Geothermal site investigation using the Geothermal Response Test (GRT) - Test analysis and enhancements

Recherche de sites géothermiques en utilisant du test de réponse géothermique - Analyse et perfectionnement de l'essai

R. Katzenbach, F. Clauss, T. Waberseck & I. Wagner
Technische Universität Darmstadt, Institute and Laboratory of Geotechnics, Germany

ABSTRACT
For an economic analysis and design of geothermal facilities a well-founded knowledge of the relevant thermal subsoil properties is indispensable. Therefore, the Geothermal Response Test (GRT) is a reliable and effective field investigation procedure. With this contribution the authors present fundamentals of the testing procedure and discuss new enhancements of the Geothermal Response Test in order to promote the application of the Geothermal Response Test into a standardized testing procedure and hereby to emphasize the practical usage of geothermal energy.

RÉSUMÉ
Pour une analyse économique et une conception des équipements géothermiques une bonne connaissance des propriétés thermiques de sous-sol est indispensable. Par conséquent, le test de réponse géothermique est un procédé fiable et efficace de recherche in situ. Avec cette contribution les auteurs présentent des principes fondamentaux de la procédure d'essais et discutent de nouveaux perfectionnements du test de réponse géothermique afin de favoriser son application dans une procédure d'essais normalisés; et par ceci, souligner l'utilisation pratique de l'énergie géothermique.

Keywords : research and development, geothermal site investigation, Geothermal Response Test, thermal soil properties, thermal conductivity, thermal borehole resistance

1 INTRODUCTION

Presently, the dimensioning of larger shallow geothermal facilities is generally based on analytical or numerical calculations. The quality of the assessments concerning the heat exchanger design, normally carried out with software support, is substantially dependent on the quality of the initial parameters. Essential factors are on the one hand a correct approach to energy requirements and power demands of the building for maintaining the desired temperature and on the other hand the knowledge of the thermal properties of the subsoil. While methods to estimate the heating and cooling demands and the overall energetic performance of buildings are scientifically based well-developed and deliver estimates with a high level of accuracy, the assessment of the thermal performance of the subsoil is still difficult up to now. Numerous parameters and their complex interactions are influencing the achievable performance of borehole heat exchangers and thereby aggravate the dimensioning considerably. Important influencing factors can be categorized as follows (Katzenbach et al. 2007):

- Physical, thermal and hydromechanical parameters of the subsoil:
  - Density and pore volume of the subsoil
  - Thermal capacity and thermal conductivity of the subsoil
  - Natural temperature and distribution in the subsoil
  - Geothermal temperature gradient
  - Groundwater level, flow direction and flow velocity
- Properties of the borehole heat exchangers (BHE):
  - Arrangement, distance, size and surface of the BHE
  - Quality of the thermal connection to the surrounding subsoil
  - External and inner diameter of the heat exchanger tubes
  - Material of the heat exchanger tubes
  - Flow of the heat exchanger fluid
  - Physical properties of the heat exchanger fluid
- Climatic conditions

One of the most relevant parameters of the dimensioning of geothermal facilities is the thermal conductivity λ [W/(m·K)] of the thermally influenced subsoil. The thermal conductivity is a material property which specifies the quantity of energy transfer in a temperature field due to a temperature gradient. Accordingly, it is a measure for the rate of energy transfer through a borehole heat exchanger for both energy injection and extraction.

The thermal conductivity depends on most of the above listed factors. Therefore, it is appropriate to determine it in a field test at an installed borehole heat exchanger under near-service conditions in order to take into account as many of the above listed influencing parameters as possible. Assuming predominantly homogeneous conditions in the testing site, the determined results of this test can be considered for the dimensioning of further borehole heat exchangers in the same site.

