On freezing resistance of borehole heat exchangers

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Introduction

The ground source heat pump (GSHP) systems used to provide heating and cooling of buildings are installed in the ground with high density polyethylene (HDPE) pipes and the surrounding empty space is filled with the grout material in the borehole. It refers to closed loop borehole heat exchangers (BHE).

Through the installed HDPE pipes, a pump that circulates anti-freeze mixture exchanges heat along the buried BHE with the ground. During the operations, the backfilling materials of BHE, particularly the grout material, must ensure an efficient thermal contact and durability. Particularly for heating purposes, BHEs can be operated below the freezing point of water. Consequently, backfilling materials contract due to cooling and the freezing water inside the pores of the grout generates expansion and growing of ice-lenses. These thermo-mechanical behaviors may damage the grout and decrease the performance of BHE.

About the thermal stress investigation of GSHP systems, several investigations have been reported about the impact of heating and cooling processes of axial stress and strain of energy piles [1-2]. However, those studies refer to axial thermal stresses and the freezing effect is clearly disregarded.

Considering the growing ice lenses in the pores of grout material, some theoretical models are described in the literature provides significant information about the behavior of freezing in a porous medium [3-5]. According to these studies, the expansion of water freezing may have a significant impact on the stress state for elevate water saturation ratio (>90%). Suction draws water at the interface between ice-lens and liquid water brings the liquid towards the freezing front. In addition, the freezing pressure correlates to the permeability. The high permeability allows the liquid to flow easily through the pore throats to decrease the pressure. In contrast, low permeability increases the pressure in the pores, and the thin water film between the ice formation and the grains acting as the disjoining force that opens new flow paths which damage the medium.

Concerning, the experimental works about the freezing of porous materials in the literature, most of the studies address the resistance of concrete mortar or Portland-cement paste to the freeze-thaw cycles caused by surface temperature conditions [6-9]. The applied boundary conditions play important role on the crack development. Concerning backfilling materials for BHE, there exist a very limited number of investigations but they do not consider realistic thermal boundary conditions of a BHE [10-11]. A recent tentative of experimental study of freezing effect on co-axial BHE has been carried out by [12]. They demonstrate a significant loss of integrity of the geothermal probe but it is to mention that the freezing effect was probably too severe.

The objective of the present study is to understand the behavior of thermo-mechanical behavior of porous grout material used for GSHP systems and in particular how the freezing process causes degradation on a grouted BHE. The study is carried out with some laboratory experiments and theoretical approaches.

Experimental investigations

The crack development is investigated in the laboratory with a permeameter created for a BHE probe in which pressure can be applied. Therefore, the water can flow through the grouted probe to determine the permeability of a BHE (Fig. 1). The conditions are oriented to a realistic operation schedule of a GSHP system, because the standard methods established for other purposes may be not representative to describe a GSHP operation of a BHE probe. Therefore, each freeze cycle takes 15 hours and the temperature of circulating anti-freeze fluid is set to -8°C. After each operation, the subsequent recovering (thawing) is approximately 30 hours. For the study, two types of grout material widely used for BHEs are considered: a thermally enhanced silica-sand based material, and a calcite based material with a lower thermal conductivity.

The permeability of both grout materials does not show significant change along the following number of cycles. The increase of permeability of calcite-based grouting after the first cycle is probably due to the grout that is not stick to the HDPE pipes. According to those experimental observations, the BHE does not seem significantly affected by the freeze-thaw cycles.

