NUMERICAL SIMULATION OF THE TEMPERATURE FIELDS IN THE SHIELDING WALLS OF FROZEN SOIL WITH MULTI-CIRCLE-PIPE FREEZING IN SHAFT SINKING

by

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In this study, the temperature fields of frozen soil wall were calculated by using numerical method, and were analyzed after the soil was actively frozen with different freezing time. The results showed that the temperature field evolved from the freezing pipes, and then formed into frozen soil cylinders. After a certain freezing duration, the cylinders of frozen soil began to connect, and frozen soil walls started to form. At initial freezing stage, the thickness of frozen soil wall was mainly determined by the freezing pipes of the inner two circles. Then, connections were found to have occurred between the inner and outer frozen soil walls. Finally, the temperature fields of the unfrozen and frozen soils reached a state of stability. The results also showed that it was feasible to use numerical method to simulate the temperature fields of frozen soil walls during shaft sinking process, and potentially provided important references for the design and construction of deep alluvium shaft.

Keywords**:** *Frozen soil, temperature field, shaft , heat transfer*

Introduction

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The artificial ground freezing method is an important construction technique which changes the pore water into ice to improve the combination of soil particles by using the refrigeration system and provide protection from the seepage of groundwater. It is not limited by the soil materials and the depth of working stratum. The frozen soil wall can be formed any shape in engineering application. This method has the advantages of adaptability of stratum, high cohesive strength of soil particle, low environmental influence, and high water-sealing performance. The artificial freezing method was first developed in Germany by Poetsch (1883), and has been widely used in many geotechnical engineering applications, such as excavation support, pollution control, and groundwater cutoff [1-4]. Compared with other groundwater cutoff and excavation support techniques, the artificial freezing method has minimal effects on the subsidence disturbances of ground surfaces and adjacent buildings [5-7].

Frozen soil wall can be formed by installing freezing pipes in the ground, and then extracting heat from the soil surrounding the pipes by circulation of a cooling liquid. The freezing pipes in the soil are usually connected in parallel series. The cooling liquid is pumped into the frozen zone, and circulates in the freezing pipes when it is cooled again [1, 8]. It is essential to design a proper freezing scheme to ensure the safety of engineering practice. The strength and thickness of frozen soil wall are related to the distribution of temperature field. The temperature field is usually used to assess the feasibility of the proposed freezing scheme. The research on the temperature fields of frozen soil wall in shaft sinking process is a key issue in the development of artificial freezing engineering. Many researches regarding the temperature fields of artificial freezing engineering have been performed [9-13].

The applications of the artificial ground freezing method become more and more common in geotechnical engineering. There remains a need to study the temperature fields of deep alluvium shaft due to the diversities of geology environment and mechanical properties of soil materials. In this study, we take a mine shaft project of Yancon as the research object. The mine shaft had been proposed to be constructed by using artificial freezing method. The analysis of temperature field by using numerical method is performed for the artificial freezing engineering. The results can provide important references for the design and construction of the deep alluvium shafts.

The governing differential equations

The calculation of the temperature fields for frozen soil wall is a nonlinear problem related to heat transference and the phase change. The soil can be classified into frozen and unfrozen states controlled by temperature. The unified governing partial differential equation of heat conduction for temperature $T(x, y, z, t)$ can be expressed as follows [14-16]:

$$C^* \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) \tag{1}$$

where C^* represents the equivalent heat capacity; and k is the equivalent thermal conductivity.

To be convenient for calculation, the process of phase change can be defined within a temperature interval ($T_d \le T \le T_r$) based on the method of sensible heat capacity. The equivalent heat capacity and equivalent heat conductivity can be determined according to Eqs.(2) and (3), respectively, and the effect of the temperature intervals of phase change has been considered. The equations can be expressed as follows [17, 18]:

$$C^* = \begin{cases} C_f & (T < T_d) \\ \dfrac{C_f + C_u}{2} + \dfrac{L}{T_r - T_d} & (T_d \le T \le T_r) \\ C_u & (T > T_r) \end{cases} \quad (2)$$

$$k = \begin{cases} k_f & (T < T_d) \\ k_f + \dfrac{k_u - k_f}{T_r - T_d}(T - T_d) & (T_d \le T \le T_r) \\ k_u & (T > T_r) \end{cases} \quad (3)$$

where C_f is the heat capacity of frozen soil, C_u is the heat capacity of unfrozen soil, L represents the latent heat of soil material, T_r is the upper limit temperature of the phase change, T_d is the low limit temperature of the phase change, k_f represents the thermal conductivity of frozen soil, and k_u is the thermal conductivity of unfrozen soil.

