Hindawi
Advances in Civil Engineering
Volume 2021, Article ID 6645139, 11 pages
https://doi.org/10.1155/2021/6645139

Research Article

Analysis of the Development Characteristics and Influencing Factors of Freezing Temperature Field in the Cross Passage

Yan Zhuang,[1] **Junhao Chen**,[1,2] **Jian Zhang**,[1] **Jianlin Wang**,[1] **and Han Li**[1]

[1]*School of Civil Engineering, Fujian University of Technology, Fuzhou 350118, China*
[2]*Key Laboratory of Underground Engineering, Fujian Province University, Fuzhou 350118, China*

Correspondence should be addressed to Junhao Chen; chjhtougao@163.com

Received 14 December 2020; Revised 16 February 2021; Accepted 24 February 2021; Published 5 March 2021

Academic Editor: bingxiang yuan

Based on the analysis of the temperature measurement data of the Shanghai Metro Line 15 cross passage freezing project, it was found that the gray silt layer of cross passage No. 2 outperforms that of cross passage No. 1 on the freezing effect, which is mainly attributed to the large loss of cooling capacity in the latter passage. Within the same stratum, the soil temperature at the duct piece is higher than that of the deep soil. When the soil freezes for 45 days, the temperatures of the sandy silt and gray silt layers of the same cross passage drop to −8.25°C and −6.91°C, respectively, indicating that the freezing effect of the sandy silt layer is better than that of the gray silt layer. Moreover, simulations were performed for deviation freezing pipes, nondeviation freezing pipes, and different freezing pipe diameters in the cross passage No. 1, respectively. It was found that the maximum difference of the closure completion time between the deviation and nondeviation freezing pipes is 6 days. Furthermore, for deviation freezing pipes and nondeviation freezing pipes at the center of the cross passage, the minimum difference in the freezing wall thickness reduces from 0.45 mm after 20 days of freezing to 0.06 mm after 45 days of freezing, indicating that the difference in the freezing wall thickness gradually weakens as freezing develops gradually. The deviation freezing pipe increases the spacing of freezing pipes in the deep soil. As the pipe spacing increases, the influence of the pipe diameter on the closure completion time of the freezing wall decreases.

1. Introduction

With the rapid development of urbanization and the advent of metropolises, urban underground space has been considered as an important space to develop urban infrastructure. Accordingly, its rational development and utilization can effectively resolve the problems originating from the shortage of above-ground urban spaces. This issue is especially more pronounced for metropolises like Shanghai. In this regard, many investigations, including theoretical analyses, analytical models, and numerical simulation, have been carried out to resolve the problems of underground engineering construction [1–3].

The cross passage is defined as the connecting passage between parallel tunnels of the subway, which is used for evacuation and escape in an emergency. The main challenge for constructing the cross passage is to use an appropriate artificial freezing method [4–8] to reinforce the soil of the excavation area and provide a certain thickness of the frozen curtain. Then, this frozen layer operates as a supporting and water insulation layer so that the tunnel can be excavated through the mining method. Although the artificial freezing method which is applied in cross passage freezing projects [9–13] is a relatively mature technology, further studies are required to determine the influence of different geological and surrounding environment conditions [14, 15] on the key technical indices, including the thickness and average temperature of the frozen wall.

Li et al. studied the measured data and analytical calculation of artificial freezing projects of Shanghai Yangtze Tunnel and proposed ideas for optimizing the analysis method [16]. Cai et al. simulated the freezing project of Shanghai subway No. 13 and analyzed the model. Moreover, various initial and boundary conditions were considered in the cross passage model [17]. Li et al. analyzed the piping collapse accident of the cross passage at the lower part of a middle air shaft of the Shanghai subway. In this regard, numerical simulations, theoretical analyses, laboratory tests, and engineering investigations were carried out to study accident mechanisms and provide a reference for similar accidents [18]. Zhang et al. combined the field test and the numerical simulation approach to analyze the temperature field distribution of soil, freezing wall thickness, and heat preservation measures of the duct piece. Accordingly, they revealed that the spacing of the freeze pipes is an important factor that affects the thickness of the frozen wall at the interface section. Accordingly, the freezing wall in the auxiliary freezing surface was introduced as one of the main risk points in the construction of cross passages [19]. Chen et al. studied a frozen shaft as a prototype to conduct an indoor multiloop pipe freezing test. They applied the finite element method to simulate models for the deviation and nondeviation freezing pipes. Accordingly, it was found that deviation freezing pipes will reduce the effective thickness of the freezing wall [20].

In summary, many studies have been conducted on the optimization and temperature field predictions of cross passage freezing projects. However, few studies have focused on the influence of the deviation freezing pipe and the size of the freezing pipe diameter on the development of the freezing temperature field. It is worth noting that these parameters have a substantial impact on the closure completion time, average temperature, and effective thickness of the freezing wall. In this paper, the cross passage between Luoxiu Road Station and Baise Road of Shanghai Rail Transit Line 15 is considered as the case study to analyze the stratum and the loss of cooling capacity on the freezing effect. Moreover, ANSYS R19.2, which is a commercial finite element software, is applied to perform 3D simulations of the cross passage. The influence of deviation freezing pipes, nondeviation freezing pipes, and different freezing pipe diameters on the temperature field development of the cross passage is considered. The present study is expected to provide a reference for the design and construction of freezing projects.

2. Engineering Background and Numerical Model

2.1. Engineering Situation. There is a total of two cross passages from the Luoxiu Road Station to the Baise Road Station in Shanghai Rail Transit Line 15. The centerline spacing of cross passage No. 1 is 18.2 m, and the elevation of the center of the cross passage is −19.38 m. The stratum of the cross passage is composed of a gray silt layer, while the strata of the pumping station are composed of a gray silt layer and sandy silt layer from top to bottom. On the other hand, the centerline spacing of cross passage No. 2 is 13.57 m, and the elevation of the center of the cross passage is −16.58 m. The strata of the cross passage are a gray silty clay intercalated with silt soil layer and a gray silt layer. Moreover, both cross passages are under Shangzhongxi and Laohumin roads. The strata are characterized by poor stability and remarkable water permeability. Meanwhile, it is highly prone to water and sand inrush accidents. To ensure safety of cross passage, the "stratum reinforcement by the freezing method and excavation by the mining method" is applied as the construction plan. Figure 1 presents the stratum profile of cross passage No. 1.

2.2. Freezing Reinforcement and the Monitoring Scheme

2.2.1. Arrangement of Freezing Holes. Based on the requirements and specifications of the Shanghai cross passage freezing project, 89 freezing holes, including 53 holes on the right line and 36 holes on the left line, are considered in cross passage No. 1. Among these holes, six holes are perforations of the cross passage and each of the left and right lines has two pressure relief holes. Furthermore, there are 68 freezing holes, including 40 on the right line and 28 on the left line, in cross passage No. 2, where four holes are perforations of the cross passage. Meanwhile, there are two pressure relief holes in each of the left and right lines. In order to investigate the temperature variations in the soil, 15 temperature measuring holes, including 11 holes on the left line and 4 holes on the right line, are considered in cross passage No. 1. Moreover, 16 temperature measuring holes (including 12 holes on the left line and 4 holes on the right line) were considered in the cross passage No. 2. Figure 2 illustrates the layout of the freezing holes of cross passage No. 1.

