Study on Deformation Control during Shield Tunnel Construction Beneath Existing Tunnels

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Abstract: This study is based on the background that the tunnel of Ningbo Metro Line 8 passes beneath the tunnel of Line 1. A three-dimensional numerical model was developed using Midas to simulate the deformation induced by the construction of the new Line 8 tunnel beneath the existing Line 1 tunnel. The results show that the maximum lateral horizontal deformation, longitudinal horizontal deformation, and vertical deformation of the Line 1 tunnel occur after the excavation of the Line 8 tunnel is completed. Notably, all deformations comply with the settlement control standards for existing tunnels in urban rail transit systems in China. After the excavation of the Line 8 tunnel is completed, the maximum surface settlement is less than the settlement control value, indicating that the excavation of Line 8 tunnel has less additional impact on the Line 1 tunnel. It is recommended that, during the construction of the new tunnel, intensive monitoring of the existing tunnel is implemented, particularly focusing on settlement in the central section, to mitigate the risk of structural damage due to excessive deformation.

Keywords: Shield tunnel, Overlapping tunnels, Tunnel deformation, Deformation control.

1. INTRODUCTION

With the continuous expansion of rail transportation, the length of metro networks is steadily increasing. New tunnels will inevitably overlap with those already built. These overlaps can be classified into different types based on the spatial relationships between the new and existing tunnels, such as vertical and oblique crossings. The different crossing angles and distances between new tunnels and existing tunnels will result in different impacts on the existing tunnels. The construction of new tunnels disturbs the surrounding soil and can cause secondary disturbances to existing tunnels, leading to structural deformation. To protect the soil and the existing structures, many scholars have conducted a series of researches in such construction scenarios. Kang *et al*. [1] studied the settlement curves of a new tunnel crossing obliquely beneath an existing tunnel. They introduced an angle factor to modify the Peck formula. The modified formula is used to calculate surface settlement during the construction of new tunnels crossing obliquely beneath existing tunnels. Lin *et al*. [2], based on a project in Changsha, studied the deformation characteristics of a new tunnel crossing obliquely beneath an existing tunnel. They analyzed the changes in surface settlement during the construction of the new tunnel and its impact on the earth pressure near the existing tunnel. Wang *et al*. [3], conducted a comparative analysis. They analyzed 23 sets of measured data and measured deformation fitting curves from 10 new shield tunnels that cross beneath existing tunnels and proposed a modified Peck formula, which provide a simple and quick prediction method for the deformation of existing tunnels during the construction of new shield tunnels in Beijing. Bai *et al*. [4], based their research on empirical settlement curves and the elastic foundation beam model. They derived a calculation formula for the longitudinal settlement curve. This curve is caused by the vertical crossing of a new tunnel beneath an existing tunnel. They also derived a formula for the longitudinal stress and the maximum settlement that the existing tunnel can withstand. Fang *et al*. [5], based on the overlapping construction of new shield tunnels and existing tunnels, proposed a method for calculating the deformation of existing tunnels caused by tunnel overlap during construction. For the soft soil in Shanghai, some scholars have used numerical simulation and on-site monitoring to analyze the impacts of the construction of new tunnels on adjacent existing tunnels and proposed reinforcement measures for existing tunnels [8]. Liu *et al.* [10] used finite element analysis to analyze the impacts of new tunnels in a high-level stress region in Sydney on the support system of vertical existing tunnels, and proposed reinforcement measures for existing tunnels.

Research on new shield tunnels crossing existing tunnels has made some progress. However, studies on deformation control during tunnel overlap construction in the clay of Ningbo are still limited. This paper

