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Research paper

Research on the influence law of tunnel underpass on settlement of existing tunnels under different factors control

Bin Qiu[1], Yuxin Ma[2], Sining Huang[3], Da Cui[4], Dongbo Cai[5]

Abstract: Regarding the disturbance effect on the structure of the existing railway tunnel during the underpass construction of a new shield tunnel, based on the underpass project of Mingyue Mountain Tunnel, a numerical model for the underpass of a new double-track highway tunnel beneath the existing tunnel was established, considering the influences of different factors such as construction methods, underpass angles of the tunnel, surrounding rock types, and burial depths. The settlement and deformation laws of the existing tunnel under the control of different key factors were explored, and the control limits for the influence of the adjacent construction of the tunnel under the control of their respective magnitudes were obtained. The results show that the impact of new tunnel excavation on the existing tunnel structure is reduced when the distance between the new and old tunnels is greater, the properties of the surrounding rock are better, the underpass angle is larger, and the tunnel depth is shallower. The research results can provide references for underpass construction of similar projects and guidance for engineering design.

Keywords: numerical simulation, settlement deformation control, underpass the existing tunnel, different factors control

[1]MSc., Eng., Tunnel Engineering Company, Ltd. of CCCC, Beijing, China, e-mail: 13961307396@163.com, ORCID: 0009-0002-4076-8922

[2]MSc., Eng., College of Pipeline and Civil Engineering, China University of Petroleum, Qingdao, China, e-mail: 2980840517@qq.com, ORCID: 0009-0004-1359-8440

[3]Prof., Eng., College of Pipeline and Civil Engineering, China University of Petroleum, Qingdao, China, e-mail: huangsining@upc.edu.cn, ORCID: 0000-0003-2771-6570

[4]MSc., Eng., No. 7 Engineering Co., LTD, CCCC First Highway Engineering Group Co., LTD, Zhengzhou, China, e-mail: 3650599405@qq.com, ORCID: 0009-0004-7473-1030

[5]MSc., Eng., No. 7 Engineering Co., LTD, CCCC First Highway Engineering Group Co., LTD, Zhengzhou, China, e-mail: 206063686@qq.com, ORCID: 0009-0005-8916-809X

1. Introduction

When a new tunnel passes beneath an existing one, the deformation caused to the existing tunnel by the construction of the new one involves complex interactions. For this reason, scholars at home and abroad have conducted a series of studies on the interaction relationship between tunnels passing beneath existing tunnel structures.

Peck [1] proposed the surface settlement curve on the basis of summarizing and analyzing the measured data of a large number of tunnel construction cases. Ocak [2] and Cording [3] found through the observation of the engineering example that the asymmetric settlement trough after the excavation of the second tunnel may be caused by the interference between the two tunnels, which increases with the decrease of the spacing between the two tunnels.

In the early stages of numerical simulation development, tunnel excavation was treated as a two-dimensional plane problem. Ghaboussi [4] used two- dimensional finite element analysis and linear elastic model to study the influence of supporting column width between double-line tunnels on the construction of parallel tunnels. Pott *et al.* [5] analyzed and summarized the application scope and constitutive relationship of finite element method in geotechnical engineering.

The stability and settlement of tunnels are predominantly influenced by the self-weight of the surrounding soil, making centrifugal model tests highly suitable for tunnel issues. Guttler and Stoffers [6] conducted a centrifugal model test to examine the deformation and failure mechanisms of circular tunnels. Grant and Taylor [7] used centrifugal model tests to study the settlement deformation mechanism caused by tunneling of soft clay on sandy soil layers. Fei, R *et al.* [8] conducted a centrifugal test to simulate the construction process of parallel shield tunnels crossing high-speed railway tunnels and studied the variation law of ground surface settlement.

Artificial neural networks (ANN) have a variety of applications in geotechnical engineering, especially in tunnel engineering. Most studies have shown that ANN can be successfully applied to tunnel engineering. C.Y. Kim *et al.* [9] proposed a hierarchical prediction program based on ANN and applied it to various geotechnical engineering problems with inherent uncertainties and defects. Zou, B *et al.* [10] described and evaluated the performance of artificial neural networks (ANN) and compared it with multiple linear regression (MLR) in the prediction of ground subsidence.

