Design and construction monitoring and deformation analysis of super-large deep foundation pit

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Abstract: Using the large and deep foundation pit of Metro Line 1 of Jinan west railway station as an example, this paper elaborated the design scheme of its retaining structure, formulated a monitoring scheme for foundation pit. In addition, through the real-time on-scene monitoring of horizontal displacement of pile top and pile body, and the monitoring data, we found the law of displacement of deep foundation pit supporting structure. The maximum horizontal displacement of pile body moves down gradually with the advancement of excavation support and the main construction. The maximum displacement occurs around 0.684H. This study has implications for similar engineering geological conditions of foundation pit supporting structure.

Key word: Super-Large deep foundation pit; Supporting structure; Design; Monitoring analysis

1. Project overview

The length of foundation pit of Jinan Metro Line 1 is 207.05m. The standard section width and excavation depth are 21.4m and 18.58m respectively; the width of shield section and excavation depth are 25.3m and 18.58m respectively (±0.00 is equivalent to the absolute elevation of 3036m), which belongs to the super-large deep foundation pit. Its plan diagram is shown in Figure1.

Figure 1. Plane layout of Jinan west railway station.

2 Engineering geological and hydrological conditions

2.1 Engineering geological conditions

According to a geological survey report, the strata within the scope of the project site is mainly...
Quaternary Holocene Alluvial-diluvial strata (Q<sub>4</sub>al+pl), which are composed of plain fill, silty clay, pebble, etc. The physical and mechanical properties of the soil in the geological strata are shown in Table 1.

### Table 1. Mechanical properties of geological soil layer.

| Sequence | Name of soils | Depth (m) | Unit weight (kN/m<sup>3</sup>) | Cohesive force (kPa) | The angle of internal friction (°) | Poisson ratio | Elastic Modulus (Mpa) |
|----------|--------------|-----------|-------------------------------|---------------------|---------------------------------|--------------|----------------------|
| 1        | Plain fill   | 3.20      | 15.4                          | 15.00               | 10.00                           | 0.32         | 6.01                 |
| 2        | Silt         | 10.00     | 16.3                          | 23.00               | 23.00                           | 0.18         | 24                   |
| 3        | Silty clay   | 4.10      | 17.8                          | 28.00               | 23.50                           | 0.21         | 26                   |
| 4        | Silty clay   | 12.20     | 19.5                          | 34.00               | 23.40                           | 0.23         | 35                   |
| 5        | Medium sand  | 8.80      | 19.0                          | 0.00                | 32.00                           | 0.17         | 55                   |

2.2 Hydrogeological conditions

In the surveyed area, the buried depth of the underground static water level measured from the borehole is 1.3-12.8m. Its absolute elevation is 26.23-27.61m. Underground water is mainly distributed in clayey strata, which is replenished by atmospheric precipitation and underground runoff, with the medium sand bed as the permeable layer. The annual variation of the underground water level is little, the absolute elevation in the high flow period can be considered as 28.5m, and the anti-floating design water level as 29.5m (southwest) - 29m (northeast). After executing the corrosive test of soil above underground water level, the results showed that the soil is classified as Grade Ⅱ environment, which does not cause the corrosion of the reinforced concrete structure.

3 Design and construction of super-large deep foundation pit supporting structure

Based on the field investigation of deep foundation pit project of Jinan Metro Line 1, and the comparative analysis of various supporting schemes, the final determination of the scheme is as follows:

(1) Bored piles (Φ1000@1500, Length 22.88m, C30)+ High pressure rotary injected waterproof curtain+ Three steel tube internal support are adopted for construction of foundation pits, as shown in Figure 2.

![Figure 2. Plane layout of foundation pit.](image)

(2) Three steel tube support system and three steel tube diagonal support system are adopted for the standard and shield section respectively in Internal Support. The steel tube supports are equipped with movable ends to apply prestress, which is 30% of the design value of the steel support axial force, as shown in Figure 3.

The design values of the first, second and third steel support axial force are 1000kN, 2000kN and 1500kN respectively. The first inner-support is Φ609 (t=12) steel tube, which is 2.1m from the top; the second and third inner-support are both Φ609 (t=16) steel tubes, which are 8.35m and 14.88m...
from the top. The strength grade of concrete top beam is C30 with the section of 1000mm×800mm, and the breast beam are steel beams (Common I-steel of Hot-rolled45b), as shown in Figure 3.

(3) Excavation Supporting Conditions of Foundation pit:

1. The first excavation was carried out at a relative elevation of -3.1m; 2. Construction of concrete top beam, while setting up the first steel tube (one for every 6m), applying prestress to the steel support; 3. The second excavation was dig to a relative elevation of -9.35m; 4. Construction of steel breast beam, setting of the second steel tube (one for every 3m), and applying prestress; 5. The third excavation was dig to a relative elevation of -15.88m; 6. Construction of steel breast beam, setting of the third steel tube (one for every 3m), and applying prestress; 7. The forth excavation was dig to a relative elevation of -18.58m, manual excavation of the remaining 300mm earthwork, as shown in Figure 3.