2.2.2. Arrangement of Temperature Measuring Holes and Measuring Points. Since the junction between the duct piece and the stratum is a weak freezing link, the first measuring points of cross passages No. 1 and No. 2 were considered at an embedded depth of 0.5 m, and the remaining measuring points were arranged along the hole depth. Figure 3 shows the layout of the measuring points in cross passage No. 1, where $i = 1{\sim}15$ denotes the serial number of the temperature measuring hole.

2.2.3. Freezing Design Parameters. Table 1 presents the main freezing design parameters of the cross passage construction.

The freezing station was arranged in upstream of cross passage No. 2. In the experiment, the refrigerating unit consists of three refrigerators, one of which is standby. Since cross passage No. 1 was located about 300 m far from the freezing station, the backup refrigerator was used if the brine temperature or soil temperature did not meet the design temperature.

2.3. Establishment of the 3D Model of the Cross Passage

2.3.1. Model Size. In this section, ANSYS software was applied to perform 3D numerical simulations of the cross passage No. 1 to establish models for deviation freezing pipes and nondeviation freezing pipes of the cross passage. In this regard, a nonlinear transient thermal analysis was carried out to investigate the temperature field of the freezing process. In order to reduce the influence of boundary effects, the boundary size of the model was set five times the actual size. The length, width, and height of the boundary size were

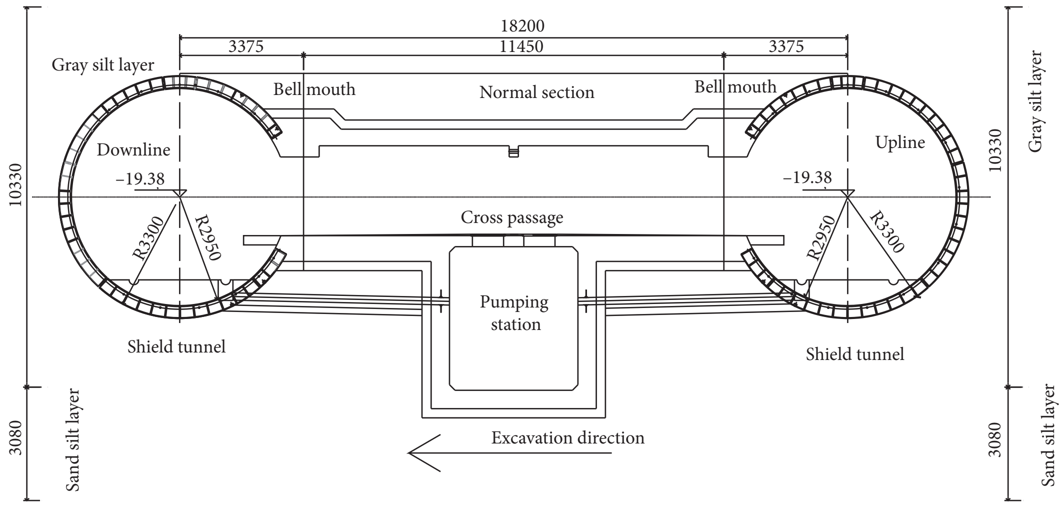

FIGURE 1: Stratum profile of the cross passage No. 1 (unit: mm).

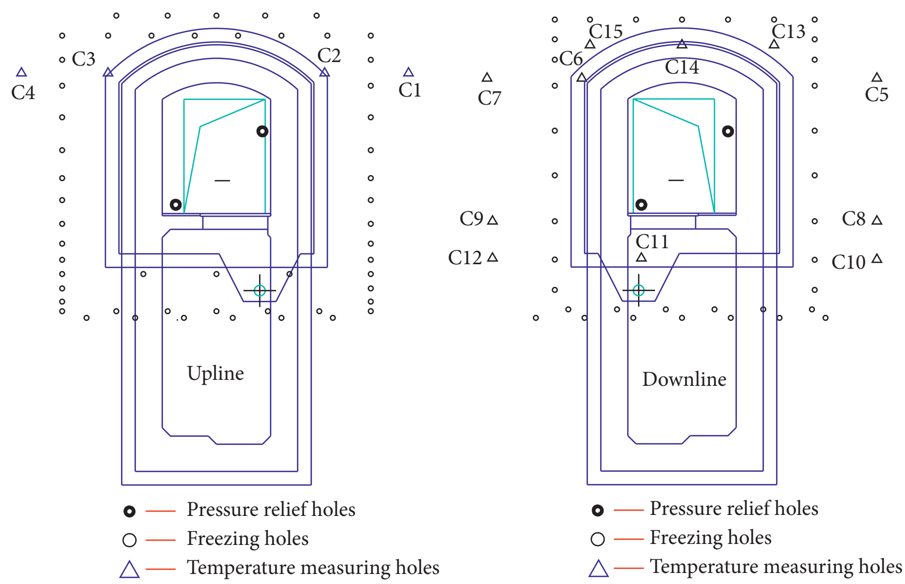

FIGURE 2: Layout of freezing holes in the cross passage No. 1.

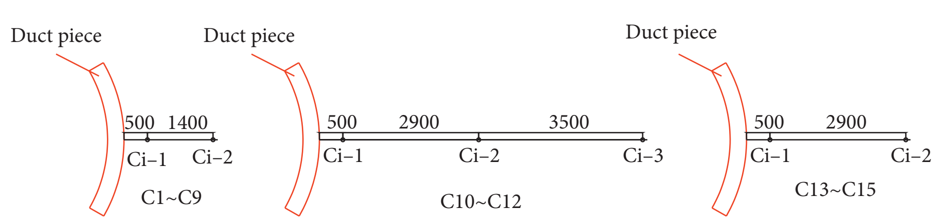

FIGURE 3: Layout of measuring points in temperature measurement hole (unit: cm).

set to 50 m, 36 m, and 18 m, respectively. In the studied cases, the distance between the centerline of tunnels and the tunnel radius is 18.2 m and 3.3 m, respectively. In a numerical simulation, it is essential to ensure that the obtained results are independent of the mesh size. In this regard, the model of deviation freezing pipes and the model of nondeviation freezing pipes are divided into 1,343,490 and 1,360,914 elements, respectively. The meshed model is shown in Figure 4. In the present study, 89 freezing pipes of diameter 89 mm were installed inside the soil. The structure of freezing pipes is shown in Figure 5.

2.3.2. Boundary Conditions and Material Parameters. In all simulations, the initial ground temperature was set to 22°C. Moreover, Table 2 presents the thermal and physical

Table 1: Main freezing design parameters of the cross passage.

