Research on development law of horizontal freezing temperature field of complex curtain

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Abstract. Artificial freezing method has been widely used in various underground projects, but the development law of freezing temperature field of complex curtain is difficult to be calculated by analytical method. As a general method, numerical method is feasible to simulate the development law of horizontal freezing temperature field of complex curtain. In this paper, the development law of temperature field in the freezing process is analyzed based on the freezing method construction of a subway connecting passage. The feasibility of this method is verified by comparing with the measured data. The results can be used to guide the design and construction of artificial freezing.

1. Introduction
Freezing temperature field is to study the change rule of soil temperature around freezing pipe with time in the process of soil freezing. In the process of soil freezing, water changes from liquid to solid and releases heat in the process of phase change. Therefore, the temperature field of soil freezing is an unstable heat conduction problem with heat source, boundary movement and phase change. The boundary between solid phase and liquid phase is moving [1]. The liquid phase changes into a solid phase during the movement, even if the frozen soil curtain is formed. In the process of soil freezing, there is not only a phase change phenomenon, but also water migration, forming a four-phase body consisting of crystal ice, unfrozen water, soil particles and gas. Considering these factors, it is actively difficult to solve the temperature field. The frozen phase transition zone of soil is always changing and its size cannot be determined, but it is still part of the final solution temperature field [2].

Scholars have studied the temperature field of frozen soil for more than a century and a half. By the early 20th century, their exploration is still at an early stage. At the beginning of the research on frozen temperature field, the analytical solution was solved, then the statistical method and empirical method were adopted, and now the numerical method has been turned to solve [3-4]. At the end of the 19th century, Russia set up a special organization to study frozen soil. The organization did a lot of research on frozen soil. The main research areas include thermo physics, thermodynamics, soil hydrothermal improvement, and analytical solutions of theoretical calculations. Subsequently, the combination of computer technology and numerical methods promoted the accelerated development of frozen soil field. There are many complicated geometric shapes and high nonlinearity in frozen soil problems, but
they have been well solved, and frozen soil research has developed deeper and wider. CyMrHHM.H, founder of thermo physics and temperature field theory, laid a solid foundation for frozen soil and made many outstanding contributions [4-6].

Some regions and countries in Western Europe and North America have developed research on freezing temperature field and related fields due to the need to develop local natural resources[7]. With the development of computer science and other technologies, the development of frozen soil science has been greatly accelerated. Fasana and Bonaicina not only obtained the numerical solution of one-dimensional nonlinear temperature field, but also conducted in-depth research on related fields of temperature field [8-9].

Freezing of soil is a long and complicated process. Designers are concerned about the change law of soil temperature field in freezing process. Engineering circles are concerned about what technical construction methods can be adopted to ensure the construction meets the design requirements. In view of these problems, the following is a study and analysis of the temperature field law of soil to solve the above problems.

2. Frost heaving temperature field model

2.1. Geometric Model

The selection of soil model size, combined with the engineering practice, the diameter of subway tunnel and the distribution of freezing pipes, takes 50m, 25m and 40m respectively in the three directions of length, width and height, in the Figure 1.

Due to the need to arrange freezing pipes, for the convenience of calculation, the positions of freezing pipes are divided here first, and then the seeds are distributed. In order to reasonably divide the grid, the model is simply divided, then the seeds are continuously distributed, and the soil around the subway tunnel is roughly meshed, while the soil in the distance is structurally meshed.

Figure 1. Layout of soil and freezing pipe.
2.2. *Calculation Parameters*

According to indoor tests, field tests, Tianjin Meteorological Bureau and relevant geological data, the calculation parameters used for finite element 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 this model, the thermal conductivity, specific heat and density are considered to change with temperature. In addition, the finite element software ABAQUS also needs to give the latent heat of phase change, solid phase temperature and liquid phase temperature of the excavated body. In this model, the latent heat of soil phase change is 1.07e8J/m³, the solid phase temperature is -2℃ and the liquid phase temperature is -1℃. The arrangement is 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     |

2.3. *Boundary Conditions*

Since the surface of the soil and the inside of the tunnel need to be in contact with air, it is also necessary to set the thermal conductivity coefficient around the soil and the constant temperature at the bottom boundary of the soil. The numerical values are shown in Table 2.

3. *Calculation results*

The purpose of finite element analysis is to provide a reference for designers and constructors. Designers need to consider the layout of freezing pipes and the temperature of cold source to
determine the freezing time and calculate the thickness and strength of frozen soil curtain according to relevant parameters. The design requires the thickness of the frozen curtain to be 1.7m-2m and the average temperature to be -10℃. When the thickness of the frozen curtain meets the design requirements, the time needed is the freezing time. As shown in Figure 3, 3~4 take 10 points with point 1 as the center and 0.25m to both sides as the spacing. The average temperature of the frozen curtain is calculated according to the following formula 1

\[ T_{\text{avg}} = \frac{T_1 + T_2 + T_3 + \cdots + T_N}{N} \]  

Where, \( T_n \) is the temperature value of each temperature extraction point, and \( N \) is the number of temperature extraction points.

According to the design requirements, the average temperature of the frozen curtain is -10℃, and the freezing time when the frozen curtain is 1.5m, 1.75m, 2m and 2.25m is calculated respectively.

Figure 3 is a temperature depogram when the soil is in thermal equilibrium with the air in the tunnel under natural conditions due to surface temperature and underground heat flow before freezing construction. In this state, the freezing construction starts, and the freezing temperature is -25℃.

Point 1 in Figure 4 is located at the freezing pipe, with equal spacing of 0.25m between points 1 and 11. Select the temperature change value from point 1 to point 10 with time, and plot the curve as follows.
The design freezing thickness and required freezing time are arranged as shown in table 3 below.

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                |

It has been determined that when the design freezing thickness is 1.75m, the freezing time is 34.21 days, that is, the active freezing period is 34.21 days.

As can be seen from Figure 6, in the 50 days before freezing, that is, in the active freezing period, the finite element calculation results are in agreement with the measured data, which shows that the model is reliable and can guide the actual construction.
4. Conclusion
In this paper, a large-scale nonlinear finite element software Abaqus is used to simulate the temperature field of soil in subway connecting passage construction by artificial freezing method. The variation of temperature field with time during horizontal artificial freezing construction of subway connecting passage is studied. The simulation results of temperature field during soil freezing are very close to the measured results, which can provide reference for design and construction.

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