Finite Element Analysis of the Influence of Deep Foundation Pit Excavation Construction on Adjacent Subway Tunnel Structure

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Abstract: Foundation pit excavation construction is a widespread underground engineering activity in urban construction. More and more foundation pit projects are adjacent to existing subway tunnels. Through the engineering example, the thesis analyzes the influence of deep foundation pit construction supported by double-row piles on the structural safety of adjacent subway tunnels. Firstly, the risks of the project are analyzed, and then the structural safety control standard is determined according to similar engineering and related specifications. On this basis, the finite element numerical simulation software is used to calculate and analyze the deformation and force of the subway tunnel structure during the foundation pit construction, and the safety impact of the subway tunnel structure during the foundation pit construction is evaluated.

1 Preface

In order to alleviate traffic pressure and improve traffic conditions, China's urban subway construction is in the peak period of rapid development, and China has become the world's largest urban subway construction market [1]. With the increase in the development and utilization of underground space in large cities, more and more various engineering activities will be carried out around the existing subway tunnels, making more and more foundation pits to be constructed near existing subway tunnels. The impact of such construction on existing subway tunnels has become a focus of urban construction management. Foundation pit construction will cause changes in the stress field and deformation field of the soil around the tunnel, which may cause additional stress and displacement in the subway structure. If the additional stress exceeds the allowable value, the foundation pit engineering will affect the normal use and safety of the subway. The existing tunnels around the pit have large differences in response due to the depth of the foundation pit excavation, the relative position of the foundation pit, the form of foundation pit support, the site geological conditions, and the construction method. This shows that the impact of foundation pit excavation on adjacent subway tunnels is complex and variable. Therefore, the impact of foundation pit excavation on existing subway tunnels and its corresponding safety control measures are paid more and more attention. Under such a background, how to correctly quantitatively evaluate and predict the impact of foundation pit excavation on subway tunnels becomes an urgent problem to be solved [2-5].

2. Engineering Overview

2.1 Proposed Project Overview

The proposed building consists of a main building and a podium. The main building is of 21 floors above ground with a frame structure and 4 floors underground with a framed-tube structure. And the podium is of 2~3 floors above and 3 floors underground with a frame structure. Both the main building and podium are
adopted piled raft foundation, and the foundation depth is about 17.8m. To the east of the foundation pit it is a certain running tunnel of the subway line 4 under construction. Both of the left and right lines of the running tunnel have been completed.

The plane size of the foundation pit is 63.35m (length from north to south) × 66.85m (width from east to west), and the maximum depth is about 18m. Double-row pile support is used on the side adjacent to the subway structure.

2.2 Overview of the Adjacent Subway Structure

The subway running tunnel is located on the east side of the project. The left line of the tunnel is constructed as the mining method and the right line is constructed as the shield method. Within the influence range of the foundation pit, there are mainly two types of cross-sections of the tunnel constructed as mining method, and movement joints are set at the transition section.

The typical cross-section 1 of the mining method is shown in Figure 1. The supporting parameters are as follows: excavation size 6.38m × 6.70m (width × height); φ 42 small duct, 150° range of arch; grid steel frame, 0.5m/truss; reinforcing mesh, φ 6.5, 150mm × 150mm, full-section inner and outer double-layer; 300mm initial support; 350mm second lining; the core soil is reserved for heading-and bench construction.

The typical cross-section 2 of the mining method is shown in Figure 2. The supporting parameters are as follows: excavation size 7.83m × 7.65m (width × height); φ 42 small duct, arch 120° range; grid steel frame, 0.667m/truss; reinforcing mesh, φ 6.5, 150mm × 150mm, full-section inner and outer double-layer; 300mm initial support; 400mm second lining; the core soil is reserved for heading-and bench construction.

The shield tunnel has an outer diameter of 6 m and a lining thickness of 300 mm for a circle.

2.3 Relationship between the project and the adjacent subway structure

The maximum depth of the foundation pit of this project is about 18.0m, the groundwater level is deep, and the dewatering construction is adopted. The double-row drilling slope-protecting pile is used in the
foundation pit near the subway section, which is divided into two types of piles. For pile No.1, the horizontal spacing is 1.8 meters, the double-row pile spacing is 2.9 meters; for pile No.2, the pile diameter is 0.9 meters, the pile spacing is 1.5 meters, and the double row pile spacing is 1.7 meters. The row piles + anchor cable support form is used for the east, west and north side of the foundation pit.

