Test and Analysis of Velocity Law of Flowing Water in Stratum of Bottom Contact Passages in Shield River-Crossing Section

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Abstract. The method of combined hole arrangement on both banks and in the middle of the river was proposed for the test and analysis of the flowing water velocity in contact passages at the bottom of the Wulong River in order to address the insufficient reliability of the existing testing method for the flowing water velocity in the bottom stratum and its failure to truly reflect the data and law of the velocity in the stratum of bottom contact passages in the shield section. Meanwhile, the measurement time of each measuring hole has experienced the fluctuation cycle of the water level, enabling the parameters and law of the flowing water velocity obtained from the test to cover the complete spatial and temporal distribution range. Compared with the existing research, the method has a greatly improved data reliability, guiding the freezing reinforcement construction of bottom contact passages successfully. At the same time, the flow distribution law, velocity range and the law of influence of water fluctuation on the flow velocity revealed in this test can provide reference for related engineering projects in the region.

1. Introduction

The freezing method has become the first choice for the reinforcement of contact passages in the strongly permeable stratum at the bottom of the river due to its characteristics such as good water sealing and high strength of the reinforced soil. However, the bottom stratum is often hydraulically connected with the upper water, resulting in a high flowing water velocity, which has an adverse impact on the freezing effect of the freezing pipe in the freezing reinforcement process and makes the freezing wall fail to reach the design thickness or unclosed for a long time in serious cases \cite{1}, causing risks such as water seepage, sand boil and even collapse of contact passages. Therefore, it is necessary to carry out a test and analysis on the law of groundwater flow in the stratum of bottom contact passages to grasp the comprehensive and accurate groundwater flow parameters and provide important support for the freezing reinforcement design and construction of contact passages.

In recent years, there have been many explorations on the measurement and law analysis of groundwater velocity and flow direction in karst tunnels and dams, etc. \cite{2-5}, but relatively few studies have been conducted on the velocity law of flowing water in bottom contact passages in the shield section. Ye et al. \cite{6} completed the measurement of groundwater velocity and flow direction in three
boreholes with the isotope single-hole dilution method, and obtained the test results of the horizontal velocity, horizontal flow direction and vertical velocity of the phreatic water and confined water on both banks of the Qiantang River. Zhang et al. [7] carried out a field test and analysis of groundwater velocity and flow direction based on the method of borehole survey and testing with a tester and obtained the characteristic data of groundwater flow in the stratum of contact passages, guiding their freezing design and construction.

However, radioactive isotopes are mainly used as tracers in the current testing of the flowing water velocity in the stratum of bottom contact passages. It is not known whether such materials have an impact on the surrounding environment. Meanwhile, test points of the underground flowing water velocity are all set on the land on both banks of the river in the existing research. For bottom contact passages, the data and law of flowing water velocity in the stratum of contact passages can only be inferred indirectly from the test results for both banks. Results obtained with the methods above must have differences that cannot be ignored from the actual situation due to the horizontal differentiation of the permeability and hydraulic gradient of the river alluvium.

The Houting-Juyuanzhou shield section of Section 4 of Fuzhou Metro Line 2 crosses the Wulong River, with a total of 4 contact passages among which 2# and 3# are located at the bottom of the Wulong River and are proposed to be constructed with the mining method after stratum reinforcement with the freezing method. However, the bottom contact passages mainly pass through the water-rich medium and coarse sand layer and the pebble layer, with a permeability coefficient up to 35-55 m/d. Besides, there is a hydraulic connection between the stratum and the Wulong River. It is very likely that there is a high flowing water velocity, bringing about great risks in contact passage construction. Therefore, how to obtain accurate velocity parameters of the flowing water in the stratum of contact passages in the river to provide guidance for the design and construction of freezing reinforcement is crucial to the success of the project.

Therefore, the method of combined hole arrangement on both banks of and in the middle of the Wulong River was proposed in this test. The measurement time of each borehole has covered at least one fluctuation of the water level, enabling the velocity parameters and law obtained to cover a relatively complete spatial and temporal distribution range. The reliability has been greatly improved in comparison to the existing research. At the same time, the distribution law of water flow in the bottom stratum of the Wulong River along the cross section, velocity range and the law of influence of water fluctuation on the flow velocity revealed in this test can provide reference for related engineering projects in the region.

In addition, the salt was used as the tracer to test the velocity of the flowing water in the stratum, causing no pollution to the ecological environment around the Wulong River in the whole process.
2. Borehole layout

2.1. Borehole layout plan
A total of 5 boreholes were set up in the test, among which 3 were located on the southern small continent near the shield section, 1 borehole was located on the east bank and 1 was located on the west bank. See Figure 1 for borehole location.

