Structural stress analysis and surface settlement study of a subway station in Beijing

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Abstract: Taking a PBA construction method station of Beijing subway as the engineering background, Simulation of station construction process by MIDAS / GTS NX finite element software, and compare the simulation results with the on-site monitoring data. The stress of steel tube column and side pile, the main load components of the station, and the surface settlement caused by construction are analyzed. The analysis results show that (1) During the second lining construction stage, the axial force increments of steel tube columns and side piles are the largest, and the axial force increments account for 59.10 % and 51.98 %, respectively. This stage is the key stage to control the axial force;(2) The horizontal displacement curves of steel tube column and side pile show 'bulging' form, and the maximum value is located near the middle of steel tube column and side pile;(3) The transverse surface settlement is symmetrically distributed along the center line of the station, and the maximum value is 47.9 mm, which is located near the center line of the station. The larger settlement is mainly distributed in the range of 20 m from the center line of the station.

1. Introduction
With the development of social economy and the increase of travel volume, traffic problems have become increasingly prominent. Subway has gradually become an important measure to solve urban traffic[1-3]. Compared with other subway station construction methods, PBA method has the advantages of clear structural force transmission and small surface settlement[4-7], which has been widely used in the construction of Beijing subway station[8-10]. In recent years, many domestic experts and scholars have studied the PBA method. Yuan Yang[11] et al. simulated the excavation process of pilot tunnel under different schemes, and optimized the excavation sequence of PBA construction method. Using numerical simulation and analytic hierarchy process, Wei Jing[12] et al. studied the optimal construction scheme of pilot tunnel in Huayuanqiao Station of Beijing Metro. Jia Shitao[13] used MIDAS/GTS NX software to simulate the construction process according to the situation of PBA subway station crossing various soil layers, and studied the law of surface settlement caused during the construction process. Using FLAC³D, Liu[14,15] et al. studied the influence of different arching sequences on surface settlement and structural mechanical
behavior in PBA method. At present, the research on PBA method mostly focuses on the optimization of construction technology, the influence and analysis of construction on surface settlement, and the research on the stress of main load components of station structure is less. During the construction of PBA method, the stress conversion is frequent. As the main load components of station structure, it is necessary to study the stress situation of steel tube column and side pile, and analyze the law of surface settlement caused by construction.

Based on the engineering background of a subway station on Beijing Metro Line 19, this paper conducts a numerical simulation of its key construction steps and compares and analyzes with field monitoring data. The stress and horizontal displacement of the main load components of the station in the construction process are explored, and the surface settlement generated in the construction process is analyzed. It provides the basis for the popularization and application of PBA station in the future.

2. Project Overview

2.1. Project Introduction

The station is an underground excavation island platform station with a total length of 266.0 m and an effective platform width of 14 m. The standard section of the station is a three-layer double-column and three-span underground structure. Overlying soil on roof is about 14.64 m, the section width is 23.5 m, and the height is 23.97 m. The PBA method of four guide holes is used to dewatering construction. The north end of the station is the mining method section, and the south end is the shield section.

2.2. Engineering geology and hydrogeological conditions

The depth of the bottom plate is about 37.7 m, and the excavation depth mainly includes the following soil layers: miscellaneous fill(1), silty fine sand(4), Silt(6), pebble(9), pebble(11); The bottom plate is located on the pebble layer(9). The station mainly contains two layers of groundwater, namely interlayer diving (3) and interlayer diving(4). The stable water level elevation of interlayer diving(3) is 34.56~36.11 m, and the water level burial depth is 12.07~13.36 m. The stable water level elevation of interlayer phreatic water(4) is 16.42~17.71 m, and the water level burial depth is 30.60~31.45 m. Engineering geological sections and groundwater distribution are shown in Figure 1.

![Figure 1. Engineering geological section and groundwater distribution](image)

3. Numerical calculation model
3.1. Model establishment

This paper uses MIDAS/GTS NX finite element analysis software for numerical simulation. When the boundary size of the model is 3–5 times the size of the structure, the influence of construction excavation on soil is not obvious [16]. Therefore, the width of the model established in this paper is set to 120 m, the height is 60 m, and the longitudinal length along the station is 40 m. Normal constraints are applied to the front, rear, left, right and lower boundaries of the model, and the surface is a free boundary. The model size and grid division are shown in Figure 2. The grid division of the main structure of the station is shown in Figure 3.

