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Effects of Foundation Excavation on Metro Tunnels at Different Locations and Performance of Corresponding Reinforcement Measures: A Case of Shenzhen Metro Line 11, China

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Abstract: Symmetrical excavation of a foundation pit inevitably causes stress redistribution and deformation in adjacent tunnels, even threatening the safety of their operation. Therefore, it is of practical significance to evaluate the deformation characteristics of adjacent tunnels and propose corresponding reinforcement measures after the excavation of a foundation pit. This study, based on the overlapping tunnel project of the section between Nanshan Station and Qianhaiwan Station of Shenzhen Metro Line 11, analyzes the influence of overlapping foundation pit excavation on adjacent tunnels by numerical simulation method. The deformation characteristics of adjacent tunnels at different locations caused by foundation pit excavation are studied, and the soil reinforcement measures applicable to tunnels at different locations are proposed, respectively. Some useful conclusions have been drawn as follows. The deformation characteristics of adjacent tunnels caused by foundation pit excavation can be divided into three areas: the settlement zone, the transition zone, and the uplift zone. Moreover, for different zones of the tunnel, corresponding soil reinforcement measures are taken, respectively. Soil reinforcement measure makes the soil more monolithic and thus make the stress and strain transfer more uniform, which is effective in reducing soil rebound displacement and tunnel uplift displacement.

Keywords: foundation pit excavation; adjacent tunnels; soil reinforcement; numerical simulation

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1. Introduction

With the development of economy, huge and dense underground space is exploited and utilized [1–5]. As of June 2022, China has 277 underground rail lines in 51 cities, with 9067 km of operation. Due to the full utilization of underground space, a considerable number of foundation pits are located adjacent to metro tunnels. On the one hand, metro tunnels are inevitably affected by underground construction during operation. In particular, the excavation of a foundation pit causes large vertical and horizontal displacements in the adjacent tunnel [6–13]. On the other hand, there are strict limits on the deformation of metro tunnels. In Shanghai, for example, the maximum displacement shall not exceed 20 mm; the radius of curvature of deformation shall be bigger than 15,000 m; the relative deflection shall not exceed 1/2500 [14]. Therefore, how to predict the impact of foundation pit excavation on adjacent tunnels and choose appropriate reinforcement measures has been the focus of many scholars.

In response to the above problems, many scholars in China and abroad have conducted numerous studies from many perspectives. The research methodology employed by many scholars includes: semi-analytical methods, field monitoring, centrifuge model tests, and numerical analysis. Analytical theories could offer fast and relatively accurate prediction results using properly simplified computational conditions. Zhang et al. (2013, 2015) [15,16] presented a simplified algorithm for the effect of foundation pit excavation on the deformation of adjacent tunnels and predicted the soil disturbance effect of foundation pit excavation by applying the Mindlin solution. During the construction of the Taipei Rapid Transit System (TRTS) tunnels, a section of the tunnel in the Panchiao line was damaged by an adjacent five-level deep basement excavation. Chang et al. (2001) [17] used in situ monitoring methods and observed that cracks appeared in reinforced concrete segments and the concrete slab on the invert was displaced and became detached from the segments. Although the data obtained from the field monitoring is only for the tunnel in individual cases, it can provide reference for the numerical simulation results. Guo et al. (2018) [18] used the three-dimensional finite difference simulation software FLAC3D [19] to study the influence law of deep foundation pit excavation and construction loading on the deformation and soil pressure changes of existing tunnels, showing that there are significant differences in tunnel deformation under different soil conditions and loads. Ng et al. (2013) [20] designed and conducted centrifuge model tests to investigate the effects of a basement excavation on the deformation of existing tunnels in the sand. To investigate the effect of reinforced ground on the tunnel response, Sun et al. (2019) [21] performed finite element analysis based on previously reported centrifugal model tests without ground reinforcement. The influence of Young's modulus and depth of the reinforced soil on the tunnel deformation was analyzed.

Moreover, the proper method to deal with the deformation of the adjacent tunnel caused by the excavation of the foundation pit is to adopt soil reinforcement measures. Zhang et al. (2017) [22] analyzed the subway tunnel deformation monitoring data and studied the impact of block excavation of the foundation pit on controlling the deformation of the adjacent subway. Criteria and measures to control soil and tunnel deformation are discussed in detail by Hu et al. (2003) [23]. These measures include cast-in-place concrete diaphragm walls with bracing structural members, pumping consolidation, hybrid cement-soil mix pile systems, and rational excavation procedures.

Although scholars have done extensive research on the deformation characteristics of adjacent tunnels caused by foundation pit excavation, mostly focusing only on specific tunnel locations, the deformation characteristics of adjacent tunnels at different locations are still not fully understood. Moreover, few quantitative studies on the effect of soil reinforcement on tunnel deformation caused by pit excavation are available. In this paper, based on the overlapping tunnel project in an interval section of Shenzhen Metro Line 11, the influence laws of overlapping pit excavation on adjacent tunnels are investigated by numerical simulation methods, and the deformation characteristics of adjacent tunnels at different locations caused by pit excavation are studied. Soil reinforcement measures applicable to the control of tunnel deformation at different locations are proposed, respectively.

2. Project Overview

2.1. Project Introduction

The section between Nanshan Station and Qianhaiwan Station of Shenzhen Metro Line 11 starts from the intersection of Guimiao Road in the east, passes under Guimiao Road to the west and finally reaches Qianhaiwan Station, with a total length of 3.63 km. The interval section of the metro tunnel overlaps with the underpass tunnel involved in the reconstruction project of Guimiao Road, and the overlapping section is located between Nanhai Avenue and Menghai Avenue, with a length of 2.96 km. The plan view of the overlapping section is shown in Figure 1.

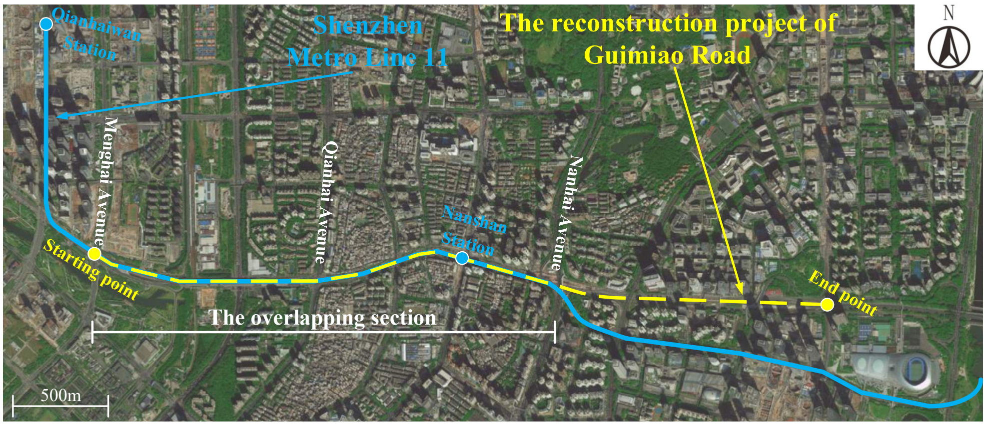


Figure 1. Plan view of the overlapping section.

In the overlapping section, the underpass tunnel is located on the side above or directly above the existing metro tunnel with a minimum clear distance of only 6.1 m. Figure 2 shows a typical design cross section of the metro tunnel and the underpass tunnel. The construction sequence of the overlapping section is to construct the metro tunnel of Line 11 by the shield method [24], and then to construct the underpass tunnel of Guimiao Road by full width open cut method [25]. In fact, this project is a longitudinal excavation of overlapping foundation pit above the existing metro tunnel, which has the characteristics of large unloading range and complicated geological conditions and surrounding environment. During the construction process, strictly controlling the influence of foundation pit excavation on the existing metro tunnel is another important feature of this project.