(4) In the earthwork excavation of foundation pit, we should follow the idea of “Time-Space Effect”, and combine the methods of separating region, separating section, “supporting while digging” in to minimize the exposure time of foundation pit and mechanical excavation as the primary method while manual excavation secondary. In general, the construction is conducted from both north and south ends to the middle. The key procedures and time points are shown in Table 2.

Table 2. The key construction procedures and time points.

| No. | Key construction procedures          | Completion time | Note                                                                 |
|-----|--------------------------------------|-----------------|----------------------------------------------------------------------|
| 1   | Start the excavation                 | March 20        |                                                                      |
| 2   | Set up the first steel support       | April 03        | In order to reduce the unsupported exposure time of the foundation pit, the steel support should be set up at any time with earthwork excavation. |
| 3   | Set up the second steel support      | April 27        |                                                                      |
| 4   | Set up the third steel support       | June 01         |                                                                      |
| 5   | Excavation to design elevation       | June 17         |                                                                      |
| 6   | Remove the third steel support       | July 17         | Steel support can only be removed when the strength of structural slab (bottom slab, middle slab, top slab) reaches 70% after concrete pouring. [1] |
| 7   | Remove the second steel support      | September 05    |                                                                      |
| 8   | Remove the first steel support       | October 21      |                                                                      |

(5) Dewatering while scaffolding the pit:
① The foundation pit is surrounded by 918 high pressure rotary injected waterproof curtain (Ф700@500, Length 23.01m). P42.5 ordinary Portland cement is used with water-cement ratio of 1:1. After the completion of piles, hydraulic conductivity should be maintained within the range of 10^-7cm/s, and the 28d unconfined compression strength of the piles should be greater than 1.0Mpa.

② In order to construct smoothly, large diameter pipes are adopted to ensure that the underground water level is less than 1m below the design elevation of the foundation pit bottom.

4 Monitoring the construction of super-large deep foundation pit

Project monitoring can not only guide the safe construction of the site, but also be equivalent to a 1:1 experiment to some extent[1]. The monitoring data can truthfully reflect the situation of engineering, which has important implication for the research of foundation pit engineering[2~6].

4.1 Analysis of monitor super-large deep foundation pit project

4.1.1 Horizontal displacement of pile top

Pile top displacement monitoring points are laid out as shown in Figure 4. E1-E9 are arranged on the east of the foundation pit, while S is on the south. W1-W9 are on the west and N is on the north. Due to the limitation of space, this paper only studied and analyzed the west side of representative foundation pit and cross-section E1-W1, E4W-4.

The horizontal displacement-time curve of pile top on the east and west sides of the foundation pit is shown in Figure 5 and Figure 6.

As can be shown from Figure 5 and Figure 6, the horizontal displacement of pile top tends to increase as the excavation depth of foundation pit increases; with the excavation, the maximum deformation of soldier pile top shows "space effect"[6,7]. The deformation of pile increases gradually from the north and south ends to the middle part of foundation pit.
It can be seen from the table that the monitoring value of horizontal displacement of pile top at the short-side monitoring points S, N and the long-side corner points (W1, W9, E1, E9) are between 6.5 to 14.1 mm, while the middle of the long-side points (W2-W8, E2-E8) are between 16.3 to 28.6 mm. Although the monitoring value of horizontal displacement of pile top at each monitoring point is less than the warning limit of 30 mm and 0.2H% (37.2 mm), the monitoring value of points at the short-side and corner of foundation pit are far less than the warning limit as specified. If the warning limit (30 mm or 0.2H%) in specification is adopted for deformation control, it will be too conservative. Therefore, the deformation control index of pile top of the foundation pit supporting structure should be divided into sections to reduce unnecessary waste. As such, the paper suggests that, for strip type deep foundation pit (length:width:depth=10:1:1) of similar geological conditions, the maximum deformation value should be less than 16 mm or 0.1H% by the control index of short-side and corner pile top deformation. Horizontal displacement contrast curve of pile top E1-W1, E4-W4 under various working conditions is shown in Figure 7 and Figure 8.

![Figure 7](image1.png)  ![Figure 8](image2.png)

**Figure 7.** Horizontal displacement contrast curve of pile top E1-W1 under various working conditions.  **Figure 8.** Horizontal displacement contrast curve of pile top E4-W4 under various working conditions.

As shown in Figure 7 and Figure 8, the horizontal displacement of cast-in-place pile top increased quickly at the beginning of foundation pit excavation. After setting up the first support and applying prestress to it, the horizontal displacement of pile top decreased sharply; with the excavation depth of foundation pit increases, the horizontal displacement rate of pile top tends to increase until the excavation reaches the bottom of the pit. During the pouring period from main bottom slab to main top slab, the displacement change rate of pile top is little, which indicates that the bottom slab, middle slab and top slab of the main structure play a certain supporting role.

