

Article

A General Framework for the Impact of Shield Tunnel Construction on Existing Tunnel in Soil

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Abstract: During the excavation process of shield tunneling, it is inevitable that the surrounding soil mass is disturbed, which will affect the adjacent structures. This paper proposes a general framework for the impact of shield tunneling construction on existing tunnels. First, the impact partition of shield tunneling construction regarding adjacent tunnels and buildings is established by a three-dimensional numerical analysis method. Then, the displacement of adjacent tunnels and buildings is predicted using fuzzy gray theory. Finally, based on the results of a numerical simulation and experiment, the risk classification standard of adjacent buildings is established. This framework has certain reference significance and value for the deformation prediction and safety evaluation of adjacent buildings.

Keywords: shield tunnel; fuzzy gray theory; general framework



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1. Introduction

During the excavation process of shield tunneling, the surrounding soil is inevitably disturbed, and the stress of the rock and soil is redistributed, causing stratum displacement, and even surface subsidence and destruction of adjacent buildings in severe cases. In some modern metropolises, such as New York and London, due to the relatively early urbanization, the construction of underground rail transit was relatively late, and the phenomenon of close construction of subway tunnels often occurs. At the same time, these areas have also accumulated much experience in subway proximity construction. Based on these experiences, scholars have performed more in-depth research.

Potts and Addenbrooke [1] believed that tunnel construction and adjacent buildings are mutually affected, and they analyzed the influence of the construction of tunnel-adjacent buildings on ground subsidence from the aspects of building structure width, axial stiffness, the relationship with the tunnel, and tunnel depth. Bernat and Cambou [2] used the finite element method to numerically simulate the displacement of shield tunnels in soft soil foundations, and they established a displacement prediction method for shield tunnels in soft soil foundations, which can effectively predict ground subsidence caused by tunnel excavation. Burd et al. [3] established a three-dimensional finite element analysis method based on analysis of the influence of traditional tunnel construction on the settlement of adjacent buildings, considering the influences of the weight and stiffness of the building on the settlement. The results showed that the interaction between the building and the ground has a significant impact on the predicted damage degree. Zhao et al. [4] predicted the affected buildings in the construction of a subway tunnel according to the requirements of the building safety control program. By comparing their results with those of a numerical simulation, the deformation mode of the formation was obtained. Strokova [5] used the

finite element model to conduct back analysis on the ground settlement caused by tunnel excavation, and they evaluated the effects of model components on a ground settlement tank by studying various parameters and performance to control the surface settlement and reduce the interference with nearby buildings and facilities. Shi et al. [6] proposed a model describing the interaction between soil and earth pressure balance in shield tunnels based on Mindlin's classical elastic theory, deriving equations for the deformation of the ground around the tunnels caused by the additional force on the shield face and the friction between the outer surface of the shield and the surrounding soil. Pan [7] established a dynamic three-dimensional finite element model of shield tunnel construction and discussed the impact of tunnel construction on adjacent ground surfaces and buildings by comparing the simulated and monitored settlements of the ground surface and adjacent buildings.

Whether it is urbanization, construction, or underground rail transit construction, it started relatively late compared in developed countries, so there are relatively few studies of the safety control of shield tunnel construction adjacent to buildings.

Wei and Zhou [8] studied the impact of shield excavation on the safety of adjacent buildings, selected the main factors affecting the safety of tunnels and buildings to build an evaluation index system, and established a risk fuzzy analytic hierarchy process model based on the fuzzy analytic hierarchy process. They verified that this model is safe, reliable, and practical. Ren et al. [9], on the basis of analyzing the main risk sources of shield tunnel construction adjacent to buildings, proposed a multi-level risk assessment model for shield tunnel construction based on the fuzzy comprehensive evaluation method. When applied to engineering practice, the obtained results were consistent with the actual situation, with positive significance for reducing the risk of shield tunneling construction. Wu et al. [10] proposed a new method for safety risk assessment of adjacent buildings during shield tunnel construction, first using matter elements to theoretically calculate the correlation degree, then determining the safety state based on the evidence theory, and finally using the Monte Carlo method to obtain sensitivity factors, providing a theoretical basis for evaluating the safety risks of adjacent buildings during tunnel construction and proposing targeted improvement measures. Based on field monitoring data, Jiao et al. [11] analyzed the deformation of a double-line shield tunnel passing under a railway in a soil-rock composite stratum, and they revealed the influence of the hard layer rate, tunnel depth, and railway subgrade reinforcement on the deformation of the railway track through numerical simulation. The subsidence mainly occurred in the middle and late stages of the shield tunnel crossing the railway. To resolve the issue of the ground disturbance effect on shield tunnel excavation and the impact on the surrounding environment, Bai et al. [12] relied on the Nonghong Section Tunnel Project of Fuzhou Metro Line 5 to analyze the excavation construction process. Performing refined numerical simulation and focusing on the influences of bank slope distance and vault depth on surface settlement characteristics, Hu et al. [13] performed shield construction based on a calculation model of stratum loss under the influence of the "soil arch effect" based on the energy method. The research on the surface settlement prediction method accurately predicted the surface settlement caused by the construction process of a deep-buried shield tunnel, and it verified that the method has good adaptability and reliability in shield tunnel engineering. To solve the problem of ground subsidence and the inclination of buildings on both sides caused by subway shield tunnel construction regarding the first building, the numerical simulation method was used to analyze the influence of the shield tunnel construction on the adjacent buildings and their pile foundations (Li et al. [14]). To determine the mechanical behavior of the special segment structure of a horizontal shield tunnel during the construction of an upward shield tunnel, Lu et al. [15] deduced a theoretical calculation formula of the internal force of the special segment structure based on the average constant stiffness ring method, using Midas GTS NX software. A numerical simulation analysis of the bending moment and axial force of the special segment was conducted. Zhang et al. [16] performed inversion analysis using test data. The engineering data of subway construction in coastal areas and the karst geological conditions in Dalian area were counted. The value range of

the settlement trough width caused by shield tunnel construction in the Dalian area was proposed. A series of finite element analyses was performed to investigate the multiple interactions between large parallel hypothetical twin tunnels constructed using the new Austrian tunnelling method [17]. Islam and Iskander [18] provided a good overview of the ground settlement caused by double tunnel excavation. Sazid and Ahmed [19] found that displacement severely affected tunnel roofs around a shallow depth tunnel in weak rock mass. The principal stresses were concentrated on the tunnel floor, while shear stress was concentrated at the tunnel corners. Tang et al. [20] performed a comprehensive analysis of the factors influencing subway settlement and proposed a prediction model on the basis of gray system theory.

In summary, the current research on the influence range of subway shield tunnel construction on adjacent buildings is relatively in depth, but the research on the risk assessment of shield tunnel construction remains scarce, and the risk assessment methods are mostly qualitative methods, which are less affected by subjectivity. Therefore, it is necessary to use quantitative or semi-quantitative evaluation methods to study the safety risks of the construction of shield tunnels adjacent to buildings and to formulate effective risk control measures to ensure project safety.

In this paper, the influence of underground tunnels on adjacent existing tunnels is set using the following three coupling modes: coupling modes with different distances between tunnels (4 m, 7 m, 10 m) and coupling modes with different thicknesses of soil overlying tunnels (12 m, 22 m, 32 m). There are different coupling modes (parallel, vertical, and cross) in the adjacent form of the tunnel. Referring to the “technical specifications for urban rail transit engineering monitoring”, it is found that, in the construction of subway tunnels, the control value of settlement is 10 mm, so in the follow-up analysis of the numerical calculation results, this value is used as the cut-off point for the standard of tunnel safety judgment and the basis for measuring the best construction conditions. Then, based on the fitting of the measured data in the test section and the establishment of the gray system, the accuracy of data prediction is improved.

2. Building 3D Numerical Model

Tunnel excavation is a typical three-dimensional problem, and soil deformation is closely related to the relative position of tunnel excavation. The finite element method can basically simulate the interaction of various working conditions and construction factors, and it has good repeatability.

