Simulation of ground deformation of subway station using pile-beam-arch method

Hui He
China University of Mining and Technology Beijing, Beijing, the People's Republic of China

Chao Wang
China University of Mining and Technology Beijing, Beijing, the People's Republic of China

Hua Jiang
China University of Mining and Technology Beijing, Beijing, the People's Republic of China

Zhengyuan Liu
China University of Mining and Technology Beijing, Beijing, the People's Republic of China

Zhiyong Yang, Yusheng Jiang, Jili Feng
China University of Mining and Technology Beijing, Beijing, the People's Republic of China

ABSTRACT: The pile-beam-arch construction method is widely used in subway station engineering. However, the mechanical response of underground is not clear during the construction of using this method, particularly in subway station with asymmetric pilot tunnels layout. Taking one of the stations of Beijing subway line 17 as an example, the construction process is simulated by 3D FEM to reveal the mechanical response of the strata. Comparing the FEM prediction with monitoring data, the underground deformations at different construction phases are analyzed. The study shows that three construction stages consisting excavating pilot tunnels, primary lining and second lining greatly disturbed the strata. Comparing with the subway station with symmetrical pilot tunnels arrangement, the curves of surface settlement and the surface horizontal displacement generate a certain offset. The region affected by surface deformation is changed, which is benefit to the arrangement for monitoring points of surface displacement.

Keywords: PBA method, Numerical simulation, Surface deformation, Asymmetry.

1 1 INTRODUCTION

The subway station features large excavation volume, shallow burial depth and large impact on the surrounding environment during construction. Generally, the pile-beam-arch (PBA) method is selected for subway construction for the sake of ensuring the normal operation of urban transportation (Han et al. 2015 and Li et al. 2017). The method based on traditional technology of concealed excavation construction employs the concept of above-ground building construction (Liu et al. 2016). It forms a longitudinal support system consisting of beams and columns in the underground without causing major disturbances to the formation by using small pilot tunnels and piles. PBA method features high safety, weak impact on the surrounding environment (Li et al. 2020, Qu et al. 2013, Wang et al. 2012, Zhang et al. 2017).

Numerical methods are usually used to simulate the construction process based on PBA method. For example, FLAC3D was employed by Liu et al (2018) to study the underground deformation, plastic zone distribution and structural forces, optimize the construction plan of pilot tunnels and predict the surface settlement caused by subsequent construction. Luo & Wang (2016) analyzed the surface deformation characters in Subway Line 6 in Beijing during the construction process, and concluded that the surface settlement during construction phase of the pilot tunnels accounted for a large proportion of the total. Huang et al. (2018) studied the construction phases when large surface settlement occurs, summarized the weight of each phase in the total settlement, and established a practical method to predict the surface settlement.

To understand the mechanical responses of the underground and surface of the subway station with asymmetric pilot tunnels during construction, the 3D finite element method is applied in the present work to simulate the various construction phases of the subway station and analyze the ground deformation in conjunction with the on-site monitoring data.

2 OVERVIEW OF STATION ENGINEERING

2.1 Location and structure of subway station

The station cladding thickness is about 10.8m and the depth of the bottom plate is about 27.2m. In view of the dense buildings around the station and the high risk in construction, the station is constructed by PBA method. Due to restriction of the ground site, some of the ground precipitation wells could not be implemented. The construction of the station uses combination of precipitation wells and the upper pilot tunnel, resulting in a large section of pilot tunnel and asymmetry of upper pilot tunnels, which exposes a risk of excavation. The station section is shown in Figure 1.

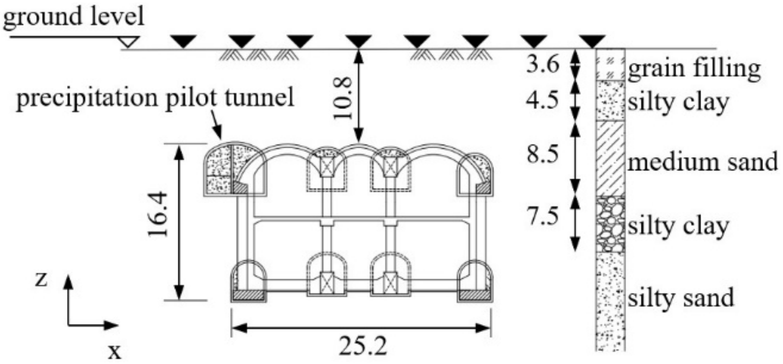

Figure 1. Engineering geological section and soil distribution.

