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Monitoring and finite element analysis of deep horizontal displacement of foundation pit enclosure pile of a subway transfer station during construction

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***Abstract*—Based on the foundation pit construction of a subway transfer station, this article focuses on studying the deep horizontal displacement and deformation law of retaining piles during foundation pit excavation, so as to accurately evaluate the safety state of foundation pit excavation. Therefore, a deformation monitoring for the deep horizontal displacement of the foundation pit pile during the whole construction process, and the excavation process is numerically simulated by using finite element analysis. The findings show that when the foundation pit keeps working down, the position of the maximum deep horizontal displacement of the pile also keeps moving down; when the foundation pit is excavated to the design height, the deformation curve of the deep horizontal displacement of the pile along the pile depth presents the characteristics of "big belly". At this time, the maximum deep horizontal displacement mostly appears in the middle and lower parts of the pile. The measured maximum deep horizontal displacement value of each pile body did not exceed the limit value, indicating that the foundation pit excavation is in a safe state during the construction process.**

Key word-Foundation pit excavation; Deformation monitoring; Numerical simulation; Safety state

I.Introduction

The complex construction environment brings a lot of inconvenience to the foundation pit excavation of subway station, but also increases the risk of subway foundation pit construction. Therefore, the deformation and stability of foundation pit retaining structure has become one of the key issues of subway construction safety[1-4].

Foundation pit construction is seriously affected by comprehensive factors such as groundwater level, pipe network, surface buildings and road traffic[5-8]. Therefore, the deformation monitoring of foundation pit retaining structure during the construction of subway station can play an effective role in ensuring the safety of the construction itself and the surrounding environment. Foundation pit deformation monitoring has become an indispensable part of subway construction[9-12].

This paper takes the foundation pit construction of a subway transfer station in Shenyang as the engineering background to carrie out the whole process deformation monitoring of maintenance pile structure during the process of foundation pit construction. The numerical simulation of the whole construction process is carried out in combination with the finite element method, and the foresight of the finite element method provides a reliable basis for making scientific construction scheme and decision-making[13-14].

II.Project overview

The foundation pit plane of the subway transfer station is in a "T" shape, in which the excavation depth of the foundation pit in the north-south direction is about 23.75m and the width is about 22.7m. The construction shall be carried out first according to the planning requirements. According to the sequence of foundation pit operation, the foundation pit excavation is divided into five stages. The specific construction contents of each stage are shown in Table 1.

Tab.1 Construction content table for each stage

Construction conditions	Construction content
Condition 1	Excavate the first layer of soil to -1.90m;
Condition 2	Erect the first steel support at -1.50m and excavate the second layer of soil to -7.90m;
Condition 3	Erect the second steel support at -7.40m and excavate the third layer of soil to -13.70m;
Condition 4	Erect the third steel support at -13.2m and excavate the fourth layer of soil to -19.20m;
Condition 5	Erect the fourth steel support at -18.70m and excavate the fifth layer of soil to -23.75m.