2 FUNDAMENTALS OF THE GEOTHERMAL RESPONSE TEST

Mogensen (1983) suggests circulating a chilled fluid as energy carrier medium in a borehole heat exchanger in the subsoil. Assuming a constant energy withdrawal rate along the length of the heat exchanger, the parameter "effective thermal conductivity" can be determined from the thermal reaction of the subsoil (thermal response) after achieving a quasi-stationary state. The thermal reaction of the subsoil is quantified measuring the inlet and outlet temperatures. Basically, this Geothermal Response Test can also be conducted with a heated energy carrier medium (Figure 1).

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-1060

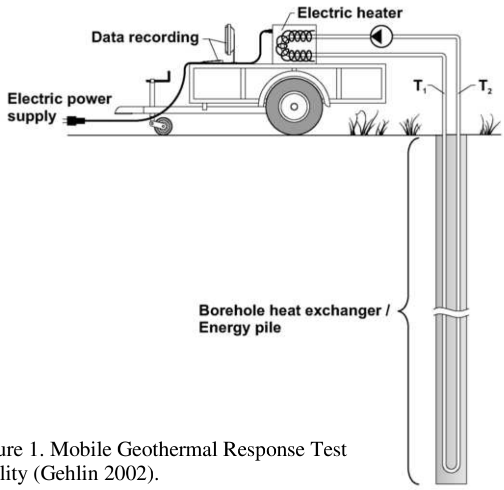

Figure 1. Mobile Geothermal Response Test facility (Gehlin 2002).

The analysis of the Geothermal Response Test is usually based on the line source theory. Looking on the theoretical description of energy transfer resulting from energy extraction, strong analogies to the theory of groundwater flow caused by groundwater withdrawal can be found. The temperature T [°C] is formally comparable with the hydraulic pressure head h [m], the specific energy extraction of the Geothermal Response Test q_t [W/m] corresponds to the groundwater withdrawal q_h [m³/sec] of a pumping test and the thermal conductivity of the subsoil λ [W/(m·K)] can be compared to the permeability coefficient k [m/s].

Assuming homogeneous conditions, a time-dependent temperature variation or pressure head difference occurs due to a constant energy extraction and a steady groundwater withdrawal respectively, until a steady state is reached.

The basic equations of these flow processes are compared in the following:

Heat transport **Groundwater flow**

$$\nabla^2 T = \frac{\rho c_p}{\lambda}\frac{\partial T}{\partial t} \quad (1a) \qquad \nabla^2 h = \frac{S}{k}\frac{\partial h}{\partial t} \quad (1b)$$

Besides, the product of density ρ [kg/m³] and volume-related specific heat capacity c_p [J/(kg·K)] is comparable with the storage coefficient S [-]. In polar co-ordinates, the basic equations (1a) and (1b) can be written as

$$\frac{\partial^2 T}{dr^2} + \frac{1}{r}\frac{\partial T}{dr} = \frac{\rho c_p}{\lambda}\frac{\partial T}{\partial t} \quad (2a) \qquad \frac{\partial^2 h}{dr^2} + \frac{1}{r}\frac{\partial h}{dr} = \frac{S}{k}\frac{\partial h}{\partial t} \quad (2b)$$

Up to the achievement of steady state conditions, the temperature gradient or the hydraulic gradient varies, i.e.:

$$\frac{\rho c_p}{\lambda}\frac{\partial T}{\partial t} \neq 0 \quad (3a) \qquad \frac{S}{k}\frac{\partial h}{\partial t} \neq 0 \quad (3b)$$

When a steady state is reached and no further time-dependent change can be noticed anymore, the flow can be described by the Laplace equation:

$$\nabla^2 T = 0 \quad (4a) \qquad \nabla^2 h = 0 \quad (4b)$$

Therefore, in the steady state the thermal or hydraulic storage capacity of the subsoil has no more influence on the heat transfer and the groundwater flow respectively.

