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Research Article

Effects of Different Construction Sequences on Ground Surface Settlement and Displacement of Single Long Pile due to Twin Paralleled Shield Tunneling

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Shield tunneling activities inevitably pass through pile foundations at close distance in densely urban areas. Various studies have investigated the interaction between newly constructed tunnels and existing pile foundations. However, the influence of different construction sequences of twin paralleled shield tunneling on single long pile is seldom considered. A case was found in the project of Changsha Metro Line 5, where the twin paralleled tunnels were constructed near the Wanjiali Viaduct piles. A three-dimensional finite element model was established to analyze the pier settlement, ground surface settlement trough, and the vertical and horizontal displacement of pile under different construction sequences in layered soil. The results show that the adjacent pile and surrounding environment are affected substantially with the change of construction sequence of twin paralleled tunnels. The construction sequence of condition (b), in which the tunnel closer to the pile foundation is first constructed and then the tunnel farther away from the pile foundation is second constructed, can reduce the settlement of pier by 13.1%, the maximum surface settlement by 7.0%, the maximum vertical displacement of pile foundation by 7.9%, and the maximum horizontal displacement by 6.9%. The present findings can provide reference for similar projects.

1. Introduction

With the increasing congestion of surface traffic, exploiting the potential and promoting the benefits of the subsurface in cities have become an indispensable approach. Shield tunneling has a lot of advantages such as its high degree automation, easy management, no climate influence, one-time hole formation, and fast construction speed, which makes a rapid development of a new layer of supplemental infrastructure possible, allowing us new combinations that serve the modern needs of the city [1–3]. Meanwhile, a growing demand on housing, viaduct, infrastructure, and open space is competing for the urban surface areas, but also the subsurface, which makes shield tunneling often needs to pass through lots of pile foundations. However, even the most advanced shield technology will inevitably redistribute the initial stress of surrounding soil, causing surface subsidence, inclination, and discontinuous deformation, which may affect adjacent pile foundations [4–8].

In order to understand the pile-soil-tunnel interaction mechanism, many scholars have conducted centrifuge model tests and field measurement analysis [9–13]. Franza and Marshall [11] presented outcomes from 24 geotechnical centrifuge tests and investigated the global tunnel-piled frame interaction scenario by using a newly developed real-time hybrid testing technique. The results illustrated that pile settlement and failure mechanisms are highly dependent on the load redistribution that occurs between piles during tunnel volume loss, which are related to structure weight and stiffness. Wang et al. [14] studied the construction schemes and influence of shield tunneling on reinforcing and rebuilding bridges in the case of shield tunnel of Hangzhou Metro 2 crossing through Fengqi Bridge. Sirivachiraporn and Phienwej [15] analyzed the field measurement data of the first Bangkok subway project to evaluate the ground movement characteristics and responses of adjacent buildings. The results indicate that buildings on long piles showed the least induced settlements. But for buildings on short piles, the settlements depend on the distance from tunnel center line and pile tip depth. In addition, the interaction between shield tunnel and adjacent pile foundation has also been studied by proposing theoretical analytical solutions and numerical simulation by some scholars [16–25]. Franza et al. [16] presented an elastic study of tunnel-pile-structure interaction through Winkler-Based Two-Stage Analysis Methods. The results illustrated how pile foundations increase the risk of structural damage compared to shallow foundations, whereas structural stiffness can reduce building deformations. Zhang et al. [17] proposed a simplified solution based on Pasternak's foundation model to predict the lateral displacements of a single pile and group piles induced by shield tunneling considering the effects of lateral soil displacements. Lee [19] studied the effects of tunneling in weak weathered rock on the behavior of a preexisting single pile by performing three-dimensional elastoplastic numerical analyses. The results showed that the reduction of the apparent allowable pile capacity due to tunneling-induced pile head settlement is significant. Huang et al. [24] analyzed the displacement process of pile vertical, horizontal and along the tunnel based on the theory of fluid-soil coupling. As a summary, the above scholars all conducted that shield tunneling adjacent to existing pile foundations will cause pile settlement, lateral displacement of pile, additional axial load on piles, and induced bending moments along piles, which is mainly dependent on the distance between piles and tunnels, the ratio of pile length to tunnel depth, and the stratum loss.

Although a lot of studies have been carried out to investigate the effects of tunneling on existing piles, the excavation of only one tunnel is often considered. The underground transportation system often involves twin paralleled tunnels, which are sometimes inevitably constructed adjacent to existing pile foundations. Different construction sequences of twin paralleled shield tunnels will certainly make some differences in ground surface settlement and displacement of pile foundation. However, it is difficult to accurately consider the influence of different construction sequences by using theoretical analysis method, especially the blocking effect of tunnel constructed first. At present, few scholars study the effects of different construction sequences by performing numerical calculation method to systematically analyze the influence on adjacent pile foundations.

In view of the aforementioned issues, it is of great significance to study the effects of different construction sequences on ground surface settlement and displacement of single pile due to twin paralleled shield tunneling.

The outline of this paper is as follows: Firstly, the disturbance zone of stratum perpendicular to the direction of shield tunneling is explained, and the mechanism of shield tunneling on adjacent single pile foundation is further discussed. Secondly, the project overview and site geology of Changsha Metro Line 5 (from South Gaoqiao Station to Guitang Station) are presented as engineering background. Thirdly, a three-dimensional finite element numerical calculation model is established. The constitutive model, calculation parameters, and construction simulation procedure of the numerical model are described in detail. Fourthly, combined with field measured data, the changing trend of bridge pier settlement and the results of ground surface settlement and displacement of pile foundation caused by shield tunneling under different construction sequences are analyzed. Finally, through the comparative analysis of the data, the most appropriate construction sequence of the twin paralleled shield tunnels passing through the pile foundation is proposed, which provides reference for similar projects.

2. Mechanism of Shield Tunneling on the Adjacent Single Long Pile

Shield tunneling inevitably causes stratum loss, and the stratum in disturbed zone will produce uneven settlement in the process of stress redistribution, which causes the wedge-caulking of soil particles. If the overburden layer of the tunnel is thick enough, the arching effect will occur in the stratum in a certain range above the tunnel. As shown in Figure 1, the strata perpendicular to the direction of shield tunneling can be divided into three zones according to the different degree of stratum disturbance caused by shield tunneling passing through pile foundation. Zone I (strong disturbance zone): the zone between shield tunnel vault, rupture surface, and collapse arch, where the strata appear plastic flow and collapse will occur if there is no support; Zone II (medium disturbance zone): a certain range of zone outside the rupture surface, where the strata have elastic deformation or increased stress, which belongs to the elastic zone; Zone III (weak disturbance zone): the zone is less affected by shield tunneling. When the thickness of overburden layer of shield tunnel is small or the tunnel section is large, the scope of Zone I and Zone II disturbed by shield tunneling will expand, even extend to the ground surface. In addition, when the distance between the two lines of the shield tunnel is relatively close, the disturbance effect of the two lines will show superposition effect, and the disturbed zone will be connected.

Pile foundations are used to support the load of superstructure by transferring it to the surrounding soil resulting in the stress concentration near the pile. On the contrary, shield tunneling is a process of releasing stress which results in the ground movements. After shield tunneling, one side of the pile is unloaded, which affects the mechanical performance of the pile.