In tunnel engineering, construction monitoring is particularly important [11,12]. Ouyang, J. *et al.* [13] conducted monitoring data analysis and nonlinear regression fitting based on the monitoring and measurement data, obtaining the displacement variation laws and characteristics of various surrounding rocks in the tunnel.

There are few existing studies on the influence of various control factors on tunnel settlement. This paper takes the Mingyue Mountain Tunnel Project as an example. Through numerical simulation and the control variable method, it comparatively analyzes the settlement and deformation laws of existing tunnels under different construction methods, surrounding rock types, under- crossing angles, and tunnel burial depths, providing valuable design references for tunnel under-crossing construction.

2. Numerical simulation

Based on the distribution of rock layers in the section of Mingyue Mountain Tunnel passing through the Shanghai Chengdu Railway Tunnel, the rock layers and pre reinforcement structure calculation parameters within the depth range of the rock layers taken by the model are shown in Table 1. The initial support cross-sectional diagram is shown in Fig. 1, and the value of its structural elastic modulus determines the support pressure and also relates to the safety of the support structure. In the numerical simulation process, the elastic modulus of the steel arch is reduced, that is, the elastic modulus of the steel arch is converted to concrete, and the elastic modulus of the entire initial support structure is expressed by the equivalent elastic modulus E. The calculation formula is shown in equation (2.1). The initial support cross-sectional diagram is shown in Fig. 1, and the value of its structural elastic modulus determines the support pressure and also relates to the safety of the support structure. In the numerical simulation process, the elastic modulus of the steel arch is reduced, that is, the elastic modulus of the steel arch is converted to concrete, and the elastic modulus of the entire initial support structure is expressed by the equivalent elastic modulus E. The calculation formula is shown in equation (2.1).

$$E = \frac{(E_c A_{cc} + E_a A_{ca})}{A_c} \tag{2.1}$$

where: E – equivalent elastic modulus after conversion, E_c – elastic modulus of sprayed concrete, E_a – elastic modulus of steel arch, A_{cc} – cross-sectional area of sprayed concrete, A_{ca} – cross-sectional area of steel arch, A_c – overall cross-sectional area of initial support.

Table 1. Calculation parameters of geotechnical layers

Lithology	Mass density /(kN·m–3)	E /GPa	μ	Cohesive force /MPa	Internal friction angle /^{o}
Grade IV surrounding rock	22	2.0	0.35	0.3	28
Small conduit reinforcement area of grade IV surrounding rock	29	2.95	0.2	0.34	39
Bolt reinforcement area of grade IV surrounding rock	24.6	2.36	0.31	0.324	33

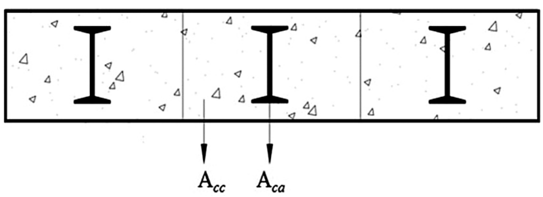

Fig. 1. Initial support cross section

The required calculation parameters for the concrete support structure in equation (2.1) are shown in Table 2

Table 2. Struct tural calculat tion paramet ters

Material	E/MPa	μ	Mass density/(kN $\cdot$ m^{-3})
C20 Shotcrete	21000	0.23	22
C30 Reinforced concrete	30000	0.2	25
C15 Rubble concrete	26000	0.2	23

According to the lithological distribution of the strata in which the Mingyue Mountain Tunnel is situated, and considering the potentially hazardous sections of the tunnel that pass beneath the Shanghai-Chengdu Railway, the model size has been determined to be 28 meters before and after the tunnel's passage under this section.

