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CASE STUDY ON THE LARGE DIAMETER PIPE JACKING FOR UTILITY TUNNEL IN MODERATELY WEATHERED SILTSTONE

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ABSTRACT

Pipe jacking has been widely used in utility tunnel constructions as an environment-friendly method in China. This study is focused on the critical technologies used in the pipe jacking for the utility tunnel in Huanggang Mingzhu road. The inner and outer diameters of this utility tunnel are 4m and 4.8m respectively, which is the largest circular pipe jacking project in China at present. This utility tunnel is designed under the urban main road with heavy traffic, so the control accuracy of pipe jacking construction is required to be high. According to the characteristics of the project and actual construction technical measures, the key construction technologies including pipe jacking equipment selection, launching of small spacing, slurry circulating, drag reduction technology, and the control of surface settlement are discussed in this paper. Meanwhile, the jacking force and surface settlement during pipe jacking construction are monitored. The results show that the selected pipe jacking machine has good adaptability to the geological conditions of the project. The actual jacking force is much smaller than the theoretical value, and the two intermediate jacking stations are not activated. In addition, the road surface deformation is -8 – 5mm during the whole process of pipe jacking construction, which has no impact on surface traffic.

KEYWORDS

Large diameter pipe jacking, Utility tunnel, Launching of small spacing, Slurry system, Settlement control

INTRODUCTION

The rapid development of urbanization worldwide and the sharp increase of urban population have brought great pressure on urban environment, surface space and infrastructure The development and utilization of urban underground space is an important way, in which some of problems such as over-concentration of population, environmental pollution, and resource shortage should be solved, moreover, to improve the quality of people's livelihood [1-2]. Pipe jacking is a trenchless method for pipe installation by pushing a prefabricated pipe from the originating shaft to the receiving shaft by a jacking cylinder. Compared to the traditional open cut method, the pipe jacking method has the advantages of fast construction speed, small impact on ground traffic and buildings. So, the pipe jacking is a widely used technology for a wide range within water supply and drainage, electricity, gas, communication, underground passage and other pipeline and tunnel construction projects [3-4].

With the development of pipe jacking technology and the increase of the requirement of the underground space regarding underground engineering, it is inevitable that a larger scale of pipe jacking section is eagerly needed, meanwhile, its construction difficulty also increases greatly. Much debated issues about to be solved concerning the pipe jacking technology focused on calculation and control of jacking force, surface settlement control and technical measures of complex strata. At present, the research on pipe jacking mainly focuses on the pipe and soil interaction, the calculation of frictional resistance and jacking force. Researchers have carried out a lot of research on the above two points through indoor tests, field tests, numerical simulation and theoretical analysis [5-9]. In addition, some researchers analysed the mechanical properties of the pipe during jacking [10-12]. However, there is little research and summary on the key technologies of pipe jacking construction, especially in complex situations. In fact, these are very valuable for the application and development of pipe jacking.

Based on the pipe jacking for utility tunnel in Huanggang Mingzhu road, this paper summarizes and analyses the difficulties and key technical measures faced in the pipe jacking construction process in the moderately weathered siltstone stratum in the urban area, which provides an excellent reference for the similar projects in the future.

PROJECT PROFILE

The total length of the utility tunnel project is 1302m, starting from Dongmen road, ending at a control centre located on the Mingzhu Road, including a 682m pipe jacking section and a 620m excavation section. The construction area is mainly located below Mingzhu Road, which is in a heavy traffic for seating as a main road (Figure 1). The pipe jacking section is currently the largest diameter circular pipe jacking in China, with its inner and outer diameter of 4m and 4.8m respectively. The prefabricated pipeline was made of C55 concrete with a compressive strength of about 55MPa. Circumferential and longitudinal reinforcements were HRBF500 hot rolled ribbed steel bars fine with a diameter of 12mm and a yield strength greater than 500MPa. The pipe jacking section consists of a launching shaft and two receiving shafts. After completion, the utility tunnel will accommodate four kinds of pipelines, including water supply, communication, 10kV power and 110kV power.

