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The paper was published in the proceedings of the 11th Australia New Zealand Conference on Geomechanics and was edited by Prof. Guillermo Narsilio, Prof. Arul Arulrajah and Prof. Jayantha Kodikara. The conference was held in Melbourne, Australia, 15-18 July 2012.

Experimental study of ground energy systems in Melbourne, Australia

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ABSTRACT

Ground energy systems use the ground as a heat source or sink to heat and cool buildings. Because the ground temperature is more stable than the ambient air, ground energy systems can be more efficient than conventional heating and cooling systems. Ground energy systems typically comprise a ground heat exchanger (GHE) connected to a building's heating and cooling system via a heat pump. The GHE is usually a closed loop of pipe embedded in the ground. Fluid circulates through the embedded pipes to exchange heat between the ground and the building. A research facility has been built at the University of Melbourne's Parkville campus to experimentally study the effects of GHE configuration on ground energy system performance and investigate the potential to improve existing design techniques. This paper provides an introduction to ground energy systems and describes the experimental set-up.

Keywords: geothermal energy, ground-source heat pumps, energy foundations, ground temperature

1 INTRODUCTION

In recent decades, significant global effort has been spent on identifying alternatives to fossil fuel based energy sources. This is because of the finite nature of these energy sources and their contribution to climate change, through greenhouse gas emissions. Geothermal energy (the heat stored within the Earth's crust) is one potential alternative. This heat energy can be used "indirectly" to generate electricity or "directly" as heat. The direct form can provide renewable energy that is available 24 hours a day almost everywhere in the world. In its simplest form, direct geothermal energy heated Roman baths and cools underground houses in Coober Pedy. Today, heat pumps are typically used to efficiently upgrade the ground's energy to heat or cool buildings.

Many terms have been used to describe the direct use of geothermal energy. In this paper "ground energy systems" describes the overall use of the ground to heat and cool buildings, "ground heat exchanger" (GHE) describes the part of the ground energy system in contact with the ground and "ground-source heat pump (GSHP) systems" describes ground energy systems that use heat pumps to draw energy from the GHE. Heat pump systems that draw energy from surface water bodies (i.e. ponds or rivers) are sometimes also described as ground energy systems, but are not discussed here.

Ground energy systems do not generate electricity, but they can significantly reduce demand. In Australia, energy use in buildings accounts for 26% of national greenhouse emissions and over half that energy is used for heating and cooling. On Australia's hottest days, air conditioners consume up to 22% of all the electricity generated nationwide (CSIRO 2010).

Ground energy systems can be "open-loop" or "closed-loop": open-loop systems extract and/or reject water into the ground while in a closed-loop system the fluid circulates in pipes embedded in the ground. Water is typically used as a heat exchange medium between the GHE and the building's heat delivery system (anti-freeze is added if temperatures close to or below freezing are expected). Closed-loop pipes can be embedded into any structure in contact with the ground; trenches, boreholes, tunnels and building foundations have been successfully used (Brandl 2006). The use of structural elements can greatly reduce installation costs because the drilling of deep boreholes may not be required. In vertical installations, closed-loops are referred to as "U-loops" because of their shape.

Just as a water pump moves water from a region of low hydraulic head to high hydraulic head (with the input of energy), heat pumps can move heat from low temperature to high temperature regions (the refrigerator is one common example). This process makes use of the refrigeration cycle and is described in more detail by Johnston et al (2011).

The efficiency of heat pumps decreases as the required temperature change across the heat pump increases. Conventional air-sourced heat pumps (i.e. split-system air conditioners) use the air as a heat source or sink. The air is cold in winter when heat is extracted and is hot in summer when heat needs to be rejected. However, below about 5-10 m depth (refer Section 3) the temperature of the ground is relatively constant throughout the year and is thus warmer than the air in winter and cooler in summer. The stable ground temperatures allow GSHP systems to be more efficient than conventional alternatives. Currently, GSHP systems typically achieve a coefficient of performance (COP) of about 4, which means that for every kW of electricity used to power the heat pump, about 4 kW of thermal energy is produced. This is roughly double the COP of conventional air-sourced heat pumps. If the ground is sufficiently hot or cool, the heat pump may not be required and even greater efficiency may be achieved. Direct exchange (DEGSHP) systems circulate refrigerant directly through copper pipes in the ground and do not require a fluid circulation pump.

Current worldwide capacity of direct geothermal systems is estimated at 50 GW_{th}. GSHP systems account for about 70% of this capacity and the equivalent of about 3 million residential size GSHP systems are installed worldwide. In Australia, current capacity of GSHP systems is about 24 MW_{th} out of a total direct geothermal capacity of about 33 MW_{th} (Lund 2010). Worldwide capacity has roughly doubled every five years since 1995 and further growth is anticipated in Australia and worldwide.

