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Observed influence of ambient temperature variations on the analysis of ground thermal response tests

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ABSTRACT: The thermal response test (TRT) is used for in-situ assessment of the thermal characteristics of the ground (principally thermal conductivity and temperature). These characteristics are required for the design of the ground heat exchanger (GHE) of a closed-loop ground-source heat pump system. Previous studies of the influence of ambient temperature on TRT results typically focus on how temperature variations affect experimental accuracy (e.g. due to poorly insulated surface pipes connecting the GHE to test equipment). The focus of this paper is on how ambient temperature fluctuations affect the net energy applied to the ground during the TRT, which can affect the interpretation of the test, particularly for relatively shallow depth energy piles. The results of a seventeen day long TRT performed on an energy pile installed in Melbourne, Victoria, together with the results of ground temperature measurements over a two-year period at the same site, are presented and discussed. Analysis of the test results suggests that ambient temperature variations could result in the calculation of thermal conductivity at different periods during the test varying by up to 20%. The implications of the observed behaviour for the performance of ground-source heat pump systems are also discussed.

1 INTRODUCTION

The ground heat exchanger (GHE) is an integral component of ground-source heat pump (GSHP) systems that use sustainable geothermal energy to efficiently heat and cool buildings. GHEs usually comprise a closed loop of absorber pipes embedded in grouted boreholes (typically up to about 100 m deep), backfilled trenches (typically about 2 m deep), or ‘energy piles’ (foundation piles fitted with absorber pipes, typically 10 m to 30 m deep) (Brandl, 2006). A heat transfer fluid circulates in the absorber pipes; if the fluid is cooler than the ground it absorbs heat, and if it is warmer than the ground it emits heat. A heat pump connects the GHEs and any distribution pipes (collectively, the ground circuit) to a building circuit. To heat the building, heat is extracted from the circulating fluid and to cool the building, heat is rejected to the circulating fluid.

To optimise GHE design, an accurate assessment of the in situ thermal properties of the ground is required: thermal conductivity (λ, in W/(mK)), thermal diffusivity (α, in mm^2/s) and vertical temperature profile or T_0, the average far-field temperature over some depth (in °C or K). Assessment of thermal conductivity is particularly important as the total design length of GHEs in a GSHP system is inversely proportional to the ground’s thermal conductivity. Accurate assessment of T_0 is required so that the range in absorber fluid temperature during GSHP system operation, which should remain within a desired range for efficient heat pump performance, can be estimated. Although the thermal properties of samples recovered from the ground can be assessed in the laboratory (e.g. Barry-Macaulay et al, 2013; Clarke et al, 2008), there can be issues associated with sample disturbance, scale and the degree to which discrete samples are representative of the ground as a whole, and in situ assessment of the ground’s thermal properties is recommended practice for the design of energy piles (GSHP Association, 2012).

In situ assessment of the ground’s thermal properties can be undertaken with a thermal response test (TRT), details of which are presented in Section 2. TRTs are usually performed in vertical borehole GHEs, but can also be undertaken in energy piles (e.g. Loveridge et al., 2014). It is recognised that ambient temperature variation can have an impact on test accuracy (e.g. Bandos et al., 2011 and Abdelaziz et al., 2015). However, previous studies of the influence of ambient temperature on TRT results typically focus on experimental considerations such as heat loss in surface pipes connecting TRT equipment to the GHE (which can cause the power applied to the GHE during testing to fluctuate) or the accuracy of temperature sensors.

The focus of this paper is on how ambient temperature fluctuations affect the net energy applied to the ground during the TRT, which can affect the interpretation of the test, particularly for relatively shallow depth energy piles. The effects are illustrated using the results of a seventeen day long TRT performed on a 30 m deep energy pile GHE and ground temperature measurements over a two year period at the same site. The ground temperature measurements also indicate that T_0 will vary depending on the time of year of the TRT and depth over which the average temperature is measured. The implications of these observations for energy pile design and performance are discussed.

