http://dx.doi.org/10.7494/drill.2017.34.2.495

Tomasz Śliwa*, Marek Kucper**

ACCESSING EARTH'S HEAT USING GEOTHERMAL RADIAL DRILLING FOR BOREHOLE HEAT EXCHANGERS***

1. INTRODUCTION

The foundation for proper designs of heating-and-cooling systems based on borehole heat exchangers is their effective thermal conductivity λ_{eff}. The value relies mainly [1] on the geological structure of a given region – the value of thermal conductivity of particular layers to be exact. It is sufficient for the initial recognition and determination of the average thermal conductivity to use the method based on data taken from literature, wherein effective conductivity is determined as a weighted average in relation to particular layers of a given profile:

$$\lambda_{eff} = \frac{\sum (l_i \cdot \lambda_i)}{\sum l_i} \tag{1}$$

where:

λ_i – thermal conductivity of a given layer, W/(m·K),

l_w – length of the exchanger in a given layer, m.

In order to optimize the average thermal conductivity and use these layers in a given geological profile which have best properties in the view of thermal efficiency, Geothermal Radial Drilling (GRD) is applied in drilling slant boreholes.

* AGH University of Science and Technology, Faculty of Drilling, Oil and Gas, Krakow, Poland

** SZRB-W "EURO-WIERT" Sp. z o.o., Tarnobrzeg, Poland

*** The paper was created within statute studies at the Faculty of Drilling, Oil and Gas at AGH University of Science and Technology in Krakow, Poland. Grant No. 11.11.190.555

Constructing GRD BHEs, i.e. BHEs starting from one place and branching out radially at different angles, enables the access to a sizeable rock mass area, which may be located even under buildings. Additionally, concentration of BHE outlets in one spot facilitates good heat carrier distribution control. A GeoDrill 4R drill rig, specially designed for the GRD technology, enables drilling boreholes at an angle of 30–65 degrees (GeoDrill 8R has the range of 30–90 degrees). Thanks to this and the knowledge of the geological profile, it is possible to design the layout of exchangers so as to ensure that the longest section of the exchanger is located in most energetic layers. Depending on their length and angle (normally 40–50 m), GRD exchangers can collect not only geothermal but also solar energy accumulating in the upper zone of the rock mass.

2. PROCESS OF CONSTRUCTING SLANT BHEs

The process of constructing slant BHEs already begins with the designing stage. Every project should be studied individually, including the recognition of the geological structure of a given region, the design of boreholes and optimization of the construction of boreholes in reference to energy efficiency. However, the drilling process itself and construction of slant exchangers consists of the following stages:

1. Installation of a drilling chamber DN 1000 in the area of planned boreholes (Fig. 1).
2. Preparation (Fig. 2) and setting the drill rig on the chamber (Fig. 3), disconnection of the drill rig carrier from the driving unit (Fig. 4) and setting the proper drilling angle (Fig. 5).
3. Depending on the geological structure and hydrogeological conditions, while the equipment is being prepared for works (Fig. 6), drilling is made with casing (Fig. 7) or done with the drilling string alone (Fig. 8). It is also possible to apply a down-the-hole hammer in very difficult working conditions.
4. If drilling was done without casing, having reached the assumed depth MD and made sure that walls of the borehole are stable, the drill string is pulled out and exchanger tubes are inserted with the use of an uncoiler (Fig. 9).
5. Next the annulus is sealed with filling slurry of increased thermal conductivity using the underwater concreting, generally known as the Contractor method. Once the annulus is filled, casing pipes are pulled out of the borehole.
6. Further BHEs are drilled according to the scheme given above.
7. The last stage is another leakage test of exchangers, closing the wells with wellheads, installation of distributors coupled with necessary fixtures (Fig. 10) and filling the whole installation with working fluid.

