

## Performance of Borehole Ground Heat Exchangers under Thermal Loads from a School Building: Full-scale Experiment in Melbourne, Australia

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### ABSTRACT

The ground at shallow depths can be used as a source of sustainable thermal energy for heating and cooling buildings. Utilisation of this energy reduces the amount of fossil fuel required to maintain comfortable temperatures inside buildings and can significantly reduce the operating costs of heating and air-conditioning. A Ground Source Heat Pump (GSHP) system is a technology that extracts geothermal energy from shallow depths and transfers it to buildings. Currently, installation costs of these systems are relatively high and this can prevent potential users from investing in these systems. Ground heat exchangers (GHEs) are the least researched and the most expensive elements of GSHP systems. Hence, further research into the performance of GHEs is needed to develop a sound basis for their optimum design and, ultimately, to reduce lengths of GHEs and decrease installation costs of the GSHP systems.

A new two storey school building of about 1500m<sup>2</sup> floor area in Melbourne, Australia was fitted with a GSHP system as part of a research and demonstration project funded by the Department of State Development, Business and Innovation (DSDBI). Twenty eight 50-metre deep borehole GHEs were installed to provide heating and cooling energy for the school and the building is being used as a full-scale experiment to study the behaviour of GHEs under real-life thermal loads. Nine of the GHEs were extensively instrumented to monitor their thermal performance. Also, eight additional monitoring boreholes were installed to study thermal influence of GHEs on the adjacent ground. The experiment will allow a better understanding of thermal processes in the ground when thermal energy is injected and extracted to/from it. This paper presents some of the initial data obtained from this unique project.

### 1. INTRODUCTION

Ground source heat pump (GSHP) or shallow geothermal systems have a potential to deliver sustainable low-carbon thermal energy for heating and cooling applications almost in any operating conditions: different climatic and geological settings, in highly urbanised and rural areas, and in small residential to large commercial applications. Compared to some other types of renewable energy such as solar, wind and wave energy, geothermal energy is available on a 24/7 basis, so it may be conveniently utilised as heating and cooling baseload power. Even though the number of shallow geothermal installations has been growing worldwide (Lund et al., 2011), some challenges have yet to be overcome to further promote this technology with potential users.

One such challenge is the financial feasibility of GSHP systems. Langniss et al. (2007) defined shallow geothermal technology as being at an early stage of market development which implies that this technology is not mature enough to compete at the mass market level without support in the form of subsidies or other incentives. The underground parts of the systems, the ground heat exchangers (GHEs), appear to be the most expensive and the least researched components of the systems. Optimisation of GHEs is required to increase overall affordability of the GSHP systems and boost the number of applications of this technology.

To improve the efficiency of GHE design solutions, the short-term and long-term thermal behaviour of GHEs has to be adequately modelled. Quite a few GHE modelling solutions have been developed to accomplish this task (for example, Yang et al. (2010) presented a detailed review of such solutions for borehole GHEs). However, the solutions developed by these models appear to vary significantly as does the amount of computation time and effort required to obtain these solutions. The preferred approach to test and validate these models is the comparison of data collected from experimental studies with the simulation results obtained by the models.

A few intermodel comparisons have been performed to date to assess differences between predictions made by commercially available GHE sizing software programs (e.g. Spitler et al., 2009; Shonder et al., 2000). These comparisons suggest that the differences between predictions can, in some cases, be considerable. Also, differences between design lengths found by different programs are not consistent from program to program and appear to be very case-dependent. This might indicate that some GHE sizing algorithms produce biased results depending on design circumstances, although it must be acknowledged that the causes and extent of this bias may not be well understood. Further validation of GHE models against experimental data is required to improve the credibility of the models.

This paper describes an experimental installation that has recently been set up to monitor a full-scale commercial GSHP system under climatic and geological conditions typical of Melbourne, Australia. The experiment aims to collect data on thermal interactions of GHEs and the adjacent ground to extend the understanding of processes behind these interactions. The experimental observations will also be utilised for further validation of established and validation of emerging models of GHEs.

## 2. EXPERIMENTAL STUDIES OF GHES

Experimental studies of GSHP systems have been undertaken since the beginning of the GSHP industry. These studies include laboratory experiments, full-scale trials and studying real-life performance of commercial systems. The main focus of many such studies was the overall performance of GSHP systems which result in obtaining coefficients of performance (COPs) of ground source heat pumps for particular site conditions. In many cases, based on such experiments, the thermal behaviour of the ground and ground-GHEs thermal interactions were described using experimental observations that implicitly obtain information about thermal ground responses.

