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Research Article

Field Temperature Data Analysis of the Water Resistance Performance of Freeze-Sealing Pipe Roof Used in Tunnel through Water-Rich Strata

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A new presupporting technology named freeze-sealing pipe roof (FSPR) method was adopted in the construction of Gongbei tunnel (Zhuhai, P.R. China), which was a critical part of Hong Kong-Zhuhai-Macau Bridge (HZMB). The method combined the pipe-roofing with artificial ground freezing (AGF). The water resistance performance of FSPR surrounded by water-rich soils was studied based on the field temperature data. The time-dependent temperature changes of the frozen soil between two adjacent pipes were presented, and the thicknesses of the frozen soil in different freeze period were calculated. Besides, the remote temperature monitoring system used in this field research was presented systematically. The thermal effects of the Hurricane Nicole on the frozen soil wall were also observed. The results showed that the closure of frozen soil wall can be classified into two different modes. The frozen soil between the pipes before excavation had met the design requirements before excavation, and the FSPR maintained satisfied water resistance performance.

1. Introduction

As a kind of presupporting technology for underground excavation, pipe-roofing method can effectively control the ground disturbance due to the excavation construction. This method has been widely used in geotechnical engineering combined with other innovative methods, such as ESA (endless self-advancing method), FJ (front jacking method), RBJ (roof-box jacking method), Okumura R&C method, TULIP method [1], SR-J method [2], and New Tubular Roof method [3]. These presupporting methods provide good construction condition for excavation but expose the weakness of water sealing in long-distance curved pipe-jacked roofs. To solve this problem, a new presupporting technology named freeze-sealing pipe roof (FSPR) method is adopted for the first time in the world at Gongbei tunnel which is a critical part of Hong Kong-Zhuhai-Macau Bridge (HZMB).

The freeze-sealing pipe roof (FSPR) method combines the pipe-roofing method with artificial ground freezing (AGF) method [4]. The pipe roof which includes a number of large-diameter steel pipes mainly plays a role in load bearing, and the soil between the steel pipes is continuously refrigerated to form a frozen wall to prevent ground water from flowing into the excavation area.

Before the FSPR method is proposed, there was a similar method that could be called pipe-shed freezing method, which had appeared in Germany, Japan, and China [4]. In that method, frozen soil wall mainly played a role in load bearing, which was essentially different from the FSPR method. Moriuchi and other researchers carried out experimental and theoretical research on the mechanical characteristics and the interaction between them [5–7].

A series of research on FSPR system has been done in recent years. Zhang et al. [8] summarized the most challenging aspects and introduced the relevant techniques

Figure 1: Section of Gongbei tunnel.

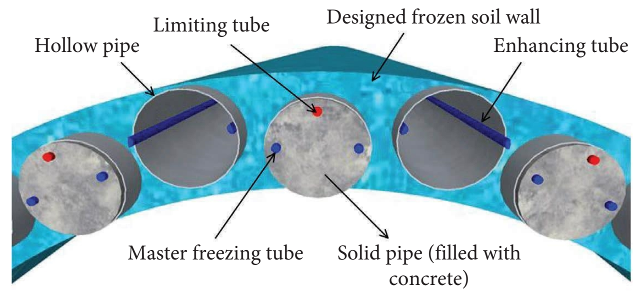


Figure 2: Schematic of the freezing scheme.

applied during construction. Liu et al. [9] elaborated on the selection of the construction method and the design of the curved pipe roof as well as the horizontal precise soil freezing curtain. Zhou et al. [10] presented a case study of this system on the mechanical responses in the construction process. Duan et al. [11] studied the feasibility of the improvement and the difference in the freezing temperature field by designing three different pipe configurations and using scaled model tests and numerical simulation. Zhou et al. [12] analyzed the vertical ground movement caused by frost heave and thawing based on the field measurement. Cai et al. [13] also simulated the frost heave and thawing settlement laws of the tunnel by the full-coupled numerical analysis method of transient temperature and displacement. Zhou et al. [14] conducted an experimental investigation on the mechanical characteristics of this waterproof system.

