Inaccuracies in geothermal field tests

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Synopsis: The institute of materials and mechanics in civil engineering (IWMB) is performing a research program titled experimental investigation for the verification of a Finite-Element-Multiphase-Model for numerical analysis heat transfer in ground supported by the Federal Ministry of Economics and Technology (BMWi). Therefore extensive field tests are currently conducted in cooperation with the institute of applied geosciences (IAG). Geothermal Response Tests as well as Enhanced Geothermal Response Tests are performed at double-U shaped and coaxial shaped borehole heat exchangers (BHE) in the same geological and hydrogeological conditions and compared to each other.

In this paper detailed description of the performed field tests as well as resulting inaccuracies in geothermal field tests (GRT and EGRT) such as outside temperature, test duration, length of the borehole heat exchanger, borehole diameter and groundwater level that influence the results of GRTs and EGRTs are discussed.

Keywords: Geothermal energy, Geothermal Response Test, Enhanced Geothermal Response Test.

1. Introduction

In times of global warming renewable energies are getting more important. Geothermal energy is the auspicious renewable energy in the field of geotechnical engineering. For the design of smaller geothermal systems the geothermal, geological and hydrogeological parameters can be estimated according to common literature. For the design of complex geothermal systems the subsoil has to be modelled with numerical approaches based on the Finite-Element-Method (FEM) or the Finite-Difference-Method (FDM) using geothermal parameters determined in laboratory or *in-situ*. Common tools for the determination of geothermal parameters *in-situ* are Geothermal Response Tests (GRT) and Enhanced Geothermal Response Tests (EGRT). Due to the assumptions in analytical solution of GRTs and EGRTs different inaccuracies with varying influence on the results have to be taken into account. Geothermal basics, their theoretical background and subsequent inaccuracies in geothermal field tests in theory and praxis are discussed in the following.

2. Theoretical background

With GRTs and EGRTs the effective thermal conductivity λ_{eff} of geothermal systems can be determined *in-situ*.

2.1 Geothermal Response Test (GRT)

During a GRT the inlet and outlet temperature of the fluid T_f of an installed borehole heat exchanger (BHE) of length H is measured while the fluid is heated with a constant thermal load $\dot{Q}$. The resulting heat conducts through the BHE wall and the filling to the surrounding subsoil. The effective thermal conductivity of the BHE system (wall, filling and subsoil) can be evaluated by the rise of temperature of the fluid in time. The most common analytical evaluating method bases on the line-source theory by Lord Kelvin, which was adapted to geothermal systems by Ingersoll & Plass (1).

According to the line-source theory the temperature $T(r,t)$ around a line-source with infinite length and negligible diameter in infinite homogeneous and isotropic subsoil can be determined with (1), see Carslaw, & Jaeger (2).

$$T(r,t) = T(t=0) + \frac{\dot{Q}}{H\,4\,\pi\,\lambda_{eff}} \int_{\frac{r^2}{4\,a\,t}}^{\infty} \frac{e^{-u}}{u}\,du = T(t=0) + \frac{\dot{Q}}{H\,4\,\pi\,\lambda_{eff}} E_1\left(\frac{r^2}{4\,a\,t}\right) \tag{1}$$

$\dot{Q}$, H, a and r is denoted as thermal load [W], length of the BHE [m], thermal diffusivity [m^2 s^{-1}] and radial distance [m]. Asuming of a constant rise of temperature at steady state condition E_1 can be simplified according to Mogensen (3):

$$E_1\left(\frac{r^2}{4\,a\,t}\right) = -\gamma - \ln\left(\frac{r^2}{4\,a\,t}\right) - \sum_{n=1}^{\infty}(-1)^n \frac{\left(\frac{r^2}{4\,a\,t}\right)^n}{n\,n!} \cong \ln\left(\frac{4\,a\,t}{r^2}\right) - \gamma \qquad (2)$$

γ is the Euler's constant. With (2) in (1) the temperature of the fluid can be defined with (3) considering the borehole thermal resistance R_b [K m W^{-1}] caused by the BHE wall and the filling.

