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Evaluation of ground thermal properties and specification of the geological structure using thermal response test, natural gamma, and resistivity data

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The primary objective of this study is to identify the ground thermal properties of the local geological structure and to investigate the geological structure. The knowledge of underground thermal properties is necessary to design borehole heat exchangers (BHE) for Ground Source Heat Pumps (GSHP). Particularly for commercial GSHP, main thermal parameters should be measured on site. A thermal response test (TRT) is performed on one or more borehole heat exchangers in a pilot borehole. This borehole is a part of the borehole field. A TRT enables to collect the data to be used for ground thermal parameters calculation, i. e. the thermal conductivity and resistivity. The heat load to be injected into the BHE is predefined in advance; the resulting temperature changes of the circulating fluid and flow rate are measured. The paper presents a short description of the basic concept and theory of TRT, shortly reviews the experience of this technology. The main aim of the presented study and calculations is to start creating efficient methodology to estimate main thermal parameters (thermal conductivity and thermal resistance) in Lithuania. The most used line-source methods and the results will be presented and compared against the numerical method. Circulating fluid and borehole temperatures would be analytically calculated in order to estimate the impact on the underground temperature field.

Key words: underground heat energy storage, geothermal energy, thermal conductivity, thermal resistivity, borehole heat exchanger, ground source heat pump, thermal response test, renewable energy source

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INTRODUCTION

The construction of the High-tech Research Center was started in Mokslininkų Street in Vilnius in 2010 (Fig. 1). The construction area is 7 776 m^2. It was an ambitious plan to build a modern building, which would use energy from different natural renewable sources, including geothermal ground energy for heating and cooling demands. Building dependents of heating and cooling are 2.2 MW/h and 0.9 MW/h, respectively. The borehole heat exchangers (BHE) for GSHP were installed under the building due to the limited area. The BHE has the following parameters: 109 single "U-shape" collectors; *rb* – borehole radius 0.085 m; depth 150 m; grout material – drilling mud and 4–16 mm ø sand.

The investigations of the geological section are required by THE UNDERGROUND LAW OF THE REPUBLIC OF LITHUANIA. Shallow underground resources can be utilized only after the evaluation of the influence on the natural environment. The underground resources must be