The influence of shield tunneling on displacement of adjacent pile foundation is mainly reflected in the effect of soil displacement caused by shield tunneling. The object of this study is single long pile, such as urban viaduct pile. As the pile toe of urban viaduct is deep, it is usually lower than the shield tunnel. Therefore, shield tunneling have less effect on the bearing capacity of pile toe. The main factors influencing the pile foundations are as follows:

(1) The stratum loss caused by shield tunneling

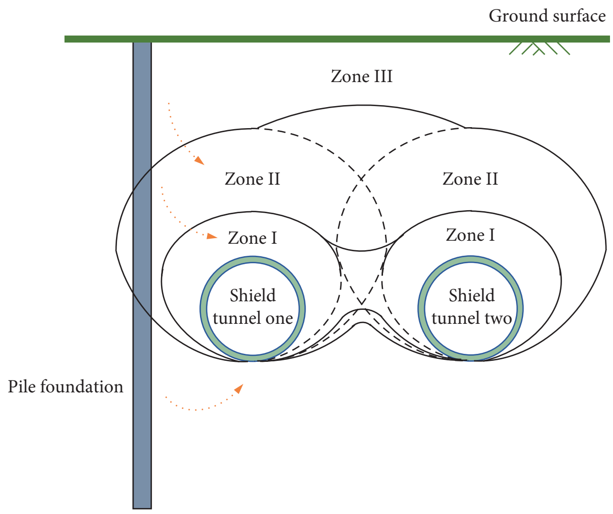


Figure 1: Stratum disturbance zone caused by shield tunneling (perpendicular to the direction of shield tunneling).

(2) The lateral displacement of pile caused by the lateral displacement of soil

(3) The negative friction caused by the settlement of soil around the pile will further lead to additional settlement of the pile

3. Engineering Background

3.1. Project Overview. Changsha Metro Line 5 is the north-south backbone line in Changsha, Hunan Province, China. The first phase of Changsha Metro Line 5 successively crosses the Guitang River, Changsha Metro Line 4, and passes through the Wanjiali Viaduct, gas stations, houses, and other major risk sources in close range. Among them, Changsha Metro Line 5 and Wanjiali Viaduct parallel up to 16.7 kilometers. As shown in Figure 2, the most representative tunnels between South Gaoqiao Station and Guitang Station were selected as the engineering background. The interval tunnels are located on the east side of Wanjiali Viaduct. Under the influence of the existing river and the Guitang River Bridge, the layout of the piles of Wanjiali Viaduct has changed when crossing the Guitang River. Comparison of site viaduct pile layout is shown in Figure 3. This makes the shortest distance between the left tunnel and two C35 bored concrete piles with a diameter of 1.2 m only 3.07 meters. The code for this pier is Pm334, and the pile length is 50 m. The twin paralleled tunnels made of C50 precast concrete segments, with an inner diameter of 5.4 m and buried depth of 19.2 m, having a lining thickness of 0.3 m, width of 1.5 m, are excavated using Earth pressure balance shield tunnel boring machine. The distance between the left line and the right line is 6.15 m.

According to the requirements of construction organization and arrangement, two shield machines are configured in this interval. The two shield tunneling machines started from the south end of South Gaoqiao Station in a staggered month and reached Guitang Station in the direction of small mileage of the line. In the actual construction of this project, the construction sequence of this project is to excavate the right tunnel which is farther from the piles and then the left tunnel which is closer to the piles. The construction sequence has not been analyzed in detail before. The finite element modeling area is located near the design mileage between ZDK27 + 352.322 and ZDK27 + 397.322. The monitoring layout of viaduct pier settlement is shown in Figure 4. Precision level, theodolite, indium steel gauge, inclinometer, and other equipment are used to measure the settlement of bridge piers and the ground surface settlement trough. Two measuring points are arranged symmetrically on each pier. The monitoring period is once a day.

3.2. Site Condition. There are 5 layers of soil from the ground surface to the depth of 70 m, which are miscellaneous fill, silty clay, pebble, strongly weathered conglomerate, and moderately weathered conglomerate in sequence. The ground water table is located at 11.4 m above the top of the twin paralleled tunnels. In addition, the bedrock of the site can be divided into two zones of high weathering and moderate weathering within the scope of investigation depth. According to previous geological drilling report, the highly weathered conglomerate is grayish white with purplish red, partly with thin layers of argillaceous siltstone, clastic structure and massive structure. The natural compressive strength is from 1.19 to 1.96 MPa, and the average value is 1.59 MPa. The moderately weathered conglomerate is purplish red with clastic structure, thick laminated structure, mainly argillaceous cementation. The natural compressive strength ranges from 6.15 to 18.67 MPa, with an average of 10.57 MPa.

As shown in Figure 5, the pile bearing layer of Wanjiali Viaduct is moderately weathered conglomerate, and the twin paralleled tunnels are located in the strongly weathered conglomerate. Physical and mechanical parameters of surrounded layers are listed in Table 1.

4. Numerical Calculation

4.1. Three-Dimensional Finite Element Model. To understand ground surface settlement and displacement of single long pile due to twin paralleled shield tunneling with different construction sequences in layered soils, Midas GTS NX was employed to conduct a three-dimensional finite element model, including twin paralleled shield tunnels, viaduct piles, segments, grouting and surrounding soils. As shown in Figure 6, based on the actual project, two different tunnel construction sequences were considered in this study. Among them, condition (a) is consistent with the actual construction sequence, that is, the right line which is farther away from the pile foundation is excavated first, and then the left line which is closer to the pile foundation is excavated. Condition (b) is opposite to condition (a), that is, the left line which is closer to the pile foundation is excavated first, and then the right line which is farther away from the pile foundation is excavated.

Considering the influence of boundary effects on the accuracy of the numerical results, the size of the three-dimensional model was determined as 60 m in length, 50 m in width, and 70 m in height. The soil was treated as the

FIGURE 2: The location of the interval tunnel.

(a) (b)

FIGURE 3: Comparison of site viaduct pile layout. (a) Normal. (b) Across the river.

horizontal layered foundation to simplify the calculation. A perspective view of the finite element model is shown in Figure 7. Segments were simulated as plate elements, while the soil mass, piles, and grouting were simulated using tetrahedral and hexahedral hybrid elements. The density of elements in critical areas, such as twin paralleled tunnels and pile foundations, was increased to improve the calculation accuracy. The mesh applied in this model consisted of 247322 elements and 155046 nodes.

4.2. Constitutive Model and Calculation Parameters. It is well recognized that in order to properly capture the ground surface settlement and displacement of adjacent piles induced by unloading, it is of great significance to take into account the effect of soil unloading caused by shield tunneling in the constitutive model. The modified Mohr–Coulomb constitutive is an elastoplastic constitutive, which is closer to plasticity theory than Mohr–Coulomb constitutive, and is a constitutive model combining nonlinear elasticity and plasticity. It can consider the different elastic modulus values according to the loading and unloading conditions. The modified Mohr–Coulomb constitutive can also consider the relationship between the soil stiffness and the stress state. Meanwhile, the modified Mohr–Coulomb constitutive can simulate the behavior of different types of soil including soft and hard soil, taking the dilatancy of soil into account. The comparison of the

