Key technology of overlapping tunnel construction with earth pressure balance shield method in rheological strata

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Abstract: Based on the existing bridge structure of Foshan Metro Line 2, this paper summarizes the engineering geological conditions of the overlapping tunnels, uses three-dimensional finite element analysis, establishes an engineering geological model, and analyzes the parameters of the upper tunnel in the disturbed surrounding rock, shield attitude control and its influence on the tunnels already built on the lower floors. Finally, the monitoring and control results during the construction of the shield tunneling of the overlapping tunnels are analyzed to verify that the construction of the overlapping tunnels in the rheological strata has a greater impact on the ground settlement of about 20m, and the soft foundation reinforcement of the lower tunnels in advance can make the soil settlement greatly reduced, and the stress concentration area is reduced. After the double-tube jet-grouting piles are reinforced, the shield tunneling of the upper overlap tunnel has little effect on the existing tunnel below, and the reinforcement effect is better, which can make the construction go successfully. The analysis results of this paper can provide decision support for the construction of overlapping tunnels in rheological strata.

1. Introduction
As the urban rail transit soars in China and gradually develops into a cluster or network in Cities in recent years, the underground tunnel construction is inevitably restrained by space, resulting in more and more overlapping tunnel cases. [1] The overlapping tunnel is a construction method for small spacing tunnels, which often involves above crossing, undercrossing, or oblique crossing. In China, the shield method is barely applied for overlapping tunnel construction in soft rheological strata, let alone the construction of small spacing tunnels. It is essential to establish a complete technology system for overlapping tunnel construction in rheological strata with the shield method.
Rao et al. (2018) [2], aiming at the short distance overlapped tunnel in silt reclamation stratum, explored the effects of the construction of the new shield tunnel on the surrounding environment and proposed a specific reinforcement scheme. Wei et al. (2020) [3] studied the impact of the upper shield excavation at the overlapping section of the tunnel on the vertical displacement of the existing tunnel underneath, and deduced the equation for calculating the vertical deformation of the existing tunnel. Wang et al. (2017) [4] took the overlapping section of Zaoshanlu-Licun Station Interval of Qingdao Metro as the research object to analyze the surrounding rock stability and construction economy under different excavation spacings. Nematollahi et al. (2019) [5] researched the impact of parallel crossing of tunnels at the two-tube section upon the pile foundation of the ring road overpass through the three-dimensional digital simulation based on the Shiraz Metro Project in Iran. Li (2020) [6] adopted the numerical simulation to study the deformation settlement of an old bridge and internal force variation of overlapping tunnels, and verified the effectiveness of the numerical simulation and reinforcement measures by monitoring data. Jiang et al. (2018) [7], based on the special construction conditions of two-tube shield tunnel of Shenzhen metro line 9 overlapped over the existing two-tube tunnel of existing metro line, studied the laws of horizontal and vertical deformation of existing tunnel tubes induced by new shield construction, and analyzed the influence of earth pressure on the deformation of existing tunnel tubes. Fang et al. (2020) [8] investigated the characteristics of vertical soil deformation induced by fully overlapping tunnels constructed using a tunnel boring machine (TBM). Li et al. (2017) [9] used the three-dimensional finite element method to simulate and analyze the tunnel with a horizontal tunnel crossing under the existing tunnel. Ngoc-Anh et al. (2014) [10] applied the full three-dimensional numerical simulation method to study the impact of the two-tube tunnel construction in soft soil on the excavated tunnel or the ground.

The above analysis reveals that although scholars both at home and abroad have fully studied the overlapping tunnel shield construction technology, there are few researches on the overlapping tunnel construction with the shield method in rheological strata. By taking Foshan Metro Line 2 as an example, this paper analyzed the settlement parameters of the ground in the shield construction area induced by the rheological strata, studied the soft strata reinforcement technologies, and summarized the mutual effect between overlapping tunnels during construction.

