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Extending thermal response test assessments with inverse numerical modeling of temperature profiles measured in ground heat exchangers

J. Raymond [a,*], L. Lamarche [b], M. Malo [a]

[a] Institut national de la recherche scientifique, Centre Eau Terre Environnement, 490 rue de la Couronne, Québec, QC, G1K 9A9, Canada
[b] Département de génie mécanique, École de Technologie Supérieure, 1100 rue Notre-Dame Ouest, Montréal, QC, H3C 1K3, Canada

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ABSTRACT

Thermal response tests conducted to assess the subsurface thermal conductivity for the design of geothermal heat pumps are most commonly limited to a single test per borefield, although the subsurface properties can spatially vary. The test radius of influence is additionally restricted to 1–2 m, even though the thermal conductivity assessment is used to design the complete borefield of a system covering at least tens of squared meters. This work objective was therefore to develop a method to extend the subsurface thermal conductivity assessment obtained from a thermal response test to another ground heat exchanger located on the same site by analyzing temperature profiles in equilibrium with the subsurface. The measured temperature profiles are reproduced with inverse numerical simulations of conductive heat transfer to assess the site basal heat flow, at the location of the thermal response test, and evaluate the subsurface thermal conductivity, beyond the thermal response test. Paleoclimatic temperature changes and topography at surface were considered in the model that was validated by comparing the thermal conductivity estimate obtained from the optimization process to that of a conventional thermal response test.

1. Introduction

Thermal response tests (TRTs), envisioned in the early 80's [1] and fully developed with mobile apparatus in the 90's [2,3], are now commonly performed to evaluate the subsurface thermal conductivity to design ground source heat pump systems. The test consists of disturbing the subsurface temperature with the circulation of heated water in a pilot ground heat exchanger (GHE) installed before the complete borefield of a given building is fully constructed [4]. Water flow rate circulating in the GHE and temperature at its inlet and outlet are analyzed to infer the bulk subsurface thermal conductivity [5,6]. This parameter is a key to determine the length of ground heat exchanger required to fulfill the energy needs of a building. TRTs are consequently performed for prefeasibility studies to design ground source heat pump systems and evaluate their economic viabilities.

The conventional TRT experiment conducted in the field aims at reproducing heat transfer that can occur during the operation of a ground source heat pump system. A heat injection rate of 50–80 W m^{-1} of borehole to create a temperature difference of 3–7 °C between the inlet and outlet of the GHE is recommend in North American industry's guidelines [7]. A source of high power varying from 8 to 12 kW is needed to operate the heating element and the pump of the mobile apparatus. The testing unit and its fuel fired generator commonly used to supply power are cumbersome. Mobilizing the equipment in the field and performing the test is a significant expense, which have found limited applications due to its cost. TRTs are mostly carried out for large ground source heat pump systems were the uncertainty in GHE length can offset the cost of a test. One test is typically conducted for the whole borefield and this single thermal conductivity assessment is considered for design although the test radius of influence is limited to less than 1–2 m [8] and the subsurface properties can vary with position at a given field due to heterogeneities.

Recent efforts to develop competitive field tests carried out with GHEs in the scope of geothermal system design resulted in the use of heating cables to inject heat underground [9–11]. The pump is avoided for thermal response tests with heating cables and heat is

* Corresponding author.
E-mail address: jasmin.raymond@inrs.ca (J. Raymond).

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injected in the standing water column of the GHE, which can facilitate installation of the equipment in the field. The use of a heating cable assembly enclosing sections of heating and non-heating wires was further proposed to perform TRTs with a low power source in GHEs that are commonly more than a hundred meter in length [12,13]. Although TRTs with heating cables provide advantages that can help reducing the test cost, the duration of a test enclosing 40–60 h of heat injection followed by an equivalent duration of thermal recovery remain its main limitation. Gamma ray log have been alternatively used to infer the subsurface thermal conductivity at different depths [14]. Such wireline geophysical log can potentially provide an instantaneous assessment method for the subsurface thermal conductivity but borehole logging have to be performed in an open hole without GHE piping. This limitation is important as pipe can be rapidly installed after drilling to avoid collapsing of the borehole wall. The interpretation of a temperature profile recorded in GHE at equilibrium with the subsurface was additionally proposed to evaluate the subsurface thermal conductivity [15]. A wireless probe was developed for that purpose to measure temperature as the probe sink along the pipe of a GHE [16]. The analysis of equilibrium temperature profiles to determine the subsurface properties was, in fact, achieved in the 70's to determine the thermostratigraphy of sedimentary rocks [17]. Although measurements are fairly simple to perform in the field, the interpretation of a temperature profile can be limited by inaccurate information about the Earth heat flow, which is essential to analyze the temperature data. The measured temperature gradient can further be affected by topography or by paleoclimatic temperature variations at surface [18,19]. Thermal conductivity assessments with temperature profiling using thermostratigraphic principles are consequently spatially limited, but deserve a broader attention to diversify tools available for subsurface characterization in the scope of geothermal system design. Previous studies described the use of temperature profiling before and after a TRT in the same GHE to improve test analysis with the identification of groundwater flow or vertical variations in subsurface thermal conductivity [20,21]. Temperature profiles can offer further advantages to extend the evaluation of subsurface properties beyond the location of a single TRT, a topic that has not been fully addressed. Evaluation of the subsurface thermal conductivity at more than one location on the same site can be useful when designing large ground source heat pump systems including tens to hundreds of boreholes drilled in a heterogeneous geological medium. Temperature profiles that can be measured at a low cost with a submersible probe in GHEs provide easily accessible data to infer the subsurface thermal conductivity without repeating TRTs on the same site.

