Journal of Civil Engineering and Urban Planning (2024)
Clausius Scientific Press, Canada

DOI: 10.23977/jceup.2024.060406
ISSN 2616-3969 Vol. 6 Num. 4

Causes and Control Measures of Floating Tube Sheet in Metro Shield Tunnel

Wang Fei[1,a], He Chanlong[1,a], Liu Qibin[1,a], Yao Shenghui[2,b,*], Zhu Chenyang[2,c], Shen Mingrui[2,d]

[1]China Communications Fourth Engineering Bureau Second Engineering Co., Ltd., Luoyang, Henan, 471000, China
[2]School of Civil Engineering, Henan Polytechnic University, Jiaozuo, Henan, 454000, China
[a]624724726@qq.com, [b]820174839@qq.com, [c]694799638@qq.com, [d]1539922047@qq.com
[*]Corresponding author

Keywords: Shield tunnel, tube uplift, groundwater, shield parameters, grouting

Abstract: During the tunnel boring construction of shield tunnel, the tunnel tubes are floated due to the influence of many factors such as tubes installation process, groundwater level, tubes grouting, and site conditions, which leads to tubes misalignment and breakage. Therefore, in order to ensure the construction quality, it is necessary to study the factors of tube sheet uplift. Relying on a rail transit project example, this paper investigates the uplift factors of tube sheet lining structure after on-site investigation and analysis of engineering quality defects. The results show that the uplift of the pipe sheet is caused by the presence of groundwater, improper setting of the tunneling parameters of the shield machine, and the failure of the grouting slurry to solidify in time. For the existence of groundwater, the grouting holes can be opened and released to reduce the impact of groundwater; the parameters of the shield machine should be adjusted according to the advancing distance, the nature of the ground surrounding rock and the tunnel design line; the grouting slurry should be adjusted according to the engineering geological conditions and the situation around the tunnel. The results of the study can provide some valuable references for the factors and treatment measures of shield tube sheet floating during the shield construction process.

1. Introduction

With the rapid development of China's underground space engineering, subway tunnel shield construction is also more and more common, construction problems are also more and more prominent, especially in the shield tunneling process, has been assembled to complete the tube piece floating problem, affecting the construction progress, bringing economic losses, prevention and treatment of shield tube floating for the safe and long-lasting operation of shield tunnels have far-reaching significance.

Therefore, scholars at home and abroad have conducted a lot of research on the causes and control of tube sheet uplift. Zhang Zhongfu[1] analyzed the causes of tube sheet uplift in forming tunnels and put forward countermeasures by combining engineering examples; Xia Ming et al[2] investigated the

law of tube sheet lining junction uplift deformation by establishing a finite element model; Zhang Zhiyong[3] analyzed the causes from the aspects of hydrological and geological conditions, the impacts of shield operation, and post-pressurization slurry of tube sheet and put forward the treatment of tube sheet uplift; Zhang Dongxiao et al[4] from the geological conditions, grouting method, slurry, grouting parameter control, tunnel overburden, shield attitude, put forward the tube sheet floating countermeasures and measures; Dong Saijiaoshuai et al[5] from the measured data, think that improve the cement mortar of the initial solidification time and the early shear strength can effectively control the tube sheet uplift; Eddie Wang[6] combined with the project, put forward to auxiliary water drainage pressure relief, grouting and filling, the effect of the check, and other treatment measures; Chang Jiang et al[7] according to the project tube sheet uplift, from the shield structure after grouting, the effect of the slurry, and other reasons, proposed tube sheet floating treatment. Floating, from the shield machinery, post-wall grouting, shield attitude and other research, put forward control measures; Wang Xinqiang et al[8] established a numerical model of grouting pressure, analyze the deformation and stress characteristics of the surrounding rock and tunnel structure under the action of synchronous grouting; Wang Xundong[9] analyzed the tube sheet floating from the shield method, grouting process and other aspects of the control of tunnel tube sheet floating in sandy soil; Wu Yong[10] based on the ABAQUS numerical simulation software to establish the control measures, and the control measures. ABAQUS numerical simulation software to establish a three-dimensional numerical analysis model in the process of shield tunnel construction, analyzed the effect of parameters such as slurry solidification time, grouting pressure, elastic modulus of slurry, soil silo pressure, thickness of the grouting layer, and groundwater on the amount of tube sheet uplift; Hu Yuchen[11] investigated the effect of tunnel depth and slurry performance on tube sheet uplift by calculating the effect of slurry on tube sheet uplift in water-rich ground; Cai et al.[12] determined that the location of the largest bulge was at the shield tail by calculating the additional thrust of the shield cutter plate, the friction between the shield shell and the soil, and the grouting pressure at the shield tail, indicating that the shield tube sheet is prone to uplift at the shield tail.

