Study of Freezing Scheme in Artificial Horizontal Ground Freezing Method in Multi-lane Road Tunnel Based on Numerical Simulation of Temperature Field

Jun Zhang

CCCC Second Highway Consultant Co. Ltd, Wuhan, Hubei, 430056, China
E-mail: 619402356@qq.com

Abstract. Artificial ground freezing method to form a frozen soil wall to cut off water and resist the soil pressure before excavation, was rarely used in Bangladesh such a vast hilly area. In this paper, connecting channel construction in Multi-lane Road Tunnel under the River Karnaphuli Chittagong – Bangladesh which is proposed to be constructed by double-row-ring freezing method, is taken as the study object. Taking the development of temperature field, the resisting ability of frost wall to thermal disturbance resulted from excavation, analysis of different freezing condition by numerical simulation is carried out for active and maintaining freezing stages, so that some guidance could be given for the final selection of freezing scheme. The results show that the design and construction scheme were reasonably practicable.

1. Introduction
Artificial ground freezing (AGF) is a technique which converts the soil water into ice by use of artificial refrigeration technology, creating a strong, watertight frost wall which can serve as temporary retaining structure[1]. The first recorded application of AGF was on a mine-shaft project near Swansea, South Wales, in 1862[2], and it has also been in use for more than 40 years in China. It is now widely used in many parts of the world to assist in the construction of shafts, tunnels, and many other structures [3]-[8].

In the highway shield tunnel, the risk of construction of cross passages which located at the sea entrance of river, such as Shanghai Yangtze River tunnel[9]. Zhou[10] analysed the thickness of the freezing wall calculated and measured from the site. Yang[11] make a research on the development rules of the frost wall and suggested an optimized design. But it is less experience of AGF used in Bangladesh with high ground temperature condition. In this paper, taking Multi-lane Road Tunnel project, as the study object, 2D temperature field analysis of freezing schemes by comsol is carried out for the active and maintaining freezing stages.

2. Background of Project
The Project of Multi-lane Road Tunnel under the River Karnaphuli, Chittagong - Bangladesh is located in Chittagong, connecting the east and west banks of River Karnaphuli, with the total length of 9265.971m. The shield tunneling method is used for crossing the River Karnaphuli. The general layout of the project is as shown in the figure 1.

Three connecting channels of the shield tunneling section are to be built at K2+975 (tunnel clear distance: 12.14m), K3+619 (tunnel clear distance: 12.34m) and K4+320 (tunnel clear distance: 10.74m) respectively to meet the design requirements and the needs of disaster prevention and rescue. The No.1
and No.2 connecting channel are located in the Stratum ④1—silty and fine sand. The No.3 connecting channel is located in the Stratum ③8—silty sand.

The 400mm thick concrete lining is used as the stress structure of the connecting channel, with its inner diameter of 3.4m. The freezing construction method is adopted, with the thickness of the frost wall of 3.1m. The frost wall at the bell mouth is 2.5m thick as shown in Figure 2. Double-row-ring freezing is to generate frost wall by 44 freezing tubes as shown in Figure 3 and Figure 4.
3. Numerical model

3.1. Model calculation and assumption
Since the affected area is small, all strata are distributed horizontally within the calculating area of the project location; Since the strata ③ and ④ of the connecting channel have the groundwater flow rate of 2.87m/d<5m/d, there is less influence from the groundwater to freezing[12], yet the application of double-row-pipe against freezing (there are lots of successful cases with groundwater flow rate of about 10m/d) can achieve higher possibility of success, so the influence from the groundwater flow will not be considered in calculation.

3.2. Parameters of stratum model

Table 1. Model material parameters [11]

| Stratum No. | Density (kg/m3) | Water content % | Heat conductivity coefficient W/(m*K) | Latent heat of phase change kJ/kg | Specific heat kJ/(kg.℃) |
|-------------|----------------|-----------------|--------------------------------------|---------------------------------|------------------------|
| 4 (28-17)   | 2050           | 2010            | 24                                   | 1.44                            | 1.64                   |
| 3-8(53-14)  | 2150           | 2115            | 19.4                                 | 1.74                            | 2.05                   |

3.3. Load
1. In calculation, the initial temperature of ground temperature before freezing shall be 18℃ and 25℃.
2. The freezing temperature of soil is -1.5℃ for strata 3-8 (53-14) and -1.5℃ for strata4 (28-17).
3. The conditions of unexcavated tunnels and saline temperature drop during freezing are as shown in the table 2:

Table 2. Plan of saline temperature drop

| Time (d) | Temperature(℃) |
|----------|-----------------|
| 1        | 18              |
| 7        | -18             |
| 15       | -28             |
| 20       | -30             |
| 30       | -30             |
| 60       | -30             |
| 90       | -30             |
| 120      | -30             |

4. During tunnel excavation, the excavated face is exposed to air, the air temperature is 10℃ and the heat transfer coefficient is 15W/(m²·K).
5. During tunnel excavation, after the excavated face is laid with wood lagging, the air temperature is 10℃ and the heat transfer coefficient is 0.4W/(m²·K).

