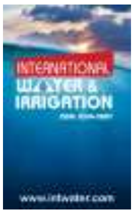

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Case Study of Pipe Jacking with Pressure Into Cabin in High Water Pressure Composite Stratum

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Abstract: The construction of large-diameter pipe jacking within high water pressure composite stratum is a complex undertaking, fraught with numerous uncertainties. Should driving parameters such as mud tank pressure and torque prove to be abnormal, it may become necessary to consider cabin inspection. In cases where the cabin cannot be opened at normal pressure, operational inspections may be conducted by entering the cabin under pressure. Within the context of the Jiaoliu River pipe jacking section of the sixth bid of the Chuo to Liao water diversion project, the ZTPΦ4400mm mud-water balance pipe jacking machine was utilized. During the construction process, abnormal noise and sudden torque increases were observed within the cabin, rendering the opening of the cabin impossible at normal pressure. In light of these challenges, this paper presents a detailed description of the cabin-opening under pressure construction utilized in this project. This includes a thorough analysis of the key technologies involved, such as the selection of the cabin-opening mode, the working principles of cabin entry under pressure, and preparations before construction. Additionally, this paper provides a comprehensive overview of mud film preparation, mud film establishment, and pipe wall grouting, all of which are essential components of the cabin-opening under pressure construction process. Through a rigorous examination of these critical factors, this paper aims to provide valuable insights into the challenges and best practices associated with large-diameter pipe jacking in high water pressure composite stratum.

Keywords: high water pressure; composite stratum; with pressure into the cabin; mud ratio; mud film establishment

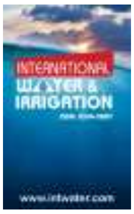
Introduction

With the advancement of domestic pipe jacking technology [1], the construction of pipe jacking tunnels has evolved to encompass larger diameters, longer distances, greater depths, and more intricate geological conditions[2][3]. In composite strata, especially in hard rock formations, tool wear and foreign object incidents are frequently encountered, necessitating tool replacements and foreign object inspections. Conversely, in loose strata with high groundwater pressure, achieving normal pressure cabin operation becomes challenging, leading to elevated risk levels. In such challenging scenarios, pressurized cabin technology has emerged as an optimal construction method due to its adaptability to complex geological conditions, elimination of the need for ground reinforcement, and high level of safety. Consequently, the utilization of pressurized cabin technology has become the preferred approach for cabin inspections and tool replacements in these demanding and intricate conditions. By enabling safe and efficient cabin operations under high groundwater pressure, pressurized cabin technology plays a pivotal role in the continuous advancement of pipe jacking technology.

Overall, the adoption of pressurized cabin technology is a crucial step forward in the pursuit of more effective and efficient pipe jacking techniques, and its continued use promises to play a vital role in the future of this important field of construction.

Research on pressurized cabin entry technology has primarily focused on the field of shield construction. Hu Weidong et al.[4] analyzed the stability of the excavation face when a tunnel passes through different strata and proposed a method for selecting a section suitable for shield cutter replacement under pressure. Sun Haibo et al. [5] employed bentonite mud plugging outside the shield and mud film plugging using high-efficiency mud on the tunnel face, along with air tightness testing and other measures, to seal the air tightness of the full-section water-rich sand layer of the earth pressure balance shield and to judge air tightness.

Zhai et al. [6] addressed the issue of pressurized chamber entry of a slurry shield under conditions where the excavation surface of an air-supported tunnel could not be realized. They accomplished this by adopting the method of slurry pressure balancing the water and soil pressure of the excavation surface under normal excavation state and saturated diving technology. Chen et al. [7] studied the pressure tool change device, normal pressure tool change device that enters the cutterhead wheel under ultra-high water pressure conditions, configuration of ultra-high water pressure operation equipment, air permeability control standard of ultra-high water pressure chamber, measures to reduce air permeability



of the excavation face, ultra-high water pressure operation procedures, determination of compressed gas pressure of ultra-high water pressure tool change, and determination of ultra-high water pressure operation mode.

Through this research [8], they concluded that the operation principle of the saturated gas shield chamber tool change is essentially the same as that of saturated gas diving operation, and has the potential for implementation. Furthermore, by studying the main difficulties and technical conditions of tunnel shield operation under pressure, the required diving technology and characteristics, the main diving equipment, the general criteria for the application of diving technology, and other factors, they were able to solve the problem of applying diving technology in tunnel shield operation under pressure.

Furthermore Meng Haifeng[9] solved the problem of stratum reinforcement and air tightness in the cutterhead cabin of the slurry balance shield machine in the city by studying the engineering example of the large diameter slurry balance shield machine in the underground diameter line project of Beijing railway.

Additionally, Min et al. [10] introduces the support scheme and stability analysis of the excavation face by taking the pressure chamber opening of the large diameter (up to 14.93 m) slurry shield tunnel under Nanjing Yangtze River as an example.

In summary, the existing research on pressurized cabin entry technology in the field of shield construction provides valuable insights for the development and implementation of this technique in other areas of construction.

