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Design and Application of a Monitoring System for a Deep Railway Foundation Pit Project

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ABSTRACT With the development of urban underground space in China, foundation pits have followed a trend toward larger area and greater depth. To ensure the safe excavation of foundation pits, it is necessary to monitor their deformation and the internal force of supporting structures and then use assessments of pit and building stability to guide construction. This paper introduces the design and development of a safety monitoring and warning system for deep foundation pits and adjacent buildings. The monitoring information management system uses Visual Studio 2013 as its development platform and adopts the SQL and C# programming languages to realize its powerful data management and visualization functions. By combined consideration of the monitoring information and the layout of the measuring points, monitoring data on the deformation of the deep foundation pit, ground subsidence and deformation of adjacent buildings are analyzed comprehensively. The results show that: first, the horizontal deformation of the side wall of the rock foundation pit achieves its peak value when 50% of the excavation has been completed and tends to change steadily after the completion of anchor construction. Second, the ground surface around the Fengjing area exhibits upward vertical deformation closest to the side wall of the foundation pit, and then downward deformation at greater distances from it. The ground surface relatively far from the side wall exhibits settlement. Third, the internal force of a plate-ribbed anchor retaining wall in the Fengjing area becomes greater at greater depths. Finally, the excavation of a rock foundation pit has relatively little influence on the inclination of adjacent buildings.

INDEX TERMS Deep foundation pit engineering, monitoring scheme, monitoring system, data management, monitoring results analysis.

I. INTRODUCTION

The area and depth of foundation pits have been increasing in recent years in parallel with the intensification of development. Deep foundation pit engineering faces many difficulties, especially in central urban areas, due to the combined effects of the complexity of the engineering geology, the harsh construction environment, and the irreversibility of such projects [1]–[4]. There is an urgent need for an effective real-time monitoring system for deep foundation pits that can dynamically track change trends in the foundation pit and predict potentially unstable areas. A foundation pit monitoring information management system can rapidly process and analyze monitoring data in batches, acquire data on dynamic changes in real time, and use algorithms to predict and provide warnings, making it of great value for data gathering from foundation pits and their management [5]–[7].

The comprehensive monitoring of foundation pits can be traced back to the 1960s, when monitoring instruments were first used for soft soil foundation pits in Oslo, Norway, and Mexico. By the 1990s, with the emergence of monitoring data acquisition systems, the monitoring of foundation pits had become automated. Zhou *et al.* (2017) proposed a prediction approach in which a support vector machine (SVM) is used

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to judge the risks that may occur during the construction process of a subway foundation pit, its effectiveness was proved by a case, the decision-makers can formulate the reasonable measures according to the monitoring results [8]. Zhu *et al.* (2019) combined optical fibers and constant resistance and large deformation (CRLD) bolts to monitor a pit-in-pit foundation, through the comparison and analysis of monitoring results obtained with optical fibers and CRLD bolts, a potentially dangerous slip surface of foundation was identified [9]. Ding *et al.* (2018) measured the surface deformation, supporting force and horizontal wall displacement of a subway foundation pit and the effects of subarea excavation on deformation under stress in the foundation pit, the results showed that zoned excavation can reduce the aspect ratio of a single foundation pit [10]. Mangushev *et al.* (2016) analyzed the causes of building settlement and deformation on the basis of a successful implementation of a deep foundation pit around buildings, and numerical simulation was used to calculate additional settlement [11]. Zhang *et al.* (2016) proposed a two-stage approach that utilizes a virtual image technique to obtain the effect of the excavation of a foundation pit on the behavior of surrounding single-piles [12]. Xu *et al.* (2015) took the deepest transfer station foundation pit in Henan Province, with a maximum depth of 31.2 m, as an example to study the effects of deep foundation pit excavation on the surrounding environment [13].

The development of information technology has recently caused engineering monitoring to enter the era of automation and information-richness. Italy and France developed the earliest engineering monitoring data processing systems, such as PANDA, MIDAS and DAMSAF, and these have had a major influence worldwide. A great deal of work has been carried out on foundation pit monitoring by many researchers, and various foundation pit monitoring information management systems with different scales and functions have been developed [14]. Based on an SQL database, Liang *et al.* (2008) used visualization and GIS technology to enable the dynamic management, analysis, prediction and visual querying of monitoring data with a system capable of printing out query results in the form of reports, through monitoring data of this system, the situation of geotechnical engineering can be precisely forecasted [15]. Wu *et al.* (2008) developed a foundation pit monitoring information management and early warning system based on GIS technology, and used a C/S structure to realize the sharing and centralized management of monitoring information on multiple foundation pits [16].

However, the foundation pit monitoring information management systems introduced above have the following shortcomings [17]–[20]. (1) The emphasis of system management is on monitoring data, and there is a lack of integrated management of basic documents including those from geological prospecting and on the progress of foundation pit construction, the monitoring instruments and measuring points, and the surrounding environment. (2) Most systems can calculate and analyze monitoring data from a foundation pit but only display the results of this analysis in the form of words or tables; thus the visualization component of such systems needs to be strengthened and, particularly, incorporate three-dimensional visualization of engineering information.

These deficiencies are addressed in the current study. A deep foundation pit is taken as the research background, and the research and development of a deep foundation pit monitoring system are further studied from the aspects of monitoring layout, data acquisition, management, processing, analysis, prediction, and warning. The three-dimensional visualization function is also substantially improved. Based on the improvements achieved, a multi-functional and efficient monitoring information management system for deep foundation pit is developed. The horizontal displacement of the side wall, surface deformation around the foundation pit, and the internal force of a plate-ribbed anchor retaining wall are analyzed according to data collected from the Fengjing area, and the influence of excavation on the adjacent buildings is also estimated.