2.1. Numerical Model Establishment

The finite difference software FLAC3D was used for numerical calculations, and the established three-dimensional numerical calculation model is shown in Figure 1a. The two tunnels are located in the clayey silt strata and are adjacent to each other in parallel, with an overlying soil layer of 12 m and a distance of 4 m. The outer diameter of the segment lining is 6 m, the inner diameter is 5.4 m, the thickness of the segment is 30 cm, the width of the segment is 1.5 m, and the thickness of the grouting layer is 30 cm. Figure 1b is divided into units with the excavated tunnel on the right and the existing tunnel on the left. The numerical calculation model area is 90 m long, 60 m wide, 45 m high, and 12 m deep. The Z-axis is the positive direction, which is the direction of shield tunneling, that is, the vertical direction. The X-axis is the horizontal direction, and the Y axis is the vertical direction. The model is divided into 149,400 solid elements and 622,721 nodes.

In the numerical model, the effect of surrounding soil disturbance caused by the jacking force and formation loss during shield machine excavation is considered through appropriate simplification. The shield tunnel lining is an integral structure, and the individual segments are connected by bolts. When using the equivalent segment lining of the mean volume, it must be multiplied by a stiffness reduction factor, which is 0.6–0.8 in the cross-section. In the longitudinal direction, this coefficient is not only related to factors such as the stiffness and number of bolts but also related to the stress state of the segment struc-

ture. According to the formula in the literature (He, [21]), the longitudinal tensile, shear, and bending stiffness reduction factors are about 0.01, while the longitudinal compressive stiffness is basically not reduced. In view of the actual situation of this model, the reduction factor of the longitudinal stiffness of the existing tunnel is taken as 0.01, while the new tunnel mainly bears the jacking reaction force of the shield machine in the longitudinal direction, so the longitudinal stiffness is not reduced. The calculated parameters of the existing tunnel segment lining material after reduction are shown in Table 1. The material parameters in the table are determined according to the unit local coordinate system (the Z direction in the unit coordinate system is consistent with the tunnel axis).

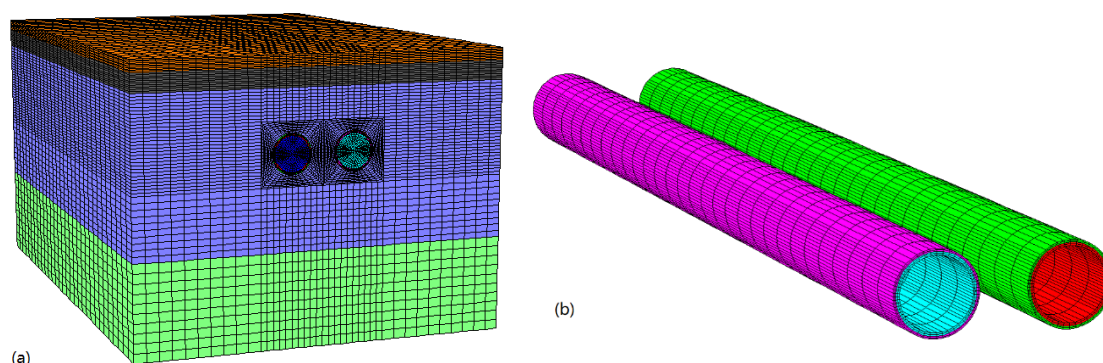


Figure 1. 3D numerical calculation model; (a) overall model, (b) segment.

Table 1. Segment lining material calculation parameters.

E_x/GPa	E_y/GPa	E_z/GPa	E_{xy}/GPa	E_{yz}/GPa	E_{xz}/GPa	μ_{xy}	μ_{yz}	μ_{xz}
27.6	27.6	0.345	11.5	0.158	0.158	0.2	0.2	0.2

In the model, the space 8-node solid element is used to simulate the shield machine, disturbance layer, and soil layer. The shield machine is an earth pressure balance shield machine with a weight of 385 t. The method of killing the element is used to simulate the shield tail gap of the shield machine. Grouting pressure is applied at the shield tail gap, the surrounding soil is disturbed during the tunneling construction of the shield machine, and the thickness of the disturbance layer is taken as 0.3 m.

2.2. Soil Layer and Material Parameters

According to the geological drilling and survey data in this interval, the numerical calculation model is divided into four soil layers. The Mohr-Coulomb strength criterion is used to simulate the shield machine and the grouting layer by increasing the corresponding calculation parameters (Rankin, [22]). The specific calculation parameters appear in Table 2.

Table 2. Soil layer and material calculation parameters.

Name	Layer Thickness/m	Cohesion/kPa	Internal Friction Angle/(°)	Soil weight/ $\text{kN}\cdot\text{m}^{-3}$	Elastic Modulus/MPa	Poisson's Ratio
Miscellaneous fill	2	17	30	17.2	4.1	0.35
Sandy silt	4	18	23	19.5	7.4	0.33
Clay silt	19	20	20	20.3	8.9	0.30
Silty clay	20	32	18	21.0	10.6	0.32
Shield machine	-	-	-	-	210,000	0.12
Grouting layer	-	-	-	21.2	1000	0.21

2.3. Excavation Simulation

In the numerical model, the dynamic simulation of shield tunneling construction is conducted by changing the material calculation parameters and the methods of the “kill” and “revive” elements. The shield machine, disturbance layer, and segment lining elements are all pre-set elements. When simulating shield tunneling, we set step 0 to the pre-excavation state (i.e., reference state), and excavate 15 m in step 1. From step 2 to step 17, we excavate 3 m in each step to reduce the influence of boundary conditions on the tunneling simulation.

3. Analysis of Numerical Calculation Results

3.1. Analysis of Calculation Results under Basic Working Conditions

The basic working condition is that the underground tunnel is adjacent to the existing tunnel in parallel with a distance of 4 m, and the thickness of the overlying soil is 12 m. The impact of shield tunneling construction on the adjacent existing tunnel is analyzed from the three aspects of plastic zone, displacement, and stress.

3.1.1. Analysis of the Plastic Zone of the Existing Tunnel

Observing Figure 2, it can be seen that shear failure and tensile failure are mixed around the tunnel, among which shear failure is the main failure, and tensile failure is distributed around the segment. The results show that the soil around the tunnel is mainly subjected to compressive stress, which is manifested as shear failure. For the segment structure, due to the joint action of pressure and tension and tensile failure, it is very likely to generate torque, causing the segment torsion phenomenon.

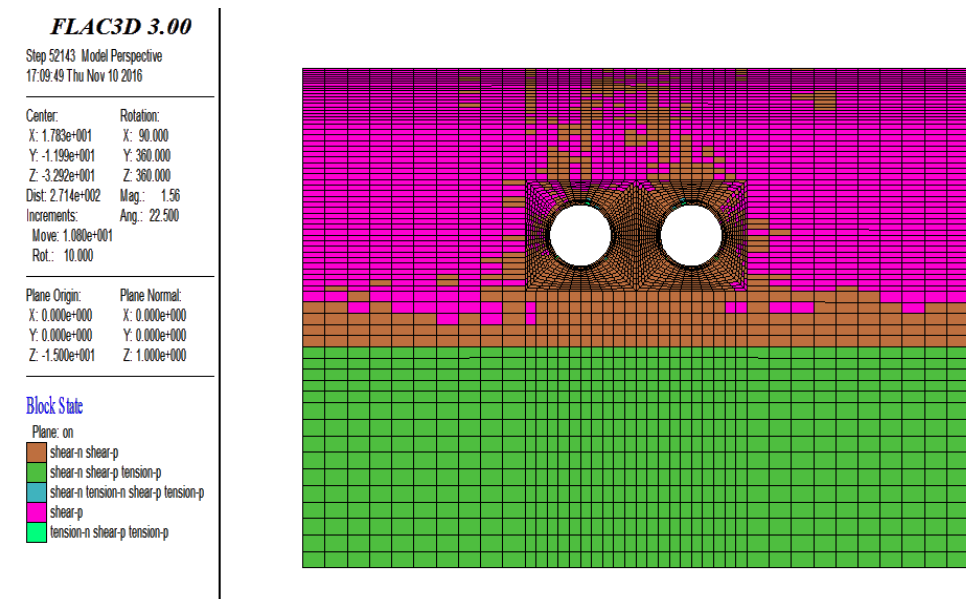


Figure 2. Plastic zone in last step.

