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Mechanical evolution law and deformation characteristics of preliminary lining about newly-built subway tunnel closely undercrossing the existing station: A case study

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Abstract. The development of a city is closely linked to the construction and operation of its subway system. However, constructing a new subway tunnel under an existing station is an extremely complex task, and the deformation characteristics and mechanical behavior of the new subway tunnel during the excavation process can greatly impact the normal operation of the existing station. Although the previous studies about the case of underpass engineering have been carried out, there is limited research on the condition of a newly-built subway tunnel that closely undercrossing an existing station with zero distance between them. Therefore, this study analyzes the deformation law and mechanical behavior characteristics of the preliminary lining of the underpass tunnel during the excavation process based on the real engineering case of Chengdu Metro Line 8. This study also makes an in-depth comparison of the influence of different excavation methods on this issue. Finally, the accuracy of numerical simulation is verified by comparing it with on-site result. The results indicate that the maximum bending moment mainly occurs at the floor slab of the preliminary lining, while that of the ceiling is small. The stress state at the ceiling position is less affected by the construction process of the pilot tunnel. Compared to the all-in-one excavation method, although the process of partial excavation method is more complicated, the deformation of preliminary lining caused by it is basically less than the upper limit value of the standard, while that of the all-in-one excavation method is beyond standard requirements.

Keywords: deformation law; mechanical behavior; preliminary lining; process correlation; undercrossing

1. Introduction

In recent years, the rapid development of rail transit construction has led to an increase in the construction of urban underground structures, with new subway lines inevitably undercrossing the existing buildings or underground structures. When the distance between the new subway tunnel and the existing underground structure is small, it may cause the redistribution of the stress and deformation of the existing underground structure, and even lead to accidents (Namazi *et al.* 2011, Cavuoto *et al.* 2019, Cao *et al*. 2021).

Scholars have carried out some researches on the deformation and failure mechanism of surrounding rock during tunnel excavation (Abdel-Meguid *et al.* 2003, Hoek 2004, Soroosh *et al.* 2006, Bi and Zhou 2015, Banerjee and Chakraborty 2018, Sakcali and Yavuz 2019a, Zhou *et al.* 2020, Chen and Lee 2020, Sakcali 2021, Sakcali 2023).

Liang *et al.* (2021) proposed a simplified analytical method to predict the response of in-service tunnels in relation to tunnelling on soft ground. It was found that when the new tunnel crossed the existing shield tunnel obliquely or in parallel, the uplift caused by the tunnel was greater than that caused by the vertical crossing of the tunnel, and increasing the elastic modulus about the stratum can effectively reduce the uplift of tunnel. Zheng *et al.* (2017) performed the extensive finite element simulations to examine the effect about excavation on adjacent tunnels and proposed two methods for predicting the effect of excavation on adjacent tunnels. Sakcali and Yavuz (2019b) proposed equations for predicting longitudinal deformation profiles of weak rock masses, and estimated the radial deformation around the tunnel by using these equations. Ahmed and Iskander (2011) studied the effect of tunnel construction on the stratum settlement by model test. The test results showed that the stratum settlement complied with the peck curve. Besides, the horizontal displacement could be expressed by the width coefficient of settlement trough and formation loss, and the maximum horizontal displacement occurred at the inflection point. Based on the Tehran Subway Line 7 project, Moeinossadat and Ahangari (2019) proposed a numerical intelligence method to estimate the maximum surface subsidence caused by subway tunnel excavation. Fang *et al.* (2019) proposed a prediction method for longitudinal surface settlement caused by shield tunnel construction through model experiments based on Gaussian curves and analyzed the effects of tunnel depth and surface volume loss. The deformation and mechanical behavior of the tunnel bottom area and lining were analyzed after construction (Kim *et al.* 2020, Mirzaeiabdolyousefi *et al.* 2022). Haeri *et al.* (2020) studied the effects of confining pressure and tunnel depth

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on the vertical settlement of the ground and found that confining pressure had a great influence on the settlement.

The mechanical behavior of underground structures has always been the research focus of scholars (Zucca and Valente 2020). At present, the mainstream of research includes the new tunnel closely undercrossing the existing structures. In addition, if multi-zone excavation was close to the existing underground structures, the stress state and the stiffness of the existing structure before excavation can make this issue more complicated (Li and Wang 2019). Sarfarazi *et al.* (2019) studied the interaction between two adjacent tunnels and found that tensile cracks were the dominant crack mode present in the model and were closely related to the inner circle diameter and rock pillar width. Ng *et al*. (2013) designed a centrifugal model test of new tunnel underpass the existing tunnels with small clearance, and it was found that the largest monitored settlement of the existing tunnel is about 0.3% of the tunnel diameter, which was large enough to affect the normal operation of tunnel. A series of centrifugal experiments on the crossing problems were conducted, then the mechanical response and deformation law of the new tunnel crossing the existing tunnel were studied and analyzed from different geometric conditions, geological conditions, and construction conditions (Boonyarak and Ng 2015). Liang *et al*. (2017) analyzed the mechanical response of the existing tunnels and obtained the numerical solution of the mechanical response of the existing tunnel by using the finite difference method. Sharifzadeh *et al.* (2017) used 3D finite element method to plan and simulate different tunnel excavation sequences, and determine the optimal excavation sequence as well as the optimal distance for minimum surface settlement.

The above researches primarily focus on the deformation law and mechanical characteristics of the existing structures caused by the construction of new tunnels, or under different stratum conditions and tunneling methods (Cao *et al.* 2021, Li *et al.* 2021), while for the case of the newly-built metro tunnel undercrossing the metro station with zero-distance and multiple construction methods is rare. Besides, in order to ensure the normal operation of the subway in the later stage, the standard for controlling the deformation of the subway structure led by the new subway tunnel excavation are very strict (MHURDPRC 2013).

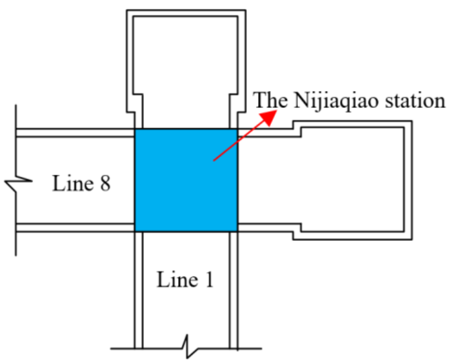
In the designing stage of the relied project of this paper, both the partial excavation method and all-in-one excavation method are optional schemes. Considering the structural safety and the lack of experience in such similar projects, the conservative partial excavation method is adopted in the actual project. Whether all-in-one excavation method can be used in this project is still unknown. Therefore, this study aims to further reveal the evolution law of the construction mechanics of the newly-built subway tunnel closely undercrossing the existing subway with zero-distance and provide an important reference for selecting the construction methods of similar projects. Based on a case study of the Chengdu Metro Line 8 project, the difference in the mechanical evolution and deformation law of the new underpass during the excavation and lining process using the partial excavation method and all-in-one excavation method is compared and analyzed in detail, and verified by on-site monitoring result.

2. Project overview

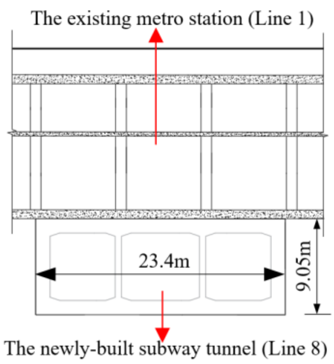
This paper is based on the engineering cases of the newly-built Nijiaqiao station of Chengdu Metro Line 8 undercrossing the existing Metro Station of Line 1 with zero distance. These two metro lines are orthogonal from the up and down direction, and the upper surface of the ceiling of Line 8 is closely contacted by the lower surface of the floor slab of Line 1 with zero distance. In order to descript more easily, the overlapping structure (the blue part) of Line 8 is called as the underpass (part of the newly-built Line 8). The underpass is approximately 23.4 meters wide, 9.05 meters high, and 21 meters long, as displayed in Fig. 1.

The existing station (Line 1) is mainly located in silty clay and pebble soil, and the underpass (Line 8) is mainly located in pebble soil and mudstone, as displayed in Fig. 2. The typical mechanical parameters of the soil are shown in Table 1, which are obtained from the design material of the relied engineering project (GMDRICL 2019). The secondary lining is equipped with two middle partition walls. The lining parameters of the existing station and the underpass are displayed in Table 2 (GMDRICL 2019).