The studies on the FSPR method mentioned above contained numerical simulation, laboratory test, model test, and in-situ test, but the conclusions were not been verified by the field data that measured in the engineering construction. The authors' former study presented the time-dependent changes of field temperature of the frozen soil between two adjacent pipes and qualitatively analyzed the water resistance performance of the FSPR system [15]. This paper further studied the water resistance performance quantitatively by calculating the thicknesses of the frozen soil and found two different closure modes of frozen soil wall.

2. Engineering Background

2.1. Pipe Roof of FSPR and the Freezing Scheme. The Gongbei tunnel, constructed by shallow tunneling method, is a double-decker integral tunnel with large section under-crossing the Gongbei Port. The length is about 255 m, and the excavation section is about 19 m high and 20 m width. The section area is about 345 m^2, and the buried depth is only 5~6 m. 36 steel pipes with diameter of 1620 mm are used as the presupporting system around the tunnel, and the soil between the pipes is refrigerated by AGF. The entire pipe roof supporting system and excavation zone are shown in Figure 1, where the odd-numbered pipes are offset radially inward by approximately 30 cm. Before the start of freezing, the odd pipes are filled with concrete, and the even pipe is an empty pipe. The solid pipes filled with concrete improve the strength and rigidity of the entire supporting system and also facilitate the transfer of cooling to the surrounding once freezing begins. The empty pipes can be used as an inspection passage during the freezing construction process to facilitate the monitoring and grouting. The empty-top pipe is filled with concrete in time after the completion of the tunnel construction.

As seen in Figure 2, in each of the odd pipes which are finally filled with concrete, two Φ108 circular freezing tubes are arranged at the middle of the pipe edge as the master freezing tube. And a Φ159 limiting tube is placed near the outer edge of the frozen soil wall, which is used to control the thickness of the frozen soil. And in the even pipes, two special-shaped freezing tubes named enhancing tube are also arranged at the edge of the tube to strengthen the freezing and ensure sealing performance between the pipes. More details about the freezing philosophy in FSPR can be seen in paper [9].

2.2. The Temperature Monitoring System. During the entire construction process, the remote temperature measurement system [16] was used to monitor the temperature of the soil and the brine loop. The schematic of the monitoring system is shown in Figure 3. It can be seen that the system includes sensors, cables, data acquisition modules, long-distance data transmission lines, data converters, and computers. Several digital thermal sensors are encapsulated inside one temperature measuring cable, and then, the cable is placed in certain temperature monitoring hole according to the design after that the cables are connected to the data acquisition modules and the modules communicate with the computer through data transmission lines, using RS485 network. The converters convert the RS485 network interface into the RS232 interface that can be recognized by the computer. Thus, the data measured by the sensors are collected and finally transferred to the upper computer. This system has much advantage such as simple distribution in site, high adaptability to the abominable surroundings, easy extensibility, and automatic data collection. For the monitoring of soil temperature, 32 measuring faces are arranged

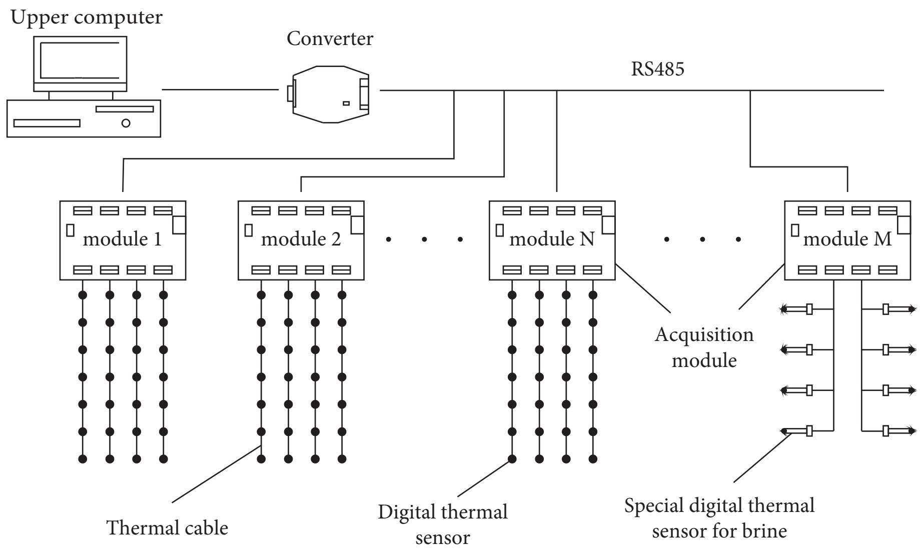


FIGURE 3: Schematic of the temperature monitoring system.

longitudinally along the tunnel, and each of the two measuring faces is separated by about 8 m. The temperature measurement points of each measuring surface are divided into the wall temperature measuring points and the soil temperature measuring points outside the pipe.

