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Geo-Ref Information Services-USA, List B of Scientific
Journals, Poland, Directory of Research Journals

International Journal
of Earth Sciences
and Engineering

www.cafetinnova.org

ISSN 0974-5904, Volume 09, No. 05

October 2016, P.P.2262-2267

Research on Key Construction Technology of Shield Tunnel Grouting in a Beijing Subway Project

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Abstract: The shield construction is used from Xitieying staiton to You'anmen outside station in a Beijing subway project. When the tube sheets break away from the the shield tail, an annular gap will be formed between the soil and the tube sheets. The paste can reduce the ground subsidence and even collapse when it is synchronously grouted to the annular gap. After filling, the soil pressure on the tube sheet can improve the early stability and the sealing property of the tube sheet lining. The hardening filling layer can also serve as waterproof; it has waterproof effect, but also can improve the strength and durability of the tunnel lining structure. Due to the flexible construction method, short construction period, low cost and so on, the synchronous grouting method has become a common method in shield construction.

Keywords: *subway, shield tunnel, synchronous grouting*

1. Introduction

1.1. Location and Coverage of the Project

There is a metro project, namely, the train section from Xitieying Station to Youanmenwai Station, which is located at the southwest corner of Beijing, between the South Third Ring Road and the South Second Ring Road, where is administrated by the District of Fengtai in Beijing. The train section starts from Xitieying Station and extends eastward along the south bank of Liangshui River, across the River at the southeast side of the Ruins of Liao and Jin Dynasties. After that it travels eastward along the north side of Liangshui River, crosses Youanmenwai Street and connects with Youanmenwai Station. Length of single track line is 704.7m.

This bidding section includes one station, namely Xietieying Station and one train section just aforementioned. It is proposed to use cut and cover method for Xietieying Station and shield tunneling method for the section. One cross passage is designed at the center of the section. No pump station is expected in this section.

1.2. Engineering Geological and Hydrogeological Conditions

1.2.1. Engineering geological conditions

The project area is located downstream of alluvial-proluvial fan of the Yongding River. As shown by the drilling data, the revealed strata mainly consist of artificial accumulation layers (Q_{ml}), Neogene sediment, Quaternary sediment, and Tertiary rock sediment. A detailed description of each stratum is given in Table 1.

Table 1: *Description of stratigraphic information based on exploration*

Geological period	Soil layer	Rock-soil	Lithology description
Artificial accumulation layer (Q_{ml})	①	Silt fill stratum	Yellowish-brown, slightly dense, wet to slightly wet, with silty clay in some parts, containing brick debris, ashes, and plant roots;
	①$_1$	Mixed fill stratum	In varied colors, slightly dense, slightly wet to wet, containing brick debris, ashes, and gravels;
	①$_2$	Find sand fill stratum	Yellowish-brown, loose, wet, containing brick debris, ashes, and a few pebble fill;
	①$_3$	Pebble and gravel fill stratum	In varied colors, slightly dense, wet, containing brick debris and ashes;
Neogene sediment	②	Silt stratum	Brown yellow to dark brown yellow, medium dense, slightly wet to wet, belonging to medium to medium high compressible soil, with silt sand, fine sand, and partial silt clay interlayers, containing mica and ferric oxide;