The research being undertaken at the University of Melbourne aims to collect information about local conditions for the design of GSHP systems and to investigate the potential to improve existing design techniques. Because this technology is relatively unknown in Australia, this paper is also partly an introduction to ground energy systems. The experimental facility constructed at the University of Melbourne (the Beaurepaire Geothermal Experiment) will be described and some preliminary results presented.

2 THE BEAUREPAIRE GEOTHERMAL EXPERIMENT

2.1 Geographical and geological setting

The Beaurepaire Geothermal Experiment is located northeast of the Beaurepaire Sports Centre at the University of Melbourne's Parkville Campus, approximately 1.5 km north of the Melbourne CBD. The mean annual temperature in Melbourne over the last 30 years is 15.9^{o}C, with mean monthly extremes of 21.3^{o}C in February and 10.2^{o}C in July (Bureau of Meteorology 2011).

At the site, a 0.3 m thick layer of sand fill (imported topsoil) overlies silty clay. Extremely weathered siltstone with minor interbedded sandstone (Silurian age Melbourne Formation) 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. Groundwater was encountered at a depth of 14 m when the GHEs were drilled (November 2010) and has since risen to a depth of about 13 m (December 2011).

2.2 Layout and configuration of ground heat exchangers

Five GHEs have been built (refer Figure 1). GHEs A to C are closed-loop systems in which water circulates through HDPE pipe. GHEs D and E are DEGSHP systems, each comprising a pair of copper U-loops embedded in the ground. Testing of the DEGSHP system has not yet commenced so this paper will focus on the closed-loop water GHEs (refer Table 1 for summary details).

GHE-A and GHE-B represent energy piles (foundation piles with embedded pipe). These piles are backfilled with concrete and are fitted with full length steel reinforcement cages. Three U-loops are attached to the reinforcing cage in each GHE. The spacing and size of the embedded HDPE pipe varies to allow the effect of this variation to be studied. Note that the dimensions of the energy piles were selected for research purposes. The piles do not carry any structural loads and piles of this diameter and depth would be rare in Melbourne, for the geological conditions encountered. However, deeper (and typically wider) piles are frequently used in parts of Melbourne where the siltstone is overlain by deep sedimentary soils.

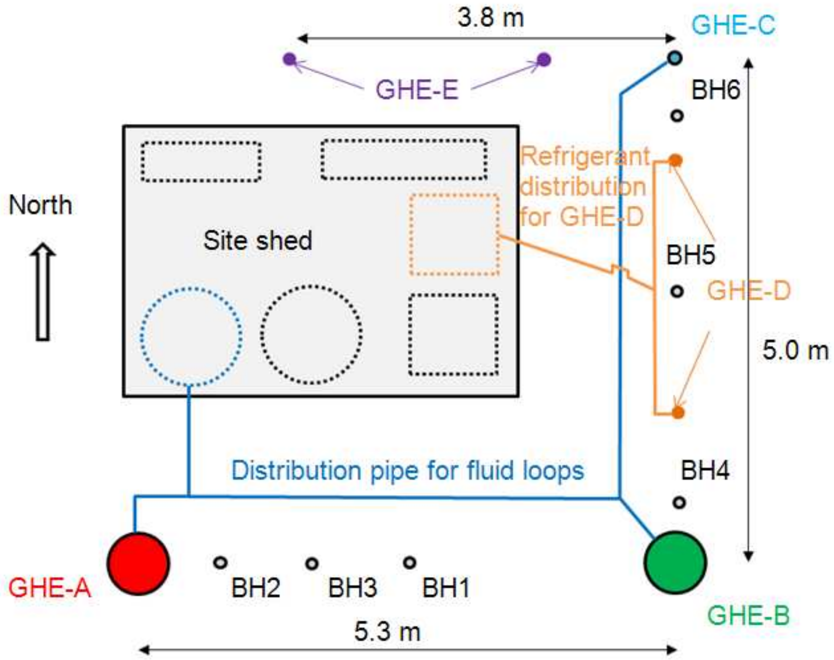

Figure 1. Layout of the Beaurepaire Geothermal Experiment

Table 1: Summary of closed-loop water ground heat exchangers

GHE ID	Base depth (m)	GHE diameter (mm)	Number of U-loops	Outer diameter of HDPE pipe (mm)	Shank spacing* (mm)
GHE-A	31.2	600	3	25	105, 165 & 230
GHE-B	31.2	600	3	32	85, 120 & 200
GHE-C	29.7	125	1	20	40

*The average distance (centre to centre) between the inlet and outlet pipes of the U-loops

GHE-C represents a borehole GHE and is backfilled with cement grout. The copper U-loops for GHE-D and GHE-E were installed in 28.7 m deep, 100 mm diameter grouted boreholes. Six 100 mm diameter boreholes (30 m to 35 m deep) were drilled to monitor ground temperatures at various distances from the GHEs. Temperature sensors were permanently grouted into BH1. Given the shallow depth to rock, BH2 to BH6 were left open for flexibility in the depth and location of the sensors.

