Hindawi
Geofluids
Volume 2022, Article ID 1004735, 15 pages
https://doi.org/10.1155/2022/1004735

Research Article

A Case Study of Energy-Saving and Frost Heave Control Scheme in Artificial Ground Freezing Project

Song Zhang[1,2] **Xiao-min Zhou**[1,2] **Jiwei Zhang**[1,2] **Tiecheng Sun**[3] **Wenzhu Ma**[1,2] **Yong Liu**[1,2] **and Ning Yang**[4]

[1]*School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing 100083, China*
[2]*Beijing Key Laboratory of Urban Underground Space Engineering, University of Science and Technology Beijing, Beijing 100083, China*
[3]*School of Civil Engineering, Shijiazhuang Tiedao University, Shijiazhuang, Hebei 050043, China*
[4]*Beijing China Coal Mine Engineering Co., Ltd., Beijing 100013, China*

Correspondence should be addressed to Xiao-min Zhou; groupzhou@163.com and Jiwei Zhang; 357102668@qq.com

Received 25 March 2022; Revised 26 April 2022; Accepted 9 May 2022; Published 3 June 2022

Academic Editor: Dongdong Ma

Copyright © 2022 Song Zhang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

In large-scale shallow buried artificial ground freezing (AGF) engineering, frost heave control and energy-saving have always been the most critical problems. By the research and analysis, this manuscript points out the applicability and superiority of intermittent freezing in large-scale shallow buried freezing projects and conducts in situ tests for the freezing project of a metro entrance. The test results show that intermittent freezing can effectively control the surface frost heave, but it has a certain hysteresis. The freezing wall thickness, average temperature, and optimization scheme during the freezing process are discussed. The results show the following: (1) Intermittent freezing would degrade the thickness of the freezing wall and the average temperature together. (2) The stop freezing scheme in intermittent freezing is not fit to frost heave control during the excavation stage. Therefore, it is necessary to establish a freezing cycle scheme with precise temperature control to control the frost heave to ensure the bearing capacity. Based on the above conclusions, a dual-circuit liquid supply scheme, the specific brine temperature control scheme, and its application method were proposed. Through this method, the development process of the freezing front can be effectively controlled, and the goal of being precise and controllable can be achieved. This research can provide practical technical guidance for frost heave control of similar AGF projects.

1. Introduction

The artificial ground freezing (AGF) method is a temporary ground reinforcement method, which mainly reduces the soil temperature by circulating a low-temperature refrigerant (brine or liquid nitrogen) in the ground to build the frozen curtain [1]. Due to the fact that it could provide a safe and reliable working space for underground engineering, it is widely used in many engineering filed such as the shaft of mine, tunnel, and foundation pit [2–6].

Since the freezing of water into ice will cause volume expansion and, at the same time, there will be continuous water migration from unfrozen soil to the frozen front during the freezing process, so with the formation of frozen curtains, continuous frost heave will occur [7, 8]. Frost heave will cause damages such as surface uplift, pipeline breakage, and structural deformation. Therefore, frost heave has always been one of the most concerning issues in artificial freezing construction. With the continuous development of China's urban infrastructure in recent years, many projects need to be reinforced by the artificial ground freezing method. Many of these projects have a shallow depth, large volume, and long freezing time [9, 10].

The research on soil frost heave can be traced back to the early part of the last century. At that time, the frost heave problem was mainly the frost heave deformation of natural

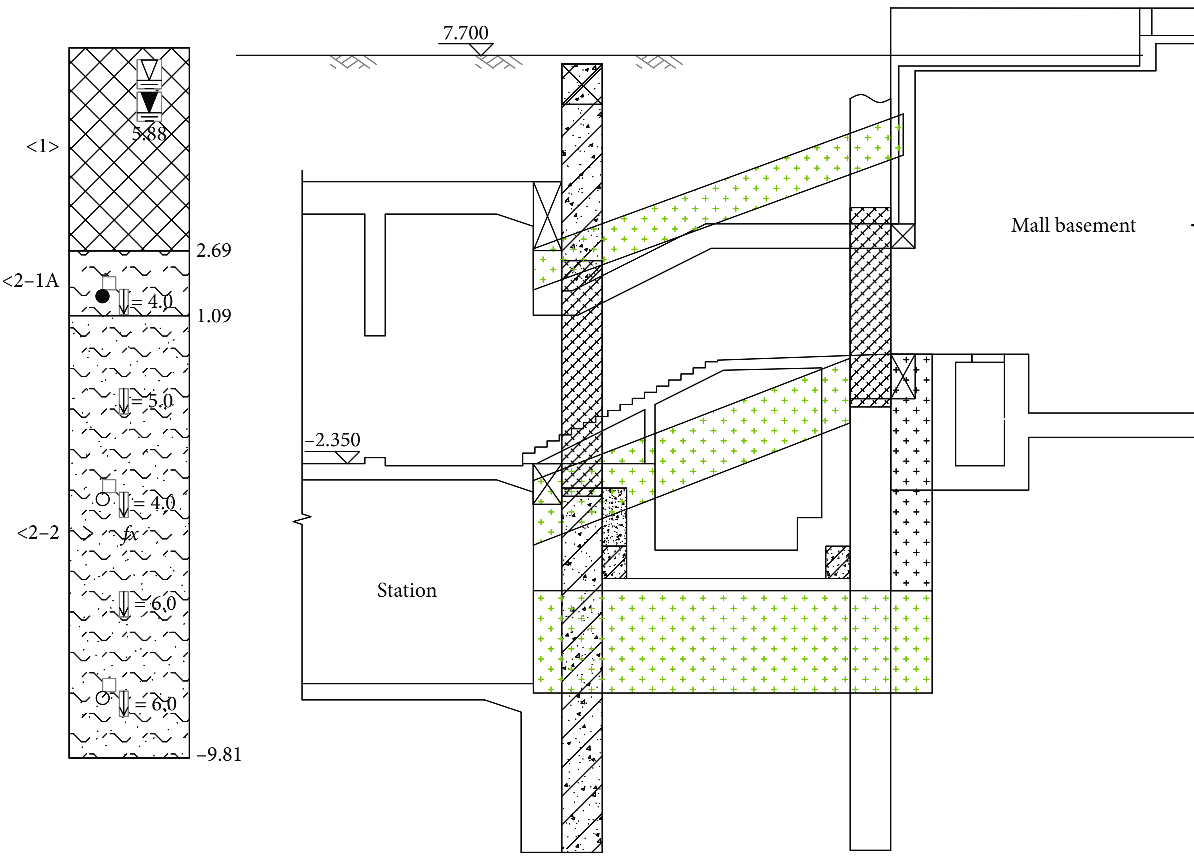


FIGURE 1: Design of freezing project and geological conditions.

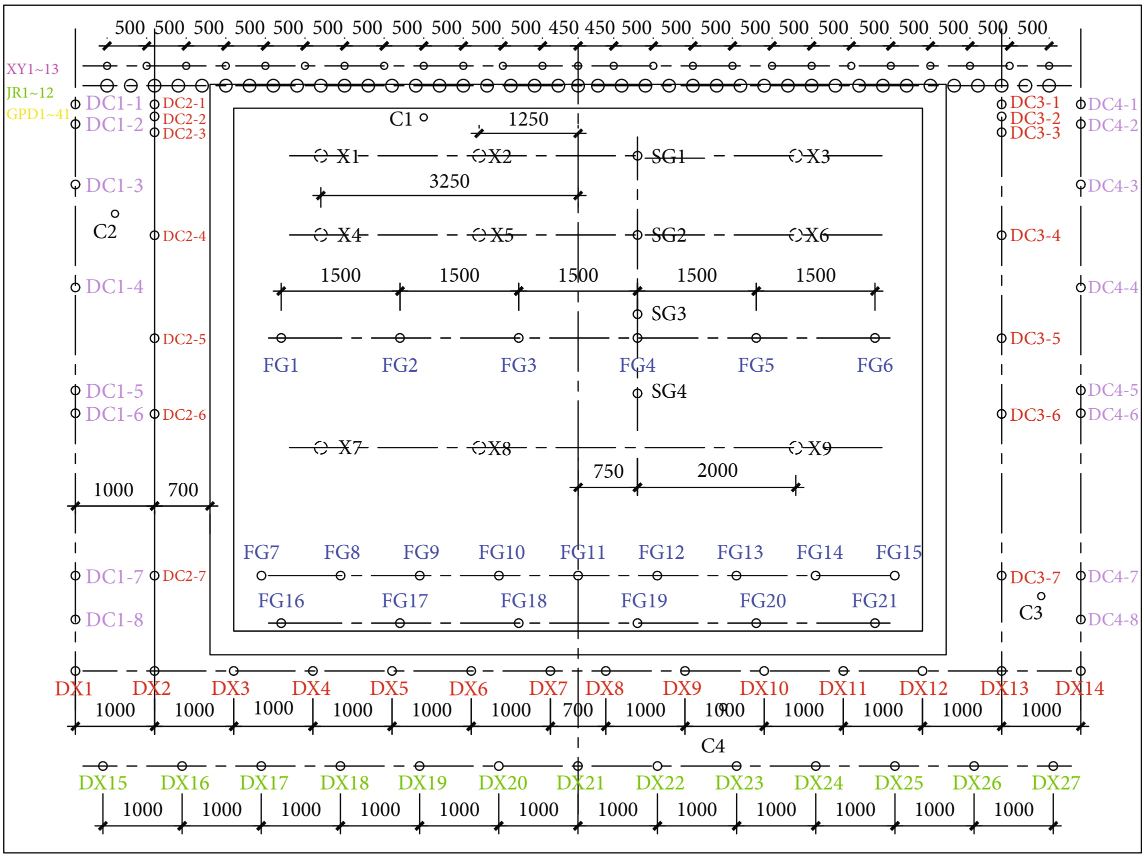
frozen soil or the frost heave deformation of road and railway subgrade [11–13]. Since then, with the increase of artificial ground freezing projects, especially in urban areas that are sensitive to frost heave problems, there are more researches on frost heave caused by artificial ground freezing [7].

