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Characterization of Geologic and Geophysical Environments Using GRT Data. Scope of Enhanced Data Interpretation

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ABSTRACT

A (enhanced) Geothermal Response Test is commonly used to determine geophysical parameters (i.e. thermal conductivity and volumetric heat capacity) of the subsoil. Such data can be utilized to get additional information on the subsoil.

Using different heat source approaches enables to evaluate measurements for different heat exchanger designs (e.g. u-tube heat exchangers, piles, baskets, etc.). It is important to choose the right approach to avoid misinterpretation and wrong values. Analog to hydro-geologic methods, time to distance calculations show the depth of the thermal investigations into the surrounding rock. Knowledge on grout and rock properties is preferable. Using this method through high resolution fiber optical measurements (enhanced GRT) allows determination of local rock properties, as well as localizing of grouting failures. Furthermore, the Darcy velocity of the groundwater affecting the heat exchanger during measurements can be calculated.

Temperature profiles vs. depth, pre and post (e)GRT, can be used to identify vertical groundwater flow through incomplete backfilling for a borehole heat exchanger (BHE). Serial profiles vs. depth over time post GRT show the quality of contact for the BHE to the surrounding rock. Determination of groundwater influence and grouting failure is also feasible.

Various information can be obtained from one data set without additional measurements. The more information available the more precise geothermal array can be designed.

1. INTRODUCTION

A Thermal Response Test, or synonymous, a Geothermal Response Test (TRT or GRT) is a field method to investigate thermo-physical properties of a borehole heat exchanger (BHE) drilled into soft or hard rock. With a TRT thermal energy is injected into or extracted from the BHE with a steady-state impulse (Ingersoll, L.R. & Plass H.J., 1948; Eskilson, P., 1984; Gehlin, S., 2002; Signorelli, S., 2004). Typically, a BHE contains one or more loop type PE-HD heat exchanger pipes where a heating carrier fluid is pumped in a circuit with a constant rate. The heater of the measurement device is heating the fluid with constant power. The input and output temperature and the circulated volume flow are measured continuously. The heat transfer mechanism from the working fluid via the wellbore completion into the geological formation is conductive. Evaluating these data leads to heat losses caused by the geological formation and the BHE construction itself. The obtained heat losses lead to integrated data over the whole length of the drillhole.

The enhanced TRT method (eTRT or eGRT) is in opposite to the TRT useful to determine the effective thermal conductivity with a highly localised resolution (Heidinger, G., Dornstädter, J., Fabritius, A.,Welter, M., Wahl, G. and Zurek, 2004; Lehr, C., Sass, I., 2014). The investigation drilling has to be equipped with additional hybrid fiberglass-copper-cable (hybrid cable) as known for distributed temperature sensing (Fig. 1). The built in hybrid cable carries along a copper cable as a heating wire beside the fiberglass. The heating power is identical along the heating wire for the whole hybrid cable. The undisturbed temperature of the subsoil and the temperature rise of the system are recorded by means of Optical-Frequency-Domain-Reflectometry measurement (OFDR). A temperature depending optical spectrum phase shift of the Raman parts (Stokes and Antistokes) enables the calculation of the temperature at its place of origin (Fig. 1). The evaluation of the recorded temperature curves follows Kelvin's line source theory (1856). For every measuring point along the hybrid cable the effective thermal conductivity of the surrounding rock can thus be determined.

Due the highly localized resolution, the resulting profile of conductivities can be differentiated for areas with mainly conductive or areas of convectively influenced heat transfer. With the knowledge of both of these parts and their parameters the incident of groundwater flow on the BHE can be calculated (Section 2.1).

Depending on the heat source geometry the evaluation of the measurements has to be done using different heat source approximations. The line source approach (Lord Kelvin, 1856; Carslaw, H.S. & Jaeger, J.C., 1959; Eq. 1) is valid for heat exchanger with a height to width ratio greater than 1000 (definitions of parameters are given at the end)

$$\Delta\upsilon(r,t) = \frac{\dot{Q}_H}{4\pi\lambda} Ei\left(\frac{r^2}{4at}\right) \tag{1}$$

The cylinder source approach (Eq. 2) is valid for radial heat exchanger geometries of any type:

$$\Delta\upsilon\left(R,0=z,t\right)=\frac{\dot{Q}_H}{2\pi\lambda}\int_{\sqrt{\frac{R^2}{2at}}}^{\infty} du\cdot\frac{e^{-u^2}}{u}\cdot I_0(u^2)\cdot Erf\left(\tfrac{H}{R}\cdot\tfrac{u}{\sqrt{2}}\right) \tag{2}$$