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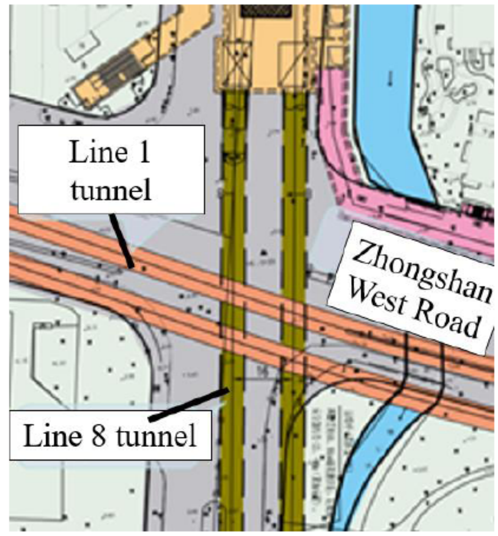
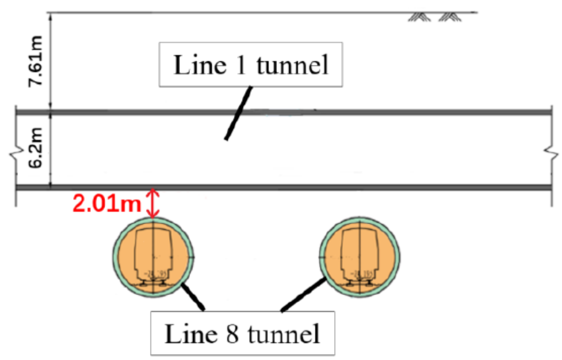
presents an analysis of deformation control for a new tunnel crossing an existing tunnel in the context of Ningbo Metro Line 8 and Line 1. By setting different construction stages, the three-dimensional numerical model can calculate the characteristics of each deformation index at different construction stages, which is more accurate and targeted than directly studying the deformation at a certain stage of construction or the final deformation. By comparing with Chinese standards and local norms, deformation control standards are proposed for the section of Line 1 between Wangchunqiao Station and Zemin Station, which is of reference value for the similar projects.

2. PROJECT OVERVIEW

The overall alignment of Phase 1 of Line 8 follows a southeast-northwest orientation, starting in the southeast at Jiangcun in Yinzhou District and ending in the northwest at Jiangbei Avenue Station in Jiangbei District. The total length is 23.3 km, all of which is laid underground. The tunnel section between Liyuan North Road Station and Zemin Station runs north along Liyuan North Road after exiting the tunnel well. It passes through Houwang River, Lantian Road, Zhoujiang'an Road, Qinyuan Street, Xitang River, and Zhongshan West Road, continuing north to reach the end well at the southern side of Zemin Station. The main structures along the alignment of this shield tunnel are diverse, including Qianwang Bridge, residential complexes, street-facing shops, a 110 - kV power line, Ningbo City Detention Center, Xinfeng Bridge, a gas station, and Line 1 tunnel. The shield segment thickness is 350 mm, the width is 1200 mm, and the tunnel's internal diameter is 5.5 meters, with an external diameter of 6.2 meters. The tunnel between Wangchunqiao Station ~ Zemin Station on Ningbo Metro Line 1 is a circular shield tunnel, running east-west along Zhongshan West Road. The tunnel structure uses prefabricated C50 reinforced concrete segments, with a segment thickness of 350 mm, width of 1200 mm, an internal diameter of 5.5 meters, and an external diameter of 6.2 meters. The shield tunneling starts at Liyuan North Road Station and extends to Zemin Station. The new Line 8 tunnel passes beneath the existing Line 1 tunnel between Wangchunqiao Station ~ Zemin Station, with a horizontal angle of 71°. The Line 1 tunnel is buried at a depth of approximately 14 meters and is located within mucky clay. The closest point between the Line 8 tunnel and the Line 1 tunnel in this section is approximately 2.01 meters. The plan and profile relationship of the Line 8 tunnel passing beneath the existing Line 1 tunnel between Wangchunqiao Station ~ Zemin Station is shown in Figure **1**.



(**a**) plan view



(**b**) profile view

Figure 1: Plan and profile relationship of the Line 8 tunnel passing beneath the existing Line 1 tunnel.

The section of the Line 8 tunnel that passes beneath the Line 1 tunnel between Wangchunqiao Station and Zemin Station is located at the intersection of Liyuan North Road and Zhongshan West Road. This area is relatively distant from nearby buildings, and the primary infrastructure within the impact zone consists of water pipelines, communication pipelines, gas pipelines, and electric power pipelines, with no large-diameter or critical pipelines present. The Line 1 tunnel between Wangchunqiao Station and Zemin Station is situated in mucky clay, while the proposed Line 8 tunnel between Liyuan North Road Station and Zemin Station is situated in silty clay.

