Numerical analysis of excavation stability of transfer station of Jinan Metro

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Abstract. The influence of the excavating deformation on the surrounding environment should be extremely controlled in the excavation of metro transfer station and it is important to study the stability of excavation. Here we establish three-dimensional finite element models with the fluid-solid coupling effect aimed to perform analysis on the stability of excavation based on the background of the Jinan metro transfer station in this paper. The location is determined through simulation in which the maximum horizontal displacement of diaphragm wall appears as well as the maximum ground surface settlement. The research results can provide useful reference in analysis and calculation for other similar underground engineering excavation and construction design.

Key Words: foundation pit, Three-dimensional numerical simulation, Diaphragm wall, ground settlement.

1. Introduction

The underground rail transit system is an important approach to alleviate urban traffic pressure and its intersections of different lines are generally designed as transfer stations resulting in that the excavation of transfer station is different from general station [1-4]. In addition, transfer stations are often located in areas with concentrated urban population and dense buildings, and thus it is necessary to strictly control its deformation and impact on the surrounding environment during the construction process as well as to perform analysis on the stability of excavation of transfer station [5, 6]. At present, the finite element method is widely used in the stability analysis of foundation pits [7, 8]. In particular, the three-dimensional finite element model can better reflect the spatial effect of the excavation, and the simulation results are closer to reality [9, 10]. Considering the hydrogeological characteristics of Jinan, a three-dimensional finite element model considering fluid-solid coupling effect is established to simulate excavation based on the metro transfer station of Jinan Long-Distance Bus station. The results of diaphragm wall displacement and ground surface settlement is analyzed,
which could provide references for the numerical simulation and design of other similar transfer station excavation projects.

2. Numerical Model

2.1. Model of soil and structure

Combined with the engineering background and the convergence requirements, the foundation pit plane is simplified to a rectangle with 90m long and 50m wide in the model, and a half of the model is taken due to the symmetry, as shown in Fig. 1. The Zone 1 is non-transfer area (two-story station), and the Zone 2 is the transfer area (three-story station), as shown in Fig. 2.

![Figure 1. Three-dimensional soil model](image1.jpg)

![Figure 2. Layout plan of diaphragm wall](image2.jpg)

The thickness of the external diaphragm wall is 0.8m and the depth is 28.9m, as shown in Fig. 3(a). While the internal diaphragm wall is located between zone1 and zone2 with a thickness of 1m and a height of 12.9m, as shown in Fig. 3(b).

![Figure 3. Diaphragm wall model](image3.jpg)

2.2. Model parameters

The Mohr-Coulomb model is used for soil and the Elastic model is used for concrete structure, as shown in Table 1.

| Soil layer                  | Bulk density / (kN·m⁻³) | Cohesion / kPa | Internal friction angle / (°) | Elastic modulus / MPa | Poisson's ratio μ | Permeability coefficient / cm/s |
|----------------------------|-------------------------|----------------|------------------------------|-----------------------|------------------|-------------------------------|
| Miscellaneous fill         | 15                      | 15             | 15                           | 20                    | 0.3              | 7×10⁻³                         |
| Silty clay                 | 15.2                    | 33             | 24                           | 9.2                   | 0.3              | 2.9×10⁻⁴                      |
| Strongly weathered diorite | 20                      | 35             | 35                           | 175                   | 0.3              | 1.2×10⁻³                      |
| Moderately weathered diorite | 23                   | 70             | 24                           | 40000                 | 0.14             | 1.2×10⁻⁶                      |
| Concrete                   | 25                      |                |                              | 31500                 | 0.3              |                               |
2.3. Modeling step

The modeling steps for the construction sequence are as follows: (1) the external diaphragm wall is constructed first; (2) the public soil layers of Zone 1 and Zone 2 would be excavated in 5 steps, and then, the internal diaphragm wall would be constructed; (3) the extra part of Zone 2 would be excavated in 3 steps. The initial groundwater level is located on the ground surface, which would be dropped lower than every bottom of the planned layer before excavating.

3. Numerical Results

3.1. Displacement of diaphragm wall

The numerical calculation results of displacement of external diaphragm wall are shown in Fig. 4 and Fig. 5, and the letters of the section are shown in Fig. 1.

![Displacement contour graph](image)

*Figure 4. Displacement contour graph in part AB of the diaphragm wall*

It can be seen from Fig. 4 that the horizontal deformation of the wall is symmetrically distributed along the center with the largest deformation at the center point and gradually decreasing toward both ends after the excavation of the public part of the Zone 1 and 2. With the Zone 2 continuing to excavate, the deformation in part AO no longer increases, while that in part OB increases, and the position of the maximum displacement point continues to move down. When the excavation is completed, the horizontal deformation of the entire AB is no longer symmetrically distributed in which the deformation of part OB is greater than AO and the maximum deformation is 17.6mm located at the depth of 18m in the OB area.
It is shown that the maximum horizontal displacement of part AB of diaphragm wall is not in its symmetry axis due to the particularity of excavation of transfer station as a result of that the supporting effect of the internal diaphragm wall between the transfer area and the non-transfer area on the part AB of external diaphragm wall. This effect would reduce the displacement of the external diaphragm wall at the vertical intersection with internal diaphragm wall, which would weaken with the increasing distance from the intersection. Therefore, the maximum displacement appears between the internal diaphragm wall and the middle of the transfer zone.

