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Technologies and environmental impacts of ground heat exchangers in Finland

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A B S T R A C T

Finland is one of the northernmost countries utilizing ground source heat pumps (GSHPs). In this north European country, GSHPs' operating conditions are characterized by the cold climate, and hard, crystalline bedrock. Environmental risks and technical problems with ground heat exchangers (GHEs) have been much discussed, but the frequency of complications has not been previously studied in Finland. This article examines the types and construction practices of GHEs, and the range of problems in GHEs experienced by the practitioners. The data was collected through a questionnaire study among Finnish GSHP practitioners, and thematic interviews of Finnish heat pump experts. Borehole heat exchangers (BHEs) proved to be the most popular GHE type in Finland with a share of 85%. The questionnaire responses indicate that the most common complications in BHEs are connected to collapsed boreholes, and artesian or otherwise abundant water yields. Also, issues relating to heat transfer fluids, drilling through multiple aquifers, and design errors are discussed.

1. Introduction

Together with Scandinavian countries and Canada, Finland belongs to the northernmost countries utilizing ground source heat pump (GSHP) technology on a large scale (Nowak & Murphy, 2012: 73, 101, 118, 132, 140). According to the Finnish Heat Pump Association nearly 8500 GSHP units were sold in Finland in 2016 (SULPU, 2017). GSHPs are installed in new buildings, and retrofitted in place of oil burners, electrical heating, wood furnaces and district heating. Since 2013 more than half of new detached houses in Finland have had a GSHP installed (Motiva, 2016: 11).

A typical GSHP system in Finland consists of a borehole heat exchanger (BHE) and a vapor compression heat pump with either an inbuilt or a separate domestic hot water tank. Single U-pipes are most commonly used in BHEs. The GSHP system is connected to hydronic heat distribution, which is usually underfloor heating in new buildings and newer retrofit sites, or wall mounted water radiators in older retrofit sites. Horizontal ground heat exchangers (GHEs), in which a single, linear pipe is installed in series, are also used, while slinky or trench collectors are not used (cf. Florides and Kalogirou, 2007; Omer, 2008). Surface water heat exchangers are installed to a lesser extent, mainly in lakes and coastal areas of the Baltic Sea. Open loop heat exchangers are very rare in Finland. Ethanol is the most commonly used antifreeze in the GHEs whereas glycols are rarely used.

Boundary conditions for the sizing and design of GHEs in Finland are set by the northern climate and distinctive geological conditions. The annual average ambient temperature in Finland varies from over 5 °C on the south coast to below −2 °C in parts of northern Finland, where the temperature may drop below −40 °C in wintertime (FMI, 2016a,b). Correspondingly, the annual average temperature of the ground surface varies from 8 °C on the south coast to 2 °C in the far north of Finland (GTK, 2017). The thermal conductivity of Finnish rocks is typically over 3 W/(m*K), and the geothermal gradient is 8–15 K/km (Kukkonen and Peltoniemi, 1998; Kukkonen, 2000).

The bedrock in Finland generally consists of hard crystalline rocks, and sedimentary rocks are rare. Practically all of Finland is located on the Fennoscandian Shield, which is relatively unbroken and tectonically stable (Korsman and Koistinen, 1998; Plant et al., 2005). Due to the hard rocks in Finland, down-the-hole (DTH) drilling method is economically superior, and more efficient than any other method (cf. Rebouças, 2004). In practice, it is the only method applied to drill boreholes for BHEs in Finland. The rotating DTH hammer's percussion is powered by compressed air (typical working pressure 35 bar), and the exhaust air is used to flush the drill cuttings out of the borehole (Jouni Lehtonen, personal communication 12 Nov 2016; Jimmy Kronberg, personal communication 24 May 2017). Another consequence of the hard rocks is that boreholes are mostly left ungrouted and usually remain open. The need for grouting is also decreased by the fact that groundwater table is in most cases within ten meters from the ground surface (Karro and Lahermo, 1999). A completely dry borehole indicates that the rock is solid enough to prevent groundwater movement, in which case the borehole is filled with water.

Environmental and functional issues related to GSHP construction and use have been studied since the 1970s. Aittomäki and Wikstén (1978) and Aittomäki (1983) compared ground, surface water and air as heat sources for heat pumps in Finland, and discussed possible

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ecological impacts of heat extraction on lake sediment fauna. Hähnlein et al. (2013) and Vienken et al. (2015) analyzed the sustainability of ground source energy use in general. Environmental risks of heat transfer fluids in GHEs were discussed by e.g. Heinonen et al. (1997, 1998), Klotzbücher et al. (2007), Ilieva et al. (2014) and Schmidt et al. (2016). Ignatowicz et al. (2017) studied the thermophysical properties of ethanol and methanol based heat transfer fluids, and how different denaturing agents affected these properties. Morofsky and Cruickshanks (1997) reviewed procedures for environmental impact assessment in underground thermal energy storage projects. Groundwater flow and potential cross-contamination between aquifers were studied by e.g. Lacombe et al. (1995) and Santi et al. (2006). Bonte (2013) investigated the hydrochemical and geomicrobial effects of GSHPs and aquifer thermal energy storage. Fleuchaus and Blum (2017), and Sass and Burbaum (2010) analyzed damage events relating to BHE construction in Germany. Bleicher and Gross (2016) discussed the unpredictability of hydrogeology in general, and experimental strategies to cope with it in GSHP projects.