In this project, the construction of the new Line 8 tunnel beneath the existing Line 1 tunnel poses significant challenges. The close proximity and specific spatial relationship between the two tunnels mean that the excavation of Line 8 tunnel will cause soil disturbance, which in turn could lead to deformation of the Line 1 tunnel. Any excessive deformation might endanger the safety and normal operation of the existing Line 1 tunnel. To assess these potential impacts, it is essential to conduct research. Numerical simulation provides a powerful tool for this purpose.

3. NUMERICAL SIMULATION MODEL

To analyze the impact of Line 8 tunnel excavation (from Liyuan North Road Station to Zemin Station) on the Line 1 tunnel (from Wangchunqiao Station to Zemin Station), a numerical simulation analysis was conducted using Midas. According to the spatial relationship between Line 8 and Line 1, a three - dimensional finite element model was established, with the effective range of the tunnel protection zone fully considered in accordance with St. Venant's principle. The computational domain for the 3D model is defined as follows: the overall dimensions of the model are 108m in length, 100m in width, and 60m in height. The lateral horizontal impact range of shield crossing construction is 4D (D is the diameter of shield), and the longitudinal horizontal impact range is between 3D and 5D [11], so the scope of the model includes the range of possible impacts of new tunnels on existing tunnels. Horizontal deformations at the side boundaries and vertical deformations at the bottom surface are fixed. The soils within the computational domain are modeled using solid elements, while the tunnel segments are modeled using plate elements. As shown in Figure **2**, the model is presented. The distribution and physico - mechanical parameters of surrounding soils are set according to the project's geological exploration report, and these parameters are summarized in Table **1**.

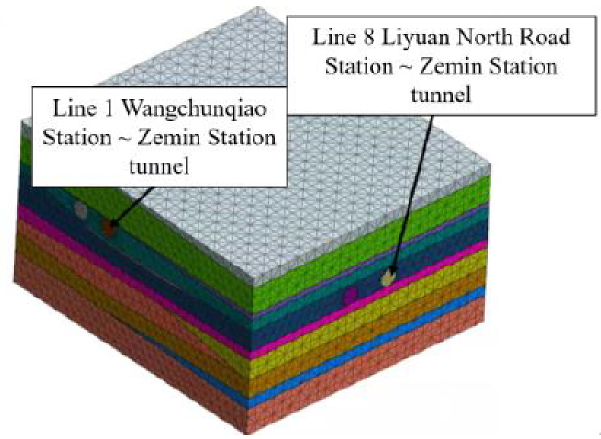


Figure 2: Numerical model.

The model construction process is as follows:

Process 1: Initial state;

Process 2: Completion of the tunnel construction between Wangchunqiao Station and Zemin Station on Line 1 (deformations reset);

Process 3: Excavation of the left tunnel and segment construction between Liyuan North Road Station and Zemin Station on Line 8;

Process 4: Excavation of the right tunnel and segment construction between Liyuan North Road Station and Zemin Station on Line 8.

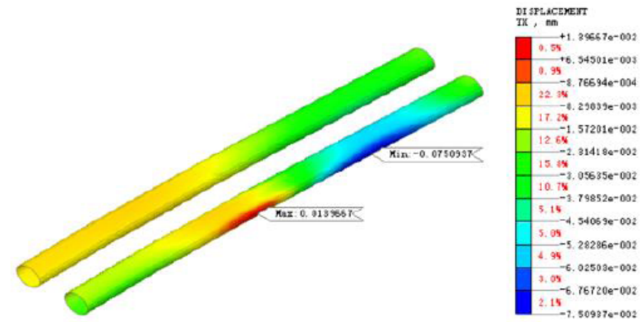
Table 1: Material Parameters

Soils	Thickness (m)	Weight (kN/m^3)	Cohesion (kPa)	Internal friction angle (°)
Miscellaneous fill (mlQ)	4.2	20	20	20
Clay (al-l Q_4^3)	10.6	17.8	20.9	10.8
Silt Mixed Clay (al-m Q_4^1)	1.7	19.0	7.0	27.0
Mucky clay (m Q_4^1)	4	17.5	13.0	12.0
Silty clay (al-l Q_3^{2-2})	9.6	19.3	38.0	18.0
Silty clay (al-l Q_3^{2-1})	4.4	19.0	33.0	17.0
Silty clay (al-l Q_3^1)	7	19.4	34.0	18.8
Medium sand (al Q_3^1)	4.6	20.5	6.5	34.5
Silty clay (al-l Q_2^2)	4	19.4	40.0	20.0
Full weathered siltstone (K_{1f})	9.9	24.0	60.0	600.0

