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Evaluation of the dynamic additional impact about foundation pit construction on the existing adjacent subway station with the PBA method

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Abstract

The existing research mainly focused on the influence of foundation pit construction on adjacent shield or square subway station, while the influence about foundation pit construction on the station with the pile-beam-arch (PBA) method is rarely involved yet, which has become one of the main concerns of people. Therefore, in order to ensure the safe operation of such adjacent subway station, based on Guangzhou Metro Line 11 project, the additional impact about the construction of foundation pit on the adjacent metro station with the PBA method is carried out using the numerical calculation, and mainly evaluated through the evolution law of the mechanics and deformation of the station. It is found that the whole bottom plate of the station shows the deformation form of "left bottom torsion", and this phenomenon is intensified with the construction process. The maximum displacement of the side wall and middle column of the station caused by foundation pit construction reaches 2.1mm and 1.5mm respectively. And the displacement increments of the two at the last stage accounts for 67% and 55.3% of the total displacement, respectively. Part of the side wall structure of station changes from compression state to tension state due to the foundation pit construction, but the increment of tensile stress is small, and the maximum stress increment of the bottom plate reaches 0.072MPa. Besides, the construction of foundation pit has a significant influence on the mechanical state of the middle column, especially for the axial force of middle column of the second layer. The increment of axial force after the construction is about 11.7% of the initial axial force of the middle column. Therefore, the disturbance effect about foundation pit construction on the adjacent station with the PBA method cannot be ignored, more attention should be paid to the last construction stage and taken some measures to strengthen the soil around station near the foundation pit side if necessary.

Keywords

Foundation pit, numerical calculation, PBA method, deformation rule, mechanical property

1. Introduction

With the continuous advancement of urbanization, more and more people settle in central cities, while the growth of the urban population has also increased the burden of transportation. To alleviate the phenomenon of urban traffic congestion, the subway has become the first choice of the main transportation mode in the city (Sun *et al.* 2023; Zhao *et al.* 2023a; Zhao *et al.* 2023b). Due to the limited land resources, many new projects are inevitably constructed close to the existing subway stations, and the new foundation pits on both sides of the stations are faced with the characteristics of "deeper, larger and more complex" (Li *et al.* 2007; You *et al.* 2019; Zhao *et al.* 2022a; Zhao *et al.* 2023c), while the construction of adjacent projects will greatly influence the existing subway stations. Because of the unloading effect about foundation pit construction, soil stress redistribution will inevitably lead to changes in the internal force and deformation of the existing subway stations that are deeply buried in the ground (Hai *et al.* 2009; Zhao *et al.* 2022b), which will further affect the smoothness and comfort level of metro operation. When the internal forces as well as deformations about the station are large, it will even cause the station to crack, joint seepage, collapse, and other safety hazards (Sui *et al.* 2021).

Therefore, for the construction of the foundation pits near the subway station, ensuring the safe operation of the subway station is an urgent engineering problem, so many scholars conducted certain studies on this issue. Zhao *et al.* (2022) analyzed the impact of foundation pit excavation on the circular subway tunnels and pointed out that compared with horizontal displacement, subway excavation has a more significant impact on the vertical displacement of adjacent subway, but both of them do not exceed the standard limit. Jiang (2019) found that symmetrical construction about the foundation pit had little impact on the existing rectangular station structure. Wang *et al.* (2020a) studied the variation law about large foundation pit construction on the deformations about existing stations and pointed out that the depth of foundation pit construction greatly influenced the lateral structure deformations about the station, while the soil weight hardly influenced it. Some scholars (Guo and Zhou 2015; Wang *et al.* 2020b; Wang *et al.* 2022) also pointed out that the clear distance between the foundation pit and the existing shield metro station had a great impact on the tunnel, and the clear distance should be strictly limited to ensure the normal operation of exiting tunnel. Ke *et al.* (2023) studied the deformation rule about a double-line circular shield tunnel led by the construction about an adjacent foundation pit and found that the excavation of the foundation pit would cause significant deformation of the tunnel, and the tunnel deformation caused by the original construction and lining parameters could still meet the requirements of the code. Liu and Huang (2023) analyzed the impact about pile installation on the ground settlement of the adjacent station with the PBA method and pointed out that the pile depth and pile spacing greatly influenced it.

To sum up, previous studies have analyzed the impact of foundation pit excavation on adjacent shield (circular) or square metro stations (Zhang *et al.* 2023; Cheng and Wang. 2019; Weng 2021), and the factors taken into consideration include clear distance of the foundation pit to the metro station, construction sequences (Zhang and Wang 2020), and construction suggestions (Liu *et al.* 2014; Yu and Chen 2022). However, the influence of foundation pit construction on the adjacent subway stations with the PBA method is rarely discussed yet based on real engineering case study. Although the subway station with the PBA method is considered as one of the methods that has little ground disturbance and can adapt to complex geological environments (Li *et al.* 2023; Yu *et al.* 2019; Yang 2021), the impact laws about new foundation pit construction on it are still not known yet. Due to the difference in construction methods, the response rules about foundation pit excavation to the existing subway station under different construction stages are not the same and the existing research results can't be simply applied, so it is still necessary to make further studies on it.

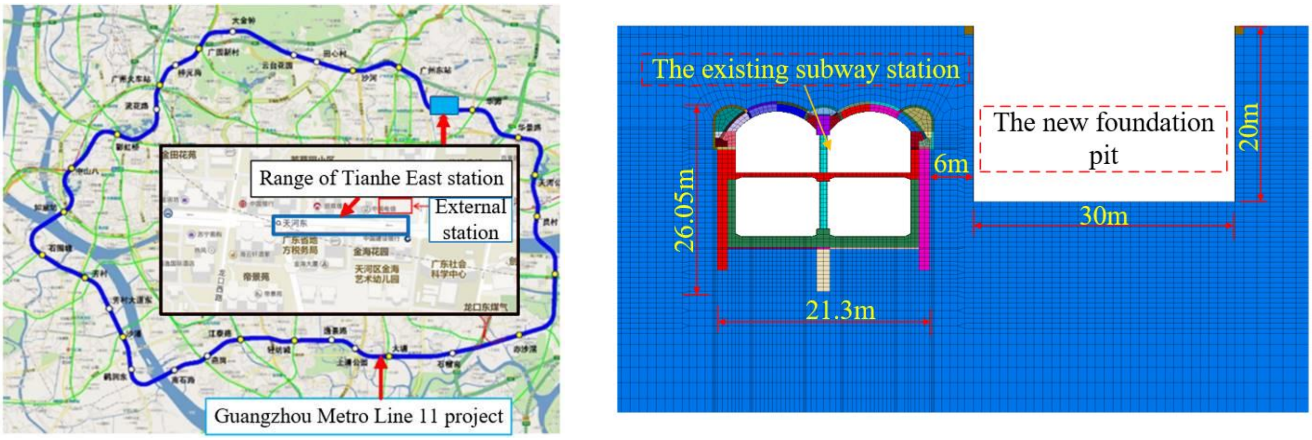
Therefore, relying on the Tianhe East Station project of Guangzhou Subway Line 11, the new foundation pit model as well as existing subway station model with the PBA method is established to deeply evaluate the mechanical and deformation effects about the foundation pit on the existing station during different construction stages. The relevant research results can provide some important references for the designing and constructing of a similar foundation fit project near the subway station with the PBA method.