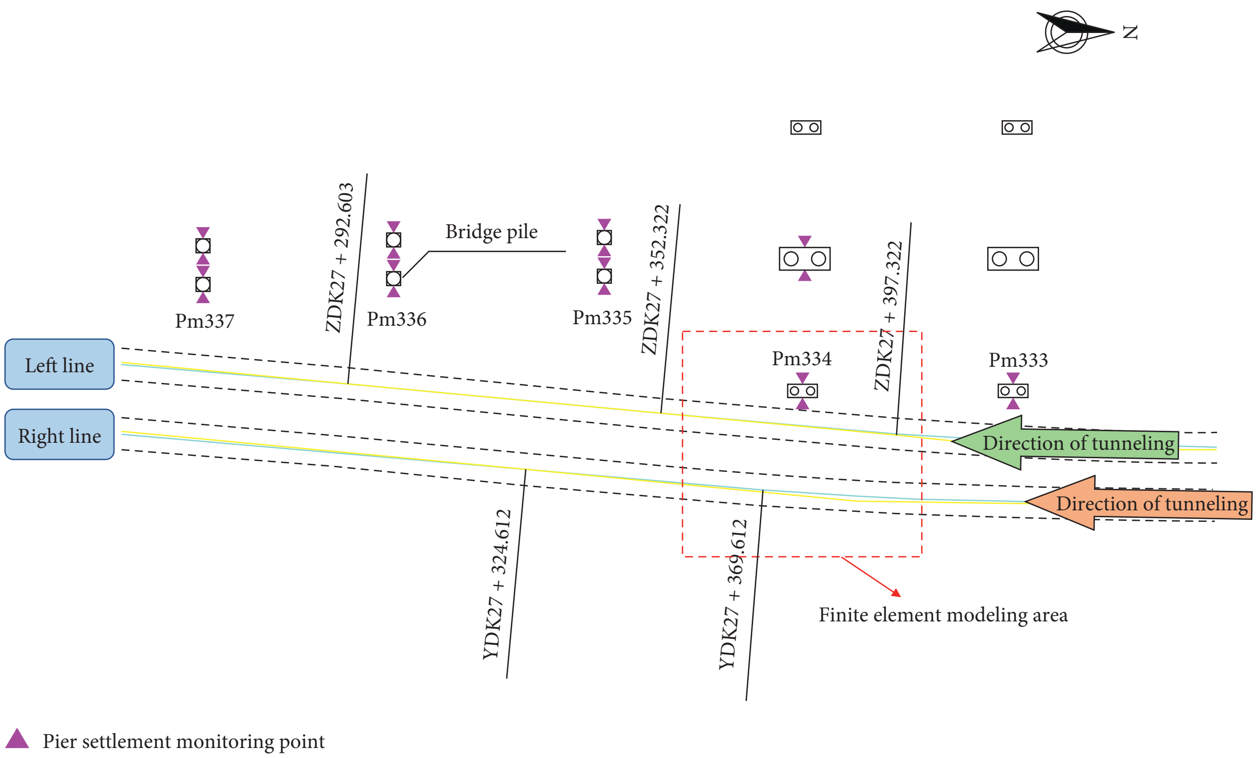


Figure 4: The monitoring layout of viaduct pier settlement.

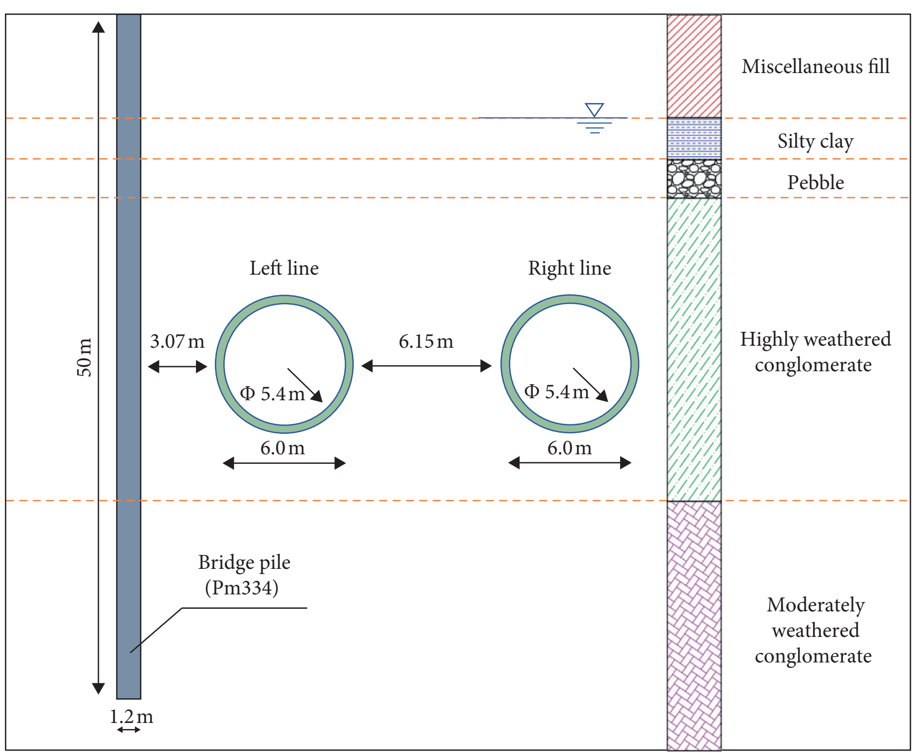


Figure 5: Engineering geology profile.

Mohr–Coulomb yield criterion and the modified Mohr–Coulomb yield criterion in the π plane is shown in Figure 8. The modified Mohr–Coulomb yield criterion adopts the rounded corner treatment in π plane, which can eliminate the unstable factors in the analysis process. Therefore, the modified Mohr–Coulomb constitutive model

Table 1: Physical mechanical parameters of surrounded layers.

Soil type at each layer	Thickness H (m)	Elasticity modulus E (MPa)	Poisson's ratio μ	Unit weight γ (kN·m^{-3})	Cohesion c (kPa)	Internal friction angle φ (°)	Permeability coefficient k (m·d^{-1})
① Miscellaneous fill	7.8	8.5	0.35	19.0	10	12	0.700
② Silty clay	3.2	15.5	0.30	20.0	30	16	0.008
③ Pebble	2.9	35.0	0.25	20.0	2	36	25.000
④ Highly weathered conglomerate	23.0	38.5	0.27	23.5	40	30	0.500
⑤ Moderately weathered conglomerate	33.1	47.0	0.24	25.0	120	35	0.100

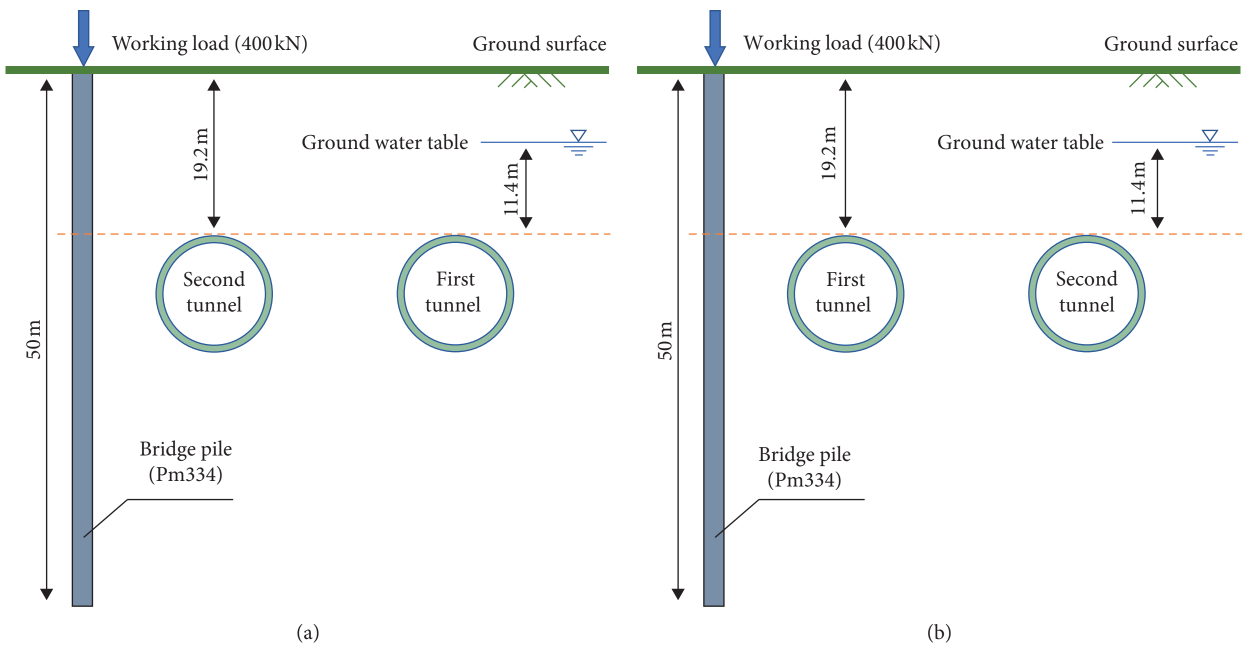


Figure 6: Different tunnel construction sequences. (a) Condition (a). (b) Condition (b).

of soil was selected from the constitutive model library of Midas GTS NX, which has better simulation results and computational convergence.