2. Engineering Overview

2.1 Engineering Geology Overview

This paper relies on a rail transit project, which is located on the hilly landscape at the confluence of the surface waters of the Jialing River and the Yangtze River, with the bedrock being terrestrial clastic rocks of sandstone and sandy mudstone, and the enclosing rock level being IV, with weak water content. The permeability of the sandy mudstone rock body is slightly permeable, and the permeability of the sandstone rock body is weakly permeable. According to the storage conditions, hydrophysical properties and hydraulic characteristics of the groundwater along the route, the groundwater along the route can be classified into the pore water of the loose layer of the Quaternary System and the bedrock fissure water.

2.2 Construction characteristics, difficulties

This project adopts composite shield machine double line shield construction, the host weighs about 458 tons, its shield host length 9985mm, excavation diameter 6900mm, equipped with 30 propulsion cylinders, the maximum thrust up to 35Mpa. the total length of construction digging is 6928.347m, the minimum turning radius of 350m. the minimum depth of the shield tube sheet is about 28m, the maximum depth of burial is about 92.7m, the depth of burial is about 28m, the construction needs to deal with the pressure of high ground and groundwater pressure to prevent groundwater leakage. The construction needs to cope with the upland pressure and groundwater

pressure to prevent the leakage of groundwater.

2.3 Selection of shield pipe sheet

The project adopts precast concrete tube sheet, assembling and completing the shield tube sheet with inner diameter of 5900mm, outer diameter of 6600mm, thickness of 350mm, width of 1500mm, concrete strength grade of the sheet is C50, impermeability grade P12. The tunnel tube sheet of this project is a general-purpose tube sheet, divided into 6 pieces, a ring tube sheet consists of 1 piece of capping piece, 3 pieces of standard piece of tube sheet, and 2 pieces of adjoining piece of tube sheet. The tube pieces are connected by curved bolts, with 12 ring bolts and 10 longitudinal bolts. The assembling of pipe pieces is shown in Figure 1.

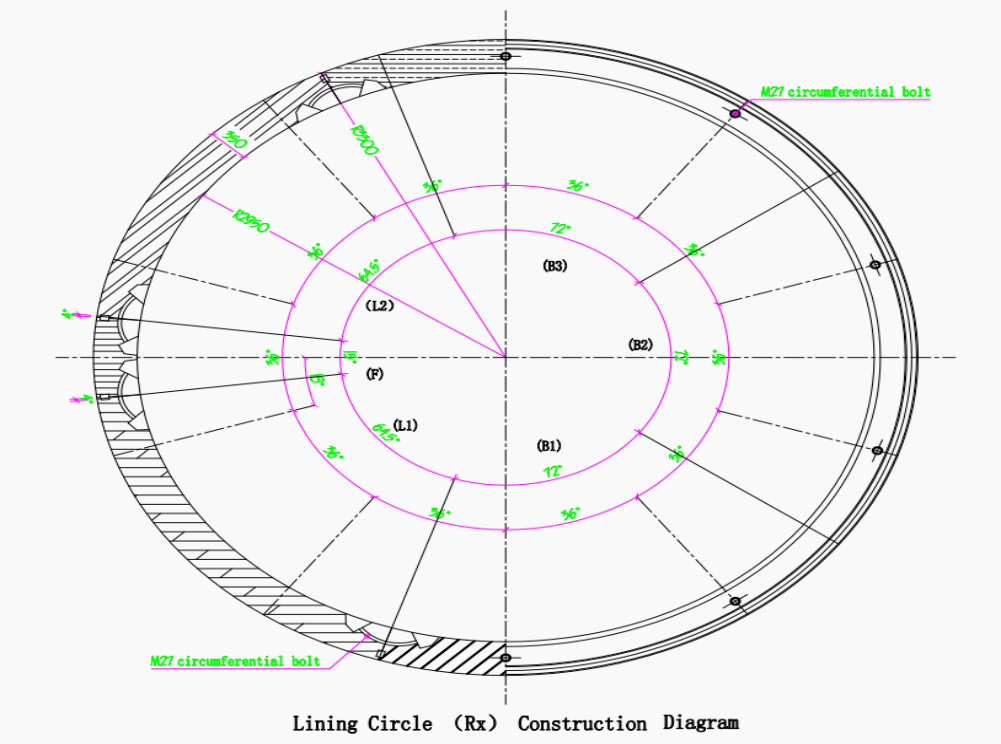

Figure 1: Pipe piece assembling structure.