With introduction of the thermal diffusivity $a = \lambda/(\rho \cdot c_p)$ [m²/sec] corresponding to the hydraulic storage capacity introduced by Theis (1935), the equations (2a) and (2b) can be integrated as:

$$T(r,t) = T_0 + \frac{q_t}{4\pi\lambda}\int_0^t \frac{e^{-\frac{r^2}{4at}}}{t}dt \quad (5a) \qquad s(r,t) = \frac{q_h}{4\pi k}\int_0^t \frac{e^{-\frac{r^2 S}{4kt}}}{t}dt \quad (5b)$$

$$= T_0 + \frac{q_t}{4\pi\lambda}\cdot W(u)$$

Here T_0 is the mean undisturbed subsoil temperature and s is the decrease of the groundwater level. Now the temperature field around a line source with constant extraction rate q can be developed from equation (5a) by substitution. With

$$u = \frac{r^2}{4at} \quad (6)$$

follows

$$W(u) = \int_0^t \frac{e^{-u}}{t}dt = \int_u^\infty \frac{e^{-u}}{u}du \quad (7)$$

By a series expansion W(u) may be described with the Euler-Mascheroni constant γ = 0,5772 as

$$W(u) = -\gamma - \ln u + u - \frac{u^2}{2\cdot 2!} + \frac{u^3}{3\cdot 3!} - \frac{u^4}{4\cdot 4!} + ... \quad (8)$$

For $t \to \infty$ follows $u \to 0$ and hence results W(u) = - γ – ln u. Accordingly, for large values of (at)/r ² equation (5a) may be transformed to

$$T(r,t) = T_0 + \frac{q}{4\pi\lambda}\int_{\frac{r^2}{4at}}^{\infty} \frac{e^{-u}}{u}du$$
$$\cong T_0 + \frac{q}{4\pi\lambda}\left[\ln\left(\frac{4at}{r^2}\right) - \gamma\right]. \quad (9)$$

The error accepted with this simplification rises to a maximum of 2.5 % for (a·t)/r² ≥ 20 and a maximum of 10 % for (a·t)/r² ≥ 5 (Eklöf & Gehlin 1996, Austin 1998). Therefore, the accuracy of the analysis of the Geothermal Response Test on the basis of this equation rises with increasing test duration and with increasing extent of the thermally influenced range whereas the speed of the thermal propagation depends on the ratio of the thermal conductivity to the thermal capacity.

The fluid temperature in the borehole heat exchanger T_f can be determined by calculating the line source temperature in the bore margin ($r = r_b$) where the thermal resistance of the borehole is considered by

$$T_f(t) = T_0 + \frac{q}{4\pi\lambda}\left[\ln\left(\frac{4at}{r_b{}^2}\right) - \gamma\right] + q\cdot R_b\,. \quad (10)$$

The thermal resistance R_b [K·m/W] considers cumulatively all thermal resistances which appear between the fluid and the borehole wall. It can be determined from the difference between the fluid temperature in the borehole heat exchanger T_f and the temperature of the borehole wall T_b and depends on the specific energy transfer rate q:

$$T_f - T_b = R_b \cdot q \quad (11)$$

For a constant specific energy transfer rate the time function of the fluid temperature from equation (10) has the form

$$T_f(t) = k\cdot\ln(t) + m\,. \quad (12)$$

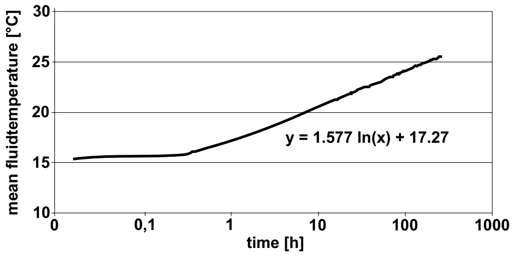

Figure 2. Characteristic temperature diagram during the conduction of a Geothermal Response Tests (Poppei et al. 2006).

