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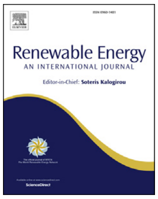

Determining thermal rock properties of soils in Canterbury, New Zealand: Comparisons between long-term in-situ temperature profiles and divided bar measurements

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ABSTRACT

This paper presents ground temperature data from a 9.1 m deep borehole located at Lincoln, Canterbury, New Zealand. Thermal properties of the soil are inferred from three years of in-situ temperature measurements, and compared to cored samples later measured in the laboratory using a divided bar thermal properties analysing system. The data show that seasonal changes affect ground temperatures to depths of approximately 7.5 m, beyond which the temperature is constant (±0.2°) year-round. This stable ground temperature is determined to be 11.8 °C, which is equivalent to the average ambient air temperature of the area, recorded at the adjoining weather station. Rain is seen to disturb ground temperatures immediately after the event, affecting depths up to 0.5 m by several degrees depending on the volume of water and ambient air temperature. Thermal diffusivity estimated from in-situ observation suggests soils in the top 9 m at Lincoln range from 3.4×10^{-7} (in shallower soils) to 10.6×10^{-7} m^2s^{-1} (deeper ground). Laboratory measurements measure the diffusivity ranging from 3.8×10^{-7} to 7.9×10^{-7} m^2s^{-1}. These values agree with the ranges measured from in situ temperature measurements. The determination of thermal properties and ground temperatures is important for the development and potential utilisation of the low enthalpy geothermal resources.

1. Introduction

Information on the thermal behaviour of the ground is important for the construction and building industry, but also more recently to aid in the understanding of low temperature geothermal resources (e.g. [1]). Solar radiation penetrates the Earth's surface warming the ground beneath. The temperature variations over depth through the near surface provides a source of energy that can be accessed and utilised for space heating and cooling using ground source heat pumps [2]. Ground temperatures at depth remain relatively constant year-round, providing a stable source of heating in the winter months or cooling in summer months. The depth of penetration of the solar energy depends on several factors, including the local climate and thermal properties of the ground. Site-specific factors such as slope orientation, terrain, wind and rain etc., can also have an influence on the ground temperature and thermal behaviour of the ground [3]. Understanding how ground temperatures vary and are influenced by climatic factors are important in understanding the size and potential of the low temperature resource.

Ground temperatures are predominately affected by the physical properties of the ground and the local climate. Near surface (<0.5 m) soils and rocks are greatly influenced by climatic factors such as diurnal air temperature fluctuations, rainfall, sunshine hours and even wind. Average annual ambient temperatures and seasonal ambient temperature variations affect soil temperatures to greater depths. Generally, three ground temperature soil zones can be identified (e.g., [1]; [4]): (1) the surface zone, where temperatures are sensitive to diurnal temperature and meteorological variations; (2) the shallow zone, where temperatures are sensitive to seasonal temperature variations; and (3) the deep zone, where ground temperatures are near constant year-round. Temperatures in the deep zone are thought to be approximately equal to the mean annual air temperature in that region [5], and are reached at depths of between 9 and 15 m [6]. The exact depth at which constant ground temperatures are reached are dependent on the physical and thermal properties of the local geology at the site.

An understanding of the thermal characteristics and behaviour

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Notation list

α	Thermal diffusivity (ms^{-1})
κ	Thermal conductivity ($Wm^{-1}K^{-1}$)
c_v	Volumetric heat capacity ($Jm^{-3}K^{-1}$)
θ_0	Mean ambient ground temperature (°C)
θ_A	Amplitude of ground temperature variation (°C)
θ_z	Ground temperature at depth z (°C)
φ	Time phase delay (radians)
ω	Angular frequency (radians)
Q	Heat flow (Wm^{-2})
A	Sample surface area (m^2)
m	Sample mass (g)
d	Sample thickness (m)
w	Sample width (m)
ρ	Density (gm^{-2})
c_p	Specific heat capacity (JK^{-1})

of soils and rocks can provide insight into addressing problems relating to engineering, geophysics, and agricultural [7]; [8]. Ground temperature measurements are easy to obtain and can be used in assessing ground water recharge (e.g., [9]; [10]; [11]), climate change (e.g., [12]; [3]; [13]), agronomical studies (e.g., [14]; [15]), meteorological studies [16]; [17], in addition to shallow low enthalpy geothermal resource assessment (e.g., [4]; [18]). Other uses included determining the ideal depth for wine cellar construction [19]; [20], and analysis of burial sites [21].

The thermal properties of a rock determine how a rock behaves in response to thermal loads. There are three basic thermal properties that describe how a material will respond to thermal loading [22]. They are (1) Thermal conductivity (κ): controls the rate of heat transfer through a material, (2) Thermal diffusivity (α): controls the speed of temperature propagation through a material, and (3) Specific heat capacity (C_p): defines the amount of thermal energy a material can store.

