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In-Situ Thermal Response Testing – New Developments

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ABSTRACT

The number of installations of ground source heat pump (GHSP) systems is rapidly growing in Switzerland. For any installation it is critical to have a correct estimation of the ground thermal properties to ensure optimal energy savings and for larger developments the in-situ thermal response test (TRT) provides a cost-effective method to achieve this. The authors have developed a compact mobile test device for the TRT, where all the required components are held in a suitcase-sized container. The compact module has been equipped with a modem to facilitate remote data-monitoring. This addition has enabled the engineer to overview the results in real time and to switch the heater on and off via a mobile phone, something that has reduced the time spent on site and therefore also the cost. The new compact test device has been used to determine the thermal conductivity for several larger GHSP systems in Switzerland and France and have shown equivalent results to previous trailer-sized equipments. The development and operation of the device is described together with a case study of a performed in-situ thermal response test.

1. INTRODUCTION

Resources of hydrothermal aquifers from which heat can be directly extracted are limited to regions with specific geological conditions. Instead geothermal heat must be extracted with the means of heat pumps. Ground Coupled Heat Pump (GCHP) systems use the earth as a heat source or heat sink by combining a geothermal heat pump with a borehole heat exchanger (BHE). The technology dates back over 50 years and due to intensified research and development over the last 20 years it is now well established. Geothermal heat pumps are one of the fastest growing applications of renewable energy in the world, with annual increase in the number of installations with 10% in about 30 countries over the last 10 years (Lund *et al.*, 2004).

GCHP systems exist worldwide and the largest market is today in the US. However, Switzerland, with a recent boom in GCHP installations, has the highest number of geothermal heat pumps per capita (Rybach and Sanner, 2000). The market is likely to continue growing with further improvements in the technology and the increasing need for energy savings.

The size and cost of a GCHP system is highly dependent on the ground thermal properties. A good design requires certain site-specific parameters, most importantly the ground thermal conductivity, the borehole thermal resistance and the undisturbed ground temperature. Estimations of these parameters are vital to the design, yet very difficult to make. Without good estimations, the GCHP system is likely to be disproportioned, resulting in either unnecessary costs if oversized or in less energy savings than predicted if undersized. Traditionally, estimations were made from tabulated data or lab testing, but both these methods disregard the site-specific conditions and effects such as groundwater flow. Moreover, the required laboratory test set-up to determine the thermal characteristics of soils subjected to in-situ stress conditions becomes highly complex and the test is difficult to carry out (Cekerevac *et al.*, 2005). This leads to a crude design, making a method of more accurate estimation of the ground thermal properties highly desirable, which is motivating the research and development of in-situ thermal response tests. Eugster and Laloui (2001) give a selection of recent developments in the field.

Figure 1: The in-situ thermal response test apparatus.

Thermal response tests (TRT) offer a good method to determine the ground thermal properties for the total heat transport in the ground with groundwater and other disturbances automatically included. This is done by injecting a constant heat power into a borehole heat exchanger and measuring the temperature response. Since the theory was established in the 1980s and the first mobile test equipments were constructed in the 1990s, the technique has developed and spread to several countries. The Soil Mechanics Laboratory (LMS) at the Swiss Federal Institute of Technology in Lausanne (EPFL) has developed test apparatus for in-situ thermal response tests since 1998. The latest apparatus (Figure 1), developed in 2005, is compact and fits into a "flight case" (0.6m × 0.3m × 0.7m). The update of the equipment also includes a data transmission system whereby the test can be followed and certain functions controlled remotely using an internet connection. These modernisations offer enhanced flexibility and application potential for in-situ thermal response testing. This article outlines the design and workings of this apparatus and shows a case study for the verification of the quality of the results.

2. THEORY

2.1 Heat conduction

The theory behind heat extraction from the ground is based on the classical heat conduction equation (1) developed by Fourier in 1822. It considers the soil to be a homogeneous and isotropic conducting medium:

$$\alpha \nabla^2 T = \frac{\partial T}{\partial t} \tag{1}$$

where T is temperature (K), t is time (s) and α is the thermal diffusivity (m^2/s) of the conducting medium and defined by:

$$\alpha = \lambda / \rho c_m \tag{2}$$

where λ is the thermal conductivity (W/(mK)), ρ is the density (kg/m^3) and c_m is the mass specific heat capacity (J/(kgK)). The higher value of α, the faster the propagation of heat within the medium. From Equation (1) it can be seen that, when the heat conduction process reaches a steady state, the temperature field becomes time-independent and thereby also independent of the thermal diffusivity. At this point the focus is transferred from the transient processes to the steady state heat conduction process. Furthermore, when the storage coefficient ρc_m in a material decreases, the influence from the steady state heat condition becomes more important.

