Research on layout optimization of freezing pipes based on numerical calculation of hydro-thermal model

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Abstract. In order to study the influence of seepage flow on the development of frozen curtain in the artificial ground freezing project and optimize the distribution of freezing pipes. A coupled hydro-thermal model base on Darcy law and thermal balance equation has established and verified by the model test. The result shows that it can effectively improve the efficiency, reduce the completed freezing time and strength of frozen soil curtain. And the best distance which is all gratefully acknowledged between freeze pipe in upstream and section of original design freeze pipes is 75% of the distance of freeze pipes. In the end, the influence range of one pipe in upstream will be 3~4 times the distance of freeze pipes.

1. Introduction

Artificial ground freezing (AGF) is a special method to reinforced soils which use brine or liquid nitrogen flow in freezing pipes and drawing heat from soils to enhance the intensity and reduce permeability of soils. In the end, the frozen curtain was generated and excavation and construction can be work under protection of frozen curtain. The principle of AFG method is shown in Figure 1. The refrigeration equipment produces low temperature brine. And the brine pump creates a brine circulation which transfer the heat from ground to refrigeration equipment. The refrigeration cycle transfers the heat to cooling water which release the heat to atmosphere. With the circulation, the temperature of soils surrounded with freezing pipe reduce quickly and pore liquid water turns to ice and the strength of ground greater than natural.

The first project use AGF was sink shaft through quicksand during coal mining in German in 1882. The method was first used in the construction of mine in 50 years of last century in China, and the it was gradually applied in the municipal engineering.

With the popularization and application of artificial ground freezing, the seepage flow is an important factor in the failure of AGF projects. The seepage flow can supply a continuous source of heat. therefore an thermal equilibrium different from normal one without seepage will rebuild. In this condition the width and average temperature of frozen curtain is far less than normal. A large number of scholars have carried out relevant studies.
In terms of theoretical analysis, Khakimov[1] formed analytical formulae about temperature field in freezing process. However, analytical formulation was difficult to use for hydro-thermal coupling problems[2]. Therefore, calculated temperature field by numerical simulation is a effectively way. A large number of calculations by numerical simulation got the temperature field under seepage flow. And the thickness of frozen curtain in upstream is thinner than downstream, and the trend increases as the velocity of seepage increases. It can be usefully reduce the effect of seepage by reduce the distance of freezing pipes[3]-[5]. With the prediction of temperature field, the optimization of design was putted forward proposed a optimization method based on Nelder-Mead method[6].

All the above research is mainly based on the state of seepage is known before work, but the discover of seepage after all the freezing holes were built has not provided an effective solution. This paper build a hydro-thermal coupling model, and verified by model test[7]. Based on the model, the optimal design of the side frozen curtain of Cross-passage under seepage is carried out.

![Figure 1. Schematic Diagram of AFG Method](image)

2. Mathematical model and equations

2.1. Basic assumption
To simplify the analysis of model, some basic assumption was considered:(1) The soil is a homogeneous, saturated isotropic porous dielectric material; (2) Soil skeleton regarded as incompressible body;(3) the porosity of porous media is constant;(4) The temperature of seepage in the soil is constant.

2.2. Temperature field equation
Thermal equilibrium equation of temperature field under seepage flow as follows:

$$ C_w \frac{\partial T}{\partial t} - \nabla (\lambda_w \cdot \nabla T) + C_v u \nabla T = Q_H + Q_G $$

Where $C$ and $w$ represent the specific heat capacity and thermal conductivity, respectively; the subscript $eq$, $f$ indicate that they are for equivalent of soil and water, respectively. $\vec{u}$ is the seepage velocity vector of water; $Q_H$ denotes the heat released by the phase transition of water; $Q_G$ is the heat source, $T$ and $t$ are temperature and time and $\nabla$ is Laplace operator. In this paper $\nabla T = \frac{\partial T}{\partial x} + \frac{\partial T}{\partial y}$.

The sensible heat capacity method is adopted to deal with the phase change. The latent heat of phase change is equal to the heat capacity within a certain temperature range. In order to describe the process of phase change, it defines a step function of $H(T)$, which transition point is -0.4°C. The function is shown in Figure 2. Therefore, the formula for latent heat of phase change as follow:
\[ L(T) = L_1 \rho \omega \cdot H(T) \] (2)

Where \( L(T) \) is quantity of heat in phase change every kilogram; \( \rho \) is the density of soil; \( L_1 \) is the total latent heat of water; and \( \omega \) denotes moisture content of soil mass. In the calculation \( L=330 \text{kJ/kg} \) [8] and the change of moisture content after freezing is 7%.

Figure 2. Step function of \( H(T) \)

2.3. Hydraulic field equations
Hydraulic field equations is show in equation (3).

\[ \frac{\partial (\theta \cdot \rho_w)}{\partial t} + \nabla \cdot (\rho_w \cdot \mathbf{u}) = Q_m \] (3)

Where \( \theta \) is the porosity of soil mass, \( \rho_w \) is the density of water, \( \mathbf{u} \) is the velocity vector of water, and \( Q_m \) the incremental of quality.