In such experimental observations, only input and output parameters to/from a system are recorded during tests. In terms of GHEs, their thermal behaviour is studied by analysing the input and output temperatures and the flow rate of the fluid circulating within the GHEs. Then, based on these implicit observations, the thermal performance of GHEs is assessed. In situ thermal response tests used in the GSHP industry also use this approach for analysis of apparent effective ground thermal conductivities. In this respect, many full-scale experimental studies of GSHP systems are simply extended thermal response tests.

Such an implicit approach to studying GHEs assists with understanding their thermal behaviour and has played an important role in the development and validation of GHE simulation models. However, this approach cannot provide explicit information about the thermal interactions of GHEs with the adjacent ground and, through the ground, between each other. Therefore, some important thermal processes such as thermal recharge and thermal energy redistribution within the ground cannot be directly captured. Most published GHE experiments do not last longer than a few years. Without a knowledge of these important processes, the long-term thermal behaviour of GHEs may not be predicted correctly since it is affected by history of energy injection/extraction from/to the ground and the ability of the particular ground to store and transfer thermal energy.

The implicit experimental approaches may also contribute to the general unstructured manner of dealing with the design of GHEs. In many cases, especially at the beginning of the GSHP industry, GHEs are treated as elements of bulk lengths without considering the specifics of their geometrical configurations (depths of GHEs, distances between individual GHEs, internal piping configurations, etc.). When collecting observation data about performance of GSHP systems, often conclusions are made regarding the amount of energy extracted by using certain lengths of GHEs. However, these conclusions may be applicable for particular installation conditions only and may not be confidently generalised because of the nature of such experiments. When temperatures along the lengths of GHEs and ground temperature around GHEs are directly monitored, more detailed information can be collected to describe the GHE-ground thermal interactions. Such observations may be used to understand the principles of those thermal interactions in more detail which may lead to more generalised conclusions.

A few experimental studies have recently been developed to address the lack of explicit observational data on thermal processes in the ground due to the operation of GHEs. For example, Beier et al. (2011) set up a laboratory experiment that reproduces real-life thermal behaviour of GHEs and the adjacent ground in the controlled environment of a laboratory. They used large boxes of sand to accommodate borehole GHEs. The temperatures along the boreholes and within the surrounding sand were observed with temperature sensors installed within the sand. This experiment provided the data sets for the validation of borehole GHE models which were collected from a series thermal response tests.

Another example of an experiment that considers temperature distributions along the depths of GHEs and in the surrounding ground is the recently published results of full-scale observations of a 61-metre borehole GHE in Canada (Olfman et al., 2014). Temperatures along different depths of that GHE and two temperature observation wells installed in the proximity to the GHEs were collected in addition to inlet and outlet fluid temperatures. The analysis of the experimental data allowed the authors to draw interesting conclusions about depth dependences of the thermal performance of different sections of the GHE.

There appears to be a need for extended experimental studies of thermal behaviour of the ground along the depths and around vertical GHEs. Such studies might allow further enhancement of GHE modelling by considering differences in thermal interaction processes along the depths of GHEs and at different distances around them. The monitoring of GHEs in a full-scale commercial GSHP system would give the opportunity to conduct such a study under real-life thermal loads. The Elizabeth Blackburn School of Sciences shallow geothermal experiment was designed to meet these research objectives.

## 3. ELIZABETH BLACKBURN SCHOOL OF SCIENCES GEOTHERMAL EXPERIMENT

In this section, some details of the experimental setup and monitoring equipment are given together with some examples of the data being gathered from this unique full scale testing facility.

### 3.1 Experimental setup

For this experiment, a 120 kW shallow geothermal system has been installed in the new two storey Elizabeth Blackburn School of Sciences which is located in Parkville, an inner-north suburb of Melbourne (Fig. 1). The building, of about 1,500 m<sup>2</sup> floor area, has been fitted with four ground source heat pumps (GSHPs), each of 30 kW capacity, to provide up to 80% of the total building heating and cooling demand. The new school will be used in conjunction with University High School (a school affiliated with The University of Melbourne) as a teaching space for around 200 high-performing high school students specialising in science and mathematics.

The underground part of the geothermal system incorporates twenty eight 50-metre deep borehole double-loop ground heat exchangers (GHEs) to be used as heat extractors/injectors (Fig. 2). The GHEs were configured in four lines with seven parallel vertical GHEs installed in each line (Fig. 3) and installed under the building footprint and along the west and south walls of the building (Fig. 2). Three out of these four GHE lines have the separations between GHEs of around six metres; the fourth line has GHEs installed at two metre spacings.