At present, the control of the frost heave of natural formations is relatively simple. Control of cold energy input [14], reduction of frost heave sensitivity of soil [15], or migration of water can effectively reduce frost heave deformation. However, in artificial freezing projects, the input of cold energy is the key to constructing a frozen curtain with a certain strength and bearing capacity, so the input of cold energy cannot be isolated. To reduce the sensitivity of the soil or reduce the migration of water, it is necessary to improve the soil on a large scale, but it is limited by engineering conditions and often does not have the operating conditions for stratum improvement.

In the current construction, soil pressure relief is more effective, and frost heave deformation can be effectively reduced through long-term soil extraction and pressure relief [16–18]. However, this method also has some problems. The first pressure relief hole must be arranged on the upper side of the frozen soil area to control the surface deformation effectively. Still, many underground projects do not have enough underground space. Second, the pressure relief hole is easy to be frozen during the freezing process, so it needs to be used in conjunction with the heating hole, which further increases the need for the top space of the frozen soil area. Therefore, this method has certain limitations.

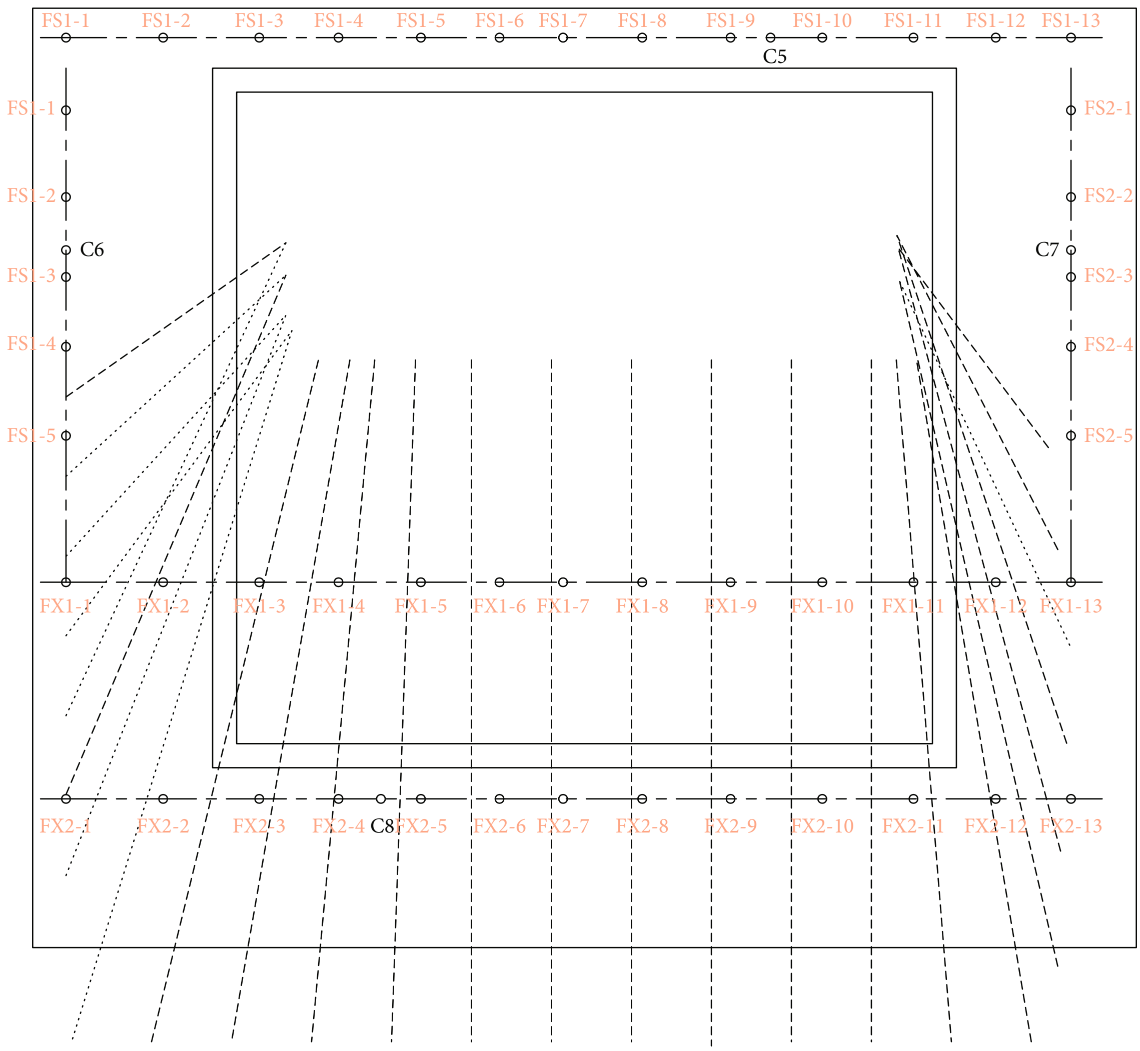
The development of active heating control frozen curtain in frozen soil areas is also used for frost heave control [19–21]. However, it still has many problems, such as occupying headspace and poor control effect, while, for large-scale freezing projects, it is due to the lack of drilling deflection control and accuracy measurement. It is difficult to evaluate the freezing effect accurately, and active heating methods can easily damage the frozen curtain. In addition, this method will cause a lot of energy waste. Therefore, this method is currently not widely used.

In summary, it is necessary to establish a method that can save energy and effectively control frost heave. Based on this, Zhou [22] proposed intermittent freezing to prevent frost heave. In recent years, the design idea of freezing on demand (FOD) based on intermittent freezing has been derived [23]. A series of experiments and numerical calculation studies have been carried out for the intermittent freezing method. The effect of controlling frost heave and the implementation plan have been discussed [24, 25]. However, intermittent freezing is rarely used in actual projects, especially in large-scale freezing projects. Therefore, this manuscript analyzes the temperature field and displacement of a shallow buried large-scale project to discuss the feasibility and effect of intermittent freezing in actual engineering. While aiming at the problem of poor temperature control of intermittent freezing, a new freezing system and freezing



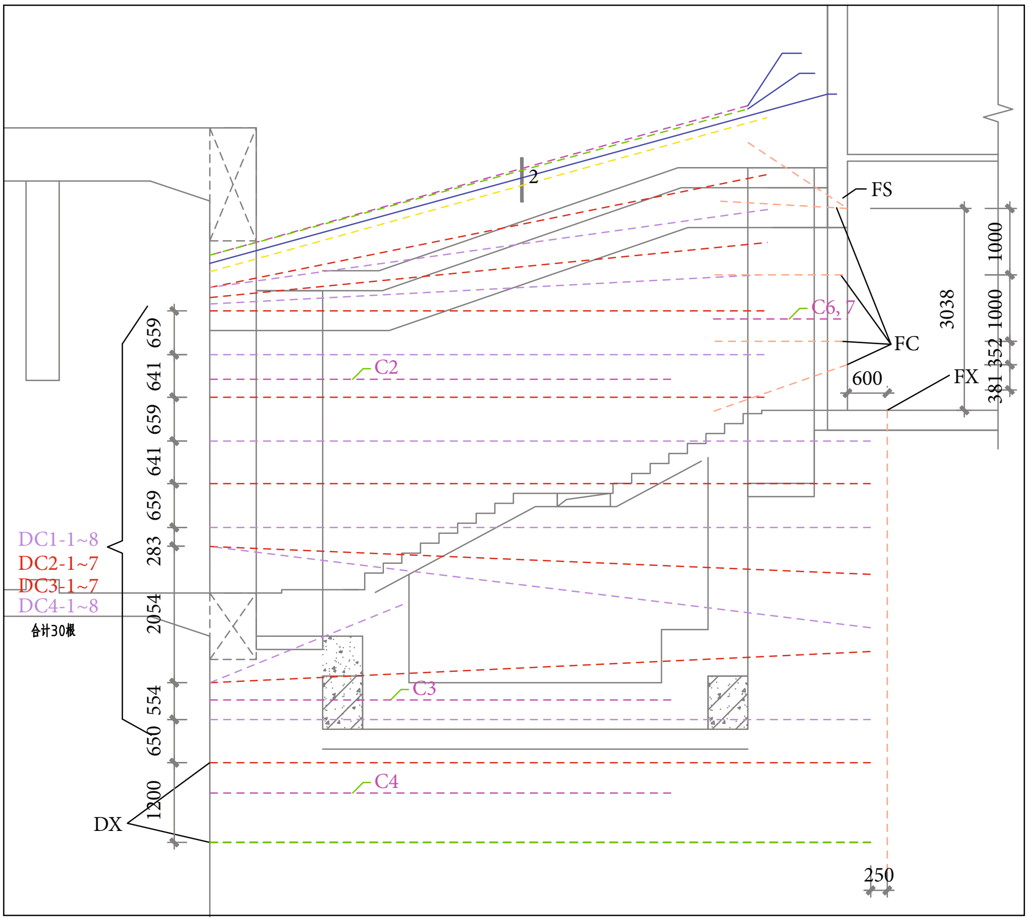
(a)