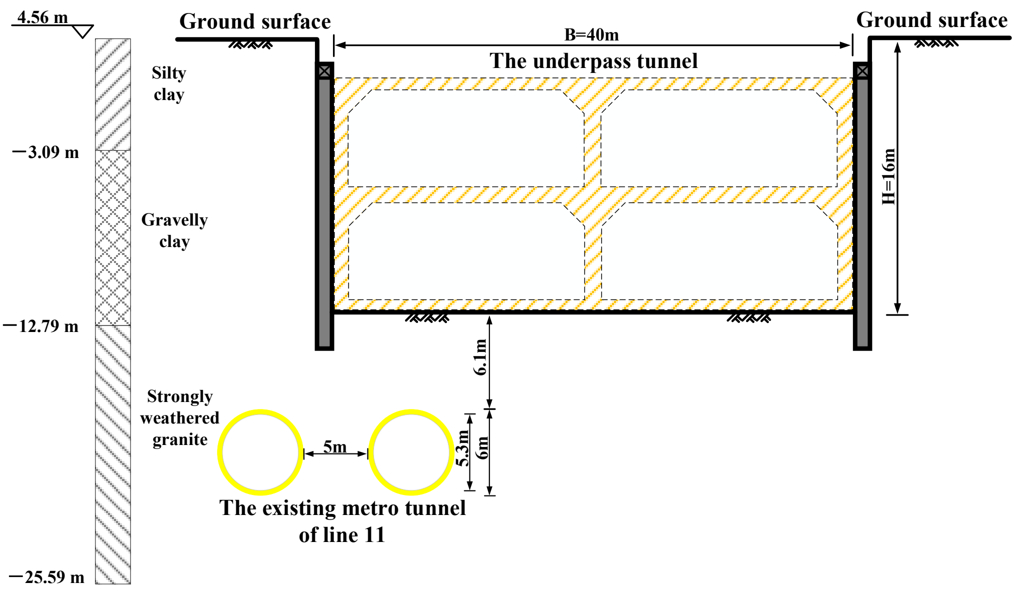


Figure 2. Typical cross section of the metro tunnel and the underpass tunnel.

The project is on a flat terrain and the landform is alluvial plain. The geological survey shows that the main strata of the site are silty clay, gravelly clay, and strongly weathered granite from top to bottom, all of which belong to soft soil. The soft soil in urban areas generally has the mechanical properties of high water content, high compressibility and low strength. The groundwater level in this site is not very high and is not the focus of this paper, so the impact of groundwater is ignored.

2.2. Foundation Pit Enclosure Structure and Excavation Scheme

The foundation pit adopts bored piles with 1 m diameter and 1.2 m spacing as the enclosure structure, with high-pressure rotary spraying measures between piles to stop water, and the inner side of maintenance piles adopts hanging net shotcrete. Among them, the shallow section of the foundation pit adopts cantilevered maintenance row piles, while the deeper section of the foundation pit sets one to three lateral supports depending on the ground load, with temporary columns under the lateral supports to enhance stability. The schematic diagram of the foundation pit enclosure structure is shown in Figure 3.

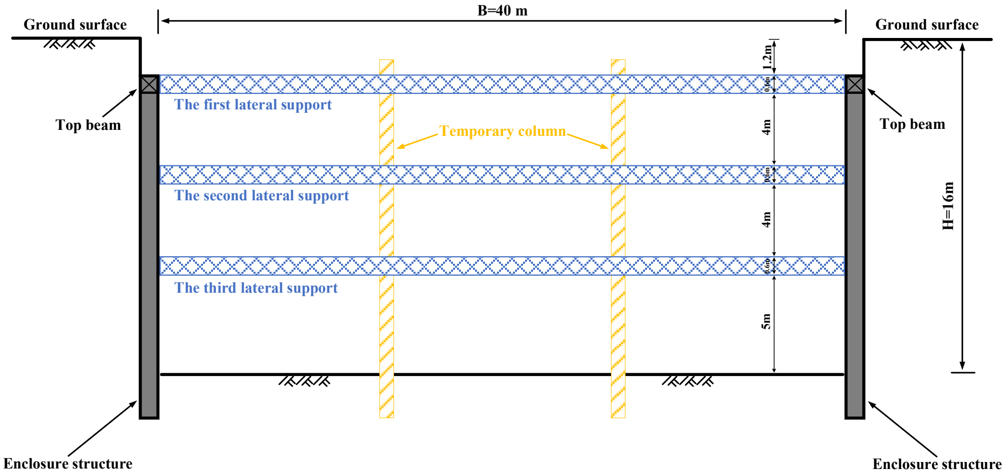


Figure 3. Schematic diagram of foundation pit enclosure structure (with three supports as an example).

The whole foundation pit is excavated symmetrically by the open cut method in the principle of vertical layering and longitudinal segmentation. The main construction steps are as follows: initially, bored piles, crown beams and other enclosure structures are symmetrically constructed; after the excavation reaches the bottom of the first to third support, the lateral support is immediately constructed; finally, the excavation reaches the bottom elevation of the foundation pit and the concrete base slab is poured.

3. Numerical Simulation of Overlapping Foundation Pit Excavation

3.1. Computation Model and Boundary Conditions

FLAC software was utilized to analyze the effects of excavation of overlapping foundation pit on the displacement and internal forces of the metro tunnel. According to the characteristics of this project, the planar position relationship between the new underpass tunnel line and the existing metro line is close to parallel; therefore, it is suitable to establish a two-dimensional plane strain model for analysis. The excavation depth H and width B of the foundation pit are taken as 16 m and 40 m, respectively, and the outer diameter of the metro tunnel is 6.0 m and the thickness of the segments is 0.35 m. Hsieh et al. (1998) [26] found that the influence range of foundation excavation on lateral surface subsidence is four times the excavation depth, therefore, the lateral size of the model is taken to 64 m beyond the enclosure structure. Liu et al. (2007) [27] found that the amount of soil rebound displacement below two times of the foundation pit excavation depth has been very small, so the model depth is taken to 54 m below the foundation pit bottom to basically meet the model boundary conditions. With the above considerations, the half plane size of the 2D model can be established as 84 m × 70 m, the lateral boundary condition of the model is fixed along the normal direction, the bottom boundary is completely fixed, and the top of the model is set as a free boundary, which are shown in Figure 4.

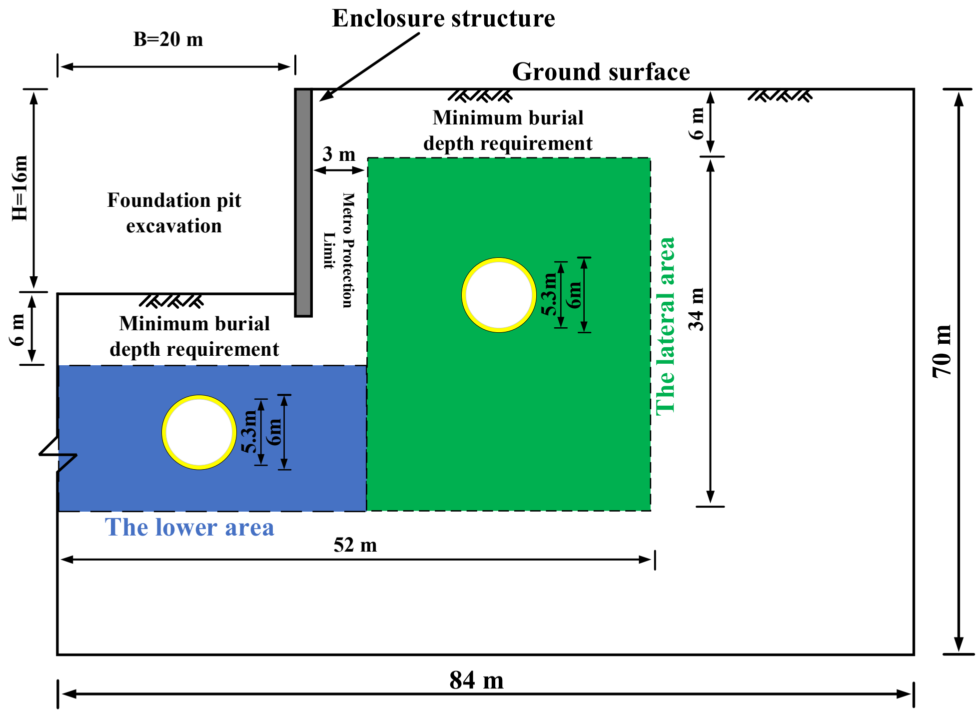


Figure 4. Schematic diagram of one-half of the model.