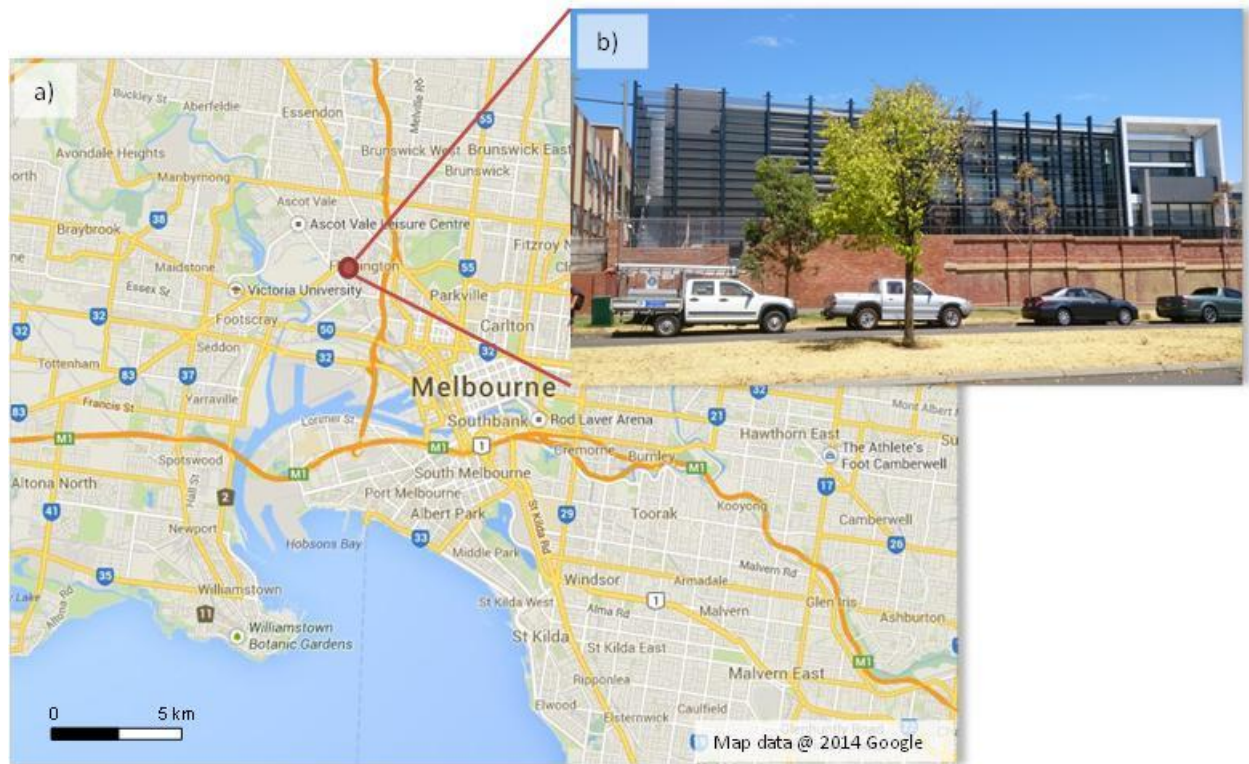


Figure 1: The Elizabeth Blackburn School of Sciences: a) Location; b) View of the building.