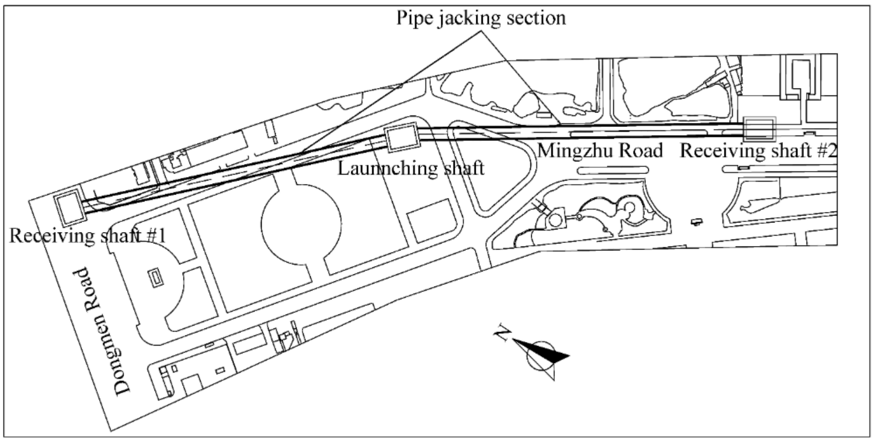

Fig. 1 – The plan and location of pipe jacking

Geological Survey and a Construction Plan have been conducted before construction, the geological profile of pipe jacking construction is shown in Figure 2, the strata from top to bottom are mixed fill, silt clay, strongly weathered siltstone and moderately weathered siltstone. The soil properties are summarized in Table 1. The pipes mainly cross the moderately weathered siltstone. The formation is sand structure, argillaceous cementation, sand content is about 35%, fractures are well developed, rock mass is relatively broken, the maximum uniaxial compressive strength is about 14MPa. Except for the area near the launching shaft, the pipe jacking is located above the groundwater level.

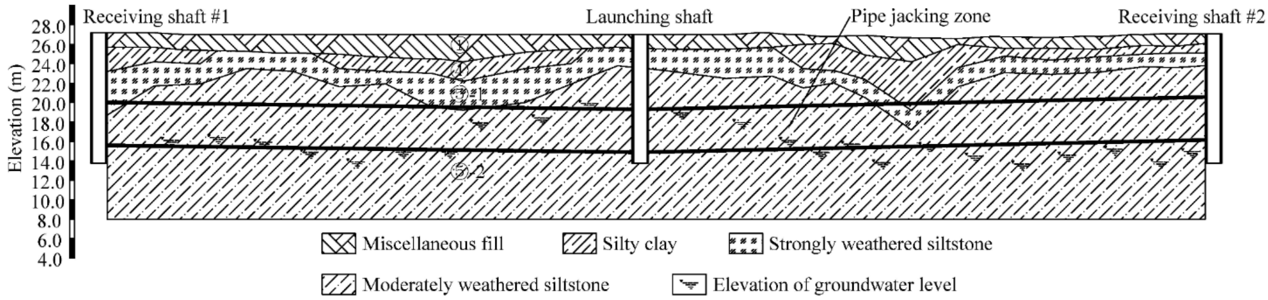

Fig. 2 – Geological profile of pipe jacking

Tab. 1 - Summary of soil properties

layer	soil	Density (g/cm3)	Cohesion (kPa)	Internal friction angle (°)	Compression modulus (MPa)	Saturated uniaxial compressive strength (MPa)
1	Miscellaneous fill	1.75	20	10	-	-
4	Silty clay	1.96	35	16	11	-
5-1	Strongly weathered siltstone	1.95	60	32	45	-
5-2	Moderately weathered siltstone	2.00	150	42	-	9.05

Difficulty analysis

(1) Pipe jacking mainly passes through moderately weathered siltstone stratum, and some areas are located in strongly weathered siltstone and silty clay stratum. Therefore, the pipe jacking machine needs to drill both in soft layer and rock stratum, and have a good slag discharge capacity.
(2) Fractured rock mass makes slurry easy to leak, leading to increased frictional resistance around the pipe. In addition, cuttings deposition due to high leakage of slurry should inevitably influence the jacking efficiency and eventually lead to some serious problems such as pipe stuck.
(3) The construction area is located under the city road and the construction process needs to strictly ensure the road safety.
(4) The distance between the second pipe jacking reaction wall and the portal hole is small, which makes it difficult to launch.