2. Research background

The Tianhe East Station belongs to the seventh station of the Guangzhou Metro Line 11 project, connecting Huashi Station in the east and Guangzhou East Station in the west. The station is located on the east side of the intersection of Tianhe North Road and Longkou West Road and is laid under the pavement of Tianhe North Road. This metro line is arranged in the east-west direction. Tianhe East Station is a two-story station with the PBA method. The width of the standard section and the height of the station are 21.3m and 26.05m, respectively. The cross-section figure of the station is displayed in Fig. 1.

Considering that the main body of the station locate in the commercial area, to effectively improve the transfer passenger flow capacity of Tianhe East Station, it is necessary to build an external station hall near the station. The external hanging station hall adopts the open excavation method, the foundation pit is 59m long and 30m wide, and the excavation depth is 20m. Among them, the underground continuous wall is 1m thick, and three concrete lining with the size of 1m×1m is installed for the foundation pit. The detailed mechanical parameters of foundation pit and subway station are shown in Table 1.

The buried depth of station is 10.2m, and the covering soil is composed of miscellaneous soil, silty clay, strongly-weathered conglomerate, medium-weathered muddy siltstone, as well as slightly weathered argillaceous siltstone from the top to the bottom, among which the main body about the station is mainly located in the medium-weathered argillaceous siltstone. Detailed physical and mechanical parameters about the surrounding rock is displayed in Table 2. *Note:* the detailed mechanical parameters in Tables 1 ~ 2 of the surrounding rock, station and lining structure of foundation pit are determined according to the site geological survey data and construction design drawings of the Tianhe East Station of the Guangzhou Metro Line 11.



(a) Location of the Tianhe East Station

(b) Relative location of the foundation pit and station

Fig. 1 Overview of the Tianhe East Station and the new foundation pit

Table 1 Calculation parameter about the lining structure

Name	Elasticity modulus E /MPa	Poisson's ratio μ	Density ρ /(kg/m^3)
Preliminary lining	25000	0.2	2500
Secondary lining	32500	0.2	2700
Top beam	32500	0.2	2700
Steel pipe column	33500	0.2	2700
Side piling	20000	0.2	2300
Middle board	32500	0.2	2700
Floor	32500	0.2	2700
Diaphragm wall	25000	0.2	2500
Foundation pit lining	35000	0.3	2500

Table 2 Calculation parameter about the surrounding rock

Name	Thickness /m	Elasticity modulus E /MPa	Density ρ /(kg/m^3)	Poisson's ratio μ	Cohesion c /kPa	Internal friction angle φ /°
Miscellaneous soil	6.00	10	1800	0.3	8	20
Silty clay	12.00	75.5	1900	0.38	5	30
Strongly-weathered conglomerate	2.00	120	1950	0.33	2	25
Medium-weathered muddy siltstone	16.00	300	2200	0.25	180	33
Slightly-weathered argillaceous siltstone	42.00	500	2200	0.25	200	35

3. Calculation instructions

3.1 Calculation model

FLAC 3D finite element software is adopted to establish the numerical calculation model of the new foundation pit as well as the existing station with the PBA method. To decrease the impact of boundary effects and consider the model range as well as the calculation accuracy, the model dimension is set as follows: length (Y direction)×width (X direction)× height (Z direction)= 96m×180m×90m. The overall model has a total of 1624,035 nodes and 1619,690 units. The calculation model as well as the grid division diagram is displayed in Fig. 2. Normal constraints are set around the model, and fixed constraints are set at the bottom of the model, and the top surface sets to be free (Vali et al. 2020; Fang et al. 2022). Only the self-weight stress is considered for the initial geo-stress balance. In this paper, the contact between various components adopts the common node as well as the attach function in FLAC^{3D}, and no separation or slip yield appears between elements (Chen and Xu 2013). The surrounding rock and lining structure adopt the solid elements in the calculation. And the former adopts the plastic-hardening constitutive model and the later obeys the elastic criterion. The calculation parameters about the surrounding rock and lining structure are the same as Table 1 and Table 2 in the previous section.

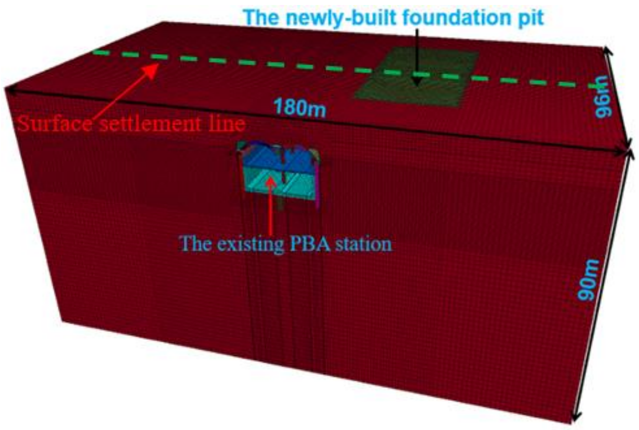
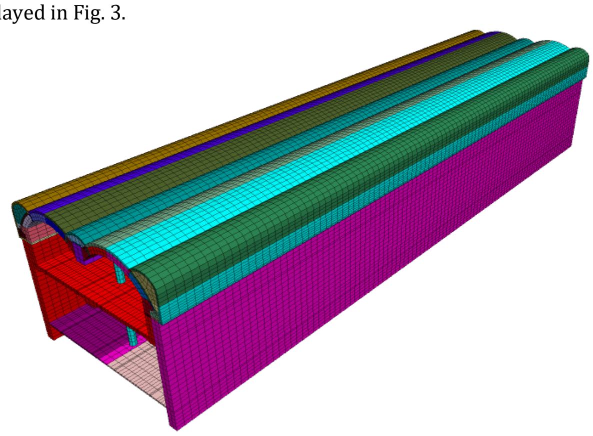
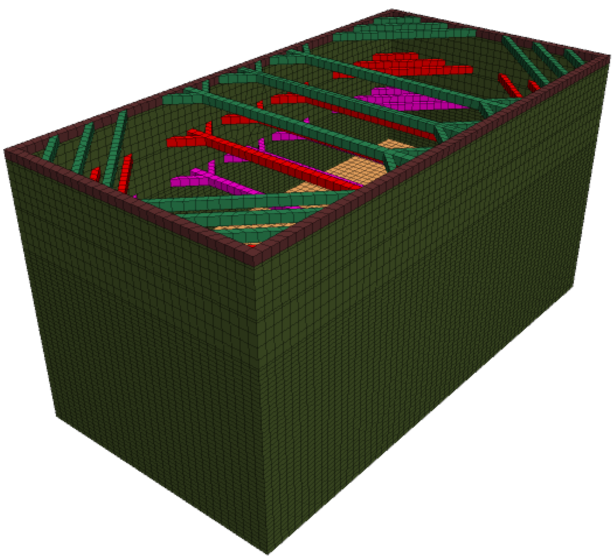


Fig. 2 Calculation model

Matching with the actual construction situation on site, the spacing from the foundation pit to the existing subway is only 6m. The size about the foundation pit is set as: length × width × height = 30m×60m×20m. The structural models of the existing station and new foundation pit are displayed in Fig. 3.



