Discussion on Monitoring Method for Horizontal Displacement of Supporting Pile Top of Deep Foundation Pit in Urban Rail Transit Project

Yiteng Xu*, Fanglong Yuan, Dayong Wang, Zhifa Yu, Lixin Li

1 Tianjin Port Engineering Institute Co., Ltd. of CCCC First Harbor Engineering Co., Ltd., Key Laboratory of Geotechnical Engineering, Ministry of Communications, Key Laboratory of Geotechnical Engineering of Tianjin, Tianjin 300222, China;
2 CCCC First Harbor Engineering Co., Ltd., Tianjin 300461, China;
*Corresponding author’s e-mail: 18710804642@163.com

Abstract. The horizontal displacement monitoring of the supporting piles plays a vital role in the safety judgment of deep foundation pit excavation and construction of main structure. In urban rail transit engineering, the monitoring of horizontal displacement of retaining pile top of deep foundation pit should be carried out according to the characteristics of the project, formulated a scientific monitoring plan, and selected a reasonable monitoring method. If necessary, the monitoring methods should be optimized and integrated, so as to get the real and effective monitoring data, which can reflect the change of the horizontal displacement of the foundation pit support structure to the greatest extent. By analyzing several common methods of deep foundation pit monitoring in current urban rail transit projects, the advantages and disadvantages of each method are summarized, and reasonable suggestions are proposed for accurate monitoring.

1. Introduction
The horizontal displacement monitoring of the supporting pile top is an important item in the monitoring of deep foundation pits in urban rail transit projects. At present, there are many methods for monitoring the horizontal displacement of the top of the supporting pile provided by the monitoring technical specifications, and the requirements for the layout of the horizontal displacement monitoring of the top of the supporting pile are becoming more and more specific [1][2]. There are many scholars have put forward new ideas and theories on the method of monitoring the horizontal displacement of the top of supporting piles in deep foundation pits. However, for specific field operations, the monitoring personnel usually choose a method to monitor randomly based on their existing experience, ignoring the disadvantages and limitations of the monitoring method, resulting in the monitoring data collected for a long time cannot reflect the change of foundation pit effectively. The construction of urban rail transit projects is in full swing, and the safety monitoring work of the project has been paid more and more attention by management departments at all levels. It is especially important to obtain real and reliable monitoring data [3]. However, how to formulate a scientific and reasonable monitoring plan and which effective monitoring methods should be adopted urgently need to be solved. There are many monitoring methods for the horizontal displacement of support pile top. This paper compares and analyzes several monitoring methods for the horizontal
displacement of support pile top, summarizes the advantages and disadvantages of each method, and the benign suggestions for monitoring horizontal displacement of support pile top are given.

2. The purpose of monitoring the horizontal displacement of the pile top in deep foundation pit
The supporting structure of deep foundation pits in urban rail transit projects generally uses supporting piles or retaining walls. At present, the excavation depth of deep foundation pit is deeper and deeper, and the structure is more and more complex. The horizontal displacement monitoring of support pile top is mainly to understand the deformation of foundation pit in the process of earthwork excavation and main structure construction. During the earth excavation process, as the soil inside the foundation pit is largely removed, the supporting structure is deformed under the action of external earth pressure, while the horizontal displacement of the top of the retaining structure is an intuitive reflection of the deformation of the retaining structure. This is an important monitoring project in the safety monitoring of deep foundation pit construction. For some deep foundation pits, when the penetration depth of the supporting structure is insufficient or there is a disturbance at the bottom of the supporting structure, the calculation data of the deep lateral displacement monitoring of the supporting structure has a large error. And the monitoring personnel need to correct the monitoring data of the deep lateral horizontal displacement of the support structure through the monitoring data of the horizontal displacement of the pile top. Therefore, scientific monitoring program and reasonable monitoring means are crucial to the horizontal displacement monitoring of support pile top. Accurate and effective monitoring data can truly determine the change of support structure, so as to guide the safe construction of urban rail transit project reasonably and avoid accidents.