II. ENGINEERING BACKGROUND

The deep foundation pit project covers an area of 6×10^4m^2, has a north–south length of 125 m and an east–west length of 540m; it is therefore classified as a super-large deep foundation pit. The environment surrounding the pit is extremely complex, with buildings such as schools, commercial districts, residential districts and transportation hubs, a situation typical of deep foundation pit engineering in a dense urban area. The foundation pit is divided into four areas: A, B, C, and D. The deepest excavation in the Fengjing area is 25.9 m. The depth of the foundation pit is 17.5–38.1 m. A top view of the foundation pit is shown in Figure 1.

According to the results of drilling, the strata of the foundation pit project are, from new to old, artificial fill (Q4ml), slope residual (Q4el+dl) strata, and siltstone, mudstone and sandstone of the Jurassic Formation (J2s). The characteristics of the strata distribution are shown in Table 1. There are two groups of joints in the sandstone; the joint planes are straight and filled with a small number of cuttings and can so be classified as hard structural planes. The occurrences of these two groups are 263°∠78° (N7°W78°SW) and 350°∠83° (N80°E/83°NW), respectively.

The main types of supporting structures used in the foundation pit are as follows: a plate-ribbed retaining wall is used to support the foundation pit near the Qingyu Building; a pile-plate retaining wall is used to support the foundation pit near Fangyuan Middle School, and a pile-plate retaining wall and weighing retaining wall are used to support the foundation pit near the And a Building. The section below a depth of 218.9 m in the Fengjing area is supported by an internal support scheme, while the section above that is supported by a plate-rib anchor retaining wall. Other foundation pits are supported by plate-ribbed anchor retaining walls and shotcrete anchor nets.

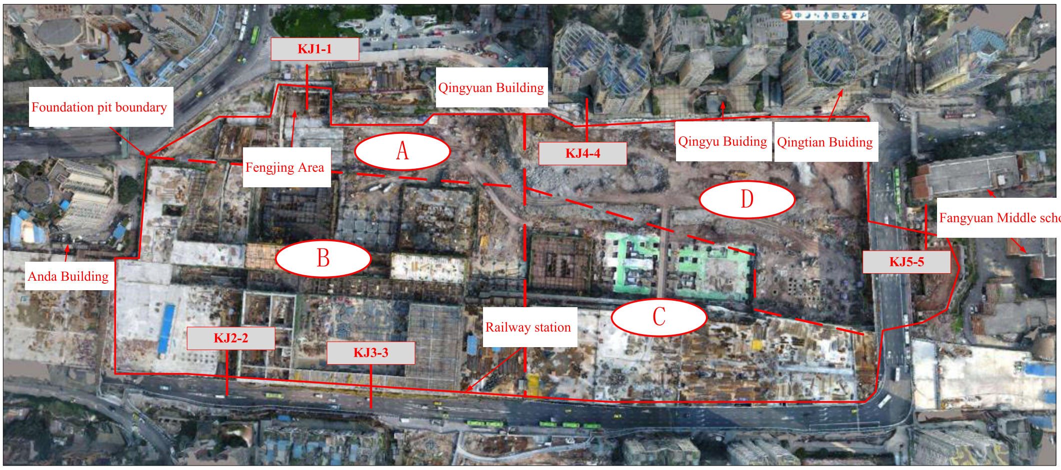


FIGURE 1. Sketch of the railway foundation pit.

TABLE 1. Details and distributions of strata.

Layer	Region	Thickness	Lithology
Q4ml	Entire	0.50–15.1 m	Mudstone, Sandstone, Concrete
Q4el+dl	Discontinuity	0.60–4.5 m	Clay
J2s	Continuity	0.20–10.0 m	Mudstone, Sandstone

III. MONITORING SCHEME

A. MONITORING CONTENT

According to the requirements of the corresponding specifications and to ensure the successful excavation of the foundation pit, monitoring focuses primarily on the horizontal and vertical displacement of the pit slope top and adjacent structures (including underground pipelines), the inclination of high-rise buildings, and the stress on anchors. This is supplemented by crack measurements, rainfall observations, groundwater and seepage observations, and the results of geological survey.

B. ARRANGEMENT OF DISPLACEMENT MONITORING POINTS

The geometric level measurement method is applied to monitor the horizontal and vertical displacement of the slope, retaining walls, adjacent buildings and supporting structures with a precise total station.

The monitoring point layout scheme is as follows. Four monitoring profiles are set across the ground and foundation pit platform on the north and west sides of tunnel foundation pitDZK0+660-ZDK0+718, comprising eight monitoring points numbered J1–J8; two monitoring profiles respectively are set at the north, east and west sides of the ground and foundation pit platform in the Fengjing area, with monitoring points numbered J9–J17; seven monitoring profiles are set across the ground and foundation pit platform near the Qingyu Building, with monitoring points numbered J18–J38; nine monitoring profiles are set across the ground and foundation pit platform on the north side of tunnel foundation pit DZK0+900-ZDK1+093, with monitoring points numbered J39–J65; the section near the Qingtian Building should be properly set monitoring points numbered J66–J89; three monitoring points are set around the Anda Building, Lixiang building, and Fangyuan Middle School, respectively. The monitoring points are numbered J90–J110, which are shown in Figure 2.

