Investigation on applied automatic monitoring of deep foundation-pit projects

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Abstract. A deep foundation-pit project in Shenzhen is studied for the application of automatic monitoring in the construction of deep foundation pit. Based on the analysis results of a three-dimensional finite element model implements with the MADIS GTS software, nine monitoring items and 59 automatic monitoring points are arranged in the key areas of the foundation pit, to monitor in real time the pit-top horizontal displacement, pit-top settlement, column pile settlement, groundwater level, horizontal displacement of deep layer, axial force in the supporting structure, anchor-cable stress, and settlement and cracks of the surrounding buildings. Based on the results of automatic monitoring, the patterns of variation are discussed of the data of the monitored items, and the accuracy and data stability are analyzed of the monitoring sensors such as measuring robot, hydrostatic level and crack gauge. The results show that: the key areas of automatic monitoring determined by the three-dimensional finite element model are in good agreement with the actual situation on site; Under the given conditions, the sensors such as measuring robot, hydrostatic level and crack gauge can meet the required monitoring accuracy, and the measured data has high stability; in addition, the sensor value is closely related to the ambient temperature. These results can provide reference for similar projects.

1. Introduction

At present, with the increase of the scales of buildings, the excavation depths of foundation pits keep rising with more varieties of supporting forms and demanding increasingly higher safety requirements, imposing challenges to the reliability and automation of safety monitoring during the construction of deep foundation pits[1-3]. At home and abroad, studies have been conducted on the automatic monitoring and early warning[4-9], building information modelling (BIM) [10-12], and visualization technology for the safe construction of underground spaces such as urban rail transit projects and building projects, and preliminary monitoring and early warning systems have been established for underground and deep foundation pit projects.

Traditional monitoring methods are greatly affected by the environment, personnel, weather and other factors; the monitoring efficiency is low and the monitoring data is lagging behind and cannot reflect the safety status of deep foundation pit project in time. These methods cannot be used to realize the automation, visualization and informatization tasks for safety monitoring in the construction of deep foundation pits. In addition, the current monitoring and early-warning platforms for deep foundation pit can only automatically collect individual index parameters.

With the gradual improvement of technologies related to automatic monitoring systems, such systems have been more and more applied in the monitoring of urban deep foundation-pit projects.
They can effectively overcome a variety of adverse factors in foundation-pit monitoring, and can efficiently and stably carry out real-time monitoring[13-14]. However, at present, clear specifications are lacking, including relevant guidance and implementation standards for monitoring urban deep foundation pits. Therefore, it is of great practical significance to demonstrate the reliability of an automatic monitoring system in monitoring urban deep foundation pits through practical applications.

2. Project case study

2.1. Project overview

The deep foundation-pit project in this study is located in the northwest of the intersection of the Yiyuan road and Zhengyun road in Nanshan District, Shenzhen. It is adjacent to the Yixue road in the north and to the Yuyuan Road in the West (see figure 1). The standard elevation of the bottom of foundation pit is 4.8-8.8 m, the perimeter is about 620 m, and the total area is about 15,800 m². The maximum excavation depth is about 12.2 m, and the safety level of foundation-pit supporting structures is grade I.

![Figure 1. Layout plan of automatic monitoring points of the foundation-pit project](image)

2.2. Design scheme of supporting structures

Considering the surrounding environment and geological conditions, the WB section on the east side of the foundation pit is supported by occluded pile combined with anchor cable. The rest sections are supported by occluded pile combined with internal support.