For the part AC and BD of the wall, the maximum horizontal displacements are at section C and D respectively due to the symmetry of the model. Curves of horizontal displacement of the wall in section C and D at different stages of excavation are shown Fig. 5.

![Figure 5. Curves of the displacement of the wall at different stages of excavation](image)

Fig. 5. indicates that after the excavation of the public part of the soil layer, the wall in the part AC stops the deformation with a maximum horizontal displacement of 18.3mm at the depth of 11m, while the deformation of part BD continues to increase as the excavation depth increases with a maximum horizontal displacement of 22.9mm at the depth of 18m.

### 3.2. Ground surface settlement

The impact of excavation on the ground surface settlement is also an important stability issue needed to be considered.
The law of ground surface settlement is similar to external diaphragm wall displacement. Fig.6 shows that after the excavation of Zone 2, the ground settlement is uneven that behind the wall of BD part is greater than that of AC part, and that of OB part is greater than AO and the maximum settlement behind the wall is 15.9 mm at 7m behind section D. The settlement curves show a groove shape within 40m behind the wall, which almost does not change outside 40m, as shown in Fig. 7.

4. Conclusion
The conclusions can be drawn as follows:
(1) The maximum horizontal displacement of the external diaphragm wall appears at the midpoint of its short side on the transfer area, which is 22.9mm at the depth of 18m.
(2) The displacement law of the long side of the external diaphragm wall is that in the excavation of the public part of the transfer and non-transfer area, the horizontal displacement of the wall is symmetrically distributed along the center, which decreases from center point to both ends. After the excavation of the transfer area, the maximum displacement appears between the internal diaphragm wall and the middle of the transfer area, which is 17.6mm at the depth of 18m.

(3) The maximum ground settlement appears at a position 7m behind the short-side middle on the side of the transfer area, which is 15.9mm; the settlement curve shows a groove shape within 40m, which almost does not change outside 40m.

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References
[1] Guo Jianmin, Wen-Jun Z. Potential Value Evaluation of Underground Space Resource Based on AHP Method [J]. Chinese Journal of Underground Space and Engineering, 2005, 5: 655-659+664. (in Chinese).
[2] Qin Yun, Dong Piling, Yu Mingjian. On the Line Planning of UMT and the Comprehensive Development of Urban Space[J]. Urban Mass Transit, 2006, 3: 9-11+17. (in Chinese).
[3] Hu Anfeng, Zhang Guangjian, Wang Jinchang, et al. Monitoring and numerical simulation of deformation of retaining structure excavation of a metro transfer station[J]. Chinese Journal of Geotechnical Engineering, 2012, 34(S1):77-81. (in Chinese).
[4] Ding Yongchun, Zhou Hongbo, Zhang Lulu. 3D numerical analysis of deep excavation for an interchange station of Suzhou Metro[J]. Chinese Journal of Geotechnical Engineering, 2008, 30(S1):173-177. (in Chinese).
[5] Fu Peishuai, Wang Shuguang, Tang Xiaowei, et al. Application of ABAQUS in Deep Foundation Design and Construction[J]. Journal of Water Resources and Architectural Engineering, 2017, 15(02):161-165. (in Chinese).
[6] Cong Aisen. Discussion on several issues of Seepage stability of deep foundation pit in multilayered formation[J]. Chinese Journal of Rock Mechanics and Engineering, 2009, 28(10):2018-2023. (in Chinese).
[7] Hsieh Pio-Go, Ou Chang-Yu, Lin Yi-Lang. Modelling of a 3D excavation in finite element analysis[J]. Acta Geotechnica, 2013, 8 (1):33-48.
[8] Ji Youjun, Liu Jianjun, Xue Qiang. Numerical simulation of seepage-stress interaction during foundationditch excavation[J]. Rock and Soil Mechanics, 2007, 28(S1):630-634. (in Chinese)
[9] Zheng Gang, Li Zhiwei. Finite Element Analysis of Adjacent Building Response to Corner Effect of Excavation[J]. Journal of Tianjin University, 2012, 45(08):688-699. (in Chinese).
[10] Finno Richard J., Blackburn J. Tanner, Roboski Jill F. Three-Dimensional Effects for Supported Excavations in Clay[J]. Journal of Geotechnical and Geoenvironmental Engineering, 2007, 133(1):30-36.