Experimental investigation on heat transfer law of multiple freezing pipes in permeable stratum with high seepage velocity

Bin Wang*[1], *Chuanxin* Rong[1], *Zhishu* Yao[1], *Bin* Tang[1], and *Haiqing* Song[1]

[1] School of Civil Engineering and Architecture, Anhui University of Science and Technology, China

1 Introduction

Artificial ground freezing method is one of the main methods for tunnel and shaft construction engineering. In recent years, the heat transfer law of freezing pipes under the action of groundwater has attracted more and more scholars' attention. Model test has always been an important method to study the freezing method of water-rich ground, and it is also the main basis for the verification of the rationality of hydrothermal coupling numerical models. Zhou et al. [1] analyzed the research results of existing model tests and found that the current studies had basically achieved the qualitative analysis of the influence of groundwater on the artificial freezing temperature field.

However, the sizes of the models were different, and there were also certain differences in the control temperatures of the low-temperature refrigerant. The maximum seepage velocity involved in the experiments reached 159 m/d [2], while the minimum seepage velocity was only 0.24 m/d [3]. There has still been no consistent research conclusion for the influence of the water flow velocity during formation on the freezing temperature field.

In this paper, based on the independently developed large-scale water-heat coupled physical model test system, the formation mechanism of the artificial freezing temperature field in high-velocity permeable formations is comprehensive and systematic studied from the closure time of the frozen wall, the spatial distribution law of the freezing temperature field and the mechanism of the "group pipe effect".

2 Model test system

The authors of this paper previously studied the heat transfer law of the temperature field of a single freezing pipe in a large-velocity infiltration configuration [4]. The previous research provided a reference for this study in terms of test methods and data processing methods. The heat transfer law of multiple freezing pipes in permeable stratum with high seepage velocity was studied based on the model test system which is shown in Figure 1.

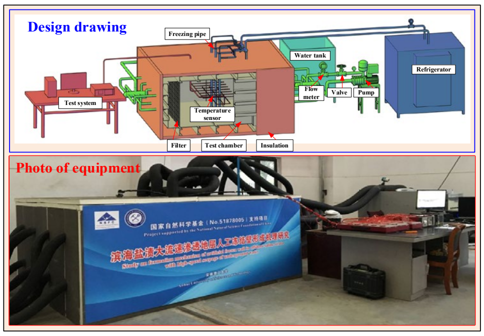


Figure 1. Model test system for heat transfer law of multiple freezing pipes.

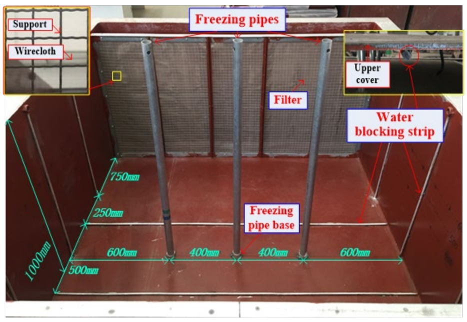


Figure 2. Internal structure of the test chamber before it was filled with porous media.

The geometric reduction ratio between the actual engineering and the test system was 3 [4]. The derivation process of similarity criterion was shown in the supplementary material of this paper. The size of the box was 2500 mm × 2000 mm × 1000 mm, 3 freezing pipes with outer diameters of 40 mm were arranged in the box, and the distance between the adjacent freezing pipes was 400 mm. The internal structure of the box was shown in Figure 2.

Table 1. Physical parameters of the sand.

	Particle size/(mm)	Dry density/(kg/m^3)	Saturated density/(kg/m^3)	Porosity	Hydraulic conductivity/(cm/s)
Sand	1±0.1	1612	2480	0.33	2.28×10^{-2}

Table 2. Thermal parameters of sand.

