Finite Element Analysis of Natural Thawing Heat Transfer of Artificial Frozen Soil in Shield-Driven Tunnelling

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1. Introduction

With the development of urban underground construction, artificial freezing method has been increasingly adopted in municipal engineering, especially in the construction of urban underground rail transit. For example, it has been used in the connection channels of subway tunnels, the reinforcement of shield tunnelling, and the repair projects of subway tunnel, obtaining a good reinforcement effect [1–5]. As a new technology to deal with various underground engineering problems, artificial freezing technology has good water-sealing performance and strong adaptability which enables pollution-free construction. However, with the increasing application of artificial freezing method in urban rail transit construction, the impact of its construction on the surrounding urban environment is becoming increasingly apparent. The ground subsidence caused by the thawing of artificial frozen soil is an important problem, which cannot be ignored in construction control. At present, most projects with artificial freezing construction adopted natural thawing methodology to thaw the artificial frozen soil after the completion of soil freezing. However, the natural thawing process usually takes a long period and it is difficult to track grouting, thus increasing the risk of ground subsidence and cracking. In order to improve the grouting efficiency and to control the melting and sinking capacity to the maximum extent, it is essential to grasp the spatial and...
temporal distribution law of thawing heat transfer behavior of artificial frozen soil.

In the past few years, researchers have explored the behavior of heat transfer of artificial frozen soil; however, most of the research studies are focused on the freezing process, [3, 6–8], [1, 9, 10], and [11–19]. In terms of the thawing process of artificial frozen soil especially for the investigation into the temperature field behavior of thawing process, there are very limited researches. A few researchers studied the microstructure and dynamic behavior of different types of soil during thawing using laboratory tests or geotechnical centrifuge model tests, [20–22] and [23–29]. Nevertheless, these studies were essentially concerned about the frozen soil itself without considering the surrounding buried structures. To solve this, Zhao et al. [30] explored the thawing temperature field of frozen soil surrounding an embedded oil pipeline. However, their research was aimed at the seasonal frozen soil in permafrost regions. He and Cui [31] examined the dynamic behavior of a thawing soil surrounding the tunnel which is subjected to vibrating loads. Li et al. [32] also reported the dynamic response of muddy clay surrounding the subway tunnel during freezing and thawing. For the study of thawing temperature field behavior of artificial frozen soil in shield-driven tunnelling, the existing database and relevant research are relatively limited, which hinders the development of thawing principle and thawing technology in the application of artificial freezing methodology.

Therefore, the objective of this study is to investigate the natural thawing heat transfer behavior of artificial horizontal frozen soil in shield-driven tunnelling using a three-dimensional finite element method. The finite element analysis is based on the real reinforcement project of Chating Station to Jiqingsmen Station Tunnel in the Nanjing Metro Line 2 which adopted both artificial horizontal freezing technology and natural thawing methodology. In the analysis, the natural thawing temperature field contours as well as the radial and longitudinal distributions of natural thawing temperature in the frozen soil surrounding the shield-driven tunnel are explicitly examined. In addition, a series of sensitivity analyses on the typical influencing factors is performed. The results and findings of this study may enrich the current limited database and enable a better understanding of natural thawing temperature behavior of artificial frozen soil surrounding shield-driven tunnels.

2. Natural Thawing of Artificial Frozen Soil and Mathematical Model for Temperature Field

The natural thawing of natural permafrost is to melt the permafrost after the end of freezing via natural energy sources such as solar radiation energy, atmosphere, and surface water heat energy. The technology of natural thawing of artificial frozen soil is similar to that of natural permafrost which mainly relies on the heat convection between the frozen soil and the air and the heat transfer of the surrounding nonfrozen soil. The temperature of the frozen soil will slowly increase until reaching the phase change temperature; as a result, the ice in the frozen soil will melt and the natural thawing will be achieved. The technology of artificial freezing is usually applied in a small scale and in deeply embedded construction projects [1]. In urban areas, due to the restrictions of the surrounding environment, it is not convenient to conduct a manual intervention in the natural thawing process, so this process is often time-consuming.