The initial temperature field and remote boundary condition of the model can be determined by the ground temperature, and can be expressed as follows:

$$T(x, y, z, t_0) = T_0 \quad (4)$$

$$T(x, y, z)\big|_{\rho=\rho_0} = T_c \quad (5)$$

The boundary condition surrounding freezing pipe can be regarded as a constant temperature, and is given as

$$T(x, y, z)\big|_{r=r_0} = T_s \quad (6)$$

where T_s is the temperature of freezing pipe.

The finite element formula of the temperature field is given by the following equation:

$$[M]\left\{\frac{\partial T}{\partial t}\right\} + [K]\{T\} = \{F\} \quad (7)$$

where

$$M_{ij} = \sum \int_{\Omega^e} C^* N_i N_j d\Omega \quad (8)$$

$$K_{ij} = \sum \int_{\Omega^e} k \left(\frac{\partial N_i}{\partial x} \cdot \frac{\partial N_j}{\partial x} + \frac{\partial N_i}{\partial y} \cdot \frac{\partial N_j}{\partial y} + \frac{\partial N_i}{\partial z} \cdot \frac{\partial N_j}{\partial z} \right) d\Omega \quad (9)$$

Eqs.(1)~(9) represent the governing differential equations, the initial and boundary conditions of the temperature field in the artificial ground freezing shaft.

The project background and numerical model

The design requirement of the freezing schemes is to ensure that the thickness and strength of frozen soil wall are thick and strong enough to effectively protect working place from the seepage of groundwater, and have the ability to resist deformation caused by the excavation in construction process. In this study, a mining shaft of Yancon is chosen as a computational model to analyze the distribution and evolution characteristics of temperature fields. The depth of the alluvium reaches more than 500 m. Due to high ground pressure, there are many difficulties during the construction process. The artificial freezing method is used to reduce the construction influences on the excavation operations of shaft lining construction and ensure the effectiveness of water-sealing during the engineering construction. The numerical method is a convenient and accurate method to solve the problem.

In this study, the shaft with different freezing durations is taken as the study object to analyze the evolution of temperature field. For simplification purpose, the model can be simplified as a plane heat conduction problem to compute the temperature field according to the freezing scheme presented previously, as shown in Figure 1.