Status	Thermal conductivity (W/m·K)	Thermal diffusivity (m^2/s)
Frozen	3.32	1.19×10^{-6}
Unfrozen	2.25	1.88×10^{-6}

* Corresponding author: wbingoo@163.com

The box was divided into 3 regions along the length by two 100-mesh screens. The middle region was the main region of interest, which had a length of 2000 mm and was filled with sand. For this experiment, round quartz sand with a particle size of 1 ± 0.1 mm was selected to simulate the porous medium. The appearance of sand was shown in Figure 3, and the parameters of sand are shown in Tables 1 and 2. Buffer chambers with lengths of 250 mm were arranged at each end of the box and were filled with stones, whose appearance as shown in Figure 4. The buffer chamber and the gravel buffer layer can evenly distribute the water flow, eliminate boundary effects, reduce impact and stabilize water temperature, ensuring the stability of the test seepage and temperature field.

Figure 3. The appearance of mesoscale quartz sand used to simulate porous media.

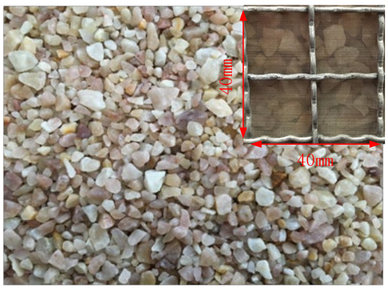


Figure 4. The appearance of stone used as buffer layer.

To prevent the external environment temperature from interfering with the freezing process, the outer surface of the box and the freezing pipeline were insulated. A layer of rubber insulation board with a thickness of 30 mm was placed on the outer surface of the box, the entire box was wrapped with a polyurethane insulation board with a thickness of 40 mm, and the joint was tightly bonded with neoprene. The exposed part of the freezing pipes was wrapped with a rubber insulation layer with a thickness of 30 mm. The arrangement of the insulation layer was shown in Figure 5.

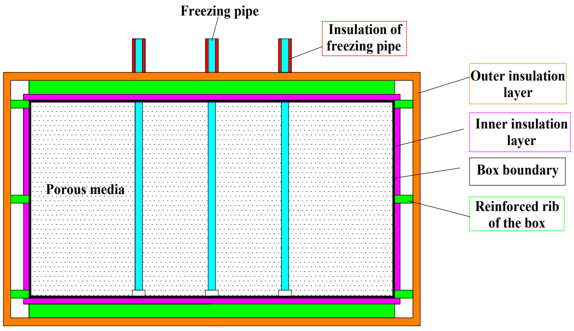


Figure 5. Schematic of the insulation of the box.

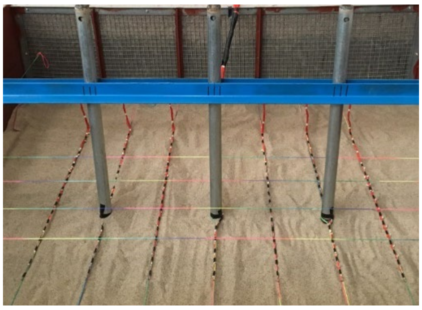
The water flow was considered to satisfy Darcy's law [4]:

$$v = -\frac{K_{(T)}}{\mu_w}\left(\frac{\Delta P}{\Delta L}\right) \tag{1}$$

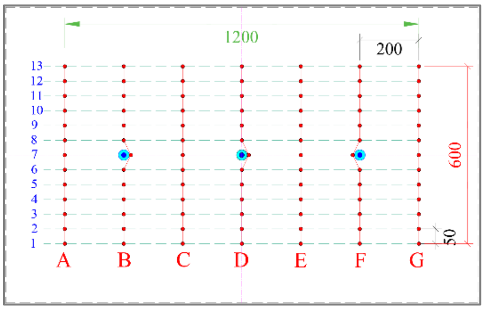
where v is the seepage velocity, $K_{(T)}$ is the permeability of the sand layer, μ_w is the viscosity coefficient of water, ΔP is the water pressure of seepage, and ΔL is the hydraulic path.