	②1	Silt clay stratum	Brown yellow to dark brown yellow, wet, plastic to hard plastic, belonging to medium high compressible soil, with silt interlayer in some parts, containing ferric oxide and mica;
	②2	Clay stratum	Brown yellow, wet, plastic, belonging to high compressible soil, containing ferric oxide and mica;
	②3	Silty sand and fine sand stratum	Brown yellow, slightly dense to medium dense, wet, belonging to low to medium compressible soil, with silt and gravel interlayers in some parts, containing ferric oxide and mica;
Quaternary sediment	⑤	Gravel and pebble stratum	In varied colors, medium dense to dense, wet, belonging to low compressible soil;
	⑤1	Medium sand and course sand stratum	Brown yellow, medium dense to dense, wet to saturated, belonging to low compressible soil, containing mica, with partial pebbles;
	⑥	Silty clay stratum	Brown yellow, wet, plastic, belonging to medium high compressible soil, containing mica and ferric oxide
	⑥2	Silt stratum	Brown yellow, slightly wet to wet, dense, belonging to medium low compressible soil, with silt sand, fine sand, and silt clay interlayers in some parts, containing mica and ferric oxide;
	⑥3	Fine sand and medium sand stratum	Brown yellow, wet to saturated, medium dense to dense, belonging to low compressible soil, containing mica, with pebbles in some parts;
	⑦	Gravel and pebble stratum	In varied colors, dense, wet to saturated, belonging to low compressible soil;
	⑦1	Medium sand and course sand stratum	Brown yellow, dense, wet to saturated, belonging to low compressible soil, containing mica, mixed with pebbles in some parts;
	⑦3	Silt stratum	Brown yellow, dense, slightly wet, belonging to medium low compressible soil, containing ferric oxide and mica;
	⑦4	Silty clay stratum	Brown yellow, wet, plastic, belonging to medium compressible soil, containing ferric oxide and mica;
	⑨	Gravel and pebble stratum	In varied colors, dense, saturated, belonging to low compressible soil;
Tertiary rock sediment	⒀	Clay rock stratum	Brownish red, wet, extremely soft rock, medium to poor cementing performance, fully-weathered to strongly weathered, containing a few mica and medium ~course sand;
	⒀1	Conglomerate stratum	Brownish red to gray brown, wet, extremely soft rock with semi-cementing to weak cementing performance and poor rock forming performance, strongly weathered; the cement mainly consists of clay particles, with sand in some parts.
	⒀2	Sandstone stratum	Grey to dusty red, wet, in fine grained texture and massive structure, strongly weathered; the rock core is in the shape of short column or in fragments.

1.2.2. Hydrogeological conditions

Along this bid section one phreatic aquifer is found in the loose sediment at about 44m depth below the ground, which is mainly contained in the sand and pebble layers under the level of 26.00～28.13m.

(1) Dynamic analysis of the groundwater

The phreatic aquifer of this bid section belongs to infiltration ~ runoff type, recharged by natural rainfall infiltration on one hand, and on the other hand, by lateral runoff when the groundwater level is lower than that of the periphery. When the groundwater level of this bid section is higher than that of the periphery, the groundwater will be discharged through lateral runoff. The groundwater level along this bid section shares similar annual dynamic variation rules to that in other districts of Beijing. Generally the groundwater level, due to infiltration of rainy season, is relatively high during November to March of the next year, and relatively low in other months due to less recharge from natural rainfall infiltration. The groundwater level normally varies by a range of 1～2 m in a year.

(2) Highest groundwater level over the years

According to the “Highest Groundwater Level Contour Map of 1959” and the available groundwater data, it is known that the highest groundwater level in 1959 is close to the natural ground, and the highest groundwater level in recent 3~5 years is

29.10～21.0m (decrease gradually from west to east, excluding perched groundwater).

(3) Corrosiveness of groundwater

According to the survey data, the groundwater along this bid section has no corrosiveness to the concrete structure; under alternate drying and wetting conditions, it has weak ~ medium corrosiveness to rebars in the concrete structures and weak ~ medium corrosiveness to steel structures.

2. Synchronous Grouting

When the segment is detached from the shield tail, an annular void will form between the soil mass and the segment, which, if not being treated in time, will easily cause ground settlement even subsidence on one hand, and on the other hand, the segment lining, due to absence of soil pressure around it, will have poor initial stability and void tightness. Synchronous grouting for the annular voids is thus required to fill such voids as early as possible, so as to reduce ground settlement or subsidence and eliminate any dangers imposed on the surrounding environment [1-4]. After fill of voids by grouting, soil pressure will be applied on the segment, which can improve initial stability and void tightness of the segment lining. The filled layer, after becoming coagulated and hardened, can serve as external waterproof layer for the segment, and meanwhile improve the strength and durability of the tunnel lining structure [5-9].

2.1. Grouting Materials and Proportioning Design

2.1.1. Grouting materials

Fly ash - cement mortar is used for synchronous grouting of this bid section, which possesses such advantages as high strength and durability after setting and hardening. Meanwhile, the grout layer can serve as waterproof layer and prevent groundwater from intrusion. According to the corrosiveness evaluation of groundwater along this bid section, under drying and wetting conditions, the groundwater has weak ~ medium corrosiveness to the rebars in the concrete structures. To improve corrosion resistance of the filled layer, it is decided to use the sulphate-resistant cement with a grade of 42.5, which will enable the filled layer to possess certain corrosion resistance after grouting, thus protecting the segment concrete and rebars from being corroded by the groundwater.