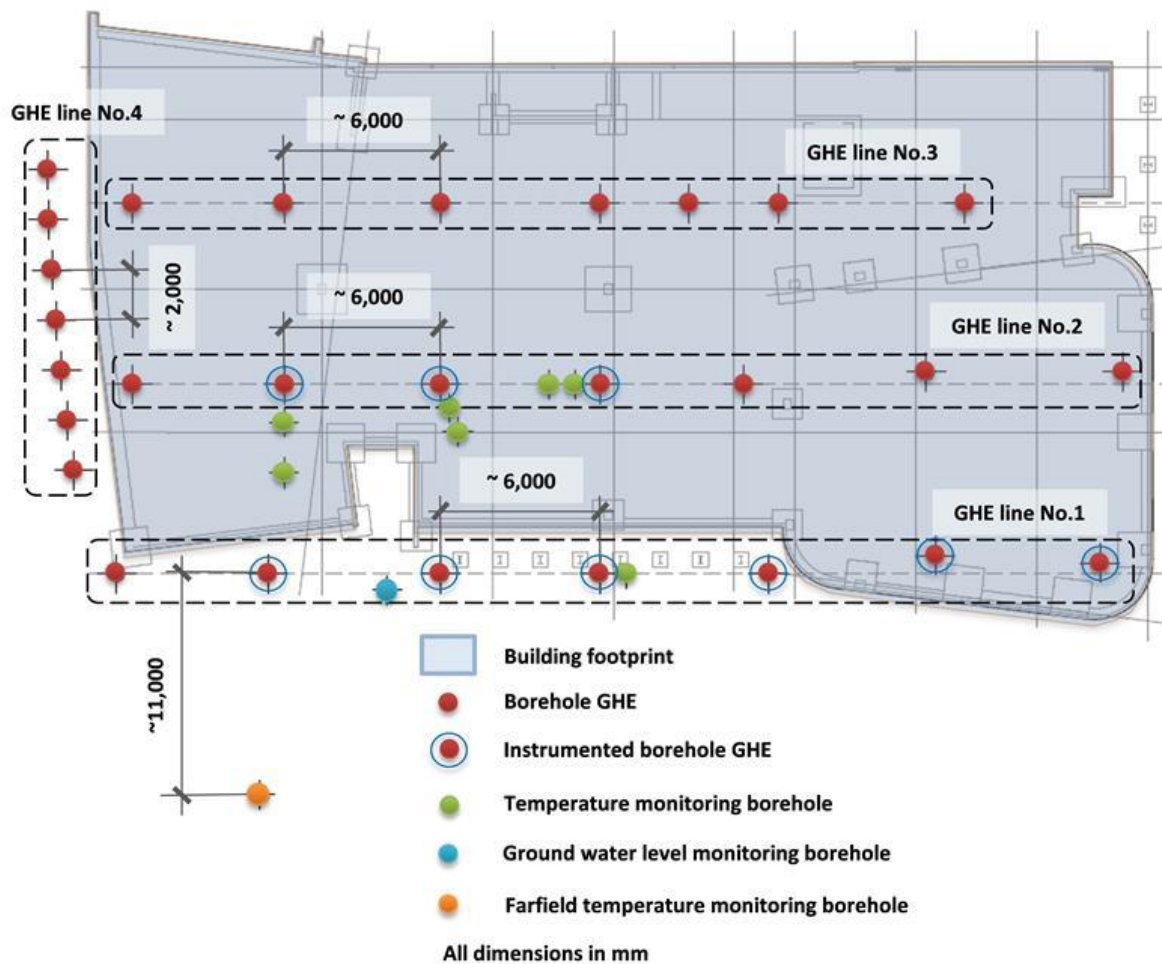
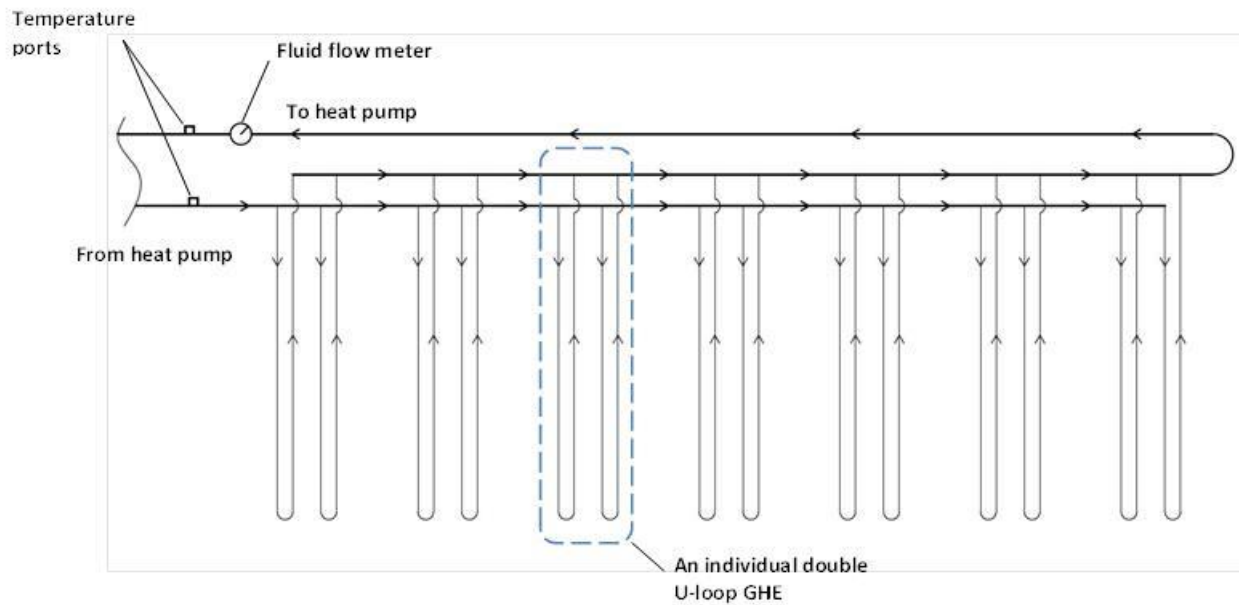
