Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Implementation of the Distributed Thermal Response Test at Characteristic Geological Regions throughout Croatia

Vladimir Soldo[*], Leon Leposa[*], Luka Boban[*], Staša Borović[**]

[*]University of Zagreb - Faculty of Mechanical Engineering and Naval Architecture, Ivana Lucica 5, HR-10000 Zagreb, Croatia

[**]Croatian Geological Survey, Sachsova 2, HR-10000 Zagreb, Croatia

vladimir.soldo@fsb.hr, leon.leposa@fsb.hr, lboban@fsb.hr, sborovic@hgi-cgs.hr

Keywords: distributed thermal response test, ground thermal properties, heat pumps

ABSTRACT

Energy Strategy of the Republic of Croatia by 2020 relies on renewable energy resources as the one of main priorities. The use of geothermal energy sources is specifically encouraged. The EU IPA (Instrument for pre-accession assistance) project entitled *Research and the Promotion of the Use of Shallow Geothermal Potential in Croatia* includes research in eight characteristic regions throughout the country. In this project a new method, the so called distributed thermal response test (DTRT) has been applied on a 100 m deep borehole heat exchanger (double U pipe) with 152 mm in the outer diameter of borehole. The fundamental difference from the TRT is the measurement of the carrier fluid temperature along the BHE using an optical fiber cable placed inside the BHE pipes. Hence, in DTRT vertical distribution of the ground thermal conductivity and borehole thermal resistance is determined along the borehole heat exchanger (BHE). With this method the undisturbed ground temperature profile along the BHE is also determined. The duration of the DTRT is about seven days. In the first three days the temperature is measured with no fluid circulation, followed by imposing a constant heat flux during the next 48 hours. Thermal properties of the ground are influenced by the soil and rock composition, porosity, moisture content and groundwater flow. This paper presents the results for the first region – the city of Osijek.

1. INTRODUCTION

Heat pumps coupled to closed-loop borehole heat exchangers (BHE) have been investigated theoretically and experimentally in the past few decades. Numerous reports show that such systems should be designed using complex mathematical simulations that have to be performed not only for peak buildings loads, but also for building loads that are calculated throughout the whole year. The long-term (years and decades) performance of BHEs is highly dependent on the balance between the heat extraction during the heating period and the heat injection into the borehole surrounding ground during the cooling period.

The theoretical models are mostly based on the assumption of a homogeneous and isotropic ground, which is often not satisfied in reality. The thermal processes between the BHE and the ground can be better interpreted if the temperatures of the BHE wall are measured. Relatively small number of reports on measurements of the temperature along the BHE is available in literature (Esen et al., 2009, Gao et al., 2006, Soldo et al., 2010 and 2011). Fujii et al. (2006 and 2009) and Acuna et al. (2008 and 2010) presented the new temperature measurement technique of the boreholes: fiber optic cables are installed along the test boreholes for measuring temperatures of the heat carrier fluid, groundwater and the borehole wall. The biggest advantage of using optic cables is the possibility of measuring fluid temperature up to every meter along the borehole, and estimating the local thermal conductivity along the depth of BHE.

For many years the performance of BHEs and determination of thermal conductivity of the soil and borehole thermal resistance have been evaluated by the Thermal Response Test – TRT (Gehlin 2002 and 2003, Sanner et al., 2005 and 2007).

In order to make a further research into a new method of technology, a team of researchers at the University of Zagreb, Faculty of Mechanical Engineering, in collaboration with the Croatian Geological Survey is conducting a research on the use of heat pumps, coupled with borehole exchangers (double U-pipe) and connected to ground, for heating and cooling of already built buildings. It is an EU IPA (Instrument for Pre-accession Assistance) project called *Research and the Promotion of the Use of Shallow Geothermal Potential in Croatia*. The research includes drilling of a 100 or 150 m deep experimental boreholes and installation of optical fiber cables for the distributed temperature measurement along the borehole that is used for measuring ground thermal response (the so called DTRT – Distributed Thermal Response Test). Along with drilling procedure, the geological supervision is carried out. Soil sampling and soil properties determination is made in order to attain the main objective of the project, i.e. the determination of thermal properties of shallow geothermal potential in characteristic regions on eight different locations throughout the Republic of Croatia (Figure 1).