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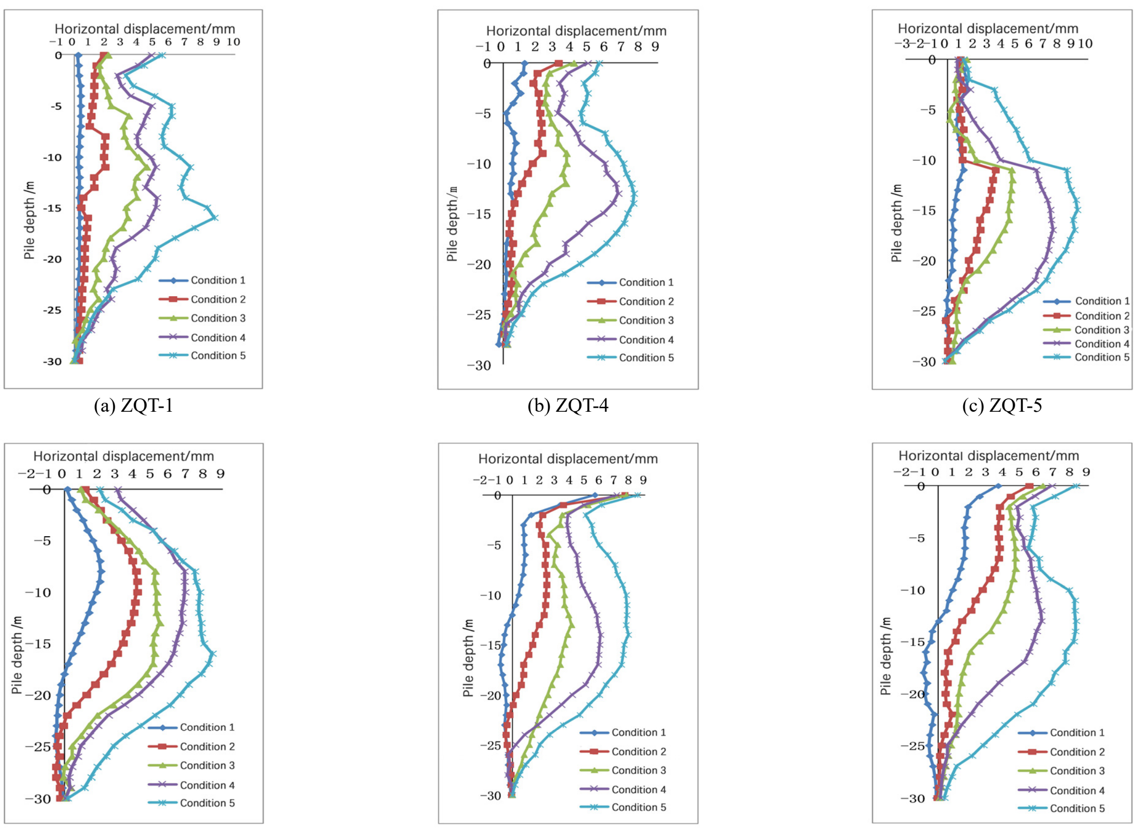
The layout of measuring points is based on the requirements of relevant specifications, and the representative pile in the foundation pit maintenance structure is taken as the monitored object. According to the volume of foundation pit, a total of 9 monitoring points are set, and the hole spacing is maintained between 20 ~ 40m. The number of monitoring points is represented as ZQT-x (X represents "monitoring hole number", for example, ZQT-1 represents "No. 1 enclosure pile inclination monitoring hole").

III.Monitoring data analysis

A.Analysis of deep horizontal displacement characteristics of pile body during foundation pit excavation

Continuous monitoring is carried out for each measuring point to obtain the relationship curve of deep horizontal displacement of pile under various working conditions, as shown in Fig.1 (The space is limited, and only the data of measuring points 1, 4, 5, 7, 8 and 9 are obtained). The curve characteristics in the figure are analyzed as follows: at the initial stage of foundation pit excavation (condition 1), the excavation depth is shallow, and the horizontal displacement of most piles towards the pit is not large, and the deep horizontal displacement of piles occurs in the middle and upper part of piles; the horizontal displacement of pile top retaining wall of ZQT-8 and ZQT-9 is obvious, and the displacement of ZQT-7 is obvious at the elevation of -8m. When the soil is excavated to the second layer (condition 2), the horizontal displacement developed from the upper part of the pile to the pit increases to a certain extent; the displacement of the middle and upper part of the pile body of ZQT-7 increases obviously, and the horizontal displacement of the pile top of ZQT-8 and ZQT-9 is still larger than that of other measuring points. When the soil is excavated to the third layer (condition 3), the deep horizontal displacement in the middle of each pile increases obviously, the curve with the change of pile height presents the characteristics of "big belly", and the position of the maximum horizontal displacement of a single pile moves downward；at this time, steel support shall be erected in time to delay the horizontal displacement of each pile to the foundation pit and ensure safety. When the soil is excavated to the fourth and fifth layers (working conditions 4 and 5), the variation trend of the horizontal displacement of each pile along the height is basically the same, and the "big belly" feature of the horizontal displacement of the pile along the height is more obvious; at this time, the maximum deep horizontal displacement of each pile appears in the middle and lower part of the foundation pit, and the horizontal displacement of the pile root is very small due to the constraint of soil.



(a) ZQT-1 (b) ZQT-4 (c) ZQT-5

(d) ZQT-7 (e) ZQT-8 (f) ZQT-9

Fig.1 Deep horizontal displacement diagram of pile at each measuring point

It can be seen from the data in the Fig.1 that the maximum horizontal displacement of each pile is between 7 ~ 10mm, which is less than the early warning value of horizontal displacement of pile. It shows that the foundation pit construction and support scheme is reasonable, and the foundation pit maintenance pile structure is in a safe and controllable state. The maximum horizontal displacement of all piles occurs at the elevation of -13 ~ -18m, about the middle of the pile.