KEY TECHNOLOGIES

Equipment selection

CTPJ4860E-440 slurry balance pipe jacking machine customized by China Railway Engineering Equipment Group Co., Ltd. was adopted for the geological conditions of the project. As shown in Figure 3, the pipe jacking machine adopted spoke and small panel cutter head, and the cutter head was mainly composed of front panel, outer ring beam, bracket and flange the front panel, outer ring beam and bracket were welded with wear-resistant layer to increase the service life of the cutter head. Beside the cutter head was equipped with centre hobs (4), general hobs (15), edge hobs (8), scrapers (32) and edge scrapers (8). The function of tool replacement was realized while ensuring the cutterhead opening rate (32%). To meet the requirement of secondary rock breaking in small silo space, the displacement shear secondary crushing device was designed by combining the theory of volumetric change crushing, grinding crushing and shear crushing.

Fig. 3 – Pipe jacking machine

Circulating slurry management

The mechanism and requirement of the circulating slurry

(1) Mechanism

The circulating slurry, also known as "mud water", contributing two features in a pipe jacking process: (1) balancing soil and water pressure on excavation surface; (2) transporting the rock debris. The mud water was pressed into and filled with mud tank through grouting pipe, and mud water penetrated into the soil of excavation surface under pressure, thus forming a layer of impermeable filter cake on excavation surface. On the one hand, the existence of the filter cake can prevent the mud water from continuing to penetrate the soil; on the other hand, the pressure of the mud water acted on the excavation surface through the filter cake, which balanced the water and soil pressure on the excavation surface. At the same time, the cutter head was constantly rotating, and the rock debris cut down was mixed with mud water, which was sent to the mud water separation system through the mud discharge pipe. Through the treatment of mud water separation system, the residue was separated and discharged, and the filtered mud water was returned to the mud water tank for recycling after being stirred by precipitation.

(2) Performance requirement

Before jacking construction, circulating mud should be set according to geological conditions. In clay and silt, on the one hand, with its low permeability coefficient, and the relatively stable soil, which can only rely on water pressure to stabilize the excavation surface. On the other hand, the soil itself generate slurry, so the relative density of mud water is not strict requirements, and even clean water can protect the wall. In sandy soil with low permeability coefficient (K ≤10-3cm/s), mud crust can be formed in a relatively short time, and mud water pressure can effectively control the stability of excavation surface. In the sand soil with moderate permeability coefficient, for 10-3cm/s< K <10-1cm/s, excavation surface instability is easy to occur. During construction in such soil layer, it is necessary to change the performance of mud water to fix it a certain viscosity and density. Stabilizer composed of clay, bentonite and CMC (Carboxymethyl Cellulose) should be added to mud water. In the sand and gravel layer with K >10-1cm/s, due to the small clay content in the soil, the clay content

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is constantly reduced in the process of recycling mud water. Therefore, it is necessary to constantly add clay and other stabilizing agents to maintain a high concentration and density of mud water.

Layout for the circulating slurry system

The circulating slurry system in this project was mainly composed of the mud pump, grouting pipe, slurry discharge pipe, mud-water separator, slurry pool and filter press, as shown in Figure 4. The slurry pool was divided into 3 zones, slag pond, primary sedimentation tank and secondary sedimentation tank. The muck cut down from the cutter head was mixed with the circulating slurry, and then transported to the mud-water separator through the slurry discharge pipe. The mud-water separator separated the muck and slurry. After sedimentation and mixing, the treated slurry was transported to the cutter head through the grouting pipe for recycling. In actual construction, the circulating slurry treated by the mud water separator still had high density and viscosity, which reduced the jacking efficiency, so the filter press was added (Figure 5). Filter press is a kind of solid-liquid separation equipment which makes use of special filter medium by applying certain pressure to make liquid dialysis out. The circulating slurry in the primary sedimentation tank was sent to the filter press, which filtered out all the solid particles in the slurry, and the clean water was discharged to the secondary sedimentation tank, and the muck directly fell into the slag pool. Seamless pipe was used in slurry pipeline in this project, which effectively reduced the wear of muck to pipe.

