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Assessment of the Influence of Shortening the Duration of Thermal Response Test (TRT) on the Precision of Measured Values

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ABSTRACT

In this paper the results of testing thermal parameters of the rock environment and measurement of borehole temperature profiles of the newly constructed experimental underground heat storage (BTES) in Paskov (Czech Republic) obtained with the thermal response method (TRT) and temperature measurement on boreholes at selected depth levels are summarised. The TRT measurement series on eight boreholes has shown the possibility to compare the differences among individual measurements in a practically identical rock environment. The temperature profiling of boreholes enabled studying the dynamics of temperature changes occurring in the rock environment as a reaction to the heat supply during the TRT.

The measurement series was performed with the aim to assess the possibility of shortening the TRT duration while maintaining the acceptable precision of the measured results. For this reason the software simulation of shortening the TRT duration to 24 hours was performed, and the influence of such shortening to the precision of determination of values λ and R_B was studied. The simulation has shown that shortening the test to 24 hours in our case would have brought an acceptable amount of inaccuracy with regard to the dispersion of measured values obtained from the real test.

1 INTRODUCTION

One of the ways to store surplus or unused heat, e.g. from solar panels, cogeneration units or waste heat from industrial technologies, is to accumulate the heat in underground heat storages. Where it is allowed by geology, the storage (known as BTES – Borehole Thermal Energy Storage, or UTES – Underground Thermal Energy Storage) can be constructed. The heat storage is performed through boreholes up to several tens of metres deep. The operating principle of this heat storage is simple. In regular distances, the system of boreholes is drilled into the earth. The boreholes are with the same well-completion as the boreholes for heat pumps. Warm water, e.g. from solar panels, is pumped into the boreholes and this water transfers (stores) heat to the surrounding rock environment. In case of the requirement for heat consumption, the process is reversed. The cooler water in boreholes is warmed by the heated rock and thus the heat of the boreholes is taken from the rock and it is used e.g. for heating buildings. The advantage of this type of heat storage is a lower cost of acquisition [16] when compared to heat storages where energy storage into subterranean water basins (natural or artificial) occurs.

The conditions of heat storage to the surrounding rock environment depend on the geological environment where the heat storage is operated. To verify the behaviour of this type of heat storage under those geological conditions during various predefined operating states, an experimental BTES consisting of 16 energy boreholes, each to the depth of 60 m, was constructed in Paskov.

In the heat storage construction phase, when the borehole field was developed and individual energy boreholes were still not connected through horizontal piping with the aboveground part of the heat storage technology, a series of thermal conductivity and thermal resistance measurements of boreholes and the rock environment using the thermal response method, and a series of borehole temperature profile measurements, was planned.

There are many factors such as the type of rocks in the site, extent of tectonic disintegration of rocks, thickness and type of quaternary covering, presence of flowing groundwater, etc., that influence the mechanism of heat storage in a BTES. These individual factors create a unique combination in each locality whilst the thermal properties of the rock environment, including boreholes as a whole, can be best assessed using a Thermal Response Test (TRT) that checks the ability of the borehole to accept the heat in the whole length under original natural conditions. In contrast to the laboratory research of the thermal conductivity of the rock samples from borehole cores, TRT determines the real thermal conductivity of the whole borehole including the influence of all factors present in the site. In this work, the results of the TRT measurement series in 8 out of the 16 charged boreholes forming the experimental heat storage in Paskov are summarised.

The result of this measurement series was the experimental determination of the dispersion of the measured values of thermal conductivity and thermal resistance in the boreholes, which are located in a square network with a side of 2.5 m, and in the same rock environment.

Simultaneously with the measurement of the thermal response of rocks, temperature profiling was performed on the boreholes of the polygon with the aim to assess the influence of TRT on temperature and its development, both in the tested borehole itself and also in the boreholes in the vicinity of the tested borehole. Based on these measurements, temperature profiles were constructed in the boreholes.

In addition to the measurement of thermal parameters characterising the rock environment where the heat storage is constructed, and which will be subsequently used for its experimental operation and assessment of individual operating modes and states, the measurement was performed with the aim to use the measured data for assessment and evaluation of the possibility of shortening the duration of TRT. The common duration of one test is currently 72 hours. In cases when lengths or numbers of boreholes are changed, or the whole borehole field is modified based on the test results, the possibility of shortening the TRT duration while maintaining the acceptable precision may shorten the duration of drilling operations in the site with a positive influence on the price of these works. In the case of our measured results, as we have seen, TRT can be evaluated already after 24 hours provided that certain conditions are met, whilst the amount of inaccuracy caused by shortening the test is acceptable when compared to the dispersion of measured values of both thermal conductivity and thermal resistance.

2 FOREIGN KNOWLEDGE

In foreign countries attention is paid to the construction of BTES both in the field of theoretical research and also practical implementations in specific sites. The study of the influence of high-temperature energy storage in the rock environment was performed by a research group of the International Energy Agency (IEA), called Energy Conservation through Energy Storage (ECES), under the supervision of prof. Burkhard Sanner, particularly under research project No. 12 – Annex 12, High-Temperature Underground Thermal Energy Storage (HT UTES). The results and the final reports and general recommendations for the construction of high-temperature heat storages can be found on the websites of ECES [10]. The TRT utilization for design of UTES is studied in ECES – Annex 21 (Thermal Response Test for Underground Thermal Energy Storages) [11]. The advantages and problems of the use of BTES are summarised in [15].

Several underground heat storages (BTES type), where the rock environment itself is used for the heat storage, have been constructed throughout the world. Nevertheless, there is not much experience with the storage of thermal energy with a higher temperature of the circulating fluid (70-90°C). The reason is that in most cases the thermal energy is supplied rather for the purposes of thermal regeneration of boreholes for heat pumps. There are not many finished projects where the heat is stored for a long time and subsequently directly used for heating without heat pumps. 7 such projects are known to the authors. They are located at the following sites – Okotoks (Canada); Golm, Neckarsulm, Crailsheim, (Germany), Anneberg, Emmaboda (Sweden), Braedstrup (Denmark). Other purely experimental heat storages have been built beside these sites, such as at the university in Swedish Lund.

3 RESEARCH POLYGONS IN THE CZECH REPUBLIC

The technology of heat storage in the rock environment through the system of boreholes is not thus far verified in practice in the Czech Republic. Whereas there was a large increase in the number of installations where geothermal heat from boreholes is used for heating, there are currently no real BTES installations in the Czech Republic. Monitoring of temperature changes in the rock massive around operating boreholes with installed heat pumps is now performed in several research polygons.