The arrangement of the measuring points of the Nth measuring surface is shown in Figure 4. Considering the arrangement of the freezing pipes, there are 7 wall temperature measuring points in the odd pipe and 6 in the even pipe; the soil temperature measuring points outside the pipe are from all the even pipes and 4-odd pipes (5# pipe, 15# pipe, 23# pipe, 33# pipe). Besides, 3 to 7 temperature measuring points are arranged in the holes. The temperature of each measuring point can be combined to judge the development and changes of the frozen soil wall. The naming rules of the measuring points are D+ pipe number-measuring surface number-B/S (B stands for wall temperature measuring point, S stands for soil temperature measuring point) + measuring point sequence. For example, D09-01-S2 represents the second soil measuring point of the 1st measuring surface of the 9# pipe.

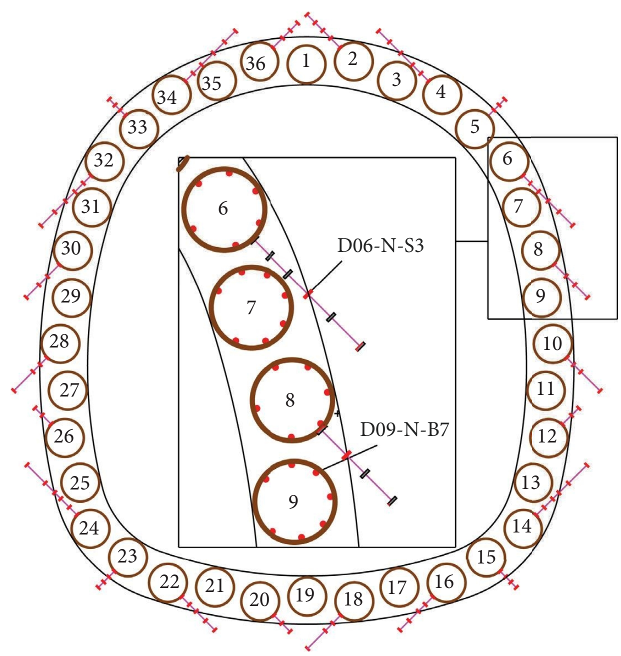


FIGURE 4: A typical measuring face N.

3. Methods to Calculate the Thickness of the Frozen Soil

A key factor that can quantify the freezing effect of FSPR is the thickness of the frozen soil. Due to the large cross-section and shallow depth of the tunnel, the frozen soil is not evenly distributed along the cross section of the tunnel. From the longitudinal direction, the distribution of frozen soil near the two ends of the tunnel is different from that in the middle. Therefore, the thickness of the frozen soil used to judge the freezing effect should not be the average thickness of the whole frozen soil at certain section, but be the thickness of the local frozen soil between the steel pipes.

The usual method for solving the thickness of frozen soil from the measured temperature is to perform linear interpolation based on temperature value of the soil measuring point to obtain the position of the freezing point, thereby calculating the thickness of the frozen soil. Although the above method is simple and convenient, it lacks theoretical basis, and the error is uncontrollable. A different method to calculate the thickness of frozen soil is proposed in this paper based on the analytical solution of the steady-state temperature field produced by multitubed freezing [17]. The formulas of temperature field of "single-tube" and "double-tube" are adopted separately in different periods of active freezing. The relevant schematic diagram is shown in Figure 5.