The permeability and hydraulic gradient of the alluvium of the river had very small differences in the vertical direction and only differed in the horizontal direction. Therefore, No. 3 and No. 5 holes were basically on the same longitudinal section of the river as contact passage 2#. The velocity law of flowing water in the stratum of the two holes can better represent the condition of contact passage 2#. The test hole arranged respectively on each bank of the river was at the position of the greatest hydraulic gradient of the Wulong River cross section. The range of groundwater velocity in the local area can be basically determined and the velocity of flowing water in the No. 3 contact passage can be inferred reasonably based on the measured velocity combined with the velocity data of the 3 holes on the central continent.

2.2. Borehole structure
In this test, permeable filter tubes were used in all test sections of No. 1 to No. 4 holes below the water level, which were φ75 PVC tubes. They were uniformly holed in quincunx with an opening rate of about 5.3% and a hole diameter of 9mm and with upper and lower holes arranged in a staggered way, and were wrapped with two layers of filter nets (80 meshes) with a permeability coefficient greater than $1 \times 10^{-4}$ cm/s to prevent sediment. The casing part above the groundwater level was not drilled and was kept in its original state and impervious, as shown in the figure. The casing placed was about 20 cm above the ground to prevent debris on the ground from falling into the test borehole.

No. 5 hole was provided with a different structure in order to test the groundwater velocity in the deep pebble layer directly and eliminate the influence of vertical flow in the hole caused by the fluctuation of the water level. Non-perforated PVC tubes were used above the burial depth 27.5 m and blocked with cement paste around. The pebble layer was below the burial depth 27.5 m, from which to the bottom of the hole the same permeable filter tubes as for No. 1 to No. 4 holes were used so that the tracer could be placed in the hole section of the pebble layer to directly measure the velocity in the layer and avoid the influence of the upper vertical flow.

2.3. Geological distribution of boreholes
The stratum distribution of the 5 boreholes in this test is shown in Figure 2. Observation wells 1 to 5 correspond to No. 1 to No. 5 holes in Figure 1 respectively. Except for the two boreholes on both banks, the three holes on the central continent have similar stratum distribution, involving silty fine sand, mucky sand and pebble layers successively from top to bottom, with only minor differences in specific depths. Their small differences represent to a certain extent the distribution characteristics of the alluvium of the river at contact passages 2# and 3# to be built.
3. Velocity test analysis

The velocity test was carried out on No.1 to No. 5 holes from June 27 to July 7. First, the tracer was cast into the entire hole. Holes 2# and 3# on the central continent had a vertical flow due to the fluctuation of the water level. Therefore, the method of point casting was added to measure the vertical flow velocity on the basis of entire casting. The change of the water level at different time points also caused the change of the horizontal velocity in the hole. The velocity measurement data of each hole is analyzed one by one below.

3.1. Analysis of test data of No. 1 hole

No obvious vertical flow was found in the No. 1 hole. The horizontal velocity distribution at different time points on June 27 is shown in Figure 3. The velocity in the hole changed at different time points due to the difference of the water level. On the whole, the velocity was relatively high in the hole section above the elevation -2m, ranging from 0.2 to 1.6 m/d, and low in the section from below the elevation -2m to the bottom of the hole (at the elevation of -32m), ranging from 0.001 to 0.2 m/d.

![Figure 3 Velocity distribution of No. 1 hole on June 27 and June 28](image)

The fluctuation of the water level of the hole basically corresponds to that of the river as shown in the Figure 4. According to Figure 3, the velocity in the hole increased in the period from 12:00 to 14:00 compared with other periods, as it was just the period of ebb when the water level of the river was low and that of the corresponding No. 1 hole was also low (see Figure 4), causing the increase of the hydraulic gradient at No. 1 hole and thereby of the velocity. However, the velocity increased only slightly.

![Figure 4 The water level change process of No. 1 hole from June 27 to 28](image)

The velocity measurement results on June 28 are shown in Figure 3, with a similar law to those on June 27. However, the hole section above the elevation -6m was the part with a higher velocity on June 28 ranging from 0.1 to 1.4 m/d). The velocity in the hole section below the elevation -6m was also low, ranging from 0.001 to 0.2 m/d. The reason for this phenomenon is also the difference in the water level of the river affected by the tide during the measurement. Although the groundwater velocity in the hole was affected by the tide of the river, the two-day measurement has gone through the process of rising and falling tides. Its velocity has not changed much.
Figure 5 shows the temperature distribution of No. 1 hole on June 27 and 28. According to the two figures, the groundwater temperature distribution law of No. 1 hole is basically unchanged, indicating relatively stable seepage in the hole. There is a low temperature valley above the elevation -5m, corresponding to the part with a higher velocity, indicating strong influence of low temperature water leakage here.

