Analysis of the Influence of Oblique Shield Tunnel Construction on Existing Tunnels: A FLAC3D Modeling Approach

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Abstract This study presents a comprehensive analysis of the influence parameters associated with the construction of a shield tunnel crossing an existing tunnel at an oblique angle. A three-dimensional model was developed using the finite difference software FLAC3D to simulate the construction process. The influence parameters, including geometric spatial position, shield construction parameters, and surrounding rock soil properties near the existing tunnel, were thoroughly examined. The degree of impact resulting from the oblique shield tunnel construction on existing tunnels was determined based on ground displacement, settlement of the existing tunnel, and changes in soil layers. The study summarizes the identified impact laws and investigates the interaction relationship between newly constructed shield tunnels, soil, and existing tunnels. The findings of this research provide a solid research foundation for ensuring the safety control of shield tunneling in proximity to existing tunnels.

Keywords Shield tunnel; FLAC3D; Oblique angle; Influence parameters;Interaction relationship

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Introduction

The construction of shield tunnels in close proximity to existing tunnels presents a common challenge in underground engineering due to the complexity and interconnectedness of the underground transportation network[1]. Various methods have been employed by researchers to analyze the construction process, including theoretical experience, physical experiments, on-site observations, and numerical analysis. Among these methods, numerical simulation has gained popularity due to its ability to simulate the dynamic impact of tunnel construction, consider the nonlinear interaction between surrounding rock, soil, and structures, and incorporate actual monitoring data to accurately depict the construction process[2].

Previous studies have utilized the finite difference method (FDM) in numerical simulation to investigate the response patterns of existing tunnels. For instance,Lia et al.[3] numerical simulation using FDM with actual monitoring data to study the behavior of existing tunnels. Avgerinos et al. focused on simplified single tunnels in their numerical model to assess the degree of influence on the tunnel directly above it. Chakeri et al. [4]selected the finite difference method to analyze the vertical underpass of existing tunnels in double tunnel systems, examining the changes in stress and displacement fields resulting from tunnel construction and intersections. Ng et al. [5] employed a three-dimensional numerical simulation method to investigate the deformation characteristics of double tunnels vertically passing through pre-existing tunnels. FLAC3D, a reliable and widely used software in underground engineering construction, has demonstrated positive application results[6].Building upon the research foundation laid by previous studies and leveraging the advantages of FLAC3D in numerical simulation analysis, this study aims to analyze the impact laws of shield tunneling near existing tunnels.

The main research questions are: (1) How to solve the problem of FLAC3D mesh partitioning in irregular models? (2) How to verify the scientificity and rationality of numerical model analysis results? (3) How to consider the interaction relationship between the newly built shield tunnel, soil, and existing tunnels?

This research contributes to : (1) Established a finite difference three-dimensional numerical model, showcasing the entire process of shield tunnel excavation construction; (2) The influence laws of various parameters in the oblique underpass of shield tunnels through existing tunnels were studied from three aspects: geometric spatial location, shield construction parameters, and soil physical properties. This has reference value for the safety control research of existing tunnels; (3) Analyzed the interaction relationship between newly built tunnels, existing tunnels and soil.

Overall, the structure of the paper is organized as follow：Section 2 reviews the basic computational principles and modeling principles of FALC3D; Section 3 introduces the three-dimensional modeling of shield tunneling through existing tunnels at oblique intersections based on actual engineering cases, analyzes the simulation results, and compares them with monitoring results to verify the scientific nature of the model; Section 4 conducts modeling and design from three aspects: geometric spatial location, shield tunneling construction parameters, and soil physical properties, studying the influence of different parameters on the deformation of existing tunnels; Section 5 discusses the interaction relationship between newly built tunnels, existing tunnels and soil; Section 6 summarizes the conclusions of this article and future work.