This paper highlights the deformation characteristics of the existing metro tunnel at different locations outside the foundation pit after the unloading effect of overlapping foundation pit excavation; therefore, the distribution range of the affected area of the tunnel outside the foundation pit needs to be determined. No underground construction activities can be carried out within 3 m on both sides of the metro line, so the metro tunnel is placed within 3 m outside of the enclosure structure. The shield tunnel buried depth should not be less than 1 times the tunnel outer diameter (about 6 m), so the tunnel is placed at 6 m below the ground surface and the bottom of the foundation pit. According to the study of Deng et al. (2014) [28], the influence range of soil horizontal deformation in the lateral area of the foundation pit is concentrated in the outer part of the enclosure structure twice the excavation depth, which is taken to 32 m beyond the enclosure structure in this paper. The burial depth of the tunnel in the actual project rarely exceeds 40 m, and the maximum burial depth of 40 m is taken as the center of the tunnel in the study. In summary, the affected area of the tunnel outside the pit is drawn with a dashed line in Figure 4 and marked with the corresponding dimensions. In addition, the affected area of the tunnel can be divided into a lower area and a lateral area according to the relative position of the tunnel to the foundation pit.

Different numerical models are established for the metro tunnel arranged in the lower and lateral areas of the foundation pit for analyzing the deformation characteristics of the metro tunnel at different locations outside the foundation pit.

3.2. Constitutive Model and Model Parameters

For simplicity, the layered soils are weighted average as a homogenous soil layer according to the thickness in the numerical simulation process. The Mohr–Coulomb model and elastic model are used as the constitutive model for the soil and reinforced soil, respectively. The elastic model is used to simulate the segments of metro tunnel. The shell structural unit model is used to simulate the enclosure structure of a foundation pit whose thickness is 0.8 m. The beam structural unit model is used to simulate the lateral supports of the foundation pit, which has a cross-sectional size of 600 mm × 600 m, and the vertical spacing of the first, second, and third support is 4 m, 4 m, and 5 m, respectively. Table 1 shows the physical and mechanical parameters required by the above constitutive model.

Table 1. Parameters required in the model.

	Elastic Modulus E (MPa)	Poisson's Ratio ν	Cohesion C (KPa)	Friction Angle φ (°)	Unit Weight γ (KN/m^3)
Soil	84	0.26	29	28	20
Reinforced soil	100	0.25	/	/	25
Segments	34,500	0.2	/	/	25
Enclosure structure	25,000	0.2	/	/	25
Lateral support	30,000	0.2	/	/	25

3.3. Numerical Modeling Procedure

In the analysis of the impact of the foundation pit excavation on the adjacent tunnels, the tunnel was already present during the initialization phase, and the specific simulation process was as follows:

(1) Generating initial ground stress and zeroing out the initial ground displacement.

(2) Excavating the tunnel, activating the segment material properties, calculating to equilibrium, and then zeroing out the ground and segment displacement.

(3) Excavating the foundation pit, activating the material properties of the enclosure structure, lateral support, and concrete base slab, and calculating to achieve equilibrium.

(4) Extracting data such as displacement of ground and tunnel for analysis.

3.4. Validation of Numerical Models

To verify the reasonableness of the selected numerical model and its corresponding material parameters, the surface deformation curves caused by the foundation pit excavation was first calculated and compared with the existing empirical formulae to judge the reliability of the numerical model.

The horizontal displacement curves of the ground surface outside the foundation pit derived from numerical simulation and empirical formula are given in Figure 5. Considering the excavation depth of the foundation pit as H and the horizontal distance from the ground surface to the enclosure structure as x, the horizontal coordinate is x/H. Schuster et al. (2009) [29] concluded that after the excavation of the foundation pit, the horizontal displacement of the ground surface at the distance of 1H from the enclosure structure reaches the maximum value. The horizontal displacement of the ground surface decreases rapidly in the range of 1H–2.5H, and decays to 0.4 times of the maximum value at 2.5H. The horizontal displacement of the ground surface gradually converges to 0 in the range of 2.5H–5H. It is obvious that although the range of the main influence zone derived from the numerical simulation is smaller than that of the empirical curve, the trends of both are basically similar.

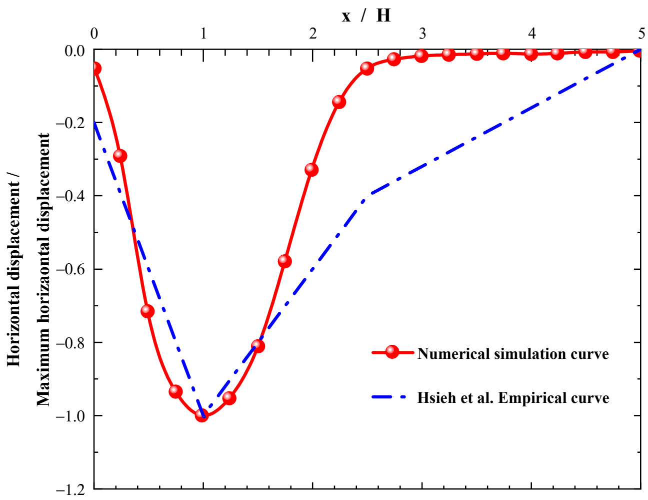


Figure 5. Horizontal displacement curve of the ground surface outside the foundation pit [26].

Hsieh et al. (1998) [26] found that after the excavation of the foundation pit, the main influence of surface settlement was concentrated within 2H outside the enclosure structure. The surface settlement reaches the maximum settlement value at 0.5H, and the surface settlement outside the 4H range is approximately 0. Figure 6 shows the surface settlement curves outside the foundation pit from the numerical simulation and the empirical formula. It is obvious that the distribution laws of the surface settlement curve obtained from the numerical simulation and the empirical curve are basically consistent. Both the location of the maximum settlement value and the range of the settlement trough can be fitted well.

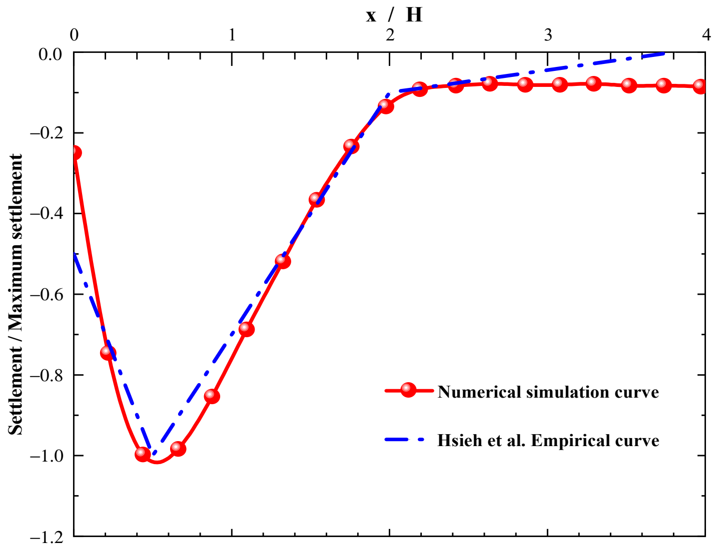


Figure 6. Settlement curve of the ground surface outside the foundation pit [26].

In summary, the surface deformation derived from the numerical model is basically consistent with the previous conclusions, indicating that the constitutive model and parameters selected in this paper can better reflect the soil deformation laws after the excavation of the foundation pit, so that the influence laws of the foundation pit excavation on the existing tunnels at different locations outside the pit can be further studied.

3.5. Results and Analysis

To investigate the deformation characteristics of the tunnel at different locations in the lower area of the foundation pit, the control variable method is fully used. Firstly, the depth of the tunnel is kept at 22 m, and the change of tunnel displacement is analyzed by adjusting the horizontal spacing between the center of the tunnel and the center of the foundation pit. Then, the horizontal spacing between the center of the tunnel and the center of the foundation pit is kept at 12.0 m, and the change of tunnel displacement is analyzed by adjusting the depth of the tunnel. In addition, the vertical displacement of the tunnel is defined as positive for uplift and negative for settlement, and the horizontal displacement is defined as negative in the direction of the center of the foundation pit and positive vice versa.