2. Project Overview

Liantang~Zhangcha station interval runs west to east, parallel to the planned Line 4, laid along Jihua 2nd Road. The minimum clear distance between the outer contours of the two tunnels is 5 m. After passing through Foshan-Kaiping Expressway and Huabao Road under-crossing tunnel, the right track of line 2 crosses the left track at YDK29 + 447, as shown in Figure 1.

![Fig. 1 Overlapping section of Liantang~Zhangcha station interval](image)

The overlapping section of Liantang~Zhangcha station interval mainly crosses the strata from top to bottom: <1-1> plain fill, <1-2> miscellaneous fill, <2-1A> silt, <2-4-2> soft plastic cohesive soil, <3-1> silt and fine sand, <6> completely weathered mudstone and sandstone, <7-1> strongly weathered mudstone, and <8-1> strongly weathered sandstone composite stratum. As shown in Figure 2, these strata feature large thickness variation, poor uniformity, and heterogeneous hardness of rock, greatly affecting the shield construction.
In addition, within the station interval, the surface water is not developed. Only a river flows 35 m away from the left side of the YDK29+100~+490 m Section. This river flows all year round with abundant water.

Groundwater is mainly divided into Quaternary pore water and bedrock fissure water. The Quaternary pore water occurs in the upper Quaternary loose accumulated, residual, and fully weathered rock stratum. Because the aquifers are slight–weak permeable and only the 1.1~3.4 m thick silt and fine sand layers lenticularly distributed in the YDK29+300~+450 Section are medium permeable, the Quaternary pore water content is low. According to the survey and borehole water level observation, the long-term stable water table depth is generally 1~2 m (elevation 1.0~3.0 m) in the station interval. The bedrock fissure water mainly occurs in the joints and fissures of strongly and moderately weathered rock strata, featuring non-uniformity. Because joints and fissures develop irregularly and unevenly, in the areas where joints and fissures of the rock mass develop, the groundwater is rich and highly permeable, but not vice versa. As the overlaying Quaternary soil layer is less permeable, forming a relative aquiclude, the bedrock fissure water has a certain bearing capacity. Generally, in the station interval, the joints and fissures in the argillaceous cemented sand and mudstone are poorly interconnected, so the bedrock fissure water is not rich.

Fig. 2 Geological conditions of the overlapping section

3. Shield Construction Plan for Overlapping Tunnels

The current shield construction method for overlapping tunnels is mainly from the lower tunnel to the upper tunnel. For the lower tunnel, the shield excavation is a conventional earth pressure shield construction, and the high-strength segments and bolts are used at the short-distance overlapping section, to build a permanent structure which acts as a stable support for the construction of the upper tunnel. In order to alleviate the impact of the upper tunnel construction on the completed tunnel, a temporary support system matching with the lower tunnel structure should be erected within a certain distance in front and rear of the TBM working plane of the upper tunnel. At the same time, the shield excavation parameters and attitude in the upper tunnel should be controlled, and the impact of the construction on the completed tunnel should be monitored in real time.

At the overlapping section of Liantang-Zhangcha station interval, the left line is mainly in the <2-1A> silt stratum, and the right line is in the <6> completely weathered mudstone and sandstone strata. During the left line tunneling, the natural water content of the silt stratum is higher than the liquid limit, the void ratio is large, the compressibility is particularly high, and the strength is extremely low, so the shield construction may disturb the silt stratum, causing uneven settlement easily. Due to the high risk, the shield construction must be optimized and controlled in the process. The thrust is controlled between 1000 KN ~ 1500 KN; the cutter head rotates at 2.0 rmp; the excavated soil volume per ring is within 56 m³; the synchronous grouting pressure is between 0.2 ~ 0.3 MPa; and the pressure at the top of the soil bin is within 0.3 MPa.