The double-row pile supporting structure is close to a subsurface tunnel of the left line of Xi’an Metro Line 4. The section size of the tunnel adjacent to No. 1 double-row pile is 6.38 m × 6.7 m, and the section size of the tunnel adjacent to No. 2 double-row pile is 7.83 m × 7.65 m. The horizontal distance from between the outermost layer of pile and the outer side of the tunnel structure is about 10.20m to 11.34m, and the horizontal clearance between the outermost layer of pile and the right-line shield tunnel is more than 28 m. Both piles are located in the subway control and protection zone. The plane relationship of the project and the subway tunnel is shown in Figure 3. The relative relationship between No.1 and No.2 double-row pile support and the subway is shown in Figure 4 and Figure 5.

3. Overview of Engineering Geology and Hydrogeology

The terrain of the proposed site is flat, and the elevation of the exploration point is between 395.56 and
396.79m, and the relative height difference is 1.23m. The geomorphic unit of the proposed site belongs to the Liang Wa (ridge and low-lying) landform. The main soil layers in the excavation area of the foundation pit are mixed fill, plain fill, new loess, loess, paleosol and silty clay. Except silty clay in layer 3-4 and silt and sand interlayer in layer 4-4, the other layers of soil are continuously distributed in the site, and the layer thickness is relatively uniform.

The groundwater depth of the site is 14.10~16.90m, and the corresponding elevation is 396.72~396.85m. The groundwater in the site is a type of phreatic water. The maximum annual variation of the groundwater level is about 2.0m. During the survey, the groundwater is at its normal level of the annual average water level. The technical parameters of each soil layer are shown in Table 1.

| Rock soil layer | 1-1 | 1-2 | 3-1-1 | 3-1-2 | 3-2-2 | 3-4 | 3-7 | 4-1-2 |
|-----------------|-----|-----|-------|-------|-------|-----|-----|-------|
| Name of soil    |     |     |       |       |       |     |     |       |
| Natural weight  |     |     |       |       |       |     |     |       |
| Dry unit weight |     |     |       |       |       |     |     |       |
| Deformation modulus | MPa | 8.4 | 9.2  | 14.8  | 7.7  | 12.1 | 8.4 | 9.2  |
| Shear parameter |     |     |       |       |       |     |     |       |

### 4. Engineering Risk Analysis and Control Standards

#### 4.1 Engineering Risk Analysis

As the project is adjacent to the Metro Line 4 tunnel, there may be the following risks:\(^{6-7}\):

1. The site is distributed with collapsible soil layer, and the collapse of the bored hole of the poured pile will cause deformation of the adjacent subway structure;
2. The soil body is deformed toward the inner side of the pit due to the normal excavation of the foundation pit, and the sectional tunnel is also deformed toward the foundation pit;
3. Due to the lateral deformation of the sectional tunnel and the one-side excavation of the foundation pit, the internal force of the tunnel is redistributed, which causes deformation, cracking and even leakage of the tunnel structure;
4. Unloading along the longitudinal direction of the sectional tunnel may cause the radius of curvature and relative variation of the longitudinal deformation curve of the undercut tunnel to exceed the limit, thus affecting the normal operation of the subway.

#### 4.2 Structural Safety Control Standards

Referring to similar engineering and related specifications at home and abroad \(^{8}\), it is determined that the deformation control criteria for the calculation of the line for the tunnel are as follows:

1. The absolute settlement of the sectional tunnel is \(\leq 20\text{mm}\), the absolute horizontal displacement is \(\leq 20\text{mm}\), and the radial convergence is \(\leq 20\text{mm}\) (including the final displacement of various loading and unloading).
2. The radius of curvature of the longitudinal deformation curve of the tunnel structure is R>15000m; the relative variation is <1/2500;
3. Differential settlement of deformation joints <4mm.

### 5. Numerical Simulation Analysis

#### 5.1 Calculation Model
The foundation pit excavation construction has a vertical unloading effect on the soil below the excavation surface, and has a horizontal unloading effect on the side soil. Unloading will cause the soil to rebound, and the foundation pit supporting structure is subjected to earth pressure. Deformation will occur in the foundation pit. At the same time, the vertical pressure of the soil will support the uplift of the soil at the bottom of the pit. When a subway tunnel passes near the foundation pit or under the bottom of the pit, the excavation of the foundation pit will inevitably cause the change of the stress field and deformation field of the tunnel surrounding rock, and cause additional stress and deformation in the adjacent tunnel. When the foundation pit is unloaded, the loss of the formation will be transmitted to the soil and structure around the subway tunnel, which will cause the change of earth pressure at the top of the subway tunnel and will change the stress and displacement of the tunnel structure. In the calculation and analysis, not only the excavation range of the foundation pit, but also the magnitude of the unloading modulus parameter has an influence on the stress field and the displacement field of the adjacent subway tunnel.