2 THERMAL RESPONSE TESTS

A detailed summary of the development and application of this test, for which there is now an international standard (ISO, 2015) is presented in Spitler & Gehlin (2015). In summary, the test setup is typically similar to that shown in Figure 1. A constant heat flux or power (Q, in W, often expressed as a power $q = Q / L_{GHE}$ per metre GHE length) is applied to the circulating heat transfer fluid. The variation in inlet and outlet fluid temperature (T_{in} and T_{out}, in °C or K) over time is measured and (as will be discussed) the rate of change in mean fluid temperature [$T_{mean} = (T_{in} + T_{out}) / 2$] provides information on the ground's thermal properties.

TRT results are typically analysed using a line-source equation approach, whereby the mean fluid temperature after some elapsed time (t, in seconds), can be estimated using Equation 1.

$$T_{mean} = T_0 + \left(\frac{2.303q}{4\pi\lambda}\right)\log\left(\frac{4\alpha t}{\gamma' r_b^2}\right) + qR_b \quad (1)$$

where, in addition to terms defined previously, r_b is the GHE radius (in m), R_b is the GHE thermal resistance term (in mK/W) and $\gamma' = 1.78$ is a constant [ln(1.78) = Euler's number].

For TRT analysis, Equation 1 is re-written in the form of the equation for a straight line ($y = mx + c$), relating ΔT_{mean} (equal to $T_{mean} - T_0$) to log(t). In this form:

$$\Delta T_{mean} = \left(\frac{2.303q}{4\pi\lambda}\right)\log(t) + \left(\frac{2.303q}{4\pi\lambda}\right)\log\left(\frac{4\alpha}{\gamma' r_b^2}\right) + qR_b \quad (2)$$

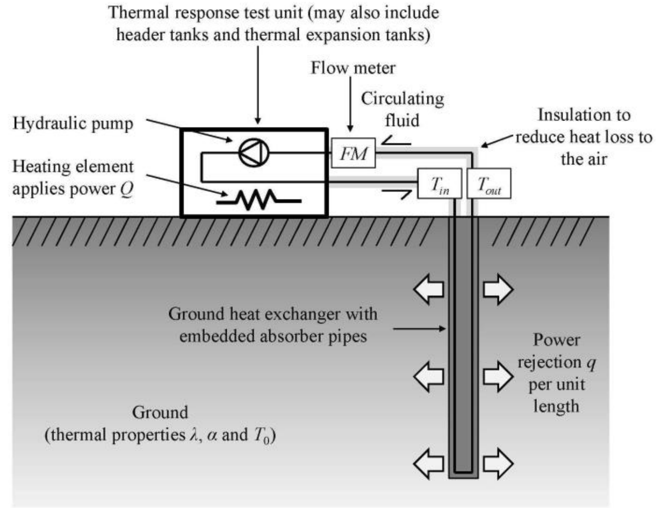

Figure 1. Typical thermal response test setup

Once T_0 has been established (methods for doing this are compared in Gehlin and Nordell, 2003), plotting ΔT_{mean} for a measured and constant q against log(t) eventually yields a linear relationship. Because of limitations on the accuracy of the line-source equation over short time periods, data from $t < 5r_b^2 / \alpha$ is usually ignored in TRT analysis and the trend-line is drawn tangential to later data. The slope (m) and vertical axis intercept (c) of the trend-line can then provide an estimate of (in turn) the ground's thermal conductivity and GHE thermal resistance (these estimates are averages over the length of the GHE):

$$\lambda = \frac{2.303q}{4\pi m} \quad (3)$$

$$R_b = \left(\frac{c}{q}\right) - \left(\frac{2.303}{4\pi\lambda}\right)\log\left(\frac{4\alpha}{\gamma' r_b^2}\right) \quad (4)$$

Note that in Equation 4, it is necessary to estimate the ground's volumetric specific heat capacity (S_{vc}, in J/m^{3}K) to calculate thermal diffusivity $\alpha = \lambda / S_{vc}$, with λ calculated from Equation 3. Specific heat capacity is an important thermal characteristic – it is a measure of the temperature change that occurs in some material volume due to the application or extraction of energy. For soil and rock, S_{vc} is typically about 2000 kJ/m^{3}K.