In this paper, the relevant data models were established, together with the GTS NX2018 software and three-dimensional finite element method, to analyze the deformation of the existing right tunnel and the ground on the left line at YDK29 453.182 during the shield construction. The calculation assumes that: (1) the ground surface and soil horizon are distributed in homogeneous horizontal layers;
(2) lining segments are regarded as a whole; and (3) the thrust of the cutter head is simulated by applying a force on the shield excavation surface. The established finite element model is a three-dimensional network with a length of 60 m, a width of 30 m, and a height of 30 m, consisting of totally 38,025 elements and 52,914 nodes. The lower is the existing tunnel on the right line, and the upper is the excavation surface of the left line, as shown in Figure 3.

This manifests the impact of the upper tunnel shield construction on the ground and the right tunnel segments. As shown in Figure 4, the soil displacements concentrate on the upper left part of the shield excavation. This is because the left tunnel is turning to the left, and the maximum ground displacement reaches 14 cm. There will be a safety risk, so the strata must be reinforced before the left tunneling. From Figure 5, to reinforce the overlapping section of the tunnel, double-tube jet grouting piles should be arranged 3 m outside the tunnel on the plane and vertically 0.5 m from the ground to the stable stratum at the bottom of the tunnel. As shown in Figure 6, double-tube jet grouting piles are Ф600 @450mm engaged and staggered.
To re-analyze the tunneling on the reinforced left line at YDK29 453.182, the deformation of the right tunnel and ground should be considered. The reinforced finite element model is a three-dimensional network with a length of 60 m, a width of 30 m, and a height of 30 m, consisting of totally 54,709 elements and 61,451 nodes, as shown in Figure 7.

As shown in Figure 8, after the double-pipe jet grouting pile is reinforced, the stress concentration area is reduced, and the soil settlement is decreased to 6.9 mm, which avoids the risk of uneven settlement induced by the disturbance to the underlying silt stratum. As shown in Figure 9, the maximum displacement of the existing tunnel segments on the right line is 0.9 mm, indicating a good reinforcement effect; therefore, the construction can be carried out smoothly.
To sum up, using the three-dimensional finite element method for numerical simulation on the construction method of the lower right tunnel first and the upper left tunnel later, the following conclusions can be drawn:

1. Before reinforcement, when the lower right tunnel is holed through, the maximum surface settlement will be 14 cm after the upper left tunnel is excavated, the stresses will concentrate along the shield construction direction, and the uneven settlement will be induced by the disturbance to the silt stratum; therefore, in the subsequent double-tube jet-grouting pile reinforcement, in addition to the soil mass around the two tunnels, the soil mass in the middle of the tunnels should also be reinforced. The simulation shows that this method can obtain good results.

2. The upper left tunnel is holed to a single side groove width of about 20 m, and within about 20 m in front of the shield construction, the soil mass is disturbed by the construction.

3. It is expected that the surface settlement will be controlled within 10 mm during the lower right tunneling. After the upper tunnel is excavated, it is expected to be controlled within 30 mm.

4. Before reinforcement, when the existing right tunnel is excavated on the upper left line, the maximum settlement of the segments reaches 1.4 mm. After the double-tube jet grouting piles are reinforced, the maximum settlement is 0.9 mm, greatly reducing the segment deformation.

4. Research on Monitoring and Control during Overlapping Tunnel Construction

The overlapping section of Liantang–Zhangcha section interval is a major risk point, and requires intensive monitoring. For this reason, when the left line is crossing the overlapping section, the monitoring focuses are:

① Surface settlement;
② Pipeline settlement;
③ Convergence of the right line segment; and
④ Right line pipeline settlement.

By observing the surface settlement and the segment convergence and settlement in the right tunnel, the deformation of the ground and segments in the right tunnel can be ascertained in time, for decision-making of the best on-site construction method.

4.1 Surface settlement

As shown in Figure 10, the surface survey points of the overlapped section concentrate on Monitoring Sections 16-18. The specific surface settlement data during the left line tunneling are shown in Tables 1, 2, and 3.