Shallow geothermal potential, however, does not have to be congruent with geothermal characteristics in the Earth's crust and upper mantle because boreholes for ground-source heat pump utilization are usually drilled to a depth of 100 m. That is why this borehole depth was chosen in the scope of the project, except for a locality in Zagreb where such a borehole is already in operation and monitoring (Soldo et al., 2010) so the new one will be drilled to a depth of 150 m. For the utilization of ground-coupled heat pumps the relevant thermal parameters also vary between the Pannonian basin system and the Adriatic Carbonate Platform (AdCP) part of Croatia. The Pannonian part is characterized by kilometres thick clastic sedimentary sequences of Paratethys, while in the AdCP part there is a domination of thick platform carbonate sequences (mostly limestone).

Figure 1: Drilling locations throughout Croatia

In accordance with diverse genesis and lithology of the regions, different thermal parameters of the ground were anticipated. Eight locations have been chosen for the research, four in each region. In the Pannonian part there is a domination of sediments with intergranular porosity. Two of the localities – Zagreb and Čakovec - represent sedimentary cover with coarser-grained sediments, while Požega and Osijek sediments are characterized by the domination of silt, partially clayey, partially sandy. In the Dinaric part (Gospić, Zadar and Dugopolje) fracture and channel porosity greatly surpass the intergranular porosity of the carbonate rocks' matrix. The differences between locations are mainly in the thickness of the topsoil and weathered zone, in the degree of limestone karstification and/or dolomitization and the presence or absence of flysch sediments.

The aim of this project is to encourage the process of „mapping" shallow geothermal potential on local scale in different regions of the Republic of Croatia, while the knowledge gained by this project will be used to promote the application of ground source heat pump technology as a renewable energy source by creating the preconditions for more effective implementation for heating and cooling of buildings. The work presented in this paper shows measurements from the first borehole heat exchanger installation located in the city of Osijek, Croatia, and determination of ground thermal conductivity of the soil using three different approaches.

2. THE BOREHOLE HEAT EXCHANGER INSTALLATION

In mid April 2014 the project implementation started with drilling of a 100 m deep borehole of 152 mm in diameter in the vicinity of Technical school in Osijek. During the drilling, geologists have carried out core sampling and determination of the soil along the borehole.

Together with the BHE in the form of a double polyethylene U-pipe, the optical fiber cable was inserted into the borehole (Figure 2). The vertical position of the heat exchanger in the borehole has been ensured using a steel tube during the probe installation which was inserted between the pipes of the heat exchanger and connected to the weight. Steel tube was also used as an injection tube for grouting of the borehole. The spacers were placed at distances of 2 m in order to centre the probe in the borehole and to maintain the distance between the PE pipes.

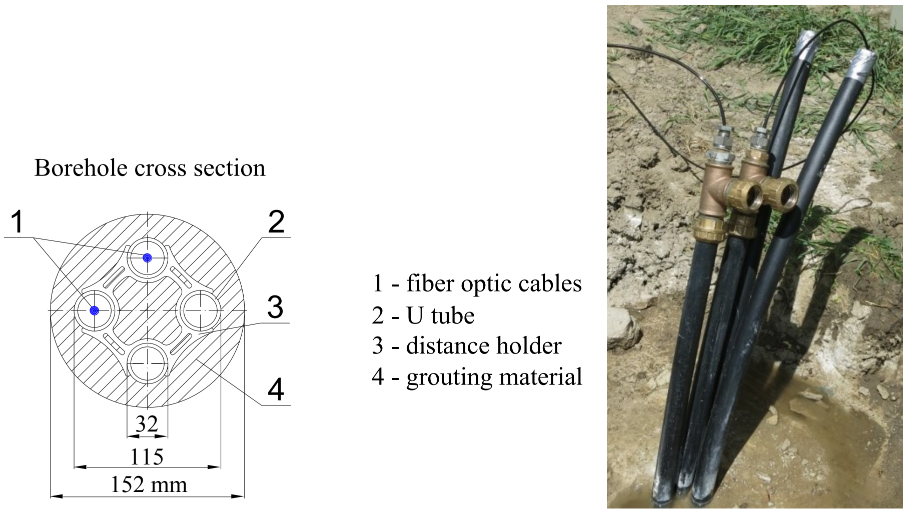


Figure 2: a) Position of the optical cables inside the U pipe BHE; b) The optical cables installed inside the U pipe

After the installation of borehole heat exchanger and the optical fiber cables, the borehole was filled with a special grouting material (Table 1). Grouting material is produced by the Fisher, type GeoSolid 235. Thermal conductivity of grouting material is 2,35 W/(m K). Subsequently, the density of the mixture is 1800 kg/m^3.