Figure 2: Continued.



(b)

Figure 2: Continued.



(c)

Figure 2: (a) The main drilling working face; (b) auxiliary drilling working face; (c) profile of freezing pipes.

Table 1: Intermittent freezing plan.

Date	State	Date	State
2020/2/5, 11:00	Stop	2020/2/9, 10:00	Run
2020/2/11, 14:30	Stop	2020/2/15, 17:40	Run
2020/2/20, 9:00	Stop	2020/2/21, 9:00	Run
2020/2/22, 9:00	Stop	2020/2/23, 9:00	Run
2020/2/24, 9:00	Stop	2020/2/25, 9:00	Run
2020/2/26, 16:00		Full load operation	

pipe design scheme were proposed, and the application of intermittent freezing in actual engineering was optimized. Relevant research content will have important guiding significance for frost heave control and energy saving of similar projects.

2. Geology and Freezing Technology

2.1. Freezing Scheme. The 2# entrance of Hualin Temple Station of Guangzhou Metro Line 8 is reinforced by the artificial ground freezing method. The length of reinforce area is 9.2 m, the height is 6.04 m, and the width is 7.7 m. The minimum overburden thickness on the frozen curtain is 1.35 m. The frozen curtain thickness is 2.5 m in design. Because the top buried depth is too shallow, the freezing process will produce a great frost heave. To avoid frost heave on the ground, the pipe shed was adopted as the main and the freezing reinforcement as the auxiliary. The frozen curtain of this area was adjusted by 1.0 m. The frozen curtain reinforcement range and ground conditions are shown in Figure 1. From top to bottom in the figure are <1> Miscellaneous Fill, <2-1A> Sea-Land Interaction Sedimentary Silt Layer, <2-2> Sea-Land Interaction Sedimentary Silty Fine Sand, and Silty Fine Sand Layer.

According to the design, it has a total of 21 shed freezing pipes, 147 freezing pipes, and 14 temperature measuring freezing pipes. The total freezing length was 1409.9 m. Among them, 21 shed pipes are made by $\Phi168 \times 8$ mm seamless steel pipes, and $\Phi108 \times 8$ mm seamless steel pipes are installed inside as the freezing pipe, while cement slurry is filled between the pipe-shed pipes and the freezing pipes. The arrangement of freezing pipes is shown in Figure 2.

The project began to freeze on October 31, 2019, and reached the design freezing time on December 19, 2019. However, due to the impact of the COVID-19, the excavation could not be organized, and the freezing time was

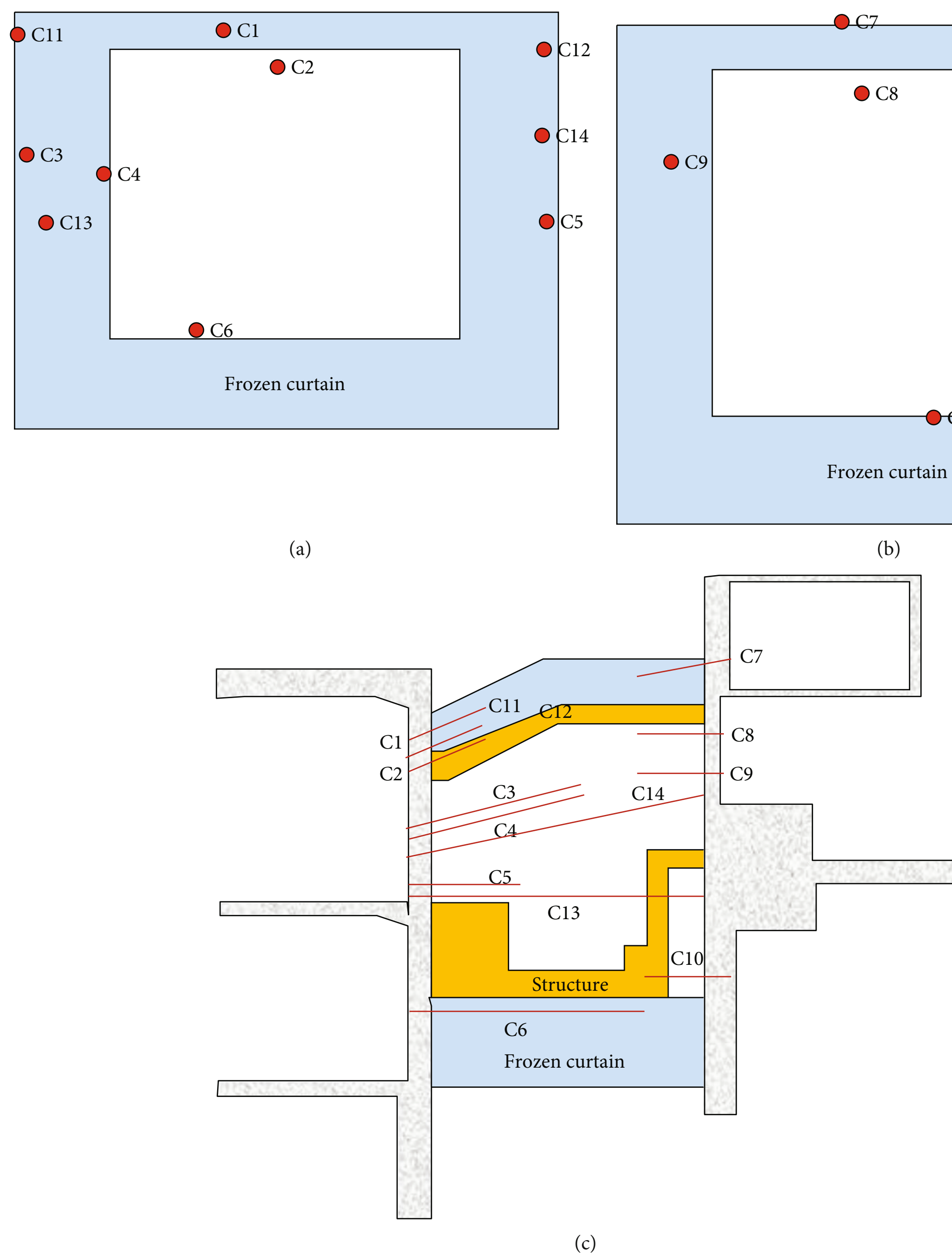


Figure 3: (a) Temperature measuring pipes in main working face; (b) temperature measuring pipes in auxiliary working face; (c) temperature measuring pipes in lateral section.

forced to be postponed to March 15, 2020. During the entire freezing process, due to the shallow buried depth and long freezing time, the ground surface frost heave and deformation need to be controlled strictly. Therefore, on January 22, 2020, they increase the temperature to -25°C by gradually reducing the load of the refrigerating units and reducing the flow rate of brine to 3 m3/h to control frost heave. As of February 3, 2020, due to continuous frost heave on the ground surface, intermittent freezing operations have begun. During the entire intermittent freezing period, a total of 5 rounds were used. The freeze and refreeze times are shown in Table 1. And the full load operation starts on February 26, 2020, to prepare for excavation.

2.2. Design of Monitoring Points. A total of 14 temperature measuring pipes are designed for this project, and the specific positions are shown in Figure 3. Each temperature measuring pipe was set with 2~5 temperature measuring points according to the depth. The temperature measuring point uses the DS18b20 temperature sensor, which test accuracy is 0.0625°C, while a series of displacement monitoring points were set up on the ground. The interval adjacent to every displacement monitoring point was 5.0 m. Due to the destruction of people and vehicles, there were only 3 points in the end. The positions are shown in Figure 4. The frequency of monitoring all test data is once a day.

