Research on Construction Mechanical Behaviour of Connecting Aisle in Shield Tunnel

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Abstract. Based on connecting aisle of shield tunnel projects in Shenzhen Metro Line 5, in accordance with the complex space structure formed by shield tunnel and connecting aisle, the study chose a three-dimensional numerical model linked by structure and surrounding rock for the calculation and analysis of the stress effect. It showed that due to the connecting aisle construction, the symmetrical deformation of shield tunnel was transformed into unsymmetrical deformation and the crossing segment produced a phenomenon of stress concentration, which caused the production of the upper and lower section of the overall tension of adverse stress form in side opening segment and contact channel structure side themselves. The tension zone of the whole structure was to connect through the lower half of the channel and the surrounding part of segment, so highly attention should be paid to the force structure and waterproof both in design and construction period.

1. Introduction

The connecting aisle of urban subway is generally in the middle part of running tunnel and the lowest position of line, and the connecting aisle construction complicated with water-collecting pump and drainage pump in order to link two tunnel, water collection, water drainage, fire proof and so on. The construction of connecting aisle is bound to change the forced state in shield tunnel, form the very adverse force way at cross connection structure, produce stress concentration and make the cross segment connected with connecting aisle become the weak link in the force [1], [2]. Many studies of mechanical behaviour in segment construction were carried out by domestic and foreign scholars, HE et al.[3] researched the segment stress change by shield tunnel connecting aisle construction. HE et al.[4] monitored and numerical simulation the segment mechanical characteristics in No.1 line of Nanjing subway construction, the segment stress characteristics of shield tunnel crossing sandy soil was studied. YE et al. [5] analyzed the influencing factors of shield segment during construction period and pointed out that construction load of lining segment has typical three-dimensional characteristics and uncertainty. Based on fluid-solid coupling, XIA et al.[6] used numerical analysis and field measurement to research structural internal force of shield tunnel construction under high hydraulic pressure. ZHOU et al.[7] conducted in-situ test on shield segment of dot shield tunnel in Shanghai metro. Through site monitoring of deep shield tunnel lining segments, Jin SAITO and Atsushi KOIZUMI [8] proposed segment erection process was a three-dimensional mechanical behaviour and researched on segment stress change during construction. Jin SAITO and Shigreu KUROSAKI [9] monitored segment stress of deep tunnel and simulated segment construction process under large depth by three-dimensional finite element. Because of the connecting aisle construction
ineffective. No.4 line of Shanghai metro accident in July 1, 2003, resulting in direct economic losses of up to 1.5 billion yuan, caused a national shock. But in the domestic design, the main tunnel shield variation of displacement and stress is not very clear in the connecting aisle construction by mining method[10], [11]. In order to ensure the safety of connecting aisle construction and reduce the impact of the main tunnel with connecting aisle construction, the process of displacement and mechanical changes during segment removal, excavation, lining application is studied by using FLAC 3D, and the feasibility of the connecting aisle construction is verified to lay a foundation for further study.

2. Engineering background

2.1. Project description

The right line of Shenzhen Subway Line 5 Yi Jing station to Huang Beiling station is 1051m, and the left line is 1078m. The shield zone includes two portal parts and one connecting aisle. According to human evacuation, the clearance of connecting aisle is determined as arches-straight wall section, size of 2.1m (wide) × 2.3m (high). The connecting aisle and pumping station are constructed by mining method with composite lining, leading conduit as an auxiliary reinforcement measure and grouting with cement mortar for the external formation. The connecting aisle and pump house are in rocks of grade V, and covering soil is 13m. The upper covering soil of shallow tunnel is about 2m, then as following: soft soil layer, gravelly cohesive soil layer, completely weathered granite, intermediary weathered granite. The cross section and the longitudinal section of the connecting aisle is shown in Figure 1 and Figure 2.

2.2. Construction Procedures of Connecting Aisle

According to the construction conditions, combined with the subway connecting aisle construction experience, through technical and economic comparison, the construction scheme was using the soil grouting reinforcement and tunnel excavation. Grouting reinforcement and excavation were carried out in the tunnel, main construction procedures were as follows: ①Ground consolidation in the tunnel(Figure 3-a); ②Erection of support in the shield tunnel(Figure 3-b); ③Check whether the effect of soil reinforcement to meet the strength, impermeability requirements; ④Removal of the opening segment in right line(Figure 3-c); ⑤Construction of the protective door; ⑥Construction of connecting aisle lining, secondary lining(Figure 4-d), tunnel portal part(Second lining at the bottom of the pumping station is not needed); ⑦ Construction of pump house initial lining; ⑧ Wallboard construction; ⑨Removal of the tunnel support. Figure 1 shows the main construction process.

