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# Supervision and protection of Shanghai Mass Rapid Line 4 shield tunneling across the adjacent operating metro line

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ABSTRACT: Shanghai Mass Rapid Line 4 shield tunnels cross the operating Line 2 with 1.03 m distance beneath the operating line 2, small angle and small turning radius. The tunneling-across was carried out without ground improvement. This project took great challenge to the operating line. The influence of the tunnel crossing was predicted and a scientific construction scheme and measures were arranged to guarantee safe operation of Metro Line 2. The construction was performed based on the following principle strictly "to push step by step slowly, to turn equably with short step, to maintain stable pressure, and to improve the foundation with lower pressure and small amount." Thanks to these measures, the shield tunnel crossed Metro Line 2 successfully.

## 1 GENERAL INSTRUCTIONS

"Zhangyang Road—Pudian Road" tunnel of Metro Line 4 was constructed with shield method. The shield tunnel crossed under the operating Line 2 the operating line with a small angle and small turning radius. Figure 1 shows you the "#" shape of the relation between Metro Line 2 and 4. Following difficulties were encountered in this project.

1. Distance. The new tunnel cross blow the existing tunnel with minimum distance 1.03 m.
2. The tunnel at the crossing area is curved with small turning radius. The radius of Line 4 tunnel is only 380 m. For the shield, to advance with a small radius curve would influence the surroundings more seriously than advancing along straight line.
3. Influence area. For Line 2, the shield advance will directly influence 60 m at the up direction line and 94 m at the down direction line. Length of the influenced range, in which the distance between the upper and lower tunnel is less than the tunnel diameter, is above 300 m.
4. No ground improvement. The construction point was located in a place where several roads cross, so that the ground traffic is very heavy. It is impossible to conduct any ground improvement.
5. Bad geological condition. Line 2 tunnel is located in the fourth layer stratum, which exhibits high compressibility and obvious rheological behavior.
6. No relevant experience. Prior to this project, the tunnel of Line 2 had ever crossed below Line 1 when constructing, but in that case the ground improvement was carried out. To sum up, tunnel crossing without soil improvement is highly risky.

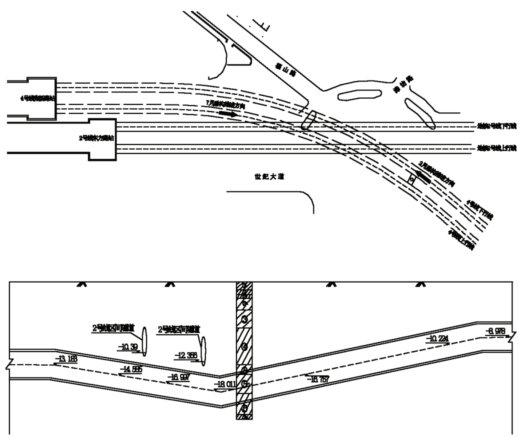

Figure 1. Plane and profile of the cross section.

## 2 PROCESS ANALYSIS AND COUNTERMEASURE OF THE SHIELD TUNNELING

### 2.1 *Process analysis*

The influence of construction to metro operation was predicted and the change of construction character was

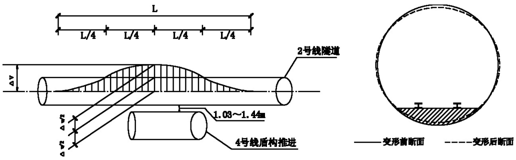


Figure 2. Deformation of tunnel Line 2.

analyzed. The theoretical analysis shows: before the shield-advance reach the centre line of Line 2 tunnel, it would disturb the equilibrating stratum stress and change the stress distribution. It would induce upward and forward deformation to Line 2. When the shield face passed through, the Line 2 tunnel would deform continuously due to the reasons including excess pore water pressure dispersing, consolidation settlement and secondary consolidation settlement and operation trains' vibration. In order to control the deformation of Line 2 tunnel, it is necessary to conduct synchronizing grouting and second grouting to Line 4 tunnel. The grouting could give a pre-heaving to Line 2 and the further settlement could be smaller. If the operating tunnel settlement approached the limitation, a re-grouting would be needed. Meanwhile ground improvement could be carried out between two tunnels to reduce settlement of Line 2. Consequently, when the shield crossed the Line 2 tunnel, longitudinal deflection in the horizontal and vertical direction might be occurred. It is composed with tunnel horizontal displacement, vertical heave or settlement and radial convergence deformation. It is shown in figure 2.

