Deformation Law of Deep Foundation Pit Excavation in Metro Station: A Case Study

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Abstract: Based on the foundation pit of a station of Nanning Metro Line 5 as the research background, the measured data of pile horizontal displacement, supporting axial force and surrounding soil settlement during the construction of the foundation pit are systematically analyzed. Monitoring analysis shows that with the increase of the excavation depth of foundation pit, the horizontal displacement of retaining pile increases and gradually moves down, among which the horizontal displacement at 11-12m is the largest; the internal support force is roughly proportional to the time in the excavation process; the settlement of soil beside the pit increases gradually, and the settlement deformation at 6-8m near the pit is the largest, and finally the settlement decreases with the increase of the distance from the pit. Based on the deformation of foundation pit caused by excavation of foundation pit, numerical simulation is carried out to establish a three-dimensional model of foundation pit. Combined with the field monitoring data, data comparison and analysis are carried out. The deformation laws of the two are basically the same, which proves the safety and stability of the bored pile combined with the internal support structure, and provides a basis for the construction design of similar foundation pit projects.

1. Introduction

With the development of urbanization, the pressure of urban ground construction and traffic is increasing, and the land resources are limited. The development and utilization of underground space, efficient and reasonable use of urban resources become the core of urban development. Under this development trend[1, 2], the construction of urban subway station is particularly important, which plays an important role in effectively bearing the ground construction and traffic pressure. For this reason, the station foundation pit also develops from the original scale to the more complex direction of "large, deep, tight, near".

At present, scholars at home and abroad have made some achievements in the study of the deformation of deep foundation pit. On the basis of analyzing the field monitoring data and the results of numerical simulation calculation, numerical simulation is used to analyze one or more factors in the construction process and environment to study the influence of the deformation of the excavation structure, so as to obtain the parameters for the optimization of the construction design of the foundation pit and get the results Process benefit. In recent years, through the comparison of monitoring data and numerical analysis results, Chen xiao wei[3] et al. Obtained the enclosure form of steel support and enclosure pile, and obtained the finite element calculation results combined with the measured data; Fu Libin[4] et al. Analyzed the influence of foundation pit through the space effect, and combined with the numerical simulation results, obtained that the critical size of foundation pit excavation can effectively reduce the deformation of the retaining structure; Chen Xinian[5] et al. Studied the deep foundation pit construction project of Nanning Metro Line 1, obtained the deformation law of deep foundation pit in the form of multi-level sloping and combined support; Li Juncai[6] et al. analyzed the deformation of deep foundation pit by studying the time and space effect of the retaining structure; Based on the characteristics of time-space effect and practical engineering cases, Libo[7] et al. Analyzed the influencing factors of foundation pit deformation.

Based on the research background of the deep foundation pit of a station of Nanning Metro Line 5, this paper analyzes the field monitoring data, combined with the finite element simulation of Midas/GTS, analyzes the deformation law of the deep foundation pit under the construction excavation, and provides some references for the parameter control and design in the construction process of the deep foundation pit with similar soil conditions.

2. General Situation of Engineering

The station is the 16th underground station from south to north of Nanning rail transit line 5 phase I project. The station is located at the T-junction of Kunlun Avenue and Jiangqiao road. It is set along the east-west direction of Kunlun Avenue, with complex surrounding environment. The specific location of the station is shown in Figure 1.

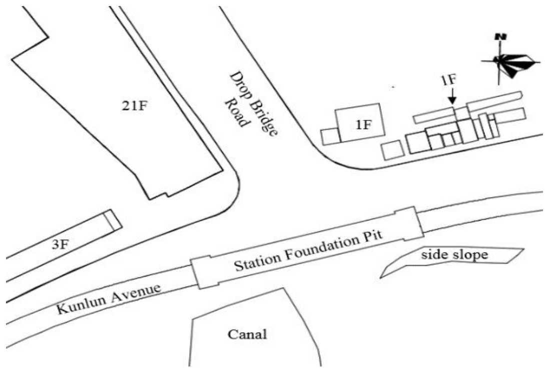


Figure 1: Schematic diagram of station location.