Methodology

FLAC3D

This study utilizes FLAC3D (Fast Lagrangian Analysis of Continua in 3 Dimensions), a numerical simulation analysis tool developed by Itasca Corporation in the United States. FLAC3D employs a three-dimensional explicit finite difference method, providing fast calculation speed and minimal computer memory requirements compared to finite element software. It accurately simulates stress and deformation in three-dimensional rock and soil media, surpassing the capabilities of many finite element software[7]. FLAC3D has gained wide application and maturity in the fields of geotechnical engineering and underground engineering. With ten constitutive models and the ability to define and

assign model materials and properties based on elasticity, plasticity, and empty elements, FLAC3D offers versatility for modeling purposes[8].
The research objective of this article is to investigate the nonlinear deformation relationship between new tunnels, soil, and existing tunnels during shield tunneling. FLAC3D's fish language function enables the definition of variables and functions, facilitating dynamic simulations of various stages in shield tunneling, including tunnel face advancement, segment splicing, and installation.
Given the complex engineering environment and irregular geometric spatial positions of the studied structure, modeling and grid partitioning are efficiently conducted using Midas GTS NX. Through programming, the nodes and unit files in Midas GTS NX are encoded and sorted into *.flac3d files that can be recognized by FLAC3D. The Import Grid operation is used to import the 3D model data into FLAC3D for post-processing analysis after grid division.

Constitutive model

In order to perform post-processing analysis on FLAC3D, there are several steps required. Firstly, the mesh needs to be divided in order to discretize the model into smaller elements. This allows for more accurate calculations and simulations.
Next, the material parameters for the selected constitutive model need to be determined. In geotechnical engineering, the selection of constitutive models for surrounding rock and soil is crucial as it greatly affects the simulation results. In this case, the Mohr Coulomb constitutive model is commonly used for surrounding rock and soil. This model has been extensively studied and recognized by many scholars[9].

The Mohr Coulomb model is relatively easy to work with as the relevant parameters can be obtained through conventional triaxial experiments. These experiments involve subjecting a cylindrical specimen of soil or rock to different levels of stress in order to determine its strength and deformation characteristics. These parameters include the cohesion and angle of internal friction, which are key factors in the Mohr Coulomb yield criterion.
Additionally, to accurately reflect the nonlinear mechanical properties of the geotechnical structure, an elastic-plastic model is used. This model takes into account the plastic deformation of the materials, allowing for a more realistic simulation of the behavior of the soil and rock in close proximity to and during oblique penetration by a shield tunneling project[10].

By properly selecting the constitutive model and determining the material parameters, the post-processing analysis in FLAC3D can provide valuable insights into the behavior of the geotechnical structure and help in making informed decisions during the design and construction phases.
In the elastic-plastic constitutive relationship, strain is divided into two parts, namely elastic strain and plastic strain, which are analyzed and calculated using elastic theory and plastic incremental theory. Among them, the yield surface function of the Mohr Columb model is:

$$F = R_{mc}q + p\tan\beta - c = 0 \quad (1)$$

$$R_{mc} = \frac{1}{\sqrt{3}\cos\beta}\sin\left(\Theta + \frac{\pi}{3}\right) + \frac{1}{3}\cos(\Theta + \frac{\pi}{3})\tan\beta \quad (2)$$

$$\cos(3\Theta) = \frac{J_3^3}{q^3} \quad (3)$$

Among them, β is $p-q$, which is the inclination angle of the Mohr Coulomb yield surface on the stress surface, i.e. the internal friction angle of the rock soil direct shear test. c is the cohesion, Θ is the ultimate deflection angle, and J_3 is the third deviator stress invariant.

Model designing

In the process of designing shield tunneling, the displacement and velocity fields of the existing tunnel after excavation should be reset first, and then the simulation of shield tunneling for new tunnels should be carried out. The specific simulation steps are shown in Figures1.