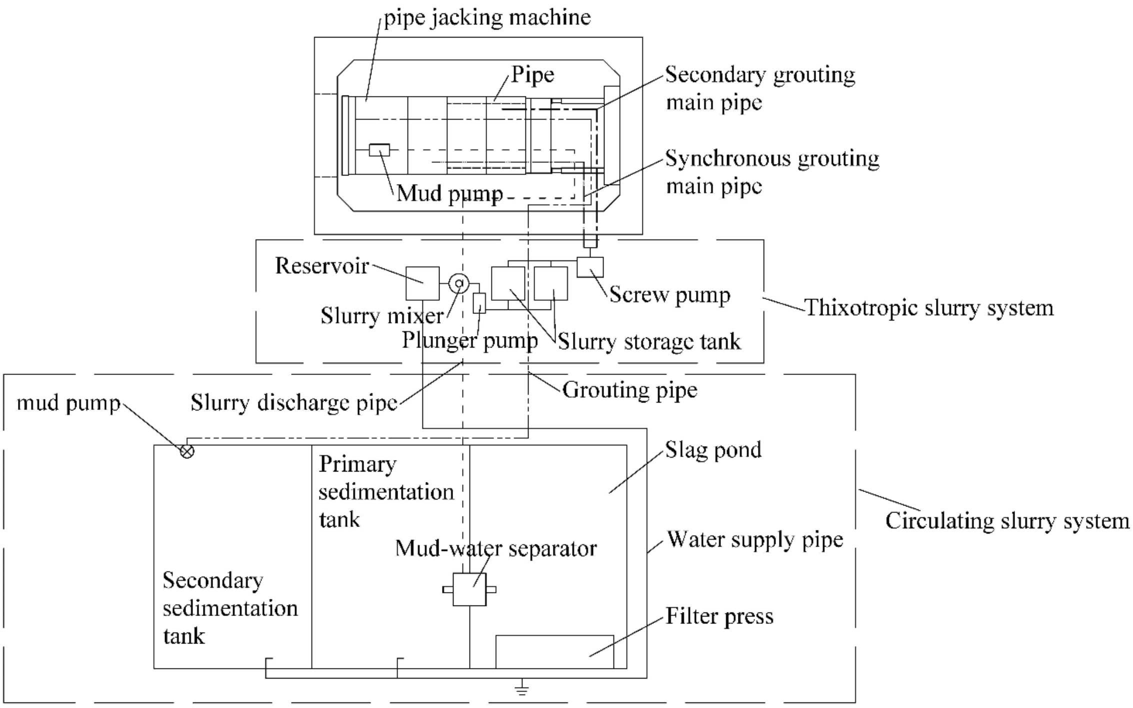


Fig. 4 – Layout of slurry system

Fig. 5 – Slurry separator and press filter

Specific gravity control for circulating slurry

According to field measurement, the maximum specific gravity of the circulating slurry was 1.3~1.4g/cm3, which was far beyond the actual requirements (The requirement specific gravity of slurry in the slurry discharge pipe was 1.2~1.3g/cm3, for the grouting pipe was 1.05~1.1g/cm3), and the muck transportation efficiency was greatly reduced. To control the specific gravity of circulating slurry, the filter press was installed. Due to the limited processing capacity of the filter press, the mud proportion will still rise after a period of time, so the mud needs to be transported out. Through the above measures, the specific gravity of circulating slurry was effectively controlled.

Thixotropic slurry management

Thixotropic slurry system

The thixotropic slurry system of this project was mainly composed of the slurry mixer, slurry storage tank, reservoir, grouting pump and grouting pipe, as shown in Figure 6. The water, bentonite and additives were initially stirred in the slurry mixer (stirring time should be more than 30 minutes), and then pumped to the slurry storage tank for secondary stirring in the mud pump (plunger pump). After full stirring, the thixotropic slurry was pressed to the grouting main pipes through the grouting pump (screw pump). The use of screw pump can make the grouting process without pulsation, at the same time, strong self-priming capacity, stable and uniform grouting pressure was observed. To ensure the continuity of slurry mixing and grouting, two slurry storage tanks with a volume of 7m3 were set up on site.

Fig. 6 – Layout of thixotropic slurry system

To ensure that the outer wall of the pipe can form a good filter cake during jacking construction, two thixotropic slurry main pipes were set up. One was specially used for synchronous grouting of the tail of pipe jacking machine and adjacent pipes, and the other was used for secondary grouting of other pipes. A grouting section shall be set every interval of one pipe, and each grouting section had 4 grouting holes. The grouting holes were evenly arranged along the socket end of the pipe section, and the grouting holes were connected with the main pipe through branch pipes. The main pipe was made of DN50 steel pipe, the branch pipe was made of DN25 rubber pipe, and a ball valve was set at the connection between each branch pipe and the main pipe. A high-pressure cleaning water pipe was installed in the tube for cleaning the cutter head. Grouting pipe is shown in Figure 7.

