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A study on impacts of groundwater seepage on artificial freezing process of gravel strata

Tianliang Wang
School of Civil Engineering, Shijiazhuang Tiedao University, Shijiazhuang, China
Ya-Meng He
State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou, China
Zhen Wu
Jinan Design Institute, China Railway Engineering Consulting Group Co., Ltd., Jinan, China, and
Jun-jun Li
School of Civil Engineering, Shijiazhuang Institute of Railway Technology, Shijiazhuang, China

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Abstract

Purpose – This paper aims to study the impacts of groundwater seepage on artificial freezing process of gravel strata, the temperature field characteristics of the strata, and the strata process, closure time and thickness evolution mechanism of the frozen wall.

Design/methodology/approach – In this paper several laboratory model tests were conducted, considering different groundwater seepage rate.

Findings – The results show that there is a significant coupling effect between the cold diffusion of artificial freezing pipes and groundwater seepage; when there is no seepage, temperature fields upstream and downstream of the gravel strata are symmetrically distributed, and the thickness of the frozen soil column/frozen wall is consistent during artificial freezing; groundwater seepage causes significant asymmetry in the temperature fields upstream and downstream of the gravel strata, and the greater the seepage rate, the more obvious the asymmetry; the frozen wall closure time increases linearly with the increase in the groundwater seepage rate, and specifically, the time length under seepage rate of 5.00 $\mathrm{m \ d^{-1}}$ is 3.2 times longer than that under no seepage; due to the erosion from groundwater seepage, the thickness of the upstream frozen wall decreases linearly with the seepage velocity, while that of the downstream frozen wall increases linearly, resulting in a saddle-shaped frozen wall.

Originality/value – The research results are beneficial to the optimum design and risk control of artificial freezing process in gravel strata.

Keywords Underground works, Gravel strata, Temperature field, Groundwater seepage, Artificial freezing, Frozen wall

Paper type Research paper

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1. Introduction

Artificial freezing is the technology of freezing the soil within the scope of work by artificial refrigeration, to form a closed, high-strength and water-resistant frozen wall, so as to provide good conditions for underground works (Ma, 2007). As the freezing technology develops, artificial freezing has been widely used in the construction of housing, tunnel, municipal works, etc (Chen, Cheng, Li, Guo, & Zhu, 2000). However, the practice shows that the excessively large seepage rate of groundwater in water-rich strata due to natural conditions and human factors has an adverse impact on the closure of frozen wall and even causes major accidents (Yao, Cai, Cheng, & Ma, 2011; Zhao, 2004).

Scholars inside and outside China have studied the hydrothermal coupling mechanism of frozen walls by model tests, numerical simulations and theoretical analyses (Frivik & Comini, 1982; Sudisman, Osada, & Yamabe, 2017; Wang, Zhou, Xu, & Liu, 2011; Yan & Fang, 2012; Zhang, Yue, Zhang, Sun, & Wang, 2020). Artificial freezing is now applied to increasingly diverse strata. In addition to strata based on soft clay, mud, muddy soil and other soil textures (Li & Xie, 2012; Qin, Yang, Jin, Zhang, & Wang, 2010), it is also applied to strata of medium-coarse sand, pebbles and gravels. Due to the high permeability and the high seepage rate of groundwater in medium-coarse sand, pebbles and gravel strata, the artificial freezing is faced with many problems such as difficulty in forming frozen wall, long freezing time and high maintenance cost (Li, Luo, & Han, 2010). Many scholars have studied the strata of silt, medium-coarse sand and other textures. Yang and Pi (2001) analyzed the evolution law of the temperature field and seepage field of silt strata during freezing based on numerical simulation of hydrothermal coupling. Liu, Liu, Zhou, and Zhu (2017), Li, Ding, and Zhang (2019), Pimentel, Sres, and Anagnostou (2012), Zhou, Wang, and Zhang (2005) explored the correlation between the groundwater velocity and the frozen wall development in medium-coarse sand strata through physical model tests. Based on the model tests, Pimentel *et al.* (2012) further verified the analytical solution of the frozen wall closure time. Li *et al.* (2019) analyzed the correlation between the frozen wall closure time and the groundwater flow velocity by the mathematical regression method and demonstrated the limit velocity of groundwater. Unlike the strata of silt or medium-coarse sand, pebbles and gravels feature large particles, significant differences in particle size and complex pore distribution, and relevant researches and technology reserves are insufficient.

