characterized by both shallow groundwater and deep confined aquifers [9]. The silt layer has a high moisture content of 47% to 68%, a high compression coefficient, and a strong creep effect. It is a typical marine soft soil, exhibiting low strength, high compressibility, and a tendency toward plastic deformation and water inrush. The site is affected by a variety of factors, including proximity to railways and rivers, combined with soft soil and high groundwater levels, which can lead to safety hazards. The excavation work is divided into six areas, and the roads around the project are relatively dense, and the deformation patterns of each area are different. These characteristics make this project a suitable case for demonstrating the advantages of intelligent monitoring.

4.2. Deployment of the intelligent monitoring system

Perception layer: This is a fully intelligent monitoring system, which was composed of four layers, namely perception layer, transmission layer, processing layer and application layer. In this project, full use was made of 3D laser scanning, digital twin and other technologies to solve the problems encountered in the process of geological monitoring of confined aquifers.

To address the monitoring blind zones, a hybrid deployment strategy combining contact-based sensors with 3D laser scanning was adopted [10, 11].

The Z + F 3D laser scanner was used to regularly scan the retaining wall of the foundation pit, the surrounding roads and the flood control wall, and a point cloud model with high density was built to make up for the shortcomings of the monitoring points arranged in the traditional way. By correcting the point cloud deformation data and combining them with inclinometer readings, the system identified localized heave and concealed settlement zones [12].

In some areas, wireless signals were seriously attenuated, and the surrounding environment was more complicated, which required the use of a hybrid network, combining 4G, NB-IoT and other

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technologies, and the use of industrial optical rings to provide support for the transmission layer, so as to set up two transmission channels and enhance redundancy.

In the processing layer, a two-level structure was built, including cloud computing platform and gateway, which could process hidden risks in different levels, and solve the problems of seepage and creep.

In the application layer, the intelligent monitoring platform was built. It provided a B/S-based interface tailored to user needs, with access channels including mobile apps, PC interfaces, WeChat mini-programs, and large-screen displays, and also integrated with the BIM model.

4.3. Comparative analysis of key monitoring results

Firstly, in terms of deformation quantification, the intelligent monitoring system determined the settlement of the surface in different areas, which occurred during the initial excavation, accounting for 85.5% to 96.1% of the total settlement. About 90% of the pile top displacement occurred during the initial excavation, while manual monitoring could only roughly judge that the initial excavation stage had a large deformation, but could not obtain accurate quantitative data. The digital twin model reproduced the "inverted triangle" deformation pattern of soil and pile, which closely matched the measured data, and demonstrated the decisive role of support stiffness in deformation behavior.

In the construction of intelligent monitoring system, the system's real-time early warning capability was put to practical test. For example, in one zone of this project, the site was overloaded, and the settlement became abnormal. Manual monitoring detected the anomaly only after three days, while the intelligent system captured the displacement rate within two hours and immediately triggered an orange alert. At this time, on-site staff quickly limited the load, stopped displacement and eliminated structural failure risks.

In addition to improving the timeliness of the response, comprehensive spatial visualization significantly enhanced monitoring efficiency. Each zone exhibited independent deformation patterns. The traditional manual monitoring method needed to compile data sets, which was time-consuming and hindered cross-zone comparisons. The digital twin model reflected the deformation level of each area through coloring, and enabled rapid comparison of the differences between the diagonal bracing area and the bracing area, so as to identify the similarities and differences between the two areas, and provide reasonable suggestions for the optimization of support strategy.

In the process of predictive analysis driven by data, real-time monitoring data were imported into the finite element simulation module, and the simulated values were compared with the measured data, with an error of less than 1mm, enabling accurate prediction of subsequent excavation-induced deformation in the next excavation process. In this way, the support pouring sequence was adjusted according to the excavation section, and the safety risks caused by soil creep were minimized.

5. Conclusion and outlook

5.1. Conclusion

In order to make up for the shortcomings of the traditional monitoring system, such as low automation and low real-time performance, this paper has proposed an intelligent monitoring system with four layers, detailed the key technologies of each layer, described the functions of each component, and explained the collaborative mechanisms between layers. In this system, the transmission technology integrates heterogeneous network, combines cloud computing technology

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with edge computing, and realizes the closed-loop operation of data collection, transmission, analysis and processing, and the whole process can be visualized.

The analysis of the application results demonstrates that this architecture has strong stability and clear hierarchy. It can not only enhance the accuracy of monitoring, but also improve the efficiency of operation and management, which can detect hidden dangers in time and issue warnings, and can provide support for the intelligent management of the project, offering strong potential for broader engineering application.

5.2. Outlook

Although the four-layer structure constructed in this paper has been validated in engineering practice, several areas warrant further investigation. Future research could focus on enhancing system robustness in electromagnetically harsh environments and improving intelligent prediction algorithms for rare geological events through few-shot learning or physics-informed neural networks. These improvements will further boost the reliability and practicality of the four-layer framework for monitoring foundation pits in complex geological conditions.

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