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ANALYSIS OF THE INFLUENCE OF SIDE WALL OPENING ON THE ARCH STRUCTURE OF METRO STATION USING THE PILE-BEAM-ARCH METHOD

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ABSTRACT

In order to meet the traffic and commercial needs, it is sometimes necessary to open the side wall of the metro station, while the current research on the mechanical properties and safety of the arch caused by the opening of the side wall of the station by pile-beam-arch (PBA) method is rarely involved. In this paper, based on the Tianhe East Station project of Guangzhou Metro Line 11 located in soft-hard uneven stratum using PBA method, the settlement law and mechanical characteristics of the arch under different side wall opening conditions are analyzed, and the influence of opening construction and opening span on the safety of arch is also further studied. The results show that the settlement caused by the opening of the side wall is mainly concentrated in the upper part of the opening area, and gradually expands around the opening area with the increase of opening span, and the maximum settlement occurs in the middle part of the arch. Opening leads to the differential settlement at both ends of the arch. With the increase in opening span, the settlement growth trend of the right side of the arch is greater than that of the left side. The opening of the side wall leads to the increase of the safety factor of the arch body and the decrease of the safety factor of the right arch foot, while the change of the safety factor of the left arch foot is not obvious, and the safety factor meets the specification requirements.

KEYWORDS

PBA method, Side wall openings, Differential settlement, Safety factor; Numerical calculation

INTRODUCTION

In recent years, the pressure on urban public transport is increasing with the acceleration of urbanization and economic development [1-2]. As a relatively environmentally friendly and low-carbon public transport with a large volume of traffic, metro travel has attracted much attention [3-4]. At present, researches on the PBA method mainly focus on the variation law of ground settlement and stratum deformation at each stage of construction [5-10]. After the completion of the metro station, due to the new line transfer or the installation of the attached structure, the demolition construction of the side wall of the station is often required. While the demolition construction will inevitably affect the mechanical system and security of the station structure, it is necessary to analyze the deformation as well as internal force change law of the side wall and the arch in the opening process of the side wall. It is worth mentioning that the mechanical properties and deformation laws of underground structures have always been the focus of scholars [11-13].

Based on this, scholars have conducted some research on the mechanical behavior of the station with side wall openings [14]. Zhang [15] took the transfer station of a subway station in Beijing as an example and found that the removal of walls by sections and the erection of temporary linings at the same time had a better control effect on the deformation and internal force about the existing structure. Du and Guo [16] found that the demolition stage of the side wall was the most sensitive construction step to the internal force and settlement changes of the existing side wall, and put forward corresponding control measures. Xu [17] analyzed the deformation and stress characteristics of the existing subway structures using the covered excavation method and pointed out that reinforcement measures should be taken before the opening of the side wall. Yuan [18] found that the opening of the side wall can cause the local deformation of the existing station structure but has little impact on the maximum deformation about the whole structure. Wang [19] pointed out that the opening of the side wall would lead to the redistribution of internal forces in the existing station structure, and it was necessary to control the opening size and the clear distance between adjacent openings to reduce the adverse effects brought by the side wall opening. Hu *et al.* [20] analyzed the influence of side wall opening on the force and deformation of station structure and found that the deformation increment met the requirements while the stress increment was higher than the control requirements and suggested that the limit opening span of side wall should be 5.75m when there was no reinforcement. On the other hand, scholars have also studied the influence of reconstruction and expansion construction of existing stations on the force of the original structure and put forward corresponding construction suggestions [21-25]. Although some studies have analyzed the deformation and internal force distribution characteristics of the side wall caused by the opening of the side wall, few studies focused on the change characteristics of the mechanical behavior of the arch caused by the opening of the side wall using PBA method.

Therefore, in this paper, based on the Tianhe East Station project of Guangzhou Metro Line 11, a study on the evolution law of the mechanics and deformation of station arch with the PBA method caused by side wall opening is carried out, and the safety of arch under different opening conditions is also analyzed. The research results of this paper can provide some important references for similar metro construction of side wall openings.

PROJECT OVERVIEW

Tianhe East Station is the seventh station of the Guangzhou Metro Line 11 project, connecting the South China Normal University 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. The line is arranged along the east-west direction and construction is carried out by the PBA method, as shown in Figure 1.