The thermal conductivity λ is one of the most important factors when designing a GCHP system. It is a material property and depends on the density, temperature, particle shape, porosity, moisture content and mineral composition of the soil. Although tabulated values for different types of soils are available in the literature, the great impact and diversity of site-specific factors mean that the effective thermal condition of a particular soil formation is very difficult to predict without carrying out a TRT at the site in question. The design of a GCHP system is also strongly dependant on the thermal resistance R_b between the heat carrier fluid and the outside of the borehole wall (K/(W/m)). R_b depends on the arrangement of the borehole, the materials involved and their thermal properties and can therefore be engineered to some extent. The actual value of R_b of the installed heat exchanger borehole can also successfully be determined with a TRT.

2.2 Data interpretation

The ground thermal conductivity and the borehole thermal resistance cannot be measured directly but must be inferred from the measurements recorded during the thermal response test. In order to do so, a heat transfer model must be adopted such as the *line source model* (Ingersoll and Plass, 1948), described below, or the *cylinder source model* (Carslaw and Jaeger, 1947).

Since the heat transfer in the ground near the borehole during the test can be assumed to be purely conductive, in the radial direction and constant along the borehole, the BHE can be approximated by a line source in a homogeneous medium. With the solution for the line source approximation, an equation can be obtained for the evolution of the mean fluid temperature $T_f(t)$ (Eskilson, 1987):

$$\begin{aligned} T_f(t) - T_0 &= \frac{q_c}{4\pi\lambda}\left(\ln\left(\frac{4\alpha t}{r_b^{\,2}}\right) - \gamma\right) + q_c \times R_b \\ &= \frac{q_c}{4\pi\lambda}\ln(t) + q_c\left[R_b + \frac{1}{4\pi\lambda}\left(\ln\left(\frac{4\alpha}{r_b^2}\right) - \gamma\right)\right] \end{aligned} \tag{3}$$

where q_c represents the constant heat injection rate used for the response test (W/m), T_0 the undisturbed ground temperature (°C), t denotes the duration of the heat injection (s), r_b the borehole radius and γ is Euler's constant (0.5772). The accuracy of the line source approximation increases with time as the flow changes from transient to steady state and the time component loses influence. The maximum error of the approximation in Equation (3) is 2.5% for $t \geq 20\ r^2/\alpha$ and 10% for $t \geq 5\ r^2/\alpha$ (Gehlin, 2002), where the latter is generally accepted in thermal response test applications.

The evolution of the fluid temperature is logarithmic and by plotting the fluid temperature against ln*(t)*, the ground thermal conductivity can be evaluated by using the slope of the line k:

$$\lambda = \frac{q_c}{4\pi k} \tag{4}$$

Once the ground thermal conductivity is known, the borehole thermal resistance can then be assessed on the basis of Equation (3). This requires knowledge of the undisturbed ground temperature, which is obtained in the beginning of the test by circulating the fluid before switching on the heating and measuring the temperature. The ground volumetric heat capacity must also be known and can normally be satisfactorily deduced from the geological information of the site. To assess the reliability of the results, the measured borehole thermal resistance can be compared with a calculated value based on the geometric and thermal characteristics of the borehole using a BHE design software.

3. THE THERMAL RESPONSE TEST DEVICE

The Swiss Federal Institute of Technology in Lausanne (EPFL) started to develop an in-situ thermal response test apparatus in 1998 and has since then performed testing for research and consulting. The latest test apparatus was constructed in 2005 and based on the former unit of the laboratory, which was trolley-based. The general operation from the former unit has remained, but now assembled in a much more compact format to fit into a transport case of type "flight case". The system was accredited by the SAS (Swiss Accreditation Service) in May 2004 according to the ISO/CEI 17025 standard.