Fig. 7 – Layout of grouting pipe

Performance of the thixotropic slurry and application effect

Following aspects should be taken into consideration for the arrangement of the thixotropic slurry process. (1) High viscosity and low filtration loss, so that the slurry can be maintained for a long time; (2) Good thixotropy allows the mud to become gelatinous quickly after injection and support the formation. During pipe jacking process, the slurry and the pipes moved relatively, the slurry shear force decreases, which reduced the frictional resistance; (3) Maintain good stability, so that the slurry will not lose stability due to groundwater intrusion and prolonged construction.

For the properties of the main crossing area, little impact concerning the ground-water, and to improve the efficiency of muck, the thixotropic slurry used on site should havee high viscosity and low water loss. The thixotropic slurry was mainly composed of compound bentonite (sodium bentonite mixed with additives) and water, with the ratio of 1:10 for bentonite and water. In the early stage of construction from the launching shaft to the receiving shaft #1, a certain amount of chemical mud powder was added to the thixotropic slurry. The chemical mud powder mainly played the role of flocculation and viscosity increase. Because the composite bentonite used already contained relevant additives, the additional chemical mud powder made the flocculation degree of the thixotropic slurry increase and the performance become worse. After stopping the chemical mud powder, the performance of thixotropic mud was improved. The properties of thixotropic slurry are shown in Table 2.

Tab. 2 - Performance for the thixotropic slurry

Number	Density (g/cm3)	Marsh funnel viscosity (s)	Filter loss (0.5h)	Bleeding rate (24h)	Remark
1	1.06	70	76	15%	With chemical mud powder
2	1.065	112	20	0	Without chemical mud powder
3	1.06	90	22	0	

Figure 8 shows the calculation results of the frictional resistance per unit area based on the measured jacking force. In the initial jacking stage, the unit frictional resistance was very large. On the one hand, the lubrication was not carried out at this time, on the other hand, the face resistance was large when the pipe jacking machine passed through the reinforcement area. In the calculation of the unit frictional resistance, the face resistance was calculated according to the pressure of the mud tank, which was less than the actual value. After grouting, with the increase of jacking distance, the lubrication performance of the slurry was better developed, and the unit frictional resistance was rapidly reduced and tended to be stable. In the first section, the unit frictional resistance was stable at about 3 kPa, and in the second section, the unit frictional resistance was about 2.5kPa. In Technical Specification for Pipe Jacking of Water Supply and Drainage Engineering (CECS246:2008) [13], there is no explanation for moderately weathered siltstone. If the jacking force is calculated according to fine silt and medium-coarse sand, the unit frictional resistance is more than 8kPa, far higher than the actual value.

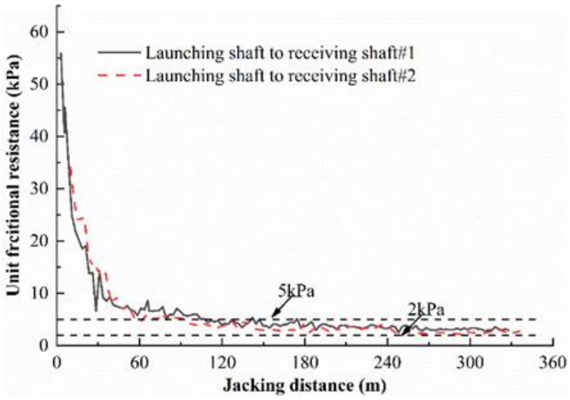


Fig. 8 – Unit area friction resistance curve

Small spacing launching technology

Due to the angle between the axis of the first jacking pipe section and the axis of the second jacking pipe section was about 12°, and the axis of the previous section was perpendicular to the wall of the launching shaft. So, the reaction wall of the second jacking pipe section was close to the hole door (the spacing is about 7.5m) to meet the deflection angle, and the operating space was narrow, as shown in Figure 9. The reaction wall was made up of rear cushion iron, H-shaped steel support and concrete. The reaction wall was made of C35 concrete with a compressive strength of about 35MPa.Two 5m-long 400×400×13×21HW steel sections were embedded in the concrete of the bottom plate and welded with the rear cushion iron. moreover, In addition, 8 pieces of 400×400×13×21HW steel were used as diagonal braces, which were welded to the backrest and fixed to the foundation by bolts. It is worth noting that 400 x 400 x 13 x 21 HW indicates a section with a height and width of 400 mm, a web thickness of 13 mm and a flange thickness of 21 mm. To enhance the stability of the rear backrest, concrete blocks were poured in the rear part, and steel diagonal supports were buried in it. The rear backrest design is shown in Figure 10.

