The Risks and Countermeasures of Shield Launching and Receiving in Soft Soil

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1. Introduction

After a large number of engineering practices and technology researches, lots of technical difficulties have been solved in shield tunneling in soft soil in Shanghai [1]. Such as the influences on surrounding environment, the axis control during tunneling, and the optimization of construction parameters. However, shield launching and receiving are still the difficulties [2]. For example, the front mud bursting and water burst into working shaft when tunneling through the working shaft in Shanghai Metro Line 7 and Line 10. The bursting is always induced by insufficient strengthen reinforcement. On the contrary, if the reinforced strength is too high, difficulties will be encountered during cutting, and project process will be delayed.

Starting from the summary on calculating methods for ground improvement, corresponding comparison and discussion are made in ground treatment method, scope, stability, intensity, and the sealing device. The problems encountered in launching and receiving are analyzed. And also, the comparison between slurry shield and EPB shield are analyzed. Finally, the technical countermeasures are put forward. Advantages of the deep mixing piles, dewatering and freezing methods are clear. The conclusions that risks in sandy soils are higher than in soft soil, the risks of slurry shield are higher than EPB shield and so on are obtained.

2. Design of soil stability and ground improvement near working shaft

There are three main objectives of ground improvement. Firstly, it is to ensure soil stability during the removal of the temporary wall, and to prevent the flow of groundwater into working shaft. Secondly, it is to prevent the leakage from shield circumference. And last, it is to prevent the adverse influences on the surrounding environment [3].

Security issues about shield launching and receiving should be concerned on planning and design stages. The softeye (tunnel portal for shield launching and receiving) should not be placed near the pipelines that can not be relocated.

2.1 Theoretical research methods of ground improvement near softeye

For now, theoretical analysis of ground improvement is still in its early stage in China [4]. The comparison between the generally adopted methods are made as below in table 1.
<table>
<thead>
<tr>
<th>Theory</th>
<th>Theory basis</th>
<th>Theoretical perspective</th>
<th>Safety factor</th>
<th>Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate theory</td>
<td>elastic thin plate theory</td>
<td>Micro-level perspective</td>
<td>The improved ultimate tensile strength</td>
<td>Sandy soil or clay</td>
</tr>
<tr>
<td>Theory of elasto-plastic mechanics</td>
<td>Thin plate theory of elasto-plastic mechanics</td>
<td>Micro-level perspective</td>
<td>The improved bending stress or shear stress</td>
<td>Sandy soil or clay</td>
</tr>
<tr>
<td>The disturbed theory</td>
<td>Critical equilibrium</td>
<td>Micro-level perspective</td>
<td>The improved ground scope</td>
<td>Sandy soil</td>
</tr>
<tr>
<td>The slip-line theory</td>
<td>Critical equilibrium</td>
<td>Overall stability perspective</td>
<td>The improved anti-slip</td>
<td>Clay</td>
</tr>
</tbody>
</table>

2.2 Engineering solutions of the ground improvement scope

2.2.1 Longitudinal length of ground improvement

If the length of soil improvement is less than that of shield machine, the cutter head and tail can not both be kept in the improved zone. Soil and water beyond the improved zone may flow into working shaft along shield shell, especially in sandy or silty stratum. Soil loss and ground settlement could occur. Therefore, the longitudinal improved length should equal to the shield length plus 1.5-2 sealing thickness, then the cutter head will be still in the improved zone after the tail has already entered and grouted. And the leakage channel will be totally blocked.

If the space between shield and improved soil is completely blocked by double-liquid slurry, the longitudinal improved length can be 3.5m while receiving. And the longitudinal improved length can also be 3.5m while receiving for the low permeable soft soil as clay, because the main function of ground improvement is to ensure stratum stability after the removal of retaining structure, not the leakage from the space.

2.2.2 Horizontal length of ground improvement

Water sealing and stratum stability are the main functions of horizontal improvement in soft soils, considering that the improved zone and shield skin can counteract the surrounding pressure together. The horizontal improved length can refer to table 2 [5]. B is the lateral improved length. D is shield diameter. H₁ and H₂ represent the improved thickness above and below shield.

| Tab.2 Experience values of transversely improved length (unit/m) |
|-------------------|-------------------|-------------------|-------------------|-------------------|
| D                 | 1≤D<3             | 3≤D<5             | 5≤D<8             | 8≤D<12            | 12≤D<15           |
| B                 | 1.0               | 1.5               | 2.0               | 2.5               | 3.0               |
| H₁                | 1.5               | 2.0               | 2.5               | 3.0               | 3.5               |
| H₂                | 1.0               | 1.0               | 1.5               | 2.0               | 3.0               |