The new apparatus comprises mainly a heater, an electrical network, a hydraulic circuit as well as regulating- and security systems for temperature, flow and pressure. Figure 2 shows a schematic layout of the assembly. Further details are given by Mattsson *et al.* (2007). The apparatus also comprises measuring devices which record the following eight parameters:

- incoming and outgoing fluid temperature
- internal and external temperature of the test unit

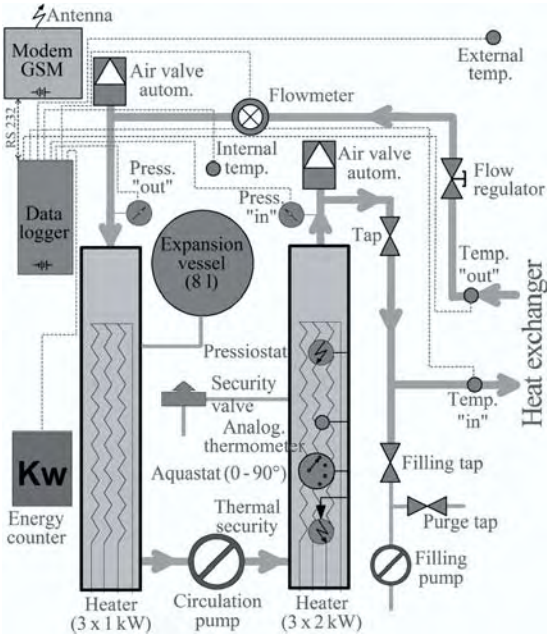

Figure 2: Schematic diagram of the apparatus.

- pressure of the incoming and outgoing heat-conducting fluid
- flow rate of the heat-conducting fluid
- energy consumption

The thermal energy is transmitted from the ground to the circulating fluid by means of a borehole heat exchanger whereby PE pipes are inserted into a borehole in the shape of a U-tube (or double U-tube) loop. The space between the pipes and borehole wall is filled with bentonite or another fill material (Figure 3) to ensure good thermal contact and prevent vertical circulation of ground water. The heat exchanger is either connected directly to the reinforcement in the foundation structure, e.g. piles (Laloui *et al.*, 2006), or installed in a borehole of appropriate depth, which is determined by the energy demand of the planned building and the expected ground conditions at the particular site.

The test apparatus is also equipped with a remote data transmission system, whereby a modem installed inside the test unit transmits the information recorded by the data-logger to an internet-connected server. Thus the test performance can be followed in real time from any location. With the latest adaptation it is also possible to switch flow and power on and off as well as altering the power level by sending an SMS. Hence the test operator only needs to be on site for the installation and dismantling of the test apparatus, which enables great savings in time and cost.

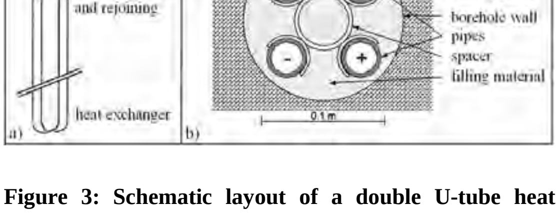

Figure 3: Schematic layout of a double U-tube heat exchanger: a) Tube branching, b) Cross-section of borehole. After Pahud and Matthey (2001).

Normally the initial part of the test is devoted to the determination of the undisturbed ground temperature and the fluid is during this time circulated without heating. Measurements are recorded every minute throughout the test which is carried out over approximately 7 consecutive days to ensure that sufficient data, fulfilling the time criteria for Equation (3), are obtained.

3.2 Setting the test parameters

The power level should aim for a temperature development in the heat carrier fluid as similar as possible to that of the final system. The temperature development can be calculated with an estimated value of the thermal conductivity as shown in Equation (7) and Equation (8). The optimal heat injection q should be between 30 and 50 W/m during the test. The power level P (W) depends on the depth H of the borehole (m) as:

$$P = q \times H \tag{5}$$

The flow regime is normally kept turbulent (a correction has to be made in case the system is later laid out for laminar flow). The flow should be chosen as a function of the desired temperature difference between the entry and exit of the heat exchanger. Ideally, the temperature difference should be kept between 3 and 5 K. This can be estimated through:

$$P = c_v \times Q \times \Delta T_{in\text{-}out} \tag{6}$$

where c_v is the volumetric specific heat capacity of water (J/(m^{3}K)), Q is the flow through the test loop (m^3/s) and $\Delta T_{in\text{-}out}$ is the temperature difference of the inlet and outlet fluid (K). During the heated part of the test, the fluid temperature rises in the heat exchanger. To avoid perturbations along the heat exchanger caused by thermal convection, the temperature increase during the test ΔT should not exceed 30 to 35°C. This increase can be estimated using the following relationship (Eskilson, 1987):

$$\Delta T = (R_q + R_b) \times q \tag{7}$$

where R_q is the thermal resistance of the ground (K/(W/m)) and can be determined from:

$$R_q = \frac{1}{4\pi\lambda}\left(\ln(4\alpha t / r_b^2) - \gamma\right) \tag{8}$$

with λ as the estimated value for the ground thermal conductivity at the particular site (W/(mK)).