2.2 Distribution and parameters of soils

The geotechnical layers are simplified as far as possible under conditions of no affection in the calculations. The soils of the project site are simplified into 6 layers. The mechanical parameters of each soil layer are shown in Table 1.

Table 1. Mechanical parameters of soils.

Soils	Poisson ratio v	γ (kN·m^{-3})	E_s (MPa)	c (kPa)	φ (°)
plain fill	0.30	19.5	4.0	8.0	10
silty clay	0.29	20.0	9.0	24	12
medium sand	0.26	21.5	25	0.0	30
silty clay	0.28	20.4	14	38	16
sand	0.26	21.0	25	0.0	28
clay	0.27	19.0	12	45	10

3 NUMERICAL MODEL AND VERIFICATION

3.1 Model establishment

The simulation of the station model was numerically implemented using Midas/GTS. The corresponding boundary is 3-5 times as large as the size of excavation. The dimensions of the model in the horizontal (X-axis), longitudinal (Y-axis) and vertical (Z-axis) directions are 150m, 36m and 51.5m, respectively. The upper surface of the model behaves as a free boundary, the lower surface is fixed, and the surrounding soil is regarded as a normal constraint. In the simulations, the influence of seepage fields is not considered in the present work. The Mohr-Coulomb model is employed to describe the constitutive response of soil layers. The model dimensions and mesh division are shown in Figure 2.

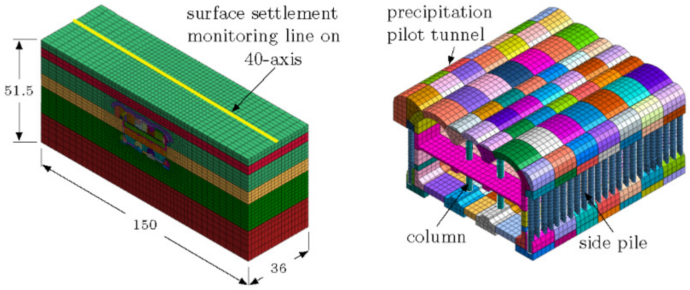

Figure 2. Dimension and meshes of the subway station model (unit: m).

3.2 Validation of the station model

Surface monitoring points arranged on the 40th axis of the subway station form a surface monitoring line. After the construction of the station is completed, the cumulative monitoring settlement values of the surface monitoring points are compared with the simulation results. As shown in Figure 3, the simulated and measured values have the similar deformation trend, but the measured values are higher than the simulated ones. There is a certain discrepancy between the stress release of the excavated soil in the model and the actual disturbance of excavated soil in the field. However, the general trend of the calculation results is basically consistent with the surface deformations monitored on site, which demonstrates that the numerical analysis model is of reliability.

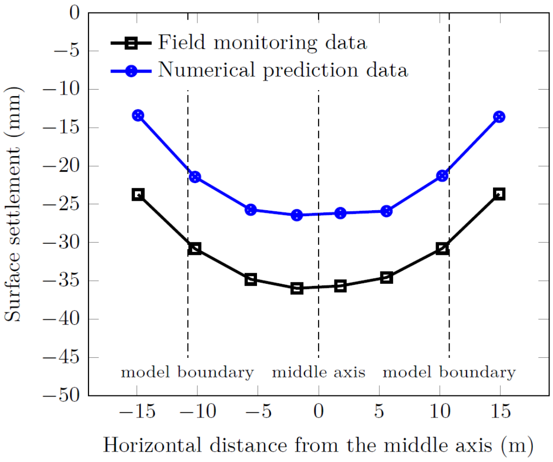

Figure 3. Comparison of simulation results with the monitoring data.

4 SURFACE DISPLACEMENT CHARACTER OF THE SUBWAY STATION

Based on the actual construction sequence, the simulation results of surface displacement in six construction phases are selected for analysis. The specific construction phases are as follows: (1) excavation and primary support of upper pilot tunnel; (2) excavation and primary support of lower pilot tunnel; (3) top stringer construction and backfill pilot tunnels concrete; (4) excavation and primary support of top arch soil; (5) second lining arch construction; (6) and excavations of the soil under the station and construct the station structure.