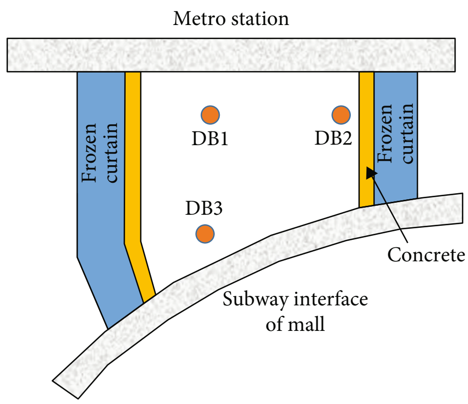


Figure 4: Position of displacement monitoring point.

3. Temperature and Displacement In Situ Test

3.1. Temperature of Refrigerated Coolant. Figure 5 shows the time history curve of the brine temperature during the entire freezing process. Corresponding to the time in Section 2.1, the entire freezing process could be divided into five stages: Stage 1 is the design freezing stage, stage 2 is the extended freezing stage, stage 3 is the flow and temperature control stage, stage 4 is the intermittent freezing stage, and stage 5 is the excavation and returning to normal freezing. At the end of stage 2, due to a power outage, there was a rapid temperature rise, and the rest of the time was normal, while drawing the brine temperature difference of inlet and outlet in Figure 6. In early stage 1, the brine temperature dropped rapidly. During the 13 days from October 31 to November 12, 2019, the temperature dropped at a rate of about 3°C/d, while the temperature difference remained at 2°C at this time. Then, the temperature drop ratio slowed down, and the temperature difference dropped to 1.5°C. After November 12, there was a rapid drop in temperature that lasted for 2 to 3 days (temperature drop rate: 1.5°C/d), and the temperature difference increased rapidly to 2°C. Subsequently, the brine temperature was basically stable, while the temperature difference continued to decrease. At the end of stage 1, the brine temperature was close to -30°C, and the temperature difference was 0.5°C. In the early time of stage 2, the freezing temperature was maintained at the original state, while the temperature difference is further reduced. In the middle time of stage 2, the temperature difference continued to be at a low level consistently which is caused by the commissioning of refrigeration equipment and the rise in brine temperature. At the end of stage 2, the temperature of brine rose rapidly due to the power outage. At this time, the brine also stopped running, which caused the return loop temperature to increase rapidly and then gradually return after the power back to normal. In stage 3, the temperature and flow rate of brine were gradually adjusted, so the temperature difference is further reduced. When the brine temperature is higher than -25°C, the temperature difference turns into a negative value. This indicates that the freezing system is in a state of reverse cooling. In stage 4, intermittent freezing was started due to the poor effect of stage 3. In the stop freezing phase, the flow of brine does not stop. Therefore, the brine temperature raised slower than in the third stage. The peak of brine temperature was maintained in the range of -12~-8°C after each stop of freezing. In this stage, the temperature difference of brine was negative most time, which indicates that the freezing system is in the state of reverse cooling during the whole stage. In stage 5, the freezing system returns to normal, and the brine temperature decreased. However, at this time, the edge of the frozen curtain was connected to the energy balance; the temperature difference continues to fluctuate around 0°C.

3.2. Temperature of Measuring Pipes. Figure 7 is the temperature history curve of the temperature measuring pipes C1 and C2 at the top of the frozen curtain, while the distance of temperature measuring pipe to axis of the freezing pipe is summarized in the figure too. In the figure, the temperature of the measuring points dropped significantly at stages 1 and 2. The power outage at the end of the second stage also had an obvious influence on the temperature of the measuring point. Because C2 was closer to the freezing pipes, the temperature raised most obviously. In stage 3, the temperature change could be ignored. In stage 4, the temperature of each measuring point has a certain rise, in which the temperature of C1 rises by 2.9~3.2°C and the temperature of C2 rises by 6°C. After entering the excavation stage (stage 5), the temperature of C1 which was located on the outer side of the frozen curtain continued to maintain its original state, while the temperature of C2 rose rapidly. It is rising by about 30°C.

Figure 8 shows the temperature curves of C13 and C14 temperature measuring pipes. As shown in Figure 7, the temperature decreased steadily in stages 1 and 2 and rebounded at the time of power outage. Afterward, there was no significant change in stage 3, in which temperature was stable. In stage 4, a temperature rise state like C2 appeared in Figure 7. In stage 5, the temperature continues to drop.

3.3. Displacement of Ground. The ground displacement curve drawn according to the measurement points arranged in Figure 4 is shown in Figure 9, and the ground displacement monitoring data of the freezing pipe drilling process are added in the figure too. Due to the upward slope of the frozen wall at the top, the distance from ground to freezing front at DB3 is less than DB1 and DB2. In the figure, due to the loss of soil during the drilling stage, displacement of each measuring point has a negative value of 10-20 mm. The freezing pipes have grouted in the later stage to keep ground stable, and the displacement recovered from a small amount. When the freezing began, the ground displacement increases linearly. Affected by the power outage at the end of Phase 2, DB2 and DB3, which are closer to the frozen curtain, dropped significantly. In stage 3, the frost heave had not been effectively controlled. In stage 4, intermittent freezing has obvious effect on frost heave control. However, there is a hysteresis in the control of frost heave by interstitial freezing. The first stop freezing of the intermittent freezing was February 5, 2020, but frost heave of DB3 growth until February 7, while frost heave of DB1 and DB2 growth until

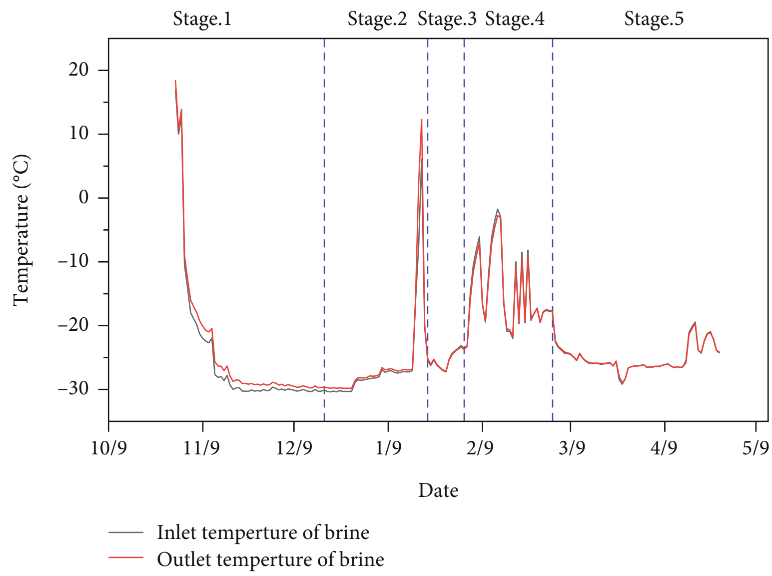


Figure 5: The temperature of brine in main pipe.

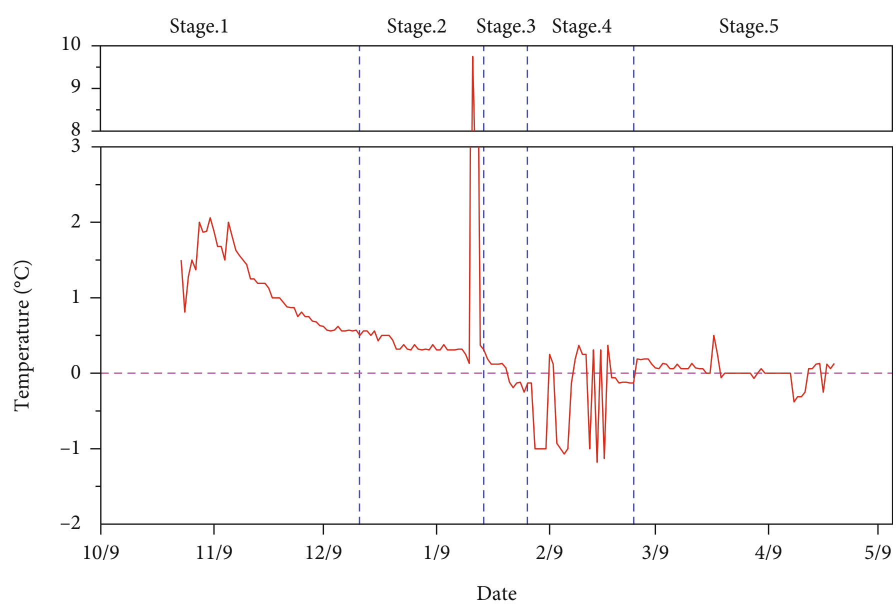


Figure 6: The temperature difference of main pipe.

