Research on Deformation Treatment and Control Technology of Tail Shield of Underwater Large Diameter Slurry Shield

Xiaoming Han¹,², Feilei Zhang¹,²,³,⁴*, Yuan He¹,² and Han Zhong¹,²,³,⁴

¹CCCC Second Harbour Engineering Co., Ltd, Wuhan, Hubei, China
²China Communications Second Navigational Bureau Third Engineering Co., Ltd., Zhenjiang, China
³Research and Development Center of Transport Industry of Intelligent Manufacturing Technologies of Transport Infrastructure, Wuhan, Hubei, China
⁴Key Laboratory of Large-span Bridge Construction Technology, Wuhan, Hubei, China

*Corresponding author’s e-mail: zhangfl_93@163.com

Abstract: The Karnaphuli River underwater tunnel in Bangladesh is located at the estuary of the Karnaphuli River and is constructed with a Φ12.12m air-cushioned slurry pressure balance shield machine. The bottom section of the river mainly passes through a dense silty fine sand stratum, of which the standard penetration value and strength are high. When the shield tunneling got into to the sea area, the tail shield was significantly and unevenly deformed, which caused the shield machine to be trapped in the river bottom. Therefore, the characteristics and causes of the deformation of the shield tail during the tunneling boring process were analyzed on this basis. Studies have shown that the deformation of the tail shield was a gradual development process. If there is a slight lack of rigidity of the outer shell and tail shield on the outside of the shield, it tells that the large resistance of the ground caused by the deviation of shield tunneling is the main reason for the deformation. Besides, given the construction characteristics of the underwater shield and the limited working space in the shield machine, a linear rectification tool was designed. By summing up the rectification methods of the hole making in the tail shield, decompression with sand discharge, and incremental launching with loaded, local deformation of the tail shield was realized, so the trapped shield machine was successfully released. Finally, through the excavation experience after the shield restart, it is concluded that within 5cm of the tail shield steel plate deformation, the experience of deformation rebound can be achieved through measures such as sand discharge through radial holes and bentonite injection, which provides a reference for similar engineering projects in the future.

1. Introduction

Shield construction, with its advantages of mild construction disturbance, low environmental impact, and high applicability, is widely used in the construction of subway tunnels underneath urban areas and cross-river tunnels. As the size of the shield machine develops in the direction of conquering large diameters and buried depths, the tail shield, as a special thin-walled ring structure, has an increasing risk of deformation during the construction phase. In the actual construction, engineering accidents caused by the deformation of the tail shield have been reported [1]. For example, the Yaohua Branch Road Tunnel in Shanghai was unable to continue construction due to the excessive deformation of the tail shield. Therefore, the development of effective deformation control and treatment technology becomes increasingly important. In this paper, the deformation characteristics and main causes of the tail shield of the underwater large diameter slurry shield are studied on the basis of the project. The rectification method of the deformation is also summarized, so that the shield in similar engineering projects can be released with the help of the experience. The study results provide a valuable reference for the deformation control and treatment of tail shields in large diameter shield tunneling projects in the future.
shield. Additionally, the West Skelt River Tunnel [2,3] in the Netherlands experienced long-term construction delays due to varying degrees of tail shield deformation during the construction of the east and west lines. The researchers believed that in impervious formations, high grouting pressure and cutting pressure caused the slurry to fill the shield and the formation space to generate excess pore water pressure, ultimately leading to the tail shield deformation. The same phenomenon also appeared in the Groene Hart tunnel.

Some scholars have researched the force state of the tail shield under the action of water and earth pressure. Guan Huisheng [4] and others adopted analytical methods to derive the internal force calculation formula of the tail shield; He Yulian [5] used finite element software to verify the strength of the tail shield and cutting head under different loads; Shao Chengmeng [6] took the earth pressure balance shield machine of Suzhou Metro as the research object, analyzed the influence of multi-point grouting method on the deformation of the tail shield structure, and put forward suggestions for the optimization of the tail shield structure; Zhang [1] and others took the shield machine used in the construction of the North Cross Passage as an example, systematically studied and analyzed the stress state of different forms of tail shield structures under high water pressure, and provided suggestions for tail shield design; In terms of tail shield deformation treatment technology, only He Zhen’an [7] proposed a treatment method to remove the grout agglomeration by opening the shield body based on the tail shield deformation in a mudstone shield project. However, there is no relevant data on the deformation analysis and treatment technology of the tail shield in the water-rich sand stratum.