3.4. Calculation model
The calculation model is built by Comsol software as shown in Figure 5:
The construction processes are simulated as follows:
1. Set the initial temperature.
2. Apply the freezing pipe temperature load for active freezing.
3. Conduct underground excavation and weaken the frozen wall with air convection.
4. Conduct underground excavation for 5 days, and keep the frost wall warm by laying wood lagging, to reduce the weakening action from air convection to frost wall.

4. Calculation results

4.1. Stratum ④- No.1 and No.2. connecting channels

(a) 20-day temperature cloud atlas (initial ground temperature 18 °C)
(b) 20-day temperature cloud atlas (initial ground temperature 25 °C)
(c) 80-day temperature cloud atlas (initial ground temperature 18 °C, reaching the design thickness)
(d) 95-day temperature cloud atlas (initial ground temperature 25 °C) reaching the design thickness
(e) 85-day temperature cloud atlas (initial ground temperature 18 °C, before excavation)

(f) 100-day temperature cloud atlas (initial ground temperature 18 °C, before excavation)

(g) 5-day temperature cloud atlas after excavation (The initial ground temperature is 18 °C), the excavation surface is exposed to the air

(h) 5-day temperature cloud atlas after excavation (The initial ground temperature is 25 °C), the excavation surface is exposed to the air

(i) 30-day temperature cloud atlas after excavation (initial ground temperature 18 °C)

(j) 30-day temperature cloud atlas after excavation (initial ground temperature 25 °C)

Figure 6. Temperature field of No. 1 and No. 2 connecting channels

The calculation result of temperature field in No.1 and No.2 cross passage are given, as shown in Figure 6. The frost wall enclose time of the No.1 and No.2 cross passage is about 20 days. When the initial ground temperature is 18°C, after freezing 80 days, No.1 and No.2 cross passages’ effective thickness of frost wall satisfy design requirement; When the initial ground temperature is 25°C, after freezing 95
days, No.1 and No.2 cross passages’ effective thickness of frost wall satisfy design requirement. So when the initial ground temperature is 18°C, the frost wall formative period of No.1 and No.2 cross passage is 85 days; when the initial ground temperature is 25°C, the frost wall formative period of No.1 and No.2 cross passage is 100 days. Freezing time for initial ground temperature 25 °C is about 15 days more than the one for initial ground temperature 18 °C.

When the initial ground temperature is 18 °C, after freezing 85 days, the average temperature of frost wall is -17.4 °C; when the initial ground temperature is 25 °C, after freezing 100 days, the average temperature of frost wall is -18.6 °C as shown in the Figure 7.

![Figure 7. Temperature change at each point on the line AB of No. 1 and No. 2 connecting channels](image)

4.2. Stratum ⑧-No.3 connecting channel

(a) 17-day temperature cloud atlas (initial ground temperature 18 ° C)  (b) 17-day temperature cloud atlas (initial ground temperature 25 ° C)
(c) 60-day temperature cloud atlas
(initial ground temperature 18 °C)

(d) 75-day temperature cloud atlas
(initial ground temperature 25 °C)

(e) 65-day temperature cloud atlas
(initial ground temperature 18 °C)

(f) 80-day temperature cloud atlas
(initial ground temperature 25 °C)

(g) 5-day temperature cloud atlas after cavation
(The initial ground temperature is 18 °C), the
excavation surface is exposed to the air

(h) 5-day temperature cloud atlas after
cavation
(The initial ground temperature is 25 °C), the
excavation surface is exposed to the air
The calculation result of temperature field in No.3 cross passage are given, as shown in Figure 8. The frost wall enclose time of the No.3 cross passage is about 17 days. When the initial ground temperature is 18°C, after freezing 60 days, No.3 cross passages’ effective thickness of frost wall satisfy design requirement; When the initial ground temperature is 25°C, after freezing 75 days, No.3 cross passages’ effective thickness of frost wall satisfy design requirement. So when the initial ground temperature is 18°C, the frost wall formative period of No.3 cross passage is 65 days; when the initial ground temperature is 25°C, the frost wall formative period of No.3 cross passage is 80 days. Freezing time for initial ground temperature 25 °C is about 15 days more than the one for initial ground temperature 18 °C.

When the initial ground temperature is 18 °C, after freezing 85 days, the average temperature of frost wall is -17.8 °C; when the initial ground temperature is 25 °C, after freezing 100 days, the average temperature of frost wall is -18.8 °C as shown in the Figure 9.