It can be seen from Tables 1, 2, and 3 that during the left line tunneling, the ground surface was slightly uplifted to the maximum value of 24.78 mm, corresponding to the survey point DBC-17-17, and the grouting was stable after the TBM passed through the point. As of July 4, the cumulative settlement value was 21.83 mm at the survey point which was stable. During the shield construction, there were no obvious abnormal conditions such as slurry eruption and collapse on the surface.
### Table 1 List of Settlement of Monitoring Section 16

| Survey Point No. | 2018/5/28 | 2018/6/1 | 2018/6/5 | 2018/6/9 | 2018/6/13 | 2018/6/17 | 2018/6/21 | Average Speed (mm/d) |
|------------------|-----------|----------|----------|----------|-----------|-----------|-----------|----------------------|
| DBC-16-08        | 0.00      | 4.21     | 9.32     | 9.71     | 7.67      | 7.22      | 7.35      | 0.31                 |
| DBC-16-20        | 0.00      | 5.22     | 4.76     | 7.62     | 6.37      | 3.98      | 3.69      | 0.15                 |
| DBC-16-21        | 0.00      | 1.47     | 1.84     | 2.18     | 3.85      | 0.89      | 0.53      | 0.02                 |
| DBC-16-22        | 0.00      | 0.73     | 1.26     | 1.49     | 5.04      | 1.54      | 1.36      | 0.06                 |
| DBC-16-24        | 0.00      | 0.79     | 1.26     | 1.00     | 9.60      | 5.31      | 5.09      | 0.21                 |
| DBC-16-25        | 0.00      | 0.92     | 1.76     | 1.22     | 5.64      | 0.16      | 0.13      | 0.01                 |
| DBC-16-26        | 0.00      | 0.85     | 1.68     | 0.68     | 6.55      | 0.37      | 0.03      | 0.00                 |
| DBC-16-27        | 0.00      | 1.56     | 1.58     | 1.28     | 9.10      | 4.88      | 4.58      | 0.19                 |
| DBC-16-28        | 0.00      | 0.84     | -0.21    | 1.04     | 8.95      | 9.62      | 9.28      | 0.39                 |

### Table 2 List of Settlement of Monitoring Section 17

| Survey Point No. | 2018/6/9 | 2018/6/12 | 2018/6/15 | 2018/6/18 | 2018/6/21 | 2018/6/27 | 2018/7/4 | Average Speed (mm/d) |
|------------------|----------|-----------|-----------|-----------|-----------|-----------|----------|----------------------|
| DBC-17-06        | 0.00      | 0.73      | 15.86     | 11.49     | 11.46     | 8.94      | 9.14     | 0.37                 |
| DBC-17-11        | 0.00      | 1.97      | 11.26     | 23.05     | 21.54     | 20.69     | 20.70    | 0.83                 |
| DBC-17-12        | 0.00      | 0.73      | 3.38      | 13.47     | 12.11     | 11.66     | 11.19    | 0.45                 |
| DBC-17-13        | 0.00      | -0.49     | 0.99      | 3.33      | 3.06      | 2.98      | 2.94     | 0.12                 |
| DBC-17-14        | 0.00      | -0.57     | 0.60      | 4.74      | 4.06      | 3.65      | 2.38     | 0.10                 |
| DBC-17-15        | 0.00      | -1.65     | -2.39     | -0.66     | 0.08      | -0.60     | -2.18    | -0.09                |
| DBC-17-16        | 0.00      | 0.88      | 20.24     | 16.96     | 16.11     | 13.85     | 13.55    | 0.54                 |
| DBC-17-17        | 0.00      | 0.24      | 23.60     | 24.78     | 21.56     | 21.82     | 21.83    | 0.87                 |
| DBC-17-18        | 0.00      | 0.02      | 13.18     | 21.57     | 18.32     | 18.64     | 18.23    | 0.73                 |