C. LAYOUT OF INCLINATION MONITORING POINTS

Inclination monitoring of adjacent high-rise buildings such as the Qingyuan Building, Lixiang Building, Anda Building, and Fangyuan school building during construction is necessary. Fourteen inclination monitoring points numbered QX1–QX14 are laid out with the distribution shown in Figure 3.

D. LAYOUT OF STRESS MONITORING POINTS

The internal forces on bolts, anchored piles, plate-ribbed retaining walls and retaining walls are measured by vibrating string extensometer (or earth pressure gauge). Of these, 180 anchor holes, 7 anchor piles, 45 rib columns

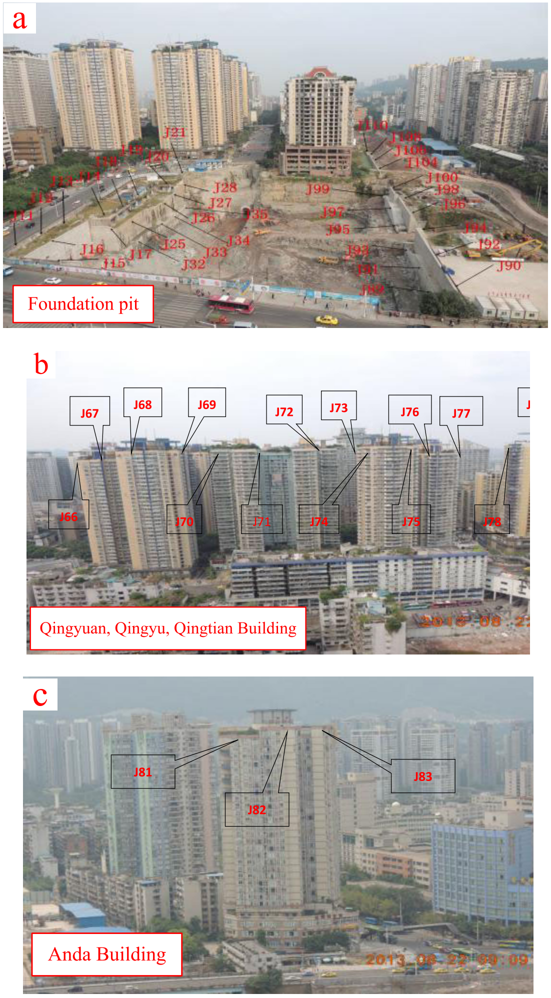


FIGURE 2. Plan view of the arrangement of displacement monitoring points.

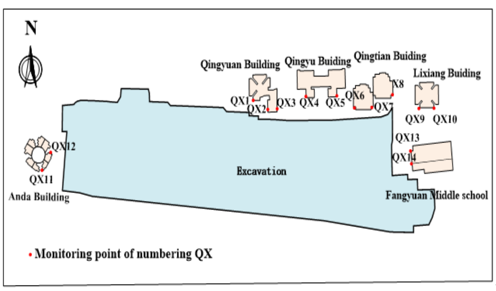


FIGURE 3. Plan view layout of inclination monitoring points for the adjacent high-rise buildings.

and 6 retaining walls are selected to have appropriate stress-monitoring equipment embedded in them in advance.

In principle, the stress monitoring points are arranged at the points best-placed to characterize the stress in the supporting structure, and the points of maximum stress and bending moment should be monitored. The stress profile is required to correspond to the displacement monitoring profile in order to carry out comprehensive stability calculation and analysis of the foundation pit. The layout of the partial stress monitoring points is illustrated in Figure 4.

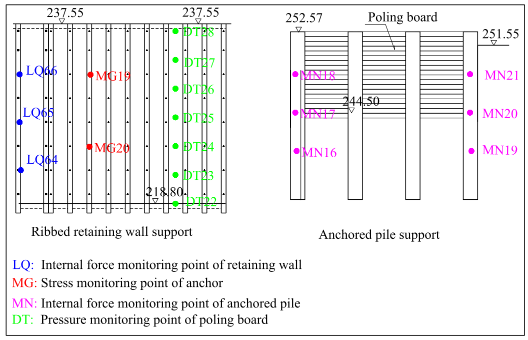


FIGURE 4. Layouts of partial stress monitoring points.

In the monitoring system, a frequency reader is used to measure the stress change in the supporting structure, vernier calipers are used to measure cracks in the ground surface, and the precise total station is used to monitor the building inclination.

IV. DEVELOPMENT OF THE MONITORING INFORMATION MANAGEMENT SYSTEM

The C# and C++/CLI programming languages were used to develop as safety monitoring and warning system for deep foundation pits and adjacent buildings (Figure 5). The system can be compiled on the Visual Studio 2013 platform and run on Windows 7 or higher versions of the Windows operating system.

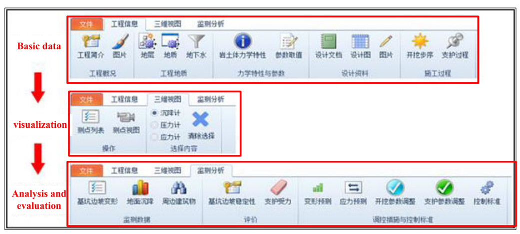


FIGURE 5. Graphical user interface of the monitoring information system.

A monitoring information management system adopting Visual Studio 2013 (VS2013) as the development platform and based on.NET as its interface program between the software and database, Excel, Word and Acrobat is designed to facilitate the management of monitoring data from the deep foundation pit.