In summary, the existing body of research on pressurized chamber technology has predominantly focused on its application within the realm of shield construction, with limited attention devoted to its utilization in pipe jacking construction. To address this research gap, the present study fills a significant void by providing a comprehensive synthesis and analysis of the essential technologies pertinent to pressurized chamber construction in the context of pipe jacking. The investigation draws insights from the esteemed Yinchuo-Jiliao water conveyance project's non-pressure tunnel jacking endeavor in the Jiaoliu River, employing a six-standard framework. Specifically, this scholarly paper delves into fundamental aspects encompassing working principles, equipment performance, mud film preparation, pipe wall grouting, and pressure tool change for jacking pipes under pressure. The findings presented herein serve as a valuable reference for future similar pipe jacking projects, thereby contributing to the advancement and practical implementation of pressurized chamber technology in the field.

1. Project profile

1.1 Introduction of project

The Jiaoliu River non-pressure pipe jacking section is located in Tuquan County, Xing'an League, Inner Mongolia Autonomous Region, as part of the tunnel section of the water diversion project. It connects No.5 tunnel and No.6 tunnel, with a length of 1115 m in a straight line from northeast to southwest. The construction consists of the starting well, pipe jacking section, non-pressure tunnel drilling and blasting section, and enlarged cavern section. The pipe jacking section has a length of 940 m, with an outer diameter of 4.3 m, an inner diameter of 3.6 m, and a vertical section ratio of 1/1100, as illustrated in Figure 1. The construction uses the ZTP Φ4400 mm slurry balanced pipe jacking machine, which is a self-developed pipe jacking equipment with a manned cabin for jacking construction.

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Figure 1 Construction plan

Based on the information provided, it seems that there is a problem with the pipe jacking machine at the jacking position of T80 + 911.814, which is located 114.29 meters into the pipe jacking section. The cutter head motor cut-off pin is broken, the cutter head torque is abnormally increased, and there is abnormal noise in the mud tank, indicating the presence of foreign bodies. It is suspected that the disc cutter cushion block or the scraper bolt has fallen into the tank. The geological conditions of the shutdown position are shown in Figure 2, and the cabin has reached 1.9 bar.

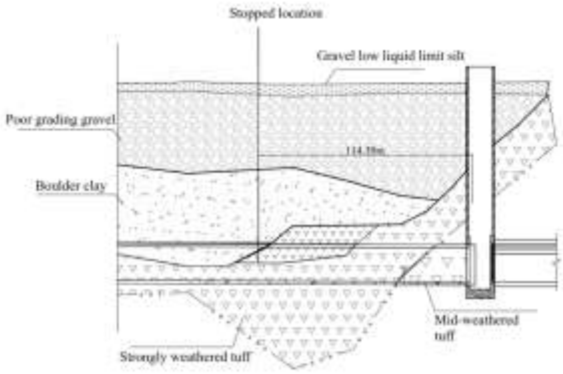


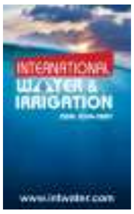
Figure 2 Geological conditions of stopping position

Through several attempts to open the cabin under normal pressure, it was found that the shutdown position was in the loose stratum with high water pressure, and it could not be checked by the way of opening the cabin under normal pressure. In order to ensure the safety of the equipment and the safety of the personnel construction, after the joint discussion of the participating units and the equipment manufacturers, it was decided to open the cabin under pressure.

1.2 Geological condition

Based on the information provided, it seems that the lithology of the stop position includes two layers: the Quaternary Holocene alluvial layer (Q4pal) and the Quaternary Upper Pleistocene ice water accumulation layer (Q_3Z fgl).

The Q_4pal layer is described as gravel-bearing low liquid limit silt, which is brown, slightly wet to wet, and has a plastic to hard plastic consistency. It also contains about 10% gravel with a diameter of 0.2-0.5 cm and roots on the surface. The layer also contains poorly graded gravel that is grayish brown, medium to dense, and wet to saturated. The gravel content in this layer is 60-70%, with a general diameter of 5-20mm and a maximum diameter of 60mm.The Q_3Z fgl layer is described as mud gravel, which is grayish yellow, dense, and saturated. The main component of the gravel is tuff, with poor roundness and poor sorting. The gravel content in this layer is 50-60%, with a general diameter of 5-20mm and a maximum diameter of 50mm.



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The lower bedrock is composed of tuff of the Middle Jurassic Fujiawazi Formation (J_2f) and Yanshanian intrusive granite ($\gamma5$). The tuff is gray in color, with a lithic crystal tuff structure and massive structure. The crystal debris mainly comprises plagioclase, followed by hornblende and biotite, occasionally quartz. The rock debris is andesitic tuff composed of plagioclase and hornblende. The weathering layer exhibits a developed joint fracture with fracture surfaces that are mostly gray-yellow or yellow-brown. The rock core is mostly fragmented and columnar. The granite is exposed in the boreholes HZK16-5 and HZK16-7, with a flesh-red, medium-coarse grain structure and massive structure. The main minerals are feldspar and quartz, followed by hornblende and biotite. The field geological map is depicted in figure 3.