The Tianhe East Station is a two-story underground station with a standard section width of 21.3m and an excavation depth of 26.05m. The cross-section of the station is shown in Figure 2. The diameters of the side pile and steel pipe column are 1.2m and 1.8m, respectively; and the thickness of the preliminary lining and secondary lining are 0.3m and 0.9m, respectively. The calculation parameters about the lining structure are displayed in Table 1.

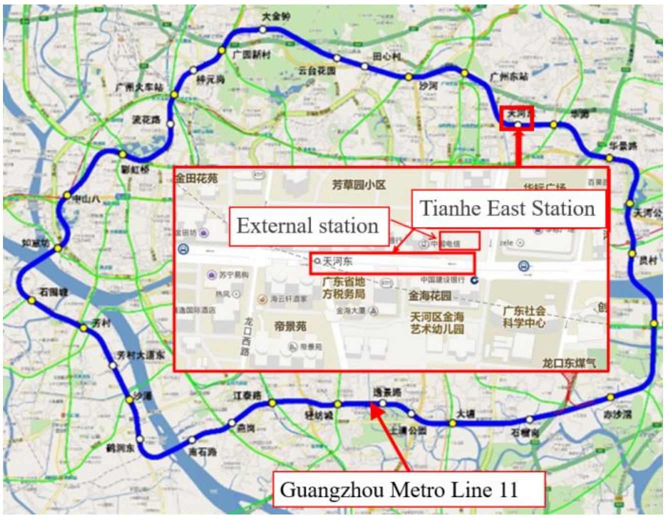


Fig. 1 - Plane view and position about the Tianhe East Station

Tab. 1 - Calculation parameters about the lining structure

Name	Elastic modulus *E* /MPa	Poisson's ratio *μ*	Density *ρ* /(kg/m^3)
Preliminary lining	25000	0.2	2500
Secondary lining	32500	0.2	2700
Crown beam	32500	0.2	2700
Steel pipe column	33500	0.2	2700
Side pile	20000	0.2	2300
Middle plate	32500	0.2	2700
Bottom plate	32500	0.2	2700

Considering that the main body of the station locating in a busy commercial area, to effectively improve the transfer passenger flow capacity of Tianhe East Station, openings are required to be constructed on the side wall of the main structure of the station to realize the connection with the external station hall. The location of the opening is selected in the red box of Figure 2. The buried depth of the station is 10.2m, and the overlying soil layer from the top to bottom is composed of mixed fill, silty clay, strongly weathered conglomerate, medium weathered argillaceous siltstone, and breezy argillaceous siltstone. The main body of the station is located at the medium-weathered argillaceous siltstone. The calculation parameters about the surrounding rock are displayed in Table 2. ***Note:*** both of the parameters in Table 1 and Table 2 are taken from the engineering design data of Tianhe East Station of Guangzhou Metro Line 11.