The first experiments with heat storage in the rock environment through boreholes including assessment of its accumulation capability to ensure heat supply were performed by so-called Large and Small Research Polygons (SRP) at the Institute of Mining and Geology (VŠB – Technical University of Ostrava) within the school boundaries in Ostrava – Poruba [3,12].

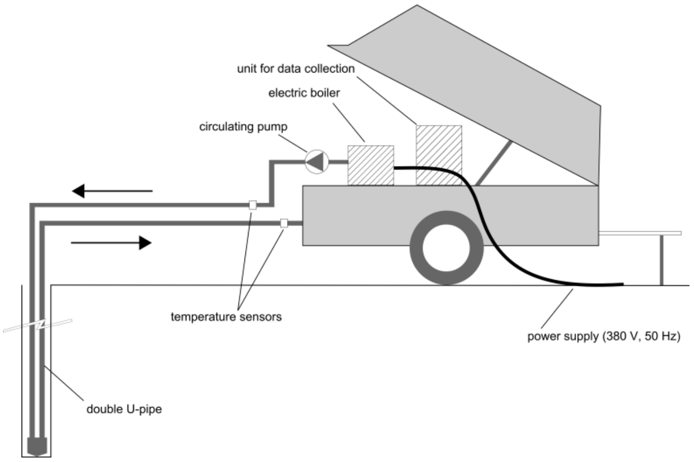

Fig. 1. Thermal Response Test Device.

A new high-temperature research polygon of Green Gas DPB, a.s.

Cooperation between the Institute of Mining and Geology (VŠB – Technical University Ostrava) and the company DHI, a.s. has overseen the first high-temperature experimental BTES in the Czech Republic operating since 2011 (16 energy boreholes, each of a length of 60 m with a max. medium temperature of 95 °C) at the site of the company Green Gas DPB, a.s. This storage, constructed with the support of the Technological Agency of the Czech Republic (TACR), stores excessive waste heat from the Combined Heat and Power (CHP) unit. The aim of the experiment is to assess the behaviour of the rock environment and the storage system as a whole, and to verify its reactions to various operating states simulated in the heat storage, both in heat storage charging and in heat consumption from the storage.

The schematic geological profile in the site of the constructed BTES is visible in Figure 3. The underground storage system itself is located in a partially closed covered object, which partly eliminates external climatic effects.

Design of the BTES

The heat storage consists of 16 energy boreholes performed to the depth of 60 m (see Figure 2). In these boreholes, warm water from the CHP unit circulates and delivers the heat to the surrounding rock environment. The energy boreholes are completed with five monitoring boreholes where the temperature in the specified depth levels of the rock massive is measured. Four out of five monitoring boreholes with the depth of 15 m are located at the edges of the heat storage and are used for monitoring temperature development in the water-bearing rock environment. The central monitoring borehole is 80 m deep and its data enable studying the temperature development in the central part of the heat storage.

The boreholes are always two in a series; therefore there are eight loops, each with two boreholes. The arrangement diagram can be seen in Figure 2, and the technical parameters are given in Table 1.

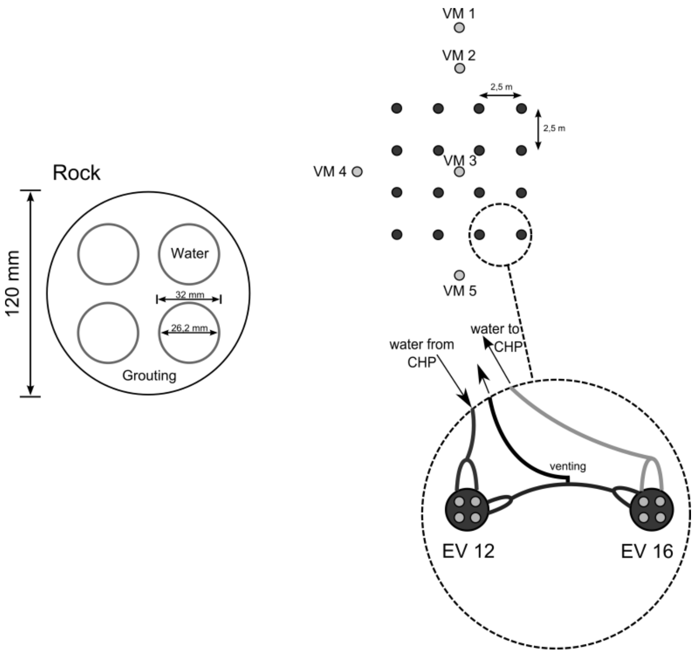

Fig. 2. Sectional view, ground plan and boreholes connection.

Table 1
Details of the borehole system.

Element	Specification
Borehole	
Effective borehole depth	60 m
Borehole diameter	120 mm
Borehole filling material	Cement – bentonite mixture
Surrounding ground type	Sedimentary rock
Heat exchanger	
Type	Double U-pipe
Material	PE-RT
Pipe outer diameter	32.0 mm
Pipe thickness	2.9 mm
Thermal conductivity	0.45 W m^{-1} K^{-1}
Shank spacing	Not controlled
Circulating fluid	
Type	Water
Thermal conductivity	0.60 W m^{-1} K^{-1}

The construction of the small experimental BTES in the Czech Republic represents a unique opportunity to experience a new thermal energy storage technology in a rock environment, and thus open other options for the use of excessive or waste heat.

4 THERMAL RESPONSE TESTS AND TEMPERATURE PROFILING OF BOREHOLES

4.1 TRT theory

A part of the research on the rock environment for construction of the heat storage was the series of thermal response tests for verification of the real thermal properties of the rocks on the site. The thermal response test is a special field test developed in Sweden and the USA in the 1990s [8, 9]. The main output of the test is the measured value of thermal conductivity λ (in W m^{-1} K^{-1}) and thermal resistance R_B (in K m W^{-1}) of the fitting and injection of the borehole and rock environment thermally influenced during the test. The thermal response test plays an essential role in the proposal of numbers, top view location and length of boreholes for heat pumps, as well as for the dimensioning of parameters for BTES systems [14].

A disadvantage of TRT is the time necessary to perform the test. According to ASHRAE [1], the TRT should take at least 36 to 48 hours, while Gehlin [8] recommends 60 hours for the test.