Based on the deformation of the tail shield of the Karnaphuli River underwater tunnel project in Bangladesh, this paper studies its deformation development characteristics and analyzes the reasons for the deformation of the tail shield structure during construction. Aiming at the deformation of the tail shield in an underwater shield tunneling project, effective rectification and treatment technology are proposed. By summarizing the control measures and experience of the tail shield deformation in the tunneling construction, the deformation prevention and treatment of the large-diameter underwater shield in the water-rich sand stratum are provided as reference in the future.

2. Project overview
The Karnaphuli River Tunnel Project in Bangladesh is located at the estuary of the Karnaphuli River in Chittagong City, connecting the east and west banks of the Karnaphuli River. The shield section is composed of two separate tunnels, and it is constructed with a \( \Phi 12.12 \)m air-cushioned slurry pressure balance shield machine. The outer diameter of the tail shield of the shield machine is 12120mm, and the inner diameter is 11960mm. The steel ring of the tail shield is divided into 4 pieces, which are X-shaped welded and assembled into a circle on site.

The bottom of the shield tunnel in the middle of the river fluctuates gently, the average covering thickness is 30 meters, the river is 12-14m deep, and the stratum is evenly distributed. From top to bottom, the stratum goes through flow plastic Muddy silty clay(Q4a\( l \)), Medium dense silty sand(Q4a\( l \)), Dense and Medium dense in local silty and fine sand(Q4a\( l \)), Dense silty and fine sand(Q4a\( l \)).

3. Analysis of the characteristics and causes of the tail shield deformation

3.1. Process and characteristics of the tail shield deformation
In the process of shield tunneling to complete segment ring 613 and then the cylinders retract, the grippers between the 19 # and 20 # cylinders cut with the guide bar on the inner side of the tail shield, leaving only 18mm of the guide bar left. The segment ring 612 is tightly attached to the tail shield guide bar and the protective layer near the end face is damaged. Because of that, construction on the site is immediately stopped. Polyurethane is injected into the radial holes of the center shield and the back of the posterior segment of the shield tail brush, and two-component grout is injected into the back of the posterior 2–3 segments. It is intended to form seal rings in the front and rear to ensure the stability of the tail shield.
Figure 1. Pictures of tail shield deformation

An electronic distance measuring device is utilized to collect typical cross-section deformation data of the tail shield exposed range on site. There is a longitudinal survey line between each group of cylinders, and a survey line is encrypted in the cylinder gap at the position of larger deformation. In this way, there are a total of 30 survey lines, and a total of 2 cross-sections are set. The measured section is calculated from the weld of the center-tail shield, and the distances are 1.1m, 1.9m. The measurement results of a typical cross-section are shown in Figure 2.

The deformation of the tail shield structure is mainly manifested by the coexistence of local concave and convex with a total of 4 parts of concave deformations and 1 part of convex deformation. Among them, the section 19-20 # cylinder, which is 1.1 m away from the weld of the center-tail shield, has the largest concave deformation with the maximum value reaching 67.5mm. The 21-1# cylinder has the largest convex deformation with the maximum value reaching 39.8mm. The deformation at other positions is within 20 mm.

Figure 2. Typical cross-section measurement results

3.2. Change of shield tail gap
The inner diameter of the tail shield is designed to be 11960 mm, and the outer diameter of the segment ring is 11800 mm. Without considering the setting of the guide bar, the theoretical value of the clearance between the segment ring and the inner wall of the shield is 80 mm on one side, and the sum of the shield tail gap in the same diameter direction is 160 mm. From the shield tail gap trend in Figure 3, it can be concluded that from ring 533 to ring 613, the sum of the total clearances of cylinders 19 #, 20 # ~ 7 #, 8 # (the sum of the diagonal clearances at the maximum deformation) gradually decreases, showing a clear downward trend. However, the sum of the total clearances of cylinders 20 #, 21 # ~ 10 #, 11 # gradually increases, showing a clear upward trend. As a result, it is considered that the deformation of the tail shield is a process of gradual development. It is manifested by the internal concave deformation of the cylinders 19 #, 20 # ~ 7 #, and 8 #, and the convex deformation of the
cylinders 20 #, 21 # ~ 10 #, and 11 #, which is consistent with the measurement results of the tail shield cross-section.

