Research on Surface Settlement of Subway Station Construction Using Pile-Beam-Arch Approach

Yushan Xu¹, Bo Tang¹ and Yanwei Duan¹

¹JiNan Geotechnical Engineering Company
Email: 957306246@qq.com

Abstract. The pile-beam-arch (PBA) approach is illustrated as a creative construction method in shallow-buried tunneling excavation of subway construction. Attention has been paid to this method due to its unique advantages of construction technology. Subway station construction by using PBA approach will make disturbance to the ground surface. Research on surface deformation caused by PBA approach is of great significance to the surrounding environment and its structure. The example of subway construction in Beijing is presented as the research background, a three-dimensional model is established by using the Midas-GTS finite element numerical simulation software to simulate the practical excavation support conditions, and to analyze the surface settlement, the initial support structure settlement and crustal stress caused by PBA construction method.

Keywords. Pile-Beam-Arch Approach, Midas-GTS, Surface Settlement and Crustal stress.

1. Introduction
The PBA method is classified as shallow-buried tunneling method (STM). It was proposed for the first time by Chinese engineer Zhijie Cui in 1991 and he applied for a patent [1] for this method. Its earliest application could be traced back to the design and construction of the Beijing Tiananmen West Station [2], which was the first success of the shallow-buried tunneling PBA method. Consequently, this construction method was also adopted in the structure designs of Line 5 Xuanwumen Station and Line 10 Suzhou Street Station [3]. It is suitable to be applied in areas with complex pipelines, heavy traffic and high requirements of surface settlement. Featured as high security and low cost, it has been gradually promoted and used in Beijing city [4]. Chenglei Gao and other researchers [5] used three-dimensional finite element method to simulate the construction process of PBA method. They compared and analyzed the displacement of the tunnel surrounding rock caused by excavation. Finally, they summarized laws about the surface settlement. Xia Wang and some other researchers [6] carried out a study on surrounding ground settlement and bridge pier settlement caused by main construction of subway station using PBA method. The analysis showed that the adjacent pile foundations located within the range of the tunnel height are significantly affected by this construction. The nearby surface settlement is almost the same with the settlement of pile foundations [7].

2. Project Profile
The total length of one section of Beijing subway is 732 m. 56 m is taken as the large-span section. The covering soil of the upper part of the tunnel is 7.6 m. The span of tunnel is 15.4 m. The height of the span is 10.42 m. The span of pilot tunnel is 3.6 m, and bored piles are constructed inside it. A big pipe shed with a diameter of 159*10 is constructed on the arch. Thereafter, the main arch lining is
built, then the excavation from the top to the bottom is performed until the design elevation is reached. Next, it is the secondary lining. Along the tunnel excavation direction, the pipelines are densely covered above the tunnel roof, mainly including rectangular-shaped power tunnels and telecommunication tunnels, water supply pipes, rainwater pipes and natural gas pipelines.

The project section is mainly located in soil environment with silty clay, cobble, medium coarse sand. The bottom-board is located in the pebble layer, which is mainly affected by phreatic water. The aquifer is located in cobble. The groundwater level is low, and the permeability of soil layer is strong. The section is a single-span tunnel, and the PBA method is used for excavation. The construction uses cross passage to enter this section, and small pilot tunnels such as temporary pilot tunnel are used to perform construction.

3. Numerical Simulation of Tunnel Construction

3.1. Mechanical Model and Parameters

The dimensions of the model are as follows. It is needed to take 80 m (6 times the width of the main tunnel) along the X axis. Along Z axis, it also needed to upward take a height to the surface, then it is needed to downward take 22m below the bottom-board. up to the surface, and the vertical size is 40 m. Along the excavation direction, it is needed to take 20m for the tunnel. Along the excavation direction The X axis is the width axis, and the Y axis is the longitudinal excavation axis, and the Z axis is the height axis. The calculation model is shown in figure 1.

The boundary conditions and loads are as follows. The top surface is a free boundary, and the remaining 5 surfaces are displacement boundaries. The value of surface load is 20KPa. The model includes 59160 elements, including 440 one-dimensional line elements, 3380 two-dimensional surface elements, and 55340 three-dimensional entity elements. There are 59556 nodes totally.

