Study on temporal and spatial variation of temperature field in horizontal freezing and thawing settlement

Changyi Yu1,2,3,4, Mingyue Lu5*

1 CCCC-Tianjin Port Engineering Institute, Ltd., Tianjin 300222, China
2 CCCC First Harbor Engineering Company, Ltd., Tianjin 300461, China
3 Key Laboratory of Geotechnical Engineering, Ministry of Communications, Tianjin 300222, China
4 Key Laboratory of Geotechnical Engineering of Tianjin, Tianjin 300222, China
5Tianjin Survey And Design Institute For Water Transport Engineering, Tianjin 300000 , China

*Corresponding author’s e-mail: 874801845@qq.com

Abstract. Artificial freezing method is commonly used in underground engineering excavation, such as mine, foundation pit and subway. The problem of post-construction thaw settlement has attracted more and more attention, but it is difficult to calculate the development law of thaw temperature field of complex frozen curtain by analytical method. Therefore, this paper adopts numerical method to study this problem. In this paper, taking the horizontal freezing construction of a subway connecting passage as an example, the development law of temperature field in the melting process is analyzed, and the results are basically consistent with the measured data. As a general means, numerical simulation is feasible to simulate the development law of temperature field in horizontal melting of complex curtain. The results of this paper can be used to guide the design and construction of artificial freezing.

1. Introduction

In the construction of subway section, the connecting channel plays the role of connecting the left and right lines with the pumping and drainage of tunnel section. The construction unit needs to adopt advanced and effective construction techniques in the construction process according to various factors such as geological conditions, underground hydrological conditions and rock stability to ensure the safety and quality of subway tunnel construction[1]. Freezing method is a special construction technology, which uses artificial refrigeration technology to freeze the water in the stratum, change the natural rock and soil into frozen soil, increase its strength and stability, and isolate the connection between groundwater and underground engineering, so that the shaft or underground engineering can be excavated under the protection of freezing wall. Its advantages are[2]: 1. Good safety and reliability, which can effectively isolate groundwater; 2. Wide adaptability. Applicable to any loose rock and soil layer with a certain amount of water, freezing technology under complex hydrogeological conditions such as soft soil, unstable soil layer with water, flowing sand, high water pressure and high ground pressure; 3. Good flexibility. The shape and expansion range of the frozen body can be controlled artificially, and the underground obstacles can be bypassed for freezing when necessary; 4. Good
controllability. The frozen reinforced soil is uniform and complete; 5. Less pollution. The "green" construction method accords with the development trend of environmental geotechnical engineering[3]. It is widely used in coastal water-rich areas. However, as a temporary support measure, improper use will also bring negative effects. Especially in the melting process, the ground is deformed.

If the control is unreasonable, it may cause adverse effects such as settlement, inclination and local inclination of the building[4-5]. Tracking grouting can be used to control thaw settlement, but there is no good theoretical formula to calculate the thaw settlement by grouting, and the applicability of traditional theoretical formula is limited, which cannot guide the engineering construction well. The temperature field of artificial frozen soil thaw settlement changes with the change of space and time, which is an unsteady temperature field.

The internal mechanism of thawing settlement is that the microstructure of soil changes under temperature load and gravity load, which leads to the change of mechanical properties. The melting and settlement characteristics of soil and the change of microstructure during melting are the main influencing factors of tracking grouting. Therefore, the study of the melting and settlement characteristics and microstructure of soil is of great significance to the control of melting and settlement and the improvement of grouting technology. At present, the consensus is that only when the water content of soil exceeds the initial water content of thawing settlement will it thaw; When the initial water content of thawing settlement is exceeded, the coefficient of thawing settlement increases with the increase of water content. Ponomarev et al. studied the compressibility of medium dense sand during thawing, and suggested that saturation should be taken as the thawing index, and the smaller the permeability coefficient of the overlying soil layer, the smaller the compressibility of the soil layer during thawing. Crory, Frederick E[6] conducted a one-dimensional thaw settlement test under load, and the results showed that the thaw settlement coefficient increased with the increase of load, and the uneven settlement of soil was taken into account. Alike, Bernard D[7] conducted a one-dimensional thaw settlement test of soil, and tested the vertical and horizontal stress and pore water pressure of soil during thawing. Compared with the three-dimensional thaw settlement test of soil, it was found that vertical stress was the most important factor affecting thaw settlement. It is pointed out that the elastic modulus and Poisson's ratio of soil will also be taken into account in the process of thawing settlement. Foriero and Sally Shoop[8] are based on the finite deformation consolidation theory, respectively, and the D-P plastic hardening model is used to numerically analyze the melting law of melting soil.