### Table 3 List of Settlement of Monitoring Section 18

| Survey Point No. | 2018/6/15 | 2018/6/19 | 2018/6/24 | 2018/6/28 | 2018/7/3 | 2018/7/8 | 2018/7/15 | Average Speed (mm/d) |
|------------------|-----------|-----------|-----------|-----------|----------|----------|-----------|----------------------|
| DBC-18-05        | 0.00      | 5.97      | 11.90     | 9.85      | 9.78     | 9.56     | 9.58      | 0.32                 |
| DBC-18-11        | 0.00      | 1.94      | 10.96     | 9.90      | 10.10    | 10.33    | 10.45     | 0.35                 |
| DBC-18-12        | 0.00      | 0.55      | 7.88      | 4.35      | 3.89     | 3.96     | 3.96      | 0.13                 |
| DBC-18-13        | 0.00      | -3.47     | -0.35     | -3.28     | -4.03    | -4.26    | -4.34     | -0.14                |

### 4.2 Pipeline settlement

The pipelines in the affected area of the overlapping section of Liantang–Zhangcha station interval are mainly water supply pipes and gas pipes, all laid along the direction of Jihua Road. The gas pipes have been temporarily relocated to the secondary affected area. The corresponding gas pipeline settlement survey points are RGXC-77 ~ RGXC-90. Table 4 shows the settlement changes at these points when the TBM on the left line was crossing above the overlapping section.
Table 4 List of Gas Pipeline Settlement

| Survey Point No. | 2018/5/28 | 2018/5/31 | 2018/6/3 | 2018/6/6 | 2018/6/9 | 2018/6/12 | 2018/6/17 | Average Speed (mm/d) |
|------------------|-----------|-----------|----------|----------|----------|----------|----------|---------------------|
| RGXC-77          | 0.00      | 4.06      | 6.12     | 8.28     | 11.49    | 11.32    | 10.25    | 0.51                |
| RGXC-78          | 0.00      | 0.52      | 3.51     | 7.03     | 7.83     | 7.94     | 7.07     | 0.35                |
| RGXC-79          | 0.00      | 1.24      | 2.02     | 0.75     | 0.39     | -0.90    | -0.11    | -0.01               |
| RGXC-80          | 0.00      | -0.58     | -0.37    | 1.34     | 1.14     | 0.61     | 1.39     | 0.07                |
| RGXC-81          | 0.00      | -1.54     | -2.24    | -1.43    | -1.10    | -1.43    | 0.57     | 0.03                |
| RGXC-82          | 0.00      | -0.66     | -1.15    | 0.59     | 0.86     | 1.42     | 0.41     | 0.02                |
| RGXC-83          | 0.00      | 0.26      | 2.30     | 4.31     | 4.59     | 6.51     | 7.91     | 0.40                |
| RGXC-84          | 0.00      | -0.24     | 1.29     | 2.91     | 2.51     | 3.69     | 3.99     | 0.20                |
| RGXC-85          | 0.00      | -0.69     | 0.39     | 1.23     | 0.96     | 1.50     | 1.82     | 0.09                |
| RGXC-86          | 0.00      | 0.82      | 0.62     | 1.05     | -0.65    | -1.26    | -2.48    | -0.12               |

It can be seen from Table 4 that during the left line tunneling, the gas pipeline settlement survey points were uplifted to the maximum value of 11.49 mm, corresponding to the survey point RGXC-77, and then became stable gradually after the TBM passed through the point. As of June 17, the cumulative settlement at the survey point was 10.25 mm, and the survey point was stable, with an average speed of 0.51 mm/d. During the Shield construction, there was no obvious abnormality such as slurry eruption or collapse around the pipelines.

4.3 Convergence of right line segment
Before the left line crossed above the overlapping section of Liantang–Zhangcha section interval, a full-hall scaffolding was erected in the existing right tunnel for reinforcement. In the reinforced area of the right line, monitoring sections were arranged every 10 rings to set out the convergence and vault settlement survey points. Table 5 shows the monitoring data changes at each survey point for convergence observation of the right line segments when the TBM on the left line was crossing above the overlapping section.

