Analysis of the influence of subway entrance excavation on tunnel and adjacent buildings

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Abstract. With the rapid development of urban subway transit construction, the construction of subway entrance and exit accessory structure in densely populated areas and near buildings is gradually increasing. Based on the open-cut foundation pit project at the entrance and exit of subway R3 line in Jinan city, this paper adopted MADIS GTS/NX 3D finite element analysis software to conduct finite element analysis on the connection tunnel and adjacent buildings by subway entrance and exit foundation pit excavation, and analyzed the displacement change trend of foundation pit excavation on the underground tunnel and building. The results show that the horizontal displacement of the connection area between the tunnel and the foundation pit is small, while the vertical displacement of the tunnel is relatively large, with a maximum value of 3.58mm. The settlement at the corner of the building adjacent to the foundation pit is relatively large, and the maximum settlement value is 3.03mm. It is in good agreement with the measured data and meets the requirement of deformation control. This study provides reference for the foundation pit engineering of subway entrance and exit of similar adjacent buildings.

1. Introduction
With the rapid development of urban subway transit construction, the underground space resources are expensive and various underground structures are more compact. The construction of subway exit and entrance accessory structures in densely populated areas and adjacent buildings is gradually increasing. Several scholars and technicians⁵-⁷ at home and abroad have analyzed the deformation law of tunnels and adjacent buildings caused by foundation pit excavation and obtained certain research results. Pan Jiurong⁵ analyzed and summarized the deformation theory of deep foundation pit engineering, and used FLAC3D to conduct numerical simulation of the whole process of deep foundation pit excavation before and after soil reinforcement. The influence law of foundation pit excavation on adjacent buildings is summarized, which provides a reference for the selection of engineering reinforcement measures. Fang xintao⁶ through the finite element software PLAXIS, the Hardening-Soil (HS) model for subway deep foundation pit excavation and supporting of the simulation, the influence of excavation on surrounding buildings are analyzed. Ma Qi’ang⁷ summarized the research status of...
surrounding stratum deformation and seepage consolidation theory caused by foundation pit excavation, and studied the influence of foundation pit dewatering speed on adjacent subway tunnel. The sensitivity analysis, unidirectional seepage stress coupling analysis and complete seepage stress coupling analysis were also done. In this paper, the open-pit excavation at the entrance and exit of the R3 line of Jinan city is taken as an example. By using the MADIS GTS/NX three-dimensional finite element analysis software, the whole-process excavation simulation of the open-pit excavation at the entrance and exit is carried out, and the influence rule of the excavation on the deformation of the west tunnel and the east building is analyzed, so as to provide reference for the design and construction of similar projects.

2. Background

2.1. Project overview
This project is located at the municipal greenbelt on the east side of Longding Avenue, R3 line, Jinan city. This area belongs to the low hill and hill geomorphologic unit, the terrain overall south high north low. The formation information from top to bottom is: (1) layer of plain fill soil, (2) layer of loess like silty clay, (3) layer of silty clay, (4) layer of gravel soil, (5) weathered limestone. Tunnel length is about 20m, section is straight wall section structure with arch roof, hole diameter is about 10m, height is about 6m, and the lining form is composite lining. The supporting structure of open excavation foundation pit consists of bored pile and internal support system, and water stop curtain is adopted to stop water. The excavation depth is about 0 ~ 12.8m. The tunnel is connected to the foundation pit, and the east side of the foundation pit is about 6 meters away from the two buildings.

2.2. Supporting form of foundation pit
The location relationship between foundation pit, underground tunnel and adjacent buildings is shown in figure 2-1. The length of foundation pit at subway entrance and exit is about 40m from north to south and 10m from east to west. The supporting form and supporting parameters adopted are: Bored pile with diameter of 800mm, pile spacing of 600mm. There are two steel support systems with a diameter of 609mm (t=16mm). The horizontal spacing of steel supports is 3.5m, and the excavation depth shall be considered as 0~12m. Section 1-1, 2-2, 3-3 of the support structure of the entrance and exit foundation pit is shown in figure 2-2, 2-3 and 2-4.

Fig.2-1 The location relationship
Fig.2-2 Section drawing of support structure
3. Numerical analysis

3.1. Establishment of computing model
In this paper, the finite element software Midas GTS/NX was used for numerical simulation analysis. The model size was 120m×100m×40m, and the excavation depth was 3~5 times as the distance from the foundation pit enclosure to the boundary of the 3D computational model. The stratum is simplified according to engineering geological data and geological survey data. The surrounding rock mass is defined as isotropic continuous medium, and is assumed to be an ideal elastoplastic material. The mole-coulomb elastoplastic model is used to simulate the soil mass with 3D solid element. 1D line element is used to simulate the foundation pit support, waist beam, building and basement structural column, and 2D plate element is used to simulate tunnel lining, floor slab and basement slab of each floor of the building. The calculation model is shown in figure 3-1 and 3-2.