In this paper, the thaw settlement temperature field of a subway connecting passage after horizontal freezing is simulated, and the law of thaw settlement temperature field of frozen soil is summarized, which provides reference for grouting range and grouting construction in the later period. The results of this paper provide strong support for thaw settlement treatment.

2. Finite element model

2.1. Geometric Model

The dimensions of the three-dimensional model of thaw settlement soil are taken as 50m, 25m and 40m in length, width and height, respectively, and hexahedron grid is used as shown in Figure 1.
2.2. Calculation Parameters

According to indoor test, field test, investigation of meteorological bureau and regional geological data, the thermodynamic parameters required for finite element simulation are shown in Table 1.

Table 1. Soil thermo physical parameters.

| 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            |

The curves of thermal conductivity, specific heat and density changing with temperature are determined by experiments, and the thermophysical parameters are controlled by temperature in simulation. Besides, the latent heat of phase change, solid phase temperature and liquid phase temperature calculated by the finite element software need to be given. In this model, the latent heat of phase change of soil is $1.07e8$ J/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/ 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

This model is the temperature field of melting and sinking after horizontal freezing of subway connecting passage, in which both the surface and the interior are constant. And the horizontal direction is affected by the earth heat flow, so it is necessary to set the corresponding thermal conductivity coefficient. The bottom is at a fixed temperature under the influence of geothermal flow,
and the specific values are shown in Table 2. The melting temperature field needs to be determined after the active freezing period of construction. According to the parameters shown in Table 2, the freezing pipe temperature is set at -25°C and the active freezing period is 50 days. The obtained temperature field is shown in Figure 2, and the temperature field at this time is the initial temperature field calculated by the melting temperature field. When calculating the temperature field of thawing settlement, the freezing pipe has not been frozen, so the freezing boundary has changed, that is, the thawing settlement process of frozen soil under the influence of multiple boundary conditions in the natural state.

Figure 2. Initial temperature field of melting.

3. Calculation results
When melting, the temperature field in soil presents nonlinear changes with time and space, and the theoretical assumptions are difficult to meet the complex nonlinear conditions, which makes the calculated results deviate greatly from the actual ones. However, the numerical model has strong adaptability and can consider the nonlinear changes of multiple boundaries and material parameters. The nephogram of partial melting temperature field after calculation is shown in Figure 3.
Figure 3. Diagram of melting temperature field.

Figure 3 shows the temperature field of soil layer at different time points. When the soil layer melts, the whole soil near the connecting channel is in the heating stage, but the melting rate is not the same. Due to the influence of air convection in the subway, the soil near the subway tunnel melts faster and the inside melts slower. Extract the temperatures of points 1 and 2 in fig. 3(c) and draw the following figure 4.

Figure 4. Change of melting temperature at two points with time.

Figure 4 shows the temperature variation curves of different points in the stratum with time, with point 1 near the subway tunnel segment and point 2 near the center of the subway connecting passage. During the temperature rise of frozen soil, there is also a phase change, which leads to the soil temperature not rising in some periods. And the temperature at point 1 rises faster than that at point 2, so the melting of soil depends on the temperature at point 2. It can be seen from the curve that the soil has melted at point 2 after melting for 60 days. When the subway connecting passage is frozen horizontally, its melting temperature field changes nonlinearly, and the melting cycle of this example is about 60 days. In addition, the temperature rises rapidly at the initial stage of melting, and after the phase transition temperature, the temperature continues to rise, and the frozen soil around the subway tunnel segment is thawed rapidly.

4. Conclusion
By simulating the frozen soil thawing temperature field after the horizontal freezing construction of a subway connecting passage, it is preliminarily concluded that the frozen soil thawing temperature field distribution of the subway connecting passage changes nonlinearly with time and space, and the thawing period is about 60 days, which provides a reference time node for later treatment. At the beginning of thawing, the frozen soil rises rapidly, and after the phase transition temperature, the
temperature continues to rise, and the frozen soil around the subway tunnel segment thaws rapidly. According to the melting cycle, rate, spatial distribution and other laws, it can provide the basis for the control measures and parameters. The results of this paper are obtained through simplified model simulation. In actual construction, it is necessary to arrange temperature measurement points to correct this model according to the results of this paper, so as to provide optimization basis for construction design.

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