In addition, the calibration of soil parameters is an important factor to ensure the reliability of finite element calculation results. The calculation parameters of surrounded layers after calibration are shown in Table 2.

Shield segments, pile foundations, and grouting were simplified with elastic materials. The shield segments were treated as homogeneous rings, made of C50 concrete, and the pile foundations were made of C35 concrete. It is assumed that perfect bond between the pile and soil is maintained, and no detachment occurs. The material parameters of bridge pile, segment, and grouting are shown in Table 3.

4.3. Numerical Simulation Procedure. Excavation construction stages were simulated step by step; each excavation stage forwards 1.5 m. The excavation construction was realized by the method of "element birth and death." According to the section size of the viaduct pile and the arrangement of the upper lane, the uniform distribution load on the single pile is set as 400 kN. Generally, when the shield passes through an important structure in a close distance, the thrust force in front of the shield machine and the grouting pressure will be controlled. Therefore, the thrust force of the shield machine is set as 8000 kN and the grouting pressure is set as 0.6 MPa in this study. The concrete numerical analysis is executed according to the following steps:

(1) Activate all the soil mass, including the tunnel excavation area and the soil at the grouting layer. Set the displacement boundary, stable ground water table, and gravity acceleration. Then, balance the initial stress field by displacement clearance.

(2) Activate the pile attribute, apply the superstructure load of 400 kN on the pile head, and reset the displacements to 0.

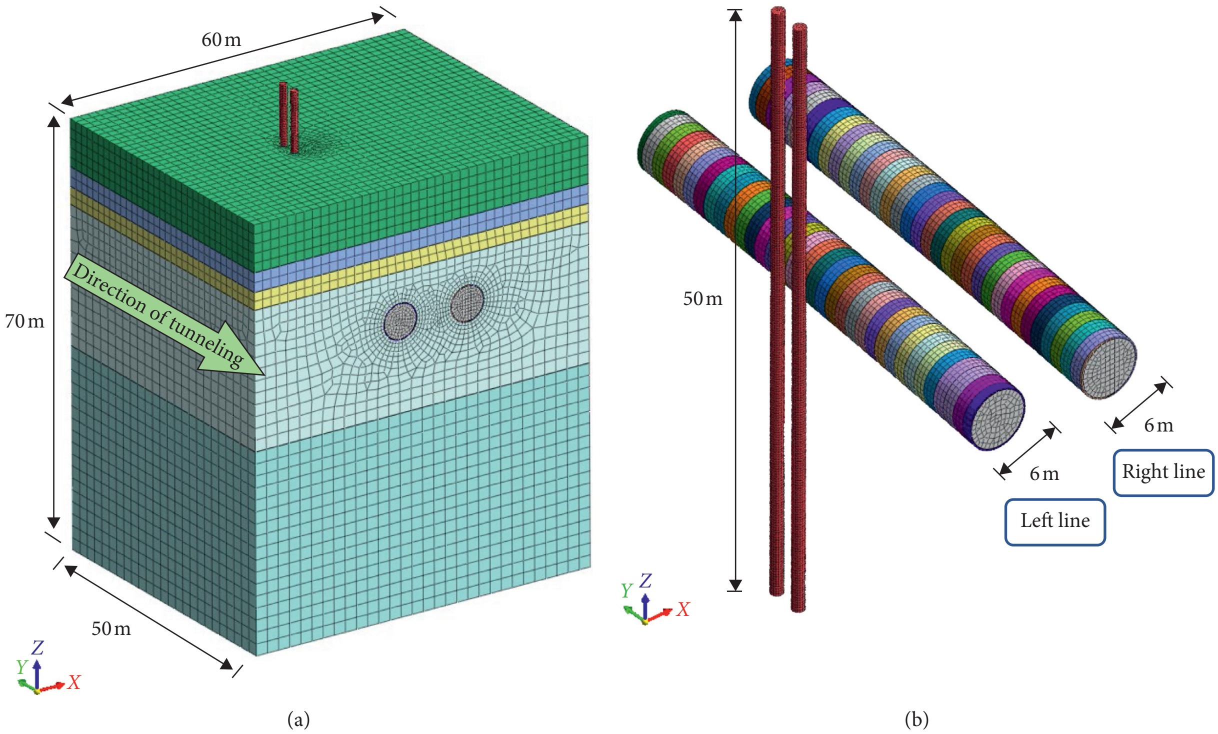


Figure 7: Three-dimensional finite element model. (a) Global model. (b) Relationship between the pile and tunnel.

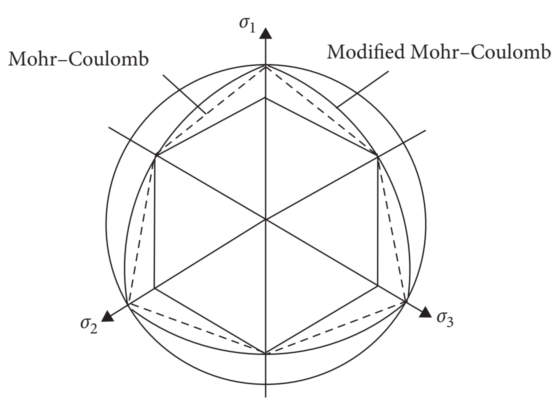


Figure 8: The modified Mohr–Coulomb yield criterion in the π plane.

Table 2: Parameters of soil surrounded layers after calibration.

Soil type	E_{50}^{ref} (MPa)	E_{oed}^{ref} (MPa)	E_{ur}^{ref} (MPa)
Miscellaneous fill	6.4	5.3	19.8
Silty clay	10.8	9.0	34.6
Pebble	23.8	19.0	78.5
Highly weathered conglomerate	28.5	24.9	115.5
Moderately weathered conglomerate	35.6	34.0	134.5

E_{50}^{ref} is the secant stiffness in standard drainage triaxial tests, E_{oed}^{ref} is the tangent stiffness in loading of main consolidation instrument, and E_{ur}^{ref} is the elastic modulus of reloading after elastic unloading. The above parameters are derived from the laboratory test of the preliminary geological survey.

(3) Taking the right line as an example, the thrust force of 8000 kN on the face of the first ring of the right tunnel is firstly applied to deactivate the soil and the grouting layer in the first ring.

(4) Continue to apply the thrust force on the face of the second ring of the right tunnel to deactivate the soil and the grouting layer in the second ring. After this step, the grouting layer, grouting attribute, and shield segment of the first ring are reactivated, and the grouting pressure is set at 0.6 MPa.

(5) Repeat the above steps (3) and (4) successively until the first shield tunnel is completely finished. Then, the second shield tunnel will be constructed.

5. Analysis of Numerical Calculation Results

5.1. Induced Pier Settlement during Twin Paralleled Shield Tunneling with Different Construction Sequences. During the construction simulation, there are 73 steps in total. Each tunnel has 35 construction steps. The settlement of viaduct pier Pm334 caused by twin paralleled shield tunnels in different construction sequences is compared with the field measured data, as shown in Figure 9. Taking the position where the shield machine enters the boundary of the model as the reference point, the changing process of the field measured settlement of pier Pm334 was recorded when the shield passed through the pile for the first time. The field measured settlement of the pier when the shield left the boundary of the model was also recorded. Compared with the field measured settlement of the bridge pier when the

Table 3: Parameters of pile, segment, and grouting material.