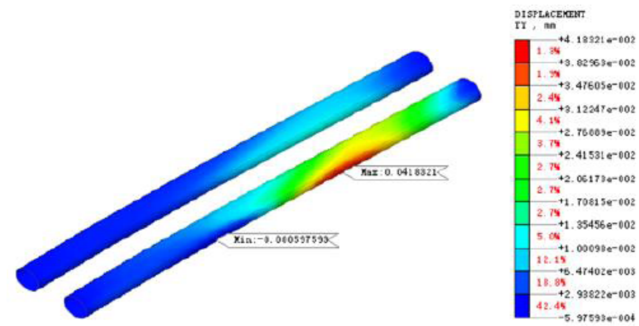
4. ANALYSIS OF RESULTS

4.1. Analysis of Tunnel Deformation

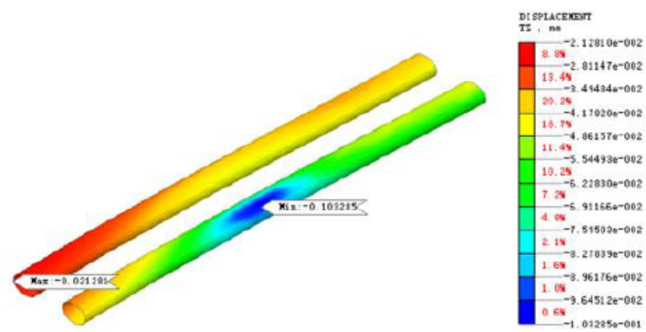
From the model construction process outlined above (The results are extracted every 20m of excavation), a total of 10 deformation stages are identified, and Figures **3**-**5** show the tunnel deformation nephogram for Stage 1, Stage 5 and Stage 10, respectively. In the deformation nephogram, the degree of deformation in an area is indicated by its color. Areas with colors closer to red or blue represent greater deformation. At Stage 1, the deformation in the three directions of the two tunnels was non - uniform. This is because the new tunnel's influence on the existing tunnels' deformation was manifested through the 'shield - soil - tunnel' interaction mechanism. At the beginning of the excavation of the new tunnel, the excavation causes a stress field in the surrounding soil. The stress field has different magnitudes of stress in the three dimensions, and the soil stress field in different directions within it has different effects on the deformation of the existing tunnel. At the same time, the soil stress field in different directions has a nonlinear superposition relationship on the deformation of existing tunnels, so it makes the tunnel deformation mechanism more complicated. The deformations of the existing right tunnel are generally larger and more heterogeneous than of the existing left tunnel, because the two new tunnels are spaced differently from the two existing tunnels. The new left tunnel is closer to the existing right tunnel, so the deformation of the soils caused by the excavation of the new tunnel has a greater impact on the existing right tunnel. The deformation form of the existing right tunnel is more complicated compared to the existing left tunnel. As shown in Figure **4**, at Stage 5, the deformation changes in all directions are essentially the same for both tunnels. This is because the changes in the soil stress field due to excavation at this stage and before are progressively consistent at the location of the two existing tunnels, and have an approximate effect on the deformation of the two existing tunnels. The change of tunnel deformation in the vertical direction is more complicated than the other two directions, so the tunnel deformation limit conditions should pay more attention to the settlement in the vertical direction, especially in the middle section of the existing tunnels. As shown in Figure **5**, the deformation of the existing tunnels in the three directions of stage 10 increases but not by much compared with that at Stage 5, indicating that the deformation of the existing tunnels is gradually maintained at a certain level and stabilized with the completion of the excavation.



