Analysis of Prestressed Steel Composite Support Technology Applied to Retaining and Protecting for Foundation Excavations in Engineering

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Abstract. In order to study the actual supporting effect of prestressed steel composite support in retaining and protecting for foundation excavations, this paper firstly introduces the advantages, construction methods and monitoring contents of prestressed steel composite support technology. Taking the engineering practice of the Yancheng’s Jinsha Square project as an example, this paper monitors the settlement of the foundation pit’s retaining wall, the settlement and horizontal displacement of the retaining piles, the settlement of the road and the house, and the groundwater level. The results show that the horizontal displacement of the foundation pit’s retaining wall increases with the excavation depth, and the overall trend is a “triangle” characterized by big middle and small ends. The settlement of roads and houses has completed about 60% of the total settlement after about 40-day support. The settlement level of the retaining piles is closely related to the plane size of the excavations. This proves the effectiveness of the prestressed steel composite support in retaining and protecting for foundation excavations, and provides a reference for the future choice of the forms of retaining and protecting for deep foundation excavations.

1. Introduction
With the progress of urbanization and infrastructure construction, the excavations of underground is becoming more and more large. Due to the complex underground environment, large differences in soil quality and the protection requirements for the surrounding environment, the construction technology of underground excavations is difficult to meet the development of underground engineering. Therefore, the technology of retaining and protecting for foundation excavations has been emphasized by more and more researchers and companies. Concrete support structures and steel pipe support are traditional supporting technologies in retaining and protecting for foundation excavations [1]. The concrete support belongs to the statically indeterminate structure with all-fixed
joints, which has high rigidity and structural redundancy, leading to shortcomings such as long construction period, high cost, large demolition noise and non-recyclability. While steel-pipe support has the disadvantages of poor integrity, weak connection and low reliability. The current new type of support method, that is, the prestressed steel composite support technology, is a combination of standard steel component modules produced in the factory, which has the advantages of safety and reliability, simple construction process, low cost, high recyclability and precision of professional installation. This form of support has been increasingly used in recent years and has broad development prospects.

Luo Guanyong et al. [2] studied the settlement mechanism and the inrush mechanism caused by confined water. Zhang Jieqing et al. explored the control design and rescue methods of confined water [3]. Some researchers introduce the process of monitoring and analysis of foundation pits in practical engineering [4]. This paper mainly introduces the system composition and support form of the prestressed steel combination. Combined with the engineering examples of the Yancheng’s Jinsha Square project, the monitoring results are used to analyze the supporting effect and provide reference for future construction.

2. Structural-steel Composite Support

The composite support of prestressed steel is a statically indeterminate structure with fully rigid connection. The high-strength bolts and gusset plates are used to connect a plurality of profile-steels to form a fabricated overall structure [5]. The section of the structural steel is mainly HW400×400×13×21 or HW350×350×12×19. A double-strand H-shaped steel purlin around is used to connect the structural steel support with top beam above the pile to transmit the load. The triangular bracket should be placed at the skew intersection of the wai purlin and the support. Moreover, the structural steel of the wai purlin needs to be welded with stiffened slab, and the joints of the steel purlin around need to be staggered from each other, and the overlap joints of the adjacent two wai purlins should not be in the same section. The prestressed steel composite support makes up for the lack of concrete support and steel pipe support.

In general, the prestressed steel composite support adopts cross-symmetry arrangement, which is advantageous for supporting the force and controlling the deformation of the foundation pit in conventional engineering. The prestressed steel composite support is convenient to construct, its speed of formation is fast, no maintenance is needed. The unsupported exposure time of the maintenance is greatly reduced. The pre-stress can be applied and added, which can effectively control the deformation of the maintenance, and also facilitates the subsequent demolition for accelerating the overall construction progress. The support rods generally cannot directly bear the dynamic load. Therefore, if the prestressed steel composite support system is adopted, a construction bridge independent of the support members should be built, which increases the construction cost to a certain extent.