2.1.2. Grout proportioning and main physical-mechanical indexes

Basic proportioning of synchronous grouting is as shown in Table 2, based on the company's years of experience in the field of shield tunneling. Such proportioning should be further improved and optimized during the construction process taking into account the raw materials performance and construction environment, etc., so as to achieve optimum performance of synchronous grouting.

Table 2: *Material proportioning for synchronous grouting*

Fly ash (kg)	Cement (kg)	Bentonite (kg)	Sand (kg)	Water (kg)	Additive
380～240	80～140	60～50	710～930	460～470	As per the test conditions

In Table 2, the fly ash is level Ⅰ, 0.045mm square hole sieve is not more than 12%. Cement is 42.5 slag portland cement.The fly ash-cement mortar should meet the following requirements on physical-mechanical indexes:

(1) The setting time of fly ash - cement mortar is normally between 3~10h. Specific duration required for setting should be determined according to the advance rate of the shield machine and the external construction environment. In case of encountering strongly permeable stratum or the shield machine is working at high advance rate, the setting duration will have to be shortened. In such case, adjustment can be realized by adding early strength agent or other additives, or by improving cement content or lowering fly ash content.

(2) After the fly ash - cement mortar becomes coagulated and hardened, the compressive strength at 1d is required to be not smaller than 0.2MPa, and that at 28d not smaller than 2.5MPa.

(3) The shrinkage percentage of the fly ash - cement mortar after setting should be less than 5%.

(4) The consistence of the fly ash - cement mortar should be between 8 ~ 12cm.

(5) The decantation rate of the fly ash - cement mortar should be less than 5%

2.2. Main technical parameters of synchronous grouting

(1) Grouting pressure

The grouting pressure should be determined based on the hydrostatic water pressure in the driven soil layer. If it is lower than the hydrostatic water pressure, groundwater will seep into annular space between the lining and the excavated ground then it makes the grout incapable of filling the space in whole, which subsequently would cause ground settlement and even subsidence. However, if it is excessively high, the segment will suffer deformation and even failure under such high pressure and meanwhile the ground uplift can occur. Moreover, the grout can easily flow into the soil chamber and possibly cause malfunction of the shield machine after its setting and hardening, Therefore, the grouting pressure commonly being 1.1 to 1.2 times of hydrostatic pressure would be considered as appropriate, but its maximum shall not go beyond the range of 300~400KPa.

During synchronous grouting, the grout is ejected from multiple points on the circumference of the shield tail. During construction, attention should be paid to see that the grouting pressure of each ejection hole is not entirely the same. Because the lower grout is being subjected to larger water-soil pressure and segment pressure than that by the upper grout, to ensure optimum effect of grouting, the grouting pressure for the lower part should be higher than that for the upper part by 50~100Kpa.

(2) Grouting amount

The void volume should be controlled within 135%~170% in theory. i.e., a grouting amount of about 3.1～3.9m3 for each segment ring. During actual process, such grouting amount should be adjusted timely based on the observation of actual grouting process.

Various parameters should be collected during actual grouting process for preparation of the time history curves of grouting pressure and grouting amount. In case of any problems identified from the monitoring results of deformation of surrounding buildings and segment lining, the grouting parameters should be timely corrected to achieve optimum grouting effect.

(3) Grouting duration and advance rate

The specific duration of grouting depends on the advance rate of the shield machine and the setting time of the grout. Advancement and grouting must be conducted concurrently. Grouting duration should be determined by controlling both grouting pressure and grouting amount. Only when these two indexes reach the set value, can the grouting be stopped; otherwise additional grouting is required.

The speed of synchronous grouting must match that of the advance rate; otherwise unfilled voids or extra grouting will occur, affecting the construction quality. The average speed of grouting can be calculated by dividing the grouting amount for one segment ring by the time required by the shield machine to finish that segment ring.