Figure 7 gives the tunnel displacement variation curves in the lower area of the foundation pit for the above two analysis cases. The horizontal displacement of the tunnel in the lower area is smaller and the vertical displacement is larger, making the total displacement curve almost coincide with the vertical displacement curve, indicating that the excavation of the foundation pit has a remarkable unloading effect on the lower soil body, and the additional displacement of the tunnel in the lower area is dominated by vertical uplift. At the same depth of tunnel condition, the horizontal displacement of the tunnel gradually increases with the increase of horizontal spacing, while the vertical displacement and total displacement gradually decrease. Moreover, at the same horizontal spacing condition, the vertical displacement, horizontal displacement, and total displacement of the tunnel all decrease sharply with the increase of the depth of tunnel.

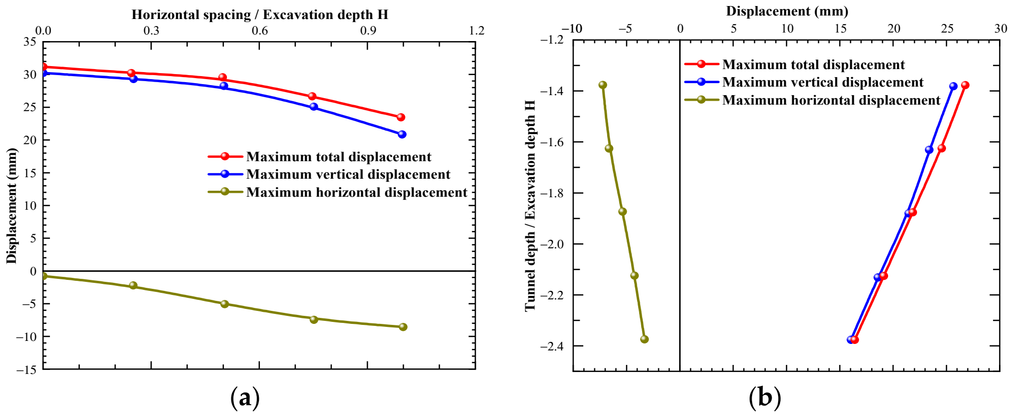


Figure 7. The tunnel displacement variation curves in the lower area: (**a**) Variation with horizontal spacing; (**b**) Variation with tunnel depth.

Figure 8 shows the displacement vectors of the tunnel nodes in the lower area when the depth of tunnel is maintained at 22 m and the horizontal spacing between the center of the tunnel and the center of the foundation pit is 0 m, 8 m, and 16 m, respectively. The upward vertical displacement occurs at the crown and bottom of tunnel, which indicates that the tunnel in the lower area has experienced different degrees of overall uplift displacement, and the horizontal displacement direction all points to the center of the foundation pit. Moreover, with the increase of horizontal spacing, the tunnel structure will rotate.

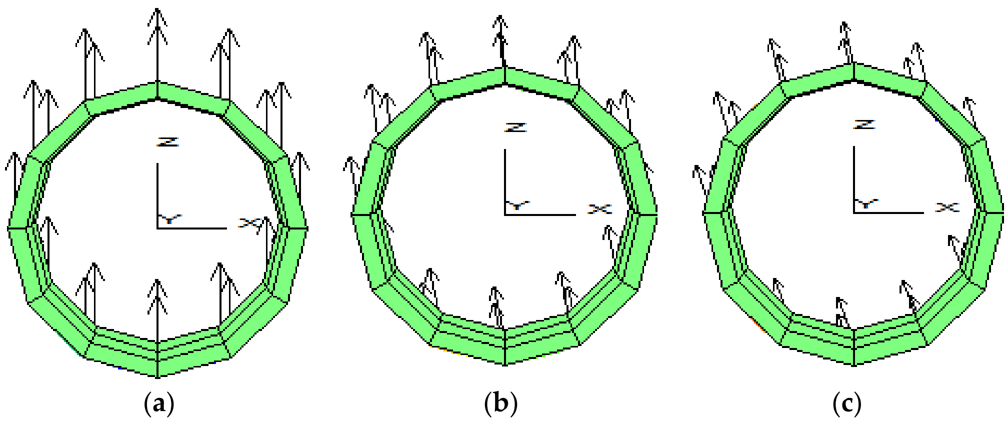


Figure 8. Tunnel displacement direction vector map in the lower area: (**a**) Horizontal spacing = 0 m; (**b**) Horizontal spacing = 8 m; (**c**) Horizontal spacing = 16 m.

Similarly, to investigate the deformation characteristics of the tunnel at different locations in the lateral area of the foundation pit, the control variable method is fully used. Firstly, the depth of the tunnel is kept at 10 m, and the change of tunnel displacement is analyzed by adjusting the horizontal spacing between the center of the tunnel and the enclosure structure of the foundation pit. Then, the horizontal spacing between the center of the tunnel and the enclosure structure is kept at 6.0 m, and the change of tunnel displacement is analyzed by adjusting the depth of tunnel. In addition, the positive and negative directions are shown above.

Figure 9 gives the tunnel displacement variation curves in the lateral area of the foundation pit for the above two analysis cases. The gap between the soil surface elevation inside and outside of the foundation pit is continuously growing as excavation depth is increased, and the unloading effect and soil surface elevation gap will cause the lateral soil of the enclosure structure to slide towards the interior of the foundation pit. The horizontal displacement and vertical displacement of the tunnel in the lateral area are relatively large. At the same depth of tunnel condition, the vertical displacement, horizontal displacement, and total displacement of the tunnel all decrease constantly with the increase of horizontal spacing. Moreover, at the same horizontal spacing condition, the horizontal displacement and the total displacement of the tunnel decrease continuously with the increase of the depth of tunnel, while the vertical displacement is relatively complicated. When the depth of the tunnel is shallow, larger vertical settlement occurs, and the settlement decreases continuously with increasing depth, and after the depth exceeds below the bottom of the foundation pit, the vertical displacement is transformed from settlement to uplift.

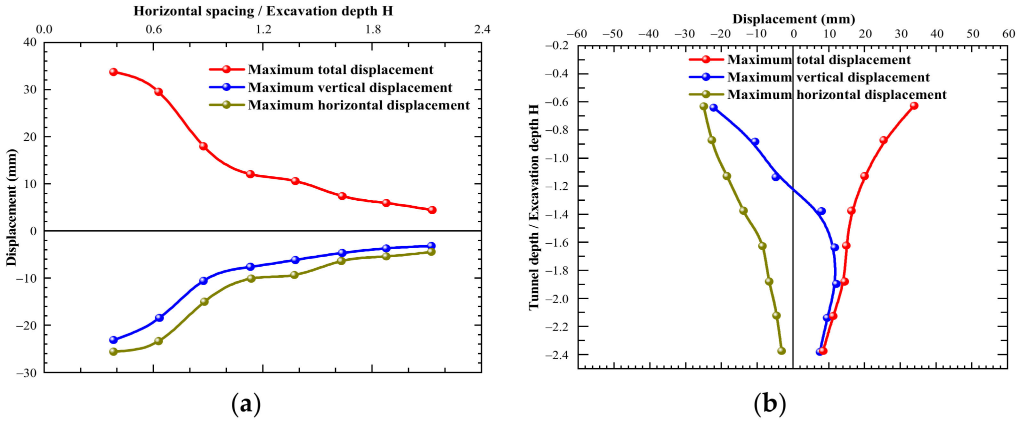


Figure 9. The tunnel displacement variation curves in the lateral area: (**a**) Variation with horizontal spacing; (**b**) Variation with tunnel depth.

Figure 10 shows the displacement vectors of the tunnel nodes in the lateral area when the horizontal spacing is maintained at 6 m and the depth of tunnel is 14 m, 22 m, and 30 m, respectively. The horizontal displacements pointing to the center of the foundation pit occurred at both the left and right waist of the tunnel. When the depth of tunnel is shallow, downward vertical displacement occurs at the crown and bottom of tunnel, and the tunnel integrally presents a settlement deformation. As the depth increases, the bottom of tunnel gradually uplifts under the influence of the uplift deformation of the deep soil, while the crown of tunnel keeps settling, and then the tunnel structure will show the phenomenon of diameter stretching in horizontal direction and diameter compression in vertical direction. After the depth exceeds below the bottom of the foundation pit, the crown of tunnel is also transformed from settlement to uplift, at which time the tunnel integrally undergoes uplift deformation.