A three-dimensional finite element model of the Mingyue Mountain Tunnel under the Shanghai-Chengdu Railway Tunnel was established using ABAQUS, as shown in Fig. 2. The new Mingyue Mountain Tunnel under the Shanghai-Chengdu Railway Paihuadong Tunnel section has a buried depth of approximately 290 m, and the model size is selected as $100 \times 56 \times 100$ m (length $\times$ width $\times$ height). The tunnel support structure of the Shanghai-Chengdu Railway and the left and right line structures of the newly built Mingyue Mountain Tunnel are simulated using elastic solid elements, and the ground stress field is considered based on the self-weight stress field.

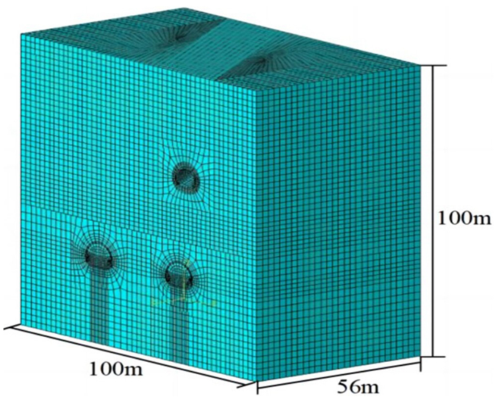

Fig. 2. Numerical model of the Mingyue Mountain Tunnel under the Hulong Railway Tunnel

2.1. Control standards for the impact of adjacent tunnel construction

Determining the influence control benchmark values during close proximity tunnel construction is a critical component of risk assessment for such projects. The control standards are established based on the following principles:

(1) It should comply with the current relevant design regulations and meet the requirements of various construction procedures, norms and guidelines;
(2) It should be determined through consultation between the design department and the construction department and included in the monitoring plan;
(3) The control benchmark values determined based on the nature of the existing structures should ensure their structural safety and normal use;
(4) The control benchmark value should fully take into account the feasibility of the engineering construction, and balance the construction period and economic principles;
(5) For the adjacent structures of tunnels where the control benchmark values have not been clearly defined, they should be determined through the analysis of monitoring data from similar overseas projects;
(6) Based on the monitoring results and referring to previous engineering experience, the stability state of the surrounding rock and the supporting structure as well as the safety condition of the surrounding environment are analyzed, and then the allowable value of displacement is corrected.

2.1.1. Structural displacement control standards

According to the Guideline for Design of Road Tunnel 17 [14] and in reference to previous engineering practical experience, the settlement control standard for the Mingyue Mountain Tunnel passing under the Shanghai-Chengdu Railway Tunnel is determined as: The settlement values of the tunnel crown and track surface shall not exceed 3.0 mm; The control value of the horizontal displacement of the side wall is 1.0 mm; The control value of differential settlement (for every 10 m of the track) is 1.0 mm.

2.1.2. Structural strength control standard

From the perspective of structural stability, the impact of a new tunnel on an existing one should be determined based on the allowable increase in stress. Specifically, the following requirements should be met: If the existing tunnel has damage that does not affect its function, the allowable increase in tensile stress is 0.5 MPa, and the allowable increase in compressive stress is 2.0 MPa; If the existing tunnel is in good condition, the allowable increase in tensile stress is 1.0 MPa, and the allowable increase in compressive stress is 5.0 MPa.

3. Influence of tunnel underpass on settlement of existing tunnels under the control of different factors

3.1. Pattern of influence of construction method on the settlement of existing tunnels

3.1.1. Settlement pattern of existing tunnels during CD method construction

The whole process of excavation and lining construction of the new Mingyueshan tunnel through the Shanghai-Chengdu railway tunnel is as follows:

(1) Excavate the top heading on the left side of the left line and apply the initial support in time.
(2) Excavation of the top heading on the left side of the left line begins at 12 m and initial support is applied in time.
(3) Excavate the bottom heading on the left side of the left line to 4 m and start the top heading on the right side of the left line and apply initial support in time.
(4) When the top heading on the right side of the left line is excavated to 12 m, the bottom heading on the right side of the left line will be excavated and the initial support will be applied in time.
(5) When the bottom heading on the right side of the left line was excavated to 30 m, the middle wall of the left line was removed and the secondary lining was applied.
(6) After the second lining of the left line at the same depth of the right line is completed, the excavation of the top heading on the left side of the right line is carried out, and the initial support is applied in time. During the excavation and support of the right line, the excavation and support of the left line are carried out simultaneously.
(7) The excavation bench of the right line are the same as that of the left line. When the top heading on the left side of the right line is excavated to 12 m, the excavation of the bottom heading on the left side of the right line is carried out.
(8) When the bottom heading on the right side of the right line is excavated to 30 m, the middle wall of the right line will be removed and the secondary lining will be applied.
(9) Repeat the above bench to complete the simulation of tunnel excavation and support.

