The Indiana Shallow Geothermal Monitoring Network: A test bed for optimizing ground-source heat pumps in the glaciated Midwest

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Ground-source heat pumps (GSHP) represent an important technology that can be further developed by collecting data sets related to shallow thermal regimes. Computer programs that calculate the required lengths and configurations of GSHP systems use specific input parameters related to the soil properties to improve the efficiency of system designs. The thermal conductivity of sediments varies significantly depending on texture, bulk density, and moisture content, and it is therefore necessary to characterize various unconsolidated materials under a wide range of moisture conditions. Regolith texture data are collected during some installations to estimate thermal properties, but soil moisture and temperature gradients within the vadose zone are rarely considered due to the difficulty of collecting sufficient amounts of data.

Six monitoring locations were chosen in Indiana to represent unique hydrogeological settings and glacial sediments. Trenches were excavated to a depth of 2 meters (a typical depth for horizontal GSHP installations) and sediment samples were collected at 0.3-meter intervals for a laboratory analysis of thermal conductivity, thermal diffusivity, bulk density, and moisture content. Temperature sensors and water-content reflectometers were installed in 0.3-meter increments to monitor changes in temperature and soil moisture with depth. In-situ thermal conductivity and thermal diffusivity were measured at 1-meter intervals using a sensor that detects radial differential temperature around a heating wire. Micrometeorological data were also collected to determine the surface conditions and the effect of water budgets that drive changes in soil moisture in the subsurface.

The preliminary results indicate that increases in water content can increase thermal conductivity by as much as 30% during wetting front propagation. Although there is a change in temperature associated with the infiltration of wetting fronts, thermal conductivity appears to be relatively insensitive to soil temperature. By establishing continuous data sets, fluctuations in seasonal energy budgets and unsaturated zone soil moisture can be determined. This information can then be used to establish accurate end members for thermal properties and improve the efficiency of geothermal systems.

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Water and energy budgets are highly variable throughout the season, and since these factors can have a large influence on the thermal conductivity of sediments, a full-year cycle of data must be collected in order to comprehensively consider how to best optimize shallow geothermal systems. However, some initial results can be inferred from the data collected thus far. In the first year of data collection, thermal conductivity was observed to vary with depth, and seasonal changes in moisture levels were also observed, affecting the thermal conductivity of the soil. This data can be used to provide a range of thermal conductivities for all depths at all sites based on seasonal changes in moisture levels and temperature.

Results

Volumetric Water Content

To allow for the correction of all correlation between volumetric water contents (WVC) measured by the CS650 probe, controlled laboratory experiments were performed on samples taken during site installations. Dried sediment was packed in a large cylinder in an attempt to match field bulk density, and known volumes of water were sequentially added and allowed to equilibrate before compaction was reached. The volume fraction of these experiments is used to establish a trend curve that allows field WVC to be transformed into actual WVC for each site using the parameter of permeability.

Sensor Calibrations

- Using the standards, a trend was developed between instruments to correct for the underestimated conductivity of the TP1 sensors.
- Known standards were measured with all sensors:
  - Agar gel (0.5%): (0.598 W/mK)
  - Agar gel (5%): (0.554 W/mK)
  - Ottawa sand (dry): (0.332 W/mK)

Thermal Conductivity

- Measured using Decagon KD2 Pro during site installations and in lab
- Known standards were measured with all sensors:
  - Agar gel (0.5%): (0.598 W/mK)
  - Agar gel (5%): (0.554 W/mK)
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Introduction

Ground-source heat pumps (GSHP) represent an important technology that can be further developed by collecting data sets related to shallow thermal regimes. Computer programs that calculate the required lengths and configurations of GSHP systems use specific input parameters related to the soil properties to improve the efficiency of system designs. The thermal conductivity of sediments varies significantly depending on texture, bulk density, and moisture content, and it is therefore necessary to characterize various unconsolidated materials under a wide range of moisture conditions. Regolith texture data are collected during some installations to estimate thermal properties, but soil moisture and temperature gradients within the vadose zone are rarely considered due to the difficulty of collecting sufficient amounts of data.

Six monitoring locations were chosen in Indiana to represent unique hydrogeological settings and glacial sediments. Trenches were excavated to a depth of 2 meters (a typical depth for horizontal GSHP installations) and sediment samples were collected at 0.3-meter intervals for a laboratory analysis of thermal conductivity, thermal diffusivity, bulk density, and moisture content. Temperature sensors and water-content reflectometers were installed in 0.3-meter increments to monitor changes in temperature and soil moisture with depth. In-situ thermal conductivity and thermal diffusivity were measured at 1-meter intervals using a sensor that detects radial differential temperature around a heating wire. Micrometeorological data were also collected to determine the surface conditions and the effect of water budgets that drive changes in soil moisture in the subsurface.

The preliminary results indicate that increases in water content can increase thermal conductivity by as much as 30% during wetting front propagation. Although there is a change in temperature associated with the infiltration of wetting fronts, thermal conductivity appears to be relatively insensitive to soil temperature. By establishing continuous data sets, fluctuations in seasonal energy budgets and unsaturated zone soil moisture can be determined. This information can then be used to establish accurate end members for thermal properties and improve the efficiency of geothermal systems.

Discussion

As Figure 1A shows, there is a roughly inverse relationship between thermal conductivity and thermal diffusivity along a certain trend. As the trend approaches zero, the inverse relationship between thermal conductivity and thermal diffusivity is stronger. However, the thermal conductivity of sediments decreases with increasing moisture content, and the inverse relationship between conductivity and diffusivity is also observed. This is true because the low thermal conductivity of water relative to common minerals (Huskey, 2012). The moisture content required to show the inverse relationship depends on sediment properties, and thermal conductivity and diffusivity are inversely related. Clay-rich soils tend to show a gradual increase in conductivity with increasing moisture and require more water to show the inverse relationship between conductivity and diffusivity. In contrast, sandy soils are more conductive and allow a greater volume of water to enter the soil. The inverse relationship between thermal conductivity and thermal diffusivity is also observed in sandy soils. Sandy soils also tend to have a higher hydraulic conductivity, which can reduce the ability to retain moisture and increase the rate of water infiltration. Since water has a much higher volumetric heat capacity than air or common minerals while quartz has one of the highest thermal conductivities of common minerals (Huskey, 2012), it follows that the ideal soil for ground-source heat pump installations would be a highly conductive quartz sand with high porosity and permeability. However, as many coarse-grained soils also tend to be well-drained, with coarse gravel or sands, these more conductive systems may be better suited to maintain higher moisture content and thermal conductivity. In Figure 5, a comparison between moisture content and thermal conductivity was developed. This was used to generate a range of thermal conductions for all depths at all sites based on moisture content. Figure 5 shows the range of conductivities necessary to produce effective GSHP systems. A more complete dataset is needed to determine effective expectations for smaller GSHP systems.

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