B.Analysis of the key parts of each pile body

In order to more intuitively understand the overall horizontal displacement of the foundation pit in the excavation process, the pile horizontal displacement of six horizontal planes such as pile top, elevation -2m, elevation -8m, elevation -14m, elevation -18m and elevation -24m is analyzed as a whole. Expand the measured data by 1000 times to draw the overall displacement of the foundation pit contour of each standard high-rise, as shown in Fig.2.

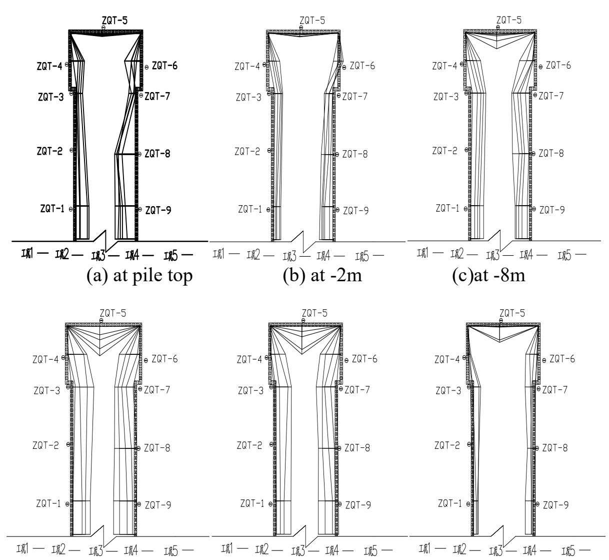
The analysis of Fig.2 shows that: at the high level of pile top elevation, the displacement at measuring points ZQT-6,ZQT-8 and ZQT-9 on the right side of foundation pit is large; according to the analysis, the soil layer at this location is mostly miscellaneous fill with poor compactness, frequent traffic of construction vehicles and stacking load; under the action of the above factors, the soil produces large compression deformation, resulting in obvious lateral displacement of the retaining wall at the top of the pile; ZQT-7 has obvious deformation in the middle and upper part of the pile in the early stage of foundation pit excavation, which is due to the large stress in the early stage of excavation because the measuring point is located at the enlarged end corner of the foundation pit; in the middle and late stage of foundation pit excavation, the maximum horizontal displacement of each pile deep layer occurs within the elevation range of -13 ~ -18m, that is, the middle of the pile and the middle and lower part of the foundation pit; at this time, within this elevation range, the deep horizontal displacement level of each measuring point is equal, which indicates that the soil in the foundation pit is under uniform stress and the excavation process is in a safe state.

Combined with the measured data, the following guiding opinions are put forward for the construction: (1) during the excavation of foundation pit, the surrounding surcharge, especially the weak parts, shall be minimized; (2) The erection of steel support shall be timely to reduce the exposure time of foundation pit without transverse support, especially after 1 / 3 of the design elevation of foundation pit excavation; (3) not only pay attention to the cumulative value of displacement of measuring points, but also pay attention to the rate change of data. In practical engineering, the two parameter deformation control method of total target value control and change rate control should be adopted.

IV. Numerical simulation analysis

According to Saint Venant's principle and previous construction experience, the influence range of foundation pit excavation is about 3 ~ 4 times of the excavation depth of foundation pit, and the influence depth is about 2 ~ 4 times of the excavation depth. Therefore, the size of the finite element model is 140m long, 130m wide and 60m deep, the numerical calculation model is shown in Fig.3 and Fig.4. The overall spatial deformation data of each stage in the process of foundation pit excavation are obtained by numerical calculation, and compared with the measured results.