![Figure 2. Overall model size and grid division](image)

![Figure 3. Grid division of station structure](image)

3.2. Model parameters

The soil in this model adopts elastic-plastic material, and Mohr-Coulomb constitutive model is selected. Station structure adopts linear elastic material, soil and station enclosure structure are established by solid element. The steel tube column is a concrete-filled steel tube composite structure, and the relevant parameters of the steel tube column are calculated according to the equivalent method. Establishment of beam element for extracting internal force of steel tube column and side pile. The soil parameters of this model are the same as those in geotechnical investigation report, and the soil layer is simplified to uniform distribution for numerical calculation. See Table 1 for calculation parameters of each soil layer, See Table 2 for Main Support Structure Parameters of Station.

| Soil layer number | Soil layer name   | $\gamma$/KN·m$^{-3}$ | $c$/KPa | $\phi$/° | $E$/MPa | Poisson ratio $v$ | $K_v$/MPa·m$^{-1}$ | $K_s$/MPa·m$^{-1}$ |
|-------------------|-------------------|-----------------------|---------|---------|---------|-----------------|-------------------|-------------------|
| ①                 | miscellaneous fill | 18.0                  | 5       | 8       | 20      | 0.30            | 35                | 40                |
| ④                 | silty fine sand    | 20.2                  | 0       | 30      | 80      | 0.22            | 32                | 42                |
| ⑥                 | silt               | 19.8                  | 21      | 30      | 40      | 0.30            | 60                | 70                |
| ⑦                 | pebble             | 21.5                  | 0       | 45      | 80      | 0.22            | 60                | 70                |
| ⑨                 | pebble             | 21.8                  | 0       | 45      | 80      | 0.22            | 60                | 70                |
| ⑪                 | pebble             | 22.0                  | 0       | 45      | 80      | 0.22            |                   |                   |

| Structural member       | $E$/MPa | Poisson ratio $v$ | $\gamma$/KN·m$^{-3}$ | $c$/KPa | $\phi$/° |
|------------------------|---------|------------------|----------------------|---------|---------|
| Steel tube column      | 39400   | 0.2              | 27.1                 |         |         |
| Side piling            | 30000   | 0.2              | 25.0                 |         |         |
| Grouting reinforcement  | 60      | 0.3              | 21.5                 | 60      | 35      |

3.3. Simulation of construction sequence
The pilot tunnel excavation shall be excavated in staggered distance according to the excavation sequence of the first side and then the middle, excavation footage set to 2m; grouting reinforcement before excavation and timely support. Further construction of side piles and steel tube columns, side crown beams and top longitudinal beams. The earthwork excavation and station structure construction are carried out in sequence from top to bottom. When excavating the soil, the middle span soil is excavated first and then the side span soil is excavated. The actual construction steps are properly integrated and simplified and divided into the following 10 main construction steps. The specific construction steps are as follows:(1) Form the initial ground stress field and clear the displacement;(2) Reinforce the stratum in advance, excavate the pilot tunnel in the order of 1342, and promptly perform initial support after excavation;(3) Construction side piles, steel tube columns, construction side crown beams, top longitudinal beams;(4) Break the middle wall and construct the second arch lining in the order of first middle and second side;(5) The excavation of the negative first layer of earthwork is completed;(6) Construction of the negative first-floor structure is completed;(7) The excavation of the negative second layer of earthwork is completed;(8) Construction of the negative second-floor structure is completed;(9) The excavation of the negative third layer of earthwork is completed;(10) The construction of the station structure is completed. The construction steps in the following are indicated by the serial numbers here.

4. Numerical simulation of steel tube column and side pile

4.1. Calculation results and analysis of axial force

Axial force calculation results are shown in Table 3.

| Construction step | Maximum axial force of steel tube column/kN | Proportion of axial force increment(%) | Maximum side pile axial force /kN | Proportion of axial force increment(%) |
|-------------------|--------------------------------------------|----------------------------------------|---------------------------------|----------------------------------------|
| (3)               | -1308                                      | 6.03                                   | -67                             | 1.83                                   |
| (4)               | -14105                                     | 59.10                                  | -1971                           | 51.98                                  |
| (5)               | -15226                                     | 5.17                                   | -2977                           | 27.46                                  |
| (6)               | -15405                                     | 0.83                                   | -3021                           | 1.20                                   |
| (7)               | -17665                                     | 10.43                                  | -3332                           | 8.49                                   |
| (8)               | -17926                                     | 1.20                                   | -3372                           | 1.09                                   |
| (9)               | -21252                                     | 15.35                                  | -3629                           | 7.01                                   |
| (10)              | -21665                                     | 1.91                                   | -3663                           | 0.93                                   |

