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Spatiotemporal variability of ground thermal properties in glacial sediments and implications for horizontal ground heat exchanger design

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ABSTRACT

Thorough characterization of the spatiotemporal variability in soil thermal properties can facilitate better designs for horizontal geothermal heat pump (HGHP) systems by reducing ground heat exchanger (GHEX) costs. Results are presented from a new monitoring network installed across a range of glaciated terrains in Indiana (USA), including the first known observations of the dynamic range of thermal conductivity that occurs at the depth of horizontal GHEX installations. In situ thermal conductivity data can vary significantly on a seasonal basis in coarse-grained outwash sediments (0.8–1.4 W m^{-1} K^{-1}), whereas clay- and silt-dominated moraine sediments have a dampened seasonal range within 10% of the annual mean. Thermal conductivity across the network ranges from 0.8 to 2.0 W m^{-1} K^{-1} depending on soil parent material, climatic setting, and particularly, soil-moisture variability. Results indicate that the standard industry practice to estimate thermal properties from soil type often leads to suboptimal GHEX design (i.e., GHEX design lengths were 44–52% longer than necessary to meet performance specifications). This research suggests that expanding the characterization of soil thermal properties in specific settings where HGHPs are targeted will improve understanding of the dynamic aspects of ground heat exchange and lead to more optimal HGHP system designs.

1. Introduction

United States Energy Information Administration (USEIA) statistics indicate that residential and commercial buildings account for nearly 40% of total energy consumption in the nation. For residential energy consumption, space heating and cooling, along with water heating, represent approximately 65% of the total use [38]. A viable option for reducing this large energy consumption lies in geothermal heat pump systems (GHPs), which combine horizontal or vertical ground heat exchangers with heat pump units (and optional desuperheaters for water heating). Previous research indicates that GHPs consume 42–62% less energy than conventional heating and cooling systems [2] and unlike alternative renewable energies such as wind and solar, GHPs transfer energy directly between the natural and built environment without the need to transmit or store electricity. Heat energy is transferred between buildings and the adjacent ground by using a ground-coupling loop to reduce or increase heat in circulating fluids. Despite their general advantages, the performance of specific GHP systems depends on a number of factors, including the local subsurface thermal properties and hydrogeologic setting.

Owing to the lower initial installation costs, horizontal trench-based ground heat exchangers are often preferred over vertical systems for residential installations. To optimize design of horizontal GHPs (HGHPs), soil thermal properties and soil-moisture variability need to be characterized on a site-specific basis and used as input parameters in system design models [6,39]. These models are increasingly capable of incorporating transient ground conditions such as thermal conductivity, soil moisture, and temperature (e.g., Refs. [33,34]). HGHP modeling by Sanaye and Niroomand [30] identified the relationship between earth's climate regions and payback potential through an analysis of HGHP systems operating costs (based on cooling loads, heating loads, and ground heat exchanger construction) for varying climatic regions. Given the higher initial installation cost of GHP systems compared to traditional systems, increasing the publicly available data on

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variability and ranges of soil thermal properties for particular terrains could help facilitate the broader adoption of GHP technology.

Previous workers have investigated the role of ambient ground conditions on heat transfer by GHEX components for single sites [10,14,24], but a regional analysis of in situ thermal properties as they relate to ground-coupled heat exchange has not been conducted. Remund [27] quantified the effects of bulk density and soil moisture on thermal conductivity for various soil textures using laboratory experiments and proposed a thermal performance index based on U.S. Department of Agriculture (USDA) mapped soil units that could be applied to soil textures. For HGHPs, soil thermal properties may alternatively be characterized by the soil parent materials. Soil parent materials and geologic settings have broad application, allowing thermal property parameter characterizations for specific terrains to be used globally. Furthermore, recent work investigating transient effects of soil thermal and moisture regimes on HGHPs indicates that quantifying the in situ variability of thermal properties and associated transient controlling parameters such as soil moisture is necessary to provide system designers with the expected ranges to achieve optimal design [14,39].

