Numerical simulation study of eye-shaped foundation pit

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Abstract. In order to study the stability of the "eye-shaped" foundation pit support, the rectangular and the "eye-shaped" deep foundation pit are studied by using the numerical simulation software Midas GTS NX. The results show that the rectangular deep foundation pit is subjected to lateral extrusion and the maximum lateral displacement exceeds 6m. In practical engineering, the foundation pit has been destroyed and collapsed. Therefore, the safety of rectangular deep foundation pit without internal support is very poor. For the "eye-shaped" foundation pit, the lateral displacement at different vertical depths shows obvious characteristics of soil layer, in which the silty clay layer increases sharply, which is a weak layer liable to damage. The tight effect of middle weathered rock is remarkable due to different strength of silty clay layer and weathered rock layer, and the negative displacement at the top appears. The lateral displacement of the wall in the transverse inner wall region is significantly smaller than that in the circular arch region. The maximum lateral displacement of the wall is 2.96 cm at the intersection of the two "arches" in the transverse region and the vertical one at the silty clay layer. Along the depth of excavation, the uplift value is excavated by 1> excavation and 3> excavation 2. The research results fully prove that the eye-shaped foundation pit has good stability and the deformation is controlled within a reasonable range.

1. Introduction

The circular deep foundation pit is more and more widely used in underground engineering practice due to its unique advantages. The circular arch effect can make full use of the compressive performance of concrete, and the strong self-stability ability can effectively reduce the lateral displacement and deformation of the retaining structure, and ensure the stability and safety of the structure. Eye-shaped deep foundation pit is a new type of foundation pit support connected by several circles. It can not only give full play to the arch effect of circular deep foundation pit, but also reduce the project area, save a lot of internal support and reduce the project cost. It has a great development prospect in the future.

The scholars at home and abroad have done a lot of research on the circular-shaped deep foundation pit. Tian Zhen[1] and others have studied the factors affecting the resilience and the resilience rate of the circular deep foundation pit, including the area of the foundation pit, the depth of excavation, the depth of soil penetration of the retaining structure, dewatering, engineering piles, seepage pressure and other factors. The influence of piles on reducing the rebound of foundation pit is very significant. In general, the anti-uplift stability analysis method of foundation pit bottom can not consider the circular soil compression. Based on the nonlinear finite element method, Wang Weidong[2] proposed the strength reduction method for the anti-uplift stability analysis of foundation pit bottom under axisymmetric condition. The results show that the shape of the slip surface of the circular foundation pit is similar to that of the general foundation pit when the strength of the circular foundation pit is reduced to failure, but the slip surface of the circular foundation pit does not pass.
through the bottom of the retaining wall, but through the soil under the wall. On the basis of a
unloading model of foundation pit excavation, Wang Hongxin\cite{3} gives a safety factor of anti-uplift
stability which can consider the influence of the plane shape, dimension and insertion ratio of
foundation pit comprehensively. The analysis shows that when the diameter of the circular foundation
pit is large, the safety factor is unified with the safety factor of the ultra-wide strip foundation pit,
which indicates that the safety factor can be applied widely. Zhu Feng\cite{4} and others monitored the
deformation and internal force of the retaining structure of the circular deep foundation pit project.
The results show that the lateral deformation of the circular retaining structure is obviously smaller
than that of other shaped foundation pits under the same excavation depth, which embodies the
characteristics of the circular foundation pit under the circumferential force and the advantages of
deformation control. The excavation process is basically stable at the static earth pressure level, which
effectively reduces the lateral deformation of the retaining structure of the foundation pit. In view of
the actual situation of a circular deep foundation pit project in southwest China, Zhangjiaguo et al.\cite{5-7}
analyzed the row piles support by means of model test and numerical simulation, and put forward the
theoretical calculation method for determining the internal force and deformation of the row piles
frame structure of circular deep foundation pit. The theoretical calculation value is in good agreement
with the model test result, which indicates the theoretical calculation. The algorithm has definite
rationality.

To sum up, the research on circular deep foundation pit is more in-depth and extensive, but the
circular deep foundation pit project covers a large area and its application is limited. This paper puts
forward a new supporting method of foundation pit named "eye shape" for the first time, which can
give full play to the arched effect of circular foundation pit, occupy a small area, save resources and
cost. Therefore, the research on stability and deformation control of "eye shaped" foundation pit is
carried out. The research results are of great significance to the future development of the new type of
foundation pit support, and play a key role in the promotion of the "eye-shaped" foundation pit.

2. Project overview
The project is located in Shenzhen, the new high-speed shield tunnel and the new subway tunnel line
crossing, as shown in figure 1, in which the diameter of highway shield tunnel is about 15 m, the
distance between the left and right lines is about 50 m; the diameter of subway tunnel is 6.2 m, the
distance between the left and right lines is about 30 m.