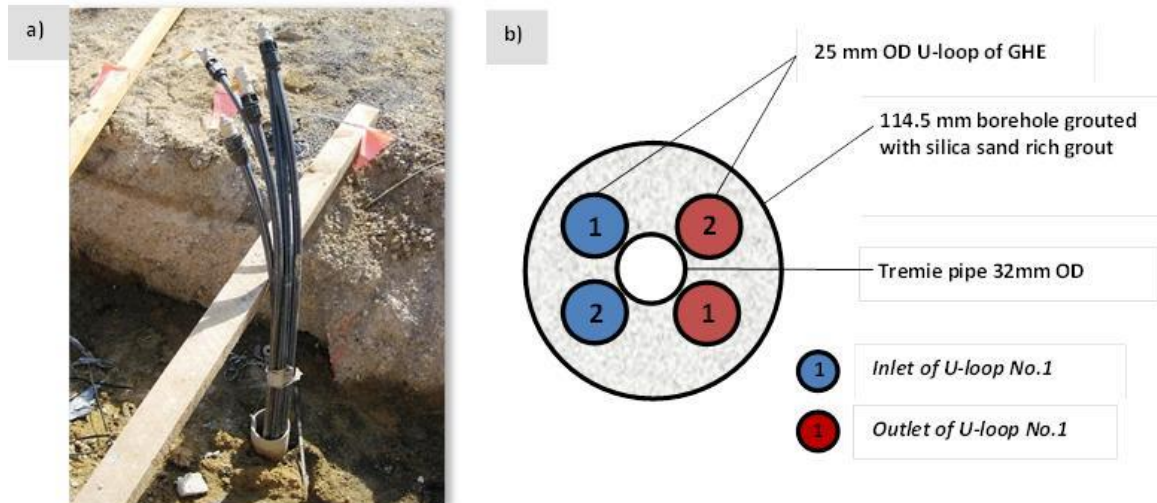