Figure 3. Change of shield tail gap

3.3. Analysis of deformation causes
Based on the above measurement results and the clearance change of the shield tail, this paper analyzes the reasons for the deformation of the tail shield in two aspects, including the structural strength of the tail and the action of external forces.

3.3.1. Structural strength of the tail shield
The force condition is set as that the surrounding load of the tail shield is the water and earth pressure, which is calculated by separated count method of water and earth pressure [1], regardless of the tail brush structure and the supporting effect of the inner shield tail grease on the rear of the tail shield.

The tail shield model is set as that the model constraint only considers one end to be fixed, and the surrounding soil adopts only compression springs. Two calculation cases are designed. In Case A, by considering the stress condition of the tail shield structure under the ideal state of the shield pipeline setting during the straight section tunneling, it is intended to verify the tail shield structure design; In Case B, taking into account the initial assembly error of the tail shield, the inversion analysis of the tail shield deformation is carried out to calculate the additional stress on the deformed area.

Figure 4. Calculation model and loads of the tail shield

After case analysis and numerical simulation, under the circumstance of Case A, the maximum stress position appears at the waist freezing pipe with the stress value of 365MPa, which is higher than the yield strength of the shield tail steel shell of 315MPa (the yield strength of 63-80mm thick steel plate material). Its maximum deformation is 15mm, while the deformation at the cylinder 19-20# position is only 5.9mm, which meets the deformation requirements of the tail shield structure. Under the circumstance of Case B, only uniform pressure is applied at the largest part of the concave. By calculation, when the passive earth pressure in this area is 4.5MPa, the maximum deformation of the shield concave can reach 58.0mm (actual deformation minus the initial assembly error value), and the maximum stress is 362MPa, reaching the yield strength. The yield area of the steel plate between the cylinders 19 # ~ 20 # in the deformed concave area is about 1.8 m².
According to the above analysis, if the shield machine is in the ideal state of straight tunneling, when the shield structure travels within the excavation space, the strength of the tail shield structure can meet the tunneling requirements. Nevertheless, when the shield tunneling attitude deviates or the large zone pressure difference is applied to correct the deviation, which causes additional stress on the shield body and the earth body, the rigidity of the tail shield structure is slightly insufficient.

3.3.2. Shield tunneling attitude

According to the calculation of the deviation between the front and the rear end of the shield at the same mileage, the additional stress on 80 segment rings before the tail shield deforms is shown in Figure 5 below. It can be seen from the figure that in the forward tunneling, the left side of the tail shield continues to be affected by defective tunneling attitude, and extrudes with the outside to produce ground resistance, which can reach a maximum of 2.38MPa. Therefore, it can be concluded that the uneven extrusion force caused by attitude of tunneling resulted by unknown changes of strata has a huge impact on the shield tail, the tunneling attitude of the shield machine in this state is an vital factor of the deformation of the tail shield.

3.3.3. Foreign objects outside of the shield

From the change of the shield tail gap in Figure 3, it can be seen that the deformation has a slow development trend, so obstacles such as shipwreck, boulder, or tool falling off in the strata can be eliminated. During the shield tunneling, there may be too much simultaneous grouting injection or excessive injection pressure, which causes the grout to move forward and consolidate on the outside of the shield to form an outer casing[2,3,7].

A magnetic drill is used to drill on-site to take cores to determine that there are hard plastic outer casings with thicknesses ranging from 12-20cm behind the deformed area wall. After laboratory analysis, there is no cement content inside the outer casing, so it is unlikely that the grout moves forward and consolidates outside the shield body.

The geological survey report shows that the stratum in this area is a sand layer with a few clay interlayers. After analysis, the main reason for the outer casings is that in the seawater environment with high water pressure, the sandy clay interlayer in the stratum selectively aggregates into clusters around the shield and becomes hardened by the loss of water. During the forward tunneling, it continuously aggregates, grows, compacts, falls off, and then aggregates, and finally forms a hard plastic outer casing.

