THERMAL ROCK PROPERTIES – COMPARISONS OF APPARENT VALUES DETERMINED FROM IN-SITU TEMPERATURE PROFILES, AND VALUES DETERMINED BY LABORATORY MEASUREMENTS.

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ABSTRACT

New Zealand's rocks and soils provide a clean, renewable, and sustainable energy source for heating and cooling of buildings. Incoming solar energy is absorbed and stored by the earth, creating a relatively constant ground temperature year round that can be utilised with a geothermal heat pump to provide heating in the winter and cooling in the summer. The amount of heat stored in the rocks and soils are largely influenced by local climatic factors, such as air temperature, sunshine hours, rainfall and the thermal properties of the rocks and soils.

This paper presents data from several shallow in-ground temperature monitoring sites in different soil types around New Zealand. Thermal diffusivity of the soils is determined from the *in-situ* temperature profiles and compared to values determined from laboratory measurements using a divided bar apparatus. Preliminary results indicate a close agreement in values. Further investigations into climatic influences and moisture content on thermal properties are underway.

1. INTRODUCTION

1.1 Thermal rock properties

Thermal properties of rocks and soils are required for understanding the heat and mass transfer processes in rock formations. Understanding these processes is important for many branches of engineering, mining, and drilling projects. Examples include burial of high-voltage power cables, drilling of oil and gas pipe-lines, planning for underground infrastructure, such as tunnels, or subways or utilising stored subsurface heat (i.e. geothermal).

There are several key properties that provide information regarding the ability of a material to store or transfer heat. These properties include:

(1) thermal conductivity (λ), which controls the rate of heat transfer through a material ($Wm^{-1}K^{-1}$)
(2) thermal diffusivity (α), which controls the speed of temperature propagation through a material (m^2s^{-1})
(3) specific heat capacity (C_ρ), defines the amount of thermal energy a material can store, per unit mass, while undergoing a temperature change ($Jkg^{-1}K^{-1}$)
(4) volumetric heat capacity (C_v), defines the amount of thermal energy a material can store, per unit volume, while undergoing a temperature change ($Jm^{-3}K^{-1}$)
(5) thermal effusivity (μ), a measure of a materials ability to exchange thermal energy with its surroundings ($Ws^{1/2}m^{-2}K^{-1}$).

These thermal properties are inter-related through the following series of equations:

$$\alpha = \frac{\lambda}{C_v} \quad [1]$$

$$\boldsymbol{C_\rho} = \frac{\boldsymbol{C_v}}{\boldsymbol{\rho}} \quad [2]$$

and

$$\mu = \sqrt[2]{\lambda C_v} \quad [3]$$

Therefore, to determine all thermal properties, only a few key values need to be determined. The easiest properties to measure include the thermal conductivity, thermal diffusivity, density and either the volumetric or the specific heat capacity of a material, or a combination of three of these properties. The effusivity of the material can be easily derived using equation [3].

The thermal conductivity, diffusivity and heat capacity of a rock are dependent on the mineral composition, porosity and fluid filling the pore spaces. The conductivity and diffusivity are also dependent of the fracture orientation, grainsize and anisotropy of the sample. All thermal properties are therefore unique to different geology, pressures, temperatures, and saturation levels. Understanding these values for a given location and geology is important for any activity that may insert or extract heat from the ground.