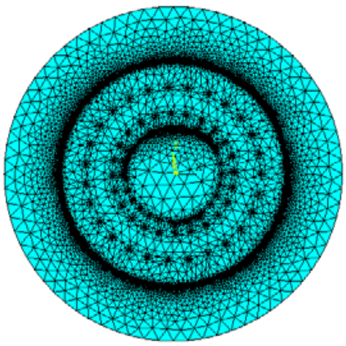
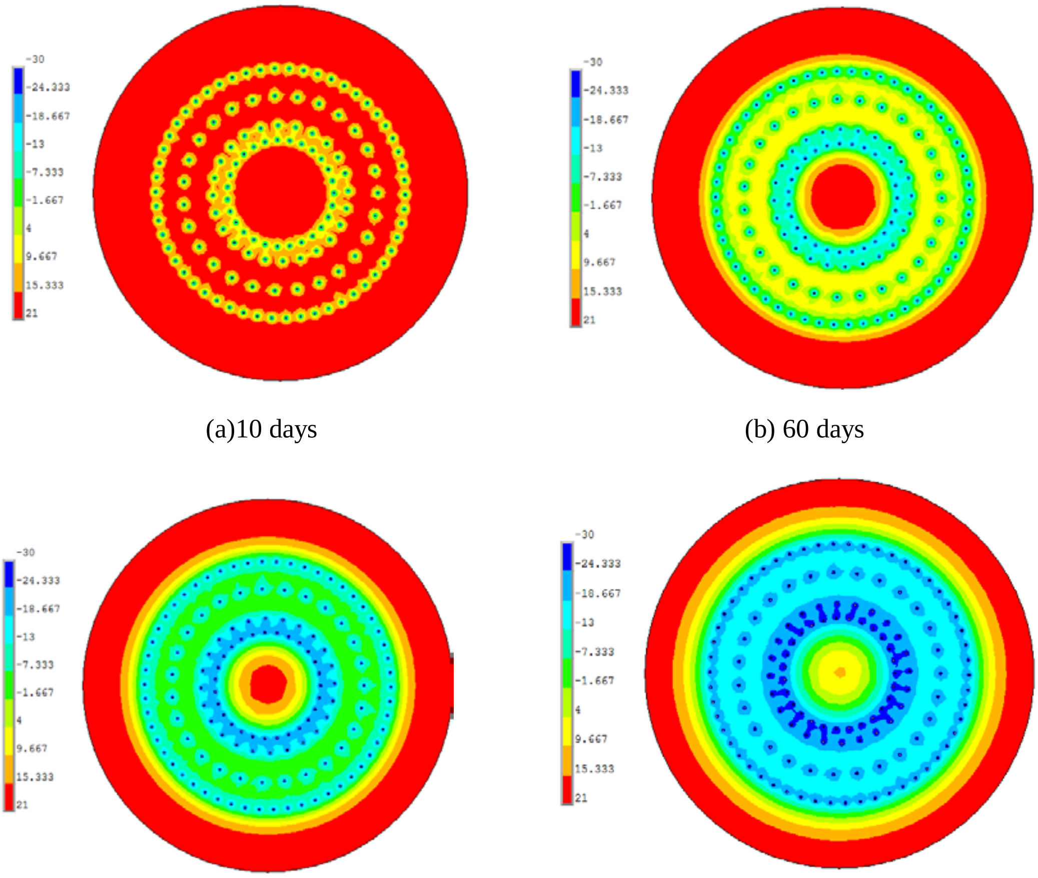


Figure 1. Computational model of the freezing shaft

The brine temperature is a constant temperature of -30°C. The remote ground boundary is set as a constant temperature of 21°C, which is also regarded as initial ground temperature. According to the practical project experience, the heat transfer coefficient is 1.32 W/(m·K) for the unfrozen soil, and 1.69 W/(m·K) for the frozen soil. The heat capacity is 1,840 J/ (kg ·°C) for the unfrozen soil, and 1,600 J/ (kg ·°C) for the frozen soil. The latent heat of soil material is 6.0×10^6 J/ m^3.

Results and analyses

The evolution characteristics of temperature fields with different freezing durations are analyzed to obtain the freezing process. The temperature fields with freezing time of 10, 60, 120, and 240 days are illustrated in Figure 2 (*a* ~ *d*), respectively.



(a)10 days (b) 60 days

(c) 120 days (d) 240 days

Figure 2. Temperature fields of the frozen soil wall after different freezing durations

It is observed that the temperature fields of frozen soil wall evolve from each freezing pipe; then frozen cylinders of soil form surrounding the freezing pipes. With the increase of freezing time, the frozen cylinders begin to connect. A closed frozen soil wall is observed to have formed after the freezing process has continued for 60 days. With the further increase in freezing time, the average temperature of the frozen soil wall continues to decrease. Also, the thickness of the wall continues to increase as further connections of frozen cylinders are made. Temperature distributions with different freezing times along the radius of mining shaft are shown in Figures 3 and 4. It can be seen that the frozen soil wall is initially formed between the inner two circles of freezing pipes; then, the thickness of frozen soil wall increases with the increase of freezing time. The temperature of the external wall of frozen soil gradually decreases due to the ground heating conduction from outside of frozen soil wall after freezing 180days. The temperature of inner wall rapidly decreases due to the lack of heating supply from the ground.

