Ground Settlement analysis of Metro Interval using PBA method in the Loess region

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Abstract. In the construction of urban subway, the control of surface settlement has become the key and difficult point in the construction. As a common method in subway tunnel construction, PBA method has been widely used in many areas in China. This method performs well in settlement control. In addition, the supporting system of piles, beams, and arches formed during the construction process of this method effectively avoids the impact of the open-cut method on urban traffic. Therefore, this paper will combine the engineering conditions and the existing research results to simulate the various construction stages of the subway interval excavation in the loess area by establishing a Midas model. Combined with the results of numerical simulation, four increasing stages of surface settlement and corresponding settlement ratios are obtained, and the characteristics of surface settlement troughs are analyzed. This research is helpful to further understand the increasing law of ground settlement during the construction of metro interval in loess area.

1. Introduction

With the explosive development of cities, in order to solve the increasingly prominent problem of urban congestion, subway projects have shown a blowout development. Metro construction in western cities such as Xi’an, Lanzhou, and Chengdu have begun since 2008. The construction environment of urban subway is mostly located in prosperous urban areas, which are characterized by complicated traffic and numerous underground pipelines. If open-cut or cover-excavation methods are adopted, there are problems such as early land acquisition and demolition and long pipeline relocation cycles. The PBA method solves this problem better and can quickly enter the physical project construction after the project enters the site. Therefore, the PBA construction method has gradually become one of the main construction methods for underground excavation of subways. The use of PBA construction method effectively solves the problem of land acquisition and demolition in the city, and only a small amount of land is needed to complete the subway construction without cutting off traffic. Since the PBA construction method of the loess layer in the northwest region is less used and started late, there is currently no complete document similar to it, and the long-term development of underground excavated station and interval technology will gradually be widely used. Therefore, this paper studies the settlement law of underground excavation interval of subway using PBA method in loess area with complex environment. This will provide a reference for similar projects in the northwest region and has
great practical guiding significance.

2. Literature review

Guan et al. [1] conducted an in-depth study on the ground motion induced by subway tunnel construction based on the Zhongjie subway station of Shenyang Line 1. The time history curve of ground motion during the whole construction process was simulated by establishing a 3D model. At the same time, combined with the surrounding environment, the potential risks in the construction process are analyzed and corresponding risk control measures are proposed.

Some studies rely on the PBA construction engineering of subway stations, using a combination of theoretical analysis, numerical simulation and on-site monitoring to study the laws and control techniques of ground settlement induced by the underground excavation of the station. The study established the calculation model of subway station side piles in loess area and deduced the structural internal force calculation formula of side piles. In addition, the design calculation method and process of PBA side piles in the loess area are given, and the rationality evaluation of the side piles of subway stations has been completed [2-3]. There are also some papers based on MIDAS or ANSYS software to complete the parameter sensitivity analysis of pilot tunnels under different excavation step distance, different side pile embedded depth and side pile diameter, and different steel pipe pile diameter and spacing. They take the minimum ground settlement as the control goal, and suggest reasonable excavation step distance, side pile embedded depth and side pile diameter, steel pipe pile diameter and spacing [4].

With the increasing development of construction technology, the technology of expanding large-diameter shield tunnels is also becoming mature. Due to the limitations of the traditional expansion method, the PBA method has been widely used due to its unique characteristics. Through the understanding of the structural characteristics of the expanded tunnel, the study calculated and analyzed the mechanical characteristics of the key nodes in the structure. The structure shows that all stressed structures are in a safe range during tunnel excavation. At the same time, the research also puts forward the corresponding ground settlement control standards based on the results of numerical simulation and on-site monitoring data analysis [5-6].

After studying the physical and mechanical properties of the loess on the working face of a shallow buried tunnel of Xi’an Metro, it is found that the strength of the loess is greatly affected by the water content. The damage stage of loess under dry-wet cyclic loading is divided into the damage stage caused by the dry-wet cycle and the damage stage caused by the combined action of the dry-wet cycle and the load.

Some scholars used FLAC3D numerical simulation software to study the surrounding rock deformation and control technology of the Xi’an subway undercut loess tunnel. The results show that the stability of the loess tunnel is closely related to the water content of the loess and the type of tunnel support [7]. The higher the water content of the loess, the lower the strength, the greater the deformation of the surrounding rock and the surface settlement of the loess tunnel. During the construction process, the water content of the loess on the excavated face must be mastered.

The structure of the underground excavation subway station, the underground excavation method, and the engineering environmental conditions are closely related to each other and restrict each other. According to the engineering environment, it is of great significance to select the appropriate structure and construction method of the subway station to control the impact on the surrounding environment. The article summarizes the structure form and construction method selection principle of underground excavated subway station by comparing and analyzing various station structure forms and construction methods, and selects the structure form and construction method of a subway station built in the upper soft and lower hard strata in Qingdao according to this principle [8].