Based on the excavation process of the CD method, finite element models were established for the new tunnel crossing the existing tunnel at depths of 22 m, 19 m, 16 m, 13 m, and 10 m, as illustrated in Fig. 3. These models were used to simulate and calculate the structural response of the existing tunnels.

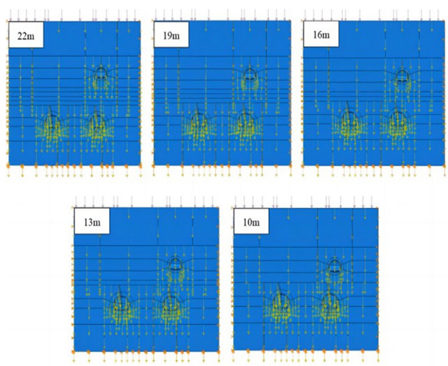

Fig. 3. Model for underpass existing tunnels with different tunnel clearances (CD method)

In Fig. 4, as the new tunnel and the existing tunnel gradually approach, the settlement of the existing tunnel generally shows that the maximum settlement value is getting larger and larger, and the maximum settlement value can be close to 3.5 mm; Secondly, when the underpass distance is reduced, the settlement curve of the existing tunnel gradually shows that the settlement above the left and right lines is large, and the intersection of the vertical plane of the new double track tunnel axis and the existing tunnel is relatively less affected by the proximity of the tunnel.

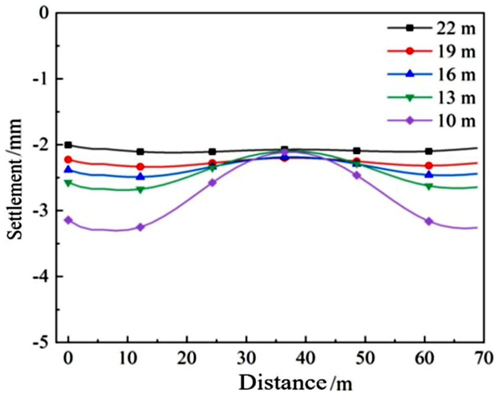

Fig. 4. Settlement deformation law of existing tunnel under different clear distance control (CD method

According to the settlement control standards for the Mingyue Mountain tunnel within the Shanghai-Chengdu Railway Tunnel project, it can be preliminarily concluded that when the approach distance to the tunnel exceeds 13 meters, the CD method of construction can effectively meet the control requirements for settlement deformation in the existing tunnel.

3.1.2. Settlement law of existing tunnel during bench method construction

The whole process of bench excavation and lining construction of Mingyueshan Tunnel through Shanghai-Chengdu railway tunnel is as follows

(1) Excavate the bench on the left line and promptly carry out the initial support work.

(2) Excavation of the left upper bench was carried out to a depth of 32 meters, at which point the excavation of the left lower bench began and the initial support was promptly installed.

(3) The secondary lining of the left line was started when the excavation of the left line bench reached 56 meters.

(4) After the secondary lining of the left line at the same depth on the right line is completed, the upper bench excavation of the right line begins and the initial support is promptly carried out.

(5) The secondary lining of the right line will be constructed once the excavation of the bench on the right line is completed.

(6) Repeat the above bench to complete the excavation and support simulation of the right tunnel line.

According to the excavation process of bench method, the finite element model is established, as shown in Fig. 5. The finite element model of the new double tunnel underpass the existing tunnel at 22 m, 19 m, 16 m, 13 m and 10 m is established, and the structural response of the existing tunnel when the new tunnel underpass is also simulated and calculated. When the tunnel excavation is completed, the settlement value of the arch bottom of the existing tunnel is extracted as shown in Fig. 6.