4. CASE STUDY

One selected test is described below to demonstrate the typical procedure and results of an in-situ thermal response test using the presented new test apparatus. The described test was carried out in Geneva (Switzerland) for a new development to obtain design values for the planned geothermal energy system of the future building.

4.1 Installation

A pilot borehole was drilled on the site for the future building in order to determine the geothermal properties. The borehole was logged on site using disturbed samples obtained during the drilling (Figure 4). Casing was used in the upper 98m where there was a larger risk of collapse of the borehole walls. Once the drilling was completed, the double U-tube was inserted using space separators at regular intervals. A bentonite/cement mix (ratio 1/1) was then

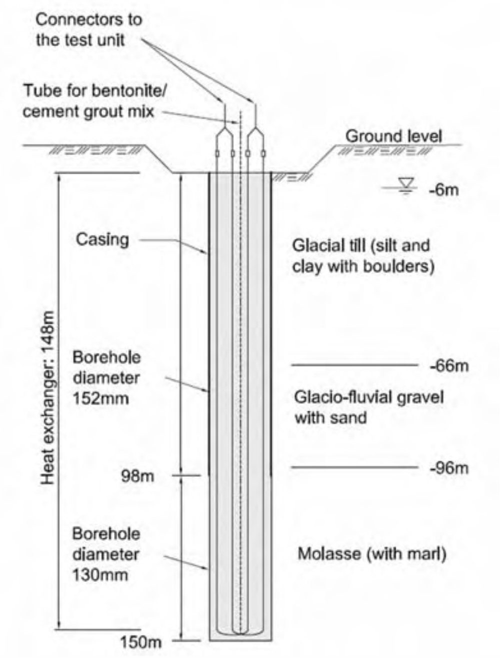

Figure 4: Schematic layout of the borehole heat exchanger with simplified borehole log.

injected from the borehole base and the casing was lifted simultaneously. The installation of the borehole and heat exchanger was carried out approximately one month prior to the commencement of the thermal response test. The purpose of this delay is to allow any temperature rise in the surrounding ground caused by the drilling process or the grout hardening to dissipate.

4.2 The response test

The power level and flow rate applied during the test were determined using Equation (5) and Equation (6) and are presented in Table 1 together with other relevant test data. The test was performed over a period of nine consecutive days. Since the test apparatus is equipped with a modem which transmits the data from the data-logger to an internet-connected server, the recorded data could be followed from the office in Lausanne to ensure that the test performance was adequate.

Table 1: Test characteristics of the thermal response test in Geneva (Switzerland).

Description	Test Characteristics
Borehole depth	150m
Borehole diameter	130mm-152mm
Heat exchanger depth	148m
Tube type	Double-U, Polyethylene (PE)
External tube diameter	32mm
Tube thickness	2.9mm
Fill material	Bentonite/Cement (1/1)
Heat exchanger fluid	Water
Average flow rate	1190 litres/h
Power level	6kW

4.3 Data interpretation and results

The following interpretations apply to the test characteristics given in Table 1 and a non-laminar flow regime. Some of the raw data recorded by the data-logger are presented in Figure 7, namely the incoming and outgoing fluid temperature, the interior and exterior temperature and the power level. Figure 7 includes the initial, non-heated part of the thermal response test, used to determine the undisturbed ground temperature. It can be seen that there is a certain level of heat injection also during this stage, which is the result of the electricity used by the circulating pump. Based on the recorded temperature during the non-heated part of the test and by subtracting the effect from the circulation pump, the undisturbed ground temperature could be estimated to 13.6°C.

For the heated part of test in Figure 7 it can be seen that the power level was maintained relatively constant and the test conditions are therefore well suited for the interpretation using the line source approximation.

In order to determine the effective thermal conductivity of the ground, the mean fluid temperature, $(T_{in}+T_{out})/2$, was plotted against the logarithm of time as illustrated in Figure 5. The conductivity was then obtained by inserting the value k of the slope of the line together with the average heat injection during the heated part of test into Equation (4); $\lambda = 40.9/(4\times\pi\times1.57) = 2.06$ W/m.