$$T_f(t) = T(t=0) + \frac{\dot{Q}}{H\,4\,\pi\,\lambda_{eff}}\ln(t) + \frac{\dot{Q}}{H}\left[R_b + \frac{1}{4\,\pi\,\lambda_{eff}}\left(\ln\left(\frac{4\,a}{r^2}\right) - \gamma\right)\right] \qquad (3)$$

Considering $\dot{Q} =$ const. (3) becomes:

$$T_f(t) = \frac{\dot{Q}}{H\,4\,\pi\,\lambda_{eff}}\ln(t) + const \qquad (4)$$

The effective thermal conductivity can be determined by the rate k of the temperature rise of the fluid within a logarithmic time interval.

$$\lambda_{eff} = \frac{\dot{Q}}{H\,4\,\pi}\,\frac{\ln(t_2)-\ln(t_1)}{T_f(t_2)-T_f(t_1)} = \frac{\dot{Q}}{H\,4\,\pi\,k} \qquad (5)$$

The most simplifying assumptions are considered in (5), which is suitable for a constant thermal load set on a BHE with infinite length and negligible diameter in infinite, homogeneous and isotropic subsoil in steady state conditions.

2.2 Enhanced Geothermal Response Test (EGRT)

With a GRT the temperature rise of the fluid in time is measured and the effective thermal conductivity of the whole BHE length λ_{eff} can be evaluated. Nevertheless the effective thermal conductivity of the surrounding subsoil changes in order to the geological and hydrogeological conditions through depths. Therefore it is most important to get an insight of the variation of the effective thermal conductivity over depth below surface $\lambda_{eff}(z)$. To evaluate $\lambda_{eff}(z)$ the function k must be determined for every incremental depths of the borehole. This can be performed with distributed fibre optic temperature sensing (DTS) technique, which is used by EGRTs.

Due to EGRTs a hybrid cable consisting of fibre optical cable and copper wire is installed to a borehole or BHE. A constant thermal load $\dot{Q}$ is set on the copper wire while the temperature rise is measured with the fibre optical cable via optical time-domain reflectometry (OTDR) in every incremental depth of the borehole. $\lambda_{eff}(z)$ can be evaluated via line-source theory and (5). A schematic comparison of GRTs and EGRTs is illustrated in Fig. 1.

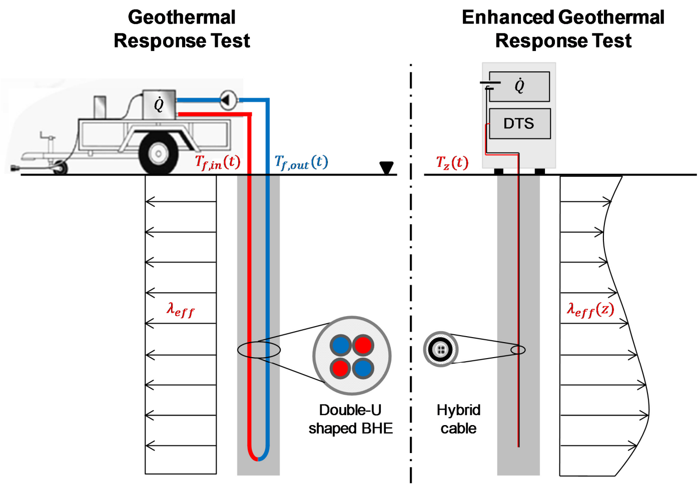

Figure 1. Schematic comparison of GRTs and EGRTs.

2.3 *Influences on geothermal field tests*

Currently the interpretation and reproducibility of GRTs are discussed by different authors. It can be stated that λ_{eff} of a geothermal system does not only depend on thermal properties of the BHE and the subsoil, but also on different external influences and inaccuracies.