This paper simulated the impacts of groundwater seepage on the artificial freezing process of gravel strata by laboratory similarity model test, analyzed the evolution law of the temperature field of artificial freezing gravel strata, and delved into the change law due to groundwater seepage in characteristic indexes such as the closure process, closure time and thickness of the frozen wall.

2. Similarity model and model test

2.1 Similarity criterion and similarity ratio

In water-rich gravel strata, cold diffusion from the freezing pipe to the strata makes soil frozen, reduces its permeability, which affects groundwater seepage. Meanwhile, the groundwater flow takes away a large amount of cold and slows down the freezing of soil. This is the coupling effect between the temperature and the seepage field. According to the similarity theory, the physical quantities in the two-field coupling equation were summarized for the similarity criterion as:

$$f\,(D, S, T_{\mathrm{N}}, T_0, T_{\mathrm{p}}, t, \rho_{\mathrm{s}}, \rho_{\mathrm{w}}, c_{\mathrm{s}}, c_{\mathrm{w}}, \alpha_{\mathrm{s}}, \alpha_{\mathrm{w}}, L_0, v_n, \Delta L, H_{\mathrm{P}}) = 0 \tag{1}$$

where D and S respectively refer to the diameter of a freezing pipe and the spacing between the two pipes, in mm; T_{N}, T_0 and T_{p} respectively refer to the strata temperature during freezing, the initial strata temperature and the temperature of the freezing pipe wall, in ℃; t is the freezing time, in days (d); ρ_s and ρ_w respectively refer to the densities of soil and groundwater in strata, in $kg\ m^{-3}$; c_s and c_w respectively refer to the specific heat capacities of soil and groundwater in strata, in $m^2\ s^{-2}\ ℃^{-1}$; α_s and α_w respectively refer to the thermal diffusivities of soil and groundwater in strata, in $W\ m^{-2}\ ℃^{-1}$; L_0 is the latent heat of fusion, in $J\ kg^{-1}$; v_n is the groundwater seepage rate, in $m\ d^{-1}$; ΔL is the infiltration length, in m; and H_P is the hydraulic head of strata, in m.

Considering the constraints such as the model box size and the workmanship of freezing pipes, the geometric similarity ratio of the model was identified as 1: 5. The model test was performed with the gravel soil taken from the strata on site, and the similarity ratio for each physical quantity was derived through dimensional analysis according to the similarity criterion, to be specific, 1: 1 for material, 1: 1 for temperature, 1: 25 for time and 5: 1 for groundwater seepage rate.

2.2 Similarity model test device

The test device for the model of the artificial freezing gravel strata is shown in Figure 1.

The model test device consists of a model box, a refrigeration system and a groundwater seepage and temperature measurement system.

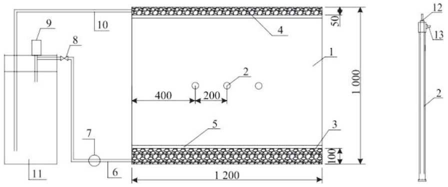
(1) Model box

The model box of artificial freezing gravel strata is 1.2 m long, 0.8 m wide and 1.0 m high, and is divided by function into the inlet chamber, the outlet chamber and the working chamber. The inlet and outlet chambers were filled with pebbles with a particle size of about 10 mm to reduce the erosion of the gravel strata by groundwater flow and make the water flow more uniform and stable in the gravel strata. The working chamber was filled with gravel soil and separated from the inlet and outlet chambers by the filter plate and cloth. During the process of artificial freezing, the model box was wrapped with insulation cotton to keep off the influence of ambient temperature.