Fig. 1. A drilling chamber with a ring mounted onto it.
Two connecting tubes are visible inside [2]

Fig. 2. Preparation prior to the integration of the drill rig carrier
and the drilling chamber [2]

Fig. 3. Setting the drill rig onto the chamber [2]

Fig. 4. The driving unit and the drill rig [2]

Fig. 5. An angle gauge set to the transporting position [2]

Fig. 6. Equipment ready for drilling [2]

Fig. 7. Casing pipes with a drilling crown [2]

Fig. 8. Drilling without casing pipes with a preventer [2]

Fig. 9. Inserting the exchanger with an injection pipe [2]

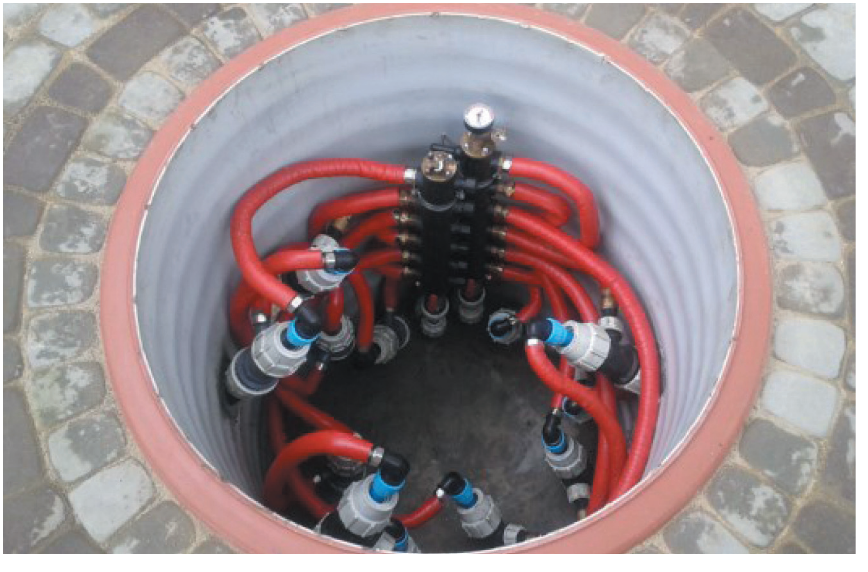

Fig. 10. A ready chamber with a complete installation [2]

3. STRUCTURE OF GRD BHEs

The number of exchangers influences the heating power transferred from or to the rock mass in given temperature conditions, but the operation of exchangers is influenced by their structure [3]. GRD technology utilizes construction solutions based on the coaxial schematic using a right circulation of the fluid (Fig. 11). The outer (casing) pipe has diameter $D = 63$ mm, while the inner (centric) has diameter $d = 32$ mm. Cold working agent flows down the inner tube and enters the outer channel at the bottom, receiving heat from the rock mass while flowing up. Direct contact between the edge of the outer pipe and the rock mass facilitates intensive heat exchange. Changing the diameters of channels may also change the character of the flow from turbulent to laminar, which facilitates lower hydraulic resistivity and energy savings spent on the pump in comparison to a U-tube [4].

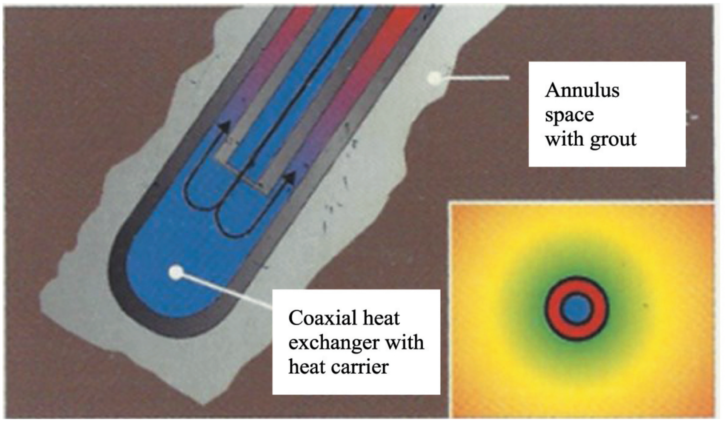

Fig. 11. Coaxial pipe (Tracto-Technik GmbH&Co)

In coaxial BHEs, the best option is to use a whole pipe string, without links, ending with a rounded shoe, since it facilitates insertion of tubes. A useful tool for inserting such pipes is a specialist uncoiler, which allows for insertion straight from spools. It is not necessary to straighten the whole section; straightening first few meters is enough to facilitate guidance. When this kind of uncoiler is applied, the shoe does not need to act as weights.