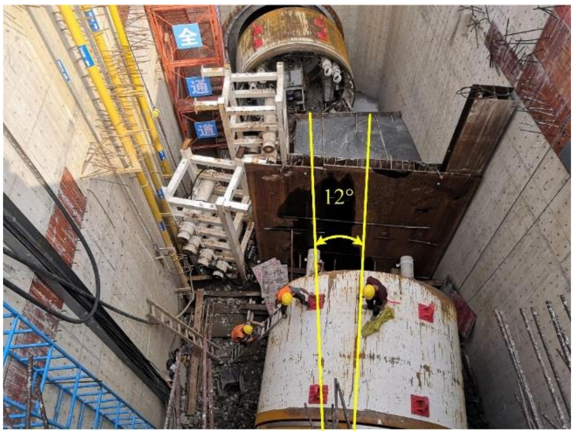


Fig. 9 – Launching of small spacing

Fig. 10 – Reaction wall

Due to the narrow origination space, it is impossible to carry out jacking after assembling the pipe jacking machine. Firstly, the front shield of the pipe jacking machine was hoisted into the initial guide rail, and its top was pushed to the hole door (not into the reinforcement area) through the two main oil jacking cylinders. Then, the tail shield was hoisted into the tail shield, and the front shield and tail shield were connected and fixed, and the circulating slurry pipelines were connected. After the pipe jacking machine was jacked for a certain distance, it started to jack the pipes. Before jacking the third pipe, install all the jacking cylinders and start normal jacking. The implementation steps are shown in Figure 11.

(a) Front shield jacking

(b) Front shield and tail shield splicing

(c) Pipe jacking

(d) Installation of main jacking cylinder frame

Fig. 11 – Launching step of pipe jacking

Control of the surface settlement

Control measures

(1) Jacking speed control

In the pipe jacking process, if the excavation surface is severely squeezed, the soil will be greatly deformed, and the surface in front of the drilling face may heave. During the jacking process, it is necessary to combine the axis deviation, grouting speed, jacking force and other factors to adjust the jacking speed in real time to ensure the stability of the jacking construction. In this project, the jacking speed was controlled at 10~20mm/min during the launching, and 20~30mm/min during the normal jacking.

(2) Pressure control in the mud tank

When the pressure of the mud tank is too large, the soil in front will be uplifted and deformed, otherwise the settlement deformation will occur. During the construction, the pressure of the mud tank can be measured by the pressure sensor in the pipe jacking machine. In this project, the pressure of mud tank was controlled at 0.01~0.015 MPa.

(3) Grouting control

A principle for grouting should be follow as "press first and then push, follow the push with pressure, and fill the slurry in time" to ensure the timely formation of a complete mud sleeve. In synchronous grouting, screw pump with stable pressure was selected for grouting to ensure the pressure of thixotropic slurry was stable and accurate when pressing into the stratum, and to prevent thixotropic mud from penetrating the stratum. The slurry pressure sensor was installed in the grouting hole at the tail of the pipe jacking machine to ensure the accurate control of the grouting pressure (the grouting pressure is controlled at about 0.3MPa). Secondary grouting mainly plays a role in ensuring the integrity of thixotropic slurry sleeve and supplementing the formation loss. The amount of grouting can be determined according to the pipe jacking thrust, formation parameters, mud performance, surface settlement and other parameters, generally 0.2~0.3 times of synchronous grouting amount. In this project, 2~3 times of secondary grouting were carried out every day, and each time of grouting was about 5 minutes.