Table 1: Borehole characteristics

Borehole depth [m]	100
Borehole radius [mm]	152
Heat exchanger type	Double U-pipe, PEHD 100
Outer pipe diameter [mm]	32
Inner pipe diameter [mm]	26,2
Grouting material	GeoSolid 235 (Fisher)
Carrier fluid	water

3. METHODOLOGY

Ground thermal properties can be determined by different methodologies. As part of this project three different approaches were applied for determination of ground thermal conductivity. Direct measurement of sediment thermal properties was conducted by the Croatian Geological Survey, while Distributed Thermal Response Test (DTRT) and conventional Thermal Response Test (TRT) was performed by the University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture.

Direct measurement of sediment thermal properties was conducted on site and in the laboratory. The measurements were conducted via the hand-held instrument ISOMET 2114 – Thermal Properties Analyzer (manufacturer *Applied Precision*). The measuring device is appropriate for both indoor and outdoor measurements in geological investigations. The principle of operation of the apparatus is a modified hot wire method described by Carslaw and Jaeger (1959) and Prelovšek and Uran (1984).

Samples for thermal properties measurements were taken based on borehole core lithology determination, i.e. properties of characteristic sediments were measured five times per sample. Since there was frequent repetition of highly similar lithology members (Table 3), the properties were only measured for a few samples of the same lithology, and the arithmetic mean was taken as a representative for the rest.

The distributed thermal response test is carried out in three stages. First, the undisturbed ground temperature is measured for 72 hours without water circulation. The second phase of measurement consists of constant heat flux injection with water circulation. Duration of this stage is 48 hours. Finally, the third stage lasts for 48 hours with no water circulation or heating as in this stage borehole recovery is observed.

Temperature measurement along the borehole heat exchanger was carried out with fibre optic cable coupled with AP Sensing Linear Pro Series DTS instrument (Figure 3). The AP Sensing Linear Pro performs measurements down to one meter spatial resolution with less than 0,1 K temperature resolution. The instrument reliability was described by Soto et al. (2007). Multimode 50/125 fibre optic cable is installed in both tubes of U-pipe heat exchanger.

Figure 3: Linear Pro Series DTS instrument

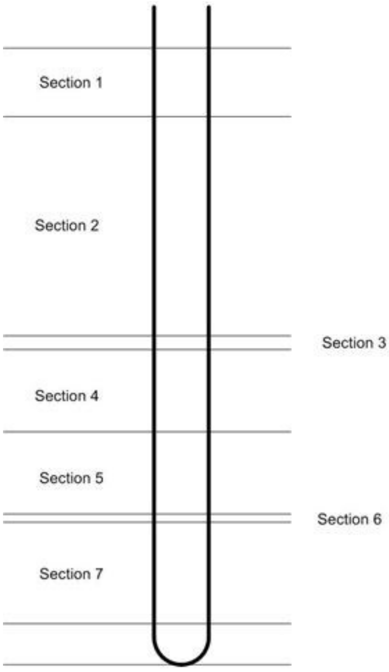
Thermal response test was performed with GeoGert 2,0 (Figure 4). General characteristics are presented in the Table 2. During the second measurement stage carrier fluid was circulated through BHE with applied constant heating power of 8,2 kW and flow rate of 1234 l/h.

Table 2: Propereties of Thermal Response Unit

Working conditions [°C]	0 – 40
Maximum pressure [bar]	16
Maximum flow rate [l/h]	2300
Maximum el. power [W]	8500
Communication	USB, GPS, GSM

Figure 4: TRT Unit

Temperature measurements were carried out with integration time of 300 seconds and measurement length interval of two meters. The obtained thermal properties are presented according to the characteristic ground layers with their respective thickness. Characteristic ground layers were recommended by experts from the Croatian Geological Survey, related to the soil properties.



Nr of section	Meters	Soil characteristics
1	8 – 18	low to medium permeability sand
2	18 – 50	high permeability sand and gravel
3	50 – 54	low permeability siltey and clayey materials
4	54 – 66	medium permeability sandy materials
5	66 – 78	low permeability sandy materials
6	78 – 80	coal and materials with high content of organic material
7	80 – 94	medium permeability sandy materials

Figure 5: Borehole sections

Borehole is divided in 7 sections, as shown in Figure 5, in which thermal conductivities and thermal borehole resistances are determined. The first 8 meters of the borehole are neglected, therefore the influence of the ambient air is eliminated. Respectively, the last 6 meters of the borehole are also neglected, due to hemispherical borehole bottom of the U-pipe heat exchanger, as the line source model (Kelvin, 1861) used for the determination of thermal properties assumes radial heat flux only. Other assumptions and considerations regarding line source theory, though providing only rough approximations to the real heat transfer process, can be found in Ingersoll and Plass (1948).

