Numerical Simulation and Experimental Research of the Temperature Field around a Single Freezing Pipe

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Abstract: Based on the boundless line heat model, the temperature field model has been built around a single frozen pipe, and its analytical solution has been provided. Owing to the experiment on a single frozen pipe, its change of temperature law has been achieved. In addition, compared with the time of freezing the frontal edge calculated by the analytical solution of the temperature field around a single frozen pipe, the phase change time calculated by the analytical solution is faster than the measured time but the gap between them is not great, which proves that the analytical calculation has significantly simulated the temperature field around a single frozen pipe..

Keywords: freezing pipe; temperature field; phase change of thermal conduction; freezing experiment.

1. Introduction

The freezing method refers to making use of the technique of artificial refrigeration to cool soil by force. The water in the soil is frozen into ice and forms frozen soil, which improves soil strength and stability and forms a water-proof curtain. It cuts off the relation between groundwater and construction space and makes it easier to construct with this special technique in underground engineering. In fact, the freezing method temporarily improves the prosperity of the soil and rock to reinforce the ground based on this freezing technique[1][2][3]. When the artificial freezing method is applied in the designing and construction process, the freezing temperature field and the freezing range of frozen pipe needs to be assured. The freezing temperature field has the problem of unstable heat conduction due to its phase change, moving boundaries, internal heat sources and complicated boundary conditions[4]. However, because many factors influence the freezing temperature field of the frozen wall, its research is not sufficient at present which leads to an uncertain freezing range. Therefore, the design and construction of the frozen wall relies mainly on experience. The research of the temperature field around a single frozen pipe is the basis to that of the temperature field around multi-pipe or multi-row pipe freezing. According to the boundless line heat model, this paper made analytical calculation and experimental research on the phase change of temperature field around a single freezing pipe.

2. Phase Change of Thermal Conduction Model

Because the frozen pipe's axial size is bigger than its radial size, the axial heat conduction is weaker than the radial one. Therefore, the temperature field around a single frozen pipe can be simplified as a horizontal freezing and heat conduction problem with phase a change of thermal conduction. The phase change interface divides the solution field into two: a non-frozen field and a frozen field[5][6], its analytical model is shown in Figure 1.

The persistent boundless line heat model is shown in Figure 2. The absorption per unit length is q (w/m) whose line heat sink is turned into a liquid which is full of boundless space. Its original temperature is in average agreement as T_0, and $T_0>T_m$, in which Tm is the phase change temperature. Starting from the time t=0, the heat sink constantly absorbs heat, which makes the liquid set. The setting process starts from R=0, and gradually extends to the positive direction of R. The phase change interface between solid and liquid is the cylindrical surface of axial symmetry.

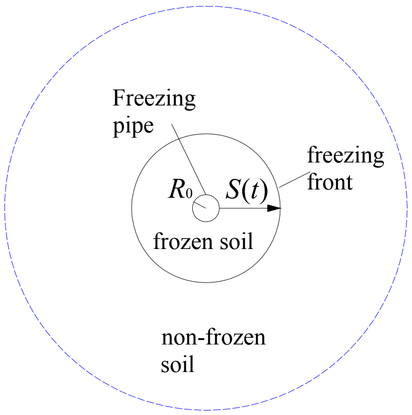


Figure 1 Analytical model

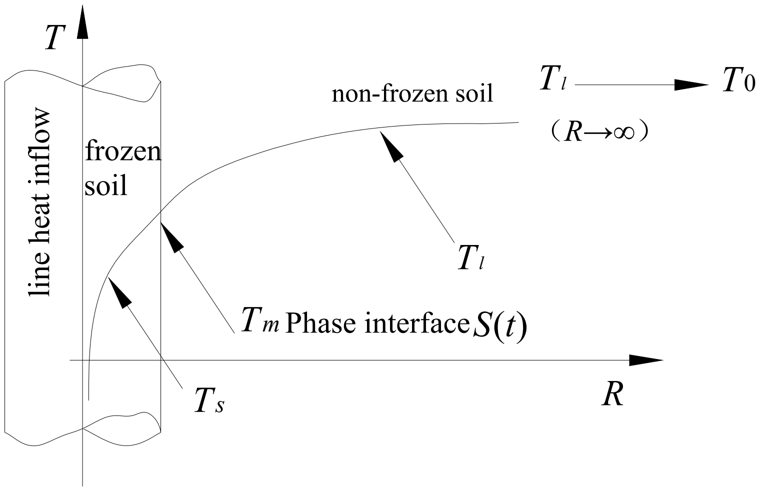


Figure 2 The persistent, boundless line heat model of the frozen soil mass

The differential equation of non-frozen soil mass in the right of phase change interface is shown as follows.