The station is an underground three-story double column three span rectangular frame island type station. The main structure of the station is 156.2m long, the standard section is 22.1m wide, and the excavation depth of the standard section is about 23.6m. The main retaining structure of the station is cast-in-place pile and internal support, which is constructed by open excavation method. The retaining pile mainly adopts Φ1000@1300 cast-in-place pile; there are four internal supports, the first one is reinforced concrete support, the section size is 800*800mm, the horizontal spacing is 9m, and the end is provided with splayed support; the second, third and fourth supports are steel pipe support with spacing of 3.25m, Φ800mm, t=16mm; the pile is supported by Φ8@150*150mm steel mesh.The station envelope structure is simplified as shown in Figure 2.

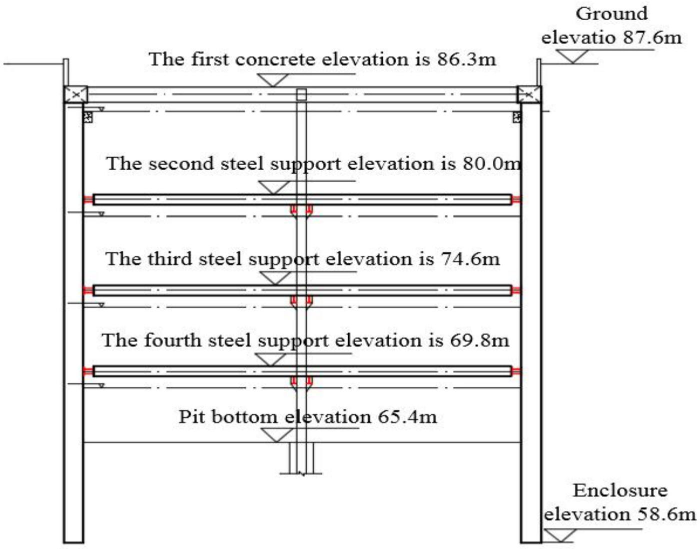
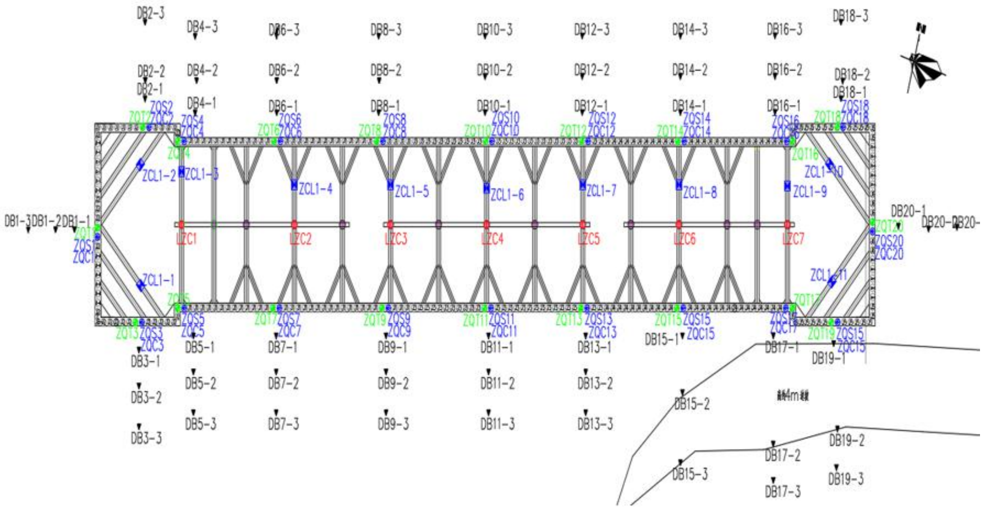


Figure 2: Standard section structure of foundation pit.

To analyze the monitoring data systematically, this paper analyzes the monitoring points of surrounding soil, foundation pit retaining structure deformation and supporting axial force caused by foundation pit excavation[8]. The excavation of foundation pit shall be carried out from east to West in layers and sections, supported first and then excavated. To understand the deformation of soil and foundation pit structure in the process of foundation pit excavation, monitoring points are arranged around the foundation pit according to the national specifications, and the layout of monitoring points is shown in Figure 3.