2. Soil parameters and system design

Numerical modeling has shown that the GHP heating-phase coefficient of performances (COPs) increase with GHEX loop lengths for horizontal systems (e.g., Refs. [18,34]. However, residential and commercial lot sizes often constrain the length of horizontal ground-coupling heat exchange loops, and systems are limited by the available space footprint. System designers must determine if soil thermal properties (including thermal conductivity, thermal diffusivity, and temperature) are amenable to providing sufficient heat injection and extraction over the available trench length while minimizing the potential for soil thermal instability and low COPs. The loop length necessary to achieve the specified fluid temperatures at design heating and cooling conditions is particularly dependent on the resistance to heat transfer in the soil surrounding the buried piping. This sensitivity is shown in Fig. 1 as the dependence of total design pipe length over a range of soil thermal conductivities for a typical residential home in northern Indiana, USA (where load determinations are dominated by the heating mode). Results in Fig. 1 were obtained by solving the design equations in Ref. [28] and are consistent with the findings of Cho and Choi [5] who determined length-to-unit capacity ratios for vertical ground heat exchangers.

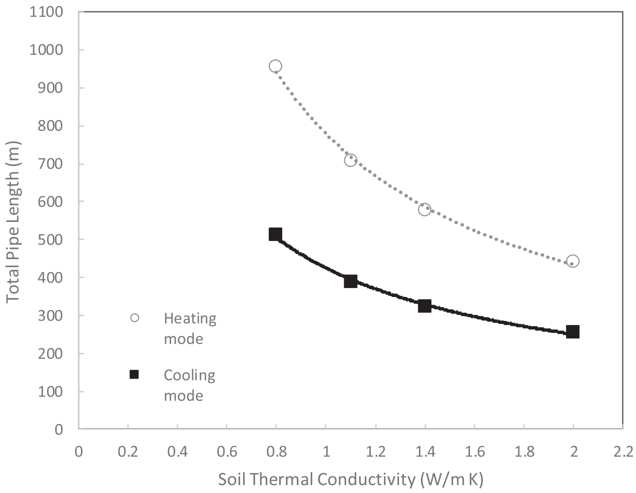

Fig. 1. Dependence of the ground heat exchanger design pipe length on soil thermal conductivity for a typical residential home in northern Indiana, USA. In this example, a home with low thermal conductivity soil of 0.8 W m^{-1} K^{-1} will require a total loop pipe length that is more than double what would be required if the soil were high thermal conductivity of 2 W m^{-1} K^{-1}.

2.1. Soil parameters that influence heat exchange

A designer's understanding of soil temperature and heat flow parameters is critical in horizontal systems because of the variability (both spatially and temporally) of temperature and moisture within the unsaturated zone relative to greater depths (>15 m) where these variables are more stable. Soil temperature fluctuates because of: 1) variations in the radiation balance between earth and atmosphere, 2) advective heat transport by processes such as moisture migration, 3) conduction of heat energy within the soil mass, and 4) latent heat transfer via phase changes. These energy exchanges occur primarily at the Earth's surface, but their effects are propagated downward through the soil profile by transport processes controlled by soil properties that vary with location and time [20]. In areas where soil moisture is relatively stable, dynamic thermal properties may require little consideration [39]. However, in more temperate climates seasonal variability in soil moisture (θ) can be significant such that near-surface thermal properties tend towards disequilibrium. Especially during the dry summer months, the relationship between soil-moisture and heat transfer parameters for various geologic settings should be further investigated to optimize systems and fully realize the energy saving potential of GHPs.

2.2. Temperature

Conduction is the dominant heat transport process in soils where at steady state, the relationship between heat flux (q_h), thermal conductivity (λ), and spatial temperature gradient (∇T) is summarized by Fourier's Law:

$$q_h = -\lambda \nabla T \tag{1}$$

Subsurface heat flux is dependent upon a temperature gradient and is proportional to the thermal conductivity and the magnitude of the temperature disparity.

Under transient conditions, conservation of energy leads to the following heat flow equation:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} \tag{2}$$

where the thermal diffusivity (α) is equal to the thermal conductivity (λ) divided by the heat capacity(C). Time (t), temperature (T), and unidirectional length (z) are the remaining variables.

In lieu of numerically solving the above differential equation and considering various heat sources and sinks, it is common to employ an analytical solution that estimates ground temperatures at depth using a harmonic function (e.g., Refs. [19,22]). Such an equation was presented by Hillel [19]:

$$T(z,t) = \overline{T} + A_0[\sin(\omega t - z/d)] \Big/ e^{z/d} \tag{3}$$

where,

t = time,
z = depth,
$\overline{T}$ = avg. annual soil surface temperature,
A_0 = amplitude of surface temperature fluctuation,
ω = radial frequency ($2\pi/365$),
d = damping depth.