Computing the average fluid temperature measured during the test procedure versus the logarithm of the time (Figure 2), the effective thermal conductivity of the thermally influenced subsoil is given as a function of the gradient k of the determined test straight line:

$$\lambda_{eff} = \frac{q}{4\pi k} \tag{13}$$

The specific energy transfer rate q can be computed by division of the energy injection or extraction Q [W] measured during the test realization by the borehole length H [m]. The hereby calculated effective thermal conductivity λ_{eff} is an integral value of the thermal conductivities of all soil layers along the borehole depth and contains the thermal influences of groundwater flow, the borehole grouting etc.

After determination of the thermal conductivity, the borehole resistance can be computed by solving equation 10 for R_b:

$$R_b = \frac{1}{q}\left(T_f(t) - T_0\right) - \frac{1}{4\pi\lambda}\left[\ln\left(\frac{4at}{r_b^2}\right) - \gamma\right] \tag{14}$$

3 ENHANCEMENTS OF THE GEOTHERMAL RESPONSE TEST (GRT)

The first mobile Geothermal Response Test pilot facilities based on the previously described concept of Mogensen were developed in Sweden (Eklöf & Gehlin 1996) and the USA (Austin 1998). In respect to Mogensen's concept these equipments are not operated using a cooled fluid but a heated fluid as energy carrier medium. After the first positive experiences with the GRT, worldwide numerous further equipments were put into operation during the following years. In the meantime the GRT became a standard test for the in situ determination of thermal subsoil properties and the dimensioning of bigger geothermal facilities.

Figure 3. Left: first GRT equipment, Lulea University of Technology, Sweden (Gehlin 2002) Right: enhanced mini GRT module, École Polytechnique Fédérale de Lausanne, Switzerland (Laloui & Steinmann 2005).

Besides an increase of mobility by the application of smaller equipments the aim of the developments of the recent years was the further improvement of the test realization and the analysis of the GRT. Furthermore, three aspects were in focus:

1. Cost optimization

Due to the relatively long time necessary for the test conduction the GRT is up to now rather cost-intensive. Hence, the test could be conducted economically up to now only in the course of the preliminary investigation for the construction of bigger facilities. A wide-spread application also for the dimensioning of smaller plants and the application of the GRT as a tool for the quality control of built facilities have not been established so far.

2. Achievement of a larger information density

By applying the conventional GRT it is only possible to determine an effective thermal conductivity of the subsoil averaged over the entire length of the borehole heat exchanger by using the measured inlet and outlet temperature curves for a constant power rate. However, for the identification of certain thermally favorable soil layers a layer-specific testing procedure is necessary.

3. Minimization of external influences

The analysis results of the GRT according to the above described line source theory significantly depend on the steady energy injection or extraction during the test conduction, usually provided by constant pumping rates and energy input resp. extraction. However, this can strongly be influenced by meteorological conditions and also fluctuations of the power supply network and the according power changes of the heating or cooling aggregate and the pump.

By the application of automated control and feedback systems for the conduction of the Geothermal Response Test Hanschke & Freund (2006) managed to eliminate respectively reduce a number of the factors influencing the quality of the GRT disadvantageously (among others Reuss et al. 2001). In their version of an enhanced GRT the desired energy input is given as a constant input quantity and is regulated continuously by controlling the variables pumping rate and flow temperature. Besides, flow and return temperature are measured inside the borehole heat exchanger, hence external temperature influences and energy losses related to the testing apparatus have no influence on the test conduction. Therefore costly isolations of various equipment components are not necessary.

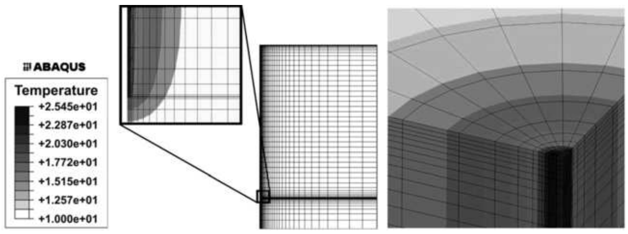

Figure 4. FE-models of a borehole heat exchanger for test interpretation; left: axisymmetric, right: tree-dimensional.