Figure 2: A plan view of installed GHEs and monitoring boreholes.



**Figure 3: A line of seven parallel vertical double U-loop ground heat exchangers.**

Boreholes of 114.3 mm (4½ inches) diameter were drilled to accommodate the GHEs. Each GHE has two U-loops of 25 mm OD HDPE pipe (Fig. 4). The legs of the U-loops are separated by a 32 mm OD tremie pipe installed at the centres of GHEs. In addition to facilitating bottom-up grouting of the GHEs, the tremie pipes provided a fixed separation of the individual legs of the U-loops. After placing the U-loops into drilled boreholes, the boreholes were grouted with a silica sand rich grout.

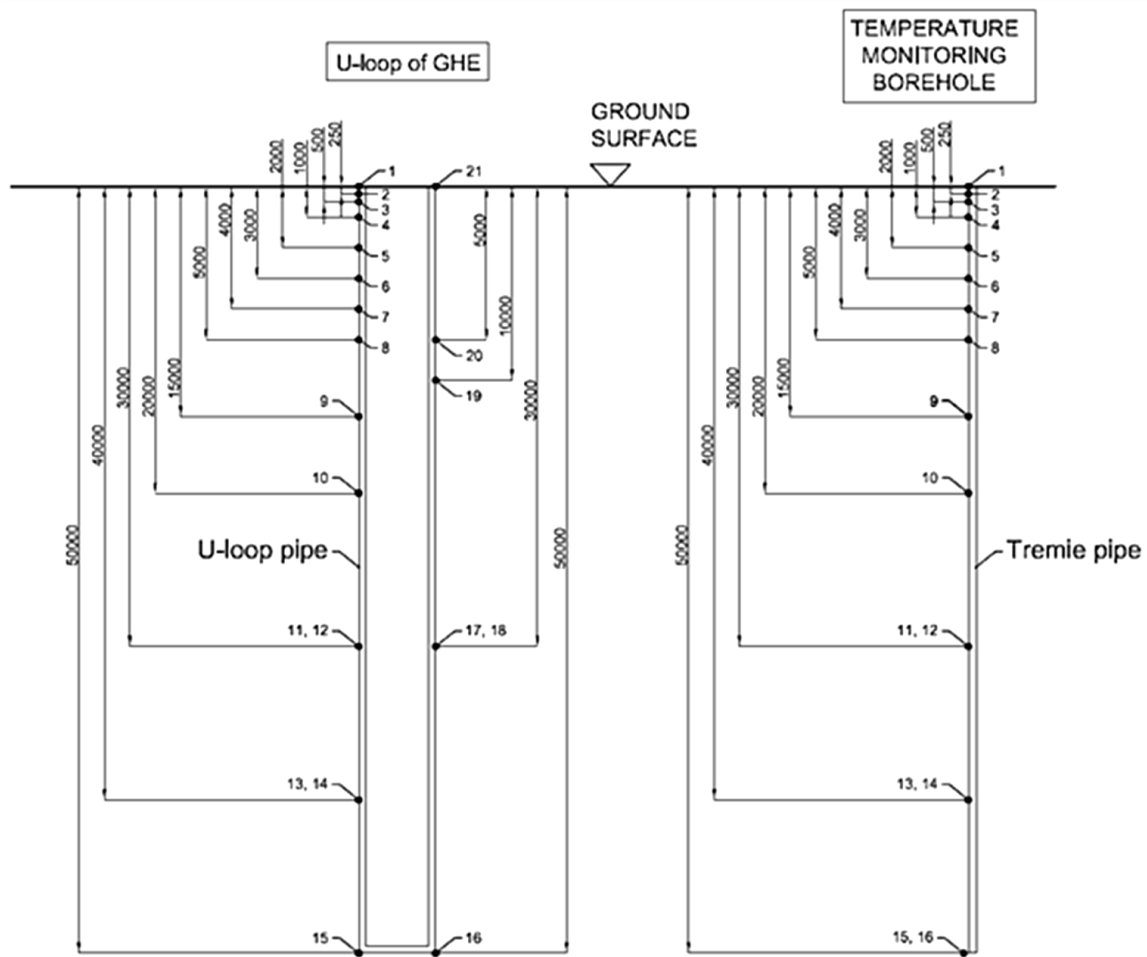


**Figure 4: GHEs at the experimental site: a) A GHE being installed; b) Cross-section of a GHE.**

The geothermal system has been heavily instrumented to monitor its performance with an emphasis on the study of the thermal behaviour of its underground part, the GHEs. For this purpose, nine out of the twenty eight GHEs were fitted with temperature sensors to monitor thermal interactions of the GHEs with the ground (Fig. 2). These sensors were installed along the pipes of GHEs at different depths. A typical arrangement of the GHE sensors is shown in Fig.5.

Apart from the borehole GHEs, seven temperature monitoring boreholes were drilled to depths of 20, 30 and 50 metres to accommodate sensors for monitoring the temperatures of the ground adjacent to GHEs at different depths (Fig.2). This was achieved by attaching temperature sensors to 32mm OD tremie pipes and installed these into the same diameter boreholes as those used for the GHEs. The temperature monitoring boreholes were grouted with the same grout mix as the GHEs. The closest radial distance of these monitoring boreholes to the centre of a GHE is about 1 m. Figure 5 shows the typical sensor arrangement along the lengths of temperature monitoring boreholes. In addition, a farfield temperature monitoring borehole was installed about 11 metres from the nearest GHE to monitor undisturbed ground temperatures at the experimental site.

In addition to temperature monitoring boreholes, a ground water monitoring borehole was installed close to the GHEs (Fig. 2). The influence of the ground water level on the system's thermal performance will be assessed using the collected observation data.



**Figure 5: Typical arrangements of temperature sensors along the depths of GHEs and monitoring boreholes (dimensions in mm).**

Each line of GHEs was fitted with a fluid flow meter along with two temperature ports installed on inlet and outlet header pipes to the line to measure the power and energy extracted/injected from/to each line during any particular period of time (Fig. 3). A temperature port is a temperature sensor installed in direct contact with the fluid circulating within a pipe. In addition, fluid flow meters and temperature ports were also installed on the building side of the system to collect information about the energy supplied to the building. The system is also fitted with power meters to measure electricity used to operate the geothermal mechanical equipment and assess coefficients of performance of the heat pumps.

The site of the experiment is underlain by Silurian mudstone (Johnston, 1992) which forms the bedrock for the most of the Melbourne area. A continuous 50m core of this material was collected during the installation of the GHEs for use for further detailed logging and laboratory testing for thermal and other properties. The thermal properties of the grout will also be assessed using samples collected during the installation.