3. Numerical simulation

Based on the comprehensive analysis of the geological prospecting report of the typical loess in Xi’an area, the study determined the properties of the materials in each layer of the numerical model. A
numerical model was established to simulate the ground settlement caused by each construction stage of the PBA method, whose maximum excavation width, height and soil thickness is 12.5m, 10.5m and 28m. A typical large section interval is selected as the research object. The range of the model is determined as: X direction is 100 meters, Y direction is 20 meters, and Z direction is 60 meters (see Figure 1-2).

![Finite element model](image1.png) ![Structural part of the model](image2.png)

The properties of each soil layer from top to bottom are miscellaneous filling soil layer, old loess layer, ancient soil layer, old loess layer, ancient soil layer, and old loess layer. Structural components such as side piles, linings and crown beams are all concrete materials. The physical parameters of each material are shown in Table 1.

| Material type         | Elastic modulus | Poisson's ratio | Cohesion | Internal friction | Density (Kg/m³) |
|-----------------------|-----------------|-----------------|----------|-------------------|-----------------|
| Filling soil layer    | 8               | 0.32            | 8        | 12                | 1600            |
| Old loess layer       | 20              | 0.28            | 28       | 23.5              | 1740            |
| Ancient soil layer    | 30              | 0.26            | 30       | 24                | 1790            |
| Side piles            | 20000           | 0.2             | /        | /                 | 2300            |
| Crown beams           | 35000           | 0.2             | /        | /                 | 2300            |
| Initial lining        | 20000           | 0.2             | /        | /                 | 2300            |
| Secondary lining      | 35000           | 0.2             | /        | /                 | 2500            |
| Backfill              | 20000           | 0.2             | /        | /                 | 2100            |

In order to better analyze the impact of various construction stages on ground settlement, some surface points were selected in the model for subsequent data analysis. The adjacent monitoring points are separated by 10 meters.

4. Numerical results analysis

The vertical displacement cloud diagram is shown in Figure 3, which shows the vertical displacement of each layer after the completion of the pilot tunnel excavation stage. It can be found that the vertical displacement of the soil layer during the excavation of the pilot tunnel is negatively related to the vertical distance from the pilot tunnel.
In the pilot tunnel excavation stage, the intersection of the centerline of the tunnel and the centerline of the left and right pilot tunnels with the ground are used as three monitoring points and their displacement curves with the construction stage are shown in Figure 4.

The surface settlement has been increasing with the excavation of the left and right pilot holes, but the maximum displacement is always above the left and right pilot holes. During the excavation of the pilot tunnel, the left and right pilot tunnel and the area near the center line of the tunnel subsided almost simultaneously with a small difference. Therefore, as shown in Figure 5, the settlement curve during the excavation stage of the pilot tunnel in the curve diagram of the ground settlement trough becomes a “bow” shape.

Figure 3: Vertical displacement cloud diagram

Figure 4: Vertical displacements

Figure 5: Variety of Surface Settlement Trough in the Whole Construction Process
Figure 6: The Settlement Time-history Curve

Figure 6 shows the time history curve of surface settlement during the entire construction process. The construction phases with the largest rate of change in surface settlement include phases 1-4 and phases 8-12. The pilot tunnel excavation stage and the arch excavation construction stage have the largest contribution rate to the surface settlement. The surface settlement caused by the excavation of the pilot tunnel accounts for 43.7% of the total settlement, and the settlement caused by the arch excavation and construction accounts for 36.8%.

5. Conclusions

Through the establishment of a three-dimensional finite element model to simulate the whole stage of the construction of the subway interval in the loess area, combined with the previous studies on the PBA construction method and the simulation results of ground settlement, the following conclusions can be drawn:

(1) In the construction of the subway interval in the loess area, the PBA construction method has an obvious control effect on the surface settlement. Therefore, in urban areas with high requirements for surface settlement, PBA construction method can be given priority.

(2) Ground settlement develops with the construction process, and it differs in different strata. In other words, the ground settlement is negatively related to the vertical distance of the ground from the vault.

(3) During the excavation of the pilot tunnel stage, the extreme point of ground settlement is at the top of the pilot tunnel. The settlement trough in the pilot tunnel excavation stage is in the shape of a "bow". Therefore, the vault position of the pilot tunnels should be used as the main monitoring points during the excavation of the pilot tunnel stage.

(4) The surface settlement mainly occurs during the excavation of the pilot tunnel stage and the excavation and construction of the arch stage.

Acknowledgments

Thanks to my supervisor Zhanping Song for his encouragement and guidance on this paper. At the same time, thanks to China Road and Bridge Corporation for its strong support to this research. I am also grateful to my colleague Junhao Zhu for his help.

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