3. Project Overview

The Jinsha Square project locates on the west side of Renmin Road and on the north side of Huanghai Middle Road in Tinghu District, Yancheng City. The project consists of a commercial and residential building, two residential buildings, two commercial buildings and a basement. The foundation depth is about 6.0 m. It is proposed to use pile foundation. The total floor area of the ground is about 57695 square meters, and the total underground construction area is about 15501 square meters. The elevation of this project is ±0.00 equivalent to 1985 national elevation of 3.100 meters, the excavation depth of foundation pit is about 7.200 m, the area is about 13200 square meters, and the circumference is about 483 meters. According to relevant specifications and the surrounding environment, damage consequences, foundation pit excavation depth, engineering geology and hydrogeological conditions, parameters can be determined as follows. The safety level of the western and the northern sidewall of the foundation pit close to the building is determined to be the first-level, that is, the importance coefficient γo=1.1, and the control deformation at the position of H/S smaller than 1.0 is not more than
2/1000. The safety level of the sidewalls of the other side of foundation pit are determined to be the second-level, that is, the importance coefficient \( \gamma_0 = 1.0 \). The surrounding situation of land for project is shown in figure 1.

4. Surrounding Environment for Current Project

4.1. Design Difficulties in Retaining and Protecting for Foundation Excavations of the Project

- There are shallow foundations and road pipelines near buildings and structures, which are sensitive to deformation, and have high control deformation requirements.
- The geological conditions of the whole site are poor. Within the influence depth range of excavation, the foundation pit is mainly composed of miscellaneous fill, plain fill, muddy-silty clay, and the excavation surface of foundation pit is located in the muddy-silty clay layer under flowing condition, resulting in large deformation of the supporting structure and difficult precipitating of the muddy-silty clay layer which is unfeasible to excavation.
- The support structure of construction site has small available space, while the excavation area and the earthwork amount is large. The support form with short construction period, low cost and feasible construction are important factors that affect the scheme of retaining and protecting for foundation excavations at the current stage.

4.2. The Method of Foundation Pit Support

The foundation pit is constructed by open-excavation and top-down operation, whose construction main methods and sequences are as follows:

- Recheck the elevation of the surrounding site.
- Measuring and stringing, excavating the trench, and constructing the SMW pile, the column pile, the engineering pile and the precipitation well.
- Earthwork is excavated by regional stratified method to 0.5 meter below the first floor support bottom elevation, casting the girth above the pile top, the support structure of first-layer reinforced concrete and construction steel.
- Excavate the earthwork to the bottom elevation of the floor, and cast the concrete pad in time. After the pad reaches the design strength, excavate the earthwork in the pit (water sump, etc.) in the foundation pit, and timely construct the main structure inside the pit.
- Carry out the construction of the bottom plate, cast the bottom plate, and change the support for the bottom plate. After the strength of the changing support meets the design requirements, the first support is demolished.
- Carry out the construction of the remaining underground structure, backfill the spare trench, and demolish the first support.
The design parameters of retaining and protecting for foundation excavations of the project are shown in table 1. The plane layout of retaining and protecting for foundation excavations is shown in figure 2.

| layer | density ($\gamma$ (kN/m$^3$)) | shear strength (UU) ($C_k$ (kPa)) | shear strength (Cq) ($\varphi_k$ (°)) | penetrating index (cm/s) $K_V$ | $K_h$ |
|-------|--------------------------------|---------------------------------|---------------------------------|----------------|-------|
| 1     | 18.0                           | (23.5)                          | (7.0)                           | (14.5)         | 4.5   |
|       |                                 |                                 |                                 | (5.10E-06)     | (1.30E-05) |
| 2     | 18.8                           | 29.7                            | 4.5                             | 28.3           | 11.5  |
|       |                                 |                                 |                                 |                 | 4.35E-08 | 2.97E-07 |
| 3     | 17.3                           | 14.2                            | 0.8                             | 14.6           | 7.1   |
|       |                                 |                                 |                                 |                 | 3.55E-07 | 3.83E-06 |
| 4     | 19.3                           | 39.8                            | 4.6                             | 34.3           | 13.2  |
|       |                                 |                                 |                                 |                 | 1.04E-07 | 8.91E-07 |
| 5     | 18.7                           | 25.2                            | 12.0                            | 22.9           | 18.8  |
|       |                                 |                                 |                                 |                 | 8.10E-07 | 8.36E-06 |
| 6     | 18.5                           | (15.0)                          | (22.0)                          | 14.4           | 24.1  |
|       |                                 |                                 |                                 |                 | 3.63E-05 | 2.54E-04 |
| 7     | 18.4                           | 23.9                            | 11.4                            | 25.0           | 18.8  |
|       |                                 |                                 |                                 |                 | 8.84E-07 | 9.00E-06 |
| 8     | 19.1                           | 41.6                            | 41.6                            | 41.6           | 41.6  |
|       |                                 |                                 |                                 |                 | 6.30E-04 | 6.26E-03 |
| 9     | 19.0                           | (13.0)                          | (25.0)                          | 12.8           | 26.9  |
|       |                                 |                                 |                                 |                 | 3.92E-05 | 3.62E-04 |
| 9A    | 18.4                           | 25.2                            | 12.5                            | 24.5           | 20.5  |
|       |                                 |                                 |                                 |                 | 8.42E-07 | 8.55E-06 |
| 10    | 18.4                           | (15.0)                          | (21.5)                          | 14.4           | 23.3  |
|       |                                 |                                 |                                 |                 | 1.75E-05 | 1.88E-04 |
| 11    | 19.4                           | 43.3                            | 5.3                             | 38.3           | 14.3  |
|       |                                 |                                 |                                 |                 | 6.34E-08 | 4.46E-07 |

