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Impact of soil heterogeneity on the functioning of horizontal ground heat exchangers

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ABSTRACT

The impact of heterogeneity in soil thermal properties on the performance of horizontal ground heat exchangers (HGHE) is closely examined using a custom-made finite element model. Ensembles of heterogeneous soil fields were generated with spatial correlation parameters derived from similar studies of heterogeneity in hydraulic parameters. Within these soil fields, a single loop HGHE was modelled as discrete pipes placed in a heterogeneous soil continuum. The effect of heterogeneity was found to be minimal relative to uncertainty of the mean soil thermal conductivity, supporting the continued use of the assumption of homogeneity when modelling and designing these systems. Multiple design techniques were identified which would allow HGHE designers to further mitigate any deleterious effects, such as preferential heat transfer between adjacent pipes which may act as a 'short-circuit' mechanism, reducing HGHE effectiveness.

1. Introduction

The use of ground source heat pumps (GSHPs) as a means of efficiently meeting building heating and cooling energy loads has been increasing in recent years. In Canada, for example, from 2005 to 2009 the market for these heat pumps has been expanding approximately 44% per year (Canadian Geothermal Coalition, 2010). Growth in the market has been seen in part due to the significantly lower operating and maintenance costs when compared to conventional heating and cooling systems. Horizontal ground heat exchangers (HGHEs) are widely used in regions of the world where there are few limitations to total system footprint size and where soil conditions are favourable for excavation. The length of piping required for an HGHE is typically determined through the combined use of analytical solutions (e.g., Eskilson, 1987; Ingersoll and Plass, 1948) and historical observations. Our limited understanding of the specific characteristics of heat transfer in these systems has hindered our ability to optimally identify ideal HGHE sizes and configurations so as to minimize both installation costs and, more importantly, land footprint. In models commonly used for determining HGHE sizes, subsurface soil thermal conductivity is assumed to be homogeneous throughout the domain of the HGHE and an average thermal conductivity will be applied uniformly. The assumption is commonly made when simulating horizontal systems but has never been examined in the literature. The uncertainty of HGHE performance associated with heterogeneity is investigated in this paper and is demonstrated to be of minor importance relative to other sources of uncertainty.

The structure of the shallow subsurface can be complex (Clauser, 2006). Signorelli et al. (2007) examined the influence of vertical heterogeneity on the results of a vertical borehole thermal response test (TRT) using a line source model. They found that a higher or lower effective thermal conductivity would be estimated depending upon whether the TRT was performed by injecting or extracting heat, and that the ordering of the heterogeneities impacted the TRT results. The investigation was limited to two layers, vertically stratified. Signorelli et al. (2007) estimated that the heterogeneous test cases indicated the resulting conductivity from a homogeneous case was generally within 10% of an equivalent, two-layer heterogeneous case. Fujii et al. (2009) developed field techniques capable of evaluating these heterogeneities in vertical boreholes. Heterogeneity in hydraulic properties has also been shown to have an effect on open loop ground source heat pumps (Ferguson, 2007). None of these studies dealt with horizontal loops, which tend to have more closely spaced pipes, more pronounced surface interactions, and less balanced energy loads.

The soil properties of thermal conductivity and heat capacity have the greatest impact on subsurface heat transport. These properties are typically assumed to be completely homogeneous when modelling HGHEs. This assumption makes the modelling of geothermal systems much more tractable by reducing the parametrization required for a model run and improving the

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mathematical properties of the underlying system of equations. Analytical models of heterogeneous systems are rare and, when they do exist, are for limited or specialized applications. Philippe et al. (2011) provides a useful literature review of horizontal analytical models. These models are fast and accurate but, again, are limited potentially by the assumption of homogeneity.

The physical phenomena occurring in and around HGHEs are generally well understood and there are many pre-existing numerical models which provide more flexibility than their analytical counterparts. These models tend to focus on vertical systems (VGHE) (Al-Khoury et al., 2005, 2010; Al-Khoury and Bonnier, 2006; Diersch et al., 2011a,b). Spitler (2005) identified HGHE modelling as being in need of further research and development, especially in systems where interaction with the above ground environment is important. The comprehensive work done by Mei (1986) includes a comparison of line source models for use in simulating HGHEs. Other models that have been used for HGHE modelling include the fluid dynamics model FLUENT, used by Wu et al. (2010) for simulating slinky loop systems and Congedo et al. (2012) for simulating loop configurations; the finite element model ANSYS, used by Pulat et al. (2009) as part of an investigation in to HGHE performance; and Li et al. (2012) who developed a novel method of simulating slinky loops using Green's function. More general subsurface process modelling packages, such as the comprehensive HydroGeoSphere (Therrien et al., 2005), capable of simulating multiple processes and their interactions, are inefficient when it comes to representing the physics involved with fluid flow through continuous pipes within the soil though have been used for investigations of thermal response tests (Raymond et al., 2011). In general, these models are computationally expensive, coupled with other transport phenomena that were superfluous to our study, and/or use very specialized meshes which need to be carefully adjusted depending upon the layout of the HGHE/VGHE being simulated.