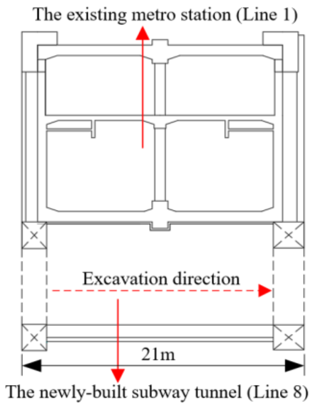
The underpass is divided into 10 excavation parts, known as pilot tunnels. The excavation sequences of the pilot tunnels are as follows: 1-1 →1-2 →2-1 →2-2 →3-1 →3-2 →4-1 →4-2, and the construction steps are shown in Fig. 3. The specific construction process is: (1) Take the pilot tunnel 1-1 as an example, the pilot tunnel 1-1 is excavated and lined at a cyclic footage of 2 m, and the preliminary and temporary lining of the pilot tunnel 1-1 is installed one excavation analysis step behind. After the excavation of soil and the installation of preliminary and temporary linings of the pilot tunnel 1-1 are all completed, the next pilot tunnel is excavated and lined with the same way as the pilot tunnel 1-1. (2) After all the pilot tunnels 1-1~3-2 are excavated and lined, the secondary lining of the corresponding parts of pilot tunnels 1-1~3-2 is installed at one time, and it is carried out in two steps. The first step is to install the secondary lining in the range of 0m~10m longitudinally of the pilot tunnels 1-1~3-2, and the second step is to install the secondary lining in the range of 10~21m longitudinally of the pilot tunnels 1-1~3-2. (3) After the installation of secondary lining of the pilot tunnels 1-1~3-2 is all completed, the excavation of soil and installation of preliminary lining of the pilot tunnel 4-1 is carried out using the same way as that of the pilot tunnel 1-1. (4) After the excavation of soil and installation of preliminary lining of pilot tunnel 4-1 are all completed, the excavation of soil and installation of preliminary lining of pilot tunnel 4-2 are carried out using the same way as that of the pilot tunnel 1-1. (5) After all the pilot tunnels 4-1~4-2 are excavated and lined, install the secondary lining of the pilot tunnels 4-1 and 4-2 in two steps. The first step is to install the secondary lining in the range of 0 m~10 m



(a) Plane view



(b) Cross-section of the station along the Line 8



(c) Longitudinal section along Line 8

Fig. 1 The relative position of the newly-built subway tunnel and the existing metro station

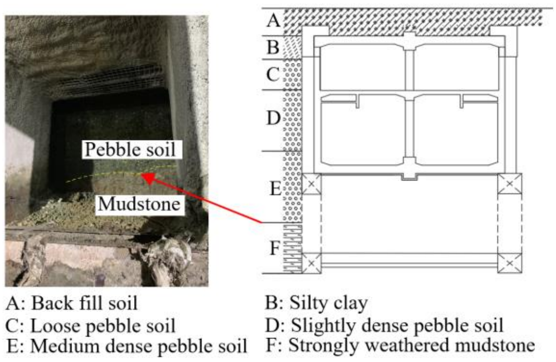


Fig. 2 The on-site soil layers of the subway station

longitudinally of the pilot tunnels 4-1~4-2, the second step is to install the secondary lining in the range of 10m~21m longitudinally of the pilot tunnels 4-1~4-2. (6) Finally, remove all temporary linings of pilot 1-1~4-2. ***Note:*** due to the large number of pictures, the excavation and lining processes of some pilot tunnels are not fully displayed in Fig. 3.

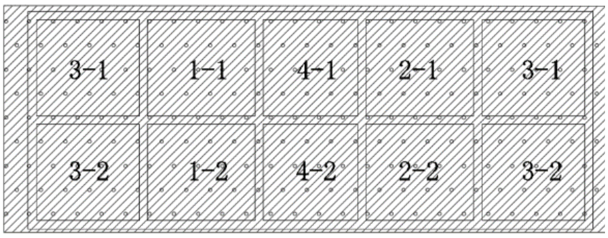
3. Numerical calculation instructions

3.1 Calculation model and parameters

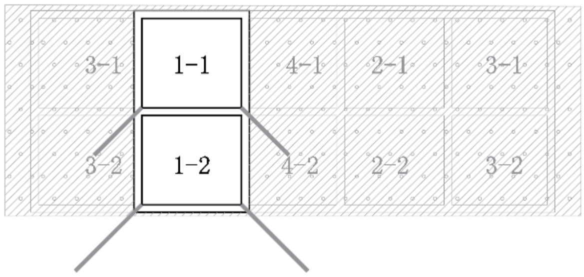
In this section, the FLAC^{3D} software is used to simulate the soil excavation and lining installation of the underpass, and the calculation model is displayed in Fig. 4.

The horizontal directions (normal) and the bottom of the model are fixed, and the top of model is free. Meanwhile, only gravity is taken into account for the initial stress. Surrounding rock and lining are simulated by solid elements, subject to the Mohr-Coulomb criterion and elastic criterion, respectively. The properties of the lining structure are displayed in Table 3. It should be noted that the influence of steel ribs in the preliminary lining is converted to shotcrete according to its elastic modulus, and the specific calculation method is as follows (Wu *et al*. 2005), namely, Eq. (1)

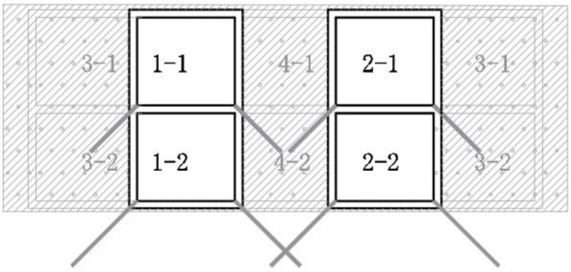
$$E = E_0 + \frac{S_g E_g}{S_c} \tag{1}$$



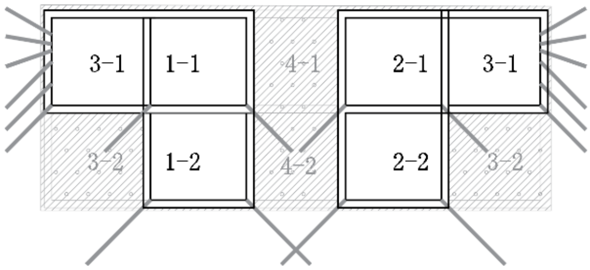
(a) Step 1 (full-face grouting)