Name	Value	
	Cross passage No. 1	Cross passage No. 2
Freezing wall thickness in normal section/m	2.1	2
Freezing wall thickness at the spell mouth/m	1.8	1.7
Freezing time/d	48	45
Freezing pipe diameter/mm	89	89
Deviation freezing hole/mm	< 150	< 150
Freezing wall average temperature/°C	−10	−10
Brine flow rate of single pipe/($m^3 \cdot h^{-1}$)	5 ~ 8	5 ~ 8
Total cooling demand/(Kcal/h)	8.137	4.438

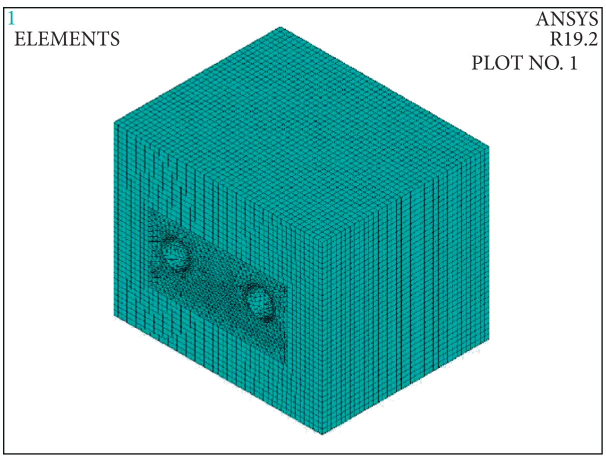

Figure 4: Generated meshes.

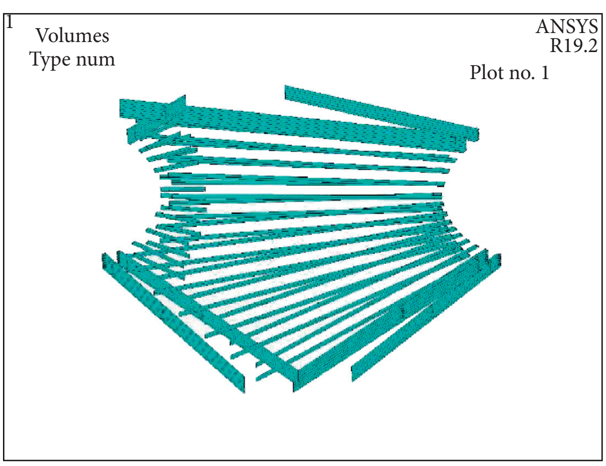

Figure 5: Structure diagram of freezing pipes.

parameters of the stratum. All parameters were obtained from the filed investigation report.

3. Numerical Simulation Results

3.1. Demonstration of the 3D Model of the Cross Passage. In this section, obtained results at the measuring point C4-2 and simulation point M4-2 are analyzed. Figure 6 presents the temperature distribution at points C4-2 and M4-2 against the number of freezing days. The comparison between measured temperatures and the results of the simulation shows that the time required for the measured value C4-2 and the simulated value M4-2 to drop to 0°C is 28 and 26 days, respectively. Moreover, it is found that the daily average cooling rate is 0.79 and 0.85 mm/d, respectively. The maximum temperature difference between the numerical simulation and the actual measured temperature is 1.12°C, which indicates that the results of the simulation are similar to the measured values.

3.2. Analysis of the Influence of Deviation Freezing Pipes and Nondeviation Freezing Pipes. Based on the model of deviation freezing pipes and the model of nondeviation freezing pipes, the difference between the two conditions on key technical indicators such as the cooling rate and the freezing wall thickness is obtained.

3.2.1. Closure Completion Time of Deviation Freezing Pipes and Nondeviation Freezing Pipes. Figure 7 shows that when the closure of the freezing wall is complete, the freezing wall develops inward and outward smoothly in the model of nondeviation freezing pipes. However, the freezing wall thickness and temperature are obviously different in the model of deviation freezing pipes. More specifically, the freezing wall requires 22 days to complete closure for the model of deviation freezing pipes. In this case, the maximum and minimum thicknesses of the freezing wall at the side walls are 1.32 and 0.35 m, respectively. In the model of nondeviation freezing pipes, the freezing wall requires 16 days for complete closure, and the maximum and minimum freezing wall thicknesses at the side walls are 1.1 and 0.7 m, respectively. It is observed that deviation freezing pipes postpone the closure completion time of the freezing wall and an uneven distribution of the freezing wall thickness.

3.2.2. Soil Cooling Rate of Deviation Freezing Pipes and Nondeviation Freezing Pipes. The embedded depths of 1 m and 8.4 m along the same drilling path of the cross passage temperature measuring hole C12 are used at simulation points M12-1 and M12-2, respectively. The simulation results are shown in Figure 8.

At the embedded depth of 1 m, the displacement caused by deviation freezing pipes is 3.75 mm, which is a small value. Moreover, the distance between the temperature measuring pipe and the closest freezing pipe is 1.03 m. The

Table 2: Characteristics of the stratum layer.

Stratum	Density (kg·m^{-3})	Angle of internal friction (°)	Specific heat capacity (kJ·(kg· K)$^{-1}$)	Thermal conductivity (W·(m·K)$^{-1}$)	
				Before freezing	After freezing
Gray silt layer	1918	32	0.90	1.120	1.896
Sandy silt layer	1990	26	1.32	1.480	2.130

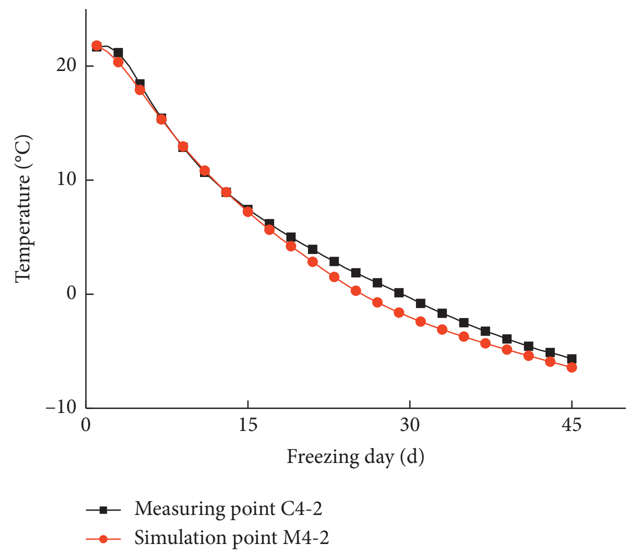

Figure 6: Comparison of the measured value and simulated value.