Note: ZQT is the horizontal displacement of pile, ZQS is the displacement of pile top, DB is the ground settlement, ZCL is the concrete support, and LCZ column is uplifted.

Figure 3: Schematic layout of monitoring around foundation pit.

3. Deformation Monitoring

3.1. Enclosure Structure

The excavation of foundation pit starts from the east to the West. Due to the influence of time-space effect, slope and surrounding buildings, the horizontal displacement of retaining structure at different positions is not the same in the excavation process. The horizontal displacement curves of pile ZQT17and ZQT9 with excavation depth are shown in Figure 4 and Figure 5.

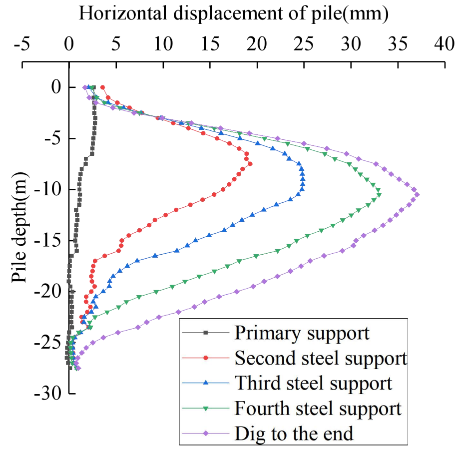


Figure 4: Horizontal displacement-depth changes monitored by ZQT17.

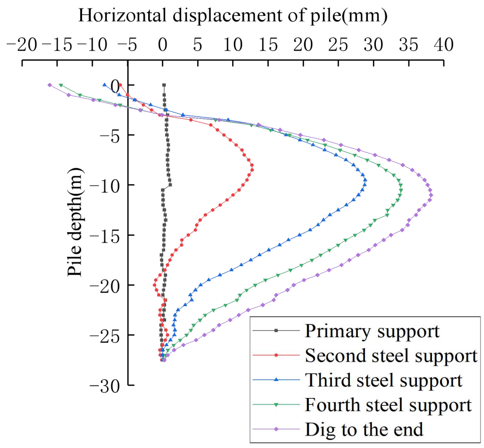


Figure 5: Horizontal displacement-depth changes monitored by ZQT9.

As the graphs show, with the deepening of the excavation depth of the foundation pit, the maximum horizontal displacement of the pile starts to move down until it moves 11-12m, and the position of the maximum horizontal displacement of the pile starts not to change with the excavation depth. The main reason for the obvious deformation is that with the unloading of the soil, the soil around the foundation pit compresses the foundation pit pile, resulting in a large amount of deformation; on the other hand, the site steel support erection lags behind, after the excavation of the foundation pit, the steel support is not erected in time, which makes the surrounding soil extrusion time too long, the rheological change, the time effect is obvious, and the displacement of the retaining structure increases significantly. For the existence of slope in the east end, the active pressure of soil mass is larger after the excavation of foundation pit, so the horizontal displacement of pile ZQT17 is slightly larger than that of ZQT9.

3.2. Support Axis Force

The variation curves of axial forces of ZCL1-7, ZCL2-7 and ZCL3-7 during excavation of foundation pit are shown in Figure 6. The second and third steel supports are pre-loaded with 500kN of axial force per support.

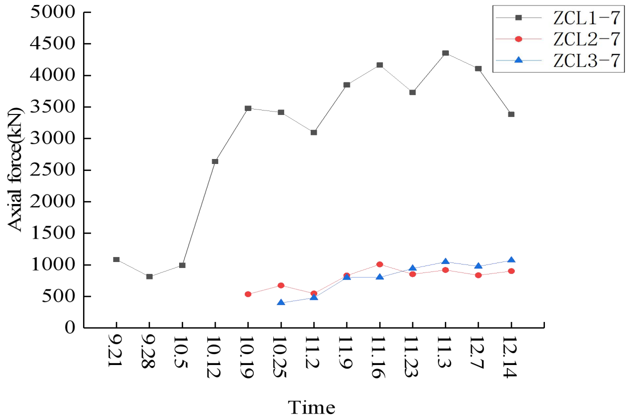


Figure 6: Axial force-time curve in the middle of foundation pit.