3.1.2. Analysis of Existing Tunnel Settlement

Figure 3 shows the variation of the settlement values of four nodes on the outer surface, bottom, left, and right of the existing tunnel segment lining with the tunneling process of the shield machine at the observation section. It can be seen that, with the advancement of the shield machine, the settlement of the existing tunnel increases gradually, the settlement of the right node is always the largest, the settlement of the left node is always the smallest, and the settlement of the upper and lower nodes is located between them.

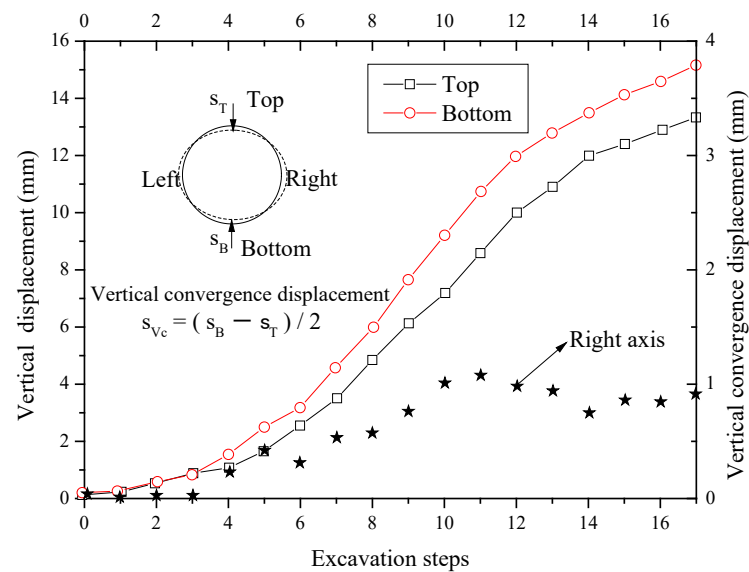


Figure 3. Vertical convergence deformation.

From Figure 3, we can see that the settlement of each node in the same section is different, and relative settlement has occurred between them. The relative settlement of the left and right nodes indicates that the segment ring has rotated, and the relative settlement of the upper and lower nodes indicates that the segment ring has deformed. The settlement of the right node (closer to the new tunnel side) is always greater than that of the left node (farther from the new tunnel side), and the relative settlement between them gradually increases with the excavation of the shield. After the construction of the new tunnel, due to the sub-consolidation of the surrounding disturbed soil, the joints in the cross-section of the existing tunnel continue to produce uneven settlement, and the amount of rotation continues to increase.

When the shield machine is advancing in the new tunnel, the lower node always settles more than the upper node, indicating that the upper and lower nodes are deforming outward. According to the force and deformation characteristics of the circular lining, the existing tunnel is subject to a “lateral load” effect, and the outward deformation of the upper and lower nodes reaches a maximum value of 1.85 mm in the 11th step. After step 11, the relative settlement of the upper and lower nodes gradually decreases and finally stabilizes at 1.44 mm.

3.1.3. Analysis of Side Shift of Existing Tunnels

Existing tunnels also shift sideways when parallel tunnels are excavated. In front of the shield machine, affected by the jacking force, the existing tunnel moves away from the new tunnel behind the shield machine; affected by the grouting pressure and formation loss, the existing tunnel still moves away from the new tunnel. The amount of lateral displacement is related to factors such as jacking force, grouting pressure, and formation loss.

Figure 4 shows the changes in side displacement of the four nodes on the outer surface, bottom, left, and right of the existing tunnel at the observation section with the tunneling process of the shield machine. Generally speaking, during the whole construction process, the lateral displacement of the bottom node is always the largest, the lateral displacement of the upper node is always the smallest, and the lateral displacement of the left and right nodes is between them. Before the shield machine is close to the observation (step 1 to step 4), the amount of lateral movement is small, and the relative lateral movement between each node is also small, so the existing tunnel basically only produces rigid body displacement when the shield machine passes through the observation surface. When the shield machine moves away from the observation surface (step 5 to 12), the side shift increases sharply,

and relative displacements occur between nodes. When the shield machine moves away from the observation surface (step 13), the side shift gradually converges to a certain value.

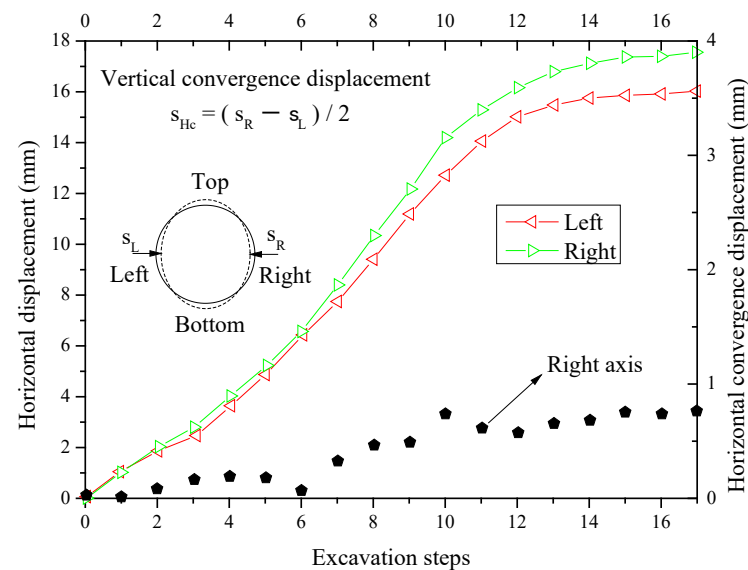


Figure 4. Lateral displacement curve and horizontal convergence deformation.

Figure 4 shows that the lateral displacement of each node in the same section is different, and there is relative lateral displacement between them. The relative lateral movement of the upper and lower nodes indicates that the segment ring has rotated, and the relative lateral movement of the left and right nodes indicates that the segment ring has deformed. The lateral displacement of the lower node is always greater than that of the upper node, and the relative lateral displacement between them gradually increases with the excavation of the shield. When the shield machine is advancing in the new tunnel, the right node always moves sideways more than the left, indicating that the left and right nodes are deforming inward. According to the force and deformation characteristics of the circular lining, the existing tunnel is affected by the “lateral loading” effect, and the inward deformation of the left and right nodes reaches the maximum value of 1.85 mm in the 11th step. After step 11, the relative lateral displacement of the left and right nodes gradually decreases and finally stabilizes at 1.48 mm.

3.1.4. Stress Analysis of Existing Tunnels

Figure 5 shows the changes in the circumferential stress on the observation surface, bottom, left, and right during the tunneling process of the shield machine. In general, the axial force of each section of the existing tunnel increases after the construction of the new tunnel. With the excavation of the new tunnel, the axial force of the upper and lower sections increases gradually. When the 11th step is excavated, the axial force of the upper section increases by 4/5, and the axial force of the lower section increases by 1/2. After the 11th step, the axial force slightly decreases. Before step 8 of excavation (the excavation surface is on the right of the observation surface), the axial force of the left section is greater than that of the right section. After step 8, the axial force of the right section (near the new tunnel side) is greater than that of the left section, and the axial force of the section varies greatly, indicating that the force of the existing tunnel structure is no longer symmetrical.

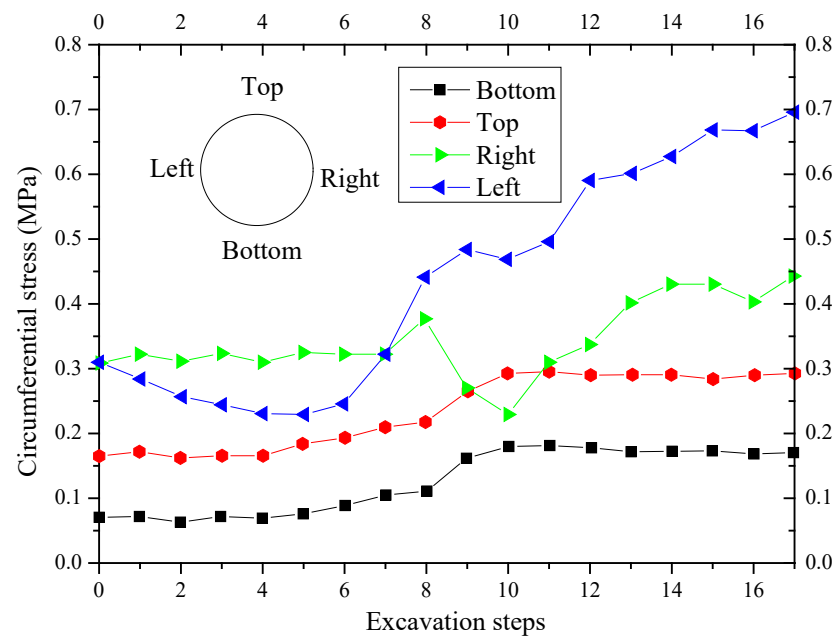


Figure 5. Hoop stress curve.