February 10. While the shallower the buried depth, the more violent the reaction to intermittent freezing. In the figure, DB1 and DB2 are affected by intermittent freezing, and the cumulative decrease is about 3 mm, while the cumulative decrease of DB3 is 40.6 mm. At the same time, DB1 and DB2 showed a rising trend after the intermittent freezing stopped on February 25, but DB3 only showed a rising trend on March 7, which was 9 days later than DB1 and BD2. In stage 5, with the normal operation of the freezing system, the ground continues to rise.

Comparing the above-mentioned measured data, the closer to the frozen curtain, the more sensitive the ground to frost heave. This is not only manifested at the beginning of intermittent freezing; the closer the distance is, the earlier the frost heave stops; it is also manifested after the recovery of freezing; the closer the distance is, the earlier the frost heave will appear. Therefore, the buried depth of the frozen curtain is the key factor to determine the intermittent freezing effect.

The hysteresis of ground displacement is because the stop freezing time of intermittent freezing is very short. With the stop freezing process, the frozen soil has not melted, or only a small amount has melted. Only after repeated intermittent freezing, the frozen soil will degrade significantly, and the settlement after melting of the soil is a long process. Therefore, it takes time for the surface deformation to respond to intermittent freezing and it must be ensured that the frozen soil body melts. This has caused the delay of thawing settlement on the ground.

Moreover, in the end of intermittent freezing, the soil will continue to settle for a period. This is because the

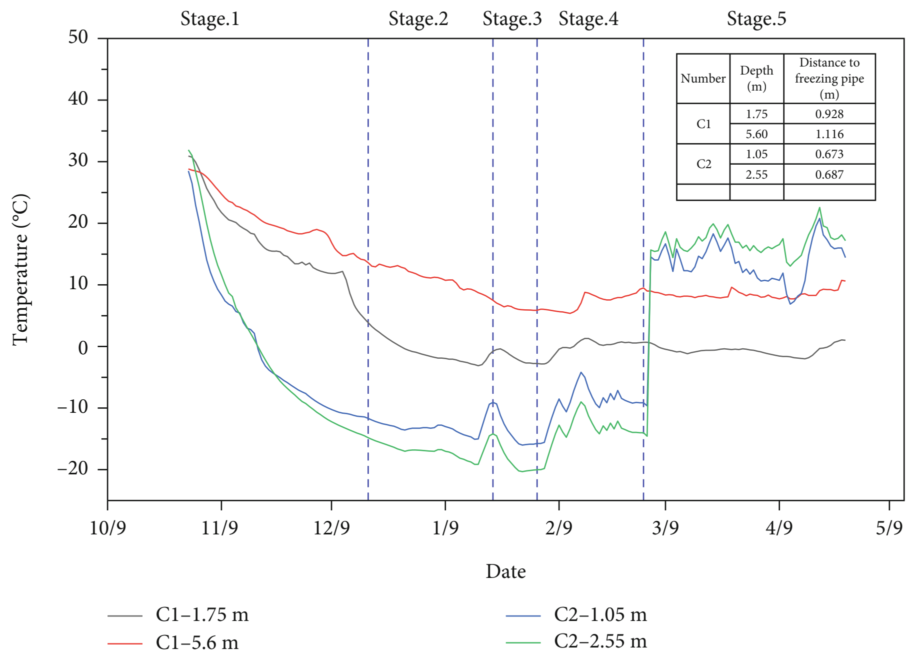


Figure 7: Temperature time history curve of C1 and C2.

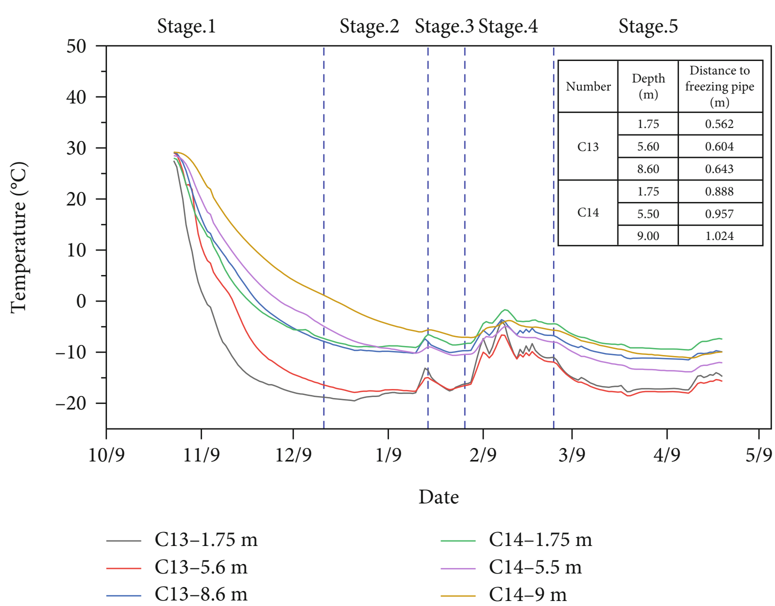


Figure 8: Temperature curve of C13 and C14.

thawing deformation has not been released. As shown in Figure 10, when the intermittent freezing stops, the soil will melt to a certain extent, and the freezing front's total dropped by h1. With the extension of the freezing time, the soil will continue to settle after thawing. Then, the freezing system is activated. However, it would take some time for low-temperature brine to affect the freezing front, whereafter the frozen front extends its thickness h2 again but is h3 away from the original frozen front. When the frost heave amount h2 in the refreezing area is less than the upper thaw settlement amount h3, the ground surface will still maintain the subsidence trend, but the subsidence rate will decrease. This has caused the delay of frost heave on the ground too.

4. Discussion

4.1. Evolvement Law of Frozen Curtain Thickness. According to the analysis in Section 3.3, the position of the freezing front is closely related to the frost heave. Therefore, the temperature measurement data is used to calculate the freezing front outside of the top frozen curtain. Select the temperature of C12 and C7 which are closest to the DB1 and DB3

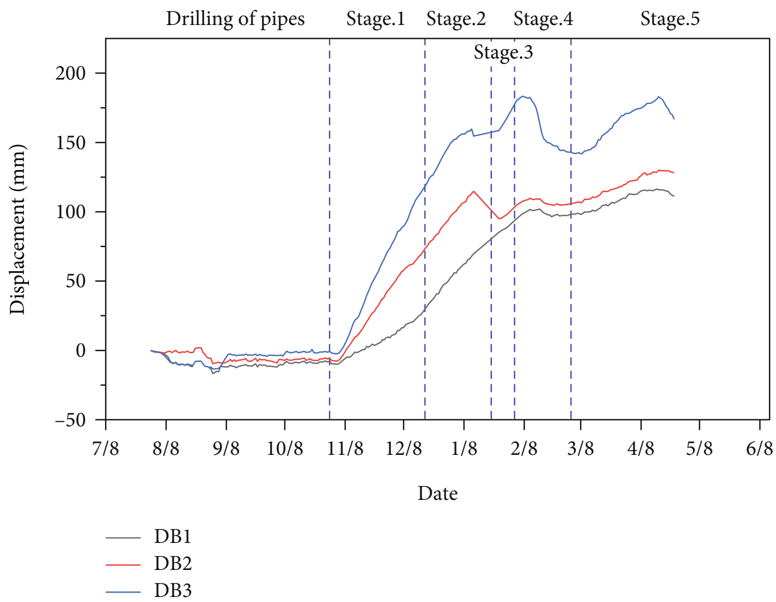


Figure 9: Displacement of ground.

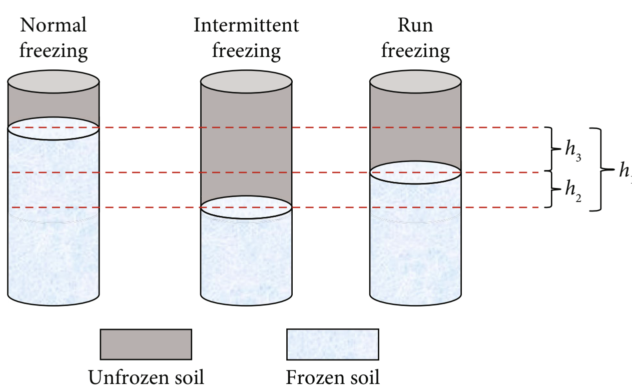


Figure 10: Schematic diagram of intermittent freezing process.

areas to calculate the position. The calculation formula [26] of frozen curtain thickness is

$$m_1(x, y) = \frac{1}{2} \ln \left[2\left(ch\frac{2\pi}{l}y - \cos\frac{2\pi}{l}x \right) \right], \quad (1)$$

$$\xi = \frac{l}{\pi} \frac{T(x, y) \ln (l/2\pi r_0) + T_{CT} m_1(x, y)}{T_{CT} - T(x, y)}, \quad (2)$$

where T_{CT} is the temperature of the freezing pipe surface, ξ is the thickness of the frozen curtain, r_0 is the radius of the freezing pipe, x and y are the coordinates of the freezing pipe, and l is the spacing of the freezing pipe. The x-direction is the direction of the freezing pipes' connection, and the y-direction is the direction perpendicular to the freezing pipe connection. The relevant parameters in this calculation are shown in Table 2.