According to Austin (4) and Sanner et al. (5) the results of GRTs depend on climatic and therefore seasonal conditions. Warm rain, sunshine and high air temperatures influence the subsoil temperature up to depths of about 15 m below surface. Additionally to the subsoil the connection tubes between BHE and the measuring device as well as the measuring device itself are highly influenced by seasonal conditions. As a result of seasonal conditions variation in the rates k_i depending on the evaluation time interval occurred at nearly every of the 22 investigated GRTs. Maximum variations of λ_{eff} of 40 % were obtained.

In Coelho et al. (6) the results of GRTs conducted at different types of BHE (coaxial, single-U and double-U shaped) in comparable geological conditions were investigated. The measuring device was installed inside of a building to exclude seasonal influences. Maximum variations of λ_{eff} were 10 - 23 %.

In Seidinger et al. (7) the influence of the length of BHE is analysed. GRTs at two BHE with length of 70 m and 99 m in nearly the same geological conditions were conducted. Maximum variations of the normalized λ_{eff} of 27 % were calculated.

Witte & van Gelder (8) investigated the influence of groundwater velocities of the effective thermal conductivity of GRTs. With a long-term pumping test at a neighboured well an artificial hydraulic gradient and a resulting groundwater flow of 3 – 6 m d^{-1} was applied. The results were compared with the results of the GRTs at natural groundwater flow velocities of about 0 m d^{-1}. Additionally the amount of the thermal load $\dot{Q}$ set on the BHE was varied. Maximum variations of λ_{eff} of 3 - 15 % were obtained.

GRTs with three different measuring devices (Groenholland, UBeG and Weihenstephan) were conducted in Sanner et al. (5). They showed a good reproducibility of the effective thermal conductivity. Maximum variations of λ_{eff} of 5 % were calculated. Only one test result differed 33 % to the others which was declared due to undefined problems. Furthermore three different fillings (Mol-sand, special graded sand and bentonite) of the BHE were analysed. Maximum variations of λ_{eff} were at 3 %.

Eklöf & Gehlin (9) investigated different time criteria t_{min} for the minimum test duration. GRTs were conducted in three different locations (Lulea University, Skogas and Bromma) and were analysed with two different time criteria (see table 1). Maximum variations of λ_{eff} of 25 % were observed.

In Gehlin & Hellström (10) the influence of variation in different evaluation methods is investigated. The data of three GRTs were analysed using the line-source theory (1), the simplified line-source theory (3) cylinder-source theory and parameter estimation. Maximum variations of λ_{eff} of 15 % were calculated.

Table 1. Influences on geothermal field tests according to literature.

influence criteria	**analysis range**	**maximum variations of λ_{eff} [%]**	**literature**
climatic influences	varying time intervals	40	Austin (4)
types of BHE	coaxial, single-U and double-U shaped BHE	23	Coelho et al. (6)
length of BHE	70 m, 99 m	27	Seidinger et al. (7)
groundwater velocity	0 m d^{-1}, 3 - 6 m d^{-1}	15	Witte & van Gelder (8)
measuring device	Groenholland, UBeG, Weihenstephan	5	Sanner et al. (5)
fillings	Mol-sand, special graded sand and bentonite	3	Sanner et al. (5)
time criteria	$t_{min,1} \geq 5\frac{r^2}{a}$ and $t_{min,2} \geq 50\frac{r^2}{a}$	25	Eklöf & Gehlin (9)
evaluation method	line-source theory, simplified line-source theory, cylinder-source theory and parameter estimation	15	Gehlin & Hellström (10)

3. Performed geothermal field tests

Due to the current research program geothermal field tests are performed by the IWMB in cooperation with the IAG. Two boreholes (B 1 and B 2) were drilled due to the construction of the Solar Decathlon building at TU Darmstadt in close distance (10.75 m) to each other. Extensive geological and geophysical field tests were performed to get an insight of the geological and hydrogeological conditions of B 1 and B 2. While both boreholes were equipped with hybrid-cables, B 1 was completed to a double-U shaped BHE and B 2 was completed to a coaxial shaped BHE (see Fig. 2). At both boreholes GRTs and EGRTs can be performed at comparable geological and hydrogeological conditions. Furthermore a groundwater standpipe (GWM 1) was installed up to a depth of 6.95 m next to B 1, so that the groundwater table (about 3.5 m) can be measured.