1.2 Measuring methods

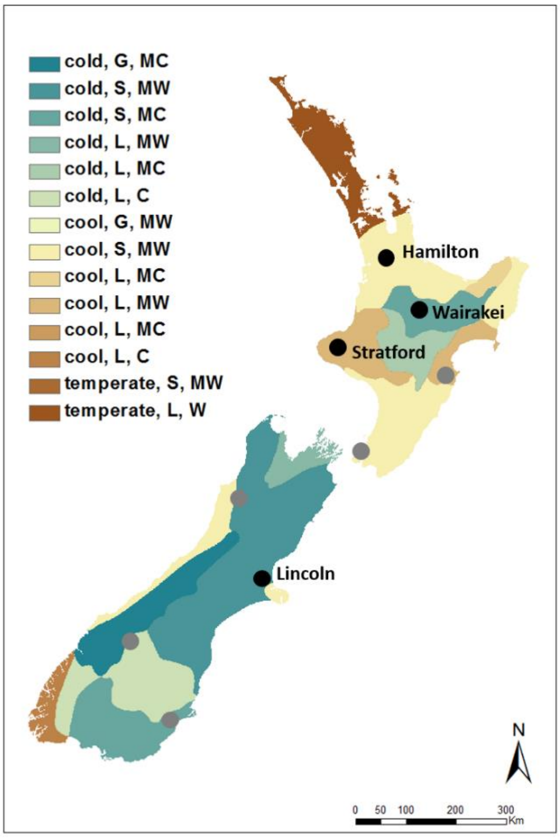
There are several methods used for determining thermal properties of rocks and soils. They include *in-situ* methods (e.g. Austin, 1995; van Manen & Wallin, 2012), thermal relaxation methods (e.g. Wilhelm, 1990), and laboratory measurements (e.g Sass et al, 1984; Popov et al, 1999; Antriasian and Beardsmore, 2014). Laboratory methods include optical scanning techniques (Popov 1983), divided-bar techniques (Antriasian, 2009) and line-source methods (Seipold & Huenges, 1998). Each method has strengths and weaknesses, although all require some disturbance to the sample. The optical scanner can only determine thermal conductivity and diffusivity on dry solid rock samples, but can measure lengths of core (up to 50 cm in length). The system is also able to determine anisotropy tensors and thermal profiling of core lengths. The divided-bar techniques allow thermal conductivity and specific heat capacity to be determined on consolidated and unconsolidated material, with a range of saturation levels. Anisotropic properties can also be determined on solid samples. The needle-probe system has three interchangeable sensors that measure thermal diffusivity, conductivity, volumetric heat capacity and thermal resistivity. It works best on unconsolidated material, although can be used on solid rock, if a narrow hole for the probe is drilled first.

In this paper, we compare thermal diffusivity calculated from in-ground temperatures measured over several years, to thermal properties determined in a laboratory on extracted core. Two laboratory techniques (divided-bar analysis and needle-probe measurements) are used on the unconsolidated material extracted from the boreholes.

2. SHALLOW BOREHOLE NETWORK

A network of nine shallow boreholes (Figure 1), in which hourly temperature measurements are made, was established in 2014, with the first borehole installed at Wairakei in 2010 and the final one in Napier, in June 2014 (Table 1). Boreholes extend from the surface to depths of between 7.5 m to 10 m. Sites have a minimum of 10 temperature sensors installed at various depths down the borehole (Seward et al, 2014).

Seward et al (2013) outlines a desktop study of New Zealand's climatic areas, common soil types and geology. Air temperature was spatially combined with soil type, soil temperature and geology to identify areas of unique temperature and ground properties (Figure 1). This regional scale study highlights areas of unique ground and climate properties in which to install the temperature monitoring boreholes.



Air Temperature:
cold: T_{min} = < 2°C ;
cool: T_{min} = 2 – 6°C;
temperate: T_{min} = 6 – 16°C ; T_{max} = 6 – 16°C
warm: T_{max} = 16 – 22°C
hot: T_{max} = 22 – 26°C

Soil Type:
L: clay and loam [k~0.3 – 0.4 $Wm^{-1}K^{-1}$]
S: sand and silt [k~1.3 – 1.6 $Wm^{-1}K^{-1}$]
G: coarse gravel [k~2.22 $Wm^{-1}K^{-1}$]

Soil Temperature:
W: warm [15 – 22°C]
MW: moderate-warm [11 – 15°C]
MC: moderate-cool [8 – 11°C]
C: cool [<8°C]

Figure 1: Location of shallow temperature borehole sites. The map of New Zealand is segmented into regions of different soil-types and climatic zones.

Table 1: Site details of ground temperature borehole network sites.