2.4 Shield tube piece floating

Relying on a city interval subway tunnel shield project, found in the construction process, the right line of the project interval has been completed tube piece tunnel tube piece floating problem. Among them, the right line uplift range between 80 and 110 rings, the maximum uplift position of 93 rings, uplift amount of 152.9mm, exceeding the molding tunnel acceptance specifications; the left line of shield 45-52 rings of tubular piece of the tendency to uplift, tubular piece of the attitude of the vertical deviation of a maximum of 27mm, although not exceeding the molding tunnel acceptance specifications, but two measurements show that there is a tendency to float the tube tunnels. The horizontal and vertical deviation of the tube sheet attitude of the left and right double-line shield is shown in Figure 2 and Figure 3.

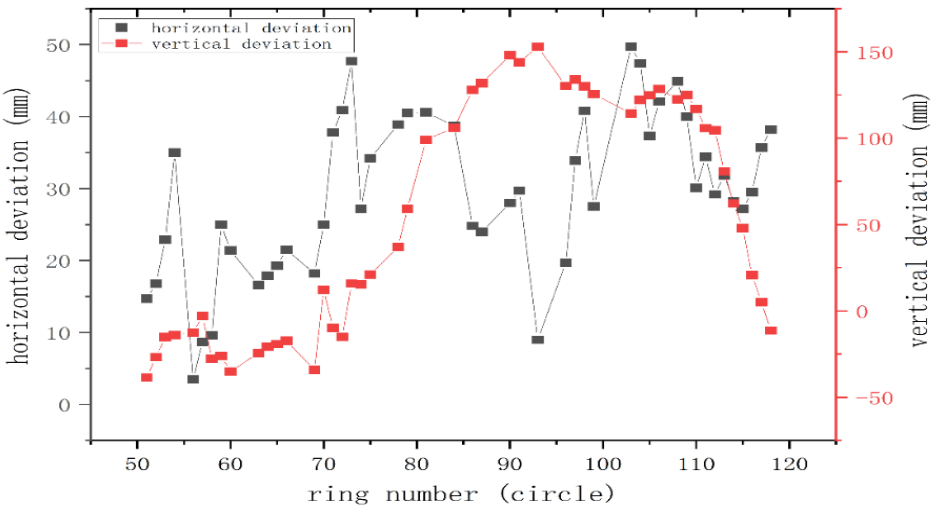

Figure 2: Right line tube sheet attitude deviation.

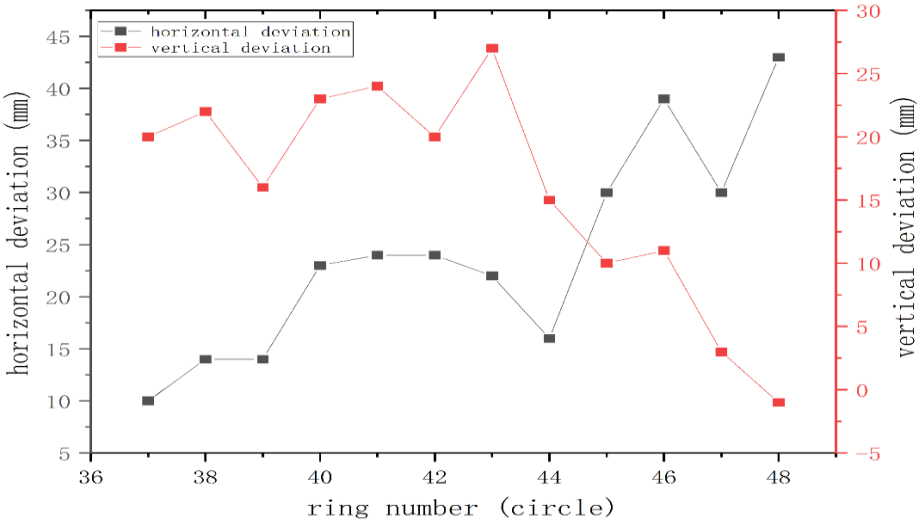

Figure 3: Left line tube sheet attitude deviation.