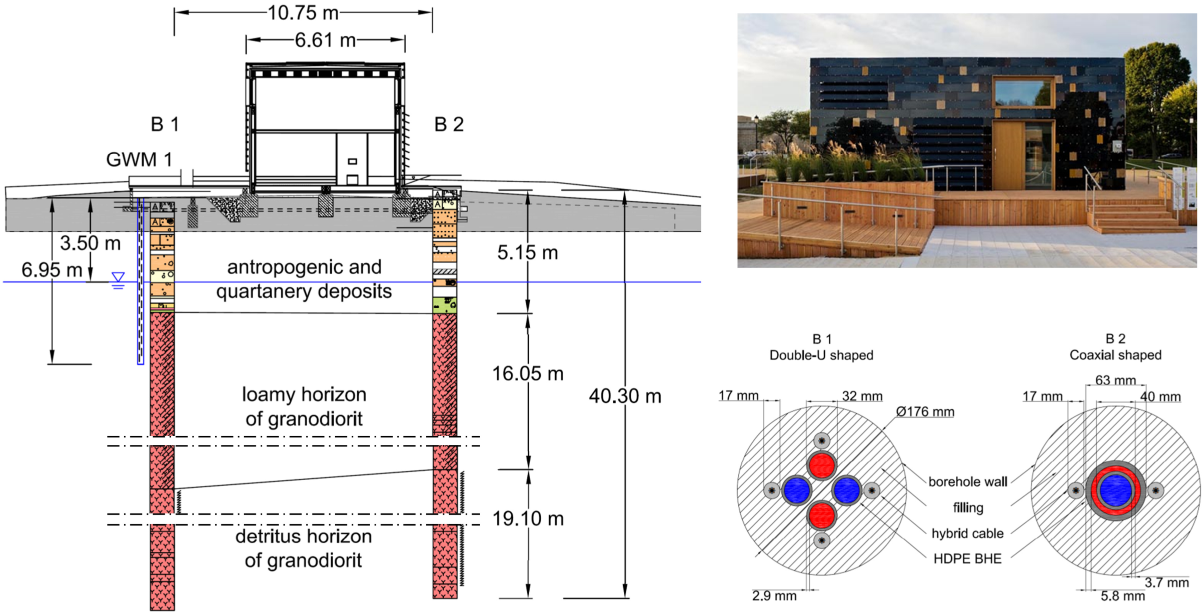

Figure 2. Drilling log and cross section of B 1 and B 2.

A total of 3 GRTs with the measuring device *Hamm & Theusner 08/01*, 2 multilevel GRTs with the measuring device *Lehr* and 4 EGRTs with the measuring device *DTS AP Sensing N4386A* were conducted since May 2010. Details of the performed geothermal field tests and their results are summarized in table 2.

Table 2. Performed geothermal field tests.

	double-U shaped BHE B 1				coaxial shaped BHE B 2			
	date	duration [h] (start time of heating period)	thermal load [W m^{-1}]	λ_{eff} [W m^{-1} K^{-1}]	date	duration [h] (start time of heating period)	thermal load [W m^{-1}]	λ_{eff} [W m^{-1} K^{-1}]
GRT Hamm & Theusner	17.05.2010	48 (10:23)	62	2.3	19.05.2010	48 (11:10)	62	1.7
	21.07.2010	48 (7:30)	62	2.5				
GRT Lehr	07.02.2011	48/48/72 (12:15)	75/50/25	data lost	17.02.2011	48/48/96 (12:40)	75/50/25	1.9/2.2/2.2
EGRT DTS AP Sensing N4386A	08.11.2010	72 (14:45)	12.3	2.3	15.03.2011	72 (13:00)	6.7	1.6
	06.12.2010	72 (14:38)	12.3	2.3				
	06.01.2011	72 (12:30)	6.7	2.1				