(4) Termination criteria of grouting work and inspection of grouting results

Whether stop grouting or not depends on two factors, grouting pressure and grouting amount. At first, the designed value of the grouting pressure should be achieved; otherwise it indicates backfilling is of insufficiency. Secondly, 85% of designed grouting amount should be completed. It can be considered as a qualified grouting if these two conditions are met.

After grouting work, inspection of grouting effect is technically required, which is a synthetic evaluation primarily based on the time history curve of grouting pressure and amount, coupled with deformation monitoring results of surrounding buildings and segment linings [10-11].As the self-weight of the grout, it can be found that void zones are easily occurred at the vault of linings rather than the invert part, where it almost never occurs. Ultrasonic testing is therefore required to apply to the vault and the complementary grouting would be performed at those void zones without backfill, detected by the testing [12].

2.3. Main technical parameters of synchronous grouting

(1) Backfill grouting equipment placed at the first rolling stock includes grout storage, grout pump, washing pump, pipes, valves and etc. Firstly, fly ash-cement mortar prepared according to Table 2 is transported to grout storage tank. Secondly, mortar is pumping by grout pumps towards four isolated transporting pipes which were connected with another four pipes for simultaneous grouting. Finally, the mortar is simultaneously grouted into the annual space outside the lining, as details shown in Figure 1.

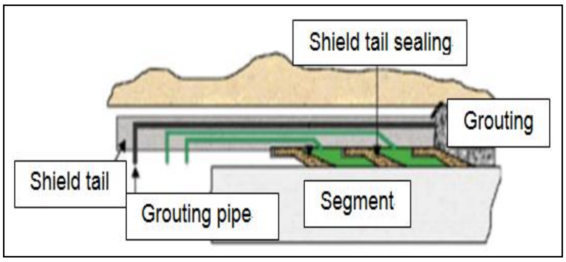

Figure 1: *Schematic diagram of simultaneous grouting*

(2) In order to meet the requirements of main technical parameters, the grouting pressure is detected by pressure sensor that is installed on each single transporting pipe. After completion of each segmental ring, the data of grouting pressure and grouting amount collected by the sensor will be sent to monitoring devices. In order to automatically control the grouting pressure, two adjusting valves are installed on each grouting pipes. When the pressure reaches the maximum, one of the valves will shut down the grout pump for stopping grouting. Likewise, when the pressure lowers to the minimum, the other valve will start the grout pump for continued grouting. In this way excessive or insufficient grouting can be prevented so as to insure the quality of grouting works.

(3) In order to avoid groundwater, subsoil, grouts and the excavated soil entering the shield machine from the annual space, the shield tail should be sealed by 3-row of steel wire brushes impregnated by grease, to ensure of smoothly performance of the subsequent simultaneous grouting.

(4) Amount of grout injected and grouting pressure for all pipes can be automatically controlled simultaneously. If the grouting pressure and grout amount is required to be adjusted for one pipe, it can be implemented by manual operation. Workflow management for simultaneous grouting is shown in Figure 2.

