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Study on the influence of water flow on temperature around freeze pipes and its distribution optimization during artificial ground freezing

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HIGHLIGHTS

- A developed coupled hydro-thermal model was applied for artificial ground freezing.
- The influence of water flow on freezing temperature around freeze pipes was investigated.
- A new combining optimization method of freeze pipes arrangement was proposed.
- Three common distribution functions were suitable to determine the optimum positions of freeze pipes.

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ABSTRACT

Artificial ground freezing is usually used to improve ground and provide temporary support. However, the freezing process is dramatically influenced by water flow. Evidently, water flow with high velocity brings large heat energy that prevents the freezing of porous media around freeze pipes. In this paper, for safety and energy-saving, the influence of water flow on freezing process is simulated by a developed coupled hydro-thermal model considering water/ice phase transition and the positions of freeze pipes around circular tunnel are optimized through combining this model with Nelder–Mead simplex method based on COMSOL multiphysics platform. According to the evolution law of freezing band under well-distribution of freeze pipes, three kinds of potential frequently-used probability distribution functions are adopted to reduce control parameters and improve the efficiency of optimization program including normal distribution, Poisson distribution and chi-square distribution. The results show that the proposed combining simulation method is suitable for optimization of freeze pipes arrangement. The freezing time is significantly reduced no matter which one of the above distribution functions is employed through careful design.

1. Introduction

Freezing of porous media has been widely studied, either natural or artificial ground freezing [1]. Artificial ground freezing method, providing temporary support and waterproof layer in geotechnical engineering construction, are extensively used in soft rock and soils [2,3]. The fundamental principle in ground freezing is to inject cold energy and convert pore water into ice [4]. When the underwater tunnels pass through the rivers or straits, the process of construction in soft rock or soils usually is very difficult because of inrush disaster. Moreover, water may flow around the underwater tunnels before excavation because of the difference of water head. Artificial ground freezing technique is very suitable to improve the soil strength and prevent water flow into the excavated area in this case. To meet the demand of frozen soil strength, the thickness of frozen arch should be greater than 1.5 m [5]. However, water flow brings much thermal energy against the formation of freezing arch and changes the freezing path. The required freezing time of forming a specified frozen arch is also considerably influenced by high seepage flow. It has been investigated the area between two freeze pipes may not freeze if the flow velocity of water exceeds 1–2 m/d in high permeability soils or fractured media [6]. Moreover, when the temperature drops below freezing point, partial water in porous media gradually freezes but some liquid water is also existed [7,8]. Therefore, the freezing process of porous media is very complicated but important to conduct artificial freezing construction, which is associated with the coupled hydro-thermal action under low temperature.

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Many freezing models of coupled heat and water flow, freezing experiments and related numerical studies on porous media have been reported in the past decades [9–12]. However, the influence of high seepage flow on freezing process is rarely considered [13]. Besides, at present, there are a lot of researches on freezing construction technology and case analysis about artificial ground freezing, in which freeze pipes are arranged evenly or empirically [14–16]. Nevertheless, the freezing rates between two adjacent freeze pipes are unequal in the presence of seepage flow and freeze pipes may satisfy a certain distribution law which needs to be further studied [17]. To our knowledge only Marwan et al. [4] has tried to optimize the positions of freezing pipes by Ant Colony Optimization and it results in a significant decrease of freezing time. Due to the special freezing process of porous media under high seepage velocity, it is necessary to study the freezing process and propose corresponding optimization method during artificial ground freezing for safety, energy saving and high efficient construction.

In this paper, the Nelder–Mead simplex method is adopted to optimize the positions of freeze pipes through combining it with a developed coupled hydro-thermal model in order to derive a required frozen arch as fast as possible. The Nelder-Mead simplex method is an efficient and derivative free optimization algorithm to find the minimum or maximum value of an objective function, which has been widely applied in many fields, including engineering materials, geotechnical and hydrologic engineering [18,19]. It is relatively simple and suitable for not too many control parameters, in which only a numerical evaluation of the objective function is required [20]. The basic idea for the simplex algorithm from geometry is shown in Fig. 1. In the three dimensional space, a simplex is a special tetrahedron determined by four points (F_1, F_2, F_3 and F_4) and their connected lines. The objective function is estimated at every point. The highest point, where the objective function is largest (e.g. Point F_3), will be perpendicularly mirrored against the opposite plain segment to a lower point, which is also accompanied with an expansion or contraction to modify step size in order to reach the optimization valley floor. A termination criteria should be given to stop this optimization procedure, generally including the maximum number of reflections or a tolerance for critical variables. Similarly, it can be extended to the N dimension in which the simplex is a special polytope of $N + 1$ vertices.