Materials	Elasticity modulus (MPa)	Poisson's ratio	Density (kN·m^{-3})
Pile foundation	3.15×10^4	0.3	23.0
Shield segment	2.415×10^4	0.2	25.0
Grouting	2×10^2	0.3	22.0

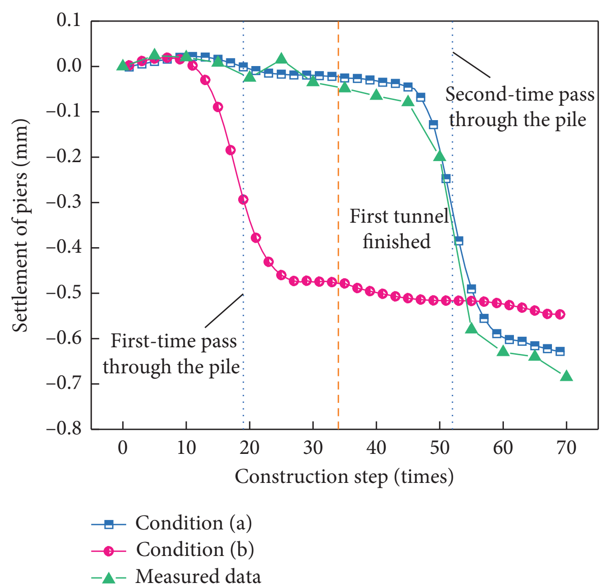


Figure 9: The settlement of viaduct pier Pm334.

shield machine reached the boundary of the model for the second time, the bridge pier settlement of non-shield construction factors was removed so as to ensure the monitoring data is comparable and reliable. Condition (a) is consistent with the sequence of site construction. To facilitate the comparison between the finite element calculation results and the field measured data, the horizontal axis adopts construction steps, and each construction step represents a drive forward by 1.5 m of the shield. The measured data take the average value of the monitoring points of the settlement of the piers at the corresponding positions of the shield tunneling. It can be seen from Figure 9 that the numerical calculation results are in good agreement with the field measured data. It can be concluded that no matter what construction sequence is adopted, the settlement of the pier begins to increase significantly when the shield reaches the 8th ring (12 m) before the pile foundation. After the shield passes through the pile foundation, the settlement of the pier gradually tends to be stable at the position of the 10th ring (15 m) after the pile foundation. It is mainly caused by the thrust force in front of the shield machine, the protective effect of the shield shell, and the displacement of the soil after shield tunneling. At the same time, different shield construction sequence will have a certain influence on the final settlement of adjacent piers. After the completion of twin paralleled tunnel construction, the final settlement of bridge pier is −0.628 mm in condition (a) and −0.546 mm in condition (b). In the comparison of pier final settlement, condition (b) is 13.1% less than condition (a). The reason for that is as follows: in condition (a), the construction of the right line which is far from the pile foundation will squeeze the soil near the pile foundation and disturb the stratum in the first construction process. Although the influence of the right tunnel on the pile foundation is relatively limited at this time, in the next construction process of the left tunnel, the strata disturbance in the early stage will aggravate the soil displacement and then cause greater settlement of the adjacent piers. However, in condition (b), first, the construction of the left line which is closer to the pile foundation will make the settlement of viaduct pier stable after the increase. Meanwhile, in the horizontal direction to the right tunnel, due to the blocking effect of the existing left tunnel and segment grouting reinforcement during the construction of the left tunnel, part of the soil displacement will be controlled, thus reducing the settlement of adjacent pile foundation. Therefore, excavating the left tunnel near the pile foundation first and then the right tunnel far away from the pile foundation is the most beneficial construction sequence to control the settlement of adjacent piers without setting protective isolation.

5.2. Induced Ground Surface Settlement during Twin Paralleled Shield Tunneling with Different Construction Sequences. In 1969, at the 7th International Conference on Soil Mechanics and Foundation Engineering, Peck [25] proposed that the surface settlement trough caused by tunneling presented a normal distribution in the lateral area, in which the width of settlement trough i and the stratum loss V_s were two important parameters in the Peck formula. However, Peck's formula does not consider stratum characteristics and construction factors. Clough and Schmidt [26], Attewell and Woodman [27], O'Reilly and New [28], Loganathan and Poulos [29] proposed different calculation methods for the value of i. After analyzing a large number of surface settlement data and engineering data after tunnel excavation, Peck [25] believed that the volume of settlement trough should be equal to the volume of stratum loss, and the surface settlement trough presented normal distribution in the lateral direction. Gaussian distribution of surface settlement trough is defined as

$$S(x) = S_{max} \cdot e^{-\left(x^2/2i^2\right)},$$
$$S_{max} = \frac{V_s}{\sqrt{2\pi} \cdot i}, \quad (1)$$
$$i = \frac{Z_0}{\sqrt{2\pi} \tan\left(45^\circ - (\varphi/2)\right)},$$

where $S(x)$ is the ground surface settlement caused by stratum loss, V_s is the stratum loss per unit length caused by shield tunneling, x is the distance from the tunnel centerline,

S_{max} is the maximum ground surface settlement caused by stratum loss, i is the distance from the tunnel centerline to the inflexion point of the settlement trough, Z_0 is the buried depth of tunnel, and φ is the internal friction angle of soil.

To predict the ground surface settlement above twin paralleled tunnels, Attewell and Farmer [30] suggested summing the Gaussian curves induced by two tunnels. In this study, the results of finite element numerical calculation in different construction sequences are compared with the results of Gaussian distribution curve at the position of pile foundation, as shown in Figure 10. As can be seen from Figure 10, influenced by the existing pile foundation, the ground surface settlement trough will stay a certain value near the pile foundation. It can be seen from the curve that the surface settlement trough will present a "hanging phenomenon" near the location of pile foundation. Under the same parameter condition, the maximum value of Gaussian distribution curve is obviously larger than that of finite element calculation. The main reason for the above phenomenon is that the stiffness of pile foundation affects the displacement of soil around the tunnel. The soil will naturally deform to the side without pile foundation after excavation and unloading. Meanwhile, due to the existence of pile foundation, it will control the displacement of soil around the pile. Therefore, the surface settlement trough caused by shield tunneling under the influence of adjacent bridge piles will present an asymmetric skewed normal distribution, and the maximum value of surface settlement will decrease. In condition (a), after the completion of construction of the first tunnel, the maximum value appears in the centerline of the first tunnel. The maximum value calculated by finite element method is −3.524 mm, which is 17.2% less than that of the Gaussian distribution curve, which is −4.255 mm. After the completion of the second tunnel construction, the maximum value appears in the middle position of the twin paralleled tunnel, and the maximum value calculated by finite element method is −5.563 mm, which is reduced by 14.2% compared with the maximum value of −6.485 mm after the cumulative Gaussian distribution curve. In condition (b), after the first tunnel construction is completed, the maximum value calculated by finite element method appeared in the right side of the centerline of left tunnel with a maximum of 3.029 mm, which is reduced by 28.8% compared with the maximum of Gaussian distribution curve. After the completion of construction of the second tunnel, the maximum value of finite element calculation results of is 5.173 mm, which is 20.2% less than that of the Gaussian distribution curve. In view of this, the maximum value of ground surface settlement will be reduced to a certain extent in the process of shield tunneling passing through the viaduct pile at close distance. At the same time, the ground surface settlement trough will have an asymmetric skewed distribution.

In order to further study the influence of different construction sequences of twin paralleled shield tunnels on the ground surface settlement trough, the finite element calculation results of the ground surface settlement trough under different construction sequences are compared with the field measured data, as illustrated in Figure 11. As can be seen from Figure 11, compared with the Gaussian distribution curve, the calculation results of finite element can better reflect the actual situation. In condition (b), the maximum ground surface settlement after the completion of the first tunnel is reduced by 14.1% compared with that in condition (a). Similarly, the maximum value of the cumulative ground surface settlement after the completion of the second tunnel in condition (b) is reduced by 7.0% compared with that in condition (a). The reason causing this difference is that the left tunnel is closer to the adjacent pile foundation than the right tunnel. Due to the influence of the stiffness of the existing viaduct pile, the ground surface settlement trough caused by excavating the left line will be limited by the pile foundation firstly, which will reduce the maximum value. On the one hand, the soil displacement caused by the excavation of the right tunnel which is farther away from the pile foundation is obstructed by the existing left tunnel. On the other hand, due to segment grouting reinforcement during the construction of the left tunnel, the strata around the left tunnel were reinforced. Therefore, from the results of ground surface settlement, the construction sequence of condition (b) is more conducive to controlling ground surface settlement.