4. DETERMINING THE NUMBER OF GRD EXCHANGERS

The construction of a BHE must always account for the geological structure and hydrogeological conditions. Installations designed exactly the same way but located in two different areas which have different geological structure will operate at a different efficiency. To ensure a sufficient thermal power at the initial stage of investment, good geological research is indispensible. Based on geological information amassed in many data bases as well as through modern research techniques, one may quite accurately define the geological profile and depths at which aquifers are present.

Also, while determining unit thermal efficiency q for a GRD exchanger, it is advisable to carry out geological research and calculate the average value of the thermal conductivity of the rock mass λ as weighted average in relation to particular layers of a given profile. The dependence between the unit thermal efficiency q and the weighted average of thermal conductivity of the rock mass λ, according to Barthel, is described by formulae [5]:

$$q = 20\lambda_{eff} \quad \text{for} \quad 1 < \lambda_{eff} < 3 \tag{2}$$

$$q = 13\lambda_{eff} + 10 \tag{3}$$

where:

- λ_{eff} – effective thermal conductivity of the whole profile accessed with borehole, W/(m·K),
- q – unit thermal power exchanged between the rock mass and the heat carrier, W/m.

Knowing the geological profile and values of the thermal conductivity of rocks, the share of particular layers is determined. It relates to the length of the borehole in a given layer l_w. Then, the weighted average of thermal conductivity of rocks of the profile λ_{eff} is determined. Next, in reference to the calculated λ_{eff}, the average unit thermal efficiency q is calculated.

When defining the share of layers, one should set the angle of the drill rig so as to take into consideration layers of highest thermal conductivity. The device should be set in such a way so as to ensure highest possible contribution of most beneficial layers.

If the standard time of operation of a heat pump compressor T_{SP} exceeds 2000 h/year, the length of the exchanger should be proportionately extended by Δl_w, taking into consideration heat regeneration in the rock mass.

Other parameters which influence the total length of exchangers and number of boreholes are the heating power of the heat pump Q_h (most frequently, the nominal parameters are B0/W35), the coefficient of performance (COP) and, resulting from the abovementioned parameters, the cooling power Q_c.

The total length of boreholes is calculated as follows:

$$L_b = \frac{Q_c}{q} \tag{4}$$

where:

- L_b – total depth of boreholes, m,
- q – unit thermal power exchanged between the rock mass and the heat carrier, W/m,
- Q_c – cooling power of the heat pump, W.

If time of operation of the compressor is more than 2000 h/year, Δl_w is introduced and the total length of boreholes L_n is calculated accordingly:

$$L_n = L_b \cdot \left(1 + \frac{\Delta l_w}{100}\right) \tag{5}$$

The value of the total length of boreholes consists of length of single boreholes, e.g. 40 or 50 meters, depending on which length will be more beneficial, taking into consideration the geological profile, time of drilling works and costs. Drilling 4 boreholes 50 m deep each is more economically sound than 5 boreholes 40 meters deep each. It should be stated that boreholes at different angles have different unit power q.

One starting chamber can normally accommodate 18 exchangers. Depending on the number of designed BHEs, the depth of a starting chamber varies between 1.0 to 2.0 m. In the case of larger installations, where exchangers would be placed in two or more starting chambers, they should be located at the right angle to directions of groundwater flows. Additionally, one should pay attention while designing the layout of exchangers so as to avoid probable collision of boreholes from different chambers.

5. POTENTIAL CAPACITIES OF GRD BHEs IN ACCESSING EARTH'S HEAT

The assumptions of drilling technology and accessing Earth's heat with GRD exchangers were studied and perfected for in Germany for a few years. To truly use their potential, proper knowledge and experience is indispensible.

To present potential capacities of GRD heat exchangers, an example from industrial practice is presented below. It compares designed vertical boreholes and potential GRD exchangers.

The analyzed boreholes were designed in Czerwony Dwór (Warmińsko-Mazurskie voivodeship). The total heat demand for the building was ca. 75 kW. The lithological profile of the designed boreholes was deduced based on a profile of a wellbore developed in Czerwony Dwór forest district and a borehole in the premises of a former state farm, Szwałk. The geological cross-section of the location devoted to the designed investment is presented in Figure 12.