3.2. Analysis of test data of No. 2 hole

The water level change of No. 2 hole is shown in Figure 6. The water level of the hole has a corresponding relationship with that of the river but lags behind the change of the latter. When the river is in the ebb period, the water level of the central continent is higher than that of the river and a downward vertical flow forms in the hole. On the contrary, the former is lower than the latter and an upward vertical flow forms in the hole when the river is in the rising tide period.
On June 30 and July 1, the water level of the river was in the ebb period when No. 2 hole was tested and a downward vertical flow formed in the hole. No. 2 hole was tested again on July 5. Vertical and horizontal velocities were measured mainly with the method of point casting at the depth of -20m. The change in tracer concentration after point casting is shown in Figure 7. There was an upward vertical flow in the hole since the test was carried out in the high tide period of the river. The measurement was taken frequently right after point casting, once every 3 to 5 minutes. The tracer concentration had few changes at the elevation of -20 to -25 m from 9:49 to 10:18, indicating a low horizontal velocity here; otherwise, the tracer concentration would decrease greatly. At 11:10, the tracer concentration peaked as the vertical flow had flowed up to an elevation of -15m at which time the vertical velocity was 26.9 m/d. It decreased significantly when measured at 13:00, reflecting a higher horizontal velocity near the elevation -16 to -14 m, which was calculated to be 0.87 m/d.

Figure 8 shows the horizontal velocity distribution of No. 2 hole on June 30. However, it should be noted that there is a possibility of overestimation of the velocity in the upper layer and underestimation of the velocity in the lower layer due to the influence of the downward vertical flow. However, such underestimation is not wide as it can be seen from the tracer concentration distribution on July 1 (see Figure 9) that although the concentration curve moved downward due to the vertical flow, it did so parallelly. That is, the mass of the tracer did not reduce significantly, indicating that the horizontal velocity was not high (the tracer was at the elevation of -20 m at 12:17 and moved down to the elevation of -24m at 14:15, and the concentration was reduced from 10.52 ms/cm to 10.25 ms/cm. The horizontal velocity calculated on this basis was 0.009 m/d).

3.3. Analysis of test data of No. 3 hole
Figure 10 shows the water level change of No. 3 hole. No. 3 and No. 2 holes were both located on the central continent, with similar stratum distribution. Similarly, the water level and flow velocity of No. 3 hole were also affected by the rise and fall of the water level of the river.
The tracer was cast into the entire No. 3 hole at 9:50 on July 1. Then the tracer concentration in the hole was repeatedly measured. The concentration distribution over time is shown in Figure 11. It can be seen that there was no obvious vertical flow in the hole before 11:30. The calculated horizontal velocity at this time is shown in Figure 11. As the water level of the river drops, a large vertical flow formed in the hole and the tracer concentration curve moved down significantly. The average vertical velocity calculated on this basis was 70.75 m/d from 11:50 to 13:15 and 84.96 m/d from 13:15 to 14:40. See Figure 11 for the horizontal velocity distribution of No. 3 hole at different time points in the morning of July 1.

![Figure 12 Concentration distribution of tracer in hole 3 on July 1 (re-dump at elevation above -20m)](image1)

![Figure 13 Tracer Concentration distribution at different time after point casting at the elevation of No.3 Hole at -20m)](image2)

The tracer was cast again above the elevation -15m in the afternoon of July 1. The tracer concentration distribution is shown in Figure 12. As can be seen from the figure, affected by the vertical flow, the concentration curve of the 4 measurements showed overall downward translation. The average vertical velocity calculated at different time points was 178.1 m/d from 16:00 to 16:15, 117.9 m/d from 16:15 to 16:40 and 83.5 m/d from 16:40 to 17:10. The average horizontal velocity between -16m and -22m was 0.135 m/d, 0.067 m/d and 0.049 m/d respectively in the sections of -16m~18m, -18m~20m and -20m~22m.

To have a deeper understanding of the permeability of the deep stratum, the tracer was cast with the method of point casting at an elevation of -20m in No. 3 hole on July 5. Then the movement and change of the peak tracer concentration were tracked. See Figure 13. The morphology and temporal variation of the tracer concentration distribution indicate that there were both vertical and horizontal flows between -20m and -30m. See Table 1 for specific velocity calculation data.