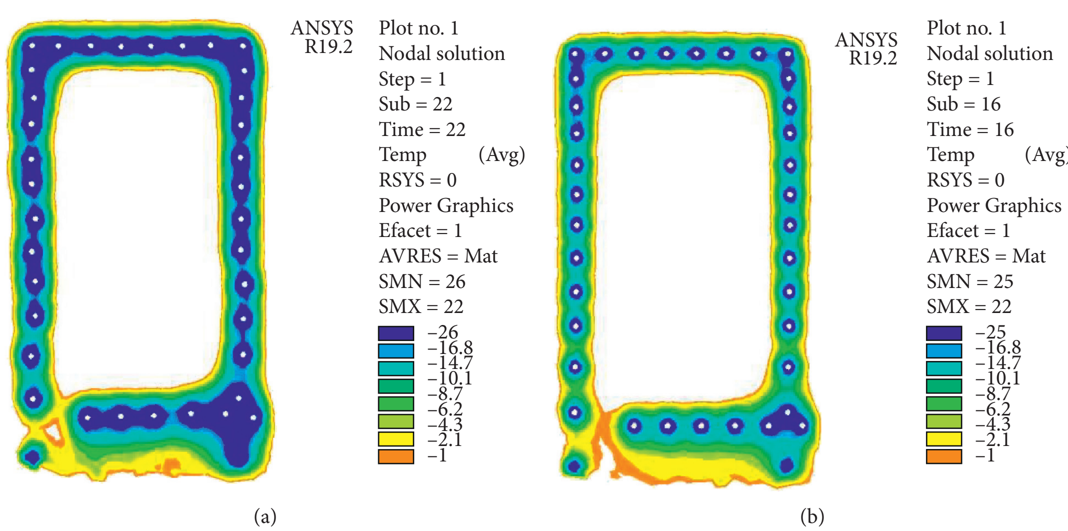

Figure 7: Temperature contours of the freezing wall in the weak section: (a) deviation freezing pipes; (b) nondeviation freezing pipes.

daily average cooling rates at embedded depths of 1 m and 8.4 m are 0.81 and 0.84°C/d, respectively. It is found that the temperature difference during freezing is less than 1°C and decreases to 0.44°C on the 45th day. As the embedded depth increases to 8.4 m, the displacement caused by deviation freezing pipes is 86.42 mm, and the distance between the temperature measuring pipe and the freezing pipe is 0.64 m. However, there is a significant difference in the cooling rates between the deviation case and nondeviation case. The daily average cooling rates are 0.97 and 1.08°C/d, respectively. On the 45th day of freezing, the temperature difference reduces to 2.04°C, with an average temperature difference of 2.95°C during freezing.

Therefore, at the location of the bell mouth, the distance between adjacent freezing pipes does not change significantly due to the small embedded depth and deviation angle.

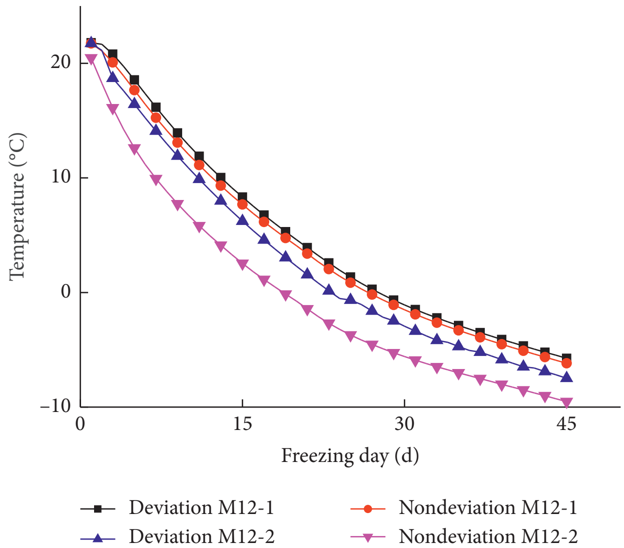

Figure 8: Temperature distributions in deviation and nondeviation freezing pipes.

However, as the embedded depth gradually increases, the deviation value of the freezing pipe increases continuously. Moreover, the distance between adjacent freezing pipes increases and the rate of diffusion of the frozen soil is significantly reduced.

3.2.3. Freezing Wall Thickness of Deviation Freezing Pipes and Nondeviation Freezing Pipes. The maximum and minimum values of the freezing wall thickness at the side walls at different periods are obtained through the numerical simulation. In this regard, Table 3 shows the corresponding data. It is found that at the initial stage of freezing, the deviation freezing pipe has a significant effect on unevenness of the freezing wall thickness. As freezing progresses, the unevenness decreases, while an effect of deviation is observed when compared with the nondeviation freezing pipe. After the completion of the active freezing, the difference between the maximum and minimum freezing wall thicknesses is the smallest.

The minimum freezing wall thickness before and after closure is significantly different between the model of deviation freezing pipes and the model of nondeviation freezing pipes. Figure 9 shows the change in the freezing wall thickness from the beginning of the freezing for 20 days. It is observed that the minimum freezing wall thickness on the same freezing day in the model of nondeviation freezing pipes is greater than that in the model of deviation freezing pipes. The difference between the minimum thicknesses is the largest at 20 days of freezing, with a value of 0.45 mm. As the freezing progresses, the difference between the minimum freezing wall thickness decreases continuously. The difference in the minimum thicknesses decreases to 0.06 mm at 45 days of freezing, which shows that the difference of the freezing wall thickness between deviation freezing pipes and nondeviation freezing pipes gradually decreases as the freezing progresses.

3.3. Influence of Different Freezing Pipe Diameters on the Simulation of the Freezing Temperature Field

3.3.1. Feature Sections. In order to investigate the effect of the pipe diameter on the development of the cross passage freezing temperature field, the cross passage freezing pipe diameters of 73 mm, 89 mm, and 108 mm are considered in simulations.

Based on the arrangement of the cross passage freezing holes, the soil in the freezing range is divided into a right line bell mouth region (0–1.5 m), expected weak region (5.8–10.1 m), and a left line freezing pipe cross region (10.1–11.6 m). Three sections, namely, sections 1-1, 2 2, and 3 3 with depths of 0.5 m, 7.8 m, and 11.1 m, respectively, are considered to study the development characteristics of the freezing temperature field in the three regions. Figure 10 shows the cross-sectional positions.

3.3.2. Effect of Different Pipe Diameters on Closure Completion Time. Figure 11 shows the closure completion times for the freezing walls with different pipe diameters. It is observed that the change of pipe diameter has a negligible impact on the closure completion time at section 1-1. In particular, the differences in the closure completion times between the pipe diameters of 73 mm, 89 mm, and 108 mm are 2 and 1 days, respectively. It is observed that the pipe diameter has the most impact on the closure completion time of the freezing wall at section 2 2. It is worth noting that the difference in the closure completion times of the freezing wall between the pipe diameters of 89 and 106 mm is 5 days. Compared with the other two cross-sections, the spacing of the freezing pipe at cross-section 3 3 is the largest. However, since this cross-section is located at the intersection of the freezing pipes, the closure completion times of the freezing wall for different pipe diameters are less than those of section 2 2. The performed analysis shows that the pipe diameter slightly affects the closure completion time of the freezing wall. It is inferred that at the section with a large freezing pipe spacing, variation of the freezing pipe diameter has a negligible impact on the freezing closure time and the time that is required for the freezing wall to meet the design requirements.