The temperature and seepage velocity of the refrigeration alcohol was set to -30°C and 7.5 m^3/h, respectively.

The arrangement of the measurement points was shown in Table 3 and Figure 6.



(a)



(b)

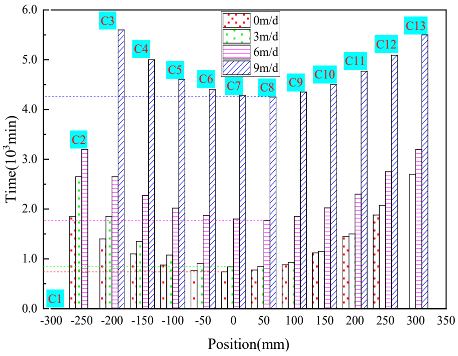
Figure 6. Temperature measurement points arrangement (a) actual layout diagram of measurement points and (b) layout diagram of measurement points.

Table 3. Setting parameters of measuring points.

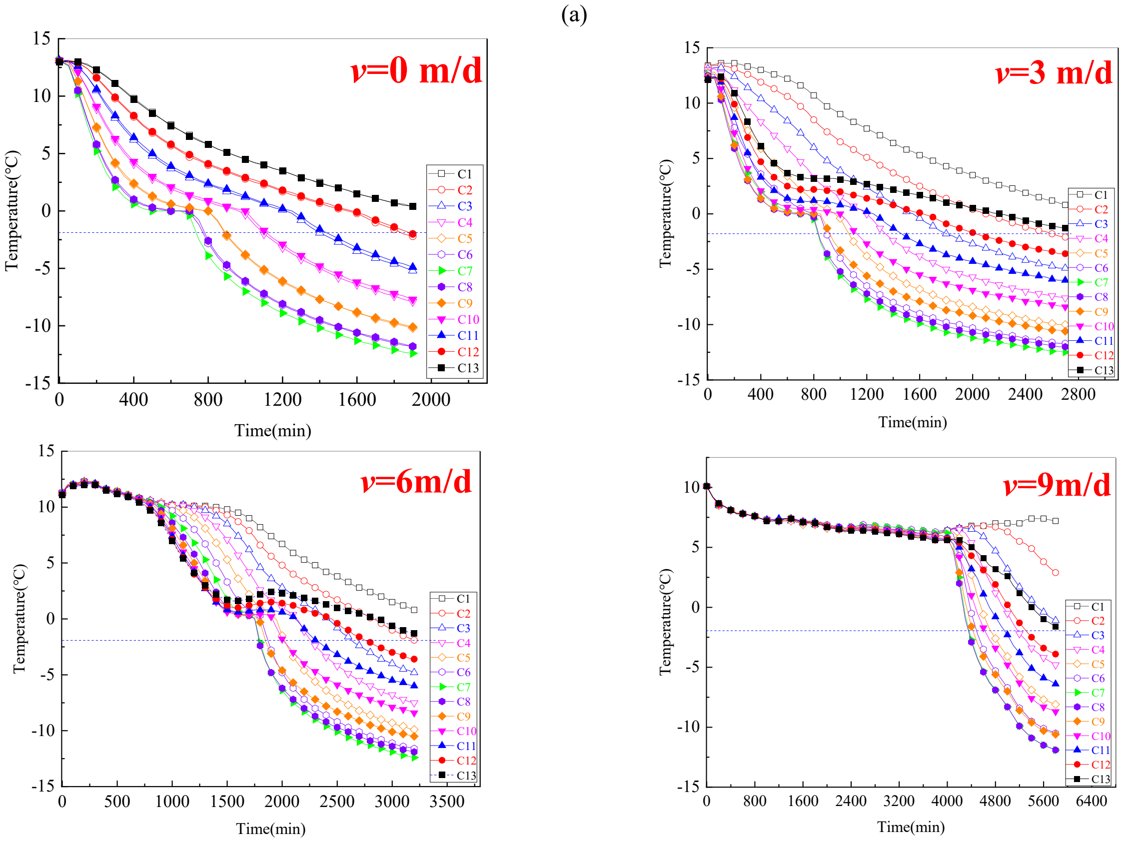
Test plane	Depth/mm	Axes	Spacing of axes/mm	Measuring points distribution/axe	Spacing of points/mm	Total number
Main test plane	500	7	200	13	50	91