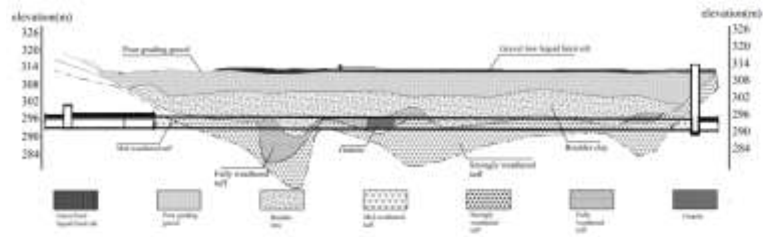

Figure 3 Geological profile

2. Entering the cabin with pressure

Currently, the examination of pipe jacking machines is predominantly accomplished through the implementation of one of two methods: the normal pressure cabin opening and the pressurized cabin entry. The choice of method is contingent upon the specific geological conditions at the site and the intended purpose of the cabin opening. In scenarios where the jacking operation encounters hard rock formations or areas characterized by robust self-stability, the normal pressure cabin opening method is employed. This method involves reducing the cabin pressure to normal levels, thereby allowing personnel to directly access and carry out operations within the cabin. However, it is imperative to acknowledge that this approach heavily relies on the stability of the geological formation and is accompanied by notable limitations, including the potential for accidents such as tunnel face instability and water ingress. Consequently, alternative approaches must be considered to mitigate these challenges and enhance the safety and effectiveness of pipe jacking machine examinations within such contexts.

The pressurized cabin is considered the safest method for opening the cabin in pipe jacking machine operations, and it can be categorized into two types: saturated gas pressurized cabin and compressed air pressurized cabin. This method is particularly suitable for strata with poor stability and high water content. The operating principle of both methods is consistent, where the working face and the surrounding soil are blocked by mud to create a sealed environment inside the cabin. The pressure value within the cabin is then determined based on the depth of the groundwater level and the tunnel's buried depth. By establishing a reasonable air pressure in the cabin, the water and soil pressure in front of the cutterhead is balanced. The formula for determining the appropriate air pressure is as follows:

$$P = P_\omega + P_r \tag{1}$$

$$P_\omega = \gamma_\omega * h \tag{2}$$

In the formula : P -the pressure of the cabin

P_ω-calculates the head pressure to the tunnel excavation center ;

γ_ω -the specific gravity of water

h - the height of the water table to the bottom of the pipe jacking machine, take 20 m

P_r - Pressure adjustment value of 0.2 bar considering different conditions, ground environment and excavation face position

This study presents a comprehensive analysis of the geological, hydrological, and structural conditions surrounding the shutdown site of the Jiaoliu River non-pressure tunnel pipe jacking project, which is an integral part of the tunnel section of the Yinchuo-Jiliao water conveyance project. Prior to the shutdown phase, the slag discharged from the slurry separator

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primarily comprised completely weathered rock and gravel. However, the current site conditions, characterized by the presence of mud gravel and composite strata, have resulted in poor self-stability at the tunnel face. Attempts to open the cabin under normal pressure have proven ineffective in addressing this issue. Moreover, considering the limitations of grouting for ground reinforcement, the high inflow of formation water, and unfavorable precipitation conditions, the decision has been made to employ the pressurized cabin entry method. Consequently, the working pressure has been calculated to be 2.2 bar. These findings highlight the necessity of adapting the construction approach to suit the specific challenges posed by the prevailing geological and hydrological conditions at the site.

3. Establishment of mud film

3.1 Slurry ratio

The aim of this part is to present the process of matching the slurry used to establish the mud film in the pipe jacking mud tank. To achieve this, a thixotropic slurry formula commonly used in similar projects [11][12] was referred to, which utilized field bentonite as the slurry clay mineral and additives such as sodium carboxymethyl cellulose, xanthan gum, and polyacrylamide. The following steps were taken for testing:

(1) A measuring cylinder was used to weigh 1L of water, which was then added to a beaker. Sodium bentonite was added to the water according to the base slurry formula and stirred for 1h until fully dissolved. The base slurry was then left indoors at room temperature for 24h to fully hydrate.

(2) The fully hydrated base slurry was stirred for 10 min, and the corresponding treatment agent was added to the slurry and stirred for 1 h. After stopping the stirring, it was left to stand for 6 h to fully dissolve.

(3) The configured slurry was then fully hydrated and stirred for 10 min. Following the 'GB/T 29170-2012 Drilling Fluid Laboratory Test[13], different formulations were tested for their rheological properties, filtration, density, and colloid rate. The testing sequence was as follows: density, pH value, funnel viscosity, dynamic shear force, plastic viscosity, initial/final shear force, and filtration loss.

The study conducted 16 groups of experiments using an orthogonal design method, as presented in Table 1. Figure 4 illustrates the test diagram used in the experiments, and the corresponding values for funnel viscosity, filter loss, and specific gravity were obtained.