![Figure 1. Connecting aisle in longitudinal direction](image1)

![Figure 2. Connecting aisle in cross direction](image2)
3. Numerical analysis of shield tunnel and connecting aisle construction

3.1. Computational mechanics model and related parameters

According to design working drawing of connecting aisle reinforcement section, numerical calculation model of connecting aisle is shown in Figure 4 and the cross connection structure is shown in Figure 5. The influence scope of stress and displacement is in the range of 3 to 5 times tunnel diameter after excavation, in order to eliminate the calculation error induced by size effect, along the tunnelling direction, the size is 60m (Equivalent to 40 rings, each ring is 1.5m) and the size is 80m along the traverse of tunnel section. However, along the vertical direction, the thickness of the casing soil can be determined according to the actual depth of connecting aisle to determine. And downward should consider the calculating influence scope, the choice of strata thickness is 22m. The study adopted ideal elastic-plastic constitutive relation and Drucker-Prager yield criterion for numerical simulation. Due to the effect of segment joint, the reduction factor of segment stiffness is taking value 0.75 s. Table 1 shows the calculation parameters of related materials.
Table 1. Computation parameters of various materials

| Soil layer                  | Density (kg/m³) | C (KPa) | Φ (°) | Poisson ratio μ | Elastic modulus (MPa) |
|-----------------------------|-----------------|---------|-------|----------------|----------------------|
| Plain fill Q°tl             | 2300            | 18      | 14    | 0.42           | 8                    |
| Silty clay Q4°pl            | 2000            | 30      | 5     | 0.38           | 18                   |
| Gravelly clay Qg°           | 1810            | 31      | 22    | 0.33           | 33                   |
| Completely decomposed granite γs° | 1770        | 45      | 26    | 0.31           | 80                   |
| Intermediary weathered migmatite γs° | 2570    | 1500    | 35    | 0.28           | 8000                 |
| Segment                     | 2500            | /       | /     | 0.17           | 31500                |
| Initial support of connecting aisle | 2500    | /       | /     | 0.2            | 28 000               |
| Secondary lining of connecting aisle | 2500    | /       | /     | 0.2            | 31 500               |

3.2. Boundary conditions and initial stress field
Adopted displacement boundary conditions, computational model applies vertical constraints in the bottom of the model and horizontal constraints in both sides of the model, while the upper surface is free surface. Because of additional load on ground surface, the load P0=20kPa is applied at the top of the model. The initial stress field is generated by the dead weight and tectonic stress is not considered.

3.3. Numerical simulation process
In order to master the complex mechanic characteristic of spatial cross connection structure composed of shield tunnel and connecting aisle, the numerical simulation process of connecting aisle construction is as follows:
To determine the release ratio of stress at excavation face, the displacement release ratio is needed to obtain. Base on the numerical calculation of node displacement results, the release ratio of horizontal and vertical displacement is obtained from the average displacement release factor of each node. It is suggested that the load release ratio and its displacement release ratio is approximately same.
① Shield tunnel excavation under the rock wool-hole state, the release rate of surrounding rocks load is 30%; after the tunnel segment application, the release rate is 70%.
② The mining method is used in connecting aisle construction, it is assumed that the whole construction process is divided into three steps, each step 2m.
③ Connecting aisle excavation under wool-hole state, the release ratio of stress is 30%, after connecting aisle initial support application, the release ratio of stress is 70%.

4. Analysis of calculation results
4.1. Analysis of Structural Stress
The principal stress distribution of segment is shown in Table 2, after the finish of shield tunnel construction but before the connecting aisle construction, there is a greater tensile stress in the vault and arch bottom of the main tunnel, the maximum tensile stress is 0.27MPa and the maximum compressive stress is 3.69MPa in both hance sides. The tensile stress of cross connection segment structure is increasing in different degree both in the open hole side and away from the side due to the connecting aisle construction, but the compressive stress of the segment in open-hole side is decreasing gradually with the construction progress, while the compressive stress of the segment away from the open-hole side is increasing gradually, shown in Figure 6 and Figure 7.
Because of the connecting aisle construction, the original force way of main tunnel is under stress redistribution, which will cause the production of stress concentration in cross segment, and will also cause the occurrence of adverse stress form which the whole tension is in upper and lower sections in the open-hole side segment. Therefore, it is very necessary to apply effective strengthening and enough supporting in the segment vicinity of the connecting aisle during the construction. The principal stress distribution of the connecting aisle in every construction stage is shown in Table 3, with the construction progress, the variation range of the maximum tensile stress in the structure decreased gradually and the maximum value is in arch bottom vicinity of the open-hole side; while maximum compressive stress increased gradually and the maximum value is in hance away from open-hole side. There is a very large tension stress zone in structure itself caused by the construction of connecting aisle, which caused overall tension situation of structure of the upper and lower section, and the situation is much unfavorable.