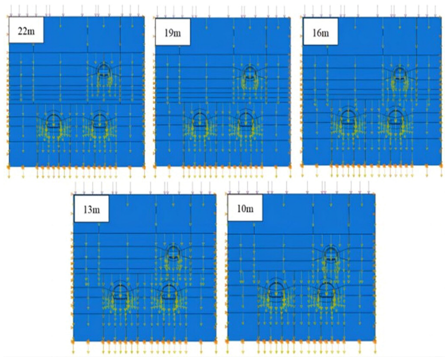

Fig. 5. Model for underpass existing tunnels with different tunnel clearances (Bench method)

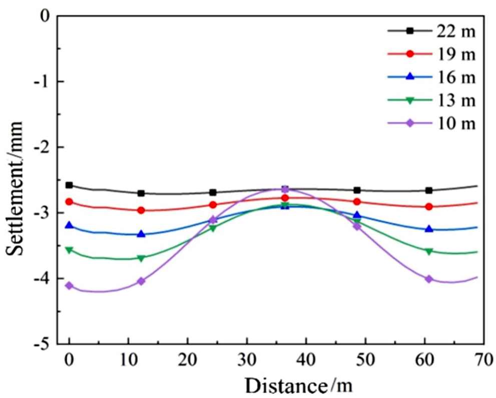

Fig. 6. Settlement deformation law of existing tunnel under different clear distance control (Bench method)

In Fig. 6, when the new tunnel adopts the bench method to cross the existing tunnel with different structural clear distances, the settlement of the existing tunnel shows similar regularity to that of the CD method. With the gradual approach of the new tunnel and the existing tunnel, the overall settlement of the existing tunnel shows that the maximum settlement value is getting larger and larger, and the maximum value is close to 4.3 mm; the settlement curve of the existing tunnel gradually shows that the settlement above the left and right lines is large when the underpass distance is reduced, and the settlement in the middle of the tunnel decreases with the decrease of the proximity distance, and the differential settlement of the tunnel arch bottom is more obvious.

When the bench method is employed for construction and the tunnel approach distance is 19 m, the maximum settlement of the existing tunnel is 3.00 mm. This measurement does not comply with the displacement control standards for tunnel approach construction structures. Preliminary assessments indicate that when the tunnel approach distance exceeds 19 m, the bench method can satisfy the control requirements for settlement deformation of the existing tunnel.

When comparing the numerical calculation results of the CD method and the bench method, it is evident that the superposition effect of ground loss in a double-track tunnel is closely related to the clear distance between the left and right tracks. The closer the distance, the greater the impact of the new tunnel on the existing tunnel. Additionally, the construction support method employed during the excavation of the new tunnel plays a crucial role. A smaller excavation face results in less impact on the surrounding rock layer of the tunnel face, thereby enhancing the safety of the existing tunnel.

3.2. Influence law of rock type on settlement of existing tunnel

According to the excavation process of bench method, simulate the structural response of existing tunnel when the new tunnel crosses under the conditions of class II, class III, class IV and class V surrounding rock. See Table 3 for the selection of physical parameters of specific surrounding rock types and materials. When the tunnel excavation is completed, the settlement value of the arch bottom of the existing tunnel is extracted as shown in Fig. 7.

Table 3. Values of physical parameters for different surrounding rock types

Surrounding rock grade	Mass density /kN · m^{-3}	E /GPa	μ	Cohesive force /MPa	Internal friction angle /^{o}
II	26	25	0.22	1.6	55
III	24	8	0.26	0.8	45
IV	22	4	0.35	0.3	35
V	20	1	0.39	0.2	25

It can be seen from Fig. 7 that the maximum settlement of the existing tunnel is 0.34 mm in class II surrounding rock, and 3.28 mm in class V surrounding rock. The construction method and support method adopted for the underpass project will not meet the settlement requirements of the existing tunnel. According to the shape of the curve, when the rock strength is high and the surrounding rock properties are favorable, the settlement of the existing tunnel remains nearly linear within the primary influence range following the excavation of the new tunnel. In this scenario, the existing tunnel exhibits an overall subsidence trend in the study section. Conversely, when the surrounding rock strength is low, the settlement of the existing tunnel begins to exhibit variations, and the superposition effect resulting from the secondary disturbance of the double-track tunnel becomes increasingly apparent.

