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Validation of a model for two horizontal ground coupled heat exchangers based on field testing

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ABSTRACT

Horizontal Ground Coupled Heat Exchangers (HGCHEs) moderate the extremes of temperature of the heat sink during the cooling or heating demand periods when air conditioners are required to be used. High (cooling) or low (heating) heat sink temperatures used by heat pumps result in increased demand for electricity. Generally, HGCHEs installed in unsaturated soils of low thermal conductivity and diffusivity require long lengths of pipe run in order to dissipate their heat. An experimental analysis was undertaken to try to validate, a new concept HGCHE 'Membrane Conduction Augmentation System' (MCAS) against that of a CFD two horizon simulation. The simulation used, measured thermo-physical properties extracted directly (where possible) from the exposed (upon excavation) site material. Measured and logged data of water temperatures entering the Direct Burial (DB) and MCAS experiments were used in the model inputs for the model simulations. The uniformly distributed transects of instruments collecting temperature data for both the DB and the MCAS showed good agreement between the experimental and modelled outcomes with high coefficients of determination (r^2) of 0.96 for the DB and 0.94 for the MCAS. With such good agreement between the model and field experiments, the model has been sufficiently validated and can be extended to analyses of other scenarios.

1. Introduction

Increases in extremes of temperature accompanied with heatwaves predicted by the Intergovernmental Panel on Climate Change (IPCC) [1] will increase stress on the existing power distribution infrastructure. In hot climates this stress will mainly occur from the demand arising from increased air conditioning, along with the physical degradation of electrical infrastructure due to overheating of power distribution cables and transformers. The overheating of the infrastructure can lead to 'thermal runaway', which is monitored and avoided by distribution authorities by restricting electrical distribution, which in turn can result in power outages at critical times. Solar panel systems offer good support in terms of providing power for air conditioning, but only when the sun shines. Energy storage has its own challenges of reliability and availability.

Evaporative air conditioning is a low power alternative to reverse cycle, but requires substantial quantities of treated water [2], which can be a scarce commodity, wasted to the environment. Evaporative air conditioning also becomes less capable of achieving the comfort temperatures required if the humidity and/or temperature rise as substantially as predicted [1]. Ground heat exchangers (GHE) offer another alternative, utilising in a passive form the vast thermal inertia of the earth's crust and taking advantage of the seasonal shift in the ground temperature wave [3]. The ground temperature wave occurs as a result of the burial depth and the thermal diffusivity of the formation. Both of these factors can be manipulated to some degree by designers and installers of GHEs.

Conventional Horizontal Ground Heat Exchangers (HGHEs) do not require expensive drilling rigs and crew as is required for Vertical Ground Heat Exchangers. In most communities of the world, an inexpensive mechanical excavator such as the 'Backhoe' is available. A modest-sized machine can easily (soils permitting) achieve up to 3.0 m depth of excavation, which is sufficient to take advantage of the ground temperature wave. HGHEs do, however, often require large areas of land and this is particularly so when installed in soils with low thermal conductivity and diffusivity [4].

The effectiveness of HGHE systems depends upon several factors, which are discussed in the next sections.

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1.1. Pipe surface area

Heat transfer rate is typically governed by contact area. As Ground Coupled Heat Exchangers (GCHE) pipes are typically small diameter, efforts to increase surface area tend to focus on increasing pipe length. A number of attempts have been undertaken to increase the efficiency of the heat transfer process in HGHEs by developing a larger surface area of the pipe in contact with the soil (for heating and cooling). Three of these techniques to date are: using multiple parallel pipes along a backfilled trench [5,6], (horizontal) slinky pipes [7,8] and (vertical) slinky pipes [9]. All these techniques rely upon increasing the pipe length (which can become considerable. Also, for construction purposes a bare minimum trench width of approximately 600 mm is required [10] to accommodate either the parallel lengths of pipe or horizontal coils [11].

1.2. Backfill material

Conventionally, the backfill process has required the pipe to be surrounded with washed sand [12]. However, this practice is arguably detrimental to the heat transfer process, when the formation has high clay content and heat is being dispersed into the formation. The reason is that the suction potential of clay type soils and silts far exceeds the suction capacity of washed sand. Therefore, the sand will surrender its moisture to the surrounding soil formation until there is suction equilibrium [4]. Moreover, following the sand placement, backfilling with the excavated parent material and appropriate compaction of backfill layers are undertaken. The latter process results in altering the structure of clay type soils from the dense layering of the parent material that has been laid down usually by sedimentation and compacted over the millennia with overburden pressure and seasonal moisture fluctuations. This disturbed structure typically results in degraded heat transfer through the backfill.