The GHEs were backfilled using tremie pipes. Manifolds were constructed above GHEs A to C to allow the various U-loops to be opened and closed. A distribution pipe connects these manifolds to a water storage tank within the site shed. Distribution piping (32 mm HDPE) is thermally insulated and buried to 0.3 m depth. The equipment within the site shed is described in Section 2.3.

Mechanical compression fittings were used to join HDPE pipes and to create U-loops and the manifolds. Typical commercial practice is to use electrical or thermal welding to join HDPE, but mechanical couplings were used because they afford greater flexibility in pipe arrangement and are cheaper on the scale used here.

2.3 Thermal Loading Equipment

Heat pumps and water tanks were installed in the site shed to allow the application of thermal loads to the GHEs. The site shed contains two hot water tanks, two heat pumps, three fluid circulation pumps and a fan coil unit. For experimental purposes, water is the preferred heat transfer medium because the power emitted across the GHE, heat pump and fan coil unit can be easily calculated by measuring the flow rate and change in temperature across the heat exchanger. The equipment in the site shed was chosen to maximise the range of experiments possible and is not strictly representative of equipment that would be installed in commercial applications.

Each hot water tank is fitted with two 3 kW resistance heating elements. A refrigerant coil is also fitted to the tanks to allow heat transfer between the heat pump and the water within. The distribution pipe from GHEs A to C is connected to one of the tanks. Thermal loads can be applied to the GHEs using the resistance element (heating only) or the heat pump (heating or cooling).

In heating mode, the heat pump extracts heat from the first tank and rejects it into the second tank, via a heat exchanger. Water in the first tank circulates through the GHE and is warmed by the ground. Water in the second tank is circulated through a fan coil unit to heat the ambient air and cool the water. This arrangement is shown schematically in Figure 2.

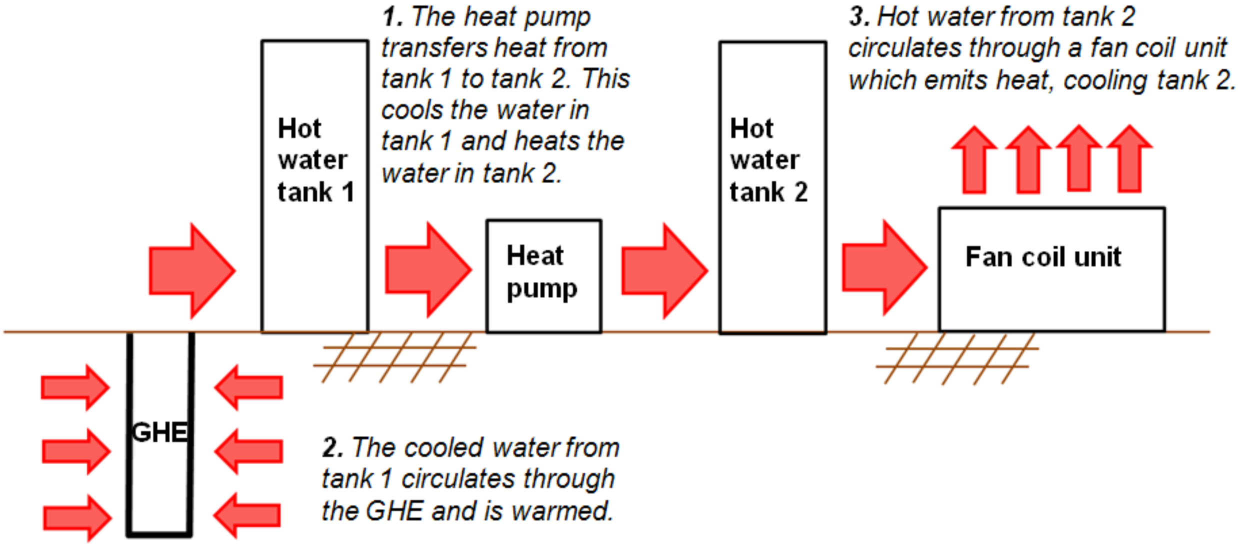

Figure 2. Schematic operation of the GSHP system for GHE-A to C. Heating mode is shown.