3 Model test analysis

The axis C was located in the middle of adjacent freezing pipes, and the temperature change rule of measuring points on these axes was important judgment basis for the closure time of the frozen wall. NMR test results of low-temperature saturated porous media indicated that the freezing temperature of sand was −0.5°C [4]. In order to ensure the closure time of frozen wall obtained had high safety, based on practical engineering experience and existing literature [5, 6], it can be considered that when the temperature at the measuring point was lower than −2°C, the frozen wall at this position was closed. Based on this, the freezing time (closure time) of the middle area of adjacent freezing pipes for different seepage velocity was obtained, as shown in Figure 7.



(a)



(b)

Figure 7. The law of closure time of the frozen wall on C axis (a) closure time of frozen wall at different position and (b) the change law of temperature of measuring points.

When v = 0 m/d and v = 3 m/d, the earliest closure position of the frozen wall was the midpoint (C7) between two freezing pipes, and the closure time were 740 min and 840 min, respectively. The closure time of the frozen wall at the remaining measuring points increased as the distance from the middle point increased. When v = 6 m/d, the temperature drop rate at the measuring point was further reduced. The closure time (1770 min) of the frozen wall at measuring point C8, 50 mm downstream of the intermediate point on the C axis, was slightly shorter than that at the intermediate measuring point C7 (1800 min). This indicated that the earliest closure position of the frozen wall under this seepage velocity shifted to the downstream position of the intermediate point. When v = 9 m/d, the temperature curves at the measuring points on the C axis changed significantly compared with those at low seepage velocity. The temperature curves of all the measuring points had no significant phase change stage. After a relatively stable period for a relatively long time, except for the points C1 and C2 upstream, the measuring points quickly dropped below the freezing temperature in a short time. The earliest closure positions (C8) were 50 mm downstream of the middle point of the measuring point layout axis, and the closure time was 4250 min.

The formation process of multi-pipe freezing temperature field under the action of seepage field is shown in Figure 8. For the convenience of analysis, the radius of the frozen area located upstream, on both sides and downstream of the axis of the freezing pipe was defined as R_u, R_s and R_d, and the distance between adjacent freezing fronts was L.

There was the following relationship between L and R_s:

$$L = d - 2R_s \tag{2}$$

In the formula, d = 400 mm was the distance between the freezing pipes; in the freezing process, when L = 0, that is, when R_s = 200 mm, it meant that the freezing wall had intersected.

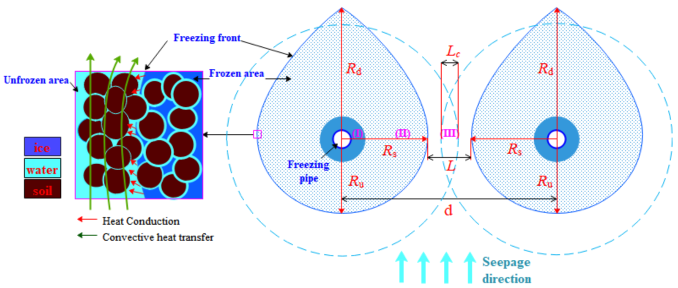


Figure 8. Illustration of the freezing process of multiple pipes under the action of seepage field.