(a) Mud mixing (b) Funnel viscosity

(c) Mud specific gravity

(d) Mud filtration loss

Figure 4 Mud ratio experiment

The overall performance of the slurry largely depends on the quality of the bentonite, which constitutes the base slurry. The bentonite used in this study was collected from the construction site. Pure bentonite slurry was found to exhibit high viscosity, and the addition of either CMC or PAM at a 8% dosage resulted in a sharp increase in viscosity. The resulting slurry quickly lost its fluidity and could not be used in the project. To meet the requirements of the mud film, which require good fluidity and low filtration to ensure normal mud film formation under high pressure environments, an optimal ratio of ingredients was determined through an orthogonal test. The ratio included 60kg of bentonite, 1kg of Na_2CO_3, and 1kg of CMC per cubic meter of clean water. The mud viscosity was found to be 197 s, and the filter loss was 8.4 ml/30 min.

Table 1 Mud ratio experiment

No.	bentonite /g	Na_2CO_3/g	CMC/g	PAM/g	funnel viscosity /s	filtration rate
1	40	1	0	0.5	64	11.6
2	40	2	0.5	0	72	10.2
3	40	3	1	1	121	9.2
4	40	2	1	0	120	9.2
5	60	1	0.5	1	176	9.0
6	60	2	0	0.5	115	9.2
7	60	3	1	0.5	/	8.0
8	**60**	**1**	**1**	**0**	**197**	**8.4**
9	80	1	1	0.5	/	8.0
10	80	2	1	1	/	7.3
11	80	3	0	0	115	9.3
12	80	2	0.5	0.5	206	8.0
13	100	1	1	0	/	/
14	100	2	1	0.5	/	/
15	100	3	0.5	0.5	/	/
16	100	2	0	1	204	8.0

3.2 Mud filling

Establishment of the mud film is a crucial step in the pressurized cabin construction, which significantly affects the success of the operation. Prior to the commencement of the construction, the sealing water stop ring around the mud tank door of the pipe jacking equipment must be thoroughly checked, and the synchronous grouting pipe should be removed.

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As illustrated in figure 5, the pipe is linked to the ball valve of the manhole diaphragm via a reducer head, and the bentonite slurry is injected into the soil cabin through this pipe to maintain continuous injection, ensuring that the bentonite mixed slurry adequately fills the stratum gap in front of the pipe jacking machine and around the shield body. Following a period of grouting, the injection is stopped, and the pressure drop rate in the cabin is observed. If the decrease is rapid, the bentonite mixed slurry injection is continued, and the aforementioned process is repeated until the cabin pressure stabilizes.

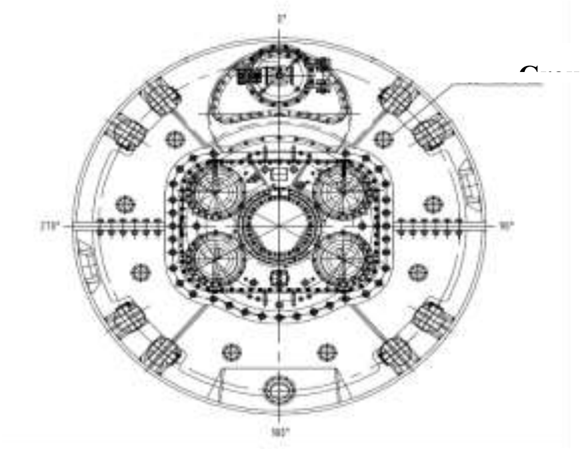

Figure 5 Grouting tube layout

In order to ensure the safety of the pressurized cabin opening in the ongoing project and prevent groundwater influx and stratum collapse, the initial pressure for the pressure holding test of the soil cabin was set higher than the calculated value of 0.3 bar, specifically at 2.5 bar. However, the results of the initial test revealed a rapid decline in the soil cabin pressure and the emergence of ground slurry directly above the pipe jacking shutdown despite multiple rounds of supplementary grouting. These observations indicated that the set pressure for the soil cabin was excessively high, leading to slurry outflow along the formation pores due to the presence of loose and fractured overlying strata. Figures 6 and 7 provide detailed illustrations of these findings, prompting the suspension of the initial soil cabin pressure holding test.

Figure 6 Pouring position

Figure 7 Oozing Slurry

To mitigate the risks of groundwater influx and stratum collapse during the pressurized cabin opening in this project, an initial pressure of 2.5 bar was employed for the pressure holding test, surpassing the calculated value of 0.3 bar. However, during the initial test, the soil cabin pressure exhibited rapid decline, and ground slurry emerged directly above the pipe jacking shutdown despite multiple supplementary grouting efforts. This occurrence was attributed to the excessively high set pressure of the soil cabin, which led to slurry flow along the formation pores due to the loose and fractured overlying strata. To address this issue, a fence enclosure was installed at the ground slurry overflow location, and dedicated personnel were assigned to monitor and continue the soil cabin pressure test. Subsequently, the pressure holding value of the soil cabin was adjusted to 2.2 bar, resulting in favorable pressure holding outcomes and the absence of slurry overflow on the ground. As a result, a cabin pressure of 2.2 bar was determined as the appropriate value for the opening operations. These observations underscore the importance of optimizing the cabin pressure to ensure the stability and integrity of the surrounding strata during the pressurized cabin opening process.