The "single-tube" formula is

$$T = T_0 + \frac{\ln r/\xi}{\ln r_0/\xi}\left(T_f - T_0\right), \quad (1)$$

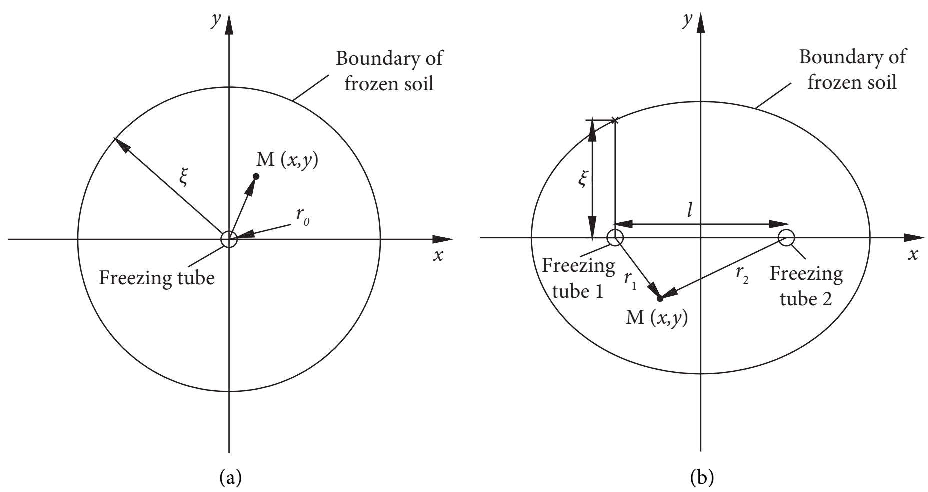


FIGURE 5: Schematic of two formulas of temperature field: (a) schematic of "single-tube" formula and (b) schematic of "double-tube" formula.

where r is the distance from the center of the freezing tube to arbitrary point $M(x, y)$; T is the temperature value of the point M; T_0 is the freezing point of soil; T_f is the surface temperature of freezing tube; r_0 is the radius of the freezing tube; ξ is the distance from the boundary of frozen soil to the center of the freezing tube, recognized as the thickness of the frozen soil.

The "double-tube" formula is

$$T = T_0 + \frac{\ln r_1/\xi + \ln r_2/\sqrt{\xi^2 + l^2}}{\ln r_0/\xi + \ln l/\sqrt{\xi^2 + l^2}} \left(T_f - T_0\right), \qquad (2)$$

where r_1 and r_2 are the distance from the point $M(x, y)$ to the center of the freezing tube 1 and freezing tube 2, respectively; l is the distance between two tubes; ξ is the distance from the boundary of frozen soil to the center of the freezing tube 1 along y direction, recognized as the thickness of the frozen soil; other symbols are the same as above.

4. Results and Discussion

The brine circulation of the frozen pipes in each area continued to start from the middle and late February of 2016. A trial excavation was carried out around June 20, 2016, and the official excavation started on about August 20, 2016. In this paper, the active freezing period refers to the time interval from start of the brine circulation to the start of official excavation.

4.1. The Closure of Frozen Soil. The closure time of the frozen soil wall is very meaningful in the AGF, which illustrates that the frozen soil wall is forming a united frozen soil curtain and the curtain starts to have the capability of water sealing. Whether or not the circle can be achieved within the required time is also one of the criteria for judging whether the new method of FSPR is reasonable or not. It should be noted that the term "closure" does not necessarily mean the closure of two ice columns in the general meaning. The closure of the frozen soil and the adjacent steel pipe in this work also mean "closure" (see below in the case of the closure mode 1 in Figure 6(a)).

In the actual construction, the opening time of the freezing tubes is not completely the same. The circular master freezing tubes are first opened, and then, the fan-shaped enhancing freezing tubes are successively opened in order to speed up the refrigeration. Two different closure modes are found based on the measured field temperature. Mode 1 is shown in Figure 6(a), in which the frozen soil has been developed from the filled steel pipe to the adjacent empty pipe to form a water barrier before the fan-shaped enhancing tube is opened; mode 2 is shown in Figure 6(b), in which, the frozen soil has not yet developed to the adjacent empty pipe when the fan-shaped tube is opened. Soon after the opening of the fan-shaped enhancing tube, the closure is achieved as a joint result of the master freezing tube and the enhancing freezing tube.