3. Computational model and results

3.1. Computational model

The Midas/GTS software is used for 3D finite-element modeling. The size of the model is 3 times larger than that of the foundation pit, and the length, width and height are 309, 271, and 31 m, respectively (309×271×31 m). The number of elements and nodes of the model are 243381 and 127448, respectively. The constitutive model of the soil in the model uses the Moore Coulomb model, the supporting piles are simulated with the plate units, the beam is simulated with the beam elements, and the prestressed anchor rod is simulated with the embedded truss element. The mesh division of the model and the layout of the supporting structures are shown in figure 2 and figure 3, respectively.
3.2. Parameters involved in computation
The computational parameters are determined based on the report of geological exploration, and they are listed in Table 1.

| Litholoty            | Modulus of Elasticity/MPa | Internal friction angle/° | Cohesion/kPa | Poisson's ratio |
|----------------------|---------------------------|---------------------------|--------------|-----------------|
| Artificial fills     | 4.5                       | 12                        | 6            | 0.37            |
| Organic gravel sand  | 11                        | 28                        | /            | 0.35            |
| Coarse sand          | 18                        | 30                        | /            | 0.32            |
| Gravel clay          | 23                        | 23                        | 24           | 0.30            |

3.3. Computational results
When the foundation pit is excavated to the bottom of the pit, the deformation cloud map of the foundation pit with supporting structure is shown in figure 4. Under this condition, the maximum deformation of the foundation pit is 38.63 mm, which occurs on the southeast side of the foundation pit. The maximum axial force of the supporting structure is 6,321 kN, located at the northeast corner brace, and the maximum bending moment of the supporting piles is 983 kN.m.

The deformation cloud map of the foundation pit without supporting structure is shown in figure 5. Under this condition, the maximum deformation of the foundation pit is 41.05 mm, which occurs on the southeast side of the foundation pit. The maximum bending moment of the supporting piles is 1,032 kN.m.
Next consider the actual construction process at this stage, when the southeast corner of the foundation pit has not been constructed yet. The calculation results demonstrate that the maximum deformation occurs at the supporting pile section near a surrounding school. Under the two working conditions, the deformations are 28.40 mm and 28.89 mm. The second largest deformation occurs at the WA section of pile-anchor support on the east side of foundation pit, and the deformations are 24.86 mm and 25.10 mm under the two working conditions.

Figure 4. Deformation cloud map of the supporting structure when excavating to the bottom of the foundation-pit

Figure 5. Deformation cloud map of the supporting structure after removing the two supports
4. Automatic-monitoring scheme and results

4.1. Automatic-monitoring scheme

Based on both supporting structure and numerical simulation results, the pile-anchor supporting section on the east side and the pile supporting section on the north side of the foundation pit are selected as the monitoring objects, and the monitoring content and number of automatic monitoring points are shown in Table 2. At the same time, the UAV tilt photography is used to construct a 3D model for correlating the monitoring points, as shown in figure 6.

Table 2. Automatic monitoring points and alarm value.

| Serial number | Icon | Monitoring content                           | Monitoring points | Control value |
|---------------|------|---------------------------------------------|-------------------|---------------|
| 1             | 🛠   | Pit-top horizontal displacement             | 11                | 30 mm         |
| 2             | 🛠   | Pit-top settlement                          | 11                | 20 mm         |
| 3             | 🛠   | Column pile settlement                      | 6                 | 35 mm         |
| 4             | 🛠   | Groundwater level                           | 3                 | 3000 mm       |
| 5             | 🛠   | Horizontal displacement of deep layer       | 2                 | 50 mm         |
| 6             | 🛠   | Axial force in the supporting structure     | 8                 | 6325 kN        |
| 7             | 🛠   | Anchor-cable stress                         | 1                 | 504 kN         |
| 8             | 🛠   | Settlement of the surrounding buildings     | 11                | 15 mm         |
| 9             | 🛠   | Cracks of the surrounding buildings         | 1                 | 3 mm          |

Figure 6. Oblique photography 3D model of the foundation-pit
4.2. Results
The automatic-monitoring equipment involved in this study had been installed by the middle of October, 2019, and the debugging was completed in November. The monitoring data obtained from November 27, 2019 to January 20, 2020 is analyzed in this study.

Figure 7 shows the cumulative variation of the horizontal displacement at the pit top. Figure 8 shows the cumulative settlement variations at the pit top and of the column pile. Different monitoring points are indicated by different colors. In the past monitoring reports, the cumulative changes of displacement and settlement usually show a gradual increase trend, while in the automatic-monitoring a fluctuating growth trend is found. In addition, 100 percent of the daily horizontal displacement variation data are within ± 2 mm, and 98.10 percent of the daily settlement change data are between ± 0.9 mm.