### Table 1: Vertical flow velocity and horizontal flow velocity at different depths in different time periods of No. 3 hole on July 5

| Period         | Vertical velocity (m/d) | Horizontal velocity (m/d) | Elevation (m) |
|----------------|--------------------------|---------------------------|---------------|
| 13:46-13:55    | 163.019                  | 0.188                     | From -20 to -21 |
| 13:55-14:14    | 76.123                   | 0.090                     | From -21 to -22 |
| 14:14-15:09    | 52.205                   | 0.081                     | From -22 to -24 |
| 15:09-15:47    | 75.789                   | 0.126                     | From -24 to -26 |
| 15:47-16:24    | 38.919                   | 0.147                     | From -26 to -27 |
| 16:24-16:57    | 43.200                   | 0.197                     | From -27 to -29 |
| 16:57-17:34    | 78.724                   | 0.192                     | From -28 to -30 |
| 17:34-17:57    | 62.383                   | 0.051                     | From -30 to -31 |

3.4. Analysis of test data of No. 4 hole

The water level of No. 4 hole was also synchronized with and slightly behind the water level of the river as shown in Figure 14. The velocity of No. 4 hole was similar to that of No. 1 hole. No obvious vertical flow was found. However, the former was generally higher than the latter due to the higher hydraulic gradient and the stratum distribution of No. 4 hole slightly different from that of No. 1 hole.
3.5. Analysis of test data of No. 5 hole

No. 5 hole was located near No. 3 hole on the central continent. To eliminate the influence of the upper vertical flow on the seepage velocity test of the deep pebble layer, impervious PVC tubes were used for the hole above the burial depth 27.5m and the hole was blocked with cement paste around. The velocity test results on July 7 indicated an obvious effect of blocking. No obvious vertical flow was found in the pebble layer.

Figure 16 Concentration of Tracer in Hole 5 and Horizontal Velocity Distribution of Pebble Layer

On July 7, a casting test was carried out on No. 5 hole from below the elevation -20m to the bottom of the hole. The distribution of tracer concentration at different time points after casting is shown in Figure 16.
4. Conclusion

In this test, a total of 5 boreholes on both banks and in the middle of the Wulong River were subjected to repeated casting and detection analysis. The following groundwater flow laws and characteristics were obtained:

(1) No obvious vertical flow was found in No. 1 and No. 4 holes located on both banks, and the measured horizontal velocity was highly reliable. No. 1 and No. 4 holes both had a higher horizontal velocity in the upper part and a lower velocity in the lower part (including the pebble layer). The maximum velocity in their bottom pebble layers was 0.2 m/d and 0.49 m/d respectively.

(2) Since No. 2 and No. 3 holes were subjected to entire casting, the measured horizontal velocity was affected by the vertical flow. There is a possibility of overestimation of the upper velocity and underestimation of the lower velocity. According to the measurement with the method of point casting of the tracer, the horizontal velocity in the lower layer of the two holes was low. The maximum horizontal velocity of No. 2 hole was 0.87 m/d and that of No. 3 hole was 0.197 m/d.

(3) For No. 5 hole located on the central continent, the upper part of the pebble layer was blocked to eliminate the interference of vertical flow. The horizontal velocity of the pebble layer could be directly measured. The measured maximum horizontal velocity was 0.479 m/d, corresponding to the elevation -27 m.

(4) It can be determined based on the velocity distribution of the five boreholes on both banks and in the middle of the river that the velocity of the formation seepage water in contact passages 2# and 3# was relatively low, much less than 5 m/d, which can be considered to have no impact on the construction with the freezing method. However, it is still necessary to pay attention to the change of the formation water velocity and focus on weak links of freezing in the construction process as the construction will change hydraulic conditions of the stratum and then affect the groundwater velocity in the stratum.

(5) There is a history of sand digging at the bottom of the Wulong River, causing the heterogeneity of the alluvium of the river. The river water would be connected to the pebble layer at the bottom of the river especially if the digging reached the depth of the pebble layer somewhere, resulting in the increase of water velocity in the pebble layer and making it even greater than that of the formation water velocity on both banks (e.g. the test data of No. 2 hole). Therefore, the formation water velocity on both banks of the river cannot represent the upper limit of the formation water velocity of the Wulong River. It is inappropriate to infer the formation water velocity at the bottom of the river based on water velocity parameters of boreholes on both banks.

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