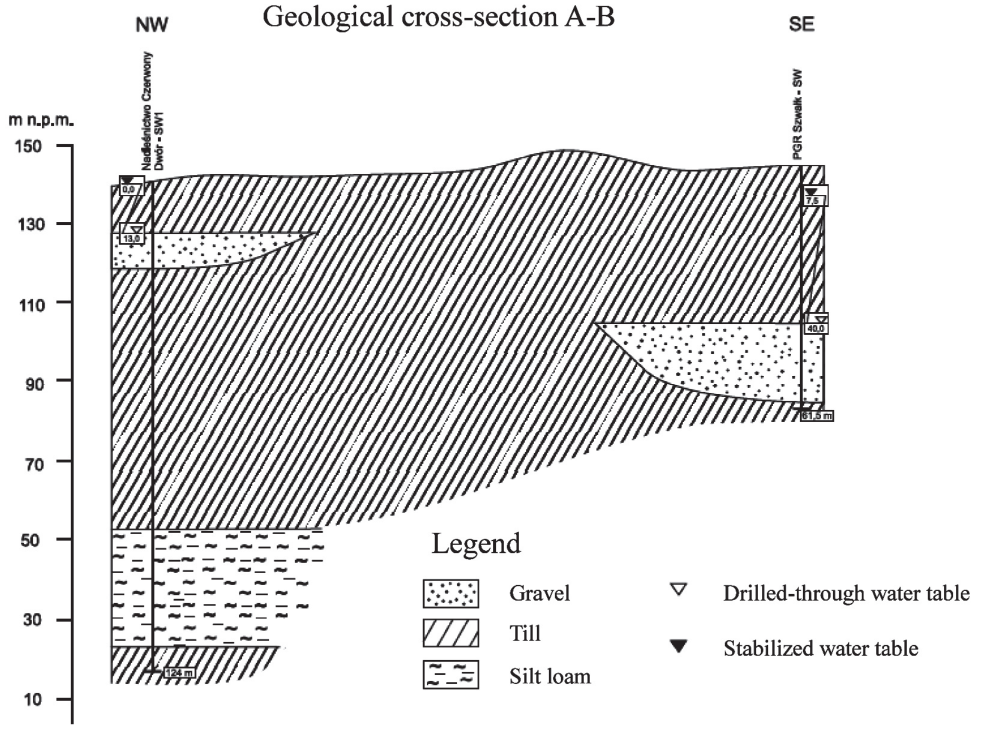

Fig. 12. Geological profile based on two boreholes [6]

For the calculation of the total length of BHEs, heat demand was assumed as $Q_h = 75$ kW, while the efficiency coefficient of the heat pump as $\text{COP}_h = 3.5$. The unit heating efficiency of the BHE was determined as $q = 30.8$ W/m. The total length/depth of BHEs can be calculated with formula (4), knowing that:

$$Q_c = Q_h \cdot \frac{\text{COP}_h - 1}{\text{COP}_h} = 53.6\ \text{kW},$$

$$L = \frac{53{,}600}{30.8} = 1738.6\ \text{m}.$$

The total length of the vertical BHE resulting from the calculations amounted to 1738.6 meters. Hence, 18 boreholes 99 m deep each was set for construction (Fig. 13).

Geological and technical project
of the borehole for vertical exchangers in a heat pump system
at plot No. 3176/1 in Czerwony Dwór, Kowale Oleckie
[repeatable project for 18 boreholes]