(2) Refrigeration system

The refrigeration system consists of a NESLAB cryostat, a circulating pipeline and freezing pipes. Seamless steel pipes with diameter of 25 mm and wall thickness of 2.5 mm were used to simulate the freezing pipes with diameter of 127 mm and wall thickness of 8 mm in practice. Three freezing pipes were placed horizontally in the middle of strata at a spacing of 20 cm. The refrigerant was cooled in the cryostat, entered the refrigerant inlet, then flowed through the inner and outer pipes of the freezing pipes successively, and exited from the refrigerant outlet.

(3) Groundwater seepage and temperature measurement system



Model box
(a)

Freezing pipe
(b)

1 – Working chamber; 2 – Freezing pipe; 3 – Inlet chamber; 4 – Outlet chamber; 5 – Filter plate and inverted filter layer; 6 – Inlet pipe; 7 – Flowmeter; 8 – Flow valve; 9 – Power pump; 10 – Outlet pipe; 11 – Thermostatic water tank; 12 – Refrigerant inlet; 13 – Refrigerant outlet;

Figure 1.
Model test device
(Unit: mm)

The groundwater seepage and temperature measurement system is comprised of thermostatic water tank, power pump, flowmeter, flow valve, inlet pipe, outlet pipe, temperature sensor and data acquisition instrument. The power pump delivered the flow at a constant temperature into the model box from the bottom to the top. The flowmeter and flow valve were used to control the groundwater seepage rate for stable groundwater seepage conditions. During the test, the evolution of the strata temperature field was monitored in real time by the platinum resistance temperature sensor and the data acquisition instrument. The vertical section in the middle of the freezing pipe was monitored and embedded with four measuring lines L1, L2, L3 and L4, each having nine measuring points, as shown in Figure 2.

2.3 Test scheme and process control

The soil used in the model test was taken from a metro connecting passage in Jinan, with the grading curve shown in Figure 3 and basic physical properties in Table 1. Belonging to gravel soil without fine particles, the mass fraction of particles greater than 2 mm was 80.7%.

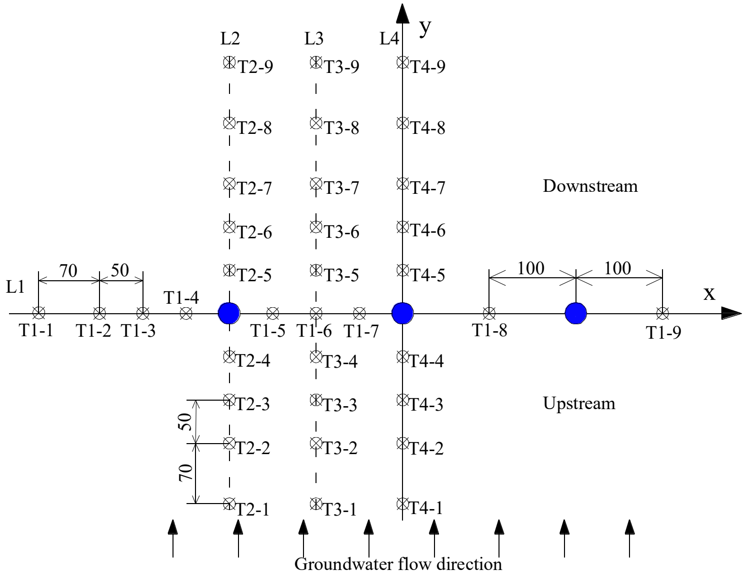


Figure 2.
Layout of temperature measuring points in gravel strata (Unit: mm)

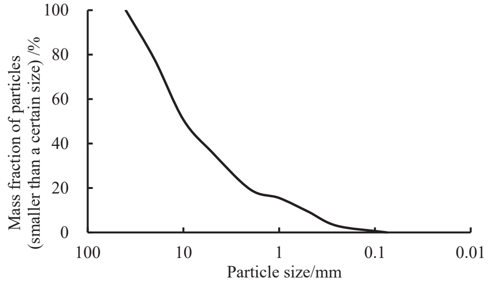


Figure 3.
Grading curve of gravel soil

A laboratory model test was conducted to study the formation process of frozen wall in freezing gravel strata with single row of pipes under the action of groundwater seepage. The test process is as follows.