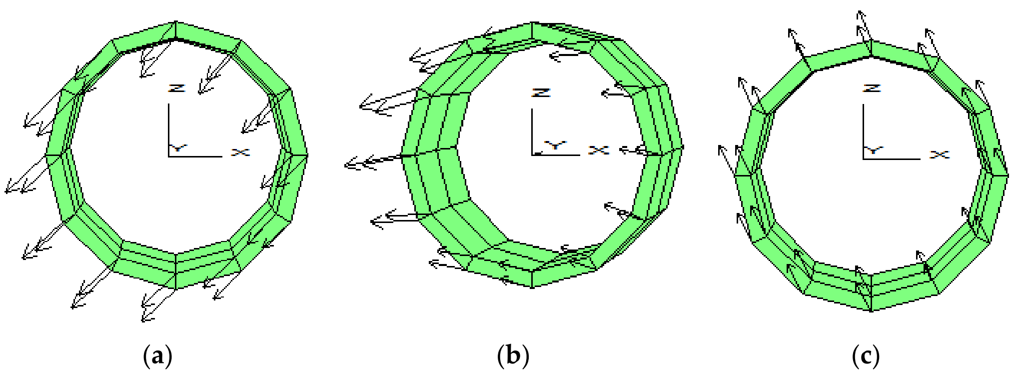


Figure 10. Tunnel displacement direction vector map in the lateral area: (**a**) Depth = 14 m; (**b**) Depth = 22 m; (**c**) Depth = 30 m.

From the above analysis, it is concluded that the tunnels in the lower area of the foundation pit all undergo overall uplift, while the tunnels in the lateral area may undergo settlement and uplift. According to the different directions of vertical displacement at the crown and bottom of tunnel, the deformation characteristics of adjacent tunnels caused by foundation pit excavation can be divided into three areas: the settlement zone, the transition zone, and the uplift zone.

(a) The settlement zone. The zone around the foundation pit where settlement occurs at the crown and bottom of tunnel, in other words, where the tunnel integrally settles in the vertical direction, is defined as the settlement zone. The settlement zone is mainly located in the lateral area of the foundation pit and in a certain shallow buried stratum below the ground surface. The displacement of the tunnel in the settlement zone is relatively significant in both the vertical and horizontal directions.

(b) The transition zone. The zone around the foundation pit where the crown of tunnel settles and the bottom of tunnel uplifts, in other words, where the tunnel integrally settles or uplifts in the vertical direction, is defined as the transition zone. The transition zone is mainly located within a certain range below the settlement zone. The displacement of the tunnel in the transition zone is small in vertical direction, but large in horizontal direction.

(c) The uplift zone. The zone around the foundation pit where uplift occurs at the crown and bottom of tunnel, in other words, where the tunnel integrally uplifts in the vertical direction, is defined as the uplift zone. The uplift zone is mainly located in the zone below the foundation pit. The displacement of the tunnel in the uplift zone is large in vertical direction, but small in horizontal direction.

4. Discussion on the Selection and Performance of Reinforcement Measures

After the excavation of the foundation pit, corresponding deformation control measures are generally required to ensure the safety operation of the existing metro tunnel. Since it is difficult to achieve effective deformation control measures in operating tunnels from improving the strength of their own structures, the main method to preserve operating tunnels is by controlling the deformation of intermediate soil, while soil reinforcement measures are a popular method. Soil reinforcement measures are usually used to reinforce the soil around the foundation pit by grouting.

From the above conclusions, the tunnel deformation in the lower area is dominated by vertical uplift while in the lateral area the tunnel deformation is dominated by horizontal displacement after the excavation of the foundation pit. Plainly, the type of soil reinforcement required for tunnels in the lower and lateral areas is distinct. Therefore, we propose soil reinforcement measures applicable to different areas of the tunnel, and then analyze the performance of the soil reinforcement measures using numerical simulations.

4.1. Analysis of Reinforcement Measures in the Lower Area

Numerical model dimensions are taken as follows for the case when the tunnel is in the lower area. We assume that the metro tunnel is located directly below the center of the foundation pit with a vertical clear distance of 12 m. The reinforcement range covers the bottom area of the foundation pit. The length L, width B, and depth H of the foundation pit were taken as 80 m, 40 m, and 16 m, respectively, and the outer diameter of the metro tunnel is 6.0 m and the thickness of the segments is 0.35 m. Since the model has symmetry about the length direction of the foundation pit, half of the model is taken for numerical simulation. The length, width, and depth of the adopted model were taken as 160 m, 200 m, and 80 m, respectively. Moreover, the constitutive models and related parameters for the soil, reinforced soil, tunnel segments, enclosure structure and lateral supports are shown above. The lateral boundary condition of the model is fixed along the normal direction, the bottom boundary is completely fixed, and the top of the model is set as a free boundary, which is shown in Figure 11.

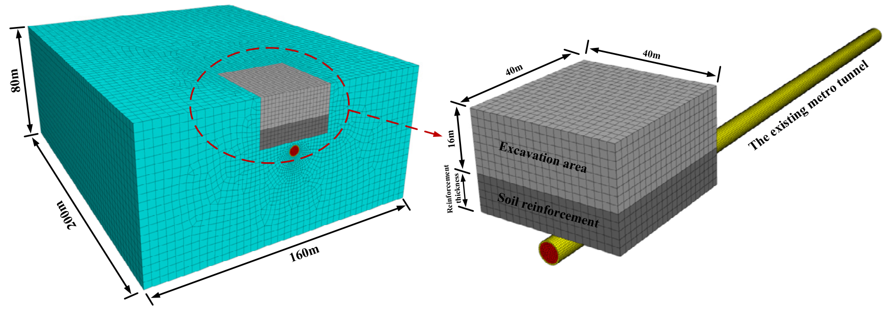


Figure 11. Schematic diagram of adopted model in the lower area.

Firstly, two cases of soil without reinforcement and with reinforcement in the lower area are analyzed. The form of soil reinforcement is selected as full-area reinforcement, and the reinforcement thickness is taken as 10 m.

Figure 12 shows the shear strain distribution of the soil lying under foundation pit with and without reinforcement. The maximum shear strain is concentrated at the foot of the foundation pit due to the restraining effect of the soil by the enclosure structure. The maximum shear strains are about 5.5×10^{-2} and 4.24×10^{-3} with discrete and uniform distributions, respectively, before and after the application of soil reinforcement measure. Therefore, soil reinforcement measure makes the soil more monolithic and, thus, make the stress and strain transfer more uniform. Moreover, the reinforced soil and the enclosure structure form a bearing community, which makes the stress and strain effectively transferred from the soil lying under the foundation pit to the enclosure structure, and the tendency of soil rebound displacement is more obviously limited.

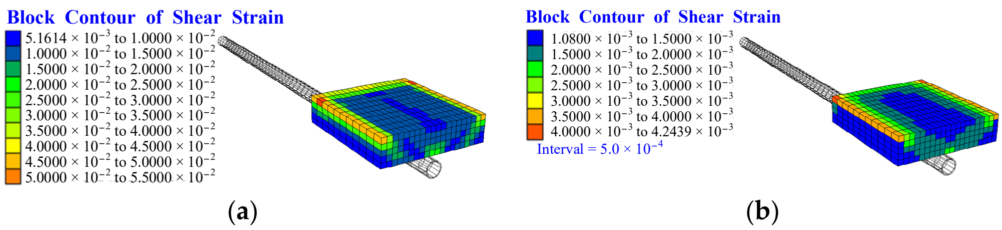


Figure 12. Shear strain distribution of soil lying under the foundation pit: (**a**) Without reinforcement; (**b**) With reinforcement.

Figures 13 and 14 show the vertical displacement distributions of the soil lying under foundation pit and the tunnel in the lower area with and without reinforcement. Without reinforcement, the maximum rebound displacement of the soil lying under foundation pit is 41.7 cm, and the maximum tunnel uplift displacement is 13.5 cm. After the reinforcement measures were applied, the maximum rebound displacement of soil lying under foundation pit is reduced to 14.0 cm and the maximum tunnel uplift displacement is reduced to 9.6 cm. Therefore, the effect of soil reinforcement measure on reducing soil rebound displacement and tunnel uplift displacement is obvious.