It is important for the power applied to the GHE during the test to be accurately measured – this measurement should be made using Equation 5 by measuring the change in inlet to outlet temperature as the fluid (usually water, for which $S_{vc} \approx 4180$ kJ/m^{3}K) flows through the GHE, and the flow rate of the fluid (F, in m^3/s).

$$Q = F\left(T_{in} - T_{out}\right)S_{vc} \quad (5)$$

Because of the potential for heat loss in pipes connecting the TRT equipment to the GHE, measurement of the electrical power applied by the heating element should not be relied on as an accurate estimate of the power applied to the GHE (this power should nonetheless be measured). Measurement of inlet and outlet temperature should be made at the top of the GHE (i.e. immediately before and after fluid flows in or out of it) rather than at the inlet and outlet of the TRT equipment which may be separated from the GHE by connecting pipes.

3 EXPERIMENTAL RESULTS

3.1 *Experimental setup*

The TRT discussed in this paper was undertaken in a 31.2 m deep, 600 mm diameter energy pile (known by site convention as GHE-A) at the Beaurepaire Geothermal Experiment (BGE), a full-scale experimental facility constructed at the University of Melbourne's Parkville campus. The setup of the BGE facility is described in Colls (2013) and Colls et al. (2012). The upper 1 m of GHE-A was thermally insulated.

Subsurface conditions at the BGE site comprise a 0.3 m thick layer of sand fill (imported topsoil) over silty clay (residual soil) and variably weathered Melbourne Mudstone (Silurian age sedimentary rock). Extremely weathered siltstone with minor interbedded sandstone was encountered below 1.0 m, grading to moderately weathered below about 20 m depth. The frequency and thickness of sandstone beds increased below 20 m. The depth to groundwater was about 13 m. Laboratory testing (refer Colls, 2013) indicates the thermal conductivity of the ground generally increases with increasing depth.

The variation in the vertical ground temperature profile was measured using thermistors grouted at various depths into a 30 m deep, 100 mm diameter borehole known by site convention as BH1. BH1 was located about 2.7 m from GHE-A (centre to centre spacing). Measurement of the ambient air temperature was also recorded.

3.2 *Ground temperature profile*

The ground temperature variation in BH1 was measured over a 2-year period at depths of 0.1 m, 0.5 m, 1 m, 2 m, 5 m, 10 m, 20 m and 30 m. Figure 2 shows data from selected depths in BH1 (selected for clarity of presentation). Over the period shown in Figure 2, the ambient air temperature fluctuated between about 2°C and 41°C. Sources of experimental error and accuracy are described in Colls (2013).

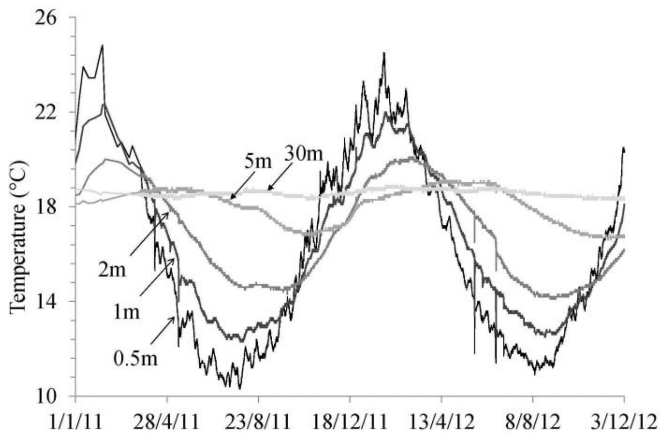

Figure 2. Selected results of ground temperature measurement in BH1

Figure 2 illustrates that the ground temperature varies seasonally; the ground absorbs heat energy from the warmer ambient air in summer, and rejects heat energy to the cooler air in winter. Any energy applied during a TRT (noting that energy is the product of power and time) will be in addition to this 'background' heat flux.