4.1.2 *Horizontal displacement of pile body*

The horizontal displacement of pile body is a physical quantity which varies with the excavation depth of foundation pit. Horizontal displacement monitoring is one of the important monitoring items to ensure the safe construction of large deep foundation pits. ZXE1-ZXE9 are arranged on the east of the foundation pit, while ZXS is on the south, ZXW1-ZXW9 are on the west and ZXN is on the north. Layout of horizontal displacement monitoring points of pile body is shown in Figure 9. A total of 19 inclinometer boreholes of pile body are arranged in the foundation pit. Due to the limitation of space, this paper only studies and analyses the representative
monitoring points ZXS, ZXE4. The horizontal displacement of pile body are shown in Figure 10 and Figure 11.

**Figure 9.** Plane layout of pile body displacement monitoring points.

**Figure 10.** Horizontal displacement of pile body (ZXS).

**Figure 11.** Horizontal displacement of pile body (ZXE).

ZXE1-ZXE9 are arranged on the east of the foundation pit, while ZXS is on the south, ZXW1-ZXW9 are on the west and ZXN is on the north. Horizontal displacement monitoring points of pile body are laid out as shown in Figure 9. A total of 19 inclinometer boreholes of pile body are arranged in the foundation pit. Due to the limitation of space, this paper only studies and analyses the representative monitoring points ZXS, ZXE4. The horizontal displacement of pile body are shown in Figure 10 and Figure 11.

As can be shown in Figure 10 and Figure 11, with the earthwork excavation depth of foundation pit increases, greater lateral soil pressure is produced by adjacent soil of foundation pit, which further increases the horizontal displacement of pile body. The horizontal displacement of support pile body mainly occurs in the stage of foundation pit excavation and steel support (excavation to -18.58m), during which the maximum deformation is about 75% of the total maximum deformation of pile body (the specific proportion are shown in Table 3). The maximum deformation of pile body during the main construction stage is about 25% of the total maximum deformation of pile body.

The maximum horizontal displacement of pile body moves down gradually with the advancement of excavation support and the main construction. The maximum displacement occurs around the
foundation pit depth of -12.7m (as shown in Table 3), that is, the maximum deformation occurs around 0.684H (H foundation pit excavation depth: 18.58m).

5 Conclusion

(1) The deformation control index of pile top of the foundation pit supporting structure should be divided into sections to reduce unnecessary waste. It suggests that for the maximum deformation value which is the control index of short-side and corner pile top deformation of the strip type deep foundation pit similar to the geological conditions of this project should be less than 16mm or 0.1H%.

(2) The maximum horizontal displacement of supporting pile in super-large deep foundation pits shows "time effect". The horizontal displacement mainly occurs in the stage of foundation pit excavation and steel support, which is about 75% of the total maximum deformation of pile body and 25% of the total maximum deformation of pile body. The maximum horizontal displacement of pile body moves down gradually with the advancement of excavation support and the main construction. The maximum displacement occurs around 0.684H.

(3) In the process of large deep foundation pit excavation, unsupported excavation should be avoided as far as possible, and the principle of "supporting while digging" must be followed. Through the implementation of project, the monitoring data is within the controllable range and has no impact on the surrounding environment, which provides a reference for the design, construction and deformation law of large deep foundation pit support structure of similar engineering geological conditions.

Table 3. Statistical table of maximum deformation analysis of pile body.

| Measuring points | Maximum deformation A (mm) | Maximum deformation position(m) | Maximum deformation at excavation support stage A1 (mm) | A1/A (%) | Maximum deformation at main construction stage A2 (mm) | A2/A (%) |
|------------------|-----------------------------|---------------------------------|------------------------------------------------------|----------|------------------------------------------------------|----------|
| ZXS              | 7.9                         | -12.7                           | 7.3                                                  | 92.4     | 0.6                                                  | 7.6      |
| ZXE4             | 31.5                        | -13.2                           | 22.5                                                 | 71.4     | 9                                                    | 28.6     |

Reference

[1] Wang X J. Inspection test and Analysis of axial force in steel brace during construction of Foundation Pit in running tunnel section adjacent to Liming Cultural Club station of Shenyang Metro[J], Railway Engineering, 4, (2007)86-88

[2] Qian Y L, Ou Q, Gao H Y, Wang J, Lv W K, Wang Y X. Analysis of Internal Force and Deformation for asymmetrically loading and irregular Deep Foundation Pite[J], Journal of Hebei University of Engineering (Natural Science Edition), 33(3), (2016)14-16

[3] Jin X, Zhao X B. Construction of Deep Foundation Pit Close to the Edge of an Important Building in Downtown Center[J], Building Construction, 30(7), (2008)532-535

[4] Wang X W, Tong H Y, Li Z Q. Monitoring Analysis on Foundation Excavation Internally Supported with Diaphragm Wall in Complex Environment[J], Construction Technology, 38(5), (2009)88-91

[5] Qian J G, Huang M S. Effect of non-coaxial plasticity on onset strain localization in soils under 3D stress condition[J], Chinese Journal Of Geotechnical Engineering, 28 (4), (2006)510-515

[6] Chi P. Research on Field Monitoring of Deformation Rule about Support Structure and It’s Optimization in Deep Foundation Fit Engineering [D], (2008)

[7] Li J P, Li Y S. Monitoring Analysis on Construction of Enclosure for Pile Foundation[J], Underground Space, 24(4), (2004)479-48