The installation of the GSHP system and monitoring equipment was undertaken from March, 2013 to March, 2014. From March, 2014 the system has been in full operation.

### 3.2 First experimental results

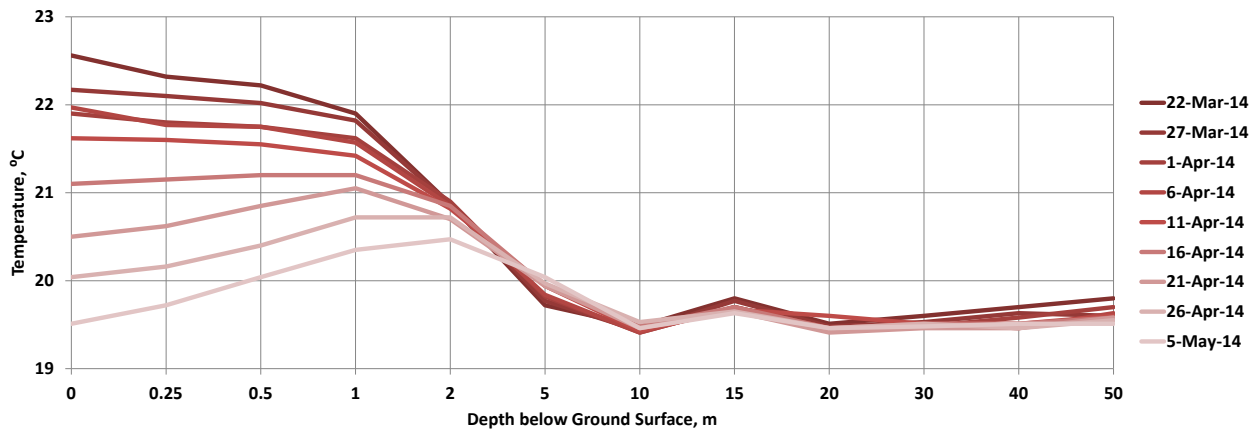
The monitoring of the experimental GSHP system started from the beginning of its operation in March, 2014. This section presents some observation data collected during the first 2 months of monitoring.

An undisturbed ground temperature is an important parameter that, among other factors, defines the required length of GHEs. There has been a limited number of experimental studies which collect data on seasonal ground temperature variations in Australia in general and in the Melbourne Metropolitan Region in particular. One of the objectives of the Elizabeth Blackburn School of Sciences geothermal experiment is to gather such data for an inner-north suburb of Melbourne. Figure 6 shows initial observations of the ground temperature measured in the farfield temperature monitoring borehole installed at the experimental site. The ground temperature was recorded at different depths along the 50-metre deep borehole from March 22 till May 1, 2014, with 5-day intervals always at the same time of a day, at 11 am.

As can be seen in Fig. 6, the ground temperature at depths 0 to 2 metres below the ground surface fluctuated following the changes in the ambient air temperatures. These fluctuations are apparent even when considering the measurements taken over such a short



observation period as presented here because of the relatively high amplitudes of such variations. At depths from 2 to 5 metres, the ground temperature still varied but with a reduced amplitude and did not always follow the same trend as the temperature at the shallower depths due to the thermal inertia of the ground. For example, at a depth of 5 metres, the ground temperature rose by around 0.3°C during the observation period, whereas the ground temperature close to the surface dropped by around 3°C during the same period.