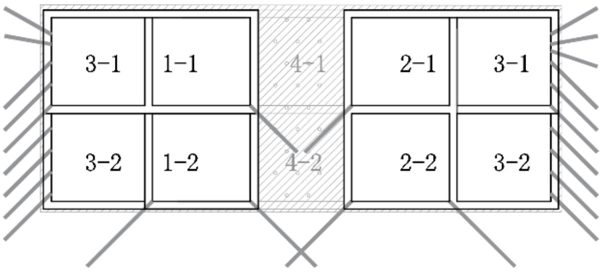
(b) Step 2



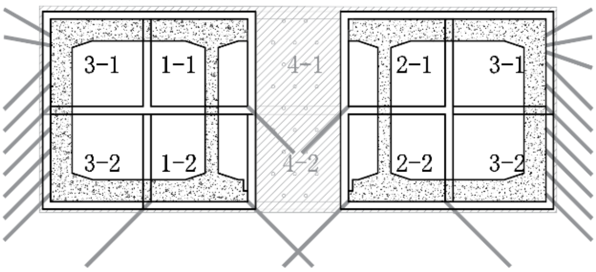
(c) Step 3



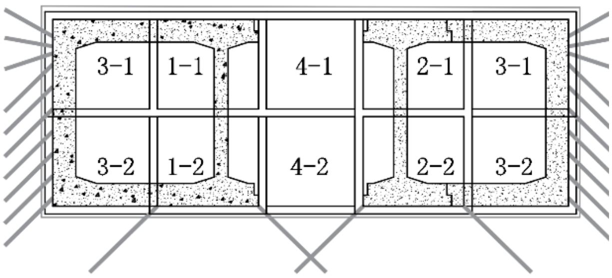
(d) Step 4



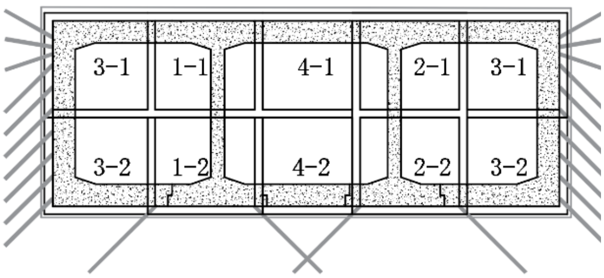
(e) Step 5



(f) Step 6



(g) Step 7



(h) Step 8

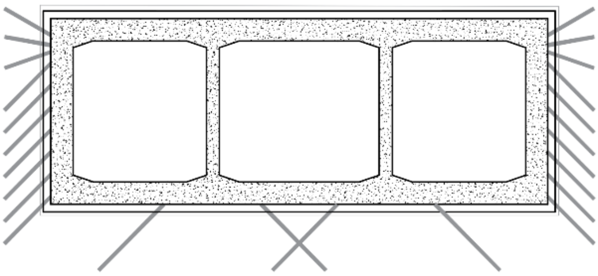

(i) Step 9

Fig. 3 Construction steps

Table 1 Physical and mechanical parameters of the soil layer

Soil type	Thickness /m	Density /(kg/m^3)	Elastic modulus /MPa	Poisson ratio	Cohension /kPa	Internal friction angle /°
Back fill soil	2.70	1800	18.3	0.30	8	10
Silty clay	2.30	1950	45.3	0.43	20	16
Loose pebble soil	3.00	2000	66	0.33	0	32
Slightly dense pebble soil	6.00	2100	90	0.30	0	35
Medium dense pebble soil	7.10	2200	105	0.25	10	40
Strongly weathered mudstone	5.60	2200	90	0.25	65	30
Moderately weathered mudstone	10	2300	180	0.15	300	35

Table 2 The lining element of the existing metro station and the underpass (GMDRICL 2019)

Engineering object	Component	Material properties	Thickness (size)	Spacing
The existing subway	Side wall	C30 reinforced concrete	0.35 m	-
	Ceiling	C30 reinforced concrete	0.80 m	-
	Middle board	C30 reinforced concrete	0.40 m	-
	Floor slab	C30 reinforced concrete	0.80 m	-
	Longitudinal beam of the ceiling	C30 reinforced concrete	1.80 m	-
	Longitudinal beam of middle board	C30 reinforced concrete	1.00 m	-
	Longitudinal beam of the floor slab	C30 reinforced concrete	2.10 m	-
	Center column	C40 reinforced concrete	1 m×0.8 m	8 m (Longitudinally)
The underpass	Preliminary lining	C25 reinforced concrete	0.35 m	0.5 m
	Temporary lining	Steel ribs	I-28a	
	Secondary lining of side wall and floor slab	C35 reinforced concrete	1 m	-
	Secondary lining of ceiling	C35 reinforced concrete	1.2 m	-
	Secondary lining of middle partition wall	C35 reinforced concrete	0.6 m	-

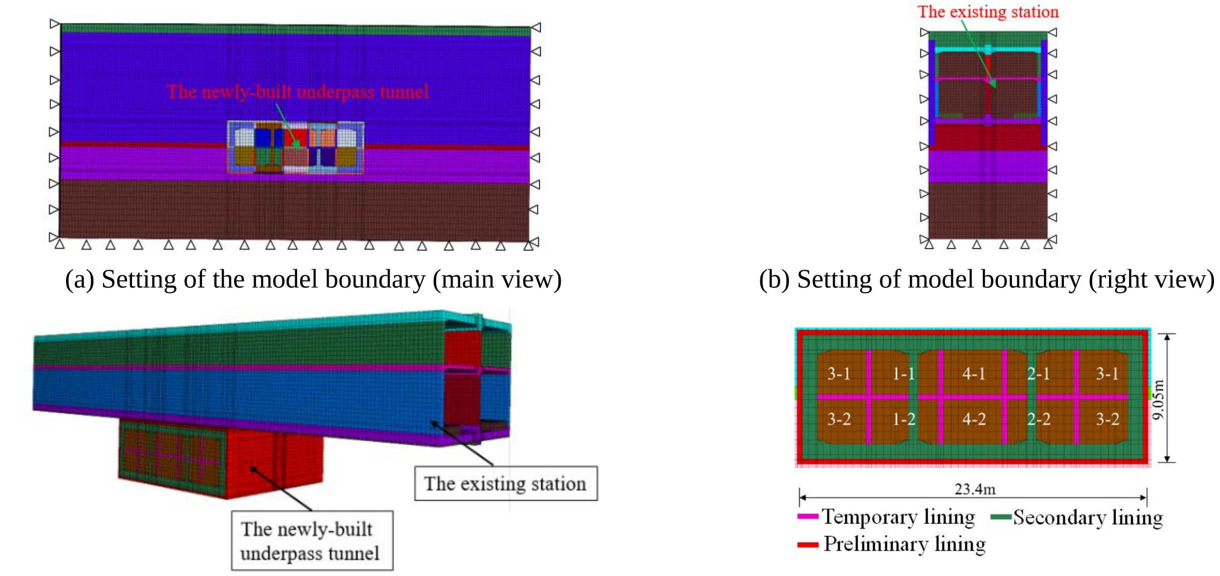
Table 3 Calculation parameters of the lining

Name		Density /(kg/m^3)	Converted elastic modulus /GPa	Poisson's ratio	Thickness /m
Preliminary lining		2300	34.9	0.2	0.35
Temporary lining		2300	34.9	0.2	0.35
Secondary lining	Ceiling	2500	31.5	0.2	1.2
	Floor slab	2500	31.5	0.2	1.0
	Sidewall	2500	31.5	0.2	1.0
	Middle partition wall	2500	31.5	0.2	0.6

Where E is the elastic modulus of concrete after conversion; E_0 is the elastic modulus of original concrete; S_g is the cross-sectional area of steel ribs; E_g is the elastic modulus of steel; S_c is the section area of concrete. Note: the elastic modules of the lining element (E) determined through designed material (GMDRICL 2019) is given in Table 3.

3.2 The realization of the construction process through numerical simulation

Based on the construction sequences of the project (GMDRICL 2019), the numerical simulation of the overall construction process is simplified as follows. Firstly, the initial gravity stress field is generated. Then the soil of Line 1 is excavated, applying 70% reaction force. After the installation of the main structure of Line 1, release the applied reaction force of lining. After the balance of calculation, the displacement is cleared as the initial state before the construction of the underpass. Because the partial excavation method is adopted in site construction, although it can ensure safety, it takes a long time. At the same time,



(a) Setting of the model boundary (main view) (b) Setting of model boundary (right view)

(c) Layout of the existing station and the underpass tunnel (d) Cross-section picture of the underpass

Fig. 4 Calculation model

Table 4 The main calculation steps of underpass through all-in-one excavation method

Calculation steps	Calculation content
1	Excavate Pilot tunnel 1-1~4-2 to 2m
2	Excavate pilot tunnels 1-1~4-2 to 4 m; install the preliminary and temporary linings of pilot tunnels 1-1 ~ 4-2 to 2 m
3	Excavate pilot tunnels 1-1~4-2 to 6 m; install the preliminary and temporary linings of pilot tunnels 1-1 ~ 4-2 to 4 m
4	Excavate pilot tunnels 1-1~4-2 to 8 m; install the preliminary and temporary linings of pilot tunnels 1-1 ~ 4-2 to 6 m
5	Excavate pilot tunnels 1-1~4-2 to 10 m; install the preliminary and temporary linings of pilot tunnels 1-1 ~ 4-2 to 8 m
6	Excavate pilot tunnels 1-1~4-2 to 12 m; install the preliminary and temporary linings of pilot tunnels 1-1 ~ 4-2 to 10 m
7	Excavate pilot tunnels 1-1~4-2 to 14 m; install the preliminary and temporary linings of pilot tunnels 1-1 ~ 4-2 to 12 m
8	Excavate pilot tunnels 1-1~4-2 to 16 m; install the preliminary and temporary linings of pilot tunnels 1-1 ~ 4-2 to 14 m
9	Excavate pilot tunnels 1-1~4-2 to 18 m; install the preliminary and temporary linings of pilot tunnels 1-1 ~ 4-2 to 16 m
10	Excavate pilot tunnels 1-1~4-2 to 20 m; install the preliminary and temporary linings of pilot tunnels 1-1 ~ 4-2 to 18 m
11	Excavate pilot tunnels 1-1~4-2 to 21 m; install the preliminary and temporary linings of pilot tunnels 1-1 ~ 4-2 to 20 m
12	Install the preliminary and temporary linings of pilot tunnels 1-1 ~ 4-2 to 21 m
13	Install the secondary lining of pilot tunnels 1-1 ~ 4-2 to 10 m
14	Install the secondary lining of pilot tunnels 1-1 ~ 4-2 to 21 m
15	Remove the temporary linings

Note: the length of the underpass is 21 m (longitudinally); “1-1~4-2” refers to “1-1, 1-2,2-1, 2-2, 3-1, 3-2, 4-1, 4-2”

the all-in-one excavation method is also the alternative scheme (although not used on site finally), which can save the construction period, while it may cause great deformation of the underpass structure, and then affect the normal operation of the existing station, and this influencing degree is still unknown yet. In order to further quantify and compare the difference between them, this paper intends to study the differences between these two methods, which are simulated as follows:

(1) *All-in-one excavation*: The excavation round is 2 meters along the longitudinal direction, and the installation of the preliminary lining is closely followed until the excavation is completed. Then the entire secondary lining is constructed. Finally, the temporary lining is removed. The specific calculation steps are displayed in Table 4.

