Study on the influence law of complex curtain horizontal freezing and freezing on the surrounding environment

Changyi Yu¹,²,³,⁴ *

¹CCCC-Tianjin Port Engineering Institute, Co. Ltd., Tianjin 300222, China
²CCCC First Harbor Engineering Company, Co. Ltd., Tianjin 300461, China
³Key Laboratory of Geotechnical Engineering, Ministry of Communications, Tianjin 300222, China
⁴Key Laboratory of Geotechnical Engineering of Tianjin, Tianjin 300222, China
*Corresponding author’s e-mail: yu_longone@163.com

Abstract. Freezing up is one of the problems that are paid close attention to in the construction of artificial freezing method, especially the horizontal freezing up of complex curtain is difficult to be calculated by theoretical formula. The adaptability of numerical calculation is strong. In this paper, numerical calculation method is used to simulate the horizontal freezing and freezing expansion of complex curtain. Thermophysical parameters considered in the simulation change with the change of temperature field. Thermodynamic parameters of each point in soil are given by way of field variables, which provides ideas and methods for accurately simulating the horizontal freezing and freezing expansion displacement field of complex curtain.

1. Introduction
More than 200 years ago, the phenomenon of frost heaving attracted people's attention, but it has been recognized that the main factor affecting the frost heaving of soil is the time of water migration for only half a century. In the 1960s, Everett[1] put forward the first frost heaving theory, which elaborated the frost heaving mechanism in detail and estimated the value of frost heaving force. However, the disadvantage of this theory is that it does not explain how discontinuous lens bodies are formed in ice after water freezes. After that, Miller[2] put forward the second frost heaving theory based on Everett's work. The theory first assumes that when freezing, there is an east interface in the frozen material, that is, there is a special area between the freezing front and the ground of the warmest ice lens, which has water content, low thermal conductivity and no frost heaving. Ma Wei and An Weidong et al. put forward a saturated thawing consolidation model of foundation soil, which takes into account the coupling effects of water pressure and water and soil. In addition, the frost heaving condition of one-dimensional coupled hydro-thermal three-field is numerically simulated.

Jessberger H L[3] used centrifuge tests and numerical simulation to study the changes of temperature field and displacement field of the cylinder wall when the freezing method was used to drill the cylinder. The results show that the numerical simulation is in good agreement with the experiment. Satoshi Akagawa[4] established the frost heaving control theory, and used the modified test equipment to determine the location of the freezing surface and further determine the freezing thickness by irradiating the freezing test with x-ray in a preset pressure environment. Mutoye and
Watanabe K[5] observed the microstructure of the freezing front under the condition of keeping the temperature constant, and found that the larger the freezing thickness, the greater the growth rate of the ice lens. Black[6] Through laboratory tests, it is found that the flow of unfrozen water in the frozen rim also conforms to Darcy’s law. Yoshiki Miyata[7] of Japan put forward the macro frost heaving theory, which is based on the moisture transfer theory, the heat transfer theory and the mechanical energy balance equation. Talamucci[8] proposed a mathematical model of frost heaving in porous media, which also believed that frost heaving of soil was caused by water migration, but the water migration was the result of coupling effect of chemical potential and pressure gradient.

In this paper, a three-dimensional model is adopted, and field variables are directly used to endow soil with thermo-physical parameters by using the results of previous temperature field.

2. Numerical model
The frost heaving displacement finite element model is shown in figure 1. The grid can be divided by adopting the grid form of the temperature field model, which requires stress and displacement analysis, so the heat conduction element cannot be adopted, and the 3D Stress element type should be adopted.

![Finite element model](image)

**Figure 1. Finite element model.**

2.1. Model Parameters
The frost heaving displacement model is mainly simulated by elastic model, and the element type is C3D8. The required calculation parameters and values are shown in Table 1 below.

| 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                        |

2.2. Boundary Conditions
The boundary conditions are the complete constraint on the bottom, the constraint on the corresponding directions on the four sides, and the complete constraint on the subway tunnel. The initial temperature field of soil is the temperature field at the beginning of freezing, and the end temperature field is the temperature field at the end of freezing, as shown in figure 2.
3. Calculation results
Frost heaving should be taken into account in the construction of freezing method for connecting passages. Frost heaving will affect the deformation of surface buildings and subway tunnels. The finite element analysis results for these two problems are as follows:

- Figure 2. Temperature field after frost heaving.
- Figure 3. Schematic diagram of vertical path displacement in the middle of tunnel.
- Figure 4. Vertical displacement curve in the middle of tunnel.
- Figure 5. Displacement vector diagram of middle vertical section of tunnel.
From the graph 4 and figure 7, it can be seen that in the freezing process, the soil displacement inside the freezing curtain is small, and the soil displacement outside the freezing curtain increases first and then decreases with the distance from the freezing curtain.

As can be seen from figs. 9 and 11, on the surface of the frozen area, the displacement directly above the frozen area is the largest, and the displacement away from the area directly above the frozen area is smaller and smaller. The freezing temperature in this area is -25 degrees, the maximum value of the frozen expansion coefficient is 3.4%, and the affected area is more than 45m along the frozen pipe direction and more than 25m along the tunnel direction.
As can be seen from figure 12, the results of finite element simulation of frost heaving are in agreement with the measured data, which shows that the finite element simulation method in this paper is reliable and can provide reference for design, predict and predict the engineering construction and guide the actual construction.

4. Conclusion
During the freezing process of the soil, the expansion of the soil will change the stress field in the original state of the soil. When there are buildings around the freezing construction and there are restrictions on the maximum frost heave displacement of the soil, it is necessary to control the frost heave range and the frost heave amount of the soil to ensure that the freezing construction will not have destructive effects on the surroundings. Frost heaving displacement is a thermal stress problem. A three-dimensional model is adopted to simulate the frost heaving 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 simulation results can provide a reference for the same type of projects, and also provide a basis for adopting freezing measures.

References
[1] Everett D H. (1961) The thermodynamics of frost damage to porous solids. Trans.Faraday Soc, 57: 1541-1551.
[2] Miller R D. (1972) Freezing and heaving of saturated and unsaturated soils. Highway Research Record, (393): 1-11.
[3] Jessberger H L. (1989) Opening address. In Jones and Holden, eds. Ground Freezing 88, Proceedings of 5th International Symposium on Ground Freezing. Rotterdam Balkema A.A, 407-411.
[4] Satoshi Akagawa. (1988) Experimental study of frozen fringe characteristics. Cold Region Science and Technology, 15: 209-220.
[5] Muto Y, Watanabe K, Ishizaki T, Mizoguchi M. (1998) Microscopic observation of ice lensing and frost heaves in glass beads. Lewkowicz A G Allard M. The 7th International Permafrost Conference. Canada: Laval University, 783-787.
[6] Black P. B. and Miller, R.D., (1990) Hydraulic conductivity and unfrozen water content of air-free frozen soil, Water Resource Research, 26: 323-329.
[7] Miyata Y. (1997) A macroscopic frost heave theory coupling equations and criteria for creation of new ice lens. Ground Freezing, Netherlands: Lulea University of Technology.
[8] F. Talamucci. (2003) Freezing processes in porous media, Formation of ice lenses, swelling of the soil. Mathematical and Computer Modeling, Volume 37, Issues 5-6, March 595-602.