The artificial horizontal freezing process will continue until the shield machine moves out of the tunnel portal. Hence, the natural thawing of frozen soil is mainly aimed at the outer annular frozen soil curtain. The natural thawing process is a heat transfer process and the mathematical model for the temperature field of the natural thawing of horizontal frozen soil curtain can, therefore, be derived. Following Hu et al. [13], in the frozen and unfrozen zones, that is, two sides of the outer boundary of frozen soil curtain, the governing differential equations of temperature field within a soil matrix can be expressed as

\[ C_i \frac{\partial T_i}{\partial t} = \lambda_i \left( \frac{\partial^2 T_i}{\partial x^2} + \frac{\partial^2 T_i}{\partial y^2} + \frac{\partial^2 T_i}{\partial z^2} \right), \]

where \( C_i \) is the volumetric specific heat of soil in the frozen or unfrozen zones; \( T_i \) is the temperature of the soil in the frozen or unfrozen zones; \( t \) is the time; \( \lambda_i \) is the thermal conductivity.

According to Rohsenow et al. [33], the temperature and heat flux on the boundaries are given as

\[ T_{|f} = f(x, y, z, t), \]
\[ -k \frac{\partial T}{\partial n}_{|f} = g(x, y, z, t). \]

At the interface between the tunnel segment and the air inside the tunnel, since the frozen soil is directly exposed to the ambient temperature inside the tunnel, there is natural convection between the air in the tunnel and the frozen soil. The heat flux at the interface can then be expressed as

\[ -k \frac{\partial T}{\partial n}_{|f} = \alpha (T - T_f), \]

where \( \Gamma \) refers to the boundary; \( f(x, y, z, t) \) is the temperature function; \( g(x, y, z, t) \) is the heat flux function; \( \alpha \) is the heat transfer coefficient; and \( T_f \) is the temperature of fluid medium, that is, the air inside the tunnel.

The natural thawing process of frozen soil is a phase change heat conduction problem where the latent heat of phase change should be considered. The latent heat of phase change refers to the heat released or absorbed due to the change between the water solid and the liquid phase. The principle of enthalpy method [34] is adopted to solve the phase change process in ADINA, and the latent heat of phase change can be calculated by

\[ Q = L \rho_s (w - w_n), \]

where \( Q \) is the latent heat; \( L \) is the latent heat of crystallization or fusion of water; that is, \( L = 334.56 \text{ kJ/kg} \); \( \rho_s \) is dry
density of soil; \( w \) is the total water content; and \( w_u \) is the 
unfrozen water content in the frozen soil.

At the phase transition interface,

\[
T_s(x, t) = T_f(x, t) = T_f,
\]

\[
T_s(y, t) = T_f(y, t) = T_f,
\]

\[
T_s(z, t) = T_f(z, t) = T_f,
\]

\[
\begin{align*}
K_s \left( \frac{\partial T_s}{\partial x} \right) - K_f \left( \frac{\partial T_f}{\partial x} \right) &+ K_s \left( \frac{\partial T_s}{\partial y} \right) + K_f \left( \frac{\partial T_f}{\partial y} \right) \\
+ L \rho \frac{dX(t)}{dt} & = 0
\end{align*}
\]

where \( X(t) \) is phase interface position; \( K_s \) and \( K_f \) are the 
thermal conductivity of the solid and liquid phase, respectively; \( T_s \) and \( T_f \) are the temperature of the solid and 
liquid phase, respectively.

Since the specific heat and thermal conductivity of soil as 
well as the location of the two-phase interface vary with 
temperature [35, 36], the energy conservation condition at 
the interface is nonlinear. To solve the nonlinear problem, 
the technology of numerical modelling is therefore adopted.

In this study, three-dimensional finite element modelling 
using the commercial software ADINA is conducted to 
investigate the behavior of natural thawing temperature field 
of artificial frozen soil in shield-driven tunnelling. This 
software has also been utilized by many other researchers in 
the study of temperature field of artificial frozen soils which 
verifies its capability [1, 37, 38].