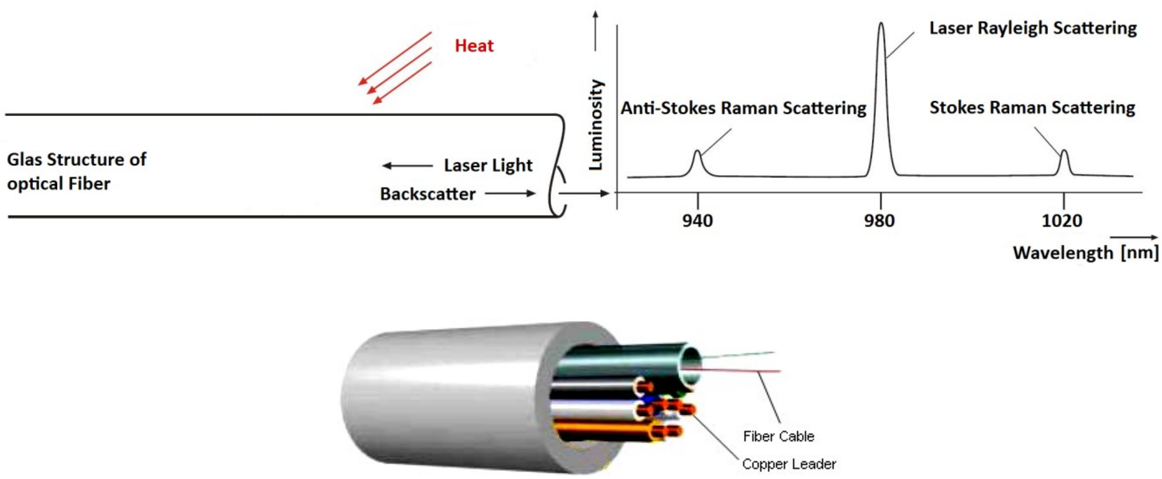

Figure 1: Hybrid cable and temperature depending displacement of the backscatter Raman spectra in a fiberglass cable

Figure 2 shows that the difference in the results between these evaluation methods, i.e. the line source and the cylinder source, gets much more significant when the width/height ratio of the heat exchanger gets smaller (Sass, I., Lehr, C., 2011). The cylinder source approach fits well over the whole runtime while the line source approach is only fitting in a late “quasi-straight-line-phase”. The error in evaluating data from measurements done at heat exchangers with such geometries - like energy baskets or energy piles - by line source approach can be larger than 100%.

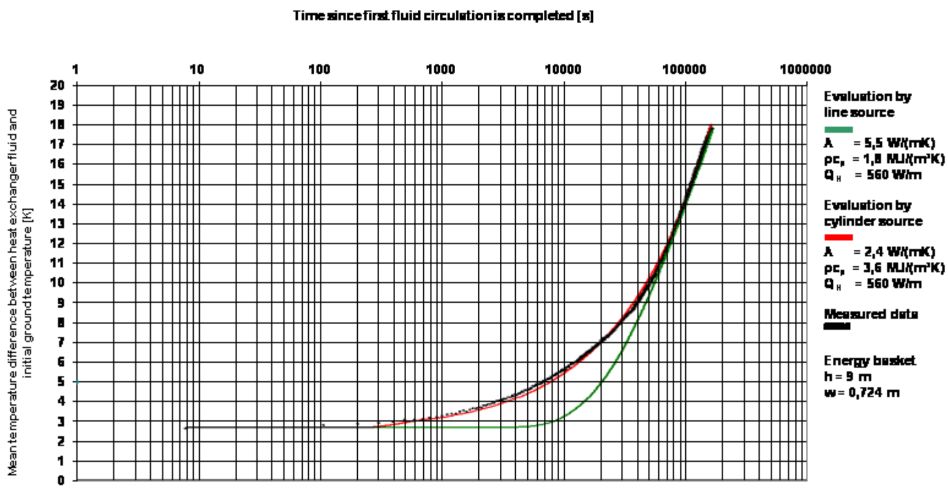

Figure 2: Evaluation of a measurement at a cylindrical energy basket by line and cylinder source approach (calculated with the TRT 1.3 Geologik Software).

