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Research Paper

# Optimization of artificial ground freezing in tunneling in the presence of seepage flow

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ABSTRACT

Artificial ground freezing is an environmentally friendly technique to provide temporary excavation support and groundwater control during tunnel construction under difficult geological and hydrological ground conditions. Evidently, groundwater flow has a considerable influence on the freezing process. Large seepage flow may lead to large freezing times or even may prevent the formation of a closed frozen soil body. For safe and economic design of freezing operations, this paper presents a coupled thermo-hydraulic finite element model for freezing soils integrated within an optimization algorithm using the Ant Colony Optimization (ACO) technique to optimize ground freezing in tunneling by finding the optimal positions of the freeze pipe, considering seepage flow. The simulation model considers solid particles, liquid water and crystal ice as separate phases, and the mixture temperature and liquid pressure as primary field variables. Through two fundamental physical laws and corresponding state equations, the model captures the most relevant couplings between the phase transition associated with latent heat effect, and the liquid transport within the pores. The numerical model is validated by means of laboratory results considering different scenarios for seepage flow. As demonstrated in numerical simulations of ground freezing in tunneling in the presence of seepage flow connected with the ACO optimization algorithm, the optimized arrangement of the freeze pipes may lead to a substantial reduction of the freezing time and of energy costs.



## 1. Introduction

Artificial ground freezing (AGF) is an effective temporary ground improvement technique in geotechnical interventions in soft soils. It is a reversible process with no environmental impact to improve the hydro-mechanical properties (strength, stiffness and permeability) of the soil and to provide a local supporting structure. AGF has several applications in geotechnical engineering including slope stabilization, ground water control and excavation support during underground construction. In tunnel construction in difficult geological and hydrological ground conditions, e.g. in water-bearing soft ground, auxiliary ground improvement measures such as soil grouting or artificial ground freezing (AGF) are often applied to provide temporary excavation support and groundwater control. AGF has been commonly used in the last 20 to 30 years as a method to reliably mitigate risks of damage of existing structures during tunnel construction, in particular in tunnel excavation with low overburden in sensible urban areas, and to efficiently control the groundwater during tunnel advancement (see e.g. [24,20,41,25,27,36,40,37]). When applying AGF in tunneling, a closed arch of frozen ground is formed after a period of time around the excavated area, which provides a protected area for the excavation of the tunnel cross-section.

The ground freezing process converts pore water into ice by withdrawing heat from the soil. Depending on the coolant, there are mainly two types of AGF in use: brine freezing and liquid nitrogen ($LN_2$) freezing. Brine freezing is characterized by a closed circulation system by using refrigeration plants. The brine (usually calcium chloride $CaCl_2$), cooled typically down to temperatures ranging from $-20\,^{\circ}C$ to $-37\,^{\circ}C$, flows through a manifold system before returning to the refrigeration plant, where it is chilled and recirculated. Liquid nitrogen freezing extracts the heat from the soil through direct vaporization of the cryogenic fluid ($LN_2$) in the freeze pipes. The $LN_2$, usually stored in an insulated pressure vessel, is fed into the inner pipes through a surface manifold system. In the annulus between the freeze pipe and the inner pipe, it starts to vaporize at $-196\,^{\circ}C$ after withdrawing heat from the soil on its way up, and is vented directly into the atmosphere. With

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the ice binding the soil particles, the strength and impermeability of the frozen soil body are significantly improved. In general, the time to establish a desired thickness of a frozen soil body with full temporary load carrying capacity depends on the type of coolant used in the freezing process and on the freeze pipes in terms of size, number and spacing.

The required freezing time is considerably influenced by the presence of seepage flow, since the flow provides a continuous source of heat. In case of large seepage flow, a state of thermal equilibrium can be reached, in which freezing stops and the closure of desired frost wall cannot be developed. Evidently, as an important indicator for energy consumption and hence operating cost, the required freezing time increases substantially with increasing seepage velocity.

For a safe and economic geotechnical design and construction, a reliable prediction of the coupled thermo-hydraulic behavior of the soil during freezing is required. The continuum mechanics description of porous materials as a multi-phase material whose behavior is influenced by the interaction of the solid skeleton and the pore fluids can be accomplished by the Theory of Porous Media (TPM) (see, e.g. [8,14]). By integration of the Theory of Mixtures [45] with the concept of volume fractions, the TPM allows a description of the individual phases and their interactions within porous media on an *a priori* macroscopic scale of observation, and constitutes a suitable basis for modeling of freezing processes in soils, such as the three-phase freezing soil models developed by Kruschwitz and Bluhm [28] and Bluhm and Ricken [1]. In addition to the TPM, another well-established description for the complex behavior of porous materials during freezing is the theory of thermo-poromechanics proposed by Coussy and Monteiro [6] and Coussy [4,5], which specifies the multi-scale physics of confined crystallization of ice and provides a more physics-based understanding by means of exploring how the macroscopic properties can be upscaled from the knowledge of properties at lower scales. As far as physics-based modeling is concerned, the premelting dynamics theory developed by Rempel et al. [39] and Wettlaufer and Worster [46] provides an excellent interpretation of the essential contribution of the premelted film water to the generation of frost heave.