Notes: Data in bracket are engineering experience values; The third layer is underconsolidated soil.

5. Monitoring Content and Requirements
The foundation pit should be monitored during excavation process of the foundation pit and construction of the basement. Foundation pit monitoring is an important measure to guide construction and avoid accidents. According to the relevant regulations and requirements, this paper determines the contents and requirements of foundation pit monitoring in combination with the support structure of the foundation pit and the characteristics of environment.

5.1. Monitoring Content and Measuring Point Arrangement
- A horizontal displacement and vertical displacement monitoring point should be arranged every 20 to 25 m along the top of the supporting structure.
• Deep horizontal displacement monitoring: About 11 deep horizontal displacement monitoring points of the retaining and protecting structure are set in the supporting structure, and the depth of inclinometer is as long as the length of pile.
• Groundwater level observation: 11 water level observation holes are arranged outside the foundation pit. The depth of the water level pipe is 3 meters below the excavation surface, and the change rate of the alarm value is 0.5 m/d., and the cumulative change value is 1 meter.
• Supporting axial force monitoring: 15 supports are selected for each layer to conduct the supporting axial force monitoring.
• Road settlement monitoring: The normal open road is arranged with a settlement monitoring point every 20 to 25 meters.
• Column settlement monitoring: No less than 10% column should be selected for column settlement monitoring.

The arrangement of the measuring points is shown in figure 3 below.

5.2. Monitoring Requirements
• Strengthening protection is required for all test points and test equipment to avoid damage.
• Measurement cycle: Excavating the earthwork of the foundation pit until the backfill of the basement side wall.
• The monitoring units need to provide monitoring results to the designers, owners, supervisors and construction units in time.
• Before the excavation of the soil mass, a comprehensive investigation of the surrounding environment should be carried out to grasp the initial condition of the monitored object.
• The buried inclinometer should be kept vertical and protected well.
• Observed items such as deep displacement and settlement are generally observed every 1 to 2 days during excavation, and the frequency of observation should be increased if the rate of change is becoming large during the process of excavation. Each observation data should be filled in the prescribed record form in time and drawn into a corresponding curve. It is necessary to analyze the development trend based on the existing data, evaluate the safety of the foundation pit, and make an immediate report.
• When there is a sharp change in the value of the monitoring project, we should call polices and put forward some suggestions to ensure the safety of the foundation pit.
• The monitoring unit of foundation pit should compile the construction organization plan according to the design requirements. The specific monitoring plan formulated by the monitoring unit should be approved by the design personnel before implementation.

5.3. The Monitoring and Control Requirements of Foundation Pit

- Support structure
  - The building side: horizontal displacement rate of pile body is less than or equal to 3 mm/d; total displacement is less than or equal to 30 mm.
  - The remaining sides: the horizontal displacement rate of the pile body is less than or equal to 5 mm/d; the total displacement is less than or equal to 60 mm.

- Building side
  - The horizontal displacement and settlement rate of the supporting structure’s top are less than or equal to 3 mm/d; total displacement is less than or equal to 20 mm.
  - The remaining sides: the horizontal displacement and settlement rate of the supporting structure’s top are less than or equal to 5 mm/d; total displacement is less than or equal to 20 mm.
  - Ground settlement rate is less than or equal to 3 mm/d; total displacement is less than or equal to 25 mm.
  - The settlement rate of the column is less than or equal to 3 mm/d; the total displacement is less than or equal to 25 mm.