3. Tube sheet uplift factor

3.1 Existence of groundwater

Shield machine digging process, the diameter of the cutter plate excavation is generally larger than the diameter of the tube sheet assembly, when the shield center axis is below the water table. A large amount of groundwater due to water pressure and infiltration will enter the grouting layer, the shield tube sheet upward force. When the shield tube sheet is subjected to buoyancy force is greater than the tube sheet's own gravity, the shield tube sheet will be generated by the tendency of upward levitation.

When the pipe sheet is surrounded by groundwater and grouting slurry, the buoyancy force can be calculated according to the buoyancy formula.

Buoyancy formula:

$$F_{buoyancy} = G_{sewerage} = \rho_{water} g V_{sewerage} \quad (1)$$

Calculation formula for buoyancy force on pipe sheet:

$$F_{shield} = \rho_{slurry} g \pi R^2 B \quad (2)$$

In the above formula:

ρ_{water} is the density of water

g is the acceleration of gravity, generally take $9.8 m/s^2$

R -- outer radius of tube sheet

B -- Width of tube sheet

The formula for calculating the gravity of the tube sheet itself:

$$G_{shield} = 2\pi R B b \rho_{shield} g \quad (3)$$

In the above formula:

ρ_{fluids} is the density of injected slurry

b -- Thickness of tube sheet

According to the above formula, when $F_{shield} > G_{shield}$,the buoyancy force on the pipe sheet is greater than its own gravity, the pipe sheet will have a tendency to float up.

3.2 Influence of shield machine parameters

Most of the main equipment of the shield machine is in the head, the shield head is too heavy. If the rear supporting can't follow up in time, it will lead to the shield tail lifting upward, and the tube sheet will be lifted upward together with the shield tail in the shield tail when it is not disengaged from the shield tail, leading to the floating of the tube sheet.

Shield machine according to the tunnel axis digging, propulsion cylinders act on the tube sheet, relying on the tube sheet to produce forward propulsion; and through the control of the propulsion cylinder pressure to adjust the direction of the cylinder pressure difference is large, the tube sheet will produce a displacement deviation, ultimately leading to the tube sheet floating.

3.3 Post-wall grouting of pipe sheet

In order to facilitate excavation and tube sheet installation, the general shield machine cutter excavation diameter will be slightly larger than the diameter of the tube sheet after installation, which provides space for the uplift of the tube sheet, the gap between the shield shell and the tube sheet is shown in Figure 4 below. Therefore, the space behind the pipe sheet wall should be filled with grout, which not only can effectively stabilize the surrounding soil structure, but also can eliminate the space for the uplift of the pipe sheet.

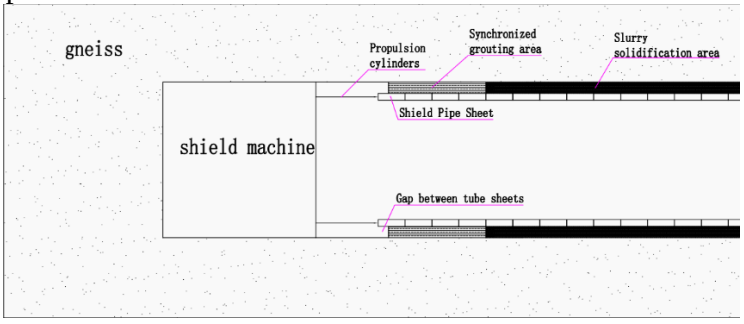

Figure 4: Schematic diagram of shield advancement.

3.3.1 Synchronized Grouting

Synchronized grouting can effectively stabilize the surrounding soil and the installed pipe sheet, but during the solidification process, due to the groundwater infiltration and synchronized grouting slurry together produce upward buoyancy on the shield pipe sheet, resulting in a tendency for the shield pipe sheet to float, so the solidification time of the synchronized grouting slurry will directly lead to the amount of shield pipe sheet floating.