It can be seen from Table 5 that during the left line tunneling, the maximum convergence value in the right line was 3.51 mm, and the corresponding survey point was GGS-Y-23 with an average speed of 0.13 mm/d. During the shield construction, there was no obvious abnormality such as cracking, dislocation, or water seepage at the arch waist of the right line segment.

4.4 Settlement of right line segment
The settlement survey points of the right line segment were set out at the interval same as that of the convergence survey points. They were arranged on the same monitoring section, and the survey points were right above the vault. Table 6 shows the changes of monitoring data at each survey point for settlement observation of the right line segment when the TBM on the left line was crossing above the overlapping section.

It can be seen from Table 6 that when the left line crossed above the overlapping section, the inner vault of the right tunnel was ascending to the maximum value of 6.72 mm, and the corresponding survey point was GGC-Y-26 with an average speed of 0.25 mm/d. During the shield construction, there was no obvious abnormality such as cracks, dislocation, or water seepage on the top of the right tunnel.

To sum up, when the left line crossed above the overlapping section, the maximum convergence value of the right tunnel was 3.51 mm, the maximum rise value of the vault on the right tunnel was 6.72 mm, and there was no obvious abnormality such as cracks, dislocation, or water seepage on the top of the segment. This indicates that after the double-tube jet-grouting piles are reinforced, the shield construction on the left line at the overlapping section has little impact on the existing right tunnel, and
that the reinforcement has good effect.

Table 5 List of right line segment convergence monitoring data

| Survey Point No. | 2018/6/2 | 2018/6/6 | 2018/6/10 | 2018/6/14 | 2018/6/18 | 2018/6/25 | 2018/6/29 | Average Speed (mm/d) |
|------------------|----------|----------|-----------|-----------|-----------|-----------|-----------|---------------------|
| GGS-Y-23         | 0.00     | 1.75     | 2.2       | 2.46      | 3.28      | 3.55      | 3.51      | 0.13                |
| GGS-Y-24         | 0.00     | 0.51     | 1.17      | 1.42      | 2.24      | 2.3       | 2.9       | 0.11                |
| GGS-Y-25         | 0.00     | 0.18     | 0.76      | 0.97      | 2.19      | 2.1       | 2.52      | 0.09                |
| GGS-Y-26         | 0.00     | 0.84     | 1.37      | 2.21      | 2.35      | 2.56      | 3.01      | 0.11                |
| GGS-Y-27         | 0.00     | 0.61     | 0.94      | 1.99      | 2.58      | 2.84      | 2.95      | 0.11                |
| GGS-Y-28         | 0.00     | 0.77     | 1.2       | 2.14      | 2.31      | 2.66      | 2.95      | 0.11                |
| GGS-Y-29         | 0.00     | 1.2      | 1.68      | 2.06      | 2.33      | 2.74      | 2.68      | 0.10                |

5. Conclusion

By analyzing the overlapping tunnel in rheological strata, the following conclusions can be made:

1. The current shield construction method for overlapping tunnels is mainly from the lower tunnel to the upper tunnel.

2. After the soft foundation of the lower tunnel is treated in advance, the stress concentration area is reduced, and the soil settlement is decreased to 6.9 mm, which avoids the risk of uneven settlement induced by the disturbance to underlying silt stratum, indicating a good reinforcement effect; therefore, the construction can be carried out smoothly.

3. The overlapping tunnel construction in rheological strata has an impact on surface settlement of about 20 m, so protection measures are generally not required for surrounding structures.

4. During the construction of the upper tunnel, the lower existing tunnel must be monitored. After the double-tube jet grouting piles are reinforced, the shield construction on the upper overlapping tunnel has little impact on the existing tunnel, indicating the reinforcement effect is good.

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