(1) Test preparation

Filled the inlet chamber of the model box with pebbles with the particle size of about 10 mm, and placed the filter plate and cloth. Filled gravel soil in 5 layers and placed the temperature sensors (see Figure 2). Each layer of gravel soil was prepared in strict accordance with the grading curve (see Figure 3) and fully mixed to ensure the uniformity of the gravel strata. Placed the filter cloth, filter plate and pebbles in sequence after the gravel soil was filled to the design height. Assembled the whole model test system and wrapped the box outside with insulation cotton.

(2) Test process

Turned on the groundwater seepage and temperature measurement system, and used the flow valve and flowmeter to control the groundwater seepage rate at 0, 1.25, 2.50, 3.75 and 5.00 $\mathrm{m\ d^{-1}}$ respectively. Calculated the water inflow and outflow through the observation of the change of water level in the thermostatic water tank. After the seepage system ran for 2 hours with the water level remaining unchanged and the initial strata temperature being 20 ℃, that is, after a steady seepage field was formed in the gravel strata, turned on the refrigeration system to artificially freeze the gravel strata, and the refrigerating temperature was −20 ℃. Turned off the refrigeration system and seepage system after 48 h of freezing, and the test was then completed.

Since the model box was much larger than the freezing pipe and the frozen wall in size, and the insulation cotton outside the box had a thermal insulation effect and effectively reduced the boundary effect of temperature and seepage in the model test, the artificial freezing process only caused local fluctuations near the freezing pipe and did not affect the whole gravel strata in terms of seepage state.

3. Test results and analysis

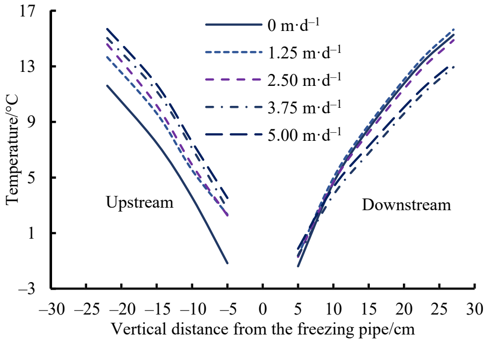
3.1 Temperature distribution characteristics at upstream and downstream sides

Figure 4 shows the temperature distribution of measuring lines L4 and L3 at different groundwater seepage rates after 8 h of freezing. It can be seen from Figure 4 that, when there was no groundwater seepage with freezing for 8 h, the upstream and downstream strata temperatures were symmetrically distributed for both sides, which indicated that the freezing pipe transferred cold to surroundings evenly and when groundwater seepage came into play, the upstream temperature was significantly higher than the downstream temperature in the mirror position from the pipe, which indicated obvious asymmetry that increased with the groundwater seepage rate.

On the upstream side of the gravel strata, the temperature increased with the groundwater seepage rate, which was significant when the seepage rate increased from 0 to 1.25 $\mathrm{m\ d^{-1}}$. It can be seen that the increase in groundwater seepage rate greatly reduced the cold diffusion

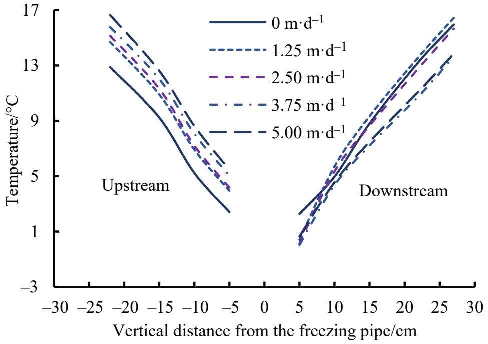
Dry density/ ($\mathrm{g\ cm^{3}}$)	Porosity	Specific gravity	Permeability/ ($\mathrm{m\ d^{-1}}$)	Thermal conductivity/ ($\mathrm{W\ m^{2}\ ℃^{-1}}$)	Specific heat capacity/ ($\mathrm{m^{2}\ s^{2}\ ℃^{-1}}$)
1.883	0.3	2.69	60	1.07	1.30

Table 1. Basic physical properties of test soil



L4 line

(a)



L3 measuring line

(b)

Figure 4.
Temperature distribution of gravel strata after 8 h of freezing

from the freezing pipe to the upstream strata, and the strata temperature remained at a high level. That is to say, groundwater seepage restricts the freezing of the upstream strata to some extent, and the higher the rate, the slower the freezing.