### 2.2 *Main disturbing factors in the shield advance process and its control measure*

Indeed, various factors would cause Line 2 tunnel deformation, the factors, however, could be reduced to the following three categories:

1. During the shield advance process, the shield shell and some projecting parts on the shield shell would cause stratum loss. The stratum loss volume, marked as $V_{e1}$, is closely relevant with the shield advance velocity. In order to reduce the stratum loss, we must limit the shield advance velocity strictly and try our best to make it suitably slow and constant. According to the theoretical analysis and the existing experience, the shield advance velocity was set as $v = 5 \sim 10$ mm/min. Furthermore, we request the shield advance must pause for 10～30 min every 10 min advance. According to the metro protection standard mentioned above and the monitoring data from automatic equipments, we would adjust and re-determine the pause time at any moment.
2. Volume loss caused by curved shield advance is marked as $V_{e2}$. When the shield is advancing in curve, in every 10 cm advance, an angle deviation, marked as $\alpha$, should occur at the shield axes. Volume of $V_{e2}$ varies directly as the shield length square and inversely as the curve radius. To reduce the volume loss, articulated equipment of shield machine must be used correctly, to reduce the shield effective length. The deviation-correcting degree per time must be limited strictly to ensure $V_{e2}$ as small as possible. Theoretically speaking, deviation-correcting at every ring advance with 1200 mm ring width is 17.6 mm. When it is divided into 12 times, however, the deviation-correcting volume per time is only less than 1.5 mm. That is to say the small degree and multi-times deviation-correcting would influence only 1/12 area as influenced by the original way. The disturbed area is therefore considerably reduced and the volume loss volume, $V_{e2}$, is also reduced consumedly.
3. Volume loss caused by unbalanced pressure at the shield face, marked as $V_{e3}$. $V_{e3}$ is the volume loss caused by difference between shield face pressure and stratum original static pressure $\Delta P$. During the course that the shield advance is approaching Line 2 tunnel, in order to reduce the metro tunnel settlement caused by shield tail grouting lack and consolidation settlement, $\Delta P$ should be a positive volume, namely the shield face pressure should be 0～5% larger than stratum original static pressure. Because the Line 4 tunnel is in a small radius curve in this section and it crosses the operating Line 2 with a small angle, pressure on the shield cutter head is unbalanced at left and right sides during the shield crossing through process. And sudden pressure change might occur during the process. To maintain the pressure at shield face stable (especially when the segment is erecting, the jack would be getting loose) and to make the soil be a little uplifting is very beneficial to Line 2 tunnel settlement control. Consequently, whether the construction is successful or not is depend on whether the soil pressure at the shield face could be controlled and maintained at a suitable level. What should be adjusted in the construction process is the parameter mentioned above: the shield advance velocity, v; pressure at shield face; and axes deviation occurred in every 10 cm advance, $\alpha$, (generally, this index is defined as the predetermined volume). General effectiveness caused by these three factors, when reflected in the Line 2 tunnel horizontal displacement, vertical uplift or settlement and tunnel radial convergence, is $\delta_v$ $\delta_h$ and the tunnel radial convergence deformation.

According to the metro tunnel deformation specification and metro safety operation requirement, for the operating Line 2 tunnel, the maximum tolerance of the longitudinal deflection in the horizontal and vertical level planes are determined as ±5 mm; and the tunnel radial convergence deformation tolerance is strictly controlled within 20 mm.