3. Monitoring method of horizontal displacement of support pile top

3.1. Laser distance measurement
The laser ranging method uses a laser rangefinder to measure the horizontal displacement of the top of a supporting pile in a deep foundation pit. This method first installs the horizontal displacement monitoring point at the top of the supporting pile on the same horizontal section of the crown beam of the foundation pit. One end is the measurement site of the fixed laser rangefinder, and the other end is the target point to be measured. The laser range finder uses a laser transceiver module to measure the distance between two measuring points, and the measuring distance range is 1 ~ 5m. The laser rangefinder supports manual measurement mode and automatic measurement mode. When the manual measurement mode is used, the measurement button is separated from the laser ranging module to ensure that there is no slight shaking or movement of the device during measurement. When the automatic measurement mode is adopted, the monitoring frequency can be adjusted according to the needs of monitoring work. The laser point-pointing device only needs to conduct angle rough adjustment, locking and fine adjustment on the plane and facade to achieve accurate point-pointing. As shown in the figure, A and I are a group of monitoring points for horizontal displacement of support pile top.

![Figure 1 Schematic diagram of laser distance measurement](image)

The advantages of the laser ranging method: it can directly and accurately measure the relative change of the horizontal displacement monitoring point on the top of the supporting pile on the same horizontal section, and the monitoring efficiency is high; meanwhile, the workload is small and the monitoring input cost is low. Disadvantages of the laser ranging method: the absolute change of a single monitoring point A and B cannot be obtained, and the horizontal displacement monitoring data
of the supporting pile top cannot be used to modify the monitoring data of the horizontal displacement of the supporting pile body. At the same time, it is necessary to arrange the monitoring points to ensure that the monitoring points are on the same horizontal section, otherwise the laser rangefinder cannot directly observe.

3.2. Polar coordinate method

The principle of the polar coordinate method is to establish a polar coordinate system based on two reference points. By observing the sum of the distance between the monitoring point and the measuring station on the working base point, and the angle between the direction and the line connecting two known points, and the coordinates of deformation monitoring are calculated directly[4]. According to the evolution of polar coordinate method, the following methods are formed:

(1) Method of coordinate observation

When the total station is used to directly monitor the horizontal displacement of the support pile top by utilizing the construction measurement coordinates in urban rail transit engineering, the reference point for horizontal displacement monitoring should not be less than 4 points. It is advisable to set a mandatory centering observation pier to reduce alignment error of the total station. The total station measurement adopts the method of rear-view orientation or rear crossing, and sequentially measures the horizontal displacement monitoring points at the top of the supporting pile, and adopts positive inverted mirror and multiple measurement to measure X and Y coordinate values.

Advantages of the coordinate observation method: The monitoring reference point can directly use the construction measurement control point. The monitoring unit does not need to separately set the reference point. At the same time, coordinate values of X and Y direction of each monitoring point for horizontal displacement of support pile top can be directly obtained by using construction measurement coordinates. Provide real and effective parameters for later data processing, the direct use of the construction measurement coordinate system for monitoring reduce the field workload of the monitoring staff. Disadvantages of the coordinate observation method: Because the sides of a deep foundation pit are not necessarily parallel or perpendicular to the X and Y axes of the construction measurement coordinate system, the X and Y direction variables obtained by monitoring cannot directly reflect the change of displacement perpendicular to the side of the foundation pit. Therefore, it is necessary to introduce a parameter of a trigonometric function, which requires higher requirements for analysis and comprehensive judgment of monitoring data by internal staff. As shown in the figure, A, B, C and D are the monitoring points of horizontal displacement at the top of support pile.

![Coordinate observation method monitoring diagram](image)

(2) Method of coordinate transformation

On the basis of the coordinate observation method, secondary calculation processing is performed on the collected monitoring data. As shown in Figure 3, A, B, C, and D are monitoring points for the horizontal displacement of the top of the supporting pile, and DM1, DM2, and DM3 are corner points of the foundation pit, which are used to set the virtual segment surface. The monitoring points set in each straight section of the foundation pit should be divided into the same section plane. For example, A, B, C, D, etc. are in the range of DM1-DM2, and E and J are in the range of DM1-DM3. DM1-DM2 section can be expressed by the following linear equation:
The other edges are similar to orientation. The distance from the point to the virtual section is calculated as follows:

A \((X_A, Y_A)\) is a point on the DM1-DM2 section, and the distance from A to the alignment is:

\[
D_A = \frac{Y - Y_{DM1}}{X - X_{DM1}} + \frac{X_{DM2} - X_{DM1}}{1 + \left(\frac{Y_{DM2} - Y_{DM1}}{X_{DM2} - X_{DM1}}\right)}
\]

(2)

The coordinate conversion method converts the X and Y coordinates in the traditional sense into the distance from the point to the virtual segment surface line, and converts the X and Y coordinate variables into a distance variable. The distance variable can directly reflect the displacement change of the monitoring point. In particular, it should be noted that the virtual sections DM1-DM2 and DM1-DM3 should be selected inside the foundation pit, and ensure that all monitoring points are distributed outside the virtual section, so as to ensure that the sign of displacement change of all monitoring points is positive, indicating the displacement of the point to the direction of outside of the foundation pit, otherwise the symbol definition of displacement change of monitoring points should be described separately.