Table 3. Stress of connecting aisle

| Construction steps                      | Tensile stress/MPa | Compressive stress /MPa |
|-----------------------------------------|--------------------|-------------------------|
|                                        | Maximum            | Position                |
| Complete double line of shield tunnel   | 0.27               | tunnel floor            |
| Excavation step 1 of connecting aisle   | 0.4                | bottom in open-hole     |
| Excavation step 2 of connecting aisle   | 1.89               | bottom in open-hole     |
| Excavation step 3 of connecting aisle   | 1.75               | bottom in open-hole     |
|                                        | Maximum            | Position                |
|                                        | 3.69               | hance                   |
|                                        | 3.83               | horizontal position in open-hole |
|                                        | 4.08               | horizontal position in open-hole |
|                                        | 4.26               | horizontal position away from open-hole |

It can be seen from Figure 8 and Figure 9, the arch bottom and vault in the connecting aisle is the max region of positive moment, but the moment when mutation is in the lower part of the interface, there is appearance of a larger negative moment. The tensile area of the whole structure was lower half part of
connecting aisle and segment in tunnel intersection, highly attention should be paid to both structure stress and waterproof functions of these regions in design and construction period.

4.2. Analysis of Structural deformation

It is shown in Table 4 and Table 5, during the connecting aisle excavation, the symmetric deformation of shield tunnel is converted into asymmetric deformation and is developing toward the side of connecting aisle. The structural stiffness is decreasing due to the segment demolition and connecting aisle construction, as a result, the deformation of the segment close to connecting aisle is significantly bigger than the segment in the other side. During excavation, the increasing amount of deformation of the segment in open-hole side is almost three times bigger than the segment in the other side. Because of connecting aisle construction, there is a remarkable additional deformation along the vertical direction and horizontal direction in the cross segment, especially in the open-hole side. The maximum additional deformation in vertical direction is 2.19mm and the maximum additional deformation in horizontal direction is 9.06mm. It can be seen from Table 5, in the process of excavation, the primary deformation of the structure is vertical deformation in vault, the maximum settlement is 24.39mm and the deformation in other part of the structure is relatively small. With the increasing of construction progress, the deformation in every part of the structure is increasing at different degrees except for uplift in the arch bottom.

| Construction steps                          | Vertical deformation(mm) | Horizontal deformation(mm) | Position              |
|---------------------------------------------|--------------------------|----------------------------|-----------------------|
|                                            | Tunnel roof              | Tunnel floor               | Tunnel roof           | Tunnel floor           | open-hole side | away open-hole side |
| Complete double line of shield tunnel       | -4.83                    | -2.16                      | 5.44                  | 0.33                  | open-hole side | away open-hole side |
| Excavation step 1 of connecting aisle       | -6.89                    | -1.19                      | -3.46                 | -0.24                 | open-hole side | away open-hole side |
| Excavation step 2 of connecting aisle       | -5.25                    | -2.21                      | -5.42                 | -0.29                 | open-hole side | away open-hole side |
| Excavation step 3 of connecting aisle       | -7.02                    | -1.15                      | -3.62                 | -0.28                 | open-hole side | away open-hole side |

| Construction steps                          | Vertical deformation     | Horizontal deformation     | Position              |
|---------------------------------------------|--------------------------|----------------------------|-----------------------|
|                                            | Tunnel roof              | Tunnel floor               | Arch foot at the top  | Arch foot at the bottom |
| Excavation step 1 of connecting aisle       | 5.78                     | 0.52                       | 1.15                  | 0.33                  |
| Excavation step 2 of connecting aisle       | 16.77                    | 0.53                       | 4.67                  | 0.35                  |
| Excavation step 3 of connecting aisle       | 24.39                    | 0.55                       | 6.32                  | 0.39                  |

