Deformation and Force Analysis of the Pile Foundation System of Deep Foundation Pits in Soil–Rock Combination

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Abstract: This study uses the construction of the Shengli Bridge Station of Qingdao Metro Line 1 as the engineering support for in-depth research of the deformation and mechanical characteristics of the retaining structure of pile-support systems during deep foundation pit excavation under the complex geological conditions of soil–rock combination. This study adopts the finite element software modeling analysis method to simulate the excavation of the foundation pit and the 3D finite element numerical calculation method to calculate the deformation. The modified Mohr–Coulomb model is selected as the constitutive model, and the natural gravity of each layer of soil is considered. The calculated load includes the dead load of structure and soil. The boundary conditions of X, Y, and Z directions at the bottom are fixed constraints, and the top ground is a free boundary. The displacement of soil around the foundation pit and the stress and deformation of retaining piles and crown beams under different working conditions are studied. The deformation law and force mechanism of the supporting structure of the pile-support system are analyzed. The research results reveal the relationship between the synergy of pile-support system and soil deformation, serving as a reference for similar engineering constructions.

Key words: Earth rock combination; deep foundation pit; pile supporting system; numerical simulation; foundation pit deformation; force mechanism
1. Introduction

With the rapid development of subway construction in major cities in recent years, the scale of urban underground space development has increased; thus, the number of super-large and deep foundation pits also increased. The design and construction of the foundation pit enclosure structure are complicated [1-4], and the current theoretical research on foundation pit engineering is still far behind the development of the actual project. Geotechnical engineering safety problems inevitably occur during construction. Therefore, in-depth research on foundation pit engineering, especially on the foundation pit envelope structure, is important [5-8]. Researchers at home and abroad have focused on the foundation pit envelope structure. Liu Jimei [9] studied the supporting structure of the foundation pit and found that the greater the prestress of the internal support of the foundation pit, the greater the internal force of the retaining piles. Xu Ling et al. [10-11] analyzed the simplified algorithm of internal bracing for pile bracing in deep foundation pits. Using the theory of elastoplastic mechanics, Zhang Dingfeng [12] calculated the balance equation of the foundation pit during demolitions, which can be used to analyze the soil parameters and predict the foundation pit settlement and deformation of the envelope structure. Hashash [13] used the finite element method to investigate the effects of different depths of continuous underground walls, different vertical spacing of supports, and different stress histories on the ground settlement around the pit. Ng et al. [14] analyzed the deep foundation pit engineering of a multi-support excavation and discussed the reasons for the deformation, bending moment, and supporting axial force of the measured enclosure structure. Carder [15] summarized the maximum displacement distribution of the surrounding wall of the foundation pit project in the hard soil area and the surface settlement distribution around the pit on the basis of several engineering cases on the hard soil site. Hsieh [16] analyzed the measurement data of multiple foundation pit projects. Basing from previous and latest engineering monitoring data, Clough G.W. and O'Rourke T.D. [17] distinguished the settlement of soil caused by excavation and support of the foundation pit to obtain the distribution of ground settlement caused by excavation in each stratum. Considering the roughness of the bottom foundation pit, Chang et al. [18] proposed a modified limit analysis method on the foundation pit deformation and sliding mechanism. Su et al. [19] analyzed the influence of the strength anisotropy, heterogeneity of soft clay, and the depth of the enclosure structure on the total stress anisotropic strength. Ou [20] used the finite element method to analyze the horizontal displacement of the typical soft soil foundation pit envelope structure. Boija et al. [21] proposed a nonlinear finite element analysis method for stress-point integration.

This study analyzed the deformation and stress of the foundation pit envelope structure of Shengliqiao Station on Qingdao Line 1 in detail. This study may serve as a reference for the design of similar projects in the future.