The support structure model consisting of primary support and side piles is shown in figure 2. The reinforced concrete structure model consisting of the linings and the side piles is shown in figure 3.
3.2. Simulation of Excavation Process

According to the flow-process diagram, the simulation of specific construction process is as follows:

1. To successively excavate small pilot tunnels on both sides by a staggered distance of 10 m. The Bench Method is used here. In the stage of grouting reinforcement, excavation and initial support, the value of 1.0 m is taken. The range of 0.8 m beyond the initial lining of the arch is the reinforcement range.

2. The artificial tunneling pile in the small pilot tunnel is simulated by pile element, with a diameter of 1.2 m. The side pile center distance is 2 m. Then, the process of crown beam at the pile top is constructed inside the small pilot tunnel. Then it is the process of initial support of side arch and the concrete is backfilled behind the primary support.

3. It is simulated to excavate the soil on the left side of the main tunnel. In the stage of grouting reinforcement, excavation and initial support, the value of 1.0 m is taken. It is needed to increase the shell body to simulate the temporary center diaphragm and complete the initial arch support and inverted arch closure of the left half part.

4. It is simulated to excavate the soil on the right side of the main tunnel. This operation is left behind 5 m of the step one. Every advance per round is 1.0 cm for excavation, the temporary center diaphragm is constructed, and it is needed to complete the initial arch support and inverted arch closure of the right half part.

5. It is needed to remove the support shells of pilot tunnels on both left and right sides through segmentation distance (10 m). It is simulated to activate the secondary lining structural elements on the upper part of the main tunnel. At the same time, the horizontal support is simulated with beam elements.

6. It is simulated to excavate the lower soil of the main tunnel and activate the secondary lining elements.

7. It is simulated to activate the secondary lining elements on the lower part of sidewall of main body.

The calculation focuses on the following six key construction steps, namely, completion of pilot tunnel construction, completion of side piles, crown beams and backfilling, completion of excavation support on the upper half of the main tunnel, completion of secondary lining on the upper half of main tunnel, completion of excavation support on the lower half of the main tunnel, completion of secondary lining on the lower half of main tunnel. All results are obtained according to the above six main steps. The main six procedures are shown in figure 4 below.
(a) Construction of diversion tunnel.  
(b) Side piles, crown beams and backfilling.  
(c) Excavation support on the upper half of main tunnel.  
(d) Secondary lining on the upper half of main tunnel.  
(e) Excavation support on the lower half of main tunnel.  
(f) Secondary lining on the lower half of main tunnel.

Figure 4. PBA is mainly the construction steps of program operation.

4. Calculation Results and Analysis

4.1. Surface Settlement
The surface settlement cloud maps and surface settlement curves caused by the main six steps of PBA method are as shown in figure 5 (the model’s longitudinal intermediate section is at Y =10 m; and the ground surface is regarded as the plane of symmetry)
The main steps and ground subsidence caused by cloud curve of PBA.

Note: For optimal viewing, it is needed to take the ground as the plane of symmetry, and the curve of surface settlement tank is symmetrical to the above ground. The Min value shown in the above figures is the maximum settlement value of settlement tank.
As it is shown in figure 6, when the construction of pilot tunnel is completed, there is almost no interaction between the constructions of the two pilot tunnels. The reason is that the horizontal clear distance between the two pilot tunnels is 10.4 m (2.5 times the span of the pilot tunnel), which is relatively far. The surface settlement tank will result in two independent peaks. The maximum value of surface settlement at this stage is 9.87 mm. After completions of cast-in piles, crown beam and concrete backfilling, this situation continues, and the maximum surface settlement is 13.95 mm. After the excavation support on the upper part of the main tunnel is completed, the shape of the surface settlement tank is changed, which is called a single peak curve. Due to excavations of support arch, upper part of main tunnel and other processes, the maximum surface settlement quickly increases to 38.83 mm. After the secondary lining on the upper half of the main tunnel is completed, the surface settlement is 41.26 mm. Then the process of excavation support on the lower half of the main tunnel continues and the settlement is 47.86 mm. Next, construction of the secondary lining on the lower part is carried out and the final settlement is 50.83 mm. In addition, the settlement caused by the excavation support of small pilot tunnel is about 20% of the final settlement value. These two results are mainly caused by the over-large excavation sections, the increased voids and soil displacement, which leads to large margin of surface settlement. In conclusion, the proportion of surface settlement caused by the six construction steps is 2: 1: 5: 0.5: 1: 0.5.

4.2. Comparison of Simulation Results with On-Site Monitoring
The comparative analysis mainly focuses on horizontal surface settlement. The results between the simulation results and the on-site monitoring is shown in figure 6.

