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Feasibility Analysis of Freezing Method in Strong Permeability Strata

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Abstract. If the underground engineering meets the strong permeable strata, such as sand and pebble strata, it will face huge challenges. Effective sealing of water has become a prerequisite for determining the safety of the project. Freezing method is currently an effective method for dealing with complex permeable strata, however, the influence of the groundwater velocity on the freezing engineering is huge. If the groundwater flow rate is too high, the freezing cannot be completed normally. Therefore, for the freezing project of strong permeable formation, the speed and flow direction of groundwater is a focus of our research. The connecting channel at the bottom of the river of Fuzhou Metro is planned to be constructed by freezing method. The main soil layers are the strong permeable strata represented by the coarse medium sand layer and the pebble layer. Therefore, the measurement of the velocity and direction of the groundwater at the bottom of the river was carried out, and the influence of the groundwater on the freezing project was judged based on the measurement results. If the groundwater velocity is too high, normal freezing cannot be achieved. Referring to the form of the cofferdam, a composite reinforcement method is proposed.

Keywords. Strong permeable strata, freezing method, groundwater velocity, feasibility.

1. Instruction

The development and utilization of underground space is the most effective way to solve the shortage of land resources, traffic congestion, expand urban space and alleviate environmental degradation [1-2]. If underground engineering encounters strong permeable strata, such as sand and pebble strata, it will face huge challenges. Effective sealing of water becomes a prerequisite for determining the safety of the project. Freezing method is currently an effective method for dealing with complex permeable strata [3-6]. Although the freezing method is widely used, its application in special projects or special formations still requires in-depth research, such as the application of freezing method in the application of freezing method in strong permeable strata [7-10].

In the freezing engineering of subway projects, refer to the Beijing Municipal Construction Engineering Technology Enterprise Standard "Technical Regulations for the Construction of the Connected Passage Freezing Method", when the aquifer water flow velocity is greater than 5m/d, the freezing plan should take corresponding technical measures to prevent the normal freezing of the ground. Referring to the Shanghai Engineering Construction Code "Technical Regulations for Bypass

Freezing Method", when the groundwater velocity is greater than 2m/d, there is concentrated water flow or the groundwater level has obvious fluctuations, the freezing design should consider the flow rate and take targeted measures. The flow of groundwater will have a greater impact on the formation of the nearby frozen wall. With the flow of groundwater, the cold will also be taken away by the water flow, resulting in the reduction of the surrounding cooling capacity. For highly permeable strata, it is extremely important to accurately determine the velocity and flow direction of groundwater [11-15].

Strong permeable strata represented by pebble stratum has high water content, large permeability coefficient, and poor self-stability. It is easy to cause deformation of the ground due to tunnel over-excavation and poor selection of construction parameters. This paper takes the connecting channel at the bottom of the river between Houting Station and Juyuanzhou Station of Fuzhou Metro Line 2 as the background, explores the measurement methods of groundwater velocity and flow direction and its influence on the freezing effect, and proposes solutions to the freezing project with excessive groundwater velocity.

2. Project Overview

The tunnel between Houting Station and Juyuanzhou Station of the Fuzhou Rail Transit Line 2 project is constructed by shield tunneling, with 4 connecting channels in the middle, of which 2# and 3# connecting channels are located under the Wulong River. The schematic diagram of the location of connecting channels is shown in figure 1. The soil layer at the construction location of the proposed 4 connecting passages is mainly coarse and medium sand, with rich water content and high pore water pressure. Especially the 2# and 3# connecting channels are located at the bottom of the river, which is prone to water inrush and sand gushing, and construction risk is higher. The recommended value of permeability coefficient for medium-dense coarse sand layer is 4.6×10^{-2} cm/s, and the recommended value of permeability coefficient for pebble layer is 6.4×10^{-2} cm/s. Coarse medium sand layer and pebble layer are phreatic aquifers. The phreatic aquifer is a highly permeable layer with good water richness. The Wulong River has a closer hydraulic connection with groundwater on both sides of the river.
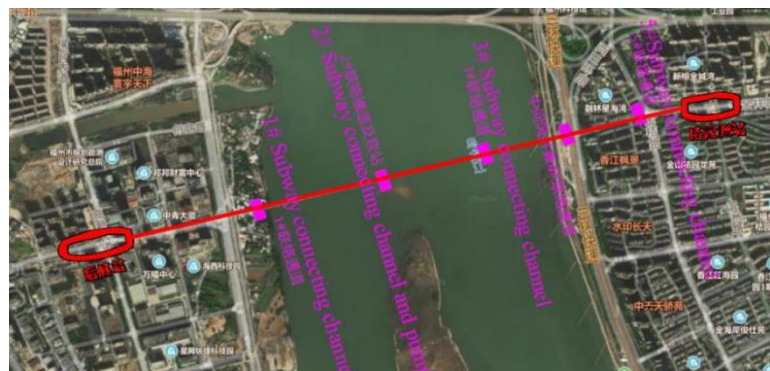

