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

Shawn Naylor^{a,c}, Kevin M. Ellett^b, and Andrew R. Gustin^a

^aCenter for Geospatial Data Analysis and Indiana Geological Survey, Indiana University, 611 Walnut Grove Ave., Bloomington, IN 47405, USA

^bIndiana Geological Survey, Indiana University, Bloomington, IN 47405, USA

^cCorresponding Author: Tel.: 812-855-2504, fax: 812-855-2862, email: snaylor@indiana.edu

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% to 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.

Keywords: soil thermal properties, geothermal heat pump, thermal conductivity, ground temperature, soil moisture

1.0 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 (USEIA, 2013). 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% to 62% less energy than conventional heating and cooling systems (Aste et al., 2013) 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 (Chong et al., 2013; Wu et al., 2014). These models are increasingly capable of incorporating transient ground conditions such as thermal conductivity, soil moisture, and temperature (e.g., Tarnawski and Leong, 1993; Tarnawski et al., 2009). HGHP modeling by Sanaye and Niroomand (2010) 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 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 (Esen et al., 2007; Gonzalez et al., 2012; Neuberger et al., 2014), but a regional analysis of in situ thermal properties as they relate to ground-coupled heat exchange has not been conducted. Remund (1994) 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 (Gonzalez, 2012; Wu et al., 2014).

2.0 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., Healy and Ugursal, 1997; Tarnawski et al., 2009a). 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

1 over the available trench length while minimizing the potential for soil thermal instability and low
 2 COPs. The loop length necessary to achieve the specified fluid temperatures at design heating and
 3 cooling conditions is particularly dependent on the resistance to heat transfer in the soil surrounding
 4 the buried piping. This sensitivity is shown in Fig. 1 as the dependence of total design pipe length over a
 5 range of soil thermal conductivities for a typical residential home in northern Indiana, USA (where load
 6 determinations are dominated by the heating mode). Results in Fig. 1 were obtained by solving the
 7 design equations in Remund and Carda (2009) and are consistent with the findings of Cho and Choi
 8 (2014) who determined length-to-unit capacity ratios for vertical ground heat exchangers.

Figure 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 $0.8 \text{ W m}^{-1} \text{ K}^{-1}$ will require a total loop pipe length that is more than double what would be required if the soil were high thermal conductivity of $2 \text{ W m}^{-1} \text{ K}^{-1}$.

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 (Hillel, 2005). In areas where soil moisture is relatively stable, dynamic thermal properties may require little consideration (Wu et al., 2014). 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.

2.11 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:

$$q_h = -\lambda \nabla T \quad (1)$$

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:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} \quad (2)$$

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., Kusuda and Achenbach, 1965; Hillel, 1982). Such an equation was presented by Hillel (1982):

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

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

The damping depth (d) is a constant that represents the depth where temperature amplitude (A_0) is decreased to $1/e$ of the surface amplitude. It is a function of soil thermal diffusivity (α) and the temperature distribution frequency (ω):

$$d = (2\alpha/\omega)^{1/2} \quad (4)$$

Hence, to effectively model near-surface earth temperatures, a reliable estimate of soil thermal diffusivity must be obtained. Kusuda and Achenbach (1965) employed a least-squares statistical analysis of measured ground temperature data at multiple depths to establish constants for his analytical model, thus using an inverse approach to determining depth-dependent α at monitoring sites. It is important to note that regardless of whether a measured α value or the inverse approach

incorporating soil temperature is used, site-specific data are necessary to accurately establish an accurate ground temperature model.

2.12 Soil moisture and bulk density

Soil, unweathered sediment, and rock are composed of various states of matter, each having its own thermal properties. Common soil porosities in glacial sediments range between 35-50%, indicating that the gas/liquid fraction exerts a strong influence on soil thermal properties. Indeed, the dependence of thermal conductivity on moisture content (θ) and bulk density (ρ_b) has been documented by several soil science and engineering laboratory studies (e.g., Abu-Hamdeh and Reeder, 2000; De Vries, 1975; Remund, 1994; Salomone et al., 1984). Soil moisture (hereafter expressed in % of total volume) is especially important for HGHP systems, because highly variable conditions are likely to be encountered where horizontal ground loops are installed. A decrease in ρ_b will diminish grain to grain contact thereby decreasing soil thermal conductivity (λ_s). For θ , the low thermal conductivity of the gases that constitute air (λ_a) relative to that of the liquid water (λ_w) and solid mineral (λ_{solid}) components is the controlling factor that lowers λ_s .

The liquid component of soils has a prominent influence on soil volumetric heat capacity, the amount of heat input required to change a unit volume of soil one temperature unit (common units are $J m^{-3} K^{-1}$). Like λ_s , soil volumetric heat capacity (C_s) is best viewed in terms of the various soil fractions as described by Hillel (2005):

$$C_s = \sum f_s c_s + f_w c_w + f_a c_a \quad (5)$$

where f_s , f_w , and f_a are the solid, water, and air fractions of the soil, respectively. The c -parameters represent the specific heat capacity of each phase, which is the product of component density and specific heat per unit mass. The air fraction is often ignored because of its low relative density. The density of quartz ($2.65 g cm^{-3}$) is often used as a proxy for the solid component density. Although the

density of quartz is more than twice that of water (1 g cm^{-3}), the specific heat capacity of water is nearly equal to the mineral component, because the specific heat of water is more than double the mineral fraction ($4.2 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1}$, compared with $2.0 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1}$).