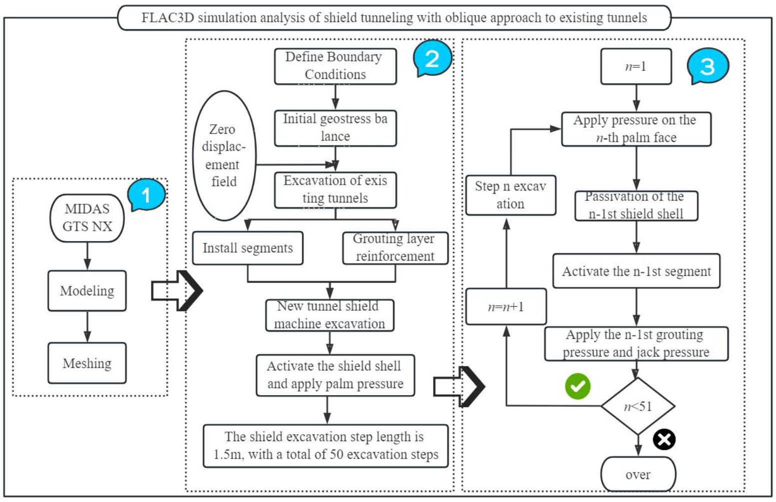


Fig1. Flow diagram of shield tunneling through existing tunnels

Case study

Background

The left line of the Binqing section of Line 5 runs under the mileage ZDK40+983.084~ZDK41+013.089, and the right line runs under the mileage YDK40+993.725~YDK41+022.693, passing through the Binzhan Xiang Station section of Line 1. The two tunnels are located at a 58 ° oblique intersection on the plane, and the minimum distance between the newly built tunnel and the existing tunnel is 3.258m. The schematic diagram of spatial location relationship is shown in Figure 2 and Figure 3.

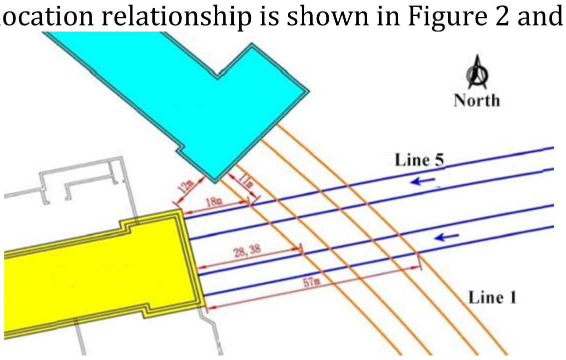


Fig2. Schematic diagram of the plane position relationship between the newly built tunnel and the existing tunnel

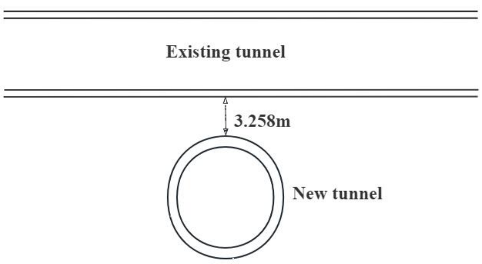


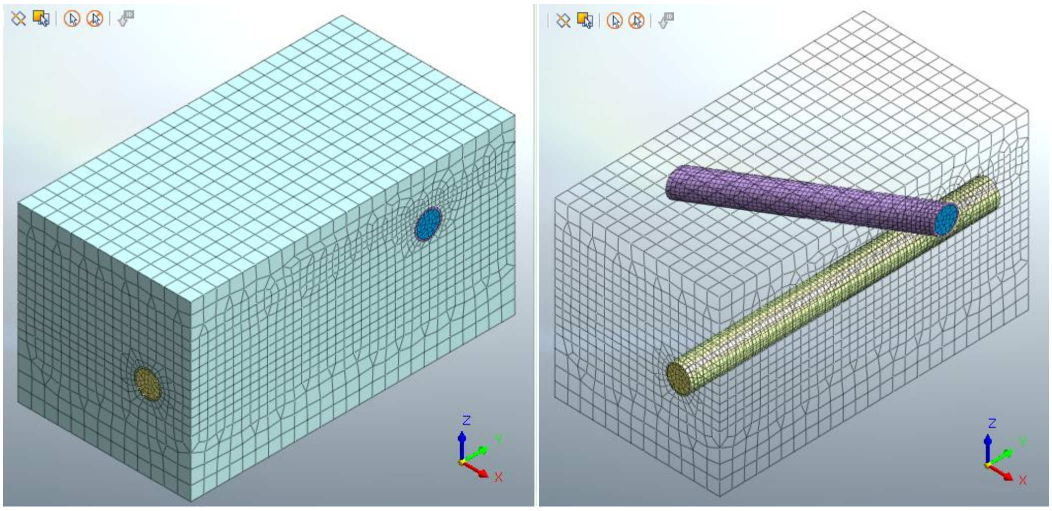
Fig3. Schematic diagram of the relationship between the elevation of the new tunnel and the existing tunnel

FLAC3D modeling

Based on the Saint Venant principle and engineering experience, the boundary range of the finite element model is ultimately set within 3-5 times the excavation diameter. This study takes the oblique intersection of Line 5 and Line 1 of a certain city's subway as an example. The upper part of the boundary is taken to the ground surface, and the calculation model size value is $40m(x)\times 75m(y)\times 40m(z)$. In the model, the excavation direction of the shield tunnel is the positive Y-axis direction, and the direction of gravity action is the negative Z-axis direction. The model is divided into 29747 nodes and 52858 units.