3.3.3. Effect of Different Pipe Diameters on Design Freezing Time. The design freezing wall thickness of the cross passage is set to 2.1 m. Figure 12 shows the required freezing time at different sections of the freezing wall.

Figures 12(a) and 12(b) show the freezing time required for the freezing wall thickness at different pipe locations. It is observed that the time required for the freezing wall thickness in section 2-2 to reach the design requirement is longer than that for the freezing wall at section 1-1. This may be attributed to the longer distance between adjacent freezing pipes in the deep soil than that in the shallow soil.

Figure 12(c) shows that as the pipe diameter increases in section 3-3, the time that is required for the freezing wall thickness of the same part to meet the design requirements decreases. However, this phenomenon does not occur in

Table 3: Freezing wall thicknesses on different freezing days (mm).

Freezing day	Deviation freezing pipe			Nondeviation freezing pipe		
	Maximum	Minimum	Difference	Maximum	Minimum	Difference
20	1.26	0.74	0.52	1.39	1.19	0.20
30	1.76	1.56	0.20	1.94	1.86	0.08
45	2.36	2.25	0.11	2.33	2.31	0.02

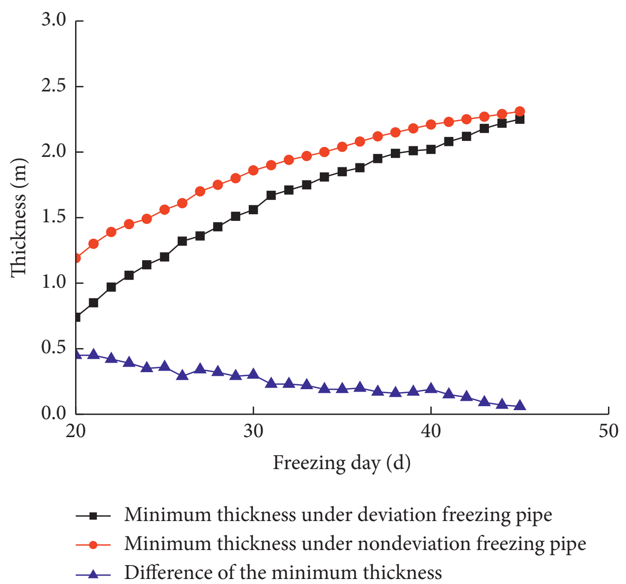

Figure 9: Minimum freezing wall thickness of deviation and nondeviation freezing pipes.

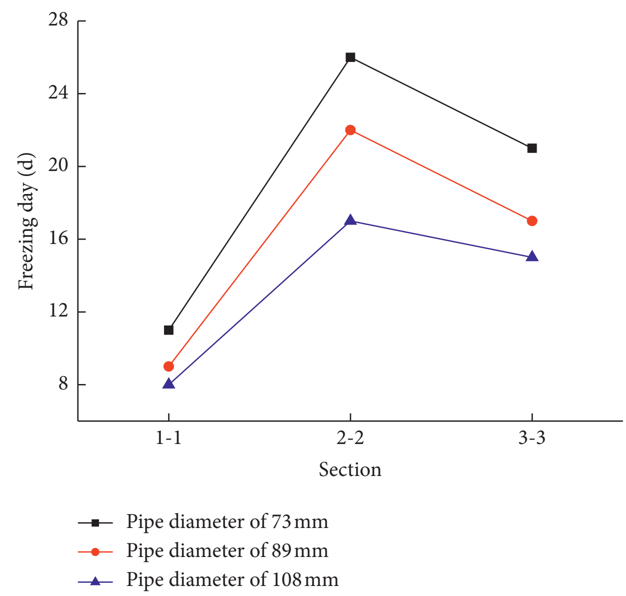

Figure 11: The time for closure completion of the freezing wall.

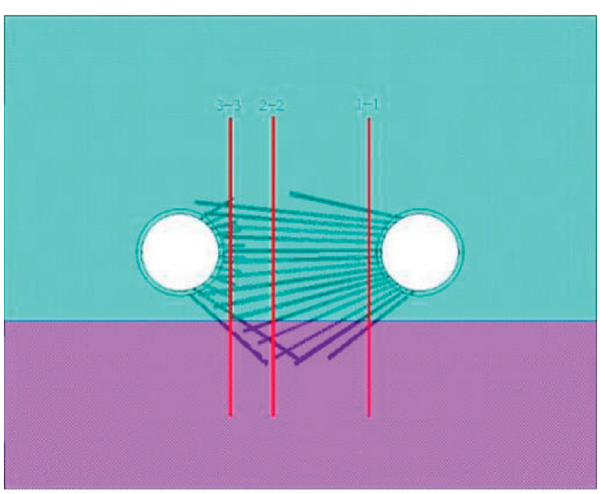

Figure 10: Position of feature sections.

sections 1-1 and 2-2. It is inferred that at the section with a large spacing of freezing pipes, an increase in the pipe diameter has a lower effect on the time required for the freezing wall to reach a certain thickness.

Figure 12(c) shows the time required for the freezing wall thicknesses of the left wall and arch bottom with the right wall and arch roof to meet the design requirements. It is found that the freezing wall thickness of the right wall and the arch roof requires a longer time to meet the design requirements. This is because the distance between the left wall and the double-row pipe at the bottom of the arch is more than that between the right wall and the double-row pipe at the vault. Therefore, increasing the row spacing of the freezing pipes within a certain range can shorten the time for the freezing wall to reach a certain thickness.

Comparing the time required for the freezing wall thickness of the left and right walls to reach the design requirements shows that at section 3-3, the time required for the freezing wall thickness of the left wall to reach the design requirement is significantly shortened. Moreover, the time required for the freezing wall thickness of the right wall to reach the design requirement is also shortened. Furthermore, the freezing pipe of the sidewall at section 3-3 changes from the single-row pipe at sections 1-1 and 2-2 to the double-row pipe. This indicates that the double-row pipe releases more cold energy than the single row of pipes and can shorten the time for the freezing wall to reach a certain thickness.

