Research on the development law of temperature field in horizontal freezing and melting of complex curtain

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Abstract. Artificial freezing method has been widely used in various underground projects, but the development law of melting 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 of temperature field in horizontal melting of complex curtain. Based on the freezing construction of a subway connecting passage, this paper analyzes the law of temperature field development in the melting process, and proves the feasibility of this method by comparing with the measured data. The results can be used to guide the design and construction of artificial freezing.

1. Introduction
For more than 100 years since the subway was built, many construction methods have been adopted for the inter-section connecting passage due to lack of geological and construction requirements. However, artificial freezing method is widely used for its good sealing property, high strength, strong adaptability, no pollution, super controllability and practicability. Especially in Shanghai, Guangzhou, Tianjin and other coastal cities, artificial freezing method sometimes becomes the only feasible construction method under complex ground[1]. However, as an effective temporary reinforcement measure for subway connecting passage construction, artificial freezing method also brings about some negative effects, especially ground deformation when frozen soil melts and settles[2]. If the control is not reasonable, uneven settlement of roads or ground buildings may be caused. At present, the most important method for thawing settlement of frozen soil is tracking grouting. However, since tracking grouting has not been solved in theory, the grouting parameters lack theoretical basis and accurate calculation, and are determined by experience. Therefore, the economic and engineering effects are not ideal. The temperature field reflects the temperature distribution of all points in space at a moment in the frozen wall[3]. Because the temperature of each point in the frozen wall space is not only different, but also changes with time. Strictly speaking, it is an unstable temperature field.

The thawing settlement of frozen soil is due to the heat accumulation in frozen soil, which reduces the mechanical properties of frozen soil and leads to the thawing settlement deformation of soil. It seriously affects the service quality and service life of pavement. How to solve the freeze-thaw damage of soil has attracted great attention from researchers at home and abroad. American scholar,
studied the thawing of frozen soil under the condition of linear increase of ground temperature. Feng-Tian Y’s solution uses equivalent ground temperature to give credible results for the total freezing and thawing depth, but the prediction error for the intermediate process is large[4-5]. Tai proposed the analytical solution and compared it with Niu Man’s solution[6-7]. It was pointed out that when the Stephen number increases, the melting zone increases nonlinearly with time[8]. Japanese scholar designed and developed a set of triaxial freeze-thaw test device using laser sensors to monitor lateral deformation. On this basis, expansion and contraction deformation during freezing process under different stress conditions were studied, and instantaneous deformation process was observed.

In this paper, the melting temperature field of frozen soil in a bypass freezing project in Tianjin is simulated, and the melting law of frozen soil is summarized, which provides the basis for the later grouting treatment and has no important guiding significance for the study of thawing settlement treatment.

2. Finite element 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, the grid is shown in figure 1.

![Figure 1. Finite element mesh.](image)

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.
Table 2. Parameters.

| Name                                           | Value     |
|------------------------------------------------|-----------|
| Latent heat of phase change(J/ m$^3$)           | 1.07e8    |
| Solid phase temperature(℃)                     | -2        |
| Liquid phase temperature(℃)                    | -1        |
| Thermal conductivity coefficient(m$^2$/s)       | 5.7e-7    |
| The soil shows a heat dissipation coefficient(W/m$^2$·℃) | 8.16    |
| Heat dissipation coefficient of tunnel inner surface(W/m$^2$·℃) | 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. The melting temperature field needs to be carried out according to the construction conditions. According to the parameters shown in Table 2, the freezing pipe temperature is set to -25℃ and frozen for 50 days. The obtained temperature field is shown in Figure 2. This temperature field is the initial temperature field calculated by melting temperature field. When calculating the melting temperature field, the temperature of the freezing pipe should be removed. In this way, the melting process of frozen soil under natural conditions can be simulated.

3. **Calculation results**

The temperature field in soil varies non-linearly with time and space, so it is difficult to use theoretical calculation. The numerical model has strong adaptability. Part of the temperature field nephogram is shown in figure 3.
According to the analysis of the temperature field in figure 3, during the melting process, the temperature of the soil inside the freezing curtain is in the overall warming phase, but it does not melt completely at once, but starts to melt from both sides of the tunnel. The temperatures of points 1 and 2 in figure 3(c) are extracted and plotted in figure 4 as follows.

From the curve in figure 4, it can be seen that the soil near the subway tunnel melts faster than the soil inside, and there is also a phase change phase during the heating process, which is consistent with the actual situation. And the soil at the connecting passage has nearly melted. It can be known from the temperature change at point 2 that the soil at point 2 has melted at 60 days. Due to the construction of the connecting passage, there is no soil at point 2 in figure 3(c), which further indicates that the melting is basically over at 60.

The thawing temperature of the connecting channel changes nonlinearly with time, and the thawing period is about 2 months. At the initial stage of thawing, the temperature of the connecting passage rises rapidly, but it does not melt directly, but hovers around the phase change temperature. After the temperature is completely melted, the temperature continues to rise, and the frozen soil around the subway tunnel thaws rapidly.
4. Conclusion
Based on the simulation of frozen soil thawing temperature field in subway connecting passage freezing construction, the distribution law of frozen soil thawing temperature field in subway connecting passage is preliminarily obtained, which provides a reference for later treatment. According to the melting cycle, melting speed and melting position of frozen soil, guidance is provided for adopting appropriate treatment measures and parameters. In this paper, the melting temperature field simulated by numerical method is partially simplified. In the actual construction process, the measured temperature field results are also needed as the construction basis.

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