Figure 1. Schematic diagram of the location of connecting channels.

3. Groundwater Velocity Test of Sand and Pebble Formation at the bottom of the River

3.1. Test Overview

The groundwater velocity and flow direction were tested at the bottom of the Wulong River between Houting Station and Juyuanzhou Station. The tests include field work, laboratory testing, calculation, and conclusion. The site mainly conducts vertical flow test, tracer release, and water sample collection at a fixed depth at a certain time interval; the laboratory test mainly carries out trace analysis on the tracer put into the collected water sample, calculates the flow rate of groundwater through the change of tracer concentration at different times, and calculates the flow direction for the water samples collected in multiple directions. The indoor laboratory test adopts catalytic polarographic analysis

method for detection and JP-303 polarographic analyzer is used. The state of indoor laboratory test is shown in figure 2 and figure 3.
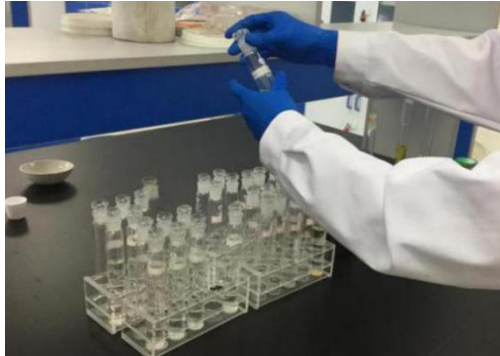

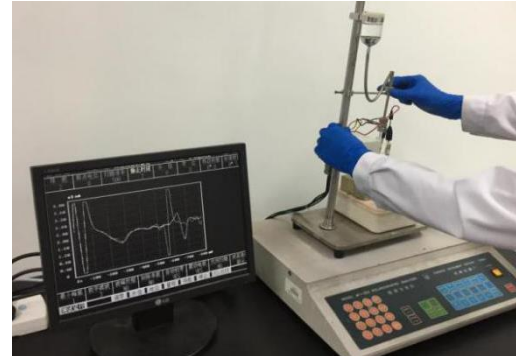**Figure 2.** Indoor catalytic polarographic analysis (sample preparation).

Figure 3. Indoor catalytic polarographic analysis (beginning of testing).

The depths of the 6 tracer drilling holes range from 20.38 m to 40.76 m and the hole diameter is 110 mm. The diameter of the built-in PVC filter tube is 90 mm, and the flow velocity and flow direction of each hole are arranged in table 1.

Table 1. Depth of measuring points of each hole.

Hole number	Depth of velocity measuring points	Depth of flow direction measuring points
1#	5 m, 10 m, 15m, 20m, 25m, 30m, 38m	5 m, 20 m, 38 m
2#	5m, 10m, 15m, 20m, 25m, 30m, 38m	5 m, 20 m, 38 m
3#	5m, 15m, 20m, 25m	5 m, 20 m, 25 m
4#	2m, 5m, 10m, 20m	5 m, 10 m, 20 m
5#	5m, 10m, 15m , 18m	5 m, 10 m, 18 m
6#	5m, 10m, 15m, 20m, 25m	5 m, 15 m, 25 m

3.2. Test Method

The water column in the filter pipe is marked by a small amount of tracer which can reach trace detection. After labeling, the concentration of tracer in groundwater is reduced (diluted) by the water flowing through the filter tube. The dilution rate of tracer concentration is related to the seepage velocity of groundwater. According to this relationship, the seepage flow velocity can be calculated. This method is usually called single hole dilution method because both tracer and concentration changes are observed in the same well [16].