According to the relationship between the cross section and the depth of shield tunneling in subway
and highway tunnels, the initial size of foundation pit is proposed. The large foundation pit on the
south side is 215 x 19 x 55 (long x wide x deep), and the small foundation pit on the north side is 125
x 19 x 55 (long x wide x deep).

Because of the large scale of the foundation pit, the optimization scheme is put forward, that is, the
"eye-shaped" foundation pit is adopted, and the concrete schematic diagram is shown in figure 2.
3. Model establishment and parameter selection

3.1 the establishment of geometric model
There are four intersections between the highway and the subway. There are two double hole foundation pits due to larger angles and foundation pit dimensions in the north, two four-hole foundation pits due to smaller angles and foundation pit dimensions in the south. Considering more disadvantageous to stress of large-scale foundation pit and saving calculation time, it is proposed to select the four-hole type foundation pit on the south side. According to the symmetry principle, The half of the rectangular deep foundation pit is selected in the original contrast scheme.

According to the design scheme, the South (left) foundation pit is selected as the main analysis object, 1:1 3D solid model was build by using a Midas GTS NX , as shown in figure 3.

3.2 Selection of parameters
According to geological investigation report, the regional strata of deep foundation pit are divided into fill, fine sand, silty clay and weathered limestone. The model parameters of various materials are shown in table 1.

| Name                  | Cohesive force (kPa) | Internal friction angle (°) | Deformation modulus (MPa) | Poisson ratio | Severe (kN/m³) |
|-----------------------|----------------------|-----------------------------|---------------------------|---------------|----------------|
| Filling               | 15                   | 8                           | 6                         | 0.3           | 18.5           |
| Fine sand             | 2                    | 32                          | 24                        | 0.28          | 17.5           |
| Silty clay            | 19                   | 17                          | 9                         | 0.3           | 18.5           |
| Moderately weathered  | 300                  | 30                          | 500                       | 0.35          | 22.5           |
| limestone             | Ground wall          | Concrete casing             |
|                       | —                    | —                           | 31500                     | 0.25          | 25             |
|                       | —                    | —                           | 32500                     | 0.25          | 25             |

3.3 calculation condition
Considering the influence of different excavation depth on the safety of foundation pit support, the same excavation conditions are set for the two types of foundation pit excavation. The support depth is the same as the excavation depth. Excavation conditions are as follows:

Excavation 1: the upper part of the silty clay layer will be dug (depth 11.3m). Excavation 2: dredge the silty clay layer to the top of the middle weathered limestone (depth 20.5M), then support. Excavation 3: Excavation in middle weathered rock to concrete casing bottom elevation (depth 47m),
support; Excavation of 3+: Construction of diaphragm wall to 10 m below the elevation of concrete casing.

4. Analysis of calculation results

4.1 rectangular deep foundation pit

![Figure 4. Schematic diagram of value position](image)

As shown in figure 5 (a) and (b), the lateral displacement decreases sharply with the increasing depth of the foundation pit at the same horizontal distance, and tends to be stable after reaching a certain depth (20m). The curves of different horizontal distances are generally similar, but the lateral displacement and the amplitude of variation are different. At the same depth, the lateral displacement increases gradually with the increasing horizontal distance, and basically does not increase after 80 m. From the above analysis, it can be concluded that in the direction of the length of the foundation pit, the foundation pit is extruded laterally into a "I-shaped type". From sides to the middle of the foundation pit, the extrusion is becoming more and more serious. In the direction of depth, the extrusion from the bottom of the foundation pit is getting more and more serious. Near the surface, the minimum lateral displacement of different horizontal distances is more than 1 m, and the maximum lateral displacement is more than 6 m. In practical engineering, the foundation pit has been destroyed and collapsed.

4.2 eye-type deep foundation pit

4.2.1 lateral displacement

For convenience of description, the special-shaped foundation pit diaphragm wall is divided into four zones according to the X-axis direction: 1, 2, 3 and 4. The values of A, B, C, D, E and F are along the X-direction respectively. A and F are in the "arch" of the boundary of diaphragm wall, B and D are in the "arch" of the 1 and 2 regions, C and E are in the "arch foot" (see figure 6). Figure 7 shows B and D lateral displacement of wall body, where (a) for area 1, (b) for area 2.
As shown in figure 7 (a), the lateral displacement at different vertical depths exhibits obvious soil characteristics. With the increase of depth, the lateral displacement of diaphragm wall decreases gradually at first, and increases sharply after entering the silty clay layer, because of the weak strength of silty clay. At the same time, with the increase of excavation depth, the overall lateral displacement of the diaphragm wall increases. From the silty clay layer, it can be seen that the lateral displacement increment of the diaphragm wall under different excavation depth is small, because the stress has been released after excavation. At the bottom of the diaphragm wall, due to the occurrence of bottom uplift and soil compression inward, so the curve of excavation 3+ is formed. Because the lateral displacement above the excavation layer is the lateral displacement of the diaphragm wall, and the lateral displacement below the excavation layer is the lateral displacement of the soil layer where the diaphragm wall has not yet been constructed, there is no curve characteristic like excavation 3+ in the case of excavation 1 and excavation 2.

