Refined Calculation of Temperature Field in Cross-passage by Artificial Ground Freezing

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Abstract. In China, the artificial ground freezing (AGF) method is widely used in the construction of cross-passages, however, it is difficult to accurately calculate the numerical solution of the freezing temperature field. In this paper, the boundary conditions in the numerical calculation are refined through in-suit measurements, and finally the freezing process of the connecting channel is effectively simulated. The calculation results show that the thickness and temperature of the frozen wall at 1.0 m near the main tunnel segment are significantly weakened. The frozen wall at the top of the cross-passage is affected by densely arranged holes, which is prone to excessive freezing. And based on the calculation results, an optimization plan for the highest cooling efficiency in the initial stage of active freezing and speeding up freezing is proposed.

1. Introduction

Artificial ground freezing method is a special formation reinforcement method that changes rock and soil into frozen through circulating low-temperature refrigerant in the stratum. The freezing soil can effectively improve the bearing capacity and anti-seepage capacity of the soil close to the excavation area [1]. In China, the freezing method was first applied in mine freezing engineering [2], and then gradually used in municipal engineering, which mainly used for strengthening water-rich weak stratum [3]. At present, the cross-passage in metro is the most widely used area of AGF method in municipal engineering [4].

Due to the complex boundary conditions and irregular layout of the freezing pipes, the consistency of the temperature field is one of the main difficulties in the construction of the cross-passage. At present, in addition to the classical calculation formula, the numerical solution is one of the important methods to solve the temperature field of the cross-passage in complex conditions to predict the frozen wall. Many scholars have carried out relevant computational research [5] [6]. However, in the above calculation, in order to simplify the calculation method, the temperature of segment is generally set as a constant temperature boundary or an adiabatic boundary, which makes it difficult to effectively simulate the temperature field in actual conditions.
In this paper, based on the measured data of cross-passage, the boundary conditions of heat dissipation of segment in the numerical calculation were redetermined through laboratory and in-suit tests, the freezing temperature field of the cross-passage was numerically calculated, and the optimization of the freezing design scheme and the effect of heat dissipation of the segment were analyzed by using the calculated results. The relevant results can effectively provide technical support for the design and construction of AGF method.

2. Numerical calculation

2.1. Project case

The numerical simulation case is analyzed based on the cross-passage in Guangzhou Rail Transit Line 7. The length of left and right lines of the shield tunnel of the cross-passage is ZDK-5-267.130 m and YDK-5-269.718 m, respectively, with the center distance being 12.0 m. The rail surface elevation of the left line is -20.477 m, and the rail surface elevation of the right line is -20.475 m. The overburden thickness of the contact passage is about 22.25 m. The arch roof is mainly silty soil and silty fine sand, the tunnel body is mainly medium coarse sand, and the horizontal passage lies under medium coarse sand, fully weathered argillaceous siltstone and strongly weathered argillaceous siltstone.

The cross-passage is located directly below Shunde Avenue. Military optical cable, gas, water supply, rainwater, electric power and communication pipelines are laid along the road. The main structures adjacent to the contact passage are 110KV high voltage tower (plane distance 46.1m) and Lintou Bridge (plane distance 43.8m). The contact passage is about 120m away from the East Tanzhou waterway.

The cross-passage has a total of 88 freezing pipes, which including 61 pipes in left line tunnels and 27 pipes in line tunnels. The total length is 629.937 m. At the same time, 5 rows of freezing pipes are laid along the segment in the opposite side of the tunnel. There are 12 temperature measuring holes, 2 on the left wire, 10 on the right wire. It has 2 pressure relief holes in each side of tunnel.

The active freezing time of the cross passage is 45 days, the lowest brine temperature is -28 °C, the effective thickness of the frozen wall is 2.0 m, the average temperature of the interface between the frozen wall and the tunnel segment on the freezing hole layout circle outside the excavation area is lower than -5 °C, and the average temperature of the frozen wall in other parts is less than -10 °C.

2.2. Model Buildings

In this research, the numerical calculation model was established for the whole cross-passage. In the calculation, the direction of the cross passage was set as the X-axis, the direction of the shield propulsion was set as the Y-axis, and the vertical direction was set as the Z-axis. According to the model size calculation formula proposed by Moller [7], the model size was finally set to 30×40×36.5m. And all sizes and angles of the freezing pipes were arranged according to the design data. The diameter of the
freezing tube was set to 89.0 mm. The calculation model was divided by tetrahedral mesh, and a total of 795323 grid units were set. The grid division and models were shown in figure 2.

![Calculation model and mesh generation](image)

Figure 2 Calculation model and mesh generation

2.3. Initial conditions and boundary conditions

The average temperature in the numerical calculation is 26.47℃ from the average value of the soil temperature measured before active freezing. The outer surface temperature of each freezing pipe was taken from the measured brine temperature. The temperature of the tunnel segment close to air was calculated by the average value of in-suit data. The temperature and time history curves of the two value was shown in figure.3.