Bozzoli et. al [2] studied the possibility of using the data from the experimental and modeled TRT, where they performed a sensitivity analysis, that showed the possibility of using the data to calculate the properties of grout (or thermal resistance of borehole) after 2-5 hours, and the calculation of the rock mass after 24 hours. There are many factors that influence measurement results. Zanchini et al. [19] in their study indicate that groundwater flow slower than 80 meters per annum has a negligible effect on the short heat pulses (such as TRT and its results). Florides et al. [7] during field measurements in Cyprus found, that the realization of the TRT at one location on the boreholes with different diameters affects the observed coefficient of thermal conductivity of rocks in the range λ = 1.4 to 2.3 W m^{-1} K^{-1} and this parameter thus has apparent effect on the results of TRT. When studying the impact of various natural and technical conditions to a results of TRT, Wagner et al. [18] discovered that an inhomogeneous distribution of vertical temperatures (up to values of 52.2 °C km^{-1}) reduces the apparent value of thermal conductivity and borehole thermal resistance, which are evaluated using conventional line source model that assumes a uniform temperature distribution along the source.

There are also studies concerned with the possibilities of performing the thermal response test of rocks already during borehole drilling [17].

4.2 TRT mathematical background

Evaluating of measured test values is based on *the Kelvin line-source theory*. The equation for the temperature field as a function of time (t) and radius (r) around a line source with constant heat injection rate (q) can be used as an approximation of the heat injection from a borehole heat exchanger (BHE) [4,13]:

$$T(r,t) = \frac{q}{4\cdot\pi\cdot\lambda}\cdot\int_{u=\frac{r^2}{4\cdot a\cdot t}}^{+\infty}\frac{\mathrm{e}^{-u}}{u}\cdot\mathrm{d}u \equiv \frac{q}{4\cdot\pi\cdot\lambda}\cdot \mathrm{E}_1\left(\frac{r^2}{4\cdot a\cdot t}\right) = -\frac{q}{4\cdot\pi\cdot\lambda}\cdot\mathrm{Ei}\left(-\frac{r^2}{4\cdot a\cdot t}\right) \tag{1}$$

Hence, the fluid temperature as a time-dependent function can be expressed as:

$$T_\mathrm{f}(t) = \frac{q}{4\cdot\pi\cdot\lambda}\cdot\left(-\gamma + \ln\left(\frac{4\cdot a\cdot t}{r^2}\right)\right) + q\cdot R_\mathrm{B} + T_0 \tag{2}$$

4.3 TRT technology

The standard measurement apparatus for TRT consists of a circulating pump maintaining the constant flow rate during the whole time of the test in the borehole collector, and also of an electric heating element ensuring the heating of the liquid circulating in the collector. The measured liquid temperature at input and output of the boreholes is recorded at regular time intervals in the inner memory of the instrument. When the test is completed, the measured data are evaluated. At present, the most used procedure for analytical evaluation of the measured data is the line-source method [5].

4.4 TRT measurement procedure

TR tests at the experimental heat storage were performed in the period from 18 July 2011 to 15 August 2011 on eight energy boreholes in accordance with the measurement time schedule presented in Figure 5.

The measurement in the boreholes was always performed so that there was no mutual thermal interference with the two adjacent boreholes. Therefore when the measurement of a borehole was finished, the neighbouring borehole was never measured. The measurement was always performed on every second borehole at least. The connecting hose between the borehole and the measurement apparatus, as well as the U-tube from/to the borehole were insulated against heat loss and fluctuation of the surrounding air temperature using foam insulation material.

In some cases the temperatures were measured in the boreholes simultaneously with the TRT measurement in the neighbouring borehole. With the distance of 2.5 m between the boreholes, no mutual thermal interference of boreholes was observed. The influence of ambient temperature and direct sunshine on measurement results was minimised while performing the tests during the thermally stable period (July and August), and also due to the fact that the heat storage was located in a covered area without direct sunlight.

The manufacturer of the used mobile measurement equipment for performance of TRT (see Figure 1) is UBeG, GmbH & Co. KG, Wetzlar, Germany. The values for thermal conductivity λ (in W m^{-1} K^{-1}) and thermal resistance R_{B} (in K m W^{-1}) were obtained using GeRT-CAL (version 2.0.6) evaluation software. Each TRT test took 70 hours at least.

4.5 Procedure of evaluating the measurement errors and uncertainties

In case of an accuracy of direct measuring undisturbed/disturbed temperature profiles, a measurement cable, equipped with a Pt1000/A sensor (also *sensor 1*), and a French datalogger of AOiP Calys 50 (also *datalogger 1*) are usually used, whereas:

for the Pt1000/A sensor only (at tolerance class A, according to the IEC 60751 standard; in °C)

$$\Delta_{T_{\mathrm{A}}} = \pm\ 0.1500 + 0.0020 \cdot\ \vartheta \tag{3}$$

and for the datalogger 1 (at connected temperature sensor, 1-year accuracy; in °C)

$$\Delta_{\mathrm{Acc.}T} = \pm\ 0.012\ \% \cdot\ \mathrm{R.V.}\ _{T} + 0.050 \tag{4}$$

and for the datalogger 1 (at connected temperature sensor, 1-year accuracy; in Ω)

$$\Delta_{\mathrm{Acc.}_R} = \pm\ 0.012\ \%\cdot\ \mathrm{R.V.}\ _R + 0.100 \qquad (5)$$

In case of accuracies of direct measuring temperature curves at the TRT test and a temperature difference between inlet and outlet, measurement cables, equipped with paired JUMO Pt500/B sensors (also *sensor 2*), and a German datalogger of ZENNER ZÄHLER Multidata S1 (also *datalogger 2*) are used, whereas:

for the Pt500/B sensor only (at tolerance class B, according to the IEC 60751 standard; in °C*)*

$$\Delta_{T_\mathrm{B}} = \pm\ 0.3000 + 0.0050\cdot\ \vartheta \qquad (6)$$

In case of evaluating calculated values of the thermal conductivity λ and thermal resistance R_B, we must consider these conditions and rules, thus:

external known parameters (e. g., BHE's geometrical configuration)

$$\begin{array}{ll} h_\mathrm{B} & \mathrm{m} \\ r_\mathrm{B} & \mathrm{m} \end{array} \qquad (7)$$

directly measured quantities (by using the datalogger 2)

$$\begin{array}{rl} Q_\mathrm{V} \equiv Q_{\mathrm{V_f}}\ t & \mathrm{m^3\cdot h^{-1}} \\ \Delta T \equiv \Delta T_\mathrm{f}\ t & \mathrm{K} \\ T_{\mathrm{f_{IN}}} \equiv T_{\mathrm{f_{IN}}}\ t & \mathrm{K} \\ T_{\mathrm{f_{OUT}}} \equiv T_{\mathrm{f_{OUT}}}\ t & \mathrm{K} \end{array} \qquad (8)$$