3.3 Cuttings-mud replacement

The equipment grouting system is employed for the injection of bentonite mixed slurry into the soil cabin to facilitate soil replacement. Throughout the injection process, the pipe jacking slurry circulation system is activated to facilitate slag discharge, while simultaneously controlling the upper pressure of the soil cabin within a range of 2.0 to 2.5 bar. In the field, a representative sample of the discharged slag is collected from the slag outlet and placed in a measuring cylinder. A color and sand content mixing experiment is conducted on the slag sample to assess the completion of the cabin replacement process.

Subsequently, the cutter head is rotated at a low speed of 0.5 rpm and turned by 60°. Another slag sample is extracted and examined at the separator outlet. The color and sand content mixing experiment is once again conducted to determine the completion of the cabin replacement. If the replacement process is deemed complete, the slurry-gas replacement stage is initiated. However, if the replacement is not deemed complete, the previous operation is repeated until the muck discharged from the cabin consists of bentonite mixed slurry, signifying the successful completion of the cabin replacement process.

3.4 Mud-gas replacement

The air compressor, as illustrated in Figure 8, is located on the ground and serves to supply air to the cabin. The pressure holding system gradually replaces the slurry tank pressure. The working pressure of the jacking pipe is predetermined, and the cutterhead is initiated at a low rotational speed of 0.5 rpm. The cutterhead rotates unidirectionally. Following 15 minutes of rotation, the slurry pump is intermittently activated at a speed range of 2-4 rpm to discharge the composite clay mixed slurry and facilitate continuous slag discharge. Suspension of the slurry discharge occurs when the slurry tank pressure drops below 1.8 bar. At this point, the pressure of the soil tank is restored to the predetermined value for the pressurized cabin opening, and the slurry pump is reactivated. To ensure an optimal working environment for the opening operation, the liquid level in the soil tank is maintained below half of the cabin capacity. Once the completion of the rock debris bentonite slurry mixture in the pressurized cabin is confirmed, the slurry-gas replacement stage is initiated.

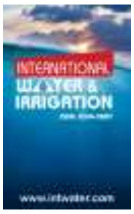

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Figure 8 Gas compression and conveying system

4. Key technology of entering cabin under pressure

4.1 Airlock

The Airlock assumes a critical role within the pipe jacking machine, facilitating the safe transition of personnel from atmospheric pressure to a high-pressure environment. Its key functions encompass enabling maintenance personnel to access the mud tank of the pipe jacking machine and providing a designated resting area for staff. Comprising two cabins and two doors, as depicted in Figures 9-11, the Airlock system embodies essential features. The primary cabin boasts a volumetric capacity of 3.1m³, accommodating a maximum of two individuals concurrently. The secondary cabin, with a volume of 1.8m³, accommodates one person at a time. The working pressure of the cabin is set at 0.45 Mpa, with a design pressure of 0.55 Mpa. Equipped with observation windows featuring a light transmission diameter of 200mm, the doors facilitate seamless observation and communication between personnel both inside and outside the cabin, as well as between the two cabins. Illumination is provided within the cabin by lighting lamps, while explosion-proof motor heaters ensure temperature regulation. The cabin is equipped with instrument panels, including explosion-proof dial telephones, acoustic telephones, and pipelines for pressure, pressure reduction, and sewage systems. External to the cabin, additional infrastructure encompasses pressure and pressure reduction pipelines, sewage pipelines, as well as external instrument panels, pressure recorders, safety valves, and other essential equipment.

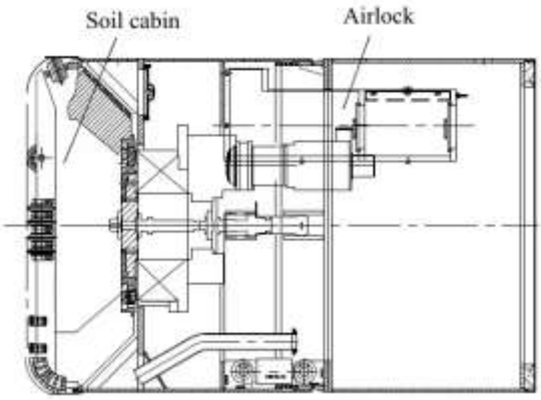

Figure 9 Pipe jacking machine structure diagram

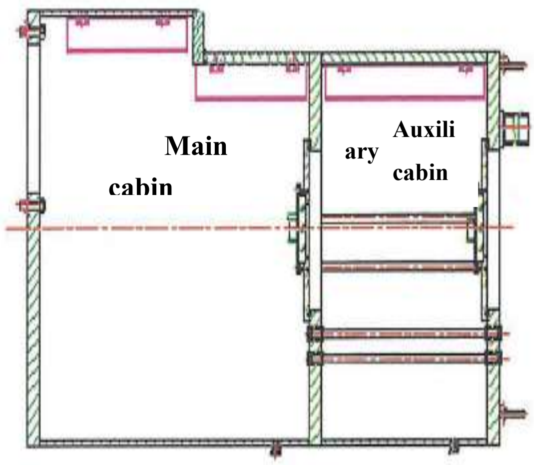

Figure 10 Airlock structure diagram

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Figure 11 Object pictures of the airlock

