Deformation Monitoring and Simulation Analysis of Deep Foundation Excavation Construction for subway station

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Abstract: Based on the excavation of deep foundation pit near water for subway, retaining structure of the foundation pit and its deformation monitoring program were designed; in-situ monitoring data of the retaining structure deformation in the foundation pit were analyzed. The horizontal deformation of the retaining structure changing with the excavation depth and time were carried out. 3D finite element model was built to simulate the do construction process of the station foundation pit; FEM results and in-situ monitoring results of retaining structure deformation were compared. The results showed that: the retaining form with steel support and supporting pile had good limit to the lateral deformation of the foundation pit soil. The results calculated by FEM were consistent with the in-situ monitor results; according to monitoring data and the results of numerical simulation, the next deformation law and maximum deformation of the foundation pit excavation were predicted, which showed that foundation pit retaining structure design was reasonable and safety. The simulated results provide valuable reference for these similar engineering.

1. Introduction
The construction of the subway is the focus of my country's urban underground space development in the 21st century. The surrounding complex environmental factors such as high-rise buildings, urban underground pipelines, cultural relics and ancient buildings, underground buildings, traffic trunk lines and other complex environmental factors have brought many new engineering and technical problems to the local foundation pit engineering construction \cite{1-3}. Due to the particularity of geological and environmental factors, the deep foundation pit of subway has the characteristics of large excavation depth, abundant groundwater and long construction period \cite{4-6}. With the rapid development of numerical calculation methods and foundation pit engineering monitoring technology, the control principle of foundation pit engineering developed from the strength failure limit state to the deformation limit state \cite{7}. Therefore, this paper took the foundation pit engineering of an intercity railway subway station as the research object. In the process of foundation pit construction, the supporting structure of the foundation pit, the soil surrounding the foundation pit and the adjacent structures are comprehensively and systematically monitored, and the numerical technique is used to simulate the construction process of deep foundation pit of railway station. Then the deformation law
of the retaining structure is obtained, and the maximum deformation and dangerous position of the retaining structure in the excavation process are predicted in advance, so as to guide the design and construction of foundation pit engineering.

2. General situation of engineering geology and hydrogeology

2.1. Engineering Geology condition
A new intercity railway yard was located in the marine plain area. According to the survey results, The top-down strata of the project site were: (1) plain fill, (2) silt, (3) mud, (4) silt, (5) muddy clay, (6) coarse sand, (7) silt clay, (8) medium sand, (9) silt clay, (10) completely weathered granite, (11) strongly weathered granite (loose), (12) strongly weathered granite (fragmentary), (13) moderately weathered granite.

2.2. Hydrogeological condition
The station yard area was 30-300m away from the seaside, and the surface water was extremely rich. The groundwater could be divided into quaternary loose rock pore water and bedrock fissure water. The Quaternary loose rock pore water mainly accumulated in the shallow artificial fill and the lower sandy soil layer, which was rich in water, good in water yield and strong in permeability of sand layer.

The bedrock fissure water was located under the \( \gamma^2 \). The bedrock fissure water mainly relied on the pore water in the upper layer to replenish along the bedrock fissure, and the amount of water was poor. According to the geological survey, there was a strong sand permeable layer at the bottom of the station foundation pit, and the groundwater was rich near the seaside, which had a great impact on the foundation pit construction.

3. Support design and monitoring plan

3.1. Foundation pit enclosure design

![Fig.1 Typical section of foundation pit enclosure structure](image-url)
The station was an underground three floors and three spans open-cut station with an island platform. The excavation structure of the open-cut foundation pit adopted the support form of 1.2m thick underground continuous wall and internal support. The excavation depth of standard section of station main structure foundation pit was 26.5m, the excavation depth of end foundation pit was 30.0m, and the depth of continuous wall was 44-56m. A total of 6-7 enclosure supports were set. The plan layout of reinforced concrete support and stress steel support were shown in Fig.1. The concrete support cross-sectional dimensions were 800mm×800 mm and 800mm×1000 mm respectively. Steel support D=800 mm, t=16mm.