The system displays abstract data with real-time curves by using GDI+ drawing technology and OpenGL three-dimensional programming technology, thus realizing the desired visualization function. The monitoring results can be used as a basis for judging whether the foundation pit and buildings are stable, providing a timely guide for construction and feedback for the design.

A. SYSTEM ARCHITECTURE AND FUNCTIONAL MODULE DESIGN

The data processing flow of the monitoring information management system is as follows: the original information and data are stored in the data management system through pretreatment; the visualization system and the analysis and query system use the data from the database management system to analyze and draw the figures; the analysis results are plotted and displayed by the visualization system and fed back to the database management system. The logic structure of this specific system is shown in Figure 6, and the functional modules are shown in Figure 7.

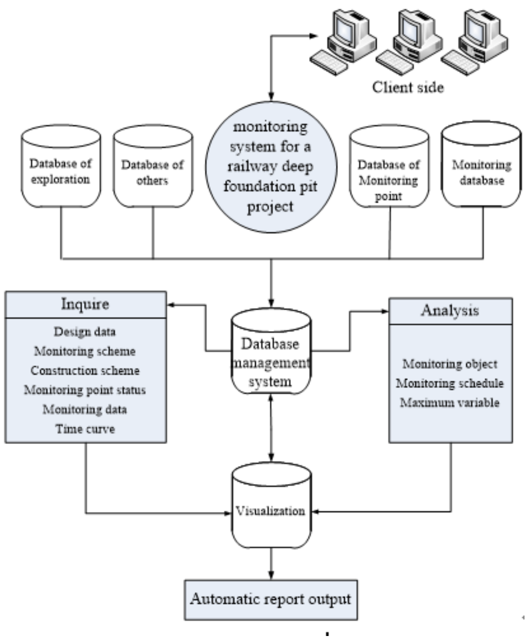


FIGURE 6. Logical structure diagram of the system.

In terms of design concepts, the system can be broadly divided into four layers: the interface layer, data layer, boundary layer and display layer; the interfaces between the four layers are set reasonably, and the connection between layers is clear.

(1) Interface layer: ADO.NET and COM technology is used to establish fast reading and writing channels between Word, Excel, AutoCAD files, the database, and software. The functions implemented at this level mainly include data input, query, error detection, Excel table output of statistical results, and Word document output of the results of calculations and monitoring comparisons.

(2) Data layer: This includes a multi-dimensional dynamic array, multi-level linked list and other data structures and is able to store the large amount of data needed by the monitoring database system and realize data transfer among the functional modules.

(3) Boundary layer: According to instructions generated by human–computer interaction, data management, calculation, statistics and analysis are carried out at the main boundary and sub-boundary of the system.

(4) Display layer: Processed data results are displayed in the form of tables and graphics (two-dimensional or three-dimensional). The functions implemented at this level are mainly graphics functions, including drawing various curves and displaying three-dimensional views.

B. VISUALIZATION SYSTEM

The graphics platform for the monitoring information management system is based on CAD. Monitoring results can be visualized in the form of curves such as those showing changes in the horizontal and vertical displacement of a foundation pit with time, changes in surface deformation around a foundation pit with time, or stress changes measured by string extensometers or earth pressure gauges in the support structures with time. Such curves are a valuable aid for estimating the stress of support structures and the stability of the foundation pit.

Three-dimensional visualization (Chen *et al.*, 2006) is one of the characteristic functions of the monitoring system. The three-dimensional visualization platform can handle the input and display of three-dimensional finite element models and mesh models by connecting the finite element system interface. Both the mesh and the monitoring points can be displayed wholly or partly according to requirements. A three-dimensional view of the deep foundation pit is shown in Figure 8.

In addition to directly displaying the three-dimensional model based on a CAD graphics file, the system can also convert the actual coordinates of the monitoring equipment and monitoring points in sectional and elevation maps into three-dimensional finite element mesh coordinates and display the monitoring layout information intuitively in the three-dimensional model, thus realizing the information display function.

C. DATABASE DESIGN

1) DATA TYPES

The database underlying the system can be divided into the foundation pit geological survey and design database, surrounding building information database, construction progress database, monitoring instrument information database, measuring point information database, monitoring database, and a database for other related data. The original data are mainly in the form of pictures, documents and CAD files that correspond and relate to each other through specific data structures.

2) DATA WAREHOUSING AND STORAGE SYSTEM

The data warehousing function of the monitoring information management system uses Access as the data platform, which can be used to input most monitoring items for the deep foundation pit project. After program conversion and follow-up calculations, information regarding engineering documents,

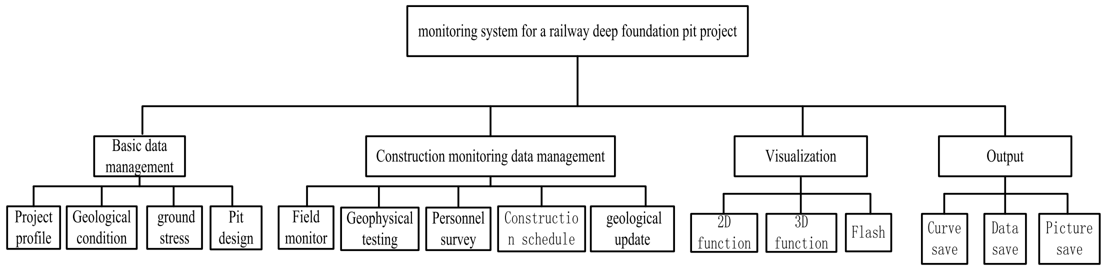


FIGURE 7. Structure diagram of the functional layers in system.

