Computers and Geotechnics 75 (2016) 80–92

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

Thermo-hydraulic modeling of artificial ground freezing: Application to an underground mine in fractured sandstone

M. Vitel [a,*], A. Rouabhi [a], M. Tijani [a], F. Guérin [b]

[a] Mines ParisTech, PSL Research University, Centre de Géosciences, 35 rue Saint Honoré, 77305 Fontainebleau, France
[b] Areva Mines, 1 Place Jean Millier, 92084 Paris La Défense, France

ARTICLE INFO

Article history:
Received 13 October 2015
Received in revised form 22 January 2016
Accepted 28 January 2016

Keywords:
Artificial ground freezing
Numerical modeling
Thermo-hydraulic coupling
Freeze pipes

ABSTRACT

The difficult geological conditions of underground mines in permeable and fractured rocks require the use of ground support and inflow management methods. Artificial ground freezing offers the opportunity to reduce the permeability of the ground and to consolidate it. However, the establishment of this technique can be made complicated by two phenomenas: the strong ground heterogeneity, which renders delicate an overall freezing prediction, and the potential presence of high seepage-flow velocities, which may have a negative impact on freezing progress. The present article presents a coupled use of the thermo-hydraulic model and the freeze-pipe ground model presented in Vitel et al. (2016, 2015) with an application to the Cigar Lake underground mine in Northern Saskatchewan, Canada. The first model allows the estimation of the temperature and pressure distribution in the ground during freezing while the second model simulates the heat transfer between a freeze pipe and the surrounding ground, which is useful to determine the boundary conditions of the thermo-hydraulic model. First, the article restates the governing equations of both models. Then, after the validation of the numerical results with respect to field measurements, a joint use of the models is proposed, in particular to (i) predict the ground temperature evolution, (ii) study the impacts of the geological conditions on the freezing progress and (iii) optimize the freezing system design.

1. Introduction

The deposit associated with the Cigar Lake mine, like other uranium deposits in the Athabasca Basin (Saskatchewan, Canada), is strategic due to its exceptional grade (18% of U_3O_8 on average). However, its access is technically challenging because of the presence of water under high pressure and because of the poor mechanical properties of the orebody and of the surrounding ground. The deposit is located at the unconformity level (about 450 m deep) between the water-bearing sedimentary basin and the basement, in a highly fractured and altered area [3].

To mitigate these difficult conditions, the artificial ground freezing (AGF) technique is used, before and during the operation. The aim is (i) to reduce the permeability of the rock mass in order to mitigate water inflow into underground workings and (ii) to consolidate the ground and thus prevent instability [4]. The freezing system includes a freezing plant on surface where calcium chloride brine is cooled to $\sim -30\,°C$ and sent underground through a pipe network in the ground to be frozen. The design of the freezing system is complex and the heterogeneous ground conditions, as well as the potential for inflows, have to be taken into consideration to operate the mine.

Since the first work of [5], many authors have elaborated ground freezing models that consider a coupling between thermal and hydrogeological mechanisms. Most of these models have been reviewed by Li et al., Liu et al., and Kurylyk and Watanabe [6–8]. These reviews especially expound the differences in theoretical formulations. Some of the models have been validated against experimental data but, to our knowledge, only the models of [9,1] have been verified under conditions of high water flow velocity (against the results of the test conducted by Pimentel et al. [10]). The model presented in [1] is fully consistent from a thermodynamic perspective and considers relatively general assumptions that are appropriate to the case of an underground mine. The model has been developed for a saturated ground, considering a variable ice pressure, a water volume expansion during freezing and a non-deformable medium (constant porosity). The validity of this assumption has been tested for our applications.

In most AGF sites, the freeze pipes are not instrumented and *in situ* measurements at the freeze pipes' wall, either temperature

* Corresponding author.
E-mail address: manon.vitel@mines-paristech.fr (M. Vitel).

http://dx.doi.org/10.1016/j.compgeo.2016.01.024
0266-352X/

Nomenclature

Greek letters

ϖ	coefficients of the differential equations governing T_c and T_a
ε	level of accuracy
λ	thermal conductivity
μ	dynamic viscosity
ξ, θ	parameters of the function S_λ (T)
ρ	density
ρ^α	apparent density of phase α
$\underline{\tau}$	friction tangential stress
$\vec{\psi}$	flux density