The decline of tracer concentration can be expressed by the following basic equation:

$$C = C_0 e^{-Bt}$$

(1)

where: C_0—tracer concentration at time $t = 0$;

C—tracer concentration at time t;

B—coefficient, $B = \dfrac{Q}{V}$;

Q—the amount of water flowing through the hole per unit time, $Q = 2r_1 h V_w$;

V—the volume of diluted water column in the hole, $V = \pi r_1^2 h$;

r_1—the inner radius of the filter pipe (m);

h—the dilution water column height (m);

V_w—the flow velocity through the hole (M / D).

Therefore,
$$B = \frac{2r_1 h V_w}{\pi r_1^2 h} = \frac{2V_w}{\pi r_1} \tag{2}$$

And because
$$V_w = \alpha V_f$$

where: α—correction coefficient of flow field distortion caused by the existence of filter pipe in aquifer;

V_f —seepage velocity, i.e. Darcy's seepage velocity in aquifer (M / D);

Therefore,
$$B = \frac{2\alpha V_f}{\pi r_1} \tag{3}$$

From (1), (2) and (3), the following results are obtained：
$$\ln \frac{C}{C_0} = \frac{-2\alpha V_f t}{\pi r_1}$$

Namely:
$$V_f = \frac{\pi r_1}{2\alpha t} \ln \frac{C_0}{C} \tag{4}$$

Considering the influence of environmental background and probe, equation (4) is changed into:
$$V_f = \frac{\pi (r_1^2 - r_0^2)}{2\alpha r_1 t} \ln \frac{C_0 - C_b}{C_t - C_b} \tag{5}$$

Equation (5) is the calculation formula of permeability velocity. Where r_0 is the probe radius (m); C_t is the tracer concentration; C_b is the background concentration of tracer; t is the time required for the tracer concentration to change from C_0 to C_t, and other symbols are the same as before.

3.3. Velocity and Flow Direction Measurement
Six tracer boreholes are arranged, numbered 1#~6#. The location is shown in figure 4.

Figure 4. Plane position of tracer boreholes.

3.3.1. Vertical Flow Test. The underground water is marked by point dropping at a certain depth of the borehole. If there is vertical flow, as shown in figure 5, the tracer will flow upward to form a vertical flow. After the time interval of △ t, the peak value of tracer curve will move upward. The vertical flow direction can be judged by the movement of the peak value of the tracer curve, thus reflecting the movement of groundwater.
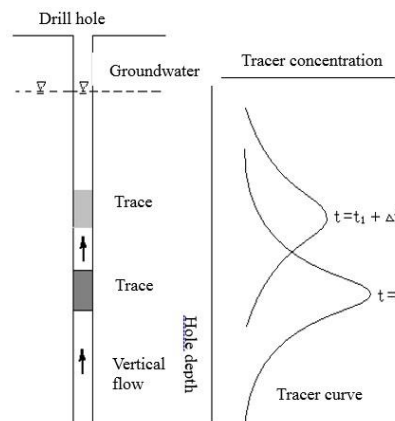
Figure 5. Tracing curve caused by vertical flow upward.