Synchronized grouting pressure is too large or too small will have an impact on the floating of the tube sheet. When the grouting pressure is too large, it may lead to the slurry can not flow smoothly to each gap, forming a gap behind the wall of the tube sheet, and the gap provides space for the uplift of the tube sheet; too large a grouting pressure will also produce thrust on the tube sheet, and the uplift of the tube sheet will be produced under the impetus of the grouting slurry. When the grouting pressure is too small, relying on its own mobility to fill the gap behind the wall of the tube sheet may be generated at the same time as the grout solidification of the slurry, leaving the gap behind the wall of the tube sheet, but also for the floating of the tube sheet to provide space; the grouting pressure is too small, but also to increase the grouting time, in the process of grouting, the tube sheet can not be supported in a timely manner, which leads to the floating of the tube sheet.

3.3.2 Secondary grouting

When the synchronous grouting reaches a certain period of time after the slurry solidification, due to the existence of groundwater, synchronous grouting may not be saturated to fill the gap behind the pipe sheet wall, which provides a certain space for the uplift of the pipe sheet. Therefore, generally after the synchronous grouting slurry solidification, the pipe sheet will also be opened and drained, and the secondary grouting holes reserved on the pipe sheet will be grouted twice to fill the voids and stabilize the shield pipe sheet.

3.4 Pipe assembling effect

In the process of assembling pipe pieces, there is a certain positional difference between neighboring pipe pieces, which will aggravate the positional movement between neighboring pipe pieces in the subsequent construction and use process, thus generating the uplift of pipe pieces.

3.5 Deformation of surrounding rock and soil bodies

Large-diameter shield tunnel in the excavation process, the additional thrust of the shield cutter plate influenced by the mud gravity, the friction between the shield shell and the soil affected by soil slippage and burial depth, and the grouting pressure of the shield tail influenced by the grouting layer hardening and circumferential dissipation can lead to the vertical deformation of the geotechnical body, and the location of the largest bulge occurring in the tail of the shield. Shield tail grouting area is the main area to produce tube sheet uplift, this deformation makes the mechanical properties of the surrounding rock structure change, resulting in the reduction of the stability of the surrounding geotechnical body structure, changing the original shield excavation interval state, making the tube sheet follow the shield excavation interval deformation to produce tube sheet uplift.

4. Control measures for tube sheet uplift

4.1 Reduce groundwater level

Shield intervals through the water-rich stratum, you can artificially reduce the groundwater level,

reduce the groundwater content, reduce the groundwater influx into the shield tube sheet and the gap between the shield shell, to avoid the buoyancy generated by the buoyancy provided by the groundwater tube sheet uplift phenomenon occurs.

4.2 Optimize shield machine parameters

In the process of shield machine propulsion, timely follow up the rear supporting facilities, enhance the rear of the shield machine head constraints, to avoid the shield machine head overweight head phenomenon leading to the shield tail is not disengaged from the floating of the tube sheet; shield machine attitude corrective, you need to reasonably control the propulsion cylinders of each partition thrust, reduce the uneven thrust caused by the floating of the tube sheet.

4.3 Strict control of grouting

Synchronized grouting grouting pressure and slurry solidification time should be adjusted according to the stratum, propulsion speed, etc., to ensure that the slurry can fill the void behind the wall completely, but not due to the solidification time is too long resulting in slurry loss.

4.4 Ensure the assembling of pipe pieces

When assembling pipe pieces, the assembling precision should be strictly controlled to ensure that the pipe pieces are installed in accordance with the construction requirements, and to prevent the floating of pipe pieces caused by the assembling precision of pipe pieces.

4.5 Reduce the ground disturbance

Pre-construction geological field survey, the existence of underground caverns are filled in a timely manner; the process of advancing, reasonable control of its propulsion speed, is to ensure that the cutter plate force uniformity, to avoid uneven force cutter plate produced strata disturbance.

5. Project example processing

5.1 Treatment of already uplifted pipe sheets

Figure 5: Pipe sheet opening for water discharge.

The uplifted section of the pipe sheet is opened and drained, as shown in Figure 5. After the water release, top grouting is carried out to fill the voids, bind the movement of the pipe sheet, and close it in time.