Through the finite element program Midas/GTS NX, the impact of the construction of the project on the subway tunnel is analyzed. Firstly, the dynamic excavation of the foundation pit is simulated, and the deformation of the sectional tunnel is observed. A two-dimensional model was built at each unfavorable location for simulation, and finally a three-dimensional overall model was built to simulate the dynamic construction of the project.

5.2 Two-dimensional Calculation and Analysis

5.2.1 Simulation calculation of No.1 double-row pile

(1) Calculation model

(2) Displacement field

Through calculation, the horizontal and vertical displacement distribution of the retaining pile and the sectional tunnel are as shown in Figure 7 and Figure 8:
It can be seen from the above figure that at the most unfavorable section of No.1 double-row pile, the maximum horizontal displacement of double-row pile after foundation pit excavation is 12mm, less than \( \min\{0.15\%h, 25mm\} \). The displacement of the tunnel in the left-line which used mining method occurs at the inverted arch, and its value is 8 mm, which is less than the control value of 20 mm. The maximum displacement of the tunnel in the right-line which used shield method also occurs at the inverted arch, and its value is 4 mm, which is less than the control value of 20 mm.

At the most unfavorable section of No.1 double-row pile, after the excavation of the foundation pit is completed, the maximum vertical displacement of the tunnel in the left-line with mining method occurs at the arch waist at the side near the foundation pit, which is 11 mm, less than the control value of 20 mm. The maximum displacement of the tunnel with shield method occurs at the vault, and its value is 11 mm, which is less than the control value of 20 mm. The radius of curvature of the longitudinal deformation curve of the sectional tunnel is \( R = (60/4)^2/0.011 = 20455 \text{m} \geq 15000 \text{m} \), which satisfies the control standard.

(3) Internal force of the tunnel constructed with mining method

Through calculation, it is found that the internal force distribution of the tunnel with mining method before and after excavation is shown in Figure 9 and Figure 10.

It can be seen that the bending moment value distribution changes from symmetry to asymmetry due to the unloading action of the foundation pit excavation, and its maximum value also increases. The maximum positive bending moment is increased from 82.1kN.m to 99.4kN.m; the maximum negative bending moment is increased from 65.7kN.m to 99.4kN.m.

In summary, under the condition of excavation of the foundation pit, the reinforcement and crack of the
tunnel structure, constructed with mining method, which related to the No.1 double-row pile meet the requirements. The construction of the foundation pit in this section will not have a significant impact on the tunnel structure of the left line of the subway.

(4) Internal force of the tunnel constructed with shield method

Through calculation, it is found that the internal force distribution of the tunnel constructed with shield method before and after the foundation pit excavation is shown in Figure 11 and Figure 12.

![Figure 11 Distribution of Bending Moment before Excavation](image1)

![Figure 12 Distribution of Bending Moment after Excavation](image2)

It can be seen that the bending moment value distribution changes from symmetry to asymmetry due to the unloading action of the foundation pit excavation, and its maximum value also increases. The maximum positive bending moment increases from 99.4kN.m to 133.2kN.m; the maximum negative bending moment increases from 100.5kN.m to 134.6kN.m. The calculation method and process are the same as the former left-line sectional tunnel. The calculation results show that the structural strength meets the requirements, and the maximum crack width is 0.075mm<0.2mm, which satisfies the requirements.

5.2.2 Simulation calculation of No.2 double-row pile

(1) Calculation model:

![Figure 13 Calculation Model](image3)

(2) Displacement field
Through calculation, the horizontal and numerical displacement distribution of the retaining pile and the sectional tunnel are shown in Figure 14 and Figure 15.

![Figure 14 Horizontal Displacement Field of Foundation Pit](image1)

![Figure 15 Vertical Displacement Field of Foundation Pit](image2)

It can be seen from the above figure that at the most unfavorable section of No.2 double-row pile, the maximum horizontal displacement of double-row pile after foundation pit excavation is 10mm, less than \( \min\{0.15\% h, 25mm\} \). The horizontal displacement of the left-line tunnel constructed with mining method occurs at the inverted arch, and its value is 8mm, which is less than the control value of 20mm. The maximum horizontal displacement of the right-line tunnel constructed with shield method also occurs at the inverted arch, which is 3mm, less than the control value of 20mm.