Temperature evaluation around BHE for constant heat flux, as described by Equation 1 of line source model, can be used for determination of ground thermal conductivity (λ) and borehole thermal resistance (R_b), Ruševljan et al., 2009. By calculating the temperature difference between undisturbed ground temperature and circulation fluid temperature, and by measuring fluid flow or applied heat flux, Equation 1 can be used in linear form (Equation 2). After linear regression slope k and intersect c are known, ground thermal conductivity (λ) and borehole thermal resistance (R_b) can be determined.

$$\vartheta_f - \vartheta_0 = \frac{q}{4\lambda\pi}\left(\ln\left(\frac{4at}{r^2}\right) - \gamma\right) + qR_b \qquad (1)$$

$$\vartheta_f = k\ln(t) + c \qquad (2)$$

Each characteristic ground layer is treated as a single section and for each temperature difference $\Delta\vartheta_s$ was calculated while real undisturbed ground section temperature and corresponding ground properties were used. Specific heat flux for each section was calculated by using inlet and outlet temperatures of both upward and downward part of U-pipe (only in one U-pipe fiber optic cables were installed) in Equation 3.

$$q = \dot{v}\rho c_p \Delta\vartheta_s \quad (3)$$

4. RESULTS AND DISCUSSION

The results of thermal properties measurements are shown in Table 3. The mode in which individual thermal parameters were obtained is described in the last column (measured/mean/analogy). "Measured" means measurement on B-1 core samples, "mean" is the arithmetic mean of the similar lithology members' thermal properties also on B-1 core samples, while "analogy" means that the measurement was not possible on the B-1 core so similar sediments from other boreholes were taken into calculation. Data in parentheses show the number of samples taken into calculation. The total thermal conductivity of the surrounding sediment along the length of the borehole was calculated as the arithmetic mean weighted by the thicknesses of individual sediment layers.

Table 3: Borehole B-1 Osijek lithological units and their thermal characteristics

INTERVAL [m]	MATERIAL	THICKNESS [m]	λ[W/mK]	Cρ[MJ/m^{3}K]	a (x10^{-6})[m^2/s]	DATA ACQUISITION
0,0 - 0,80	Anthropogenic - construction material	0,80	1,08	2,17	0,50	measured
0,80 - 1,80	Humus	1,00	1,05	1,95	0,54	measured
1,80 - 5,50	Sandy silt	3,70	1,61	2,24	0,72	mean (4)
5,50 - 6,50	Silty sand	1,00	1,76	2,26	0,78	measured
6,50 - 11,00	Clayey silt	4,50	1,49	2,12	0,71	mean (2)
11,00 - 18,00	Sandy silt	7,00	1,61	2,24	0,72	mean (4)
18,00 - 37,50	Fine to middle-grained sand	19,50	2,21	2,09	1,06	measured
37,50 - 38,50	Sandy gravel	1,00	2,33	1,92	1,21	analogy (2)
38,50 - 39,80	Clayey silt	1,30	1,37	1,99	0,69	measured
39,80 - 49,00	Course-grained sand with rare silt intercalations	9,20	2,15	2,33	0,69	measured
49,00 - 51,00	Silt with small calcareous concretions	2,00	1,62	2,21	0,73	mean (4)
51,00 - 51,50	Sandy silt	0,50	1,61	2,24	0,72	mean (4)
51,50 - 52,00	Silty clay with small amount of sand	0,50	1,28	2,22	0,58	analogy (2)
52,00 - 53,00	Silt with high organic content, dark brown with a lot of mica	1,00	1,62	2,21	0,73	mean (4)
53,00 - 53,10	Sandy silt with large calcareous concretions	0,10	1,61	2,24	0,72	mean (4)
53,10 - 53,60	Sand, mildly silty, blue-grey	0,50	1,62	2,20	0,73	mean (4)
53,60 - 55,0	Fine blue-grey sand	1,40	1,54	2,24	0,68	measured
55,00 - 57,20	Medium- to course-grained sand	2,20	1,44	1,84	0,78	measured
57,20 - 58,20	Grey silt with small calcareous concretions	1,00	1,62	2,21	0,73	mean (4)
58,20 - 58,60	Sandy silt, grey	0,40	1,61	2,24	0,72	mean (4)
58,60 - 60,00	Silty sand, fine-grained	1,40	1,76	2,26	0,78	measured
60,00 - 65,50	Interchange of silty sand and sandy silt of blue-grey colour with small Mn- and Fe-oxide vains	5,50	1,69	2,25	0,75	mean (2)
65,50 - 71,00	Grey fine- to medium-grained sand with increasing grain size and thin silt intercalations	5,50	1,36	1,94	0,70	measured
71,00 - 73,00	Silt, slightly sandy, brown-grey colour, with calcareous concretions	2,00	1,53	2,24	0,68	measured
73,00 - 73,60	Silt, very sandy	0,60	1,61	2,24	0,72	mean (4)
73,60 - 74,50	Fine-grained grey sand	0,90	1,62	2,20	0,73	mean (4)
74,50 - 78,40	Medium- to coarse-grained grey sand	3,90	1,57	2,28	0,69	measured
78,40 - 78,60	Sandy silt	0,20	1,61	2,24	0,72	mean (4)
78,60 - 79,10	Black peat coal with wood fragments	0,50	1,76	2,15	0,82	measured
79,10 - 79,50	Medium-grained sand with peat fragments	0,40	1,78	2,16	0,81	mean (5)
79,50 - 81,60	Sandy gravel, pebbles up to 1 cm	2,10	2,33	1,92	1,21	analogy (2)
81,60 - 82,0	Silty sand	0,40	1,76	2,26	0,78	measured
82,0 - 83,50	Sandy silt with intervals containing large calcareous concretions	1,50	1,61	2,24	0,72	mean (4)
83,50 - 87,30	Fine-grained sand	3,80	1,62	2,20	0,73	mean (4)
87,30 - 91,20	Medium-grained sand	3,90	2,38	2,42	0,99	measured
91,20 - 91,70	Low-plasticity silt, grey, partially sandy	0,50	1,61	2,24	0,72	mean (4)
91,70 - 93,40	Fine-grained sand, partially silty	2,70	1,81	2,35	0,77	measured
93,40 - 94,00	Medium- to coarse-grained sand	0,60	1,35	1,94	0,69	measured
94,00 - 94,60	Sandy gravel	0,60	2,33	1,92	1,21	analogy (2)
94,60 - 97,0	Silt, sandy intervals, grey calcareous comcretions and fossil snails	2,40	1,61	2,24	0,72	mean (4)
97,00 - 100,00	Clayey silt, high plasticity, calcareous concretions and small Fe-oxide vains	3,00	1,6	2,24	0,72	measured
	CUMULATIVE ALONG BOREHOLE LENGTH		**1,80**	**2,18**	**0,81**	