Advantages of the coordinate conversion method: Regardless of whether the long and short sides of the deep foundation pit are parallel to or perpendicular to the X and Y axes of the metro measuring coordinate system, the X and Y variables obtained from the monitoring can be directly converted into the variable D perpendicular to the side of the foundation pit, which can intuitively reflect the change of the displacement of the top of the foundation pit supporting pile. Disadvantages of the coordinate conversion method: The indoor workload is increased, and indoor operators are prone to calculation errors during coordinate conversion, resulting in incorrect monitoring data.

Figure 3 Coordinate transformation monitoring diagram

(3) Method of Virtual coordinate system

The virtual coordinate system method adopts the principle of establishing an independent coordinate system, and sets an X axis along a direction parallel to the long side of the foundation pit and the Y axis perpendicular to the X axis direction to establish an independent coordinate system. The horizontal displacement monitoring points on the top of the supporting pile are directly observed by the method of total station back vision orientation or resection, and the X and Y coordinates are obtained according to the mode of forward and backward mirror multi survey. As shown in Figure 4, A, B, C, and D are monitoring points for the horizontal displacement of the top of the supporting pile. Since independent coordinate systems are established, for monitoring points in the long side direction of foundation pits such as A, B, C, and D, the change amount of the Y-axis coordinate value of the monitoring point is the change amount of the horizontal displacement of the supporting pile top at the measuring point. For the monitoring points in the short side direction of the foundation pit such as E, J, the change amount of the X-axis coordinate value of the monitoring point is the change of horizontal displacement of the support pile top of the measuring point.
Advantages of the virtual coordinate system: by establishing an independent coordinate system with the X-axis parallel or perpendicular to the long side of the foundation pit, the change of horizontal displacement of the support pile top of the monitoring point can be obtained accurately and directly, and the internal workload is less, which is convenient for checking the accuracy of data. Disadvantages of the virtual coordinate system method: Because the shape of the deep foundation pit is not necessarily completely rectangular, after the independent coordinate system is established, it cannot be guaranteed that all structural edges of the deep foundation pit can be parallel or perpendicular to the X axis of the coordinate system. Meanwhile, the symbol definition of change quantity of monitoring point should be strictly distinguished. For example, the change quantity of monitoring points such as A, B, C, D, and E is positive, indicating that the point is displaced outside the foundation pit; the change quantity of monitoring points such as F, G, H, I, and J is positive, indicating that the point is displaced into the foundation pit. In addition, because it is an independent coordinate system, it is difficult for the coordinate system to recover once multiple failures occur at the reference point.

3.3. Collimation method
The collimation method is to bury two working base points at both ends of the straight edge of the foundation pit. The working base point should be within the range not affected by the construction of the foundation pit, and the monitoring points should be arranged on the line connecting the two working base points. Set up the instrument on the work base point and look back at another work base point. Set the scoring reading target or T-shaped ruler on the monitored point, and directly read the scoring value d with the telescope of the instrument and the sign of d is determined according to the relationship between the point and the sight line.

The advantages of collimation method: less indoor work. Disadvantages of the collimation method: The requirements for the deployment of monitoring points are high. At the same time, due to the increase in the workload of the field, more personnel are deployed in the field.

3.4. The small angle measurement method
(1) The small angle measurement method
The small angle measurement method is to first determine a reference line parallel to the side of the foundation pit, and then use a total station to determine the angle between the reference line and the line of sight of the monitoring point, and the distance between the reference point and the monitoring point. The change value of the displacement of the monitoring point is calculated by measuring the Angle change. Advantages of measuring small angle method: high monitoring accuracy. Disadvantages of measuring small angle method: It is only applicable to the foundation pits with a regular shape. At the same time, due to the influence of monitoring accuracy, the monitoring point should not be too far away from the reference point. The narrow and long foundation pit is not suitable for this method.

(2) Single stop correction method
The single-station correction method is a method that combines the collimation line small angle method with the monitoring point setting method, which only requires the instrument to set the station
once, and calculates the displacement of all the monitoring points by adding the correction number. The advantages of the single-station correction method: to some extent, the distance limitation of small angle measurement is overcome. Disadvantages of the single-station correction method: the angle of the survey site must be observed every time, and the survey site must be corrected, which increases the workload of the internal and external industry and also increases the difficulty of burying monitoring points.