By adopting the theory of thermo-poromechanics and the theory of premelting dynamics, the authors have developed in an earlier publication [47] a three-phase finite element model for the description of coupled thermo–hydro-mechanical behavior of freezing soils. In this numerical model, solid particles, liquid water and crystal ice are considered as separate phases, and the mixture temperature, liquid pressure and solid displacement as primary field variables. Through three fundamental physical laws (overall entropy balance, mass balance of liquid water and crystal ice, and overall momentum balance) together with corresponding state relations, the model captures the most relevant couplings between the phase transition associated with latent heat effect, the liquid transport within the pores, and the accompanying mechanical deformation. In this paper, since the ground freezing operation will only be investigated as a means for groundwater control during tunneling, with the analysis focusing on the influence of groundwater flow on the formation of the required frozen arch, the mechanical aspect (i.e. the displacement field) will be neglected for the sake of simplification. In other words, a coupled thermo-hydraulic freezing soil model is deduced from the original numerical model and will be used for the simulations presented in this paper.

Considering the high energy costs connected with soil freezing, there is an strong economic interest to minimize the time needed to establish a fully frozen soil body with the desired dimensions, considering the influence of seepage flow. With this background, the main focus of this paper is on the optimization of the arrangement of freeze pipes during ground freezing in tunneling in the presence of seepage flow. Among the few available publications concerned with optimization of AGF operations in tunneling [48] have presented two optimized placements of freeze pipes, both of which have showcased a significant reduction in the freezing time with two extra freeze pipes. In contrast, the goal of the present paper is on the investigation of optimal pipe placements considering different levels of seepage flow, however, without increasing the pipe numbers.

To this end, the multi-field finite element model for the numerical modeling of the freezing process is connected with a suitably designed optimization algorithm. For the highly nonlinear, multidimensional problem at hand, meta-heuristic methods have significant advantages as compared to gradient based methods [22]. Instead of computing the gradient or Hessian matrix of the objective function, stochastic approaches are used in meta-heuristic approaches. This significantly increases the ability to find optimal or near optimal solutions specially for complex problems with multiple local minima. Within the family of meta-heuristic optimization methods a number of specific algorithms such as Simulated Annealing, Tabu Search, Genetic Algorithms, Ant Colony Optimization and Particle Swarm Optimization has been developed (see [16,2] for an overview). Ant Colony Optimization (ACO) is a probabilistic technique, belonging to the class of swarm intelligence algorithms, which aims to search the optimal path within a graph. Inspired by the foraging behavior of ants, this approach mimics the behavior of the ants seeking a path between their colony and a source of food [11]. Ants use pheromones as a communication medium when searching for food. They deposit pheromone trails on the ground to mark food paths where these trails should be followed by other ants of the colony [17]. While along successful (shorter) paths the pheromone level increases, the pheromone level also may "evaporate" along less successful (longer) paths. Similarly, ACO uses artificial pheromone trails as an indirect communication tool to find the most efficient path towards the optimum of a target function. The pheromone trails and its update scheme serve as numerical information that improves the search probability to select optimal solutions. Pheromone evaporation avoids convergence to local minima of the objective function.

The first algorithm for ACO was proposed in the early 1990s as a novel technique for solving difficult combinatorial optimization problems (see e.g. [9,13]). Subsequently, different algorithms including ant colony system [12] and Max–Min Ant System [44] were introduced. Later, ACO was extended to solve multi-objective optimization problems. Multi-objective ACO is composed of an underlying ACO algorithm plus specific algorithmic components to tackle multi-objective optimization. This can be achieved in different fashions such as using different pheromone matrices for each objective or using multi-colony approach with one colony for each objective (see [23,33]). ACO was also adopted to continuous optimization problems. Socha and Dorigo [42] proposed $ACO_R$; the most popular ACO algorithm for continuous domains. Extensions of $ACO_R$ to Diverse ACO ($DACO_R$) and Incremental ACO ($IACO_R$-LS) were proposed in Leguizamon and Coello [30] and Liao et al. [31]. $DACO_R$ uses the same basic principle of $ACO_R$. However, it generates new solutions by considering an alternative approach to select probabilities for producing solutions. $IACO_R$-LS is an $ACO_R$ with an extra search diversification mechanism and a local search procedure that enhance its search intensification abilities. Recently, a unified algorithm, which includes the previous algorithmic components for continuous optimization with ACO, was presented in Liao et al. [32].

A successful implementation of a meta-heuristic search shall provide a balance between the exploration and the exploitation Exploration achieves diversification; it aims to efficiently explore the whole search space. Exploitation means intensification as it