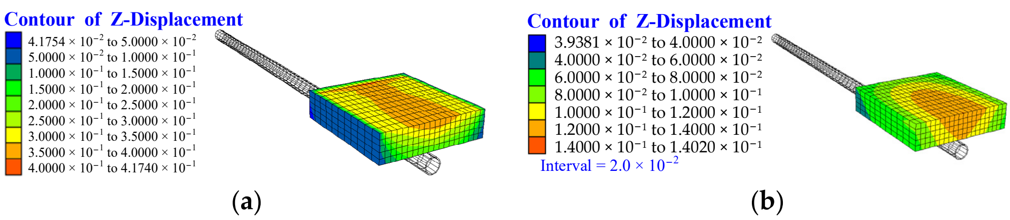
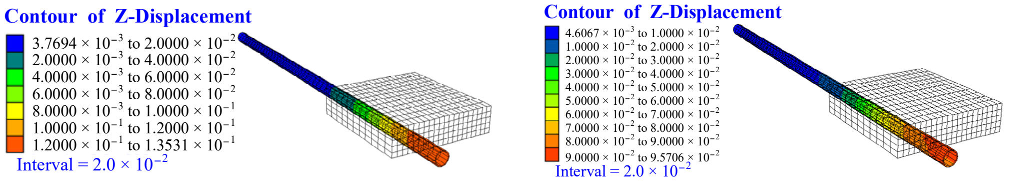


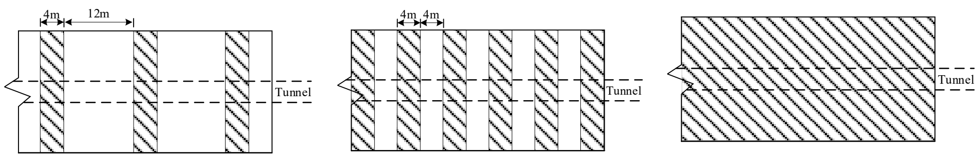
Figure 13. Vertical displacement distribution of the soil lying under the foundation pit: (**a**) Without reinforcement; (**b**) With reinforcement.



(**a**) (**b**)

Figure 14. Vertical displacement distribution of the tunnel in the lower area: (**a**) Without reinforcement; (**b**) With reinforcement.

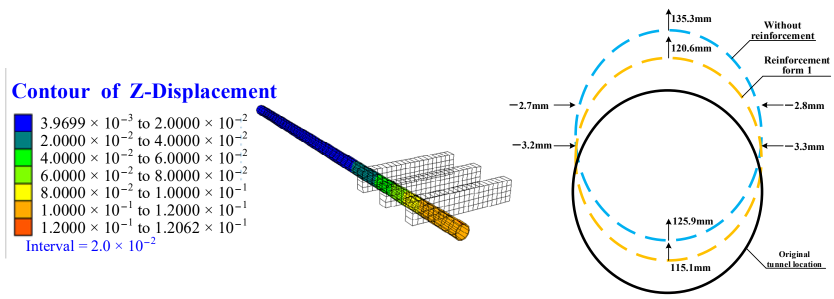
Secondly, according to the soil conditions of the project site, the extent of the unloading area and the spacing between the unloading area and the existing tunnel, there are two main forms of soil reinforcement: strip reinforcement and full-area reinforcement. To investigate the law of reinforcement forms on controlling deformation of tunnel, we use the three reinforcement forms shown in Figure 15: reinforcement form 1 represents the case of sparse reinforcement strips; reinforcement form 2 represents the case of dense reinforcement strips; reinforcement form 3 represents the full-area reinforcement. The shaded part in the figure is the soil reinforcement range, and the reinforcement thickness is taken as 10 m.



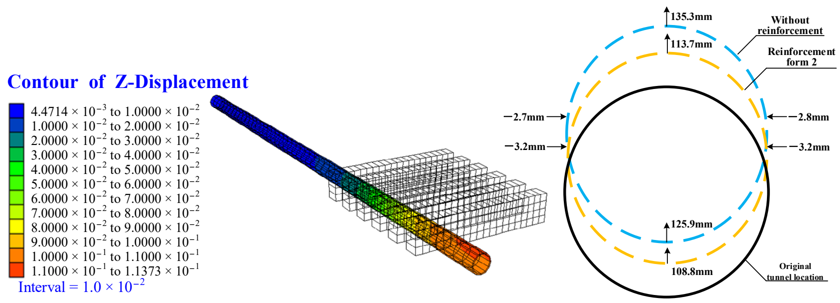
(**a**) (**b**) (**c**)

Figure 15. Forms of soil reinforcement: (**a**) Reinforcement form 1; (**b**) Reinforcement form 2; (**c**) Reinforcement form 3.

Figure 16 shows the vertical displacement distribution of the tunnel under the three forms of reinforcement and compares the displacement with that of the case without reinforcement. Compared with the case without reinforcement, all three forms of reinforcement can reduce the vertical displacement of tunnel to different degrees, among which the full-area reinforcement form has the most obvious effect on controlling the deformation of tunnel.

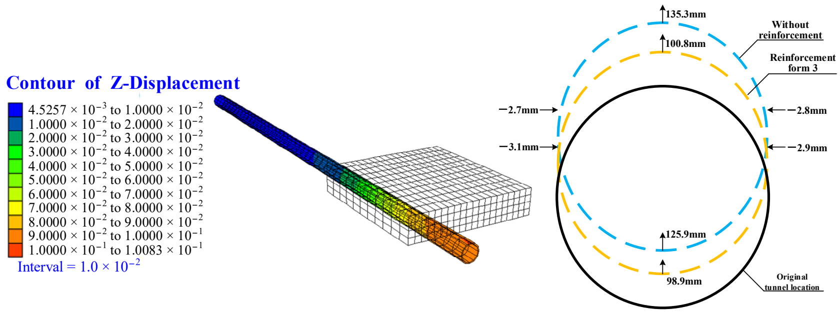


(**a**)



(**b**)

Figure 16. *Cont.*



(**c**)

Figure 16. Influence of different reinforcement forms of reinforcement on tunnel in the lower area: (**a**) Reinforcement form 1; (**b**) Reinforcement form 2; (**c**) Reinforcement form 3.

The results show that after the excavation of the foundation pit, the vertical displacement of the tunnel in the lower area is significantly larger than the horizontal displacement, the tunnel integrally uplifts in the vertical direction. The horizontal displacement pointing to the center of tunnel occurs in both the left and right waist of tunnel, which makes the tunnel section undergo a relative tensile deformation in the shape of "vertical ellipse", defining the vertical tensile rate as:

$$u_v = \frac{(v_1 - v_2) + (w_1 - w_2)}{D} \tag{1}$$

where ν_1 and ν_2 are the vertical displacement of the crown and bottom of tunnel, respectively (the vertical displacement is defined as positive for uplift and negative for settlement); ω_1 and ω_2 are the horizontal displacement of the left and right waist of tunnel, respectively (the horizontal displacement is defined as negative in the direction of the center of the foundation pit and positive vice versa); and D is the tunnel diameter.

Without reinforcement, reinforcement form 1, reinforcement form 2, and reinforcement form 3 applied, the vertical relative tensile rates of the tunnel section are 2.5‰, 2.0‰, 1.9‰, and 1.3‰, respectively. Therefore, increasing the range of soil reinforcement not only limits the overall uplift of tunnel in the lower area, but also plays a role in reducing the relative deformation of the tunnel section.

Figure 17 gives the longitudinal distribution curves of the tunnel uplift in the lower area under different reinforcement forms. The maximum vertical displacement of tunnel is 120.6 mm, 113.7 mm, and 100.8 mm under reinforcement form 1, reinforcement form 2, and reinforcement form 3, respectively, which are reduced by 10.9%, 16.0%, and 25.6%, compared to the case without reinforcement. Therefore, with the increasing extent of reinforced soil, the integrity of the bearing soil is strengthened, the ability to limit tunnel deformation is enhanced, and the tendency of tunnel uplift is more obviously controlled.