6. The Analysis of Horizontal Displacement Monitoring Results of Foundation Pit Wall

6.1. Analysis of Horizontal Displacement Monitoring Results of Foundation Pit Wall

Figure 4 shows the changing curve of measured-point wall CQ1, horizontal displacement of wall with the excavation depth. It can be seen from the figure that the horizontal displacement of the wall gradually increases as the depth of excavation increases, the overall performance is big in the middle but small at both ends. On 65th day, the horizontal displacement of the foundation pit wall is 10 mm. Figure 5 shows the horizontal displacement of the wall at the measured point from CQ1 to CQ11 for 65 days. It can be seen that the horizontal displacement of CQ9, CQ10 and CQ11 is small because there are residential communities near these measured points. To prevent excessive settlement in residential communities, it is reinforced with two layers of steel concrete piles and two layers of cement-soil mixing piles. In addition, the measured point 3 is located in the place where the plane size of the foundation pit is large, but the horizontal displacement of the wall is consistent with the small plane size of the measuring point 1, indicating that the supporting effect is remarkable.

Figure 4. Horizontal displacement-depth curves of measured point CQ1.

Figure 5. Horizontal displacement-depth curves of foundation pit wall.
6.2. Analysis of Test Results of the Road and House Settlement around the Foundation Pit

Figures 6 and 7 show the changing curve of road settlement near the foundation pit over time. It can be seen from the figure that the settlement is in a evenly increasing state from 20 to 40 days or so, and the settlement rate becomes slow after 60 days, and continues to be more and more slower. Comparing Figures 6 and 7, it can be found that the settlement of the measuring points 9 and 10 are increased by about 0.6 mm than the settlement of the measuring points 1 and 3. Figure 8 shows the changing curve of house settlement near the foundation pit over time. It can be seen that the trends of house settlement and road settlement are basically the same, but the house settlement is smaller than road settlement. And the closer the house is to the foundation pit, the greater the settlement.
6.3. Monitoring Results Analysis of Settlement and Horizontal Displacement of Retaining Piles in Foundation Pit

Figures 9 and 10 are the changing curves of settlement of the retaining pile in foundation pit over time. On the 40th day or so, the settlement trend changes abruptly, and the settlement of the measuring points WY1, 2, 3, 4 in figure 9 increases sharply to about 6 mm in the initial stage. After that, the settlement still increases at a low rate. The rate of settlement change is 57% with a total increase of 2 mm. It can be seen from figure 10 that the settlements of the measuring points 13, 14, 15, 16 tend to be stable after 40 days, and the settlement reaches a maximum of 60 mm. The rate of settlement change is 3.7% with a total increase of 4 mm. It can be seen from the position of the measuring point that the measuring points 13, 14, 15, 16 are mainly distributed in the large area of the foundation pit where the supporting effect is not as good as the small area of the foundation pit. Therefore, it can be seen that the settlement level of the retaining pile is closely related to the plane size of the foundation pit. In the future design, the support stiffness should be considered to control the settlement. Figure 11 shows the
changing curve of horizontal displacement of the retaining pile over time, it can be seen that its increasing rate in the later period is significantly lower than that in the previous period.

6.4. Test Results Analysis of Pressure Water Level in Foundation Pit
In order to ensure the safety of the foundation pit and prevent the sudden damage to the foundation pit caused by the pressurized water, the tube well is used in the foundation pit to drain the rainfall, and monitor the pressure water level at the same time. The monitoring results are shown in figures 13 and 14. It can be seen that the elevation of water level decreases evenly over time, and the rate of decline gradually becomes slower and tends to be stable in the later stage. During the construction period, the water level dropped by about 5 m in total, and the foundation pit was in a safe state.

![Figure 13](image1.png)  
**Figure 13.** The changing curves of pressure water level in foundation pits SW1, SW2 and SW3 over time.

![Figure 14](image2.png)  
**Figure 14.** The changing curves of pressure water level in foundation pits SW5, SW6 and SW7 over time.

7. Conclusion
- The horizontal displacement of the foundation pit wall increases with the excavation depth, and the overall trend is a “triangle” characterized by big middle and small ends.
  - The settlement of roads and houses has completed about 60% of the total settlement after about 40 days of support. The closer the settlement to the foundation pit, the greater the settlement is, and the support should be strengthened where the foundation pit is close to houses and roads.
  - The settlement level of the retaining pile is closely related to the plane size of the foundation pit. The prestressed steel composite support is constructed in larger foundation pit, and its settlement is consistent with a small size, indicating that the supporting effect is remarkable.

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