Since this formula is applicable after the frozen curtain closed, the calculation of the frozen curtain thickness starts

Table 2: Parameters for calculation of frozen curtain.

Parameter	Value	Parameter	Value
T_{CT}	-28°C	r_0	0.054 m
l of C12	1.05 m	l of C7	1.15 m
m_1 of C12	2.6	m_1 of C7	2.17

from stage 2. The calculated frozen curtain thickness and ground frost heave are plotted in Figure 11. According to the figure, the freezing temperature control's influence in stage 3 on the thickness of the frozen curtain could be ignored. In this stage, the frozen curtain calculated by C12 and C7 maintains the original thickness. During the intermittent freezing of stage 4, the frozen curtain melts obviously.

Because the frozen curtain about C12 is far from the ground, it is less disturbed by the ground temperature, and the frozen soil thaws slowly than others. There were two obvious frozen curtain thaws in stage 4. The time is from February 5 to February 9 and February 11 to February 17; the thickness of the frozen curtain thawed 11 mm and 7.3 mm.

The soil over C7 is shallower, and the frozen curtain thawed 3 times during stage 4, which were from February 5 to February 9, February 11 to February 16, and February 21 to February 26, respectively. The thickness of the frozen curtain was 20.6 mm, 14.9 mm, and 6.6 mm, respectively. In other periods, the frozen curtain continued to expand or remained stable, while the change of the freezing front verifies the hysteresis analysis assumption of the ground displacement in Section 3.3 (similar to the length of the shaded area in Figure 11).

Base on the data of stage 3, the scheme of frost heave control through a small increase of brine temperature was

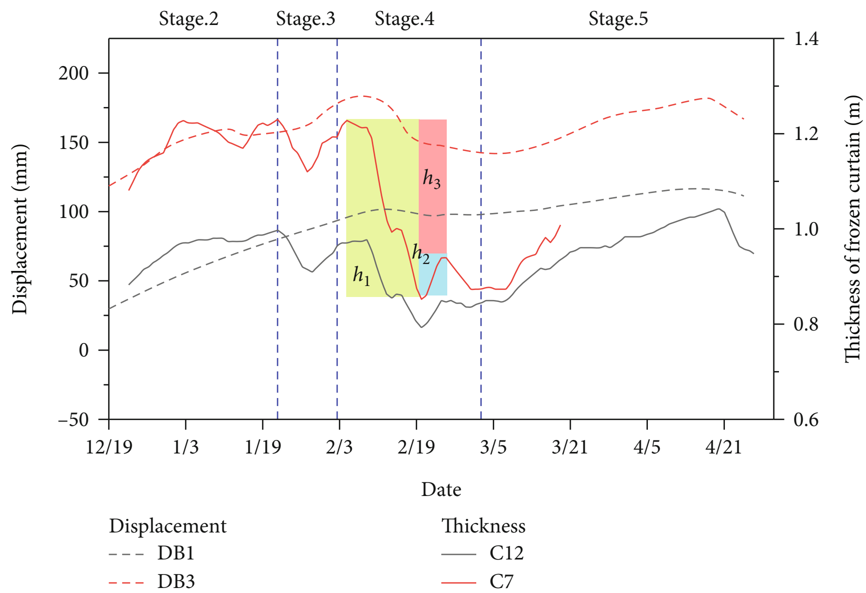


Figure 11: Scheme of frozen curtain thickness and ground displacement.

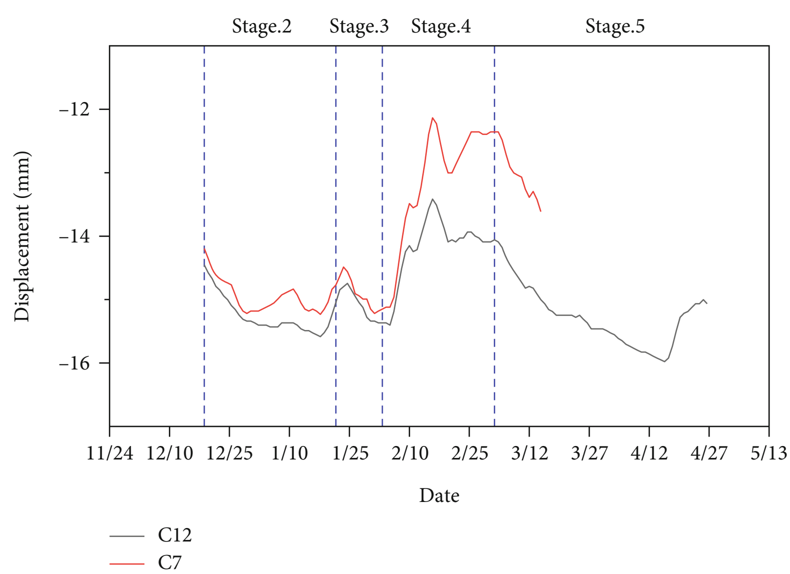


Figure 12: The average temperature in different zone.

not successful. However, the intermittent freezing scheme adopted in stage 4 effectively controls the frost heave, while, in stage 4 intermittent freezing process, the frost heave control is better in the early stage and the later stage control effect is poor. This indicates that factors such as brine temperature and intermittent freezing time in the intermittent freezing process are the key parameters for controlling intermittent freezing. In this case, the treatment plan of stopping freezing and circulating can not effectively control the brine temperature, so the freezing front changes cannot be accurately controlled.

4.2. The Average Temperature of Frozen Curtain. The average temperature of the frozen curtain is a key indicator to measure the strength of frozen curtain, and the soil temperature field would change significantly during the intermittent freezing process. According to Hu's analytical solution [27, 28], the formula for calculating the average temperature of the frozen curtain is

$$\bar{T} = T_{CT} \frac{(\pi\xi/l) - \ln 2}{\ln (l/2\pi r_0) + (\pi\xi/l)}. \quad (3)$$

According to this formula, the average temperature of the frozen curtain about C7 and C12 is shown in Figure 12. In stage 2, the average temperature dropped significantly. However, affected by stop freezing at the end time of stage 2, there was a rapid rising. Therefore, in stage 3, a

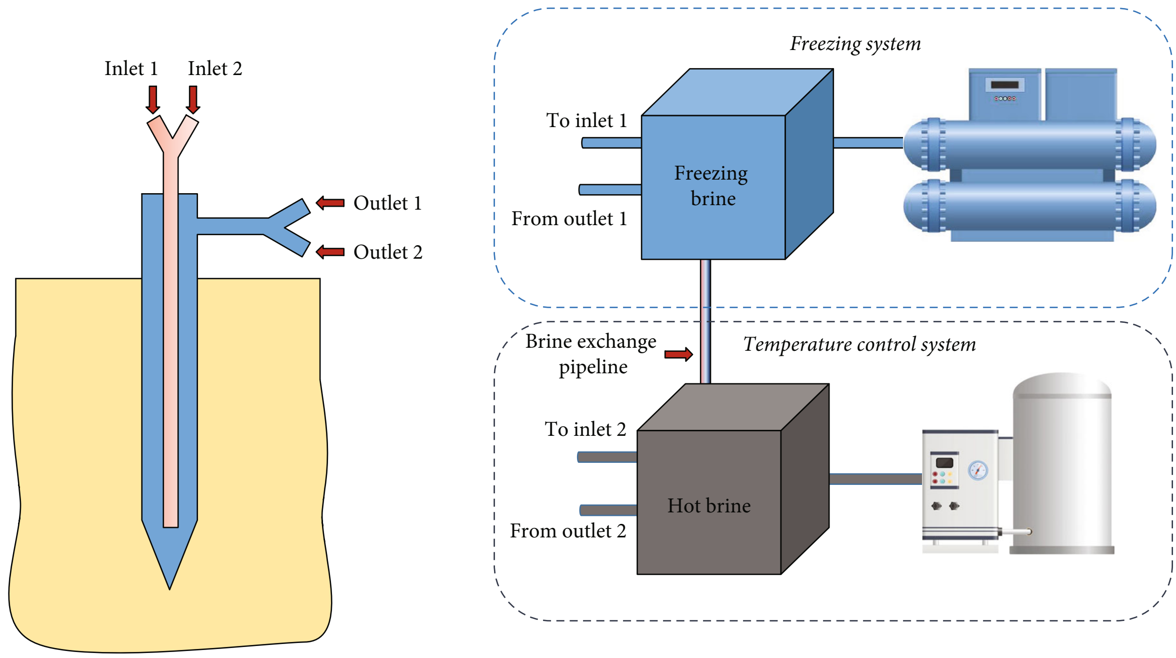


Figure 13: The dual-circuit liquid supply scheme.

downward trend was formed after the freezing system turn on. Affected by intermittent freezing in stage 4, the average temperature rose rapidly. In stage 5, with the normal operation of the freezing system, the average temperature continues to drop steadily.