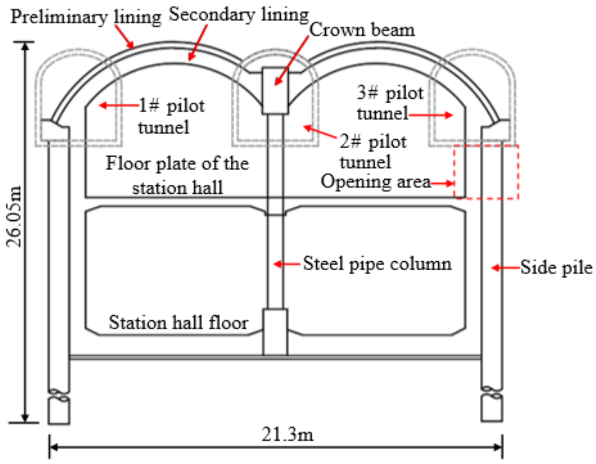


Fig. – 2 Cross section of the Tianhe East Station

Tab. 2 - Calculation parameters of the surrounding rock

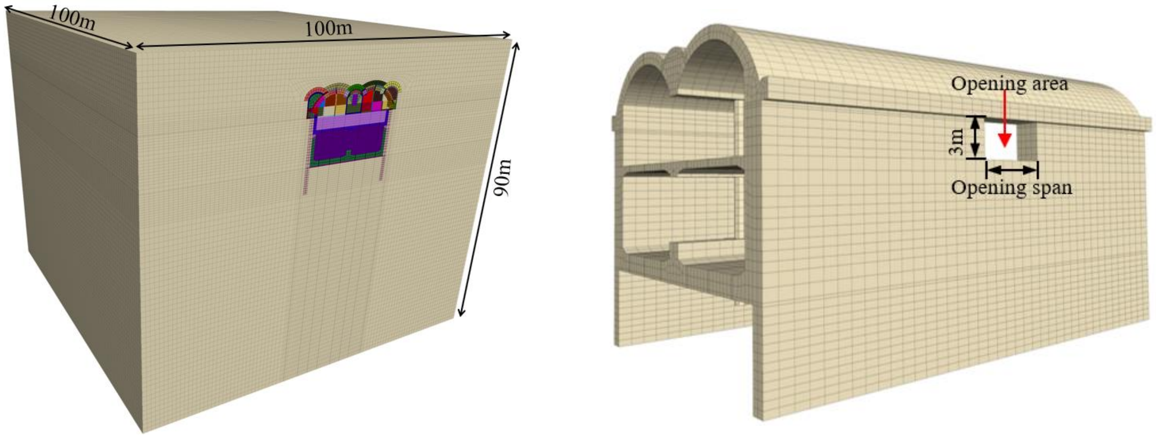
Name	Thickness /m	Elastic modulus *E* /MPa	Density *ρ* /(kg/m^3)	Poisson's ratio *μ*	Cohesion *c* /kPa	Internal friction angle *φ* /°
Miscellaneous fill	6.0	10	1800	0.3	8	20
Silty clay	12.0	75.5	1900	0.38	5	30
Strongly weathered conglomerate	2.0	120	1950	0.33	2	25
Medium-weathered argillaceous siltstone	16.0	300	2200	0.25	180	33
Breezy argillaceous siltstone	42.0	500	2200	0.25	200	35

NUMERICAL CALCULATION INSTRUCTION

The finite element software FLAC3D is adopted to build the three-dimensional finite element model of the station, and the calculation model is shown in Figure 3. To reduce the impact about the boundary effect, the model size is set as 100m×100m×90m (length × width × height). The whole model contains 1330107 nodes and 1327313 units. Normal constraints are applied to the lateral side of the model, fixed constraints are adopted at the bottom, and the upper surface is set to free. Only gravity is considered to carry out the initial ground stress balance. The surrounding rock and lining structure are simulated by solid element, in which the surrounding rock obeys the Mohr-Coulomb strength criterion and the lining structure obeys the elastic criterion. The calculation parameters about the surrounding rock and lining structure are the same as in Tables 1~2.

The construction process of PBA method is realized by numerical simulation. The main construction procedures are: excavate the pilot tunnels → install the side piles → install the middle column and crown beam → install the middle longitudinal beam and buckle arch of both sides of pilot tunnel and concrete backfill → install the buckle arch of preliminary lining at the arch→ install the buckle arch of secondary lining at arch → excavate the soil of station and install the lining structure.

Since the focus of this paper is the influence of the opening of the side wall on the arch structure, the displacement of the station structure is cleared after the completion of the main structure of the station, then the sidewall opening is carried out.



(a) Overall model *(b) Metro station model*

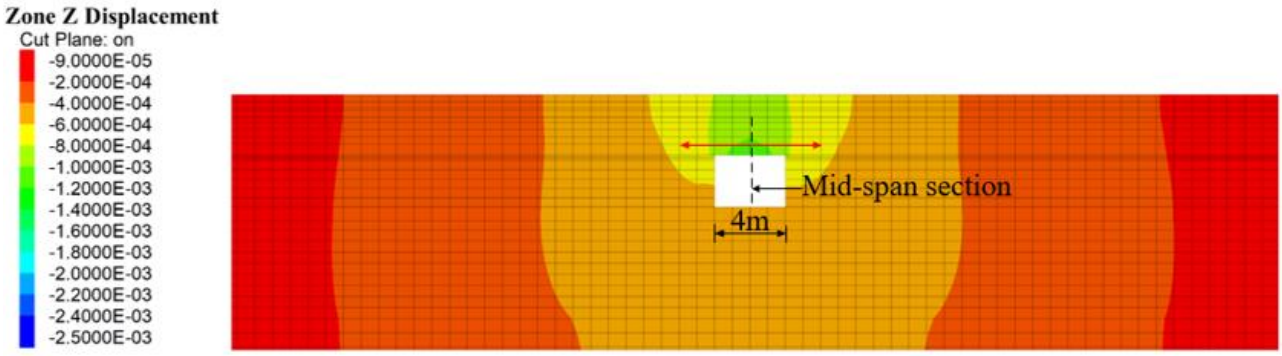
Fig. – 3 Calculation model

The finite element model of the opening area of the side wall is shown in Figure 3b by the actual on-site construction situation. To consider the mechanical response difference of the structure under different opening spans, the calculation conditions of opening spans of 4m, 6m, and 8m are set respectively, and the opening height is set to 3m.