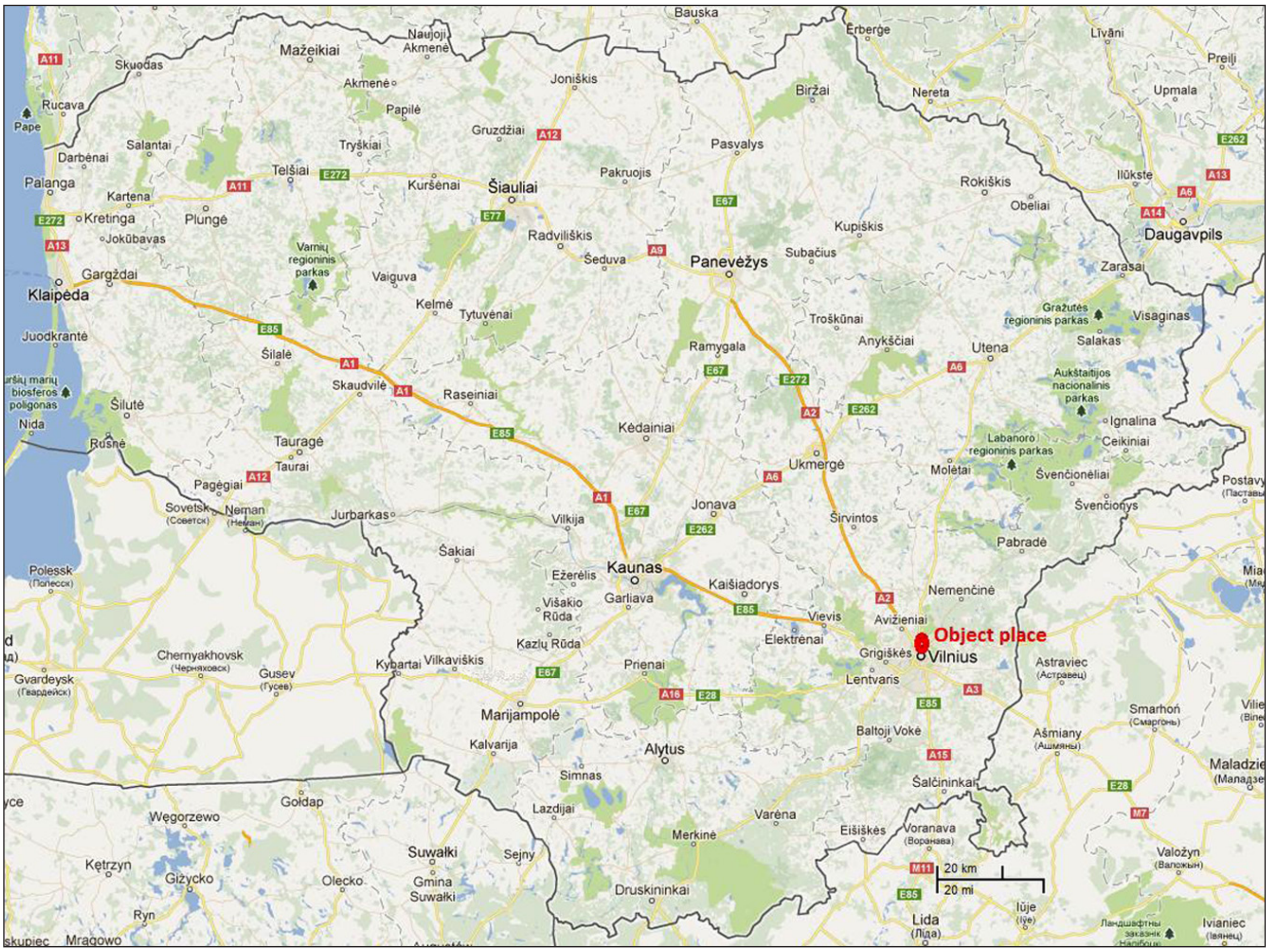

Fig. 1. Study site location
1 pav. Objekto situacinė schema

exploited rationally, it is obligatory to monitor the state of the resources, to predict changes in their quantity and quality and the exploitation influence on the environment, and carry out accounting of the deposits which are extracted and remaining in the deposit (Article 15–16. The Conditions for Exploitation of the Underground Resources). The main point of geological investigations was to identify the geological layers, estimate the thermal parameters and present the state of the whole geological section.

In order to ensure high efficiency of GSHP, the collected data were analysed and computed by the mathematical methods; the optimum size of GHE must be counted according to the identified geological section and estimated soil parameters. Geological interpretation of the collected data was performed to estimate thermal parameters of the geological section.

The most important parameters are the thermal conductivity and thermal resistivity of the geological layers. Thermal Response Test (TRT, also called "Geothermal Response Test", GeRT) is a convenient and suitable method to determine the effective thermal conductivity of the underground and the borehole thermal resistance (or the thermal conductivity of the borehole filling, respectively). During past two decades TRT has been developed to measure the underground thermal properties on site (Gehlin, 1997). A mobile equipment has been built for these measurements in several countries.

A fluid temperature curve will be evaluated by different line-source methods. Other effects like convective heat transport (in permeable layers with groundwater) and further disturbances are automatically included, so it may be more correct to speak of an "effective" thermal conductivity λ eff.

There are many possible sources of error when performing a TRT. They can be grouped in two categories:

- Underground influence (high regional groundwater flow, confined or artesian groundwater in combination with not or poorly grouted BHE, karst, etc.);
- Technical influence (fluctuations of thermal power, sensor errors / failures, system leakage, etc.; also poor thermal insulation in combination with solar irradiation or ambient temperature changes).

Some external influence by groundwater flow or by power fluctuations can be accounted for when using numerical simulation for test evaluation. However, there are practical cases where a meaningful test result cannot be obtained at all due to this external influence.

THE GEOLOGICAL INTERPRETATION OF LOGGED DATA

During the initial project stage (Fig. 2) a number of parameters were obtained in order to have a proper

Fig. 2. Initial phase of the project: *a* – drilling the borehole; *b* – performing gamma log; *c* – installing the BHE; *d* – performing a TRT test; *e* – BHE field; *f* – completed building

2 pav. Įvairūs projekto etapai: *a* – gręžskylės įrengimas; *b* – natūralaus geologinių sluoksnių radioaktyvumo ir elektros varžos matavimai; *c* – gręžskylinio šilumokaičio įrengimas; *d* – terminės reakcijos tyrimo duomenų kaupimas; *e* – gręžskylinių šilumokaičių laukas; *f* – pabaigtas pastatas description of the geological layers of the test borehole. The identification of the geological structure was performed in the test borehole gathering the samples of the soil during the drilling, logging the data of natural gamma and electrical resistivity (Fig. 3). The ground thermal properties were estimated using the data received from the thermal response test, which was executed *in-situ*. The data