At the most unfavorable section of No.2 double-row pile, after the excavation of the foundation pit is completed, the maximum vertical displacement of the tunnel in the left-line with mining method occurs at the arch waist at the side near the foundation pit, and its value is 11 mm, which is less than the control value of 20 mm. The maximum vertical displacement of the tunnel with shield method occurs at the vault, and its value is 9 mm, which is less than the control value of 20 mm. The radius of curvature of the longitudinal deformation curve of the tunnel is \( R = \frac{60}{420.011} = 20455m \geq 15000m \), which satisfies the control standard proposed by the pre-evaluation.

(3) Internal force of the tunnel constructed with mining method

Through calculation, it is found that the internal force distribution of the tunnel with mining method before and after excavation is shown in Figure 16 and Figure 17.

![Figure 16 Distribution of Bending Moment before Excavation](image3)
Figure 17 Distribution of Bending Moment after Excavation

It can be seen that the bending moment value distribution changes from symmetry to asymmetry due to the unloading action of the foundation pit excavation, and its maximum value also increases. The maximum positive bending moment increases from 108.1kN.m to 132.9kN.m; the maximum negative bending moment increases from 95.0kN.m to 143.3kN.m.

In summary, under the condition of excavation of the foundation pit, the reinforcement and crack of the tunnel structure, constructed with mining method, which related to the No.2 double-row pile meet the requirements. The construction of the foundation pit in this section will not have a significant impact on the tunnel structure of the left line of the subway.

(4) Internal force of the tunnel constructed with shield method

Through calculation, it is found that the internal force distribution of the tunnel constructed with shield method before and after excavation is shown in Figure 18 and Figure 19.

Figure 18 Distribution of Bending Moment before Excavation

Figure 19 Distribution of Bending Moment after Excavation

It can be seen that the bending moment value distribution changes from symmetry to asymmetry due to the unloading action of the foundation pit excavation, and its maximum value also increases. The maximum positive bending moment increases from 101.7kN.m to 134.2kN.m; the maximum negative bending moment increases from 97.5kN.m to 130.3kN.m. The calculation method and process are the same as the former left-line tunnel. The calculation results show that the structural strength meets the requirements, and the maximum crack width is 0.072mm<0.2mm, which satisfies the requirements.

5.3 3D Calculation and Analysis

5.3.1 Establishment of three-dimensional model of foundation pit
According to experience, the determination of model size follows the rule that the model boundary shall be more than 3 times of the pit depth. And finally the model size is: 150m×100m×50m. The three-dimensional model is shown in Figure 20 and Figure 21.

5.3.2 Calculation Results
The horizontal and vertical deformation of the tunnel structure under the most unfavorable working conditions in the foundation pit excavation are shown in Figure 22 and Figure 23.
(1) The foundation pit is obliquely above the tunnel. Due to the unloading effect, after the foundation pit is excavated, the subway sectional structure is deformed toward the foundation pit, the maximum horizontal displacement is 5.1mm, and the maximum vertical displacement is 4.7mm;
(2) The deformation mainly occurs in the tunnel with mining method, which is near the foundation pit, and the tunnel with shield method, which is far away from the foundation pit, is basically free of deformation;
(3) In the range of 10m, under different excavation and loading conditions, the differential deformation at the tunnel track is 2mm, not exceeding 4mm.
6. Conclusion

By summarizing the examples of foundation pit engineering along the Xi'an subway, this paper proposes a targeted technical route for subway protection assessment, and studies the quantitative analysis method of the influence of foundation pit construction on the subway tunnel structure\cite{11}, which can be used for similar engineering design and construction. To learn from. The main conclusions are as follows:

(1) In order to meet the requirements of structural deformation control indicators for subway tunnels, foundation pit engineering should adopt different support systems according to different geology and depth. For double-row pile support, if necessary, the pile diameter, pile spacing, row spacing and the crown beam can be adjusted, and anchor cables can be added, for controlling deformation;

(2) The tunnel located near the foundation pit changes from the symmetrical stress state to the bias state after the excavation of the foundation pit. The earth pressure on the tunnel side far away from the foundation pit increases, and the earth pressure on the tunnel side near the foundation pit decreases due to the influence of the excavation and unloading of the foundation pit. Finally, it expresses that the bending moment of the tunnel spandrel near the foundation pit is increased, and the earth pressure on the tunnel spandrel far away from the foundation pit is reduced.

(3) From the analysis of the influence range of the surrounding stratum deformation caused by the excavation of the foundation pit, the deformation of the stratum and the tunnel structure outside the foundation pit decreases rapidly with it going away gradually from the foundation pit. The general influence range is about 1.5 times the pit depth.

(4) The foundation pit is obliquely above the sectional tunnel. Due to the unloading effect, after the excavation of the foundation pit, the overall structure of the subway section is deformed toward the direction of the foundation pit.

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