ANALYSIS OF THE CALCULATION RESULTS

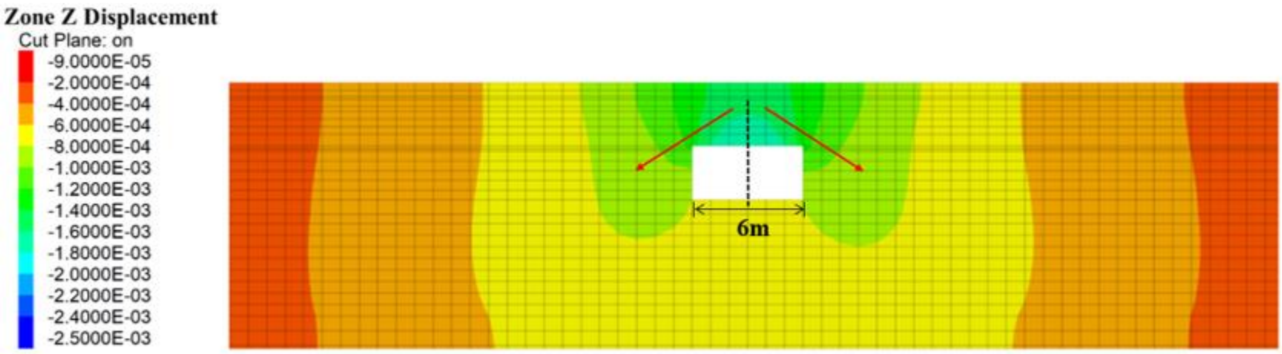
Influence of side wall opening on the deformation law of the side wall

The vertical displacement nephograms of side walls of different opening schemes are extracted after construction, as shown in Figure 4. In Figure 4, the settlement contour lines are symmetrically distributed and centered on the mid-span section. The settlement of the side wall is mainly concentrated above the opening area and spreads from the middle span to the perimeter of the opening. With the increase of opening spans, the settlement influencing area gradually wraps around the opening and expands to the opening periphery.

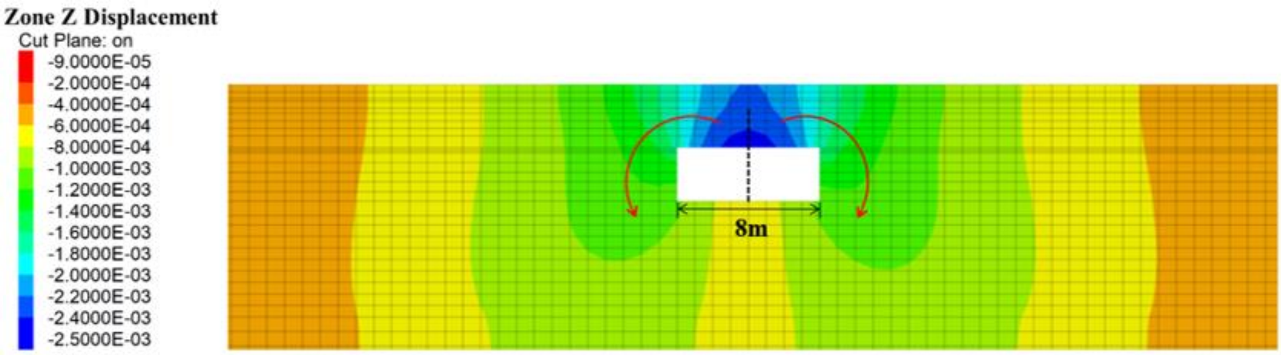


(a) The opening span is 4m

Fig. – 4 Settlement nephogram of the side wall under different opening spans of the side wall /m



(b) The opening span is 6m



(c) The opening span is 8m

Fig. – 4 Settlement nephogram of the side wall under different opening spans of the side wall /m

To analyze the structural deformation law under different opening spans, the settlement curve above the opening circumference of the opening area is extracted by taking the mid-span section as the origin of coordinates, as displayed in Figure 5.