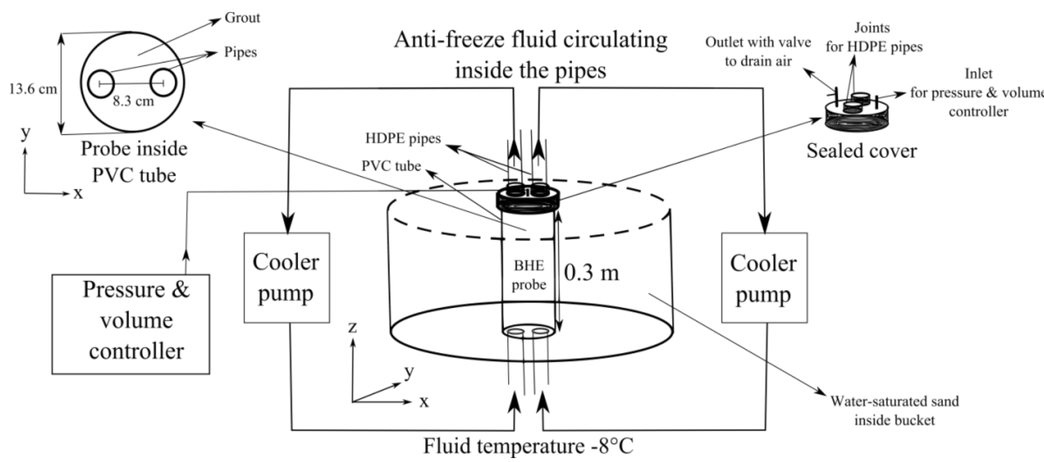

Figure 1. The scheme illustrating the experimental setup for determining the permeability of a grouted BHE.

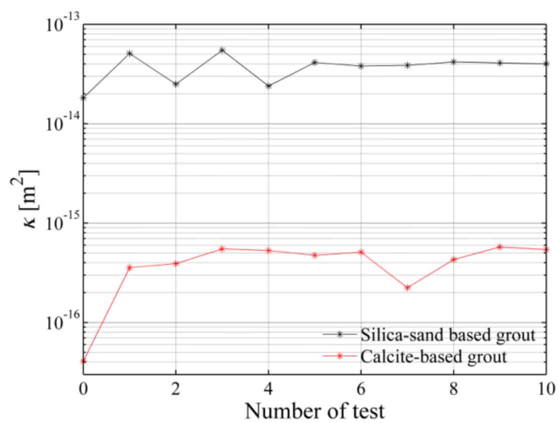

Figure 2. Intrinsic permeability over number of operations.

Analytical solution

A thermo-mechanical analytical model has been developed in order to estimate the thermal stress induced in the section of the BHE based on a hollow cylinder analytical approach. Both elastic thermal dilation/contraction and freezing ice pressure are considered [13-14], according to the work of Penttala and Al-Neshawy [15]. The developed model shows that the induced stresses in the grout material are not large enough to lead to a possible crack compared to the grout tensile and compression resistances. On the other hand, the tangential stresses occurred in the HDPE pipes reaches more than 5 MPa which can cause relative sliding at the pipe/grout interface. The results also demonstrate that the ice pressure close to the pipe increase the stress non-linearly, but the ice could not propagate further than 1.5 cm away from the pipe in 15 h of operation. It can be mention that in a real operation schedule of a GSHP system, the BHE is used for a couple of hours in a day, and the rest of the day can be considered as the recovery phase. Therefore, to observe a fully frozen BHE and significant thermal stress results caused by daily operations, the system must run for decades.

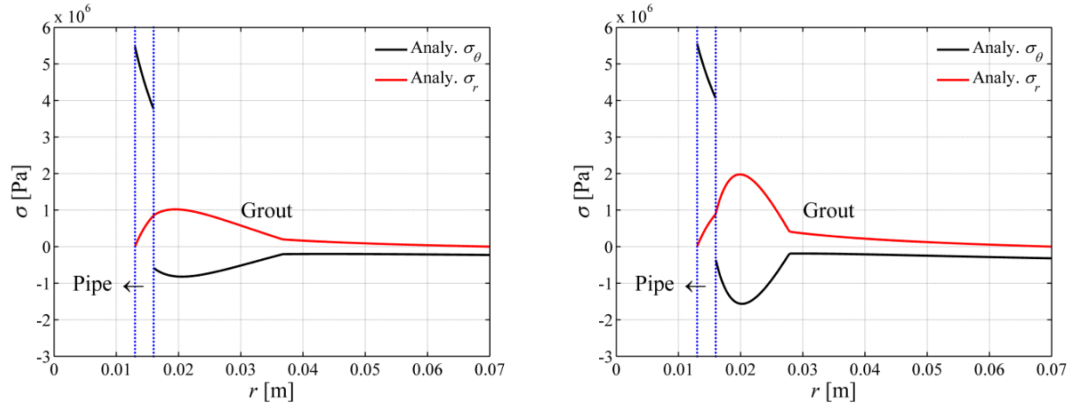

Figure 3. Analytical solution of thermal and freezing stresses in the BHE as a function to axial distance (a) Silica-sand based grout; (b) Calcite-based grout.

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Topic of scientific programme:
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