5.3. Induced Vertical and Horizontal Displacement of the Pile during Twin Paralleled Shield Tunneling with Different Construction Sequences. The unloading effect and the squeezing action of shield tunneling will cause a certain vertical and horizontal displacement of adjacent pile foundation. When the superstructure load continues to be applied on the deformed pile foundation, the pile foundation will be in an unfavorable state of eccentric compression, which impedes normal load transfer and causes damage to the superstructure. Therefore, induced vertical and horizontal displacement of pile during twin paralleled shield tunneling with different construction sequences should be discussed and analyzed as a significant research direction. Figures 12 to 15 show the vertical and horizontal displacement of pile foundation and tunnel under different construction sequences of twin paralleled shield tunnels. In order to more visually reflect the displacement, the displacement of pile foundation and tunnel shown in Figures 12 to 15 is exaggerated on the basis of actual displacement. It can be seen from the figures that no matter which tunnel construction sequence is adopted, the adjacent pile foundation will produce displacement. When the construction of twin paralleled tunnels is completed, the overall displacement of pile presents an S-shaped distribution. In terms of the vertical displacement, the pile head settles downward, and the pile toe is jacked. In terms of the horizontal displacement, the maximum displacement appears near the buried depth of tunnel, which is manifested as that the pile body which overlaps with the buried depth of the tunnel moves away from the tunnel, while the upper part of pile body and the lower part of pile body deform towards the tunnel. The reason is that with the continuous construction of tunnel, the soil above the top of tunnel settles. And the upper part of pile foundation, driven by the surrounding

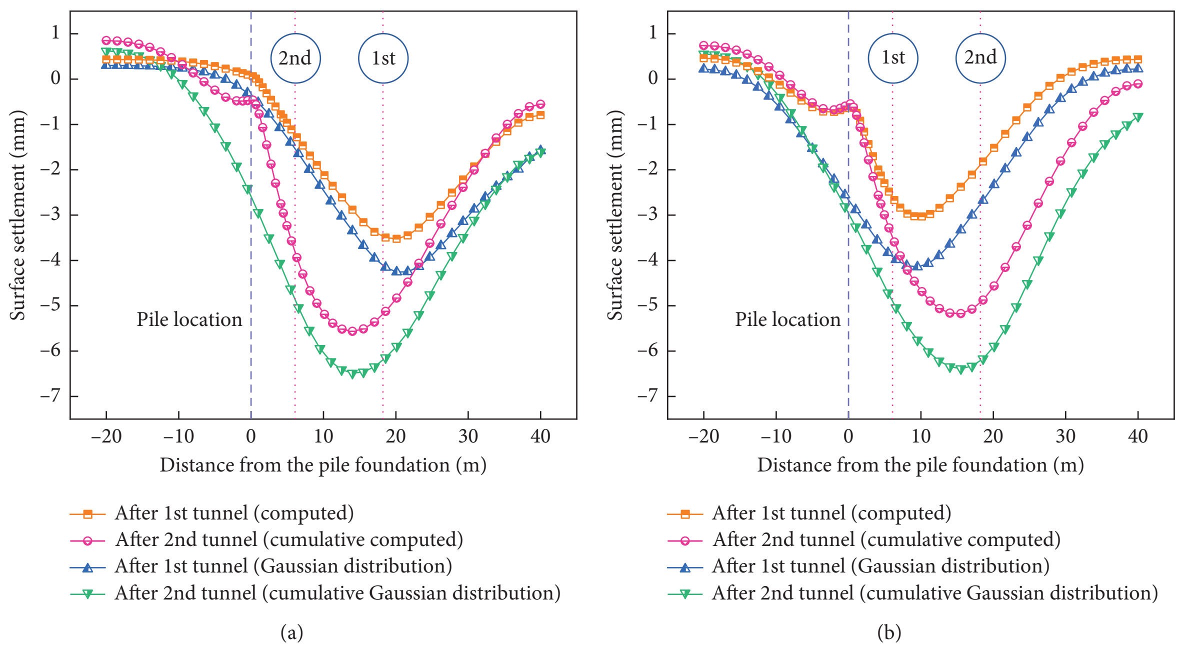


Figure 10: Ground surface settlement trough at pile location. (a) Condition (a). (b) Condition (b).

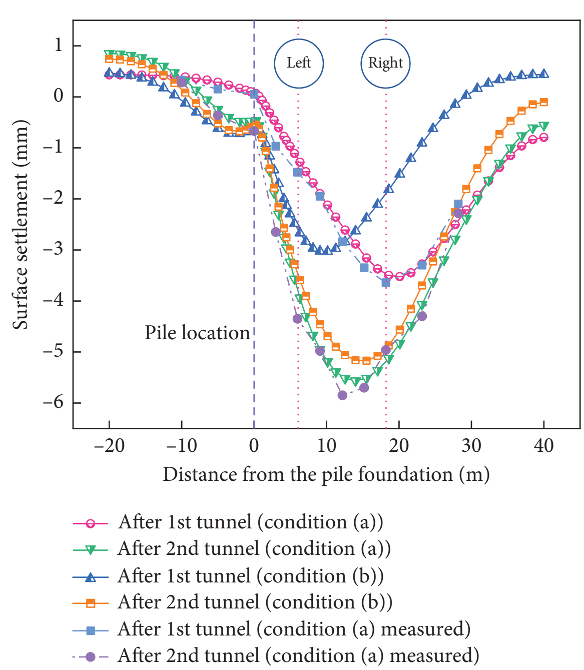


Figure 11: Comparison of calculation results and field measured data under different construction sequences.

soil, deforms downward and toward the direction near the tunnel. The soil below the tunnel bottom will rebound upward due to excavation and unloading, and the lower part of pile will deform upward and toward the direction near the tunnel driven by soil. Under the combination action of these forces, the pile will be bent.

Figure 16 illustrates the induced vertical and horizontal displacement of pile under different construction sequences. For each tunnel construction sequence, the vertical and horizontal displacement of pile due to the first tunnel and the second tunnel and after twin paralleled tunneling which is cumulative are shown in Figures 16(a) and 16(b). In condition (a), after the completion of the first tunnel construction, the vertical displacement of the pile is small due to the long distance between the right tunnel and the pile foundation, and the maximum value appears at the pile toe, which is +0.166 mm. The maximum horizontal displacement of the pile appears at 3 m below the buried depth of the tunnel, which is −1.165 mm. It is different from the situation after the completion of the construction of the first tunnel in