Figure 6 shows the changes in the longitudinal stress (axial stress in the Z direction) of each node outside the observation surface. During the propulsion process of the shield machine, the existing tunnel experiences a process of compression first and then tension. Before the arrival of the shield machine, the maximum compressive stress of 0.101 MPa appears on the lower side of the observation surface at the fourth excavation step. After the shield machine passes, the maximum tensile stress of 0.105 MPa appears on the left side of the observation surface at the 13th excavation step. It can be seen that, in the case of straight-line construction, the jacking reaction force of the shield machine has basically no effect on the existing tunnel, and the existing tunnel does not appear to be under pressure after the shield machine passes through it. Due to the low longitudinal tensile capacity of the segment structure, during the construction process, the stress state on the left side of the existing tunnel (away from the new tunnel side) is unfavorable and should be monitored emphatically.

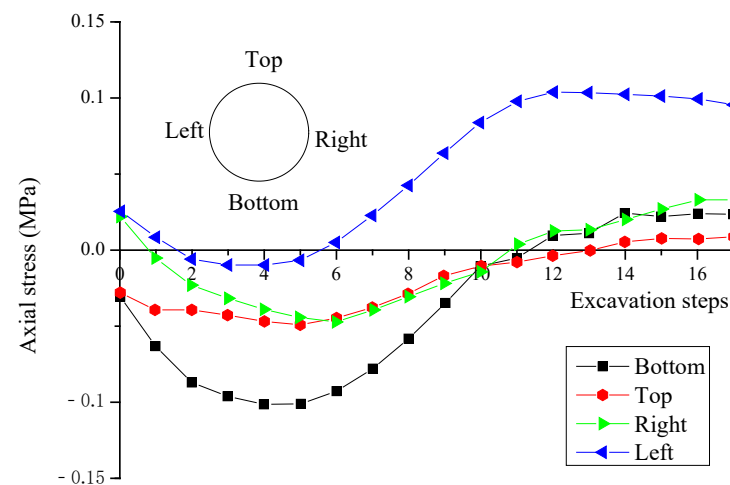


Figure 6. Axial stress curve.

Based on the analysis process of the numerical simulation calculation results under the basic working conditions, it is known that the three aspects of plastic zone, displacement,

and stress accurately reflect the deformation and stress of the existing tunnel and the evidence from different aspects is also realized, but the plastic zone and Yuntu can only determine the deformation and stress of the existing tunnel from the phenomena. In the later research process, the analysis process of this aspect is downplayed. The stress data performance can accurately reflect the stress evolution process of the existing tunnel, corresponding to the deformation of relevant parts of the tunnel.

Compared with the performance of the displacement data, the disadvantage of the stress data is that they are not intuitive enough, but the displacement data are different; and the deformation of different parts of the existing tunnel can be clearly seen, and it can also accurately reflect whether the existing tunnel is safe or not, as well as the focus of control position; and if the displacement data are fitted, the fitting curve can be obtained, and the curve can be applied to other similar working conditions.

3.2. Analysis of Calculation Results under Different Proximity Distance Conditions

On the basis of the above, this section studies the different proximity distances between the excavated tunnel and the existing tunnel. In this section, we only focus on the analysis of the existing tunnel settlement and lateral displacement and give the corresponding fitting curves to prepare for the subsequent analysis and evaluation standards and the analysis and evaluation system.

The model has a height of 45 m, a width of 60 m, a length of 90 m, and a buried depth of 12 m. The distance between the excavated tunnel and the existing tunnel is 4 m, 7 m, or 10 m. During excavation simulation, the state before excavation is set as the reference state (step 0). To reduce the influence of the boundary, the excavation is 15 m in the first step, 3 m in each step from the 2nd to the 17th, and 3 m in each step after the 18th step. For the remaining 27 m, the settlement and lateral displacement data above the existing tunnel are selected to analyze the calculation results of different distances from the existing tunnel. The analysis process is as follows.

3.2.1. Analysis of Existing Tunnel Settlement

Figure 7 below shows the settlement of the roof of the existing tunnel at different distances between the excavated tunnel and the existing tunnel. The X-axis is the excavation progress, and the Y-axis is the deformation. It is observed that, with the advance of the shield machine, the settlement of the existing tunnel gradually increases.

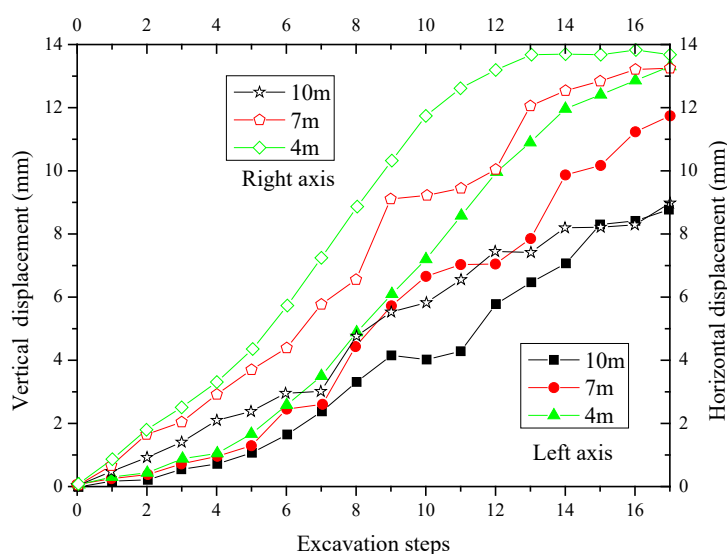


Figure 7. Displacement curve.

The settlement of each tunnel model in the same construction step is different at different proximity distances, among which the distance of 4 m is the largest, followed

by 7 m, and the settlement of the existing tunnel under the working condition of 10 m is relatively the smallest. The difference in settlement is also greater, among which the maximum settlement of the tunnel near 4 m is 13.4 m, the maximum settlement of the tunnel near 7 m is 11.7 m, and the maximum settlement of the tunnel near 4 m is 8.8 m, and it can be clearly seen that the difference continues to grow.

The displacement data of different curves are fitted, and the following fitting formula is obtained:

$$y = -0.0742x^2 + 0.282x + 13.415, (x \text{ is the thickness of the soil layer}), R^2 = 1 \quad (1)$$

Using Formula (1) to check and calculate, it can be concluded that the maximum settlement above the tunnel is about 10 mm at a distance of about 9 m. After the distance of 9 m, the settlement of the tunnel decreases sharply. When the distance is 13 m, the settlement is only 4.5 mm. The existing tunnel has no stability impact. With the deformation amount of 10 mm as the dividing line, that is, with the adjacent distance of 9 m and closer is the main affected area of the tunnel, the area greater than the adjacent distance is the secondary affected area. Since the diameter D of the tunnel section is 6 m, it can be determined that $1.5D$ is the main affected area of the tunnel. This finding is also basically consistent with the tunnel project impact zoning based on the Peck formula in the “Technical Specifications for Urban Rail Transit Engineering Monitoring”.

In summary, it can be shown that the main impact area of excavated tunnels on the adjacent existing tunnels is $1.5D$, and the final settlement above the existing tunnels can be calculated using the formula $y = -0.0742x^2 + 0.282x + 13.415$ (x is the adjacent distance).

3.2.2. Analysis of Side Shift of Existing Tunnels

The right axis of Figure 7 shows the lateral movement of the roof of the existing tunnel at different distances between the excavated tunnel and the existing tunnel, the X -axis is the excavation progress, and the Y -axis is the deformation amount. It is observed that, with the advancement of the shield machine, the lateral movement of the existing tunnel gradually increases.