### 2.3 *Real time information construction*

During the shield advance process, the vertical deflection of the Line 2 tunnel, both in vertical level horizontal level, marked as $\delta_{v,}$ and in the vertical plane, marked as $\delta_h$ must be controlled strictly. Whenever the shield advances a step, the change rate of $\delta_v$ and $\delta_h$ must be analyzed and the construction parameters must be adjusted within ±5 mm tolerance, so that to control the tunnel deformation. In the shield advance process, high-automatic and high accurate monitoring system was adopted to supervise Line 2 tunnel status lively. High-precise automatic electrical level supervision system was adopted to measure the tunnel longitudinal settlement and transverse subsidence difference between two tracks; and Bassett convergence system adopted to supervise the tunnel convergence status. After the train service finished, we adopt additional manual supervision to monitor settlement, displacement, and convergence status of the Line 2 tunnel (to set 3 settlement monitoring points at each profile; 1 on the track bed and the other 2 on the segment the monitoring profiles are set every 2 m along the tunnel.)

### 2.4 *Analysis on grouting and foundation improvement*

After the shield cross over the Line 2 tunnel centre line, whether the interspace at the shield tail could be refilled timely and suitably is a key factors that cause tunnel longitudinal deformation. In this process, the shield jack stress on the tunnel segment would cause an opposite longitudinal deflection, but control volume of $\delta_h$ must be less than −5 mm. After the shield passed, the consolidation settlement of the layer beneath the tunnel is also an unneglectable factor. Therefore, after the shield passed below the Line 2 tunnel, several timely grouting with low pressure and small amount is very important and directly related to the success of Line 2 tunnel settlement control.

## 3 TECHNOLOGY KEYS OF THE SHIELD ADVANCE AND PRE-CONTROL OF MAIN CONSTRUCTION PARAMETER

Based on the deep analyses and clear understanding on the construction difficulties, the operator conducted a 45 kph speed limit in the relevant section of Metro Line 2.

We comply with the following principle carefully and strictly in the construction – "to push step by step slowly, to turn equably with short step, to maintain stable pressure, and to improve the foundation with lower pressure and small amount." The technology keys are decomposed into the following points:

1. Settlement or uplift control volume of the Line 2 tunnel is ±5 mm. When the uplift volume reaches 50% and settlement, 30%, of the control volume, the monitoring system will alarm. That makes the tunnel always in a slight deformed condition.
2. The shield advance slowly and constantly; the shield advance speed is maintained at 5∼10 mm/min. And the shield advance must pause for 10∼30 min every 10 min advance. The pause time length depends on whether the Line 2 tunnel has "uplift ∼ fall back" to the protection standard.
3. The shield face soil pressure should be adjusted to a correct volume so that it would cause minimum influence onto the Line 2 tunnel. To maintain a stable face soil pressure is extremely important. The shield face pressure should be 100∼105% of stratum original static pressure, however, the volume is flexible and should be adjusted based on the live monitoring data. When the segments are erecting, there should be effective precaution to prevent the face soil pressure from descending; and the erecting time should be as short as possible.
4. Shield Advance Deviation-correcting. The deviation-correcting degree per time is the smaller the better. The deviation-correcting is required to taken every 10 cm advance. And the articulated equipment of shield machine must be used correctly, to reduce the shield effective length.
5. Synchronizing grouting pressure should be less than 0.4 mpa or even lesser. Grouting amount is 1.1∼1.8 times of the interspace cubage. Detailed grouting amount depends on the monitored Line 2 tunnel data.
6. Second liquid grouting would be adopted in the second grouting. The grouting conduct principle is: low pressure, multi-times, moderate and timely. The pressure should be maintained at 0.2 mpa. Grouting amount per time per ring is 50∼100 liter. We request the grouting should be conducted every other ring, to reduce its influence to Line 2 above. Generally, we request the grouting only be conducted when the train service finishes.
7. Foundation improvement is necessary to prevent the Line 2 tunnel from settling continuously. In this process, all relevant parameters such as, grouting pressure, grouting amount, grouting time, grouting pipe withdrawing velocity, and grout mix proportion and consistency, should be limited carefully to reduce the harmful influence to the tunnel above as much as possible.
8. Set automatic and high-precise electrical level system along the Line 2 tunnel. The electrical level is set to acquire data every 5 minutes and deliver the data to shield operation control centre. The operation centre would adjust construction parameter and