2.4. Permeability coefficient
In order to simplify the calculation, unfrozen soils and frozen soils’ coefficients are respectively taken as \( k_u \) and \( k_f \). And the change of them define by Heaviside function in equation (4).

\[ k(T) = k_u \cdot H(T) + k_f \cdot (2 - H(T)) \approx k_u \cdot H(T) \] (4)

Where \( k(T) \) is the permeability coefficient with temperature, \( k_u \) is permeability coefficient of unfrozen soils, \( k_f \) is permeability coefficient of frozen soils and \( H(T) \) is the Heaviside function which step position is -0.2°C. In this model, defined \( k_f \) as 1×10-20m/d and \( k_u \) by Geological exploration data

3. Model validation
Ji Zhiqiang[7] has work a model test of artificial ground freezing under seepage. Medium sand was filled in a box with inner dimensions 1.0×1.0×1.0m. and diameter of freezing pipe is 16mm. Distance of freezing pipe is 110mm. The model and meshing as Figure 3

Figure 3. Calculation model and grid division
In this calculation, the temperature of brine is -25℃, seepage direction is from bottom to top. The velocity of seepage \( v = 7.5 \text{m/d} \). The soil parameter selection is shown in Table 1.

| Parameter                 | Density (kg/m³) | Heat conductivity coefficient (W/(m·K)) | Specific heat (J/(kg·K)) | Porosity (%) |
|---------------------------|-----------------|----------------------------------------|--------------------------|--------------|
| Unfrozen soil             | 1340            | 1.41                                   | 2360                     | 39           |
| Frozen soil               | 1340            | 1.92                                   | 1603                     |              |

The calculated data and model test data when the frozen curtain closed are shown in Figure 4. The distribution trend of soil temperature field is basically the same. And the peak point of temperature of numerical calculation move to downstream. According to Shibing Huang[6], Ahmed[9], the axial section of frozen soil will move to downstream. Therefore, the distance of peak point due to lack of test point of model test.

Above all, the numerical calculation can describe the change of temperature field effectively. Especially the temperature distribution in the frozen area.

4. Optimization of freezing pipes

The main solution to the problem of AGF projects under seepage flow is to adjust the position of the freezing pipes so as to change the form of the freezing curtain. However, it must obtain the seepage data before work. In many project seepage is a positional factor which often discovered after boring construction. Therefore, it is an effective scheme to add freezing pipe on the original design. Modify the model and add freezing pipe as shown in Figure 5. Add four pipes which distance 110mm in the center and one pipe in the upstream to section III with 110mm.

![Figure 5. Optimization design of freezing pipes](image)

The isotherm of 0℃ in active freezing for 3.6h shown in Figure 6. where the black line is 0℃ before optimization and the red line 0℃ after optimization. It shows that add freezing pipe can rise the thickness of frozen curtain. And the first and third gap between freezing pipe closed in the same time.
By comparing the thickness of frozen curtain with section I. It can be seen that the optimized frozen curtain has basically the same expansion direction in the upstream and downstream, and can effectively form a uniform frozen soil curtain around the frozen hole, while the unoptimized frozen curtain has poor uniformity in the upper and lower reaches. The temperature of section II in different condition shown in Figure 7, it shows that the frozen curtain after optimization is similar to the frozen curtain without seepage. And the thickness and average temperature of frozen curtain significantly improved after optimization.

Figure 6. Comparison of frozen curtain between optimization

![Comparison of frozen curtain between optimization](image)

Figure 7. Temperature distribution curve of section II before and after optimization

In this research, one freezing pipe can impact 3 gaps between pipes. Mostly AGF projects have 7~9 freezing pipes in one side, therefore, 2~3 freezing pipe in upstream can change all the frozen curtain effectly. This method is a better way suitable for undiscovered seepage after drill work.

5. Study on freezing pipe layout

In order to choose a best distance of freezing pipe in upstream, a new model was established. Define the distance of freezing pipe and section III as L like Figure 8. The results of active freezing temperature filed of 3.6h with L=60, 90, 110, 150 and 200mm were calculated respectively and the isotherm of 0°C of different L shown in Figure 9. As the result, the parameter L has little influence on thickness of frozen curtain in downstream, and have larger influence on frozen curtain in upstream. When L is too long, the frozen curtain will separate. The effect thickness of frozen curtain will decrease. Therefore, the best distance of L is 6m~90mm that the main freezing pipe spacing of 50~70%.
entrance of seepage

export of seepage

Figure 8. The new model for numerical simulation

Figure 9. Frozen curtain of different L

The temperature distributes curve of L=60, 90, 110mm in section I and II shown as Figure 10 and Figure 11. As the result, L=90mm is the best choice for maintain the thickness of frozen curtain. And the average temperature in design frozen area (between the cyan lines) is lowest.

Figure 10. Temperature distribution curve of section I
6. Conclusion
A combination of studies can be found that the thickness of frozen curtain of upstream and downstream would make a big difference under seepage flow. The location of frozen curtain will move away from design position and cause the thickness of frozen curtain and average of temperature can’t fit to the need of project. Therefore, it takes research about add freezing pipe on upstream of design frozen zone to improve the effect. And the following conclusions can be drawn:

The addition of freezing pipes on the upstream can partially solve the problem of weakening of the frozen curtain under seepage flow. Single optimized freezing pipe can improve 3~4 times of pipe spacing’s area about intersection of frozen curtain and thickness.

The best position to add pipe is 70~80% distance of pipe spacing. It can improve overall freeze effectively.

Acknowledgments
The research was financially supported by Special Funds for Scientific and Technological Innovation of Tiandi science @ Technology CO.,LTD(2019-TD-QN009;2018-TD-QN008), National Science Foundation of China(51804157), Key Laboratory of Roads and Railway Engineering Safety Control(Shijiazhuang Tiedao University),Ministry of Education(STKF201719) and Graduate Innovation Funding Project of Hebei Province(CXZZSS2019061) which are all gratefully acknowledged.

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