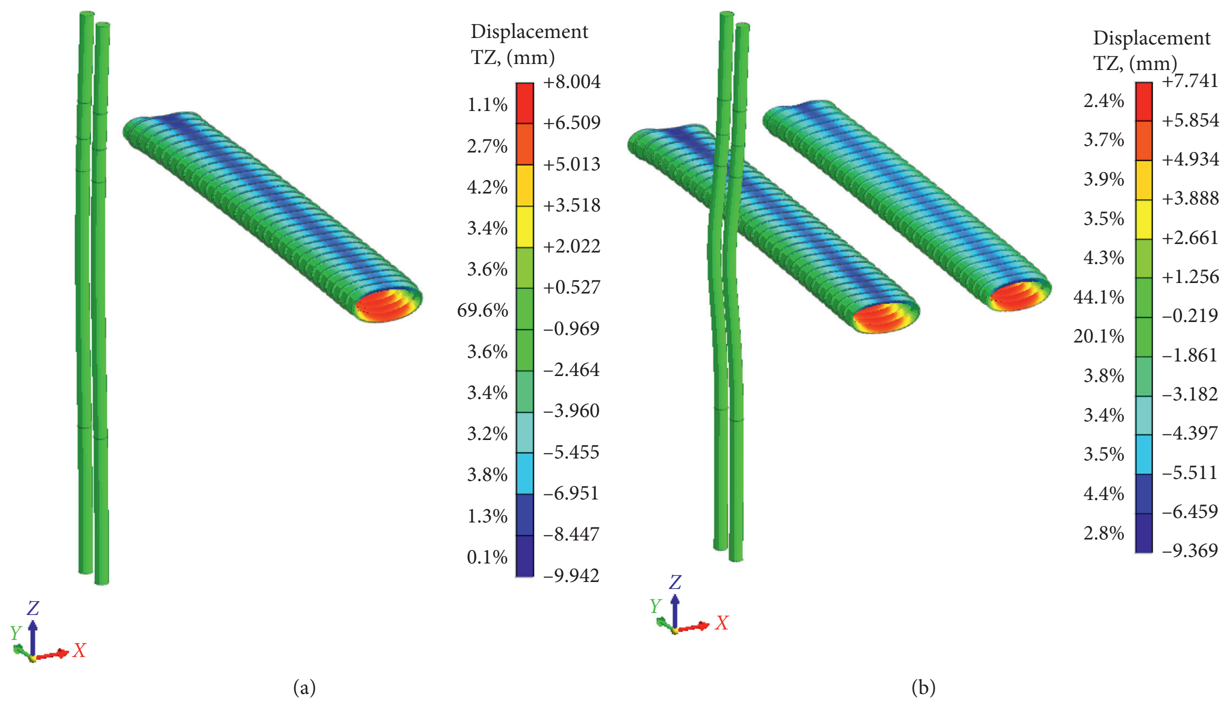


Figure 12: Vertical displacement of pile and tunnel in condition (a). (a) Right line finished. (b) Left line finished.

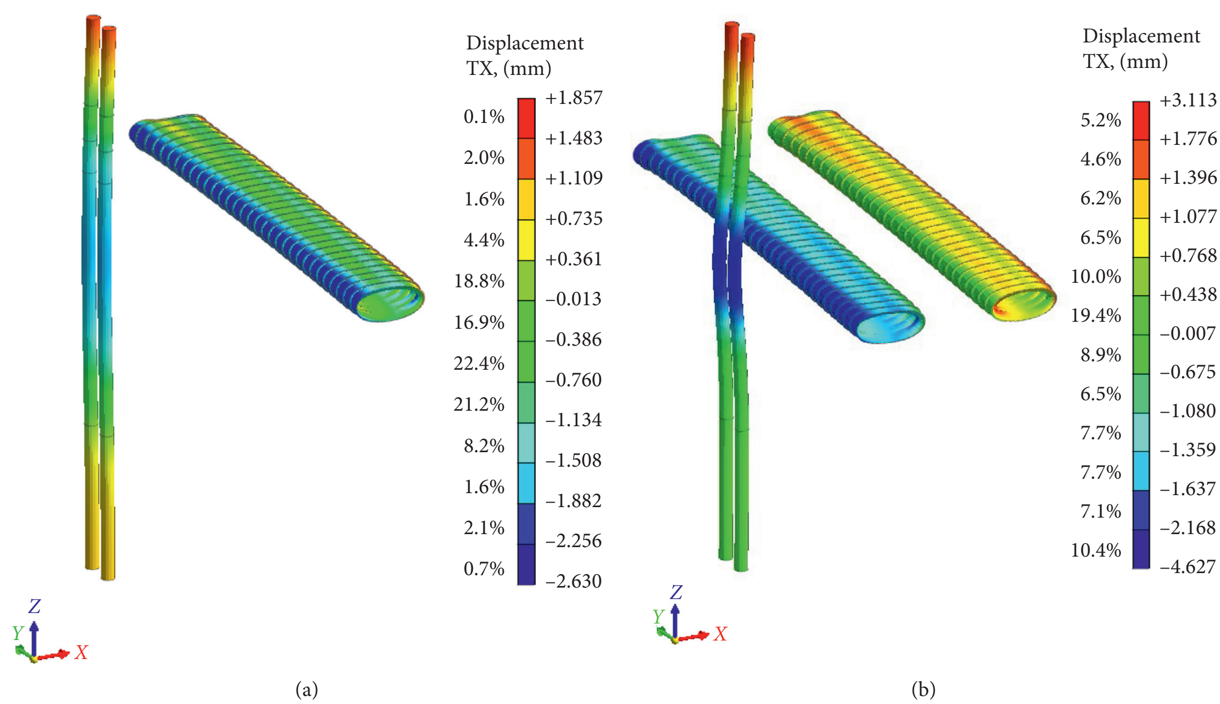
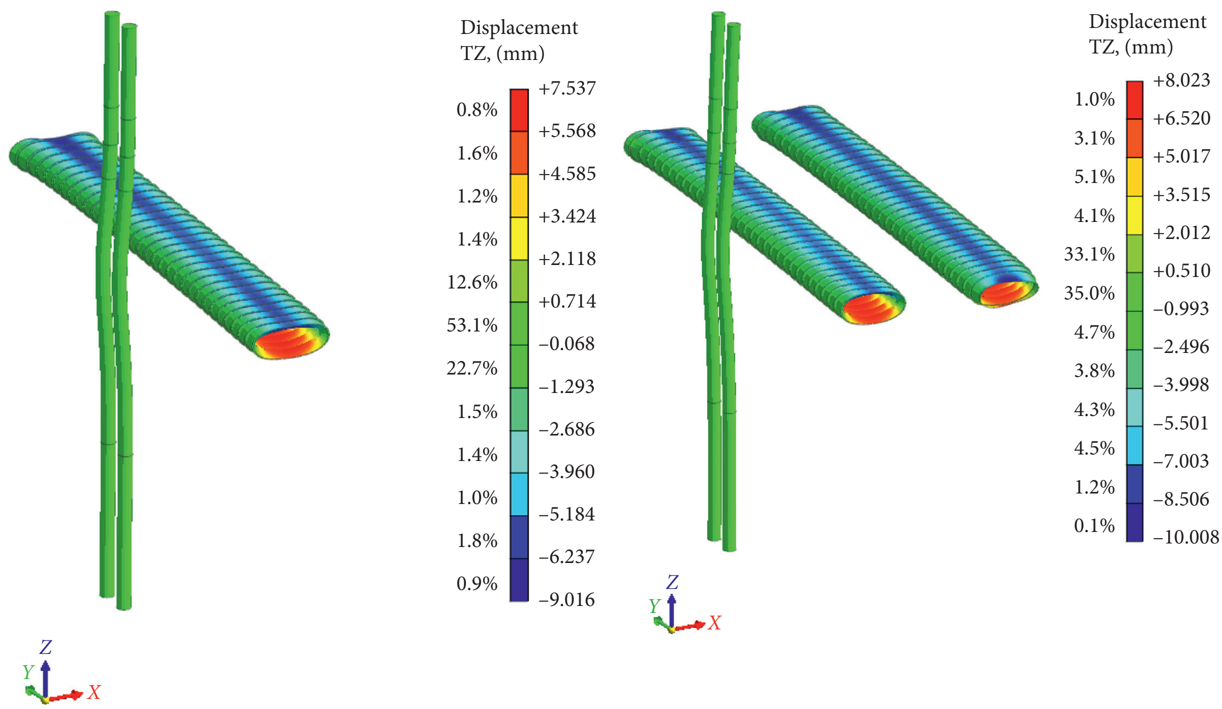