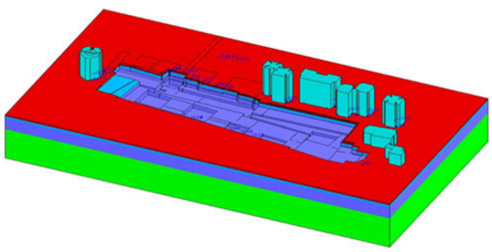


FIGURE 8. 3D view of the foundation pit.

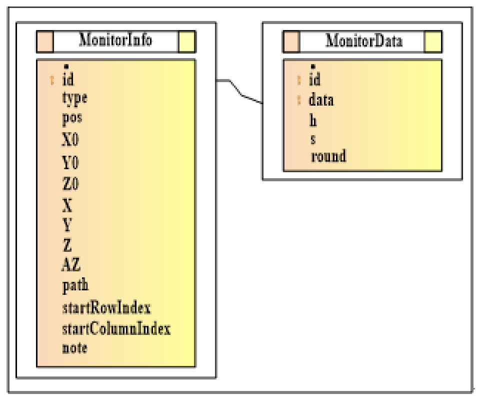


FIGURE 9. The relationship between data tables.

monitoring equipment and measuring points labeled on CAD drawings (such as coordinates, types, update paths, etc.) can be stored in the database in a structured way. In addition, the database can also invoke and input general data in Excel (such as the displacement of measuring points, surface deformation, and the stress of supporting structures) according to a relational structure.

The monitoring information system uses a relational SQL database to store the monitoring data. According to the characteristics of various types of information, two types of data table structure are designed, namely a ''monitoring equipment and measuring point information table'' and ''monitoring data table.''

Establishing a clear structural relationship between data enables a precise description of properties, improves work efficiency, and provides convenience for software development. The data structure of the monitoring system is relatively simple. The tables containing data relating to the monitoring equipment and measuring points are linked by equipment number, as shown in Figure 9.

3) DATA ANALYSIS AND QUERY SYSTEM

The system can process the monitoring data in real time according to the requirements of the monitoring cycle and store the processing results in a corresponding results table for the inspectors to query or output as needed.

The query function is closely related to the visualization system. When the data are stored in the database according to the prescribed format, full information on the project of interest, including design information, monitoring scheme, construction progress, and original monitoring data and their processing results, can be viewed by inputting the project identifier and specific scope into an interactive query box on the system interface. The system also can draw process curves showing variation in displacement, surface deformation and stress in retaining structures with time. The intuitive representation of charts and tables in the program allows the state of each measuring point to be viewed clearly, and the data can be summarized, counted and compared, thus avoiding the inconvenience of manual management and querying for a large amount of data.

V. DYNAMIC SYNCHRONIZATION ANALYSIS OF MONITORING DATA AND EXCAVATION CONDITIONS

The analysis of the deep foundation pit includes measurements of the deformation of the foundation pit and of adjacent buildings and determinations of the internal force of the supporting structures.

A. OBJECT OF ANALYSIS AND SIMPLIFICATION OF THE EXCAVATION PROCESS

Because of the large excavation depth in the Fengjing area and the steady changes seen in its monitoring data, this area is selected as the object for analyzing the deformation of the side wall of the foundation pit and the surrounding ground surface.

Inclination monitoring is carried out for adjacent buildings including the Qingyu Building, Lixiang Building, Anda Building and Fangyuan Middle School, but the foundation pit

TABLE 2. Simplified construction schedule.

Step	Condition	Depth	Construction schedule
1	Surface soil removal	0.5 m	2014/10/01–2014/10/26
2	First floor excavation	8.4 m	2014/10/26–2014/11/15
3	Second floor excavation and anchor construction	8.5 m	2014/11/15–2014/12/1
4	Third floor excavation and anchor construction	8.5 m	2014/12/1–2015/1/2

has only been fully excavated adjacent to the Anda Building, so this building is selected as the analysis object to characterize the adjacent buildings.

The foundation pit in the Fengjing area is excavated to as deep as 25.9m. For ease of analysis and of combining with the supporting design scheme, the excavation process is simplified into four stages and three excavation steps, as shown in Table 2.

B. DEFORMATION MONITORING AND ANALYSIS OF THE SIDE WALL

On the basis of the simplified construction schedule for the foundation pit in the Fengjing area described above, actual monitoring data from the initiation of excavation (2014/10/26) to completion of foundation pit excavation (2015/01/02) are selected for analysis.

The change in the horizontal displacement of the side wall with time during excavation and unloading of the foundation pit can be used as a reflection of the real-time deformation and change trend of the foundation pit, which is the key monitoring item for a foundation pit. Due to differences in geological conditions and construction technology, the deformation of a rock foundation pit is different from that of a soil foundation pit, as shown in Figure 10.