The conductivity meter with temperature correction function is used to measure the electrical conductivity of groundwater in a certain range above and below the input point, so as to measure the vertical flow. The vertical conductivity change in each hole is shown in figure 6.
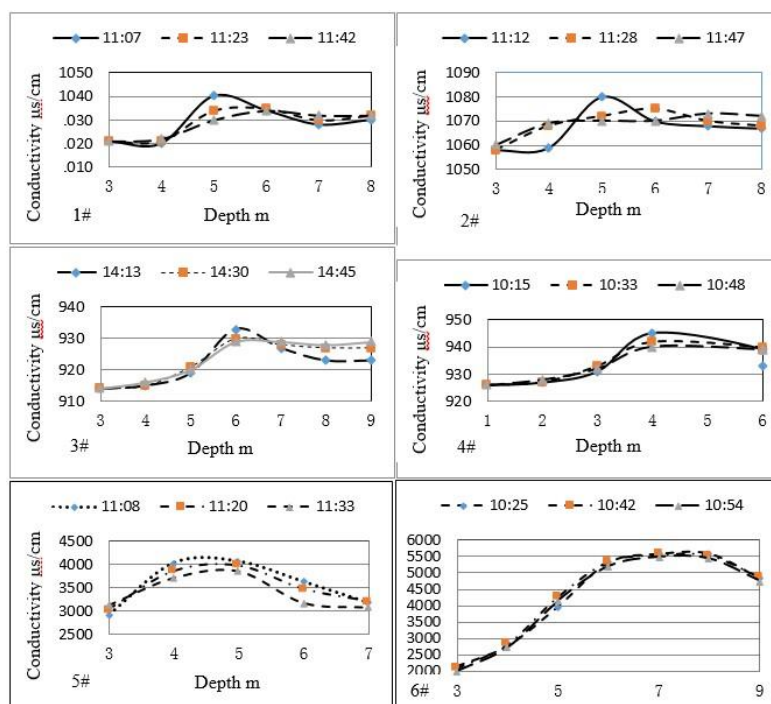

Figure 6. Conductivity change of hole 1-6#.

It can be seen from the figure that the peak positions of hole 1 and hole 2 move downward, indicating that there is a certain vertical flow, which is mainly caused by the influence of ebb tide. However, the peak positions of holes 3, 4, 5 and 6 did not move, indicating that the vertical flow in the four holes was not obvious.

3.3.2. Horizontal Velocity Test. According to equation (5), the background value of tracer concentration should be obtained first. The measured background values of tracer concentration in each borehole are shown in figure 7.
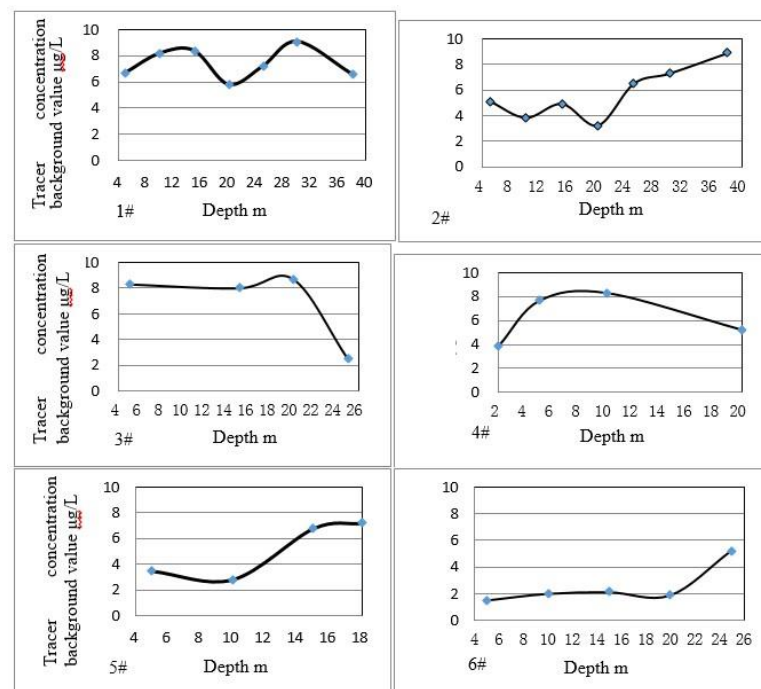
5

Figure 7. Background value of tracer concentration in groundwater of each hole.