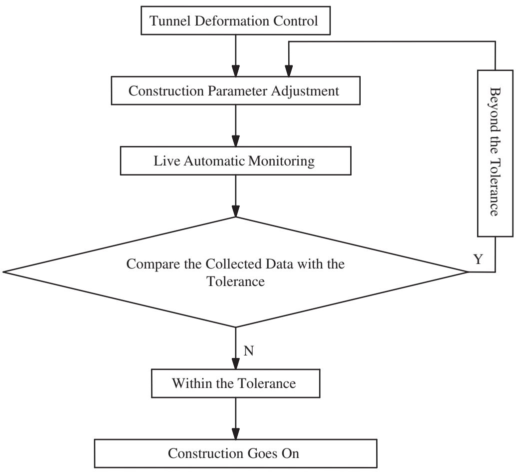


Figure 3. Pre-control system sketch.

guide shield construction based on these data. The construction technology keys and quantified construction parameter are together formed an effective and reliable pre-control system, which is shown in figure 3.

## 4 SUPERVISION ON THE SHIELD CONSTRUCTION AND THE OPERATING TUNNEL DEFORMATION ANALYSES

### 4.1 *Construction process*

The shield machine is 8.625 m long and the outer diameter $\Phi = 6.34$ m. The segments are 350 mm thick and single segment longitudinal length is 1.2 m. The whole construction process is as follows:

1. The first tunneling across process of the shield. Shield at Line 4 down line tunnels across Line 2 up line first, and then tunnels cross Line 2 down line.
2. After the shield machine arrived Zhangyang Road Station, soil between the tunnels at the crossed section was improved to ensure the metro Line 2 operation safety.
3. The second tunneling cross process of the shield. The shield turned back to advance in the Line 4 down line. It cross Line 2 down line first, and then tunnels cross Line 2 up line.
4. After the tunneling finished, soil of this section was improved. Four tunnels at the cross through section formed a "#" shape with small angle on a projection plane. The project therefore influenced very large range of Line 2. Length of the range, in which the distance between the upper and lower tunnels is less than the tunnel diameter, is above 300 m.

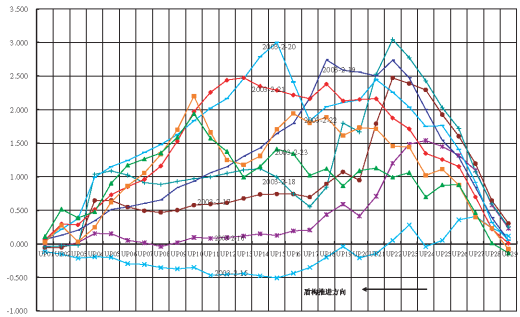

Figure 4. The Line 2 up line tunnel settlement/uplift data during the first tunneling cross process.

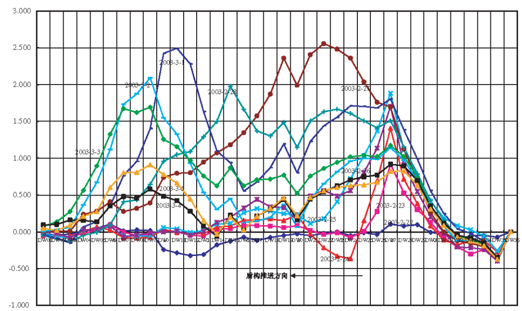

Figure 5. The Line 2 down line tunnel settlement/uplift data during the first tunneling cross process.

### 4.2 *Process description and site monitor of the first tunneling cross*

The first shield tunneling cross process was started from Pudian Road Station. The first tunneling cross process lasted for 15 days.

At the very beginning of the shield advance, the preset construction parameter makes the Line 2 tunnel to maintain a slight uplifting trend.

When the shield cutterhead was approaching below the Line 2 up line tunnel projection, the shield advance velocity and face soil pressure were adjusted, but the Line 2 tunnel still maintained uplifting trend and the uplift volume was up to 0.2～0.5 mm. During the shield advance process, soil at different points had different stress, thus caused different influence in the Line 2 tunnel. When deviation-correcting conducted, soil at head and left of the shield machine was stressed but stress of soil at head and right was released; meanwhile, at the shield tail, soil at the right side was stressed but stress of soil at left side was released.

When the shield advanced just below the axis of Line 2 tunnel (the shield was only 1.44 m away below Line 2 tunnel then), the face pressure onto soil had been adjusted speedily from the previous 0.23～0.27 mpa to 0.166 mpa, much smaller than the previous pressure.