For interpretation of TRTs and GHE design, it is also important to recognise that the average ground temperature, T_0, will vary depending on the time of the year it is measured and the depth range it is measured over. Table 1 presents the range in measured average ground temperature in BH1 over different depth ranges.

Table 1. Average ground temperature measured over different depth ranges, BH1.

Depth range	Range of average temperature	Mean average temperature
	°C	°C
0 to 5 m	14.5 to 20.5	17.5
0 to 10 m	16.3 to 19.6	17.8
0 to 20 m	17.4 to 19.4	18.4
0 to 30 m	17.8 to 19.4	18.6

For ground at a constant temperature year on year the 'average' heat flux from the air to the ground will be zero. A simplified estimate of the heat flux that occurs as the ground warms from winter to summer and cools from summer to winter can be made by assuming the yearly temperature range in Table 1 occurs over a six month period and that the ground has a specific heat capacity of 2000 kJ/m^{3}K (the volume of ground affected to 5 m depth, for example, would be 5 m^3 per m^2 surface area). By this approach, the average 'background' heat flux is estimated to be about 3.8 W/m^2 to 6.0 W/m^2.

Note that the surface temperature boundary conditions above the GHE could change from the time of the TRT to operation of the GSHP system. For example, energy piles are generally located beneath buildings, which may not be present during testing.

Any change in the surface temperature boundary could therefore change both the shallow vertical temperature profile and the average ground temperature over the GHE depth. It is therefore important that the vertical ground temperature profile, and not just the initial mean ground temperature over the GHE depth, is measured during TRTs so that the effect of any change in the surface temperature over time can be assessed during GHE design.

3.3 *TRT results*

Figure 3 shows the measured change in T_{mean} during a seventeen day long TRT (known by site convention as TRT18) performed in GHE-A, together with the variation in the average daily ambient temperature (based on hourly measurements in a location shaded from direct sunlight). During the test, which commenced on 5 December 2011, a nominal 3kW power was applied to the GHE by an electrical heating element (the average power applied to the GHE as measured using Equation 5 was 2.86 kW). Note that for this paper, data from the first four days of the test has been ignored because of the minimum time criteria typically applied to TRT interpretation (see Section 2). The average ground temperature over the length of the GHE at the start of the test (T_0) was 18.1°C.

During TRT18, four time periods (4 to 6 days, 7 to 10 days, 11 to 13 days and 14 to 17 days) have been identified during which the average daily ambient temperature (based on hourly measurements) is 2.8°C to 3.5°C above or below the average ambient temperature (21.3°C) over the 'overall' test period.