3. Finite Element Modelling

3.1. Background. The Chating Station to Jiqingmen Sta-
tion Tunnel in the Nanjing Metro Line 2 was constructed 
using Earth Pressure Balanced Shield (EPBS). The 
diameter of the shield tunnel is 6.34 m; the ground eleva-
tion is +7.57 m; the elevation of the uplink tunnel is 
−4.275 m; and the buried depth of the shield tunnel is 
11.845 m. The geological conditions surrounding the 
tunnel are complex; the soil layers mainly include filled 
soil, silty clay, mucky silty clay, and silty sand (Figure 1(a)). The soil in front of the opening for shield 
tunneling was reinforced using three-axis cement 
mixing piles which form a waterproof diaphragm wall 
(Figure 1(a)). However, slight liquefaction in the silty 
clay and silty sand layers was observed which bears the 
risk of water and sand gushing during shield tunnelling. 
To overcome this, the artificial horizontal ground 
freezing technology was therefore adopted.

The layout of horizontal freeze pipes in and out of the 
shield tunnel is shown in Figure 1. A total of 57 freeze 
pipes were arranged in parallel and there are four freeze 
hole circles in the cross-sectional view. The length of 
the freeze pipes varies due to the complex geological 
conditions. For the upper half of the outer circle, the length of 
freeze pipes is 3 m, while for the lower region, the length of 
freeze pipes was designed to be 6 m because this region lies 
in the silty sand layer which is more likely to cause the 
danger of water and sand gushing. For the region inside 
the tunnel, the length of freeze pipes is 2 m which can 
generate frozen soil blocks with sufficient compressive 
strength. The temperature of brine during active freezing 
ranges between −25°C and −30°C. The time required for 
the closure of frozen soil curtain is approximately 22 days, 
while the time for achieving the designed strength is 
around 30 days. The ultimate thickness of the outer frozen 
soil curtain reaches 1.6 m and its average temperature is 
about −10°C.

3.2. Model Setup. Figure 2 shows the schematics of the three-
dimensional finite element model. Due to symmetry, only 
half of the soil and tunnel was modelled. The dimensions of 
the soil domain are 18 m × 12 m × 30 m. The embedment 
depth of tunnel is the same as the field situation. The distance 
between the tunnel axis and the bottom boundary of soil is 
21.17 m which is more than five times the radius of outer 
freeze pipe circle; hence, it is sufficient in the computation of 
a freezing problem. The width of the soil domain was taken 
as two times the length of lower freeze pipes, that is, 12 m. 
The thickness of the diaphragm wall is 1 m. The freezing 
pipes are arranged according to the actual site situation; 
Figures 2(a) and 2(b) provide the cross-sectional and side 
views of the finite element model. The three-dimensional 
models for the processes of artificial horizontal freezing and 
natural thawing are shown in Figures 2(c) and 2(d), re-
spectively. The 8-node hexahedral element type was adopted 
and finer meshes were applied in the reinforced region near 
the tunnel portal. According to the freezing plan, the 
freezing process and the natural thawing process take 50 
days and 120 days, respectively. The time step was set to be 
24 h and 48 h for these two processes, respectively.

The transient heat conduction model with phase 
transition was used for the computation of temperature 
field in the processes of freezing and thawing. The initial 
temperature load at the brine inlet was programmed as a 
time function in accordance with the brine cooling plan 
(i.e., Table 1) and applied directly to the surface of the 
freezing pipe. The temperature at the ground surface and 
the temperature at the interface between the diaphragm 
wall and the air are set to be 4.9°C which is the average 
temperature of Nanjing during construction. The boundary 
at the interface between the air inside the tunnel and the 
concrete tunnel segments is a heat dissipation boundary. 
During the period of natural thawing, the ambient tem-
perature in the tunnel rose somewhat; the average site 
monitoring temperature is around 10°C. The heat dissis-
pation coefficient was set to be 50 kJ/(h m² K). In the 
computation, the initial temperature field was taken as the 
measured original ground temperature of −35°C; this value 
is slightly high due to the hydration heat of cement which 
was generated from the reinforcement construction work 
at the north end of the station using the methods of deep 
stirring pile and compaction grouting before freezing. The 
temperature value of each node calculated in the ultimate
**Table 1: Brine cooling plan.**

| Freezing time (h) | Inlet brine temperature (°C) |
|------------------|-----------------------------|
| 0                | 20.0                        |
| 24               | 20.0                        |
| 168              | −24.0                       |
| 350              | −27.5                       |
| 720              | −27.5                       |

**Figure 1:** Layout diagram of horizontal freeze pipes in and out of shield tunnel: (a) longitudinal sectional view; (b) cross-sectional view.