4.1 Horizontal displacement analysis of strata

Using simulation results of surface settlement at all nodes on the monitoring line, the curves of surface horizontal displacement are shown in Figure 4, and the horizontal displacement contours are given in Figure 5. It is shown that the surface horizontal displacement curves at each construction stage are not symmetrical about the station middle axis. The peak of the horizontal displacement on the right side of the station's middle axis is greater than that on the left side. The point of zero horizontal displacement is not on the middle axis. The value of horizontal displacement from zero displacement point to two sides gradually increases to the peak value. Then, the horizontal displacement gradually decreases to zero. It is observed that the horizontal displacement mainly occurs during the three construction stages, including excavating pilot tunnels, primary lining and second lining, accounting for about 85.8% of the total displacements.

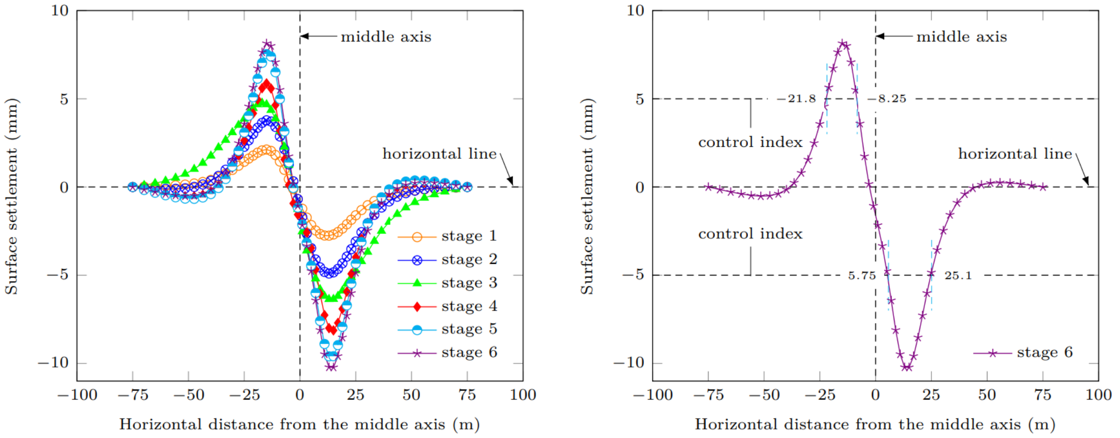

Figure 4. Horizontal displacements and horizontal displacement-control indices.

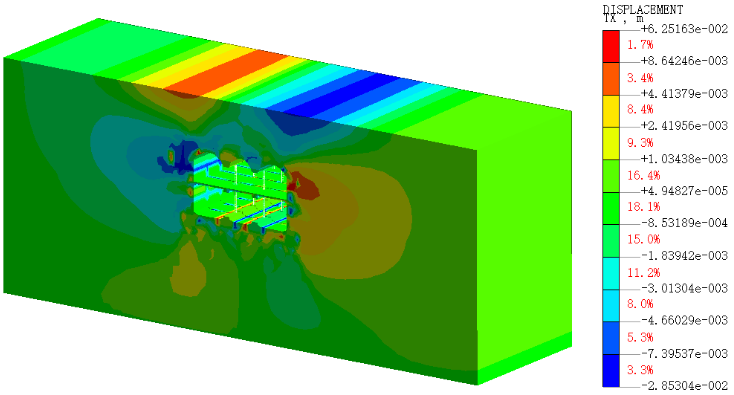

Figure 5. Horizontal displacement contours of the model.

Due to the shallow depth of the subway station and the complex geological and environmental conditions, the surface displacement caused by construction can lead to deformation or even damage to surrounding underground pipelines. Therefore, it is necessary to monitor horizontal surface displacement regularly during the construction of subway stations to protect the underground pipelines. According to Code for monitoring measurement of urban rail transit engineering (2013), the displacement of underground pipelines needs to be controlled between 10mm and 30mm. Surface horizontal displacements of ±5mm are taken as the control index for the analysis of surface horizontal displacement after the construction of the station is completed. As shown in Figure 4, the surface horizontal displacement is significantly affected by the excavation in the range of 8.25 to 21.8m on the left side of the middle axis and 5.75m to 25.1m on the right side of the middle axis. During the construction of the station, monitoring points need to be placed within the above-mentioned areas and monitored more frequently. It provides a reference for the layout of monitoring points.

