Numerical Simulation of Ground Settlement Caused by Overlapping Tunnel Shield Construction and Measures of Stratum Reinforcement

Xiaotao Wu¹,² and Zengwei Liu²

¹School of Civil Engineering and Architecture, Jiangsu University of Science and Technology, Zhenjiang, China
²School of Civil Engineering and Architecture, Jiangsu University of Science and Technology, Zhenjiang, China

*Corresponding author e-mail: 547303136@qq.com

Abstract. In order to predict and control the ground settlement caused by the overlapping construction of the upper and lower lines of the shield tunnel in Foshan area effectively, this paper takes the overlapping section of the left and right lines of the Ludao Lake-Liantang segment of Foshan Metro Line 2 as the main research object, simulate the construction process of overlapping sections by finite element software and combined with field measured data, predict the ground settlement caused by the overlap section construction effectively, so as to take targeted control measures and verify the reliability of the formation reinforcement measures. The results show that reasonable reinforcement measures can be taken to effectively control the ground settlement before the construction of the overlapping section.

1. Introduction

In order to make rational use of underground space and meet the design requirements of underground tracks, the overlap arrangement of upper and lower line is sometimes adopted in tunnel design. In the construction of overlapping tunnels, the ground subsidence grooves formed in the construction of the upper and lower line tunnels are overlapping with each other, which can easily cause the large settlement of the ground. At present, some scholars have studied the ground subsidence caused by overlapping tunnel construction, Linsheng Xu¹ used FLAC 3D software to simulate the construction situation of Shanghai Pearl Line overlapping section under the condition of soil reinforcement and non-reinforcement, and obtained the ground settlement law of the overlapping section under the condition of reinforcement and non-reinforcement; Jun Sun² using Ansys to simulate the soil displacement of overlapping tunnels and propose that pre-grouting reinforcement must be carried out in the construction of the upper and lower tunnels to control the ground subsidence within the allowable range. Mingming Tang used the construction of the overlapping section of the Linyi line of Xi'an subway as the background to study the deformation law of the surrounding stratum under the cross-conversion construction of the tunnel. Jianzhong Ye studied the ground settlement caused by shield tunnel construction and the influence of post-construction tunnel on the first construction tunnel by establishing a three-dimensional numerical model and combining empirical calculation formulas.

At present, the research on the cross-conversion of the left and right lines of the tunnel is relatively lacking and most of the research results only carry out finite element analysis, lacking the support of
measured data. On the other hand, most scholars use horizontal straight lines instead of curved paths of tunnels when they studied overlapping tunnels. This has a certain deviation from the actual construction conditions of tunnels, which leads to the fact that the calculation results can not truly reflect the actual construction conditions, and the guiding significance for practical engineering is insufficient.

Based on the shortcomings of the above research status, combined with the research results of the above-mentioned scholars, we take the overlapping sections of the left and right lines of the Lu-Lian segment of Foshan Metro Line 2 as the main research object and the excavated area adjacent to the overlapping section as the test section, simulate the construction of the test section by the finite element software Madis-GTS before the shield machine digs into the overlap section, obtained the calculated value of the ground settlement of the test section and compared with the measured value of the field so as to verify the reliability of the calculation result of the model. And then use the finite element model to simulate the stratum reinforcement measures of the overlapping section, and the feasibility of the stratum reinforcement measures of the overlapping section can be verified according to the predicted settlement value.

2. Engineering overview
The left line of the Ludao Lake-Liantang section is 2201.42m long and the right line is 2219.88m long. The tunnel passes through the Dongping waterway on the north side of the Jihua Bridge, and the distance is about 22m in parallel with the bridge. The left line passes through the right line and enters in the YCK27+622.88~YCK27+754.92 segment. The buried depth of the tunnel is 10.1~26.7m and the interval plan is shown in Figure 1.

The soil layer of the overlapping section is mainly filled, silty soil, strongly weathered sandstone, argillaceous sandstone, moderately weathered calcareous sandstone. The tunnel passes through under the rivers such as Huangpuyong, Dongping Waterway and Nanbei Eryong, so the ground water is very rich. The interval groundwater is mainly Quaternary pore diving and bedrock fissure water. The geological profile is shown in Figure 2.

3. Analysis of field measured data
3.1. Page Numbers Monitoring section and monitoring point layout
In this paper, 90m before the overlap section is used as the test section of this study. According to the site layout plan, a monitoring section is laid every 40m on the test section, and three sections are arranged, namely DBC-25, DBC-26, DBC-27, a monitoring section DBC-29 is set at the overlap, and each monitoring section is arranged with 9 to 12 monitoring points according to the ground conditions. The monitoring point layout is shown in Figure 3.
3.2. Actual measurement analysis of transverse ground subsidence in test section

According to the field measured data, the data of each section of the test section is collated, and the settlement values of each section are as shown in figure 4–6.