The lateral displacement of each tunnel model at the same construction step is different at different proximity distances, among which the distance of 4 m is the largest, followed by 7 m, and the settlement of the existing tunnel under the working condition of 10 m is relatively the smallest. The difference in the settlement is greater as the distance between the tunnels increases continuously. The maximum settlement of the tunnel near 4 m is 13.7 m, the maximum settlement of the tunnel near 7 m is 13.2 m, and the maximum settlement of the tunnel near 4 m is 8.9 m. It can be clearly seen that the gap keeps widening.

The displacement data of different curves are fitted, and the following fitting formula is obtained:

$$y = -0.008x^2 + 0.1397x + 13.164, (x \text{ is the proximity distance}), R^2 = 1 \quad (2)$$

Using Formula (2) to check and calculate, it can be concluded that the maximum side shift above the tunnel is about 10.8 mm at a distance of about 9 m, the side shift of the tunnel decreases sharply after the distance of 9 m, and the settlement is only 0.9 at the distance of 13 m mm, with no influence on the stability of the existing tunnel. With the deformation amount of 10 mm as the dividing line, that is, the adjacent distance of 9 m and within is the main affected area of the tunnel, the area greater than the adjacent distance is the secondary affected area. Since the diameter D of the tunnel section is 6 m, it can be determined that $1.5D$ is the main affected area of the tunnel. This finding is also basically consistent with the tunnel project impact zoning based on the Peck formula in the “Technical Specifications for Urban Rail Transit Engineering Monitoring”.

In summary, it can be shown that the main impact area of the excavation tunnel on the adjacent existing tunnel is $1.5D$, and the final lateral movement above the existing tunnel can be modeled using the formula $y = -0.2129x^2 + 2.1959x + 8.3064$ (x is the adjacent distance).

Quantitative estimation, in the next section, also uses the fuzzy gray theory combined with this formula to perform research on the deformation prediction of existing tunnels.

3.3. Analysis of Calculation Results under Different Overlying Soil Thickness Conditions

On the basis of the foundation conditions in the previous step, change we the thickness of the soil layer between the excavation tunnel and the existing tunnel to study the influence of different overlying soil layers on existing tunnels. Due to the analysis of the calculation results based on the basic working conditions in Section 3.1, the plastic zone, stress cloud diagram, and displacement cloud diagram can only qualitatively express the comparative differences in different working conditions, but they cannot be quantified. In addition, the stress cloud diagram is due to the complexity of the stress path. The specific stress law can only be seen through comparative analysis with the displacement evolution law, and the displacement analysis shall prevail.

The height of the model is 45 m, the width is 60 m, the length is 90 m, and the adjacent distance is 4 m. The thickness of the overlying soil layer of the excavated tunnel and the existing tunnel is 12 m, 22 m, or 32 m. The simulation of the thickness of the overlying soil layer is realized by loading on the surface of the model. During the excavation simulation, the state before excavation is set as the reference state (step 0). To reduce the influence of the boundary, the excavation is 15 m in the first step, 3 m in each step from the second to the 17th step, and the remaining excavation from the 18th step. The settlement and lateral displacement data above the existing tunnel are selected to analyze the calculation results of the existing tunnel based on different thicknesses of the overlying soil layer.

3.3.1. Analysis of Existing Tunnel Settlement

Figure 8 below shows the settlement of the top of the existing tunnel under the different thicknesses of the overlying soil layer between the excavated tunnel and the existing tunnel. The X-axis is the excavation progress, and the Y-axis is the deformation. It is observed that, with the advance of the shield machine, the settlement of the existing tunnel gradually increases, and the increase in the thickness of the overlying soil layer is the main reason for the increase in deformation.

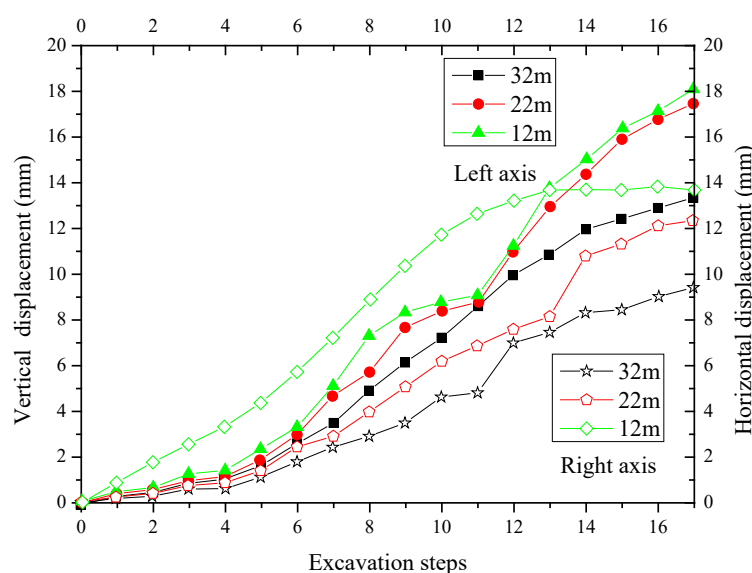


Figure 8. Displacement curves of existing tunnels under different overlying soil layer thicknesses.

Due to different thicknesses of the overlying soil layer, the settlement of each tunnel model in the same construction step is different, among which the thickness of the overlying soil layer of 32 m is the largest, followed by 22 m, and the settlement of the existing tunnel under the working condition of 12 m is relatively the smallest. As the thickness of the

overlying soil layer continues to increase, the difference in settlement is also greater. The maximum settlement of the tunnel with the thickness of the overlying soil layer of 32 m is 18.1 m, the maximum settlement of the tunnel with the thickness of the overlying soil layer of 22 m is 17.5 m, and the thickness of the overlying soil layer is 12 m. The maximum settlement of the tunnel is 13.4 m, and it can be clearly seen that the gap continues to widen.

The displacement data of different curves are fitted, and the following fitting formula is obtained:

$$y = -0.0177x^2 + 1.0161x + 3.7125, (x \text{ is the soil thickness}) \quad (3)$$

Using Formula (3) to check and calculate, it can be concluded that the maximum settlement above the tunnel with an overlying soil layer thickness of about 8 m is about 10.7 mm, which is a relatively safe overlying soil layer thickness in the numerical calculation results of the tunnel, meeting the requirements of the specification. As the thickness increases, the settlement above the tunnel increases gradually, and the rate of increase also increases. When the thickness of the overlying soil layer reaches 15 m, the settlement reaches 15 mm. However, when the thickness of the overlying soil layer reaches 30 m, the settlement reaches a maximum of 18.27 mm, and then the increase in the buried depth of the tunnel gradually reduces the subsidence of the existing tunnel, and it gradually remains stable. The result is that the consolidation strength of the soil layer becomes larger, which is beneficial to prevent the deformation of the existing tunnel.

In summary, it can be seen that the safe overlying soil thickness in the tunnel numerical calculation results is 8 m, the extreme value appears under the working condition of a buried depth of 30 m, and the formula $y = -0.0177x^2 + 1.0161x + 3.7125$ (x is the near distance) is used to calculate the final settlement above the existing tunnel.

3.3.2. Analysis of Side Shift of Existing Tunnels

The right axis of Figure 8 shows the lateral movement of the top of the excavated tunnel and the existing tunnel with different thicknesses of the overlying soil layer. The X-axis is the excavation progress, and the Y-axis is the deformation. Observation found that, with the advancement of the shield machine, the lateral movement of the existing tunnel gradually increases, and as the thickness increases, the lateral movement gradually decreased. The soil structure is more stable and mainly bears vertical stress, so the lateral movement becomes smaller.

With different thicknesses of the overlying soil layer, the settlement of each tunnel model in the same construction step is different, among which the thickness of the overlying soil layer at 12 m is the largest, followed by 22 m, and the settlement of the existing tunnel under the working condition of 32 m is relatively the smallest. In addition, with the thickness of the overlying soil layer continuing to increase, the difference in lateral displacement is greater. The maximum lateral displacement of the tunnel with the thickness of the overlying soil layer of 12 m is 13.7 m, and the maximum lateral displacement of the tunnel with the thickness of the overlying soil layer of 22 m is 12.4 m. The maximum lateral displacement of the 32 m-thick tunnel is 9.4 m, and it can be clearly seen that the gap continues to widen.