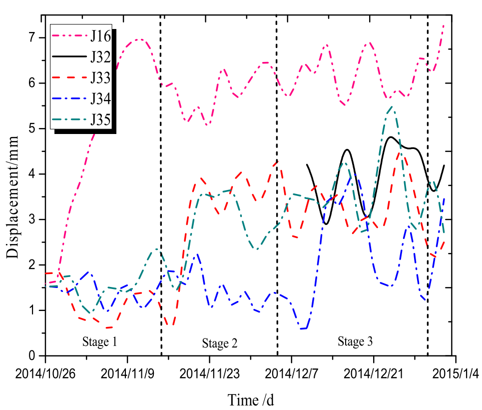


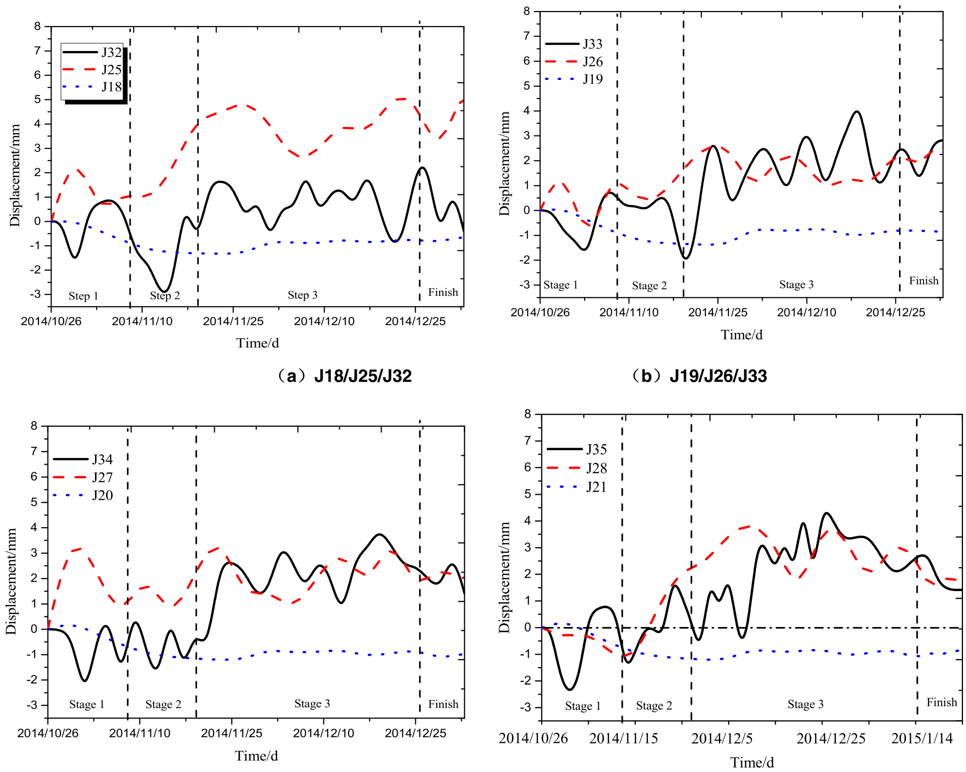
FIGURE 10. lateral displacement- time curves for the sidewall in the Fengjing area of the foundation pit.

When the first layer of the foundation pit (mainly mudstone and sandstone) is excavated, the horizontal displacements of monitoring points J32, J33, J34 and J35 firstly increase and stay at a certain level. However, due to the influence of vibration during excavation by field blasting, monitoring point J16 shows a trend of first increasing and then decreasing slightly. The horizontal displacement of the side wall remains basically unchanged and stable from beginning of excavation of the second layer (mainly sandstone). When the second layer is excavated, 56% of the total excavation depth has been reached, but the horizontal displacement of the side wall has reached its maximum level of the whole excavation process; thus, there is little change in deformation during the later excavation. The displacement values of J16, J32, J33, J34 and J35 fluctuate around 6 mm, 4 mm, 3.5 mm, 2.0 mm and 3 mm, respectively. Generally speaking, the deformation is smaller than the norm value given within the specifications, which value is 20 mm, according Chinese technical regulations for foundation pit support. Comparing the displacement of each monitoring point, it can be seen that the final displacement value of J16 is larger than that of the other monitoring points. This is because J16 is close to the Fengjing area part of the foundation pit, where the excavation depth is deep and the deformation is large.

C. ANALYSIS OF GROUND SURFACE SETTLEMENT AROUND THE FOUNDATION PIT

On the basis of the layout of ground surface deformation monitoring around the foundation pit and the simplified excavation schedule, curves plotting the vertical ground surface displacement for four sections J18/J25/J32, J19/J26/J33, J20/J27/J34 and J21/J28/J35 against time (Figure 11) are selected for further analysis.

When the first layer is excavated, the monitoring points nearest to the side wall (J32, J33, J34,and J35) mostly show downward vertical deformation, with a displacement value that varies from −2.0 mm to 1.0 mm. Monitoring points further from the side wall (J25, J26, J27, and J28) show upward and downward vertical deformations ranging from −1.0 mm to 3.0 mm at that time. The monitoring points that are farthest from the side wall of the foundation pit (J18, J19, J20, and J21) show vertically downward ground surface deformation, reaching a settlement value of −1.0 mm after the first layer has been excavated. The ground surface deformation during the excavation of the second layer is different from that at the completion of first-layer excavation: measuring points



(a) J18/J25/J32 (b) J19/J26/J33

(c) J20/J27/J34 (d) J21/J28/J35

FIGURE 11. **Vertical displacement- time curves for surrounding surface in the Fengjing area of the foundation pit.**

relatively near the side wall and at a middling distance from it show upward vertical deformation, while those farthest from the side wall show an increasing degree of settlement. During the excavation of the third layer, the deformation trend of the surrounding surface is similar to that during the excavation of the second layer.