Environmental risks and technical problems related to GHEs have been commonly discussed in public, and between authorities and GSHP practitioners in Finland. Yet, little is known about the frequency of complications in GHEs in Finland. Therefore, this article examines 1) the types and construction practices of GHEs in the northern conditions typical of Finland, and 2) the range of problems in GHEs experienced by the practitioners.

2. Materials and methods

I utilized questionnaire responses, thematic interviews of heat pump professionals, and enquiries to insurance companies, to explore the construction practices and environmental impacts of GHEs in Finland. The same questionnaire study and interviews provided data also for Majuri (2016), which presented the questionnaire and interview outlines.

2.1. Questionnaire study

The questionnaire study was conducted between January and March 2014 among GSHP professionals, utilizing the Webropol online survey software (www.webropol.com). The questionnaire contained questions on various GSHP related topics. In this article, I will concentrate on the questions that aimed at 1) gathering information of the technologies and construction practices applied to GHEs in Finland, and 2) approximately quantifying the frequency of complications related to GHEs in Finland. The target groups for the questionnaire were engineering offices, GSHP contractors and borehole contractors, and the aim was to gather company-specific information.

To achieve a broad sub-sectoral and geographical coverage, six organizations associated to the heat pump industry were asked to deliver the questionnaire link to their members. The link was also e-mailed directly to 126 unorganized companies. Since the organizations and their members distributed the questionnaire link freely, the exact number of questionnaire recipients is not known (Majuri, 2016). It is anyway clear that nearly all practitioners in the field received the questionnaire.

In the questionnaire, the respondents were asked to estimate the percentage values of different GHE types in the GSHP projects that their companies had completed in different years (Fig. 1). The questionnaire also included a multiple-choice question: 'When your company constructs or orders the construction of a borehole heat exchanger, how often do you apply or require the application of the following equipment or properties?' This question charted (1) the construction phase practices of BHEs, i.e. how dust and cuttings are handled, and (2) the properties of the completed BHEs, specifically sealing against surface water, the use of manholes, inclined drilling and borehole diameters (Figs. 2–4). For the borehole diameter questions the data was complemented so that if a respondent had ticked 'always' for one diameter and nothing for the two others, option 'never' was added for the other diameters. Similarly, if a respondent had ticked e.g. 'often' for one diameter and 'seldom' for another, 'never' was added for the third one. To determine whether the borehole contractors' experience correlated with their borehole construction practices, Fisher's exact test was used to compare the companies that had up to 10 years of experience with those that had more than 20 years of experience in well drilling. Fisher's exact test is a non-parametric statistical significance test, which can be applied to small sample sizes (Ranta et al., 2012).

In the questionnaire, there were two questions on the occurrence and frequency of complications and environmental problems related to GHEs. In relation to BHEs (Fig. 5), 19 types of possible complications and environmental risks were listed. The items on this list (apart from 'Discharge of artesian water during drilling' and 'Heat exchanger pipes stuck during installation') were derived from Juvonen and Lapinlampi (2013). Correspondingly, in relation to horizontal GHEs and surface water heat exchangers (Fig. 6), 11 types of possible complications and environmental risks were listed. The respondents were asked to estimate the number of cases their company had encountered of each type. They were also asked to describe more closely these situations, their causes and consequences, and how the problems were managed.

There were 64 respondents in total. However, one respondent (a borehole contractor) was excluded from the analyses due to exceptionally aberrant and unrealistic responses. The decision was based on an expert opinion by a borehole and GSHP practitioner. Additionally, another respondent (also a borehole contractor) was excluded from the analysis of complications and environmental problems because the respondent noted that, instead of estimating the number of cases, he or she had marked "1" for each type that the company had encountered.

When examining the questionnaire responses, some potential sources of bias are to be kept in mind: First, relating to some of the numerical questions, the respondents were asked to give estimates as they were not expected to remember exact numbers for incidents that may have occurred over two decades. Second, it is possible that some respondents were reluctant to disclose full details of their companies' failures. It may even be that contractors with the worst problems were less likely to participate in the questionnaire.

2.2. Thematic interviews of heat pump experts

I interviewed seven heat pump experts (Table 1) representing different sectors of the heat pump industry and research. The interviewees were chosen based on their long experience in the GSHP sector in Finland. The interviews recorded their observations of the construction and potential complications of GHEs more broadly than was possible in the questionnaire responses. Since most of them were not contractors in active working life, they could also provide different perspectives compared to the questionnaire respondents. The interviewees were asked how they see environmental conservation within the GSHP industry in Finland, including stakeholders' attitudes towards it, available methods to promote it, and observed environmental problems.

2.3. Insurance companies

I contacted eight Finnish insurance companies to obtain objective information about problems and accidents related to GSHPs. Four of the companies could supply some kind of information whereas the rest of them notified that their data systems did not enable the identification of GSHP claims. Some of the insurance companies provided qualitative data. One company in particular was able to provide more detailed qualitative information and even some general statistics. I interviewed a claim adjuster from this company who is specialized in heat pump claims. None of the companies could provide detailed statistics of different kinds of GSHP damage or accidents.