(a) Existing metro structure



(b) New foundation pit structure

Fig. 3 The existing metro station model as well as the new foundation pit model

3.2 Calculation process

The excavation and lining conditions of the model are determined according to the on-site construction situation. Firstly, the initial stress balance is carried out before the construction of the new foundation pit. Secondly, the construction about the foundation pit enclosure structure is carried out, and then the construction of layered excavation and internal lining is carried out. Because this paper only evaluates the impact about foundation pit construction on the adjacent subway station with the PBA method, the displacement of the existing subway station is cleared, and the stress state is retained. The specific construction processes are displayed in Table 3.

Table 3 Simulation of the excavation process of the new foundation pit

Calculation step	Name	Construction simulation content
1	Initial stress balance	Clear the displacement
2	Construction of the underground enclosure structure	Installation of the foundation pit retaining structure
3	Stage A	Excavate the soil of the foundation pit to the depth of -1.3m; install the corresponding lining of the excavated area
4	Stage B	Excavate the soil of the foundation pit to the depth of -6.6m; install the corresponding lining of the excavated area
5	Stage C	Excavate the soil of the foundation pit to the depth of -11.8m; install the corresponding lining of the excavated area
6	Stage D	Excavate the soil of foundation pit to the depth of -20m (the foundation pit base)

4. Discussion on the calculation results

4.1 Surface settlement characteristics

To evaluate the impact about new foundation pit excavation on the surface settlement as well as reduce the impact of the boundary effect, some monitoring points are set in the model middle section (i.e., y=48m section, as indicated in Fig. 2). The surface settlement curve under various construction stages is displayed in Fig. 4.

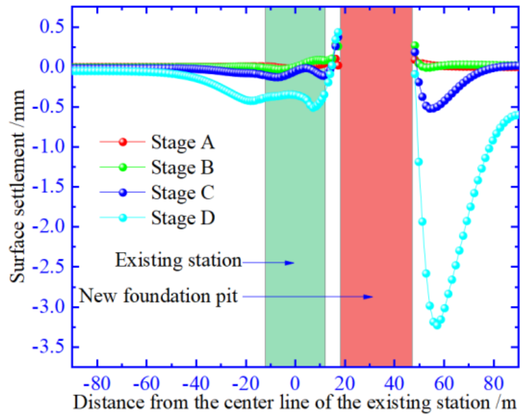


Fig. 4 Surface settlement curve under various excavation stages

In Fig. 4, the surface settlement gradually increases with the construction of the foundation pit and the soil mass within a small range around the foundation pit appears as the uplift form, which are led by the excavation as well as unloading about the soil mass in the foundation pit. This phenomenon gradually is becoming more and more obvious with the construction depth about the foundation pit, and the deformation value near the foundation pit reaches 0.44mm. In addition, the construction leads the soil around the foundation pit to move towards the inside foundation pit, but there are existing stations on the left side of foundation pit, the distribution law of surface settlement on two sides of the foundation pit is quite different. On the side near the existing station, the overall surface settlement is small, and because the overall stiffness of the station is large, the largest settlement appears at the station edge. The maximum settlement of this side is -0.51mm, while that of the side far from the station is -3.2mm due to the influence about construction unloading of the foundation pit, while the deformation on both sides decreases with the increase of the spacing from the foundation pit. The soil near the foundation pit has a certain uplift, and the surface deformation near the subway station is relatively small due to the "blocking" effect of the existing station, and the overall deformation distribution law is similar to the mentioned phenomenon of the previous research (Cheng and Wang 2019).

4.2 Deformation analysis about the existing subway station with the PBA method

Deformation law about surrounding rock

The deformation cloud map about the surrounding rock around the existing subway station is extracted for analysis, as shown in Figs. 5-6.

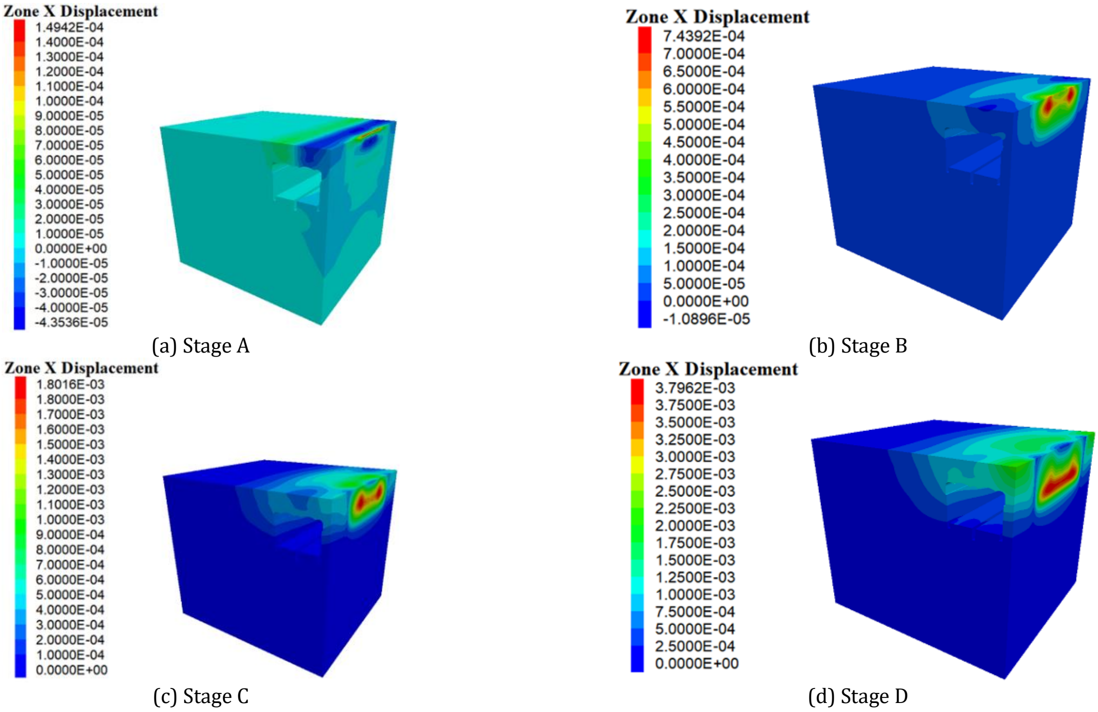


Fig. 5 Horizontal displacement of the surrounding rock under different construction stages of the new foundation pit