(4) Jacking attitude control

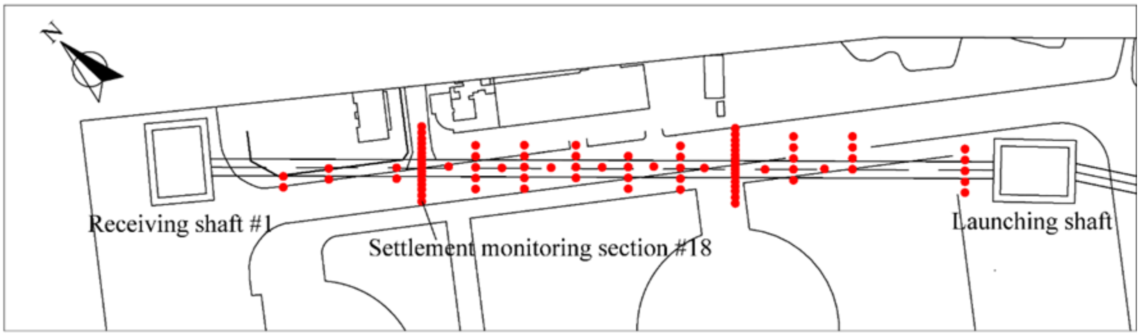
In the process of pipe jacking, it is necessary to adjust and control the jacking orientation. If the deviation of the pipe jacking axis is too large, overcutting or undercutting will occur, which will cause the loss of the stratum around the pipe or the change of soil pressure.

(5) Displace grouting

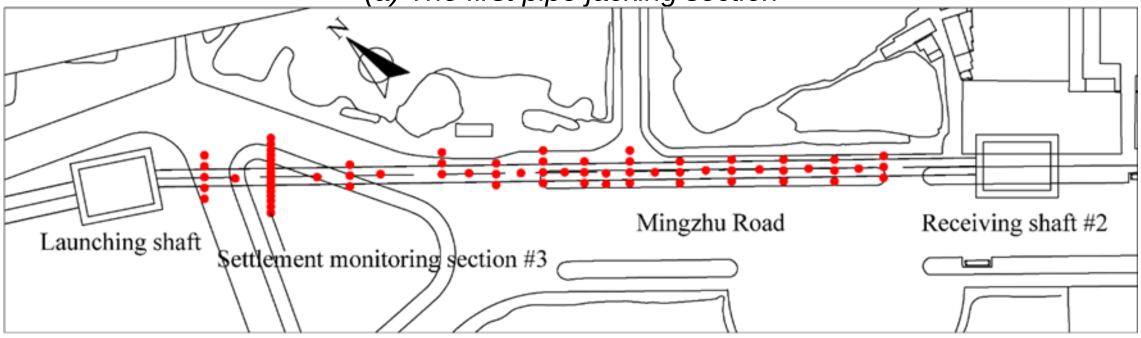
After pipe jacking is completed, displacement grouting is needed to prevent settlement caused by water loss of thixotropic slurry. In the process of grouting, cement grout was observed to flow out of the grouting hole at the top, that is, displace grouting was completed. In the process of grouting, special attention should be paid to prevent the replacement grout from damaging the existing surrounding buildings by monitoring the channels and the formation cracks.

Monitoring and analysis of ground deformation

The layout of surface settlement measuring points is shown in Figure12. Since it cannot be drilled through the road surface, the settlement measuring points are arranged with steel nails. The first pipe jacking section was arranged with 21 settlement monitoring sections, a total of 85 settlement monitoring points, and the distance between each section is 10m (extended when the terrain is limited). Among them, monitoring sections No.6 and No.18 were strengthened monitoring sections, and each section had 17 settlement monitoring points. The second pipe jacking section was arranged in the second section of the pipe jacking, with a total of 72 subsidence monitoring points, of which the No. 3 section was a strengthened monitoring section, including 15 measuring points.



(a) The first pipe jacking section



(b) The second pipe jacking section.

Fig. 12 – Layout of the monitoring points

The ground deformation of the monitoring section 18 of the first pipe jacking section is shown in Figure 13. In the figure, -27m – +19m represented the distance from the pipe jacking machine to the monitoring section, -27m represented that the pipe jacking machine still has 27m to the monitoring section, and +19m represented that the pipe jacking machine passes through the section for 19m. Since the settlement measuring point did not penetrate the road surface, the measured settlement change was different from the actual stratum settlement, and it did not appear in the form of a settlement tank. During the process of the pipe jacking machine passing through the section, the overall settlement of the section changes to uplifted first (or settlement decrease), and then settled (or settlement increase). The left side of the monitoring section was mainly the roadway, which had large settlement due to the influence of vehicle load, while the right side was the sidewalk, and the ground deformation showed the decrease of uplift. The reason may be that the measuring nails sprang back after measuring the initial value of the settlement point.