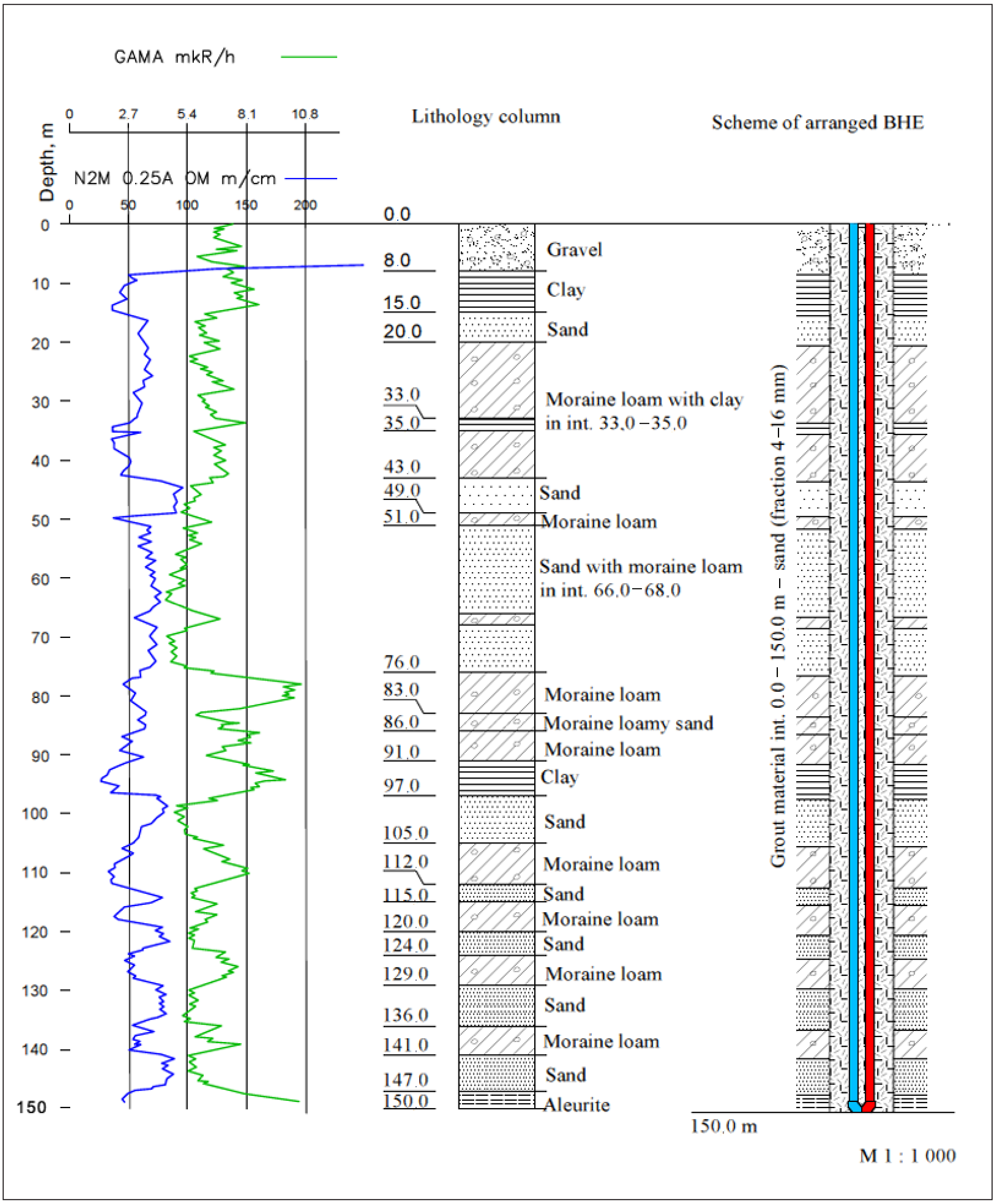

Fig. 3. Gama-ray logging and electric resistivity of the test borehole and the scheme of the arranged borehole heat exchanger

3 pav. Geologinių sluoksnių natūralaus radioaktyvumo ir elektros varžos kreivės, gręžskylinio gruntinio šilumokaičio įrengimo schema are used only for the purposes of analysis, geological interpretation and evaluation of ground thermal properties of the given local geological structure.

DEVELOPMENT OF THE THERMAL RESPONSE TEST

Nowadays, TRT is widely utilized to determine the ground thermal properties as well as the heat-transfer performance between the ground and the BHE. Thermal response of the borehole is the change occurring in its temperature when a heat carrier fluid circulates through the borehole heat exchanger for a certain period of time. It is based on constant heat (or cool) flux extraction by means of a heat carrier fluid which circulates through a BHE system. The temperature data of the inlet and outlet fluid from the BHE are measured and logged. The study of the fluid temperature versus time enables the estimation of thermal properties in and around the borehole. There are different methods to estimate the ground thermal properties at the location of the BTES system by means of standard values for the type of rock or laboratory methods (Sundberg, 1998). However, these methods do not offer complete information of the ground characteristics. Mogensen (1983) was the first who applied this method to determine the *in-situ* ground thermal conductivity and thermal resistance of the borehole. Although conventional TRT is not an accurate system, it has been widely applied to determine the optimum design BHE. Determination of ground parameters was first suggested by Claesson and Eskilson (1988). In 1995–1996, "TED", the Swedish response test apparatus, was developed at the Luleå University of Technology (Eklöf, Gehlin, 1996; Gehlin, Nordell, 1997) to determine ground thermal conductivity and the influence of the effect such as groundwater flow and natural convection in the boreholes. More details about the response test apparatus can be found in Gehlin (1998) and practical application was made by Hellström (1997) (Fig. 4). A similar development has been going on independently since 1996 at Oklahoma State University in the USA (Austin, 1998).