Site ID	Latitude	Longitude	Equipment Type	Borehole Depth	Number of Sensors	Installation Date
Hamilton	-37.7740	175.3051	ECT / EM50	9.0	10	Oct 2013
Wairakei	-38.6317	176.0942	LM35	7.5	31	Jul 2010
Stratford	-39.3355	174.3050	ECT / EM50	9.4	10	May 2014
Lincoln	-43.6262	172.4707	DS18B20	9.4	12	Dec 2012

3. APPARENT THERMAL DIFFUSIVITY FROM *IN-SITU* TEMPERATURE DATA

In-situ temperature measurements can be used to determine thermal diffusivity, by using a least-squared inversion of an annually varying sine waves fitted to the recorded data (Figure 2). The recorded data at any depth, can be split into three components, an average steady state temperature (θ_0), a maximum temperature variation (amplitude, θ_A) and a time delay (phase, ϕ).

$$\theta_z = \theta_0 + \theta_A \sin(\phi) \qquad [4]$$

The determined phase delay (ϕ) and amplitude (θ_A) at each depth are used to determine apparent diffusivity of the ground between depth using the following equations.

$$\alpha_\phi = \left(\frac{\omega}{2}\right)(z_2 - z_1)^2\left(\frac{1}{(\phi(z_1) - \phi(z_2))}\right)^2 \qquad [5]$$

$$\alpha_A = \left(\frac{\omega}{2}\right)\left(\frac{z_2 - z_1}{\ln\left(\left|\theta_A(\omega, z_1)\right| \big/ \left|\theta_A(\omega, z_2)\right|\right)}\right)^2 \qquad [6]$$

where z_1 and z_2 are the selected depths, and ω is the angular frequency given by $\frac{2\pi}{T}$, where T is 365.25 days. In a homogeneous material equations 5 and 6 should be equal.