4.2 Operation in the cabin

Following the establishment of the mud film, the ball valves positioned at the 3 and 9 o'clock positions in the mud tank are opened to facilitate the replacement of air in the soil tank, resulting in a decrease in temperature within the tank. Subsequently, the MSA gas detector is employed at the ball valve outlet to measure the concentration of CO2 and O2 gases, ensuring that the gas levels in the cabin remain within acceptable limits. Additionally, a designated individual monitors the loading and unloading of the air compressor at 10-minute intervals to assess the rate of air loss in the cabin. If the loading time is shorter than the unloading time, it indicates satisfactory mud film quality and sufficient air-holding capacity within the soil cabin. A larger disparity between the loading and unloading times signifies greater stability at the face and higher mud film quality. Conversely, if the loading time equals or exceeds the unloading time, it signifies a failed mud film establishment, necessitating its re-establishment. Once the stability of cabin pressure is confirmed, and qualified gas detection is conducted, personnel can safely enter the cabin to carry out construction operations.

Under normal circumstances, the process of construction personnel entering the cabin is depicted in Figure 12. During this procedure, construction personnel enter and exit the main cabin, while the auxiliary cabin maintains a normal pressure level. In emergency situations, emergency personnel can swiftly access the soil cabin through the auxiliary cabin.

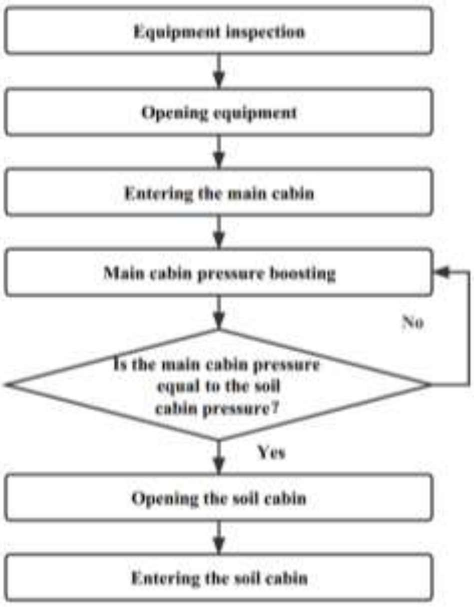

Figure 12 Process of entering the cabin

4.3 Changing cutter under pressure

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During the inspection and maintenance of the mud tank, construction personnel undertake various tasks to evaluate the condition of tools and their components. These tasks encompass the examination of tools for damage and wear, the assessment of the wear-resistant layer on the stir bar and cutterhead, and the evaluation of the tightness of tool installation parts, including wedges, mounting blocks, and bolt protection caps. When necessary, worn-out tools are replaced, and the cutterhead is thoroughly cleaned to remove any accumulated mud cake.

Upon conducting the tool inspection, it was observed that the hob, cutter, and edge scraper exhibited varying degrees of wear. The central hob demonstrated an overall wear of 2-3mm, while the single-edged hob displayed 1-2mm of wear. Notably, the central hob exhibited a curling phenomenon. Moreover, the scraper and cutter exhibited substantial wear, with the alloy block completely detached. Nonetheless, no missing tools were identified. Consequently, all hob and scraper cutters displaying severe wear were replaced. Furthermore, it was observed that seven hob bolt caps and one triangular block from the central hob were lost. Regrettably, neither of these items could be recovered from either the mud tank or the slag outlet. Figure 13 provides a visual representation of the tool wear, while Figure 14 showcases the replaced tools.

Figure 13 Tool wear detection

Figure14 Center disc cutter replacement

4.4 Secondary establishment of mud film

During the pressurized cabin operation, it is imperative to conduct periodic analysis of the air compressor loading and unloading time to determine the air loss rate. Upon analysis, a consistent increase in air loss rate was observed with continuous operation. Notably, when reaching the 13th cabin, monitoring revealed an alarming air loss rate of 52.2%, as depicted in Figure 15. This observation indicates that the air-tightness of the mud film in the cabin is insufficient, and tunnel face instability may occur, thus posing a danger to the cabin. In response, the operation in the cabin was immediately halted, and a second mud film construction was necessary to ensure safety and quality.

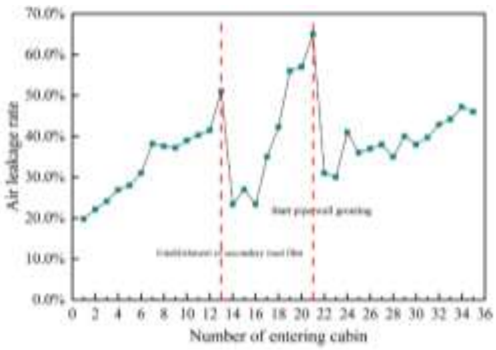
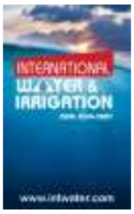


Figure 15 Air leakage rate

The grouting process was repeated, and the grouting volume and pressure drop time were monitored meticulously. The grouting was carried out via the grouting pipe in the soil chamber. The injection was ceased when the pressure inside the soil chamber reached 2.2 bar, and the injection was resumed when the pressure reduced to 2.0 bar. Halting the injection



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when the pressure reaches 2.2 bar facilitates the circulation of grouting. The grouting volume is illustrated in Figure 16, and the decision to proceed with the subsequent slag gas replacement is based on the injection volume and the pressure reduction time, as depicted in the figure. During the 60th grouting in the cabin, the grouting volume was 5.6m3, and the pressure reduction time was 81 minutes and 15 seconds, as shown in Figure 17. At this stage, the pressure-holding effect was satisfactory, and the mud film in the cabin was deemed to be successfully established, allowing the restoration of normal entry operation.

