Study on temporal and spatial distribution law of thaw settlement displacement by horizontal freezing method

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Abstract. After freezing construction, the damage caused by thawing settlement mainly comes from the displacement and settlement of strata, which leads to uneven settlement of underground pipelines and surface buildings in the project area. In this paper, based on the three-dimensional finite element analysis, the settlement displacement field of artificial frozen soil in a subway connecting passage is analyzed, and the parameters such as elastic modulus, density and specific heat change with temperature are considered in the model. The change of mechanical parameters in the soil layer is given by the temperature field, which makes the mechanical parameters of each point in the soil layer different. In addition, the temperature field of the soil layer changes with time, and finally makes the mechanical parameters change point by point, so as to ensure that the simulated melting and settlement calculation process is more in line with the actual working conditions. The calculation results of settlement displacement show that the settlement displacement field of soil layer changes nonlinearly with time and space. The research results of this paper provide reference for the position and time node of the control measures of thawing settlement.

1. Introduction
Melting soil, which is in the process of temperature rise below 0°C and the ice crystals gradually decrease. For the positive melting soil, there is a moving boundary problem of freeze-thaw interface. At present, there are many researches on melted soil, and most of the researches on melted soil are frozen first and then melted, and the comprehensive action of water supplement state and actual traffic load cannot be considered in the freezing process. High-temperature frozen soil refers to frozen soil that is greater than 1°C but less than but close to zero or freezing point[1]. Melting settlement of natural frozen soil is the most common disease in subgrade engineering in seasonal frozen soil area, and it is not uncommon for roads to frost heave, frost boil and collapse caused by melting consolidation of artificial frozen soil. It is of great significance to study its generation mechanism, influencing factors and development law for controlling the melting and sinking and ensuring the safety of engineering construction [2].
Experimental and theoretical studies on the phenomenon of soil melting and sinking have been carried out for more than half a century [3]. Melting and sinking research can be divided into basic research and applied research, and the basic research focuses on the manifestation and mechanism of melting and sinking; Applied research mainly studies the prediction model of thaw settlement and the measures to prevent thaw settlement. As early as 1930s, Tsytovich[4] worked out the test method of frozen soil melting and compression, and developed a special thermal insulation compression instrument by himself, which studied the compaction process of the same soil under load at normal temperature and after melting. Then Tsytovich et al.[5] studied the calculation method of the total melting settlement of frozen soil with different soils. After that, Dubina[6] put forward a mathematical model of melting and sinking of stress, strain, temperature and humidity fields in frozen soil structure and soil system. In the model, the influence of thermophysical parameters on the evolution of stress-strain state is explained by the content of pore ice, which is determined by the temperature, type and salt content of soil. At the same time, Russian scholars formulated the compression test method when frozen soil melts, which is a compaction process without lateral expansion and uniform load, and developed a special thermal insulation compression instrument, which can ensure that the top of frozen soil sample melts in parallel plane with time through the heat of heater with filter bottom plate, and can apply an external load of 0.7~0.8Mpa during the experiment[7]. The self-developed instrument is used to study the compaction process of the same kind of soil under normal temperature and freeze-thaw action[8].

In this paper, the three-dimensional thermo-mechanical coupling finite element is used to simulate the thaw settlement displacement field of a subway connecting passage. Because of the strong adaptability of the finite element numerical simulation, the simulation can comprehensively consider multiple boundary conditions.

2. Theory

The melting and consolidation calculation of frozen soil is essentially a typical thermal, mechanical and fluid coupling calculation [11], that is, thermal calculation is carried out in the whole calculation area, and consolidation calculation is carried out in the melting area at the same time. In thermal calculation, considering the influence of latent heat of ice-water phase transition of frozen soil on its specific heat capacity, it is necessary to use heat conduction considering ice-water phase transition.

\[
\begin{align*}
-h_{li} + h_v &= \rho c \frac{dT}{dt} \\
\lambda \frac{\partial T}{\partial t} &= -h_v
\end{align*}
\]

Where: T is temperature, °C; \( h_v \) is the volume heat source, W/m³; C is considering ice water phase Variable specific heat capacity, J/kg°C; \( \lambda \) is the thermal conductivity considering ice-water phase transition, W/m°C; \( r \) is medium density, kg/m³; t is time, S.

According to the thermal calculation of formula (1), the thermal state of the calculated area can be obtained. According to the thermal state, the consolidation theory is used to describe the mechanical behavior of soil skeleton and fluid in the melted area.

3. Finite Element Model

Stress and displacement analysis is required, and the eight-node hexahedron 3D Stress element type should be adopted, as shown in Figure 1.
3.1. Model Parameters

The calculation of frost heave displacement does not involve damage, and the soil and tunnel lining structure are mainly simulated by elastic model, and the unit type is C3D8. The values of finite element simulation calculation parameters are shown in Table 1 below.

Table 1. Constitutive parameters for frost heave calculation.

| Temperature (°C) | Density (kg/m³) | Modulus (Pa) | Poisson's ratio | Expansion coefficient (m/K) |
|------------------|-----------------|--------------|-----------------|-----------------------------|
| -10              | 1840            | 1.3E+08      | 0.25            | -0.033                      |
| -2               | 1883            | 1.05E+08     | 0.28            | -0.021                      |
| -1               | 1320            | 20000000     | 0.32            | -0.002                      |
| 10               | 1364            | 3320000      | 0.34            | 0                           |

Because the settlement displacement calculation is a static problem, it is necessary to set the displacement boundary. The bottom of the soil is restrained in three directions, and the side of the soil and both ends of the subway tunnel are restrained in normal directions, so as to avoid the influence of boundary on the stratum stress when in-situ stress is balanced.

The grid of the melting settlement finite element model is similar to that of the frost heave model, and the initial temperature field of the melting temperature field needs to be imported into the model as the initial temperature boundary and the final temperature field boundary, as shown in Figure 2(a) and the melting termination temperature field as shown in Figure 2(b).
4. Calculation results
The finite element analysis results as follows:

![Figure 3. Melt displacement vector diagram.](image)

![Figure 4. Schematic diagram of the directional path.](image)

![Figure 5. Vertical path displacement diagram.](image)

It can be known from the curve in fig. 5 that due to the constraint of the freezing wall itself, the settlement displacement inside the communication channel is small, that is, the displacement of the soil after the settlement of the excavated communication channel is very small. The settlement displacement is the largest outside the freezing curtain of the horizontal connecting channel.

![Figure 6. Path chart along the tunnel direction.](image)

![Figure 7. Displacement along the tunnel direction.](image)
By analyzing the curves in Figures 7 and 9, it can be known that the maximum land surface subsidence is located just above the center of the connecting channel. With the distance from the center, the range of subsidence is expanding, but the displacement of subsidence is also decreasing.

5. Conclusion
The process of soil melting is accompanied by soil settlement and changes the stress field in the original state of the soil. When there are buildings around the freezing construction and the maximum displacement of soil thawing settlement is limited, it is necessary to control the thawing settlement range and amount of soil thawing settlement to ensure that the freezing construction will not have destructive influence on the surroundings after it is completed. The problem of thaw settlement displacement is a thermal stress problem. A three-dimensional model is adopted to simulate the thaw settlement displacement field of the connecting channel. The displacement field is highly nonlinear with the change of spatial position and time. The numerical simulation method has high universality and wide adaptability. The results can provide basis for taking measures to control melting and settling.

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