(a) z = 0.3 m

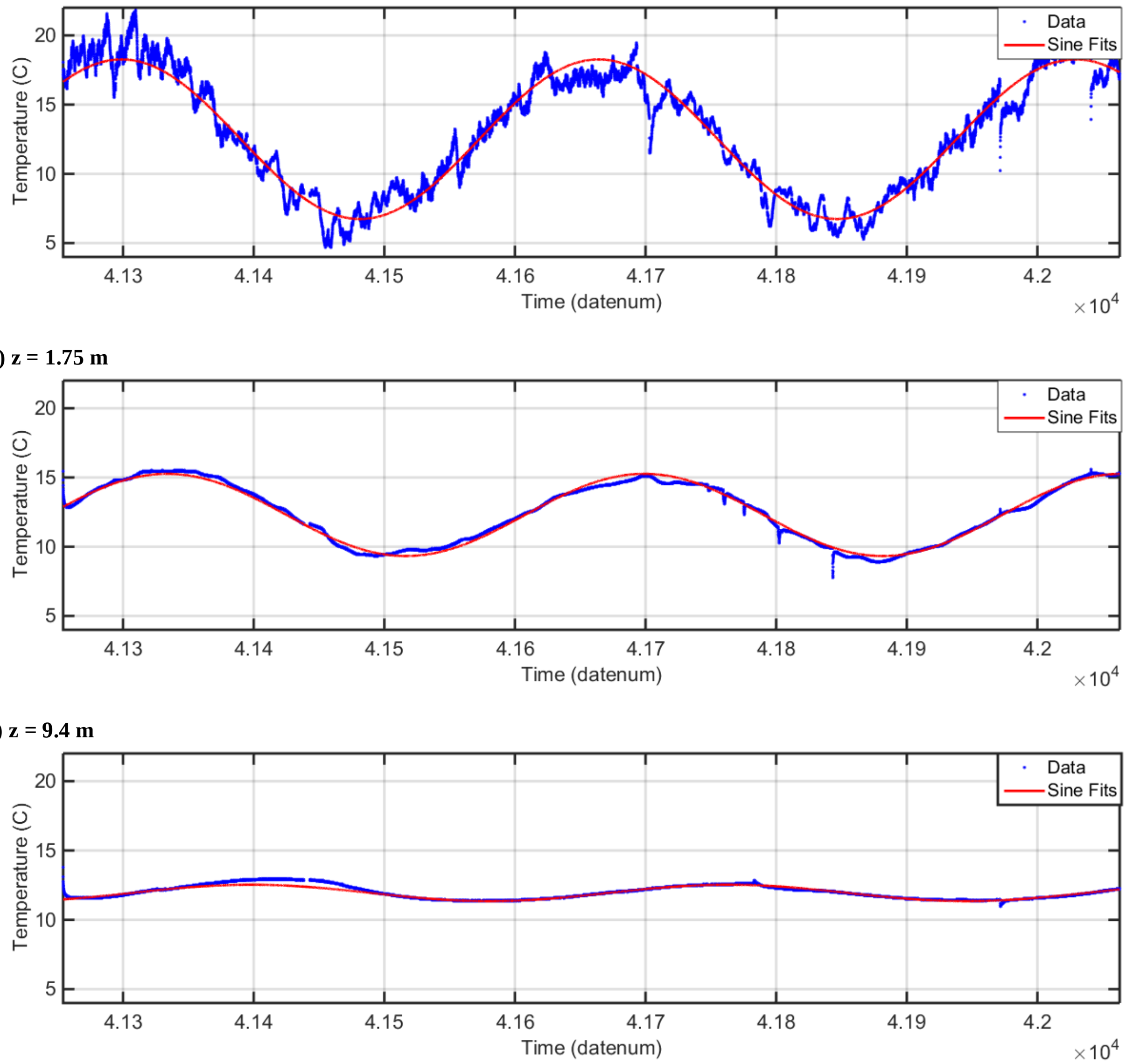


Figure 2: An example of annually varying sine waves (red) fitted to recorded temperature data (blue) at different depths ((a) z= 0.3 m; (b) z= 1.75 m and (c) z= 9.4 m) within a borehole

4. THERMAL PROPERTIES DETERMINED USING A DIVIDED-BAR

The divided bar technique for determining thermal conductivity of rocks is widely used. Here we use a divided bar apparatus to determine thermal conductivities of soils and muds extracted from the boreholes during excavation. We used an adapted method described by Antraisian and Beardsmore (2014) to determine the specific heat capacity of the samples and therefore determine the diffusivity.

The divided bar equipment (Figure 3) consists of a heat source and heat sink, a hot plate and cold plate, isothermal material, and a reference material. It has four sensors positioned within the hot plate, cold plate, and the isothermal material. Unconsolidated material (extracted soils) are placed in a hollow cell, and compressed and fully saturated overnight.

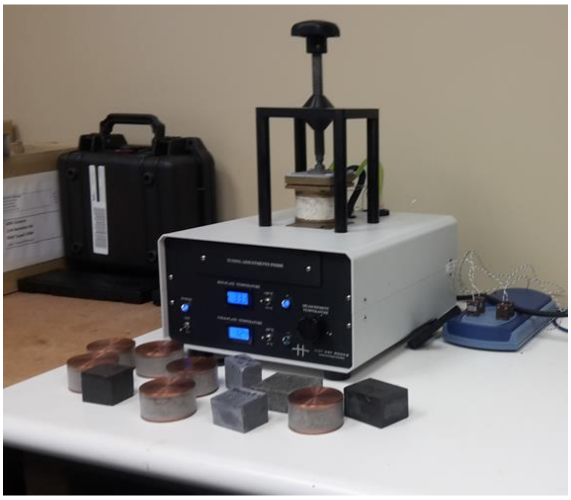


Figure 3: The Portable Electronic Divided Bar apparatus used to determine thermal properties of extract core samples.