**Figure 2:** Schematics of finite element model: (a) cross-sectional views of shield tunnel; (b) section \( y = 0 \); (c) 3D model for the horizontal freezing process; (d) 3D model for the natural thawing process. Notes: in Figure 2(a) from left to right, the monitor points are in the sequence of 1, 2, 3, and 4; in Figure 2(b) from right to left, the monitor points are in the sequence from 5 to 16.
time step in the horizontal freezing model is extracted via the software postprocessing module which is subsequently imported into the natural thawing model as the initial temperature field. The bottom boundary and side boundaries were set to be adiabatic without heat transfer. Note that the heat transfer between the frozen soil and the shield is not considered in this study for simplicity.

The basic geotechnical physical parameters for different soil layers are given by the engineering geological investigation (Table 2). The thermal physical parameters are based on the laboratory results of typical soil layers in Nanjing District (Table 3).

3.3. Validation. The initial temperature field before thawing process was first computed. Figure 3 shows the three-dimensional contour of temperature field after 50 days’ freezing time. As can be seen, the horizontal frozen soil curtain with a length of ∼3 m in the upper half part and a length of ∼6 m in the lower half part was well generated surrounding the tunnel in the regions near the diaphragm wall. The minimum and maximum temperature are 35°C and −27.5°C, which correspond to the ground temperature and the temperature at the brine inlet, respectively. This verifies the rationality of the established model and applied initial conditions.

The computed finite element results are validated with the measured natural thawing results at the temperature recording point (Figure 4). The temperature recording point lies 0.5 m below the axial plane and 3 m off the diaphragm wall (X = 3 m) (Figure 1(b)). Due to the requirement for engineering progress, the natural thawing temperature was only recorded for 30 days. On the other hand, the monitor point 2 on Path 1 in the YZ-plane at X = 3 m which locates on the freezing pipe was taken for comparison (Figure 2(a)). As shown in Figure 4, the computed results agree reasonably well with the measured results although some hysteresis occurs. This hysteresis is probably due to the following reasons. Firstly, the hydrodynamic effect on the heat exchange process which existed in the real situation was not modelled in the finite element analysis. For example, a phenomenon such as a seepage on the ground may occur which may in turn affect the temperature distribution during freezing. Secondly, the numerical simulation assumed the real inhomogeneous and discontinuous soil to be homogeneous isotropic. Thirdly, the thermal physical parameters in the computations were taken from those of the typical soil layers in Nanjing District; however, for the specific region of the tunnel near Jiujingmen Station, the real values may be somewhat different. Fourthly, compared with the monitor point 2 in the computations, the position of the temperature recording point is slightly farther away from the thermal convection boundary of the tunnel segments. As a result, the measured temperatures in the same time should be slightly lower than the computed values.

4. Results and Analysis

4.1. Temperature Field Contour Plot. The temperature field contour plot of the cross section in the YZ-plane at X = 3 m at different natural thawing time (i.e., 0 days to 120 days) is shown in Figure 5. This cross section locates at the end of the upper 3 m long frozen pipes above the tunnel axis plane and at the middle of the lower 6 m long frozen pipes below the tunnel axis plane. As can be seen, the frozen zone lies in the surrounding of tunnel and the minimum temperature occurs at the outer freeze pipe circle. In the region outside the outer freeze pipe circle, the temperature increases with the radial distance away from the outer pipe circle. As the natural thawing time accumulates from 0 days to 120 days, the temperature of soil surrounding the tunnel rises progressively, whereas the temperature of soil far away from tunnel reduces gradually. Due to the difference in the length of freeze pipes above and below the tunnel horizontal axis plane, the frozen soil curtain above the axis plane thaws faster than that below the axis plane. For instance, the frozen curtain above and below the axis plane fully thaws after times of about 40 days and 60 days, respectively.