Downstream of the gravel strata, the strata temperature at the same position decreased significantly on the whole as the groundwater seepage rate increased, even lower than when there was no groundwater seepage. As the groundwater seepage rate increased, the temperature of gravel strata showed a significant downward trend, which indicated that groundwater seepage facilitated cold diffusion from the freezing pipe to the downstream area. At the same time, the greater the seepage rate, the more cold taken from the freezing pipe to the downstream strata and the better freezing effect of strata in the downstream area. Therefore, in artificial freezing process of gravel strata, groundwater seepage will promote temperature reduction of downstream areas and accelerate the formation of the frozen wall in downstream area to some extent.

3.2 Distribution law of strata temperature field

The frozen wall closure time refers to the time period from the beginning of gravel strata freezing, the soil around the frozen pipe then forming frozen soil columns, to the time required for frozen soil columns to intersect and connect to form frozen wall. During the test, the time required for the middle measuring point T1-6 between two freezing pipes to reach 0 ℃ was selected as the frozen wall closure time. Figure 5 shows the relationship between the groundwater seepage rate and the frozen wall closure time, from which it can be seen that the frozen wall closure time showed approximately linear increase as the groundwater seepage rate increased, and when the groundwater seepage rate reached 5.00 m d^{-1}, the closure time increased abruptly, which was 3.2 times longer than that of the nonseepage situation. This indicates that the greater the groundwater seepage rate, the more difficult it becomes for the frozen wall to close, and the more artificial freezing cold and time required.

Figures 6–10 respectively show the temperature nephograms of gravel strata at different groundwater seepage rates and the comparison of the development of the frozen wall with 8 h of freezing and that at the frozen wall closure time. The following conclusions can be drawn from these figures.

(1) The cold diffuses outward with the freezing pipe as the center and freezes the surrounding soil into frozen soil columns, which further develop and gradually close up to form frozen wall with a certain thickness.

(2) When there is no groundwater seepage, the frozen soil columns in the gravel strata expand with neat edges rapidly and evenly to the surroundings until closed into a uniformly thick frozen wall without any obvious weak areas. In this process, the upstream and downstream temperatures of the gravel strata are evenly distributed,

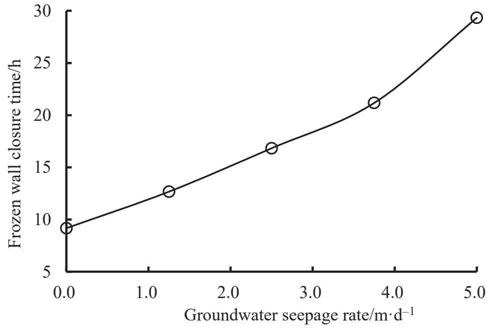
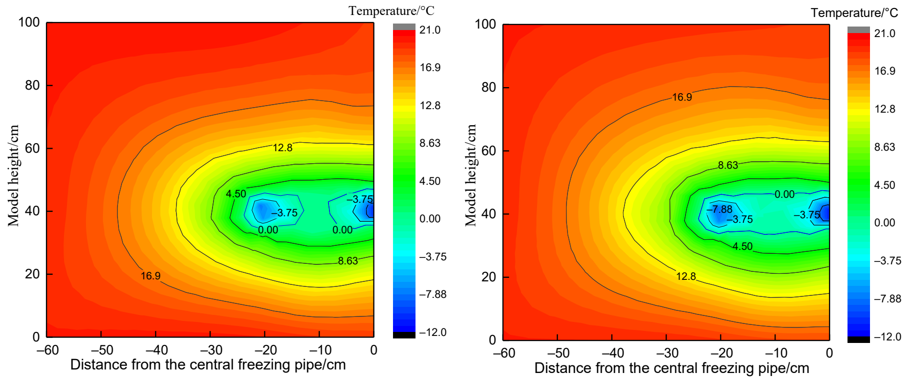