At the same time, a variety of analytical and numerical data analyses have been developed to improve this method. In Europe, the common model for evaluation of the response test data is line-source due to its ease of operation and speedy response. However, the cylinder source combined with numerical models is usual in the USA.

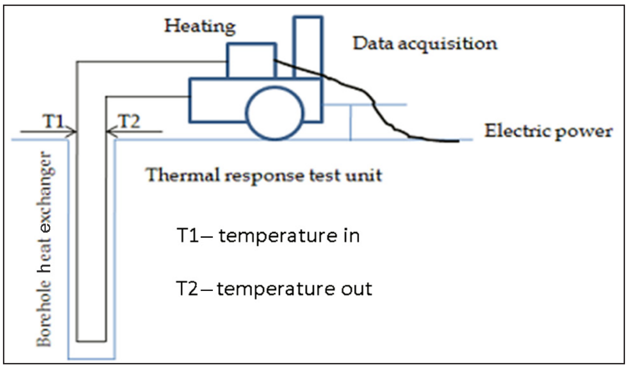

Fig. 4. Outline of the principle of the thermal response test (Gehlin, 1997)
4 pav. Principinė terminės reakcijos tyrimo schema (Gehlin, 1997)

For good results, it is crucial to set up the system correctly and to minimize external influences. With resistance heating, the fluctuations of voltage in the grid may result in fluctuations of the thermal power injected into the ground. Another source of deviation is climatic influences, affecting mainly the connecting pipes between the test rig and BHE, the interior temperatures of the test rig, and sometimes the upper part of the BHE in the ground. Insulation and sometimes shading is required to protect the connecting pipes. With open or poorly grouted BHE, also rainwater intrusion may cause temperature changes. A longer test duration allows for statistical correction of the power fluctuations and climatic influence, and results in a more trustworthy evaluation.

ANALYSIS OF THERMAL RESPONSE TEST DATA

Analytical and numerical models are developed to evaluate the circulating fluid temperature data of TRT, which are described in detail by Gehlin (2002). For the purpose of the thermal response test evaluation, the following assumptions are taken into account in analytical and numerical models:

- Convective heat transfer in the ground is neglected.
- Thermal process is symmetry in the radial direction from the borehole axis.
- Heat conduction is negligible in the direction along the borehole axis.

Analytical and numerical models

The main analytical models are used to evaluate thermal response data by line-source and cylinder source approaches. The heat transfer problem between the borehole and the nearby infinite region is assumed as an analytical solution of the line and cylinder source model.

Line-source models

The temperature field of the ground can be written as a function depending on time (t) and radius (r) around a line source with a constant heat injection rate (q) from a line along the vertical axis of the borehole in an infinite solid (Carlslaw, Jaeger, 1959):

$$T_b^a(r,t) = \frac{q}{4\pi\lambda}\int_{\frac{r^2}{4\alpha t}}^{\infty}\frac{e^{-u}}{u}du = \frac{q}{4\pi\lambda}E_1\left(\frac{r^2}{4\alpha t}\right). \tag{1}$$

It should be noted that the line-source temperature is evaluated at the borehole radius ($r = r_b$). The effect of the thermal resistance Rb between the fluid inside the pipe and the borehole wall can be written by a fundamental relation:

$$T_f^q(t) - T_b^a(t) = q \cdot R_b. \tag{2}$$

The following assumptions might be included that the heat extraction rate q [W/m] along the vertical axis of the borehole is constant, the ground temperature is undisturbed before the injection to the underground and its BHE surrounding is homogeneous and isotropic. In 1983 Mogensen applied the line-source model to estimate the ground thermal conductivity by means of an experimental field test. The exponential integral E1(r2/4αt) can be simplified and the equation (2) can be written as:

$$T_f^q(t) = \frac{q}{4\pi\lambda_{\text{eff}}}\left(\ln\left(\frac{4\alpha t}{r_b^2}\right) - \gamma\right) + q \cdot R_b + T_{ug}. \tag{3}$$

It is analysed that the maximum error is 2.5% for values of $\left(\frac{\alpha t}{r^2}\right) \geq 20$ and 10% for $\left(\frac{\alpha t}{r^2}\right) \geq 5$.