Core determination has yielded enough data to determine that the sedimentary environment which produced the sediments underlying Osijek was fluvial, more specifically, a meandering river. The sedimentation at the location of the borehole corresponds to the floodplain facies, with the domination of sandy silt and silty sand that account for 85% of the core. Parts of the core are also correspondent with channel deposits (gravel and coarse sand) as well as cut-off meander lakes (peat), but the domination of floodplain deposits determines the overall ground thermal conductivity around B-1 borehole.

As already stated the undisturbed ground temperature was measured without water circulation, meaning no heat gains from friction or pump work. In Figure 6 temperature distribution along upward and downward tube of U-pipe is presented. Negative temperature gradient can be noticed form 10 to 40 meters depth where minimum temperature of 14,29 °C was measured, after that point positive gradient starts. The average undisturbed ground temperature for this borehole is ϑ_0=14,92 °C, or 14,85 °C if the first 10 meters of borehole are neglected due to ambient air influence.

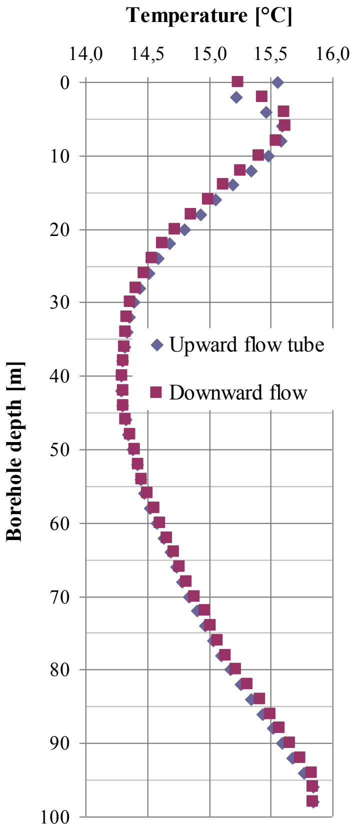


Figure 6: Undisturbed ground temperature profile (location Osijek)

Temperature distribution along the pipe of BHE presented in two different time intervals of DTRT can be seen in Figure 7. Red one represents distribution in the beginning of DTRT, while blue at the end of the DTRT. Shape and pattern of the temperature curves are the same with different absolute temperature values. By evaluating temperature distribution at the end of the DTRT (blue dots) temperature drop in the first 100 m of the borehole of 3,47 °C can be seen, while remaining temperature drop of 2,02 °C is related to the upward flow, as the temperature difference of circulation fluid and undisturbed ground is the greatest at the water inlet and it becomes smaller as the circulating water exchanges heat with ground. In this figure mean fluid temperature along the borehole is also presented. It is easy to see how true average temperature is different in comparison to the estimation of mean temperature when measuring only inlet and outlet temperature of the borehole. Mean fluid temperature profile also suggests that temperature difference between circulation fluid and ground is not constant along borehole heat exchanger or along characteristic sections when taking account of both downward and upward flow.