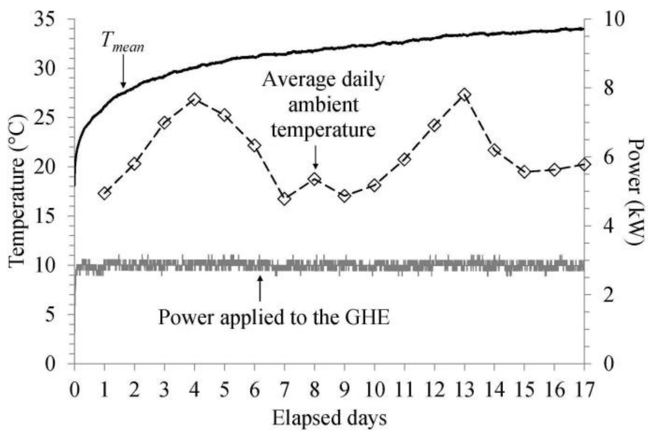

Figure 3. Data from TRT18 in GHE-A

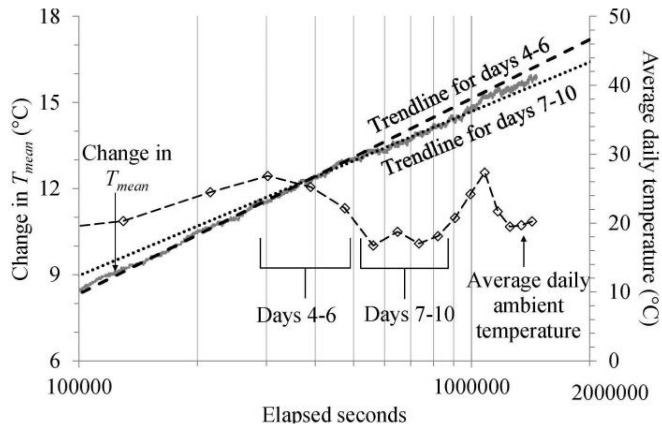

Figure 4. Influence of ambient temperature variations on the change in mean water temperature during TRT18, GHE-A.

The impact of ambient temperature on the results of TRT18 is not readily apparent on the scale of Figure 3. However, as Figure 4 shows, there is a distinct change in the slope of the TRT analysis plot (the change in T_{mean} from T_0 versus log time) during the relatively warm and cool periods. This change occurs despite the power applied to the GHE (measured using Equation 5, refer Table 3 and discussion below) remaining relatively constant during the warmer and cooler periods. If the slope of the TRT plot changes while the applied power remains relatively constant, from Equation 3 the estimate of thermal conductivity will also change; a steeper slope indicates relatively low thermal conductivity (heat dissipates more slowly into the ground around the GHE) and a shallower slope indicates relatively high conductivity (heat dissipates more rapidly).

Estimates of thermal conductivity and GHE thermal resistance, based on the applied power measured (over the 30.2 m long GHE-A below the 1 m long thermally insulated section) and the slope of the TRT analysis plot during different time periods, are presented in Table 3. The trend-lines used to estimate the thermal conductivity and GHE thermal resistance for days 4 to 6 and days 7 to 10 are shown on Figure 4. Trend-lines were also drawn for the other time periods but for clarity are not shown on Figure 4.

Table 2. Influence of ambient temperature on the interpretation of TRT18.

Time period	Ave. ambient temperature	q	λ	R_b
	°C	W/m	W/mK	mK/W
4 to17 days	21.3	94.5	2.73	0.055
4 to 6 days	24.8	95.4	2.57	0.051
7 to 10 days	17.7	94.0	3.02	0.060
11 to 13 days	24.1	94.7	2.47	0.047
14 to 17 days	17.8	94.0	2.89	0.060

Important points to note from Table 3 are as follows:

The variation in ambient temperature results in small fluctuations in the applied power (less than 1% of the average power applied over for the total test duration). This result suggests that for the test setup, pipes connecting the TRT equipment to the GHE are relatively well insulated, noting that the inlet and outlet temperature measurements used to calculate this power were from thermistors in direct contact with the circulating water. Slightly more power is applied during warmer periods and slightly less power is applied during cooler periods.

The estimated thermal conductivity based on the different time periods varies between about -9.5% and +10.5% of the estimated value for the total test duration. The estimate of thermal conductivity is lower during relatively warm periods than in relatively cool periods. The estimated GHE thermal resistance varies by a similar proportion. This suggests that, for the range in the ambient temperatures during the test, estimates of these parameters could range by about 20% if protracted warm or cool periods are observed during testing. Larger variations could potentially be observed between tests undertaken in winter and summer.

Possible reasons for the observed variation in the estimate of thermal conductivity are discussed below. At this time it is unclear what the relative contribution of these mechanisms to the observed change is, or if there are other contributing factors that have not been considered.

Firstly, it is reasonable to assume that the average thermal conductivity of the ground adjacent to the GHE will not change over the course of the test. Although some thermal properties are temperature dependent, given the relatively small change in ground and average ambient temperature, it is not considered to be a significant contributing factor.