The displacement data of different curves are fitted, and the following fitting formula is obtained:

$$y = -0.008x^2 + 0.1397x + 13.164, (x \text{ is the proximity distance}) \quad (4)$$

Using Formula (4) to check and calculate, it can be obtained that the maximum lateral displacement above the tunnel is about 9.8 mm when the thickness of the overlying soil layer is about 30 m, which is a relatively safe overlying soil layer thickness in the numerical calculation results of the tunnel, meeting the requirements of the specification. As the thickness continues to decrease, the lateral displacement above the tunnel gradually increases, and the increase rate becomes larger, which is inconsistent with the settlement analysis results above the tunnel. The result occurs because one is under vertical force, and

the other is under lateral force. The change in the thickness of the overlying soil layer is mainly the change in the vertical stress, which is not sensitive to the lateral deformation and even limits the development of the lateral displacement to a certain extent with the increase in the vertical stress.

With displacement analysis, it can be seen that the safe overlying soil thickness in the numerical calculation results of the tunnel is 30 m. For the calculation of the final lateral displacement above the tunnel, in addition, we consider that the main influencing factor of the tunnel is the vertical deformation, and in the analysis of the calculation results with different thicknesses of the overlying soil layer, the results of the tunnel settlement analysis prevail.

3.4. Analysis of Calculation Results under Different Proximity Modes

In the approach of the excavated tunnel to the existing tunnel, two approach methods are used to study the influence of excavated tunnels and existing tunnel approach methods. Due to the analysis of the calculation results based on the basic working conditions in Section 3.1, the plastic zone, stress cloud diagram, and displacement cloud diagram can only qualitatively express the comparative differences in different working conditions, but they cannot be quantified. In addition, the stress cloud diagram is due to the complexity of the stress path. The specific stress law can only be seen through comparative analysis with the displacement evolution law, and the displacement analysis prevails.

The distance between the excavated tunnel and the existing tunnel is 4 m. During excavation simulation, the state before excavation is set as the reference state (step 0). To reduce the influence of the boundary, the excavation is 15 m in the first step, 3 m in each step from the second to the 17th step, and the remaining excavation from the 18th step is 27 m; the settlement and side shift data above the existing tunnel are selected to analyze the calculation results of different adjacent methods of the existing tunnel.

3.4.1. Analysis of Existing Tunnel Settlement

Figure 9 shows the settlement of the roof of the existing tunnel under different approach methods between the excavated tunnel and the existing tunnel. The X-axis is the excavation progress, and the Y-axis is the deformation. It was observed that, with the advance of the shield machine, the settlement of the existing tunnel gradually increases.

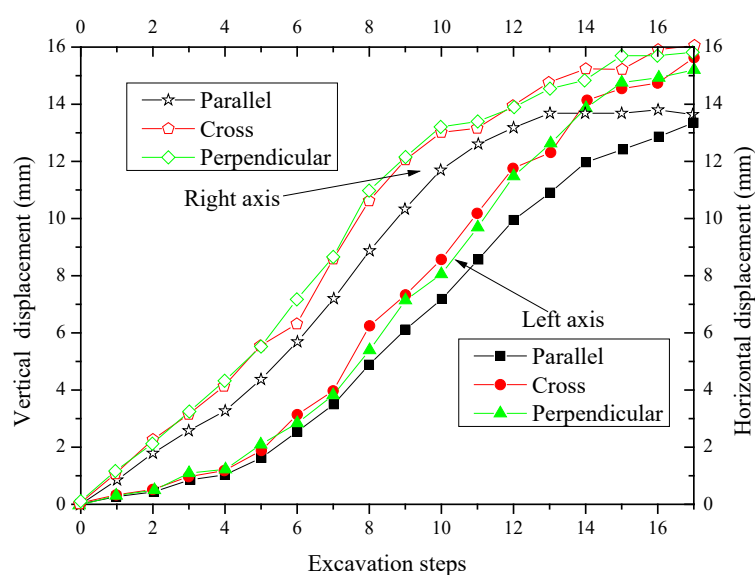


Figure 9. Displacement curves of existing tunnels under different proximity modes.

With different approach methods, the settlement of each tunnel model in the same construction step is different, among which the settlement of the existing tunnel with the

approach of horizontal is the smallest, which is 13.4 mm, and the settlement above the vertical and cross tunnels is basically the same, at about 15.3 mm. There is no continuity in the approach method, and it is impossible to find the law through the fitting formula. It can only be obtained qualitatively. The best approach method is a horizontal approach, and vertical or cross approaches are not recommended.

3.4.2. Analysis of Side Shift of Existing Tunnels

The right axis of Figure 9 shows the lateral movement of the top of the existing tunnel with different approaches between the excavated tunnel and the existing tunnel; the X-axis is the excavation progress, and the Y-axis is the deformation. It is observed that, with the advancement of the shield machine, the lateral movement of the existing tunnel gradually increases.

With different approach methods, the lateral displacement of each tunnel model in the same construction step is different, similar to the settlement curve; the lateral displacement of the existing tunnel with the horizontal adjacent method is the smallest, at 13.7 mm; and the settlement above the vertical and cross tunnels is basically the same, at about 15.9 mm, because there is no continuity in the approach method. It is also impossible to find the law through the fitting formula. It can only be qualitatively concluded that the best approach method is the horizontal approach. Vertical or cross approaches are not recommended. The results of the settlement analysis above the tunnel are consistent.

4. Engineering Section Test

4.1. Overview

Zhengzhou Metro Line 5 is a ring line project of the Zhengzhou Metro. Relying on the bid section, the excavation tunnel and the existing tunnel in the shield construction are selected at a suitable distance, and the engineering test research on the influence of the underground tunnel on the adjacent existing tunnel is performed, as shown in Figure 10. There are engineering sections with adjacent distances of 4 m, 7 m, and 10 m. The buried depth of the tunnel is about 22 m, and the diameter of the tunnel is 6 m. The left side is the adjacent existing tunnel, and the right side is the tunnel. The working conditions of this test section correspond to the working conditions in the numerical simulation research, which is convenient for interactive comparative analysis.

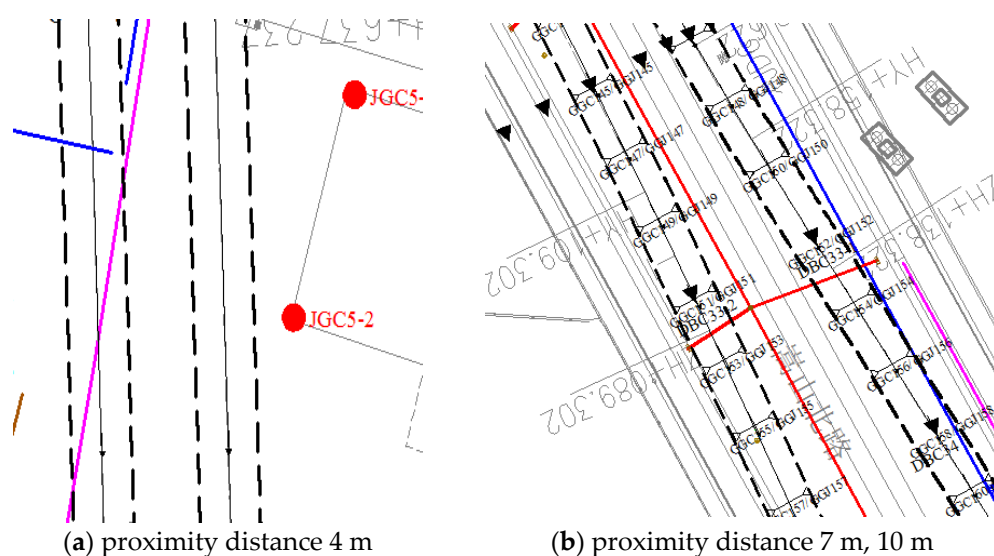


Figure 10. Test object.

4.2. Monitoring Data Analysis

Due to the limited layout conditions of the monitoring points, only the vertical displacement of the segment is selected as the main reference index for the impact of the underground tunnel on the adjacent existing tunnels. The method is similar to the numerical simulation section.