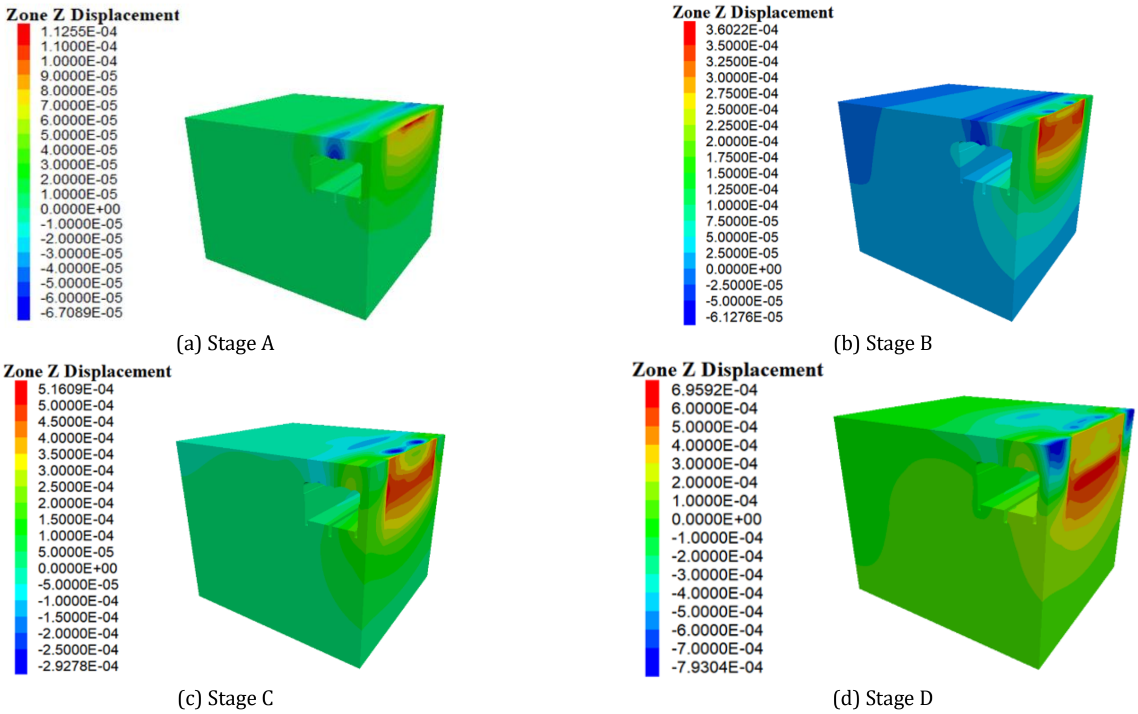


Fig. 6 Vertical displacement of the surrounding rock under various excavation stages about the new foundation pit

In Figs. 5~6, due to the excavation and unloading action of foundation pit, the soil around the foundation pit deformations to the inside of the foundation pit, and the horizontal deformation of surrounding rock increases with the excavation depths. The maximum horizontal deformation occurs in the soil outside the diaphragm wall and decreases from the largest horizontal deformation position to the two sides, and the maximum deformation position shifts with the construction depth of the foundation pit to the excavated position of the up layer. Because of the construction as well as unloading about the foundation pit, the soil at the base of the foundation pit shows the deformation form of "uplift", which will drive the soil near the foundation pit to uplift and deform in a small range, then the local soil above the existing station shows uplift form.

When stage B is completed, the deformation values about surrounding soil are very small, and the largest positive vertical deformation about some soil around the foundation pit reaches 0.3mm. The horizontal displacement of the surrounding rock between the foundation pit as well as the existing station increases first and then decreases from the top to bottom along the depth direction, and the largest horizontal deformation increases with the construction depth of the foundation pit. When the foundation pit is constructed to the foundation pit base, the maximum horizontal displacement about the soil in the middle range reaches 3.8mm, which appears at 5m above the foundation pit base. The vertical deformation of the surrounding soil increases with the construction depth about foundation pit, and the soil in the range about foundation pit is subjected to excavation unloading, leading to the soil uplifting at the foundation pit base. Constrained by the diaphragm wall on the south and north sides, the vertical deformations at the corners of the foundation pit are small. After the completion of stage D, the uplift displacement reaches a maximum value of 0.7mm and decreases around the foundation pit with the radioactivity form. The obvious settlement position appears in the soil within a certain spacing around the foundation pit, and the largest settlement reaches 0.8mm.

Deformation rules about the existing station

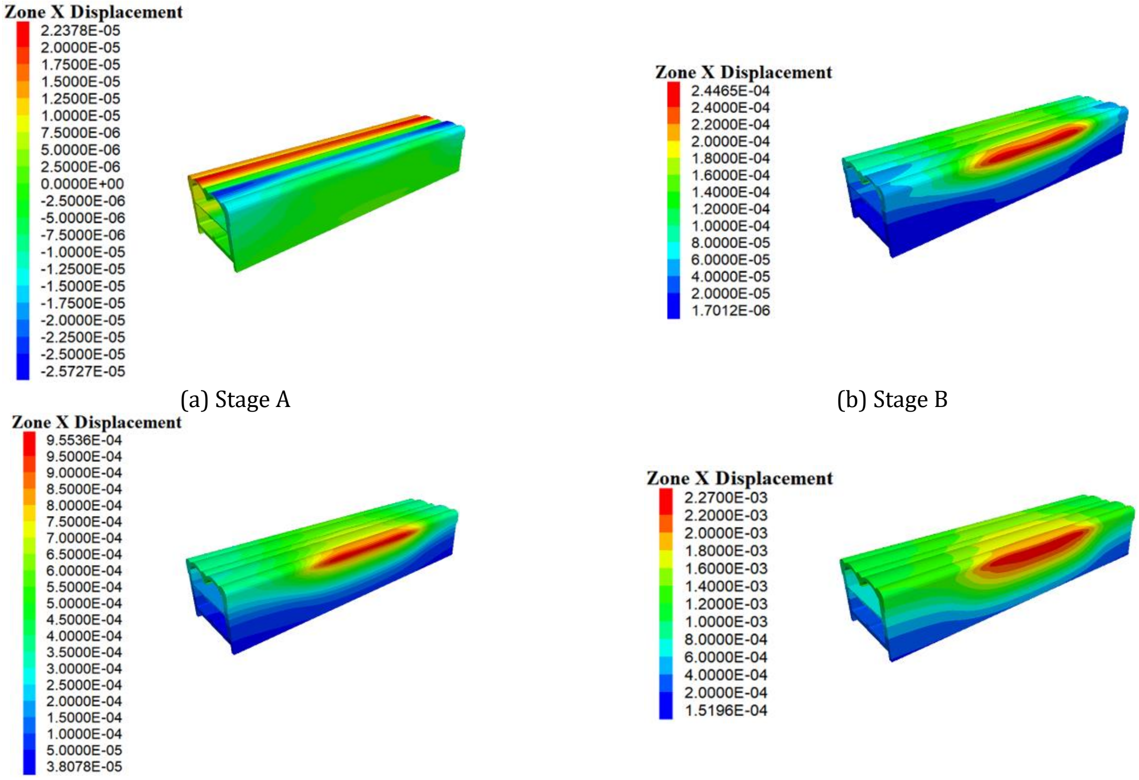
(1) Overall structure

The horizontal deformation of the existing station led by the construction of new foundation pit in different stages is displayed Fig. 7.

In Fig. 7, the largest horizontal deformation about the whole existing station led by foundation pit construction is 2.27mm, and the structure deformation of the station near the foundation pit are obviously larger than that on the other side. With the increasement about construction depths, the largest deformation of the station also increases correspondingly, but the position corresponding to the maximum displacement is almost unchanged. It is at the position where the preliminary lining of the small pilot tunnel is contacted with the side wall, which also corresponds to the largest horizontal displacement position about the soil near the foundation pit analyzed in the previous section. The displacement about the foundation pit in stage D are the largest, reaching 2.27mm, accounting for 58.1% of the final displacement, which is greater than the total displacement of the first three stages, and more attention should be paid to this stage in the actual construction.