Ground thermal conductivity and borehole thermal resistance are presented in Figure 8 and Figure 9, respectively. Ground thermal conductivity varies from 1,52 W/(m K) to 2,3 W/(m K), which is in accordance with the results obtained by the experts from the Croatian Geological Survey (Table 3). The difference between thermal conductivity in each sector occurs because of the different soil layer along the borehole. The result of averaging all the sectors results is equal to 1,93 W/(m K).

Similar results of ground thermal conductivity obtained via direct measurement (Table 3) and distributed thermal response test (Figure 8) are very encouraging. The discrepancy of 11% between the two methods can be attributed to various reasons. Firstly, the direct measurement includes a small volume of the sediment for a short period of time in comparison to TRT. Secondly, it is impossible to get the core out of the borehole with its original water content due to drilling technology and mud infiltration. The third reason is the inability to measure thermal parameters momentarily after the core is taken out (only one instrument, not enough field days) so some part of the water content inevitably evaporates. There are also problems related to the field measurement devices: the assessment of thermal contact quality, temperature fluctuations and non-homogeneity and anisotropy of the measured material sample. Adding to that, each device included in different measurement technique has its own source of error.

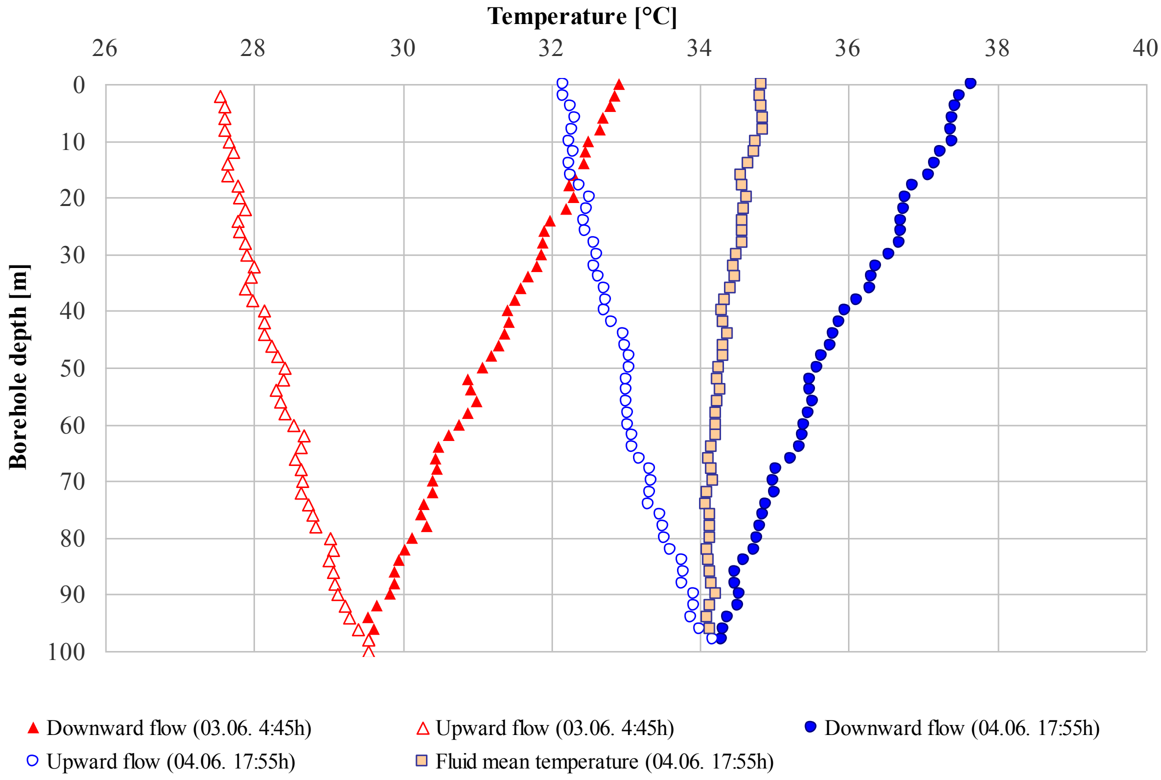


Figure 7: Temperature distribution along borehole during the DTRT

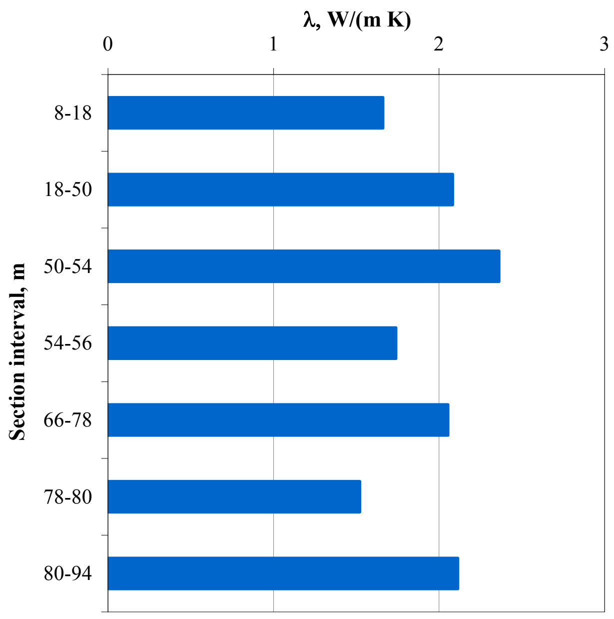


Figure 8: Thermal conductivity of the ground

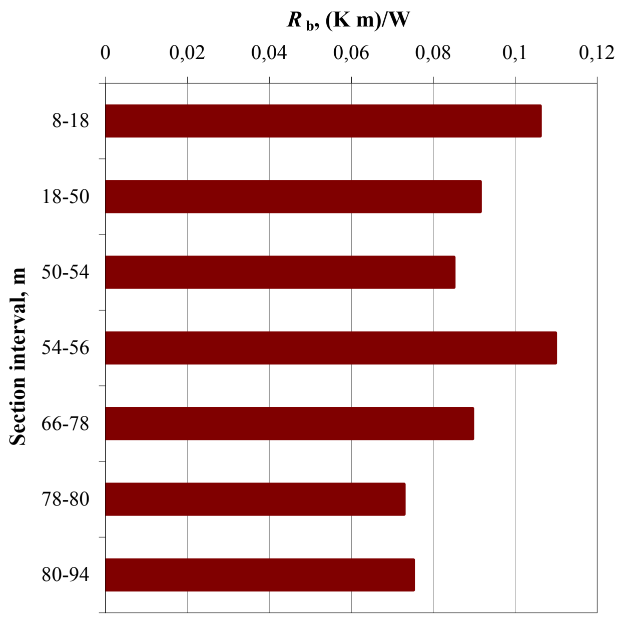


Figure 9: Borehole thermal resistance