2. DATA INTERPRETATION AND BORDER CONDITIONS

Similar to groundwater pump tests results, the early TRT (see Fig. 3) phase behaviour shows the level of disturbance of the drilled BHE in detail. The following phases show the surrounding formation and changing border conditions. This requires an evaluation of the single phases and over the whole measured period. The running time of a GRT fixes the investigation depth into the surrounding formation. Additionally the geometry and mass of the heat exchanger has to be considered when a GRT is planned and executed.

Using 1st derivation data, the floating conductivities can be determined (Eq. 3) if the line source approach is valid.

$$\lambda_{eff} = \frac{\dot{Q}_H}{4\pi \cdot \phi} \qquad (3)$$

Thereby the graph can be divided into sections of different conductivities which represent the skin zone, grout and formation (see Fig. 4). If a high resolution data set from an eGRT is analyzed in that way, the quality of the grout is testable and sections of grout failure are detectable.

Fig. 5 shows that more than 2500 min (ca. 2 days) are needed to reach the temperature response of the surrounding formation. The formation temperature reaction on the Duplex-U-BHE can be seen after ca. 800 min (< 1 day). If an energy pile is measured, then it takes 4 days or more to get the temperature response of the geologic formation. This is due to the high mass of the pile which needs a long time to be loaded by thermal energy. Therefore the measurement time has to be adapted to the exploration task.

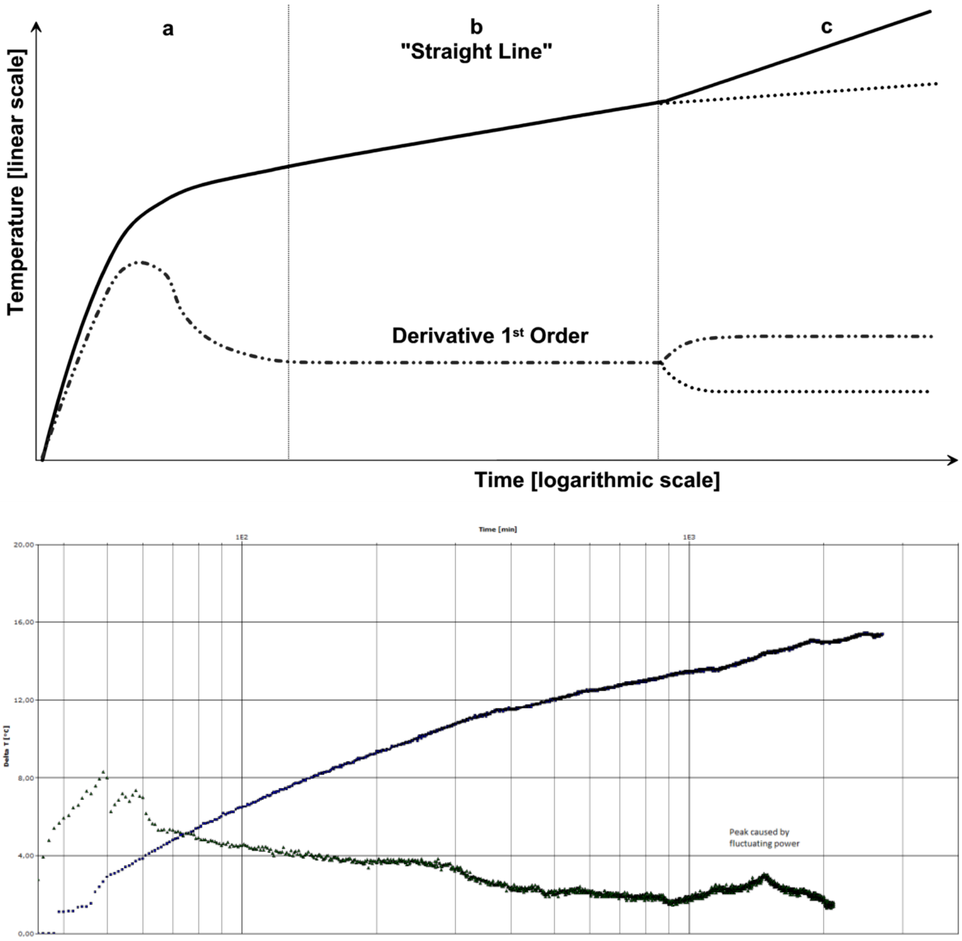

Figure 3: A typical TRT measurement result, showing the 1st derivation of the data acquisition function with a) completion affected unsteady-state in the initial phase b) transient "infinite acting radial flow" [IARF] behaviour (straight line phase) and c) phase where boundary conditions for the heat conduction into the neighbouring formations are changing. The upper figure shows the theoretical behaviour - the graph below shows a real measurement.