Figure 11 below shows the settlement of the top of the existing tunnel at different distances between the excavated tunnel and the existing tunnel; the X-axis is the date, and the Y-axis is the deformation amount. It is observed that, with the advance of the shield machine, the settlement of the existing tunnel gradually increases, and the jacking force and formation loss during the shield construction are the main reasons for the movement of the surrounding soil.

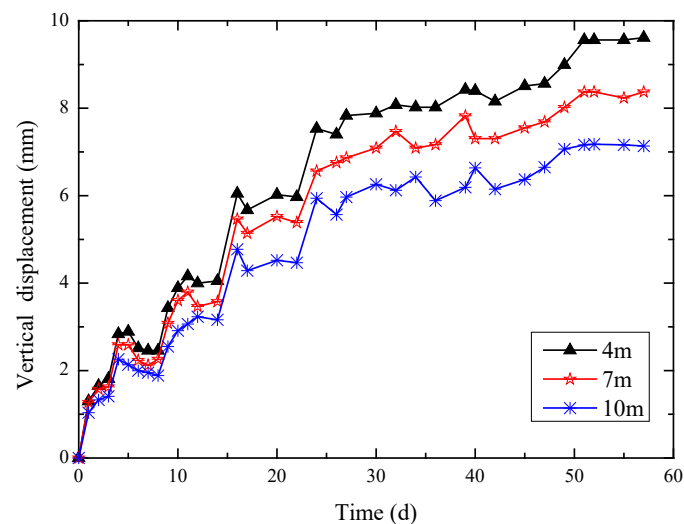


Figure 11. Measured settlements at the top of the existing tunnel.

The settlement of each tunnel model in the same construction step is different at different proximity distances, among which the distance of 4 m is the largest, followed by 7 m, and the settlement of the existing tunnel under the working condition of 10 m is relatively the smallest. The maximum settlement of the tunnel near 4 m is 9.6 mm, the maximum settlement of the tunnel near 7 m is 8.3 mm, and the maximum settlement of the tunnel near 10 m is 7.1 mm.

The displacement data of different curves are fitted, and the following fitting formula is obtained:

$$y_4 = -0.0044x^2 + 372.97x - 8 \times 10^6, (x \text{ is time/d}), R^2 = 0.9695 \quad (5)$$

$$y_7 = -0.0033x^2 + 277.96x - 6 \times 10^6, (x \text{ is time/d}), R^2 = 0.9714 \quad (6)$$

$$y_{10} = -0.0049x^2 + 420.04x - 9 \times 10^6, (x \text{ is time/d}), R^2 = 0.9397 \quad (7)$$

$$y = 0.0053x^2 - 0.4731x + 11.375, (x \text{ is the proximity distance/m}), R^2 = 1 \quad (8)$$

Using Formula (8) to check the calculation, it can be concluded that the maximum settlement above the tunnel is about 9.6 mm at a distance of about 5 m. After the distance of 5 m, the settlement of the tunnel gradually decreases, with no impact on the stability of the existing tunnel. With the deformation amount of 10 mm as the dividing line, that is, the adjacent distance of 5 m and within is the main affected area of the tunnel, the area greater than the adjacent distance is the secondary affected area. Since the diameter D of the tunnel

section is 6 m, it can be determined that 0.8D is the main affected area of the tunnel. This finding is also basically consistent with the tunnel engineering impact zoning based on the Peck formula.

In summary, it can be seen that the main impact area of the excavation tunnel on the adjacent existing tunnel is 0.8D, and the final settlement of the existing tunnel can be calculated using the formula $y = 0.0053x^2 - 0.4731x + 11.375$ (x is the adjacent distance). In the following section, the fuzzy gray theory is combined with this formula to conduct research on deformation prediction of existing tunnels.

5. Gray System

5.1. Establishment of Membership Function for Fuzzy Processing of Historical Data

For tunnel surrounding rock deformation data, generally speaking, the importance of each historical datum and its impact on future data gradually increases from far to near. According to historical data, different membership degrees are given at different times; that is, the membership degree of recent data is relatively large, and the membership degree of long-term data is small. This fact can strengthen the effect of recent data and weaken the influence of long-term historical data. Therefore, for tunnel surrounding rock, regarding deformation, time is selected as a variable. In this paper, ascending half Cauchy distribution is used to establish the membership function of deformation data of tunnel surrounding rock.

5.2. Establishment of FGM (1,1) Forecasting Model

On the GM (1,1) prediction model, this paper proposes applying fuzzy technology to the gray FGM (1,1) prediction model. The new model first takes the fuzzy membership degree of the original sequence at each time point as each time point. The weight value of the fuzzy weakening buffering sequence is obtained under the action of the weighted average weakening buffer operator, and then the prediction is made according to the GM (1,1) prediction model modeling. The specific algorithm design is as follows:

- (1) Assuming that the original sequence is, $X_0 = \{x_1, \dots, x_n\}$. the original sequence is fuzzified by $X_0 = ((x_1, s_1, t_1), (x_2, s_2, t_2), \dots, (x_n, s_n, t_n))$, introducing a fuzzy membership degree for each sample datum s_i , where $t_1, t_2, \dots, t_n$ is the time of corresponding data collection.

Then it uses the weakening buffer operator to act on the fuzzy sequence to obtain the fuzzy weakening buffer sequence.

$$x_k f d = \frac{s_k x_k + s_{k+1} x_{k+1} + \dots + s_n x_n}{s_k + s_{k+1} + \dots + s_n} = \frac{\sum_{i=k}^n s_i x_i}{\sum_{i=k}^n s_i} (k = 1, 2, \dots, n) \quad (9)$$

- (2) Model the fuzzy weakening buffer sequence FX according to the GM (1,1) model, and then calculate the two parameters in the fuzzy gray FGM (1,1) prediction model.
- (3) Use the model built in the second step to predict.

Based on the on-site monitoring data of Zhengzhou Metro Line 5, the FGM (1,1) model was established. The measured data are the following (Table 3).

Set the measured data as the training data set from 15 March to 1 April, then $t = 1, 2, 3, \dots, 9$ we can obtain:

$$X_0 = ((4.12, 0.2809, 1), (6.07, 0.3378, 2), (5.73, 0.4098, 3), (6.05, 0.5000, 4), (6.10, 0.6098, 5), (7.53, 0.7353, 6), (7.43, 0.7353, 7), (7.91, 0.7353, 8), (7.94, 0.7353, 9)) \quad (10)$$

Using the fuzzy gray FGM (1,1) prediction model, the calculated prediction values are shown in Table 4.

Table 3. The actual measurement data of existing tunnel deformation with a distance of 4 m.

Date	3–15	3–17	3–19	3–21	3–23	3–25	3–27	3–29	4–1
Existing tunnel training data (mm)	4.12	6.07	5.73	6.05	6.10	7.53	7.43	7.91	7.94
Date	4–3	4–5	4–7	4–9	4–11	4–13	4–15	4–17	4–19
Displacement measured value (mm)	8.16	8.05	8.10	8.42	8.43	8.49	8.52	8.63	8.99
GM (1,1) predicted value (mm)	7.92	7.97	8.02	8.17	8.21	8.32	8.44	8.52	8.69
Error percentage	3.03%	1%	0.99%	3.05%	2.67%	2.04%	0.9%	1.3%	3.4%

Table 4. Adjacent grade division.

Adjacent Grade	Proximity Definition	Criteria for the Classification
1	very close	The distance between the structure and the center of the tunnel is less than $0.8D$ – $1.5D$.
2	near	The distance between the structure and the center of the tunnel is $1.5D$ – i .
3	nearer	The distance between structure and tunnel center is i – $2.5 i$.
4	not adjacent	The distance between the structure and the center of the tunnel is greater than $2.5 i$.

Note: (1) i —the settlement trough width coefficient (m) in the calculation formula of tunnel surface settlement curve per Peck. (2) According to the calculation formula of Peck, the range of inflection point (i) is $(0.8$ – $1.6)D$; here, we take $1.6D$. (3) D is the shield tunnel span.