According to the data in the table, the axial force curves of steel tube column and side pile are drawn, which reflect the axial force changes of steel tube column and side pile under various construction conditions as shown in Figure 4 and Figure 5. Analyzing the graph can draw: Steel tube column and side pile are mainly compressed in the construction process. As the construction progresses, the axial force continues to increase, and the axial force reaches the maximum after the structure construction is completed. The axial force values of steel tube column and side pile increased significantly during the construction of second lining. In this stage, the axial force increment of steel tube column accounts for 59.10 %, and the axial force increment of side pile accounts for 51.98 %. Indicates that this stage is the key stage for controlling the axial force. The reason is that with the completion of the second lining construction, the stress redistribution of the station structure occurs, and the upper load originally borne by the initial support of the arch is transferred, which is jointly borne by the steel tube column and side pile. After the completion of the second lining construction, both the steel tube column and side pile produce large axial force increment in the process of soil excavation. The reason is that the soil is no longer applied lateral resistance and side friction to the steel tube column and side pile after excavation, and the top arch further transmits the load downward. The internal force of steel tube column is larger than that of side pile, which plays a major supporting role and is one of the unfavorable positions of the structure.
4.2. **Horizontal displacement calculation results and analysis**

The horizontal displacement curves of steel tube column and side pile all show the “bulging” form. The maximum value of horizontal displacement increases with the construction sequence, and the maximum value is located near the middle of steel tube column and side pile and has a downward trend. Among them, the negative one layer, negative two layer and negative three layer earthwork excavation and structure construction curve almost coincide, which shows that the structure construction has little effect on the horizontal displacement. Fig.6 shows the variation curve of horizontal displacement of steel tube column with construction sequence. Fig.7 shows the variation curve of horizontal displacement of side pile with construction sequence.

The maximum horizontal displacement of steel tube column appears in the construction of the station structure, and the maximum is 3.8 mm. The maximum horizontal displacement of side pile appears in the construction of the station structure is completed, and the maximum is 12.2 mm. The maximum horizontal displacement of the side pile from the completion of the second lining construction to the excavation of the negative first layer of earthwork excavation has a large mutation, the change is 4.95 mm, accounting for 40.6% of the maximum horizontal displacement. It indicates that this process is a key stage for controlling horizontal displacement.

The steel tube column mainly produces displacement to the outside of the structure, and the side pile mainly produces displacement to the inside of the structure. The reason is: the soil on both sides of the steel tube column is excavated, and the upper load produces horizontal thrust to the outside of the structure on the steel tube column. The steel tube column is deformed to the outside. The excavation of the structure soil on the inner side of the side pile is affected by the lateral pressure of the soil behind the pile, which causes the deformation of the side pile to the inside of the structure.

5. **Numerical simulation of surface subsidence**
The surface settlement cloud chart after the completion of the station structure construction is shown in Figure 8. After the construction of the station structure, the maximum surface settlement is about 47.9 mm, and the maximum settlement occurs at the center line of the station. The larger settlement is mainly distributed within 20 m from the center line of the station. The surface transverse mid-section settlement curve shows a symmetrical distribution with the station centerline as the axis, as shown in Figure 9. The maximum value of surface settlement completed by the second lining construction is 42.5 mm, accounting for about 88.7% of the total settlement. It indicates that after the completion of the secondary lining construction, the surface settlement value changes little, and the surface settlement tends to be stable.

The surface settlement during the whole construction process is mainly caused by the excavation of the guide hole and the construction of the second lining buckled arch. After the formation of the support system by the side piles, steel tube columns, beams and the top of the arch, the surface settlement value no longer changes significantly. Thus, it can be concluded that the pile-beam-arch system formed in the PBA method has a significant effect on controlling the surface settlement.

6. Comparison of numerical simulation results and on-site monitoring results
The subway station is located in a location with heavy traffic and high traffic flow, and the internal force of the steel tube column is monitored according to the requirements. The negative second floor was completed when the station monitoring points were installed and the negative third floor was being excavated. Strain monitoring with vibrating wire strain gauge, The layout of the measurement points is shown in Figure 10.

The axial force variation of standard section steel tube column is obtained by monitoring and calculation as shown in figure 11.
Due to the late entry of the monitoring, the measured and simulated axial force increment are compared. Measured point B2 - Z22B-JM4 was selected for analysis: the increment of axial force monitored by steel tube column in the excavation stage of negative three-layer earthwork was 1938 kN, the increment of axial force of numerical simulation steel tube column in this stage was 3326 kN, and the increment of measured axial force was 58.3 % of the increment of simulated axial force. During the construction stage of the negative third floor structure, the steel tube column monitored the axial force increment of 238kN, and the numerical simulation showed the axial force increment of 413kN, in this stage, and the maximum value of the measured axial force increment was 57.6% of the maximum value of the simulated axial force increment. The reason is that the numerical simulation of earthwork excavation span is large, resulting in a large range of soil excavation around the steel tube column, making the axial force increment larger than the measured value. The simulation error is within the acceptable range of the project, and the simulation value can be used as a reference for guiding the project.