Figure 6 also shows the 0°C-thawing isotherm plot in the XZ-plane at Y = 0 with different thawing times. As can be seen, the zone enveloped by 0°C-thawing isotherm shrinks as the thawing time increases and the rate of shrinkage varies a
lot in different regions. For example, the shrinkage rate at the side closer to the tunnel is very consistent, while at the other side farther from the tunnel, the rate is more affected by the surrounding ground temperature field, thus exhibiting inconsistent behavior. This behavior is more obvious in the regions near the end of freezing pipes which manifests a markedly faster rate than its counterparts in other regions. Moreover, the shrinkage behavior mainly occurs in the first 50 days of natural thawing; after 50 days’ time, the change in the 0°C-thawing isotherm is relatively minor indicating that the thawing rate has slowed down in this period and the natural thawing has almost finished.

4.2. Radial and Longitudinal Distributions of Temperature.
Two paths with 16 monitor points were selected for examination of the radial and longitudinal variations of temperature with natural thawing time (Figures 2(a) and 2(b)). Path 1 with monitor points 1 to 4 lies along the radial direction in the YZ-plane at $X = 3$ m (Figure 2(a)), while Path 2 with monitor points 5 to 16 locates in the longitudinal direction along the bottom freezing pipe in the XZ-plane (Figure 2(b)). The spacing distance between adjacent monitor points is 0.5 m.

Figure 7 shows the variation of temperature with natural thawing time at monitor points 1 to 4 along Path 1. As can be seen, the variation of temperature with thawing time mainly consists of three stages. In stage 1, the temperature increases sharply with thawing time within two to seven days which is probably attributed to the effects of boundary convection and ground temperature. In terms of the ascending rate, monitor point 2 which sits on the freeze pipe gives the highest rate of 3.8°C/day, whereas the rates of monitor points 1 and 3 respectively, have 0.5 m offset inwardly and outwardly from freeze pipe are very close, although the inward monitor point 1 shows a slightly higher rate value, that is, 2.6°C/day versus 1.7°C/day. This may be because the frozen soil around monitor 1 directly contacts the tunnel segments; as a result, it is more influenced by the air convection in the tunnel. As for the monitor point 4 which lies the furthest away from the freeze pipe, it unexpectedly shows the lowest ascending rate of 0.3°C/day. The behavior of the initial ascending rate in the radial direction is also reflected in Figure 8(a) which plots the radial variation of temperature time at monitor points 1 to 4 along the radial direction, that is, Path 1. Stage 2 is the phase change stage in which the temperature becomes more stable and remains almost unchanged. In this stage, the maximum phase change time occurs at the position of freeze pipe, that is, monitor 2, which is approximately 22 days, while at the other positions, the phase change time remains relatively short; that is, the phase change time at monitor 1 is around 2 days. At the position with 1 m offset outwardly from freeze pipe, that is, monitor 4, although there is no phase change process, the temperature ascending rate slows down significantly within the time range of 10 days and 40 days due to the heat absorption during the nearby ice-water phase change process in the frozen zone. Following the phase change stage, the variation
Figure 5: Temperature field contour plots at section of $X = 3$ m with different natural thawing times: (a) 0 days; (b) 10 days; (c) 20 days; (d) 30 days; (e) 40 days; (f) 50 days; (g) 60 days; (h) 70 days; (i) 80 days; (j) 90 days; (k) 100 days; (l) 110 days; (m) 120 days.
Figure 6: $0^\circ$ isotherm plots at section of $Y = 0$ with different natural thawing times of (a) 0 days, (b) 10 days, (c) 20 days, (d) 30 days, (e) 40 days, (f) 50 days, (g) 54 days, (h) 58 days, and (i) 62 days.
of temperature enters stage 3 in which the temperature increases rapidly until reaching the maximum value. In this stage, the temperature at the inward monitor point 1 peaks first followed by monitor points 2, 3, and 4. This three-stage behavior is similar to that reported by Zhou and Tang [22, 29] which investigated the thawing behavior of mucky clay using centrifuge model tests. According to the curve of the variation of the minimum temperature in the horizontal frozen soil curtain with natural thawing time (i.e., Figure 9), the required thawing time for the whole frozen soil curtain is approximately 72 days. The minimum temperature during thawing is located near the position of freeze pipes. Moreover, in this figure, the three-stage behavior for the whole frozen curtain can also be well observed.