Firstly, the area between 08# and 09# pipe at 11th measuring face is selected for the illustration closure mode 1. This area is at the middle of the tunnel longitudinally and vertically, and there is no thermal disturbance around. Figure 7 shows the temperature variations of the measuring points at the above area and the corresponding thickness of the frozen soil calculated by "single-tube" formula. The position of the measuring points is shown on the top left corner with a box around it. When the two master freezing tubes of the 9# pipe were opened on March 11, the temperatures of D09-11-B6 and B7 decreased rapidly. The thickness of frozen soil increased fast and reached the required thickness of the closure on about March 19th. At this time, the enhancing tube of the 8# pipe had not been opened yet. This kind of closure is classified as closure mode 1.

However, for some areas at the upper part of the tunnel, the initial temperature of the soil is higher, and the temperature field is easily affected by the thermal disturbance from ground surface. The boundary of frozen soil expanded

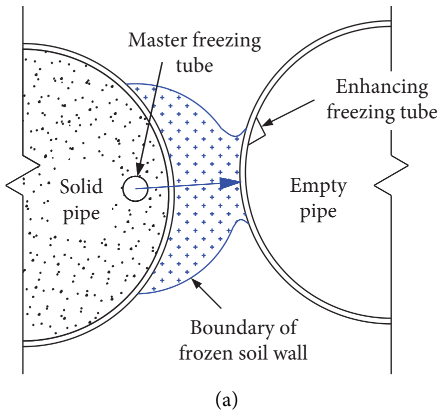


FIGURE 6: Schematic of two closure modes: (a) closure mode 1 and (b) closure mode 2.

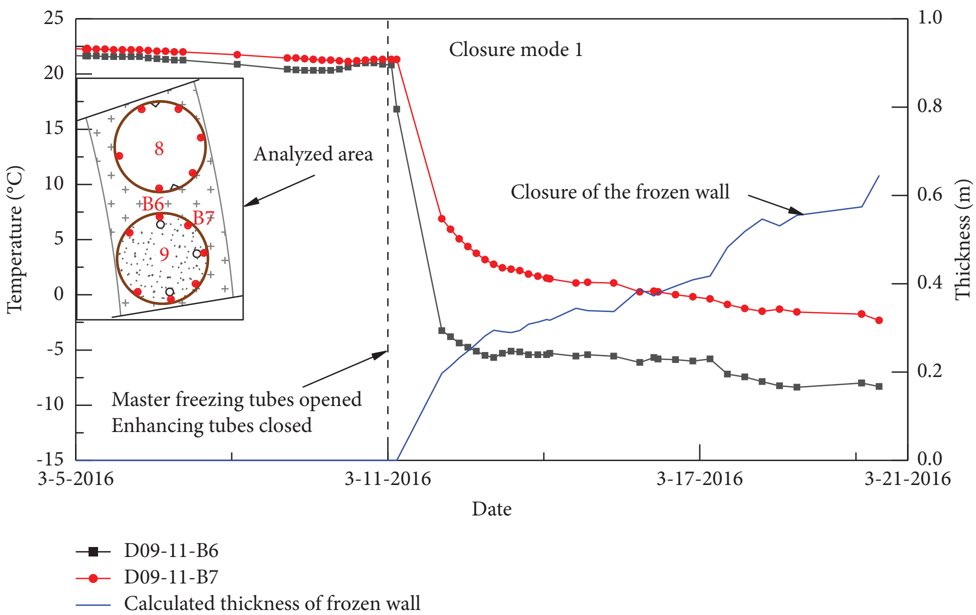


FIGURE 7: Temperatures of measuring points and calculated thickness of frozen soil in closure mode 1.

more slowly in the upper area, forming a situation of the closure mode 2. Figure 8 shows the measured temperature of the area between 35# and the 36# pipe at 11th measuring face. The variation of the thickness of the frozen soil with time is also illustrated. The area is located at the end of the tunnel near the east working shaft. The circular freezing tube has been opened since late February. The temperatures of corresponding measuring points did not decrease as fast as the points in Figure 7, either the thickness of frozen soil. The mode 1 closure had not been achieved with only master freezing tubes in the 35# pipe opened. When the enhancing tube was opened on March 23, the frozen soil between pipes began to develop rapidly. After about 4 days, the closure of the frozen soil in the area was completed in form of closure mode 2.