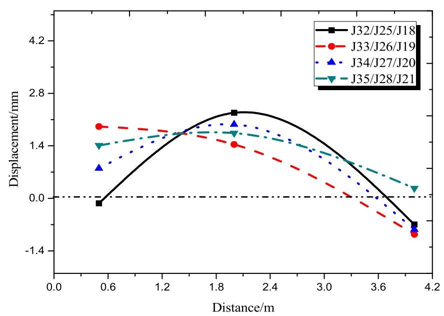


FIGURE 12. **The relationship between and distance from the sidewall and vertical deformation of the surrounding surface after excavation is completed.**

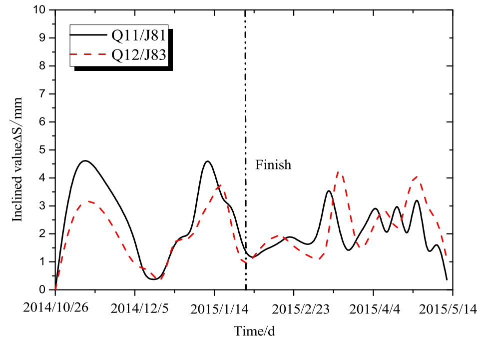
The relationship between the vertical deformation of the ground surface and the distance from the side wall of the foundation pit after the excavation of the four sections is plotted in Figure 12. It can be concluded that the ground surface deformation around the rock foundation pit is quite different from that of a soil foundation pit. Settlement generally occurs around the soil foundation pit, while the ground surface adjacent to the rock foundation pit first deforms vertically upward, peaks and then transitions to downward deformation with an increase in distance from the side wall. Positions relatively far from the side wall show settlement, which is similar to the ground deformation surrounding the soil foundation pit.

D. MONITORING AND ANALYSIS OF IMPACT ON ADJACENT HIGH-RISE BUILDINGS

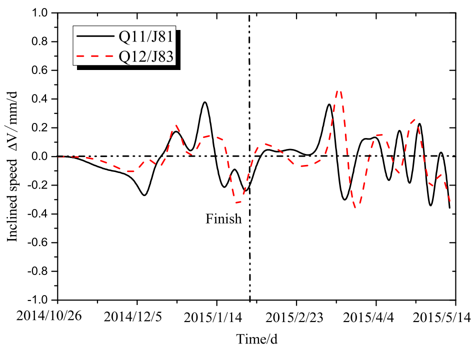
1) INCLINATION MONITORING AND ANALYSIS OF ADJACENT BUILDINGS

The Anda Building is selected as the object for studying the inclination of the surrounding buildings. Monitoring data from measuring points QX11/J81 and QX12/J83 near the Anda Building are used to draw the charts of inclination value and inclination change rate in Figure 13. During the excavation and construction of the foundation pit, the inclination of the Anda Building gradually increases to a peak value of about 4.5 mm during the first quarter of the construction period, then begins to decrease and then increases again after its first trough. After excavation has finished, the inclination value of the building remains basically stable due to the poor plastic fluidity of the rock foundation pit.

During the excavation of the foundation pit, the change in the rate of building inclination occasionally increases or decreases, but it always meets the specified requirement

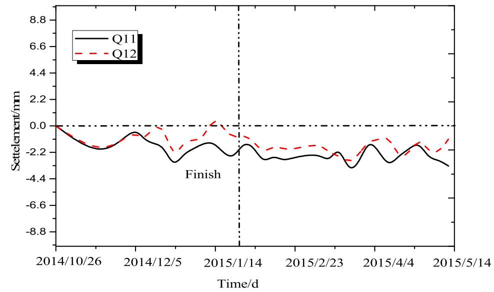


(a)Inclination

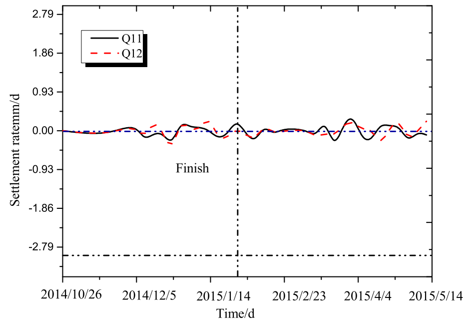


(b)Inclination change rate

FIGURE 13. Inclination- time curves for Anda building.



(a) settlement



(b) settlement rate

FIGURE 14. Settlement of the foundation pit of the Wengda and Ping'an mansion.

that the inclination change rate should be less than 0.1H/1000mm/d.

2) FOUNDATION SETTLEMENT ANALYSIS OF ADJACENT BUILDINGS

The foundation settlement of adjacent buildings is key to foundation pit monitoring. Data from monitoring points QX11 and QX12 were used to determine the settlement value and settlement change rate of the foundation of the Anda Building, as shown in Figure 14. This settlement increases gradually during the excavation of the foundation pit. The maximum value, 2.5 mm, occurs when excavation is half completed. During the later excavation of the foundation pit, settlement of the building's remains basically stable at its peak level, which is less than the settlement warning value of 10–60 mm set in the monitoring specifications for the foundation pit. The maximum settlement rate of the foundation is 0.5 mm/d, which is also less than the standard early-warning value, 3 mm/d.