Model boundary conditions

Set the surface of the model as the surface of the space where the research project is located, with an existing tunnel buried at a depth of 8.8 meters, that is, the distance between the arch of the existing tunnel and the upper boundary of the model is 8.8 meters. The buried depth of the new tunnel is 18.3 meters, which means that the arch bottom of the new tunnel is 25.5 meters away from the lower boundary of the model, and the interval between the new and old tunnels is 3.3 meters. The upper part of the research space is for highways and green land, without large structures. So the model only needs to consider its own gravity effect, and the upper boundary of the model can be designed as a free boundary. Due to the fact that the soil is an elastic-plastic body in infinite space, while the soil in the model is a finite geometric body, constraints should be placed on all surfaces except the upper surface. Among them, normal constraints are set on the side of the model, and vertical displacement constraints are set on the bottom of the model.



(a) Grid division effect (b)Grid division perspective effect

Fig4 .Calculate the grid division effect of the model

Formation parameters

The disturbance of adjacent excavation of shield tunneling to existing tunnels is caused by the joint action of surrounding rock and soil, and soil properties and parameters are important factors affecting the research results. The soil parameter values should be selected based on the geotechnical investigation report of the research section and the detailed investigation stage of the entry section, as shown in Table 1.

Tab1. Main Physical and Mechanical Parameters of Rock and Soil Mass

Stratum name	Natural density(kg/m^3)	Elastic modulus(MPa)	Poisson's ratio	Cohesive force(kPa)	Internal friction	Thickness(m)

					angle(°)	
Plain fill	1860	6.2	0.35	15	16	6.0
Silty clay	2020	8.0	0.39	21	18.4	5.4
Silt	1900	8	0.32	21	30.5	8.3
Silty and sludge clay	1740	6	0.41	18	9	9.7
Containing muddy gravel and pebbles	2500	48	0.38	29	14	8.6

Structure parameters

In the design of model parameters, the ideal linear elastic constitutive model is usually used. The dimensions and calculation parameters of the shield tunneling machine and pipe segments are respectively shown in Tables 2 and Tables3.

Tab 2. Calculation parameters of lining and grouting body

Material name	Gravity density (kN/m3)	Elastic modulus (MPa)	Poisson's ratio	Thickness (m)
Existing tunnel segments	2550	31500	0.20	0.30
New tunnel segments	2550	31500	0.20	0.30
Shield shell	7850	210000	0.25	0.13
Grouting layer (before hardening)	1800	200	0.25	0.13
Grouting layer (after hardening)	1800	1800	0.20	0.13

Table 3 Dimensions related to shield tunneling machines and segments

Parameter(mm)	Shield machine length	Shield machine diameter	Knife disc diameter	Segment outer diameter	Segment inner diameter	Segment length
EPBM	7500	6200	6200	6000	5400	1500

Result analysis

The cloud map of soil response during the new shield tunneling is shown in Figure 5. Compare the settlement curves of the left and right arches of the existing tunnel that change with shield tunneling, as shown in Figures 6. Among them, Figures 6(a) show the settlement curve of the right arch waist of the existing tunnel (the side where the shield tunnel passes first). Figure 6(b) shows the settlement curve of the left arch of the existing tunnel (passing through one side after the shield tunneling). From the figure, it can be concluded that:

1) With the increase of shield excavation steps, the development trend of settlement on the left and right arches of the existing tunnel and the location points where the maximum settlement value is located have changed, indicating that the oblique angle of the new and old tunnels leads to the disturbance of the existing tunnel being unable to be analyzed in a symmetrical manner.
2) The excavation disturbance on the right arch waist of the existing tunnel is significant, indicating that the existing tunnel itself has a "barrier" effect on the disturbance of the new tunnel before the shield passes through the intersection of the old and new tunnels.
3) In the 40th step of excavation, the shield has already passed through the intersection of the new and old tunnels, and the settlement and deformation rate of the left arch of the existing tunnel has significantly increased compared to before. This further verifies that the stability of the existing tunnel itself has a "weakening" effect on the fluctuation of shield tunneling.