![Time history curve of brine temperature and segment surface](image)

Figure 3 Time history curve of brine temperature and segment surface

2.4. Calculation Parameters

In order to determine the thermal physical parameters of unfrozen soil (18 ℃) and frozen soil (-10 ℃), undisturbed soil was taken for thermodynamic test, as shown in figure.4. In order to improve the calculation efficiency, thermophysical parameters only distinguish between frozen and unfrozen states. In the calculation, only the thermal physical parameters of the main formation where the contact passage is located are selected, and the calculated parameters are shown in Table 1. The freezing temperature of soil was measured by remolded soil, and the average freezing temperature of the four groups was -0.2 ℃.
Table 1: Calculation parameters of soil mass

| Soil                | Thermal conductivity W/(m•°C) | Specific heat capacity kJ/(kg•°C) | Density kg/m³ | Freezing temperature °C |
|---------------------|-------------------------------|----------------------------------|---------------|-------------------------|
| Unfrozen soil       | 1.21                          | 1.66                             | 1840          | -0.2                    |
| Frozen soil         | 1.41                          | 1.8                              |               |                         |

3. Result
The temperature field distribution in the active freezing process is shown in figure 5. With the gradual expansion of the temperature field during the freezing process, when the active freezing lasts for 20d, the freezing wall gradually presents a cross-ring state, and with the passage of time, the cross-ring is gradually completed and a frozen wall with a certain thickness is formed. At the end of active freezing, the freezing wall around the connecting passage and the collecting well is effectively formed, and it has obvious weakening in the area near the tunnel segment. The overall effect is basically consistent with the measured trend. Figure 6 shows the comparison between the measured wall thickness temperature and the numerical calculation results at 50d after active freezing.

As shown in the figure 6, the longitudinal distribution of soil along the connection passage obtained by numerical calculation is consistent with the decline trend of the measured data, with only a small error. It is concluded that the error is mainly due to the fact that the calculation parameters used in the numerical calculation are the test parameters of the remolded soil, which are different from the actual conditions. It can be seen from the above comparison that the accurate prediction of temperature field can be realized more effectively by adjusting the boundary conditions of numerical calculation.
4. Discussion

4.1. Evolution law of temperature field

As shown in figure 5, the freezing effect of the side wall, vault and bottom of the cross passage is greatly different. In order to compare the freezing effect of different positions more effectively, the average temperature within the freezing wall range of 2.0m of the three positions is extracted respectively, and the curve is plotted in figure 7. As shown in the figure, the average temperature of the three sections all showed a logarithmic decline during the active freezing process, which have a faster decline in the early stage and a slower decline in the later stage. The time of the average freezing temperature of three sections reaching the standard is $t_{Top} > t_{left} > t_{Down}$. This is mainly due to freezing at the top of the hole arrangement of intensive, group of freezing hole thermal interference effectively accelerate the decline of soil temperature and lateral and bottom area is relatively loose, so the average temperature drop is relatively slow. However, in the actual project, the excavation of the collection well is about 20d later than the excavation of the passage, so the premature reaching of the freezing wall at the bottom will cause the excessive freezing of the lower area, resulting in the waste of a large amount of cold.
4.2. Thickness of frozen wall in different section

In the construction of freezing method, the thickness of the frozen wall is the key technical index to measure the effect of freezing development. However, in actual engineering, only the thickness of the frozen wall at a certain position is often used to replace the average temperature of the whole frozen area, while the frozen wall caused by the heat dissipation of pipe fins is ignored. In order to verify the longitudinal attenuation of the frozen wall along the cross passage, the temperature curves of 0.25 m, 0.5 m, 1.0 m and 2.0 m section along the cross passage in 50 d of active freezing time were extracted, respectively. The results are shown in figure 8. The $X=1.0$ m position in the figure is the projected position of the freezing tube. As shown in the figure, the thickness of the frozen wall at 0.25 m behind the tube plate wall is about 1.3 m, and that at 0.5 m behind the tube plate wall is close to 2.0 m, while both 1.0 m and 2.0 m behind the tube plate wall are far beyond the designed thickness, indicating that it is difficult for the frozen wall on the side close to the tube plate to travel to the frozen wall with sufficient thickness and bearing capacity. This is also the main incentive for the excavation of a large number of cross passages to occur near the side of the cross passages.

By comparing the distribution of the freezing temperature fields of the four sections, it can be seen that the temperature field changes significantly within 1.0 m from the tube section, while the temperature field of the frozen wall changes slightly outside 1.0 m from the tube section. Therefore, it is determined that the 1.0 m range on both sides of the cross passage is the area seriously affected by the heat dissipation of the pipe fins, which is basically consistent with the previous research results. Therefore, in order to ensure the freezing effect, 0.5–1.0 m deep freezing hole should be constructed in the area close to the section of the pipe for strengthening freezing, so as to ensure the freezing effect.
4.3. refrigeration efficiency
The figure 9 shows the change curve of the heat flux on the outside surface of a freezing tube. As shown in the figure, the heat flux at the early stage of active freezing is at a relatively high stage, with good refrigeration effect. However, with the decrease of the temperature gradient around frozen soil, the heat flux shows an exponential decline. The green area in the figure is the stage when the temperature of saline continues to decrease. In this stage, the heat flux increases to a certain extent due to the change of temperature gradient, and the subsequent heat flux continues to decrease. This indicates that the initial freezing stage is the key to the refrigeration effect, and how to rapidly reduce the temperature of saline and increase the temperature gradient is the key to ensure the freezing effect.

![Figure 9 heat flux of freezing pipe](image)

5. Conclusion
(1) The design of boundary conditions in the numerical calculation of the cross passage can effectively improve the calculation accuracy. By comparing the measured data with the numerical calculation results, the calculation error can be controlled in ±1.0℃.

(2) The heat dissipation of the tube plate will significantly reduce the thickness of the frozen wall on the side close to the tube plate, and the calculation results show that the zone is greater than 1.0m thick.

(3) The top area of the contact passage is affected by the density of the freezing hole layout, and the freezing effect is the best. Excessive freezing often occurs. In order to ensure the freezing effect, the freezing hole layout and hole spacing in the top area should be adjusted appropriately.

(4) The initial freezing stage of the cross passage is the highest freezing refrigeration efficiency stage, so the temperature of brine should be reduced rapidly to improve the freezing effect.

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