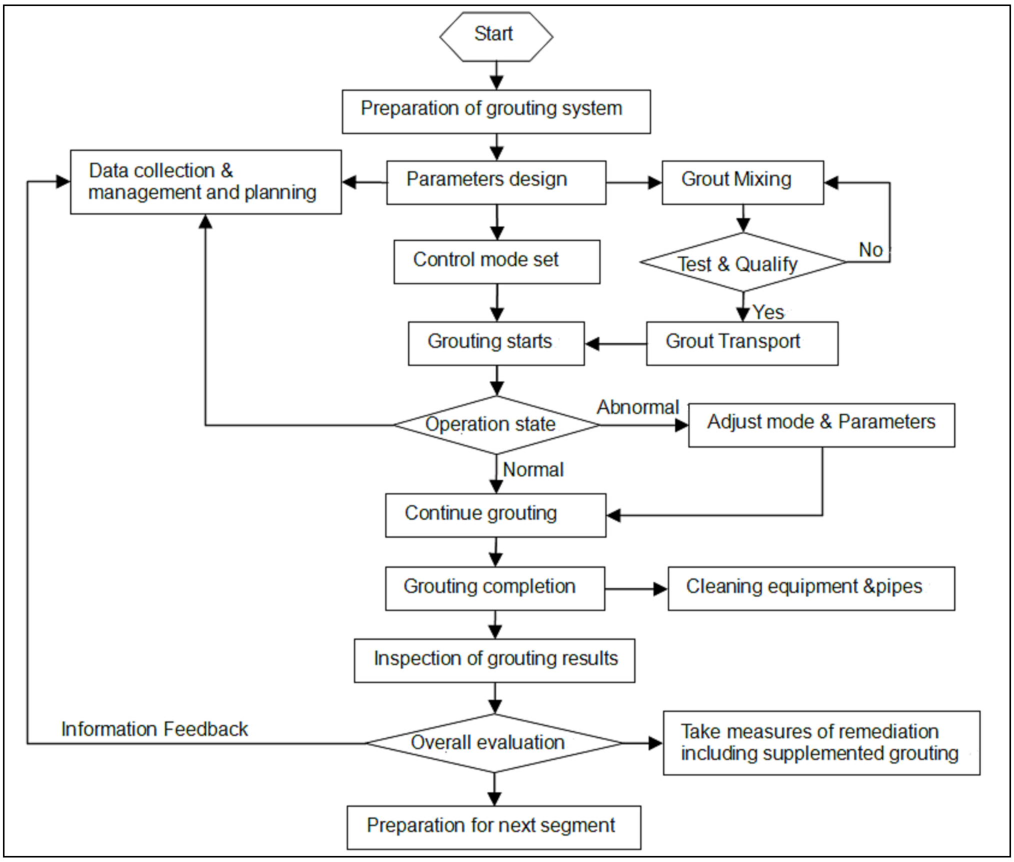

Figure 2: *Workflow management of simultaneous grouting behind segmental lining*

2.4. Matters need attention for simultaneous grouting

(1) Preparation prior to engineering start. Detailed guide for grouting works should be prepared before engineering start. A suitable mix proportion shall be selected based on necessary trial batches with reference to the mix proportion listed in Table 2, so as to meet the desired physical-mechanical properties designed for mortar.

(2) Beforehand control. The purpose of the stage eliminates the hidden dangers. Detailed design of grouting and workflow shall be made at first. Moreover, a thorough technical disclosure shall be carefully conducted for construction team, making them aware of quality control procedure that has to be strictly followed during grouting. Besides, the grouting equipment also needs regular check and maintenance to ensure normal operation. One last point is sufficient grout shall be stored, preventing a sudden stop of grouting.

(3) In-process control. The purpose of this stage solves the problems in time. Quality control procedure of grouting shall be strictly followed during grouting, say a loop "grouting-check-record-analyze". All relevant parameters shall be collected and plot time history curves of grouting pressure and grouting amount. Meanwhile, based on deformation monitoring data of surrounding buildings and segmental linings, any issues shall be identified and solved by correction of grouting parameters, just aiming at optimization of grouting and considered as a feedback and guidance for next time. To prevent setting and hardening of the mortar from blocking the pipes, it is necessary to clean the pipes and equipment timely to avoid the suspension of grouting works. Once the malfunction happens during the grouting, the shield driving and grouting works shall stop immediately until it returns to normal prior to construction.

(4) Afterwards control. The purpose of this stage remedies the problems that have already occurred after completion of grouting works, if ground subsidence occurs, it indicates the annual space is not fully filled or the shrinkage of the grout happens. As such, supplemented grouting is required, which is pumped from injected hole at the center part of the segment. So the grout should meet the requirement of quick-setting. In this project, cement-sodium silicate double

solution grout is selected for the supplemented grouting by specified slurry pump. It has proved that the supplemented grouting can reduce ground settlement and improve waterproof performance and it turns out be an effective measure after simultaneous grouting.

3. Summary

Simultaneous grouting, which can be used to fill the annual space outside the segment so as to reduce the risk of ground settlement and even subsidence and improve the early stability of segmental lining as well as its sealing performance, can either serve as waterproofing for segment or can act as reinforcement of tunnel lining structure because of its function of waterproof and durability as well as a certain strength. Therefore, simultaneous grouting has been commonly used in the construction of shield tunnel due to its economy and flexibility. It turns out that it has been successfully applied in one metro project in Beijing from Xitieying Station to Youanmenwai Station.

4. Acknowledgement

This work was financially supported by the School-level Research Project of Beijing Vocational College of Agriculture(No. XY-BS-15-03).

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