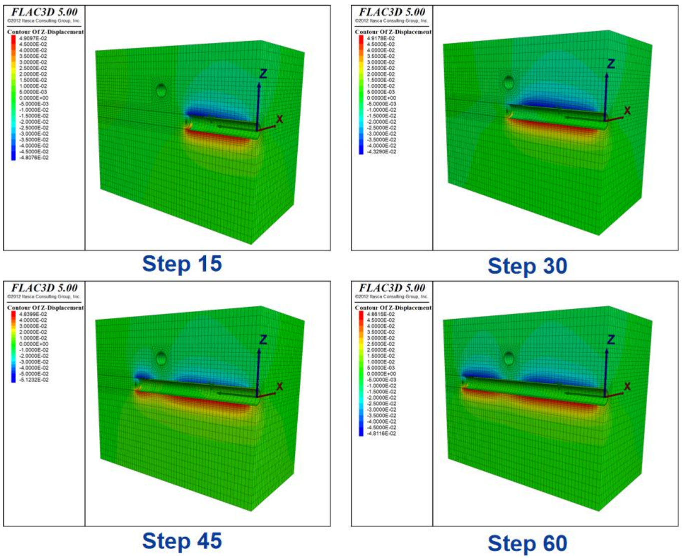
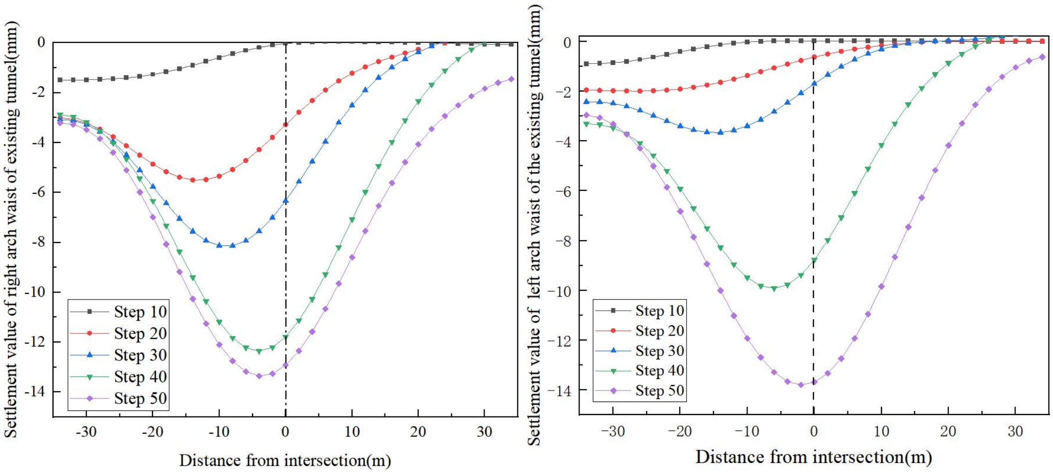


Fig.5 Cloud map of soil deformation at different excavation steps



(a) the right (b) the left

Fig.6 Settlement Curve of Existing Tunnel Arch Waist

Model validation

Compare the surface settlement monitoring curve obtained from the monitoring location above the axis of the intersection of the new and old tunnels with the settlement curve obtained from numerical simulation, as shown in Figure 7. From the graph, it can be seen that the curve variation patterns obtained from the measured data have good consistency with the numerical simulation conclusions, proving the scientific and reliable nature of the numerical simulation results.