4. Discussion of the Field Measured Data

Due to the different freezing times of the two cross passages, 45-day cooling data are used to ensure the comparability of the results. The changes in the temperature field have the following four characteristics:

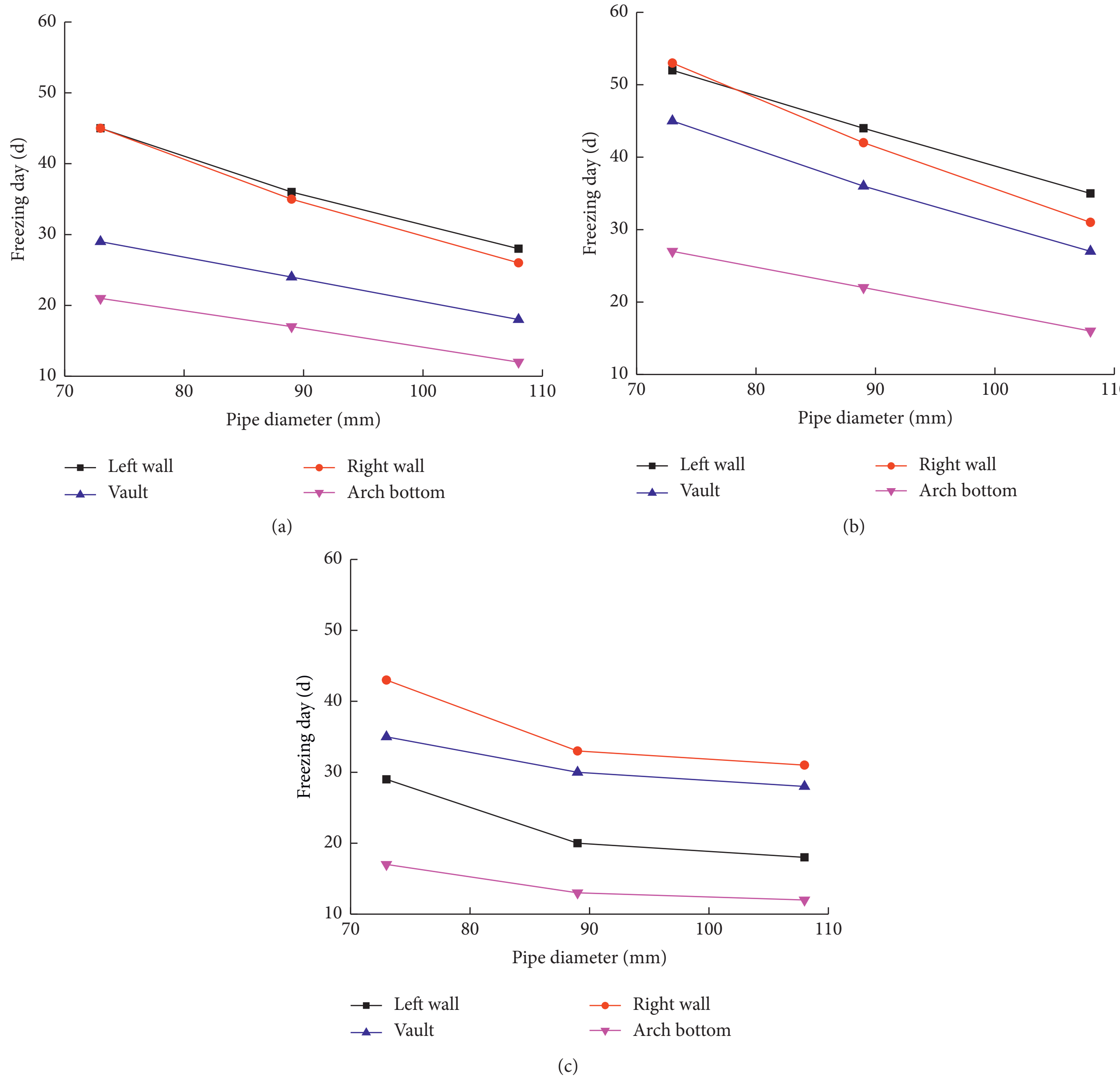

Figure 12: The time for the freezing wall thickness to meet the design requirement: (a) section 1-1; (b) section 2-2; (c) section 3-3.

4.1. Analysis of the Loss of Cooling Capacity. Figure 13 shows the temperature curves of gray silt layers of the two cross passages. It is found that the gray silt layers of cross passages No. 1 and No. 2 essentially have the same law of drop temperature. The number of days to drop to 0°C is 30 and 26 days, respectively. When frozen for 45 days, the average temperature difference between the two cross passages in the same stratum is 1.23°C. Although the distance of the No. 2 temperature measurement hole to the freezing pipe is 50 mm less than that of the No. 1 temperature measuring hole to the freezing pipe, the cooling curve shows that the temperature drop of the same stratum of the cross passage No. 2 is faster than that of cross passage No. 1. This is primarily because cross passage No. 1 is about 300 m from the freezing station, while cross passage No. 2 is only 20 m from the freezing station. Moreover, the brine water is transported through the pipeline, resulting in the brine water temperature difference of 1.5°C between the two cross passages. So, it indicates that the loss of cooling capacity affects the freezing efficiency of the cross passage.

4.2. Analysis of Different Strata. Figure 14 shows the temperature curves of the gray silt layer and the sandy silt layer of the cross passage No. 1. The times required for the gray silt layer and the sandy silt layer to drop to 0°C are 28 and 27 days, respectively. Moreover, the average cooling rates are 0.85°C/d and 0.89°C/d, respectively. It is found that the sandy silt layer has a faster cooling rate. When the temperature decreases to 0°C, the cooling rates of the two layers decrease slightly and then continue increasing until the layers are frozen for 45 days. Moreover, the temperatures of the sandy

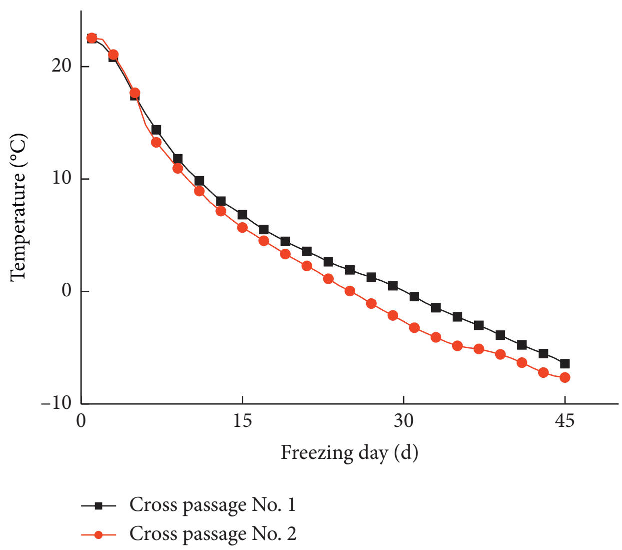

FIGURE 13: Temperature curves of the gray silt layer.

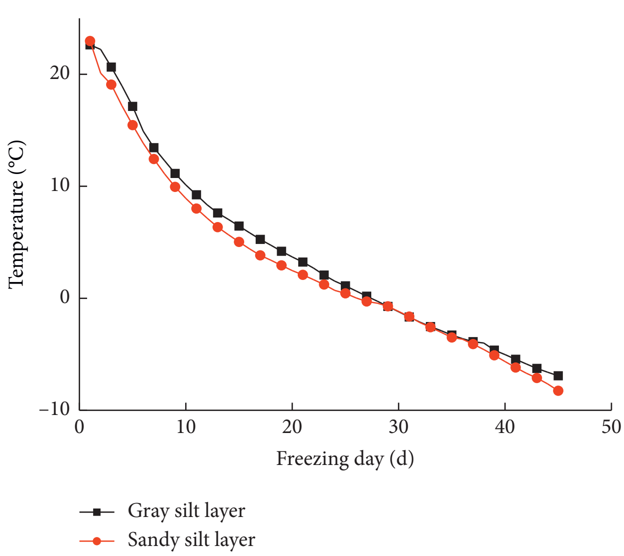

FIGURE 14: Temperature drop curves of different strata.

silt layer and the gray silt layer after 45 days are −8.25°C and −6.91°C, respectively. Therefore, the freezing effect of the sandy silt layer is better than that of the gray silt layer.