Terrain ordinate: ca. 140 m above sea level

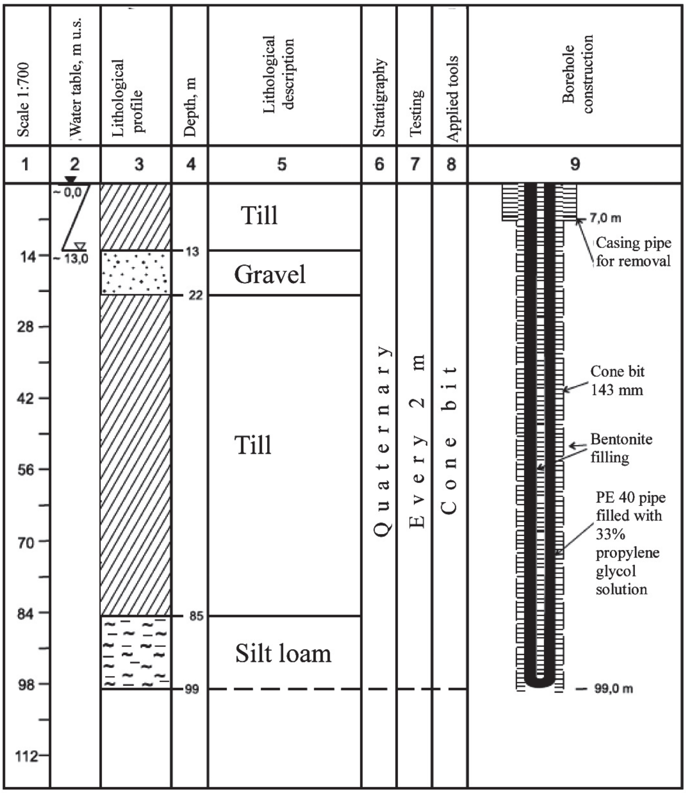

Fig. 13. Geological and technical project of a 99 m deep borehole for geothermal heat production [6]

If GRD exchangers were taken into consideration in the described investment, first step would be to analyze the lithological profile and to plan the layout and angles of exchangers. In the presented profile, the most energetically beneficial layer is the watered layer made of gravel whose real thickness is 9.00 m, and its top is at 13.00 m below ground. The water table is tense and stabilizes on the depth of 0.0 m. The value of the thermal conductivity coefficient for the layer was determined as λ =2.40 W/(m·K), which translates into unit power of ca. q = 45 W/m of thermal efficiency.

The layer of gravel of real thickness equal to 9.00 m allows for only 405 W if vertical BHEs are used. If the same layer is drilled through at the angle of 65 degrees and an exchanger is placed within, the active length of heat exchange (apparent thickness) in the layer rises from 9.00 m to 9.93 m (which gives 467 W), while at the angle of 35°, the length expands even more, to 15.69 m (which offers 706 W). Table 1 shows in detail the calculations presented above, supplying additional variant of a borehole at the angle of 50°.

Table 1

Thickness of particular layers depending on the angle of drilling and their effective thermal conductivity

Lithology	Thermal conductivity, λ, W/(m·K)	Thickness in a vertical borehole 99 m depth, m	Thickness in a GRD borehole 40.0 m depth, m		
		Angle of the borehole in reference to horizon			
		90°	65°	50°	35°
Till	2.0	13.00	14.40	16.70	22.70
Watered gravel	2.4	9.00	9.90	11.60	15.60
Till	1.6	63.00	15.70	11.70	1.70
Dry silt loam	0.4	14.00	0.00	0.00	0.00
Total depth/length	m	99.00	40.00	40.00	40.00
Average effective conductivity λ_{av} in the borehole	W/(m· K)	1.56	1.94	2.00	2.14
Unit heating power, q	W/m	30.8	35.22	36	37.82

The weighted average of the thermal conductivity coefficient rises from 1.56 W/(m·K) for vertical exchangers, through 1.94 W/(m·K) slant exchangers at 65° and 2.14 W/(m·K) in case of 35W/(m·K).

The example shows, that even in regions where the geological structure is unfavorable and thermal conductivity of rocks is low, it is possible to use a heat reservoir more effectively, in the form of underground thermal energy storage (UTES).

For the examined example, the cooling power demand is 53.6 kW. Based on the values (Tab. 1), Table 2 presents the necessary length of slant exchangers.

As visible above, if slant drilling is applied and BHEs are at different angles, which in turn makes the active length of the exchanger bigger in layers of best thermal conductivity, the total length of drilling is lower than in the case of vertical exchangers.

Table 2

Total length of slant BHEs depending on the angle of drilling

Drilling angle	Total BHE length demand, m
35	1246,50
40	1276,19
45	1285,37
50	1291,56
55	1294,68
60	1300,97
65	1307,32
90	1468,49

When compared to the total length of the designed vertical drilling, depending on the angle, the length of GRD is lower by 431 m in case of 65°, whereas 492 m in case of 35°. In sizeable installations, such as the studied one, the real length is a value averaged between two extreme values, because exchangers are installed in the starting chamber alternately at given angles.