To evaluate the deformation properties about the subway station, the side wall of the existing station near the foundation pit with the most significant displacement is served as the object of study, and its overall deformation cloud map and distribution curve of the horizontal displacement at various construction stages are extracted, as displayed in Figs. 8~9.

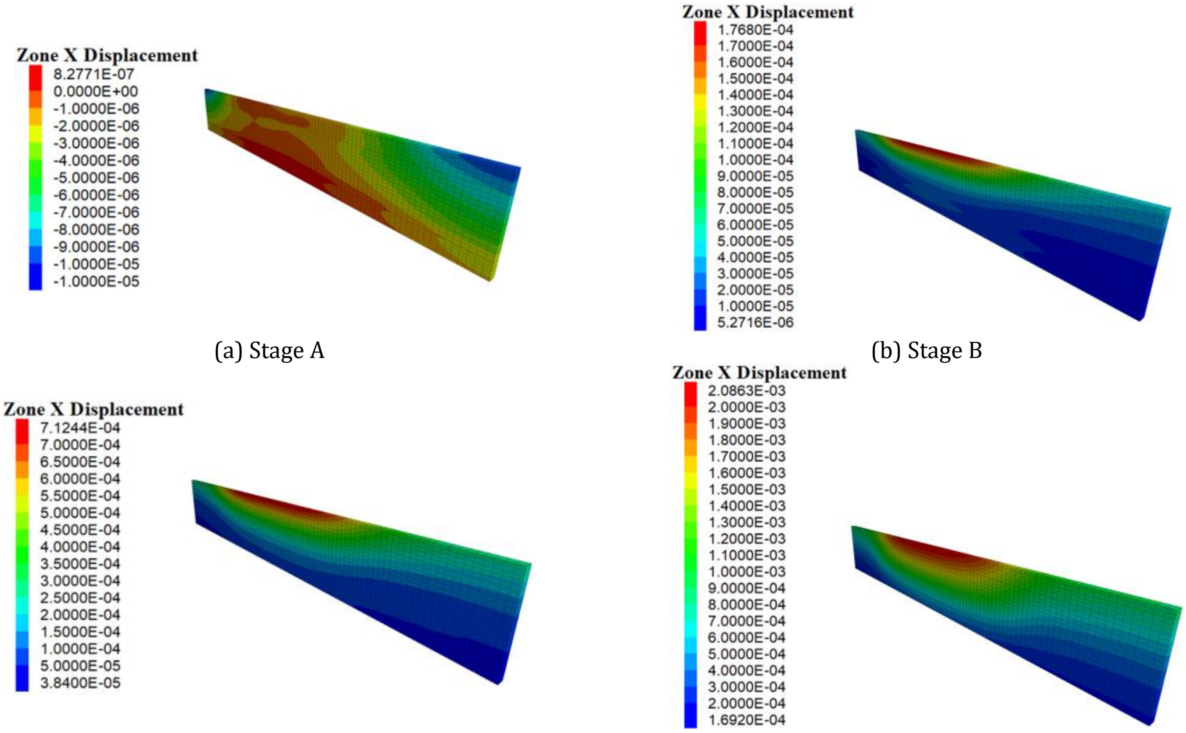
In Figs. 8~9, the displacement of the side wall of the subway station is greatly influenced by the construction of the adjacent foundation pit. The displacements about the subway station led by the excavation about the foundation pit are manifested as moving to the side near the foundation pit. The deeper the construction depth about the foundation pit, the more significant the displacement about the adjacent station, and the greater the horizontal deformation about the side wall towards the foundation pit. For stages A~D, the largest horizontal deformation of the side wall caused by the construction of foundation pit are 0.01mm, 0.17mm, 0.7mm, and 2.1mm, respectively. The largest horizontal deformation about the station after the completion of stage D is located on the side wall and shifts towards the foundation pit. The horizontal deformation increment generated in stage D reaches 1.4mm, accounting for 67% of the total displacement.



(a) Stage A (b) Stage B

(c) Stage C (d) Stage D

Fig. 7 Horizontal deformation of the existing station structure under different construction stages



(a) Stage A (b) Stage B

(c) Stage C (d) Stage D

Fig. 8 Horizontal displacement of the sidewall of station under different construction stages

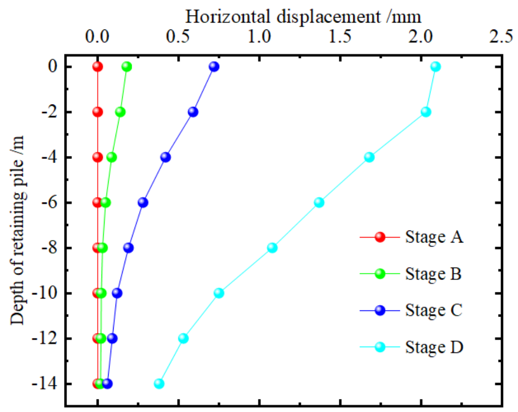


Fig. 9 Horizontal displacement curves of the side wall of station under different construction stages

(2) Middle column of the subway station

Taking the deformation of the middle column about the existing station as the object of study, the horizontal deformation mode in various excavation stages is amplified 500 times, as displayed in Fig. 10.

In Fig. 10, with the progress of construction, the largest values about horizontal deformation of the middle column in the existing subway station gradually moves to the middle and upper part of the middle column within the excavation range, and the deformation about the upper and lower part of the middle column is the largest and the smallest, respectively. When constructed to the foundation pit base (i.e., in stage D), the largest deformation is 1.5mm, which appears in the middle and upper part of the middle column. This is because there is no corresponding lining in the process and the foundation pit base is just a bit lower than the floor of first layer of the station. The horizontal deformation about the middle column caused by stage D is 0.83mm, accounting for 55.3% of the total displacement. The deformations of the middle column on both sides are smaller than that of the middle column because the former is far away from the foundation pit.