7. Conclusion

Taking a station of Beijing Metro Line 19 as the engineering background, a combination of field monitoring and numerical simulation was used to study the force and horizontal displacement of steel tube columns and side piles, which are the main load members of the station, and to investigate the surface settlement law caused by construction. The main conclusions are as follows:

(1) The maximum axial force of steel tube column and side pile gradually increases with the construction steps, and the axial force of the secondary lining arching stage significantly increases. The axial force increment of steel tube column accounts for about 59.10 % of the total axial force, and the axial force increment of side pile accounts for about 51.98 % of the total axial force. It indicates that the secondary lining arching stage is the axial force control stage. In the subsequent construction process, earthwork excavation will have a certain influence on the axial force value, and the construction of the middle plate and the side wall has little influence on the axial force value.

(2) The horizontal displacement of steel tube column and side pile shows a 'drumming' form, and the maximum horizontal displacement increases with the construction stage. The maximum horizontal displacement of steel tube column is 3.8mm, and the maximum horizontal displacement of side pile is 12.2 mm. The maximum horizontal displacement is located near the middle of the steel tube column and the side pile and has a downward trend with the construction stage.

(3) Surface settlement in the transverse mid-section of each construction stage was symmetrically distributed with the centerline of the station, and the settlement value increased continuously with the construction stage, and the maximum surface settlement was 47.9mm. The surface settlement reached 42.5 mm after the completion of the second lining construction, accounting for about 88.7% of the total settlement. It is said that most of the surface settlement has been completed after the completion of the secondary lining construction, and the pile-beam-arch system formed in the PBA method has a significant effect on controlling the surface settlement.
8. References
[1] QIAN Qihu. Meet of climax of China city underground space development[J]. Chinese Journal of Geotechnical Engineering, 1998, 20(1): 112-113.
[2] QIAN Qihu. Evaluation and prospect of the development and utilization of urban underground space in China[J]. Civil Defense Court, 2006(S1): 1-5.
[3] WANG Runqing, YOU Yingying. Summary and Prospect of the construction of urban subway[J]. Science and Technology, 2016(5): 34.
[4] LIU W, LUO F, MEI J. A new construction method for a metro station in Beijing[J]. Tunnelling and Underground Space Technology, 2000, 15(4): 409-413.
[5] LI Xiaolin. Numerical simulation on PBA job practice of metro station[J]. Chinese Journal of Underground Space and Engineering, 2007(5): 928.
[6] REN Jianxi, CAO Xitailang. Research on the Surface Settlement of Subway Station Induced by PBA Construction Method[J]. Journal of Railway Engineering Society, 2018(9): 88-92.
[7] REN Jianxi, LIU Tiantian, YUN Mengchen, et al. Analysis of the Influence of Side-pile on the Surface Deformation of Loess Station by PBA Method[J]. Journal of Railway Engineering Society, 2020, 37(01): 109-114.
[8] HU Shimin, WANG Mengshu, ZHANG Li, et al. Study of metro station deformation regularity based on deflection distribution control method[J]. Chinese Journal of Rock Mechanics and Engineering, 2013, 32(2): 266.
[9] NIU Xiaokai, ZHANG Dingli, LIU Meilin, et al. Scheme comparison and measurement analysis of new-build subway station parallel under through existing tunnel in tight contact[J]. China Civil Engineering Journal, 2015, 48(S1): 270-274.
[10] LI Zhao-ping, WANG Ting, ZHENG Hao. Controlling measurements for metro station construction on enlarging large diameter shield tunnel[J]. Chinese Journal of Rock Mechanics and Engineering, 2015, 34(9): 1869-1876.
[11] YUAN Yang, LIU Weiming, DING Deyun, et al. Analysis on heading excavation optimization in metro station constructed by drift-PBA method[J]. Chinese Journal of Underground Space and Engineering, 2011, 7(S2): 1692.
[12] WEI Jing, DU Linlin, SUN Mingzhi. Study of optimization of construction plan of pilot tunnel of subway station excavated by Pile-Beam-Arch method[J]. Architecture Technology, 2014, 45(09): 796-799.
[13] JIA Shitao. Analysis on Procedural Surface settlement of Metro Station Constructed by PBA Method[J]. Railway Construction Technology, 2018(11): 72-76.
[14] LIU Jun, ZHANG Liangbing, XUN Guifu, et al. Optimization analysis of buckle-arch construction sequence for PBA method[J]. Journal of Beijing University of Civil Engineering and Architecture, 2016, 32(1): 36-41.
[15] LIU Jun, XUN Guifu, ZHANG Liangbing, et al. Influence of Side-pile Parameters of PBA Construction Method on Structural Stability[J]. Railway Standard Design, 2016(9): 118-122.
[16] HAN Jianyong, ZHAO Wen, GUAN Yongping, et al. Deformation laws of subway station excavation by PBA method[J]. Chinese Journal of Applied Mechanics, 2015, 32(4): 623-629, 707.