To investigate heterogeneity, a model was required which could allow for a conductivity field with a fine enough discretization to represent the expected scale of heterogeneity. This required discretization, particularly in handling important near-pipe effects, would be prohibitive using existing models when performing simulations on a timescale of years. A horizontal model must also simulate the pipes as independent entities in order to represent inter-pipe energy fluxes within trenches rather than using, e.g., the bar assumption of Fujii et al. (2012) where the cross-section of each trench is assumed to interact with the surrounding soil continuum as if it were a closed rectangle rather than several discrete pipe sections. For the purpose of investigating the impact of heterogeneous thermal properties on the performance of HGHEs, a new 3D numerical code was developed using the finite element method (FEM). The created model was capable of fully representing multiple HGHE trenches and connecting manifolds in shallow subsurface environments with heterogeneous soil thermal properties. Simplifying assumptions and efficient numerical solvers allowed the model to simulate annual temperature fields in multiple heterogeneous soils on a modest computational budget.

In this paper, the annual performance of HGHEs in soils with heterogeneous thermal conductivity is examined. An iteratively coupled model was developed for efficient HGHE simulation. This model was then applied to a simplified loop and simulated for a time period of 365 days using parameters and loadings collected from a field site in southern Ontario (Haslam, 2013). Multiple realizations of heterogeneous thermal conductivity fields were created using the software GSLIB (Deutsch and Journel, 1992). Investigations were made in to the effects of different means, standard deviations, and other properties of the conductivity field. Design aspects of HGHEs were then evaluated in the context of heterogeneity.

Table 1
Hybrid geostatistical model of thermal conductivity.

Parameter	Value
Model type	Exponential
Mean	1.5 W/m K
Sill	0.2 W/m K
Nugget	0.0 W/m K
Correlation length (horizontal)	12.8 m
Correlation length (vertical)	1.6 m

2. Methodology

2.1. Subsurface heterogeneity

To assess the impacts of heterogeneity on HGHE performance, a statistical model of the thermal properties had to be developed which was capable of representing statistically similar realizations of a randomly correlated conductivity distribution. Unfortunately, there was no prior geostatistical model of thermal conductivity available in the literature. In the past, the lack of information on spatial correlation has meant that other investigations have either assumed homogeneous conditions (e.g., Fujii et al., 2009) or a non-spatially correlated Gaussian distribution (e.g., Ferguson, 2007). The only study investigating spatial correlations in soil thermal properties found was one performed by Usowicz et al. (1996). The study examined 220 measurements of topsoil properties in an agricultural field and analysed them using both classical statistics and geostatistics. Unfortunately the measurements were only made in two dimensions, without any vertical profiling, and the variograms they collected would not be sufficient for an investigation at the depth of a HGHE. Due to the limitations of this information, studies on soil hydraulic properties were used to generate the spatial distributions.

Subsurface hydraulic conductivity heterogeneity has been studied in detail for its impacts on contaminant transport in groundwater (Sudicky, 1986). Empirical relationships using parameters such as grain size, porosity, and grain orientation can provide good approximations of hydraulic parameters (Schwartz and Zhang, 2002). These variables are very similar to the variables used in empirical equations for thermal conductivity and heat capacity such as the de Vries (1963) model. Based on these relationships, it was assumed in this study that the spatial distributions of soil components that cause spatial variations in hydraulic conductivity will cause variations in thermal conductivity at a similar spatial scale.

The hybrid geostatistical model of thermal conductivity (Table 1), which was used as the base model in this investigation, used the spatial correlations found by Rehfeldt et al. (1992), the variance found by Usowicz et al. (1996), and a mean found through parameter estimation based on field conditions at a site in southern Ontario. Realizations of these statistical models were generated using the software GSLIB (Deutsch and Journel, 1992). An example of such a realization is presented in Fig. 1, note that the vertical variation is much greater than the horizontal variations. The black lines represent part of a HGHE pipe network, included here for scale, buried 1.5 m below the ground surface.

2.2. Numerical model

A new finite element heat transport code was developed to simulate heat flow in and around a HGHE. The developed code is composed of two iteratively coupled models, one for the soil continuum and one for the ground loop network. For the purpose of this paper, the full model is referred to as the Heat Exchanger Network (HEN) model.