3.2. Monitoring programs

According to the relevant regulations and the design requirements of the envelope structure, the monitoring items and content of this foundation pit project were shown on Fig.2.

3.3. Analysis of monitoring results

In the construction process of foundation pit excavation, with the excavation of soil in the pit, the pressure of the soil outside the ground connection wall caused the ground connection wall to move in the horizontal direction. Typical excavation conditions were shown in Table 1.

| serial number | content |
|---------------|---------|
| 1             | Excavate the first layer of soil, construct the top ring beam and the first reinforced concrete support. |
| 2             | Excavate the second layer of soil and construct the second reinforced concrete support. |
| 3             | Excavate the third layer of soil and construct the third reinforced concrete support. |
| 4             | Excavate the fourth layer of soil and construct the fourth steel support. |
| 5             | Excavate the fifth layer of soil and construct the fifth steel support. |
| 6             | Excavate the sixth layer of soil, and then carry out the construction of the sixth layer of ring beams, steel supports and connecting beams. |
| 7             | Excavate the seventh layer of soil. |

In the monitoring scheme, a total of 36 measuring points were arranged for horizontal displacement of the ground connecting wall. Monitoring data of two typical sections were selected for analysis. CX1 was at the horizontal middle of foundation pit at small mileage end, and CX9 was at 1/2 mileage of...
standard section.

The maximum displacements of the two monitoring points in different periods of foundation pit excavation were calculated in Table 2. With the increase of the excavation depth, the horizontal displacement of the ground connection walls at different monitoring points was gradually increasing. Because CX1 was in the width direction of the foundation pit, the influence of the diaphragm wall excavation was small, and the maximum displacement here was the smallest. The maximum displacement at CX9 was the largest, which reflected the spatial effect of the excavation. From the change of the maximum displacement in the adjacent stage, it could be seen that the increase in displacement increases sharply in the excavation 2 and excavation 3 stages, and there was a small increase in the excavation 4 stage. This was mainly due to the fact that after the end of excavation 3, the excavation depth had been more than half in the later stage of excavation. Meanwhile, the first three layers were supported by reinforced concrete, which had strong compression performance and stability, and could be used as internal force support system to delay the deformation of diaphragm wall.

| measuring point | excavation 1 | Excavation 2 | Excavation 3 | Excavation 4 |
|-----------------|--------------|--------------|--------------|--------------|
| CX1             | 1.0          | 3.6          | 5.6          | 7.5          |
| CX9             | 3.0          | 11.2         | 16.2         | 16.6         |

4. Finite element model and verification

4.1. Numerical calculation model

The length × width of railway station is about 254m × 35m. After trial calculation, the size of this model is 650m×316m×416m. In the finite element model, the upper surface was assumed to be a free boundary, and the lower surface was constrained by a displacement perpendicular to the surface or a fixed end, while the lateral side of the model only constrained its horizontal displacement.

In order to ensure the accuracy of the calculation results and to control the overall number of grids of the three-dimensional model, the grid size was controlled between 1 and 4m, the grid size was controlled at 20m at the boundary of the foundation pit. The schematic diagram of grid division was shown in Fig.3.

![Fig.3 Calculation model of foundation area and mesh scheme](image)

4.2. calculation parameters

The modified Mohr-Coulomb model was adopted for the soil unit. According to the field geotechnical investigation and laboratory test, the mechanical parameters of foundation pit soil were shown in Table3

| name | Deformation modulus/(MPa) | Natural density/(g/cm³) | internal friction angle/(°) | cohesion/(kPa) |
|------|--------------------------|-------------------------|-----------------------------|----------------|
| mud  | 2.45                     | 1.65                    | 13.68                       | 12.80          |
muddy clay | 4.00 | 1.76 | 13.15 | 24.00
---|---|---|---|---
clay | 4.00 | 1.76 | 13.15 | 24.00
clay | 4.50 | 1.83 | 13.15 | 31.23
silty | 4.00 | 1.90 | 28.00 | 2.00
silty | 8.00 | 1.90 | 28.00 | 2.00
medium sand | 25.00 | 1.90 | 35.00 | 0.00
medium sand | 30.00 | 1.90 | 35.00 | 0.00
medium sand | 40.00 | 1.90 | 35.00 | 0.00
coarse sand | 40.00 | 1.95 | 38.00 | 0.00