(2) *Partial excavation*: Firstly, pilot tunnels of 1-1, 1-2, 2-1, 2-2, 3-1, 3-2 are excavated and lined in sequence, then the secondary lining will be installed; then, pilot tunnels 4-1 and 4-2 are excavated and lined, finally the temporary lining is removed. The specific calculation steps are shown in Table 5.

4. Results and discussion of the subway tunnel undercrossing the existing metro station based on different excavation methods

4.1 All-in-one excavation method

The deformation characteristic and internal force

Table 5 The main calculation steps of the underpass through partial excavation method

Calculation steps	Calculation content
1	Excavate the soil of pilot tunnel 1-1 to 2m
2	Excavate pilot tunnel 1-1 to 4m; install the preliminary and temporary linings of pilot tunnel 1-1 to 2m
3	Excavate pilot tunnel 1-1 to 6m; install the preliminary and temporary linings of pilot tunnel 1-1 to 4m
…	…
11	Excavate pilot tunnel 1-1 to 21m; install the preliminary and temporary linings of pilot tunnel 1-1 to 20m
12	Install the preliminary and temporary linings of pilot tunnel 1-1 to 21m
…	Same as pilot tunnel 1-1 (i.e., steps 1~12), complete the excavation of soil and installation of preliminary and temporary linings of pilot tunnels 1-2, 2-1, 2-2, 3-1, 3-2 in sequence
73	Install the secondary lining of pilot tunnels 1-1, 1-2, 2-1, 2-2, 3-1, 3-2 to 10 m
74	Install the secondary lining of pilot tunnels 1-1, 1-2, 2-1, 2-2, 3-1, 3-2 to 21 m
…	Same as pilot tunnel 1-1 (i.e., steps 1~12), complete the excavation of soil and installation of preliminary lining of pilot tunnels 4-1, 4-2 in sequence
99	Install the secondary lining of pilot tunnels 4-1 and 4-2 to 10 m
100	Install the secondary lining of pilot tunnels 4-1 and 4-2 to 21m
101	Remove the temporary linings

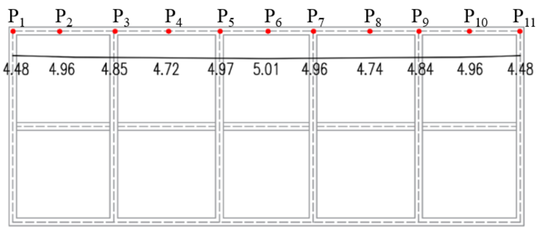


Fig. 5 Settlement law of the ceiling of preliminary lining of the underpass through all-in-one excavation method /mm

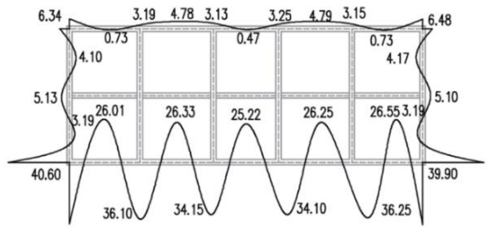


Fig. 6 Bending moment of the preliminary lining of the underpass through all-in-one excavation method /(kN·m)

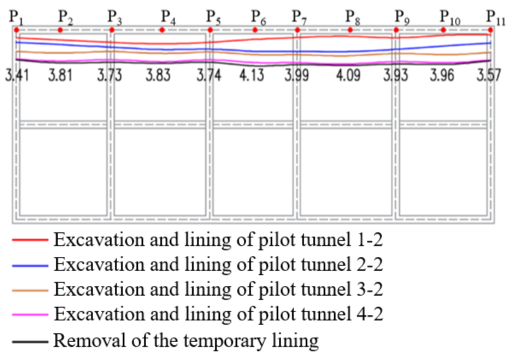


Fig. 7 Settlement of the ceiling of preliminary lining under different calculation steps /mm

distribution law of the preliminary lining about the underpass are analyzed through the all-in-one excavation method, respectively.

4.1.1 Deformation characteristic

The test points are set to P_1~P_{11} in the ceiling of preliminary lining, and the specific position of the test points is displayed in Fig. 5. Also, the distribution of the final settlement of the ceiling of preliminary lining is extracted, as displayed in Fig. 5.

In Fig. 5, the settlements of the preliminary lining basically present a symmetrical distribution with a maximum value of 5.01 mm (at P_6), located in the middle part of pilot tunnel 4-1. The settlement line shows "settlement trough" form, and the maximum difference value of the side and middle of the ceiling is only 0.53 mm.

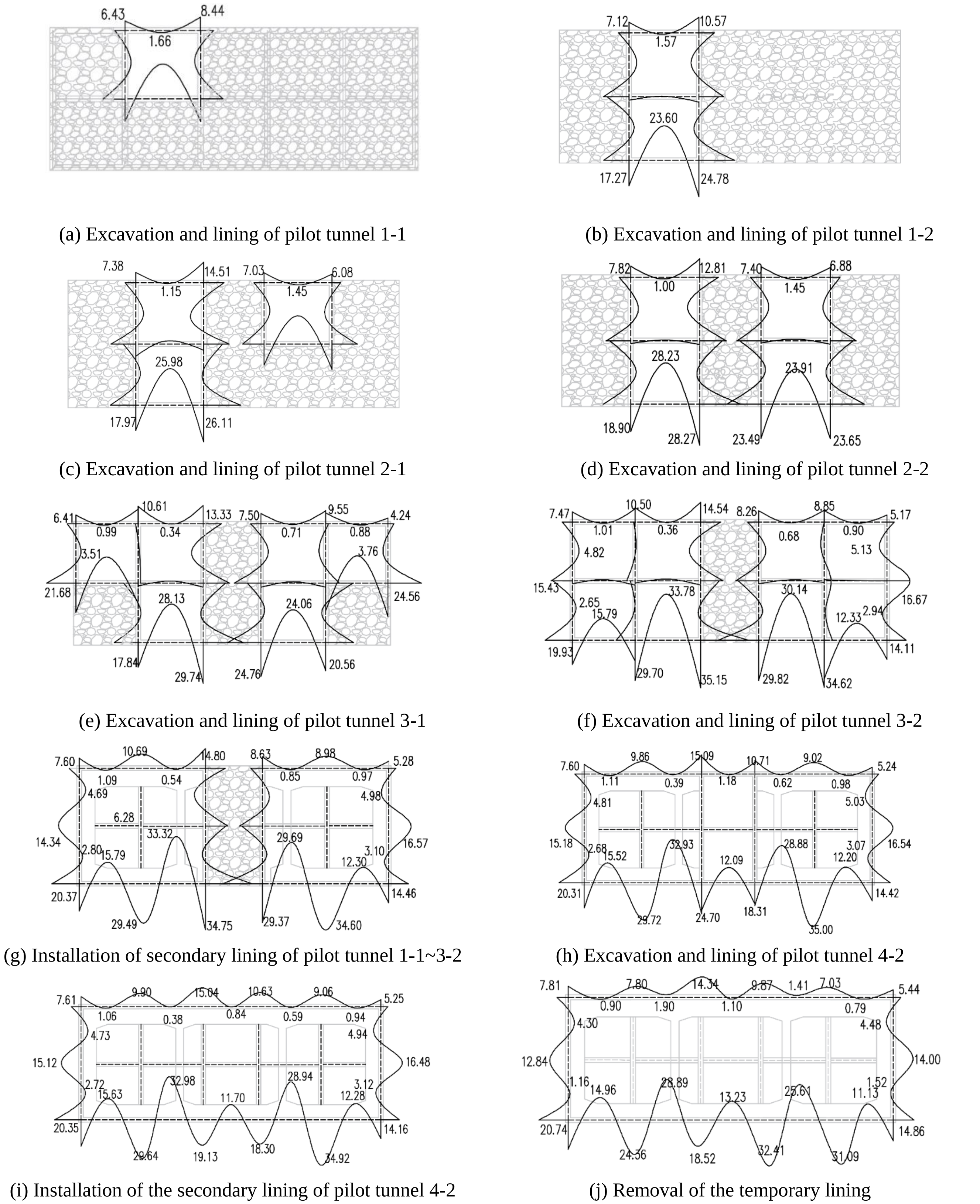
4.1.2 Mechanical distribution law

The distribution law of the bending moment of the preliminary lining are shown in Fig. 6.