Finally, the reinforcement thickness is an important factor affecting the performance of the reinforcement. In general, the greater the reinforcement thickness, the more obvious the effect of controlling tunnel deformation, but also the higher the project cost. To investigate the law of reinforcement thickness on controlling deformation of tunnel, taking the reinforcement form of full-area reinforcement as an example. Figure 18 gives the longitudinal distribution curves of the tunnel uplift in the lower area under different reinforcement thicknesses. It is obvious that, compared with the case without reinforcement, the maximum vertical displacement of the tunnel in the lower area is reduced by 11.1%, 22.1%, and 29.2% when the reinforcement thickness is 2 m, 6 m, and 10 m, respectively, and the impact area of the tunnel uplift is also reduced.

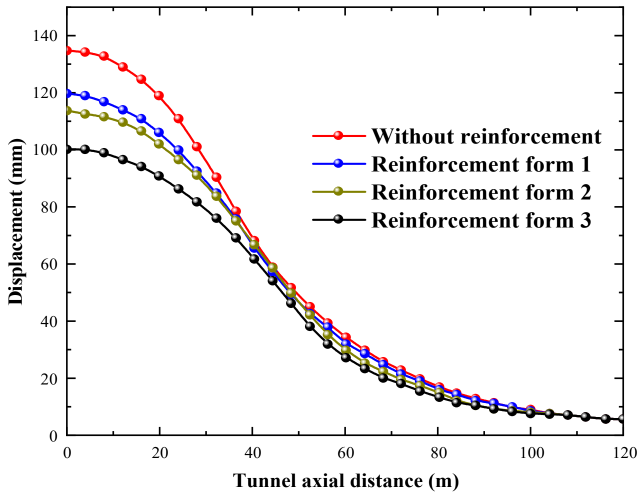


Figure 17. The longitudinal distribution curves of the tunnel uplift in the lower area under different reinforcement forms.

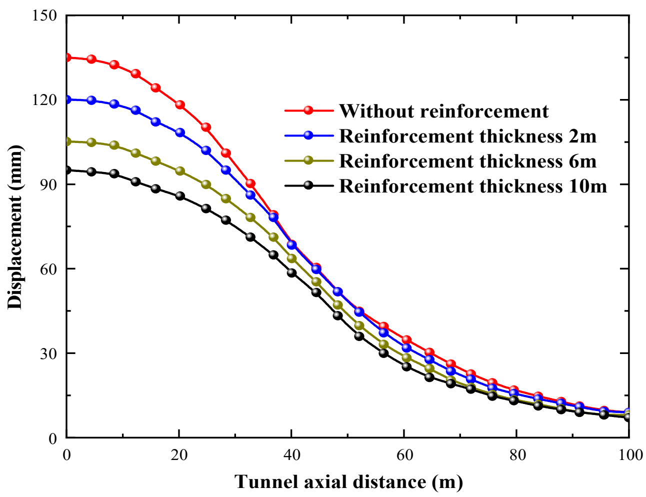


Figure 18. The longitudinal distribution curves of the tunnel uplift in the lower area under different reinforcement thicknesses.

Figure 19 gives the variation of the maximum vertical displacement of tunnel with the reinforcement thickness for different reinforcement forms. Clearly, the maximum displacement decreases with the increase of the reinforcement thickness, and the larger the reinforcement range, the greater the reduction of displacement. When the reinforcement thickness is increased from 2 m to 10 m, the maximum displacement of the tunnel is reduced by 21.5% in the case of reinforcement form 3, but only by 11.0% and 6.9% in the cases of reinforcement form 2 and 1, respectively. The reason for this is that with full-area reinforcement, the integrity of the reinforced soil is strong, and as the reinforcement thickness increases the integrity of the reinforced soil is better, and its ability to resist deformation is stronger, resulting in a significant reduction in tunnel uplift. However, in the case of strip reinforcement, the reinforced soils are independent of each other and cannot play an integral bearing effect with the increase of reinforcement thickness, and the larger the spacing of the strip reinforced soils, the less effective the increase of reinforcement thickness is in reducing the tunnel uplift.

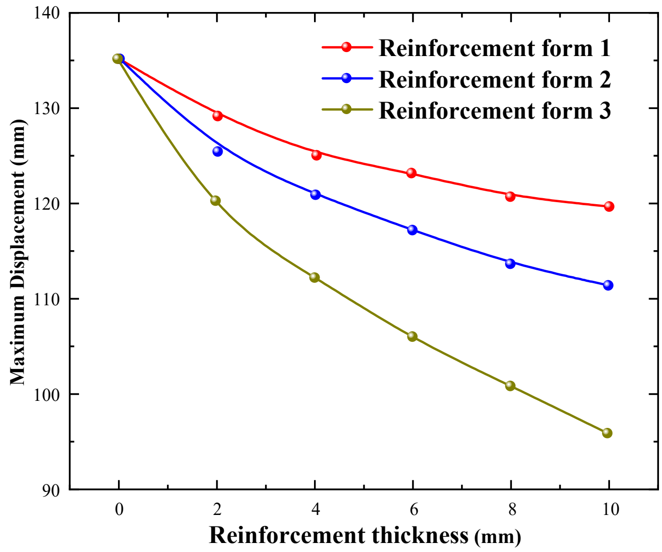


Figure 19. The variation of the maximum vertical displacement of tunnel with the reinforcement thickness for different reinforcement forms.

4.2. Analysis of Reinforcement Measures in the Lateral Area

When the tunnel is in the lateral area, we assume that the horizontal clear distance between the metro tunnel and the enclosure structure is 7 m, and the burial depth of the metro tunnel is 13 m. The reinforcement range covers the lateral area of the foundation pit with 10 m exceeding the bottom of the foundation pit in the depth direction, and the form of soil reinforcement is selected as full-area reinforcement. The dimensions of the foundation pit, the metro tunnel and the adopted model are the same as above. Finally, the adopted model in the lateral area is shown in Figure 20.

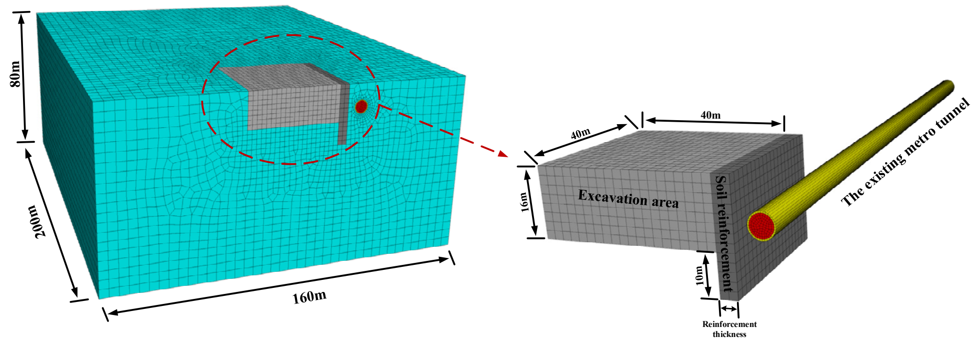


Figure 20. Schematic diagram of adopted model in the lateral area.

Figure 21 shows the horizontal displacement distribution of the tunnel without reinforcement and with reinforcement thickness of 2 m and 4 m, respectively, and compares the displacement with that of the case without reinforcement. As the tunnel is in the settlement zone, without reinforcement, both the crown and bottom of the tunnel settle, while after the soil reinforcement is applied, both the crown and bottom are transformed from settlement to uplift. The reason for this situation is that the depth of the reinforced soil is large and it has penetrated deep into the uplift zone below the bottom of the foundation pit, which makes the stiffer reinforced soil move upward with the soil in the uplift zone, thus driving the adjacent tunnel to uplift. Therefore, properly deepening the reinforced soil can offset the settlement of the tunnel in the settlement zone.