$$\frac{1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial T_l}{\partial R}\right)=\frac{1}{a_l}\frac{\partial T_l}{\partial t}, \; S(t)<R<\infty, t>0 \qquad (1)$$

In the above equation, T_l is the temperature of the non-frozen soil mass, and its unit is ºC; a_l is thermal diffusivity of non-frozen soil mass, $a=\frac{\lambda}{\rho c}$, and its unit is m^2/s; ρ is soil mass density, and its unit is kg/m^3; c is specific heat capacity, its unit is J/ (kg•K); λ is thermal conductivity, its unit is W/ (m•K).

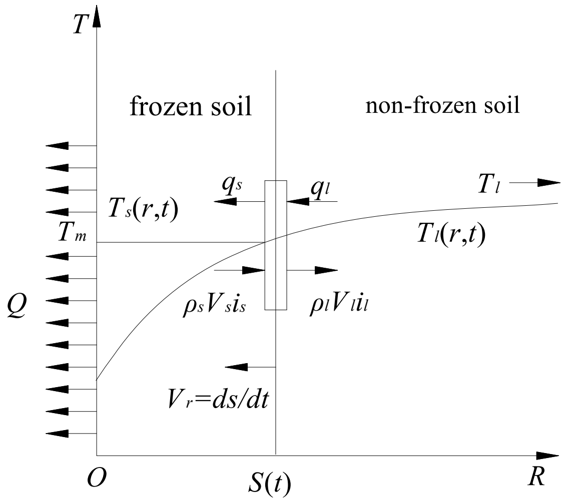


Figure 3 Phase change of thermal conduction in the freezing process

The differential equation of the non-frozen soil mass in the left is shown as follows.

$$\frac{1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial T_s}{\partial R}\right)=\frac{1}{a_s}\frac{\partial T_s}{\partial t}\ ,\ R_0<R<S(t),t>0 \tag{2}$$

In this equation, T_s is the temperature of the frozen soil mass, and its unit is ºC; a_s is the thermal diffusivity of the frozen soil mass, and its unit is m^2/s;

The boundary single value condition is when $R\to\infty$, $T_l\to T_0$; when $t=0$, $T_l=T_0$ (original temperature); on the phase change interface, when $R=s(t)$, $T_l=T_m=T_s$.

The phase change process is shown in Figure 3. According to the equation (1) and (2), the following equation can be achieved.

$$\lambda_s\frac{\partial T_s}{\partial R}-\lambda_l\frac{\partial T_l}{\partial R}=\rho\gamma\frac{ds(t)}{dt} \tag{3}$$

In the above equation, λ_s and λ_l are respectively the thermal conductivity of the frozen soil mass and that of the non-frozen soil mass, whose unit is W/(m•K); γ is phase change (freezing) latent heat, whose unit is J/kg; when $R\to R_0$, the energy balance relation should be met as the following equation shows.

$$\lim_{R\to R_0}\left(2\pi R\lambda_s\frac{\partial T_s}{\partial R}\right)=q \tag{4}$$

Based on the deduction, the location expression of the frozen frontal edge is shown as follows.

$$\frac{q}{4\pi}e^{-\delta^2}+\frac{\lambda_l(T_0-T_m)}{E_i\left(-\delta^2\frac{a_s}{a_l}\right)}e^{-\frac{a_s}{a_i}\delta^2}=\delta^2a_s\rho\gamma \tag{5}$$

In this equation, T_0 is the original average temperature of the frozen soil mass, which is 10ºC; T_m is the phase change temperature of the frozen soil mass, which is T_m=0ºC.