Presuming that the solid soil fraction is stable, it is apparent that C_s , λ_s , and soil thermal diffusivity (α_s) are all strongly dependent upon θ . Experimental data as early as De Vries (1975) showed that λ_s of sand, loam, and peat media increases with θ ; however, before reaching 20% water content, α_s reached its maximum and continued to decrease until saturation was achieved. This phenomenon could be interpreted as the result of c increasing at a faster rate than λ_s as soil approaches saturation, but the underlying processes are nonlinear and complex. As noted by Hillel (2005), the thermal response of soil to fluctuating moisture and temperature regimes is not merely a product of changing volume fractions for soil constituents. Changes in pore geometry and soil-water phases influence the mode of heat transfer between soil particles and through pore spaces. Smits et al. (2010) demonstrated the sharp decline in λ_s below residual water content for sands that they attributed to the disconnection of particle-water paths. Numerical simulations of a HGHP system under transient moisture and temperature conditions by Wu et al. (2014) showed that temperature gradients induce water fluxes away from GHEXs during the cooling phase, when heat is injected into the ground. Moreover, previous researchers (Groeneveld et al., 1984; Salomone et al., 1984; Remund, 1988) developed methods to measure soil thermal instability and worked toward developing predictive equations that could allow engineers to estimate soil conditions that lead to poor heat transfer. Both Groeneveld et al. (1984) and Remund (1988) stressed the importance of initial moisture content in limiting the tendency of certain soils to move toward thermal instability. This highlights the need to couple field measurements that quantify predominant soil moisture regimes with soil thermal properties.

3.0 Thermal properties of glacial sediments

3.1 Monitoring locations and sampling

U.S. Census data indicate that approximately 36% of the U.S. population lives in areas that are underlain by glacial sediments, making such settings an ideal starting place for quantifying in situ dynamics of soil thermal properties. Accordingly, six monitoring locations of differing hydrogeologic settings and near-surface glacial sediments were chosen in the Midwestern U.S. (Table 1, Fig. 2). The monitoring approach entailed excavating trenches to a depth of 2 m (a typical depth for horizontal GHP installations) and collecting sediment samples from trench walls at 0.3-m intervals to determine λ_s , α_s , and C_s in the laboratory using the transient line heat source method. Qualitative sediment and soil characteristics were also recorded at each sampling depth (e.g., weathering features and bedding).

Table 1. Monitoring locations and glacial environments

Site #	Soil parent material	Terrain	Latitude
1	alluvium	floodplain	39.50° N
2	glacial till (end moraine)	upland	39.64° N
3	glacial till (supraglacial)	terrace	39.58° N
4	glacial till (ground moraine)	plain	40.22° N
5	glacial outwash	terrace	41.26° N
6	glacial till (end moraine)	upland	41.25° N

Figure 2. Geologic map of the Great Lakes region (generalized from Fullerton et al., 2003) and site locations in Indiana.

1

2 **3.2 In situ instrumentation**

3 Temperature sensors and water-content reflectometers were installed at 0.3-m intervals to
 4 continuously measure thermal and moisture gradients, respectively. Campbell Scientific thermocouples
 5 were used to measure temperature with $\pm 0.5^\circ \text{C}$ accuracy and 0.02°C precision. Campbell Scientific
 6 water-content reflectometers having probe rods 30 cm in length and a cylindrical measurement area 7.5
 7 cm in diameter and 35 cm long were used to determine θ . Permittivity readings were related to θ using

the Topp equation (Topp et al., 1980) unless laboratory-derived field moisture content of samples indicated that a site-specific calibration was necessary (the manufacturer lists θ accuracy at $\pm 3\%$ using the Topp equation).

In situ λ_s and α_s were measured at a 1.2-m depth using the Hukseflux TP01 thermal properties sensor (Hukseflux Thermal Sensors, 2011), which incorporates a thermopile to measure radial differential temperature around a heating wire. The device relates heating power and temperature gradient to λ_s , while α_s is determined based on the time it takes to establish a steady gradient across the thermopile. At one of the sites (site 2, Fig. 2), transient line source sensors were placed in situ adjacent to the TP01 sensor to validate readings with independent measurements of λ_s , α_s , and C_s . Additionally, each site includes co-located thermocouples and water-content reflectometers at a depth of 1.2 m.

Micrometeorological data (precipitation, insolation, ambient air temperature, relative humidity, and wind speed) were also collected to determine surface energy and water budgets that drive fluxes of energy and moisture in the shallow subsurface (Fig. 3).

Figure 3. Photographs of the instrument array employed at each site showing above-ground micrometeorological sensors and underlying in situ soil physical property sensors.

3.3 Laboratory sample characterization

Bag samples collected at 0.3-m depth increments were subjected to particle size analysis using the simplified clay fraction procedure described by Gee and Or (2002). Particle densities were determined at each site using a gas pycnometer and these data were used to determine porosity through a method outlined by Flint and Flint (2002).

Cylindrical cores (5 cm diameter x 10 cm long) collected at depth increments of 0.3 m were used to determine bulk density (ρ_b) using standard methods described by Grossman and Reinsch (2002). These cores were also subjected to λ_s and α_s measurements using the Decagon KD2-Pro SH-1 sensor (dual 1.3 mm diameter x 30 mm long needles using 6 mm spacing). Volumetric water content (θ) was determined from cores using the approach of Topp and Ferre (2002). To compare the dynamics

1 between θ and λ_s using data from several sites, degree of saturation (S_w) was calculated by dividing θ by
2 primary porosity (ϕ), thus removing the effect of varying porosity when comparing θ between soil
3 types.

4 Larger cylindrical cores (7.5 cm diameter x 15 cm long) were collected at five of six sites so that
5 the Decagon KD2-Pro TR-1 sensor (single 2.4 mm diameter x 10 cm long needle) could be used to
6 measure λ_s following the ASTM D5334-08 method for λ_s determination (ASTM, 2008). The samples
7 were slightly shorter than the ASTM guideline for undisturbed soil samples (17 cm), but were beyond
8 the recommended length for calibration standard cylinders (20% longer than thermal needle). The SH-1
9 and TR-1 measurement approaches use algorithms that isolate heat-pulse from ambient temperature
10 changes as outlined in Decagon Devices (2012).