It is well known that the power heat flux is not constant during the TRT (Gehlin, Eklöf, 1996). For this purpose Eskilson (1987) and Hellström (1991) described this heat pulse analysis. The difference between the borehole temperature and undisturbed ground temperature could be defined by the following equation:

$$\Delta T(q_1, q_2, \ldots, q_n) \equiv \Delta T(q_1) + \Delta T(q_2) + .. + \Delta T(q_n). \tag{4}$$

The heat injection or / and extraction may be accounted as stepwise of constant heat pulses that are then superimposed in time. For a heat pulse analysis, the following method is used:

$$q(t) = \begin{cases} q_{1,}\, t_1 < t < t_2 \\ q_{2,}\, t_2 < t < t_3 \\ \\ q_n, t_{n-1} < t < t_n \end{cases}. \tag{5}$$

Notice that q_o and t_1 are equal to zero and *qref* can be given in any value except zero. The equation (2) can be also defined as:

$$T_f^q(t) = \frac{q_{ref}}{4\pi\lambda_{\text{eff}}}\tau_N(t) + q_N\left(\frac{1}{4\pi\lambda_{eff}}\left(\ln\left(\frac{4\alpha}{r^2}\right) - \gamma\right) + R_b\right) + T_{ug}, \tag{6}$$

where $\tau_N(t) = \sum_{n=1}^{N}\frac{q_n - q_{n-1}}{q_{ref}}\ln(t - t_n)$ and the time t should be in the interval $t_N + \frac{r_b}{5\alpha} < t < t_{n+1}$.

Gehlin (2002) has got the results about the continuous line-source described in the equation (2), in which the exponential integral E1(rb2/4αt) is assumed as an approximation of a serial function (Abramowitz, Stegun, 1964):

$$E_1(x) \approx -\gamma - \ln x + Ax - Bx^2 + Dx^3 - Ex^4 + Fx^5, \tag{7}$$

where constants are described by values A = 0.99999193, B = 0.24991055, D = 0.05519968, E = 0.00976004, F = 0.00107857, accordingly. Here rb2/4αt = x and the equation for analysis is as follows:

$$T_f^q(t) = \frac{q}{4\pi\lambda_{eff}}E_1(x) + q \cdot R_b + T_{ug}. \tag{8}$$

The numerical method developed by Eskilson (1987) is used to compare the calculated estimates of thermal resistivity and thermal conductivity of the above mentioned analytical models. The g-function has a similar expression as well as the equation (3):

$$q\left(\frac{t}{t_s};\frac{r_b}{H}\right) = \begin{cases} \ln\left(\frac{H}{2r_b}\right) + \frac{1}{2}\ln\left(\frac{t}{t_s}\right), \frac{5r_b^2}{\alpha} < t \leq t_s \\ \ln\left(\frac{H}{2r_b}\right), t \geq t_s \quad t_s = \frac{H^2}{9\alpha} \end{cases}. \tag{9}$$

Using the equation (8) the circulated fluid temperature is as follows:

$$T_f^q(t)=T_{ug}+\frac{q}{2\pi\lambda_{eff}}g\left(\frac{t}{t_s};\frac{r_b}{H}\right)+q\cdot R_b. \qquad (10)$$

The necessary formulas of the borehole thermal resistance and thermal conductivity will be expressed from this equation.

Expression of thermal conductivity

The line-source theory was used in the 40s to calculate the temperature in the ground over time for ground source heat pump plants (Ingersoll, Plass, 1948). An approximation is possible with the following formula, given by Eklöf and Gehlin (1996):

$$k=\frac{q}{4\pi\lambda_{eff}}, \qquad (11)$$

where k is the inclination of the curve of mean fluid temperature versus the logarithmic time t.

To calculate thermal conductivity, the formula has to be transformed according to the equations (3), (6), (10), there is a linear relation between the temperature and parameters $\ln(t)$, $\tau_N(t)$, $\ln(t)$. It should be noted that line-source approximation requires the quasi steady-state regime for good results.

Spitler (1999, 2000), Shonder and Beck (1999) proposed estimation of parameters using numerical modelling to get results in a transient thermal regime. This is time-consuming way, but it would enhance accuracy of estimates when heat flux is not constant during TRT, and convective influence from groundwater is accounted for.

Expression of borehole thermal resistance

The thermal conductivity of the underground is site-specific and cannot be influenced by engineering constructions. The thermal resistance from the borehole wall to the circulating fluid inside the pipes is controlled by the borehole diameter, pipe diameter and material, and the filling (grout) (Fig. 5).

These following equations are valid below when the thermal process

- within the borehole is near steady-state condition and
- the initial 500 minutes of TRT are neglected in a TRT.

The borehole thermal resistance ($R_b(t)$) can be determined using the following formula:

$$R_b(t)=\frac{T_f^q(t)-T_{ug}}{q}-\frac{1}{4\pi\lambda_{eff}}\left(\ln\left(\frac{4\alpha t}{r_b^2}\right)-\gamma\right). \qquad (12)$$

In a similar way expressions of $R_b(t)$ would be expressed according to the equations (3), (6), (8), (10). If the thermal conductivity of the borehole filling (grout) would be increased, the borehole thermal resistance R_b is decreased.