Because $-E_i(-s)=\int_s^\infty\frac{e^{-t}}{t}dt$, it can be assumed that $t=u^2$, $dt=2udu$, and

$$\int_s^\infty\frac{e^{-t}}{t}du=2\int_{\sqrt{s}}^\infty\frac{e^{-u^2}}{u}du \tag{6}$$

Therefore, the equation can be deduced as follows.

$$-E_i(-s)=2\Omega\left(\sqrt{s}\right) \tag{7}$$

In the above equation, because

$$\Omega(p)=\int_p^\infty\frac{e^{-u^2}}{u}du\ , \tag{8}$$

a new equation can be achieved thus

$$f(\delta)=\frac{q}{4\pi}e^{-\delta^2}+\frac{\lambda_l(T_0-T_m)}{E_i\left(-\delta^2\frac{a_s}{a_l}\right)}e^{-\frac{a_s}{a_l}\delta^2}-\delta^2a_s\rho\gamma=0\,. \tag{9}$$

When the equation（8）is substituted in equation（9）, the equation of the frozen frontal edge can be extracted as follows.

$$f(\delta)=\frac{q}{4\pi}e^{-\delta^2}+\frac{\lambda_l(T_0-T_m)}{2\Omega\left(\delta\sqrt{\frac{a_s}{a_l}}\right)}e^{-\frac{a_s}{a_l}\delta^2}-\delta^2a_s\rho\gamma=0 \tag{10}$$

According to $\delta=\frac{s(t)}{2\sqrt{a_st}}$, the location of the frozen frontal edge can be attained as follows.

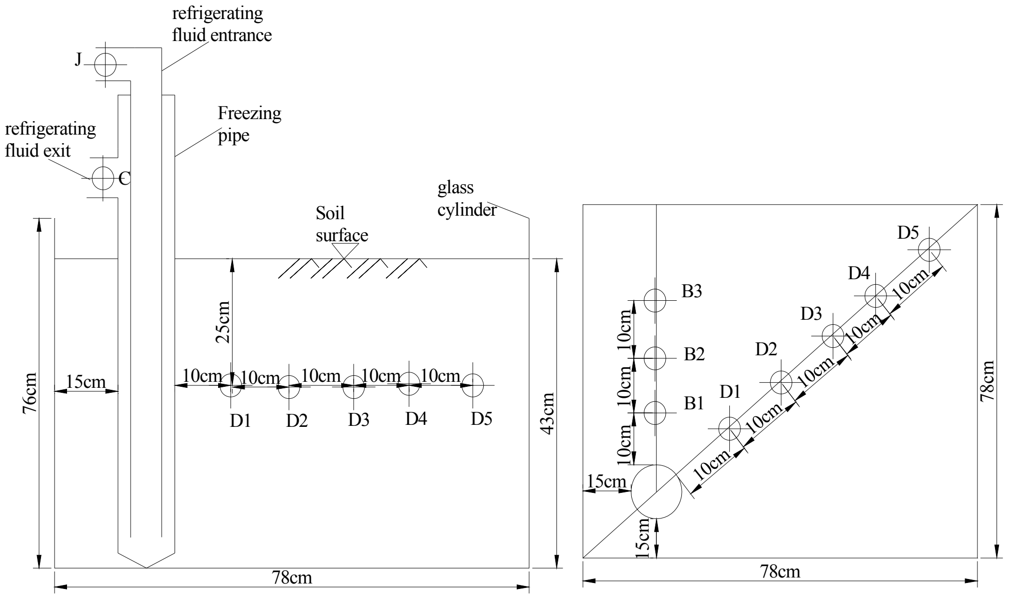
$$s(t)=2\delta\sqrt{a_st} \tag{11}$$

3. Experimental research with a single frozen pipe

3.1. Experimental plan

As shown in Figure 4, there is a sealing glass groove (size: length × width × height = 780mm × 780mm × 760mm) which is full of silted clay to be frozen. Inserting frozen pipes into the groove, the LT-60A2 low temperature refrigeration unit is made use of to cool and freeze the soil mass. A temperature sensor is buried in the soil mass which measures the temperature change in the freezing process. The burying of the temperature sensor is shown in Figure 5. The inlet and outlet pipes for the refrigeration fluid are set respectively at the points for measuring temperature, bearing the letters J and C. Near the frozen pipes and along the diagonal direction of the glass groove are five points set for measuring temperatures, these being D1, D2, D3, D4, D5. The temperature data is collected by the GPRS temperature collection system.

Figure 4 Experiment with **a single frozen pipe**



Profile of diagonal direction

vertical view

Figure 5 Layout of Temperature Sensor

The soil mass used for measuring is silted clay located 2.5~3m beneath the ground in the campus of Changchun Engineering College which is the typical soil mass in the ground for Changchun. The thermo-physical property of silted clay is shown in Table 1.