4.3. Sensitivity analysis of air convection temperature during excavation

Taking the ④1 soil layer and the initial ground temperature 25 °C as an example, the air temperature is 5 °C, 10 °C, 15 °C respectively when analysis of tunnel excavation is carried out.
When the air temperature is 5 °C, 10 °C, 15 °C, the temperature change of A and B for 30-day excavation is shown in the Figure 10. During the excavation of the cross passage, the temperature of point B is still decrease that means the frost wall of the cross passage continues to develop. The frost wall on the excavation surface is exposed to the air, and the temperature of the soil on the excavation surface at point A rises. When the wooden backboard is laid, the temperature of the excavation surface at point A begins to decrease.

4.4. Sensitivity Analysis of Heat Transmission Coefficient of Unfrozen Soil

Taking ④1 soil layer and the initial ground temperature 25 °C as an example, the thermal transmission coefficient of the frozen soil is 1.296 W/(m*K), 1.44 W/(m*K), 1.584 W/(m*K) respectively, which has impact on the development of frost wall.

The main effect is that the frost wall enclosure time will be extended or shortened by about 5 days when the unfrozen heat transmission coefficient of the frozen soil floats 10% up and down as shown in figure 11.
5. Conclusions
Based on a numerical model for the computation and analysis of the temperature field of connecting channel construction in Multi-lane Road Tunnel under the River Karnaphuli Chittagong – Bangladesh by using AGF as an auxiliary method, it can be concluded as follows:

1. When the initial ground temperature is 18°C, the frost wall formative period of No.1 and No.2 cross passage is 85 days, the frost wall formative period of No.3 cross passage is 65 days.
2. When the initial ground temperature is 25°C, the frost wall formative period of No.1 and No.2 cross passage is 100 days, the frost wall formative period of No.3 cross passage is 80 days.
3. According to computation and analysis of the temperature field during excavation, the thermal disturbance has little effect on the frozen soil. But it is necessary to pay attention to laying the wooden backboard in time to prevent the frozen soil from weakening on the excavation surface.
4. Hence the effect of the water flow is simplified to the change of the heat transmission coefficient of the unfrozen soil. According to the sensitivity analysis of the heat transmission coefficient of the unfrozen soil, the overall impact is relatively small.

Acknowledgments
The research work described herein was funded by the National Key Research and Development Project of China (No. 2016YFC0800208, 2017YFC0806003, 2017YFC0806004, 2017YFC0806010 and 2018YFC0809602) and Research and Development Project of China Communications construction company Ltd. (No.2017-ZJKJ-01, 2018-ZJKJ-09). These financial supports are gratefully acknowledged.

References
[1] Chen Xiang-sheng. (2014). Ground Freezing Method. Beijing: The People's Communication Publishing Company. [M]
[2] Chen Ruijie, Cheng Guodong, Li Shuxun, et al. (2000). Development and prospect of research on application of artificial ground freezing., Chinese Journal of Geotechnical Engineering., Vol.22 No.1: 40-44.
[3] Zhou Xiaomin, Su Lifan, HE Chang-jun. (1999). Horizontal ground freezing method applied to tunneling of Beijing underground railway system., Chinese Journal of Geotechnical Engineering., Vol.21 No.2: 319-322.
[4] Chen Mingxiong, Guo Ronggen, Liu Ting. (2003). Artificial ground freezing applying to metro and tunnel., Journal of PLA University of Science and Technology., Vol. 4 No.6: 69-72.
[5] Shuangyang Li, Yuanming Lai, Mingyi Zhang, et al. (2006). Minimum ground pre-freezing time before excavation of Guangzhou u subway tunnel., Cold Regions Science and Technology., Vol.46 181 – 191
[6] Xiao Zhao-yun, Hu Xiang-dong, Zhang Qing-he. (2006). Design of freezing method for recovering collapse tunnels in Shanghai Metro., Chinese Journal of Geotechnical Engineering., Vol.28:1716-1719
[7] Wang Ling-min, Wang Jin-xing, Liu Song-ke. (2002). Application of soil stabilization method by freezing to shield tunneling., Journal of Jiaozuo Institute of Technology (Natural Science)., Vol.21 No.5:346–348.
[8] Zhang Jie, Xu Wei, Zhong Jian-chi. (2005). Numerical analysis of overall thermal field change in construction of south anchorage foundation pit support with ground freezing method for Runyang Yangtze Bridge., Building Construction., Vol.26 No.1:15–17.
[9] Yang Chao, Yue Fentian. (2012). Study on Freezing in Construction of Connection Galleries of Yangtze River-crossing Tunnel in Shanghai. Tunnel Construction., Vol. 32 No. 6: 843-848.
[10] Zhou Zhiyong, Hu Xiangdong. (2008). Numerical simulation and site measurement of freezing construction of shield tunnel cross passage. Modern Tunnelling Technology(S). 275–277.

[11] Yang Chao, Yue Fengtian. (2012). Study on Freezing in Construction of Connection Galleries of Yangtze River-crossing Tunnel in Shanghai. Tunnel Construction., Vol. 32 No. 6: 843-848.

[12] DG/TJ 08-902-2016 Technical code for crosspassage freezing method[S].