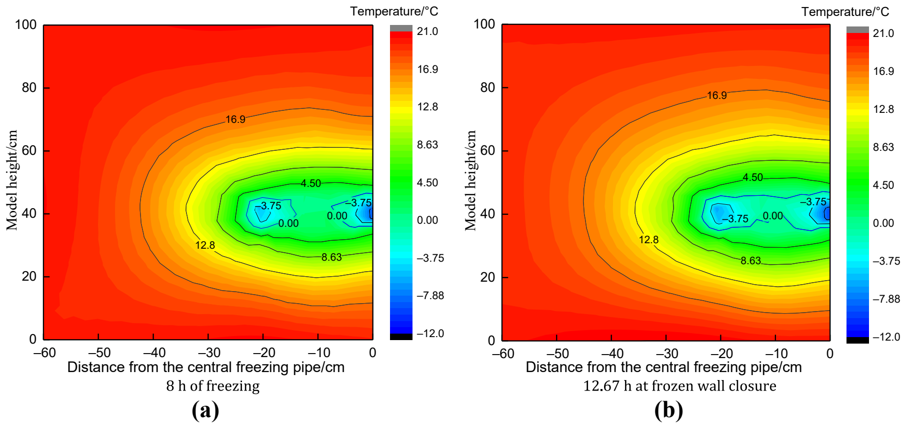
Figure 5. Relationship between groundwater seepage rate and frozen wall closure time



8 h of freezing
(a)

9.17 h at frozen wall closure
(b)

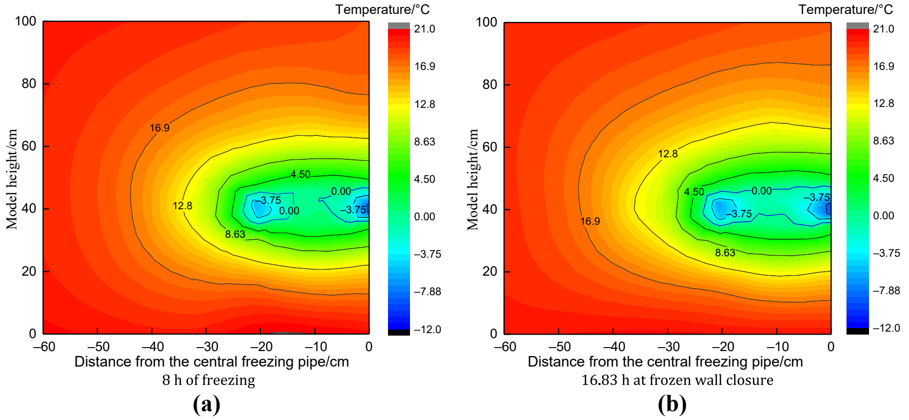
Figure 6. Temperature nephogram of gravel strata without seepage



8 h of freezing
(a)

12.67 h at frozen wall closure
(b)

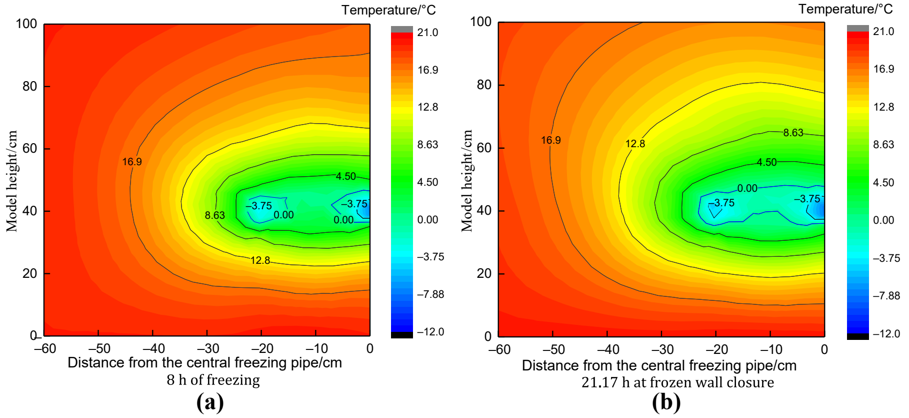
Figure 7.
Temperature nephogram of gravel strata at groundwater seepage rate of $1.25\ \mathrm{m\ d^{-1}}$