(**a**) Excavation of the left line of the proposed tunnel and segment application (lateral horizontal deformation)



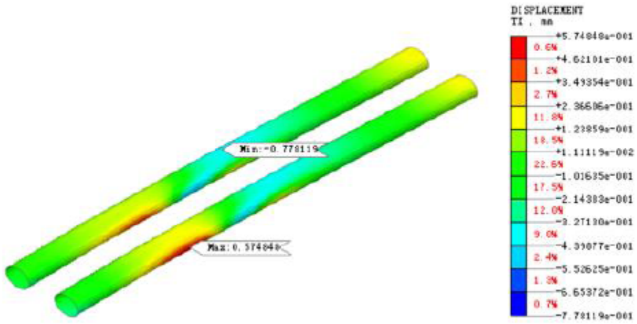
(**b**) Excavation of the left line of the proposed tunnel and segment application (longitudinal horizontal deformation)



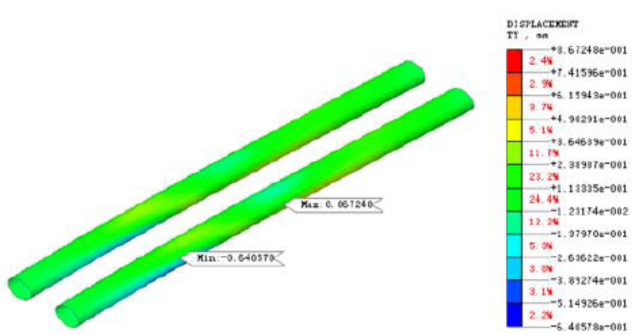
(**c**) Excavation of the left line of the proposed tunnel and segment application (vertical deformation)

Figure 3: Stage 1 Deformation nephogram of excavation and segment application on the left line of the proposed tunnel (mm).

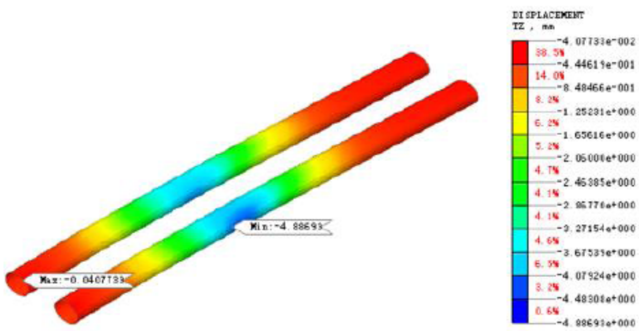
Table **2** shows the deformation change of the existing tunnels at Wangchunqiao Station ~ Zemin Station of Line 1 after the completion of the construction of the new tunnels at Liyuan North Road Station ~ Zemin Station of Line 8. The results show that the maximum horizontal deformations in both the lateral and longitudinal directions, as well as the vertical deformation of the existing Line 1 tunnel, occur after the excavation of the Line 8 tunnel. The corresponding maximum values are -0.83 mm, 1.12 mm, and -5.62 mm, respectively. These values are within the settlement control standard for existing tunnels in urban rail transit in China (10 mm).



(**a**) Excavation of the left line of the proposed tunnel and segment application (lateral horizontal deformation)

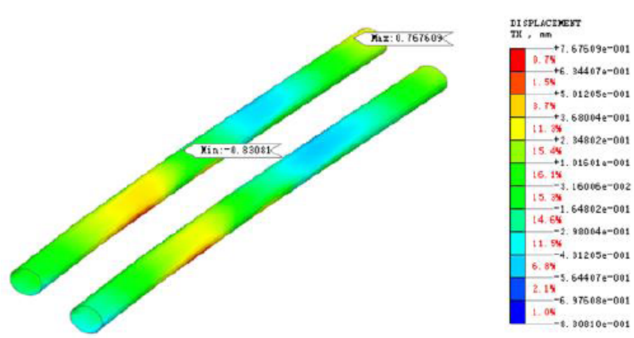


(**b**) Excavation of the left line of the proposed tunnel and segment application (longitudinal horizontal deformation)