According to equation (5), the maximum groundwater velocity at different measuring points of each hole is calculated as shown in figure 8.
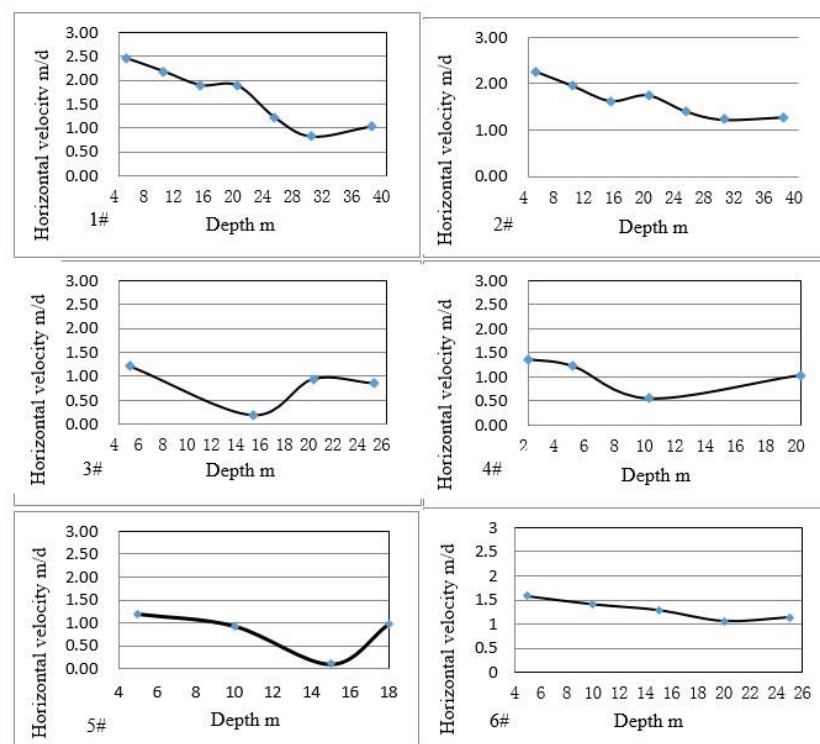

Figure 8. The horizontal velocity of groundwater at the measuring point.

3.3.3. Flow Direction Test. The tracer put into the borehole will be mainly carried out by groundwater along the flow direction with a certain angle of divergence, which is related to the velocity, aquifer structure and particle size. But in general, the concentration of tracer in the borehole is the largest in the downstream direction, the smallest in the upstream direction, and the concentration in other directions changes in turn. Therefore, the flow direction of groundwater can be determined according to the different tracer concentrations measured around the borehole. The tracer diffusion in the borehole along the flow direction is shown in figure 9. As shown in figure 10, according to the synthesis of tracer concentrations C1 ~ C8 in eight different directions, the groundwater flow direction at 355 °can be calculated.
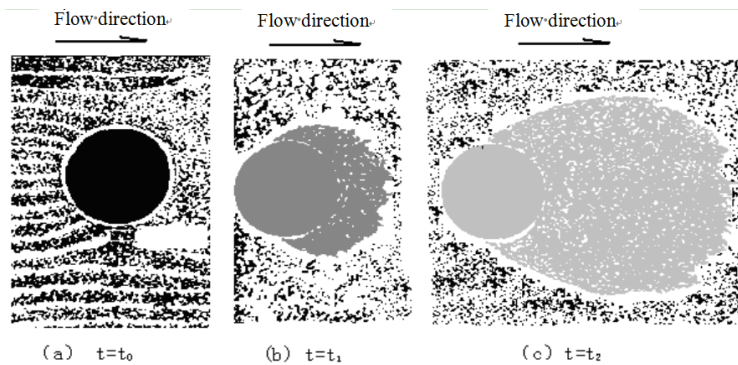

Figure 9. The tracer in the borehole disperses along the water flow direction.
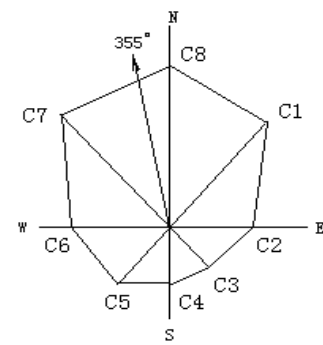
Figure 10. Schematic diagram of flow direction measurement.