The effective thermal conductivity varies for the double-U shaped BHE between 2.1 - 2.5 W m^{-1} K^{-1} and between 1.6 - 2.3 W m^{-1} K^{-1} for the coaxial shaped BHE depending on different outer influences. The temperature inside and outside of the measuring device, inlet flow, outlet flow [°C] as well as the power supply [W], the calculated effective thermal conductivity [W m^{-1} K^{-1}] and the coefficient of determination of the regression line [-] of the GRT performed in July 2010 is illustrated in Fig. 3. The temperature inside the measuring device (19 – 32°C) corresponds moderately to the variation of the outside temperature (19 –

37°C). These high inside and outside temperatures have a deep impact on the measured inlet and outlet flow temperatures. Due to mains voltage fluctuations the power supply is not constant but shows a bandwidth from 2400 W to 2680 W (12 %) calculated by the measured current and voltage.

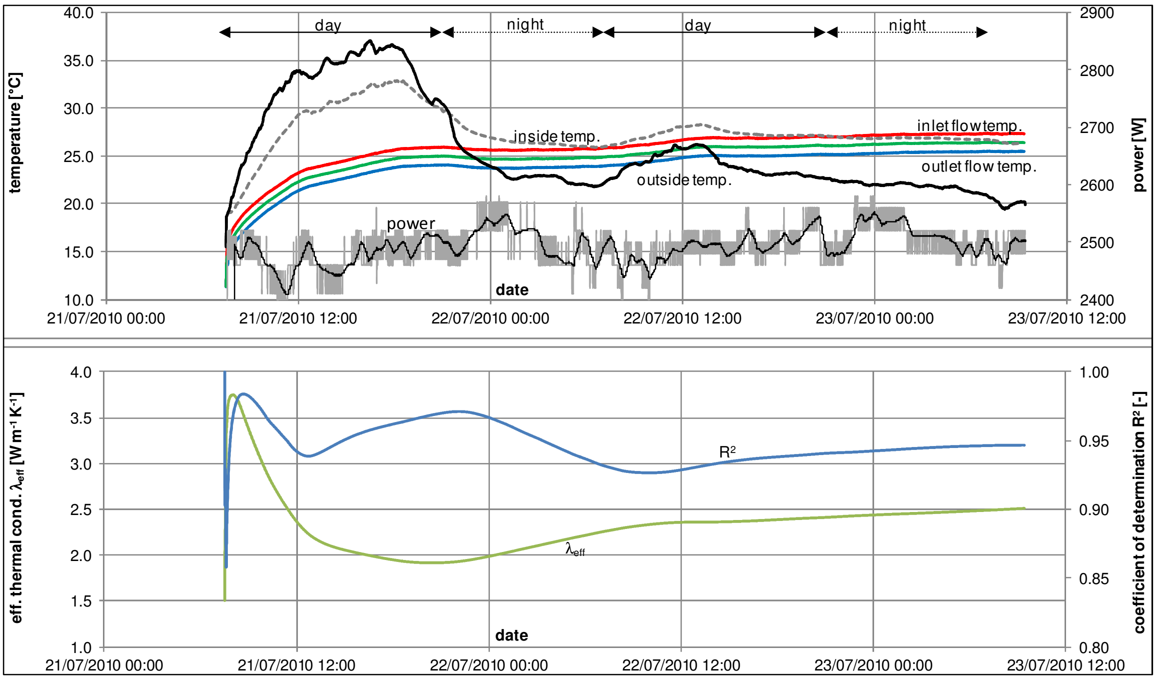

Figure 3. GRT double-U shaped BHE 21.07.2010.