It can be seen from the field-measured statistical data that after the right-line tunnel passes, there is obvious settlement on the ground, the maximum point is located above the right-line tunnel and the settlement value gradually decreases from the center of the cross section to both sides. The maximum ground settlement values of section DBC-25, DBC-26, DBC-27 are -14.16mm, -15.56mm, -17.36mm, accounted for 44.9%, 44.3%, and 43.1% of the total settlement respectively. The settlement value of the section ground increases sharply after the left-line tunnel passes, the maximum settlement of each section reaches -31.52mm, -35.12mm, -40.31mm, accounted for 55.1%, 55.7%, and
56.9% of the total settlement respectively, and the maximum point of ground settlement is shifted to the left in a different degree.

It can be obtained that in the overlapping construction of the left and right lines of the tunnel, the construction of the upward tunnel will produce a large sharp settlement on the existing settlement, and the settlement amplitude is larger than caused by the excavation of downward tunnel, this is mainly due to the fact that the disturbance of the soil caused by the downward tunnel excavation has not been completely reconsolidated when the upward tunnel passes, and it’s easy to cause large ground settlement if the soil is disturbed once again in this case; on the other hand, compared with the downward tunnel, the buried depth of the upward tunnel is shallower, so its disturbance to the ground is more obvious.

4. Numerical simulation analysis

4.1. Model parameter

In this paper, Midas-GTS finite element software is used to simulate the construction process of tunnel. The surrounding rock adopts Mohr-Coulomb elastoplastic model, and the overlapping soil layer is simplified into four layers. The specific soil parameters are shown in Table 1. The shield shell, the Lining segment and the grouting layer adopt elastic model, and the grouting layer is regarded as a homogeneous layer of equal thickness and equal thickness. The specific structural parameters are shown in Table 2.

| Soil name                                | Cohesion (kPa) | Internal friction angle (°) | Elastic Modulus (Mpa) |
|------------------------------------------|----------------|----------------------------|-----------------------|
| Plain fill                               | 8.0            | 20                         | 4.68                  |
| Muddy soil                               | 8.0            | -                          | 11.0                  |
| Strongly weathered sandstone, Mudstone   | $2 \times 10^6$ | 21                         | $5.2 \times 10^3$     |
| Medium weathered calcareous sandstone    | 3.1            | 40                         | $2.93 \times 10^4$    |

| Structure                  | Poisson's ratio | Density ($\text{kg/m}^3$) | Elastic Modulus (Mpa) |
|----------------------------|-----------------|---------------------------|-----------------------|
| Lining segment             | $3.45 \times 10^4$ | 0.18                      | 2500                  |
| Grouting layer             | $5.0 \times 10$   | 0.25                      | 2200                  |
| Shield shell               | $2.1 \times 10^5$ | 0.3                       | 7850                  |

In order to reduce the boundary effect, the model length is 145m, the width is 100m, the height is 50m, and the diameter of the lining is 6m. The boundary conditions of the three-dimensional global model are: the Z-direction displacement at the bottom of the model, and the horizontal displacement of the model around the model. When creating the model, taking into account the difference between the outer diameter of the segment and the inner diameter of the shield shell and the thickness of the shield shell, a 2-3 cm gap will be generated in the outer periphery of the shield tail after the segment is removed from the shield tail, if the slurry is not timely or the amount of grouting is insufficient, the surrounding soil will move in the direction of the segment in the case of the soil is disturbed, and the resulting formation loss will be greater than the theoretical value. Therefore, when the model is created, a 2 cm gap is reserved between the outer diameter of the segment and the surrounding soil to compensate for the factors such as the delay of grouting at the end of the finite element analysis, so that the numerical simulation is closer to the actual value. The calculation model and the sedimentation clouds of each section after the passage of the left line are shown in Figures 7–10.
4.2. Analysis of numerical calculation results of test section

Figure 11~13 are the settlement curves of each section after the left line passes. According to the results of numerical calculation, the ground settlement curve is normally distributed, the maximum value is at the center of the cross section, and gradually decreases from the center to the sides, and has obvious symmetrical shape, the ground settlement value caused by the construction of the right-line tunnel of each section is small. After the right line passes, the maximum ground settlement values of DBC-25, DBC-26 and DBC-27 are -9.55mm, -9.75mm and 9.57mm, it accounts for 36%, 32%, and 27.8% of the total settlement of the section respectively.