The spatial distribution of the natural thawing temperature of frozen soil curtain is shown in Figure 8. This includes the radial and longitudinal distributions of thawing temperature along Path 1 and Path 2, respectively. As shown...
in Figure 8(a), the initial lowest temperature occurs at the position of freeze pipe which is $-27.5^\circ$C, while the initial temperature at the two sides of the freeze pipe rises approximately linearly with the offset radial distance. As mentioned above, the temperature rise rate at the position of freeze pipe is faster than its counterparts at the other positions; in return, the temperature at different positions along the radial direction, that is, Path 1, tends to converge when the temperature starts to turn positive. After that, the temperature at the other positions continues to increase gently except for that on the freeze pipe which has to go through a long period of phase change. In accordance with the linear interpolation principle, the position of the phase interface and its advance speed can be evaluated. As can be seen in Figures 10 and 11, at the beginning when the natural thawing time is less than $\sim 5$ days, the phase interface approaches the freeze pipe rapidly with a speed of around 16 cm/day. When the thawing time exceeds $\sim 5$ days, its advance speed starts to drop dramatically which finally stabilizes when the thawing time is more than $\sim 12$ days.

Figure 8(b) shows the longitudinal variation of temperature along Path 2 which is in the direction of X-axis. As can be seen, before the completion of thawing, the temperature in the X-axis direction along Path 2, that is, the direction of tunnelling, is relatively uniform and it is basically unaffected by the thermal conductivity in this direction. After entering the positive temperature zone, it gradually presents the behavior that the farther away from the diaphragm wall, the higher the temperature. This is mainly due to the high temperature of the soil below Path 2 and the lower ambient temperature inside the tunnel. From the perspective of required thawing time at different positions along Path 2 (i.e., Figure 12), at the position with 2 m offset from diaphragm wall, the required thawing time is the longest which is 50 days, while when deviating from this position, the required thawing time decreases successively. The shortest time required for thawing occurs at the furthest position away from the diaphragm wall which is around 20 days; thus, the influence of ground temperature on the natural thawing of the horizontal frozen soil curtain in the tunnelling direction cannot be ignored.

5. Sensitivity Analysis of Influencing Factors

Based on the aforementioned mathematical model of temperature field of natural thawing of horizontal frozen soil curtain as well as the above finite element results, the influencing factors of the temperature field of natural thawing of horizontal frozen soil curtain mainly involve thermal conductivity, volumetric heat capacity, latent heat of phase change, ambient temperature inside tunnel, freezing time, and original ground temperature. In the following, sensitivity analysis of these factors will be carried out.

5.1. Effect of Thermal Conductivity. Thermal conductivity refers to the amount of heat flowing through a material per unit temperature gradient per unit time which is a typical thermal physical parameter to characterize the thermal conductivity performance of a material. It is related to the composition, density, moisture content, and temperature of the material [39]. To examine the effect of thermal conductivity on the natural thawing temperature field, the thermal conductivity of the soil layer where the tunnel is located, that is, mucky silty clay layer, was reduced and increased by 20% and 40%, respectively, in the finite element modelling. Since the initial conditions of the natural thawing
Table 4: Temperature gradient inwardly and outwardly from freeze pipe with different thawing times.

| Thawing time (day) | Temperature gradient outwardly (°C/m) | Temperature gradient inwardly (°C/m) |
|--------------------|--------------------------------------|-------------------------------------|
| 0                  | 28.0                                 | 14.9                                |
| 2                  | 8.8                                  | 7.0                                 |
| 4                  | 3.1                                  | 0.6                                 |
| 10                 | 4.6                                  | 9.7                                 |
| 20                 | 4.3                                  | 9.6                                 |
| 30                 | 2.5                                  | 7.4                                 |
| 40                 | −3.1                                 | 1.7                                 |
| 50                 | −3.4                                 | 0.1                                 |
| 80                 | −0.6                                 | −1.1                                |
| 120                | −0.1                                 | −1.2                                |

Figure 10: Variation of distance between phase interface and freeze pipe with natural thawing time.