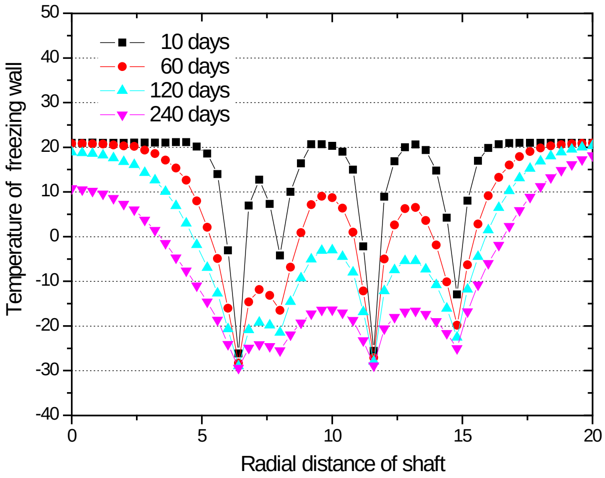


Figure 3. Temperature distributions along a radius from the center of shaft

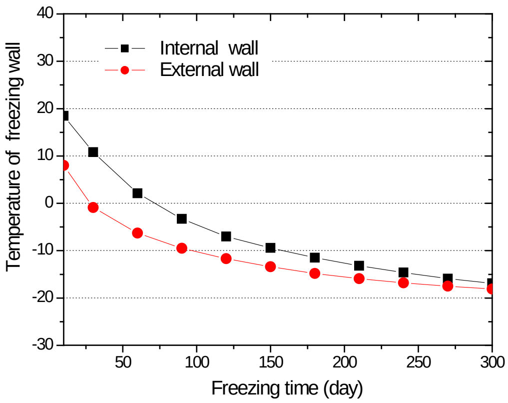


Figure 4. The temperature evolution characteristics of frozen soil wall

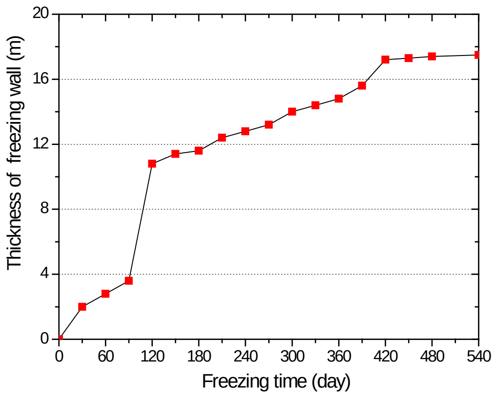


Figure 5. The thickness of frozen soil wall versus freezing time

The evolution process of the thickness of the frozen soil wall is shown in Figure 5. It can be seen that the thickness of the frozen soil wall is significantly affected by the freezing time. During the initial freezing stage, the frozen cylinders surrounding freezing pipes of inner two circles are observed to influence each other. The increase of freezing time results in the formation of a closed frozen soil wall, and the growth of thickness following the closure of frozen soil wall. The thickness of the frozen soil wall is mainly affected by the inner two circles of freezing pipes. It is also observed that, with the further increases of freezing time, the connections of frozen soil walls between the inner and outer circles of freezing pipes occur. The thickness of frozen soil wall increases to about 17.7m. The temperature fields of unfrozen and frozen soils reach an approximate equilibrium state.

Conclusions

In this study, the artificial freezing process of shaft is simulated by numerical method, and the temperature field of frozen soil wall is analyzed. At the initial freezing stage, the decrease rate of soil temperature surrounding freezing pipes is found to be rapid; and then gradually decreases with the further increase in freezing time. The temperature in the center of mining shaft is observed to have slowly decreased during the initial freezing stage; and then rapidly decreases with the further increase in freezing time. It is found to take approximately 60 days for a minimum thickness of frozen soil wall to form, and the thickness is about 2.8m. The temperatures of the inner and outer frozen soil wall are approximately 2.1°C and -6.3°C, respectively. When freezing time reaches 240 days, the temperatures of the inner and outer frozen soil wall have decreased to -14.6°C and -16.8°C, respectively.

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Nomenclature

x, y, z —coordinate axis, [m]
C —heat capacity, [J/ (kg ·°C)]
M, K —matrices, [–]
T —temperature, [°C]
k —thermal conductivity, [W/(m·K)]
t —time, [s]

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