3. Sealing devices and ground improvement methods

3.1 Softeye sealing devices and the selection categories

The most commonly used devices and the selection categories are shown in table 3.
<table>
<thead>
<tr>
<th>Device</th>
<th>Principle</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hinge plate with rubber</td>
<td>Using the protection of unidirectional hinge plate and the fastened sealing</td>
<td>① It is perfect in blocking the annular space between shield skin and surrounding soil.</td>
<td>① The inflow of pressurized slurry can not be stopped for slurry shield, and the balanced slurry pressure can hardly be established again. ② Not suitable for the confined water strata. ③ The ageing of rubber will lead to sealing failure.</td>
</tr>
<tr>
<td>sealing device (Fig.1)</td>
<td>rubber plate to stop the inflow of soil.</td>
<td>② Relatively lower cost.</td>
<td></td>
</tr>
<tr>
<td>Airbag</td>
<td>Using the airbags imbedded between lining and softeye circle to ensure the</td>
<td>Multiple layers of airbags can be arranged behind hinge plate to improve sealing effect.</td>
<td>① Difficulties for the precise setting of air pressure. ② the inflow of soil and water can not be completely stopped.</td>
</tr>
<tr>
<td>sealing device (Fig.2)</td>
<td>sealing effect.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Box structure</td>
<td>Using the box arranged with sealing rubber and hinge plate, and layers of</td>
<td>① The distance between shield skin and hinge plate can be adjusted. ② Many grouting holes are arranged to ensure the sealing effect.</td>
<td>① Complex process. ② Relatively higher cost.</td>
</tr>
<tr>
<td>sealing device (Fig.3)</td>
<td>sealing brush filled with grease to stop the inflow of soil and water.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filled box</td>
<td>Using the compacted filled box embedded between the softeye circle and</td>
<td>① Adjustable compaction degree of the sealing filler. ② Simple process and relatively lower cost.</td>
<td>① The inflow of pressurized slurry and water can not be stopped. ② Just for shield launching.</td>
</tr>
<tr>
<td>sealing device (Fig.4)</td>
<td>lining as sealing device[6].</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2 Ground improvement methods and the selection categories
The softeye structure forms are different for different types of tunnels. So, the ground improvement methods should be adjusted and optimized accordingly.

3.2.1 Dewatering method

Compared with other methods, dewatering is the most economical to stabilize the excavated soil and to prevent quicksand when in soft aquifer stratum.

Under the circumstance of confined water, dewatering is reliable. However, a large area of dewatering will result in obvious settlement. So it will be restricted if high environment protection is required.

3.2.2 Soil freezing method

The technology has been widely applied in coal mine construction, and also in tunnel construction, and it is suitable for saturated soil, but not for unsaturated soil.

Steel pipes should be pulled out of frozen soil before shield arrival. The pulling failure due to the fracture of freezing pipe will result in the delay of launching or receiving. Therefore, liquid nitrogen freezing method and ordinary PVC pipes are adopted. But it will lead to comparatively high cost. In addition, the freezing method still has the thawing settlement problems.

3.2.3 Decent grouting method

The grout adopted and the injection modes are the keys for grouting. Decent grouting can be used as complementary measure for other ground improvement methods, and it should not be adopted alone [7].

3.2.4 Deep mixing piles (combined with Soil Mixing Wall)

The technology has the advantage of little influence on the surroundings, good water sealing effect, less environment pollution, and H steel can be inserted according to certain distance to enhance the retaining ability and the bending resistant ability.

It is widely adopted in sand, clay, silt and in soft soils in Shanghai. The technology can not be carried out close to structure wall, so partial stratum is left to be treated by other methods.

3.2.5 Jet grouting piles

The technology is suitable for clay, silt and compound geotechnical stratum. But the impermeability can not be guaranteed for sandy aquifer stratum. Failure of the overlap between any two piles will lead to the failure of the entire sealing effect, and the resulting ground settlement and accident can often be seen during construction. The technology was adopted in Zhongxing Road Station for shield receiving in Shanghai Metro Line 8, and leakage from the test drilling hole, after the removal of retaining wall, showed the failure of sealing effect.

3.2.6 Mixed method

Two or more methods will be applied when single method or the improved effect can not meet the requirements [8].

The intention of ground improvement is to obtain the required strength and the soil self-reliance after the removal of sealed softeye. But the uniformity of the improved soil can not be guaranteed, so inspection should be enhanced to ensure the intensity, uniformity and improved range.