8 h of freezing
(a)

16.83 h at frozen wall closure
(b)

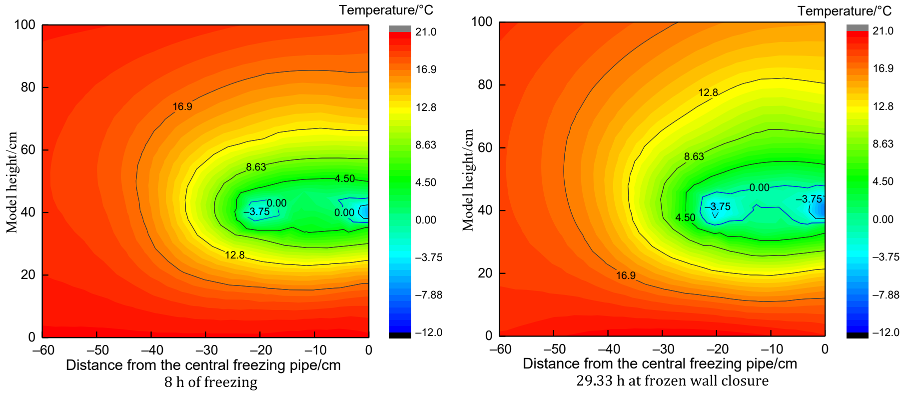
Figure 8.
Temperature nephogram of gravel strata at groundwater seepage rate of $2.50\ \mathrm{m\ d^{-1}}$



8 h of freezing
(a)

21.17 h at frozen wall closure
(b)

Figure 9.
Temperature nephogram of gravel strata at groundwater seepage rate of $3.75\ \mathrm{m\ d^{-1}}$



(a)

(b)

Figure 10. Temperature nephogram of gravel strata at groundwater seepage rate of 5.00 m d^{-1}

with isotherms equally spaced, showing centrosymmetric distribution form. The frozen wall formed has a regular shape and uniform thickness (see Figure 6).

(3) Due to the involvement of groundwater seepage, the temperature distribution upstream and downstream of the gravel strata isa obviously asymmetric, which is consistent with the conclusion of the reference (Liu *et al.*, 2017). As the groundwater seepage rate rises, this asymmetry becomes more and more significant, and the uniformity of isotherm distribution decreases significantly. This is mainly because the seepage groundwater hinders the cold diffusion to the upstream area and carries more cold to the downstream area, resulting in a large temperature difference at the same distance from the freezing pipe (see Figures 7–10).

(4) Irregular sharp points occur on the edge of frozen soil columns on the downstream side between two freezing pipes, and the greater the groundwater seepage rate, the smaller the expansion range of frozen soil columns at the same time. With the passage of freezing time, the two frozen soil columns develop and close up to frozen wall, and the closure position shifts downstream, which is consistent with the direction of groundwater seepage, resulting in a saddle-shaped wall. The frozen wall is relatively thin at the closure position, which becomes an obvious weak area. The greater the groundwater seepage rate, the more obvious the shift of the frozen wall downstream, the thinner the frozen wall and the larger the weak area (see Figures 7–10).

3.3 Thicknesses of frozen soil columns and frozen wall

The evolution laws of frozen soil column thickness and frozen soil wall thickness under different groundwater seepage rates are obtained by measuring the column thickness after 8 h of freezing and the wall thickness at the closure time, as shown in Figures 11 and 12. In the two figures, the upstream and downstream thickness is the average distance from the boundary, respectively of the frozen soil column and the frozen wall, to the center plane of the freezing pipe.

The following conclusions can be drawn from these figures.

(1) When there is no groundwater seepage, the thickness of the upstream and downstream frozen soil columns is consistent with the thickness of the frozen wall; the groundwater seepage leads to obvious differences in these two thickness values (see Figures 11 and 12).