Latin letters

$\mathcal{A}$	cross sectional area
C_f	friction coefficient
C_p	specific heat capacity at constant pressure
$\vec{g}$	gravity acceleration
h	specific enthalpy
h_{ij}	heat transfer coefficient
$\hbar$	overall heat transfer coefficient
k_r	relative permeability
$\underline{\underline{K}}$	intrinsic permeability
$\underline{\underline{K}}_H$	hydraulic conductivity
L	length
m	parameter of the function $k_r(S_\lambda)$
n	porosity
n_α	volumetric content of phase α
$\mathcal{P}$	perimeter
p	pressure
Q	mass flow rate
r	radius
r, z	coordinates
S_λ	degree of liquid water saturation
T	temperature
t	time
v	velocity

Subscripts

a	annular
α	phase α
c	central tube
γ	ice
eq	apparent properties of the ground
i	inner
λ	liquid water
o	outer
p	pipe
σ	soil particle
w	wall
0	reference

Superscripts

h	heated
w	wetted

or flux, are not available. As a result, the thermal boundary conditions of the AGF numerical model are unknown and must be assumed. The model developed by Vitel et al. [2] adopts an innovative approach where the full heat transfer problem constituted by a freeze pipe and the surrounding ground is simulated. As a result, the boundary conditions at the pipe, as required in AGF models, are explicitly calculated.

In this paper, the models developed by Vitel et al. [1,2] are applied jointly to the case of the Cigar Lake mine. In a first part, the thermo-hydraulic (TH) coupled model and the freeze pipe–ground model are briefly presented to restate the problem to be solved. Then, the models are tested against *in situ* measurements provided by the mine site. The third part of the paper investigates the potential effect of seepage flows on freezing. The last part of the paper focuses on the influence of the freeze pipes layout on the freezing efficiency.

2. Thermo-hydraulic model of artificial ground freezing

The overall study of the thermo-hydraulic problem of artificial ground freezing involves a double coupling. The first coupling is phenomenological: the thermal state of the freezing porous medium is influenced by its hydraulic condition and, conversely, its temperature condition directly impacts its hydraulic state. That it is why the model presented in [1] solves simultaneously two main equations for the thermal and the hydraulic problems in the ground, the two main unknowns being the common temperature to all phases T and the liquid water pressure p_λ. The second coupling is purely structural: the heat transfer problems in a freeze pipe and in the surrounding ground are interdependent. Thus, the model presented in [2] solves this interrelated problem by simulating simultaneously heat transfers in the pipe, in the ground and between the pipe and the ground, while the coolant flows within the pipe. The two following sections set out the final equations solved by both models. The reader may refer to [1,2] for the details of the demonstration.

2.1. Coupled thermo-hydraulic model of ground freezing

A porous medium subjected to subzero temperatures and fully saturated by water assumed totally pure is considered. The porous medium is then constituted of three phases α: soil particles ($\alpha = \sigma$), pure liquid water ($\alpha = \lambda$) and pure ice ($\alpha = \gamma$). Its thermal and hydraulic behavior is governed by the balance equations of mass and energy. These equations may be obtained via the volume averaging method, adopted over a Representative Elementary Volume (REV) of the porous medium.

Firstly, the conservation equation of the water mass ($\alpha = \lambda, \gamma$) is found to be:

$$n\partial_t[\rho_\lambda S_\lambda + \rho_\gamma(1 - S_\lambda)] + \vec{\nabla} \cdot (\rho_\lambda n S_\lambda \vec{v}_\lambda) = 0 \quad (1)$$

where $n = \sum_{\alpha\neq\sigma} n_\alpha$ is the porosity, n_α is the volume fraction of phase α defined as the ratio of the volume of the REV part occupied by phase α to the total REV volume, ρ_α is the phase density, $S_\alpha = n_\alpha/n$ is the saturation degree of phase α (with $S_\lambda + S_\gamma = 1$), and $\vec{v}_\alpha$ is the velocity of the phase's particles. In (1), the porosity n is considered constant and it is assumed that the soil matrix is a fixed rigid body and that ice follows the movement of the soil matrix ($\vec{v}_\gamma = \vec{v} = \vec{0}$).

Secondly, the heat equation of the porous medium is found to be, assuming a thermal equilibrium instantaneously established between the phases ($T_\sigma = T_\lambda = T_\gamma = T$):

$$(\rho C_p)_{eq}\partial_t T + \rho_\lambda C_{p\lambda} n S_\lambda \vec{v}_\lambda . \vec{\nabla} T = -\vec{\nabla} . \vec{\psi} \quad (2)$$