calculated quantities based on the direct measurements and known values of physical parameters (by using the datalogger 2, DL2, and for evaluation software tool of GeRT-CAL, SW)

$$\mathbf{DL2}\text{:}\quad Q\ t\ = \underbrace{c_\mathrm{f}\cdot\rho_\mathrm{f}}_{\text{known}}\cdot\underbrace{\Delta T_\mathrm{f}\ t\ \cdot Q_{\mathrm{V_f}}\ t}_{\text{measured}} \qquad \mathrm{W}$$

$$\mathbf{DL2\ \ SW}\text{:}\quad Q = \overline{Q\ t} \qquad \mathrm{W} \qquad (9)$$

$$\mathbf{SW}\text{:}\quad T_0 = 0.5\cdot\ \underbrace{T_{\mathrm{f_{IN}}}\ 0}_{\text{measured}}\ + \underbrace{T_{\mathrm{f_{OUT}}}\ 0}_{\text{measured}} \qquad \mathrm{K}$$

output indirectly measured quantities (for λ*)*

$$\begin{array}{rl} \lambda_\mathrm{IN} = g_1\ \ h_\mathrm{B}, r_\mathrm{B}; Q, T_{\mathrm{f_{IN}}}, T_0 & \mathrm{W\cdot m^{-1}\cdot K^{-1}} \\ \lambda_\mathrm{OUT} = g_2\ \ h_\mathrm{B}, r_\mathrm{B}; Q, T_{\mathrm{f_{OUT}}}, T_0 & \mathrm{W\cdot m^{-1}\cdot K^{-1}} \\ \lambda = g_3\ \ \lambda_\mathrm{IN}, \lambda_\mathrm{OUT} & \mathrm{W\cdot m^{-1}\cdot K^{-1}} \end{array} \qquad (10)$$

output indirectly measured quantities (for R_B*)*

$$\begin{array}{rl} R_{\mathrm{B_{IN}}} = h_1\ \ h_\mathrm{B}, r_\mathrm{B}; Q, T_{\mathrm{f_{IN}}}, T_0, \lambda_\mathrm{IN} & \mathrm{K\cdot m\cdot W^{-1}} \\ R_{\mathrm{B_{OUT}}} = h_2\ \ h_\mathrm{B}, r_\mathrm{B}; Q, T_{\mathrm{f_{OUT}}}, T_0, \lambda_\mathrm{OUT} & \mathrm{K\cdot m\cdot W^{-1}} \\ R_\mathrm{B} = h_3\ \ R_{\mathrm{B_{IN}}}, R_{\mathrm{B_{OUT}}} & \mathrm{K\cdot m\cdot W^{-1}} \end{array} \qquad (11)$$

Finally, values of the thermal conductivity and the thermal resistivity are dependent on:

- external known parameters, see Eq. (7) – their values influence a correctness of final results very much, whereas the characteristic borehole depth h_B is more significant than the characteristic borehole radius r_B,
- directly measured quantities, see Eq. (8) – their values are given by used measurement methodology and properties of a measurement device, whereas it is possible to determine some measurement errors and uncertainties; e. g., for estimating a value of inlet fluid temperature $T_{\mathrm{f}_\mathrm{IN}}$ or outlet fluid temperature $T_{\mathrm{f}_\mathrm{OUT}}$, we consider A-type uncertainty to be zero [i. e., $u_\mathrm{A}\ y\ = 0$] due to only one temperature measurement (at measuring the TRT curves, it is very difficult to carry out repeated measurements) and B-type uncertainty $u_\mathrm{B}\ y$ is based on Eq. (6) ~ Eq. (8),
- calculated quantities, see Eq. (9) – they are based on the direct measurements and known physical parameters, useful not only for internal calculating $Q\ t$ by using the *datalogger 2*, but also for calculations of Q and its average value $\overline{Q\ t}$ and standard deviation s_Q by using the evaluation software tool of GeRT-CAL, see Eq. (9),
- in case of output indirectly measured values, we consider estimations of the directly measured quantities, whereas relationships among them are taken account from viewpoint of so-called law of propagation of uncertainty; e. g. there is no significant correlated relationship between Q_V and ΔT, but there is direct relationship between Q_V and $Q\ t$, see Eq. (9).

4.6 Procedure of borehole temperature profiling

The temperature profile measurements were performed in three phases. The first phase was performed in the period from 12 July 2011 to 27 July 2011 and the temperature profiles of all energy, monitoring and hydrogeological boreholes were recorded during this time. They were undisturbed temperature profiles, or the least disturbed by the running TRTs.

The second phase of the measurement was performed in the period from 10 August 2011 to 11 August 2011 and 9 temperature profiles through BTES in boreholes EV2, EV5, EV6, EV10, EV11, EV13, EV14 and EV16 were recorded. Two of the profiles were measured on borehole EV11, namely 1.5 and 4 hours after finishing the TRT on the profile. This determined the temperature changes in the boreholes caused by TRT performed on the selected boreholes for 30 days and heating of the rock environment where the BHE is located.

The third phase of the measurement was performed during the period from 6 September 2011 to 8 September 2011 and the temperature profiles of all energy boreholes and monitoring borehole MV3 were recorded during it. This phase was performed 23 days after finishing the last TRT and its aim was to obtain the view of temperature changes after a certain rock massive cooling period.

During the whole measurement, the data on changes of the temperature profile in the boreholes after TRT performance, namely in the period from 90 minutes to 20 days after its finishing, were recorded.

The temperature measurement in the boreholes is performed for the determination of the course of the temperature profile enabling the identification of the depth level with presence of groundwater, determination of the depth of temperature interferences due to climatic factors and flow of groundwater, estimation of geothermal gradient and, of course, temperature which can be used e.g. for heating.

The temperature profiles were measured with the Pt1000 temperature sensor with the precision of 11.17-12.63 °C, ΔT = ± 0.17 °C under BHE conditions. The temperatures were recorded with Calys 50, with an instrument error of ± 0.09 °C in the specified temperatures, using the Pt1000 sensor. The borehole profiles were first measured in an interval of 1 m with the aim of identifying the depth levels where significant changes of temperatures may occur. After their identification at 8, 12 and 15 m, the measurement in shallow locations was profiled in the same way. At deeper locations (≥ 20 m) in intervals of 10 m, the temperature profiling was started together with TRT and was allocated so that the original temperatures could be read in the boreholes without influencing TRT.