The analysis of temperature profiles measured in GHEs undisturbed by heat injection of a TRT and in the absence of accurate information about the Earth heat flow was investigated in this study. The objective of the work presented was to develop and verify a methodology to evaluate the subsurface thermal conductivity from the temperature profile of GHEs recorded with a wired probe and taking into account limitations arising from the unknown site heat flow. Temperature measurements undisturbed by heat injection were achieved in two GHEs located at the same site and that are approximately 140 m deep, a relatively shallow medium where the temperature gradient is affected by topography and the recent climate warming. An inverse numerical analysis method was developed to infer the Earth heat flow at the study site from the temperature profile and a conventional TRT assessment conducted in a first GHE. The numerical simulations took into account the site topography and the historical changes in ground surface temperature that occurred over the past centuries. The same inverse modeling approach was then used to analyze the temperature profile of the second GHE to evaluate the subsurface thermal conductivity beyond the location of the TRT, considering the heat flow value inferred in the first GHE. If the Earth heat flow was known at every surface location where temperature had remained constant, Fourier's Law of heat conduction would be sufficient to infer the subsurface thermal conductivity with an equilibrium temperature profile. Such conditions are seldom if not never meet and the proposed method was developed to overcome those constrains. The field and numerical analysis method relying on wired temperature profiling is fully described in this manuscript, providing an original contribution showing how to extend TRT assessments when more than one test has to be conducted at the same site or within a region of similar heat flow.

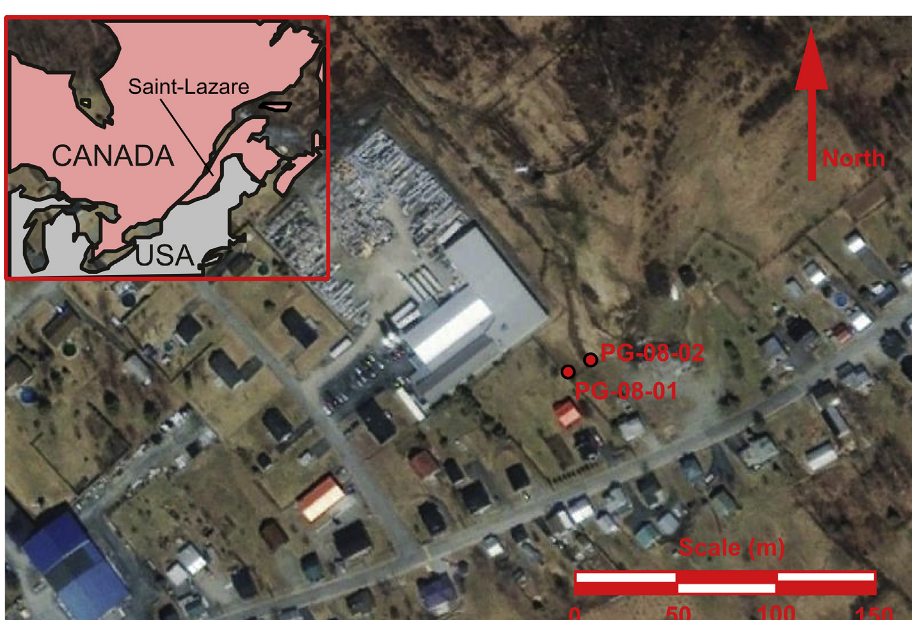

Fig. 1. Localisation of the studied site hosting two GHEs numbered PG-08-01 and PG-08-02.