As shown in Figure 6, the first concrete support axial force of the foundation pit of Jiangqiao Station is the largest, and the second and third steel support axial force gradually increases. In the initial stage of the first concrete support, with the increase of excavation depth, the variation fluctuates greatly. The main reason is that after the soil is unloaded, the soil around the foundation pit is squeezed into the pit, the concrete support plays a role of restraining, and the axial force changes greatly. In addition, the steel support is affected by the temperature change, and the temperature difference in Nanning is large, and the axial force fluctuates obviously.

3.3. Settlement of Pit-side Soil

The excavation unloading of the soil in the pit results in the deformation and settlement of the soil outside the pit. The points DB17-1, DB17-2 and DB17-3 are analyzed as shown in Figure 7.

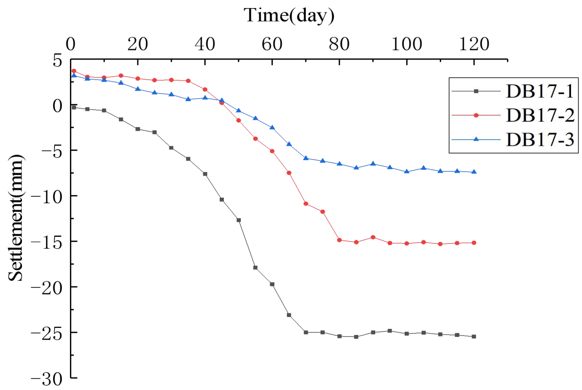


Figure 7: Soil settlement curve.

Soil displacement field is complex, which involves pile foundation as a protective structure. The active earth pressure of the soil on the retaining structure increases, while the pile foundation under load hinders the movement of the soil and restricts the displacement of the adjacent soil. Figure 7 shows the curve of settlement of the side near the slope with time. With the excavation of the foundation pit, after the unloading of the soil, the soil around the foundation pit has uneven settlement, and the settlement amount and settlement rate gradually increase; after the excavation to the bottom, the soil settlement tends to be balanced and stable. The maximum settlement of soil is about 25.22mm, close to the early warning value of 30mm.

4. Finite Element Simulation and Analysis

4.1. Computational Model, Parameters and Working Conditions

In this paper, the finite element software Midas/GTS[9] is used to simulate the construction condition of foundation pit[10], and the modified Mohr-Coulomb[11-13] constitutive model is adopted in the soil model. The width of standard section of excavation foundation pit is 22.1m and the excavation depth is 20.6m. Establish a three-dimensional model. The model size is shown in Fig. 8. The retaining structure includes the underground continuous wall and internal support. And the underground continuous wall is a disjunctive plate unit, and the support is a beam unit. The specific model shown in Figure 9. The physical parameters of each soil layer are selected as shown in Table 1.

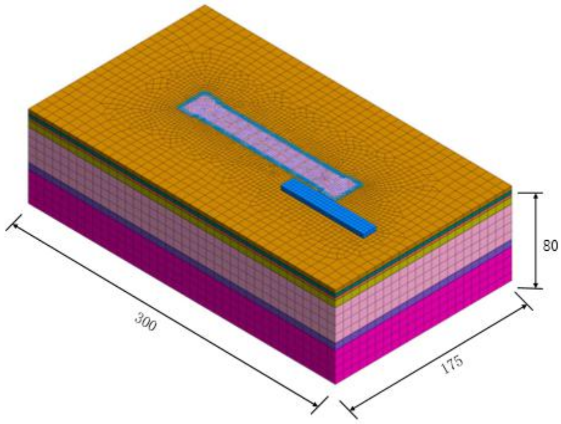


Figure 8: A numerical model.

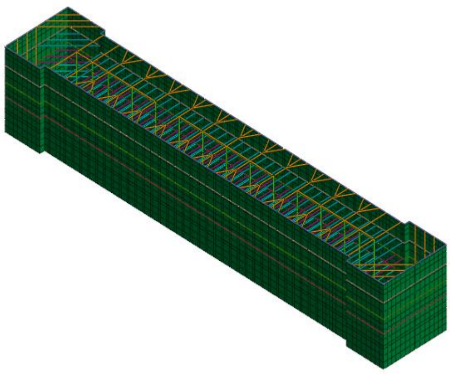


Figure 9: Enclosure structure model.