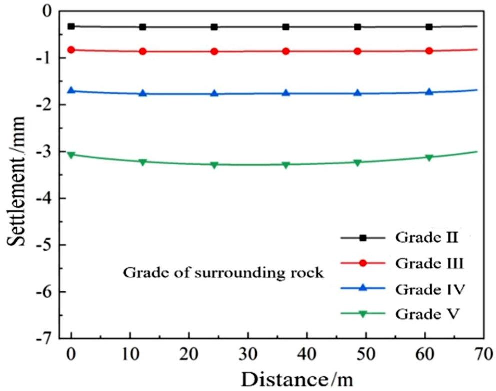

Fig. 7. Settlement curves of existing tunnel arch bottom under different levels of surrounding rock conditions

Comparing the surrounding rock parameters in Table 1 and Table 3, when the elastic modulus of grade IV surrounding rock is 2 GPa and 4 GPa, the maximum settlement of the arch bottom of the existing tunnel is 2.31 mm and 1.77 mm, respectively. Therefore, the elastic modulus of rock mass with the same surrounding rock grade is different, and the degree of formation loss is also different. Specifically, the greater the elastic modulus, the more stable the surrounding rock, and the smaller the impact of new tunnel excavation on the existing tunnel.

3.3. Influence law of underpass angle on settlement of existing tunnel

For deep-buried tunnels, the surrounding rock pressure is calculated based on the weight of the rock mass within the natural arch. The vertical pressure for the single-track railway tunnel designed according to the probability limit state is:

$$q = rh_q = 0.41 \times 1.79^s \times r \tag{3.1}$$

The vertical pressure for single-track, double-track and multi-track railway tunnels designed according to the failure stage is:

$$q = rh_q = 0.41 \times 2^{s-1} \times rw \tag{3.2}$$

where, h_q is the equivalent load height value; s is the surrounding rock grade; r is the surrounding rock unit weight; w is the width influence coefficient, its value is:

$$w = 1 + i(B - 5) \tag{3.3}$$

where, B is the Tunnel width; i is the rate of increase or decrease of the surrounding rock pressure when the tunnel width increases by 1 m, When $B > 5$ meters, $i = 0.2$; when $B > 5$ meters, $i = 0.1$.

Taking the Mingyue Mountain tunnel underpass project as the technical background, the bench method is used to excavate the double track tunnel, and the settlement deformation characteristics of the existing tunnel arch bottom under the four working conditions of 90, 60, 30 and overlapping tunnel underpass are analyzed as follows:

3.3.1. Underpass angle 90°

The finite element model of 90° underpass existing tunnel is established as shown in Fig. 8 When the new double track tunnel is excavated, the settlement deformation curve of the arch bottom of the existing tunnel is extracted as shown in Fig. 9.

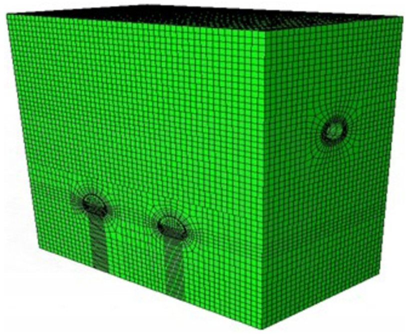

Fig. 8. Finite element model of 90° underpass existing tunnel

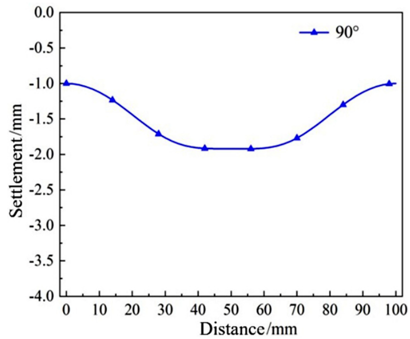

Fig. 9. Settlement curves of the arch bottom of the existing tunnel under 90°

3.3.2. Underpass angle 60°

The finite element model of the 60° underpass existing tunnel is established as shown in Fig. 10. When the new double track tunnel is excavated, the settlement deformation curve of the arch bottom of the existing tunnel is extracted as shown in Fig. 11.