The geological composition is well-known from exploring boreholes and from the course of the drilling itself. From the surface to the depth of 8 m, the geological profile is formed by the clay, sand and gravel of river terraces of the Ostravice River; at interval of depths from 3 to 8 metres there are aquifers. Under these quaternary sediments up to the final depth of 80 m there are claystones with thin layers of siltstones and sandstones. These layers are absolutely without aquifers. The schematic geological profile is shown in Figure 3.

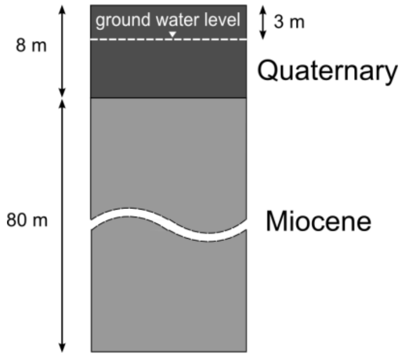

Fig. 3. The schematic geological profile.

5 RESULTS

5.1 Results of TRT measurement

Due to the fact that the distance between the boreholes is only 2.5 m, there was a unique opportunity to perform the series of TR tests in a practically identical rock environment. The TR test results are summarised in Table 2. The duration of the individual measurements varied between 70 to more than 90 hours, for the reliable comparison of the results the data after 70 hours of measurement of all boreholes were evaluated.

Table 2

The measured values of thermal conductivity λ (in W m^{-1} K^{-1}) and thermal resistance R_B (in K m W^{-1}).

	Borehole #3	Borehole #5	Borehole #7	Borehole #9	Borehole #10	Borehole #11	Borehole #12	Borehole #15
λ	2.32	2.48	2.15	1.80	2.10	2.02	2.16	2.29

R_B	0.076	0.079	0.066	0.088	0.081	0.092	0.065	0.074

Results from TR tests are also summarised in Figure 4.

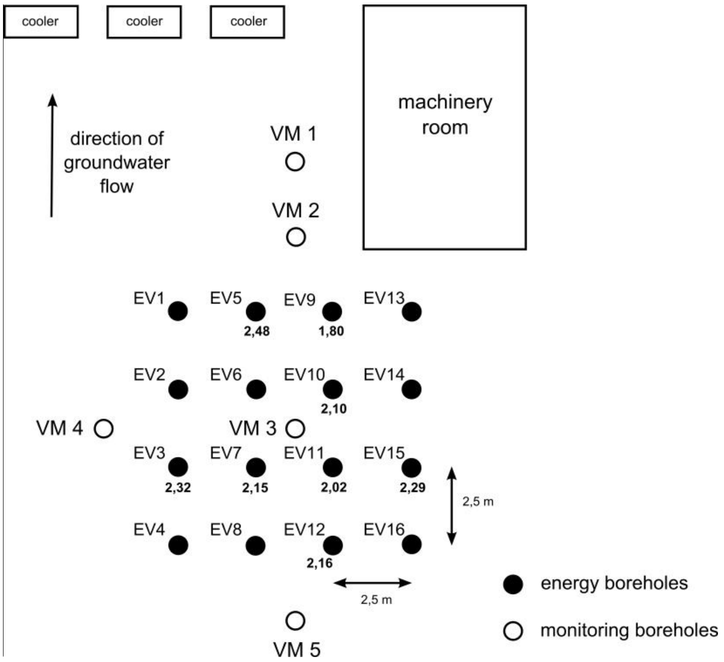

Fig. 4. The arrangement diagram of the boreholes of experimental BTES. VM 1-5 designate the location of monitoring boreholes (black circle). EV 1-16 designate energy boreholes symbolised by black circles. The numbers below the selected energy boreholes symbolise the measured value λ (in W m^{-1} K^{-1}).

The difference between the maximum (borehole No. 5) and minimum (borehole No. 9) value of λ is 0.68 W m^{-1} K^{-1}, which is a higher dispersion of the values than expected. The average value of λ of all measurements is 2.17 W m^{-1} K^{-1}. This value is in agreement with the values presented for dry claystone in other literature.

The highest differences of thermal conductivity from the average value of 2.17 W m^{-1} K^{-1} were recorded on borehole No. 5 (+14.30 %) and borehole No. 9 (-17.05 %). The absolute average value of λ deviations from the central value 2.17 W m^{-1} K^{-1} is 6.91 %.

The average value of thermal resistance R_B is 0.078 K m W^{-1}. The highest differences of thermal resistance from the average value of 0.078 K m W^{-1} were recorded on borehole No. 11 (+17.94 %) and borehole No. 12 (-16.67 %). The absolute average value of R_B deviations from the central value 0.078 K m W^{-1} is 9.45 %.

The measured deviations of λ and R_B values from average values show no mutual dependence.

Although the measuring conditions were comparable, there were differences among the values of individual measurements. Only the ambient air temperature changed during the measurement. The measured boreholes are drilled in a big, partly open hall with a solid roof and zero influence of rainfall or direct sunshine. The rate and direction of the groundwater flow in the gravel-sand quaternary layer was the same for all boreholes and therefore there could be no observable influence among the measured results.

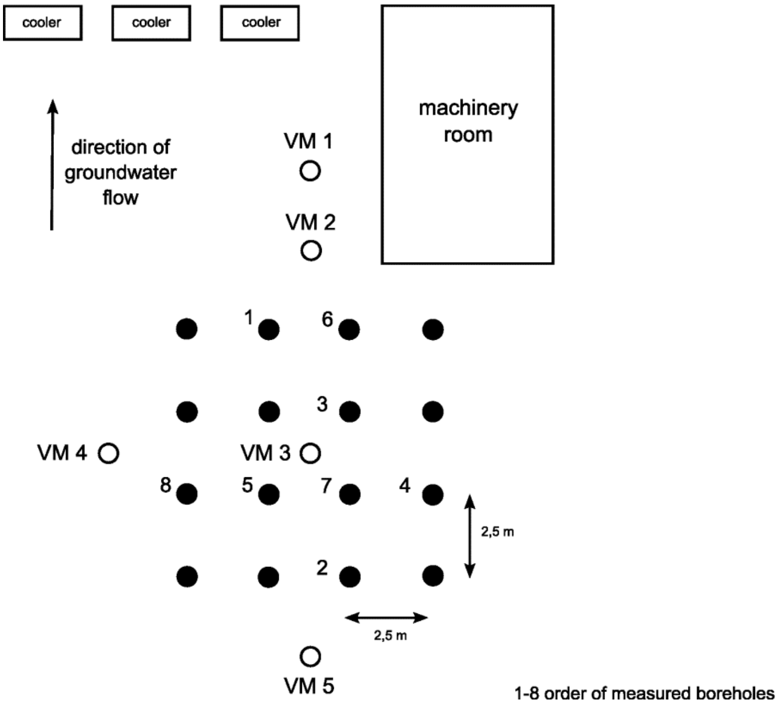

Fig. 5. Measurement time schedule of boreholes.