2. Project overview

Shengliqiao Station is the 24th station of Qingdao Metro Line 1, which is located on the west side of the intersection of Siliu South Road and Zhengzhou Road. The station is an underground three-story double-column three-span box-shaped concrete frame structure. The effective platform center mileage of Shengliqiao Station is YSK46 + 015, the starting point mileage is right YSK45 + 931.768, and the ending point mileage is right YSK46 + 106.168. The main body of the station is 172.4 m in length, the standard section width is 20.1 m, and the limited platform width is 11 m. The station’s island platform has an effective platform length of 118 m and a width of 13 m. The height of the station is 21.41–23.0 m, the roof is covered with soil about 3.3 m, and the floor is basically located in the slightly weathered rock layer (fragmented). The roof of the station was covered with soil about 2.05 m, and construction was carried out by the method of the open cut. Two sets of ground air pavilions and a cooling tower were set up in the station. The public area of the station has three entrance and exit channels. The enclosure structure is in the form of a pile and an internal support system. The small-mileage end section was constructed by dark excavation, whereas the large-mileage end section was constructed by TBM. The schematic of the station is shown in Figure 1.
3. Monitoring content and analysis of measurement results

3.1. Monitoring content

The monitoring of supporting pile deflection and internal support axial force is analyzed. The monitoring point layout diagram is shown in Figure 2. Two inclined measuring pipes are arranged to monitor the supporting piles, and 15 transverse brace strain gages are arranged to monitor the internal supporting axial force.

3.2. Horizontal displacement of retaining piles

During the foundation pit construction, the slope deformation of supporting piles is continuously monitored. Figure 3 shows the deformation distribution curve of the monitoring points in the middle of the foundation pit under different construction steps. On the basis of the measurement results, the following deformation laws are summarized:
Figure 3. Change in horizontal displacement of retaining piles with construction steps

(1) During foundation pit excavation, the displacement and deformation of piles to the inner direction of the foundation pit occur. The active soil pressure on the pile body increases linearly with the increase in excavation depth because the soil outside the foundation pit exerts active soil pressure on the retaining pile during excavation. Therefore, in the initial excavation stage, the deformation of the pile top is relatively small, and the horizontal displacement of the pile body shows an approximate linear growth trend with the increasing depth of foundation pit excavation.

(2) During excavation, the horizontal displacement deformation degree of the pile top and pile tail is relatively small, the displacement deformation amplitude in the middle of the supporting piles is large, and the displacement deformation in the middle of the supporting piles is large. The overall deformation trend initially increases and then decreases, and the maximum displacement point of the pile body moves downward gradually with the construction. Enclosing piles have the largest deformation during the fourth support construction, and the maximum deformation is located near the fourth support, which is 5.3 mm.

3.3. Support axial force

The supporting axial force is calculated from the strain measured with a cross brace strain gage. Three cross brace strain gages for each support are installed, as shown in Figure 2. The frequency of the support shaft is monitored from the beginning of the support erection to the completion of the excavation with the frequency of 1 time/day. On the basis of the monitoring data, the change in each supporting axial force during the on-site construction are illustrated in Figure 4. The following rules are summarized:
At the excavation stage of the foundation pit, the axial force of the cross brace increases continuously with the increase in excavation depth. Before the second brace is erected, the axial force of the first brace increases significantly, and the maximum axial force of the first brace during the entire construction occurs before the second brace is applied. With the erection of the second support, the axial force of the first support reduces significantly, and the axial force of the first support shows a significant decrease throughout the excavation.

(2) The axial force of the support near the excavation surface increases with time. The change in the other axial force of the support has no certain regularity, and different degrees of fluctuation or a small will decrease. In other words, the axial force of the upper steel support is effectively controlled. When the excavation is completed, the growth rate of the axial force of each support significantly declines.

(3) The supporting axial force is related to the deformation of the diaphragm wall. During the excavation of the foundation pit, the supporting axial force changes because of the lateral deformation of the diaphragm wall. Further deformation of the wall is limited because of the increase in supporting axial force. Therefore, the deformation of the continuous wall can be effectively reduced as long as the soil of the foundation pit is excavated, the steel support is immediately erected, and reasonable pre-axial stress is applied to reduce the exposure time of the foundation pit without support. In addition, the axial force must be applied as soon as possible after the support is installed to ensure that the support is tight against the wall, reduce the lateral displacement of the wall, and improve the stress conditions of the wall.