4.3. Comparison of calculated value and monitoring value on ground settlement.

Figure 10 is the monitoring point arrangement on ground settlement of connecting aisle, to analyze the difference of calculation results and measured results based on numerical simulation. The maximum settlement value of monitoring section in connecting aisle by numerical simulation is 6.71mm, the maximum settlement is above the axis center of connecting aisle, shown in Figure 10 and Figure 11.
Field monitoring data shows that the maximum settlement is 5.93 mm, from the position and value of the maximum settlement, the position of maximum settlement is consistent with calculation results. The maximum settlement by numerical simulation is close to the monitoring value and calculated value is 10% larger than the monitoring value. From the influence scope, calculated results are similar with monitoring results.

![Figure 10. Monitoring points layout](image1)

![Figure 11. Calculated and measured value of settlement](image2)

5. Conclusions
By applying numerical simulation to further investigate mechanical behavior of complicated spatial structure composed of shield tunnel and connecting aisle, four conclusions are listed as follows:
① With the construction process, the deformation of cross structural of shield tunnel and connected aisle change from symmetric deformation to unsymmetrical deformation of connected aisle, and the local deformation is significantly in cross connection segment.
② Because of the connecting aisle construction, the original force way of main tunnel is under stress redistribution, which will cause the production of stress concentration in cross segment, and will cause the occurrence of the adverse force way in open-hole side and connecting aisle segment.
③ The symmetrical deformation of shield tunnel was transformed into unsymmetrical deformation and stress concentration of connecting aisle due to the connect aisle construction. The adverse force way was occurred in segment with openings and connecting aisle.
④ The tensile area of the whole structure was lower half part of connecting aisle and segment in tunnel intersection, highly attention should be paid to both structure stress and waterproof functions of these regions in design and construction period.

6. References
[1] Zhang Z Q and He C 2005 Study on construction of cross connection of shield tunnel and connecting aisle by freezing method[J]. Chinese Journal of Rock Mechanics and Engineering. 24, 18(Sep.2005), 3211-3217.
[2] Zhang Z Q and He C. 2002 Research on mechanical behaviour of construction of link line and shield tunnel on No.2 line of Guangzhou metro[J]. Journal of the China Railway Society. 24, 6(Dec.2002), 89-92.
[3] He M D, Le G P and Liu J 2007 Channel of shield tunnel construction segment longitudinal stress change[J]. Urban Rapid Rail Transit.20, 3(Jun.2007), 56-59.
[4] He C and Zeng D Y. 2007. Research on mechanical characteristics of metro shield tunnel segment in sandy strata[J]. Rock and Soil Mechanics. 28, 5(May.2007), 909-914.
[5] Ye F, He C and Wang S M. 2011 Analysis of mechanical characteristic of shield tunnel segments lining and its influence during construction[J]. Rock and Soil Mechanics. 32, 6(Jun.2011), 1801-1807+1812.
[6] Xia W Y, He C, Yan Q X, et al. 2007. Structural internal force analysis of rock shield tunnel under high water pressure during construction[J]. Chinese Journal of Rock Mechanics and Engineering. S2 (Dec.2007), 3727-3731.

[7] Zhou W B, Zheng Y F and T Li 2005 Mechanics characteristics study of segment in double-o-tube tunnel under In-situ test method during its construction process [J]. CHINESE QUARTERLY OF MECHANICS. 3 (Sep.2005), 459-463.

[8] Jin S, Shigeru K, Akira T et al 2008. The damage control of the segment during tunnelling in a large depth shield tunnel[J]. Doboku Gakkai Ronbunshuu F. 64, 2(Jun.2008), 173-184.

[9] Jin S, Shigeru K, Akira T, et al. 2007. Damage factors of the segment during tunnelling in a large depth shield tunnel[J]. Doboku Gakkai Ronbunshuu F. 63, 2(Jun.2007), 200-211.

[10] Wang H and Zhu W B 2004 Study on the control technology of frozen method for connecting passage in shield-driven metro tunnel in soft soil[J]. Modern Tunnelling Technology.41, 3 (Jun.2004), 17-21.

[11] Li X L, Peng L M, Wu T, et al 2009 Numerical simulation on mechanical behaviour of connecting passage in shield tunnel [J]. RAILWAY STANDARD DESIGN. 4(Aug.2009), 102-105.