In Fig. 6, the bending moments of the preliminary lining show symmetrical distribution, and the maximum bending moment is 40.60 kN·m, located at the intersection of the floor slab and sidewall. The overall bending moment of the ceiling is small (ranging 0.73 kN·m~6.48 kN·m), while the bending moment of the floor slab is the largest (ranging 25.22 kN·m~40.6 kN·m). The main reason for this is that the underpass is built after the completion of the existing subway construction, the deformation of the existing subway has become stable, and the lower pilot tunnel of the new subway is closely attached to the ceiling with zero distance, and the material rigidity of the two is close, so the ceiling is more little stressed. However, the bending moments of the floor slab of the new underpass are large, the reason is that the rigidity of the lining of underpass and soil are inconsistent, resulting in the large force at the floor slab. In particular, the bottom of the sidewalls on both sides also bears part of the existing subway weight from the upper part, leading to the large bending moment value of the side walls.

4.2 Partial excavation method

The deformation characteristic and internal force



(a) Excavation and lining of pilot tunnel 1-1

(b) Excavation and lining of pilot tunnel 1-2

(c) Excavation and lining of pilot tunnel 2-1

(d) Excavation and lining of pilot tunnel 2-2

(e) Excavation and lining of pilot tunnel 3-1

(f) Excavation and lining of pilot tunnel 3-2

(g) Installation of secondary lining of pilot tunnel 1-1~3-2

(h) Excavation and lining of pilot tunnel 4-2

(i) Installation of the secondary lining of pilot tunnel 4-2

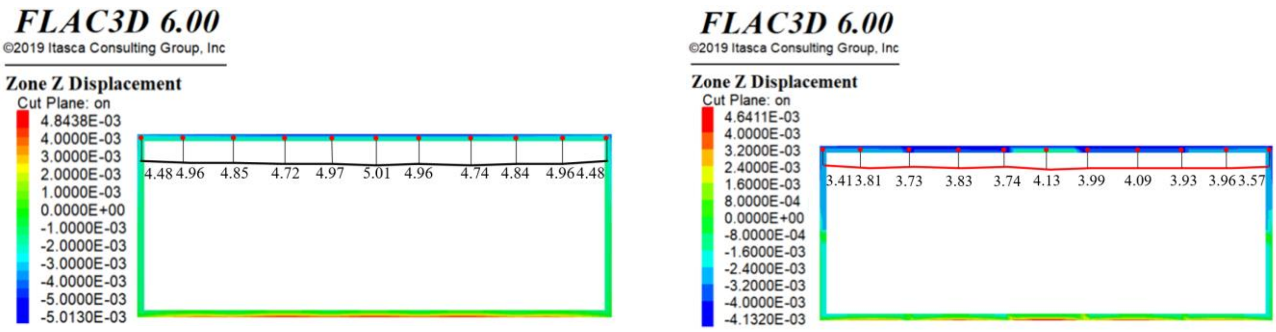
(j) Removal of the temporary lining

Fig. 8 Mechanical evolution law of preliminary lining under various calculation steps by partial excavation /(kN·m)

distribution law of the preliminary lining about the underpass are analyzed through the partial excavation method, respectively.

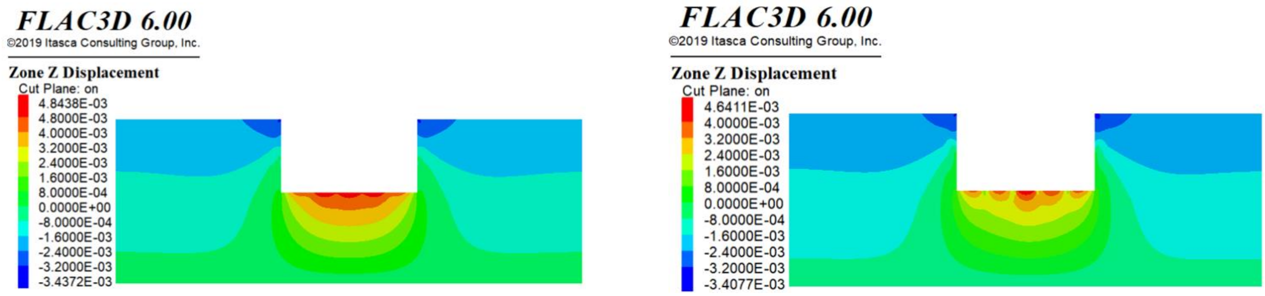
4.2.1 Deformation characteristic

The settlement of the ceiling of preliminary lining is extracted after the removal of the temporary lining and the



(a) All-in-one excavation method (b) Partial excavation method

Fig. 9 The cloud map distribution of the final vertical displacement of the preliminary lining



(a) All-in-one excavation method (b) Partial excavation method

Fig. 10 The final vertical displacement cloud map of the soil /m

completion of excavation and lining of the pilot tunnels 1-2, 2-2, 3-2, and 4-2, respectively, as displayed in Fig. 7.

In Fig. 7, the results indicate that the settlement of the ceiling of preliminary lining increases gradually with the excavation of the pilot tunnels, and the shape of the settlement curve also changes, generally showing a weakening of the asymmetry. After the completion of the construction, the settlement on the right side is slightly greater than that on the left side, which indicates that the settlements of the later-advancing pilot tunnel are slightly greater than that of the former-advancing pilot tunnel, and the maximum settlement is 4.13 mm, appearing after the final calculation step at the middle of pilot tunnel 4-1. Also, the difference between "removal of the temporary lining" and "completion of the excavation and lining of the pilot tunnel 4-2" is little, this is because the deformation of the lining tends to be stable after the installation of the secondary lining, so the influence of the removal of the temporary lining on it is very small.

4.2.2 Mechanical evolution law

The evolution law of the bending moment of preliminary lining during the main calculation steps is displayed in Fig. 8. It can be concluded in Fig. 8 that:

(1) Overall, the distribution of bending moment of the preliminary lining of the underpass presents the characteristics of the frame structure, and in the same span, the bending moment across the side is larger than that in the middle span. The comparison of the value of bending moments among each component is as following: floor slab > side wall > ceiling.

(2) The partial excavation has a more significant influence on the preliminary lining force of the former-advancing part, and the closer the distance is, the greater the influence will be. The influence of the construction of the lower part is less than that of the adjacent part on the left and right sides. Taking the left side bending moment of the ceiling of pilot tunnel 1-1 as an example, the excavation of pilot tunnel 1-2 (right under the pilot tunnel 1-1) causes the bending moment to increase by 10.7%, while the excavation of pilot tunnel 3-1 (adjacent to the left side of the pilot tunnel 1-1) causes the bending moment to increase by 35.7%. Similarly, the bending moment of the right side of the ceiling of pilot tunnel 2-1 increases by 38.8% after the excavation of pilot tunnel 3-1 (adjacent to the right side of pilot tunnel 2-1) but only increases by 13.2% after the excavation of pilot tunnel 2-2 (right under the pilot tunnel 2-1).

(3) With the advance of construction, the bending moments of the preliminary lining of the underpass change in different places, and the final state value after completion is not necessarily the maximum value. The calculated maximum value of bending moment is 35.15 kN·m, which appears at the right span of the bottom of pilot tunnel 1-2 after the excavation and lining of pilot tunnel 3-2, and the final value of bending moment at this position is 18.52 kN·m. On the other hand, the bending moment of the preliminary lining of the underpass shows an asymmetric distribution after the final construction stage, which is led by the asymmetric excavation way of the partial excavation method.

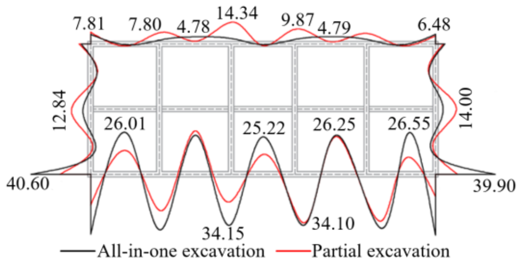


Fig. 11 Comparison of the bending moment of the preliminary lining of underpass /(kN·m)

4.3 Comparison of the calculation results of all-in-one excavation and partial excavation

4.3.1 Deformation characteristic

The final vertical displacement of the ceiling of preliminary lining of the underpass using all-in-one excavation method and partial excavation method is displayed in Fig. 9.