The result obtained with DTRT is compared to the result obtained with TRT. Accordingly, resulting ground thermal conductivity measured with TRT is 1,92 W/(m K). Deviation between TRT and DTRT is less than 1% which is consistent with the results of other researchers (Acuna et al., 2008).

Figure 9 represents borehole thermal resistance for the location Osijek. As thermal conductivity, borehole thermal resistance varies along the borehole with minimum of 0,073 (K m)/W and maximum of 1,09 (K m)/W. The average borehole resistance is 0,900 (K m)/W.

Comparing results from DTRT to results obtained with TRT (R_b=0,0932 (K m)/W), it is possible to conclude that deviation is less than 4%. The results obtained are lower than the one obtained with TRT, which can suggest that conventional Thermal Response Test overestimates borehole thermal resistance. This can be explained with different principles of the two tests. While one test takes into account "real undisturbed temperature" and data processing is done for each segment, the other uses average undisturbed temperature and data processing is done for the whole borehole.

5. CONCLUSION

Thermal parameter values measured for sediments in B-1 Osijek are characteristic for a sedimentary environment which the core uncovered. All of the parameters are within the boundaries of worldwide reported values for such deposits. The sedimentary environment of meandering river is not appropriate for ground thermal properties prediction due to its lateral variability. On the other hand, predominance of sandy silt and silty sand with similar thermal properties makes the extrapolation more reliable. The data on thermal properties of characteristic sediments at depth usually considered for BHE utilization are now collected and can be used for the prediction of ground thermal properties in this area for smaller BHE installations with due caution. For larger scale utilization it is recommended to use thermal response test and not an analogy.