3.2. Structural model
In order to simplify the model for easy calculation, this model simplifies the equivalent stiffness of retaining pile into underground diaphragm wall according to the principle of equivalent flexural stiffness, and adopts 2D element. Assuming that the diameter of piles is $D$ and the clear distance between piles is $t$, as shown in figure 3-2, a single pile is equivalent to an underground diaphragm wall of $D+t$ length and the wall thickness is $h$. From the principle of stiffness equivalence, it can be concluded that:

$$
\frac{1}{12} (D + t) h^3 = \frac{1}{64} \pi D^4, \\
h = 0.838 \sqrt[3]{\frac{1}{\frac{1}{D} + \frac{1}{t}}}
$$

3.3. Model calculation parameters
The mechanical parameters of each material are shown in table 1.
3.4 Simulation of construction conditions

Before the excavation of subway entrance and exit foundation pit, the simulation of original ground stress and underground tunnel excavation at the entrance and exit should be carried out first. After the displacement is cleared, the simulation of foundation pit excavation can be started. The construction conditions are: (1) calculation of initial stress field. (2) excavation of the first layer of soil. (3) erection of the first steel support. (4) excavation of the second layer of soil. (5) erection of a second steel support. (6) excavation to the bottom of the foundation pit. (7) pour foundation pit floor.

4. Finite element simulation results and analysis

4.1 Impact of entrance and exit foundation pit excavation on tunnel deformation

Based on the results of 3D numerical simulation, the deformation of underground tunnel under the excavation condition of subway entrance and exit foundation pit can be obtained. Figure 4-1, 4-2 and 4-3 are respectively the displacement cloud images of X, Y and Z directions of underground tunnels after foundation pit excavation. Figure 4-4, 4-5 and 4-6 are the displacement curves of X, Y and Z directions of underground tunnels under three working conditions of excavation, namely, the first layer of soil, the second layer of soil and the bottom of the pit. It can be seen from the figure that the excavation of the foundation pit causes additional horizontal stress moving towards the tunnel near the tunnel opening at the side of the foundation pit. The maximum X-direction deformation is at the pit wall on the right side of the mouth of the tunnel, with the maximum displacement of 0.42mm, and the maximum Y-direction deformation is at the arch of the mouth of the tunnel, with the maximum displacement of 0.38mm. Due to the influence of soil excavation unloading and other factors, the soil in the tunnel near the foundation pit bounceback greatly, resulting in vertical upward displacement. The maximum vertical displacement occurs at the bottom of the tunnel pit, and the maximum displacement is 3.58mm.

![Fig.4-1 X-direction displacement](image)

![Fig.4-2 Y-direction displacement](image)

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Tab.1 Material mechanics parameter list

| Serial number | Item          | Bulk density $\gamma$(kN/m$^3$) | Internal friction angle $\phi_k$(°) | Cohesive force $c$(kPa) | Compression modulus $E_s$(MPa) | Thickness (m) | Poisson ratio $\nu$ |
|---------------|---------------|----------------------------------|-----------------------------------|-------------------------|-------------------------------|----------------|---------------------|
| 1             | plain fill    | 19.0                             | 20.1                              | 44.0                    | 4.91                          | 3              | 0.4                 |
| 2             | Loess - like silty clay | 18.0                             | 14.8                              | 20.6                    | 5.48                          | 7.5            | 0.26                |
| 3             | silty clay    | 18.8                             | 13.1                              | 22.5                    | 4.78                          | 1.5            | 0.29                |
| 4             | Gravel soil   | 21.0                             | 37.0                              | 10.0                    | 30.00                         | 11.6           | 0.20                |
| 5             | Weathered limestone | 26.9                             | 39.0                              | 7.00.0                  | /                             | 43.0           | 0.23                |
| 6             | steel         | 78.50                            | /                                 | /                       | 6×10$^7$                      | /              | 0.20#               |
| 7             | concrete      | 25.00                            | /                                 | /                       | 6×10$^6$                      | /              | 0.30#               |

(Notice: “#” Indicates that the value takes empirical value.)
4.2. Influence of entrance and exit foundation pit excavation on deformation of adjacent buildings

Based on the results of 3D numerical simulation, the deformation of the building under the excavation condition of subway entrance and exit foundation pit can be seen. Figure 4-7, 4-8 and 4-9 are respectively the displacement cloud images of buildings in the X, Y and Z directions after foundation pit excavation. Figure 4-10, 4-11 and 4-12 are the displacement curves of the X, Y and Z directions of the buildings under three working conditions: excavation of the first layer of soil, excavation of the second layer of soil, and excavation to the bottom of the pit. It can be seen from the figures that in the process of foundation pit excavation, both the X and Y directions of buildings A and B tend to shift towards the direction of foundation pit, and the displacement of building B is relatively large. The maximum X-direction horizontal displacement of building A is 1.30mm, and the maximum Y-direction horizontal displacement is 1.21mm. The maximum X-direction horizontal displacement of building B is 2.02mm and the maximum Y-direction horizontal displacement is 2.34mm. The maximum Z-direction vertical displacement of the two buildings appeared at the corner point near the foundation pit, and the maximum settlement was 1.68mm and 3.03mm respectively.
5. Conclusion and summary

(1) The influence of excavation on tunnel excavation can be effectively reduced by using bored pile and internal support system. After foundation pit excavation, only slight displacement occurs in the tunnel opening area near the foundation pit, and the maximum displacement appears at the bottom of the tunnel mouth pit.

(2) The influence of entrance and exit excavation on the surrounding buildings is directly related to the distance. The building appears partial tilt, its maximum settlement appears in the corner of the building, the horizontal direction has the tendency of displacement to the foundation pit direction.

(3) Through three-dimensional numerical simulation, the displacement of each structure is obtained. Due to the good effect of the envelope structure, the construction process is relatively standard, the displacement changes of each structure do not exceed the control value, and the construction risk is safe and controllable, providing a reference for similar projects.

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