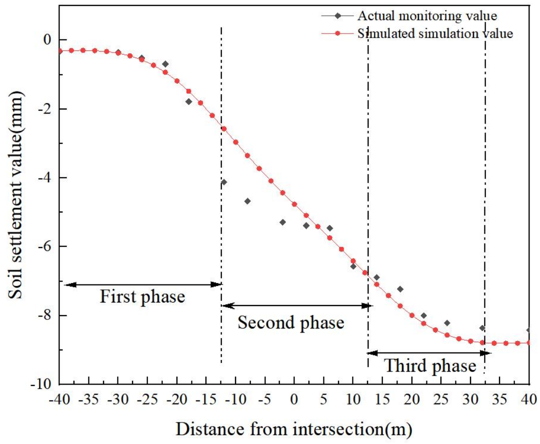


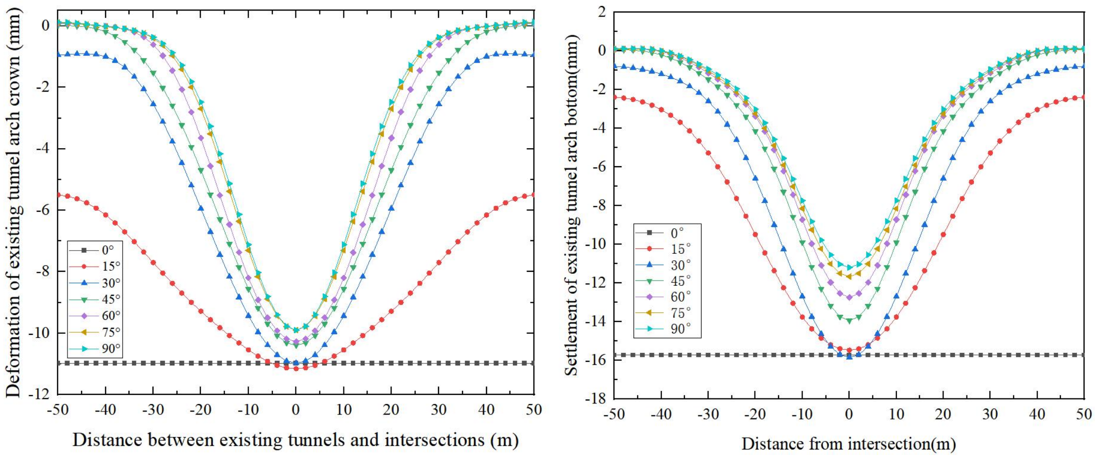
Fig. 7 Comparison between measured values and numerical simulations of surface subsidence at intersections

The influence law of different parameters

Different spatial location parameters

Different oblique angles

To study the impact of the intersection angle of new and old tunnels on the shield tunneling approach engineering, while keeping other parameter settings and spatial positions unchanged, only the angle of the shield tunneling approach underpass is considered as a single variable, and the intersection angles are designed as 0 °, 15 °, 30 °, 45 °, 60 °, 75 °, and 90 °, respectively. The deformation of the existing tunnel is shown in the Figure 8. It can be observed that the maximum settlement value of the existing tunnel caused by shield tunneling construction decreases with the increase of the intersection angle between the new and old tunnels.



(a)

Deformation of arch crown (b) Deformation of arch bottom

Fig. 8 Deformation of existing tunnels at different oblique angles

Different burial depths of newly built tunnels

To study the impact of new tunnel burial depth on shield tunneling proximity engineering, the existing tunnel burial depth is taken as the only variable, and the unit of excavation diameter D (6.2m) of the shield tunneling is taken. The four groups of new tunnel burial depths studied are approximately 3D, 4D, 5D, and 6D, respectively. The comparison of settlement at the arch bottom of the existing tunnel is shown in the Figure 9. It can be observed that the maximum settlement value of the existing tunnel caused by shield tunneling construction decreases with the increase of the burial depth of the newly built tunnel.