11 To test the accuracy of the three thermal properties measurement methods (including in situ
12 measurement with the Hukseflux TP01), a calibration exercise was conducted to compare sensor
13 readings for five materials having previously published λ values:

- 14 -Glycerin ($0.292 \text{ W m}^{-1} \text{ K}^{-1}$; ASTM, 2008)
- 15 -Dry Ottawa silica sand ($0.332 \text{ W m}^{-1} \text{ K}^{-1}$; Tarnawski et al., 2009b)
- 16 -5% agar gel ($0.554 \text{ W m}^{-1} \text{ K}^{-1}$; Zhang et al., 2010)
- 17 -0.5% agar gel ($0.598 \text{ W m}^{-1} \text{ K}^{-1}$; Zhang et al., 2010)
- 18 -Saturated Ottawa silica sand ($3.310 \text{ W m}^{-1} \text{ K}^{-1}$; Tarnawski et al., 2011)

Figure 4. Graph showing sensor readings vs. published thermal conductivity values for known standards. A one-to-one line is also plotted to indicate sensor results relative to expected values.

1

2

Readings from the Decagon single-needle sensor (TR-1) closely matched standard λ values (Fig.

3

4) while the Decagon SH-1 sensor underestimated expected values by approximately 24%. Calibration

4

standards were also measured using five of the six Hukseflux TP01 sensors installed in situ. Data for the

5

sensor installed at site 2 (Fig. 4) indicate that the sensor underestimates λ_s by 28% relative to the

6

Decagon TR-1 sensor at $3 \text{ W m}^{-1} \text{ K}^{-1}$. This is similar to the findings of previous researchers (Liebethal and

7

Foken, 2006), who noted that the Hukseflux sensor underestimated λ_s by 31% at the high end of its

8

range.

9

The SH-1 sensor and five of six Hukseflux TP01 sensors installed in situ were used to measure λ_s

10

for laboratory soil samples, enabling a linear transform equation to be used to calibrate the readings to

11

be consistent with TR-1 measurements. Laboratory soil samples included a fine-grained sand standard

12

material and a silt loam from site 1 to provide additional control in the 1 to $3 \text{ W m}^{-1} \text{ K}^{-1}$ range. For each of

the standard materials and the laboratory soil samples, an average value of the five TP01 sensor readings was taken for the transform equation. In situ readings for all three sensors installed at site 2 were also used to develop linear transform equations (Table 2) for consistency with TR-1 readings.

Table 2. Parameters for the sensor transform equations used to calibrate measurements to the TR-1 sensor.

Sensor	N	slope	y-intercept	R ²
TP01	24	1.28	-0.217	0.98
SH-1	21	1.11	-0.0532	0.98

4.0 Results

4.1 Soil physical properties

Geologic setting or soil parent material for the study sites can generally be divided into two categories based on depositional environments. Three of the sites (1, 3, and 5) are underlain by soils having parent materials from a proglacial depositional environment, i.e., the sediments were deposited beyond an ice front. Site 5 is an outwash terrace and has the coarsest sediments with the highest sand contents (Fig. 5). The site located at the edge of a floodplain (1) is underlain by overbank deposits having the highest silt content of all sites. Site 3 is a terrace composed of debris flow deposits; these sediments contain a slightly higher percentage of clay compared to the floodplain and outwash sites. Soils from the remaining sites (2, 4, and 6) are glacial sediments associated with moraines. End moraines (sites 2, 6) are relatively high relief landforms that are deposited at the terminus of a glacier, whereas ground moraines (site 4) consist of rolling hills or plain landforms. These sites are characterized by high clay contents (16-34%) owing to the nature of ice deposition, which also affects other physical properties such as bulk density, porosity, and soil-moisture retention characteristics.

Figure 5. Ternary plots showing monitoring site particle size data using: a) the Hydraulic Properties of European Soils (HYPRES / FAO) database classification scheme, b) the U.S. Dept. of Agriculture (USDA) soil classification scheme. The texture data are for sample depths 1.2, 1.5, and 1.8 m – a typical depth range for two-layer horizontal GHPs in North America.

1

Table 3. Summary of soil physical properties and thermal conductivity at six monitoring sites. Core samples were capped, sealed, and refrigerated to preserve moisture following sampling, and the field thermal conductivity (λ_{field}) was determined immediately upon opening.

Site / Depth ^a (m)	clay	silt	S&G ^b	ρ_b (g cm ⁻³)	ϕ	θ_{field}	S_w	λ_{field} (W m ⁻¹ K ⁻¹)	λ_{sat} (W m ⁻¹ K ⁻¹)	λ_{dry} (W m ⁻¹ K ⁻¹)
1 / 1.2	13%	67%	20%	1.48	0.45	0.36	0.79	1.74	1.83	0.550
1 / 1.5	15%	80%	5%	1.35	0.49	0.40	0.82	1.60	1.80	0.296
1 / 1.8	17%	78%	6%	1.35	0.49	0.41	0.83	1.76	1.61	0.352
2 / 1.2	20%	74%	6%	1.41	0.48	0.36	0.75	1.49	1.60	0.517
2 / 1.5	16%	42%	42%	1.88	0.31	0.27	0.89	2.01	2.02	0.474
2 / 1.8	19%	37%	44%	1.87	0.31	0.28	0.89	1.81	2.07	0.520
3 / 1.2	26%	56%	18%	1.34	0.50	0.15	0.30	1.36	1.76	0.319
3 / 1.5	23%	51%	26%	1.41	0.47	0.17	0.36	1.50	1.67	0.446
3 / 1.8	16%	73%	11%	1.51	0.43	0.10	0.24	0.88	2.06	0.221
4 / 1.2	34%	46%	20%	1.76	0.36	0.21	0.59	1.47	1.81	0.864
4 / 1.5	30%	49%	21%	1.74	0.36	0.23	0.64	1.49	1.74	NA
4 / 1.8	29%	56%	15%	1.88	0.31	0.25	0.80	1.99	1.95	NA
5 / 1.2	10%	18%	72%	1.54	0.42	0.17	0.39	1.12	1.89	0.578
5 / 1.5	6%	26%	68%	1.50	0.44	0.17	0.38	1.50	1.89	0.351
5 / 1.8	10%	34%	56%	1.67	0.38	0.20	0.54	1.67	2.08	0.396
6 / 1.2	28%	44%	27%	1.74	0.35	0.22	0.63	1.80	1.87	0.703
6 / 1.5	28%	49%	22%	1.83	0.32	0.24	0.75	1.73	1.90	0.623
6 / 1.8	26%	51%	23%	1.88	0.31	0.27	0.88	1.87	1.93	0.715

^aSite numbers and sample depths in italics denote proglacial soil parent materials.