3.5. The method of corner intersection
The corner intersection method usually measures the angle between the known point and the monitoring point and then calculates the coordinates of the monitoring point. The corner intersection method is generally divided into the forward intersection method and the backward intersection method.

1) The forward intersection method
The forward intersection method is to measure the angle between the observation point and the observation point by setting a station on the two known points, and then calculate the coordinates of the observation point. The advantages of the forward intersection method: the field of vision is wide, and there are many monitoring points for each observation; the disadvantages of the forward intersection method: the need to set up a station on at least two working points, and the workload is large.

2) The rear intersection method
The rear intersection method is to measure the angle between the monitoring points and the three known points, and then calculate the coordinates of the observation point. Advantages of the rear intersection method: only set stations on unknown points, with less field work and convenient operation; disadvantages of resection method: large internal work and low monitoring accuracy.

3.6. The method of control network
The control net method is to measure the change of monitoring points by closing or attaching wires from the stable working base point outside the foundation pit to the observation point inside the foundation pit. Advantages of the control network method: the working base point and the monitoring point are not restricted by the sighting conditions. Disadvantages of the control network method: large monitoring workload, tedious operating procedures, and low monitoring accuracy.

3.7. The method of GPS measurement
The GPS measurement method is an automatic monitoring implemented using GPS global satellite positioning technology [5]. Advantages of GPS measurement method: station visibility is not required, and it can provide three-dimensional displacement information, all-weather monitoring, simple operation and easy automation, etc. Disadvantages of GPS measurement method: high investment cost.

4. Conclusion
With the continuous development of surveying and mapping technology and the continuous improvement of the monitoring concept, there are more and more methods for monitoring the horizontal displacement of the supporting pile top. Each monitoring method has its obvious advantages, disadvantages and its applicable range [6]. In the face of complex deep foundation pit projects, no monitoring method is perfect. With the continuous progress of urbanization, the structure of deep foundation pits in urban rail transit projects is becoming more and more complicated [7]. Faced with various forms of horizontal displacement monitoring work of the top of the deep foundation pit supporting piles, the monitoring staff should continuously optimize the monitoring plan based on the characteristics of the project to overcome the shortcomings and disadvantages of the single plan, improve the monitoring accuracy, reduce manpower and material resources, and improve work efficiency. In the field monitoring work, the instrument alignment error can be reduced by setting up the mandatory observation pier and the mandatory observation point, and select the high-precision
instrument and equipment, and regularly check the instrument itself to reduce the error [8]. Measures to improve the accuracy of monitoring work are to arrange highly professional monitors to reduce human observation errors, choose a good monitoring time to reduce the impact of the external environment, strengthen internal reviews and self-checks to reduce calculation errors, so as to ensure the safety of urban rail transit engineering construction.

References

[1] Zhang Xianfeng. Technical Guide for Metro Engineering Survey [M]. Beijing: People's Communications Press, 2013.
[2] GB50911-2013 Technical Specification for Monitoring Urban Rail Transit Project [S]. Beijing: China Construction Industry Press, 2013.
[3] GB50308-2017 Urban Rail Transit Engineering Survey Specifications [S]. Beijing: China Construction Industry Press, 2017.
[4] Hu Weidong, Application of Polar Coordinate Method in Horizontal Displacement Monitoring of Deep Foundation Pits [J]. Tianjin Construction Science and Technology, 2017 (1): 64-65.
[5] GB / T18314-2009 Global Positioning System (GPS) measurement specifications [S]. Beijing: China Construction Industry Press, 2010.
[6] Liu Qian. Li Xiaozhu, Applicability of various monitoring methods of pile top horizontal displacement in the monitoring of deep foundation pit construction [J]. Engineering and Construction, 2012 (6): 845-848.
[7] Dai Xiaolei. He Yueguang et al. Monitoring method of horizontal displacement of pile top under complicated terrain conditions [J]. Journal of Transportation Science and Engineering, 2012 (4): 21-24.
[8] Yiteng Xu. The Research of Error Calibration Methods and Comparative Analysis for Digital Level “i” Angle[C]. Information Engineering Research Institute, USA、Asia Pacific Human-Computer Interaction Research Center, Hong Kong. Proceedings of 2018 5th International Conference on Key Engineering Materials and Computer Science (KEMCS 2018). 2018