In Fig. 9, the ceiling of preliminary lining mainly shows settlement, while the floor slab mainly shows upward uplift. the overall settlement of the ceiling of preliminary lining using partial excavation method is generally smaller than that of the all-in-one excavation method, and the maximum value of the former (4.13 mm) is about 82.4% of that of the latter (5.01 mm) at the same position (for P_6). Although the settlement difference of each point is not very large (ranging from 0.88 mm~1.23 mm), the settlement control limit of the lining structure is extremely high in the underpass construction for subway engineering, which has a great impact on the normal operation of the underpass in the later stage. Therefore, compared with the all-in-one excavation method, the settlement of the lining structure can be more effectively reduced by the partial excavation method.

The final vertical displacement cloud map of the soil around the underpass under these two excavation methods is displayed in Fig. 10.

In Fig.10, the soil at the sidewall position mainly show settlement, while the soil at the floor slab position shows uplift. At the same time, the floor slab of the underpass using all-in-one excavation method shows overall uplift, while that of the partial excavation method shows "split-point" mode, and the uplift range and value are smaller than those of the all-in-one excavation.

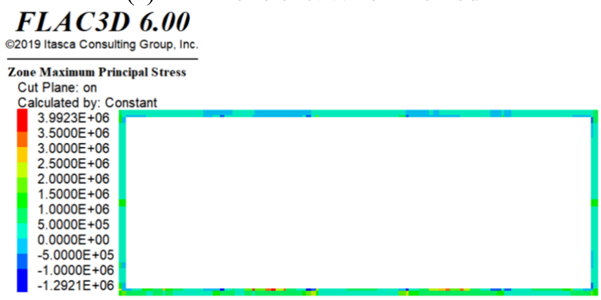
To sum up, partial excavation method can effectively control the deformation of the preliminary lining and soil, so that the structure is in a safer state, which is more conducive to the normal operation of the subway in the later stage.

4.3.2 Mechanical evolution law

The comparison of the bending moment characteristics of the preliminary lining using the all-in-one excavation method and partial excavation method is displayed in Fig. 11.

In Fig. 11, the shape of the bending moment of the preliminary lining is generally symmetrical in the case of all-in-one excavation, while that of the partial excavation case is a certain asymmetry, and the difference is obvious.

(a) All-in-one excavation method



(b) Partial excavation method

Fig. 12 The comparison of the distribution law of the maximum principal stress cloud map of the preliminary lining /Pa

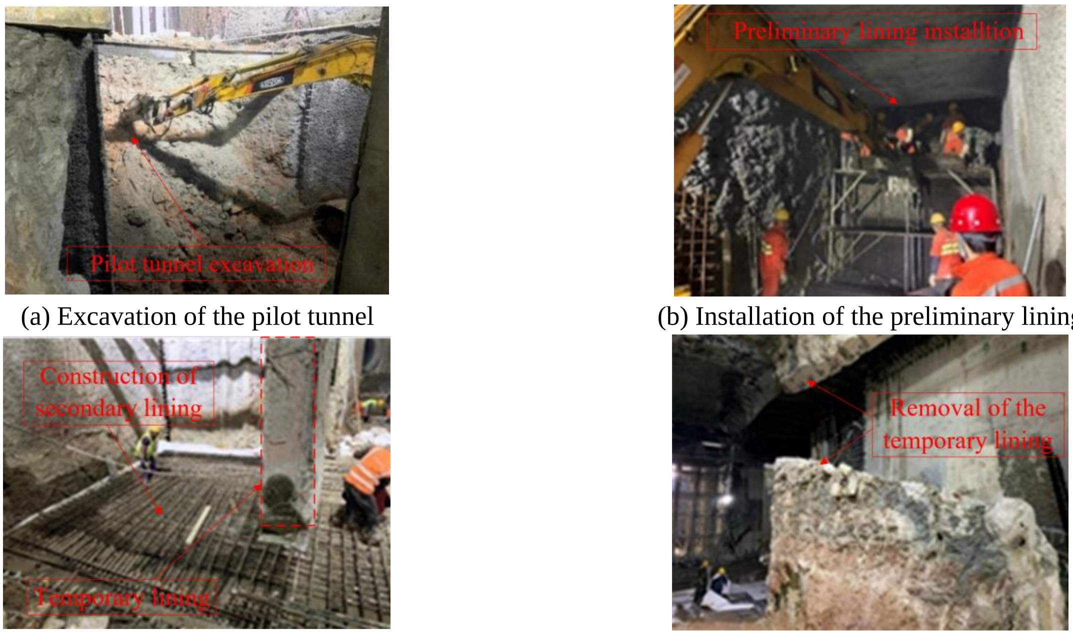
The bending moment values at the floor slab and sidewall of the preliminary lining using the all-in-one excavation method are much larger than that of the partial excavation method. The bending moment values of the ceiling using the partial excavation method show relatively large fluctuations, but the absolute value is obviously smaller than that of the floor slab and sidewall. The maximum bending moment (35.15 kN·m) of the preliminary lining using the partial excavation method is about 86.6% of that of all-in-one excavation method (40.60 kN·m). Therefore, the use of the partial excavation method can better improve the mechanical state of the lining structure than the all-in-one excavation method, thereby making the structure safer.

Fig. 12 is the distribution law of the maximum principal stress cloud map of the preliminary lining of the underpass using the all-in-one excavation method and partial excavation method.

In Fig. 12, the floor slab of the underpass is mainly subjected to tensile stress, while the ceiling is mainly subjected to compressive stress. At the same time, the maximum tensile stress difference between the all-in-one excavation method and partial excavation method is only 0.3Mpa. The floor slab and the connection position between the floor slab and the sidewall using all-in-one excavation bear great tensile stress (in an unfavorable state), while only a smaller area of the floor slab bears large tensile stress using the partial excavation method. Therefore, under comprehensive consideration, partial excavation method is more conducive to the stress state of the underpass.

5. On-site monitoring

In this section, to further verify the rationality of the numerical simulation, the on-site monitoring data are sorted



(a) Excavation of the pilot tunnel (b) Installation of the preliminary lining

(c) Installation of the secondary lining (d) Removal of the temporary lining

Fig. 13 On-site construction

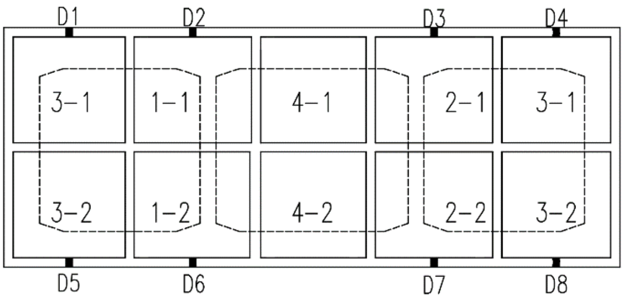
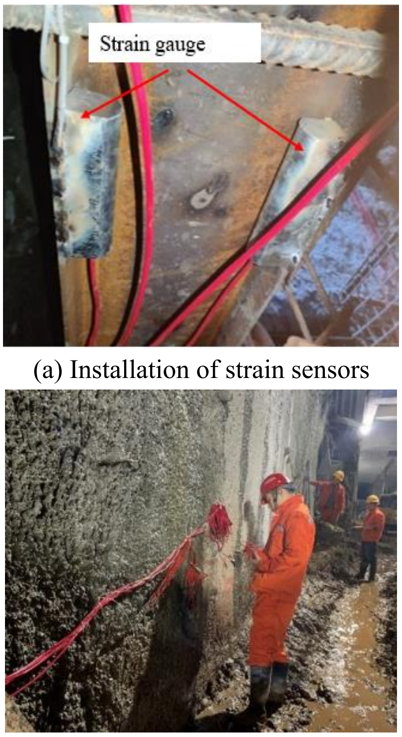


Fig. 14 Monitoring points of the preliminary lining of the underpass



(a) Installation of strain sensors

(b) Data acquisition

Fig. 15 On-site monitoring

and summarized, and the differences between the numerical results and the monitoring data are obtained. The on-site construction is carried out as the partial excavation method (the same excavation steps in Table 5). Some on-site photos are taken during the construction, as displayed in Fig. 13.

5.1 Layout of the on-site monitoring points

The on-site monitoring points are numbered as D1~D8 respectively, and the specific position of each monitoring point is displayed in Fig. 14.