According to the average temperature curve of stage 4, the change rule of the average temperature during the first and second intermittent freezing matches with the stop and run time. During the above two intermittent freezing phases, the temperature dropped slightly in the first two days but then dropped rapidly (especially the second intermittent freezing). For the 3rd to 5th intermittent freezing, the temperature continued to rise due to the small-time conversion interval between stop and run. However, the temperature rise rate is significantly less than the first and second intermittent freezing. Taking the average temperature about C7 as an example, the temperature rise rate of the first intermittent freezing is 0.4°C/d, and the second intermittent freezing is 0.34°C/d. Then, the average temperature of the next three intermittent freezing rose back to 0.11°C/d (including the freezing time in the calculation).

4.3. Optimization of Intermittent Freezing. In the above case, the intermittent freezing method was circulating the brine after the freezing stopped. This method does not control the brine temperature, and the slow temperature rise of the brine further causes the hysteresis of the frozen curtain thickness. At the same time, this method cannot accurately control the freezing front changes. In order to reduce the hysteresis reflected by the frozen curtain and realize the precise controllability of intermittent freezing, the manuscripts design a dual-circuit liquid supply scheme, in which the freezing pipe and freezing system transformation scheme is shown in Figure 13.

In the new scheme, each group of freezing pipes has two inlets and two outlets, which are connected to the freezing system and the temperature control system, respectively. While two brine systems are set up at the freezing station, one is a conventional freezing system, and the other is a brine temperature control system.

The optimized intermittent freezing scheme is used as follows:

(Step 1) The ground displacement reaches the prewarning value, and preparations for intermittent freezing are carried out. Start the temperature control system to control the temperature of the hot brine tank to -5°C.

(Step 2) Close the freezing system circulation pipeline, start the temperature control system pipeline, and perform the first high temperature cycle in the freezing system. At the same time, stop the brine circulation in the freezing system pipeline and the brine tank to keep the brine in the area at a low temperature. The duration of this stage is 3~4 days.

(Step 3) Adjust the pipeline valve, start the low-temperature freezing system, and carry out the low-temperature cycle.

(Step 4) Transfer to the normal intermittent freezing stage, so that the brine will circulate repeatedly between the design intermittent freezing temperature T_u and the design minimum brine temperature T_d.

The above method can effectively control the brine temperature during the entire intermittent freezing process. At

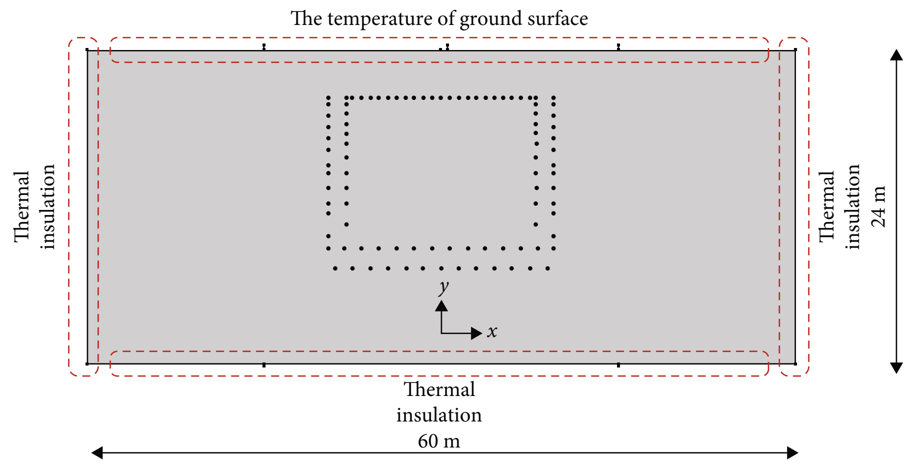


Figure 14: The numerical model and boundary condition.

Table 3: Parameters for numerical simulation.

	Density (kg/m^3)	Heat conductivity coefficient (W/(m ∗ °C))	Specific heat (J/(kg ∗ °C))	Heat latent (kJ/kg)
Soils	1571	4.3	816	
Water	1000	0.6	4200	334.88
Ice	917	2.2	2100	

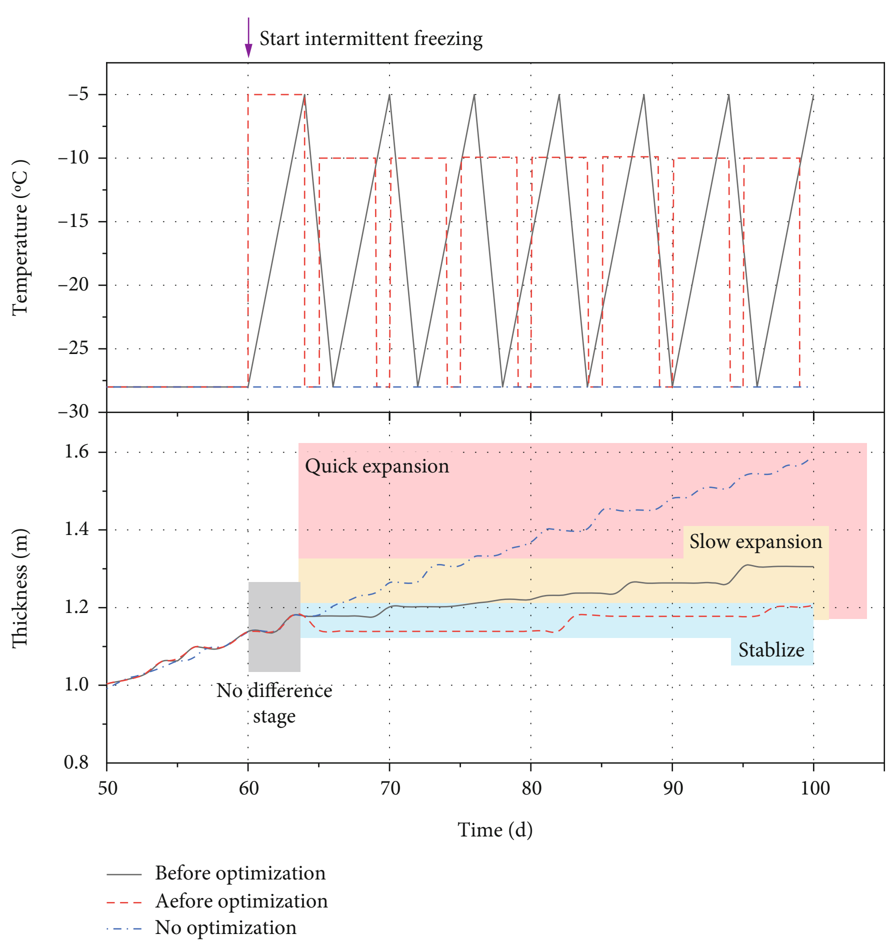


Figure 15: The comparison of different freezing scheme.

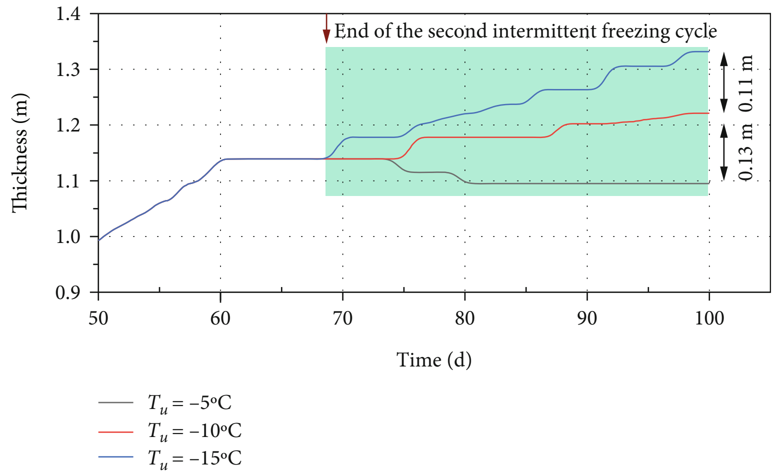


Figure 16: The comparison of different T_u.

the same time, the continuous switching of the dual-circulation system realizes the rapid and precise change of the brine temperature.

In order to compare the difference before and after the optimization, the numerical calculation model base on the design of above case was built and is shown in Figure 14. The parameters in the calculation are listed in Table 3. And the brine temperature was set to -28°C in the early stage, and two optimization schemes were adopted in the later stage. The brine temperature curve and frozen curtain thickness of the two schemes are shown in Figure 15.

As shown in the figure, the two intermittent freezing schemes do not affect the thickness of the frozen wall in the first cycle. At this stage, the temperature field distribution inside the frozen soil is mainly adjusted. After the first cycle of intermittent freezing, the changes of the soil frozen curtain were different, and the frozen curtain continued to expand in a slow state before optimization. And after optimization, the frozen wall remains in a stable area and does not change.