Table 1: Mechanical parameters of soil layer.

Layer	γ / kN/m^{-3}	c / kPa	φ / (°)	E_{S1-2} / MPa	ν
Miscellaneous fill	19.0	8	5	6	0.35
Prime fill	19.9	10	8	5.8	0.35
Silty clay	20.2	45	15	11	0.33
Silty mudstone 1	20.3	47	14	11.7	0.28
Silty mudstone 2	21.4	53	16	14.5	0.31
Pelitic siltstone	20.7	37	19	12.5	0.25

The main body of the station foundation pit is constructed by open-cut method, and the supporting system of bored cast-in-place pile and internal support is adopted as the enclosure structure. The construction simulation conditions are shown in Table 2.

Table 2: The construction procedure.

Working condition	Content
1	Excavation to 1m, construction of crown beam and first concrete support
2	Excavate to 0.5m below the second steel support and erect the second steel support.
3	Excavate to 0.5m below the third steel support and erect the third steel support
4	Excavate to 0.5m below the fourth steel support and erect the fourth steel support.
5	Excavate to the bottom and pour the floor

4.2. Simulation Analysis of Construction Stage

The passivation of Midas/GTS construction simulation step and activation unit are used to simulate the excavation of foundation pit support. The specific working conditions are as follows: firstly, soil layer model is established, mesh is divided, displacement boundary conditions are applied; then, initial stress field is balanced and displacement is cleared; secondly, construction envelope structure, column and internal support are activated sequentially according to the order of foundation pit construction to passivate the excavated soil. Until the end of the excavation.

4.3. Calculation Results

4.3.1. Horizontal Displacement of Enclosure Structure

The calculation results after the foundation pit excavation to the end are shown in Figure 9 and 10..

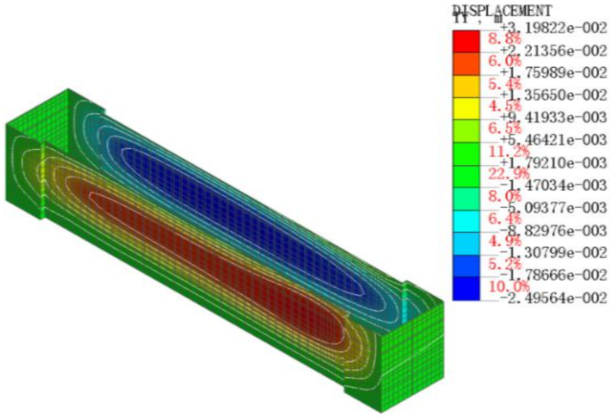


Figure 10: Excavation of foundation pit to the bottom of the retaining structure Horizontal Displacement Map.

(Y Direction)

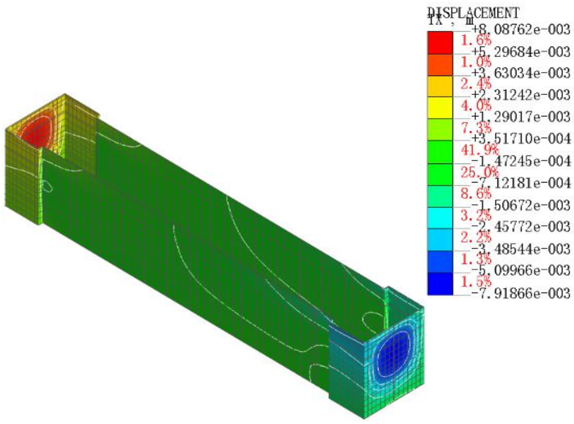


Figure 11: Excavation of foundation pit to the bottom of the retaining structure Horizontal Displacement Map.