4. Finite element model building

4.1. Basic assumptions
This study establishes a 3D numerical model to analyze the deformation and force characteristics of the foundation pit enclosure structure.

The numerical calculation of the Shengli Bridge Station of Qingdao Metro Line 1 is carried out with a 3D finite element numerical simulation method, which satisfies the following basic assumptions [22]:

(1) The soil is an ideal elastoplastic homogeneous material, and the damage follows the Mohr–Coulomb criterion.

(2) The stress and deformation of the retaining piles and supports of the foundation pit fully conform to the characteristics of the linear elastic body.

(3) Before simulating excavation, during the zero displacements of the soil, the displacement caused by gravity is ignored.
(4) No friction exists between the supporting structure and the surrounding soil. Friction can cause problems of convergence and consume many computing resources. The displacement caused by the friction between the structure and the surrounding soil is relatively small compared to the displacement of the entire soil. Thus, no relative sliding is assumed to occur with the surrounding soil.

(5) The time effect of the enclosing pile entering the soil is not considered. Different types of piles have different soil insertion processes. The loading process of soil loading is not a completely static process, which involves large deformation. Excavation is the focus of this simulation, and the supporting piles are fully in place during excavation. At this time, ignoring the process of entering the soil can greatly reduce the probability of non-convergence of results on the one hand and reduce the calculation time on the other hand.

(6) Ignoring the time effects. The foundation pit project has a strong space–time effect. A 3D simulation solves the problem of spatial effects to a certain extent. The static analysis is still used. Time parameters in the static analysis have no practical significance, which are essentially different from the traditional time. Ignoring the time effect weakens the effects of soil and concrete creep, which can influence the calculation results.

(7) Overloading around the foundation pit is not considered during the simulation because of three reasons. First, the neglect of the time effect weakens the effect of overload. Second, the setting of overload around the foundation pit must additionally divide a certain area on the top of the soil body as the loading surface. In this way, the originally symmetrical surface of the soil becomes asymmetric, which may exert serious adverse effects on the subsequent meshing. Last, considering the actual situation and spatial effect of the project, the influence of overload outside the foundation pit on the horizontal deformation is only about 5%. Thus, it is ignored in this simulation.

4.2. Model material

For the choice of the constitutive model, accuracy and reliability are necessary. A modified Mohr–Coulomb model based on the actual engineering characteristics is adopted. This model is an improved elastoplastic constitutive on the basis of the Mohr–Coulomb model. Compared with the Mohr–Coulomb model, it is closer to the plastic theory and can combine nonlinearity and plasticity. It can be considered to input different elastic modulus values according to the loading or unloading conditions. Considering the correlation between the stiffness of the soil and the stress state, it is a double hardening model that does not affect shear yield and compression yield. The parameters of density, elastic modulus $E$, Poisson’s ratio, friction angle, and cohesive force $c$ are needed for the model. The specific model parameters are selected with the Shengliqiao Station of Qingdao Metro Line 1, as shown in Table 1.

| Materials                        | Miscellaneou s fill | Silty clay | Gravel       | Middle weathered granite |
|----------------------------------|---------------------|------------|--------------|--------------------------|
| Elastic modulus (MPa)            | 6                   | 16         | 22000        | 24000                    |
| Density (kN/m³)                  | 1800                | 2020       | 2100         | 2200                     |
| Poisson's ratio                  | 0.4                 | 0.35       | 0.3          | 0.3                      |
| Internal friction angle (°)      | 5                   | 24         | 30           | 30                       |
| Cohesion force (kPa)             | 4                   | 22.2       | 0            | 3000                     |

In the whole model, the solid unit is used to simulate the soil, and the beam unit is used to simulate the surrounding piles, concrete support, and steel support.
4.3. Loads and boundary constraint

In the natural state, the soil is a semi-infinite space body, and the range selected in modeling is a limited soil space. Hence, constraints are added to make the calculation results converge. The constraints of this calculation are as follows:

(1) Stress condition

Each soil layer in the model is considered according to the natural weight, and the calculated load includes the structure, soil reinforcement, and the self-weight load of the soil.