Here a coupled hydro-thermal model considering the influence of water/ice phase transition, which is firstly studied by Tan et al. [22], is proposed and validated by a previous large-scale experiment of artificial ground freezing considering the effect of water flow on the freezing process in Section 2. Then an optimization method of freeze pipes arrangement, combining the coupled hydro-thermal model with an efficient optimization algorithm (Nelder-Mead simplex method), is proposed and applied in a circular tunnel constructed by artificial ground freezing method in Section 3. The freezing temperature around freeze pipes and the minimum freezing time under different seepage flow conditions is investigated before and after optimization in Section 4. In Section 5, some issues about the topic are discussed. Finally, some significant conclusions are drawn in the last section.

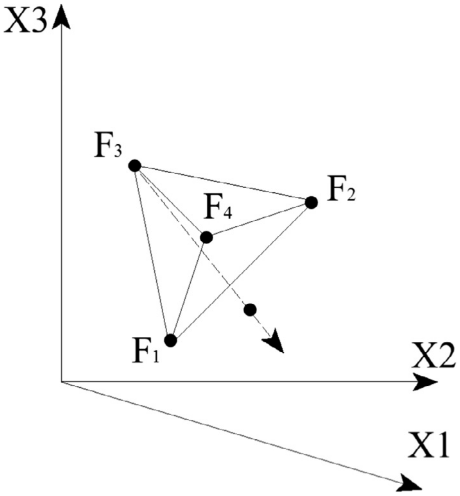

Fig. 1. Nelder-Mead simple for three optimization parameters [21].

2. Coupled hydro-thermal model considering water/ice phase transition

Thermal transfer and water flow during freezing around freeze pipes should be considered when investigating the influence of water flow on freezing temperature around freeze pipes during artificial ground freezing. Therefore, two crucial functions should be presented, heat conduction equation with phase change deduced from energy conservation and continuity equation considering water flow deduced from water mass conservation.

2.1. Governing equations

2.1.1. Basic assumptions

Considering the actual physical process, some basic assumptions are introduced as below: (1) The rocks or soils are saturated, homogeneous and isotropic porous media; (2) the evaporation process of water is ignored, and the Darcy's law is suitable to describe the groundwater flow in porous media; (3) the heat conduction in freezing porous media satisfies Fourier's law.

2.1.2. Heat conduction equation

A fully coupled hydro-thermal model has been firstly proposed by Tan et al. [22]. The heat conduction equation deduced from energy conservation in freezing porous media is expressed as

$$C_v\frac{\partial T}{\partial t} + \rho_l c_l \mathbf{v}_l\cdot(\nabla T) + \nabla\cdot(-\lambda_e \nabla T) = 0 \tag{1}$$

where ρ and c are density and specific heat capacity, respectively. Subscript s, l and i represent solid matrix, water and ice, respectively. T is temperature. $\mathbf{v}_l$ is the seepage velocity vector of water.

Water density is the function of pressure and temperature:

$$\rho_l = \rho_{l0}[1 + \alpha_T(T-T_0) + \beta_p(p_l-p_0)] \tag{2}$$

where ρ_{l0} is the density corresponding to the initial pressure p_0 and initial temperature T_0; α_T is the thermal expansion coefficient of water related with temperature; β_p is water compressibility; p_l is water pressure. When $p_0 = 101\,\text{kPa}$ and $T_0 = 20\,^\circ\text{C}$, there are $\alpha_T = (-9T-80) \times 10^{-6}/^\circ\text{C}$ and $\beta_p = 5 \times 10^{-6}/\text{Pa}$. The change of water density with temperature when $p_0 = 101\,\text{kPa}$ is shown in Fig. 2.

λ_e is the effective thermal conductivity of porous media, which depends on the thermal conductivity of its components (solid, unfrozen

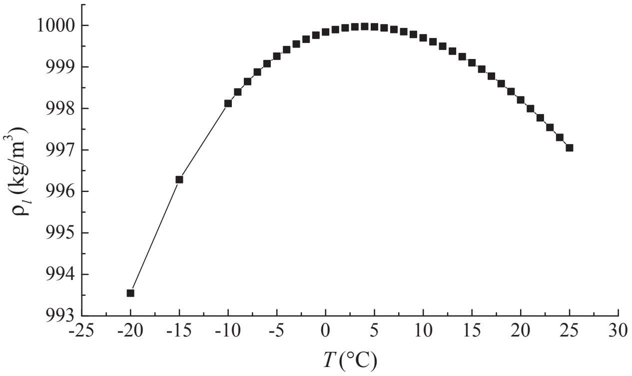

Fig. 2. The change curve of water density with temperature [23].