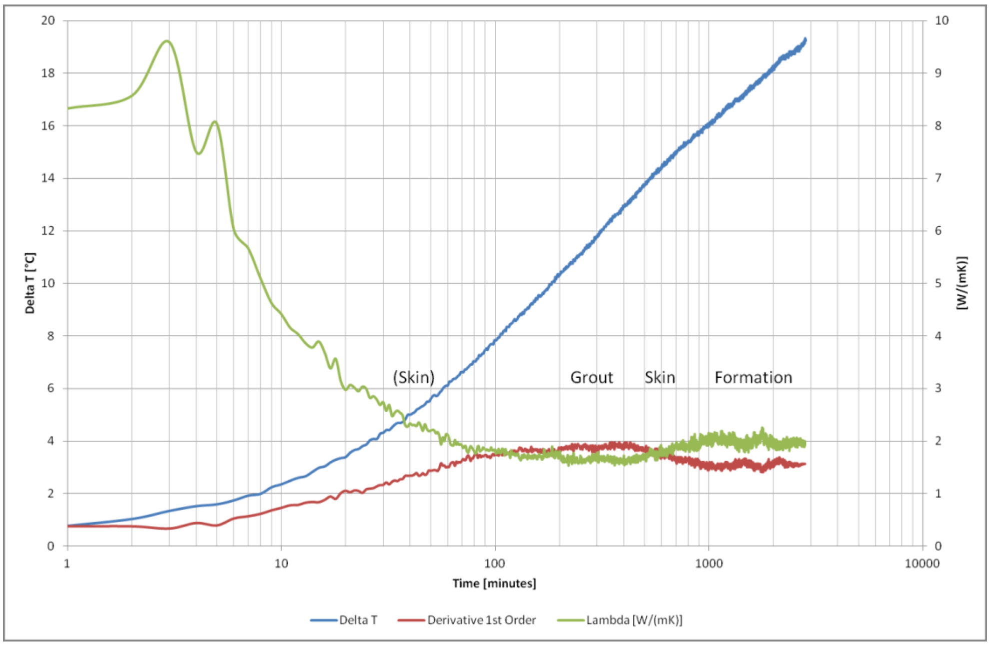

Figure 4: Data from a GRT measurement (Duplex-U-BHE) and associated properties of skin, grout and formation.

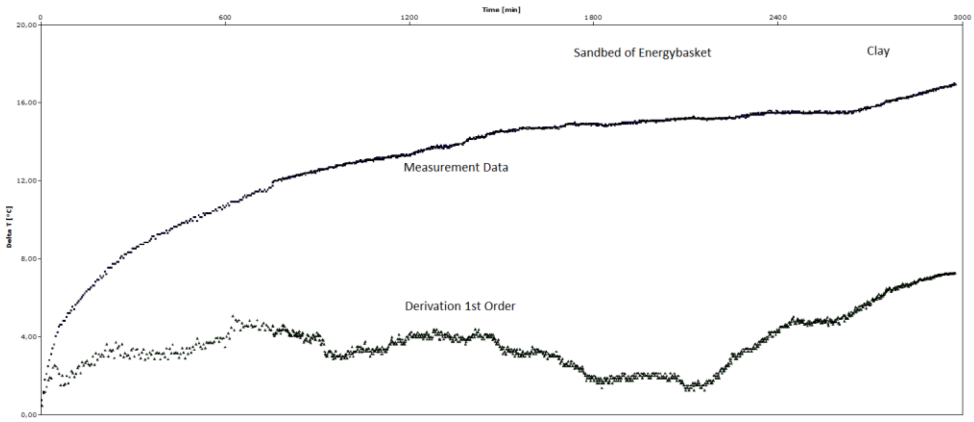

Figure 5: Measurement in an energy basket; the 6.5 m high basket was installed in a 0.6 m diameter sandbed. The surrounding formation is clay.