Alternatively a more complicated test analysis is useful for the technical optimization of the test. Simplifications of the complex three-dimensional transient heat transfer problem which are connected to the application of analytic solutions may be avoided by using numerical models for the test interpretation (Figure 4). The advantage of an inverse modeling is the possible consideration of more complex boundary conditions (e.g. power variations during the test) and spatially variable thermal subsoil properties as well as the possible reverse determination of thermal subsoil parameters such as the thermal capacity and the overall effective thermal conductivity (among others: Spitler et al. 1999, Wagner & Clauser 2005).

Fiber optical measurement facilities are useful for the depth depending determination of the thermal conductivity. By a glass fiber cable which is installed in the borehole heat exchanger temperature changes during the testing can be measured in small time intervals over the depth with a spatial resolution range of 25 cm to 50 cm (Hurtig et al. 2000). Based on these measurements the GRT may be evaluated partially and eventual changes of the effective thermal conductivity may be detected.

In order to be independent of the meteorological influences during the test Heidinger et al. (2004) developed a further variation of the GRT installing a hybrid cable in the borehole heat exchanger used for measuring and heating at the same time. By electric heating of the cable an over the entire length defined energy input is injected into the subsoil and the temperature changes along the glass fiber are recorded by the fiber optical measurement technique. The effective thermal conductivity of subsoil layers along the measured length can be determined by the theoretical attempt of the line source theory.

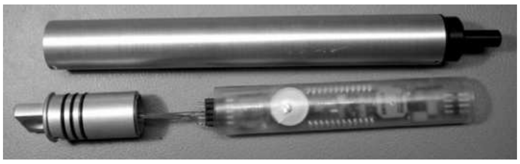

Figure 5. Wireless measuring probe (length 235mm, ∅ 23mm) called “micro fish” (Rohner et al. 2004).

A different development to enhance the in-situ determination of the thermal subsoil properties is a wireless probe called “micro fish” (Figure 5), which is lowered into the completed borehole by its own dead weight and which is continuously recording the temperature and the pressure ratio. The probe developed by Rohner et al. (2004) in Switzerland delivers vertically differentiated information of the completed boreholes up to 300 m depth within less than 60 minutes. After the readout of the measurement data the geothermal gradient can be determined for each layer. In a further step the thermal conductivity of the subsoil can be specified for each depth section of the borehole by applying the local heat flow value q_{loc} given by regional heat flow charts, which are presently only available for Switzerland.

Based on the above described enhancements, extensive R&D-activities with an own Geothermal Response Test (GRT) equipment are currently conducted at the Institute and the Laboratory of Geotechnics of Technische Universität Darmstadt (Figure 6). New test conduction as well as transient evaluation and analysis procedures are being developed for a significant shortening of the test duration in order to enable an economic application of GRTs even for smaller geothermal plants and for the quality control investigations.

Figure 6. Mobile GRT equipment of Technische Universität Darmstadt.

4 SUMMARY AND CONCLUSIONS

The thermal use of the subsoil as renewable base load energy source can be a solution for the sustainable reduction of the emission of CO_2 and other greenhouse gases. In order to establish a wide acceptance for the respective technologies, geothermal systems of any size have to be dimensioned and designed properly.

For providing the necessary thermal subsoil parameters, an extensive geothermal site investigation is indispensable. One of the most relevant tools in this context is the Geothermal Response Test. In order to make this field test widely available and to establish it as a standard test procedure even for small geothermal systems, various developments are currently under way. Furthermore, a mandatory final inspection of borehole heat exchanger systems would be desirable for quality management purposes.

Today and in future, research and development will promote the common use of geothermal energy. Innovative new investigation technologies such as enhanced Geothermal Response Tests will improve the sustainable and economic dimensioning and design of geothermal energy facilities and hereby rise the attractiveness of this resource- and climate-protecting renewable energy source.

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