Comprehensive comparison of the methods for shield launching and receiving is made in table 4 [3].
<table>
<thead>
<tr>
<th>method</th>
<th>Specialty, applicability and environment influence</th>
<th>safety</th>
<th>construction period &amp; cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dewatering</td>
<td>Convenient. Fast construction speed and effect. Individual damage will not affect the entire system. Reusable and low cost.</td>
<td>Great security combined with other methods.</td>
<td>Fast construction. Relatively lower cost</td>
</tr>
</tbody>
</table>

3.3 Innovative technologies and methods

3.3.1 Auxiliary device for shield receiving

Recently, the special steel sleeve device for shield receiving has emerged. It is a whole airtight container which is open at one end and closed at the other end. The open end is connected with the pre-embedded ring plate on softeye. A certain pressure, the same as the chamber pressure, is pre-applied in the container to effectively prevent water and sand bursting [9]. Besides, the principle of the anti-risk device for shield launching and receiving researched by Shanghai Tunnel Engineering Co., Ltd is similar as the steel sleeve device.

3.3.2 Direct cutting method

Shield can directly cut the wall such as fiber improved concrete. The advantage is no need of ground improvement. The cost is low, the period is relatively short and it is relatively safer.

The method has been widely adopted in Germany, Thailand, India, Hongkong, Japan and other places. And it was also applied in Honghuayan Station for launching in Chengdu province, China, and in Yishan Road Station for receiving in Shanghai Metro Line 9.

The concrete design and shield cutting ability should be changed accordingly.

3.3.3 Shield receiving in water or soil

The method is to use the backfilled water or soil in working shaft to balance earth pressure. Meanwhile, the backfilling can be taken as a special foundation treatment. Then, the receiving and launching can be transformed as normal tunneling.

The shield was received in water in Shanghai Metro Line 10 and in Shanghai Yangtze River Tunnel. And the shield was received in soil in Shanghai Metro Line 7.

3.3.4 Blasting method

Blasting of the retaining diaphragm usually adopts conventional drilling method or embedded-hole method. Special diaphragm treatment should be considered for blasting.

The technology was adopted in Shanghai Metro Line 9 when tunneling through the
diaphragm of East Fuxing Highway Road Tunnel. The strength of diaphragm concrete was reduced, and the steer bar was instead by glass fiber.

3.3.5 Electrical erosion method
The steel bar in retaining wall will be dissolved under electrical erosion effect. The material will be deteriorated to the extent that can be directly cut by shield cutter.

The method was once adopted in Osaka, Japan.

3.3.6 Decentralization method
The softeye position is always perpendicular to tunnel trend, but the intersection angle can still be designed as acute. Then, the stratum in the range of softeye can be divided into many shares. There will be several shares, not the whole shares, in the cutting range in certain time while tunneling, and the overall stability will be transformed into the stability of partial stratum.

4. The risks and countermeasures of shield launching and receiving
The main risks and corresponding factors and countermeasures are shown in table 5 [10].

<table>
<thead>
<tr>
<th>Risks</th>
<th>Risk factors</th>
<th>Risk countermeasures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil and water bursting due to sealed softeye removal</td>
<td>Large permeability out of softeye. Groundwater pressure change. Long soil exposure time out of sealed softeye</td>
<td>Launching as soon as possible. Take measures for softeye reinforcement and block such as grouting, dewatering and freezing. Enhance inspection and support system.</td>
</tr>
<tr>
<td>Soil loss through softeye circle</td>
<td>Bad effect of ground improvement. Sealing device becomes invalid.</td>
<td>Ensure the strength and uniformity of ground improvement. Precise arrangement of softeye sealing and prevent its damage from cutter. Lubricating effect can be improved. Consider the protrusion on shield skin, and set adjustable structure to ensure the sealing performance.</td>
</tr>
<tr>
<td>Deviation from the designed axis</td>
<td>Improper base installation or deformation. Displacement or deformation of back-support system. Improper simultaneous grouting while launching. Over or lack excavation.</td>
<td>Keep the base central axis consistent with tunnel axis. While tunnel axis is curve, the base can be placed on the tangential direction of tunnel axis. Keep the consistent of tunnel axis and base central axis. Keep the contact between base underside and shaft meet the requirements</td>
</tr>
<tr>
<td>Instability of the backup-support system</td>
<td>Failure of the reaction force frame. Damage of the negative lining. Instability of the steel support.</td>
<td>Ensure the strength, rigidity, stability of each component and the reliability of each connection point. Each component should be arranged precisely, and ensure the welding quality and strength of bolt connection. Install the upper support as soon as possible to open the upper shield jacks and to enable uniform force on back-support system.</td>
</tr>
<tr>
<td>large ground deformation or collapse</td>
<td>Bad effect of ground improvement. Inaccurate excavated soil dumping. Improper parameters such as tunneling speed.</td>
<td>Choose reasonable ground improvement and improve management. Set a reasonable dumping of excavated soil. Work out the set rules of parameters as soon as possible, and strictly control the balance pressure and tunneling speed.</td>
</tr>
<tr>
<td>Submerged working shaft</td>
<td>Water accumulation is larger than discharge in a certain time due to heavy rain; blasting of nearby pipelines due to ground deformation.</td>
<td>Increase pumping and drainage facilities. Completely investigate the surrounding pipelines, rigorous monitor about the relevant sewage and rainwater pipelines. Prohibition of construction machinery, concentrated loads which will lead to excessive ground subsidence.</td>
</tr>
</tbody>
</table>