2.1 Peclet number correlation

The Peclet number analysis [Eq. 4] is a one dimensional evaluation method to determine the Darcy flow from GRT data. The Peclet number [Pe] describes the balance between conductive and convective thermal conductivity in correlation to the thermal flow by mass (Zschocke, 2005).

$$P_e = \frac{\lambda_{cond+conv} - \lambda_{cond}}{\lambda_{cond}} = \frac{\lambda_{cond+conv}}{\lambda_{cond}} - 1 \tag{4}$$

If the conductive thermal conductivity is known or can be estimated (Fig. 6), the convective thermal conductivity can be determined. Furthermore the Darcy flow can be calculated by Peclet number analysis [Eqs. 5 – 7]. Therefore a high resolution eTRT is needed to identify layers of groundwater flow with affected thermal conductivity, and those of none (Lehr, C., Sass, I., 2014).

$$P_e = \frac{q_a}{q_c} = \frac{\rho c_p v_f \Delta T}{\lambda \left(\frac{\Delta T}{l_c}\right)} \tag{5}$$

$$v_f = \frac{P_e \lambda}{l_c \rho c_p} \tag{6}$$

$$v_f = \frac{\lambda_{cond+conv} - \lambda_{cond}}{l_c \rho c_p} \quad (7)$$

2.2 Temperature profiles

A short time GRT (Heat-Pulse-Test) is used for thermal activation of the subsurface. This is not done to determine geophysical properties of the subsoils. The heat pulse will be combined with serial temperature profiles over depth. The profiles show the groundwater influenced profile sections (Fig.7). Additionally, grout failures can be detected. Sections with missing or defect grout have bad thermal contact to the surrounding geologic formation and therefore abnormal lasting times of temperature decay.

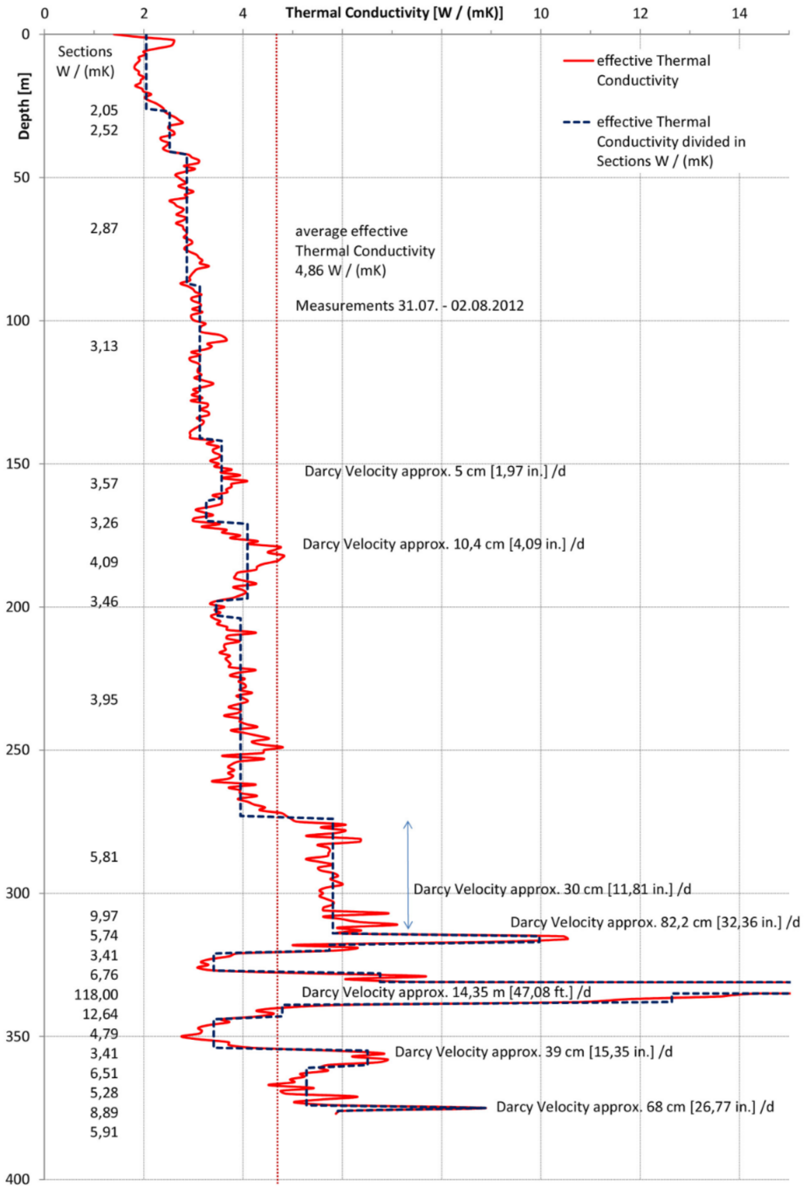

Figure 6: Determination and correlation of the effective thermal conductivity with the groundwater flow regime (Sass & Lehr, 2013).