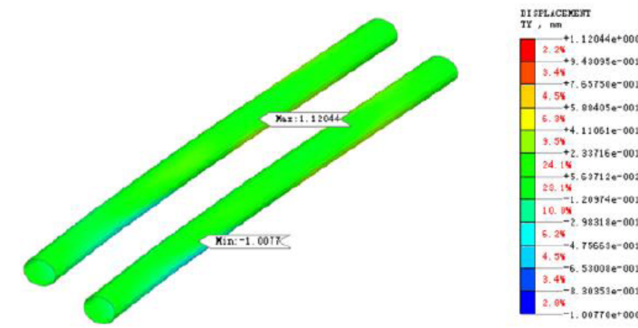


(**c**) Excavation of the left line of the proposed tunnel and segment application (vertical deformation)

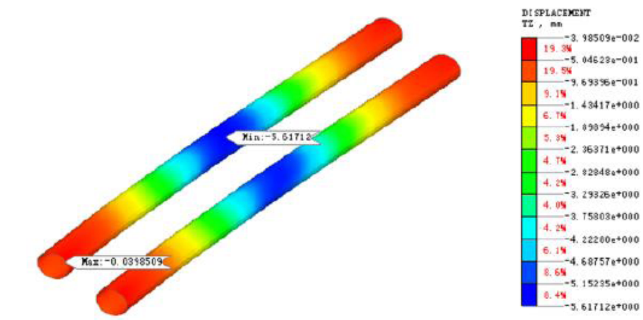
Figure 4: Stage 5 Deformation nephogram of excavation and segment application on the left line of the proposed tunnel (mm).



(**a**) Excavation of the left line of the proposed tunnel and segment application (lateral horizontal deformation)



(**b**) Excavation of the left line of the proposed tunnel and segment application (longitudinal horizontal deformation)



(**c**) Excavation of the left line of the proposed tunnel and segment application (vertical deformation)

Figure 5: Stage 10 Deformation nephogram of excavation and segment application on the left line of the proposed tunnel (mm).

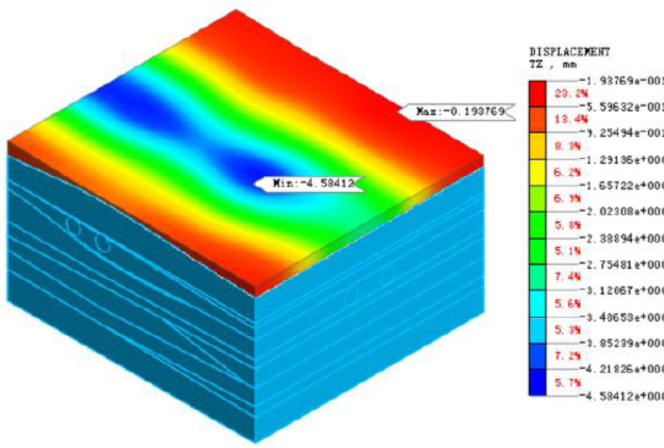
As shown in Table **2**, the deformation values of the tunnel in all three directions generally show an increasing trend as the phases progress. However, in the middle stages, the deformations in the lateral horizontal and longitudinal horizontal directions exhibit a decrease, which contrasts with the overall growth trend. This anomaly is likely attributable to the accuracy limitations of the numerical simulation.

4.2. Analysis of Surface Settlement

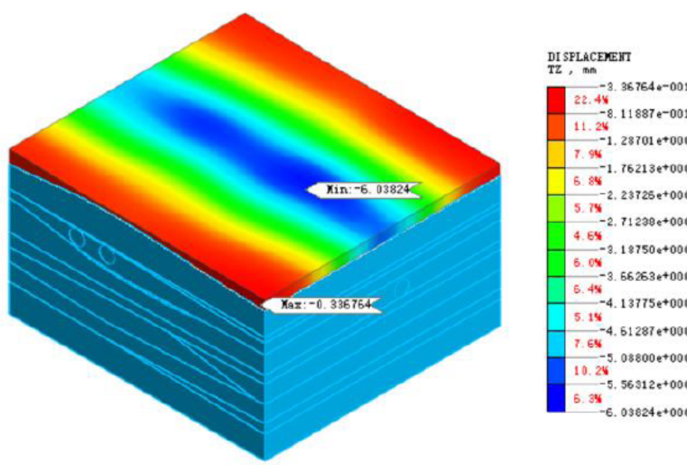
Figure **6** illustrates the surface settlement nephogram at the completion of the excavation of the Line 8 tunnel. The figure shows that the surface settlement takes on a 'V' shape, with the axis generally aligned along the direction of Line 8. After the completion of the left line tunnel construction of Line 8 Liyuan North Road Station ~ Zemin Station, the maximum value of surface settlement is 4.58mm; after the completion of the right line tunnel construction, the maximum value of surface settlement is 6.04mm. It can be seen that compared to the left tunnel excavation, the right tunnel excavation contributes less to the surface settlement. After the excavation of the entire tunnel between Liyuan North Road Station and Zemin Station on Line 8, the maximum surface settlement