It can be seen from the error percentage in Table 4 that the fuzzy gray system can more accurately predict the deformation of the tunnel surrounding rock, overcome the shortcoming that the gray system can only be used for short-term prediction, and improve the prediction accuracy. Due to the large fluctuations in the original sequence, the predicted result is not ideal, and the average relative error of the predicted result is relatively high. The relative error is greatly reduced, and the prediction accuracy is greatly improved. The system can effectively eliminate the interference of the shock disturbance system data sequence in the modeling and prediction processes and improve the prediction accuracy.

Through curve fitting in Python software, the mean square error, root mean square error, mean absolute error, and coefficient of determination of the quadratic polynomial (cubic polynomial, hyperbolic) fitting function are 0.020 (0.038, 0.049), 0.140 (0.196, 0.222), 0.130 (0.142, 0.156), and 0.982 (0.964, 0.954), respectively.

6. Evaluation Criteria for the Impact of Underground Tunnels on Three-Dimensional Space Structures

On the basis of the research in the previous section, according to the calculation method of surrounding rock pressure, failure mode, stability criteria, and stability control measures, combined with the numerical simulation research and engineering test research results of the influence of underground tunnels on three-dimensional space structures, using fuzzy methods, the prediction method of three-dimensional space structures based on gray theory proposes an evaluation standard for the impact of underground tunnels on three-dimensional space structures. This standard gives results such as failure modes, stability criteria, deformation prediction methods, and evaluation criteria for three-dimensional space structures.

6.1. Adjacent Classification of Three-Dimensional Space Structures

The division of adjacent grades is related to the spatial distance between the existing three-dimensional space structures and the excavated tunnel, including their positional relationship, distance, and how the tunnel passes through the building. In addition, factors such as the buried depth of the tunnel need to be considered. The degree of damage to the

buildings is closely related. Obviously, the closer the buildings are to the tunnel, the more seriously they are affected, and the easier it is for them to be damaged.

According to the numerical simulation research results and engineering test results of the influence of underground tunnels on three-dimensional space structures, the main and secondary areas of underground tunnels' influence on three-dimensional space structures are obtained. On this basis, the adjacent grades are divided, as shown in Table 4.

6.2. Damage and Risk Classification of Three-Dimensional Space Structures

According to the division of its adjacent grades, the degree of influence on the tunnel can be determined, and then combined with the data performance of specific working conditions, the damage level and risk level can be determined. Therefore, according to the numerical simulation research results and engineering tests, as a result, relevant data on the impact of underground tunnels on three-dimensional space structures are obtained. On this basis, the damage level and risk level are classified, as shown in Table 5.

Table 5. Classification of damage based on deformation.

Damage Level	Deformation	Damage Description
1	Less than 5 mm	Ignorable
2	5–10 mm	Normal
3	10–20 mm	Light
4	20–40 mm	Heavy
5	Greater than 40 mm	High

In addition to the classification of damage levels and risk levels based on specific deformation values, various factors should be considered comprehensively for the safety of buildings, which is the mutual comparison between their own bearing capacity and external deformation, which are summarized as follows:

- ① The importance and current safety level of the building;
- ② Adjacent relationships between the tunnel and building;
- ③ Overview of related projects.

In building safety evaluations, different weights should be selected depending on the degree of influence of the three factors. When dividing the risk level, the ability of the building to bear additional deformation should be evaluated first, and then the engineering conditions of the tunnel construction, such as adjacent grades, ground conditions, etc., should be considered. To analyze its risk level, this paper is summarized in Table 6.

Table 6. Classification of risk levels based on appearance observation.

Damage Level	Severity Description	Risk Description
1	very big	There are large cracks or serious sideways movement in the existing tunnel. The structure or foundation bearing capacity of the building is lost, and the building has a large inclination.
2	big	Cracks or slight lateral shifts in existing tunnels; structural or foundation bearing capacity of buildings is partially reduced, requiring extensive repair work.
3	average	Slight lateral movement of the existing tunnel; no cracks found; doors and windows of the building are deformed and have problems opening.
4	smaller	Slight deformation of existing tunnels but not obvious and does not affect normal use. Micro-cracks in buildings that are easy to repair.
5	normal	The deformation of the existing tunnel within the control value can only be found by instrument measurement. The normal settlement of the building occurs within the control value, and no cracks are found.

6.3. Safety Evaluation of Three-Dimensional Space Structures

The purpose of safety assessment is to evaluate whether the existing structures are safe before tunnel construction and to identify their risk levels to adopt pre-protection measures according to different safety risk levels. It is a comprehensive subject, combined with the division of risk levels such as deformation and appearance observation, and it adopts a three-stage analysis method to conduct comprehensive safety evaluation research. The specific evaluation methods are as follows.

- (1) The first-stage evaluation method (Greenfield model method): This stage evaluation method is suitable for the safety evaluation of “closer” or hierarchical three-dimensional space structures. The evaluation method at this stage is assumed to be the case of Greenfield; that is, the existence of structures is not considered first. Judging according to Rankin [22], the maximum settlement value of a structure dominates the potential damage of the structure, and when the maximum settlement value is less than 10 mm, the damage of the structure can be ignored.

Therefore, the structures located in the settlement tank area defined by the above values can be ignored. We use Peck’s [23] empirical formula or numerical calculation to determine its land subsidence. The evaluation steps at this stage are, according to the observed settlement, to obtain its damage level and safety risk level from Tables 4 and 5, respectively. If the limit is exceeded, the second stage evaluation should be performed.

- (2) The second-stage evaluation method (isolation method): When the adjacent level of the structure is 2, the “secondary evaluation” method should be adopted. This evaluation method assumes that the structure is an elastic structure, the foundation is assumed to be flexible, and the settlement curve at the foundation of the structure can be obtained by matching the deformation of the settlement curve so that the deflection ratio and maximum horizontal strain (including compression and tension) of the flexible foundation can be obtained by calculation. The basic strain can be further calculated, and then the damage degree of the structure can be evaluated according to the magnitude of the strain.
- (3) The third-stage evaluation method (overall analysis method): When the structure is very close to the tunnel, that is, when the proximity level is level 1, the degree of damage to the building is the greatest. The third-stage method must be used for evaluation, that is, the three-dimensional finite element method. The three-dimensional finite element evaluation is a detailed numerical simulation of a house. During the simulation, the relationship among the tunnel, soil, and structures must be considered, and the structure, tunnel excavation process, and contact interface between the foundations must be modeled. In a detailed simulation, the specific steps are as follows:
 - a. Establish a tunnel-soil-structure interaction model in finite element software according to field data;
 - b. Adjust the numerical model according to the measured field data to cause the model parameters to conform to the actual project;
 - c. Use numerical models to predict the possible impact of construction on buildings;
 - d. Use the fuzzy gray forecasting system to make forecasts and then refine them to determine more accurate forecast data;
 - e. Compare the predicted value (mainly the settlement and inclination value) with the allowable value to judge its safety.

7. Conclusions

This article proposes a universal framework for the impact of shield tunnel construction on existing tunnels. Based on numerical analysis, experiments, and gray system theory analysis, this framework proposes a practical evaluation standard for the impact of three-stage underground tunnels on three-dimensional spatial structures.

- (1) Through numerical analysis methods, it was found that the main impact area of tunneling on adjacent existing tunnels is 1.5D. Through the study of coupling methods with different thicknesses of overlying soil layers, it was found that a relatively safe overlying soil layer thickness in the tunnel numerical calculation results is 8 m, and the extreme value occurs under the working condition of a burial depth of 30 m. Through research on different coupling methods of proximity, horizontal proximity is the best approach, and vertical or cross-proximity is not recommended.
- (2) Through the analysis of measured data, it can be concluded that the main impact area of tunneling on the adjacent existing tunnel is 0.8D, and the final settlement of the existing tunnel can be calculated using the formula $y = 0.0053x^2 - 0.4731x + 11.375$ (x is the proximity distance).
- (3) The fuzzy gray system accurately predicts the deformation of tunnels surrounding rock (with error of less than 5%), overcoming the disadvantage that the gray system can only be used for short-term prediction and improving the prediction accuracy.
- (4) A method for classifying the proximity level, damage level, and risk level of three-dimensional spatial structures has been proposed, and based on this method, a more practical evaluation standard for the impact of three-stage underground tunnels on three-dimensional spatial structures has been proposed.

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