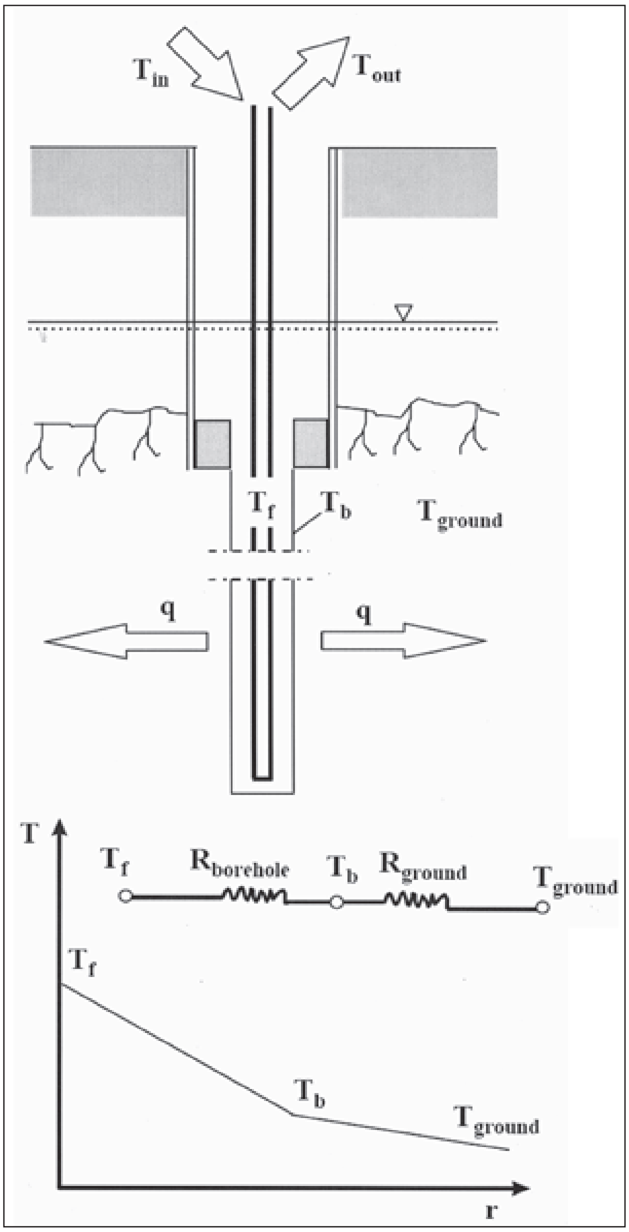

Fig. 5. Thermal resistance fundamental in the borehole heat exchanger (Gehlin, 2002)
5 pav. Šiluminės varžos gręžskylėje principinė schema (Gehlin, 2002)

VALIDATION OF THERMAL CONDUCTIVITY AND THERMAL RESISTANCE

Calculation results

The results from TRT data were used in formulas that are mentioned above. During TRT the circulated fluid temperatures are logged and presented in Fig. 6. Every 10 seconds the values of fluid temperatures were measured and collected.

The circulated fluid mean temperature is evaluated by simple regression where the first member of simple regression is expressed by the logarithmic function (Fig. 7). For further calculations the injected heat power was simulated using normal distribution with the mean value equal 6.656 kW.

In such a way the thermal conductivity values λ_{eff} have been written in the formula (12). Using these formulas estimates of thermal conductivity are given in Tables 1, 2.

It would be good to have different TRT-rigs and test BHE-field in order to get more experience in doing sufficient TRT research.

Table 1. **Calculated mean values of thermal conductivity and thermal resistivity**

1 lentelė. **Apskaičiuotos šilumos laidumo ir gręžskylės šiluminės varžos vidutinės vertės**

Model	λ, W/mK	Rb, mK/W
Mogensen	2.208259	0.154947
Eskilson-Hellstrom	2.176731	0.153017
Abramowitz-Stegun	2.144866	0.151054
Eskilson	2.208259	0.154881