(X Direction)

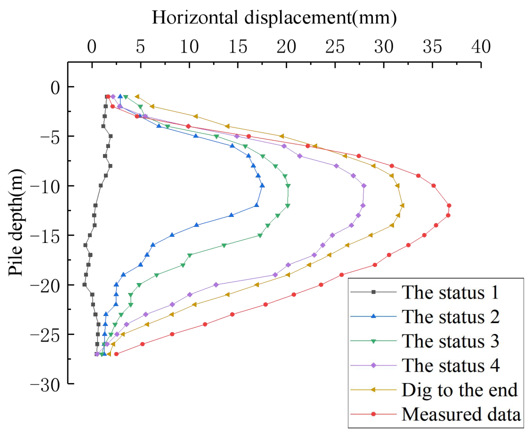


Figure 12: Simulated and Measured displacements of pile.

Comparing and analyzing the results of calculation and monitoring data for each working condition and after excavation in the software, the calculation and analysis of standard section concrete support are given as shown in Figure 12. From the Figure 12, we see that the calculated value is slightly less than the measured value. The reason is that during the construction and excavation on site, overbreak occurs and steel support is not applied in time. The soil around the foundation pit has a long time of creep, which results in the increase of the horizontal displacement of the pile. On the other hand, during the software simulation, the environment is simplified and only the earth pressure is used, so the measured value is greater than the calculated value. Both results show the deformation trend of the excavation depth of the retaining structure under different working conditions, and the change rule of the retaining structure is basically the same, which proves the feasibility of the finite element method in the foundation pit.

4.3.2. Axis Force

After the foundation pit is excavated to the bottom, the numerical calculation results of concrete support axial force are shown in Figure13.

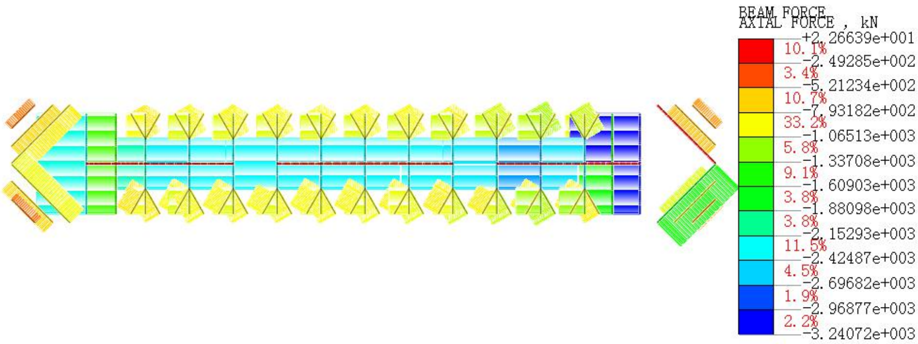


Figure 13: Concrete support axial force.

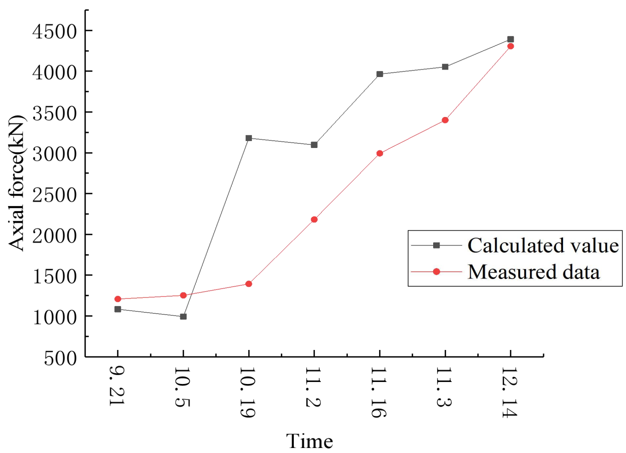


Figure 14: Simulated and Measured values of concrete bracing axial force.

In the comparison of monitoring axial force changes and calculation results after each working condition, along with the excavation time of foundation pit, the axial force is approximately proportional to excavation time; the fluctuation of two axial forces is different, in the first part, the monitoring value is larger than the calculated value, and the fluctuation of monitoring value is larger, which may be due to the lag of steel support erection on site, the existence of over-excavation phenomenon, making the surrounding soil extrusion too long. Over-large, complex surrounding environment and large fluctuation of axial force monitoring value lead to deviation between monitoring value and calculated value.