The boundary conditions of the above two areas are very different. The soil around the former is thicker, and the thermal disturbance is smaller. The latter is close to the land surface and is greatly influenced by the external thermal disturbance. The two represent different freezing effects at different regions in the early active freezing period. For areas with less thermal disturbance, the speed of the development of frozen soil is fast enough, and the mode 1 closure can be achieved with only the master freezing tubes within the required time. While for the areas where the heat dissipation is more serious, it is quite difficult to form the closure with only the circular master freezing tube. The thickness can be achieved in required time as a joint result of the master freezing tube and the enhancing freezing tube.

4.2. The Development of the Frozen Soil Wall after Closure. After the closure, the frozen soil wall continues to develop. Figures 9(a) and 9(b) show the temperature variation of the measuring points and the corresponding brine temperature at the upper and lower part of the roof, respectively. The thickness of the frozen soil between the tubes, calculated by "double-tube" formula, is also drawn in each of the figure.

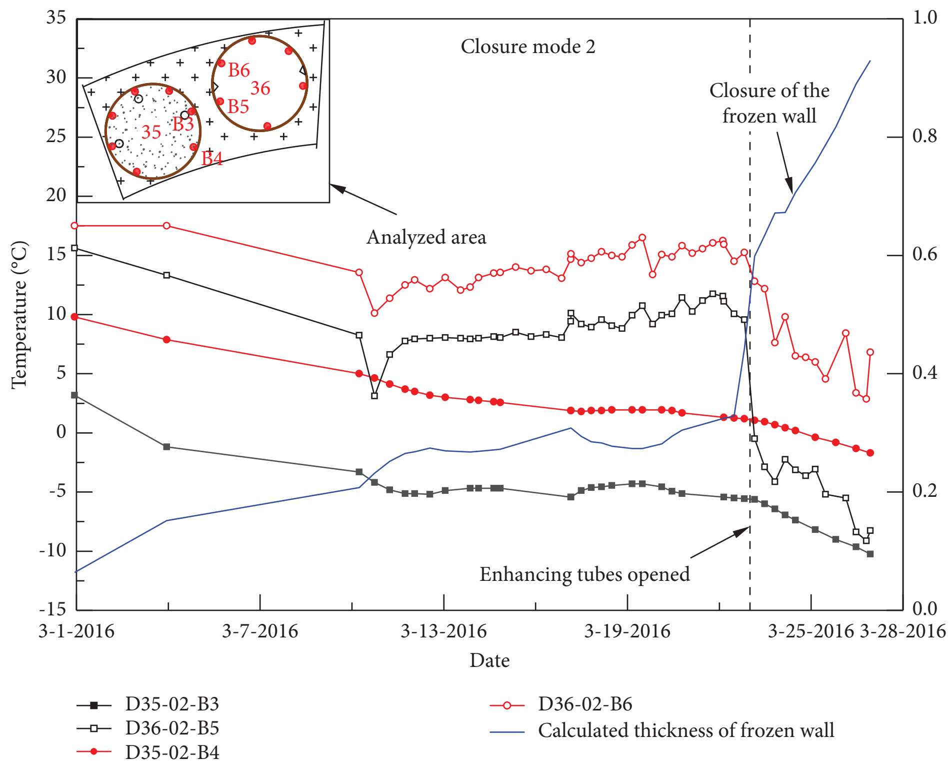


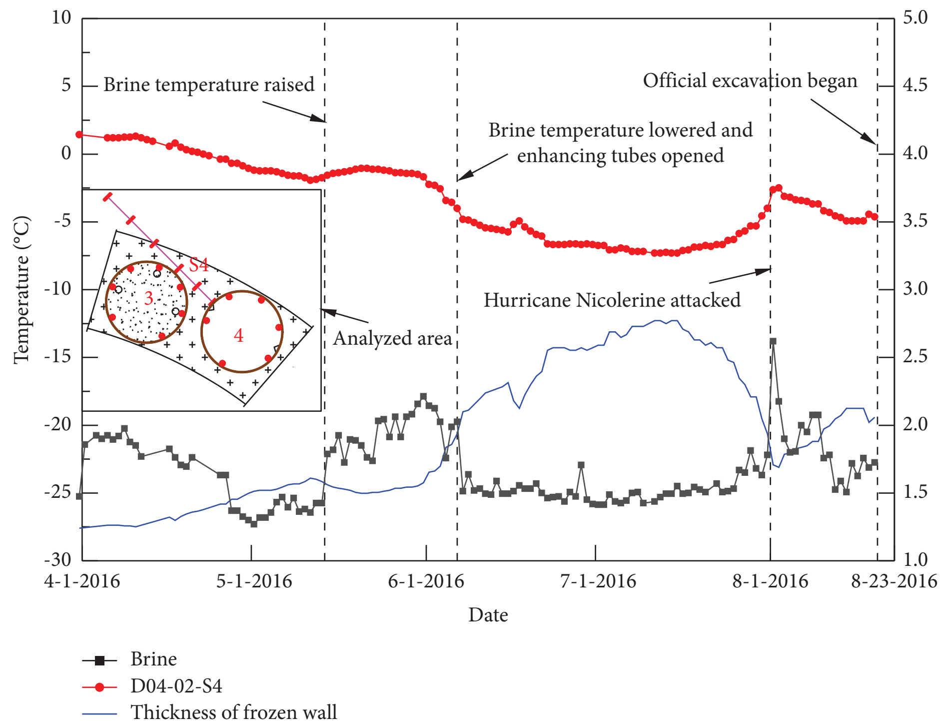
Figure 8: Temperatures of measuring points and calculated thickness of frozen soil in closure mode 2.