3.3.4. Summary

In summary, the main reason for the tail shield deformation this time is that during the tunneling process...
in dense sand layer, the shield body squeezes the outer soil to form ground resistance due to the defective attitude of the shield machine. During this period, the outer silt fine sand and the sandy clay interlayer aggregate. After a long time of squeezing between the stratum and the shield body, a hard plastic outer casing with a certain thickness is formed after continuous water loss. The ground resistance is directly transmitted to the shield steel plate through the outer casing, so under the premise that the rigidity is slightly insufficient and the circumference is unchanged, the tail shield shows uneven deformation of convex and concave.

4. Rectification technology for tail shield deformation

4.1. Process of tail shield rectification

Before rectification, the weld quality of the tail shield segmentation and pipeline structure within the deformation range is inspected to ensure the safety of the tail shield. The rectification goal is to make the outer clearance between the segment and the shield tail guide bar not less than 10mm, and the shield tail gap not less than 40mm, so as to meet the requirements of the shield machine. The specific rectification construction process flow is shown in Figure 6.

4.2. Rectification tooling design and assembly

4.2.1. Rectification tooling design

Due to the space limitation of the deformation rectification area and the assembling machine in the tail shield, a linear rectification tool is designed on the premise of making full use of the auxiliary functions of the existing segment assembling machine. The main beam is designed in sections, and the length of each section is different. The cross-section of the main beam is a double H-section formed by double-splincing HW400 steel. Both ends of each section of the main beam are welded with flanges and connected by M28 high-strength bolts. The supporting beam is cut into different lengths according to
the design requirements and welded to the main beam.

According to the rectification requirements of the incremental launching method, two wedge block structures are designed. The first structure is a single independent wedge block, with the usage of a single jack acting on a single-point incremental launching. The second structure is a single wedge block, with the usage of two jacks acting on a single-point incremental launching.

![Figure 7. Rectification tooling for tail shield deformation](image)

4.2.2. Rectification tooling assembly
After determining the range of the assembling machine occupied by the rectification tooling according to the definite shield tail rectification range, the auxiliary equipment and related pipelines of the shield machine are removed within the range.

The installation sequence of the single beam is ③-②-④-①. The main beams of each section are docked in turn, which are connected with M28 high-strength bolts through the flange of the beam end. After the connection is completed, the whole is hoisted and positioned, and the rear end of the main beam and the arc steel plate are welded and reinforced.

Then it is necessary to position and weld the rear inclined support, and the upper tension diagonal is welded to the H-shaped beam of the center shield, so that the lower support leg stands on the platform of the assembling machine. The lower part of the main beam of the assembling machine is welded to the upright column and connected by the connecting beam.

With reference to the above method, the assembly of supporting beams 1 #, 2 #, 3 # is completed in sequence and they are arranged side by side with a center distance between beams of 600mm. One-meter-length steel is used to connect and strengthen the upper and lower surfaces of the joists 1 #, 2 #, 2 #, and 3 # (add 1 tie beam for a distance of 1 meter).

4.3. Hole making in tail shield
The hole making in the shield body should avoid pipelines and patch welds in the deformed area and follow the principle that any three holes are not in the same straight line. A magnetic drill is used to make holes around the rectification area.

For insurance, the hole is determined to be a φ32 hole, and the hole is completed in sequence according to the following steps, including painting positioning → drilling with M27 drill (60 mm) → M32 tap threading → DN50 ball valve installation → drilling with M24 drill (20 mm) → closing the ball valve.

4.4. Sand discharge
4.4.1. How to discharge sand
After the hole is formed, a three-way ball valve is welded. The three-way ball valve is connected to a high-pressure bentonite pipe on the main road and a high-pressure water pipe on the branch, so that bentonite and water can be injected into the back of the shield wall by opening and closing the valve. Then the high-pressure bentonite pipe is removed and the hose is installed, at the same time turning on all the valves, which allows to cooperatively flush and discharge the sand with the high-pressure water.

After many attempts in the site, high-pressure water is used for repeatedly flushing, the sequence of
discharging first, then flushing, and back to discharge is adopted to discharge sand.