Three measuring points ZQT-1, ZQT-4 and ZQT-5 are selected for comparative analysis. The deformation curve of deep horizontal displacement of pile along pile depth of these three measuring points is shown in Fig.5.Compared with the displacement changes corresponding to Fig.1 (a), (b) and (c), it can be seen that the characteristics of the numerical calculation curve are very similar to the measured curve. In the numerical calculation, in the initial stage of foundation pit excavation (condition 1), the horizontal deformation of the pile is mainly in the middle and upper part. Then (working conditions 2 ~ 5), the position of the maximum horizontal displacement in the deep layer gradually moves down to the middle of the pile, and the numerical curve shows a typical "big belly" feature. The increase of the maximum horizontal displacement of the numerical calculation curve in the later stage of foundation pit excavation (working conditions 4 ~ 5) is not obvious, only the position of the maximum horizontal displacement moves downward. The maximum displacement in numerical calculation is obviously less than the measured value: the maximum horizontal displacement of ZQT-1 numerical simulation result is 6.8mm, while the measured maximum value is 8.71mm; the maximum horizontal displacement of ZQT-4 numerical simulation results is 5.82mm, and the measured maximum value is 7.60mm; the maximum horizontal displacement of ZQT-5 numerical simulation results is 8.57mm, and the measured maximum value is 9.24mm. The reasons are as follows: the looseness of soil in the actual construction process, the untimely application of steel support preload, the surcharge around the foundation pit and passing vehicles, etc. But, the overall law of numerical simulation results is consistent with the measured data, which can not only check the monitoring data, but also use the foresight of numerical simulation to prevent and control unknown risks.



(a) at pile top (b) at -2m (c)at -8m

(d) at -14m (e) at -18m (f) at -24m

Fig. 2 Horizontal displacement diagram of pile at different elevations

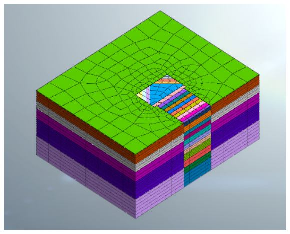


Fig. 3 Foundation pit excavation model

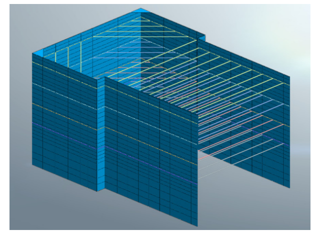
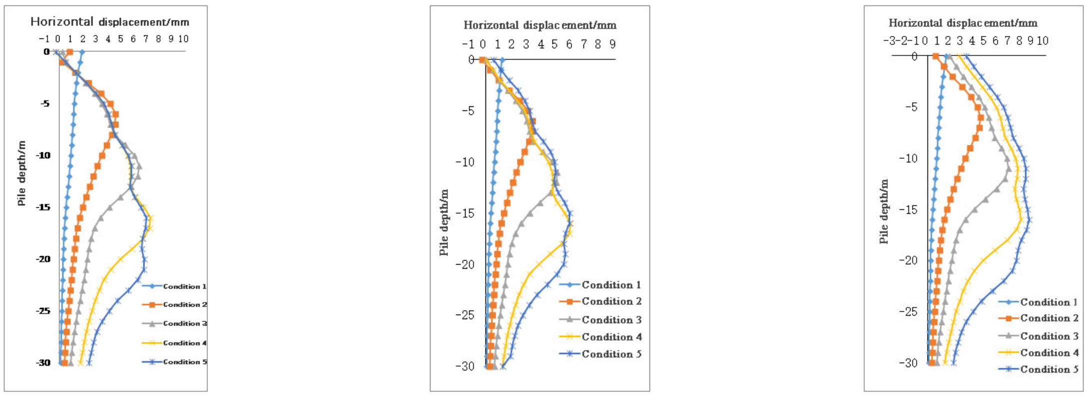


Fig. 4 Foundation pit enclosure structure model



(a) ZQT-1 (b) ZQT-4 (c) ZQT-5

Fig.5 Numerical calculation results of the variation of deep horizontal displacement with pile height of ZQT-1, ZQT-4 and ZQT-5

V. Conclusion

Based on a transfer station of Shenyang Metro, through the measured data analysis and numerical simulation calculation of the deep horizontal displacement of the foundation pit pile, the following conclusions are obtained:

(1) With the increase of excavation depth, the maximum horizontal displacement of the pile will gradually move downward. When the foundation pit is excavated to the design elevation, the deformation curve of the deep horizontal displacement of the pile with the depth of the foundation pit presents the characteristics of "big belly", and the maximum deep horizontal displacement of the pile appears in the middle of the pile.

(2) The measured maximum horizontal displacement of each pile does not exceed the limit value. Therefore, the foundation pit is in a safe state during construction.

(3) The field monitoring often lags behind the actual changes. The project establishes a numerical model to simulate the foundation pit excavation, and establishes an information construction scheme for simulation and monitoring, so as to guide the safe construction.

Acknowledgments

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