4.3.3. Foundation Pit Soil

The numerical simulation results are shown in Figure 14. The soil monitoring point DB17-1 close to the slope is taken for analysis.

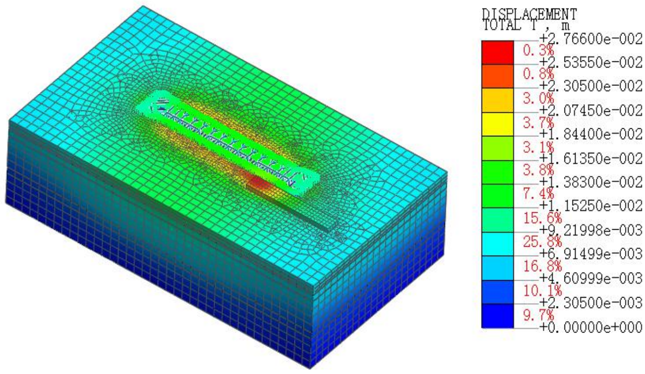


Figure 15: Ground settlement.

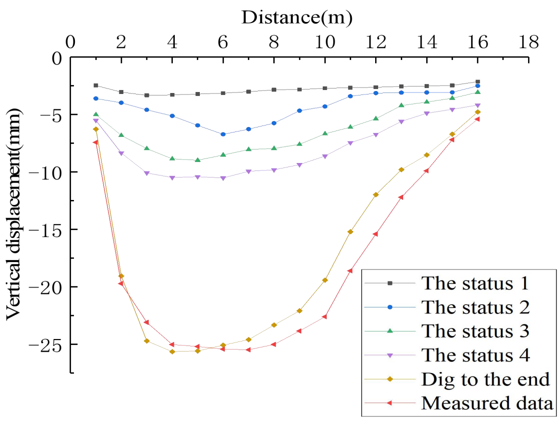


Figure 16: Comparisons of measured and simulated soil settlement.

From the Figure 16, it can be seen that with the increase of excavation depth, the settlement displacement of soil around the foundation pit increases. The maximum ground settlement displacement is 6-8m away from the foundation pit, and the maximum settlement is 26.62mm. The farther away from the foundation pit, the settlement is gradually not obvious. The displacement of the soil near the slope is generally larger than that in other areas. When the foundation pit is monitored, the displacement of the soil near the slope is also larger than that in other areas. Comparing the numerical calculation value with the simulation value, the displacement of the soil near the slope of the foundation pit is approximately identical.

5. Conclusions

Based on the analysis of the monitoring data of a deep foundation pit of Nanning Metro Line 5, this paper studies the deformation characteristics of the foundation pit. On this basis, the finite element software is used to carry out the numerical simulation of the foundation pit. Through the comparative analysis of the numerical calculation results and the monitoring data, the deformation law of the whole foundation pit under the construction condition is further obtained, and the feasibility of the finite element numerical simulation is verified, and the following conclusions are drawn：

1) Through the analysis of measured data and numerical simulation, the form of cast-in-place pile and mixed internal support has played a safe and stable role in the construction of foundation pit and ensured the safety of foundation pit engineering.

2) The main deformation of cast-in-place bored piles is at the top of the pile body at the initial stage of excavation. With the increase of excavation depth, the maximum horizontal displacement point moves downward with the excavation until it is 11-12m below the pile body. The maximum horizontal displacement does not increase with the excavation depth, and finally tends to be stable. From the finite element calculation and analysis, it can be seen that the deformation of the retaining structure can be reduced by assuming the steel support and the site excavation according to the regulations in time.

3) The internal support of the foundation pit plays a supporting role, in which the first concrete axial force is significantly greater than the second and third steel support. With the increase of the excavation depth, the axial force of the lower two steel supports gradually increases, among which Nanning has a large temperature difference, the steel supports are affected by the temperature to produce Xu Bian, and the axial force is floating.

4) With the unloading of foundation pit soil, the surrounding soil of foundation pit settlement occurs. Because of the complex nature of soil, with the increase of excavation depth, the surrounding settlement increases until the soil reaches a new equilibrium trend, and the maximum settlement point is 6-8m.

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