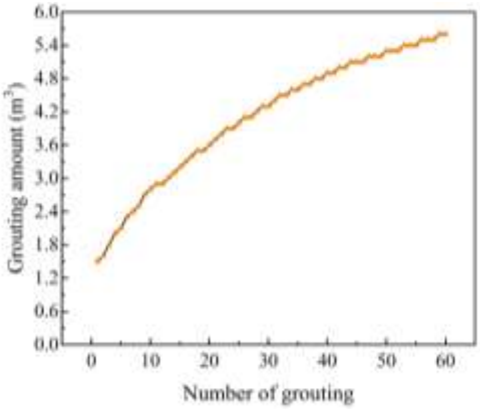

Figure 16 The amount of slurry added during the pressure holding period of the soil cabin

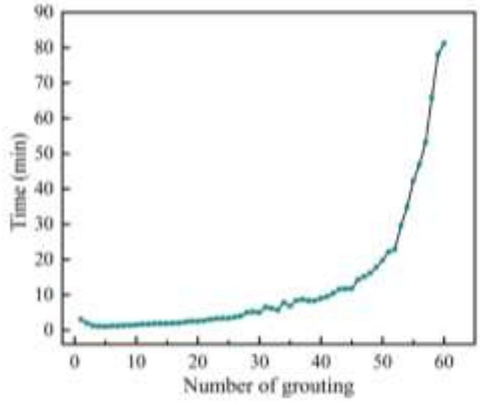

Figure 17 Time of depressurization to 2.0 bar after slurry added

4.5 Grouting filling outside the pipe

To prevent slurry leakage in the annular space of the pipe jacking ring, whole bed cotton wool was used to seal the gap when personnel from the first pressurized cabin entered the soil bin. However, during operation in cabin 21, a sharp increase in air loss rate was observed, and the cabin pressure remained stable at 2.1 bar, lower than the set working pressure of 2.2 bar. Inspection revealed that a left upper cotton wool had moved to the space gap of the rear pipe joint ring under air pressure, indicating a potential leakage point in the rear stratum. To address this, the first 5 pipe walls behind the pipe jacking machine were grouted before work in the 22nd cabin began. Figure 18 shows the grouting volume for the first 2 hours and 10 minutes of grouting, during which 13.4m3 of grout was injected into the annulus of the pipe wall. However, the presence of slurry on the surface during injection led to an immediate stop of the grouting process. The air loss rate decreased to less than 20%, indicating that the air leakage channel had been blocked by thixotropic mud filling the outer annulus of the pipe jacking machine and the rear pipe section. Subsequent monitoring of the pressure in the cabin showed that the working pressure of 2.2 bar was stabilized, confirming the integrity of the mud film and the pressure holding capacity of the cabin. As shown in Figure 19, the air leakage rate in subsequent jacking cabins remained at a normal level, and the pressure in the soil cabin remained stable.

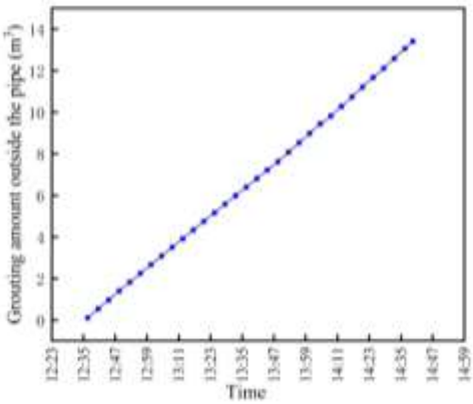

Figure 18 Grouting amount outside the pipe

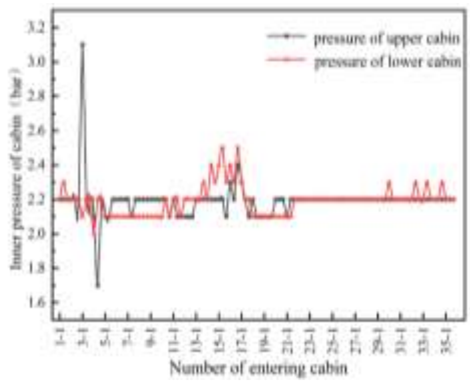

Figure 19 Pressure of the soil cabin

4.6 Gas detection

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To ensure the safety of personnel working in the pressurized cabin, it is necessary to carry out gas detection at appropriate locations. Specifically, gas detection should be performed at the opening of the human hatch or the partition of the excavation bulkhead before the opening of each cabin, and after the opening of the cabin, the detection should be conducted inside the cabin. It is recommended to perform gas detection at a frequency of 1-2 hours under normal conditions, and increase the frequency if any abnormalities are detected. In the event that the concentration of toxic or harmful gases exceeds the allowable range, all pressurized workers must evacuate the working chamber until the gas concentration reaches acceptable levels.