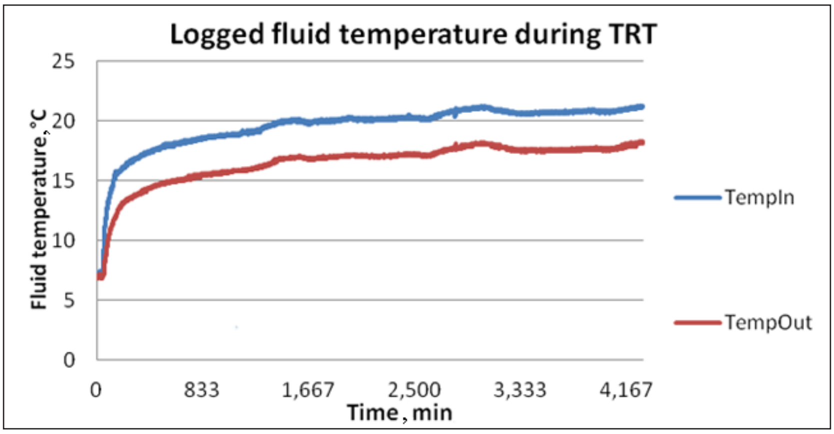

Fig. 6. Time plot of fluid temperatures
6 pav. Skysčio temperatūros kitimo laiko grafikas

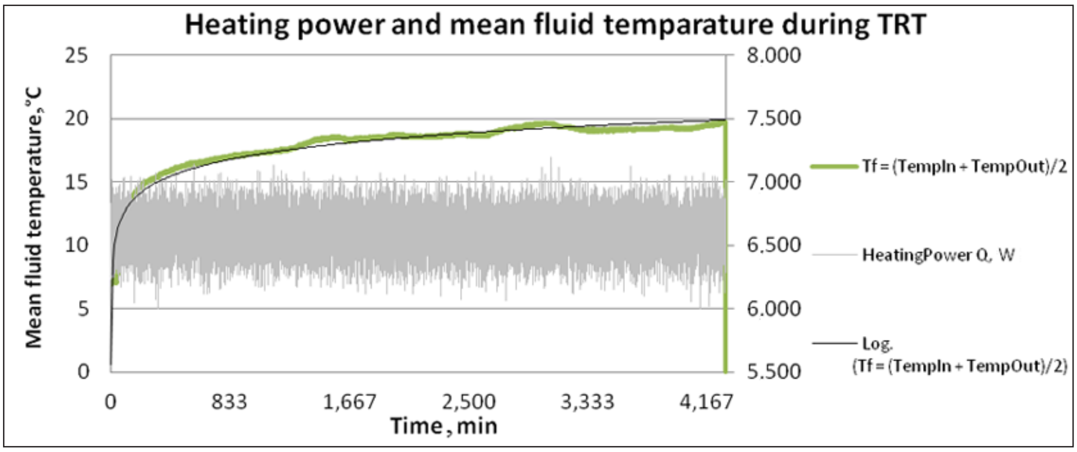

Fig. 7. Mean fluid temperature and injected heat power during TRT
7 pav. Vidurkinė skysčio temperatūra ir TRT tyrimo metu įpumpuotos energijos kiekis

Table 2. **Calculated values of thermal resistance R_b**

2 lentelė. **Gręžskylės šiluminės varžos medianos ir standartinio nuokrypio vertės**

Rb, mK/W	Mogensen	Eskilson-Hellstrom	Abramowitz-Stegun	Eskilson
Median	0.153383	0.151422	0.149478	0.153317
Standard deviation	0.005256	0.005155	0.005333	0.005256

External influences

A useful method to check for excessive groundwater flow in the standard line-source evaluation is the step-wise evaluation with a common starting point and increasing length of dataseries. The resulting thermal conductivity for each time-span can be calculated and plotted over time. Usually in the first part of such a curve the thermal conductivity swings up and down, converging to a steady value and a horizontal curve in the case of a perfect test. If this curve continues to rise (i. e. the more heat is carried away the longer the test lasts), a high groundwater flow exists and the test results may be useless. This method also shows other external factors (Fig. 8).

CONCLUSIONS

The comparison of results was performed for the site constructing a new BHE-field in February 2012 (Visoriai, Vilnius). The results are similar and with good accuracy compared with those the experts have presented. Confidential results would be not presented here until the permissions are not given.

From this size BHE (109 single "U" shape BHE, 150 m depth each) and this geological formation it is possible to extract up to 700 MWh of heat, and up to 600 MWh of cooling energy during the year cycle only in the passive way. The extraction of heating and cooling energy would be increased if the additional heat energy is injected into the underground.

The rational exploitation of underground thermal storage must be provided for every GSHP system according to the seasonal building demands of heat or lower temperature heat energy.

Ensuring the quality of the ground heat storage and high efficiency of GSGP, according to the identified geological structure the following must be forecasted: the time periods and the quantity of injected thermal energy to the underground for the forced regeneration of the ground thermal storage.

It is obligatory to monitor the state of the ground heat storage and predict the ground temperature changes in its quantity and quality, seeking to account the potential on the ground thermal energy.

ACKNOWLEDGEMENTS

I am deeply grateful to professors and lectors from the Faculty of the Natural Sciences of the Vilnius University for my first acquaintances with the new geology science. Special thanks to Prof. Saulius Šliaupa for his support and advices during the very first experience of the TRT in Lithuania.