![Figure 6. The surface of the final settlement contrast figure of PBA.](image)

It can be found that the simulated data basically accords with the measured data. The following conclusions can be included:

1. The final settlement value and the historical maximum settlement value are basically the same.
2. The distance from the final settlement value and the settlement rate to the tunnel central axis, the farther, the settlement is smaller.

5. Control of Surface Settlement
The surface settlement is mainly caused by the excavation support of the pilot tunnel and the main tunnel. When excavating the tunnel, there is a displacement of the loose circle, which causes the surface settlement. The following measures should be taken:

1. A 24-hour stand-by system should be implemented during construction. Construction guidelines of Pipe Roof in Advance, Strict Grouting, Strong Support, Short Length of Excavation, Early Closure and Frequent Measurement should be strictly followed.
(2) The footprint should be controlled as 4 m - 5 m. The steel skeleton should be connected as a whole integration as soon as possible to prevent the settlement of structure.

(3) The lining should be constructed according to the prescribed time to ensure that the surface settlement will not exceed the design requirements.

(4) There should be a geological detection in advance in the project area. It is needed to have an acquaintance of the property, location and dimensions of geological and hydrogeological conditions, which helps us obtain an accurate, comprehensive and systematic detection and judgment. In addition, it also helpful to strengthen the management of grouting, to block passageways of mud outburst and water outburst. It is necessary to achieve consolidation, to increase rate of stone formation, to enhance the reinforcement effect of surrounding rock, to reduce the permeability for excavation, to ensure that sidewall and tunnel roof have no collapses caused by opening of cracks resulted from flowing water.

6. Conclusion
In this paper, the following results can be drawn through modeling of PBA methods, simulation of detailed construction stages and analysis of influence on itself structure and its surrounding environment. Construction method will cause surface settlement, but the minimum surface settlement caused by PBA method is 50.83 mm.

Surface settlement differences caused by different construction steps of PBA method are presented as follows. When the construction of pilot tunnel is completed, there is almost no interaction between the constructions of the two pilot tunnels. The reason is that the horizontal clear distance between the two pilot tunnels is relatively far. The surface settlement tank will result in two independent peaks. After completions of sides pile, crown beam and concrete backfilling, this situation will continue. After the excavation support on the upper part of the main tunnel is completed, the shape of the surface settlement tank is changed. Due to excavations of support arch, upper part of main tunnel and other processes, the surface settlement increases. After the secondary lining on the upper half of the main tunnel is completed, the surface settlement has a a slight increase. Then the process of excavation support on the lower half of the main tunnel is carried out and the settlement continues to increase. Next, the construction of the secondary lining on the lower part is carried out and the settlement still has a slight increase. The proportion of surface settlement caused by the six construction steps is 2:1:5:0.5:1:0.5.

References
[1] Zhijie Cui, Yu Bao, Xinjie Wang, Zhongheng Shi, Zhaomin Wang, Zijun Shen, Liping Hui, Xiao Yu, Yichuan Liu and Wenku Du. Methods of Building Large Underground Spaces [P]. Beijing: CN1055214, 1991-10-09.
[2] Jingbin Wang, Hailiang Wang. Construction technology of tunnel pile method for subway station[A]. New Developments in Mine Construction and Geotechnical Engineering[C], 1997: 4.
[3] Hanfu Song. Summary and Discussion on the Construction Development of Shallow-Buried Pile-Beam-Arch Approach [J]. China Water Transport, 2008, 08: 221-223.
[4] Hanfu Song. Summary and Discussion on the Development of Shallow Buried and Undercutting Pile Construction [J]. China Waterway, 2008, 08: 221-223.
[5] Chenglei Gao, Shuxue Luo and Yongquan Zhu. Three-Dimensional Finite Element Simulation Analysis of Shallow-Buried Pile-Beam-Arch Approach [J]. Journal of Shijiazhuang Tiedao University, 2002, 03: 44-47.
[6] Xia Wang, Liang Ma, Pengwu Zheng. Research on Adjacent Bridge Foundation Using Pile-Beam-Arch Approach [J]. Shanxi Architecture, 2007, 23:126-128.
[7] Yun Zhang, Zongze Yin, Yongfu Xu. Analysis of ground deformation caused by shield tunnel [J]. Chinese Journal of Rock Mechanics and Engineering, 2002, 03:388-392.