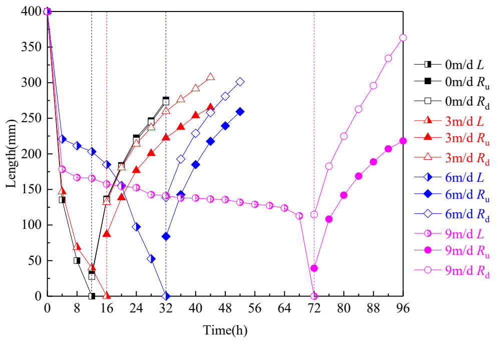


Figure 9. Variations of the frozen radii facing different directions with time under different seepage velocities.

In order to analyze the conditions of the "group pipe effect", the change laws of L, R_u and R_d with time during the freezing process of the three freezing pipes under different seepage velocity conditions were plotted as a graph, as shown in Figure 9, L_c was defined as the critical value of the distance between adjacent freezing fronts when the "group pipe effect" occurred.

As shown in Figure 6, it can be seen that the time for L to decrease from 400 mm to 0, that is, the closure time of the frozen wall under the action of seepage with seepage velocity of 3 m/d was slightly longer than that without seepage. It can be observed that when the distance between adjacent freezing fronts is 400 mm, the "group control effect" can be considered to occur. When the seepage velocity was greater than 6 m/d, the change law of L with time was divided into different stages. When the freezing time reached 4h, L decreased rapidly to 186 mm and 220 mm corresponding to the flow velocity of 6 m/d and 9 m/d, respectively, then L entered a stage of slow development. When L was reduced to 77 mm (6 m/d) and 65 mm (9 m/d) respectively, L entered the second rapid reduction stage, and this stage continued until L decreases to 0. Therefore, the L_c corresponding to the flow velocity of 6 and 9 m/d was 77 and 65 mm, respectively.

4 Conclusions

In this paper, the model testing system accurately reveals the formation mechanism of artificial freezing temperature field and the critical law of "group pipe effect" in high seepage velocity permeability formation.

1. When v = 0 and 3 m/d, the earliest closure position of the frozen wall was the middle point between adjacent freezing pipes, and the closure times were 740 and 840 min, respectively. When v = 6 and 9 m/d, the earliest closure position of the frozen wall moved from the intermediate point downstream by 50 mm, and the closure times increased to 1770 and 4250 min, respectively.

2. When there is no seepage and v = 3 m/d, the closing time of the frozen wall is similar. When the adjacent freezing front spacing is 400 mm, the "group pipe effect" occurs. When v > 6 m/d, L changes periodically with time. The critical spacing L_c for the "group pipe effect" corresponding to the flow velocities of 6 and 9 m/d is 77 and 65 mm, respectively.

References

1. Zhou, X.M., Wang, M.S., Zhang, X.Z. Model test research on the formation of freezing wall in seepage ground. J. of China Coal Soc. **30**(02), 196-201 (2005)
2. Li, F.Z., Ding, H., Zhang, X.Z. Model test research of formation law of double-row-pipe freezing wall in water rich sand layer under seepage. Chin. J. Rock Mech. Eng. **38**(02), 386-395 (2019)
3. Frivik, P. E., Comini, G. Seepage and heat flow in soil freezing. J. Heat Transfer. **104**(2), 323-328. (1982)
4. Wang, B., Rong, C.X., Cheng, H., Cai, H.B., Dong, Y.B., Yang, F. Temporal and Spatial Evolution of Temperature Field of Single Freezing Pipe in Large Velocity Infiltration Configuration. Cold Reg. Sci. Technol. **175**, 1-14 (2020)
5. Levin, L., Golovatyi, I., Zaitsev, A., Pugin, A., Semin, M. Thermal monitoring of frozen wall thawing after artificial ground freezing: Case study of Petrikov Potash Mine. Tunn. Undergr. Space Technol., **107**, 103685 (2021)
6. Wu, T., Zhou, X.M., Zhang, L.G., Zhang, X.J., He, X.N., Hu Y. Theory and technology of real-time temperature field monitoring of vertical shaft frozen wall under high-velocity groundwater conditions. Cold Reg. Sci. Technol., **189**, 103337 (2021)