According to the flow direction test principle, water samples in different directions at the depth of the chromium measuring point are collected at the same time, and the tracer concentration is tested. The calculated flow direction azimuth results are shown in figure 11. In general, groundwater flows to the southeast, and the azimuth of the flow varies from 126 °to 175 °.
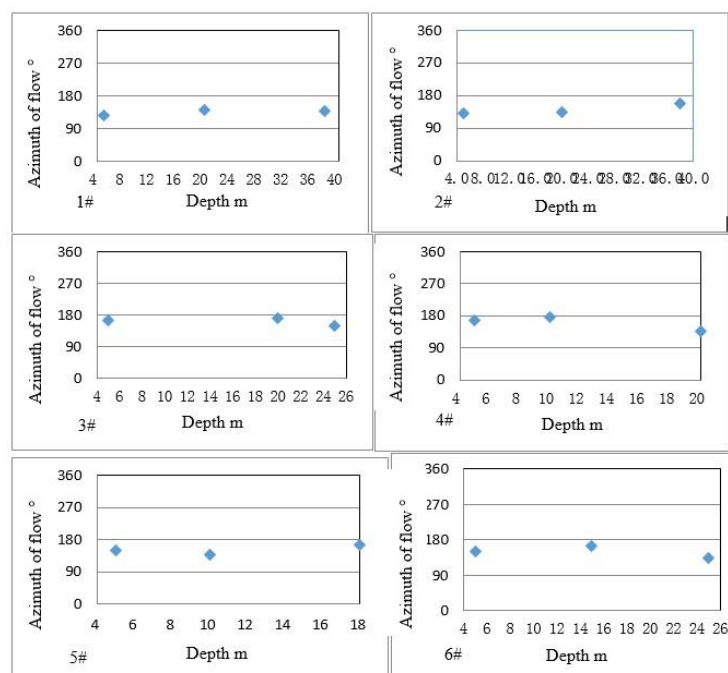

Figure 11. Azimuth angle of groundwater flow in holes 1-6#.

3.3.4. Summary. The azimuth angle of groundwater flow varies from 126° to 175°, and the groundwater generally flows to the southeast. See table 2 for the azimuth angle of the flow direction of each measuring point depth. The maximum groundwater velocity at each measuring point depth is 2.46m/d and the minimum is 0.10m/d. See table 3 for details.

The velocity and direction of groundwater are affected by various environmental factors. As long as the environmental conditions in the freezing zone of the connecting passage in this section do not change much from the environmental conditions during the test period, the velocity and direction of groundwater will not change significantly.

Table 2. Azimuth angle of groundwater flow at each measuring point.

| Measuring point depth /m | Azimuth of flow (°) | | | | | |
	1#	2#	3#	4#	5#	6#
5	126	130	165	166	149	150
10				175	138	
15						164
18					166	
20	140	133	170	137		
25			149			135
38	137	158				

Table 3. Groundwater velocity at each measuring point.

| Measuring point depth /m | Velocity(m/d) | | | | | |
	1#	2#	3#	4#	5#	6#
2				1.37		
5	2.46	2.26	1.21	1.22	1.18	1.58
10	2.19	1.95		0.55	0.92	1.41
15	1.90	1.63	0.18		0.10	1.29
18					0.97	
20	1.89	1.75	0.95	1.04		1.06
25	1.23	1.41	0.86			1.14
28						
30	0.83	1.23				
38	1.04	1.28				

4. Implementation Plan for Freezing of Connecting Channel at the Bottom of the River

According to the test results of groundwater velocity, the maximum value of groundwater velocity at each measuring point depth is 2.46 m/d. Although the value exceeds the requirement of 2 m/d of groundwater velocity in technical specification for side channel freezing method in Shanghai engineering construction code, it is less than the requirement of 5 m/d of groundwater fluidity in Beijing construction engineering technology enterprise standard "technical specification for construction of connecting channel freezing method" Instead of taking other water-proof measures, the conventional measures such as increasing the thickness of the frozen curtain, strengthening the freezing, setting temperature measuring holes on the upstream surface of the frozen curtain, and monitoring the development of the weak surface of the frozen curtain, are adopted. The freezing curtain is shown in figure 12.
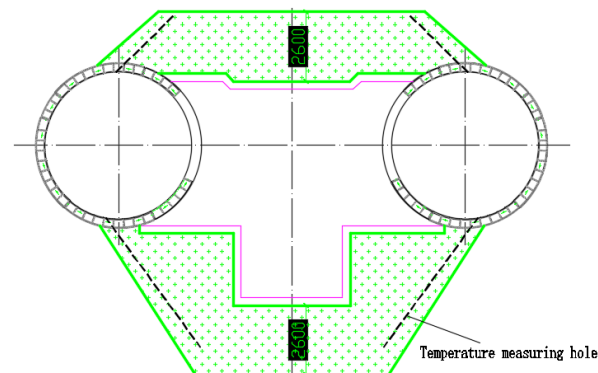
Figure 12. The freezing curtain and the temperature measuring holes on the boundary.