Table 1 The Thermo-physical Property of Silted Clay

ρ/g•cm^{-3}	ω(moisture content) /%	λ_l/W/(m•K)	λ_s/W/(m•K)	c_s/kcal/(kg•K)	c_l/kcal/(kg•K)
1.93	23.15	1.023	1.233	0.33	0.2

3.2. Experimental Result

The experimental refrigeration unit controlling the refrigeration fluid is set at -25ºC, which means the inlet temperature of refrigeration fluid is -25ºC. The change of inlet and outlet temperatures is shown in Figure 6, from which it can be seen that the starting temperature of refrigeration fluid is 10.56ºC. After seven hours, the temperature of refrigeration fluid approaches the controlled temperature, where it reaches -24ºC when the refrigeration enters the frozen pipe and it is -21.5ºC when leaving. The temperature gap between entering and leaving the frozen pipes is -2.5ºC.

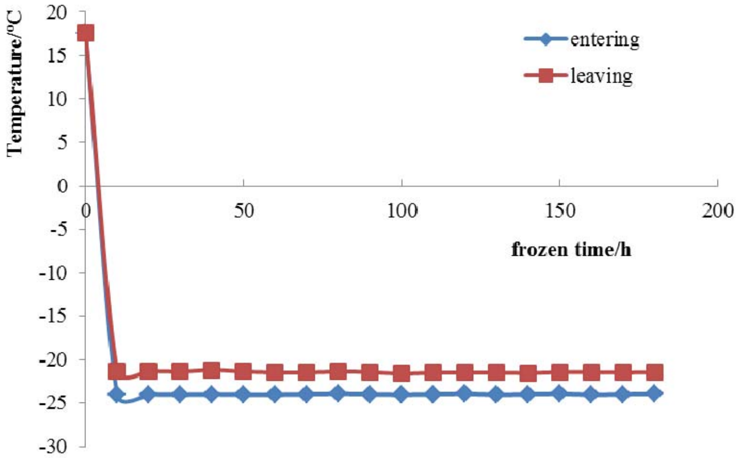


Figure 6 The temperatures of the refrigeration fluid entering and leaving the frozen pipes

As the freezing time increases, the freezing range gradually increases. According to the above experimental conditions and the equations（10） and（11）, the time needed to freeze to s(t), different locations, can be revealed.

The temperature sensor monitors the temperature change of the soil mass. The time for which the points from D1 to D5 respectively reach phase change, can also be monitored from each point.

Figure 7 shows the curve from D1 to D5 changes when the freezing time becomes different. The original soil mass temperature is about 10.1ºC, and the time of which the mass reaches the freezing point increases when the freezing distances becomes longer. After the mass is frozen, its temperature will be lowered to a certain subzero one. Even if the freezing time extends, the mass temperature will keep still at a certain subzero one. For example, when the freezing time of D1, whose freezing distance is 10cm, reaches over 140h, its mass temperature will decrease significantly, and then basically stay still between -12.13ºC and -12.68ºC.

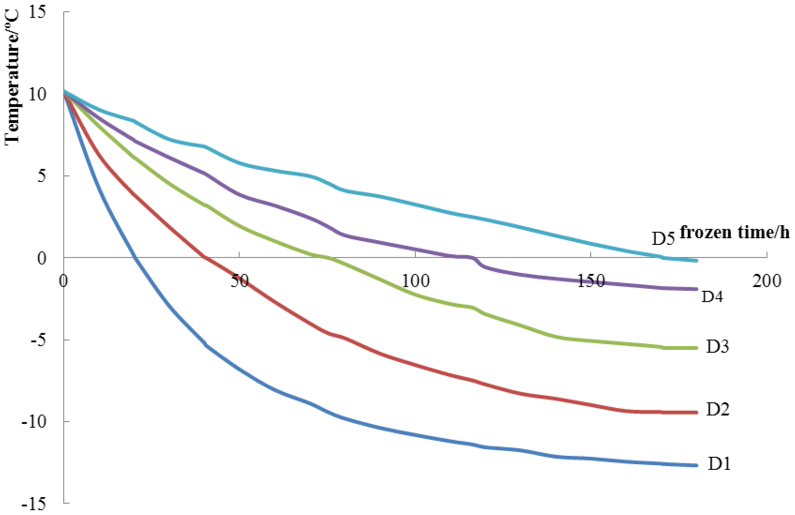


Figure 7 The curve of measured temperature about D1~D5 monitoring points with freezing time increasing

The measured time and the time calculated by analytical solution, of which the points from D1 to D5 respectively go across the single freezing temperature field, are shown in Figure 8. From this figure, it can be seen that as the freezing field expands, the time to reach freezing phase change becomes longer. Within the same freezing distance, if the time calculated by analytical solution is shorter, the freezing range becomes bigger, and also the gap between calculation time and measured time becomes bigger. Seeing from the radius of freezing frontal edge from 10 to 50cm, the gap is within 15~28h. There are three reasons why this phenomenon happens.