The divided bar measures thermal conductivity (λ) by subjecting samples to a constant heat flow from the heat source to the heat sink (Antriasian, 2009). The thermal gradient across the sample is used to determine the thermal conductivity by applying Fourier's Law [6].

$$Q = A\lambda \frac{\Delta\theta}{d} \qquad [6]$$

Where Q is the rate of heat flow through a body, A is the cross-sectional area, λ is the thermal conductivity, d is the thickness of the sample and $\Delta\theta$ is the change in temperature over the thickness of the sample. The thermal conductivity of a sample is determine using the PEDB by applying equation 7 to the measured temperatures of the heating and cooling plates.

$$\lambda = {}^{d}\!\Big/_{A\left(\frac{\Delta\theta - c}{a(w+b)}\right)} \qquad [7]$$

Where A is the surface area of the sample, w is the width of the sample, and a, b, and c are calibration constants (Antriasian, 2009).

To determine the specific heat capacity of the sample, Antraisian and Beardsmore (2014) introduce a temperature perturbation and employs a time-series record of temperature changes. The net thermal energy absorbed by the sample is compared to its changes in temperature during the time it takes for the sample to re-equilibrate from one steady-state temperature to another (Figure 4). The heat capacity is then determined by numerical integration of the measured temperature differences.

The thermal diffusivity of the sample is then determined using the measured conductivity, specific heat capacity and the density of the sample.

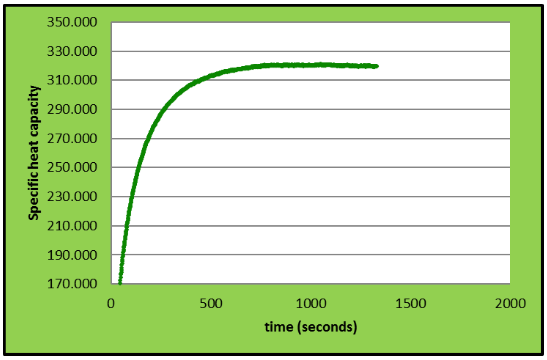


Figure 4: An example of determining specific heat capacity of a sample after introducing a temperature perturbation. The specific heat capacity is determined when the sample re-stabilises.

5. THERMAL PROPERTIES DETERMINED USING A NEEDLE-PROBE

The needle-probe system (Figure 5) is a quick and portable apparatus that can measure thermal conductivity, diffusivity, volumetric heat capacity and resistivity using a transient line heat source (Decagon Devices, 2006). Single sensors can measure thermal conductivity and resistivity, and a dual-needle sensor can measure the thermal diffusivity and volumetric heat capacity. The thermal properties of a material are determined by fitting a time series of temperature data over a pre-define measurement time-length, through a heating a cooling stage. The thermal conductivity is obtained from the temperature of the heated needle of a known radius, while the thermal diffusivity is obtained by fitting the temperature measured at a known distance from the heating source. The volumetric heat capacity is determined from the conductivity and diffusivity measurements using equation (1).

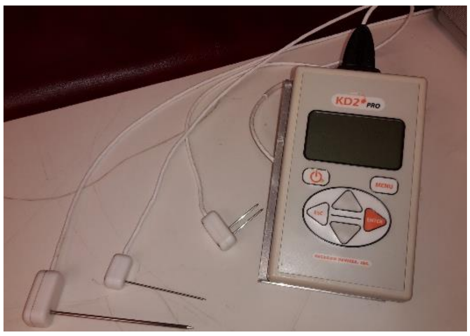


Figure 5: KD2 Pro needle-probe

6. RESULTS

Thermal properties of soils at four locations were determined from in-ground temperatures recorded over a minimum of 3 years. Measurements were also made on extract cores and soils samples using either a KD2 pro needle-probe or a divided-bar apparatus. Figure 6 compares the determined thermal diffusivities of shallow soils from Hamilton, Wairakei, Stratford and Lincoln.