^bS&G: sand and gravel.

As seen in Table 3, variability in thermal conductivity (λ_s) exists between sites (or parent materials) and also with depth at each site, as is the case with ρ_b . To demonstrate end members for each sample, saturated thermal conductivity (λ_{sat}) was measured after saturating each core sample in a vacuum chamber, and dry thermal conductivity (λ_{dry}) was subsequently determined after oven-drying samples for 24 hours at 105° C. The influence that degree of saturation (S_w) has on λ_s at the time of sampling (λ_{field}) is most prominent at site 3 (1.8 m depth) and at site 5 (1.2 m depth) where λ_{field} was below 1 W m⁻¹ K⁻¹.

To further elucidate the relative roles of S_w , ρ_b , and soil texture on λ_{field} , a multiple regression analysis was applied to an extended data set that included all samples collected between 0.3 m and 1.8 m at each of the six sites (N=35). This approach has the advantage of simultaneously testing multiple independent variables; by using it, the relative control that each variable has on λ_{field} was quantified by standardizing the input data to yield standardized regression coefficients (beta coefficients listed in Table 4). The null hypothesis (that each independent variable does not explain variation in λ_{field}) was tested via t-ratio confidence intervals. The statistical model has the following form:

$$\lambda_{field} = b_0 + b_1 S_w + b_2 \rho_b + b_3 T_{clay} + \mu_t \quad (6)$$

where b_1 through b_3 represent regression coefficients, b_0 is an intercept term, T_{clay} is clay content, and μ_t is a random error term.

Table 4. Multivariate regression analysis results comparing relative control of S_w , ρ_b ,

and texture on λ_{field} .

Parameter	Regression coefficient	Beta coefficient	Standard error (beta)	t-ratio	Significance level ^a
Degree of saturation	0.86	0.68	0.16 (0.13)	5.45	99%
Bulk density	0.57	0.39	0.18 (0.12)	3.16	99%
Clay content	-0.57	-0.26	0.29 (0.13)	-1.95	90%
^a 31 degrees of freedom					

The results of the multivariate analysis (Table 4) indicate that S_w has the strongest positive control on in situ thermal conductivity and is statistically significant at the 99% confidence level. Bulk density also has a statistically significant positive influence (99% confidence level), but the beta coefficient (indicating the relative impact of independent variables on λ_{field}) is slightly more than half that of saturation. The influence of soil texture was investigated using clay content, which showed a statistically significant (90% confidence level) negative control on λ_{field} . This may be attributed to clay-sized particles being dominated by aluminosilicate minerals having lower thermal conductivity relative to quartz and ferromagnesian minerals, which appear to be more abundant in the silt and sand fractions. The silt fraction was also included (in lieu of clay) on another model run; the variable coefficient indicated a positive influence on thermal conductivity, but the result was not statistically significant (50% confidence level). To more completely understand the dynamics of soil thermal conductivity and implications for HGHP designs, in situ data are necessary to ensure that realistic ranges are predicted.

Continuously recorded in situ soil volumetric water content (θ) and λ_s data support the contention that λ_s is strongly dependent on S_w . The data and linear regression fit shown in Fig. 6 indicated that 50% of the variance in thermal conductivity across all sites can be explained by soil moisture alone. Proglacially deposited soil parent materials (sites 1, 3, 5) show variations in θ between 0.07 and 0.43, coinciding with values of λ_s ranging between 0.8 and 2 W m⁻¹ K⁻¹. This implies that conductivity can vary by 1.5 times or more within glaciated regions. However, daily data from moraine

settings indicate that these predominantly fine-grained deposits have more limited variability in θ , as well as λ_s values that remain relatively high throughout the year ($1.6\text{--}1.75\text{ W m}^{-1}\text{ K}^{-1}$). Although these sites maintain near-constant λ_s regimes, shallow subsurface seasonal temperature fluctuations around the mean air temperature require some consideration for optimal HGHP design.

Figure 6. Daily in-situ volumetric water content data (θ) plotted against thermal conductivity (λ_s) at 1.2 m depth (Sept. 2011– June 2013). Continuous λ_s data are not available for site 6 owing to contact resistance caused by installation error. Moraine sites (in black) show less variability in θ than sites underlain by proglacially deposited sediments, and thus more constant λ_s .

4.2 Shallow ground temperature fluctuations

Continuous monitoring of ground temperatures indicates that temperatures vary significantly from the mean annual air temperature within the 1.2- to 1.8-m depth interval (Table 5). Expected stable ground temperatures (Table 5) are based on data from the Parameter-Elevation Regressions on Independent Slopes Model (PRISM, 2004), which uses air temperatures compiled from 1970 to 2000.

The measured ground temperatures at 1.5 m are skewed warmer than the PRISM averages, suggesting that in Indiana, cooling mode GHP performance might be most affected by assuming a stable ground temperature. Furthermore, a comparison of PRISM average annual air temperatures and ground temperature ranges at 1.5 m indicates that ground temperatures at HGHP depth vary as a result of more than just the air temperatures between sites. This is especially true for the 2 sites located north of 41° N latitude (sites 5 and 6) where modeled 1.5-m ground temperatures have associated root mean square errors (RMSE) well above the other 4 sites that lie between 39° and 40° N (average RMSE is 2.8° C for the 2 northern sites and 1.4° C for the other sites). Previous work by Xu and Spitler (2014) highlights the importance of frozen ground and snow cover for temperature predictions and these processes are very likely the cause of increased model error at sites 5 and 6.