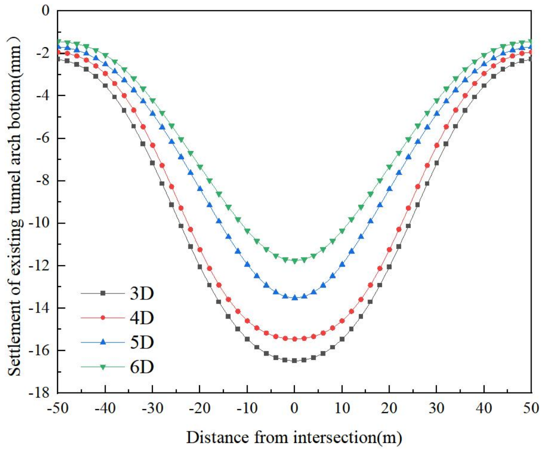


Fig. 9 Settlement of existing tunnel arch bottom

Different shield construction parameters

Soil warehouse pressure

In order to study the influence of soil silo pressure on existing tunnels in shield tunneling proximity engineering, the soil silo pressure ratios were set to 0.6, 0.8, 1.0, 1.2, and 1.4, respectively. The deformation of the existing tunnels is shown in the Figure 10. It can be observed that the maximum settlement value of the existing tunnel decreases with the increase of soil chamber pressure, indicating that the greater the soil chamber pressure, the more stable the cutterhead advance, and the less disturbance the shield tunneling has on the surrounding soil and the existing tunnel. However, excessive soil pressure will cause uplift and deformation of the soil above the shield excavation, and even endanger the safety of existing tunnels. Therefore, the appropriate range of pressure ratio for soil silos should be controlled within 1.1~1.3, and should not be too large or too small. Choosing an appropriate soil pressure can better control the settlement and deformation of the existing tunnel arch bottom and reduce the destructive effects of shield tunneling.

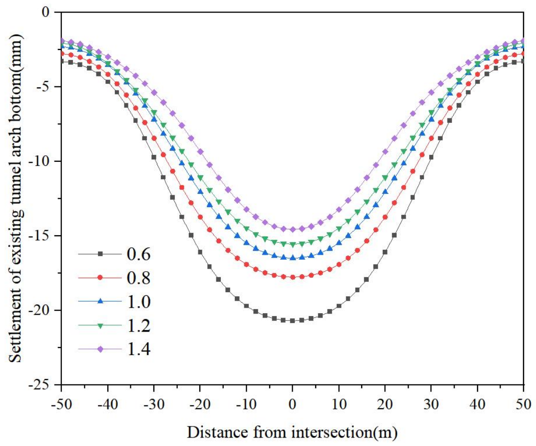


Fig. 10 Settlement of Existing Tunnel Arch Bottom under Different Soil Silo Pressure Ratios (mm)

Grouting pressure

Set the grouting pressure ratios for three working conditions, namely 0.6, 1.0, and 1.4, with corresponding grouting pressures of 0.18MPa, 0.3MPa, and 0.42MPa, respectively. The deformation of the existing tunnel under three working conditions is shown in the Figure 11. With the advancement of excavation, the settlement deformation curve of the arch bottom of the existing tunnel is basically the same. Although the rate of change in settlement values changes around step 15, after the shield tunneling leaves the affected area, the settlement values at the arch bottom of the existing tunnel tend to stabilize with small differences in values.

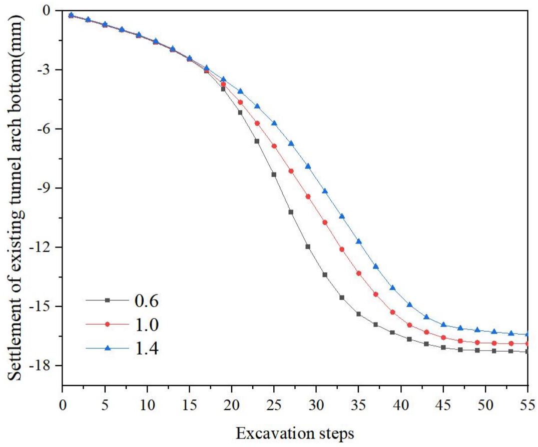


Fig. 11 Settlement of existing tunnel arch bottom under different grouting pressures

Different soil properties parameters

The elastic modulus of soil is used as a single variable to establish numerical simulation, which serves as a simplified version of the analysis of the influence of surrounding rock parameters on existing tunnels in shield tunneling proximity. Compare and analyze the deformation curves of the existing tunnel arch bottom under different rock and soil elastic moduli corresponding to the working conditions, as shown in the Figure 12.

The elastic modulus value of the stratum where the shield tunneling is located is within a certain range, and a larger value can play a role in controlling the settlement and deformation of the existing tunnel, while also increasing the lateral stress disturbance of the existing tunnel in the excavation direction; When the value is small, it will lead to an increase in the degree of longitudinal stress disturbance of the existing tunnel in the excavation direction. Therefore, in the design stage of shield tunneling construction, measures can be considered to improve the elastic modulus value of the soil layer and reduce the impact of shield tunneling on the soil and existing tunnel structure.