What is more, when comparing lengths calculated based on the average thermal conductivity of the profile (Tabs 1 and 2), shorter distance is necessary to ensure a proper heating power in the case of slant drilling. This time, however, the values are not as big as above, but still significant – 222–161 meters.

The example presented above shows how to influence maximal heat collection from Earth, and consequently how to decrease installation and exploitation costs.

Designers of one of biggest GRD investments in Poland, at the newly built MoonOffice in Krakow, were also put to a test. Given the small room available, limitations related to land ownership, deep sheet piles and an underground garage, it was possible to design an initial project of a lower source with the assumed power of 186 kW. GRD exchangers will be placed in four starting chambers and their total length will amount to 4650 m. Drilling from two chambers is planned to be carried out from surface, whereas the remaining two will be placed 3.0 m below ground. To achieve the planned power, it was necessary to use the rock mass under the analyzed building, whose deeply set foundation and near borders with adjacent plots prevented works on the surface. Figure 14 presents a ground plan of GRD boreholes designed for this investment.

Another practical application of slant exchangers is transfer and storing thermal energy originating in asphalt roads, which heat up through most of the year, and especially in summer [7]. Constructing BHEs radially from one place at different angles would do perfectly at many roundabouts, both in cities and on routes. A series of GRD exchangers could be constructed, starting in the chamber that would be placed in the middle of the roundabout, which is mostly not used for anything. They would collect thermal energy to supply heating demands of other facilities.

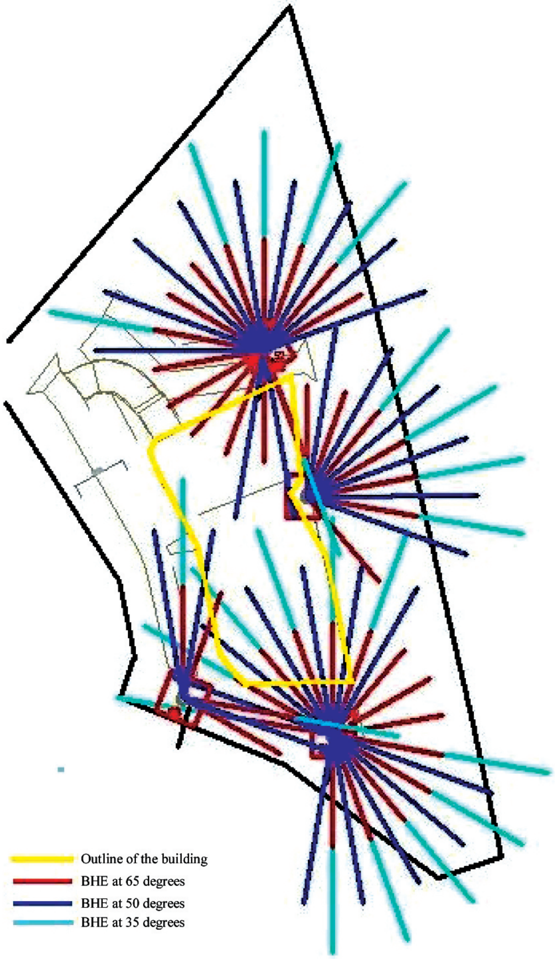

Fig. 14. Layout of exchangers [2]

6. EXAMPLES OF GRD APPLICATION IN LOCATIONS WHERE CONVENTIONAL BHEs WOULD NOT SUFFICE

In the case where identical conditions are at disposal and it does not matter whether vertical or slant BHEs are at hand but there is a lack of terrain necessary to maintain proper distance between exchangers, GRD solutions are very useful. Such a problem had been foreseen and solved. Thanks to its compact size, the GeoDrill 4R drill rig enables drilling in dense urban infrastructure, while the ability to detach the driving unit from the drill rig allows for carrying out works inside buildings, houses (basements, garages). An additional advantage, and thus very important to the investor, is that exchangers drilled and installed from one chamber of DN1000 located in a house are treated as an indoor installation, and so they are subject to only 8% VAT, not 23% as it is in the case of outdoor boreholes. Many indoor boreholes were made in Germany, however, such operations took place also in Poland, e.g. for a 150 m^2 residential building in Podlaskie voivodeship, 8 slant BHEs were made, amounting to total length of 300 running meters (Fig. 15). Currently, works are being conducted on another investment, in which the boreholes will be carried out in a garage in Tyniec.