There are three methods commonly used to determine thermal properties of soils, laboratory measurements, on-site measurements or determination of thermal properties through continuous *in-situ* observations. On-site measurements of thermal properties are often used by the construction industry for quick determination of ground properties to aid in design of ground loops for geothermal heating and cooling [23]. These measurements are often done using a needle probe apparatus, which can determine thermal properties within 20–30 min [24]. These values don't take into consideration the saturation level, or ambient air temperature at the time of measurement. Thermal properties determined in a laboratory can provide information on a range of sample states, ranging from fully saturated samples to oven-dried samples (e.g., [24]; [25]). This method can provide good insight into how moisture content, pore space and compaction can affect the soils type sampled, however, not necessarily under “natural” conditions. During the retrieval of samples the natural conditions (density, moisture content, compaction) are disturbed through drilling or digging techniques which will affect results. Additionally, removing the sample from site, removes it from its natural environment and influences from local climate. Long term monitoring of *in-situ* temperatures allows *in-situ* thermal properties of the soils to be determine [26]. By installing a small network of temperature sensors within a vertical borehole, at different depths, inhomogeneity's in the ground, seasonal influences and their effects on thermal properties can be monitored. As the thermal properties need to calculated through a series of analysis, they are generally referred to as apparent or inferred properties.

In New Zealand, ground temperature profiles and core analysis are being used to determine thermal diffusivity, thermal conductivity, and volumetric heat capacity, of local soils and rocks (e.g. [4]; [27]; [28]). These parameters are particularly important for understanding the potential of shallow geothermal resources and efficient, cost-effective heat recovery using geothermal heat-pumps.

This paper presents thermal properties of soils within the top 9 m from the surface, determined through *in-situ* temperature variations and through laboratory measurements. The borehole is located just outside the town of Lincoln in Canterbury, New Zealand. Canterbury is located on the eastern margin of the South Island of New Zealand, and is the region with the largest use and uptake of geothermal heat pump technology for heating and cooling of commercial and domestic buildings in New Zealand [29]; [28]. The region also experiences some of the largest annual ambient temperature variations, with the average seasonal air temperatures ranging from 0 to 35 °C [30]. Soil temperatures also experience a seasonal variation, but not to such extremes [27], making it ideal for heating and cooling systems.

Many of the large commercial installations make use of the shallow aquifer systems located beneath the city of Christchurch, where shallow (<100 m) underground water remains at a constant temperature of 12–13 °C year-round [29]. For many of the smaller domestic installations the upfront cost associated with drilling to aquifer depths is unrealistic, and opt for horizontal ground loop designs to utilise the heat stored in the shallow geology to efficiently heat and cool their buildings. Understanding the thermal properties of the shallow geology aids in designing efficient ground loops.

2. Data

A 9-m borehole was drilled in December 2012, at the NIWA (National Institute of Water and Atmosphere) weather station located at Lincoln, Broadfield [30], near Christchurch, Canterbury, New Zealand. The borehole was collocated with a weather station (Lincoln, Broadfield Ews, Agent number 17603) which records hourly temperatures, rainfall, wind and daily soil temperatures to a depth of 1 m.

A string of twelve DS18B20 digital thermometer integrated circuits sensors, was installed in the borehole [31]. These sensors have an accuracy of ±0.5 °C over a temperature range of −10 °C to +85 °C, with a resolution of 0.06 °C. Calibration of the sensors was done prior to deployment, by placing the sensors in an ice water bath (with automated stirrer), which was then allowed to warm gradually to room temperature. A calibration relationship was determined between each sensor and a PT100 platinum thermistor. It is assumed that the sensors remained in equilibrium with the water and that the automated stirring minimised temperature gradients in the bath.

The sensors were installed in the 9-m borehole at Lincoln, and were located at depths of: 0.30 m, 0.30 m, 0.31 m, 0.35 m, 0.4 m, 0.5 m, 1.75 m, 3.0 m, 4.5 m, 6.0 m, 7.5 m, and 9.1 m (Fig. 1). The top three sensors are located linearly in a horizontal trench that connects the vertical bore to the data logger. A 5-cm diameter core was extracted during drilling for laboratory thermal property measurements. The lithology of the borehole is predominately interleaved silt and sand to a depth of 2.8 m after which several coarse gravel layers exist (Fig. 1). Once the sensors were in place, the hole was backfilled with bentonite slurry. Data was recorded on a custom data logger, and temperature measurements were made every hour. *In-situ* ground temperatures were recorded hourly between December 2012 and February 2015.