5. Comparison between slurry shield and EPB shield
The front pressure has to be adjusted according to the improved soil strength and self-reliance for the both kinds. While receiving, in order to stabilize the retaining structure, the front pressure has to be reduced gradually according to earth pressure. While launching, the front pressure has to be increased gradually. The phenomenon of surface subsidence or cracks due to improper front pressure adjustment often happens.

Slurry shield is generally adopted in large-diameter cross-river tunnels [11], as EPB shield in subway tunnels. The main difficulties for slurry shield are the establishment and control of the slurry balance system. High technologies of slurry balance control and softeye sealing are required. The main difficulty for EPB shield is the set of front earth pressure.

In comparison, the soil stability for slurry shield is more important. The slurry pressure balance can hardly be rebuilt if the soil near softeye has been disturbed and destructed. Because the soil disturbance will lead to the reduction of slurry retaining capacity, the sealing effect of slurry membrane, slurry overflow on the ground and so on. So, the requirements of slurry shield are higher.

Slurry shield can be received in water. It is good for the control of slurry pressure and is very important for large-diameter shield. And also, the risk of softeye leakage is prevented. But the sinking influence of working shaft imposed by water pressure should be considered.

6. The countermeasures of shield launching and receiving for risk prevention

There are many effective pertinent measures in shield launching and receiving, but the following aspects still should be strengthened.

(1) Reliable ground improvement should be chosen according to the hydrological and geological conditions. If receiving in plastic soil, the improved length should be larger than shield length.

(2) If confined water exists, water will burst along the steel piles being pulled out. So, dewatering wells should be pre-arranged for emergency use. If conditions are complicated, the filled box sealing technology should be considered, as in Shanghai Yangtze River Tunnel.

(3) Instead of high pressure jet grouting piles, deep mixing piles should be adopted as far as possible, especially in the existence of confined water. If high pressure jet grouting piles must be adopted, assistant dewatering measures should be prepared.

(4) The monitoring and detection should be strengthened. (1) Deep monitoring points must be arranged in urban sensitive areas; direct monitoring points must be arranged on large-diameter pipelines within the influence. (2)The uniformity of the improved ground should be tested by vertical, inclined and horizontal sampling methods.

(5) For the soft saturated clay-based shallow geological conditions, freezing is widely adopted. Freezing is reliable in water leakage prevention, but not in unsaturated stratum and the working shaft constructed by pneumatic caisson, because the air in soil can not be frozen.

7. Conclusions and recommendations

Through the analysis and comparison above, some ideas and suggestions can be obtained.

(1) Ground improvement should be decided by the hydrological and geological conditions. Deep mixing piles should receive the priority. Dewatering can effectively increase soil density and strength, especially in sand and confined water layers. Freezing can be considered if abundant groundwater and large permeability of sandy soil are encountered. Deep mixing
piles and freezing are the most two frequently used methods in soft soil. (2) Although the soil failure mechanism is the same, not only the front soil stability problems, but also the soil and water pressures should be considered while launching. But, there is only the front soil stability problem while receiving. So, the technical difficulty for launching is bigger. Though the longitudinal improved length can be 3.5m while receiving, the corresponding requirements are higher. Great risks will happen in sand soil. So, the length should be the same as launching as recommendation. (3) Risks of launching and receiving in sandy soil are higher than in soft soil, especially in the existence of confined water. (4) Compared with EPB shield, the construction control requirements and the unexpected loss are higher for slurry shield. So, the risks of slurry shield are greater than EPB shield. (5) Uncertainties and high-risk exist in underground engineering. New technologies and methods are the effective means to solve the high-risk. So, we should vigorously strengthen the development and application of new technologies.

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References