Fig. 15. Preparation prior to drilling in a garage (OPTIMA POLSKA 2015)

Another example is slant boreholes in Padwa Narodowa, Podkarpackie voivodeship. The only location where BHEs could be made in the premises of a coal depot was a narrow wooded area, which plays the role of an anti-dust barrier. Given the fact that a heavy drill rig could not enter the wooded area, the investor chose GRD boreholes. Because the GeoDrill 4R drill rig is a small device and boreholes can be carried out from one spot, preparation and drilling was completed without cutting trees (Fig. 16). 10 BHEs were made and their total length is 400 running meters.

a) b)

Fig. 16. Transport of the drilling rig through a forest (a) and its operation (b) [2]

7. CONCLUSIONS

1. In low temperature heat source installations using GRD technology, heat from the rock mass is used. The share of the geothermal heat rises along with the depth of the exchanger. Solar radiation dominates in near-surface layers. The rock mass can act as a heat storage, receiving and emitting thermal energy cyclically.
2. The depth of periodic heat penetration into the rock mass is normally higher in urban areas than in rural areas. Asphalt roads, pipelines and squares cause additional heat transfer into the rock mass, thus more heat can be produced.
3. GRD slant drilling allows for reaching heat reservoirs in the rock mass under buildings, roads, in dense urban infrastructure and inside buildings.

4. Coaxial exchangers used in GRD operate in the normal (right) circulation. Hence, the exchanger can transfer heat to the rock mass more efficiently; the circulation does not influence the operational efficiency while energy production, thus using the exchanger for either production or storage does not necessitate change in the direction of the heat carrier's flow.
5. Proper selection of angles of the drilling rig in GRD allows for using the full thermal potential of the rock mass, by installing exchangers in layers of best thermal conductivity.

REFERENCES

[1] Śliwa T.: *Badania podziemnego magazynowania ciepła za pomocą kolektorów słonecznych i wymienników otworowych* [*Research on underground thermal energy storage by use solar collectors and borehole heat exchangers*]. Wydawnictwa AGH, Kraków 2012, p. 272.

[2] Kucper M.: *Pozyskiwanie ciepła Ziemi z otworowych wymienników ciepła wykonanych w technologii GRD*. Master Thesis, Faculty of Drilling, Oil and Gas, AGH University od Science and Technology, Krakow 2016, p. 90.

[3] Śliwa T., Gonet A.: *Analiza efektywności wymiany ciepła w wymiennikach otworowych o różnej konstrukcji*. Wiertnictwo Nafta Gaz, vol. 28, No. 3, 2011, pp. 555–570.

[4] Gonet A. (ed.), Śliwa T., Stryczek S., Sapińska-Śliwa A., Jaszczur M., Pająk L., Złotkowski A.: *Metodyka identyfikacji potencjału cieplnego górotworu wraz z technologią wykonywania i eksploatacji otworowych wymienników ciepła* [*Methodology for the identification of potential heat of the rock mass along with technology implementation and operation of the borehole heat exchangers*]. Wydawnictwa AGH, Kraków 2011, p. 439.

[5] Barthel P.: *Grundsätliche Überlegungen zur regionalenhydrogeologischen Beurteilung von Standorten für den Eisatz von Erdwärmepumpen*. Hydrogeologie und Umwelt, Heft 33, Würzburg, 2005.

[6] Tatarata M., Stadie E.: *Projekt robót geologicznych w celu wykorzystania ciepła ziemi dotyczących wykonania 18 otworów wiertniczych dla potrzeb instalacji kolektorów pionowych w układzie pompy ciepła na dz. Nr 3176/1 w Czerwonym Dworze*.

[7] Śliwa T., Rosen M.A., Poniedziałek M.: *Use of heat from a snow melting installation in a parking lot surface as a heat regeneration source for underground heat storage via borehole heat exchangers. eSim 2016 Hamilton, Ontario, May 3rd to 6th Conference proceedings,* McMaster University Engineering, Canada 2016, p. 247–256 http://esim.mcmaster.ca/index.php/2016/index/pages/view/program.