The formed tunnel is first detected by geo-radar, after detection, there is localized point-like de-voiding behind the tube sheet, and supplementary grouting is carried out on the detected de-voiding parts; and then the tunnel impact echo acoustic frequency method is used to re-test the formed tube sheet, and the effect of re-testing is shown in Figure 6.

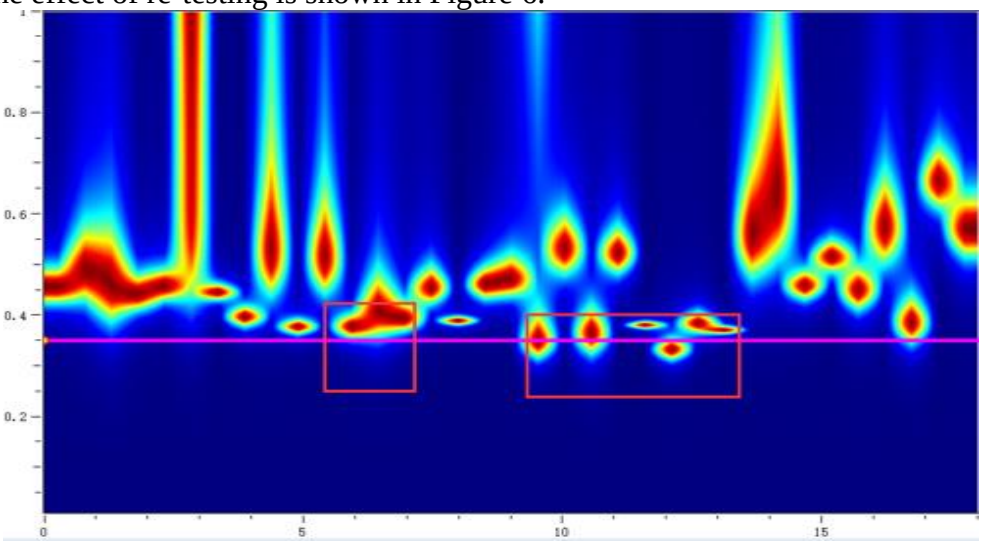

Figure 6: Shock wave remeasurement map.

5.2 Grouting adjustment

5.2.1 Prevention in advance

The shield machine is modified with synchronized grouting lines to ensure that the slurry is controlled in the shortest possible time from production to completion of grouting to avoid slurry solidification during transportation or grouting.

5.2.2 Prevention in advance

Different slurry raw material ratios can get different solidification time, different fluidity of the slurry suitable for different water content strata. The slurry should be adjusted according to different construction environments and water contents of the strata, so as to achieve the grouting material applicable to the current strata.

5.3 Shield construction control

5.3.1 Shield tunneling parameters

Shield machine in the process of digging, attitude deviation adjustment for partition cylinder thrust operation, strict control of shield digging parameters, to prevent the shield machine parameters are too large; shield machine should be combined with the actual situation on the site, optimize the shield attitude, the shield machine attitude adjusted to the upward trend, to prevent the upward flotation caused by the shield machine planting the head caused by the tube sheet out of the tail of the shield; shield correcting deviation to follow the principle of “diligently correcting the less corrected, moving to correct the deviation”. When correcting the deviation of the shield, the principle of “correcting the

deviation while moving" was followed.

5.3.2 Tube sheet fastening

The assembling machine strictly implements the three-tightening system of pipe bolts after assembling the pipe pieces. The principle of three-tightening system of bolts includes initial tightening, re-tightening and final tightening. Initial tightening refers to the initial tightening after the completion of pipe sheet installation to ensure that the pipe sheet does not undergo significant displacement during the initial connection. Re-tightening is usually carried out for the second time on all bolts after the installation of all pipe sheets of a ring is completed, so as to improve the strength of the connection by re-tightening the pipe sheets. Final tightening is usually carried out after a fixed period of time after the completion of re-tightening, which allows time for the pipe sheets and bolts to adapt to the geological conditions and construction loads, thus eliminating the loosening of bolts due to the settlement and deformation of the pipe sheets and other factors.

5.4 Follow-up control measures

5.4.1 Prevention in advance

Measurement work is followed up in time, every 10 rings for straight line section, every 5 rings for curve section, and re-measurement is carried out again after grouting is completed to ensure real-time controllable attitude of pipe sheet.