GHE-D (the DEGSHP system) works with a second heat pump which is connected to the refrigerant coil of hot water tank 2. This allows GHE-D to heat or cool the water in the second tank so the fan coil unit can heat or cool the ambient air. Alternatively, the DEGSHP GHEs could be used to reject heat from the closed-loop water GHEs, or vice versa.

2.4 Monitoring and Instrumentation

There are few published studies of ground energy systems that include measurement of ground temperatures within or near the GHE. As a consequence, thermistors were installed in the GHEs at the Beaurepaire site to monitor temperature changes. Electrical connections within thermistors are sensitive to moisture ingress and care must be taken to fully seal all sensor and cable joints, particularly when these will be below the water table.

A total of 41 thermistors have been installed in the GHEs. Thermistors are typically at 5 m depth intervals in GHEs A to D (with multiple thermistors at each depth in GHE-A and GHE-B, spread between the inlet and outlet of the three U-loops) and are less frequent in GHE-E. Only one borehole in each pair of DEGSHP boreholes is instrumented. Thermistors within GHEs are attached directly to the outside of the HDPE or copper pipe. There are also 25 thermistors shared between BH1 (where 9 are permanently installed) and (typically) two other open monitoring boreholes. Experimental data suggests the error between measurements in the grouted borehole BH1 and open boreholes BH2 to BH6 is small. Thermistors are also used to measure the entering and exiting water temperatures at ground surface level in GHEs A to C and at the various outlet and inlet points (water and refrigerant lines) on the hot water tanks and heat pumps. In all, 86 thermistors are installed. Nominal thermistor error is less than 0.4^{o}C, although experimental checks suggest that error is typically less than 0.1^{o}C.

Temperature readings are recorded using a data logger. Readings are recorded at least hourly – during experiments readings are typically taken every 1 to 5 minutes. Power consumption is measured with a kW transducer and flow rates from the three pumps using analogue vane wheel water meters.

2.5 Experimental Testing

Testing of the performance of the closed-loop water GHEs has generally followed the procedure for thermal response tests (TRTs) described by Gehlin (2002) and Katzenbach et al (2009). TRTs are routinely used in the design of GSHP systems to estimate the average thermal conductivity of the ground (over the GHE length) and the thermal resistance of the GHE. However, it is necessary to first assume a value for the volumetric heat capacity of the ground. A constant thermal load is applied to the water circulating in the GHE and the change in the mean water temperature over time reflects the ground's thermal properties.

TRTs (with a 3 kW thermal load applied) have been carried out on all of the single U-loops in GHE-A to C and on multiple (two or three) U-loops within GHE-A and GHE-B. Test duration has typically been limited to between 24 and 72 hours to reduce the time required for ground temperatures to re-equilibrate after testing. However, one test of about 400 hours duration has also been completed.

A test of heat extraction using a heat pump was also performed over five consecutive weeks in August and September 2011.

3 PRELIMINARY RESULTS

While the focus of this paper is to introduce ground energy systems and describe a unique experimental set-up, some preliminary results are included here.

3.1 Ground temperature

Figure 3 shows the measured variation in ground temperature in BH1 (at various depths) over the course of one year. Prior to late March 2011, temperatures were recorded manually and since then the data logger has been used. Below about 10m, Figure 3 shows that the ground temperature is relatively constant at about 18.5^{o}C, while seasonal variations can be seen at shallower depths. Minor effects of the testing program may be evident from about July 2011, but in general (and particularly at shallow depths) the testing has not significantly affected temperatures in BH1.