5.2 Results of TRT measurements for a 24 hour test – simulation

The dispersion of the measured λ and R_B values observed in an identical rock environment confirmed that a possible shortening TR test duration may not have a great influence on the precision of obtained results. GeRT-CAL enables simulating shortened test duration to 24 hours. Only the data from the first 24 hours from the beginning of the test duration were selected and evaluated in the evaluation software. We thus worked with data identical to those that would be measured during the 24 hour test duration. The comparison of λ and R_B values measured using the full 70 hour TRT test with the values calculated for the theoretical 24 hour TR test is presented in Table 3 and Table 4.

Table 3
The comparison of λ values for normal (70 h) and shortened (24 h) test duration.

	Borehole #3	Borehole #5	Borehole #7	Borehole #9	Borehole #10	Borehole #11	Borehole #12	Borehole #15
λ	2.32	2.48	2.15	1.80	2.10	2.02	2.16	2.29
$\lambda_{24\ \text{h.}}$	2.29	2.35	1.98	1.72	1.85	1.79	1.99	2.24
Δ_{λ} %	-1.3 %	-5.2 %	-7.9 %	-4.4 %	-11.9 %	-11.4 %	-7.9 %	-2.2 %

Table 4

The comparison of R_B values for normal (70 h) and shortened (24 h) test duration.

	Borehole #3	Borehole #5	Borehole #7	Borehole #9	Borehole #10	Borehole #11	Borehole #12	Borehole #15
R_B	0.076	0.079	0.066	0.088	0.081	0.092	0.065	0.074
$R_{\mathrm{B}\ 24\,\mathrm{h.}}$	0.076	0.071	0.063	0.089	0.071	0.080	0.061	0.085
$\Delta_{R_\mathrm{B}}\ \%$	0.0 %	-10.1 %	-4.5 %	1.1 %	-12.3 %	-13.0 %	-6.2 %	14.9 %

The average absolute difference of λ value between the normal and shortened TR tests is 6.53 %, for R_B 7.76 %. When considering the fact that the λ value may fluctuate within the range +14.3 % (borehole #5) up to -17,05 % (borehole #9) from the average λ value 2.17 W m^{-1} K^{-1} for dry claystone, shortening the duration of the test to 24 hours may bring substantial time and energy savings while maintaining the acceptable precision. The really measured maximum dispersion of measured R_B values is for borehole No. 11 (+17.94 %) and for borehole No. 12 (-16.67 %); shortening the test to 24 hours brings an acceptable amount of inaccuracy with regard to the spread of measured values obtained from the real test, even in the case of R_B measurement.

The comparison of the λ and R_B values after 36 h, 48 h and 60 h of the test duration is presented in Table 5 and Table 6.

Table 5

The comparison of λ values for 36 h, 48 h and 60 h test duration.

	Borehole #3	Borehole #5	Borehole #7	Borehole #9	Borehole #10	Borehole #11	Borehole #12	Borehole #15
$\lambda_{\ 36\,\mathrm{h.}}$	2.25	2.39	2.03	1.73	1.99	1.74	2.08	2.28
$\lambda_{\ 48\,\mathrm{h.}}$	2.28	2.40	2.10	1.75	2.03	1.92	2.15	2.27
$\lambda_{\ 60\,\mathrm{h.}}$	2.30	2.46	2.13	1.76	2.10	1.99	2.16	2.27

Table 6

The comparison of R_B values for 36, 48 and 60 h test duration.

	Borehole #3	Borehole #5	Borehole #7	Borehole #9	Borehole #10	Borehole #11	Borehole #12	Borehole #15
$R_{B\ 36\,\mathrm{h.}}$	0.074	0.075	0.064	0.086	0.076	0.077	0.063	0.074
$R_{B\ 48\,\mathrm{h.}}$	0.075	0.075	0.066	0.085	0.078	0.087	0.066	0.074
$R_{B\ 60\,\mathrm{h.}}$	0.075	0.078	0.066	0.085	0.081	0.090	0.065	0.073

However, the proposal for possible shortening of tests is valid only in cases where there is not a lot of running groundwater influencing the rate of temperature curve stabilisation. The above described methodology will be verified during the performance of subsequent TRT tests.

5.3 Results of borehole temperature profiling

The first phase of temperature profiling in BHE boreholes enabled determination of the undisturbed temperature in a rock environment, which varied from 11.17 °C at the depth of 60 m up to 11.9 °C at the depth level of 15 m of the borehole length, see Figure 6. The average temperatures and their ranges in individual depth levels are given in Table 7.

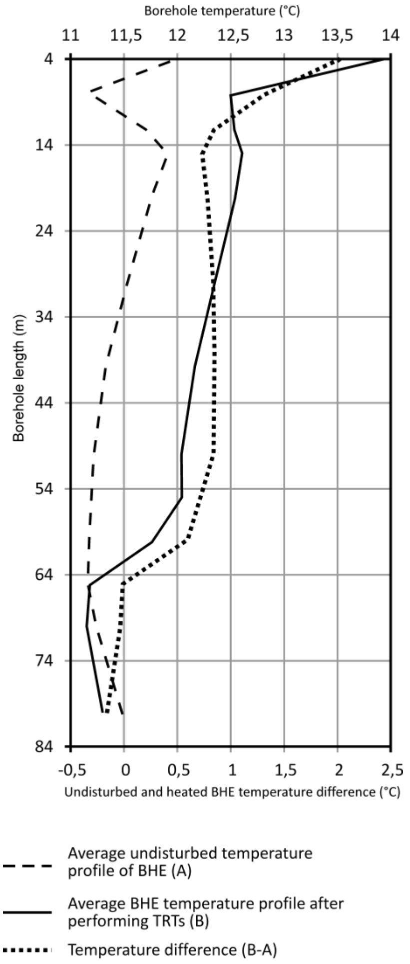

Fig. 6. The temperature in BTES boreholes thermally undisturbed and after heating of the rock environment due to performance of the TRT series.

Table 7

The average measured temperatures and their ranges in individual depth levels of BTES before TRT and 23 days after performing the TRT series.