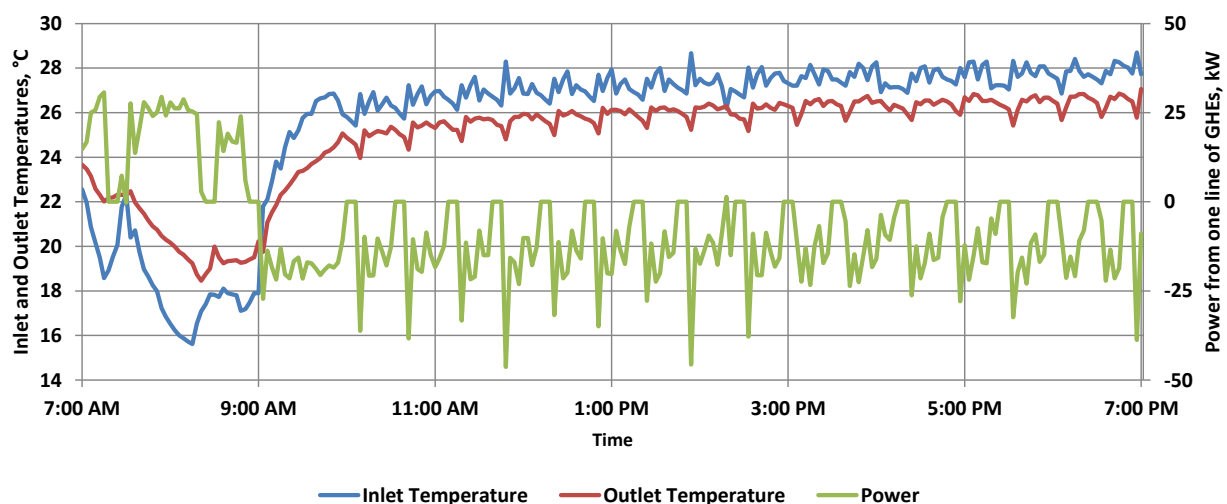


**Figure 6: Undisturbed ground temperature at different depths below the ground surface at the experimental site (the depth axis is not to scale for better visualisation).**

During the observation period, the ground temperature from around 10 metres down to 50 metres stayed nearly stable at 19.5°C except for some minor fluctuations around this value. This may lead to a preliminary conclusion that the ground temperature below between about 5 to 10 metres is not directly influenced by the daily variations of the ambient air temperature. This finding is consistent with similar published observations (Colls et al., 2012; Wang et al., 2012). At this experimental site, the ground temperature below 10 metres is equal to about 19.5°C. This temperature is higher than previously reported for the Melbourne area: 18.5°C by Colls et al. (2012) and 17-18°C by Wang et al. (2012). The reasons for this relatively minor ground temperature difference need further investigation.

The performance of the experimental GSHP system will be studied under the real-life thermal demand of a school building. The required heating or cooling energy at any particular point of time is determined by the automatic building management system which was designed to maintain comfortable temperatures inside the premises. The building management system activates one or more heat pumps which, in turn, activate one or more lines of GHEs. Hence, the required thermal power and, consequently, the thermal loads on the GHEs during the experiment, will be governed by weather and the behaviour of building occupants.

As an example, the thermal power delivered by one GHE line on March 25, 2014 is presented in Fig. 7. On this particular autumn day, it was relatively cool during the early morning but as the solar radiation increased during the day, the air temperature rose significantly. Therefore, from the beginning of system operation at 7 am, the GHEs worked in an energy extraction mode following a building demand for heating until around 9 am. Between around 9 am and 7 pm, the GHEs worked in an energy injection mode delivering the required cooling energy to the building, thus rejecting heat to the ground. These extractions and rejections are apparent when one considers the difference between the inlet (into the ground) and outlet (from the ground) temperatures also shown in Fig. 7.



**Figure 7: Heating and cooling power delivered by one line of GHEs on March 25, 2014.**

Monitoring of the temperatures of the ground adjacent to GHEs has also been commenced. However, no significant changes in those temperatures have been recorded yet, since only around two months with moderate thermal energy requirements have passed since the beginning of the system operation, indicating that less than a 1 m ground radius around the GHEs has been thermally affected in this two month period. It is expected to see the thermal effect of the GHE operation on the nearest ground during the next heating period starting from June where substantial heating power has to be delivered to the building. The results of these observations will be published later.

#### 4. SUMMARY AND CONCLUSIONS

The Elizabeth Blackburn School of Sciences geothermal experiment was set up to study a full-scale commercial GSHP system under real-life thermal loads from a school building in climatic and geological conditions typical of Melbourne, Australia. The experimental GSHP system of 120 kW installed capacity utilises twenty eight 50-metre deep double-loop borehole GHEs to provide thermal interaction with the ground. The system, especially its underground part, is extensively instrumented to observe its performance. This includes 20, 30 and 50- metre deep ground temperature monitoring boreholes which were installed next to GHEs to investigate the thermal effect of the system's operation on the adjacent ground.

Some initial observation data from the experiment has been presented. The ground temperature at depths from 0 to around 2 metres showed considerable fluctuation with changes in the ambient air temperature. At depths from around 10 to 50 metres, a stable undisturbed ground temperature of 19.5°C was recorded. This temperature was a little higher than previously recorded at similar depths for the Melbourne Metropolitan Region.

This experimental study has a potential to investigate the influence of ambient air temperature swings, typical for Melbourne, on the performance of GHEs. The Melbourne weather pattern as well as building users' behaviour will shape the real-life thermal loads in the experimental study. The effect of such thermal loads on the performance of GHEs and the temperature of the ground adjacent to GHEs will be reported in the future publications.

#### ACKNOWLEDGEMENTS

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