Doc. Mykolas Dobkevičius had inspired and encouraged guidance during my Bachelor and Master Thesis. The recommendations given by

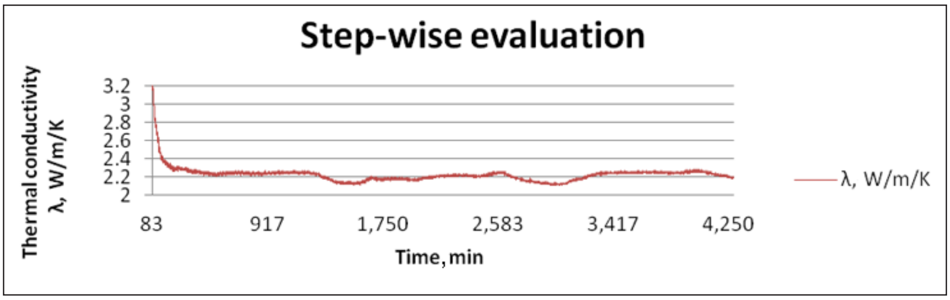

Fig. 8. Perfect thermal conductivity convergence and unstable heating power
8 pav. Idealaus šilumos laidumo konvergavimas pagal įpumpuotą energijos kiekį

Prof. Vytautas Juodkazis, Prof. Robert Mokrik and Prof. Kastytis Dundulis were used indirectly in this paper. Special thanks to the company BOD GROUP for the possibility to use their test borehole and TRT data for the geological research. They as I wish to consume less imported fuel and produce less CO_2 by using the ground thermal energy. These patriotic ideas should make our land a better place where everyone wants to live. There are many more people in Lithuania and abroad who have helped, one of them being Vytautas Sakalauskas who has blessed me for a successful cooperation in the work with geologists when performing the TRT test.

Without all the above mentioned support this work would not have been realized. I want to thank once more everyone who have taken part in this important and perspective research.

Abbreviations

α – ground thermal diffusivity [m^2/s];
cp – volumetric heat capacity [J/m^3K];
c – volumetric heat capacity [J/m^3];
$E_1(r^2/4\alpha t)$ – exponential integral;
H – effective borehole depth [m];
γ – oiler constant, 0.5772;
k – slope;
R_b – borehole thermal resistance [K m/W];
R_r – rock thermal resistance [K m/W];
R_T – total ground thermal resistance [K m/W];
r_b – borehole radius [m];
Q – injected heat power rate [W];
q – heat flux [W/m];
t – time [min];
T_b – borehole wall temperature;
T_f – circulating fluid mean temperature in the collector;
T_{ug} – undisturbed ground temperature [°C].

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GEOLOGINĖS STORYMĖS ŠILUMINIŲ SAVYBIŲ ĮVERTINIMAS IR APIBŪDINIMAS NAUDOJANT ŠILUMINĖS REAKCIJOS METODĄ BEI NATŪRALAUS RADIOAKTYVUMO IR ELEKTROS VARŽOS DUOMENIS

Santrauka

Pagrindinis šio tyrimo tikslas yra apibūdinti vietovės geologinę sandarą, nustatyti storymės šilumines savybes ir sutapatinti jas su nustatytais geologiniais sluoksniais. Geologinės storymės šiluminių savybių pažinimas yra būtinas projektuojant geoterminių šilumos siurblių sistemas, ypač komerciniuose ar pramoniniuose objektuose. Pagrindiniai šiluminiai uolienų parametrai turi būti matuojami vietoje. Priklausomai nuo vietovės geologinių sąlygų vienalytiškumo terminės reakcijos tyrimas (Thermal Response Test – TRT) yra atliekamas viename ar keliuose tiriamuose gręžskyliniuose šilumokaičiuose, kurie paprastai yra geoterminės sistemos lauko kontūro dalis. TRT tyrimas leidžia surinkti duomenis, kuriais remiantis nustatomi pagrindiniai Žemės gelmių šiluminiai parametrai. Apskaičiuojamos uolienų šiluminio laidumo, temperatūros perdavimo ir papildomos gręžskylės varžos vertės. Straipsnyje aprašoma TRT metodika, apžvelgiama šios metodikos istorija ir sukaupta patirtis. Šio darbo ir skaičiavimų pagrindinis tikslas – sukurti metodiką, kuri leistų racionaliai naudoti ne tik Žemės gelmių šiluminius išteklius, bet ir efektyviai panaudoti geologinę uolienų struktūrą šiluminės energijos kaupimui Lietuvoje.

Raktažodžiai: požeminės šiluminės energijos kaupimas, geoterminė energija, šiluminis laidumas, šiluminė varža, gręžskylinis šilumokaitis, geoterminis šilumos siurblys, terminės reakcijos tyrimas, atsinaujinantys energijos ištekliai