Figure 11: Variation of advance speed of phase interface with natural thawing time.
temperature field are based on the final temperature field of the freezing process, the freezing process was recomputed after changing the thermal conductivity.

Figure 13 shows the results of temperature-thawing time response and required thawing time for frozen soil curtain for cases with different thermal conductivity. Monitor point 2 with $X = 3$ m (i.e., Figure 2) was taken for analysis. As shown in Figure 13(a), the effect of the change in thermal conductivity on the natural thawing process is mainly reflected in the phase change time. Specifically, the phase change time...
Figure 14: Effects of latent heat on the temperature-thawing time response and required thawing time for frozen soil curtain: (a) temperature-thawing time response at $X = 3$ m (monitor point 2); (b) variation of required thawing time with latent heat change.

Figure 15: Effects of ambient temperature inside tunnel on the temperature-thawing time response and required thawing time for frozen soil curtain: (a) temperature-thawing time response at $X = 3$ m (monitor point 2); (b) variation of required thawing time with ambient temperature inside tunnel.
change time reduces with the increase of thermal conductivity and rises otherwise. This is mainly because the moisture content is the main factor affecting thermal conductivity. Under the same conditions, the increase of thermal conductivity indicates the corresponding increase of moisture content or the enhancement of thermal conductivity performance of soil; as a result, the thawing speed is accelerated, and the time required to reach the phase change is shortened. On the other hand, as shown in Figure 13(b), the required time for the fully thawing of frozen soil curtain decreases approximately linearly with the increase of thermal conductivity. When the thermal conductivity decreases by 40%, the thawing time increases by 20 days, while when the thermal conductivity increases by 40%, the thawing time decreases by 8 days. Therefore, the effect of reducing thermal...
conductivity on thawing period is greater than that of increasing thermal conductivity.

5.2. Effect of Latent Heat of Phase Change. Figure 14 provides the results of temperature-thawing time response at monitor point 2 and required thawing time for frozen curtain for cases with varying latent heat of phase change. Likewise, the latent heat of phase change for the mucky silty clay layer was reduced and increased by 20% and 40%, respectively, in the finite element computation. As the latent heat of phase change increases, the phase change time is extended accordingly; namely, a 20% increase in latent heat results in an extension of ~5 days in the phase change time (Figure 14(a)). On the other hand, in Figure 14(b), the required thawing time for the whole frozen soil curtain also increases approximately linearly with the augment of latent heat of phase change; its increase gradient is around 10 days per 20% change in latent heat.

5.3. Effect of Ambient Temperature inside Tunnel. The effect of ambient temperature inside tunnel on the thawing temperature of artificial frozen soil is also investigated. Five different ambient temperatures of 5°C, 10°C, 15°C, 20°C, and 25°C were examined. The computed results of temperature-thawing time response at monitor point 2 and required thawing time for the whole frozen curtain are presented in Figure 15. It can be seen in Figure 15(a) that the phase change time decreases with the increase of ambient temperature in the tunnel, notably when the ambient temperature increases from 5°C to 10°C. Similarly, in Figure 15(b), the required thawing time for the whole frozen soil curtain also decreases with the ambient temperature inside tunnel. For instance, the required thawing time is almost halved when the ambient temperature is increased from 5°C to 25°C. It can be found that the decrease of ambient temperature in the tunnel would exert increasing influence on the phase change period in the natural thawing process of horizontal frozen soil curtain. As the phase change period accounts for a large proportion in the whole three-stage thawing process, the decrease of ambient temperature will, therefore, prolong the completion time of natural thawing.

5.4. Effect of Freezing Time. With the extension of freezing time, the average temperature of frozen soil curtain will decrease gradually. In this section, the effect of freezing time on the natural thawing temperature field is analyzed by changing the length of freezing period. Five different freezing periods of 40 days, 60 days, 80 days, 100 days, and 120 days were selected in the analysis. As shown in Figure 16, the phase change time and the required thawing time for frozen soil curtain increase with the extension of freezing time. In contrast, the heating rate declines with the freezing time; namely, when the freezing time increases from 40 days to 80 days, the average heating rate slows down by around 0.3°C/day, while when the freezing time increases from 80
days to 120 days, the reduction in the rate is much lesser which is smaller than 0.1°C/day. Moreover, by comparing the freezing time with the thawing time in Figure 16(b), when the freezing time is increased by two times from 40 days to 120 days, the increase in the corresponding thawing time is only ~20 days indicating a percentage increase of around 67%. This means a 10% extension of freezing time will give rise to an increase in the corresponding natural thawing time by only 3.3% implying a relatively small effect.