3. CONCLUSIONS

GRT and eGRT data are analyzable in many ways. With respect to the deployed heating source geometry it is important to use the adequate evaluation method to get proper results. Aditionally the run time of the measurement has to be adapted to the investigation task.

Heat and heat transport mechanisms are widely useable to characterize geologic environments, determine geophysical properties of the subsoil and grout as well as the detection of groundwater and groundwater flow. The knowledge of geophysical parameters like temperature, heat conduction and groundwater flow are important for geothermal engineering, modelling and monitoring. The measuring and evaluation methods and their considerable benefits for engineering and characterization of geologic environments are presented.

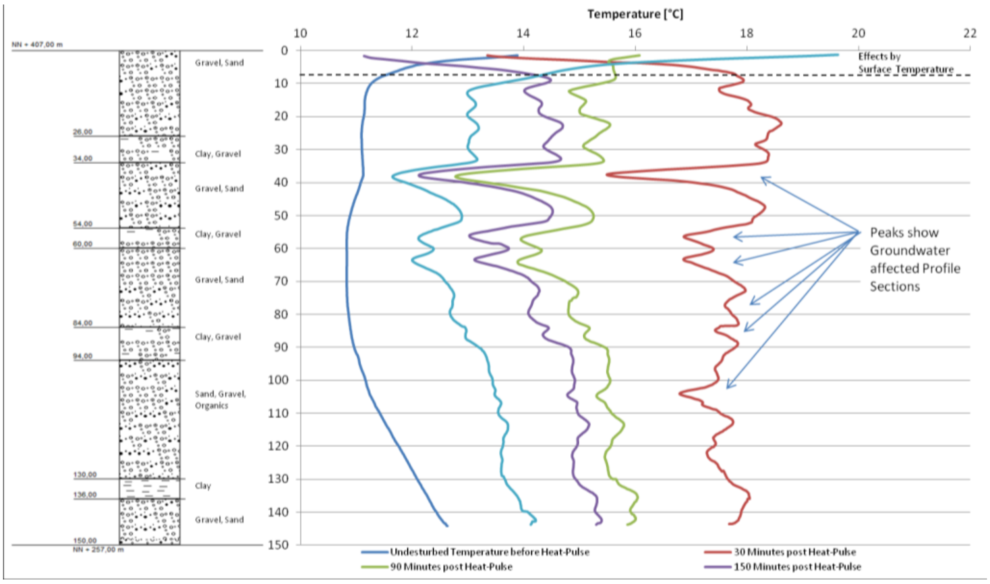

Figure 7: Serial temperature profiles over depth before and post Heat-Pulse.

TABLE OF SYMBOLS

a	Thermal diffusivity	[m²/s]
ρc_p	Volumetric heat capacity	[MJ/(m³ K)]
$\mathrm{erf}(x)$	Gaussian error function	
H	Length of BHE	[m]
$Ei(x)$	Exponential integral	
$I_0(x)$	Cylinder function after Bessel	
l	Length of pipe	[m]
$\dot{Q}_H$	Specific heat input	[W/m]
r	Effective radius of the heat source	[m]
R	Radius of cylinder source	[m]
T_f	Mean temperature of the heat exchanger fluid	[°C]
T_0	Average undisturbed temperature of ground	[°C]
t	Time	[s]
x, y, z	Cartesian coordinates	
τ	Function of time	
$\Delta\vartheta$	Difference of temperature	[K]
π	Pi 3.141….	
ϑ	Temperature	[°C]
φ	Time dependent function over radius	
ζ, ψ, ξ	Time dependent functions over x,y,z Direction	
λ	Thermal conductivity	[W/(mK)]
λ_{Eff}	Effective thermal conductivity	[W/(mK)]
ϕ	Inclination of temperature curve over logarithmical time scale	
q_a	Convective thermal flow	[W/m²]
q_c	Conductive thermal flow	[W/m²]
ρ	Density of fluid	[kg/m³]
c_p	Specific heat capacity of fluid at constant pressure	[J/(kg/K)]
v_f	Darcy velocity of fluid	[m/s]
ΔT	Thermal spread	[K]
λ, λ_{cond}	Thermal conductivity of solid	[W/(mK)]
λ_{conv}	Thermal conductivity of fluid	[W/(mK)]
l_c	Characteristic length	[m]

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