The sites in Table 5 are listed in order of decreasing 1.5 m measured ground temperature ranges; this order compares well with measured 1.2-m diffusivity (α) and calculated damping depth (d) for each site. The first three sites listed are all from proglacial geologic settings and show much greater ranges than their subglacial counterparts. It is important to note that two site pairs (5/6 and 2/3) lie within 15 km of one another but have damping depths that differ by approximately 0.5 m, indicating significant variability in shallow ground temperature regimes over short distances.

Table 5. Summary of measured ground temperatures and damping depth (d) variability. Three sites having soil parent materials deposited in proglacial settings and relatively high thermal diffusivity values are listed prior to sites having moraine parent materials. The PRISM average air temperatures are based on a 30-year record and are used to represent the expected stable ground temperature at each site.

Site # (parent material)	PRISM avg. T_{air} (°C)	T_{air} measured range (°C)	1.5-m depth measured $T_{\text{max}} / T_{\text{min}}$ (range) (°C)	1.5-m depth ^a modeled $T_{\text{max}} / T_{\text{min}}$ (range) (°C)	Avg. 1.2-m diffusivity ($\text{mm}^2 \text{s}^{-1}$)	Damping ^b depth (cm)
5 (outwash)	9.7	46.2	21.6 / 3.4 (18.3)	23.7 / 6.5 (17.2)	0.837	290
3 (supraglacial till)	10.6	43.1	23.1 / 5.6 (17.4)	21.4 / 7.2 (14.2)	0.581	241
1 (alluvium)	11.0	43.3	21.8 / 6.8 (15.0)	21.7 / 7.3 (14.4)	0.529	230
6 (moraine till)	9.6	45.8	18.9 / 4.9 (13.1)	22.1 / 7.5 (14.6)	0.560 ^c	237
4 (moraine till)	10.3	42.5	19.3 / 6.2 (13.1)	20.8 / 7.5 (13.3)	0.456	214
2 (moraine till)	10.2	44.4	18.8 / 7.3 (11.6)	20.6 / 8.1 (12.5)	0.398	200
^a Temperatures are modeled using equation (3)						
^b Damping depth (d) is calculated using equation (4).						
^c Continuous conductivity and diffusivity sensor failed at site 6, so an average of four trench face and lab measurements is used						

4.3 Impact of seasonal fluctuations on HGHP system design

Continuously recorded in situ data related to soil thermal properties and moisture content are essential for understanding the feedback mechanisms between ground conditions and HGHP performance. Data shown in Fig. 7 were collected between fall 2011 and summer 2013 from three proglacial settings (sites 1, 3, 5) and one subglacial setting (site 2) (note that data from monitoring sites 4 and 6 did not have the same continuous record of quality data and thus are not shown in Fig. 7). The strong relationship between θ and λ_s is clearly evident in these time series. Thermal conductivity variability is greatest for the alluvium and outwash monitoring sites where the range is 0.53 and 0.60 $\text{W m}^{-1} \text{K}^{-1}$, respectively. The outwash terrace monitoring site (site 5) is most problematic from a heat exchange standpoint; this is due to a combination of the sandy loam texture and terrace topographic setting, which create a well-drained soil profile having low thermal conductivity during dry periods. The end moraine monitoring site (site 2) is a more stable setting for ground heat exchange owing to the higher bulk density at depth and higher relative clay and silt contents that allow for higher soil moisture retention during dry periods.

Figure 7. Time series of seasonal trends in 1.2-m-depth volumetric water content (grey) and thermal conductivity (black) at four sites. The thermal conductivity data were corrected using the linear transform (Table 2). Mean thermal conductivities are $1.81 \text{ W m}^{-1} \text{ K}^{-1}$ for site 1, $1.69 \text{ W m}^{-1} \text{ K}^{-1}$ for site 2, $1.75 \text{ W m}^{-1} \text{ K}^{-1}$ for site 3, $1.71 \text{ W m}^{-1} \text{ K}^{-1}$ for site 4 (not shown), and $1.10 \text{ W m}^{-1} \text{ K}^{-1}$ for site 5.

To evaluate how seasonal variability in soil conditions impacts HGHP system design, in-situ data from the monitoring sites were used in the design ground loop calculations of Remund and Carda (2009) for hypothetical residential-scale installations. The modeled loop field design for each site included four parallel trenches with four straight pipes per trench in two planes (e.g., Sanaye and Niroomand, 2010). Pipes were of 2.54-cm-diameter high-density polyethylene having a thermal conductivity of $0.39 \text{ W m}^{-1} \text{ K}^{-1}$. The modeled trench width was $\sim 0.6 \text{ m}$ with $\sim 3.3\text{-m}$ spacing between trenches. Pipes were located at depths of 1.2 m and 1.8 m within each trench. Heating conditions were simulated using the site-specific atmospheric and subsurface data for a month-of-January peak heating load scenario, while July data were used to simulate peak cooling load conditions. Design loop lengths

were calculated with the LoopLink™ software package assuming building loads from Burdick (2011) for an energy efficient one story 207 m² home located in Chicago, Illinois, and the manufacturer's specified parameters for a ClimateMaster® TSo36 heat pump unit (ClimateMaster, 2013).

Design GHEX loop length calculations were also conducted in accordance with the International Ground Source Heat Pump Association (IGSHPA) guidelines that provide two tiers of estimates of soil thermal properties (Remund and Carda, 2009). In the standard method, the soil type at the HGHP installation site is determined by simple field classification of soil texture or from published soil maps (see Table 5.14 in Remund and Carda, 2009). A second tier of thermal property estimates are provided when better information is available from a site-specific assessment of soil particle size analysis, bulk density, and the soil's susceptibility to drought (see Table 5.15 in Remund and Carda, 2009). Comparing the calculated design loop lengths derived from these two tiers of estimated parameters versus the observed in-situ parameters provides a unique evaluation of the effectiveness of the conventional industry practice in achieving optimal installations of ground heat exchangers in HGHP systems (i.e., meeting system fluid temperature specifications with the minimum ground loop length installation).