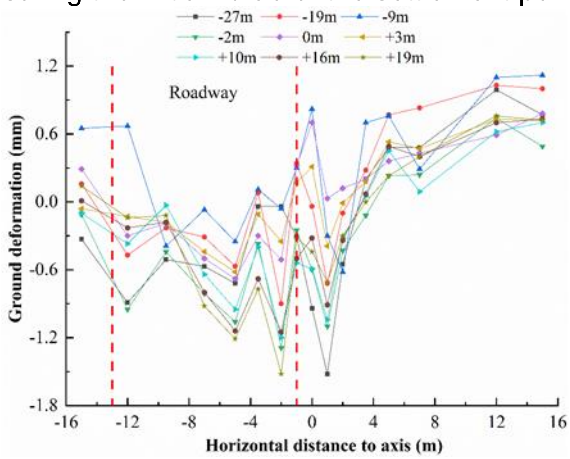


Fig. 13 – Ground deformation of monitoring section 18

Figure 14 illustrates the ground deformation of the monitoring section 3 of the second pipe jacking section. The 12 measuring points of this monitoring section were located in the soil, and 3 were located on the sidewalk. When the pipe jacking machine was close to the monitoring section, the monitoring section had a certain uplift. After the pipe jacking machine passed through the monitoring section, the settlement first increased rapidly and then tended to be stable. In the soil layer, the settlement of the area near the pipe jacking axis was large, while the deformation of the measuring point on the sidewalk was basically the same.

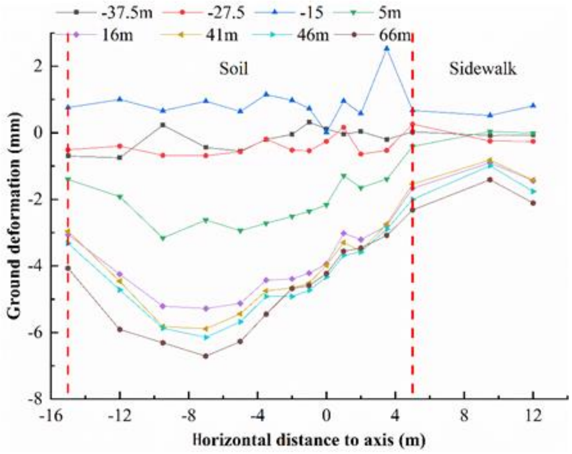


Fig. 14 – Ground deformation of monitoring section 3

According to the monitoring results, in the whole process of pipe jacking construction, the ground deformation was -8 ~ 5mm, and the settlement control of pipe jacking construction has achieved good results.

CONCLUSION AND DISCUSSION

In this investigation, the aim was to analyse several possible difficulties in an unfavourable stratum pipe jacking project, and propose some practicable solutions to those existing issues (equipment selection, small interval launching, management of recycling slurry, resistance reduction by grouting) on perspective of a practical pipe jacking engineering application conducted in Huang Gang, to be specifically:

(1) The slurry balanced pipe jacking machine and cutter head used in this project had good adaptability to the fractured moderately weathered siltstone stratum, and it had high construction efficiency in weathered rock stratum and rock-soil composite layer.

(2) The specific gravity of circulating slurry had great influence on jacking efficiency. When the specific gravity was too high, the rock debris cut by the cutter head cannot be discharged smoothly, resulting in a reduction in the jacking speed or even failure to jacking. On the contrary, if the specific gravity was too low, the rock debris cannot be carried. In this project, the specific gravity of circulating slurry was better controlled by adding filter press and timely transporting mud, but it also had a certain impact on the construction efficiency.

(3) The performance of thixotropic slurry has a direct impact on its drag reduction effect. When the thixotropic slurry has a high-water loss and water separation rate, a good filter cake cannot be formed around the pipe. After stopping grouting, the slurry will leak out quickly, increasing the frictional resistance. Therefore, the performance of thixotropic slurry should be monitored on site and adjusted in time when the slurry performance decreased.

(4) The small spacing pipe jacking launching technology adopted in this project effectively solved the problem of narrow launching space, enabling the pipe jacking machine to launch smoothly, and has no impact on subsequent construction.

(5) By controlling the jacking rate, slurry chamber pressure, grouting pressure, grouting amount, the volume of excavated earth and other construction parameters, the road surface deformation is controlled within -8~5mm, and the surface traffic is not affected.

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