During the construction process, the concentration of CO_2 was found to increase significantly during each shift, as shown in Figure 20 below. However, the concentration was still within the range of acceptable levels for personnel health, and there was no significant change in the concentration of O_2.

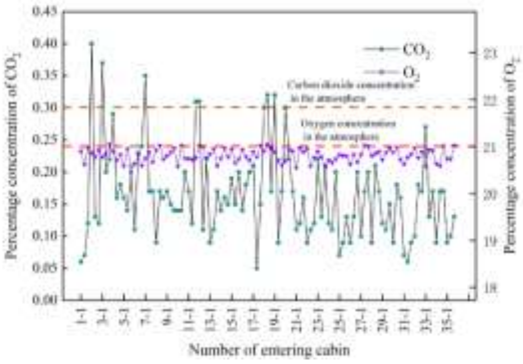


Figure 20 Detection of gas concentration in cabin

4.7 leaving the cabin

The decompression operation during the pressurized cabin construction is conducted in accordance with the "Technical Specification for Shield Tunneling and Pneumatic Operation" (CJJ217-2014) [14]. The process involves opening the exhaust pressure reducing valve gradually to lower the cabin pressure, while closely monitoring the cabin pressure gauge. During the decompression procedure, the ventilation rate is adjusted based on the body sensations of the cabin personnel and the duration of pressure retention at each stage until the normal pressure state is achieved. The decompression process is illustrated in Figure 21 below:

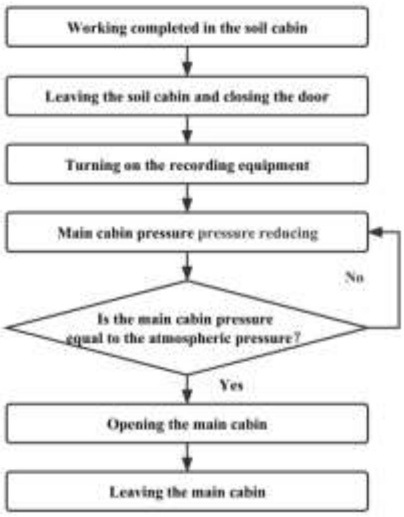
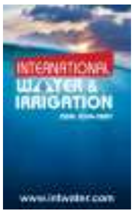


Figure 21 Process of leaving the cabin

5. Conclusion



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The pipe jacking project in the sixth bid section of the Jiaoliuhe non-pressure tunnel, which is part of the Yinchaojiliao water conveyance project, was successfully completed within a period of 28 days in the high-pressure composite stratum. Despite the occurrence of abnormal noise and an abnormal increase in torque during the project, the root cause of these occurrences could not be identified. Nonetheless, there were no similar incidents following the project's restart. However, due to the long working period of the pressure opening, extended periods of shutdown resulted in a significant increase in the jacking force required when restarting the jacking process.

This project marks the first domestic practice of pipe jacking equipment with pressure into the cabin, which highlights the significance of research and implementation of the key technology of pressure opening. The following conclusions have been drawn from this practice:

(1) The safety of pipe jacking with pressure into the cabin is primarily determined by the quality of the established mud film. Hence, it is essential to conduct on-site mud ratio tests based on specific project requirements and mud film characteristics. The raw materials and additives, including bentonite, should be sourced from the construction site, and an orthogonal experiment should be designed to obtain the optimal ratio.

(2) Unlike shield construction, pipe jacking construction involves the dynamic movement of the pipe section with the pipe jacking machine[15]. The movement of the pipe section may result in gaps in the annulus. During the process of opening the chamber under pressure, attention should be paid to whether the mud outside the pipe wall fills the annular space completely. If not, gas in the chamber is easily lost to the annulus, leading to poor pressure retention in the chamber, particularly in loose strata where the gas will continue to dissipate from the annulus.

(3) When gas is continuously lost to the shield tail, pipe wall thixotropic mud injection may be employed to plug the shield tail gap and the annular space gap, thereby reducing the rate of gas loss.

(4) In pipe jacking construction in composite strata, especially in soft and hard uneven strata, it is essential to be attentive to tool wear, and opening inspections should be selected at appropriate positions to prevent more serious tool and equipment damage. If the atmospheric opening safety is ensured, the appropriate position for opening inspection can save time and is conducive to the re-jacking of the pipe jacking project. For instance, the pressurized opening chamber can be selected for inspection. Continuous thixotropic mud injection into the entire annulus is recommended to ensure that the jacking force does not increase sharply when starting again.

(5) This project utilized China's independently developed pipe jacking equipment with a pressure chamber, and the project's smooth implementation indicates the technical progress achieved in China's pipe jacking equipment with a pressure chamber. This practice provides useful reference for similar pipe jacking with pressure into the cabin construction.

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Data sharing agreement: The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

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