Results in Fig. 8 demonstrate the sensitivity of calculated design pipe lengths to soil thermal properties and the significance of seasonal variability on design calculations. Despite the observed climate divergence to severe drought conditions in 2012, followed by above normal precipitation in 2013, sites 2, 3 and 4 exhibited remarkably stable thermal properties over the period. As a result, the design total pipe length of the GHEX component is relatively invariant leading to the expectation that near-optimal HGHP system performance can be achieved with a total installed pipe length of approximately 500 meters for the specified system configuration. Because of the markedly different soil characteristics at sites 1 (alluvium) and 5 (outwash), seasonal variability has a more significant impact on design loop lengths with the calculated total pipe lengths varying as much as 200 meters

1 beyond the length calculated for the mean in-situ condition. These results indicate that achieving an
 2 optimal HGHP system design in such settings is difficult since GHEX designs based on average thermal
 3 properties cannot always provide the expected level of heat transfer year round. Suboptimal conditions
 4 also exist if the ground loop length were designed to accommodate the driest periods observed during
 5 monitoring since the ground heat exchanger would be effectively overbuilt for much of the operational
 6 period. Optimal HGHP design requires an understanding of the local variance in soil thermal conditions
 7 such that periods of potentially reduced energy efficiency can be weighed against the higher initial
 8 installation cost of a GHEX designed to handle the highest level of soil thermal resistance. Alternative
 9 approaches such as irrigating the trench areas during drought conditions might also prove to be more
 10 cost effective than installing a larger ground loop.

Figure 8. HGHP design loop lengths calculated for ground heat exchangers at the five monitoring sites following the IGSHPA recommended standards (Remund and Carda, 2009). Soil thermal properties are estimated from either published soil maps (standard method; circles) or from site-specific assessments of soil texture, density, and drought susceptibility (triangles). In-situ calculations are shown for the mean conditions (bar) and the observed range in seasonal fluctuations (gray shaded bar; see Fig. 7 for commensurate ranges in λ_s).

Fig. 8 also illustrates how design loop lengths calculated from the conventional industry practice of applying estimated thermal properties often results in overbuilt ground loops. Across all five sites the analysis indicated that following the standard method for estimating soil thermal properties led to overbuilt ground loops that were on average 52% longer when compared to designs that use the observed mean in situ thermal conditions. Results improved slightly to an average of 44% overbuilt length when using the second tier of soil thermal property estimates based on the more detailed site soil assessment (Table 5.15 in Remund and Carda, 2009). A noteworthy improvement occurred at site 4 where the design pipe lengths using the second tier estimates provided a good match to the in situ based calculations. Results at site 5 were also noteworthy in that the design lengths using estimated parameters were longer than the length calculated from the mean in situ observations, but within the large range covering the driest observed conditions for design length calculations.

5.0 Discussion/Conclusions

This study provides the first known in situ observations of the dynamic range of λ_s that occurs within the depth of standard HGHP trench installations. The analysis of both in situ continuous λ_s data and laboratory data suggests that soil moisture and bulk density have a dominant control on thermal conductivity relative to soil texture. Although sandy sediments, such as those encountered at site 5, can theoretically have λ_s far in excess of $2.2 \text{ W m}^{-1} \text{ K}^{-1}$ when compacted and saturated, geomorphic settings like the elevated outwash terrace can exhibit well-drained soils that may never achieve saturation without irrigation or system design modification. The seasonality of soil moisture dictates that designs may need to consider late summer conditions when seasonal water tables are low and pore space heat transfer may be much lower as the more conductive liquid components (λ_w) diminish and are replaced by less conductive gases (λ_a). However, this impact on design may be mitigated if heating loads

dominate the final loop length design in a region, as was the case in this study (soil moisture was largely replenished across the monitoring sites during the January period used for heating design calculations).

Consistent with previous work modelling the impacts of transient thermal and moisture conditions on HGHPs (Wu et al., 2014), modelled loop lengths for the monitoring network sites suggest that the conventional industry design approach using constant and low-range λ_s values provides somewhat conservative results for ground loop installations. The tendency towards overbuilt loops is primarily the result of applying the low range of recommended parameter values at most sites. In the case of fairly limited site-specific data, the tier one estimates must be applied and the low range values are recommended as satisfactory unless better information is available. Even when a more detailed site soil assessment is conducted, the selection of parameter estimates requires an understanding of how susceptible the soil at a particular site is to drought conditions. Depending on the sediment type and setting, a conservative design approach using soil wilting point thermal property estimates can result in much longer loop designs than those incorporating wetter field capacity estimates. Especially when combined with recent advancements in ground heat exchanger configurations (Chong et al., 2013; Hajmohammadi et al., 2013), these results suggest that more detailed assessments of regional soil/sediment thermal properties will result in better ground loop designs.

Site-specific thermal properties data are especially critical for research investigating new HGSHS technologies and such studies should consider incorporating continuous λ_s measurements like those presented herein. The Hukseflux TP01 sensor provides long-term continuous λ_s data and can be installed in a trench face during horizontal loop emplacement. An apparent underestimation of λ_{sf} similar to the findings of Liebethal and Foken (2006), was corrected by applying the linear transform in Table 2 and other users are encouraged to conduct laboratory experiments/calibrations prior to field placement. There is a general need for laboratory λ standards in the 1-3 W m⁻¹ K⁻¹ range to supplement

reference materials used in this study (ASTM, 2008; Tarnawski et al., 2009b; Zhang et al., 2010; Tarnawski et al., 2011). In situ trench face installation entailed cutting a vertical pre-insertion slot for the sensor and then gently pressing the surrounding soil against the sensor to establish good contact. The method worked well with predominantly cohesive soils derived from glacial parent materials, but may not provide satisfactory results in granular sediments.