As shown in figure 7(b), the overall trend and mechanism are consistent with that of figure 7 (a). The most obvious difference is that the lateral displacement at the top of the diaphragm wall is large, which is caused by the uneven distribution of strength due to the diaphragm wall arch effect.

The distribution of horizontal displacement (X direction) of C and E is shown in figure 8, where (a) for area 1, (b) for area 2.
The greater difference is that the top of figure 8 produces outward deformations between figure 7 and figure 8. Negative displacement occurs at the top of the diaphragm wall due to the lower strength of the soil layer above the silty clay layer and the stress release at the surface. Where under the silty clay layer, due to the larger lateral extrusion of the weathered limestone, negative displacement disappears.

Under different excavation conditions, the relationship between the lateral displacement (X direction) and the node in the filling depth is obtained as shown in figure 9, in which the node is considered to be equidistant distribution, where (a) for lateral displacement of wall under the same depth, (b) for maximum lateral displacement under different working conditions.

It can be seen from figure 9 (a) that the lateral displacement of the wall exhibits obvious fluctuation characteristics at the same depth. In the region with transverse inner wall, the lateral displacement of the wall is significantly smaller than that in the area with circular arch, which indicates that the lateral inner wall area has obvious supporting effect on the lateral wall of foundation pit. At the same time, due to the size effect of the foundation pit (the length direction is much larger than the thickness direction), the maximum lateral displacement occurs near the middle of the "arch 2" area. The maximum lateral displacement of the wall can be obtained at the intersection of the two "arches" in the transverse region and the silty clay layer vertically. Under different excavation conditions, the maximum lateral displacement outside the wall is shown in figure 9 (b), and the maximum lateral displacement outside the wall is 2.96 cm.

4.2.2 Bottom uplift
As shown in figure 10, the bulge at the center of the circular diaphragm wall is larger, because the circular side is blocked by the diaphragm wall, so the bulge at the center is larger and the bulge at the side is smaller. The overall uplift value of 1 excavation is larger due to the bottom is weak silty clay layer. Because the bottom of excavation 2 and excavation 3 are both weathered limestone, but the depth of excavation 3 is larger and there is greater in-situ stress, so the bottom uplift value of excavation 3 is greater than the bottom uplift value of excavation 2.

5. Conclusions and Recommendations

This paper analyzes the lateral deformation characteristics and the uplift stability of rectangular deep foundation pit and eye shaped deep foundation pit. The conclusions are as follows:

(1) For the rectangular deep foundation pit, the pit is extruded into I-shape by lateral compression in the length direction of the foundation pit. The minimum lateral displacement of different horizontal distances is more than 1 m and the maximum lateral displacement is more than 6 m near the surface. In practical engineering, the foundation pit has been destroyed and collapsed. It can be seen that the safety of rectangular deep foundation pit without internal support is very poor.

(2) For the "eye-shaped" foundation pit, the lateral displacement at different vertical depths in the arch shows obvious soil characteristics. With the increase of excavation depth, the lateral displacement of diaphragm wall increases, and the lateral displacement of silty clay increases sharply, which is a weak soil layer prone to failure. When excavated to the bottom of the diaphragm wall, due to the bottom uplift, the soil will be squeezed inward, and the lateral displacement curve will appear obvious extreme point. The lateral displacement of the arch foot is similar to that of the arch. On both sides of the wall, negative displacement occurs at the top, that is, the diaphragm wall deforms to the outside, and the great difference of strength between silty clay and weathered rock leads to the significant tightening effect of the weathered rock layer, which results in negative displacement at the top of the wall.

(3) In the weak soil layer, the lateral displacement of the wall at the same depth shows obvious fluctuation characteristics. In the region with transverse inner wall, the lateral displacement of the wall is significantly smaller than that in the area with circular arch, indicating that the lateral inner wall area has obvious supporting effect on the lateral wall of foundation pit. At the same time, the maximum lateral displacement occurs in the 2 "arch center" near the middle area, which has obvious size effect. The maximum lateral displacement of the wall is 2.96 cm at the crossing of the 2 "arch" in the transverse region and the vertical one at the silty clay layer.

(4) The uplift of the center of the diaphragm wall is larger and the side heave is small. Along the depth of excavation, the uplift value is excavated 1> excavation 3> excavation 2.

(5) The silty clay layer is the weak layer in the process of excavation, and the problem of supporting and excavation depth of silty clay layer can be further studied.
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