The methodology of distributed thermal response test was presented in this paper and the comparison of results gathered by conventional TRT and DTRT shows good agreement, while TRT slightly overestimates borehole thermal resistance (by 4% percent). Also, the main difference between the two procedures regarding temperature measuring and temperature profile was presented as the possible error of the estimation of mean temperature and undisturbed ground temperature based only on measuring inlet and outlet temperatures in conventional TRT.

NOMENCLATURE

ϑ_f - fluid temperature [°C]

ϑ_o - undisturbed ground temperature [°C]

q - heat injection rate per length of the borehole [W/m]

λ - thermal conductivity of the soil [W/(m K)]

a - thermal diffusivity of the ground [m^2/s]

t - time [s]

r - radial distance [m]

y - Eulers constant [≈0,5772]

R_b - borehole thermal resistance [K m/W]

v - volumetric flow rate [m^3/s]

ρ - fluid density [kg/m^3]

c - specific heat capacity [J/(kgK)]

$\Delta\vartheta_s$ - section fluid temperature difference [°C]

REFERENCES

Acuña, J., Palm, B.: A novel Coaxial Borehole Heat Exchanger: Description and First Distributed Thermal Response Test Measurements, Proceedings World Geothermal Congress 2010, Bali, Indonesia, (2010).

Acuña J, Palm B. 2008, Characterization of boreholes – results from a U pipe borehole heat exchanger installation, *9th IEA Heat Pump Conference*, Zurich (2008)

Acuña, J., Mogensen, P., Palm, B.: Distributed thermal response test on a U-pipe borehole heat exchanger, The 8th IIR Gustav Lorentzen Conference, Copenhagen (2008)

Carslaw, H.S., Jaeger, J.C., Conduction of heat in solids, Clarendon Press, (1959), Oxford.

Esen H., Inalli M., Esen Y. 2009, Temperature distributions in boreholes of a vertical ground-coupled heat pump system, *Renewable Energy* 34, 2672–2679

Fujii, H., Okubo, H., Itoi, R.: Thermal Response Tests Using Optical Fiber Thermometers (Journal) – Kyushu University, Fukuoka. GRC Transactions - Vol 26, 2006

Fujii, H., Okubo, H., Nishi, K., Itoi, R., Ohyama, K., Shibata, K.: An improved thermal response test for U-tube ground heat exchanger based on optical fiber thermometers, Geothermics, 38, (2009), 399-406.

Gao Q., Yu M., Qiao G., Li M., Jiang Y. 2006, Enhanced heat transfer for vertical borehole ground heat exchangers, *ECOSTOCK 2006 Conference Proceedings*

Gehlin, S., 2002, Thermal Response Test – Method Development and Evaluation, Doctoral Thesis, Luleå University of Technology, Sweden

Gehlin, S., Hellström, G., 2003, Influence on Thermal Response Test by Groundwater Flow in Vertical Fractures in Hard Rock, Renewable Energy 28, pp. 2221-2238

Ingersoll, L.R., Plass, H.J.: Theory of the Ground Pipe Heat Source for the Heat Pump, Madison Wis, ASHVE Transactions, Vol.54, (1948)

Prelovšek, P., Uran, B., Generalised hot wire method for thermal conductivity measurements, *Journal of Physics E: Scientific Instruments*, **17**, (1984), 764-677.

Ruševljan, M., Soldo, V., Ćurko, T.: Optimal sizing of borehole heat exchangers, Strojarstvo 51 (2009), 5; 473-480

Sanner, B. et al., 2005, Thermal Response Test – Current Status and World-Wide Application, Proceedings World Geothermal Congress, 24-29 April, Antalya, Turkey

Sanner, B. et al., 2007, Technology, Development Status, and Routine Application of Thermal Response Test, Proceedings European Geothermal Congress, 30 May - 1 June, Unteraching, Germany

Soldo, V., Ruševljan, M., Grozdek, M, Ćurko, T.: Impact of the Ground-Source Heat Pump Running Time Duration on the System Efficiency // CD Proceedings of the 23rd IIR International Congress of Refrigeration, Prag, (2011)

Soldo, V.; Rusevljan, M., Curko, T., Grozdek, M.: Ground-source heat pump with a 100 m deep borehole heat exchanger – start up and first results // IIR/Eurotherm Sustainable Refrigeration and Heat Pump Technology Conference, Stockholm: KTH (2010)

Soto, M. A., Sahu, P. K., Faralli, S., Sacchi, G., Bolognini, G., Di Pasquale, F., Nebendahl, B., Rueck, C.: High performance and highly reliable Raman-based distributed temperature sensors based on correlation-coded OTDR and multimode graded-index fibers, *Proc. SPIE* 6619, Third European Workshop on Optical Fibre Sensors, Napoli (2007)