As seen in both of Figures 9(a)and 9(b), brine temperature is one of the main influencing factors of the developing trend of the frozen soil. At the beginning of the refrigeration, the temperature of the measuring point dropped, and the frozen soil developed steadily. However, from the middle of May to the beginning of June, the brine temperature was generally increased due to the maintenance of the refrigeration system, which caused slowdown of temperature decrease of the soil measuring point, even a slight increase. After the brine temperature was lowered again, the frozen soil wall restarted to develop. During the three days from July 30th to August 1st, the arriving of Hurricane Nicole affected the construction and the power cut out. The temperatures of the measuring points rebounded. Comparing Figure 9(a) with Figure 9(b), it can be concluded that the upper area is greatly affected by the Hurricane, while the lower part is less influenced.

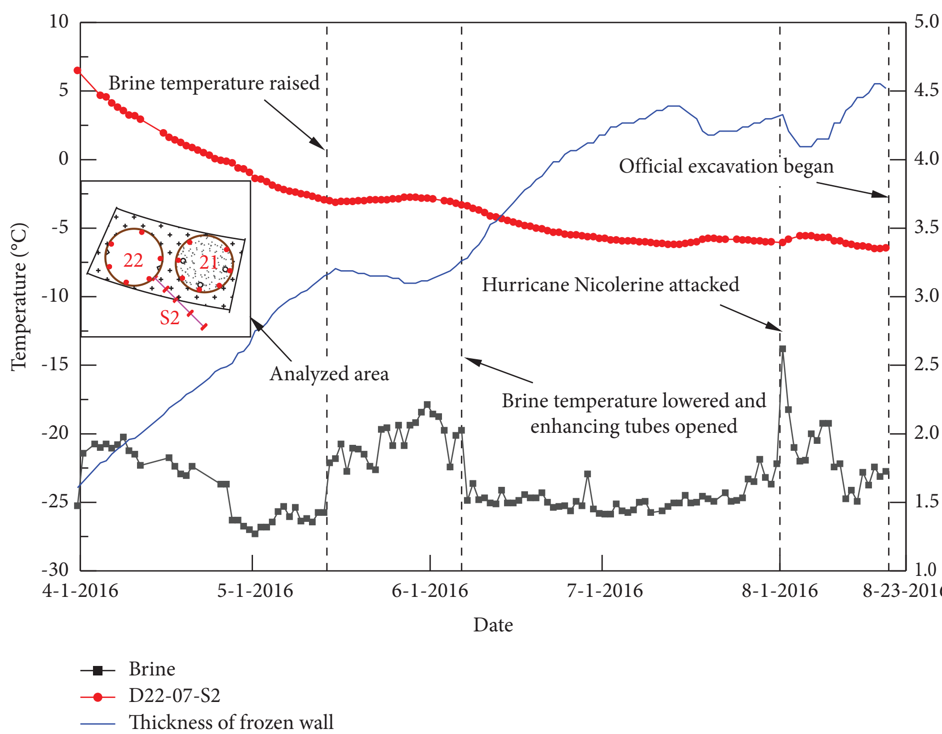
In addition, the active freezing effect of the area in Figure 9(a) is not as good as that in Figure 9(b). The main reason is that the analyzed area in Figure 9(a) is closer to the ground, and there is a drainage pipe above it. The flow of water causes a large amount of heat exchange. The analyzed area shown in Figure 9(b) has a deeper depth. The external thermal disturbance is small, and the development of frozen soil is stable. The freezing effect of FSPR in most areas is similar to that of Figure 9(b).