4.3. Analysis of Different Embedded Depths. Figure 15 shows that two temperature measuring holes C2 of cross passages No. 1 and No. 2 are utilized to measure temperatures at embedded depths of 0.5 m and 1.9 m in the soil. During the initial period of freezing, the soil near the duct piece absorbs the cold energy before the deep soil, and the cooling rate and trend are slightly greater than that of the deep soil. With increasing the freezing days, the soil temperature near the duct piece is affected by the heat exchange between the pipe segment and the outside air, resulting in a large loss of cooling capacity at the duct piece. Therefore, the cooling rate reduces, and the temperatures of the deep soil of cross passages No. 1 and No. 2 are lower than those of the soil at the duct piece on the 18th and 10th day, respectively. Furthermore, with increasing the freezing days, the temperature difference between the soil at the duct piece and the deep soil gradually increases until the temperature difference between the two is more than 5°C on the 45th day. Therefore, in order to ensure the freezing effect near the duct piece, it is necessary to strengthen the heat preservation and heat insulation of the duct piece during the freezing period to reduce the loss of cooling capacity.

4.4. Analysis of Different Parts. The vault of the auxiliary surface No. 1 and the vault and the arch bottom of the auxiliary surface No. 2 are frozen with a single row of holes, while the arch bottom auxiliary surface of No. 1 is frozen with the double-row holes. In this section, the temperatures of No. 1 arch bottom C11, vault C14, No. 2 vault C12, and the arch bottom C15 are studied. Figure 16 shows the temperature drop curves at different parts of the cross passage. It is observed that in 23 days, the soil temperatures at vaults No. 1 and No. 2 drop to 0°C, and the soil temperature drop rates are 1.06 and 0.93°C/d, respectively. Moreover, the soil temperatures at arch bottoms No. 1 and No. 2 dropped to 0°C in 22 and 15 days, respectively, and the soil temperature drop rates are 1.39 and 1.03°C/d, respectively. The results indicate that the arch bottom soil of the auxiliary surface No. 1 has the fastest cooling rate. The distance between the No. 1 temperature measuring hole C11 and the closest freezing pipe of the arch bottom is 939 mm, while the maximum distance between the other temperature measuring holes and the closest freezing pipe is 466 mm. So, it indicates that the double-row hole significantly enhances the freezing effect.

4.5. Freezing Wall Thickness and Freezing Wall Average Temperature. Considering the temperature of the measuring point near the freezing hole D1 as the research object, the inward development speed and the development radius of the freezing wall after 48 days are 30.92 mm/d and 1484.16 mm, respectively. Meanwhile, the outward development speed and the development radius of the freezing wall after 48 days are 26.40 mm/d and 1267.2 mm, respectively. Furthermore, it is found that the effective freezing wall thickness is 2413.36 mm. The development speed of the freezing wall is substituted into the formula for calculating the freezing wall average temperature, which is −11.54°C. Therefore, both the effective freezing wall thickness and the effective freezing wall average temperature meet the design requirements.

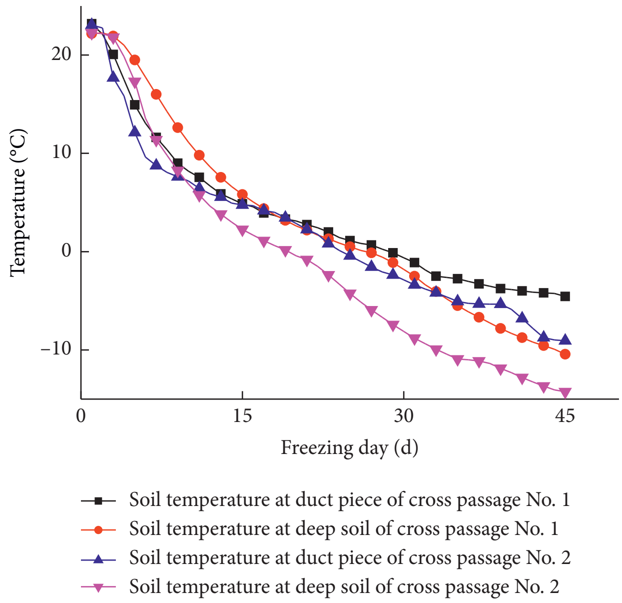

Figure 15: Temperature drop curves at different embedded depths.

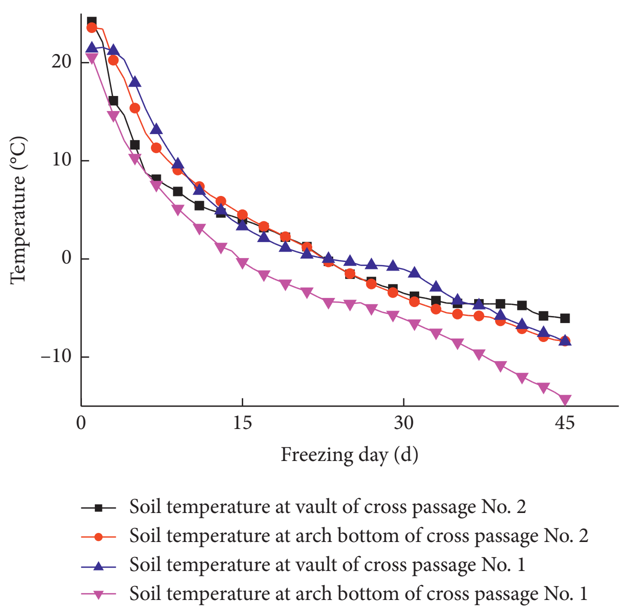

Figure 16: Temperature drop curves at different parts.

5. Conclusions

In this study, the cross passage freezing project of Shanghai Metro Line 15 is taken as the background. The freezing differences of the cross passages are obtained by comparing the measured data. Moreover, the ANSYS software is used to analyze and compare the freezing effects of the deviation freezing pipe model, nondeviation freezing pipe model, and different pipe diameter models based on deviation freezing pipes. The main conclusions of this study are as follows:

(1) The freezing effect of the gray silt layer of the cross passage No. 2 is better than that of the gray silt layer of the cross passage No. 1 due to the loss of cooling capacity. The freezing speed of the sandy silt layer is faster than that of the gray silt layer, and the stratum temperatures are −8.25 and −6.91°C when frozen for 45 days. The temperature of the soil at the pipe segment is higher than the temperature of the deep soil for the same stratum. The double-row hole can improve the freezing efficiency.