If the groundwater velocity is too high (more than 10 m/d), the water flow will take away most of the cold capacity, and the freezing requirement is insufficient, and normal freezing cannot be achieved. If the freezing method is still to be adopted, measures need to be taken to reduce the velocity of groundwater around the freezing curtain. Referring to the form of the cofferdam, the soil to be frozen is surrounded with a cofferdam, so that water flows through the periphery of the cofferdam, thereby blocking the interior flow. For similar projects, a composite reinforcement method is proposed: 800 mm thick plain concrete wall on the outside and freezing on the inside. Before the concrete wall is grooved, the $\varphi 650$ mm@400 mm triaxial mixing piles are used to reinforce the trough wall. The depth of triaxial mixing pile is about 3.0 m to the top of the tunnel, and the depth of 800 mm thick plain concrete wall is 5.0 m below the excavation floor. The schematic diagram is shown in figures 13-14.
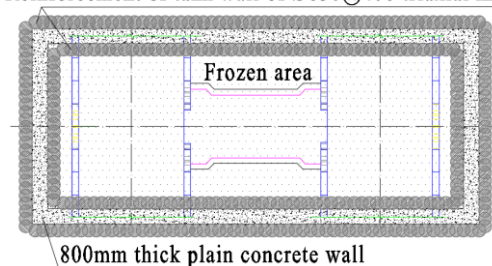

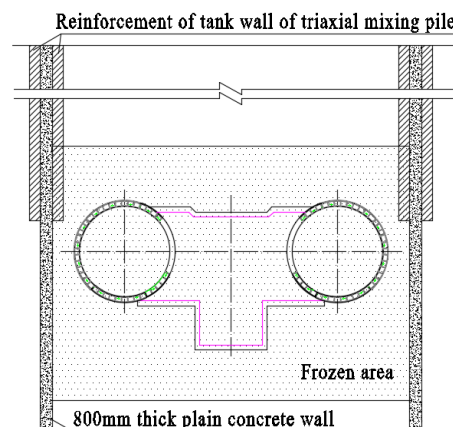**Figure 13.** Ground reinforcement plan.

Figure 14. Schematic diagram of stratum reinforcement section.

5. Conclusions

Based on the freezing method construction of the connecting channel at the bottom of the river between Houting Station and Juyuanzhou Station of Fuzhou Metro, this article focuses on the velocity and direction of groundwater in the strongly permeable formations at the bottom of the river, and judges the influence of groundwater on the freezing project based on the measurement results. And put forward a freezing engineering solution when the groundwater velocity is too high.

(1) 6 tracer boreholes are arranged at the bottom of Wulong River, numbered 1#~6#;

(2) According to the principle of radioisotope tracing groundwater, the single hole dilution method is used to test the vertical flow in the field, tracer release, and fixed-depth water sample collection at a certain interval;

(3) Trace analysis was carried out on the tracer in the water samples collected by laboratory test. The velocity of groundwater was calculated by the change of tracer concentration at different times, and the flow direction of multi-directional water samples was calculated;

(4) The azimuth angle of groundwater flow varies from 126° to 175°, and the groundwater generally flows to the southeast. The maximum groundwater velocity at each measuring point depth is 2.46 m/d, and the minimum is 0.10m/d;

(5) According to the test results of groundwater velocity, the maximum value of groundwater velocity is 2.46 m/d, which is not very large. Instead of taking other water-proof measures, the conventional measures such as increasing the thickness of the frozen curtain, strengthening the freezing, setting temperature measuring holes on the upstream surface of the frozen curtain, and monitoring the development of the weak surface of the frozen curtain, are adopted.

(6) If the groundwater velocity is too high (more than 10m/d), the normal freezing cannot be achieved. Referring to the form of the cofferdam, a composite reinforcement method is proposed: 800mm thick plain concrete wall on the outside and freezing on the inside. Before the concrete wall is grooved, the φ650 mm@400 mm triaxial mixing piles are used to reinforce the trough wall.

Acknowledgements

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