Since there is a brine exchange pipeline between the optimized temperature control system and the freezing system, the high temperature state of intermittent freezing can be strictly controlled. Figure 16 shows the development of the frozen curtain at different T_u. As shown in the figure, the expansion trend of the frozen curtain is controlled by controlling T_u, while the frost heave and bear capacity is controlled too. Therefore, the precise and controllable intermittent freezing method can also be used for the excavation stage, while the difference in frozen curtain thickness generally starts from the end of the second intermittent freezing cycle.

5. Conclusion

This article focuses on the research on frost heave control of large-scale shallow buried underground excavation projects. Through comparative analysis, the intermittent freezing method has a wide application range and a small occupation area, while it can save energy effetely. Therefore, it is suitable for frost heave control of large-scale freezing projects. Furthermore, a systematic analysis of the application of intermittent freezing in engineering is carried out, and the following conclusions are drawn:

(1) Engineering practice has proved that intermittent freezing can effectively control surface deformation, but there is an obvious hysteresis. This is mainly caused by the inability of changing the brine temperature in time and the thermal diffusion efficiency of frozen soil. In addition, intermittent freezing construction will significantly weaken the average temperature and thickness of the frozen wall. Therefore, it is must design an accurate and controllable intermittent freezing method

(2) Aiming at the problem of inaccurate brine temperature control, a dual-circuit liquid supply scheme is proposed. Accurate temperature control in the intermittent freezing stage has been achieved through the transformation of the freezing system and the freezing pipe. According to numerical calculations, the new scheme can effectively control the position of the freezing front and realize the purpose of controlling frost heave while ensuring the bearing capacity of the frozen curtain. It improves the applicability of the intermittent freezing scheme in the excavation stage

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The research was supported by the National Natural Science Foundation of China (grant No. 52178340) and the Science Foundation of Tiandi Technology Co., Ltd. (grant No. KJ-2021-JJZD-07), which are all gratefully acknowledged.

References

[1] M. A. Alzoubi, X. Minghan, F. P. Hassani, S. Poncet, and A. P. Sasmito, "Artificial ground freezing: a review of thermal and hydraulic aspects," *Tunnelling and Underground Space Technology*, vol. 104, p. 103534, 2020.

[2] J. Huang, W. Yang, F. Li, and Z. Wang, "Field measurement research on temperature changing law of vertical shaft lining," *Journal of Liaoning technical university(natural science edition)*, vol. 26, no. 3, p. 360, 2007.

[3] D. Meng, C. Rong, and T. Zheng, "The numerical simulation of freezing temperature field and the reason of freezing pipe broken," *Journal of Anhui Jianzhu University*, vol. 22, 2014.

[4] J.-w. Zhang, J. Murton, S.-j. Liu, L.-l. Sui, and S. Zhang, "Detection of the freezing state and frozen section thickness of fine sand by ultrasonic testing," *Permafrost Periglacial Process*, vol. 32, no. 1, pp. 76–91, 2021.

[5] J.-w. Zhang, J. Murton, S.-j. Liu et al., "Sensitivity and regression analysis of acoustic parameters for determining physical properties of frozen fine sand with ultrasonic test," *Quarterly Journal of Engineering Geology and Hydrogeology*, vol. 54, no. 2020, pp. 1–12, 2020.

[6] P. Wang and G. Zhou, "Frost-heaving pressure in geotechnical engineering materials during freezing process," *International Journal of Mining Science and Technology*, vol. 28, no. 2, pp. 287–296, 2018.

[7] J. Zhou, W. Zhao, and Y. Tang, "Practical prediction method on frost heave of soft clay in artificial ground freezing with field experiment," *Tunnelling and Underground Space Technology*, vol. 107, p. 103647, 2021.

[8] S. Akagawa, "Artificially frozen ground and related engineering technology in Japan," *Sciences in Cold and Arid Regions*, vol. 13, no. 2, pp. 77–86, 2021.

[9] Y. Tang, S. Xiao, and J. Zhou, "Deformation prediction and deformation characteristics of multilayers of mucky clay under artificial freezing condition," *KSCE Journal of Civil Engineering*, vol. 23, no. 3, pp. 1064–1076, 2019.

[10] S. Zhang, *Study on Damage Mechanism of Artificial Frozen Wall and Disaster Prevention and Control Caused by Sudden Seepage*, Shijiazhuang Tiedao Univeristy, Hebei China, 2021.

[11] F. Niu, H. Hu, M. Liu, Q. Ma, and S. Wenji, "Studies for frost heave characteristics and the prevention of the high-speed railway roadbed in the Zoige Wetland, China," *Frontiers in Earth Science*, vol. 9, p. 570, 2021.

[12] Q. Feng, Z. Yang, W. Liu, and W. Zhao, "Experimental study of the anisotropic frost heave characteristics of rock surrounding tunnels in cold regions," *Journal of Cold Regions Engineering*, vol. 35, no. 4, p. 04021014, 2021.

[13] U. B. Fattoev, A. V. Brushkov, A. V. Koshurnikov, and A. Y. Gunar, "The frost heaving and heave properties of soils on the projected Moscow–Kazan railway," *Moscow University Geology Bulletin*, vol. 76, no. 3, pp. 343–351, 2021.

[14] Q. Feng and B. Jiang, "Analytical method for insulation layer thickness of highway tunnels with multilayer dielectric in cold regions," *Chinese Journal of Geotechnical Engineering*, vol. 36, no. 10, pp. 1779–1887, 2014.

[15] B. Jianqing and T. Wang, "(2015) "Influences of freeze-thaw and fines content on mechanical properties of coarse-grained soil."," *Chinese Journal of Geotechnical Engineering*, vol. 34, no. 2, pp. 608–614, 2015.

[16] W. Xianguo, H. Wang, K. Zhang, and H. Liu, "Control of freezing and reinforcement of metro linkage channel on frost heave of existing railway," *Journal of Civil Engineering and Management*, vol. 35, no. 5, pp. 1–5, 2018.

[17] W. Li, "Design and application of frost heave control zone in shallow buried subway passage reinforcement," *Mine Construction Technology*, vol. 39, no. 2, pp. 50–53, 2018.

[18] H. Wang, W. Zhu, and D. Li, "Construction method and control measure for connecting passage in water-enriched sand bed," *Journal of Railway Engineering Society*, vol. 9, no. 2010, pp. 82–87, 2010.

[19] H. Jun, H. Wei, Y. Liu, and L. Zhao, "Numerical simulation of temperature field based on frozen soil curtain tube with thermal heat limit," *Forest Engineering*, vol. 32, no. 4, pp. 70–74, 2016.

[20] J. Zhang, P. Shi, and J. Pan, "Study of ground frost heave control technology used in Gongbei tunnel constructed by pipe roof and ground freezing method," *Tunnel Construction*, vol. 38, no. 5, pp. 809–817, 2018.

[21] H. Xiangdong, T. Fang, J. Chen, H. Ren, and W. Guo, "A large-scale physical model test on frozen status in freeze-sealing pipe roof method for tunnel construction," *Tunnelling and Underground Space Technology*, vol. 72, no. 2018, pp. 55–63, 2018.

[22] G. Zhou, "Analysis of mechanism of restraining soil freezing swelling by using intermission method," *Journal of China University of Mining and Technology*, vol. 28, no. 5, pp. 413–416, 1999.

[23] M. A. Alzoubi, A. Zueter, A. Nie-Rouquette, and A. P. Sasmito, "Freezing on demand: a new concept for mine safety and energy savings in wet underground mines," *International Journal of Mining Science and Technology*, vol. 29, no. 4, pp. 621–627, 2019.

[24] G. Zhou, H. Kun, X. Shang, and J. Zhou, "Test and numerical simulation on frost heave in frozen soils in intermittent freezing mode," *Procedia Earth and Planetary Science*, vol. 1, no. 1, pp. 512–518, 2009.

[25] Z. Yang and G. Zhou, "Intermittent freezing mode to reduce frost heave in freezing soils - experiments and mechanism analysis," *Canadian Geotechnical Journal*, vol. 49, no. 6, pp. 686–693, 2012.

[26] H. Xiangdong, "Average temperature calculation for the Straighe single-row-pipe frozen soil wail," *Journal of Glaciology and Geocryology*, vol. 32, no. 4, pp. 778–785, 2010.

[27] H. Xiangdong, T. Fang, and L. Zhang, "Analytical solution to temperature distribution in frozen soil wall with wavy boundaries by single-row- and double-row-piped freezing," *Cold Regions Science and Technology*, vol. 145, no. 2018, pp. 208–228, 2018.

[28] S. Zhang, Z. Yue, T. Sun et al., "Evolution laws for frozen wall formation under conditions of sudden seepage," *Mathematical Problems in Engineering*, vol. 2020, 13 pages, 2020.