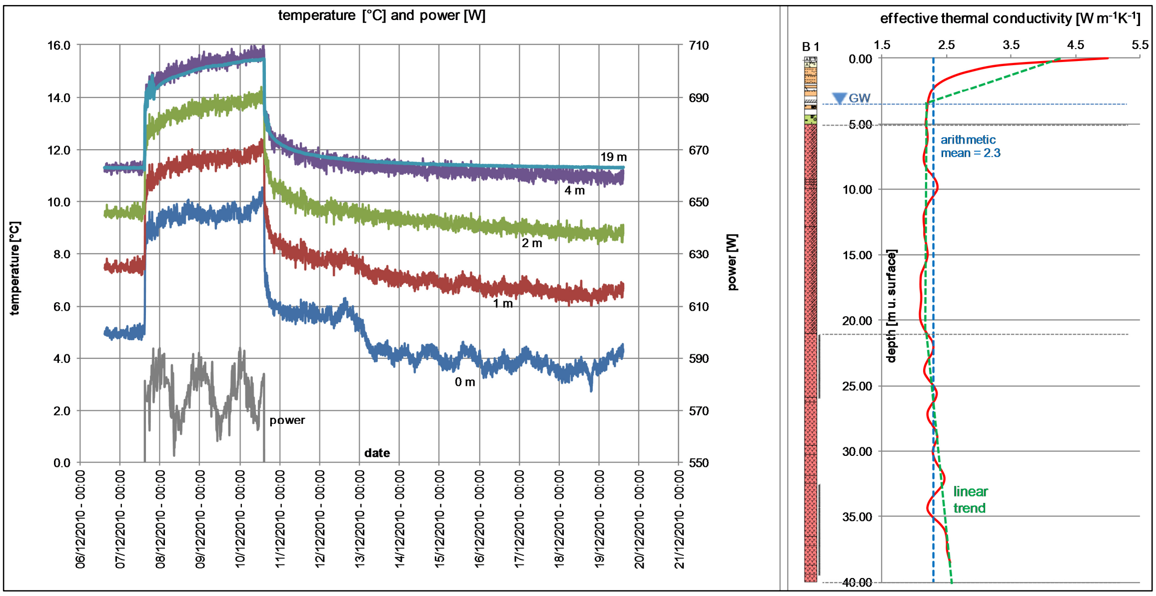

Figure 4. EGRT double-U shaped BHE 06.12.2010.

The results of the EGRT performed at the double-U shaped BHE in December 2010 are shown in Fig. 4. The temperature on the surface (0 m) varies depending on the air temperature. Clear temperature peaks can be identified every day at 17:00 to 18:00 o'clock. A moderately trend can also be seen in 1 m, 2 m and 4 m below surface. In 19 m depth no outside temperature influence can be seen. On the right hand side of Fig. 4 the effective thermal conductivity over depths $\lambda_{eff}(z)$ is illustrated. While the arithmetic mean is 2.3 W m^{-1} K^{-1} a linear trend can be determined corresponding to the geology. While the effective thermal conductivity in the loamy horizon of granodiorit is relative constant a linear rise of $\lambda_{eff}(z)$ in the detritus horizon of granodiorit can be detected. The high thermal conductivity of the topsoil can be explained by the low outside temperatures conducting the thermal load away from the BHE.

According to mains voltage fluctuations the power supply is not constant but shows a bandwidth from 550 W to 595 W (8 %) calculated by the measured current and voltage. For both power lines in Fig. 3 and Fig. 4 clear trends depending on day (low values) and night (high values) can be detected.

4. Conclusions

Beside geological, hydrogeological and geothermal conditions outer influences such as outside temperatures and mains voltage fluctuations affect the results of geothermal field tests. Based on these influences the coefficient of determination of the regression line can be less than 0.99 and therefore the calculated effective thermal conductivity of geothermal field tests, especially of GRTs vary without an asymptotic approximation to a constant value. Therefore the results of GRTs influenced by high outside temperatures and mains voltage fluctuations differ depending on the evaluation period.

For a climatic independent reproducibility interpretation of geothermal field tests outer influences have to be eliminated as far as possible. The measuring device of GRT as well as its connections to the BHE must be constructed isolated. The temperature sensors must be installed below surface directly in the BHE. The surface can be covered with isolators such as foamed polystyrene plates to minimize thermal influences by the sun. Furthermore the thermal load has to be kept constant with suitable methods, such as laboratory power supply units.

5. References

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