(1) Based on monitoring the temperature of refrigeration fluid entering and leaving the frozen pipes, the fact can be seen that it needs 7h changing from the original temperature 10.56ºC to the stable refrigeration temperature of -24ºC. During this process, though the soil mass is partially frozen, the temperature of the refrigeration fluid does not reach the set experimental temperature. However, the set temperature theoretically calculated, is an ideal one for entering and leaving and the freezing time of the refrigeration fluid is not considered. Therefore, the time reaching the frozen frontal edge is longer in the practical freezing process than in the theoretical calculation.

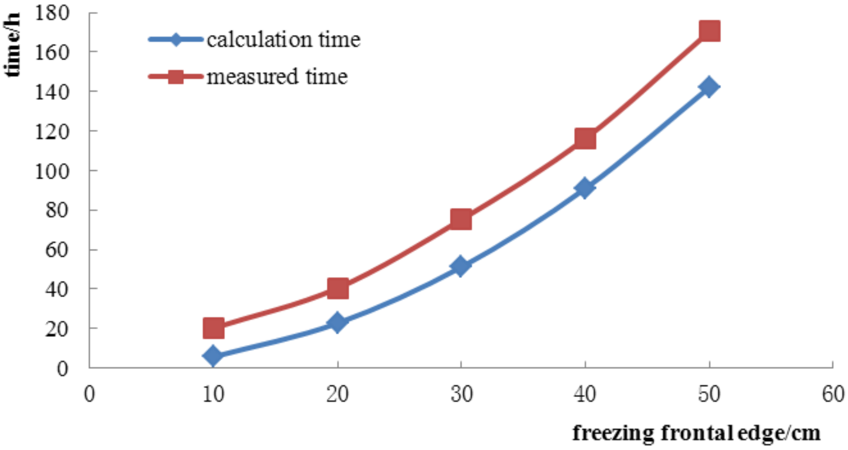


Figure 8 The change of the radius of the frozen frontal edge with freezing time

(2) In the theoretical calculation, it is ignored in that the refrigeration capacity is absorbed from the frozen pipe wall and it is lost when the system is running in the experimental process.

(3) In the freezing experimental process, because the soil mass is extracted from beneath the ground and then put into the experimental glass groove, its state must be disturbed and its physical property must be different from the original state which is not considered when theoretically calculating.

Though the phase change time of the frozen frontal edge calculated by the analytical solution is different from the measured time in the temperature field around a single frozen pipe, the analytical solution has significantly simulated the temperature field around a single frozen pipe. It has also simulated the changing law of the frozen frontal edge, refrigeration fluid temperature and freeing time under a situation with certain soil properties, density and rate of moisture content. In addition, the gap between the time calculated by the analytical solution and the time measured in the experiment is not great. Therefore, based on the analytical solution of the freezing temperature field, it is easy to obtain the freezing law which provides a theoretical basis for design and construction of the freezing method.

4. Conclusion

(1) Based on the boundless line heat exchange model, the temperature field model around a single frozen pipe has been built and the location's analytical solution of the freezing phase change interface has been given.

(2) Based on the experiment on a single frozen pipe, its temperature change law has been achieved. According to the built model of a single frozen pipe, when the temperature of refrigeration fluid is set at -24ºC, the soil mass in the freezing range from 10 to 50cm will be frozen and its phase change time is faster than the measured time, yet, their time difference will be within from 15 to 28h. The phase change time calculated by analytical solution is faster than the measured time but the gap between them is not great, which proves that the analytical calculation has significantly simulated the temperature field around a single frozen pipe.

(3) The reason why the phase change time calculated by analytical solution is faster than the measured time mainly includes the two aspects, the consumed time to refrigerating the refrigeration fluid and the system loss of refrigeration capacity during the process of equipment's running.

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