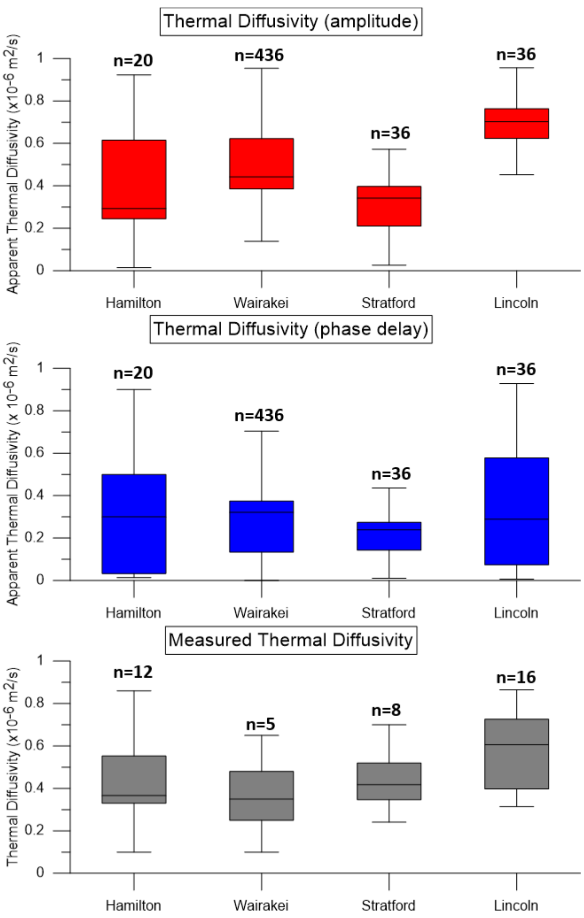


Figure 6: Comparisons of thermal diffusivities determined at four borehole located at Hamilton, Wairakei, Stratford and Lincoln. "n" states the number of measurements represented in the box-whisker plot.

The borehole located at Wairakei, was the first to be installed and contains 31 sensors ranging in depths from the surface to 7.5 m (Table 1). Thermal diffusivities were calculated using 5 years of in-ground temperatures, and using a needle probe on 5 samples extracted from the top 1 m. The geology of site is predominately pumice, with a top soil approximately 10 cm deep. After removing anomalous results, thermal diffusivities determined from the in-situ ground temperatures range between 0.14 x 10^{-6} to 1.1 x 10^{-6} m^2s^{-1}. The variation of diffusivities will be due to differences in compaction and saturation levels within the pumice. Van Manen and Wallin (2012) determined that the optimum apparent thermal diffusivity of the pumice soils at Wairakei was 0.25 x 10^{-6} m^2s^{-1}. This value was determined from the initial 6 months of the deployment of the down-hole sensors.

Figure 7 shows that annual ground temperatures recorded at Wairakei over an averaged year. Ground temperatures become more stable with depth, as the surface meteorological conditions have less influence. Figure 8 (a) shows how the apparent thermal diffusivities between sensor depths varies over the depth of the borehole. It suggests that the diffusivities become more stable below 3m depth. This is likely the depth from which saturation levels are no longer influenced by surface rainfall.

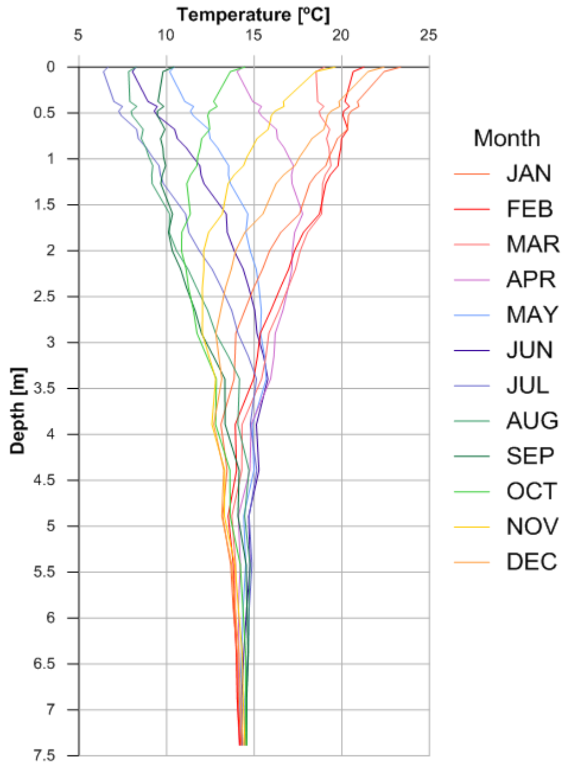


Figure 7: Annual ground temperatures recorded within the 7.4 m deep borehole at Wairakei.