With reference to Equation 3 and the discussion of background heat flux in Section 3.2, it is likely that the *measured* power applied to the GHE during the relatively warm periods underestimates the *net* power applied by the TRT equipment plus the background heat flux. If, for example, the net power applied fluctuates by about ±10% during the relatively warm and cool periods, it would explain the different thermal conductivity estimates. The background heat flux would then need to be in the order of 300 W compared to the nominal 3 kW heating power. This value seems high given the estimate of average background heat flux of up to about 6.0 W/m^2; i.e. the test result would need to be affected by about 50 m^2 of ground (the ground to a radial distance of about 4 m from the centre of the GHE), which for the initial part of the test in particular seems large given the slow speed at which heat propagates through the ground. However, the 'background' heat flux is based on average temperature changes over a six month period, and there are many days in summer when the air is cooler than the ground (and vice versa in winter) hence there will be periods when the background heat flux is much higher – Banks (2012) indicates that solar insolation can be up to a few hundred watts per square metre.

In some situations there may be 'external' sources of heat, such as sewers, subway tunnels or basements near GHEs that add or extract heat from the ground during the TRT, and will not be accounted for in the measured power. However, the BGE site is not known to be close to external heat sources.

Another explanation could be that variation in the near surface temperatures affects the power rejected at different depths along the GHE axis. Although a constant rate of power rejection per metre GHE length is assumed in TRT analysis, in reality the heat rejection rate is unlikely to be constant with depth because the temperature gradient between the circulating fluid and surrounding ground will vary, and is typically highest near the surface where the warm fluid first enters the ground. Changes to the vertical temperature profile due to ambient temperature variations may therefore alter the relative contribution different ground layers make to the average thermal conductivity measured over the total GHE length. However, at the BGE site the thermal conductivity of the ground typically increases with depth and an increase in the average thermal conductivity (not observed) would be expected if warmer ambient temperatures mean a higher proportion of the heat is rejected at depth than when the near surface but lower conductivity ground is relatively cool.

Note that the influence of ambient temperatures on TRT interpretation and GSHP system performance is in general expected to be more significant for relatively shallow energy pile GHEs than for typical borehole GHEs, which can extend to depth of 100 m or more hence have a greater proportion of their length below the depth of the seasonal temperature influence. The relatively long duration of TRTs in energy piles compared to TRTs in narrower diameter borehole GHEs (typically about 50 hours' duration) could also contribute to the impact of ambient temperatures on TRT analysis, as the area/volume of ground around the GHE affected by a TRT increases over time, hence the ratio of 'background' heat flux to applied power could increase over time.

It is also important to recognise that changes in ambient temperatures will affect the operation of GSHP systems as well as TRT results. For example, in summer the ground around the GHE should be expected to heat more rapidly than if only the power rejected by the GSHP system (to cool a building) was applied.

4 CONCLUSIONS

In this paper, observations from full-scale field experiments are presented to illustrate the potential impact of ambient air temperatures on the measurement of the average ground temperature, T_0, and estimates of thermal conductivity and GHE thermal resistance interpreted from energy pile TRT results. These are important parameters for the design of GHEs. The key points raised are summarised as follows:

T_0 will be affected by the time of year and depth over which it is measured. It may change from the time of testing to when the GSHP system is operating if ground surface conditions are altered, for example due to construction of a building floor slab.

TRT interpretation should take into account the time of year of testing and whether, in addition to the measured power applied to the GHE by the TRT equipment, the ground surrounding the GHE is gaining or losing power from the ambient air or external energy sources. From the results presented in this paper, the variation in the estimates of thermal conductivity and GHE thermal resistance could be up to about 20%. However, larger variation could potentially be observed where the ambient temperature variation is greater than occurred during this test.

These points should be taken into account in the interpretation of TRTs and the design of GSHP systems based on TRT results.

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