Figure 9 shows that the maximum rate of variation of horizontal displacement W4 is located in the middle of the QR section of the supporting piles near the school, and the amount is 2.60 mm/d. Figure 10 shows that the maximum rate of variation of settlement LZ12 is located at the column at the northeast corner of the foundation pit, and the amount is -1.19 mm/d.

The maximum variation of cumulative displacement W9 of 2.85 mm is located in the middle of the TU section on the north side of the deepest location in the foundation pit. The largest cumulative settlement change is located at the W12 point in the middle of the WA section on the east side of the foundation pit, and the amount is -3.65 mm, which is consistent with the actual situation on site.
The hydrostatic levels used to measure the settlement of surrounding buildings are set at the corners around the school building. Because the hydrostatic level is affected by the air temperature, the data collected by a sensor at the same monitoring point within 24 hours on different days are selected, and the variations of data with the temperature are shown in figure 11. The variations of the data collected by sensors at different monitoring points on the same day with the temperature are shown in figure 12. From 8:00 to 18:30, the data collected by the sensors change with the increase of temperature, so the data collected from 18:30 every day to 8:00 on the next day are extracted for analysis. For the convenience of statistics, take the data at 0:00 every day. During the monitoring period, the trend of variation is relatively flat of the cumulative settlement of surrounding buildings, and the largest change of -3.25 mm is located at the X002 point near the middle of the RS section of supporting piles, as shown in figure 13. For 99.67% of the data of daily settlement change, the range of variation is ± 1.0 mm. The maximum settlement rate is located at the X005 point near the middle of the QR section of supporting piles, and the amount is -1.30 mm, which is consistent with the result of finite element analysis, as shown in figure 14.
Three water level points are arranged in the foundation pit to observe the effect of the water-stop curtain: the SW5 point on the north side of the foundation pit, the SW4 point at the exterior side of the northwest corner of the foundation pit and the SW3 point on the west side of the foundation pit. The monitoring results are shown in figure 15. During the monitoring period, the variation of water level does not surpass ± 0.5 m.

The points for monitoring axial force ZL9-ZL10, ZL11-ZL12, and ZL13 are arranged in the first, third and fifth bracing of the QRS section of foundation pit, respectively. Among them, the axial force of the first brace is similar to that of the third truss, ranging from 2033.12 kN to 3877.31 kN, both greater than that of the fifth truss, which is in the range of 556.05 kN- 1307.47 kN. The ZL18 point is arranged at the northeast corner brace of the foundation pit, and the axial force is in the range of 2532.28 kN - 3418.95 kN. The monitoring results are shown in figure 16. During the monitoring period, the maximum axial force of 3877.31 KN occurs at the ZL11 point.
5. Conclusions

(1) The three-dimensional finite element model can well simulate the areas with large deformation and stress in the foundation-pit project. The simulation results are in good agreement with the actual situation on site, so they can provide reference for the selection of critical regions to arrange automatic-monitoring points.

(2) The measuring robot can monitor the horizontal displacement of pit top and settlement within 100 m; in this monitoring range, it can meet the required monitoring accuracy and the monitoring data has high stability. The hydrostatic level has high accuracy, but it is greatly affected by environmental factors; the measured value is positively correlated with the air temperature, so the data collected from 18:30 to 8:00 of the next day are used for analysis, which can meet the required accuracy of on-site monitoring and have high stability. The error of the crack meter is about 0.1 mm, and the measured value is inversely correlated to the air temperature. The replacement of manual reading with water-level gauge and stress-acquisition module promotes the realization of real-time, effective monitoring.

(3) Fully automatic monitoring of deep foundation-pit projects can realize automatic data collection, transmission, processing and releasing for a number of key monitoring tasks of the projects. The comprehensive use of high-precision monitoring sensors can effectively reduce the labor cost, obtain accurate real-time data to guarantee the safe construction of foundation pits.

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