E. ANALYSIS OF INTERNAL FORCE

The internal forces in a plate-ribbed anchor retaining wall in the Fengjing area are analyzed by way of the internal force and stress of retaining walls and the anchor stress, as shown in Figure 15. Figures 15 (a) and (c) show that the internal forces of slab-ribbed retaining walls increase gradually with foundation pit excavation and then gradually stabilize from the second stage of excavation onwards. The force reaches its highest value, 17 kN, at point LQ64. According to the distribution of monitoring points LQ64, LQ65 and LQ66, the internal force of the retaining wall becomes larger with an increase in depth. Except for monitoring point DT32, the earth pressure on the retaining wall fluctuates significantly, and remains at 0.0005 MPa. This is mainly because measuring points DT29, DT30 and DT31 are buried shallowly and are strongly influenced by other external factors. The stress at monitoring point DT32 increases gradually with the excavation of the foundation pit, and a higher level of stress is maintained. Therefore, the monitoring results for the deep internal force on the wall are reliable and can reflect the actual stress condition of the wall. More attention should thus be paid to the change in deep internal force during monitoring. Figure 15 (b) indicates that the internal forces of bolts increase gradually with foundation pit excavation and are likely to continue to increase after its completion. Therefore, more attention should be paid to change in the internal force of the bolts in the later stage. At the same time, the internal forces of the supporting structure are not stable and show an increasing trend.

Unlike soil foundation pit, the deformation of rock foundation pit is difficult to predict. A specific monitoring system need to be established and to analyze the deformation data. Additionally, for rock foundation pit, the internal force of retaining wall is most important, because when displace of side wall keep stable, but the internal force continue to increase, And the foundation pit is not safety. Therefore, the change of internal force should be warning index.

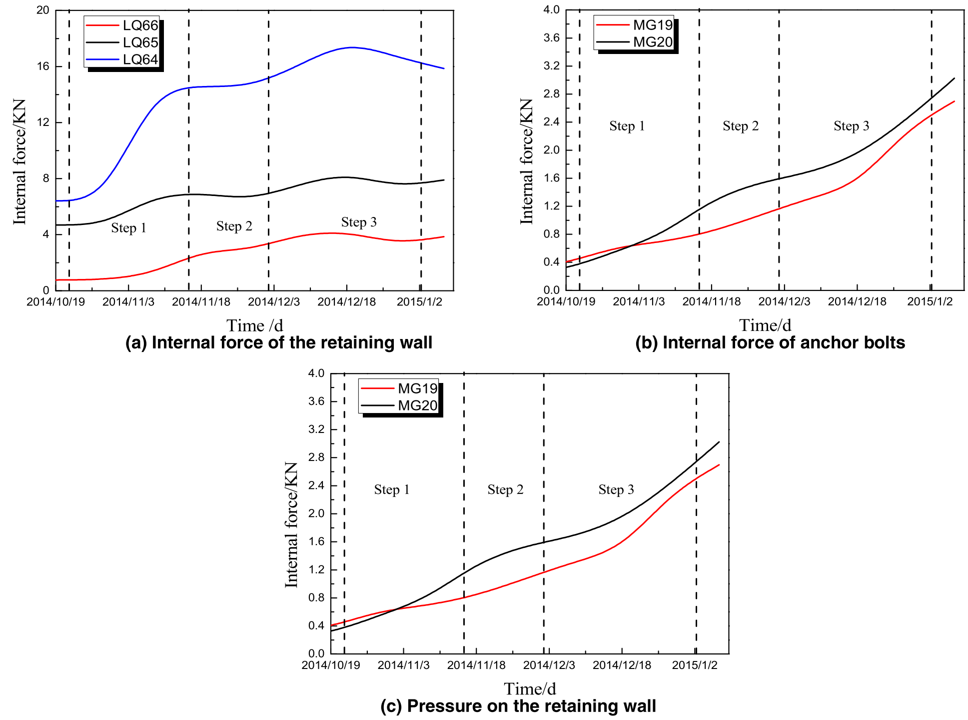


FIGURE 15. Internal force–time curves for the anchor rod retaining wall.

VI. CONCLUSIONS

A safety monitoring system for deep foundation pits and adjacent buildings has been developed that enables basic information management, data collection, and management, processing and analysis of the deformation in and around a foundation pit, including by way of a powerful three-dimensional visualization function. This system is of great benefit for the efficient construction of foundation pits.

(1) Deep foundation pit projects have the characteristics of a deep excavation depth and a large scale. To ensure the successful excavation of such pits, a complete monitoring scheme is designed, and deformation monitoring of the foundation pit side wall, inclination monitoring of adjacent high-rise buildings and stress monitoring of anchors are carried out.

(2) A multi-functional and efficient monitoring information management system for deep foundation pits is developed through a detailed study of the necessary data collection, management, processing and analysis functions and implementation of a superior three-dimensional visualization function.

(3) The deformation of the side wall and the surrounding surface, the inclination of adjacent buildings and the internal force of a ribbed-plate anchor retaining wall as revealed by the monitoring data are analyzed in detail. It is concluded that the deformation of the foundation pit in the Fengjing area has been basically stable during excavation, but the internal force of the supporting structure has seen an increasing trend.

(4) The excavation of a foundation pit is a dynamic process. Quantitatively predicting the development trend of a foundation pit and providing a scientific basis for adjusting the foundation pit support scheme on the basis of existing data is a new requirement for foundation pit monitoring information management systems. In future research, a prediction function should be added in order to improve the system.

(5) The monitoring management system has successfully applied in the railway foundation pit, but deformation warning function does not consider and corresponding supporting method need to be designed. In the future, those functions will add in this system.

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