The Lincoln borehole was installed in 2012, and contains 10 functional temperature sensors. The average thermal diffusivities determined from *in-situ* temperatures range from 0.34 x 10^{-6} to 1.1 x 10^{-6} m^2s^{-1}. Figure 8(b) shows how the thermal diffusivities vary over the depth of the borehole. It is apparent that the variation with diffusivity over depth is not only influenced by compaction and saturation, but also influenced by differences in geology. Extracted cores show a distinct change from sandy soils and clays at depth shallower than 3 m, to a predominate wet clay layer which contained distinctive pebbles (0.5-2 cm in diameter). Another change in lithology is seen at 6 m, where the clay becomes smoother and contains larger stones (2-4 cm in diameter).

Similar relationships between changes in lithology and thermal diffusivities are seen at both Stratford (Figure 8(c)) and Hamilton (Figure 8(d)) boreholes. Changes in lithology are seen at depths of ~ 1m, 2m, and 4.5 m are seen at Stratford, with the top layer consisting of sandy soils underlain by larger grain sandy soils, then clays with some stone and gravel, and a finer grained sandy clay below 4.5m. Similar lithology's are seen at the Hamilton borehole, with transitions occurring at 1 m, 3 m, and 4.5 m.

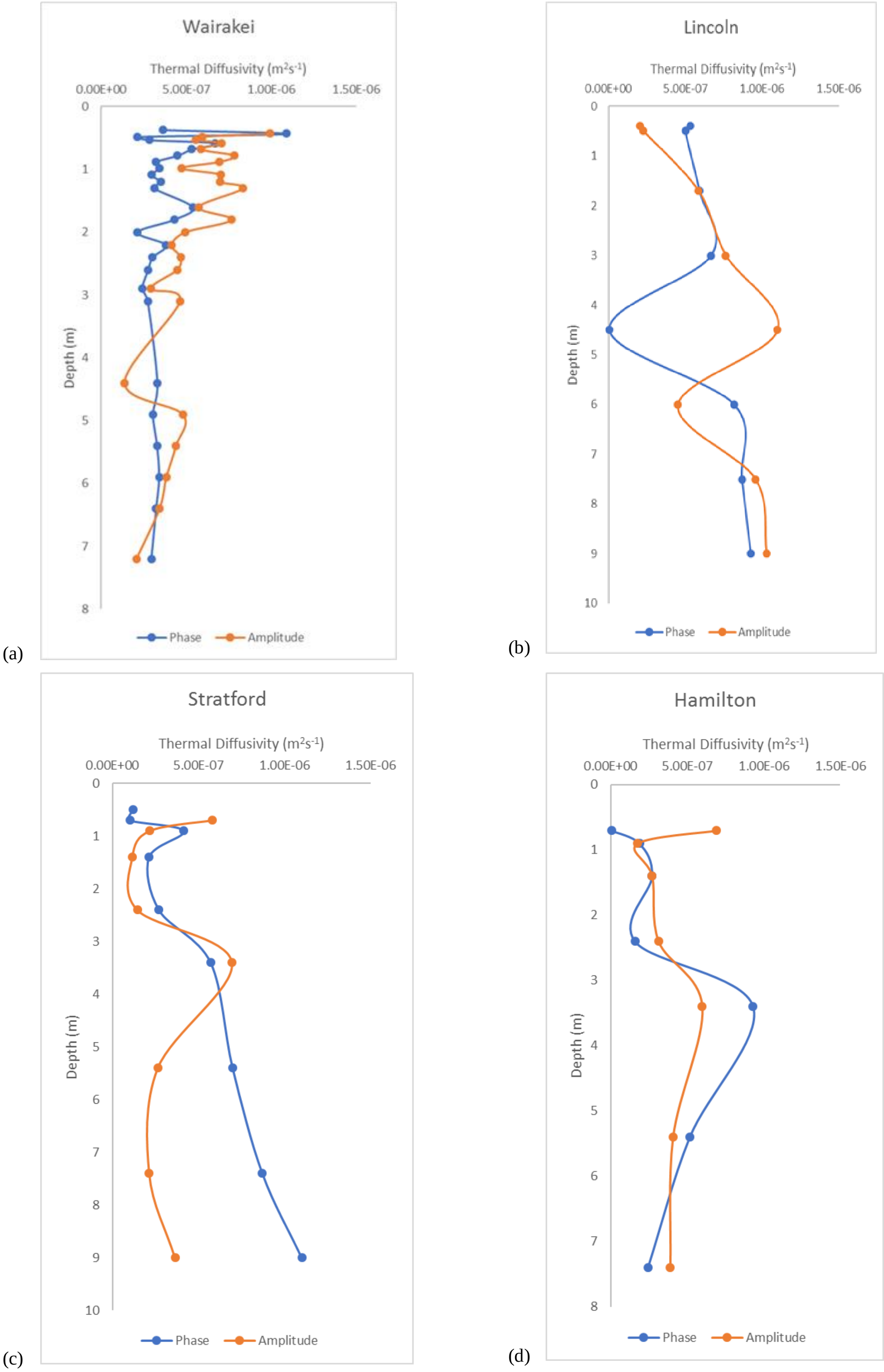


Figure 7: Apparent thermal diffusivity variation over depth at (a) Wairakei, (b) Lincoln, (c) Stratford and (d) Hamilton.

Measured thermal diffusivities for the top 1m at Wairakei shows a variation of between 0.1 x 10^{-6} to 0.65 x 10^{-6} m^2s^{-1}. The variation in these values is like due to differences in re-compaction of the samples and variations in saturation levels. For Lincoln, Stratford and Hamilton, measured thermal diffusivities range from 0.1 x 10^{-6} m^2s^{-1} to 0.95 x 10^{-6} m^2s^{-1}. Part of the larger spread in these values is due to different lithology's over the depths of the boreholes, in additional to the uncertainties introduced by re-compacting and saturating the extracted core samples. It is near-impossible to recreate *in-situ* compaction and saturation levels from extracted and disturbed samples. This is the key draw-back of laboratory measurements versus *in-situ* measurements.