4.4.2. **When to discharge sand**

Before the tail shield rectification, a test of the timing and effect of sand discharge is carried out. According to the timing of sand discharge, four test conditions are determined, including loading without sand discharge, sand discharge before loading, sand discharge during loading, and sand discharge after loading. The loading method is double-beam single-point incremental launching, and all loads to the maximum load, the representative test results are as follows:

![Loading and decompression test of sand discharge](image)

The following conclusions were obtained through the results of multiple tests and the actual feedback on site:

1. The decompression of sand discharge had a positive effect on the incremental launching and rectification. The first discharge can release the earth pressure around the hole to a certain extent, and realize the rebound of the elastic deformation of the tail shield steel plate, but the effect of the second discharge was not significantly obvious;

2. The rectification effect of the sand discharge before loading was the most obvious through the experiment of different sand discharge timing. After the jack was unloaded, the maximum rectification deformation reaches 20mm, so it can be determined that the decompression of sand before loading is the best rectification combination of incremental launching;

3. One single discharge volume of less than 0.5m³ had no adverse effects on the water level of slurry chamber, the grease pressure at the shield tail, and the parameters of the shield machine.

4.5. **Rectification sequence and method of the incremental launching**

The two-round rectification plan is determined according to the combination mode of the tooling beam and the position of the vertex. The first round is carried out in a counterclockwise direction, according to the tail shield first followed by the center shield, and the area with large deformation first followed by the area with small deformation. The specific rectification sequence is as figure 9; The second round is determined according to the roundness measurement data of the shield tail at the end of the first round and the change of the shield tail gap.

![Schematic diagram of tail shield rectification sequence](image)
4.6 Rectification process of loading

Before each loading of the incremental launching, the launching area is discharged with about 0.5m³ of sand. After the sand discharge is completed, the initial value of the deformation of the shield tail steel plate in the launching area is collected by the electronic distance measuring device and the cross method. Two 500t jacks are loaded step by step starting from 0MPa synchronously, and the pressure increase of each step does not exceed 5MPa (82t). According to the hydraulic pump station, the maximum pressure-bearing capacity of the oil pipe, and the rectification deformation of the shield tail measured by the electronic distance measuring device during the loading process, the maximum loading pressure is jointly determined. After each step of loading is completed, the voltage is stabilized for 5-10 minutes. Based on the position number of the reflector, the electronic distance measuring device is used to collect the rectification deformation value one by one. The loading can be continued only after the compared data are recorded in detail.

In order to enhance the loading effect, when the jack is loaded to the maximum pressure, it should be stabilized for 2-6 hours, and the specific time is determined according to the deformation of the shield tail. If the pressure of the pressure gauge drops more than 5MPa during the stabilization process, restart the pump station and load to the maximum pressure again. The electronic distance measuring device is used to measure the rectification deformation every half an hour. If the deformation change does not exceed 5 mm after three consecutive measurements, it is necessary to stop the voltage stabilization, restart the pump station, and unload step by step. When the jack cylinder is completely separated from the wedge block, the unloading ends.

The electronic distance measuring device is applied to collect the former rectification deformation value. Compare it with the initial value before loading to determine the rectification deformation this time. The electronic distance measuring device and the reflector are kept unchanged, and the rectification deformation value is measured again after 24 hours to determine the final one.

4.7 Analysis of rectification effect

With the help of simple rectification tooling to carry out different combined loading methods and different launching methods, the shield tail rectification has achieved the expected purpose. The maximum deformation of the tail shield steel plate has obvious convex, and the upper convex also has different degrees of centripetal concave, the deformation of at each points has a tendency to be a circular. Figure 13 shows the comparison before and after typical cross-section rectification.

Comparing the measurement results of the 1.1 m cross-section (maximum deformation section) at the rectification point of the shield tail, the maximum deformation is deformed from 67.5 mm concave to 6.5 mm convex. Besides, the maximum deformation area has an average concave deformation of 14 mm. Compared with the maximum 12 mm concave of the shield tail when the shield is assembled, the shield tail in the maximum deformation area has returned to the initial state of assembly.