(2) Before the frozen wall closes up, the thickness of the upstream frozen soil columns shows a linear decrease with the increase in groundwater seepage rate. While the groundwater erosion has a direct bearing on the development of upstream frozen soil columns, those downstream are obviously thicker because of the "shelter" by the upstream frozen soil columns and thus the more efficient diffusion of cold from the freezing pipe. This indicates that groundwater seepage is more conducive to the development of frozen soil columns downstream. In addition, when the groundwater seepage rate is less than 2.50 m d^{-1}, the seepage has little impact on the thickness of the downstream frozen soil columns. Marwan, Zhou, Abdelrehim, and Meschke (2016) also found a smaller groundwater seepage rate actually contributes to cold diffusion from freezing pipes (see Figure 11).

(3) Different from the development process of frozen soil columns, the upstream frozen wall thickness decreases linearly while the downstream frozen wall thickness increases linearly with the increase in groundwater seepage rate. Due to the erosion by groundwater seepage, a weak area appears at the closure position of the frozen wall in the upstream area. When the groundwater seepage rate reaches 5.00 m d^{-1}, the excessively high groundwater seepage rate leads to the closure of the frozen wall in the downstream area. Compared with the "erosion effect" of groundwater in the upstream area, the "shelter effect" of the upstream frozen wall results in a reduction in groundwater seepage rate near the downstream frozen wall, and the cold carried by the low-flow groundwater is more conducive to the development of the downstream frozen wall (see Figure 12).

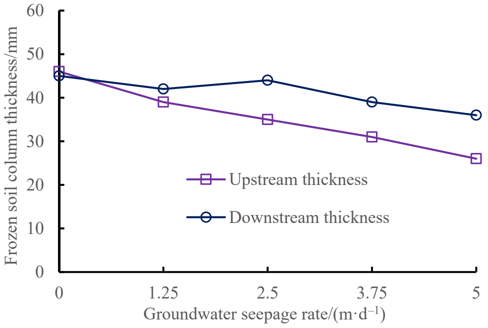


Figure 11. Relationship between the thickness of frozen soil column and seepage rate after 8 h of freezing

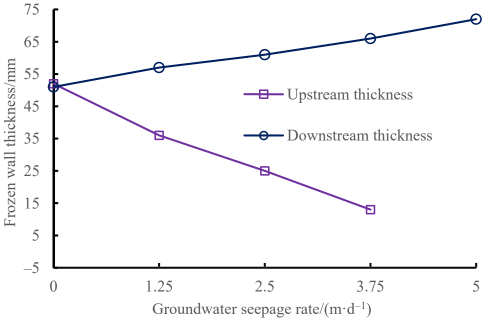


Figure 12. Relationship between the frozen wall thickness and seepage rate at closure time

4. Conclusions

(1) When there is no groundwater seepage, the upstream and downstream temperatures of the gravel strata show symmetrical distribution characteristics. Due to groundwater seepage, the upstream temperature of the gravel strata is higher than the downstream temperature in the mirror position, and the greater the groundwater seepage rate, the more significant the asymmetry of the temperature field.

(2) Groundwater seepage delays the frozen wall closure time. When the groundwater seepage rate increases from 0 to 5.00 $\mathrm{m \ d^{-1}}$, the frozen wall closure time is 3.2 times longer than the original. The edge of the frozen soil column and the frozen wall is irregular and the closure position of the frozen wall shifts to the downstream direction, resulting in a saddle-shaped wall.

(3) The thickness of the upstream frozen soil column decreases linearly with the increase in seepage rate due to the "erosion effect" by groundwater seepage. The downstream frozen soil column is thicker than the upstream frozen soil column due to the cold of the freezing pipe and the "shelter effect" by the upstream frozen soil column.

(4) When the frozen wall closes up, the thickness of the upstream frozen wall decreases linearly with the increase in the groundwater seepage rate due to the "erosion effect" by groundwater seepage and the "shelter effect" by the upstream frozen wall. When the seepage rate increases from 0 to 5.00 $\mathrm{m \ d^{-1}}$, the frozen wall closes in the downstream area, and the thickness of the downstream frozen wall increases linearly by 40%.

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Corresponding author
Tianliang Wang can be contacted at: wangtl@stdu.edu.cn