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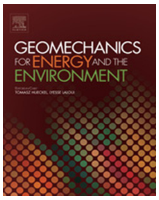

# Freeze damage of grouting materials for borehole heat exchanger: Experimental and analytical evaluations

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## HIGHLIGHTS

- We developed an analytical model to predict freeze damage of borehole heat exchange.
- The model prediction is compared with obtained results on an experimental set-up.
- Crack occurrence predicted by the model agrees well with experimental observation.
- Permeability and porosity of grout have primary role on the freeze-induced failure.

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## ABSTRACT

The closed-loop ground source heat pump (GSHP) systems can be operated below the freezing point of water with anti-freeze mixture through the installed borehole heat exchangers (BHE) in the ground for the heating purposes of buildings. During the operations, the BHE is exposed by the thermal stresses due to heat loading. In addition if the porous grout material is immerged in water, the freezing-induced ice pressure may damage the grout. In this paper, the freezing impact on BHEs is investigated analytically and experimentally. For the theoretical approach, an analytical solution is developed by using the hollow cylinder model that accounts for both the high density polyethylene (HDPE) pipe and the grout material. Firstly, the frozen pore water pressure is incorporated in the generalized Hooke's law equations in 2D plane stress, and secondly the model is solved for the considered boundary conditions. In order to validate the developed model, the experimental setup is conducted in agreement with the geometry of the considered analytical model and the BHE specimens are prepared with three different grout materials having large difference in the thermal and hydraulic characteristics (i.e. silica-sand based, calcite based and homemade thermally enhanced with graphite). According to the experiments for 50 h of freezing operation, the calcite based grout and the homemade grout, having lower permeability and relatively higher porosity, are fractured. In contrast, the silica-sand based grout having higher permeability did not exhibit any damage. Compared with the theoretical results, the observations from the experiments are consistent. The effective tangential stress induced by the frozen pore water pressure causes the crack development and agrees with the crack patterns. It is concluded that the porosity and the permeability play significant role on the grout failure upon freezing.

## 1. Introduction

In the context of geological energy production, borehole heat exchangers (BHEs) allow to extract or store

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heat from the ground. Those operations may modify significantly the temperature of the ground and produce thermo-mechanical disturbance of the system. In particular, for heating purposes, BHEs can be operated below the freezing point of water with the heat carrier fluid, and the anti-freeze mixture circulating through the pipes. This operation at low temperatures not only causes contraction of the backfilling materials, but also freezing of the water inside the pores of the grout with an expansion of growing ice-lenses. These complex hydraulic and thermo-mechanical behaviors may damage the grout. Therefore, in order to avoid an early-damage on the geothermal installation due to the system overload during the peak demands, the grout material used for ground source heat pump (GSHP) systems should be frost-resistant to sustain the heat transfer between the ground and the pipes, and also to prevent aquifers from pollution, most likely, due to the leaking of anti-freeze mixture.

The freezing of pore water is a non-linear heat transfer process which leads the concurrent changes of thermo-hydro-mechanical properties. For a borehole heat exchanger in an infinite ground medium, the ice growth is controlled by the heat source and the permeability of the medium. Based on the mechanism of growing ice formations in the pores, some theoretical models are described in the literature. Among the pioneering investigations about the freezing of porous materials, Powers and Helmuth[1] presented a model of hydraulic pressure inside the pores. On the one hand, their model predicts that the larger pores freeze faster than the small ones causing high hydraulic pressure and cracks in the material. On the other hand, the pores that contain empty air voids slow down the growing ice formations. Litvan[2] provided a theoretical model which demonstrates that the surface forces of pores play a significant role to hinder the freezing process. More recent studies present models to approximate the pressure in the fully water-saturated pores involving the stress and strain states during freezing of porous materials.[3–6] Vlahou and Worster[5] investigated the symmetrically growing ice lens in a spherical cavity within a porous rock as a function of permeability. The high permeability allows water to flow easily to release the pressure. In contrast, low permeability causes a reduction in the ice formation in the cavity, but it increases the pressure by a thin water film acting as the disjoining force to separate the ice and the rock. These forces expand and open new paths enhancing the ice formation by sucking water toward the ice front. Furthermore, Walder and Hallet[7] showed that the rate of the ice growth considerably increases in a temperature range of −4 °C to −15 °C. If the temperature range is more than −4 °C and close to 0 °C, the existing pore ice cannot increase the pressure sufficiently to lead to a significant fracture.

Concerning experimental works about the freezing of porous materials, most of the studies focus on the determination of the resistance of concrete mortar or Portland-cement paste to the freeze-thaw cycles caused by surface temperature conditions.[8–13] In some situations, the durability of the materials can be clearly jeopardized by the mechanical impact of freezing. Borinaga-Treviño et al.[14] summarized all these experimental studies showing the applied methods and the boundary conditions directly applied to the issue of borehole heat exchanger. According to Borinaga-Treviño et al.,[14] except the cement, the mortars containing limestone or silica-sand are not affected by the freeze-thaw cycles. However, in contrast, they also mentioned that, due to the larger thermal expansion coefficient of the HDPE pipe (the thermal expansion coefficient being approximately 10 times higher compared to the mortar), the HDPE pipe creates tangential tension in the mortar and causes a failure in the pipe/grout interface and the crack propagates until the overall failure. This observation clearly underlines that the freeze-thaw damage is not only a function of the freezing resistance of the porous material itself, but also on the boundary conditions and the interactions with the other systems (i.e. pipes, ground).

In order to ensure a frost-proof grout material for a BHE, a standard method for freeze-thaw cycles can be conducted, but the established norms refer only to conventional applications and do not consider the specific case of BHE. Herrmann[15] conducted three different tests to investigate the reliability of grouting materials for freeze-thaw cycles. Two methods are in accordance with the standard test methods DIN 52104-1 and DIN CEN/TS 12390-6, and the third method is more oriented to the practical temperature range with a single-pipe geothermal BHE specimen. According to Herrmann,[15] the standard test method DIN 52104-1 is not suitable for grout material, because the samples are fatally damaged after only one freeze-thaw cycle and unable to perform any measurement test after the experiment. The applied temperatures on the samples are considerably lower than for a GSHP system (i.e. −20 °C). The DIN CEN/TS 12390-6 provided comparatively more reasonable results. The freeze-thaw cycles cause fractures on most of the ready-made grouts and lead to a decrease of 4%–20% on the thermal conductivity while the permeability values are raised by up to one order of magnitude. The third method is to operate a small-scale BHE specimen under dry sand or water-saturated sand conditions, to monitor the temperature distribution in the vicinity of the BHE specimen and to observe visible damage of the specimen after dismantling. According to their results, under low thermally conductive ground, the impact of freeze-thaw cycles is more significant on the BHE specimens due to lower thermal gradient. Recently, Anbergen et al.[16] studied the behavior of BHEs submitted to freeze-thaw cycles, by measuring the permeability of different grouted single-pipe BHE specimens with a parameter setup. According to Anbergen et al.,[16] the grouted specimens containing swelling clay minerals reduce the impact of freeze-thaw cycles on the permeability, because the micro-fractures that occurred due to thermal stresses are likely filled with swelling clay in the grout.

The resistance of grout/mortar materials has already been studied by many authors. Therefore, the objective of the present study is to understand the hydro-thermal and thermo-mechanical behavior of porous grout materials used for GSHP systems to determine how the freezing process causes the degradation on a grouted BHE. This study combines some laboratory experiments with theoretical approaches. The theoretical model used to evaluate the stress in a freezing BHE is derived by an analytical solution considering a hollow cylinder model. For the experimental part, similar to the hollow cylinder approach,