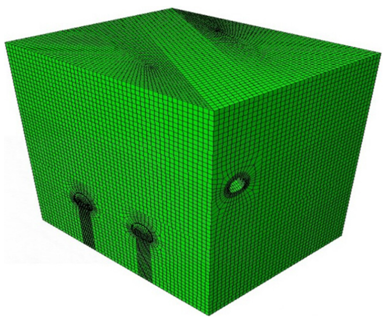

Fig. 10. Finite element model of 60° underpass existing tunnel

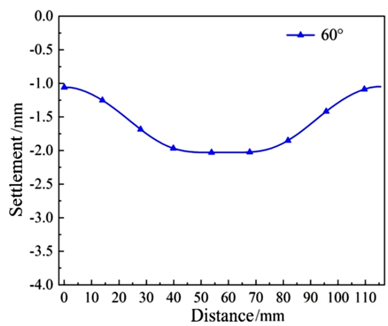

Fig. 11. Settlement curves of the arch bottom of the existing tunnel under 60°

3.3.3. Underpass angle 30°

The finite element model of the 30° underpass existing tunnel is established as shown in Fig. 12. When the new double track tunnel is excavated, the settlement deformation curve of the arch bottom of the existing tunnel is extracted as shown in Fig. 13.

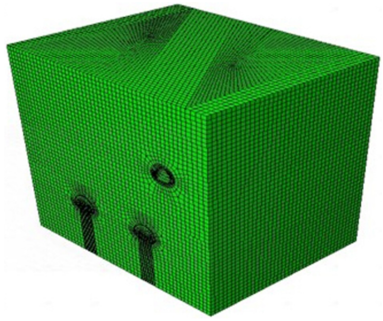

Fig. 12. Finite element model of 30° underpass existing tunnel

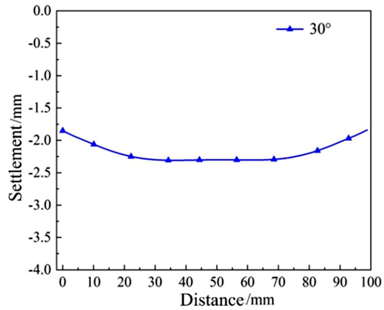

Fig. 13. Settlement curves of the arch bottom of the existing tunnel under 30°

3.3.4. Overlapping tunnel underpass

The finite element model of the new tunnel crossing the existing tunnel in parallel is established as shown in Fig. 14. When the new double track tunnel is excavated, the settlement deformation curve of the arch bottom of the existing tunnel is extracted as shown in Fig. 15.

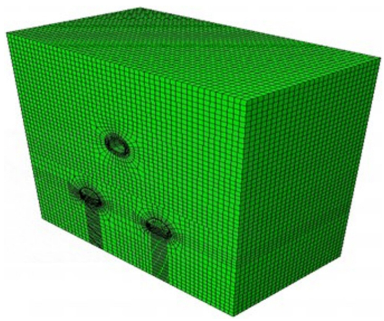

Fig. 14. Finite element model of overlapping tunnel underpass

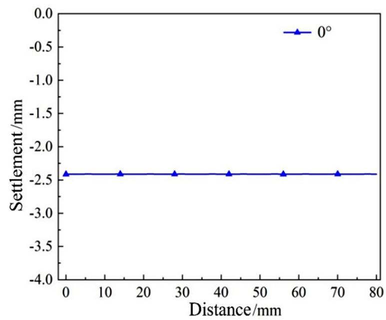

Fig. 15. Settlement curves of the arch bottom of the overlapping tunnel underpass

It is noted that the depth range of the tunnel exceeding 80% of the maximum settlement value of the existing tunnel is the main influence area of the existing tunnel. The simulation results of comparing the above four working conditions are shown in Table 4.