5.5. Effect of Original Ground Temperature. For the reinforcement construction project in this study, the original ground temperature is relatively high due to the distribution of hydration heat of cement arising from the deep mixing of cement and soil and the reinforcement of chemical grouting at the end of the tunnel before the implementation of artificial horizontal freezing. According to the measured data, the original ground temperature is around 35°C~40°C which is rare in previous municipal freezing projects. There is no doubt that different original ground temperature will exert some influence on the freezing process, but how much it will affect the natural thawing process after the completion of freezing still lacks theoretical and practical investigation. To solve this, seven different original ground temperatures before freezing are considered, that is, 10°C, 15°C, 20°C, 25°C, 30°C, 35°C, and 40°C. These values are determined based on construction experience because the measured original ground temperature in the construction of urban rail transit is normally less than 40°C. As shown in Figure 17, when the original ground temperature increases from 10°C to 40°C, the corresponding phase change time and the required thawing time for the whole frozen soil curtain decrease gradually. When the temperature is less than 35°C, the gradient of decrease in the required thawing time is around 2 days/°C, while when the temperature is more than 35°C, the required natural thawing time becomes almost the same which is approximately 68 days.

6. Conclusions

Based on the horizontal freezing reinforcement project of Chating Station to Jiqingmen Station Tunnel in the Nanjing Metro Line 2, this study systematically investigated the natural thawing heat transfer of artificial frozen soil in shield-driven tunnelling using a three-dimensional finite element method. The spatial variations of temperature field with natural thawing time were explicitly examined. Furthermore, the influencing factors such as the thermal conductivity, latent heat of phase change, ambient temperature inside tunnel, freezing time, and original ground temperature were analyzed in a rational manner. This study may enrich the existing database on the natural thawing behavior of artificial frozen soil surrounding shield-driven tunnels which is currently scarce in both academic and industrial domains. For example, the provided temperature measurements of the thawing process validated the finite element analysis and implied some qualitative agreement. In addition, the reported reinforcement project in this study adopted ununiformed layout of horizontal freezing pipes due to the complex geological conditions; that is, the length of the lower half freezing pipes is twice that of the upper half freezing pipes. This may provide a reference for the assessment of natural thawing heat transfer behavior of frozen soil in projects with similar scenarios.

Based on the sensitivity analysis, some findings are summarized as follows:

1. The effect of the change in thermal conductivity on the natural thawing process is mainly reflected in the phase change time. The required time for the fully thawing of frozen soil curtain decreases approximately linearly with the increase of thermal conductivity. The effect of reducing thermal conductivity on thawing period is greater than that of increasing thermal conductivity.

2. As the latent heat of phase change increases, the phase change time is extended accordingly. The required thawing time for the whole frozen soil curtain increases approximately linearly with the augment of latent heat of phase change.

3. The phase change time decreases with the increase of ambient temperature in the tunnel. The required thawing time for the whole frozen soil curtain decreases with the ambient temperature inside the tunnel.

4. The phase change time and the required thawing time for frozen soil curtain increase with the extension of freezing time. In contrast, the heating rate declines with the freezing time.

5. When the original ground temperature increases, the corresponding phase change time and the required thawing time for the whole frozen soil curtain decrease gradually.

It should be noted that this study only considered the typical soil type in Nanjing District and did not account for the influence of geometric dimensions such as the thickness of frozen soil curtain, the length of freezing pipes, and the diameter of tunnel. In addition, the water flow in the ground has not been examined. Therefore, future research might consider the seepage flow in the ground and explore the effects of different soil type and geometric dimension on the natural thawing heat transfer behavior of artificial frozen soil during shield-driven tunnelling.

Data Availability

The figures/tables data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.
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