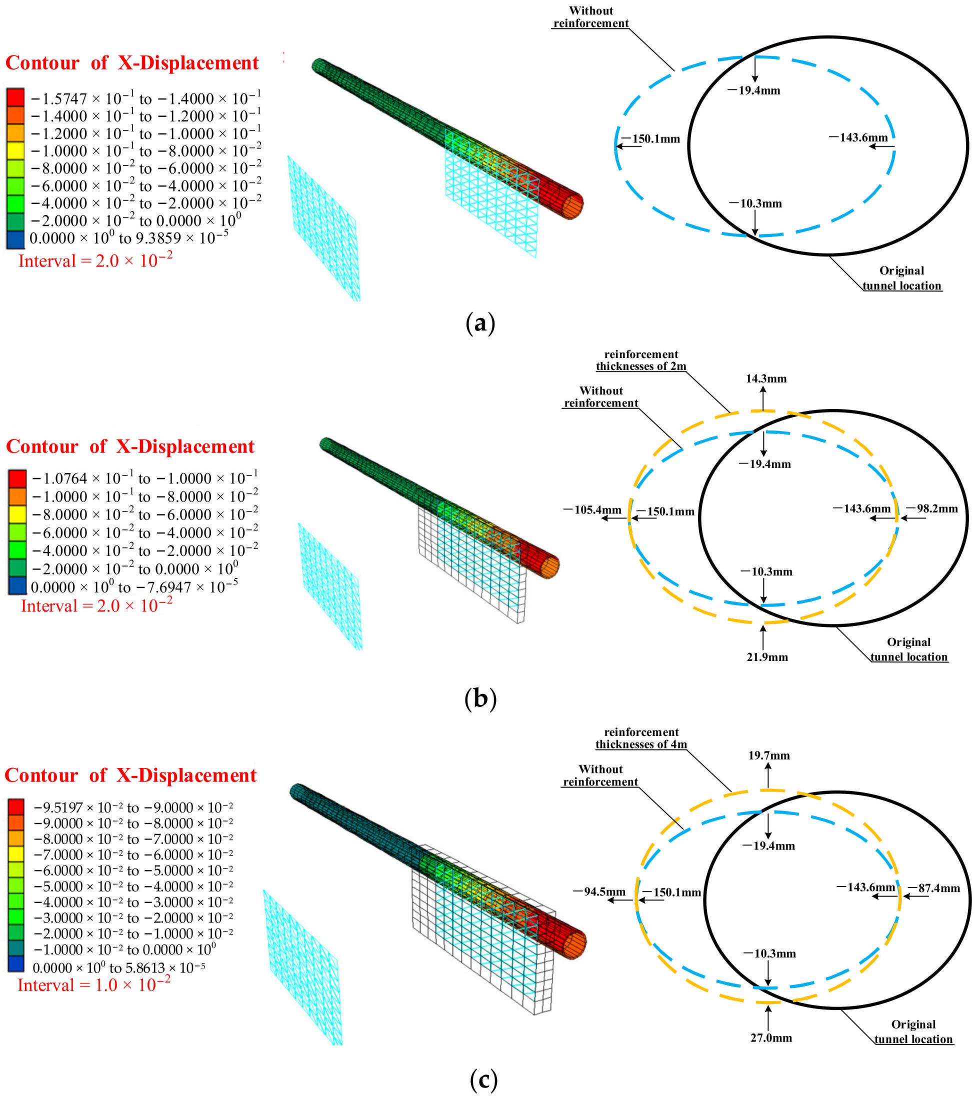


Figure 21. Influence of different reinforcement thicknesses of reinforcement on tunnel in the lateral area: (**a**) Without reinforcement; (**b**) Thickness of 2 m; (**c**) Thickness of 4 m.

The results show that after the excavation of the foundation pit, the tunnel in the lateral area has horizontal displacement towards the center of the foundation pit integrally, and the horizontal displacement of the left waist is larger than that of the right waist, which makes the tunnel section undergo a relative tensile deformation in the shape of "horizontal ellipse", defining the horizontal tensile rate as:

$$u_v = \frac{(v_2 - v_1) + (w_2 - w_1)}{D} \quad (2)$$

The horizontal relative tensile rates of the tunnel section for the cases without reinforcement and with reinforcement thicknesses of 2 m and 4 m are 2.6‰, 2.5‰, and 2.4‰, respectively. It shows that the soil reinforcement plays a role in reducing the relative deformation of the tunnel section.

Figure 22 shows the horizontal displacement longitudinal distribution curves of the tunnel in the lateral area obtained by numerical simulation. Without reinforcement, the maximum horizontal displacement is 147.0 mm, while the reinforced soil is a heterogeneous body with high stiffness and has a barrier effect, so that the magnitude of horizontal displacement and the longitudinal influence range of the tunnel are obviously controlled, and the larger the reinforcement thickness, the smaller the tunnel deformation. When the reinforcement thickness is 2 m and 4 m, the maximum horizontal displacement is 101.7 mm and 91.0 mm, which is reduced by 30.8% and 38.1%, respectively.

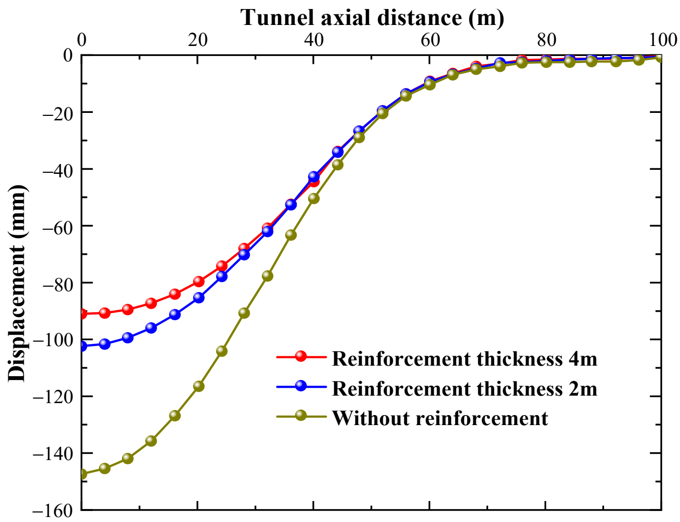


Figure 22. The horizontal displacement longitudinal distribution curves of the tunnel in the lateral area.

5. Conclusions

(1) In this paper, a numerical simulation method is used to analyze the influence of overlapping foundation pit excavation on adjacent tunnels. The deformation characteristics of adjacent tunnels at different locations caused by foundation pit excavation are studied, and the soil reinforcement measures applicable to tunnels at different locations are proposed, respectively. Based on the above analyses, the following conclusions were drawn:

(2) The deformation characteristics of adjacent tunnels caused by foundation pit excavation can be divided into three areas: the settlement zone, the transition zone, and the uplift zone. Firstly, the settlement zone is mainly located in the lateral area of the foundation pit and in a certain shallow buried stratum below the ground surface. The displacement of the tunnel in the settlement zone is relatively significant in both the vertical and horizontal directions. Secondly, the transition zone is mainly located within a certain range below the settlement zone. The displacement of the tunnel in the transition zone is small in the vertical direction but large in the horizontal direction. Finally, the uplift zone is mainly located in the zone below the foundation pit. The displacement of the tunnel in the uplift zone is large in vertical direction, but small in horizontal direction.

(3) In the lower area, the reinforced soil shows a strong integrity, which makes the stress and strain transfer more uniform. The relative tensile deformation in the shape of "vertical ellipse" of the tunnel section is effectively controlled. Moreover, the integrity of soil is stronger under full-area reinforcement, and increasing the thickness of reinforcement can reduce tunnel deformation more effectively. When the reinforcement thickness is increased from 2 m to 10 m, the maximum vertical displacement of the tunnel is reduced by 21.5%. However, the integrity is weaker under the two kinds of strip reinforcement, and increasing the thickness is ineffective in reducing tunnel deformation. When the reinforcement thickness is increased from 2 m to 10 m, the maximum vertical displacement of the tunnel is only reduced by 11.0% and 6.9%, respectively.

(4) In the lateral area, the reinforced soil has a similar effect as the reinforced soil in the lower area, the reinforced soil has a barrier effect, which significantly reduces the horizontal displacement of tunnel in the lateral area. The relative tensile deformation in the shape of "horizontal ellipse" of the tunnel section is effectively controlled. Moreover, compared with the case without reinforcement, the maximum horizontal

displacement decreases by 30.8% and 38.1%, respectively, when the full-area reinforcement thickness is 2 m and 4 m.

(5) The conclusions in this paper are drawn without considering groundwater, so they are applicable to practical projects without groundwater and can also provide a guideline for similar projects. Subsequent research can be carried out around the influence of groundwater and the refinement of soil layers.

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