Table 2: Changes in Deformation

Stage	Lateral Horizontal Deformation (mm)	Longitudinal Horizontal Deformation (mm)	Vertical Deformation (mm)
1	-0.08	0.04	-0.10
2	-0.26	0.23	-0.91
3	-0.59	0.62	-2.87
4	-0.73	0.85	-4.78
5	-0.78	0.86	-4.89
6	-0.68	0.87	-4.96
7	-0.69	0.85	-5.01
8	-0.72	0.84	-5.16
9	-0.71	0.91	-5.31
10	-0.83	1.12	-5.62



(**a**) Surface settlement after completion of excavation and segment application on the left side of the proposed Line 8 tunnel



(**b**) Surface settlement after completion of excavation and segment application on the right side of the proposed Line 8 tunnel

Figure 6: Settlement nephogram of the ground surface (mm).

reaches 6.04 mm, which is well below the surface settlement control limit of 20 mm. This suggests that the proposed Line 8 tunnels has a minimal additional impact on the existing Line 1 tunnels between Wangchunqiao Station and Zemin Station.

5. CONCLUSION

With the background of Ningbo rail transit tunnel excavation, for the construction of Line 8 tunnel beneath Line 1 tunnel, Midas software was used to do three-dimensional numerical simulation of the deformation of Line 1 tunnel, and the results show that:

(1) The maximum values of horizontal deformation in both the lateral and longitudinal directions, as well as the vertical deformation of the existing tunnels from Wangchunqiao Station to Zemin Station of Line 1 occurred after the excavation of the proposed Line 8 tunnels was completed, and all of them meet the standards for settlement control of existing tunnels for urban rail transit in China (10mm). With the advance of the tunnel excavation of Line 8, the deformation of the existing tunnel gradually tends to be stable, which indicates that if the tunnel can reach this stable state smoothly by controlling the construction process or adopting special technology, the long-term safety of the existing tunnel can be better guaranteed;

(2) After the completion of tunnel excavation at Liyuan North Road Station ~ Zemin Station on Line 8, the maximum value of surface settlement is smaller than the surface settlement control value, indicating that the proposed Line 8 tunnels has less additional impact on the existing tunnels at Wangchunqiao Station ~ Zemin Station on Line 1;

(3) During the construction process, the deformation in the vertical direction of the existing tunnel, especially in the middle of the tunnel, is more complicated, which indicates that the vertical settlement should be the focus of attention in deformation control, so as to avoid structural damage due to excessive deformation of the existing tunnels. High-precision monitoring equipment can be installed in the middle of the existing tunnel to obtain real-time, accurate data. If the vertical deformation approaches the control limit, immediate measures should be taken, such as soil grouting reinforcement or adjustment of shield tunneling parameters.

(4) The study area of this paper involves various soil layers such as miscellaneous fill, clay, and silty clay. The research findings can provide reference for projects with similar geological conditions and construction techniques. If a project is located in an area with significantly different geological conditions from this study, such as sandy soil areas or soft rock areas, when referring to the research results, it is necessary to adjust the numerical simulation model and parameters in combination with the physical and mechanical parameters of the local soil, and re - evaluate the impact of new tunnel construction on the deformation of existing tunnels.

(5) In different tunnel projects, the spacing and crossing angles between new and existing tunnels vary. There are also differences in construction techniques and equipment among different countries and regions. When referring to the calculation results of this study, it is necessary to consider the characteristics of the project as well as local construction techniques and standards, and develop a reasonable deformation control and protection plan.

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