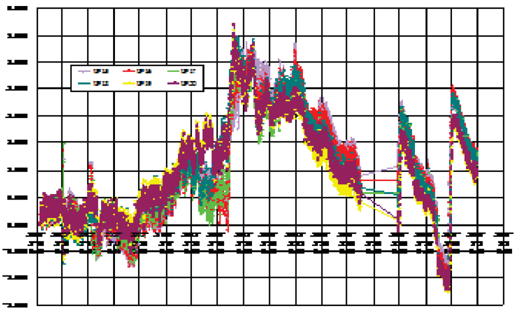

Figure 6. Settlement/uplift data of the closest point from the Line 2 up line tunnel during the first tunneling cross process.

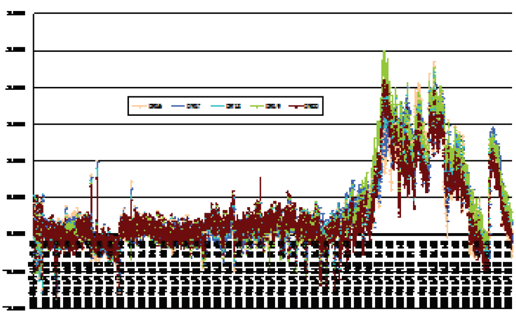

Figure 7. Settlement/uplift data of the closest point from the Line 2 down line tunnel during the first tunneling cross process.

At that time, the up line of Line 2 tunnel had uplifted for 2.5~3.1 mm.

When the shield cutterhead was escaping from the projection of Line 2 tunnel, because of incorrect and unsuitable deviation-correcting and synchronized grouting, instantaneous uplift volume of Line 2 tunnel was up to 3.3 mm. Figure 4 and figure 5 show the settlement and uplift condition during shield cross through Line 2 up line tunnel and down line tunnel respectively.

Figure 6 and Figure 7 show the settlement and uplift condition of the closest settlement point during shield cross through Line 2 up line tunnel.

### 4.3 *Process description and site monitor of the second tunneling cross*

The second shield tunneling cross process was started from Zhangyang Road Station. By June 24, 2003, when the shield of Line 4 construction arrived 2 m away from the projection line of the Line 2 down line tunnel, the shield advance had caused settlement and uplift at Line 2. On June 30, the shield cutterhead entered the projection line of Line 2 down line tunnel, then it crossed over below the Line 2 down line and up line one after another. By July 22, the shield

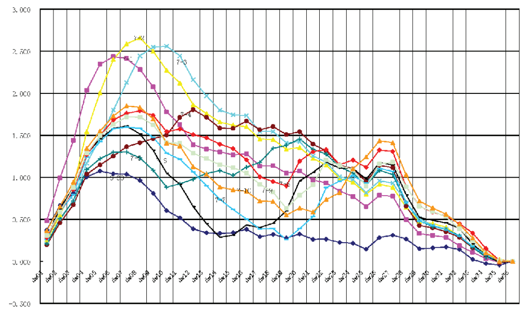

Figure 8. The Line 2 down line tunnel settlement/uplift data during the second tunneling cross process.

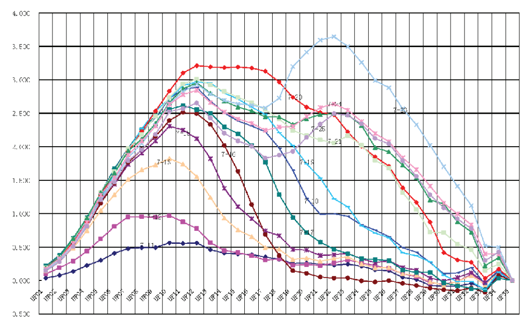

Figure 9. The Line 2 up line tunnel settlement/uplift data during the second tunneling cross process.

escaped from Line 2 projection completely. The second shield tunneling cross process totally lasted for 23 days.