As the distance between the tunnels decreases, the influence of the excavation of the trailing tunnel on the ground settlement increases. The ground settlement cause by left-line tunnel excavation at DBC-25 (the distance between the left and right lines is 7m) is -26.6mm, accounting for 64% of the final settlement, the ground settlement of the left-line tunnel excavation at DBC-26 (the distance between the left and right lines is 5m) is -30.5mm, accounting for 68% of the final settlement, and at DBC-27 (the distance between the left and right lines is 1.5m), the ground settlement of the left-line tunnel excavation is -34.4mm, accounting for 72.2% of the final settlement. At the same time, the maximum point of ground settlement is shifted from the right axis to the top of the left line. This is mainly because the distance between the left and right lines is shortened, so that the interference range of the construction to the soil tends to be concentrated, and the superposition effect is more obvious. And the right line is closer to the ground, so the interference to the ground is more obvious. So, after the left line is excavated, the maximum point of the settlement is shifted to the left.
4.3. Comparison of calculated and measured values of the test section

Compared with the measured values, the results of numerical analysis are lower than the measured values caused by single-line construction or double-line construction. This is mainly due to the assumption that the soil is homogeneous and the groundwater and complex underground conditions is neglected, so the calculated value is smaller than the measured value, but overall the two are similar and the trend is basically the same. It can be seen that in the process of simulation analysis this time, the establishment of physical model, the selection of constitutive model, the selection of parameters and the setting of boundary conditions are reasonable, so the model can provide effective prediction for ground settlement in subsequent construction intervals.

4.4. Prediction of ground settlement values in overlapping sections

Figure 14 and Figure 15 show the nephogram of ground settlement and settlement numerical calculation results of DBC-29 after the left line passes. According to the prediction result, after the right line is crossed on the left line, the ground settlement value reaches 47mm, which exceeds the safety control standard, and the 22m on the right side of the overlap section is the Jihua Bridge, excessive ground settlement will pose a threat to the safety of the bridge. Therefore, it is necessary to reinforce the stratum of the overlapping section before construction to effectively control the settlement of the overlapping section.
5. Reinforcement solution of overlapping section and numerical analysis of reinforcement solution

5.1. Reinforcement solution
The overlap of the left and right lines of Lu-lian segment of Line 2 is reinforced with high-pressure jet grouting piles. The design elevation of the pile top is -11m to -16m, the elevation of the pile bottom is -26m to -28m, the total length of reinforcement is 160m, and the reinforcement range is 3m on both sides of the tunnel, 1m above the top of the tunnel, and the bottom enters the relative stable layer 1m. The high-pressure jet grouting pile has a diameter of 600mm and a spacing of 450mm, it is arranged in a plum-shaped shape. The plan and longitudinal section of the stratum reinforcement range are shown in Figures 16 and 17 respectively. Simulate the shield construction according to the reinforcement solution, and the trata model is shown in Figure 18.

Figure 14. Nephogram of ground settlement before reinforcement of DBC-29

Figure 15. Calculation of ground settlement before reinforcement of DBC-29

Figure 16. Plan view of the strata reinforcement range

Figure 17. Vertical section of the strata reinforcement range

Figure 18. Strata reinforcement model
5.2. Numerical analysis of reinforcement effect

Figure 19 and Figure 20 show the nephogram of ground settlement and settlement numerical curves of the left line passing through the DBC-29 after reinforcement. According to the numerical simulation results, the ground settlement caused by the left line construction is 7.2mm after grouting reinforcement. Referring to the comparison between the calculated value and the measured value of the test section, the actual settlement result of the ground will be slightly larger than 7.2mm, but the total settlement value should be controlled to the safety standard of (-30, +10)mm. Significantly less than the ground settlement caused by shield construction before reinforcement. This is mainly because the cement slurry is injected into the formation to increase the integrity and strength of the soil, improve the stability of the soil around the tunnel, thereby greatly reducing the impact on the ground. Therefore, the reinforcement solution is feasible.

Figure 19. Nephogram of ground sedimentation after reinforcement of DBC-29  
Figure 20. Calculated value of ground settlement after reinforcement of DBC-29

6. Conclusion

(1) In the overlap construction of the left and right lines of the tunnel, the upward tunnel will cause a large settlement after passing through the built down tunnel. The construction of the upward tunnel is the main factor affecting the ground settlement.

(2) With the decrease of the distance between the tunnels, the overlap effect of the strata deformation caused by the shield construction increases, and the ground settlement value caused by the rear excavation tunnel also increases.

(3) Reasonable selection of constitutive models, model parameters and boundary conditions, combined with field measured data, finite element model for effective prediction of ground settlement.

(4) Before the construction of the overlapping tunnel, a reasonable and effective grouting reinforcement measures is adopted for the stratum, and the cohesion and shear resistance of the soil can be improved, which can effectively reduce the ground settlement, thereby controlling the final settlement value of the ground to a safe range.

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