The in situ data presented in this paper suggest that truly optimized HGHP designs must consider the seasonal and spatial variability in soil thermal properties. Soil-moisture fluctuations result in soil thermal conductivity variability by an average of 27% at the five sites when comparing maximum relative to minimum in situ values, indicating that appropriate ranges in λ_s should be considered during the HGHP design phase. Furthermore, spatial variability in soil thermal diffusivity must be considered when estimating annual shallow subsurface temperature swings (equation 3), evidenced in this study by measured 1.5-m temperature amplitude differences as great as 5.2° C for two sites within 1.5 km of one another. Accordingly, improved collaboration between earth scientists and engineers will result in better GHP system designs. Soil-moisture and ground temperature data must be made more readily available, and peer-reviewed GHP design literature should more accurately convey information related to geologic setting (or soil parent material) so that designs can be tailored to geographic regions where conditions may be similar.

More extensive data sets are necessary to test the mineralogical and textural controls on thermal conductivity so that a GHP thermal performance index for soils as suggested by Remund (1994), can be developed. The statistical analysis of field sediment/soil samples presented herein indicates that a thermal index for soils must include degree of saturation and bulk density components. Further work is needed to refine the texture component, and once a calibrated multiple regression model is developed, soil survey data can be used along with soil moisture proxies to map thermal

performance indices at sufficient resolutions to assist HGHP designers. Additionally, it is recommended that the ternary plots (e.g., Fig. 5) become a more widely used means of conveying information regarding the sediment/geologic conditions adjacent to a ground-coupling loop for all studies that aim to improve HGHP design.

Acknowledgements

This research was supported by a grant from the Geothermal Technologies Program of the U.S. Department of Energy to the Association of American State Geologists (subaward: IN-0002850). The authors wish to thank all site access providers (ACRES Land Trust, Ball State University, The Yoder Farm LLC, Bradford Woods of Indiana University, and Aurora Vista Farms). Field and laboratory contributions were made by Paul Levy, Mary Nicholas, and Connor Waldoch. GeoConnections Inc. is gratefully acknowledged for their provision of a LoopLink software license used in this study.

References

- Abu-Hamdeh, N. H. and Reeder, R. C. (2000). Soil thermal conductivity effects of density, moisture, salt concentration, and organic matter. *Soil Science Society of America Journal* 64(4): 1285-1290. doi:10.2136/sssaj2000.6441285x
- Aste, N., Adhikari, R.S., and Manfren, M. (2013). Cost optimal analysis of heat pump technology adoption in residential reference buildings. *Renewable Energy* 60: 615-624. doi:10.1016/j.renene.2013.06.013
- ASTM (2008). Standard test method for determination of thermal conductivity of soil and soft rock by thermal needle probe procedure. D5334-08. ASTM International, West Conshohocken, PA: 8 p. doi: 10.1520/D5334-08
- Burdick, A. (2011). Strategy Guideline: Accurate heating and cooling load calculations. Oak Ridge, TN, U.S. Dept. of Energy, Building Technologies Program: 47 p.
- Cho, H. and Choi, J. M. (2014). The quantitative evaluation of design parameter's effects on a ground source heat pump system. *Renewable Energy* 65: 2-6. doi:10.1016/j.renene.2013.06.034
- Chong, C. S. A., Gan, G., Verhoef, A., Garcia, R. G., and Vidale, P.L. (2013). Simulation of thermal performance of horizontal slinky-loop heat exchangers for ground source heat pumps. *Applied Energy* 104: 603-610. doi:10.1016/j.apenergy.2012.11.069

- 1 ClimateMaster (2013). Tranquility (R) 20 Single-stage (TS) Series Submittal Data. ClimateMaster Inc.,
2 Oklahoma City, OK: 72 p.
- 3 Decagon Devices (2012). KD2 Pro Thermal Properties Analyzer Operators Manual, Version 12. Decagon
4 Devices, Inc., Pullman, WA: 68 p.
- 5 De Vries, D. (1975). Heat transfer in soils. *Heat and mass transfer in the biosphere* 1: 5-28.
- 6 Esen, H., Inalli, M., Esen, M., and Pihtili, K. (2007). Energy and exergy analysis of a ground-coupled heat
7 pump system with two horizontal ground heat exchangers. *Building and Environment* 42(10): 3606-
8 3615. doi:10.1016/j.buildenv.2006.10.014
- 9 Flint, L. E. and Flint, A. L. (2002). 2.3 Porosity. *Methods of Soil Analysis: Part 4 Physical Methods*, Soil
10 Science Society of America, Madison, WI: 241-254.
- 11 Fullerton, D.S., Bush, C.A., and Pennell, J.N. (2003). Map of surficial deposits and materials in the
12 eastern and central U.S.: U.S. Geological Survey Map, scale 1:2,000,000.
- 13 Gee, G. W. and Or, D. (2002). 2.4 Particle-Size Analysis. *Methods of Soil Analysis: Part 4 Physical*
14 *Methods*, Soil Science Society of America, Madison, WI: 255-293.
- 15 Gonzalez, R. G., Verhoef, A., Vidale, P. L., Main, B., and Gan, G. (2012). Interactions between the
16 physical soil environment and a horizontal ground coupled heat pump, for a domestic site in the UK.
17 *Renewable Energy* 44: 141-153. doi:10.1016/j.renene.2012.01.080
- 18 Groeneveld, G. J., Snijders, A. L., Koopmans, G., and Vermeer, J. (1984). Improved method to calculate
19 the critical conditions for drying out sandy soils around power cables. *Generation, Transmission and*
20 *Distribution*, IEE Proceedings C 131(2): 42-53. doi:10.1049/ip-c.1984.0007
- 21 Grossman, R. B. and Reinsch, T. G. (2002). 2.1 Bulk Density and Linear Extensibility. *Methods of Soil*
22 *Analysis: Part 4 Physical Methods*, Soil Science Society of America, Madison, WI: 201-228.
- 23 Hajmohammadi, M. R., Eskandari, H., Saffar-Avval, M., and Campo, A. (2013). A new configuration of
24 bend tubes for compound optimization of heat and fluid flow. *Energy* 62: 418-424.
25 doi:10.1016/j.energy.2013.09.046
- 26 Healy, P. F. and Ugursal, V. I. (1997). Performance and economic feasibility of geothermal heat pumps
27 in cold climate. *International Journal of Energy Research* 21(10): 857-870. doi: 10.1002/(SICI)1099-
28 114X(199708)21:10<857::AID-ER279>3.0.CO;2-1
- 29 Hillel, D. (1982). *Introduction to soil physics*. Academic Press, New York: 365.
- 30 Hillel, D. (2005). *Thermal Properties and Processes*. *Encyclopedia of Soils in the Environment*. Editor-in-
31 Chief: Daniel Hillel. Elsevier, Oxford: 156-163.
- 32 Hukseflux Thermal Sensors. (2011). TP01 Thermal Properties Sensor: User manual including thermal
33 diffusivity and volumetric heat capacity measurement. Hukseflux Thermal Sensors, Delft, NLD: 35.