The shield crosses below the Line 2 down line tunnel first with the minimum vertical distance 1.03 m. Its influence on the Line 2 tunnel is obvious, although we have made very strict limit on the construction parameter. By July 1, the Line 2 down line tunnel has uplifted up to 2.5 mm. Because the up line tunnel of Line 4 is very closed to Line 2 tunnel, the Line 2 tunnel assumed obvious dynamic settlement during cross through process. It can hardly be controlled except by synchronized grouting and second grouting method. Figure 8 to Figure 11 shows detailed condition.

### 4.4 *Grouting and foundation improvement issues*

In the shield advance process, in order to control the Line 2 tunnel settlement after shield advance, unreactive-grout-synchronized grouting was conducted, so that the grout would refill interspace at the shield tail. Meanwhile, synchronized grouting and second grouting was conducted at the cross section where dynamic settlement occurred. Double liquid grout was used in second grouting to improve the stratum's mechanical properties. 16 grouting holes are

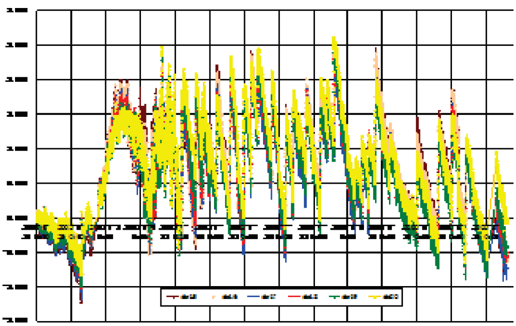

Figure 10. The Line 2 down line tunnel settlement/uplift data at every time during the second tunneling cross process.

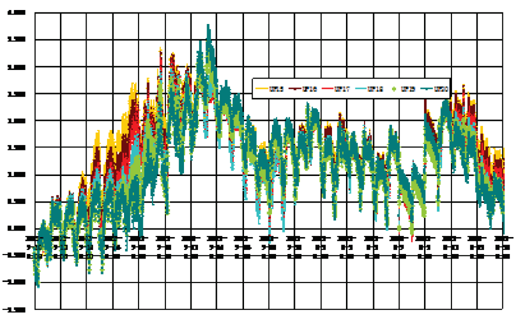

Figure 11. The Line 2 up line tunnel settlement/uplift data at every time during the second tunneling cross process.

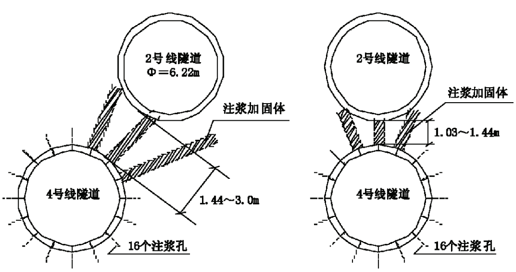


Figure 12. Schema of the Foundation Improvement.

reserved at every segment in the cross section, so that it would be easy to conduct stratum grouting improvement after the shield escaped from the section. The arrangement of the foundation improvement grouting point is shown in figure 12. After the shield passed, by repeating foundation improvement in the recent year, the Line 2 tunnel settlement situation is now well in hand.

## 5 CONCLUSION

After the elaborate construction and strict site supervision and protection, the Line 2 tunnel settlement situation is now well in hand and the safe metro operation during the project are also realized. Valuable experience, which could be reference for the future construction, was accumulated in this case.

1. When the shield advancing in curve with small radius, because of different stress condition at different point of the shield, it would cause various influence to the upper metro tunnel.
2. The shield advancing velocity is an important factor that causes upper tunnel uplift. The influence, however, could be reduced by suitable construction parameter adjustment.
3. Shield deviation-correction is another important factor that causes upper tunnel uplift. The uplift or settlement condition is dependent on relative position of the two tunnels.
4. Shield tail grouting would influence quite a large range, up to 10～15 m. It is necessary to maintain low pressure, small amount and correct grout in the grouting process, to reduce the influence to the surroundings.
5. Dynamic settlement caused by train running is very dangerous. Synchronizing grouting and second grouting could be adopted to correct that. Foundation improvement and double liquid grouting are important method to control tunnel settlement.
6. The principles "to push step by step slowly, to turn equably with short step, to maintain stable pressure, and to improve the foundation with lower pressure and small mount" are proved correct technical keys.
7. Strict high-precise automatic monitoring and information based construction is one of the most important technical support.

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