5.4.2 Prevention in advance

Under the hard rock water-rich stratum, combined with the actual situation on site, the shield attitude can be adjusted appropriately, and the vertical axis can be adjusted downward by about 30-50mm to prevent the tube sheet from floating over the limit.

6. Conclusion

The article summarizes the classification of the reasons for the floating of the tube sheet of shield structure, combines the processing measures of a rail transit project example. For the floating of the tube sheet during the construction of the shield structure, the study of the reasons for the floating of the tube sheet and the processing measures have reached the following conclusions:

(1) The root cause of tube sheet floating is that the diameter of the shield excavation area is larger than the outer diameter of the tube sheet after assembly, which provides space feasibility conditions for tube sheet floating, especially in the process of grouting the tube sheet wall thickness cavity has not been filled sufficiently, the space left behind to provide favorable conditions for tube sheet floating.

(2) In the process of shield tunneling machine, the numerical value of construction parameters should be set in a reasonable and compliant manner, and improper operation will make the relative displacement of the tube sheet caused by uneven force, the tail of the shield upward caused by planting the head, and the extrusion of the tube sheet, and the floating of the tube sheet caused by the strata disturbance caused by inappropriate propulsion speed and thrust.

(3) Grouting slurry and grouting pipeline need to be adjusted according to the propulsion area, the fluidity of the slurry and the solidification time is the key to ensure that the slurry is filled smoothly in every place; grouting pressure is directly on the tube sheet, excessive grouting pressure squeezes the tube sheet and produces tube sheet floating. Good grouting pipeline can not only ensure the timeliness of grout injection but also add materials for grout adjustment during the grouting process.

(4) During the construction period, continuous monitoring of shield machine attitude and tube sheet is the main means to prevent tube sheet floating. The shield attitude is corrected in time according to the monitoring data to avoid the uplift caused by excessive corrective pressure; the radar and shock wave are detected after grouting of the tube sheet, and the dehollowed parts are grouted in time for reinforcement.

References

[1] ZHANG Zhongfu. Analysis of reasons and countermeasures for uplift of tube sheet in formed shield tunnel[J]. Urban Construction Theory Research(Electronic Edition),2024,(21):167-169.

[2] XIA Ming,ZHANG Huipeng,ZHANG Zhiqiang,et al. Influence factors of tube sheet uplift of shield tunnel in muddy siltstone stratum[J]. Urban Rail Transportation Research,2024,27(07):120-126.

[3] ZHANG Zhiyong. Analysis of reasons and countermeasures for tube sheet uplift in shield tunnel[J]. Value Engineering, 2018,37(06):143-145.

[4] ZHANG Dongxiao,LI Chao,LU Dazhan,et al. Mechanism analysis and control research of tube sheet floating in shield tunnel[J]. Railway Standard Design,2011,(07):95-97.

[5] DONG Saishuai, YANG Ping, JIANG Chunyang, et al. Analysis of mechanism and control of tube sheet uplift in shield tunnel[J]. Journal of Underground Space and Engineering,2016,12(01):49-54.

[6] Yun Wang. Research on uplift mechanism and prevention technology of tube sheet in subway tunnel in hard rock area[J]. Railway Construction Technology,2022,(12):170-173+206.

[7] CHANG Jiang, ZHAO Yi, WANG Yan. Analysis of reasons and control measures for floating of tube sheet in shield tunnel[J]. Municipal Technology,2010,28(03):123-125.

[8] WANG Xinqiang,YAN Qixiang,SUN Minghui,et al. Analysis of the effect of synchronized grouting on tube sheet uplift in shield tunnel[J]. Railway Construction,2022,62(02):118-122.

[9] WANG Xuandong. Analysis and control technology of uplift factors of shield tunnel tubes in sandy soil layer[J]. Shanghai Construction Science and Technology, 2020,(02):36-38.

[10] WU Yong. Research on the mechanism and control technology of shield tunnel tube sheet floating[D]. Anhui University of Architecture,2023.

[11] Hu Yuchen. Analysis of factors affecting the uplift of shield tunnel tubes in water-rich strata[J]. Shanxi Construction,2023,49(13):164-166.

[12] CAI Xiaoming,PAN Hong,LUO Guanyong,et al. Calculation of vertical deformation of soft soil caused by large diameter shield construction[J]. Journal of Henan University of Science and Technology (Natural Science Edition), 2023, 42(01): 185-193.