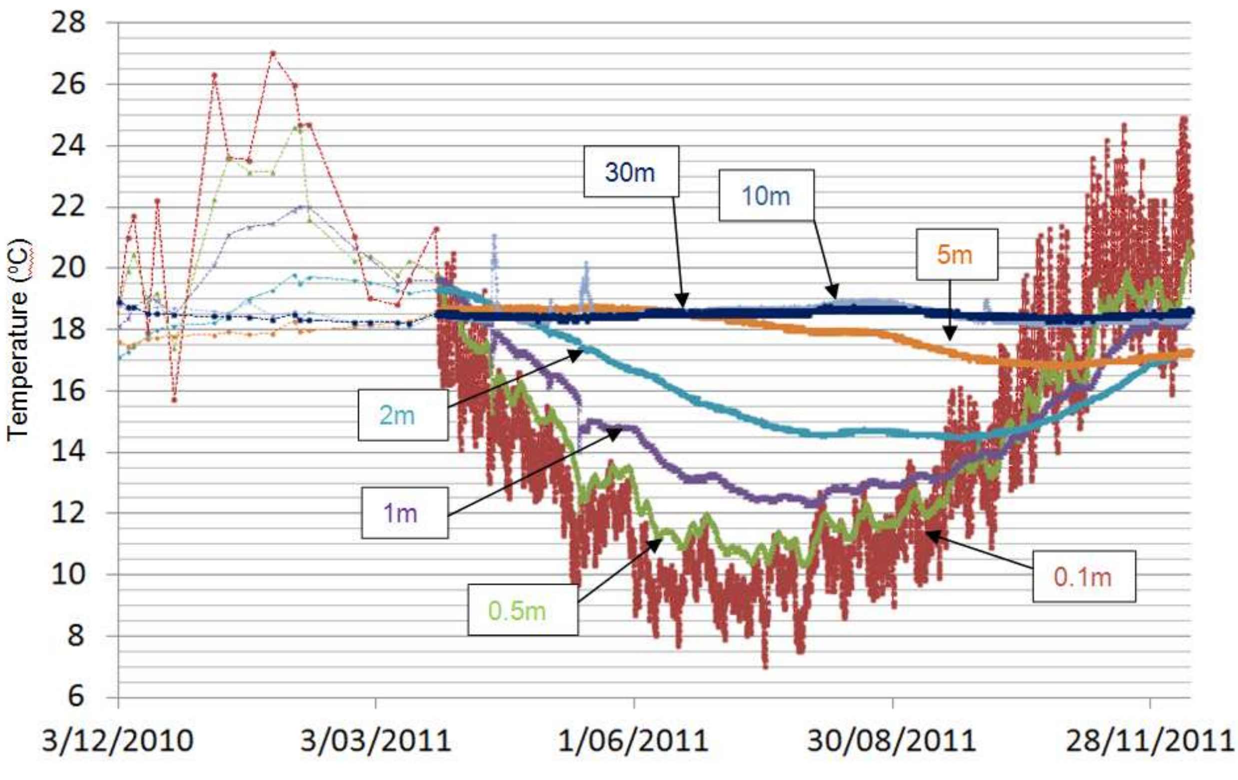

Figure 3.Temperature measurements at various depths in BH1, Dec 2010 – Dec 2011

3.2 Pile curing temperatures

The maximum temperatures measured in piles GHE-A and GHE-B were between 55^{o}C and 65^{o}C, about 16 hours after concrete pouring. These readings were taken manually at discrete intervals and may not be the peak temperature. This suggests that the ground or rock surrounding concrete piles is routinely subject to an extreme of temperature (that is unlikely to be exceeded during normal operation of the ground energy system), which has implications for studies of the effect of thermal loads on the structural and geotechnical performance of energy foundations.

3.3 Thermal conductivity of the ground

TRTs undertaken in GHE-C give an average thermal conductivity for the Melbourne Formation (over the borehole length) of about 1.9-2.0 W/mK. Higher “effective” thermal conductivities were measured in the energy piles. These results (and implications for GHE design and TRT use) will be discussed in detail in future publications.

4 CONCLUSIONS

Ground energy systems are one alternative to reduce reliance on non-renewable energy sources. In most geographical locations, the ground at a relatively shallow depth can provide a heat source or sink that is much closer to the desired building temperature than the air is. Heat pumps can be used to efficiently upgrade the energy extracted from the ground to heat and cool buildings.

Excavation beneath the ground surface is expensive, and is a major part of the cost of ground energy systems. Incorporating ground energy systems into building foundations or other ground contact structures can potentially reduce cost. Improving the efficiency of GSHP systems can also significantly reduce costs, but confidence in the ability of designers to predict system performance is required.

The experimental facility constructed at the University of Melbourne will allow the detailed study of a number of different GHE configurations in relatively simple and uniform geological conditions. The information gathered from the experiments will provide a more detailed understanding of the behaviour of ground energy systems in local conditions, assist in the development of design techniques and provide confidence in the performance of ground energy systems.

Ground temperatures at the site have been measured for over a year and a number of TRTs undertaken. Results of the testing will be presented in detail in future publications.

5 ACKNOWLEDGEMENTS

The authors would like to thank the Melbourne Energy Institute, Geotechnical Engineering, Direct Energy, Supaflow Plumbing, Emerson Climate Technologies, University of Melbourne Property and Campus Services, Melbourne University Sport and Mr. Dezso Kiraly of the CSIRO for their assistance with setting up the experimental facility. The support of Golder Associates and fellow students and staff at the Department of Infrastructure Engineering is also gratefully acknowledged.

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