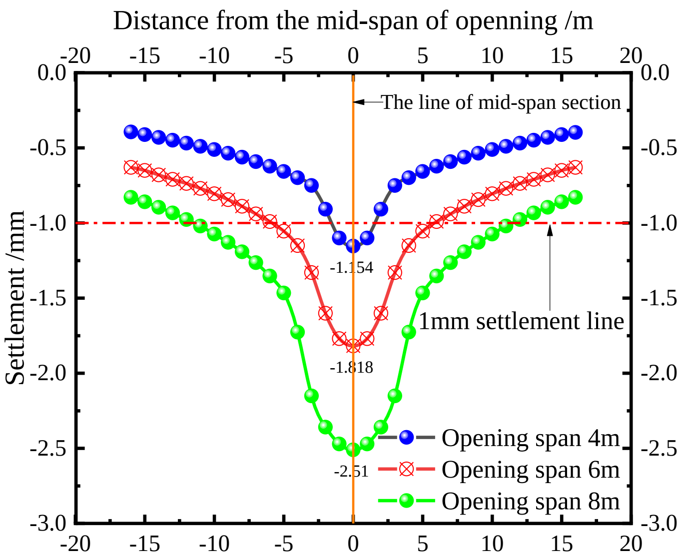
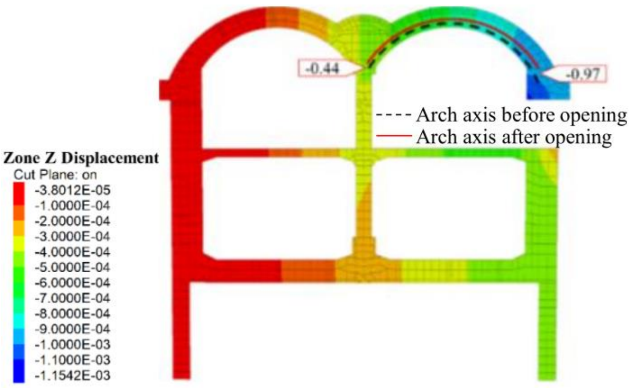


Fig. – 5 Settlement variation laws of the entrance and surrounding locations under different opening spans

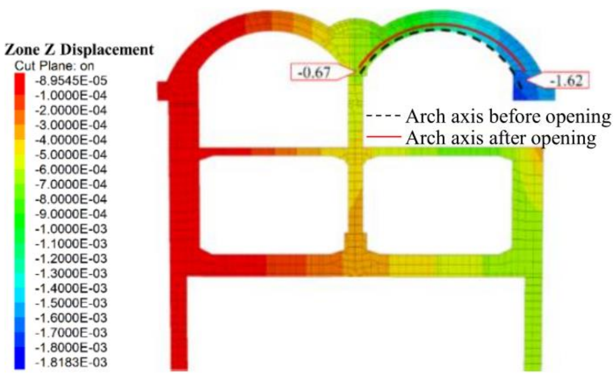
In Figure 5, the settlement of the side wall increases with the opening span, and the maximum settlement occurs in the mid-span position. When the opening span is 4m, 6m, and 8m, the maximum settlement is 1.15mm, 1.81mm, and 2.51mm, respectively. The ratio of settlement increment to span variation under adjacent opening conditions is taken as the gradient, and the two settlement growth gradients are 0.33 and 0.35, respectively, and the gradient increases slightly with the increase of opening span, namely, the growth rate of the maximum settlement value increases slightly with the opening span. Taking 1mm as the reference line of settlement (as shown in the red line in Fig. 6), when the opening span is 4m, the settlement is only slightly larger than 1mm within the opening span. When the opening span is 6m and 8m, the settlement within 6m and 11m from the middle span is greater than 1mm. From the shape of the settling trough, when the distance from the middle span is 1D (D is the opening span), the changing trend of settlement becomes slow. Based on this index, it can be considered that the influence range of the opening span is nearly 1D.