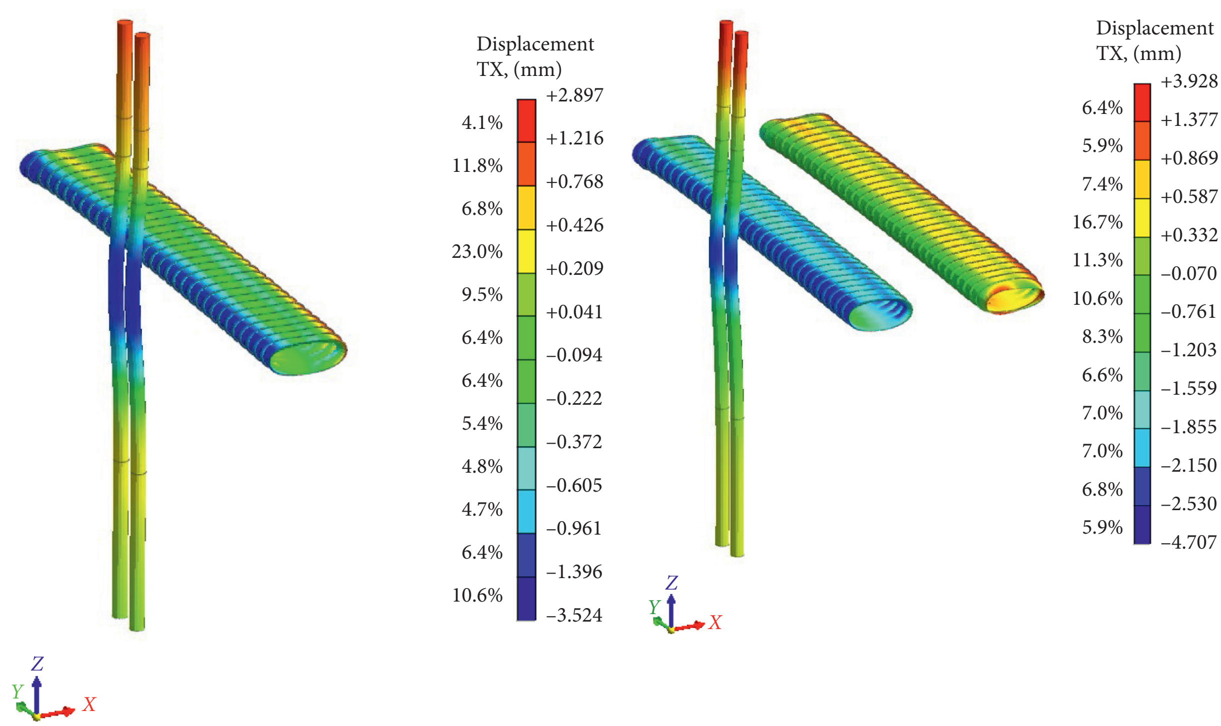
Figure 13: Horizontal displacement of pile and tunnel in condition (a). (a) Right line finished. (b) Left line finished.

condition (b). The maximum vertical displacement of the pile is +0.780 mm due to the close distance between the left tunnel and the pile foundation, and the maximum value still appears at the pile toe. The variation range of horizontal displacement curve of pile is more obvious than that in condition (a), and the maximum horizontal displacement of the pile is −1.575 mm. When the construction of the twin paralleled tunnels is completed, the maximum vertical displacement of the pile in condition (a) is +1.037 mm, which is 7.9% larger than that in condition (b) of +0.955 mm. The maximum values all appear at the pile toe. Meanwhile, the maximum horizontal displacement of the



(a) (b)

Figure 14: Vertical displacement of pile and tunnel in condition (b). (a) Left line finished. (b) Right line finished.



(a) (b)

Figure 15: Horizontal displacement of pile and tunnel in condition (b). (a) Left line finished. (b) Right line finished.

pile in condition (a) is −2.526 mm, which is 6.9% larger than that in condition (b). The maximum values all appear at 3 m below the depth of the tunnel. Therefore, it can be concluded that the construction sequence of condition (b) can reduce the vertical and horizontal displacement of piles to a certain extent. In the future, we expect to carry

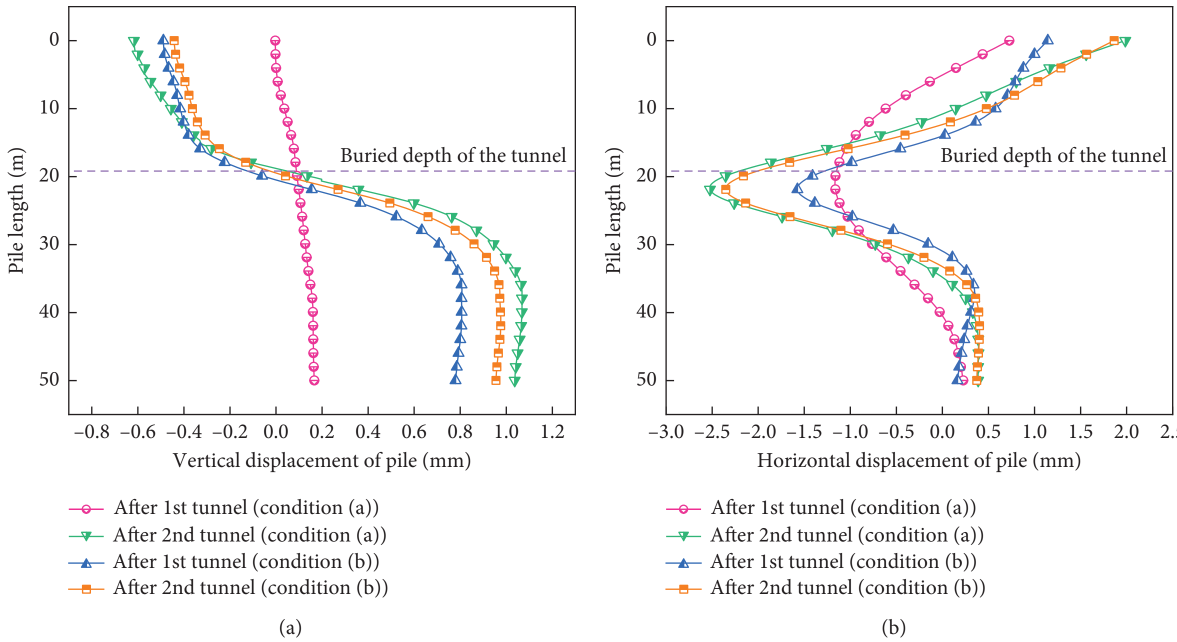


Figure 16: Displacement of pile foundation. (a) Vertical displacement. (b) Horizontal displacement.

out centrifuge model tests to further study this content. And we will actively strengthen the cooperation with the site construction company and the design department to jointly develop the most appropriate shield construction sequence to reduce the impact on the adjacent pile foundation.

6. Conclusions

This paper presents a three-dimensional finite element model to analyze ground surface settlement and displacement of single long pile due to twin paralleled shield tunneling with different construction sequences in layered soil. To accurately verify the calculation results, the monitoring data of piers settlement and measured ground surface settlement are compared with the numerical results. The main conclusions are as follows:

(1) The numerical results are in good agreement with the measured data. The computed results of induced pier settlement, ground surface settlement, and induced displacement of single pile due to twin paralleled shield tunnel reveal that the adjacent pile and surrounding environment are affected substantially with the change of construction sequence of twin paralleled tunnels. In comparison to the final pier settlement, condition (b) is 13.1% less than condition (a).

(2) Influenced by the existing viaduct pile, Gaussian distribution is no longer applicable to predict the displacement of ground surface settlement caused by shield tunneling. According to the comparison between the numerical results and the field measured data, the ground surface settlement trough will present a "hanging phenomenon" near the location of pile. Meanwhile, when the tunnel is close to the pile foundation, the surface settlement trough will develop into an asymmetric skewed distribution. The construction sequence of condition (b) is more conducive to controlling ground surface settlement.

(3) After the construction of twin paralleled tunnels, the overall displacement of pile presents an S-shaped distribution. The pile body which overlaps with the buried depth of the tunnel moves away from the tunnel, while the upper part of pile body and the lower part of pile body deform towards the tunnel. By comparing the effects of different construction sequences on induced pile displacement, it is found that the construction sequence of condition (b) can reduce the vertical and horizontal displacement of pile.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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