Length (m)	Average (°C)	Range (°C)	Average (°C)	Range (°C)
4	11.95	1.03	13.90	1.52
8	11.21	0.45	12.40	1.16
12	11.72	0.41	12.43	1.14
15	11.87	0.29	12.53	1.06
20	11.78	0.18	12.45	0.92
30	11.53	0.08	12.26	0.89
40	11.33	0.08	12.07	0.89
50	11.21	0.11	11.97	0.89

55	-	-	11.97	0.88
60	11.18	0.17	11.71	0.61
Date	12-27 July 2011		6-8 Sept. 2011	

Above this interval there is a clear influence of groundwater with the level of 3 m below the terrain surface with the temperature of 10.70 °C (measured on 27 July 2011). The direction of water flow is parallel with the plain interposed through boreholes EV4 – EV1 of the heat storage. It follows from the temperature profile that the so-called transition zone (area without the influence of thermal changes due to climatic conditions) is located at the depth of 60 m below the terrain surface.

After finishing the TRT series on 8 energy boreholes, the third phase of temperature profiling was performed on the BTES boreholes. The average temperatures to the level of 60 m of the borehole length were up to 11.70-12.63 °C. The average temperatures and their ranges in individual depth levels are given in Table 7. The difference of the average undisturbed temperature of boreholes and their average temperature after performing the TRT series, during which 4,456.36 kWh of heat was supplied to the rock environment, at the levels of 12-60 m of the borehole length was 0.60-0.85 °C. The levels below 60 m of the borehole length were not thermally disturbed and the temperatures in the level of 15-50 m of the borehole length were increased identically, only with small differences (Figure 6).

The comparison of temperature profiles of boreholes after a certain time from the performance of TRT and the borehole without the influence of TRT is shown in Figure 7.

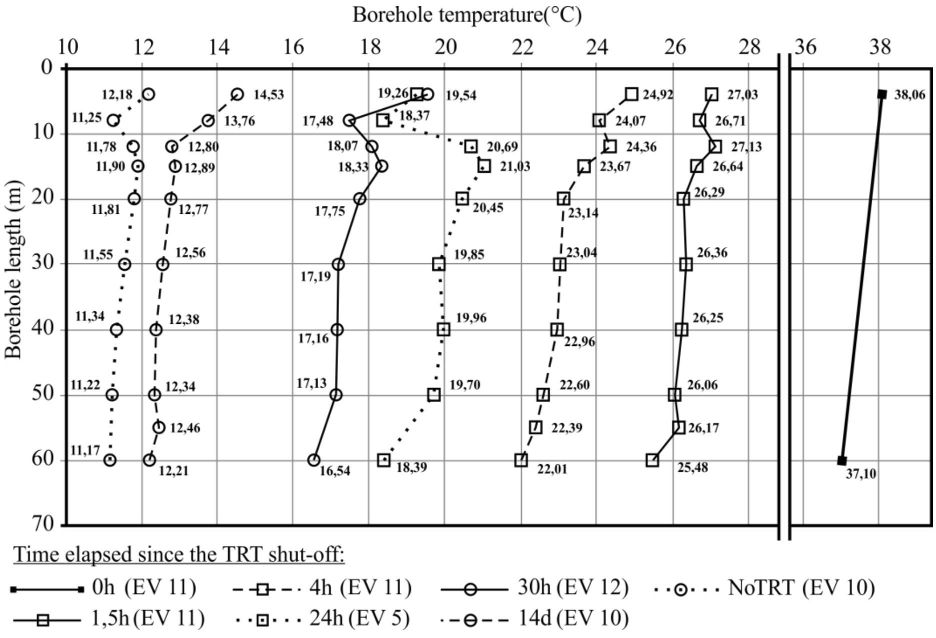

Fig. 7. The comparison of temperature profiles of boreholes after a certain time from the performance of TRT and the borehole without the influence of TRT.

Figure 8 shows the interpolated curves of the course of increased temperature in the borehole during TRT, and the course of borehole cooling after TRT and undisturbed temperature of the rock massive before TRT. The cooling curves and the lines of undisturbed temperature are supplied for the level 40 m below the terrain surface undisturbed by groundwater flow.

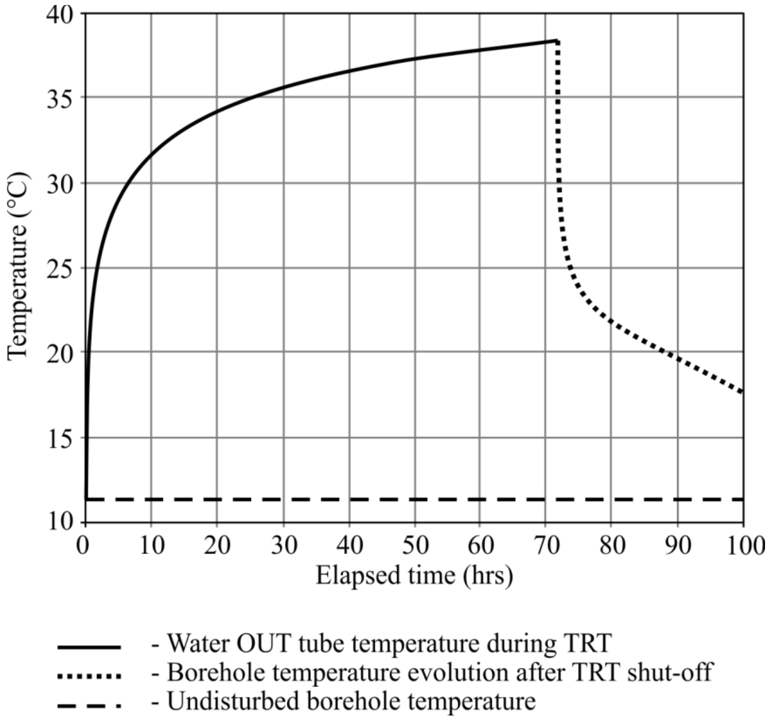

Fig. 8. Interpolated curves of the course of increased temperature in the borehole during TRT, course of the borehole cooling after TRT and undisturbed temperature of the rock massive before TRT.

The planar temperature distribution at individual depth levels of BTES after 23 days of the last performed TRT measurement is obvious from Figure 9. The temperature field shape corresponds to the heat spreading from 8 heat sources (TRT), and it is not disturbed by the groundwater flow in the quaternary layer.