The thickness of the frozen soil wall between the pipes of multiple parts on the day just before the official excavation was calculated through the double-tube formula, and the results are shown in Tables 1 and 2. Considering that the frozen soil within the tunnel boundary would be dug away during excavation, the data in the above tables were calculated as the result of corresponding reduction of the thickness according to the design tunnel boundary.

Tables 1 and 2 show that freezing effects of the upper part are worse than that of the lower part, whether the section is at the middle or near the two ends of the tunnel. Along the longitudinal axis of the tunnel, the thickness of the frozen soil wall near the both two shafts is very narrow (less than 2 m), under the influence of the heat dissipation, while the frozen soil wall at the middle area is much thicker (all more than 2 m). As far as the entire tunnel is concerned, the frozen



(a)



(b)

Figure 9: Temperatures of measuring points, the brine, and calculated thickness of frozen soil vs. time: (a) area between 3# and 4# pipe at 02 measuring face and (b) area between 21# and 22# pipe at 07 measuring face.

Table 1: Thickness of the frozen soil wall calculated by the selected measuring points of the upper soil.

Near east shaft		At the middle		Near west shaft	
Selected measuring point	Thickness of calculated frozen soil (m)	Selected measuring point	Thickness of calculated frozen soil (m)	Selected measuring point	Thickness of calculated frozen soil (m/m)
D02-01-S4	1.56	D36-10-S3	3.42	D36-26-S3	2.49
D02-04-S4	1.45	D36-13-S3	2.78	D36-28-S3	2.72
D36-01-S4	0.84	D36-14-S3	3.07	D36-29-S3	2.19
D36-03-S4	0.43	D36-15-S3	2.62	D36-31-S3	1.35
D36-05-S4	0.52	D36-20-S3	2.74	D36-32-S3	0.96

Table 2: Thickness of the frozen soil wall calculated by the selected measuring points of the middle and lower soil.

Near east shaft		At the middle		Near west shaft	
Selected measuring point	Thickness of calculated frozen soil (m)	Selected measuring point	Thickness of calculated frozen soil (m)	Selected measuring point	Thickness of calculated frozen soil (m/m)
D16-01-S3	3.69	D16-08-S3	4.17	D16-29-S3	2.05
D16-02-S3	2.58	D16-13-S3	5.03	D16-30-S3	1.64
D16-03-S3	2.23	D16-14-S3	3.72	D16-31-S3	2.66
D30-01-S3	2.31	D30-08-S3	3.71	D26-29-S1	2.73
D30-02-S3	3.70	D30-10-S3	5.85	D26-30-S1	2.93
D30-03-S3	3.85	D30-13-S3	3.16	D26-31-S1	2.32
D30-04-S3	3.05	D30-16-S3	2.30	D26-32-S1	2.00

soil between the pipes before excavation has come to closure, and the water sealing requirements between the pipes can be satisfied.

5. Conclusion

In this paper, the water resistance performance of the FSPR system used in Gongbei tunnel construction through water-rich strata was studied based on the field temperature data. The time-dependent changes of temperature of the frozen soil between two adjacent pipes were presented, and the thicknesses of the frozen soil in different freezing period were calculated. The conclusions obtained are as follows:

(1) The closure of frozen soil wall can be classified into two modes. The enhancing tubes have a great impact on closure mode 2. Both two modes of closure can be achieved within required time.

(2) The development of frozen soil wall is not uniform. The thickness of frozen wall at the middle of the tunnel is much higher than the ends. For same tunnel section, the frozen soil wall near the middle and lower parts develops better than that of the upper parts.

(3) When Hurricane arrived, the upper area is greatly affected but the whole frozen soil walls remained good performance.

(4) The frozen soil between the pipes before excavation had met the design requirements before excavation, and the FSPR maintained satisfied water resistance performance.

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

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