Influence of side wall opening on the deformation law of the whole metro structure

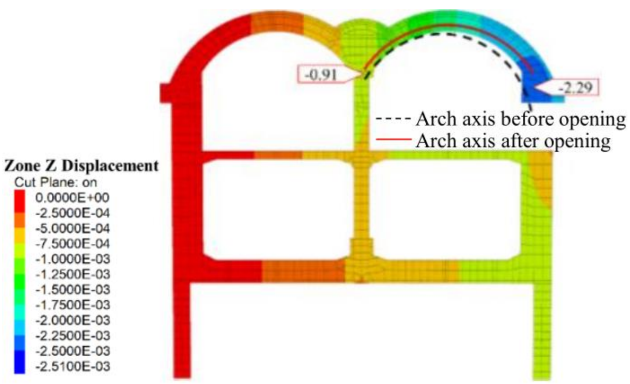
It can be seen from the above analysis that the mid-span part of the opening area is the most unfavorable section about the structure. The vertical displacement diagram of the overall structure of the station under different opening spans of this section is taken, as shown in Figure 6. The settlement curve of the right arch with different opening spans is extracted, as shown in Figure 7.



(a) The opening span is 4m



(b) The opening span is 6m



(c) The opening span is 8m

Fig. – 6 *Settlement nephogram of the whole metro structure under different opening spans of the side wall /m*

In Figure 6, due to the opening of the right side wall, the lining structure above the opening loses original support and then redistribution of the internal force occurs, resulting in significant downward settlement of the structure until the structure reaches equilibrium state, with a maximum value of 2.29mm (for opening span = 8m). The left side wall has not been opened, so its settlement is very small, i.e., forming the asymmetric phenomenon of displacement distribution of the left and right side walls. With the increase of the opening span of the side wall, the overall settlement of the station structure gradually

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increases, but the settlement distribution law remains unchanged. From the distribution law of structure settlement, the structure settlement value decreases gradually as it leaves the opening area, and the right arch structure is in the most unfavorable state, and this law is basically consistent with the literature [22].

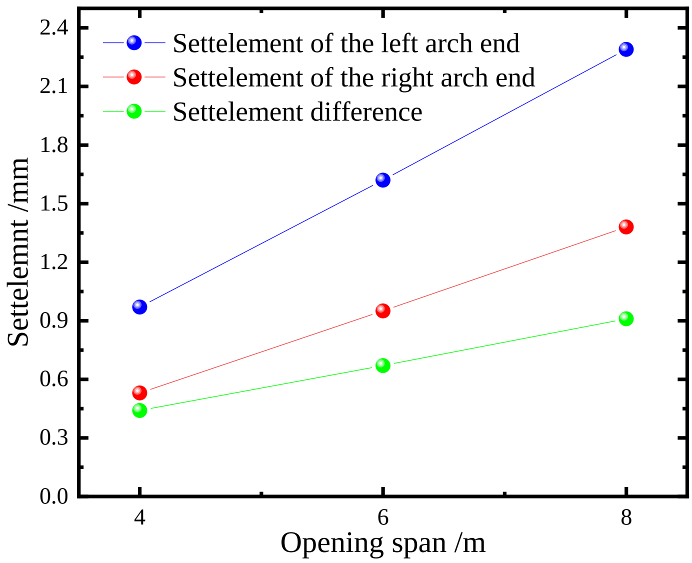


Fig. – 7 Change law of the settlement of the arch end under different opening spans of the side wall

In Figure 7, when the opening span is 4m, 6m, and 8m, the maximum settlement of the left end of the right arch reaches 0.44mm, 0.67mm, and 0.91mm respectively. The ratio of settlement increment to span variation is taken as a gradient, and the two sedimentation gradients are 0.115 and 0.12, respectively, and the gradient increases slightly with the increase of span. The maximum settlement value of the right end of the right arch under different opening spans is 0.97mm, 1.62mm, and 2.29mm, respectively, and the gradient is 0.325 and 0.335, respectively. Obviously, the gradient increases slightly with the increase of the opening span, and the settlement gradient at the right end is greater than that at the left end. With the increase of the opening span, the increased rate of settlement at the right end of the right arch is greater than that at the left end of the right arch. When the opening span is 4m, 6m, and 8m, the differential settlement at both ends of the right arch even reaches 0.53mm, 0.95mm, and 1.38mm, respectively, and the variation gradient is 0.21 and 0.215 respectively. Namely, the gradient of differential settlement increases slightly with the opening spans.