- 1 Kusuda, T. and Achenbach, P. R. (1965). Earth temperature and thermal diffusivity at selected stations
2 in the United States, ASHRAE Transactions 71(1): 61-76.
- 3 Liebethal, C. and Foken, T. (2006). On the use of two repeatedly heated sensors in the determination of
4 physical soil parameters. Meteorologische Zeitschrift 15(3): 293-299. doi:
5 <http://dx.doi.org/10.1127/0941-2948/2006/0125>
- 6 Neuberger, P., Adamovský, R., and Šedová, M. (2014). Temperatures and heat flows in a soil enclosing
7 a slinky horizontal heat exchanger. Energies 7(2): 972-987. doi:10.3390/en7020972
- 8 PRISM Climate Group (2004), Oregon State University, <http://prism.oregonstate.edu>. Accessed August
9 1, 2012.
- 10 Remund, C. P. (1988). Predicted effects of soil dry density and initial water content on performance of
11 heat exchanger buried in an unsaturated loess parent material, University of Nebraska. Ph.D.: 343 p.
- 12 Remund, C. P. (1994). Thermal performance evaluation of common soils for horizontal geothermal heat
13 pump application. The 1994 International Mechanical Engineering Congress and Exposition, Chicago,
14 IL, 11/06-11/94: 45-62.
- 15 Remund, C. P. and Carda, R. (2009). Ground Source Heat Pump Residential and Light Commercial
16 Design and Installation Guide. The International Geothermal Heat Pump Association, Stillwater, OK:
17 560 p.
- 18
- 19 Salomone, L. A., Kovacs, W. D., and Kusuda, T. (1984). Thermal performance of fine-grained soils.
20 Journal of Geotechnical Engineering 110(3): 359-374. doi: [10.1061/\(ASCE\)0733-9410\(1984\)110:3\(359\)](https://doi.org/10.1061/(ASCE)0733-9410(1984)110:3(359))
- 21 Sanaye, S. and Niroomand, B. (2010). Horizontal ground coupled heat pump: Thermal-economic
22 modeling and optimization. Energy Conversion and Management 51(12): 2600-2612.
23 doi:10.1016/j.enconman.2010.05.026
- 24 Smits, K. M., Sakaki, T., Limsuwat, A., and Illangasekare, T. H. (2010). Thermal conductivity of sands
25 under varying moisture and porosity in drainage-wetting cycles. Vadose Zone 9(1): 172-180.
26 doi:10.2136/vzj2009.0095
- 27 Tarnawski, V., Momose, T., and Leong, W. H. (2011). Thermal conductivity of standard sands II.
28 Saturated conditions. International Journal of Thermophysics 32(5): 984-1005. doi: 10.1007/s10765-011-
29 0975-1
- 30 Tarnawski, V. R. and Leong, W. H. (1993). Computer analysis, design and simulation of horizontal
31 ground heat exchangers. International Journal of Energy Research 17(6): 467-477.
32 doi: 10.1002/er.4440170603
- 33 Tarnawski, V. R., Leong, W. H., Momose, T., and Hamada, Y. (2009). Analysis of geothermal heat
34 pumps with horizontal ground heat exchangers for northern Japan. Renewable Energy 34(1): 127-134.
35 doi:10.1016/j.renene.2008.03.026

1 Tarnawski, V. R., Momose, T., Leong, W. H., Bovesecchi, G., and Coppa, P. (2009). Thermal
2 conductivity of standard sands. Part I. Dry-state conditions. *International Journal of Thermophysics*
3 30(3): 949-968. doi: 10.1007/s10765-009-0596-0

4 Topp, G. C., Davis, J. L., and Annan, A. P. (1980). Electromagnetic determination of soil water content:
5 Measurements in coaxial transmission lines. *Water Resources Research* 16(3): 574-582.
6 doi: 10.1029/WR016i003p00574

7 Topp, G. C. and Ferre, P. A. (2002). 3.1 Water Content. *Methods of Soil Analysis: Part 4 Physical*
8 *Methods*, Soil Science Society of America, Madison, WI: 417-545.

9 U.S. Energy Information Administration (USEIA) (2013). Consumption and expenditures tables, 2009
10 RECS survey data, release date January 11, 2013. Available online at
11 <http://www.eia.gov/consumption/residential/data/2009/>. Accessed November 22, 2013.

12 Wu, R., Tinjum, J. M., and Likos, W. J. (2014). Coupled thermal conductivity dryout curve and soil-water
13 characteristic curve in modeling of shallow horizontal geothermal ground loops. *Geotechnical and*
14 *Geological Engineering*: 1-13. doi: 10.1007/s10706-014-9811-2

15 Xu, H. and Spitler, J. D. (2014). The relative importance of moisture transfer, soil freezing, and snow
16 cover on ground temperature predictions. *Renewable Energy* 72: 1-11.
17 doi:10.1016/j.renene.2014.06.044

18 Zhang, M., Che, Z., Chen, J., Zhao, H., Yang, L., Zhong, Z., and Lu, J. (2010). Experimental
19 Determination of Thermal Conductivity of Water– Agar Gel at Different Concentrations and
20 Temperatures. *Journal of Chemical & Engineering Data* 55(4): 859-864. doi: 10.1021/jc100570h

21