Besides, D1~D4 are selected for the monitoring of the ceiling settlement of the underpass, and D1~D8 are used for the monitoring of the internal force (bending moment) of the preliminary lining. Since the bending moment of preliminary lining is mainly borne by the steel ribs, these strain sensors are installed on the inner and outer flanges of the steel ribs, respectively. The on-site pictures of installation of strain sensors and data acquisition are displayed in Fig. 15.

5.2 Comparison of the on-site monitoring results and numerical results

5.2.1 Settlement of the ceiling of preliminary lining

The changing curve of the settlement of lining of ceiling with time is displayed in Fig. 16, and the settlement comparison of the monitoring data and numerical results of D1~D4 are displayed in Table 6. ***Note:*** in Table 6, absolute error= $|A-B|$, A refers to the numerical settlement and B refers to monitoring settlement.

Table 6 Comparison of the monitoring result and numerical result of the settlement of the ceiling of preliminary lining

Name		D1	D2	D3	D4
Monitoring settlement /mm		1.50	3.80	3.10	3.40
Numerical settlement (partial excavation) /mm		3.81	3.83	4.09	3.96
Numerical settlement (all-in-one excavation) /mm		4.96	4.72	4.74	4.96
Absolute error	Partial excavation /mm	2.31	0.03	0.99	0.56
	All-in-one excavation /mm	3.46	0.92	1.64	1.56

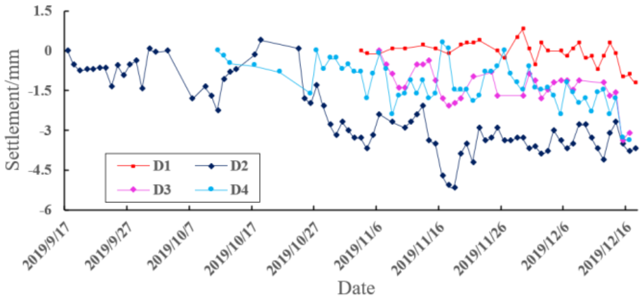


Fig. 16 The changing law of ceiling settlement of the preliminary lining about underpass with time

In Fig. 16, under the influence of construction, the settlement values fluctuate significantly. Besides, the settlement of the ceiling of lining increases gradually with the progress of construction. But the settlement values change little in the last few days, and the final settlements of D1~D4 are 1.50 mm, 3.80 mm, 3.10 mm, and 3.40 mm, respectively. On the other hand, the on-site settlement is acquired after the completion of the excavation of each pilot tunnel, leading to the settlement difference error when compared with the numerical simulation.

In Table 6, although the numerical value is a little larger than the monitoring value, the overall difference between the monitoring and numerical simulation (through partial excavation method) is small, namely, the absolute error of the two is basically between 0.03~0.99 mm, verifying the rationality of the numerical simulation. Also, the numerical simulation is more conservative and safer. On the other hand, the absolute error of the all-in-one excavation method is larger than the monitoring settlement and even reaching 1.64 mm. According to the standard requirement (MHURDPRC 2013), the deformation of the bottom position of existing station structure led by the nearby excavation is extremely strict (no more than 4 mm). Therefore, based on the above analysis and the data in Table 6, partial excavation method is more conducive to the controlling of the settlement of preliminary lining (basically around 3.9 mm) when compared with that of the all-in-one excavation method (more than 4.7 mm).

5.2.2 Mechanical evolution law

The bending moment of the preliminary lining is converted from the strains of the steel ribs, which are monitored on-site. The bending moment is converted using Eq. (2)

Where M is the bending moment of the preliminary lining;

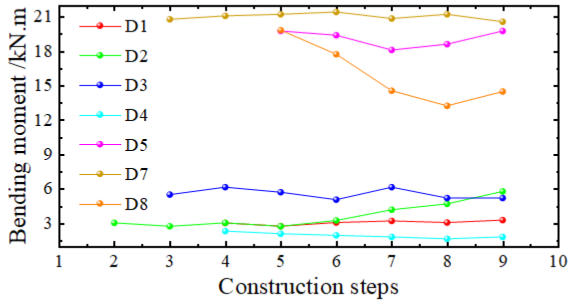


Fig. 17 Bending moment of the preliminary lining with construction steps

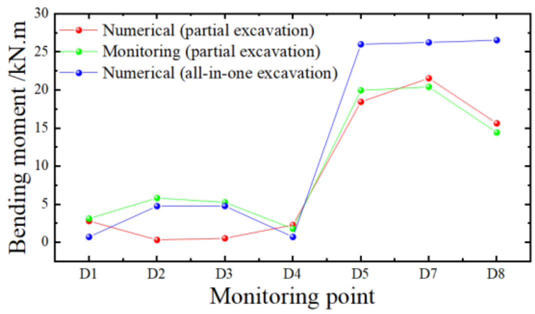


Fig. 18 The comparison between the monitoring results and numerical results

$$M = \frac{1}{2}(\varepsilon_1 - \varepsilon_2)WE_s \quad (2)$$

ε_1 is the inner edge strain of steel ribs; ε_2 is the outer edge strain of steel ribs; W is the flexural section coefficient of the steel ribs; E_s is the elastic modulus of the steel arch.

The change law of the monitoring bending moment of preliminary lining under each construction step is displayed in Fig. 17, and the comparison between the monitoring results and numerical results is displayed in Fig. 18.

In Fig. 17, the maximum monitoring bending moment of the ceiling of preliminary lining is 6.11 kN·m, located in the middle of pilot tunnel 1-1. The maximum bending moment of the floor slab of preliminary lining is 21.44 kN·m, located at the middle of pilot tunnel 2-2, but all the maximum value is not the final state value. Most of the monitoring bending moments of the ceiling of preliminary lining are less than that of the floor slab of the preliminary lining.

According to Fig. 18, for the modelling of partial excavation, due to the interference of construction, only the monitoring values of D2 and D3 are quite different from the numerical values, while the values of other points are relatively consistent with the monitoring values, and the maximum difference is only 1.52 kN·m (for D5). Therefore, the numerical method used in this paper is reasonable. For the modelling of all-in-one excavation, the bending moment values of monitoring pint (D1~D4) at ceiling is more closer to the monitoring value, while that of the floor slab point

(D5~D8) is significantly larger than that of the monitoring value when compared with the partial excavation method, and the largest difference value even reaches 12.1 kN.m at D8. Therefore, the modelling of partial excavation method is more closer to the on-site situation.

6. Conclusions

In this paper, the deformation law and mechanical evolution characteristics of the preliminary lining of the underpass during the excavation process are analyzed based on a case study of Chengdu metro Line 8 project, and the in-depth comparison of the differences between partial excavation method and all-in-one excavation method on this is also made. The main conclusions are listed below.

• The deformation of the preliminary lining caused by partial excavation method and all-in-one excavation method is basically less than 3.9 mm and larger than 4.7 mm, respectively. The maximum absolute error of partial excavation and all-in-one excavation is basically 0.99 mm and 1.64 mm respectively when compared with the on-site deformation of the preliminary lining. Combined with the limited value in standard, the partial excavation method can better meet the standard requirements.

• The final bending moment and deformation of the preliminary lining are distributed asymmetrically due to the asymmetric form of partial excavation method. The final bending moment of the preliminary lining is not the maximum due to the influence of excavation process and the installation of secondary lining. Additionally, because of the large difference in stiffness between the floor slab and soil, the maximum bending moment of the preliminary lining mainly appears in the floor slab, while that of the ceiling is negligible.

• The ratio of the maximum bending moment of the preliminary lining caused by partial excavation method and all-in-one excavation method is 86.6%. The maximum bending moment difference of the preliminary lining between partial excavation method and all-in-one excavation method is 1.52 kN.m and 12.1 kN.m, respectively when compared with that of on site, indicating that partial excavation method can better improve the stress state of the preliminary lining on site.

It is worth mentioning that the influence of the excavation footages and thickness of lining structure of the underpass are not considered yet in this paper, so more future work on it can be conducted.

Acknowledgments

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References

Ahmed, M. and Iskander, M. (2011), "Analysis of tunneling-induced ground movements using transparent soil models", *J. Geotech. Geoenviron. Eng.*, **137**(5), 525-535. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000456.

Abdel-Meguid, M., Rowe, R.K. and Lo, K.Y. (2003), "Three-dimensional analysis of unlined tunnels in rock subjected to high horizontal stress", *Can. Geotech. J.*, **40**(6), 1208-1224. https://doi.org/1208-1224. 10.1139/t03-057.

Banerjee, S.K. and Chakraborty, D. (2018), "Behavior of twin tunnels under different physical conditions", *Int. J. Geomech.*, **18**(8), 06018018. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001216.