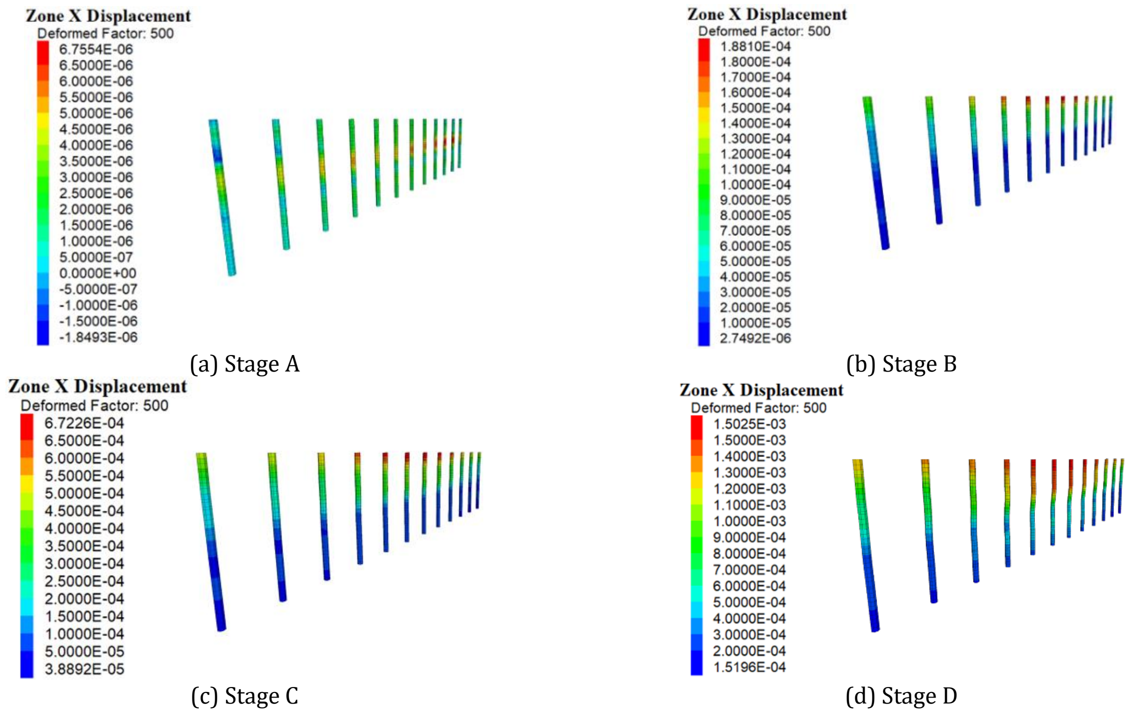


Fig. 10 Horizontal displacement of the middle column of the station under various excavation stages

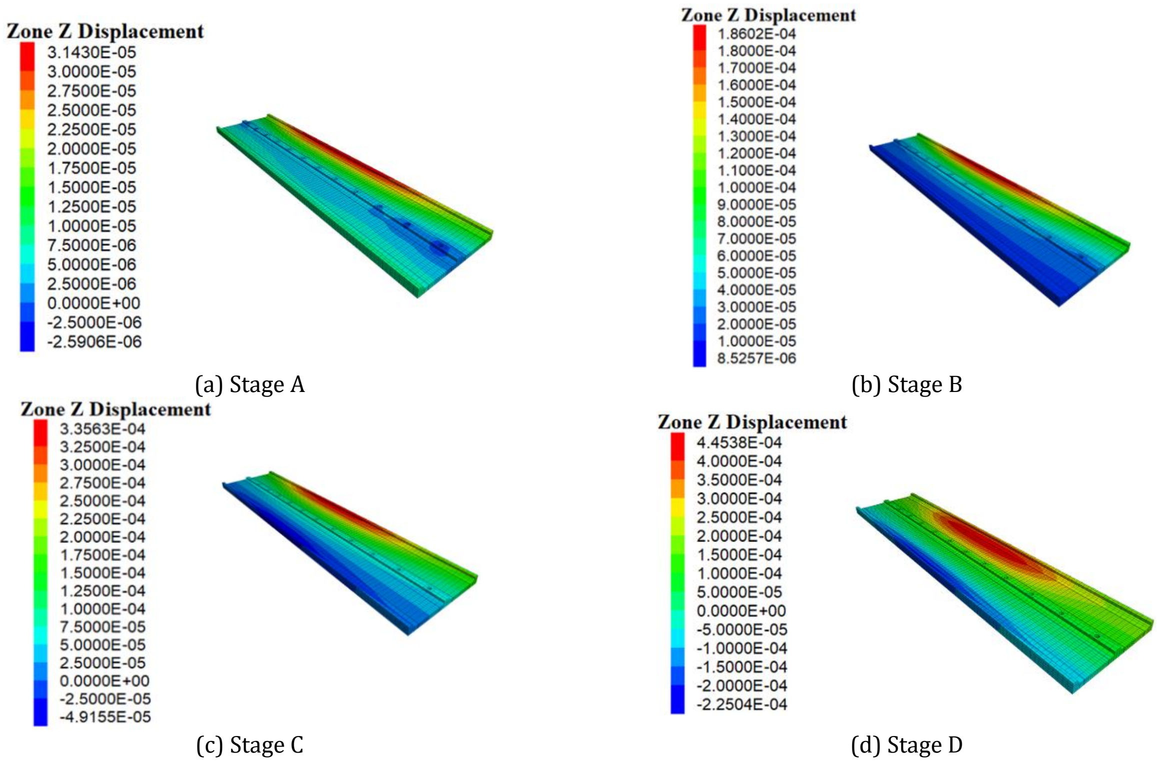


Fig. 11 Vertical displacement of the floor of the subway station under various construction stages

(3) Settlement of the bottom plate of station

The cloud map of settlement and the distribution curve of the monitoring section of the bottom plate of station under various construction stages are displayed in Figs. 11~12.

In Figs. 11~12, due to the impact of the construction unloading about the foundation pit, the deformation of the bottom plate of subway station caused by the excavation is mainly uplift. Moreover, the deeper the construction depth of the foundation pit, the more significant the deformation of the adjacent subway station, and the larger the uplift value of bottom plate (near the foundation pit side). Because of the large overall stiffness of the existing subway station, the distribution of the overall trend of vertical displacement of the station is consistent in different construction stages, and the settlement value on the right side of the bottom plate of the station is the largest, reaching 0.4mm.

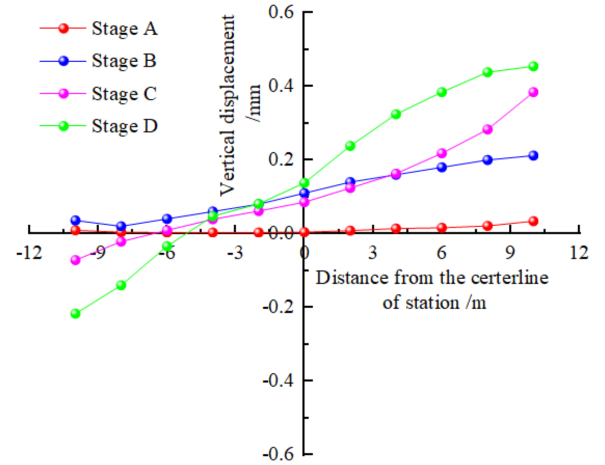


Fig. 12 Comparison curves about the settlement of the bottom plate of a subway station under different construction stages

4.3 Mechanical characteristics of the existing subway station

The safety as well as the stabilities about the existing station structure are not only concerned with the deformation but also greatly concerned with its mechanical state. As the right side wall as well as top beam about the existing subway station are directly affected by the construction of the adjacent foundation pit, their stress states are closely related to the open excavation process of the foundation pit, and thus indirectly affects the stress state of the middle column and bottom plate that directly connected to the side wall. Therefore, this section focuses on analyzing the mechanical state of the right side wall as well as the middle column of the station.