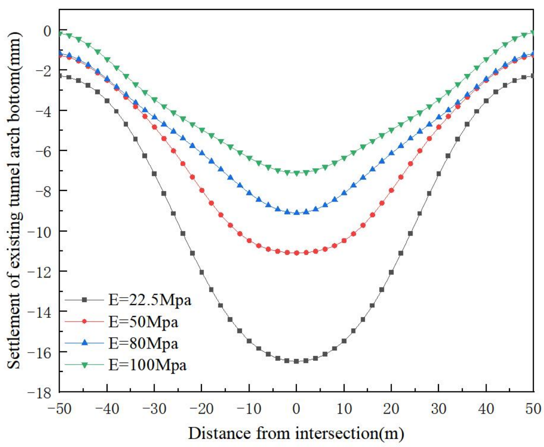


Fig. 12 the existing tunnel arch bottom under different soil properties parameters

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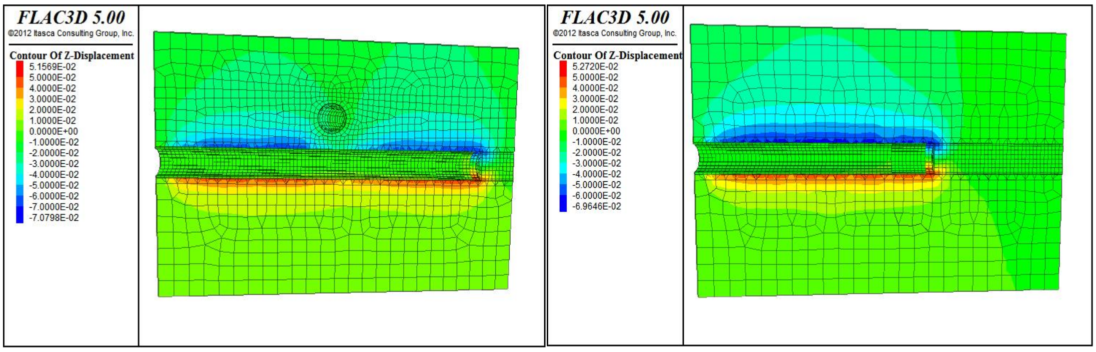
Discussion

By analyzing the impact of existing tunnels on shield tunneling, model the working conditions without existing tunnels, and compare the results with those of models with existing tunnels, as shown in Figure 13. It was found that the existence of existing tunnels changed the stress and displacement fields of the original soil layer, resulting in uneven and non-uniform strength of the original environment disturbed by shield excavation under the working conditions of existing tunnels. In the deformation cloud maps of the two working conditions, there is a "peak" above the shield tunnel and two "peaks" due to the "cutting" effect of the existing tunnel, indicating that the existence of the existing tunnel has a certain constraint on soil settlement deformation.



(a) Existing tunnel (b) without existing tunnel

Fig.13 Deformation cloud map of soil and existing tunnel under two working conditions

Conclusion

The FLAC3D finite difference software is used to conduct numerical simulations for studying the mechanical response and deformation characteristics of existing tunnels under special working conditions of shield tunneling construction. The process involves converting the mesh model from MIDAS GTS NX software to FLAC3D format through conversion programming.

Firstly, this study sets the required geometric dimensions, material properties, and soil parameters based on actual cases. This includes defining the geometry of the existing tunnel and the new tunnel, assigning appropriate material properties to the surrounding soil and rock layers, and specifying soil parameters such as cohesion, angle of internal friction, and elastic-plastic behavior using constitutive models like Mohr Coulomb.

Secondly, considering the asymmetric simulation of oblique tunnels. The simulation should take into account parameters such as spatial location, shield construction parameters (such as face pressure and advance rate), and soil properties (e.g., strength, stiffness, and permeability). This can help analyze the impact of these factors on the response and behavior of the existing tunnels during shield tunneling.

Finally, the post-processing analysis includes examining the mechanical response and deformation characteristics of the existing tunnels, such as displacements, stresses, and potential failure zones. This information can provide insights into the performance of the existing tunnels and help identify potential risks and challenges during shield tunneling.

It is important to note that the numerical simulation used in this study simplifies the curvature of the shield tunneling route. Future research may require more refined modeling and simulation approaches to accurately capture the complex behavior of the actual tunneling process.

Overall, the simulation analysis using FLAC3D provides a theoretical basis for studying the risk of existing tunnels in proximity to shield tunneling projects. It allows for the evaluation of various scenarios and can guide decision-making related to tunnel design, construction methodology, and risk mitigation strategies.

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