By then inserting the obtained thermal conductivity and undisturbed ground temperature together with an assumed value of the heat capacity into Equation (3), the borehole thermal resistance R_b could be plotted (Figure 6). The estimated value for R_b was then determined to 0.069 K/(W/m) by taking the average value during the test.

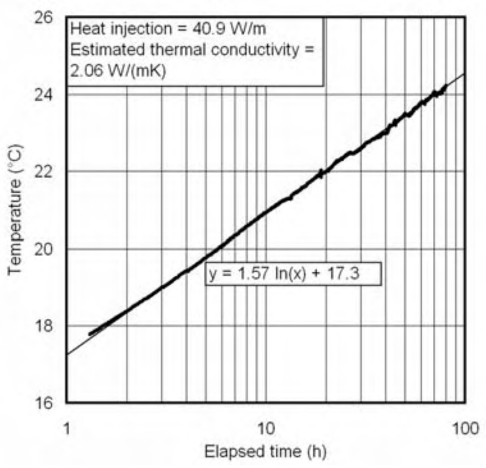

Figure 5: Evaluation of the thermal conductivity using the line source approximation.

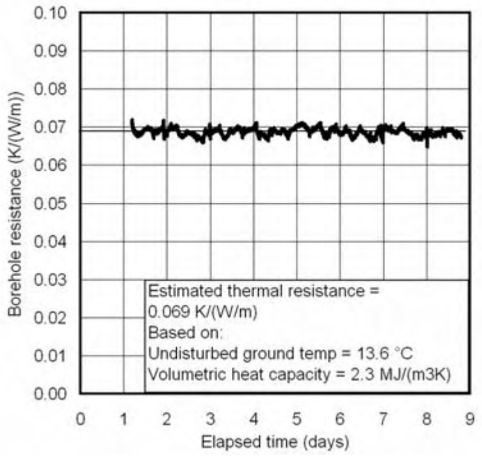

Figure 6: Estimated thermal resistance R_b of the borehole heat exchanger during the test.

5. CONCLUSIONS

The in-situ thermal response test provides an effective method to determine the ground thermal properties required for the design of a geothermal energy installation, by performing the test in-situ, i.e. on a soil volume identical to that of the future installation. The authors have developed a unique compact testing device for in-situ thermal response testing which has shown results of equal quality to the previous trolley-based unit. The new device is equipped with a data transmission system, whereby the test can be followed and certain functions controlled remotely using an internet connection. These modernisations reduce the time and cost of the test and offer enhanced flexibility and application potential for in-situ thermal response testing. The number of GSHP installations is rapidly growing in Europe and with future need of further energy savings, geothermal energy and the thermal response test is likely to gain importance.

6. ACKNOWLEDGEMENTS

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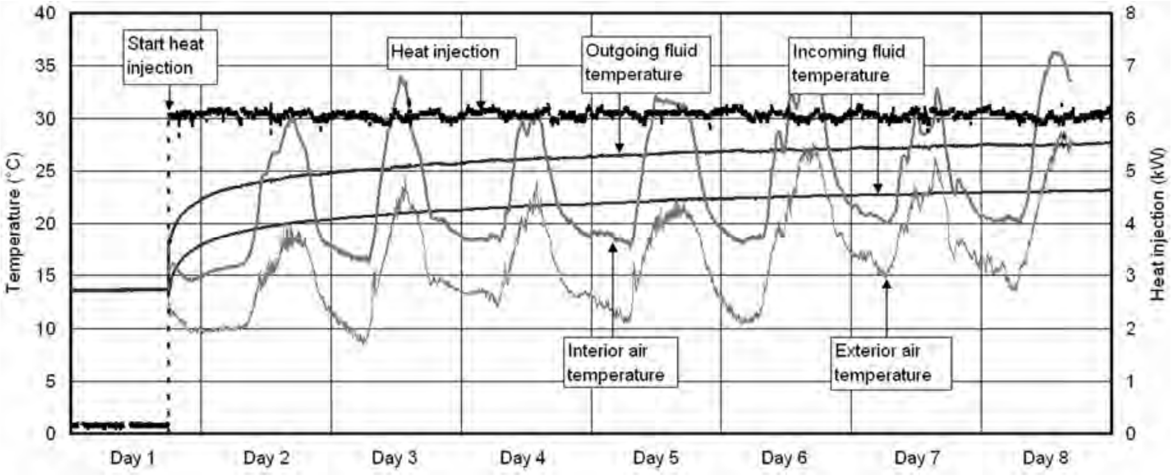

Figure 7: Evolution of fluid temperature, air temperature and power level during the entire test.