![Figure 10. Comparison of deformation before and after rectification](image)
the shield tail gap of the segment ring 612 is measured. The shield tail gaps at cylinders 18~20# are encrypted and measured. The measurement positions are the middle positions of the 23 groups of cylinders with a total of 23 locations. During the two-round rectification process, the shield tail gap of the cylinders 19 # ~ 20 # and 21 # ~ 23 # changes, and the remaining shield tail gaps are stable without significant changes.

In the segment ring 612 at the maximum deformation area, the shield tail gap between cylinders 19 # ~ 20 # increased from 40mm to 68m, and the shield tail gap between cylinders 21#~22# reduced from 123cm to 97cm, indicating that the overall rectification effect is productive.

![Figure 11. Change of shield tail gap](image)

5. Deformation control measures during tunneling

After restarting tunneling, due to the uneven force of the shield body, the tail shield will inevitably be deformed again. The deformation control measures and experience of restarting tunneling on-site are summarized as follows:

1. Strengthen the monitoring of the shield tail gap, expand monitoring from 8 measuring points to 23 measuring points, and fully grasp the relative position relationship between the segment ring and the tail shield;

2. Set the deformation threshold of the shield tail. The maximum allowable deformation value of the shield body is when the cylinder grippers are in contact with the guide bar, and measures must be taken when the clearance is less than 1 cm;

3. Prepare the copy cutter in the corresponding range of the deformation area, and create conditions for expanding the space of the shield deformation area in advance and controlling the horizontal attitude of the shield;

4. If the tail shield deforms again, radial holes in the corresponding range should be continuously making on the segment rings to discharge sand and reduce pressure. Single discharge per hole is 0.2-0.4m³, and the total discharge volume of one ring does not exceed 1.6m³;

5. Take the initiative to reduce the thrust of shield tunneling, and inject bentonite grout into the radial holes of the center shield to lubricate and reduce casings. Bentonite injection and sand discharge are performed alternately, the total grouting volume of one ring does not exceed 1.6m³, and the injection is divided into 3-4 times;

6. By observing multiple local deformations of the tail shield at the construction site, it is concluded that the deformation of the tail shield steel plate can be effectively controlled by taking the above measures within 5 cm. In addition, the initial roundness can be restored through its own elasticity, without the need for incremental launching again for rectification.

6. Conclusions

Based on the tail shield deformation case of the Karnaphuli River underwater tunnel in Bangladesh, this paper studied the deformation characteristics and development process of the tail shield, and analyzed
the causes of its deformation in detail. Finally, the tail shield deformation rectification technology was summarized to successfully release the trapped shield machine. Through the cause analysis of the tail shield deformation of the underwater shield tunneling and the research on the rectification technology, the following conclusions are drawn:

1) The tail shield takes a long time to deform and is a process of gradual development. During the shield tunneling, the monitoring of the changing trend of the shield tail gap should be strengthened, especially in the stratum with clay minerals that are prone to aggregate. It is recommended to add an automated measurement and statistics system for shield tail gap in the shield machine to grasp the trend of shield tail gap in real-time;

2) The main reason for the deformation is that the shield body and the soil layer squeeze each other to produce extra ground resistance when the attitude is bad or the deviation is corrected. It is suggested that the thickness or material grade of the shield steel plate should be appropriately increased while comprehensively considering the equipment manufacturing and engineering costs when designing to guarantee safety; At the same time, it is suggested to strictly follow the principle of diligent and less correction to avoid large-scale correction;

3) The tail shield steel plate within 5cm of elastic deformation can be effectively controlled by turning on the copy cutter, discharging sand in the radial hole to reduce pressure, and bentonite injection, and restore its initial roundness;

4) This paper proposes the tail shield deformation rectification technology in the underwater shield tunneling, which has been successfully implemented in the Karnaphuli River underwater tunnel project to help release the trapped shield tunneling machine. Field operations have verified its rationality and feasibility, not only breaking the conventional cognition that the tail shield deformation in the dense iron sand stratum cannot be effectively modified, but also providing a reference for similar engineering projects;

5) During the tunneling construction, many factors are affecting the deformation of the tail shield, and the geological conditions are also complex and changeable. The deformation rectification technology described in this paper needs to be further optimized and improved in the application. What’s more, further research is needed to deal with the outer casings outside the shield body in underwater tunneling.

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