4.2 Surface settlement analysis

Based on the simulation results of surface settlement at all nodes on the monitoring line, the surface settlement curves are mapped, as shown in Figure 6, and the settlement contours are shown in Figure 7. It is shown that the surface deformation is greatest near the middle axis of the station and gradually decreases in the lateral direction towards both sides of the station, forming a settlement trough. The surface settlement curves are not symmetrical about the middle axis of the station. Due to the large excavation section of the upper left pilot tunnel, the maximum surface settlement point of each construction stage moves to the left of the station middle axis. The proportion of surface settlement during the excavation of the pilot tunnels, primary lining and buckle arch construction accounts for 86.0% of the total settlement so that the three construction phases are essential to controlling surface settlement.

The surface settlement value of －10mm is taken as the control indicator and the surface settlement curve of construction stage 5 was analyzed. As shown in Figure 6, the surface settlement is greatly affected by the construction within the range from 17.16m to the left from the middle axis to 16.65m to the right from the middle axis. During the construction of the station, monitoring points should be placed within the above-mentioned areas and monitored more frequently. It is beneficial to the layout of monitoring points.

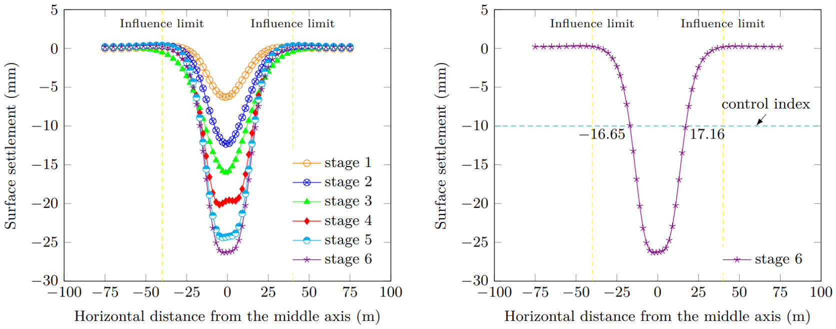

Figure 6. Settlements of each construction stage and surface settlement-control indices.

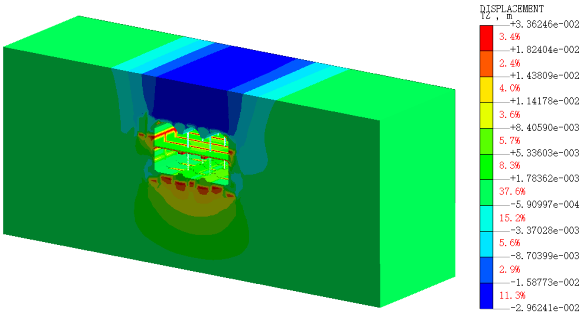

Figure 7. Settlement contours of the model.

5 CONCLUSIONS

The construction process of the subway stations with asymmetrical pilot tunnels is simulated by 3D finite element method. The simulation results are compared with the on-site monitoring data. It is concluded that:

(1) As the construction progresses, the surface deformation is phased. The three construction stages consisting of excavating pilot tunnels, primary lining and second lining greatly disturb the strata. Surface settlement varies significantly within 20m of the station middle axis.

(2) Comparing with the subway station of symmetrical pilot tunnels layout, the surface settlement and horizontal displacement curves of the subway station with asymmetric pilot tunnels layout shift relative to the axis of the station. Owing to the large excavation section of the upper left pilot tunnel, the position of the maximum surface settlement and the point of zero horizontal displacement of the vault at each construction stage are not at the station medial axis but move to the left. The peak of horizontal displacement on the right side of the station is higher than that on the left side of the station.

(3) By contrast with the subway station with symmetrical pilot tunnels layout, the area with larger surface displacement of the subway station with asymmetric pilot tunnels layout is not symmetrical about the station middle axis. The area where the surface horizontal displacement is greatly affected by the construction on the left side of the middle axis is decreased, while the area on the right side of the middle axis is increased. The area where the surface settlement is greatly affected by the construction moves to the left of the station middle axis. It provides a reference for the layout of the surface displacement monitoring points during the construction process.

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