Influence of side wall opening on the mechanics of the arch

It can be seen from the above analysis that the right arch deformation is the largest after the opening of the side wall, which is the most unfavorable structural part. This is because the opening of the side wall will cause the missing part of the lining structure on the right side of the arch, resulting in a large differential settlement on the left and right side of the right arch, thus affecting the safety of the structure. Therefore, this part mainly analyzes the mechanical evolution laws about the right side of the arch under different side wall openings. The secondary lining structure on the right side of the arch is taken as the research object, as shown in Figure 8. The bending moment as well as axial force values about the secondary lining structures of the arch before and after the opening of the side wall are extracted to study the influence of the opening span of the side wall on the mechanical properties of the arch. The internal forces distribution about the secondary lining of the right arch is shown in Figure 9.

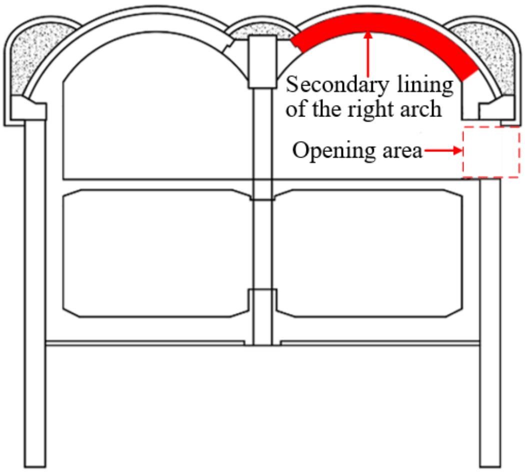
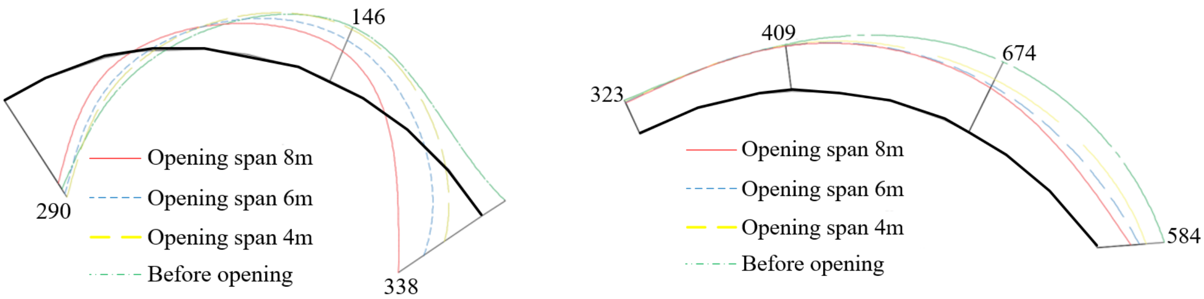


Fig. – 8 Secondary lining diagram of the arch



(a) Bending moments /(kN·m)

(b) Axial forces /kN

Fig. – 9 Internal force distribution of the right arch under different opening spans of the side wall

According to Figures 8~9, before the opening of the side wall, the distribution of bending moment is manifested as tension on the left side of the arch and compression on the outside. The right side of the arch is strained externally and compressed inwards. After the opening of the side wall, the position of the arch foot on the right side of the arch is changed from the outside tension to the inside tension. The tensile and compressive state of the arch has no obvious difference before and after the opening of the side wall, and the axial force value decreases from the arch to the foot of both sides.

In terms of bending moment, the bending moment value of the right arch foot before the opening of the side wall is 68.0kN·m, which is manifested as inner compression and outer tension. The bending moment of this position corresponding to the opening span of 4m, 6m, and 8m is 115.0kN·m, 216.0kN·m, and 338kN·m, respectively, increasing by 69.11%, 217.65%, and 397.06% compared with that before the side wall opening respectively. The stress state is all manifested as inner tension and outer compression, so the tension state of the left side of the arch changed little before and after the opening. For the axial force, the influence caused by the opening is also mainly concentrated on the right side of the arch, that is, near the opening area. Before the opening of the side wall, the axial force value is 584kN, while the axial force value corresponding to the opening span of 4m, 6m, and 8m is 425kN, 364kN, and 294kN respectively, which decreases by 27.23%, 37.64%, and 49.66% compared with that of before the side wall opening. That is, the increasement of axial forces is less than that of the bending moment. Therefore, the opening construction greatly influences the bending moment at the arch foot of the arch structure above the opening area.