(2) The maximum difference between the closure completion times of the freezing wall for deviation and nondeviation freezing pipes is 6 days. When the closure of the freezing wall is completed, the difference between the maximum and the minimum thickness of the freezing wall in the deviation and nondeviation freezing pipes is 0.97 m and 0.4 m, respectively. Meanwhile, the minimum difference between freezing wall thicknesses in the deviation and nondeviation freezing pipes at the center of the cross passage varies from 0.45 mm after 20 freezing days to 0.06 mm after 45 freezing days. This indicates that the difference in the freezing wall thickness between the deviation and nondeviation freezing pipes gradually weakens as the freezing progresses.

(3) As the diameter of the freezing pipe increases, the freezing closure completion times for the freezing wall thickness to meet the design requirements are shortened. Comparing the sections with large and small spacing between freezing pipes presents that at the section with a large freezing pipe spacing, the change of freezing pipe diameter has a lower effect on the freezing closure time and the time required for the freezing wall thickness to meet the design requirements.

Data Availability

The 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.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (51504070 and 41672278), the Key Laboratory Open Subject Fund of Fujian University of Underground Engineering (KF-T18014), the Outstanding Young Scientific Research Talents Cultivation Program of Fujian University (GY-Z17070), the Research Development Fund of Fujian Institute of Engineering (GY-Z17158), the Fujian Provincial Natural Science Foundation Projects (2017Y4001), and the projects of Fuzhou Science and Technology Bureau (2017-G-59 and 2018-G-77).

References

[1] B. Yuan, M. Sun, L. Xiong, Q. Luo, S. P. Pradhan, and H. Li, "Investigation of 3D deformation of transparent soil around a laterally loaded pile based on a hydraulic gradient model test," *Journal of Building Engineering*, vol. 28, no. 03, Article ID 101024, 2020.

[2] C. Zheng, "Calculation and Application Research of Freezing Wall Thickness of Subway Connection Passage in water-Rich Gravel," *Xi'an University of science and Technology*, Xi'an, China, 2020.

[3] B. X. Yuan, M. Sun, Y. X. Wang, L. H. Zhai, and Q. Z. Luo, "Full 3D displacement measuring system for 3D displacement field of soil around a laterally loaded pile in transparent soil," *International Journal of Geomechanics*, vol. 19, no. 05, Article ID 04019028, 2019.

[4] L. C. Lu, Z. Zhang, W. J. Feng, W. Du, B. H. Liu, and C. L. Chen, "Research on variability of freezing-thawing cycle on basic physical and mechanics properties of clay minerals," *Hydrogeology & Engineering Geology*, vol. 44, no. 04, pp. 118–123, 2017.

[5] L. F. Zheng, Y. T. Gao, Y. Zhou, and S. G. Tian, "Research on surface frost heave and thaw settlement law and optimization of frozen wall thickness in shallow tunnel using freezing method," *Rock and Soil Mechanics*, vol. 41, no. 06, pp. 2110–2121, 2020.

[6] X. D. Hu, X. Y. Li, Y. H. Wu, L. Han, and C. B. Zhang, "Effect of water-proofing in Gongbei Tunnel by freeze-sealing pipe roof method with field temperature data," *Chinese Journal of Geotechnical Engineering*, vol. 41, no. 12, pp. 2207–2214, 2019.

[7] Z. S. Yao, L. X. Zhao, H. Cheng, and H. S. Xu, "Optimization design and measurement analysis on inter lining of high strength reinforced concrete frozen shaft lining with deep topsoil," *Journal of China Coal Society*, vol. 44, no. 7, pp. 2125–2132, 2019.

[8] G. Z. Li, D. C. Chen, and W. GAO, "Research on design method for thickness of freezing wall in thick alluvium over 600 m," *Coal Science and Technology*, vol. 48, no. 1, pp. 150–156, 2020.

[9] Z. Q. Rao, *Numerical Simulations for Freezing Method in Connecting Channel Excavation of Nanchang Subway*, Nanchang University, Nanchang, China, 2018.

[10] J. Ma, P. Yang, Z. G. Liu, Z. Y. Li, and L. Chen, "Study on thawing law of the connecting passage in changzhou sandy formation," *Chinese Journal of Underground Space and Engineering*, vol. 15, no. 01, pp. 167–173+180, 2019.

[11] X. Y. Chen, Z. S. Tan, J. Yuan, G. Wang, and J. W. Li, "Case study on soil reinforcement method for the cross-passage construction of shield tunnel in water-rich round gravel stratum," *China Civil Engineering Journal*, vol. 50, no. S1, pp. 105–110, 2017.

[12] Y. Yang, *Study on Influence of Groundwater Seepage on Freezing Temperature Field of Contact Channel*, China University of Mining and technology, Xuzhou, China, 2017.

[13] P. Yang, J. Chen, S. G. Zhang, and C. D. Wang, "Whole range monitoring for temperature and displacement fields of cross passage in soft soils by AGF," *Chinese Journal of Geotechnical Engineering*, vol. 39, no. 12, pp. 2226–2234, 2017.

[14] B. X. Yuan, L. Xiong, L. H. Zhai et al., "Transparent synthetic soil and its application in modeling of soil-structure interaction using optical system," *Frontiers in Earth Science*, vol. 7, no. 01, p. 276, 2019.

[15] J. J. Cao, W. Wu, P. F. Zheng et al., "Analysis of artificial freezing temperature field for connected adit in water-rich sandy pebble stratum," *Railway Engineering*, vol. 59, no. 12, pp. 55–59, 2019.

[16] P. Li and X. Y. Xie, "Research on optimization of freezing-temperature monitoring design and method of data analysis in Shanghai Yangtze river tunnel," *Chinese Journal of Underground Space and Engineering*, vol. 8, no. 01, pp. 122–128, 2012.

[17] H. B. Cai, Y. C. Huang, and T. Pang, "Finite element analysis on 3D freezing temperature field in metro connected aisle construction," *Journal of Railway Science and Engineering*, vol. 12, no. 06, pp. 1436–1443, 2015.

[18] Z. H. Li, *Research on the Mechanics about Accident of Subway Engineering with Refrigeration Construction Technology and its Repairing Technology*, China University of Mining & Technology, Beijing, China, 2013.

[19] S. Zhang, Z. R. Yue, J. W. Zhang, T. C. Sun, and L. Wang, "Distribution of soil temperature field close to tunnel end and optimization of segment insulation measures in cross-passage construction by artificial ground freezing method," *China Railway Science*, vol. 41, no. 03, pp. 95–102, 2020.

[20] J. H. Chen, H. B. Xia, and D. W. Li, "Multi-circle-tube frozen wall temperature field development and deviation pipes influence," *Acta Scientiarum Naturalium Universitatis Sunyatseni*, vol. 55, no. 04, pp. 56–62, 2016.