Side wall of the subway station

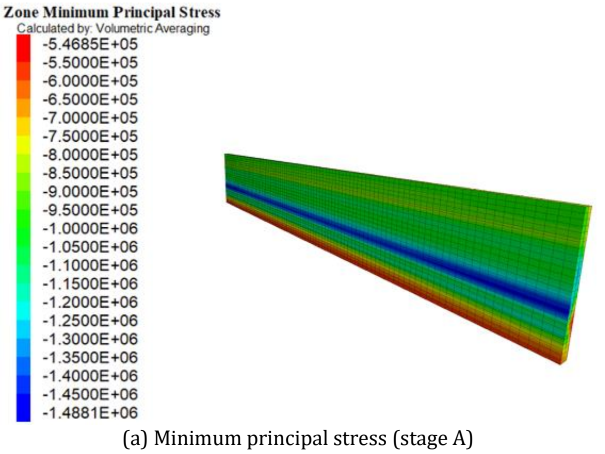
The variation law about the principal stress of the side wall of the existing subway led by the construction of foundation pit under stage A and stage D is displayed in Fig. 13. In FLAC3D software, the negative stress values represent the compressive stress, while the positive values refer to the tensile stress.

In Fig.13, when the construction of the foundation pit is in stage A, both the minimum and maximum principal stresses of the side wall are negative, that is, the overall compression and the largest compressive stress of the two are 1.488MPa and 0.545MPa respectively. After constructed to the foundation pit base (i.e., at stage D), the peak value of the minimum principal stress of the side wall reaches 1.455MPa, which is reduced by 0.033MPa compared with the stage A. This phenomenon is caused by the construction and unloading of the foundation pit. The maximum principal stresses of the side wall are positive, that is, the tensile stress appears at the two excavation corners of the existing station that near the foundation pit, where the largest tensile stresses as well as compressive stresses reach 0.0127MPa and 0.546MPa respectively. Compared with stage A, the maximum compressive stress increases by 0.001MPa, and the stress state changes little before and after construction. The stress state of the excavation corner corresponding to the side wall has changed, and the main stress of part of the side wall has changed from the compressive stress to the tensile stress.

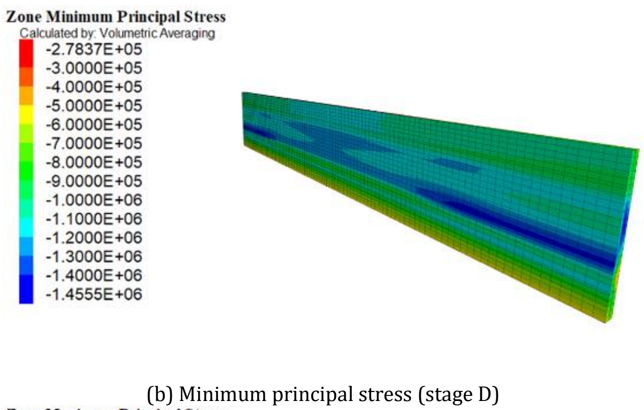
Middle column of the subway station

Since the total length of the existing station along the y direction is 96m, and the cross-section of y=48m is a symmetrical structure, six middle columns along the y direction from 0 to 48m are selected for analysis, and the axial forces diagram about the middle column in the existing subway under various construction stages is extracted, as displayed in Fig. 14.

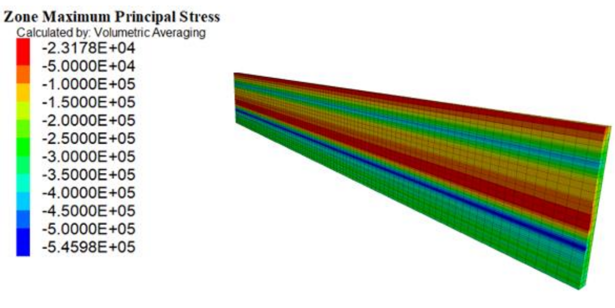
In Fig. 14, when the construction of the foundation pit is in stage A, the axial forces of each middle column have little difference. The axial forces about the middle column in the first layer are about 5900kN, and those in the second layer are about 6290kN. With the construction of the foundation pit, the axial forces about the middle column increases. After excavated to the foundation pit base (i.e., in stage D), the axial forces about the middle column increases to the maximum. This is caused by the soil unloading led by the construction of the unilateral foundation pit, which causes the whole subway structure to move in the direction of the foundation pit, leading to greater pressure transmitted to the middle column. After the completion of the foundation pit construction, the maximum axial forces as well as the minimum axial forces about the middle column in the first layer of the existing subway station reach 6371kN and 6310kN, respectively. The maximum axial force of the middle column of the second layer of the existing subway station locates at the middle column near the middle part of the foundation pit, reaching 7016kN. While the minimum axial force locates at the farthest position from the middle part of the foundation pit, reaching 6583kN.



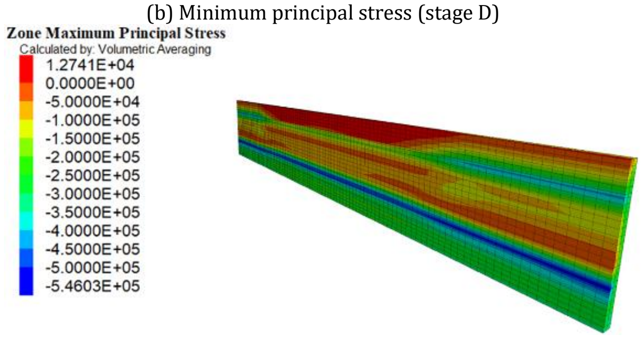
(a) Minimum principal stress (stage A)



(b) Minimum principal stress (stage D)

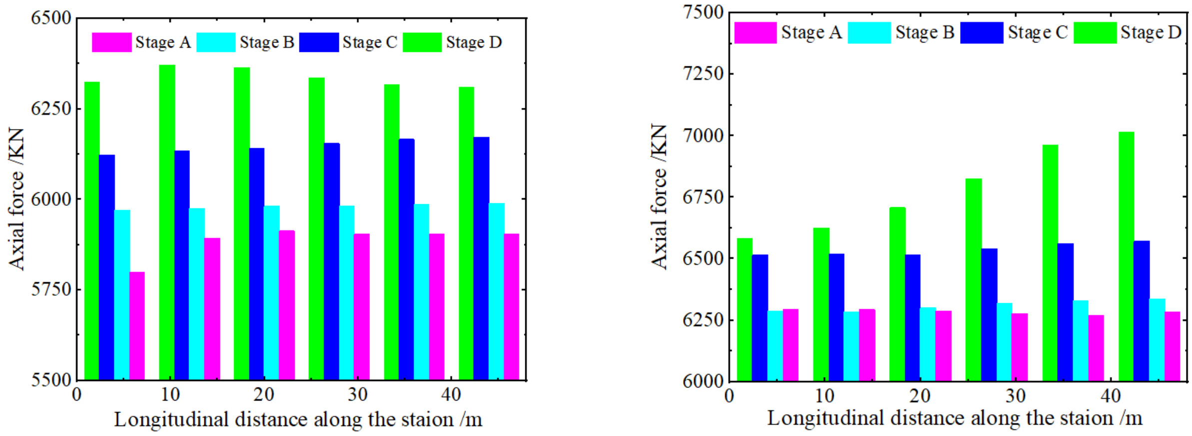


(c) Maximum principal stress (stage A)



(d) Maximum principal stress (stage D)

Fig. 13 Variation law of the principal stress of side wall of the existing subway station under various excavation stages