Despite the spread in values, thermal diffusivities determined from in-ground temperatures and those determined from laboratory measurements are in relatively good agreement. Further testing of varying saturation levels will help quantify its effect on measured thermal properties.

7. SUMMARY

The uncertainty of soil thermal properties is a large problem facing geothermal heat pump system designers and engineers. The thermal properties describe the soils ability to store and transfer heat. The key properties include thermal conductivity, thermal diffusivity and volumetric heat capacity. This paper has compared two methods for determining thermal diffusivity of shallow soils and compared the results. Thermal diffusivities determined from in-ground temperature measurements allows site specific characteristics to be determined, while laboratory measurements often give more accurate results, they have introduced errors due to the samples having been disturbed during extraction. Variations in saturation levels and porosity or compaction have a large effect on the soils ability to transfer heat.

Attempts have been made to recreate *in-situ* conditions in the lab as best possible. Measurements have been made on samples cut directly from cores. Other measurements were made on fully saturated and compacted samples. Comparisons of results from four sites in New Zealand indicate that thermal diffusivities determined in the laboratory on fully-saturated samples are comparable to those determined from in-ground temperature measurements.

Future directions of this research include determining thermal conductivity and specific heat capacity of soils from in-ground temperatures by optimizing the least square inversion. These results will be compared to values determined using the divided bar apparatus. Additionally investigations into rainfall and saturation levels on the thermal diffusivity of soils will be undertaken.

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