Table 4. Maximum settlement and main impact width

Underpass Angle/°	90	60	30	0
Maximum settlement/mm	1.92	2.11	2.38	2.45
Main influence area/m	52	60	90	–

It can be observed from Table 4 that as the intersection angle between the old and new tunnels decreases, the settlement of the existing tunnels increases. This indicates that the impact of double-track tunnel excavation on the existing tunnels intensifies as the intersection angle diminishes, and the area of influence also expands. When the intersection angle between the new and old tunnels is 90 degrees, the impact of the new tunnel excavation on the existing tunnel is minimal. Conversely, when the new tunnel runs parallel to the existing tunnel, the impact is maximized. In such cases, it is essential to carefully manage the construction of the entire adjacent section.

3.4. Influence of tunnel buried depth on settlement of existing tunnel

In order to study the structural response of existing tunnels after excavation of tunnels with different buried depths, the same numerical model of Mingyue Mountain tunnel underpass engineering is used, and the bench method is also used to excavate the new double track tunnel to study the deformation law of existing tunnels caused by tunnel excavation under different buried depths. The buried depth of the tunnel is simulated by applying equivalent load on the top of the tunnel. The buried depth of the tunnel and the corresponding surface load are shown in Table 5.

Table 5. Load parameters corresponding to different tunnel burial depths

Working condition	Mass density /($kN \cdot m^{-3}$)	Buried depth /m	Area load /($kN \cdot m^{-2}$)
1	22	250	4180
2	22	270	4620
3	22	290	5060
4	22	310	5500
5	22	330	5940

The finite element model of the new tunnel under different buried depths passing through the existing tunnel is established, and the settlement curve of the arch bottom of the existing tunnel under different buried depths is drawn according to the numerical simulation results.

The settlement characteristics of the existing tunnel, as shown in Fig. 16, are analyzed. The settlement of the existing tunnel increases with the depth at which it is buried. As the burial depth of the tunnel increases, the stress on the surrounding strata also increases. Following the excavation of the tunnel, the stress is released; consequently, greater deformation of the upper strata results in a more significant impact on the existing tunnel structure.

By comparing and analyzing the theoretical calculation results with the actual monitoring results **Błąd! Nie można odnaleźć źródła odwołania.**, it can be found that the theoretical calculation results are larger than the monitoring results. This is because the influence of the construction method of the new double-track tunnel on the ground loss was not considered in the theoretical calculation process.

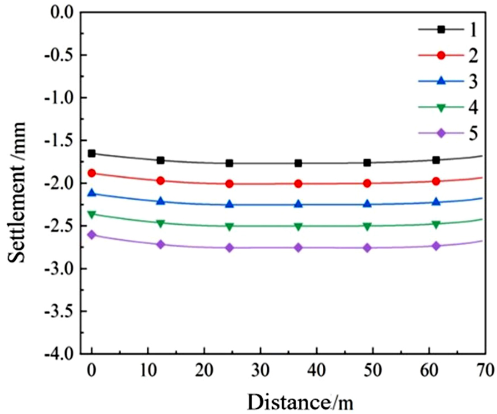

Fig. 16. Settlement curve of existing tunnel arch bottom at different burial depths

4. Conclusions

This paper examines the settlement laws of existing tunnels under various factors and presents the following conclusions:

(1) By comparing the structural response of the existing tunnel under various construction methods, it is evident that these methods significantly impact the settlement of the existing tunnel.

(2) By establishing numerical models of new tunnels intersecting with existing ones, it is demonstrated that the angle of intersection significantly affects ground loss.

(3) Furthermore, the deformation patterns of existing tunnels at varying burial depths are investigated, providing valuable design references for controlling deformation during tunnel underpass construction.

(4) The settlement and deformation laws of existing tunnels under the control of different key factors are analyzed. The results show that the greater the distance between new and old tunnels, the better the nature of surrounding rock, the greater the underpass angle, and the shallower the tunnel buried depth, the smaller the impact of new tunnel excavation on the existing tunnel structure.

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