1.3. Soil drying with heat pump in cooling mode losing heat to the formation using a horizontal ground coupled heat exchanger (HGCHE)

HGCHEs used for the disposal of heat and installed in unsaturated soil have been identified to have the problem of drying out of the soils in the immediate vicinity of the buried heat source, due to the temperature gradient from the pipe into the soil [13], resulting in reduced thermal conductivity and diffusivity. The water volume around the soil particles is lowered with increased temperature due to moisture migration away from the heat source (pipe), thereby reducing the soil particle conductive pathway into the formation. This effect was demonstrated by Gurr et al. [14] and later given credence by Phillip and deVries [15]. Tarnawski and Gori [16] showed that a range of soils, having clay contents of 1% to 35% experienced reduced thermal conductivity as moisture contents were lowered. Those experiments were conducted on the chosen soils over a range of temperatures on named categories of four domains of water content from dry to water saturation. Soils having greater clay content displayed lower thermal conductivity and less capacity to retain heat through the range of testing temperatures from 5 °C to 90 °C. Thermal performance improved as quartz content of the soil increased.

A number of investigations have sought to resolve or mitigate this limiting condition. Couvillion and Cotton [17] investigated preparations of localised backfill material for comparison of thermal performance. The geo-materials included 'native soil', which was classified loosely as sandy silt with sand; 'dry masonry sand'; 'sand with latex resin'; and 'sand with paraffin wax'. The sand with paraffin wax was discarded quickly on account of its low thermal conductivity (0.69 W/m.K). The computer modelling of the comparative effectiveness of the backfills was validated with experiments conducted over a period of 360 days. The sand with acrylic latex resin showed no signs of losing its moisture, unlike the masonry sand. However the sand with acrylic latex resin (thermal conductivity of 1.05 W/mK) proved to have less capability in the heat transfer process than did the native soil (1.19 W/mK).

Remund et al. [18] investigated through numerical modelling moisture replenishment by trickle irrigation to counteract movement of moisture away from the heat source. A variation on Remund et al.'s trickle water supply to the zone of lost moisture was introduced by Piechowski [19], whereby underground drainage/irrigation pipes of 100 mm diameter supplied water to the soil near the heat source. Both these suggested means of overcoming the moisture movement away from the heat source are acceptable in situations where water is in plentiful supply and/or where the HGCHE is not installed in a freely draining soil or sand. In many parts of the world, especially in hot, dry regions, water is already a critically scarce commodity; therefore, like evaporative air conditioning, such replenishment systems for HGHEs may not be the most appropriate cooling solution.

Gao et al. [20] studied the effect of moisture migration associated with both pipe heat dispersal into the formation and acquisition from the formation. The research confirms that of [13–15,17–19] that soil with increased level of moisture have an increased thermal conductivity as opposed to the converse happening with a decrease in soil moisture content. A rainwater harvesting technique was proposed also whereby rainwater is discouraged from flowing from a property. It is proposed that it be contained and allow to percolate down through the soil and into the vicinity of a buried GHE thereby increasing the moisture content and the thermal conductivity of the formation.

Extending the early research into the vapour heat transfer cycle [15,18] a modified thermal conductivity representing the importance of vapour transfer in porous unsaturated soils has been investigated both experimentally and analytically by Wang et al. [21]. The outcome of the research places a greater importance on the porosity of the unsaturated soil in its ability to promote the vapour transfer cycle.

Summarising, HGCHEs continue to have several problems with heat transfer in unsaturated soils as a result of:

1. The relatively small surface area of the pipe in contact with the soil for dispersing heat into the formation;
2. The convention of surrounding the pipe with low conductivity unsaturated sand to provide support and protection against pipe damage from unscreened backfill [12]
3. The elevated temperature gradient of the soil adjacent to the hot pipe resulting in increased moisture migration away from the pipe and therefore lower soil thermal conductivity in its vicinity [14]

In the context of the current paper, a reduced temperature gradient produces less moisture migration away from the heat source, thereby maintaining an elevated thermal conductivity and diffusivity.

1.4. The objective of the study

This paper seeks to address the aforementioned problems by investigating experimentally a proposed concept for a Membrane Conduction Augmentation System (MCAS) for a Horizontal Coupled Ground Heat Exchanger, (HGCHE), which has been investigated theoretically in a previous paper by Platts et al. [4]. Experimental field results are presented for the MCAS and the more conventional Direct Burial (DB) construction method. However the primary