Study on development characteristics of horizontal freezing temperature field in subway connecting passage

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Abstract: The freezing method is often used in underground excavation projects with high requirements for water stop and support. However, with the increasing complexity of the project, the freezing form is becoming more and more complex, and it is difficult to calculate the temperature field law by theoretical analysis. As a powerful simulation method, numerical calculation can be used to simulate the development of temperature field in complex horizontal freezing engineering. Based on the horizontal freezing construction of a subway connecting passage, this paper analyzes the development characteristics of horizontal freezing temperature field, and the results are in good agreement with the measured data. It is proved that the numerical simulation method can be used to simulate this kind of project, and the results can be used to guide the design and construction of related projects.

1. Introduction
In the process of artificial freezing of soil, the development characteristics of its temperature field are affected by different arrangement modes and soil parameters, and the most important concern in engineering is the characteristics of temperature field changing with time. The essence of soil freezing is the process that the free water in soil becomes solid below freezing point. Therefore, the freezing temperature field is a dynamic problem with cold source, boundary heat conduction and material phase transition. The freezing cold front is moving, during which the free water becomes solid and forms a horizontal freezing curtain. Microscopically, the freezing process is accompanied by phase change, water migration, phase change of bound water in soil, air and other factors, and its solution is very difficult. Especially, the size of the phase change zone is difficult to determine, which brings challenges to solving the temperature field.

The research on the development characteristics of soil temperature field has lasted for more than 150 years, and the early research tends to solve its analytical solution. Finally, the statistical method is introduced, and the simple temperature field distribution can be solved after empirical correction. At the end of the 19th century, Russian professional institutions carried out a lot of research on frozen soil, mainly from the theoretical calculation of thermophysics, thermodynamics, soil hydrothermal
improvement and so on. With the development of computer and numerical method, it is possible to solve the complex temperature field distribution and accelerate the development of artificial frozen soil. For example, the complex boundary and nonlinear temperature field in frozen soil calculation have been well solved, which greatly promotes the research and development of frozen soil. In addition, when countries near the Arctic actively exploit local natural resources, it is inevitable to solve the frozen soil problem. For example, Denmark, the United States and Canada have invested a lot of manpower and material resources to study frozen soil, which has greatly developed frozen soil science. Fasana A and Bonaicina C (1973) not only got the numerical solution of one-dimensional nonlinear temperature field, but also made in-depth research on related fields of temperature field.

The freezing process of soil is extremely long and complex. Engineering designers are concerned about the development characteristics of freezing temperature field, and construction workers are concerned about what technical means can be used to meet the design requirements. Therefore, under complex geological conditions, it is necessary to study the development characteristics of soil temperature field in detail to solve practical engineering problems.

2. Frost heave temperature field model

2.1 geometric model
The subway connecting passage is located in a complex location with many strata, which is affected by the structure and layout. The model adopts a three-dimensional model, and the soil is 50m, 25m and 40m in the length, width and height directions respectively.

![Image](image_url)

(a) Three views of freezing pipe position

(b) Horizontal and sectional drawing of freezing pipe layout

Fig. 1 Layout of soil and freezing pipe

When freezing pipes are laid out by artificial freezing method, the layout form is complicated in order to meet the requirements. In addition, in finite element calculation, the grid at the freezing pipe should be dense. In order to achieve the above purpose, firstly, the grid at the freezing pipe is arranged, and then the grid is scanned and other parts of the grid are subdivided.
2.2 calculation parameters

According to the statistics of meteorological bureau and geological data, combined with field test and indoor test data, the parameters required for numerical simulation calculation are shown in Table 1:

| Temperature(℃) | Thermal conductivity(W/m²·℃) | Specific heat(J/kg·℃) | Density(kg/m³) |
|----------------|-----------------------------|-----------------------|----------------|
| -10            | 2.22                        | 1022                  | 1840           |
| -2             | 2.1                         | 1080                  | 1883           |
| -1             | 1.54                        | 1330                  | 1320           |
| 10             | 1.44                        | 1453                  | 1364           |

In the finite element calculation, the change of thermophysical parameters with temperature is considered, such as specific heat, thermal conductivity and density. Moreover, the latent heat of phase change of soil can be considered. The top of the model represents the earth's surface, and the inside of the tunnel is air. The constant temperature is set at 18℃. The specific parameters are shown in Table 2:

| Name                                      | Value            |
|-------------------------------------------|------------------|
| Latent heat of phase change(J/m³)         | 1.07e8           |
| Solid phase temperature(℃)                | -2               |
| Liquid phase temperature(℃)               | -1               |
| Thermal conductivity coefficient(m²/s)    | 5.7e-7           |
| The soil shows a heat dissipation coefficient(W/m²·℃) | 8.16             |
| Heat dissipation coefficient of tunnel inner surface(W/m²·℃) | 2               |
| Tianjin annual average temperature(℃)    | 13               |
| Average temperature in tunnel(℃)          | 18               |
| Average underground temperature(℃)        | 15               |

3. calculation results

According to the layout of freezing pipes provided by design data, and the freezing liquid is cold brine, the freezing time when the specified freezing requirements are met is calculated, and the thickness and strength of the frozen curtain are measured on site. It is required in the design data that the thickness of the freezing wall is 1.7~2m and the average degree of freezing wall is -10℃. As shown in fig. 4, point 1, where the freezing pipe is located, is the design center position of the freezing wall, taking it as the center, with an interval of 0.25m, and taking 10 temperature characteristic points. The formula for
calculating the temperature of the freezing wall is as follows:

\[ T_{\text{average}} = \frac{T_1 + T_2 + T_3 + \Lambda + T_N}{N} \]  

(1)

Is the temperature value of each temperature extraction point, and \( n \) is the number of temperature extraction points.

Fig. 3 Temperature field in soil before freezing

Before the freezing pipe begins to freeze, it is necessary to calculate the temperature field of the original stratum. According to the above boundary conditions, the local temperature field of the tunnel air, formation heat flow and surface air in the natural state is calculated as shown in the figure.

Fig. 4 Calculate the temperature extraction point of the average thickness of the frozen curtain

The time-temperature curve of each characteristic point in fig. 4 is plotted as shown in fig. 5.
When the freezing curtain is 1.5m, 1.75m, 2m and 2.25m respectively, and the average dimension in the frozen soil wall is -10℃, the freezing time table is shown in Table 3.

Table 3. Calculation data of design freezing thickness and required freezing time.

| Design Freezing Thickness (M) | Freezing Time (Days) |
|------------------------------|----------------------|
| 1.5                          | 23.45                |
| 1.75                         | 34.21                |
| 2                            | 37.22                |
| 2.25                         | 33.49                |

Figure 6 compares the measured data with the numerical simulation data. It can be seen from the comparison that the changes of the two data are very consistent during active freezing, which shows that the finite element model has good reliability and can provide effective guidance for construction.

4. Conclusion

In this paper, nonlinear finite element method is used to study the development characteristics of horizontal freezing temperature field in subway connecting passage. Unsteady temperature field when
thermophysical parameters change with temperature is considered in the simulation. The simulation results show that the temperature field obtained by numerical simulation is in good agreement with the measured temperature field during active freezing, which verifies the validity and reliability of finite element simulation.

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