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The influence of side wall opening on the arch safety

From the above analysis, it can be concluded that the side wall opening greatly influences the force as well as the deformation of the right arch foot. The bending moments as well as axial forces about the secondary lining structure are obtained to check the safety factor, and the safety of the secondary lining of right arch before and after the opening is analyzed. The distribution law of safety factor of the arch body is shown in Figures 10.

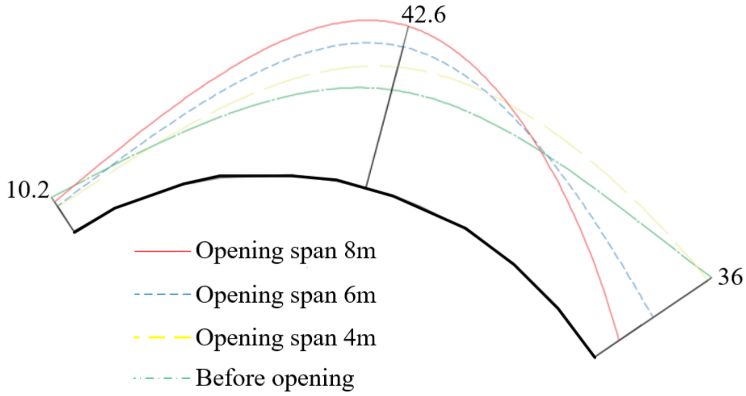

Fig. – 10 Distribution law of the arch safety factor under different opening spans of the side wall

In Figure 10, the influence of side wall opening construction on arch safety factors mainly focuses on the arch body and right arch foot. With the increasement about the excavation span, the safety factor about the arch continues to increase, but that of the right arch foot continues to decrease. Before the opening of the side wall, the safety factor of the right arch foot is 36.0. When the opening span of the side wall is 4m, 6m and 8m, the safety factor of this position is 34.9, 14.6 and 7.5, which is 3.06%, 59.44% and 79.17% lower than that before the opening of the side wall, respectively. When the excavation span increases from 4m to 6m, the safety factor of the position drops sharply. The safety factor of the left side of the arch changes little with the increase of the opening span. From the overall safety factor distribution, when the opening span is less than 6m, the most dangerous position is located at the left arch foot. When the opening span is 8m, the most dangerous position shifts to the right arch foot.

CONCLUSION

Based on the Tianhe East Station Project of Guangzhou Metro Line 11, this paper studies the change law deformation and mechanics of the arch structure of the metro caused by the opening of the side wall with the PBA method. The important findings are listed below.

(1) The settlement caused by the opening of the side wall is mainly concentrated in the upper part of the opening area and gradually expands around the opening area with the increase of the opening span. The affected area is mainly concentrated in the range of 1 time the opening span. The maximum settlement occurs in the middle and upper span, and the growth rate increases with the opening spans.

(2) The arch near the opening area is greatly affected by the opening of the side wall. With the increase of the opening span, the settlement growth trend of the right side of the arch is significantly larger than that of the left side of the arch, and the difference in settlement on both sides is up to 1.38mm.

(3) The construction of the side wall opening causes the arch foot of the opening position to be strained from the outside to the inside. When the excavation span is 4m, 6m, and 8m, the bending moment increases by 69.11%, 217.65%, and 397.06%, and the maximum axial force decreases by 27.23%, 37.64%, and 49.66%, respectively, compared with that before the construction of the side wall.

(4) The influence of side wall opening construction on arch safety factors mainly focuses on the arch body and right arch foot. With the increasement in the excavation span, the safety factor about the arch body continues to increase, while that of the right arch foot continues to decrease, and the safety factor of the left arch foot change little. When the excavation span increases from 4m to 6m, the safety factor at the right arch foot drops by 59.44%.

(5) From the overall safety factor distribution, when the opening span is less than 6m, the most dangerous position is located at the left arch foot. However, when the opening span is 8m, the most dangerous position shifts to the right arch foot.

It should also be noted that the influence of the conditions about symmetrical/asymmetrical opening of left and right side walls as well as the opening shapes on the arch structure of station with PBA method is not considered yet in this paper, more future work can be conducted on it.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

DATA AVAILABILITY

All data, models, and code generated or used during the study appear in the submitted article.

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