(2) Boundary conditions

The boundary around the model restricts the displacement in the horizontal direction, and the displacement is free in the vertical direction. The bottom X, Y, and Z directions are fully constrained, which is a fixed boundary condition. The top ground is a free boundary.

(3) Initial conditions

The initial condition of the simulation is that the Shengli Bridge Station of Qingdao Metro Line 1 has been completed, and it has reached a stable equilibrium with the ground as the initial.

(4) Groundwater level

The groundwater level is not considered separately. The groundwater in Qingdao is mainly pore water, closely related to atmospheric precipitation. The rainy season of atmospheric precipitation is from July to September every year in Qingdao. The groundwater level rises from July, reaching the highest level from September to November, and then decreases gradually. The annual maximum precipitation is 1225.2 mm, and the annual average precipitation is 714 mm. Therefore, groundwater exerts minimal effect on the deformation and force of the deep foundation pit pile-support system in the soil–rock combination in the Qingdao area. In addition, the influence of “groundwater” on the deformation and stress of the deep foundation pit in the soil–rock composite stratum in the Qingdao area is not considered in the modeling.

4.4. Model building

The calculation area is selected according to the actual foundation pit engineering of Shengli Bridge Station of Qingdao Metro Line 1. A 3D numerical model is established, and the 3D eight-node solid reduction integral unit method is used for soil calculation. According to the geotechnical engineering survey report, the simulation situation of each soil layer is divided into four layers of soil from top to bottom, namely, miscellaneous fill layer, silty clay layer, sand gravel layer, and moderately weathered granite layer. When the model is established, the overall mesh density becomes finer as the foundation pit is reached because the stress is emphasized at the foundation pit. In addition, the maximum and minimum grid sizes are about five times different.

Figure 5. 3D model diagram
In the actual construction process, the retaining piles and crown beams are regarded as being anchored together. Therefore, when modeling, the retaining piles and crown beams are combined into one component for calculation, and the binding constraints are designed so that they do not produce relative sliding (Figure 6). The model foundation pit pile bracing system is shown in Figure 7.

Figure 6. Plan of retaining piles and crown beams

Figure 7. Foundation pit pile-support system plan

5. Numerical simulation results analysis

Before the excavation of the foundation pit, the construction of the enclosing pile and crown beam is first simulated. The model displacement and the calculation cloud of the enclosing pile and crown beam are shown in Figures 8 and 9, respectively.
**Figure 8.** Stress nephogram of displacement at the end of construction of retaining piles

**Figure 9.** Stress nephogram of retaining piles and crown beams

As shown in Figure 9, the enclosing pile produces an obvious embedded section regardless of whether it is in the middle or at the positive corner when the foundation pit is not excavated and the enclosing pile is separately stressed. The pile body is in the embedded section and the soil. A sudden change in stress value occurs at the boundary of the body, the stress concentration area is 2–3 m, and the stress value on the upper part of the pile body is relatively small. Before excavation, the maximum stress is the connection between the retaining piles and the crown beams.

The soil displacement around the foundation pit changes with excavation, as shown in Figures 10(a)–10(d).
The simulation calculation of foundation pit excavation is shown in Figure 10. With the continuous increase of the excavation depth of the foundation pit, the horizontal displacement area of the soil near the empty surface in the pit gradually expands to the outside, and the amount of soil deformation inside the foundation pit also continuously increases. During excavation, the soil is displaced and deformed into the pit, and the shear stress value continues to increase to form a plastic zone. This result is attributed to the active soil pressure inside the pile. When the excavation is completed, the maximum displacement of soil around the foundation pit occurs in the middle area, and the maximum displacement is 8 mm. The displacement calculation nephogram shows that the distribution law of the displacement field of the soil around the foundation pit is similar to that of the circular slip surface, which indicates that the circular sliding slice method can be reasonably and effectively used to evaluate the overall stability of the foundation pit in the retaining structure of the foundation pit. The stress changes in the excavated layer are shown in Figures 11 (a)–11(d), and the stress changes of the retaining pile and support at the end of excavation are shown in Figures 12 and 13.
Figure 11. Stress nephogram during foundation pit excavation: (a) excavation to first support, (b) excavation to second support, (c) excavation to third support, (d) excavation to fourth support.