The ground connection wall adopts C40 reinforced concrete material. According to the conversion of concrete material and its reinforcement ratio, the elastic modulus E of the ground connection wall was 34.7 GPa, the equivalent thickness of the wall section was 1.2m, the Poisson's ratio \( \nu \) was 0.20, and the weight was 25 kN/m³. The steel support was simulated by a linear elastic rod element, the elastic modulus E was 200 GPa, and the Poisson's ratio \( \nu \) was 0.25. Dewatering treatment of foundation pit had been carried out before foundation pit excavation, so the influence of groundwater on the deformation of foundation pit envelope structure was not considered.

4.3. Comparison of simulation and monitoring results
Taking deep horizontal displacement as the main index, two monitoring points at typical locations were selected for verification. Fig.4 was comparison diagram of the horizontal displacement of the ground-connected wall between the numerical simulation data (S for short) of the monitoring (M for short) points CX1 and CX9 at each stage of excavation. During the first stage of excavation (E-1 for short), the numerical simulation and monitoring data of the monitoring points CX1 and CX9 reflect that this was the stage of "cantilever" displacement. Both excavation stages were in the "parabolic" deformation phase, the actual excavation deformation at CX9 was smaller than the simulated value, and the actual excavation deformation at CX1 was consistent with the numerical simulation value. The stages of excavation 3 and excavation 4 were still in the "parabolic" deformation stage, and the actual excavation deformation of the two monitoring points was less than or close to the simulated value, this was because in the construction process, the deformation of the foundation pit was affected by comprehensive factors such as construction machinery, construction method, construction time, meteorology, hydrology, etc., and these factors were properly simplified in the actual simulation, which cannot fully reflected all factors of actual excavation.

In a word, the trend reflected by numerical simulation results and monitoring results was the same, which indicated that the model established in this time was scientific and reasonable.
5. Deformation prediction of foundation pit excavation

Using the verified three-dimensional numerical model of foundation pit excavation, the deformation of foundation pit in the subsequent excavation of 5, 6 and 7 was simulated. It mainly analyzed the horizontal displacement of the ground connection wall.

Fig.5 was the numerical simulation inclinometer curve of the corresponding positions of the monitoring points CX1 and CX9.

The analysis of the two monitoring points showed that in the first stage of excavation, the ground connection wall exhibited a "cantilever" displacement, and the embedded depth of the ground connection wall was large. At this time, the displacement was completely determined by the stiffness of the ground connection wall itself. The maximum displacement points were all located at the top of the ground connecting wall, the maximum displacement of the monitoring point CX9 was 6.14mm, and the maximum displacement of the monitoring point CX1 was 1.21mm.

In the stages of excavation 2 and 3, large displacement changes and "parabolic" displacement patterns were generated due to larger excavation depth, and the increase in the two excavations was larger. The maximum horizontal displacement point of the ground connection wall also moved downward with the increase of the excavation depth. The maximum displacement point of excavation 3 level was near excavation 13m, and the maximum displacement point of excavation 3 level was near 18m, which were all near excavation surface. The displacement of the tip at the monitoring point CX9 was reduced to a certain extent, while the displacement of the tip at the monitoring point CX1 was further increased. This is because the monitoring point CX9 was at the top position of the lateral support, and the earth pressure difference after excavation 2, excavation 3 makes the ground connection wall rotate around the supporting point to the outside of the foundation pit, which showed a trend of gradually decreasing the displacement of the top part of the connecting wall. One hand, monitoring CX1 was located in the place without direct action of support, and on the other hand, the excavation place at the end well was only inclined support action. The above-mentioned effect was not obvious as the trend of the top displacement continues to increase.