Boonyarak, T. and Ng, C.W.W. (2015), "Three-dimensional influence zone of new tunnel excavation crossing underneath existing tunnel", *Jap. Geotech. Soc. Spec.Publication*, **2**(42), 1513-1518. https://doi.org/10.3208/jgssp.HKG-09.

Bi, J. and Zhou, X.P. (2015), "Numerical simulation of zonal disintegration of the surrounding rock masses around a deep circular tunnel under dynamic unloading", *Int. J. Comput. Method.*, **12**(3), 1550020. https://doi.org/10.1142/S0219876215500206.

Chen, S.L. and Lee, S.C. (2020), "An investigation on tunnel deformation behavior of expressway tunnels", *Geomech. Eng.*, **21**(2), 215-226. https://doi.org/10.12989/gae.2020.21.2.215.

Cavuoto, F., Manassero, V., Russo, G. and Corbo, A. (2019), "Urban tunnelling under archaeological findings in Naples (Italy) with ground freezing and grouting techniques", *Proceedings of the WTC 2019 and the 45th General Assembly of the International Tunnelling and Underground Space Association*, Naples, Italy, May.

Cao, R.L., Peng, L.J. and Zhao, Y.F. (2021), "Control of strata deformation in subway interval tunnels crossing a high-speed rail shield tunnel at a short distance", *Arabian J. Sci. Eng.*, **46**, 5013-5022. https://doi.org/10.1007/s13369-020-05225-8.

Fang, Y., Chen, Z.T., Tao, L.M., Cui, J. and Yan, Q.X. (2019), "Model tests on longitudinal surface settlement caused by shield tunnelling in sandy soil", *Sustain. Cities Soc.*, **47**, 101504. https://doi.org/10.1016/j.scs.2019.101504.

Guangzhou Metro Design and Research Institute Co. Ltd (GMDRICL) (2019). Engineering design material of the Chengdu Metro Line 8.

Haeri, H., Sarfarazi, V. and Marji, M.F. (2020), "Numerical simulation of the effect of confining pressure and tunnel depth on the vertical settlement using particle flow code (with direct tensile strength calibration in PFC Modeling)", *Smart Struct. Syst.*, **25**(4), 433-446. https://doi.org/10.12989/sss.2020.25.4.433.

Hoek, E. (2004), "Numerical modelling for shallow tunnels in weak rock", Unpublished notes. http://www.rocscience.com

Kim, N.Y., Park, D.H., Jung, H.S. and Kim, M.I. (2020), "Deformation characteristics of tunnel bottom after construction under geological conditions of long-term deformation", *Geomech. Eng.*, **21**(2), 171-178. https://doi.org/10.12989/gae.2020.21.2.171.

Li, B. and Wang, Z.Z. (2019), "Numerical study on the response of ground movements to construction activities of a metro station using the pile-beam-arch method", *Tunn. Undergr. Sp. Tech.*, **88**, 209-220. https://doi.org/10.1016/j.tust.2019.03.014.

Liang, R.Z., Xia, T.D., Huang, M.S. and Lin, C.G. (2017), "Simplified analytical method for evaluating the effects of adjacent excavation on shield tunnel considering the shearing effect", *Comput. Geotech.*, **81**, 167-187. https://doi.org/10.1016/j.compgeo.2016.08.017.

Li, Y., Zhou, G.Y., Tang, C.A., Wang, S.Y., Wang, K.K. and Wang, T.T. (2021), "Influence of undercrossing tunnel excavation on the settlement of a metro station in Dalian", *Bull. Eng. Geol. Environ.*, **80**, 4673-4687. https://doi.org/10.1007/s10064-021-02128-2.

Liang, R.Z., Kang, C., Xiang, L.M., Li, Z.C., Lin, C.G., Gao, K. and Guo, Y. (2021), "Responses of in-service shield tunnel to overcrossing tunnelling in soft ground", *Environ. Earth Sci.*, **80**(5), 1-15. https://doi.org/10.1007/s12665-021-09374-3.

Ministry of Housing and Urban-Rural Development of the People's Republic of China (MHURDPRC) (2013), Code for design of metro (GB 50157-2013). China Architecture and Building Press, Beijing.

Moeinossadat, S.R. and Ahangari, K. (2019), "Estimating maximum surface settlement due to EPBM tunneling by Numerical-Intelligent approach–A case study: Tehran subway line 7", *Transportation Geotech.*, **18**, 92-102. https://doi.org/10.1016/j.trgeo.2018.11.009.

Mirzaeiabdolyousefi, M., Nikkhah, M. and Zare, S. (2022), "Assessment of time-dependent behaviour of rocks on concrete lining in a large cross-section tunnel", *Geomech. Eng*., **29**(1), 41-51. https://doi.org/10.12989/gae.2022.29.1.041

Ng, C.W.W, Boonyarak, T. and Mašín, D. (2013), "Three-dimensional centrifuge and numerical modeling of the interaction between perpendicularly crossing tunnels", *Can. Geotech. J.*, **50**(9), 935-946. https://doi.org/10.1139/cgj-2012-0445.

Namazi, E., Mohamad, H., Jorat, M.E. and Hajihassani, M. (2011), "Investigation on the effects of twin tunnel excavations beneath a road underpass", *Electron. J. Geotech. Eng.*, **16**(1), 1-8.

Sakcali, A. and Yavuz, H. (2019a), "Zayıf kaya kütlesinde açılan dairesel kesitli bir tünelde radyal deformasyonların sayısal modelleme ile analizi", *Süleyman Demirel Üniversitesi Fen Bilimleri Enstitüsü Dergisi*, **23**(1), 66-73. https://doi.org/10.19113/sdufenbed.443405.

Sakcali, A. and Yavuz, H. (2019b), "Estimation of radial deformations around circular tunnels in weak rock masses through numerical modelling", *Int. J. Rock Mech. Min. Sci.*, **123**, 104092. https://doi.org/10.1016/j.ijrmms.2019.104092.

Soroosh, A., Foroozan, R. and Asadollahi, P. (2006), "Simulation of 3D effect of excavation face advancement using a neural network trained by numerical models", *Tunn. Undergr. Sp. Tech.*, **21**(3), 375-375. https://doi.org/10.1016/j.tust.2005.12.190.

Sakcali, A. (2021), "Zayıf kaya kütlelerinde açılan modifiye at nalı kesitli tünellerdeki deformasyon dağılımının sayısal modelleme ile belirlenmesi", *Afyon Kocatepe Üniversitesi Fen ve Mühendislik Bilimleri Dergisi*, **21**(4), 934-944. https://doi.org/10.35414/akufemubid.935746.

Sakcali, A. (2023), "Establishment of longitudinal deformation profile (LDP) for non-circular tunnel sections by using numerical modelling", *Proceeding of the 5th International Underground Excavation Symposium*, İstanbul, Turkey, June.

Sarfarazi, V., Haeri, H., Safavi, S., Marji, M.F. and Zhu Z.M. (2019), "Interaction between two neighboring tunnel using PFC2D", *Struct. Eng Mech.*, **71**(1), 77-87. https://doi.org/10.12989/sem.2019.71.1.077.

Sharifzadeh, M., Ghorbani, M. and Yasrobi, S. (2017), "Observation-based design of geo-engineering projects with emphasis on optimization of tunnel support systems and excavation sequences", *Rock Mech. Eng.*, **4**, 449-486. https://doi.org/10.1201/b20406.

Wu, B., Gao, B., Suo, X.M. and Shi, Y.X. (2005), "Mechanical simulation and analysis of construction behavior of urban metro tunnelling with small interval", *China J. Highway Transport*, (3), 84-89. https://doi.org/10.19721/j.cnki.1001-7372.2005.03.019.

Zucca, M. and Valente, M. (2020), "On the limitations of decoupled approach for the seismic behaviour evaluation of shallow multi-propped underground structures embedded in granular soils", *Eng. Struct.*, **211**, 110497. https://doi.org/10.1016/j.engstruct.2020.110497.

Zhou, H., Song, M., Zhang, C.Q., Hu, D.W. and Lu, J.J. (2020), "Physical model tests of the surrounding rock deformation and fracture mechanism of mixed-face ground under TBM tunneling", *Eur. J. Environ. Civil Eng.*, **24**(11), 1744-1760. https://doi.org/10.1080/19648189.2018.1483841.

Zheng, G., Du, Y.M., Cheng, X.S., Diao, Y., Deng, X. and Wang, F.J. (2017), "Characteristics and prediction methods for tunnel deformations induced by excavations", *Geomech. Eng.*, **12**(3), 361-397. https://doi.org/10.12989/gae.2017.12.3.361.

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