Figure 12. Stress nephogram of retaining pile after foundation pit excavation.
**Figure 13.** Stress nephogram of the brace after foundation pit excavation

As shown in Figure 13, with the continuous increase of the excavation depth of the foundation pit, the unloading of the free surface of the excavation leads to the continuous release of the soil stress and the downward extension of the stress release area. As the excavation continues, the relative position of the maximum displacement generated by the pile also moves downward. The computational cloud image shows that the enclosing pile body produces a significant stress concentration area, and the deformation of the enclosing pile body gradually changes from a forward inclination into a “)” type curve as the excavation process continues. The brace is the main force-bearing member in this calculation. Through calculation, the maximum stress value is the connection between the fourth steel brace and the retaining pile, and the maximum value is 58.6 MPa.

During excavation, when the support begins functioning, most stress of the envelope structure will be transferred to the support. With the continuous excavation, each support gradually begins to bear the load, and the force of the retaining pile and the crown beams becomes more uniform. This result indicates that the pile-support system can perform coordinated force work well. When the first support is stressed, although the depth of a single excavation is equivalent to the previous excavation distance, the incremental displacement of each time gradually decreases. When the fourth support is in effect, the incremental displacement is only the first 10% in the case of three supports, which shows that the pile-support system has a strong control effect on soil deformation.

The cumulative graph of axial force with the excavation process is obtained by calculating the axial force of the first concrete support, as shown in Figure 14.
With the continuous excavation of the soil, when the second support is erected and starts to function because the second support takes part of the force at this time, the force of the first support shows a gradually decreasing trend, and then the force of the first support no longer fluctuates greatly.

6. Conclusions and discussion

This study used the Shengli Bridge Station of Qingdao Metro Line 1 as an engineering example. The combination of monitoring analysis and numerical simulation was adopted to investigate the stress characteristics and mechanical mechanism of the pile brace system envelope during deep foundation pit excavation under complex geological conditions that soil and rock are mixed. The main conclusions are as follows:

(1) During foundation pit excavation, the deformation of the envelope pile gradually changes from the forward inclination to the arch curve “).” With the construction, the maximum displacement point of the pile gradually moves downward. The maximum deformation is observed during the installation of the two supports behind the foundation pit, which indicates that the erection of the latter two supports significantly influences the spatial effect and other construction factors during the foundation pit excavation.

(2) Due to the action of active earth pressure on the inner side of the pile, the displacement and deformation of the soil moving into the pit occur. The shear stress value also increases continuously, thus forming a plastic zone. The distribution law of the soil displacement field around the foundation pit is similar to the circular arc slip surface, which shows that the arc sliding strip method can be reasonably and effectively used to check the overall stability of the foundation pit when designing the foundation pit retaining structure.

(3) When the axial force is applied, the soil is subject to horizontal compression, which will produce compaction deformation. However, creep occurs with time, causing the local stress of soil to dissipate and the axial force of support to reduce. Meanwhile, the continuous excavation of earthwork and the erection of the next support make the axial force gradually stable and finally reach a reasonable value. Therefore, the change in supporting axial force is basically synchronous with the displacement of the retaining piles. In the construction processes of similar projects, the period that the foundation pit has no support should be reduced to decrease the rate of engineering accidents.

(4) During the excavation and support of the foundation pit, support is the main force member of the foundation pit enclosure structure. When the support begins functioning, most stress of the envelope
structure is transferred to the support. With the continuous increase in the excavation depth of the foundation pit, each support gradually begins to bear the load. When the first support is stressed, the incremental displacement of each time gradually decreases; when the fourth support is in effect, the incremental displacement is only the first 10% in the case of three supports. At this time, the force of the retaining pile and the crown beams became more uniform. The above results show that the pile-support system can perform coordinated force work well.

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**Data availability**
The data adopted to support the findings are included in the article.

**Conflicts of interest**
The authors declare no conflicts of interest regarding the publication of this paper.

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