In the fourth stage of excavation, the horizontal displacement of the ground-connected wall was further increased, but the magnitude of its maximum displacement was significantly reduced compared with that before. CX9 only increased by 2 mm with a relative increase of 9%, CX1 only increased by 0.9 mm with a relative increase of 1.4%, at which time a total of 17.2 m of excavation was excavated.
In the stages of excavation 5, 6, and 7, the maximum horizontal displacement of the ground connection wall at the monitoring point CX9 remained basically unchanged, and the maximum horizontal displacement of the ground connection wall at the monitoring point CX1 remained basically unchanged. That was, after the end of excavation 4, the overall horizontal displacement of the ground connection wall remains basically unchanged, the maximum horizontal displacement of the ground connection wall remained basically unchanged, and the maximum displacement occurs near 2/3H (H is the height of the ground connection wall). The application of the fourth, fifth and sixth prestressed steel supports effectively reduced the large deformation caused by the excavation. The maximum displacement in the standard section of the ground connection wall was 23mm, which is 0.1% of the excavation depth.

According to the above analysis, the excavation 1, 2, and 3 in the supporting stage of the reinforced concrete support stage all produced large deformation. The deformation increase of excavation 4, 5, 6, and 7 in the prestressed steel supporting stage was relatively small. It can be seen that the prestressed steel support could control the horizontal displacement of the connecting wall.

Combining the monitoring data and simulation results, it could be found that the measured values were basically smaller than the calculated values. At the same time, the maximum displacement of monitoring point CX1 and CX9 at each stage were compared and analyzed. The ratio of maximum displacement of monitoring point CX9 to monitoring CX1 at each excavation stage was 5.08 times, 4.06 times, 3.45 times, 3.27 times, 3.27 times, 3.26 times and 3.23 times, respectively. It could be seen that during the excavation of the foundation pit, the horizontal displacement of the ground connection wall in different spaces was quite different, and the horizontal displacement of the ground connection wall had a strong spatial effect. According to the numerical simulation and monitoring data, the horizontal displacement at the monitoring point CX9 was the largest horizontal displacement of the whole ground connection wall. According to the law of numerical simulation, after excavation 4, the maximum deformation value of the foundation pit would remain stable, and the maximum horizontal displacement of the ground connection wall in the numerical simulation was 23.80mm. Therefore, it was predicted that the maximum horizontal displacement value of the connecting wall in the excavation of this foundation pit was within 30 mm, which was located at 2/3H times the excavation depth of the foundation pit and within the range of 36 mm of the alarm value of the foundation pit. This will guide the subsequent construction and ensure the safety of foundation pit excavation, which was of great significance to improve the safety of the project.

6. Conclusion
A three-dimensional finite element model was established in conjunction with the deep foundation pit excavation project of an intercity railway station, and the numerical model was verified by monitoring results. Then the deformation rule and the maximum displacement of the foundation pit were predicted by numerical simulation, and the following conclusions were drawn:

(1) In the excavation of foundation pit, the deep horizontal displacement of the ground-connected wall gradually changed from the "cantilever" form to the "parabola" form when it was not supported. With the excavation and support construction of the foundation pit, due to the good compressive performance of the concrete support, the prestressed steel support could offset part of the soil and water pressure, effectively delaying the horizontal deformation of the supporting ground and the wall.

(2) The deformation of the connecting wall of the foundation pit had obvious spatial effects, and the final displacement in different spaces had a certain ratio relationship. The first step excavation of foundation pit had a great influence on the deformation of foundation pit and supporting structure. It was suggested that the transverse foundation pit area where the tower crane pile foundation was located should be excavated first during the construction, so as to reduce the deformation caused by the first step excavation, and then reduce the overall deformation.

(3) The finite element numerical analysis method was used to simulate the construction process of the foundation pit excavation, and the calculation results were compared with the monitoring results. The basic trend of the deformation of the diaphragm wall and the surface deformation around the
foundation pit was generally consistent, which reflected the rationality of the establishment of the FE calculation model and the selection of the parameters.

(4) Through numerical simulation, the maximum horizontal displacement value of the connecting wall of the foundation pit was predicted to be 30mm. Within the range of alarm value, the dangerous position was 2/3H times of the height of diaphragm wall, which indicated that the design of retaining structure of foundation pit was safe and reasonable. At the same time, the numerical simulation guided the construction process of foundation pit excavation.

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