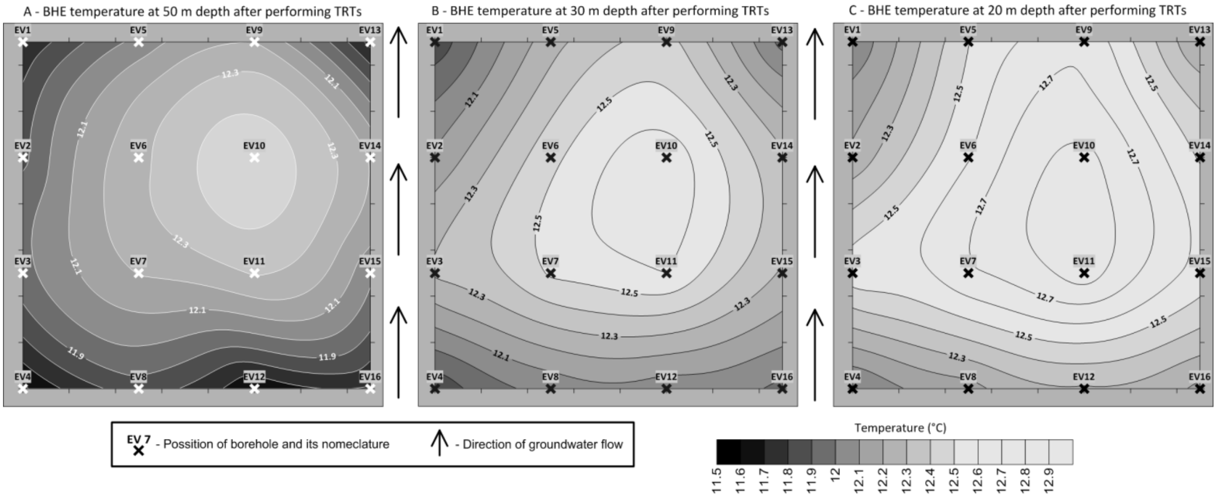

Fig. 9. The planar temperature distribution in the depth levels of BHE after 23 days of the last performed TRT measurement: A – 50 m; B – 30 m; C – 20 m below the terrain surface.

6 DISCUSSION OF RESULTS

The testing of a greater number of boreholes using the TRT method was recently studied by Saqib Javed and Per Fahlén [6] from the Technical University in Chalmers, Gothenburg, Sweden. Their testing polygon consisted of nine 80 m boreholes drilled in a square configuration. There are distances of 4 m between the boreholes, one U-tube is inserted into each borehole and the boreholes are filled with groundwater. All the boreholes were individually measured by the TRT method within 12 weeks.

The results from this testing show that the greatest difference between measured λ values of individual boreholes was 0.39 W m^{-1} K^{-1}. In our case, the greatest difference in measured λ values equalled to 0.68 W m^{-1} K^{-1}. The maximum dispersion of λ values from the testing in Sweden may be expressed as 3.01 W m^{-1} K^{-1} ± 7%. The dispersion of λ values measured by us is greater (2.17 W m^{-1} K^{-1} +14.30 %, -17.05 %).

The maximum dispersion of values of thermal resistance R_B from the measurement in Sweden is 0.062 K m W^{-1} ± 20 %. In our measured polygon the maximum dispersion of R_B values is expressed as (0.0781 K m W^{-1} +17.94 %, -16.67 %). There is a similar dispersion of the measured values of thermal resistance R_B on the research polygon at Chalmers University and on the boreholes tested by us.

On the Swedish testing polygon the influence of shortening the TRT duration on the precision of the determination was studied on two boreholes as well. The λ values on two boreholes after 50 and 100 hours of test duration were compared. The results differed in the case of the first tested borehole by 2 %, of the second borehole by 0.3 %. The maximum difference of λ value between the standard and TRT shortened to 24 hours simulated by us on borehole No. 10 is 11.9 %. The average absolute difference of λ value between the standard and shortened TR tests is 6.53 %.

The smaller difference between λ values of two tested boreholes in Chalmers and our measurement is probably caused by a different duration of the compared TRTs. On two boreholes of the Swedish polygon, λ values after 50 and 100 hours of test duration were compared; in our case the simulation was prepared for 24 hours vs. typically 70 and more hours of real tests. The Swedish test, due to a longer duration, shows higher convergence to stabilised values and thus a lower difference between the longer and shortened versions of the test.

The results from the research of temperature characteristics in the rock environment on SRP at the VŠB – Technical University of Ostrava site can be compared to the BTES results in Paskov. The two storages are located at an altitude of 250 and 260 m above the sea level. The climatic conditions and the rock environment where claystones are prevailing in the borehole profile are comparable. On SRP situated in the VŠB – Technical University of Ostrava site the transition zone is located at the depth of 40 m (temperature of 9.5 °C). For comparison, on the boreholes of the heat storage in Paskov the temperature at the level of 80 m is 10.5 °C. The boreholes of this temperature polygon reach to a depth of 140 m. The influence of groundwater was identified with thermometry at the level of the weathered Carboniferous surface, below the level of the depth reach of the BHE boreholes in Paskov.

The transition zone of the boreholes in Paskov is at a greater depth, but the BTES is located here in a covered area without plant covering. The increase of the depth of the transition zone in the rock environment might have been caused by such influence of this construction over terrain without direct sunlight energy and separated for the period of ca. 50 years (mine settled in 1959). The undisturbed temperature in BHE Paskov reaches values 1.4-1.7 °C higher. These values could also be influenced by the Saale glaciation which occurred in this north-eastern part of the Czech Republic. This factor will also be the subject of subsequent research.

7 CONCLUSIONS

This paper presents the results of the Thermal Response Tests (TRT) and temperature profiling of boreholes performed within the high-temperature BTES construction in Paskov, Czech Republic. Using the TRT method, 8 of the total 16 boreholes in the storage container were measured. The results show rather substantial dispersion of the measured values of thermal conductivity of soil and the thermal resistance of boreholes. Subsequently, the computer simulated shortening of tests to 24 hours was performed. The differences between the calculated values of soil thermal conductivity and thermal resistance of boreholes due to the shortened duration of tests to 24 hours are smaller than the differences of these values between individual boreholes during real measurement.

Temperature profiling as an additional measurement helped to determine the depths of temperature disturbance and the character of heat transfer at individual depth levels of the high-temperature BTES. The data from 9 temperature profiles measured in various phases of temperature disturbance of the rock environment helped to obtain the view of the behaviour of the high-temperature storage during operation. The comparison of these measurements from BTES sites in Paskov, SRP in the VŠB – Technical University of Ostrava site and other sites in this region has shown the possibility of future research on the influence of paleoclimate on present temperature characteristics of the rock environment of Northern Moravia.

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