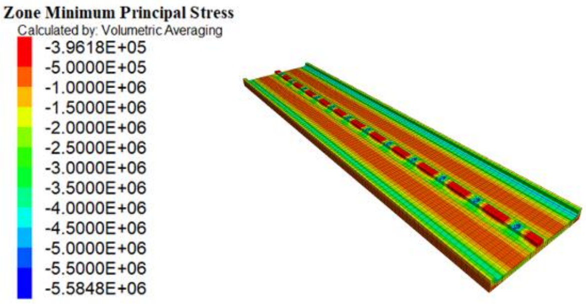


(a) Axial force of the middle column in the first layer (b) Axial forces of the middle column in the second layer

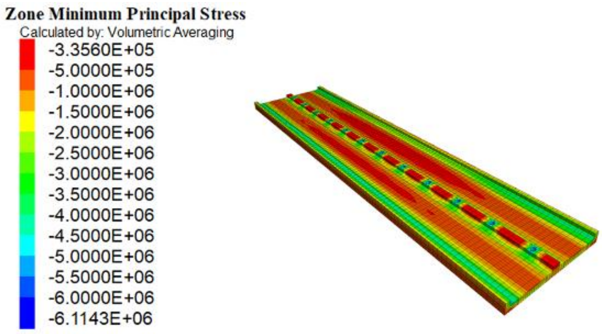
Fig. 14 Variation of the axial forces in the middle column of the existing subway station under various construction stages

Table 4 Axial forces in the middle column about the existing subway station

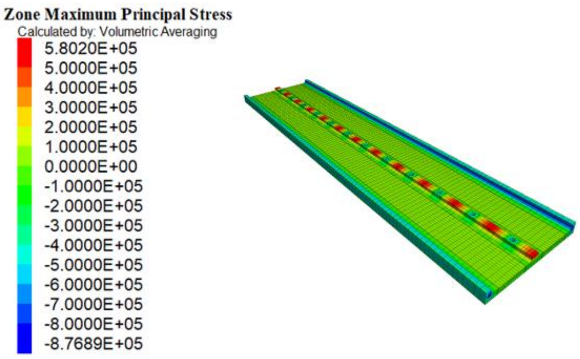
The axial forces about the middle column	Middle columns in the first layer		Middle columns in the second layer	
	Maximum increment /kN	Minimum increment /kN	Maximum increment /kN	Minimum increment /kN
Stage A	5800	5905	6283	6294
Stage D	6324	6310	7016	6583
Axial force increment	524	405	733	289
Proportion of axial force increase	9.1%	6.8%	11.7%	4.6%



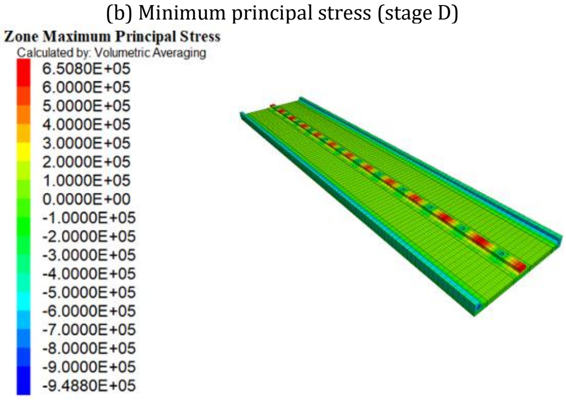
(a) Minimum principal stress (stage A)



(b) Minimum principal stress (stage D)



(c) Maximum principal stress (stage A)



(d) Maximum principal stress (stage D)

Fig. 15 Variation law of the principal stress of the bottom plate of existing station

The increment of the axial force of middle columns in the existing subway stations in the early and final stages of foundation pit construction (stages A and D) is calculated and summarized in Table 4. In Table 4, the variation law about the axial forces of the middle column in the first layer is smaller than that in the second layer, and the incremental rate of the axial forces of the middle column in the second layer after the foundation pit construction is about 11.7% that of the initial construction stage.

Bottom plate of the subway station

The cloud diagram of the principal stress of the bottom plate of the existing subway station is displayed in Fig. 15.

In Fig. 15, at the beginning stage of the foundation pit construction (i.e., in stage A), the minimum principal stress about the bottom plate of existing station is negative, that is, the whole bottom plate of station is in compressed state, and the maximum compressive stress reaches 5.585MPa, which is located at the contact position between the middle columns and the bottom longitudinal beams. At this time, the compressive stress is 1.435MPa at the contact position between the bottom plate and the side wall near the foundation pit. After the completion of foundation pit construction (i.e., in stage D), the minimum principal stresses of the overall bottom plate increase, and the largest compressive stress is 6.114MPa, which is 0.529MPa higher than that in stage A. At this time, the compressive stress at the contact position between the bottom plate and the side wall of the foundation pit reduces to 1.233MPa, which is 0.202MPa less than that in stage A. It indicates that the unloading of the foundation pit causes the deformation of the bottom plate driven by the side wall, thus decreasing the tensile stress on the bottom plate of station. The maximum principal stress of the bottom plate of the station is mainly tensile stress, and the compressive stress locates at the place where the middle column in the bottom longitudinal beam that contacting the floor. In stage A, The largest compressive stress as well as tensile stress of the bottom plate are 0.877MPa and 0.580MPa respectively. After constructed to the foundation pit base, the largest tensile stress as well as the maximum compressive stress increase to 0.949MPa and 0.651 MPa, respectively, with an increment value of 0.072MPa and 0.071MPa, respectively.

5. Conclusion

(1) During the construction stages of the new foundation pit, because the overall stiffness about the subway station with the PBA method is large, the deformation trend of the side wall as well as the middle column is basically the same. The largest deformation of the side wall as well as the middle column is 2.1mm and 1.5mm respectively, and the deformation generated in the final construction period accounts for 66.7% and 55.3% of the total deformation, respectively.

(2) Because of the unloading action about the foundation pit construction, the bottom plate of the existing station appears as the uplifted state on the side near the foundation pit, and the largest uplift value is 0.4mm. With the process of foundation pit excavation, the bottom plate as a whole presents the deformation form of "left bottom torsion", and the trend of this torsion deformation is more obvious. When the construction of the foundation pit is finished, the maximum compressive stress and tensile stress about the side wall and bottom plate of the station are 6.114MPa and 0.651MPa respectively, which do not reach the limiting values of the concrete strength stipulated by the standard and are in a relatively safe state.

(3) The axial force about the middle column of the station gradually increases with the construction depth, and the variation is the largest when constructed to the foundation pit base. The largest axial force value about the middle column of the first layer is 6324kN, while that of the second layer is 7016kN. The variation law about axial forces of the middle column in the first layer is smaller than that in the second layer and the incremental rate of the axial forces in the second layer after the completion of construction accounts for about 11.7% of the axial force in the initial stage of the foundation pit excavation.

Therefore, the influence about new foundation pit excavation on subway stations with the PBA method cannot be ignored and should be sufficiently taken into account in the designing and constructing of similar actual project cases. Also, it is worth mentioning that the influence of different excavation depth intervals of foundation pit, distance from the foundation pit to the station is not considered yet in the paper, so further research about these factors can be carried out in the future.

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Data Availability

The data that appeared in this paper will be available upon reasonable request.

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